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March 26, 2003

Organizers:

H. En'yo, M. Hayakawa, H. Kawai, N. Saito, T.-A. Shibata, T. Tada, Y. Watanabe, and K. Yazaki

Nishina Memorial Hall of RIKEN
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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

During the first year, the Center had only a Theory Group. In the second year, an Experimental Group was also established at the Center. At present, there are seven Fellows and seven Research Associates in these two groups. During the third year, we started a new Tenure Track Strong Interaction Theory RHIC Physics Fellow Program, with six positions in the first academic year, 1999-2000. This program had increased to include ten theorists and one experimentalist in academic year, 2001-2002. With recent graduations, the program presently has eight theorists and two experimentalists. Beginning last year a new RIKEN Spin Program (RSP) category was implemented at RBRC, presently comprising four RSP Researchers and five RSP Research Associates. In addition, RBRC has four RBRC Young Researchers.

The Center also has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are fifty-two proceeding volumes available.

The construction of a 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998. A 10 teraflops QCDOC computer in under development and expected to be completed in JFY 2003.

T. D. Lee
November 22, 2002

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

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Introduction

The RIKEN School on QCD titled "Topics on the Proton" was held on March 26th, 2003 at the Nishina Memorial Hall of RIKEN, Wako, Saitama, Japan, sponsored by RIKEN (the Institute of Physical and Chemical Research). The school was the third of a new series with a broad perspective of hadron and nuclear physics.

The organization and the size of the school were a little different from those of the previous ones.

Prof. John Ellis, known as the world best theorist in particle and nuclear physics, has been appointed in RIKEN as an Eminent Scientist, which enables us to plan a collaboration with him for coming three years. As the first year activity, we asked him to give a keynote talk in the JPS spring meeting focussing on the structure of proton, and also to give lectures in RIKEN for younger Japanese scientists on the subjects related the structure of the proton. He kindly agreed on both and we then decided to have a one-day school by supplementing his course with a course on experimental aspects of the proton structure. One of us (N.S.) agreed to give the latter.

This time, Theoretical Physics Laboratory joined Radiation Laboratory to organize the school.

The purpose of the school was to offer young researchers an opportunity to learn theoretical aspects of the proton structure with a broad perspective including supersymmetry and the related experimental aspects.

We had a theoretical course consisting of 3 one-hour lectures by Prof. Ellis and a experimental course consisting of 2 one-hour lectures by Prof. Saito. The titles of their lectures are given below.

Lecturers

J. Ellis (CERN/RIKEN)	"From the Mass and Spin of the Proton to the Dark Matter in the Universe"
N. Saito (Kyoto Univ.)	"Physics with the Precise Measurements of the Proton Spin Structure"

At the beginning of his first lecture, Prof. Ellis informed us of the sad news about Prof. Vernon Hughes and he dedicated his lectures to the memory of Prof. Hughes. Totally 46 participants including 20 graduate students attended the school. The titles as well as the lecturers attracted not only young researchers but also relatively senior ones, who contributed greatly to activating and clarifying the discussions.

The lecturers gave excellent courses which were both pedagogical and inspiring. The two courses, one theoretical and one experimental, matched nicely, giving a broad but unified perspective of the proton structure. There were relatively long intervals between the lectures and the lecturers were kind enough to talk to students and respond to their questions during the breaks.

We are grateful to RIKEN for the financial support which enabled us to organize this school. The school was held as an activity related to the collaboration with the RIKEN-BNL Research Center and we thank the director of the Center, Professor T.D. Lee, for the approval of publishing this proceedings as a volume of the RBRC Workshop Proceedings Series and general support. We are obliged to the lecturers and the students, both young and senior, for making the school exciting and fruitful.

Special thanks are due to Ms.N. Kiyama and Ms.K. Sakuma, who did most of the administrative works and took care of drinks and snacks during the breaks, and Dr.M. Hirai, who prepared the poster of the school.

Hideto En'yo, Masashi Hayakawa, Hikaru Kawai, Naohito Saito
Toshi-Aki Shibata, Tsukasa Tada, Yasushi Watanabe and Koichi Yazaki

RIKEN,
June, 2003

From the Mass and Spin of the Proton to the Dark Matter in the Universe

John Ellis

Theory Division
CERN
Geneve, Switzerland

Abstract

The naive non-relativistic quark model works very well to describe the hadron spectrum and some decays, but it has never been derived from QCD. It is thought that the u, d and s quarks weigh much less than the typical QCD scale, leading to an approximate chiral symmetry in low-energy dynamics. According to this picture, baryons should be described by solitons, as in the Skyrme model. The predictions of the naive non-relativistic quark model do not work very well for polarized structure functions, whereas the chiral soliton model successfully predicts a small net contribution of quarks to the baryon spin. An alternative interpretation invoking polarized gluons may be tested in the forthcoming polarized RHIC and COMPASS experiments. If the baryon wave function contains s quarks, as suggested by the chiral soliton model and by measurements of polarized structure functions, these may also manifest themselves via production of phi mesons in excess of the naive Okubo-Zweih-Iizuka rule, as reported in several experiments at CERN's LEAR ring. Polarization of the s quarks in the baryon wave function may reveal itself in the polarization of Lambda baryons produced in deep-inelastic neutrino, muon and electron scattering, measured in the NOMAD, COMPASS and HERMES experiments. As an example of the possible importance of s quarks in the baryon wave function for searches for physics beyond the Standard Model, we note that s quarks influence theoretical predictions of the matrix elements for the scattering of supersymmetric relic particles on nuclei. The constraints from searches for supersymmetric particles at LEP and elsewhere can be combined with calculations of the supersymmetric relic density and WMAP limits on it to suggest that supersymmetric relic particles may be detectable in forthcoming experiments.

From the Mass & Spin of the Proton

- to the Dark Matter in the Universe

1 - Models of Nucleons confront data
non-relativistic quark model vs soliton
deep-inelastic scattering

2 - How strange is the nucleon?
'violations' of the OZI rule
Λ production to probe s polarization

3 - Nucleon structure and supersymmetry
searches at colliders
searches for supersymmetric dark matter

dedicated to the memory of

Vernon Hughes

1.1 Ideas about Nucleon Structure

Non-relativistic quark model

$$|p\rangle = |u\,u\,d\rangle \quad , \quad |n\rangle = |u\,d\,d\rangle$$

nucleons each contain 3 slow-moving quarks

$$m_N \simeq 3 m_q \quad : \quad m_q \simeq 300 \text{ MeV}$$

naïve decomposition of nucleon spin:

$$|p_\uparrow\rangle = |u_\uparrow u_\uparrow d_\downarrow\rangle + \cdots\cdots \quad \leftarrow SU(6) \text{ wave function}$$

many phenomenological successes:

spectroscopy, transition matrix elements, ..

can be 'improved' with perturbative QCD

$$q \to q + g, \quad g \to \bar{q} + q$$

BUT

Never derived from QCD

QCD Lagrangian

$$\mathcal{L}_{QCD} = \mathcal{L}_{YM} - \sum_{q=1}^{N_f} (\bar{q}_L \not{D} q_L + \bar{q}_R \not{D} q_R) - \underbrace{\sum_{q=1}^{N_f} m_q (\bar{q}_L q_R + \bar{q}_R q_L)}_{\text{how big are these?}}$$

is invariant under chiral transform^{ns}:

$$q_L \to U_L q_L \,, \quad q_R \to U_R q_R$$

unitary

apart from

symmetry group:

$$SU(N_f)_L \times SU(N_f)_R \times U(1)_B = \underset{\text{broken non-perturbatively}}{L+R} : L-R$$

non-perturbative dynamics breaks chiral symmetry spontaneously:

$$\langle 0 | \bar{q}_L q_R + \bar{q}_R q_L | 0 \rangle \neq 0 \quad \leftarrow \text{quark condensate}$$

$$SU(N_f)_L \times SU(N_f)_R \times U(1)_B \to \underset{L+R}{SU(N_f)_V} \times U(1)_B$$

$N_f^2 - 1$ Goldstone bosons:

$$\pi^{\pm,0} \,, \quad K^{\pm,0,\bar{0}} \,, \quad \eta_8 \qquad \text{for } SU(3)$$

"small" masses: $m_P^2 f_P^2 \simeq (m_q + m_{\bar{q}}) \langle 0 | \bar{q} q | 0 \rangle$

decay constant

Effective Lagrangian

$m_q \ll \Lambda_{QCD}$

$$\mathcal{L}_{eff} = \frac{f_\pi^2}{16} \mathrm{Tr}(\partial_\mu U \partial^\mu U^+) + \frac{1}{32e^2} \mathrm{Tr}[(\partial_\mu U)U^+, (\partial_\nu U)U^+]^2 +$$

kinetic term, $\pi\pi$ scattering

vector-meson exchange
quark loops

$$+ \frac{f_\pi^2 m_\pi^2}{8} (\mathrm{Tr}\, U - 2)$$

where $U = \exp\left[\frac{2i}{f_\pi} \underline{\pi} \cdot \underline{\tau}\right]$ $N_f \times N_f$ matrix

describes dynamics for $E \ll \Lambda_{QCD}$ if $m_q \ll \Lambda_{QC}$

magnitudes of quark masses:

$m_K^2 \gg m_\pi^2$ $\qquad m_s \sim 20\, m_{u,d}$

estimates $\qquad m_s \sim 100$ MeV, $m_{u,d} \sim$ few MeV

"current" or "short-distance" quark masses

$\ll$ constituent quark masses $\sim$ few 00 MeV

quarks should be relativistic $\quad m_q \ll E_q$

important role for collective excitations $\pi, \ldots$

Light Quark Masses

to leading order in chiral symmetry breaking

$$\frac{m_u + m_d}{m^2_{\pi^\pm}} = \frac{m_u + m_s}{m^2_{K^\pm}} = \frac{m_d + m_s}{m^2_{K^0}}$$

removing electromagnetic self-energies:

$$\frac{m_u}{m_d} = \frac{m^2_{K^+} - m^2_{K^0} + m^2_{\pi^+}}{m^2_{K^0} - m^2_{K^+} + m^2_{\pi^+}} \simeq 0.55$$

$$\frac{m_s}{m_d} = \frac{m^2_{K^0} + m^2_{K^+} - m^2_{\pi^+}}{m^2_{K^0} - m^2_{K^+} + m^2_{\pi^+}} \simeq 20.1$$

applying second-order corrections, etc.

$$\frac{m_u}{m_d} = 0.553 \pm 0.043, \quad \frac{m_s}{m_d} = 18.9 \pm 0.8$$

(Leutwyler: hep-ph/0011049

absolute mass scale: depends on log(scale)

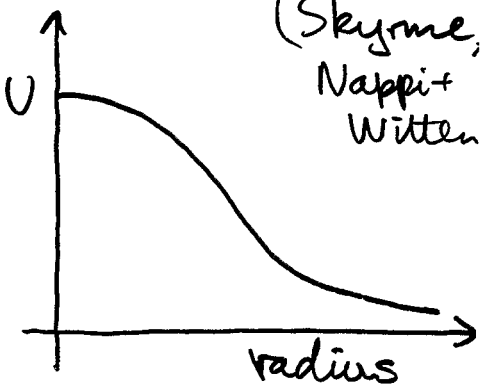
τ decay $m_s(2\,\text{GeV}) = 114 \pm 23$ MeV

QCD sum rules $= 118.9 \pm 12.2$ MeV

lattice $\simeq 90$ MeV

Baryon as Soliton

(Skyrme, Nappi + Witten)



$\parallel$

coherent "lump" of mesons

$$U(\underline{x}) = \cos\Theta(r) + \frac{i\underline{\tau}\cdot\underline{x}}{r}\sin\Theta(r)$$

radius

mix internal, external coordinates

1) soliton has non-zero topological number

$$B = \frac{1}{24\pi^2}\epsilon_{ijk}\int d^3\underline{x}\, \mathrm{Tr}\left(\partial_i U U^\dagger \partial_j U U^\dagger \partial_k U U^\dagger\right)$$

$$= \frac{1}{\pi}\left[\Theta(0) - \Theta(\infty)\right]$$

identified with baryon number : $B = 1$

2) quantization of soliton $\Leftrightarrow$ coherent rotation

$$U(\underline{x},t) = V(t)\, U(\underline{x})\, V^{-1}(t)$$

internal rotation

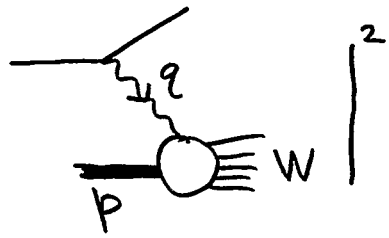
to get state with definite spin, isospin

soliton has $I = J = \frac{1}{2}$

- angular momentum entirely orbital
- wave function contains strangeness

$$U(\underline{x},t) \ni \pi^{\pm,0}, K^{\pm,0,\bar{0}}, \eta_8$$

1.2 - Deep-Inelastic Scattering

$\sum$ 

$\Big|^2 \propto \langle p | \int d^4x\, e^{iq\cdot x} \underset{\text{current}}{\underset{\parallel}{J(x)}} J(0) | p \rangle$

kinematic variables

$$\underbrace{\nu \equiv \frac{q\cdot p}{m}, \quad Q^2 \equiv -q^2}_{x_{Bj} \equiv \frac{Q^2}{2m\nu}}, \quad W^2 = (p+q)^2 = m^2 + 2m\nu - Q$$

generic structure function: $F(q^2, \nu)$

Bjorken limit: $Q^2 \to \infty$, x_{Bj} fixed

$\updownarrow$

$x^2 \to 0$ limit of $J(x)J(0)$

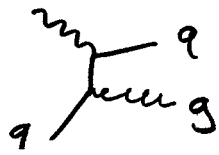
scaling hypothesis: like point-like particles

$$F(q^2, \nu) \to F(x_{Bj})$$

motivated originally by current algebra

(motivated in turn by quarks)

subject to logarithmic corrections in QCD



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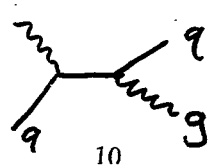

$+$

$+ \cdots$

PHYSICAL REVIEW VOLUME 148, NUMBER 4 26 AUGUST 1966

Applications of the Chiral $U(6)\otimes U(6)$ Algebra of Current Densities*

J. D. BJORKEN
Stanford Linear Accelerator Center, Stanford University, Stanford, California
(Received 14 March 1966)

Consequences of the local commutation relations of vector and axial currents proposed by Gell-Mann are explored: (1) A recipe for detecting and isolating Schwinger terms in the commutators, proportional to derivatives of the δ function, is discussed. (2) Under assumptions of smooth asymptotic behavior of form factors for forward scattering of the isovector current from a proton, we show that the $U(3)\otimes U(3)$ algebra for the time components of the currents implies the $U(6)\otimes U(6)$ algebra for space components, at least for spin-averaged diagonal single-particle states. (3) The derivation of the Adler-Weisberger formula for G_A/G_V is sharpened by giving arguments that, at fixed energy, the forward π-p Green's function satisfies an unsubtracted dispersion relation in the pion mass. (4) A lower bound for inelastic electron-nucleon scattering at high momentum transfer is derived on the basis of $U(6)\otimes U(6)$. (5) The contribution of very virtual photons to the hyperfine anomaly in hydrogen is shown to be related to an equal-time commutator of currents; this contribution is crudely estimated to be <4 parts per million (ppm). (6) The logarithmically divergent part of electromagnetic mass differences of hadrons is shown to be proportional to matrix elements of the equal-time commutator of the electromagnetic current with its time derivative. It is suggested that this "divergent" part be identified with the Coleman-Glashow "tadpoles"; this suggestion is discussed in the framework of a simple quark model. (7) The logarithmically divergent part of the electromagnetic correction to the process $\pi^- \to \pi^0 + e^- + \bar{\nu}$ is, on the basis of the $U(6)\otimes U(6)$ current algebra, shown to be nonvanishing, and is computed. (8) A speculative argument is presented that the rate $e^- + e^- \to$ hadrons is comparable to the rate $e^- + e^- \to \mu^- + \mu^-$ in the limit of large energies.

Scaling!

I. INTRODUCTION

IN this paper we apply the chiral $U(6)\otimes U(6)$ algebra of current densities proposed by Gell-Mann[1] and by Feynman, Gell-Mann, and Zweig[2] to various processes. We propose a criterion for detecting and isolating singular terms proportional to gradients of delta functions. These Schwinger terms[3] have inhibited the use of the full information contained in the algebra of current densities. In particular, the behavior of matrix elements of currents as the momentum q carried by the currents approaches infinity can be determined in terms of the current algebra. Some applications involving electromagnetic corrections to hadron processes have been found. The program of the paper is as follows:

Section II: We propose a criterion for identification of Schwinger terms. The crux of the matter is that the T product of currents used in making sum rules is in general not covariant. This was recognized and discussed[4] by Johnson in 1961. We give a rule for constructing the T product from the corresponding covariant amplitude. The difference of the two objects is the Schwinger term.

Section III: The claims of Sec. II are illustrated for the vacuum expectation value of the T product of two currents. This section is essentially a summary of Johnson's paper.

Section IV: We next take the T product of two isovector currents between protons at rest and show that the only Schwinger terms are in the disconnected graphs, provided certain form factors behave reasonably at infinity. If this is the case, we can furthermore show that if the time components of the current densities satisfy a $U(3)\otimes U(3)$ algebra, the space components satisfy the $U(6)\otimes U(6)$ algebra, at least for diagonal matrix elements between single-particle states, spin averaged.

* Work supported by the U. S. Atomic Energy Commission.

[1] M. Gell-Mann, Phys. Rev. 125, 1067 (1962); Physics 1, 63 (1964).

[2] R. Feynman, M. Gell-Mann, and G. Zweig, Phys. Rev. Letters 13, 678 (1964).

[3] J. Schwinger, Phys. Rev. Letters 3, 296 (1959).

[4] K. Johnson, Nucl. Phys. 25, 431 (1961).

of $M_{\mu\nu}$, defined as in (2.3) with j_μ replacing $j_\mu^{\pm}$, is given by

$$M_{\mu\nu}^{(c)}=\tfrac{1}{2}\bar{u}\{[\gamma_\nu,q]P_\mu-[\gamma_\mu,q]P_\nu+[\gamma_\mu,\gamma_\nu]P\cdot q\}uG_1(q^2,\nu)$$
$$+\tfrac{1}{2}\bar{u}\{[\gamma_\nu,q]q_\mu-[\gamma_\mu,q]q_\nu+[\gamma_\mu,\gamma_\nu]q^2\}uG_2(q^2,\nu). \quad (6.4)$$

From crossing symmetry,

$$M_{\mu\nu}^{(a)}(q,\cdots)=+M_{\nu\mu}^{(a)}(-q,\cdots)=-M_{\mu\nu}^{(c)}(-q,\cdots)$$

and

$$G_1(q^2,-\nu)=G_1(q^2,\nu),$$
$$G_2(q^2,-\nu)=-G_2(q^2,\nu). \quad (6.5)$$

We assume unsubtracted dispersion relations for both G_1 and G_2.

For $q^2=0$, $M_{\mu\nu}^{(c)}$ is related to the spin-dependent part of the forward Compton-scattering amplitude; for $q^2<0$, the absorptive part of $M_{\mu\nu}^{(c)}$ is related to the spin-dependent part of inelastic electron-proton scattering. Specifically,

$$\frac{d\sigma^{\uparrow\uparrow}}{dq^2dE'}-\frac{d\sigma^{\downarrow\uparrow}}{dq^2dE'}=\frac{4\alpha^2}{q^2E^2}$$
$$\times[M(E+E'\cos\theta)\,\mathrm{Im}G_1+q^2\,\mathrm{Im}G_2], \quad (6.6)$$

where $d\sigma^{\uparrow\uparrow}$ is the cross section when the spins of electron and proton are parallel and along the direction of motion of incident electron, and $d\sigma^{\downarrow\uparrow}$ is the cross section for antiparallel spins. E, E', and θ are energies and scattering angle of the electron, $q^2=-4EE'\sin^2(\theta/2)$, and $\nu=E-E'$. We have set m_e equal to 0.

The photoproduction cross section for $q^2=0$ is given by the optical theorem:

$$e^2\,\mathrm{Im}G_1=(1/2M)[\sigma^{\uparrow\uparrow}-\sigma^{\downarrow\uparrow}], \quad (6.7)$$

where $\sigma^{\uparrow\uparrow}$ is the cross section for photon and proton spins aligned. The Born terms are given by

$$G_1^{\mathrm{Born}}=\frac{-2q^2F_1(F_1+F_2)}{M(q^4-4M^2\nu^2)},$$
$$G_2^{\mathrm{Born}}=\frac{-2\nu F_2(F_1+F_2)}{q^4-4M^2\nu^2}. \quad (6.8)$$

We extract a useful result by considering the limit $q_0\to i\infty$ of $M_{\mu\nu}^{(c)}$. Using (2.6) and (6.1) we find

$$\lim_{q_0\to i\infty}M_{\mu\nu}^{(c)}=\frac{-2i\epsilon_{\mu\nu0\sigma}}{q_0}\langle P|j_5^\sigma(0)|P\rangle$$
$$=\frac{-2i\epsilon_{\mu\nu\lambda\sigma}q^\lambda}{q^2}\langle P|j_5^\sigma(0)|P\rangle. \quad (6.9)$$

We define

$$\langle ps|j_5^\sigma(0)|ps\rangle=Z\bar{u}\gamma_5\gamma^\sigma u=-Zs^\sigma. \quad (6.10)$$

Δq !

Upon identification of this with the asymptotic behavior of G_1 and G_2 we find that

$$G_1\to-2Z/Mq^2,$$
$$G_2\to O(1/q_0^4)\quad(q_0\to i\infty). \quad (6.11)$$

On the other hand, we may evaluate G_1 by using an unsubtracted dispersion relation

$$G_1(q^2,\nu)=\frac{2}{\pi}\int_0^\infty\frac{d\nu'\nu'\,\mathrm{Im}G_1(q^2,\nu')}{\nu'^2-\nu^2} \quad (6.12)$$

and[17] as $q_0\to i\infty$

$$G_1(q^2,\nu)=\frac{2}{\pi}\int_0^\infty\frac{d\nu'}{\nu'}\mathrm{Im}G_1(q^2,\nu')=G_1(q^2,0), \quad (6.13)$$

or

$$\int_0^\infty\frac{d\nu'}{\nu'}\mathrm{Im}G_1(q^2,\nu')\xrightarrow[q^2\to-\infty]{}\frac{-\pi Z}{Mq^2}. \quad (6.14)$$

Using Eq. (6.6) as $E\to\infty$ at fixed q^2

$$\mathrm{Im}G_1(q^2,\nu)\to\frac{q^2E}{8\alpha^2M}\left[\frac{d\sigma^{\uparrow\uparrow}}{dq^2d\nu}-\frac{d\sigma^{\downarrow\uparrow}}{dq^2d\nu}\right] \quad (6.15)$$

and we find

$$\lim_{q^2\to-\infty}\lim_{E\to\infty}\int_0^\infty\frac{d\nu'}{\nu'}\left[\frac{d\sigma^{\uparrow\uparrow}}{dq^2d\nu'}-\frac{d\sigma^{\downarrow\uparrow}}{dq^2d\nu'}\right]=\frac{-8\pi\alpha^2Z}{q^4E}. \quad (6.16)$$

Single

It will be a long time before these cross sections are measured. Furthermore, we do not know the value of Z, although $SU(6)$ predicts $Z_p=5/9$ and $Z_n=0$. However, if we take the difference between proton and neutron we know from (6.2), assuming always the $U(6)\otimes U(6)$ current algebra, that

$$Z_p-Z_n=\frac{1}{3}\left(\frac{G_A}{G_V}\right). \quad (6.17)$$

Thus,

$$\int_0^\infty\frac{d\nu'}{\nu'}\frac{d}{dq^2d\nu'}$$
$$\times[\sigma_p^{\uparrow\uparrow}-\sigma_p^{\downarrow\uparrow}-\sigma_n^{\uparrow\uparrow}+\sigma_n^{\downarrow\uparrow}]\to\frac{-8\pi\alpha^2}{3q^4E}\left(\frac{G_A}{G_V}\right). \quad (6.18)$$

Bj

Something may be salvaged from this worthless equation by constructing an inequality[18]:

$$\lim_{q^2\to-\infty}\lim_{E\to\infty}q^4E\int_0^\infty\frac{d\nu}{\nu'}\left[\frac{d\sigma_p}{dq^2d\nu'}+\frac{d\sigma_n}{dq^2d\nu'}\right]$$
$$>\frac{8\pi\alpha^2}{3}\left|\frac{G_A}{G_V}\right|. \quad (6.19)$$

[17] Compare Eqs. (5.7)–(5.9).
[18] $\sigma_p=\sigma_p^{\uparrow\uparrow}+\sigma_p^{\uparrow\downarrow}$.

Structure Functions for Vector Currents

J_μ^{em}, J_μ^{NC}, J_μ^{CC}

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x, Q^2) + \frac{\hat{p}_\mu \hat{p}_\nu}{p\cdot q} F_2(x, Q^2)$$

e.m. →

$$- i\, \epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha p^\beta}{2p\cdot q} F_3(x, Q^2) \leftarrow \text{parity-violating}$$

$$+ i\, \epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha}{p\cdot q} \left[s^\beta g_1(x, Q^2) + \left(s^\beta - \frac{s\cdot q}{p\cdot q} p^\beta\right) g_2(x, Q^2) \right]$$

spin-dependent

$+ \cdots$ ← contributions $\propto m_{lepton}, \ldots$

in quark-parton model

spin $\frac{1}{2}$: $F_L \equiv F_2 - 2x F_1 \to 0$

parton distribution functions

$$F_2^{(\gamma, \gamma Z, Z)} = x \sum_q \left(e_q^2, 2e_q g_V^q, g_V^{q\,2} + g_A^{q\,2}\right)\left(q(x) + \bar{q}(x)\right)$$

$$F_3^{(\gamma, \gamma Z, Z)} = \sum_q \left(0, 2e_q g_A^q, 2 g_V^q g_A^q\right)\left(q(x) - \bar{q}(x)\right)$$

$$g_1^\gamma = \frac{1}{2} \sum_q e_q^2 \left(q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)\right)$$

spins parallel - antiparallel to proton spin

quark quantum numbers from $\gamma \Leftrightarrow W$ comparison

Spin of the nucleon

angular momentum sum rule

$$\frac{1}{2} = \frac{1}{2}\left(\sum_q \Delta q\right) + \Delta G + L_z$$

commonly refered to as spin: actually helicity in ∞-momentum frame

$$\Delta q \equiv \int dx \left[q_\uparrow(x) + \bar{q}_\uparrow(x) - q_\downarrow(x) - \bar{q}_\downarrow(x) \right]$$

$$\Delta G \equiv \int dx \left[G_\uparrow(x) - G_\downarrow(x) \right]$$

L_z = z component of orbital angular momentu

can be decomposed into q, G parts

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Sum rule for deep-inelastic electroproduction from polarized protons*

John E[illegible]†

Lauritsen Laboratory of Physics, California Institute of Technology, Pasadena, California 91109 and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

Robert Jaffe‡

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

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A sum rule is derived for the asymmetry in deep-inelastic scattering of polarized electrons from polarized protons: $\int_0^1 d\xi\, g_1^{ep}(\xi) \approx 0.15 g_A$. The result follows from the quark light-cone algebra and the assumption that strange quarks do not contribute to the asymmetry. The latter is justified by conventional parton-model arguments.

Measurements of the asymmetry in the inelastic scattering of polarized electrons from polarized protons will begin soon.[1] Several years ago Bjorken[2] derived a sum rule for the difference in polarization asymmetry in deep inelastic scattering from protons and neutrons. The sum rule has been rederived recently using the parton model[3] and the quark light-cone algebra.[4,5] Unfortunately, testing the Bjorken sum rule would require data on scattering from polarized deuterons which will be unavailable for some time. Here we derive a sum rule for the asymmetry in scattering from polarized protons alone. We use the standard quark light-cone algebra, the usual parton-model assumptions that the only isosinglet (λ-type) quarks in the proton are in the "sea" (Pomeranchukon) and that the spins of partons in the "sea" are paired. These are discussed further later.

The structure functions for scattering polarized electrons from polarized protons are defined as follows:

$$\tfrac{1}{2}(W_{\mu\nu} - W_{\nu\mu}) = i\epsilon_{\mu\nu\lambda\sigma}\frac{q^\lambda n^\sigma}{M^2}G_1(\nu, q^2) + i\epsilon_{\mu\nu\lambda\sigma}\frac{q^\lambda}{M^4}(\nu n^\sigma - n\cdot q p^\sigma)G_2(\nu, q^2),$$

where $\nu \equiv p\cdot q$, n^σ is the proton's polarization vector ($n^2 = -M^2$, $p\cdot n = 0$) and

$$W_{\mu\nu}(q,p) = \frac{1}{4\pi}\int d^4x\, e^{iq\cdot x}\langle p, n|[J_\mu(x), J_\nu(0)]|p, n\rangle .$$

It is expected that νG_1 and $\nu^2 G_2$ should scale in the Bjorken limit ($\nu, q^2 \to \infty$, $\xi \equiv -q^2/2\nu$ fixed):

$$\lim_{\text{Bj}} \frac{\nu}{M^2} G_1(q^2, \nu) \equiv g_1(\xi),$$

$$\lim_{\text{Bj}} \frac{\nu^2}{M^4} G_2(q^2, \nu) \equiv g_2(\xi).$$

Conventional quark light-cone algebra[6] yields the following expression for $g_1(\xi)$:

$$g_1^{ep}(\xi) = \frac{1}{4\pi}\int_{-\infty}^{\infty} d(x\cdot p)e^{i\xi x\cdot p} \times\left[\tfrac{1}{6}S_3^5(x\cdot p) + \frac{1}{6\sqrt{3}}S_8^5(x\cdot p) + (\tfrac{2}{27})^{1/2}S_0^5(x\cdot p)\right],$$

$$g_1^{en}(\xi) = \frac{1}{4\pi}\int_{-\infty}^{\infty} d(x\cdot p)e^{i\xi x\cdot p} \times\left[-\tfrac{1}{6}S_3^5(x\cdot p) + \frac{1}{6\sqrt{3}}S_8^5(x\cdot p) + (\tfrac{2}{27})^{1/2}S_0^5(x\cdot p)\right], \tag{1}$$

where the $S_a^5(x\cdot p)$ are defined from the bilocal operators:

$$\langle p, n|S_{a\sigma}^5(x|0)|p, n\rangle|_{x^2=0} = n_\sigma S_a^5(x\cdot p) + \cdots,$$

where $S_{a\sigma}^5(x|0)$ is the axial-vector bilocal which is symmetric under interchange of x and 0, and has the following form in free-field theory:

$$S_{a\sigma}^5(x|0) = \bar\psi(x)\frac{\lambda_a}{2}\gamma_\sigma\gamma_5\psi(0) + \bar\psi(0)\frac{\lambda_a}{2}\gamma_\sigma\gamma_5\psi(x).$$

Bjorken's sum rule follows from inverting the Fourier transform in Eq. (1), setting $x\cdot p$ to zero, taking the ep, en difference and noting that

$$\langle p, n|S_{3\sigma}^5(0|0)|p, n\rangle = 2g_A n_\sigma$$

since the local limit of the bilocal is just the neutral isovector axial-vector current.

In trying to derive a sum rule for scattering off polarized protons it is necessary to know $\langle p, n|S_{8\sigma}^5(0|0)|p, n\rangle$ and $\langle p, n|S_{0\sigma}^5(0|0)|p, n\rangle$. The first of these can be estimated using SU(3) for the

E~~~~ + Jaffe

baryon matrix elements of the axial charges. Hyperon decays are known to agree well with SU(3) and the Cabibbo theory, and the F/D ratio for axial charges is well determined.[7] However, nothing is known *a priori* about $\langle p,n|S^5_{0\sigma}(0|0)|p,n\rangle$. To evaluate it we argue on the basis of the parton model that the matrix elements of the combination

$$\frac{1}{\sqrt{2}}S^5_{0\sigma}(x|0)-S^5_{8\sigma}(x|0) \tag{2}$$

between nucleons are expected to be small.

The combination (2) gets contributions only from λ- and $\bar{\lambda}$-type quarks. Data from neutrino reactions[8] already suggest that the nucleons' wave functions have small $(\lambda,\bar{\lambda})$ components, and that it is reasonable to assume they only occur in the "sea" associated with the Pomeranchukon. The Pomeranchukon does not contribute to the spin-dependent structure functions G_1 and G_2,[9] so one might suspect that the $(\lambda,\bar{\lambda})$ contribution to them should be small. In fact

$$\left\langle p,n\left|\left[\frac{1}{\sqrt{2}}S^5_{0\sigma}(0|0)-S^5_{8\sigma}(0|0)\right]\right|p,n\right\rangle \propto \int_0^1 d\xi[\lambda_+(\xi)+\bar{\lambda}_+(\xi)-\lambda_-(\xi)-\bar{\lambda}_-(\xi)],$$

where $\lambda_\pm(\xi)$ are the distributions of λ quarks in the nucleon with helicities parallel (antiparallel) to the helicity of the nucleon itself,[3] and $\bar{\lambda}_\pm(\xi)$ are defined similarly. The usual spin and charge conjugation properties of the Pomeranchukon imply

$$\lambda_+(0)=\bar{\lambda}_+(0)=\lambda_-(0)=\bar{\lambda}_-(0).$$

Our assumption is that this remains at least approximately valid for $\xi\neq 0$ for the "sea" of $q\bar{q}$ pairs:

$$\lambda_+(\xi)\approx\bar{\lambda}_+(\xi)\approx\lambda_-(\xi)\approx\bar{\lambda}_-(\xi). \tag{3}$$

Assuming that the "sea" has the property (3) it follows that[10]

$$\langle p,n|S^5_{0\sigma}(x|0)|p,n\rangle \simeq\sqrt{2}\,\langle p,n|S^5_{8\sigma}(x|0)|p,n\rangle$$

and separate sum rules for the proton and neutron asymmetries follow immediately:

$$\int_0^1 g_1^{ep}(\xi)d\xi=\frac{g_A}{12}\left(1+\frac{5}{3}\frac{3(F/D)-1}{(F/D)+1}\right), \tag{4}$$

$$\int_0^1 g_1^{en}(\xi)d\xi=\frac{g_A}{12}\left(-1+\frac{5}{3}\frac{3(F/D)-1}{(F/D)+1}\right). \tag{5}$$

The difference of Eqs. (4) and (5) is just Bjorken's sum rule.[2] In writing (4) and (5) we have used SU(3) to reexpress the ratio

$$\frac{\langle p,n|S^5_{3\sigma}(0|0)|p,n\rangle}{\langle p,n|S^5_{8\sigma}(0|0)|p,n\rangle}$$

in terms of the F/D ratio of the axial charges. Since the axial charges seem to form an excellent octet[7] we regard this as a minor assumption. Using the currently accepted value[7]

$$\frac{F}{D}=0.581\pm0.029,$$

we obtain[11]

$$\int_0^1 d\xi\, g_1^{ep}(\xi)=\frac{g_A}{12}(1.78), \approx 0.19 \tag{6}$$

$$\int_0^1 d\xi\, g_1^{en}(\xi)=\frac{g_A}{12}(-0.22), \approx -0.23 \tag{7}$$

where $g_A=1.248\pm.010$.

We do not expect the sum rules, Eqs. (6) and (7), to be exact because of SU(3) breaking, the uncertainty in the F/D ratio, and the parton-model assumption about the $(\lambda,\bar{\lambda})$ distributions. However, as long as the momentum of strange quarks extracted from neutrino experiments (see footnote 8) remains small, we expect Eqs. (6) and (7) to be quite accurate estimates of polarization asymmetries in scattering off protons and neutrons separately. The proton sum rule (6) is particularly interesting because experiments using polarized proton targets will soon be performed, and because (following Bjorken[12]) it predicts that a large mean asymmetry of the order of 35% will be observed.

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†Address after 1 September 1973: Theory Division, CERN, 1211 Geneva 23, Switzerland.

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History of (polarized) DIS

1966 Bjorken sum rule

fundamental test of current algebra (QCD)

led to concept of scaling

"do not know p, n separately ...

... something may be salvaged

1968 Discovery of DIS scaling

experiment on polarized p prepared

1973 Heuristic proposals for p, n targets

naïve quarks → axial current matrix elements

hypothesize no $\bar{s}s$ in nucleon

or unpolarized if present

"not expected ... to be exact ....

SU(3) breaking ... $\bar{s}s$ assumption"

1970's Pioneering SLAC experiments

measurements @ large x

~ agreement with EJ

The Helen of spin
>1000 citations

A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON–PROTON SCATTERING

European Muon Collaboration

Aachen, CERN, Freiburg, Heidelberg, Lancaster, LAPP (Annecy), Liverpool, Marseille, Mons, Oxfo
Rutherford, Sheffield, Turin, Uppsala, Warsaw, Wuppertal, Yale

J. ASHMAN [a], B. BADELEK [b,1], G. BAUM [c,2], J. BEAUFAYS [d], C.P. BEE [e], C BENCHOUK [f], I.G. BIRD [g,3], S.C. BROWN [e,4], M.C. CAPUTO [c], H.W.K. CHEUNG [h], J. CHIMA [i,5], J. CIBOROWSKI [b,1], R.W. CLIFFT [i], G. COIGNET [j], F. COMBLEY [a], G. COURT [e], G. D'AGOSTINI [f], J. DREES [k], M. DÜREN [l], N. DYCE [g], A.W. EDWARDS [k,6], M. EDWARDS [i], T. ERNST [m], M.I. FERRERO [n], D. FRANCIS [e], E. GABATHULER [e], J. GAJEWSKI [b,1], R. GAME V. GIBSON [h,7], J. GILLIES [h], P. GRAFSTRÖM [o,7], K. HAMACHER [k], D. VON HARRACH [p], P. HAYMAN [e], J.R. HOLT [e], V.W. HUGHES [c], A. JACHOLKOWSKA [d,8], T. JONES [e,9], E.M. KABUSS [m,3], B. KORZEN [k], U. KRÜNER [k], S. KULLANDER [o], U. LANDGRAF [m], D. LANSKE [l], F. LETTENSTRÖM [o], T. LINDQVIST [o], J. LOKEN [h], M. MATTHEWS [e], Y. MIZUNO [p], K. MÖNIG [k], F. MONTANET [f,7], J. NASSALSKI [b,10], T. NIINIKOSKI [d], P.R. NORTON [g], G. OAKHAM [i,11], R.F. OPPENHEIM [c,12], A.M. OSBORNE [d], V. PAPAVASSILIO N. PAVEL [k], C. PERONI [n], H. PESCHEL [k], R. PIEGAIA [c], B. PIETRZYK [f], U. PIETRZYK [k,13], B. POVH [p], P. RENTON [h], J.M. RIEUBLAND [d], A. RIJLLART [d], K. RITH [m,3], E. RONDIO [b,1], L. ROPELEWSKI [b,1], D. SALMON [a,9], A. SANDACZ [b,10], T. SCHRÖDER [m], K.P. SCHÜLER [e], K. SCHULTZE [l], T.-A. SHIBATA [p], T. SLOAN [g], A. STAIANO [p,14], H. STIER [m], J. STOCK [m], G.N. TAYLOR [h,15], J.C. THOMPSON [i], T. WALCHER [p,16], S. WHEELER [a,7], W.S.C. WILLIAMS [h] S.J. WIMPENNY [e,17], R. WINDMOLDERS [q], W.J. WOMERSLEY [h,18] and K. ZIEMONS [l]

[a] *Department of Physics, University of Sheffield, Sheffield S3 7RH, UK*
[b] *Physics Institute, University of Warsaw, PL-00681 Warsaw, Poland and Institute for Nuclear Studies, PL-00681 Warsaw, Poland*
[c] *Physics Department, Yale University, New Haven, CT 06520, USA*
[d] *CERN, CH-1211 Geneva 23, Switzerland*
[e] *Department of Physics, University of Liverpool, Liverpool L69 3BX, UK*
[f] *Centre de Physique des Particules, Faculté des Sciences de Luminy, F-13288 Marseille, France*
[g] *Department of Physics, University of Lancaster, Lancaster LA1 4YB, UK*
[h] *Nuclear Laboratory, University of Oxford, Oxford OX1 3RH, UK*
[i] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK*
[j] *Laboratoire de Physique des Particules, IN2P3, F-74019 Annecy-le-Vieux, France*
[k] *Fachbereich Physik, Universitat Wuppertal, D-5600 Wuppertal, Fed. Rep. Germany*
[l] *III Physikalisches Institut A, Physikzentrum, D-5100 Aachen, Fed. Rep. Germany*
[m] *Fakultat fur Physik, Universitat Freiburg, D-7800 Freiburg, Fed. Rep. Germany*
[n] *Istituto di Fisica, Universita di Torino, I-10125 Turin, Italy*
[o] *Gustaf Werners Institut, University of Uppsala, S-75121 Uppsala, Sweden*
[p] *Max-Planck Institut fur Kernphysik, D-6900 Heidelberg, Fed. Rep. Germany*
[q] *Faculte des Sciences, Universite de L'Etat à Mons, B-7000 Mons, Belgium*

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For footnotes see next page.

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EMC data

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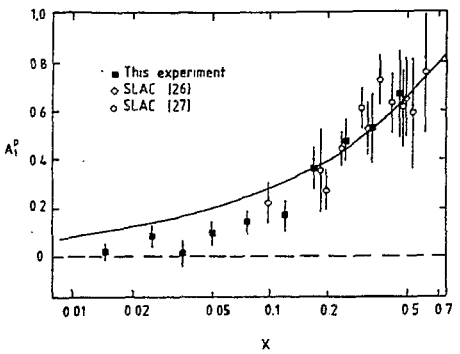

Fig. 1. The asymmetry A_1^p plotted versus x together with results from previous experiments [26,27]. The curve is from the model of ref. [28].

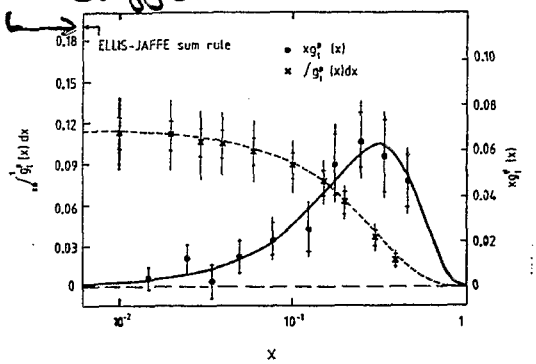

Fig. 3. The quantity $xg_1^p(x)$ (right-hand axis and solid circles) versus x. The left-hand axis and the crosses show the values of $\int_{x_m}^1 g_1^p(x)dx$ where x_m is the value of x at each lower bin edge. The inner error bars are statistical and the outer error bars are the total errors obtained by combining the statistical and systematic errors (table 1) in quadrature. The curves are described in the text.

taken from ref. [7] but corrected from the value $R=0$ assumed in that paper to the QCD value of R. Fig. 3 shows $xg_1^p(x)$ as a function of x. The solid curve is

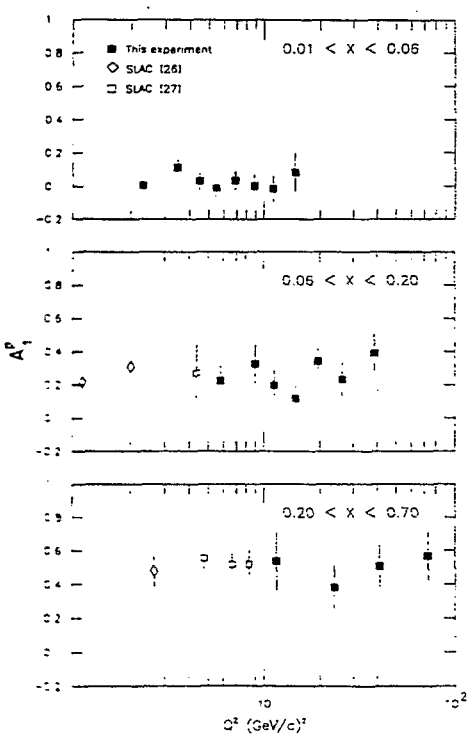

Fig. 2. A_1^p versus Q^2. The data in each x range have been corrected to the same mean x using a fit to the data as a function of x.

derived from the fitted function to $A_1^p(x)$. The integral of $g_1^p(x)$ over the measured region was found to be

$$\int_{0.01}^{0.7} g_1^p(x)dx = 0.111 \pm 0.012(\text{stat.}) \pm 0.026\ (\text{syst.})\ .$$

The convergence of this integral is also shown in fig. 3 where $\int_{x_m}^1 g_1^p(x)dx$ is plotted as a function of x_m, the value of x at the lower edge of each bin. It can be seen that the integral converges well towards $x=0$. The dashed curve is the integral of the solid curve and this was used to extrapolate to $x=0$. The data covered 98% of the value of the integral. The value obtained at a mean Q^2 of 10.7 GeV^2 was

$$\int_0^1 g_1^p(x)dx = 0.114 \pm 0.012(\text{stat.}) \pm 0.026(\text{syst.})\ .$$

Here the systematic error was obtained from the individual systematic errors, added in quadrature and includes a further uncertainty of 10% on the value of the integral to allow for possible errors on the value of F_2 for the proton. The uncertainty due to the extrapolation outside the measured range of x is small providing that $xg_1(x)$ is well behaved and approaches zero reasonably as x tends to zero. It is expected from Regge theory [30] that $xg_1(x)$

1987 "Helen of Spin"

the experiment that launched 1000 pape

1058 @ last count

consistent with SLAC @ high x

extend measurements → smaller x

exploiting higher-energy μ beam

new results < naive extrapolation

$$\int_0^1 g_1^p(x)\,dx = 0.114 \pm 0.012\,(\text{stat}) + 0.026\,(\text{syst}$$

integral < EJ : $\simeq 0.19$

SU(3) breaking? extrapolation?

1987 intrinsic $\bar{s}s$ in nucleon

$$\Delta s = -0.25 \pm 0.07$$ (J.E.+Flores+Ritz

1988 contribution from polarized gluons

$$\Delta q \to \Delta q - \frac{\alpha_s}{2\pi}\Delta G$$ (Efremov+Teraev
Altarelli+Ross
Carlitz+Collins+Mueller

Relation to axial-current matrix elements

in original Bjorken sum rule : current algebra

$$[J^i_a , J^j_b] \ni d^{ijk} \epsilon_{abc} A_c$$

internal SU(3) — space indices

matrix element:

$$\langle p | A^a_\mu | p \rangle = \langle p | \bar{q} \gamma_\mu \gamma_5 q | p \rangle$$

$$= \langle p | \bar{q}_R \gamma_\mu q_R - \bar{q}_L \gamma_\mu q_L | p \rangle$$

where $q_{L,R} = \frac{1}{2}(1 \mp \gamma_5) q$

$$= \Delta q \cdot S_\mu \leftarrow \text{spin vector}$$

where $\Delta q = \int_0^1 dx \left[q_\uparrow(x) + \bar{q}_\uparrow(x) - q_\downarrow(x) - \bar{q}_\downarrow(x) \right]$

known combinations:

β decay + isospin SU(2): $\Delta u - \Delta d = 1.2573 \pm 0.0028$

hyperon decays + $SU(3)_f$: $\dfrac{\Delta u + \Delta d - 2\Delta s}{\sqrt{3}} = 0.34 \pm 0.02$

two equations for three unknowns : is $\Delta s = 0$?

$$\Gamma_1^p \equiv \int_0^1 dx\, g_1^p(x) = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s \right)$$

n n $\frac{1}{9}$ $\frac{4}{9}$

implications of EMC for dark matter detection

IMPLICATIONS FOR DARK MATTER PARTICLES OF SEARCHES FOR ENERGETIC SOLAR NEUTRINOS

John ELLIS, R.A. FLORES
CERN, CH-1211 Geneva 23, Switzerland

and

S. RITZ
Physics Department, University of Wisconsin, Madison, WI 53706, USA

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We investigate whether recent searches for energetic solar neutrinos give new constraints on candidate dark-matter particles such as photinos $\tilde{\gamma}$ and higgsinos $\tilde{h}$, in view of the astrophysical and particle physics uncertainties. Previous quark model estimates of the elastic cross sections responsible for $\tilde{\gamma}$ or $\tilde{h}$ capture in the sun can be improved using hyperon decay data, but are thrown into doubt by recent European Muon Collaboration data on the spin-dependent proton structure function, which reduce the estimate of $\sigma(\tilde{\gamma}p)$ by a factor up to four. We emphasize the need to include charm and bottom quark fragmentation effects when calculating the flux of neutrinos from dark matter annihilation events, which may reduce the observable flux by a factor ~ 2. Even the most stringent upper limits from the Fréjus experiment still allow a local $\tilde{\gamma}$ or $\tilde{h}$ density considerably above the range of 0.20–0.43 GeV/cm^3 favoured by astrophysics, and no range of $m_{\tilde{\gamma}}$ or $m_{\tilde{h}}$ can yet be excluded.

There is an emerging consensus that non-dissipative dark matter is prevalent in galactic halos [1]. One of the prime possibilities is that the halo dark matter consists of some species of massive, non-relativistic, neutral, weakly-interacting particle. A possible candidate for this dark-matter particle is the lightest supersymmetric particle (LSP), which could be a photino $\tilde{\gamma}$, higgsino $\tilde{h}$ or sneutrino $\tilde{\nu}$ [2]. Methods of detecting dark-matter particles are now being actively pursued [3]. The most convincing would be direct detection of the elastic scattering of dark-matter particles off nuclei in the laboratory [4], unsuccessful searches for which have already been used to exclude sneutrinos in the range 16 GeV $< m_{\tilde{\nu}} <$ 1 TeV [5]. An elegant but less direct method [6] is based on the observation that certain candidate dark-matter particles have some probability of being trapped in the sun after losing energy through elastic scattering [7,8]. Evaporation is negligible for masses above 2.5 GeV [9,10], in which case the solar population is stabilized by annihilations. Such annihilations, e.g., $\tilde{\gamma}\tilde{\gamma} \to f\bar{f}$, can produce energetic neutrinos via the prompt decays of heavy flavours: $f = \tau, c, b, t$. This idea has been pursued extensively [11–15] and varying estimates given of the resulting ν flux.

Data are now becoming available from underground detectors [16–18], most recently the Fréjus experiment [18], both on contained ν interactions and on upward-going muons induced by ν_μ interactions in rock. These provide upper limits on the energetic solar ν flux which can be confronted with different dark-matter predictions. Some candidates seem to be clearly excluded by such analyses, e.g., $\tilde{\nu}_\mu$ and $\tilde{\nu}_e$ with masses $\gtrsim 4$ GeV [13,14]. However, the confrontation is much more delicate for some candidates, such as the $\tilde{\gamma}$ and $\tilde{h}$, for which the experimental upper limits can be comparable with the ν event estimate. For $\tilde{\gamma}\tilde{\gamma}$ annihilation, this is approximately

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determination of proton spin content

Recent EMC data [26] on polarized μp scattering cast doubt on the assumption that $\Delta s \simeq 0$. They measure the spin-dependent structure function $g_1^p(x,Q^2)$, for which there is a QCD sum rule

$$\int_0^1 dx\, g_1^p(x,Q^2) = \frac{1}{2}\left(\sum_q Q_q^2 \Delta q\right)[1+O(\alpha_s/\pi)]$$

$$\simeq \tfrac{1}{2}(\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s)\,. \qquad (16)$$

The $O(\alpha_s/\pi)$ correction in (16) is $(-1\cdot\alpha_s/\pi)$ for non-singlet combinations [34] of the Δq, and $(-\frac{1}{3}\cdot\alpha_s/\pi)$ for the singlet combination [35]: these do not give a large Q^2-dependence for $Q^2 > 3$ GeV^2. Note that EMC measures the same combination of the Δq as appears in $\sigma(\tilde{\gamma}p \to \tilde{\gamma}p)$ (7a) if all the $m_{\tilde{q}}$ are approximately equal as we expect. The prediction using Hβ (15) is

$$\int_0^1 dx\, g_1^p(x,Q^2) = 0.20$$

$$\simeq \tfrac{1}{2}(\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s)\,, \qquad (17)$$

whereas the EMC measure [26]

$$\int_0^1 dx\, g_1^p(x,Q^2)\Big|_{Q^2 > 3\,\mathrm{GeV}^2}$$

$$= 0.113 \pm 0.012 \pm 0.025\,. \qquad (18)$$

If one neglects any possible dependence on the renormalization scale $\mu \simeq Q$, this can be combined with (14) to yield

$$\boxed{\text{EMC:}\quad \Delta u = 0.70(8)\,,\quad \Delta d = -0.54(2)\,,\quad \Delta s = -0.25(7)\,.} \qquad (19)$$

each with errors ±0.08(4) if the statistical and systematic errors in (18) are added in quadrature [#7]. Different estimates of the factor $(\sum Q_q^2 \Delta q)^2$ appearing in eq. (7a) are shown in table 1. The reduction in the observed value (18) compared to that previously expected (17) suggests a reduction in the prediction of $\sigma(\tilde{\gamma}p \to \tilde{\gamma}p)$ by a factor ~4. As already mentioned, we do not expect significant renormalization scale (μ) dependence that decouples the EMC measurements at $\mu^2 \simeq Q^2 \geqslant 3$ GeV^2 from the values of the Δq at $\mu^2 \simeq m_{\tilde{q}}^2 \sim 10^4$ GeV^2 required in $\tilde{\gamma}p$ scattering. Moreover, the EMC Collaboration sees no evidence for any Q^2-dependence [#8]. Until the EMC result is confirmed, one should nevertheless perhaps regard the range (15), (19) as a legitimate uncertainty in dark-matter detection estimates.

We now consider the possibility that the dark-matter particle is a higgsino $\tilde{h}$, for which [21]

$$\sigma(\tilde{h}p \to \tilde{h}p)$$

$$= \frac{6 m_{\tilde{h}} m_p^2}{\pi(m_{\tilde{h}} + m_p)^2} G_F^2 \cos^2(2\beta)\left(\sum_q I_{3q}\Delta q\right)^2\,, \qquad (20)$$

where $I_{3u} = +\frac{1}{2}$, $I_{3d,s} = -\frac{1}{2}$, Δq is given by (7b), (15) and (19) as before, and β is given by $\tan\beta \equiv v_2/v_1$ where v_2 (v_1) is the VEV of the Higgs giving masses to the u (d,s) quarks. Notice that the squark masses do not affect $\sigma(\tilde{h}\tilde{h} \to f\bar{f})$ or $\sigma(\tilde{h}p \to \tilde{h}p)$ (20), but it is possible [2] to find an acceptable choice of β which gives $\Omega_{\tilde{h}} = 1$ whenever $m_{\tilde{h}} > m_t \approx 6$ GeV.

The factors a_i in (1) are simple numerical constants in νN scattering cross sections. For n and p targets they are [15]

$$a_{\nu p} = 4.2\,,\quad a_{\bar{\nu}p} = 4.1\,,$$

$$a_{\nu n} = 9.5\,,\quad a_{\bar{\nu}n} = 2.2\,, \qquad (21)$$

corresponding to

isoscalar target: $a_\nu = 6.85$, $a_{\bar{\nu}} = 3.15$,

Fe = 26p + 30n: $a_\nu = 7.04$, $a_{\bar{\nu}} = 3.09$,

H_2O = 10p + 8n: $a_\nu = 6.56$, $a_{\bar{\nu}} = 3.26$. (22)

The factors B_f in (1) are the branching ratios for $\tilde{X}\tilde{X} \to f\bar{f}$ which are determined by the couplings in the particular model studied. We use the Monte Carlo procedure detailed in ref. [15] to model the annihilation events in the sun and calculate the factors

[#7] The estimates (19) correspond to a fraction −0.09(1) ± 0.24(2) of the proton spin being carried by quarks. They also correspond to a singlet/octet matrix element ratio of −0.13(3) ± 0.37(1) times the quark model value previously estimated assuming $\Delta s = 0$.

[#8] Jaffe [27] has pointed out that there could in principle be significant μ-dependence between $\mu^2 = 3$ GeV^2 and $\mu^2 \ll 1$ GeV^2. This is irrelevant to $\sigma(\tilde{\gamma}p \to \tilde{\gamma}p)$, but could invalidate the derivation of the individual Δq in (19). This introduces an uncertainty in the subsequent estimate of $\sigma(\tilde{h}p \to \tilde{h}p)$, which is fortunately not large.

Quark Contributions to Proton Spin

(J.E+Floratos+Ro (EMC) (Glück+Reya (1987))

EMC provides 3rd equation for 3 unknowns

$$\frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right)\left(1 - \frac{\alpha_s(Q^2)}{\pi} + \ldots\right) = 0.126 \pm 0.0$$

solution:

$\Delta u = 0.78 \pm 0.06$, $\Delta d = -0.47 \pm 0.06$, $\Delta s = -0.19 \pm 0.06$

$\neq 0$, x E****-Jaffe

total contribution of quarks to proton spin

$$\Delta u + \Delta d + \Delta s = 0.12 \pm 0.17$$

consistent with zero!

Not a "spin crisis"

No conflict with perturbative QCD

A surprise for non-perturbative QCD

"Its (EJ) verification, or failure, would have a most decisive effect on the direction of future high energy physics."

Anon (1987)

QCD corrections to spin sum rules

Bjorken sum rule:

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{1}{6}|g_A| \times \quad \simeq \Delta u - \Delta d$$

$$\left[1 - \frac{\alpha_s}{\pi} - 3.5833\left(\frac{\alpha_s}{\pi}\right)^2 - 20.2153\left(\frac{\alpha_s}{\pi}\right)^3 - 130\left(\frac{\alpha_s}{\pi}\right)^4 + \cdots\right]$$

$\overline{MS}$, $N_f = 3$ estimate

higher twist small?

$$\delta_{HT}(\Gamma_1^p - \Gamma_1^n) \equiv \frac{C_{HT}}{Q^2} \simeq \frac{0.02 \pm 0.01\ \mathrm{GeV}^2}{Q^2}$$

QCD sum rule

singlet combination:

$$\Delta\Sigma(Q^2) \times \left[1 - \frac{\alpha_s}{\pi} - 1.096\left(\frac{\alpha_s}{\pi}\right)^2 + \cdots\right]$$

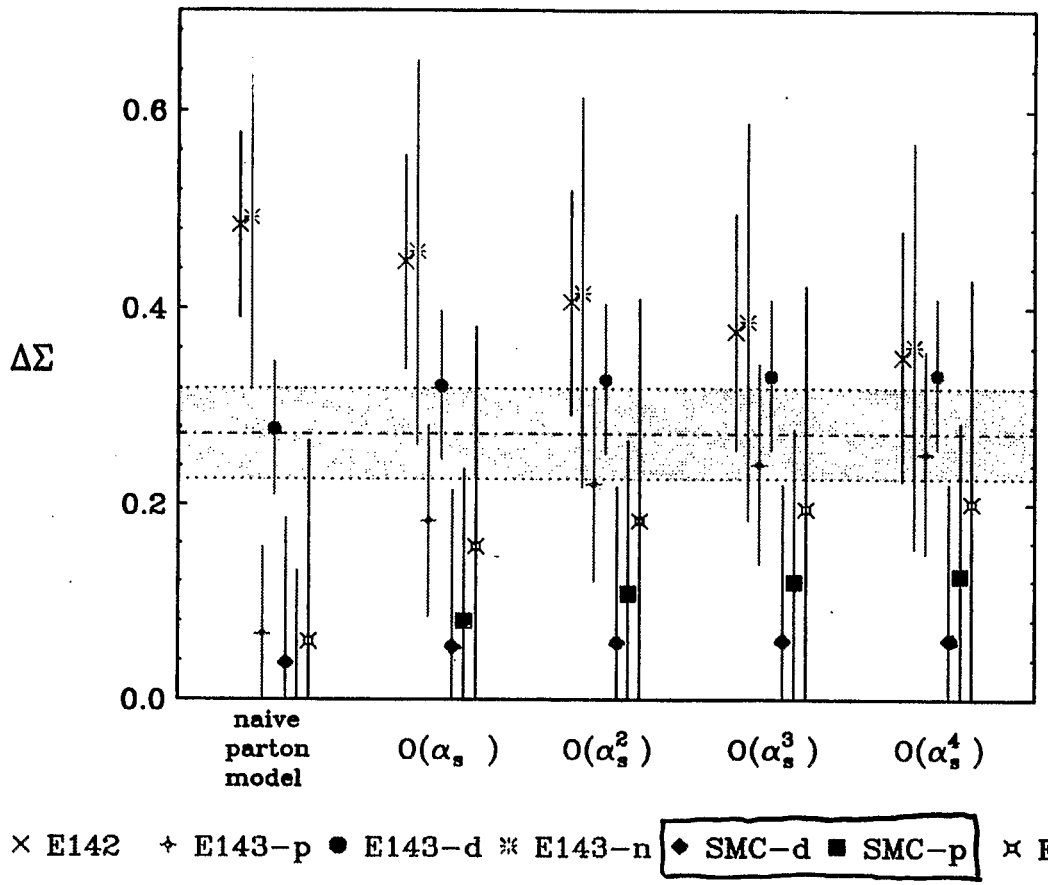
$\overline{MS}$, $N_f = 3$

renormalon in non-singlet combination?

singlet combination has well-behaved series

Proton spin fraction carried by quarks vs. order of QCD pert. theory

better consistency if go to higher orders $O(\alpha_s^{3 \text{ or } 4})$



extracted from $\Gamma_1^{p,n,d}$

average: 0.27 ± 0.05

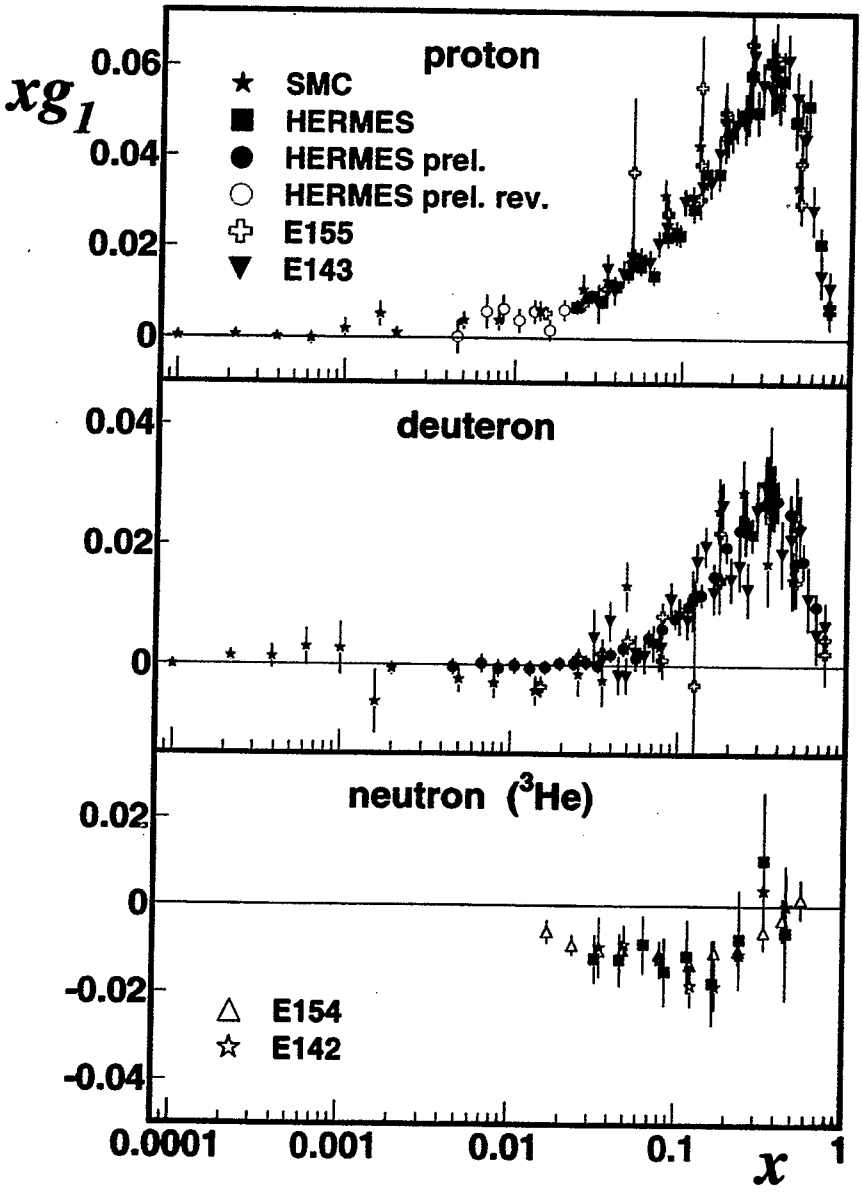
$\chi^2 = 3.9$

all ΔΣ values evolved to Q^2=10 GeV^2

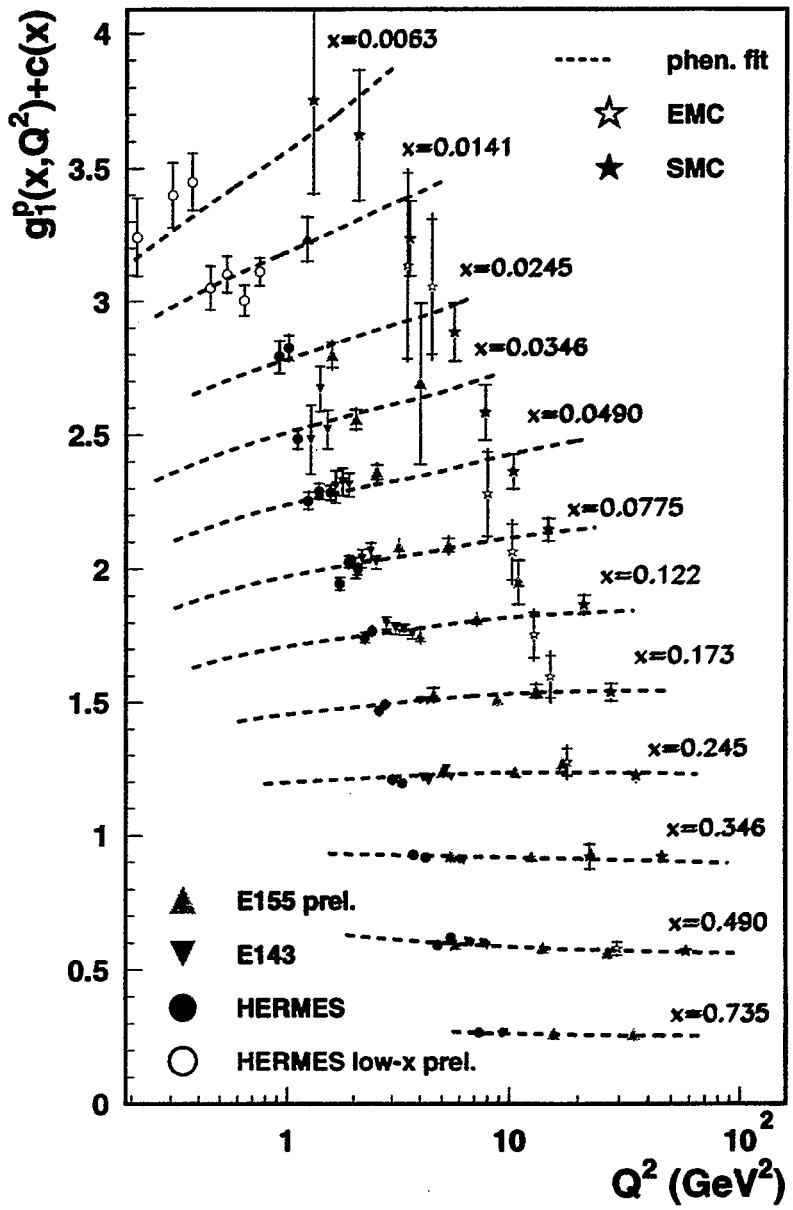
(J.E.+M. Karliner

J. Ellis & M. Karliner
Phys. Lett. B341(1995),397
updated April 1998 for DIS '98

xg_1 WORLD DATA



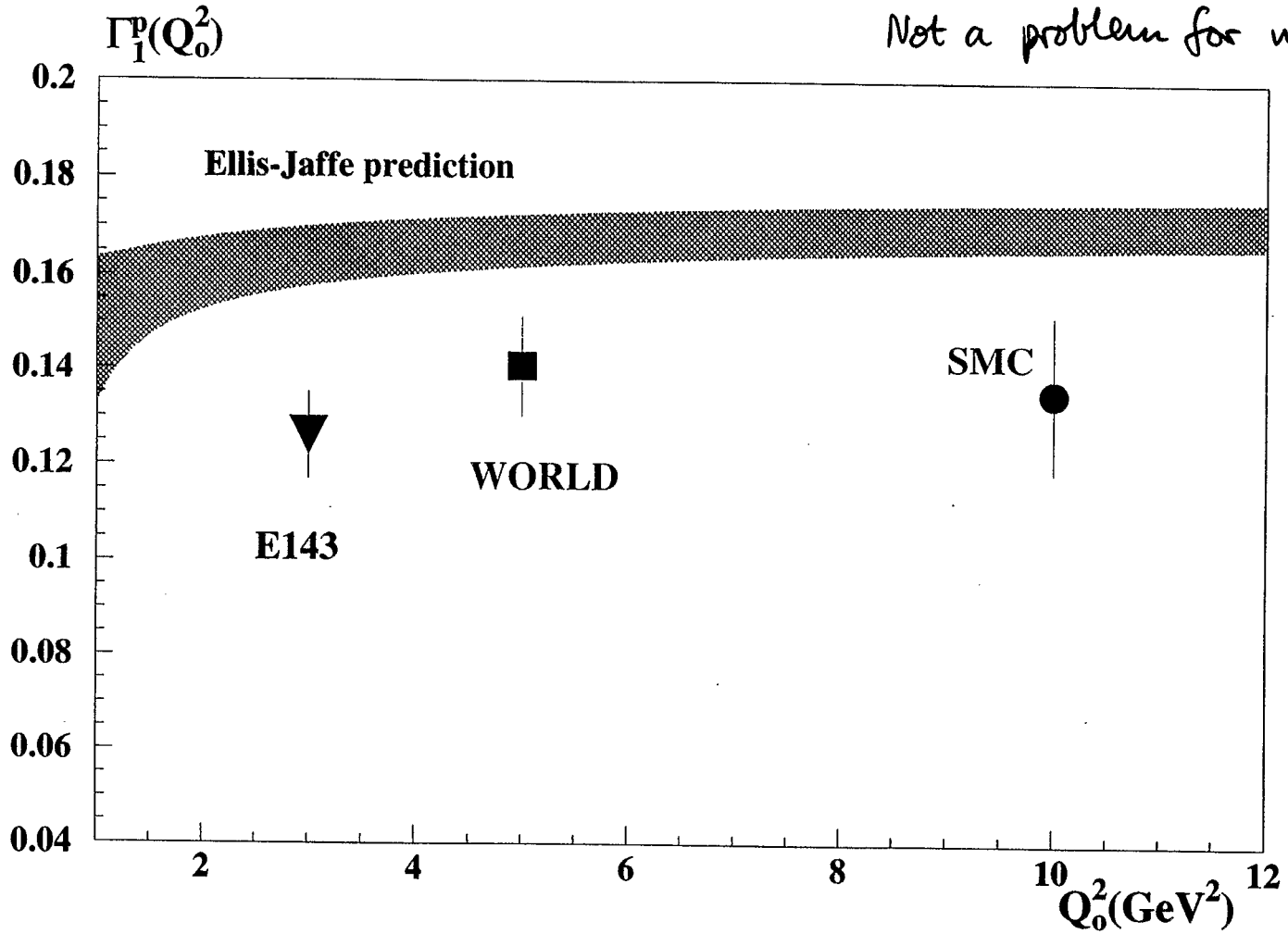
$g_1^{\mathrm{p}}(x)$ vs Q^2



C. Weiskopf, DIS2001

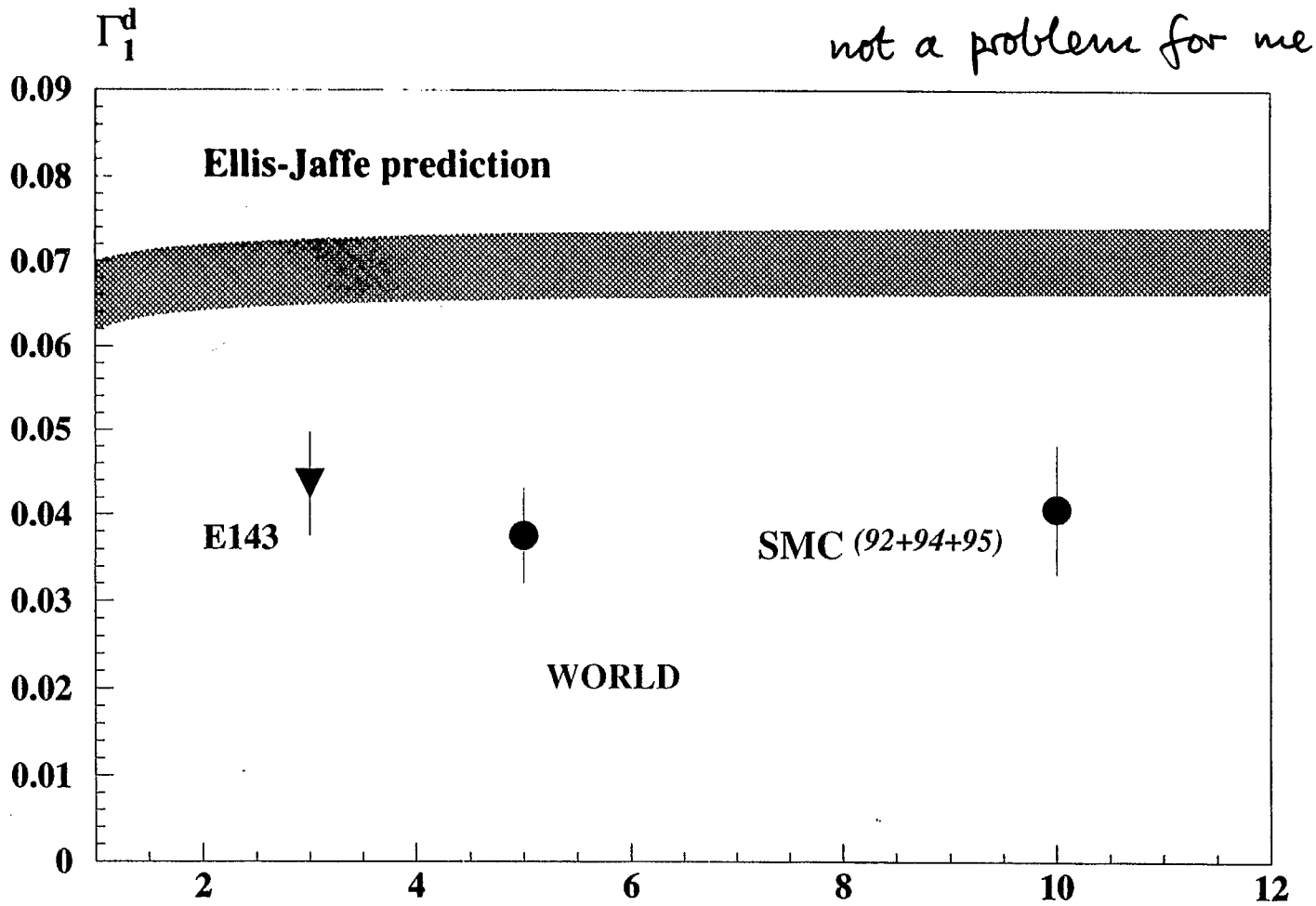
R.I.P. E**** - Jaffe

Not a problem for me!



R.I.P. E**** - Jaffe

not a problem for me!



Analysis of Data

(Altarelli et al.

Bjorken sum rule:

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{1}{6}|g_A|$$

$$\times \left[1 - \frac{\alpha_s}{\pi} - 3.5833\left(\frac{\alpha_s}{\pi}\right)^2 - 20.2153\left(\frac{\alpha_s}{\pi}\right)^3 - 130\left(\frac{\alpha_s}{\pi}\right)^4 - \ldots\right]$$

use world value of α_s to extract

$$g_A = 1.18 \pm 0.09 \qquad \text{cf } 1.257 \pm 0.003$$

or use value of g_A to extract

$$\alpha_s(M_Z) = 0.120 \underset{-0.005}{+0.004} \underset{-0.006}{+0.009}$$

(exp) (theory)

Singlet current matrix element:

$$a_0(\infty) = 0.10 \pm 0.05 \underset{-0.10}{+0.17}$$

(exp) (theory)

$\ll 1$ consistent with zero

First moment of gluon spin

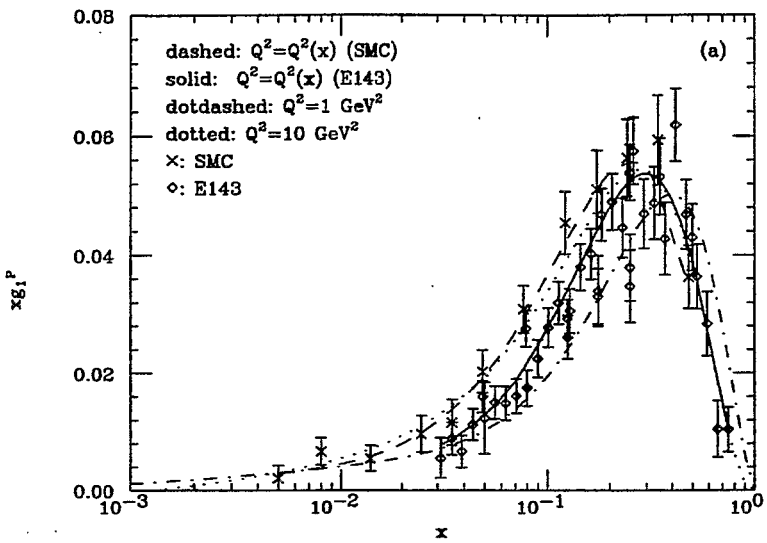
$$\Delta G = 1.6 \pm 0.4 \pm 0.8$$

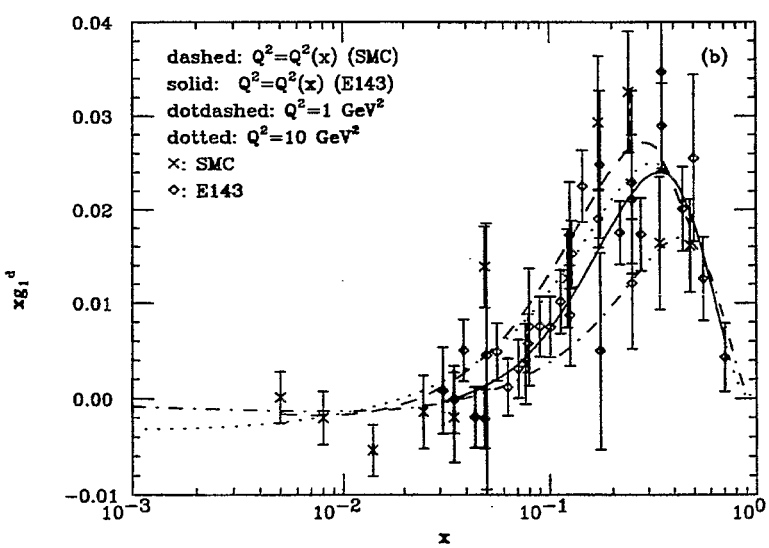
(exp) (theory)

from QCD fit to polarized structure functions

is ΔG really $\neq 0$?

QCD Fits to Polarized Structure Functions





(Altarelli et al.

Compilation of results on Δs

polarized DIS:

$$\Delta s = -0.10 \pm 0.02$$

"impossible that $\Delta s > 0$": Leader + Stamenov hep-ph/0211083

elastic νN:

$$\Delta s = -0.15 \pm 0.07 \pm ?$$ (Garvey et a

large systematic error?

baryon magnetic moments:

$$\Delta s = -0.19 \pm 0.05$$ (Gerasimov

model-dependence?

lattice calculations:

$$\Delta s = -0.12 \pm 0.01$$ (Dong et al

$$-0.109 \pm 0.030$$ (Fukugita et a

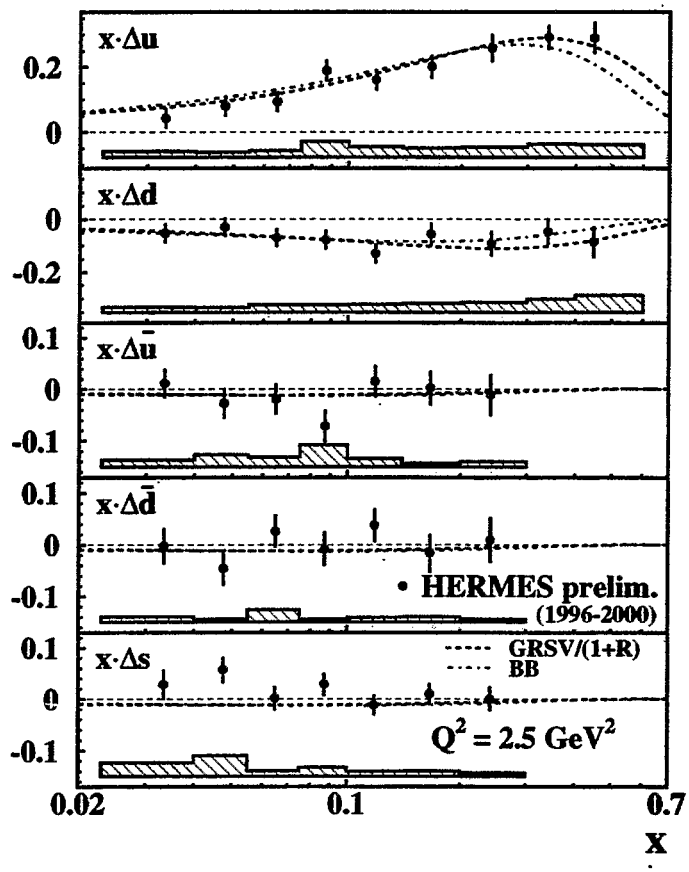
DIS final states:

$$\Delta s > 0$$ (HERMES

BUT "neglect some hadron production mechanisms

(Kotzinian

HERMES flavor decomposition



H. E.Jackson, hep-ex/0208015,
Int.J.Mod.Phys.A17:3551-3570,2002

- Light sea quarks are not significantly polarized
- Strange sea appears to be positively polarized

Soliton Interpretation

(Brodsky + J.E. + Karliner

chiral symmetry $\Rightarrow$ PCAC

$$\langle X | A_\mu | Y \rangle \simeq \langle 0 | A_\mu | P \rangle \, g_{PXY}$$

coupling

pseudoscalar meson: π, K, η_8

baryon as chiral soliton (Skyrmion) is lump of

$$U = \exp\left[\frac{2i}{f_P} \underline{P} \cdot \underline{\tau}\right]$$

$\langle 0 | A_\mu | P \rangle$ $\qquad$ $SU(N_f)$

does not contain singlet meson η_0

hence $\quad g_{0B\bar{B}} = 0$

hence $\quad \langle B | A^0_\mu | B \rangle = 0$

hence $\quad \Delta u + \Delta d + \Delta s = 0$

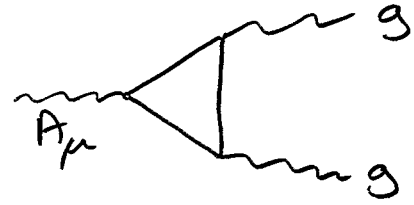
BUT corrections $\propto$ quark masses

also higher orders in $1/N_c$

Anomalous U(1) interpretation

(Efremov + Teaer
(Altarelli + Ross
(Carlitz + Collins
Muelle

axial anomaly:



$$\partial^\mu A_\mu \ni F_a^{\mu\nu} \epsilon_{\mu\nu\rho\sigma} F_a^{\rho\sigma}$$

should modify singlet axial current

$$\langle p | A^0_\mu | p \rangle = \langle p | \bar{u} \gamma_\mu \gamma_5 u + \bar{d} \gamma_\mu \gamma_5 d + \bar{s} \gamma_\mu \gamma_5 s | p \rangle$$

$$= \Delta u + \Delta d + \Delta s$$

proposed interpretation:

$$\Delta q \to \Delta \tilde{q} = \Delta q - \frac{\alpha_s}{2\pi} \Delta G$$

can preserve naïve OZI expectation: $\Delta s = 0$

if ΔG quite large and > 0

$$\underset{<0}{\Delta \tilde{s}} = \underset{\simeq 0}{\Delta s} - \frac{\alpha_s}{2\pi} \underset{>0}{\Delta G}$$

Chiral soliton vs axial anomaly?

- reason why $\sum_q \Delta q \ll 1$

  all proton angular momentum orbital

- predicts $\Delta s < 0$

whereas

- gluon contribution to Δq depends on renormalization scheme
- no particular reason why $\sum_q \Delta q \ll 1$
- 'peculiar' decomposition of proton spin:

  $\Delta G \gg \frac{1}{2}$ must be compensated by L_z

experimental question!

need direct probes of ΔG, L_z

17- Strange matrix elements in proton

operators $\langle p | \bar{s} \Gamma s | p \rangle$

<u>momentum</u>: $\Gamma = \frac{1}{2}\{\gamma_\mu, \gamma^\nu\}$

$\nu + s \to \mu + c$

$$\int_0^1 dx\, x\,(s(x) + \bar{s}(x)) = 0.04$$

(also $\gamma + s \to \phi$)

$\sim \frac{1}{2}$ of fraction in sea u or d quarks

<u>scalar</u>: $\Gamma = 1$

$$y_N \equiv \frac{2\langle p|\bar{s}s|p\rangle}{\langle p|\bar{u}u + \bar{d}d|p\rangle}$$

can be extracted from πN scattering σ term

$y_N = 0.2 \pm 0.1$ (?) (Gasser + Sainio: hep-ph/0002283

but could be larger:

lattice: $y_N = 0.39$ to 0.59 (Dong et al. (Gusken et al.

new σ-term analysis:

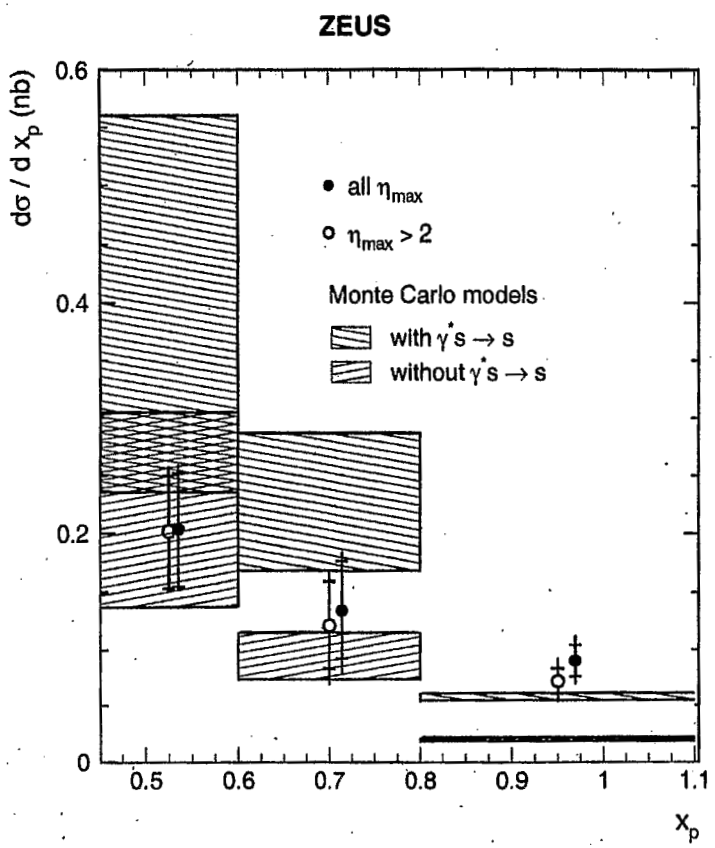
$y_N = 0.36$ to 0.48 (Pavan et al.: hep-ph/0111066

Recall large <u>density in vacuum</u>:

$\langle 0|\bar{s}s|0\rangle = (0.8 \pm 0.1)\langle 0|\bar{u}u + \bar{d}d|0\rangle$ (QCD sum rule

BUT <u>em form factors</u> $G_E^s + 0.39\, G_M^s = 0.016 \pm 0.049$ (HAPPEX

Leading $\phi(1020)$ mesons in the current region

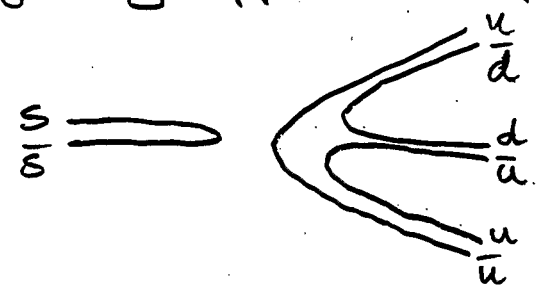


- Any additional gluon emissions are not important for x_p >0.8 and the scattering is given by the well-understood process, $\gamma^* s \to s$
- Cross sections are for the inclusive DIS and with removed a diffractive contribution ($\eta_{max} > 2$)
- The hatched bands represents uncertainties in the simulation of the $\phi(1020)$ mesons production (λ_s=0.2-0.3) with the CTEQ5D parton density
- High-momentum ϕ mesons (x_p >0.8) in the current region of the Breit frame give clear evidence for the strange sea in the proton.

Okubo-Zweig-Iizuka rule

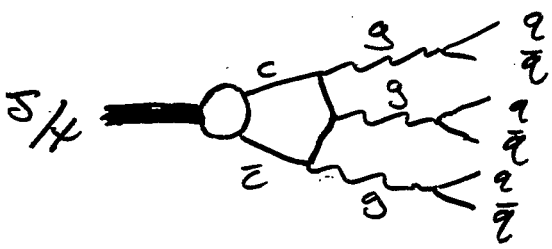
disconnected quark diagrams suppressed

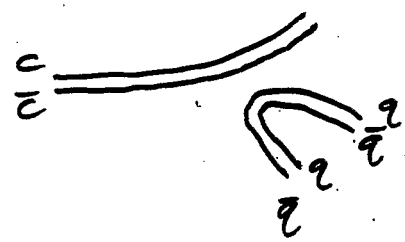
originally applied to explain small $\Gamma(\phi \to 3\pi)$



became popular to explain small $\Gamma(J/\psi \to \text{hadrons})$

$\Gamma(\psi' \to J/\psi\, \pi\pi)$





orders of magnitude:

$$\frac{g^2_{\phi 3\pi}}{g^2_{\omega 3\pi}} \sim 10^{-2} \; ; \; \frac{g^2_{f'\pi\pi}}{g^2_{f\pi\pi}} \sim 10^{-3} \; ; \; \frac{\Gamma_{J/\psi}}{\Gamma_{had}} \sim 10^{-3} \; ; \; \frac{\Gamma_{J/\psi\pi\pi}}{\Gamma_{had}} \sim 10^{-2}$$

not so well checked for baryons...

(J.E. + Erwin + Karliner

2- The OZI rule does not apply to baryons

evidence for non-trivial $\bar{s}s$ in nucleon

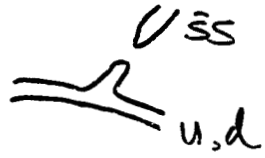
πN scattering (σ term) $\Rightarrow$ $\dfrac{\langle p|\bar{s}s|p\rangle}{\langle p|\bar{u}u+\bar{d}d+\bar{s}s|p\rangle} \simeq 0.2$

EMC et al. $\Rightarrow$ $\Delta s \neq 0$

motivates evasion of OZI rule

disconnected quark diagrams suppressed

$\underset{u,d}{\supset\!\!\supset}$ $\underset{s}{\subset}$ $\to 0$ cf ϕ production



ϕ wave function contains $\sim 7\times10^{-3}(\bar{u}u+\bar{d}d)$

expect suppressed ϕ production rate

$$\frac{\sigma(p,n,\pi \to \phi X)}{\sigma(p,n,\pi \to \omega X)} \sim 4\times10^{-3}$$

violated at different levels in different experiments, particularly $\bar{p}p \to \phi X$ at rest

OZI or not OZI?

$$Z \equiv \frac{\sqrt{2}\, M(A+B+C+\bar{s}s)}{M(A+B\to C+\bar{u}u)+M(A+B\to C+\bar{d}d)} = 0$$

if A, B, C contain no strange quarks

ϕ production still possible via OZI-allowed diagrams, because $\phi \ni \bar{u}u + \bar{d}d$:

$$|\phi\rangle = -\cos\Delta\theta\,|\bar{s}s\rangle + \sin\Delta\theta\,|\bar{q}q\rangle$$

$$|\omega\rangle = \cos\Delta\theta\,|\bar{q}q\rangle + \sin\Delta\theta\,|\bar{s}s\rangle$$

departure from ideal mixing can be estimated from masses: $\tan^2(\underbrace{\theta_i}_{35.3^\circ}+\Delta\theta) = \frac{m_\phi^2 - m_{\omega_8}^2}{m_{\omega_8}^2 - m_\omega^2}$; $m_{\omega_8}^2 = \frac{4m_{K^*}^2 - m_\rho^2}{3}$

including departure from ideal mixing:

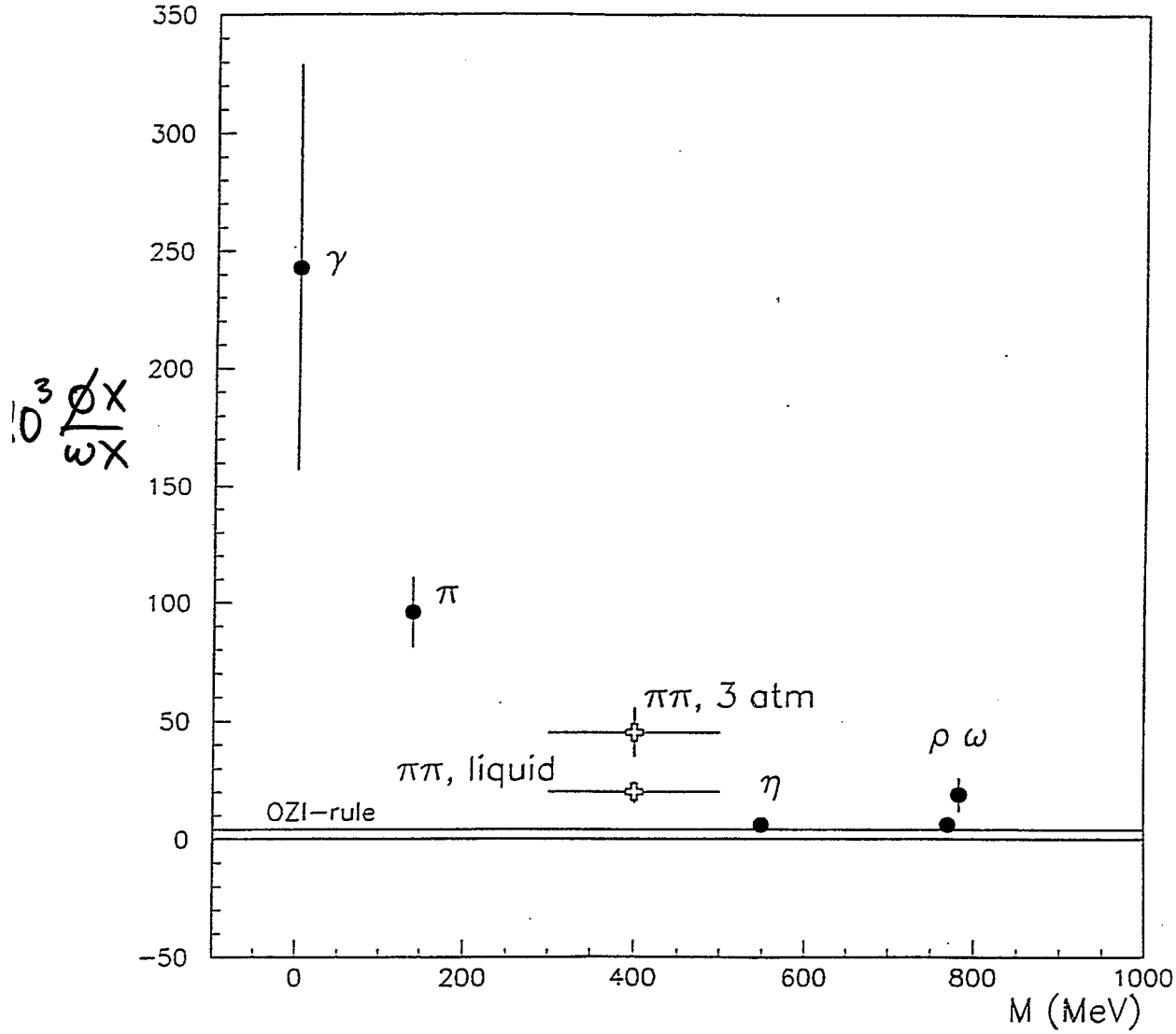
$$\left|\frac{M(A+B\to C+\phi)}{M(A+B\to C+\omega)}\right|^2 = \left|\frac{Z+\tan\Delta\theta}{1-Z\tan\Delta\theta}\right|^2 \to \tan^2\Delta\theta \simeq 4.2\times10^{-3}$$

if $Z=0$

similarly for $f_2'(1525)$ production:

$$\frac{\sigma(A+B\to C+f_2'(1525))}{\sigma(A+B\to C+f_2(1270))} \to 16\times10^{-3}$$

$\phi X / \omega X$ Production Ratios



updated

(EKKS)

$\bar{p}p \to \phi\pi^0$ depends on target density

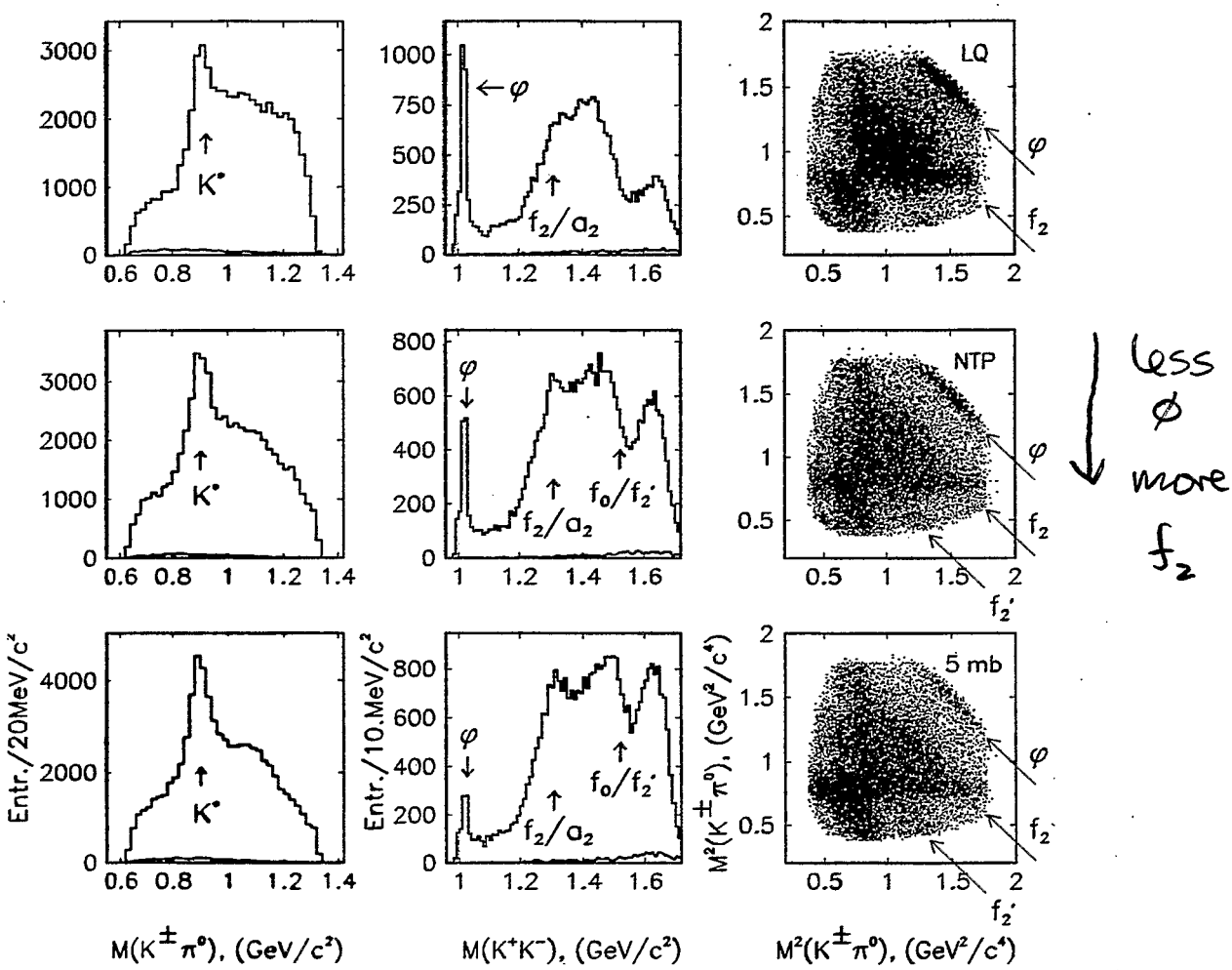
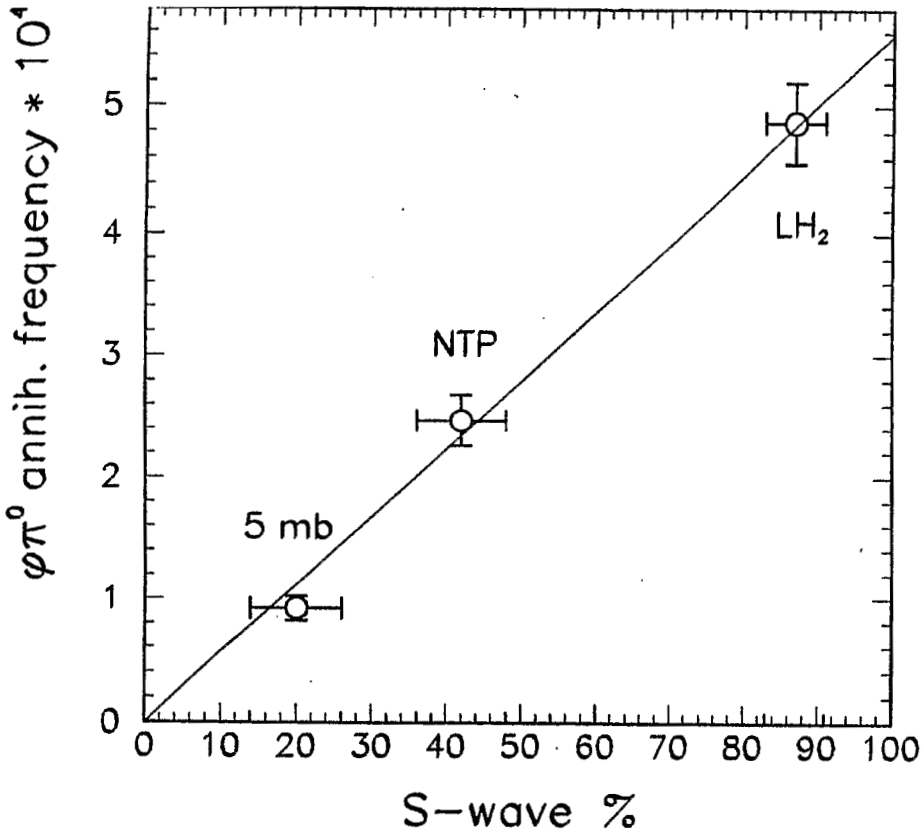


Figure 6: Invariant mass distributions of the K^+K^- (middle columns) and $K^\pm\pi^0$ (left) systems and Dalitz plots (right) for reaction $\bar{p}p \to K^+K^-\pi^0$ at three different target densities: for the liquid target (up line), for the gas target at NTP (middle line) and for the gas target at 5 mb (bottom line) [48].



$\bar{p}p \to \phi\pi^0$ depends on angular momentum

$^3S_1 \gg {}^1P_1 \simeq OZI$

Figure 7: Dependence of the $\bar{p}p \to \phi\pi^0$ annihilation frequency on the percentage of annihilation from the S-wave [48]. The values of the S-wave percentage at different target densities are from [86] .

R.I.P. OZI

Table 1: The ratio $R = \phi X/\omega X$ of the cross sections for production of ϕ and ω - mesons in pp, $\bar{p}p$ and πp interactions. P_L is the momentum of the incoming particle. Z is the parameter of the OZI–rule violation. No corrections on the phase space volume difference were made except the cases marked *).

magnitude of OZI-violating (-evading) amplitude

Initial state	P_L (GeV/c)	Final state X	$R = \phi X/\omega X \cdot 10^3$	$\lvert Z\rvert$ (%)	Refs.
$\pi^+ n$	1.54-2.6	p	21.0 ± 11.0	8 ± 4	[26],[27]
$\pi^+ p$	3.54	$\pi^+ p$	19.0 ± 11.0	7 ± 4	[28]
$\pi^- p$	5-6	n	3.5 ± 1.0	0.5 ± 0.8	[29]
$\pi^- p$	6	n	3.2 ± 0.4	0.8 ± 0.4	[30]
$\pi^- p$	10	$\pi^- p$	6.0 ± 3.0	1.3 ± 2.0	[31]
$\pi^- p$	19	$2\pi^-\pi^+ p$	5.0^{+5}_{-2}	0.6 ± 2.5	[32]
$\pi^- p$	32.5	n	2.9 ± 0.9	1.1 ± 0.8	[33]
$\pi^- p$	360	X	14.0 ± 6.0	5 ± 3	[34]
pp	10	pp	20.0 ± 5.0	8 ± 2	[31]
pp	24	pp	26.5 ± 18.8	10 ± 6	[35]
pp	24	$\pi^+\pi^- pp$	1.2 ± 0.8	3 ± 1	[35]
pp	24	pp m$\pi^+\pi^-$, m=0,1,2	19.0 ± 7.0	7 ± 3	[35]
pp	70	pX	16.4 ± 0.4		[36]
pp	360	X	4.0 ± 5.0	0.1 ± 4	[37]
$\bar{p}p$	0.7	$\pi^+\pi^-$	19.0 ± 5*)	7 ± 2	[38]
$\bar{p}p$	0.7	ρ^0	13.0 ± 4*)	5 ± 2	[38]
$\bar{p}p$	1.2	$\pi^+\pi^-$	$11.0 \pm^{+3}_{-4}$	4 ± 1	[39]
$\bar{p}p$	2.3	$\pi^+\pi^-$	17.5 ± 3.4	7 ± 1	[40]
$\bar{p}p$	3.6	$\pi^+\pi^-$	9.0^{+4}_{-7}	3 ± 3	[39]

Table 2: The ratio $R = f_2'(1525)X/f_2(1270)X$ of the cross sections for production of $f_2(1270)$ and $f_2'(1525)$ - mesons. P_L is the momentum of the incoming particle. In some cases, marked by *) , the cross section of $f_2(1270)$ was not separated from the production of $a_2(1320)$ and the sum of these cross sections is given.

Initial state	P_L , GeV/c	Final state X	$R(f_2'/f_2) \cdot 10^3$	Ref.
$\pi^- p$	100.0	n	1.5 ± 0.7	[42]
$\pi^- p$	10.0	n	44 ± 10	[43]
$\bar{p}p$	0	π^0	26 ± 10	[3]
$\bar{p}p$	2.32	$\pi^+\pi^-$	21 ± 10*)	[44]
$\bar{p}n$	2.3	π^-	< 15	[45]
$\bar{p}p$	$1.5 - 2.0$	$\pi^+\pi^-$	28 ± 9*)	[46]
$\bar{p}p$	$7.02 - 7.57$	π^0	64 ± 28*)	[47]

also excess of $f_2' = (\bar{s}s)_{2^{++}}$ production? (Samoshin, Witkow

Features to be explained

(J.E. + M. Karliner + Kharzeev + Sapozhnikov)

1 - Non-universal enhancement factors

strong for $\phi\pi$, $\phi\gamma$

smaller for $\phi\rho$, $\phi\omega$, $\phi\pi\pi$

none for $\phi\eta$

2 - Smaller enhancements in

πp, pp scattering

higher-energy $\bar{p}p$ annihilation

3 - Where initial $\bar{p}p$ state is known:

large enhancements in S wave: π, $\pi\pi$

none in P wave

[Any model of OZI $\left\{\begin{matrix}\text{violation}\\ \text{evasion}\end{matrix}\right\}$ should predict or accommodate these channel-dependent features

Model for OZI evasion

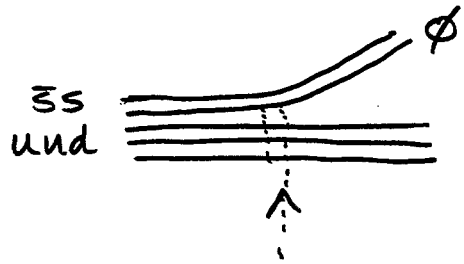
(J.E.+Gabathuler+Karliner
(J.E.+Karliner+Khazeev
+Sapozhnikov

$\bar{s}s$ component in nucleon wave function

$$|p\rangle = |uud\rangle + \epsilon\,|(uud)(\bar{s}s)\rangle + \cdots$$

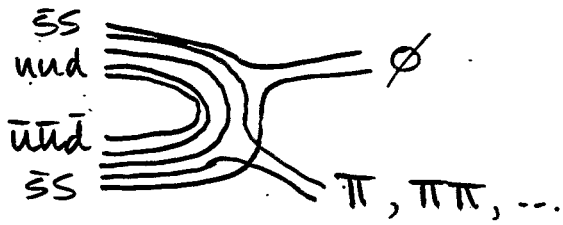
new possibilities for ϕ production in collisions

<u>shake-out</u>



no obvious pattern of non-universality for $\frac{\phi X}{\omega X}$

<u>rearrangement</u>



$\frac{\phi X}{\omega X}$ depends on relative state of $\bar{s}s$

depends on relative state of $\bar{p}p$

expect largest enhancement in $^3S_1$ of $\bar{p}p$

maximize probability of $^3S_1$ of $\bar{s}s = \phi$

$\Rightarrow$ suppressed production in $^1P_1$ of $\bar{p}p$

@ higher energies

more partial waves

Quantum numbers of $\bar{s}s$ system?

plausible candidates: cf low-lying mesons

$$J^{PC} = 0^{-+}, 1^{--}, 0^{++}$$

0^{-+}? would expect large, universal deviation from OZI due to shake-out for $\eta_{\bar{s}s}$

1^{--}? would expect large, universal deviation from OZI due to shake-out for ϕ

neither effect seen

0^{++}? present in QCD vacuum:

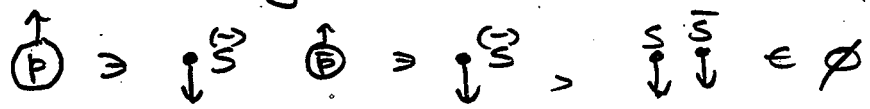
$$\langle 0|\bar{s}s|0\rangle = (0.8 \pm 0.1)\langle 0|\begin{matrix}\bar{u}u\\ \bar{d}d\end{matrix}|0\rangle$$

relatively easy to excite?

(J.E. + Karliner + Khazzeev + Sapozhnikov)

Predictions of polarized $\bar{s}s$ model

- $\bar{p}p \to \phi\pi$ mainly from S-wave



- reduction in $\phi\pi/\omega\pi$ as energy increases
- $\bar{p}p \to \phi\phi$ large in spin-triplet states
- $\bar{p}p \to f'(1525)\pi$ mainly from P-wave
- large ratio $p+p \to p+p+\phi / p+p+\omega$
- large ratio $\bar{p}+d \to \phi+n/\omega+n$ (Pontecorvo reaction)
- polarization of Λ in target fragmentation region of ν, μ, e deep-inelastic scattering

OZI 'Violation' in other channels

$$\frac{\sigma(\bar{p}p \to f_2'(1525)\pi^0)}{\sigma(\bar{p}p \to f_2(1270)\pi^0)} = \begin{cases} 47 \pm 14 \\ 149 \pm 20 \end{cases} \times 10^{-3} \quad \begin{matrix} \text{S-wave} \\ \text{P-wave} \end{matrix}$$

(OBELIX

also $(26 \pm 10) \times 10^{-3}$ S-wave

(Xtal barrel

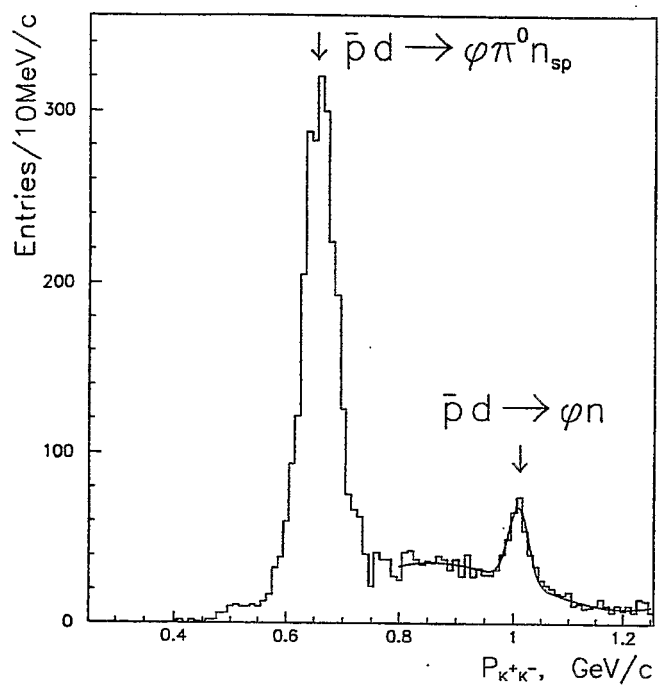
large OZI violation in P-wave?

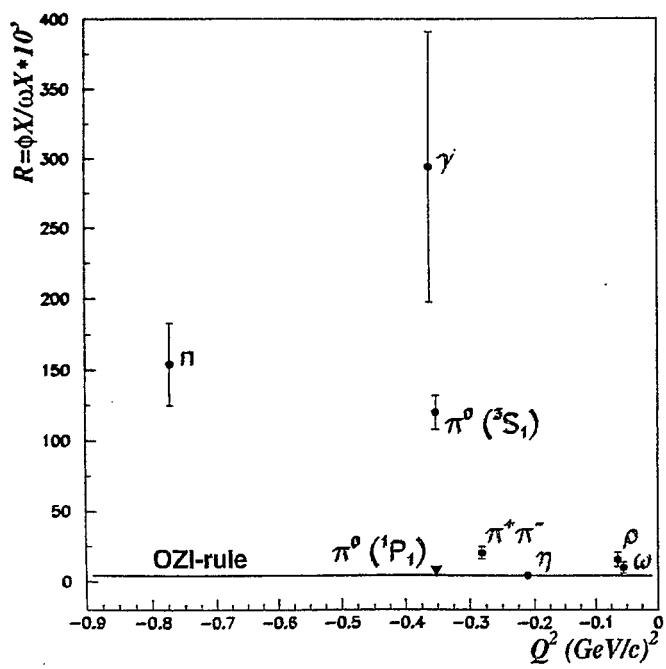
$$\sigma(\bar{p}p \to \phi + \phi) = (2 \text{ to } 4)\ \mu b$$

cf $\sigma(\bar{p}p \to \omega + \omega) \sim 0.5$ mb

naive OZI $\Rightarrow$ $\dfrac{\sigma(\phi\phi)}{\sigma(\omega\omega)} \simeq \tan^4 \Delta\theta \Rightarrow 10$ nb!

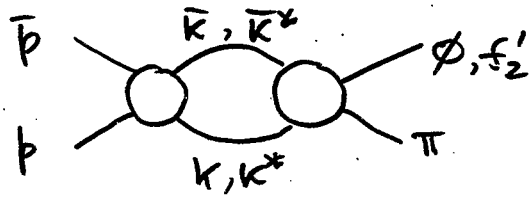
ϕ production in Pontecorvo reaction





among the largest deviations from OZI rule

OZI 'Violation' due to rescattering?



(Locher et al.

difficulties:

- does not explain differences in $\phi\pi$ partial waves
  $\phi/\omega\ (^3S_1) \gg (^1P_1)$
- different energy dependences of KK^*, $\phi\pi$
- does not explain large ratio $f_2'\pi / f_2\pi$
- does not explain large rate in Ponteconvo reaction:

$$\frac{\bar{p}d \to \phi n}{\bar{p}d \to \omega n} = (192 \pm 27) \times 10^{-3}$$

because $\sigma(\bar{p}d \to \Sigma K) \sim \sigma(\bar{p}d \to \Lambda K)$

+ yields too small

theoretically:

- need to include many intermediate states, $\sim 10{,}000$?
because of delicate cancellations

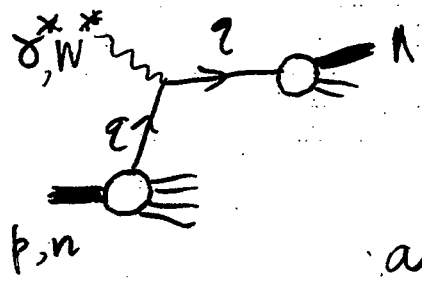
3- Λ production in deep-inelastic scattering

(J.E. + Khazeev + Kotzinian (+ Naumov)

decay $\to p\pi^-$ analyzes polarization

remembers polarization of struck quark

current fragmentation region

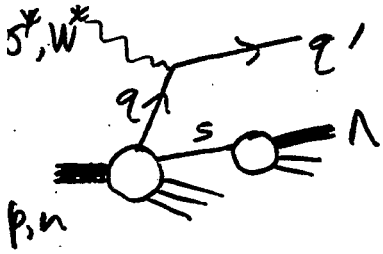


most important contribution:

$$u, d_\uparrow \to \Lambda_\uparrow = (sud)_\uparrow$$

also $e^+e^- \to Z \to \bar{q}q \to \Lambda$

target fragmentation region



contribution from spectator

$$|p,n\rangle_\uparrow \ni |(qqq)_\uparrow (\bar{s}s)_\downarrow\rangle$$

deep inelastic scattering removes $q_\uparrow$

$$s_\downarrow \to \Lambda_\downarrow$$

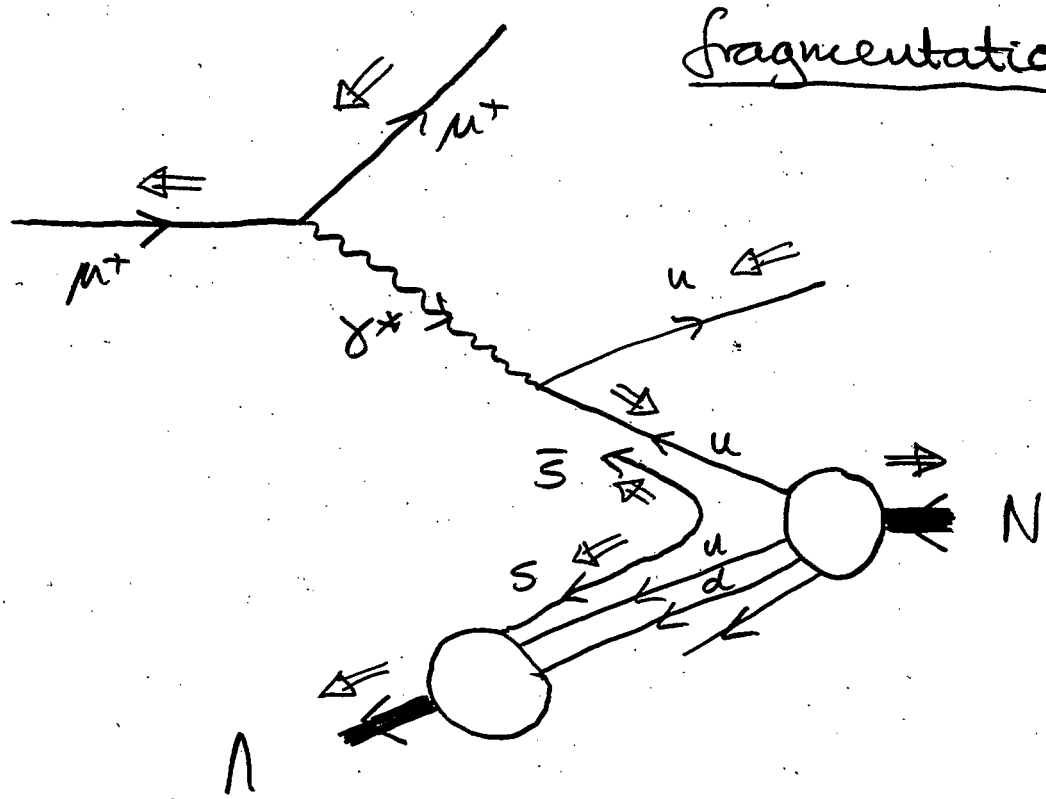
relies on (negative) correlation between polarizations of struck quark and spectator strange quark

possible models:

$$|p\rangle_\uparrow = |(uud)_\uparrow (s\bar{s})_\downarrow\rangle \qquad |p\rangle_\uparrow = |u_\uparrow (s\bar{s})_\downarrow u_\uparrow d_\downarrow\rangle + |d_\downarrow (s\bar{s})_\uparrow u_\uparrow u_\uparrow\rangle$$

preferred by NOMAD data

Mechanism for Λ polarization in target fragmentation



⇐ polarization vectors

⇒

← momenta

→

Model for Λ polarization in target fragmentation

(J.E. + Khazeev + Kotzinian

proton wave function:

$$|p\rangle = v \sum_{x=0}^{\infty} |uud, x\rangle + \sqrt{1-v^2} \sum_{x=0}^{\infty} |uud, \bar{s}s, x\rangle$$

assume spin-correlation: $s\,(\bar{s}) \Leftrightarrow$ struck quark

$$c_{sq} \equiv \frac{P_{s/\!/q} - P_{s\not/\!/q}}{P_{s/\!/q} + P_{s\not/\!/q}}$$

probability antiparallel

probability parallel

net longitudinal polarization of remnant s:

in νN: $$P_s = \frac{\sum_q c_{sq} N_q - \sum_{\bar{q}} c_{s\bar{q}} N_{\bar{q}}}{N_q + N_{\bar{q}}}$$

assume 100% anticorrelation: $c_{sq_{valence}} = -1$

final-state Λ polarization

$$P_\Lambda = D_F P_s$$

early νN data $\Rightarrow$ dilution factor $= 0.55$ to 0.90

in μ or e DIS:

$$P_s = \frac{\sum_q e_q^2 \left[P_T \Delta q(x) - P_B D(y) q(x)\right] c_{sq}}{\sum_q e_q^2 \left[q(x) - P_B P_T D(y) \Delta q(x)\right]}$$

$$D(y) = \frac{1-(1-y)^2}{1+(1-y)^2}$$

beam polarization

target polarization

Λ polarization predictions for COMPASS

(J.E. + Kotzinian + Naumov

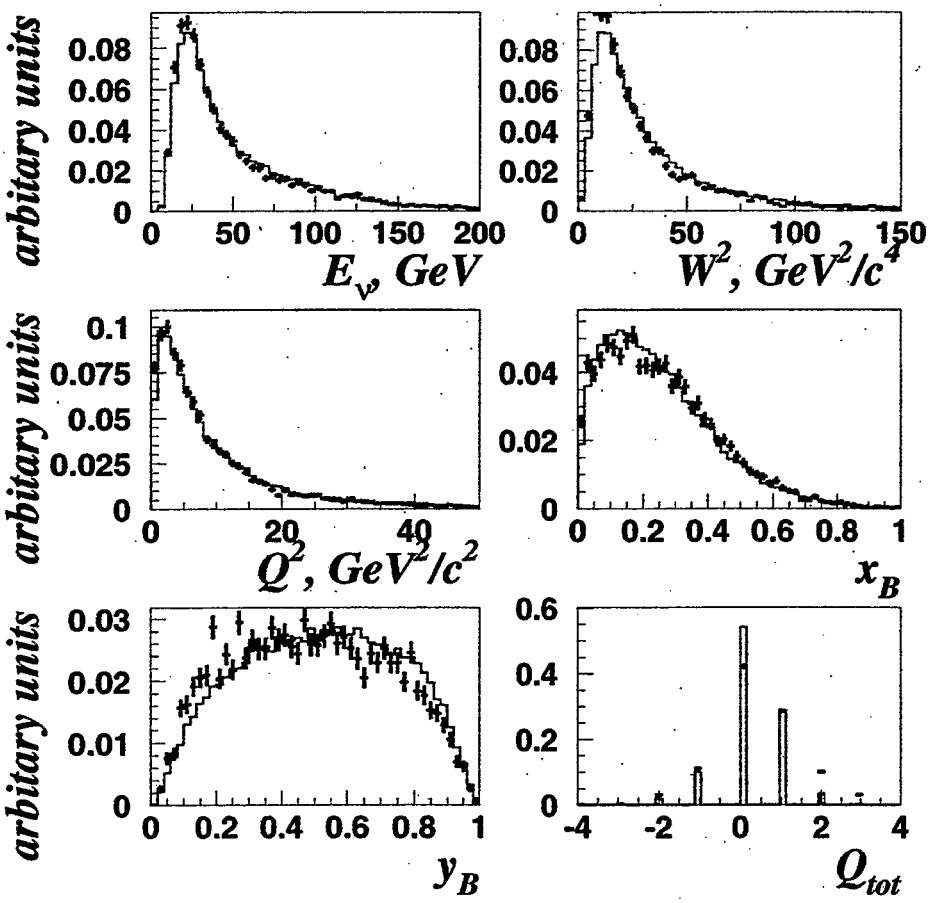
- Based on Lund JETSET Monte Carlo
- Two variants used

  how seriously does one take tagging given by JETSET : A: completely / B: partially
- Parameters fixed using NOMAD data
- Predictions for:

μ^+ DIS, $Q^2 > 1$ GeV^2, $x_F > -0.2$, $0.5 < y < 0.9$

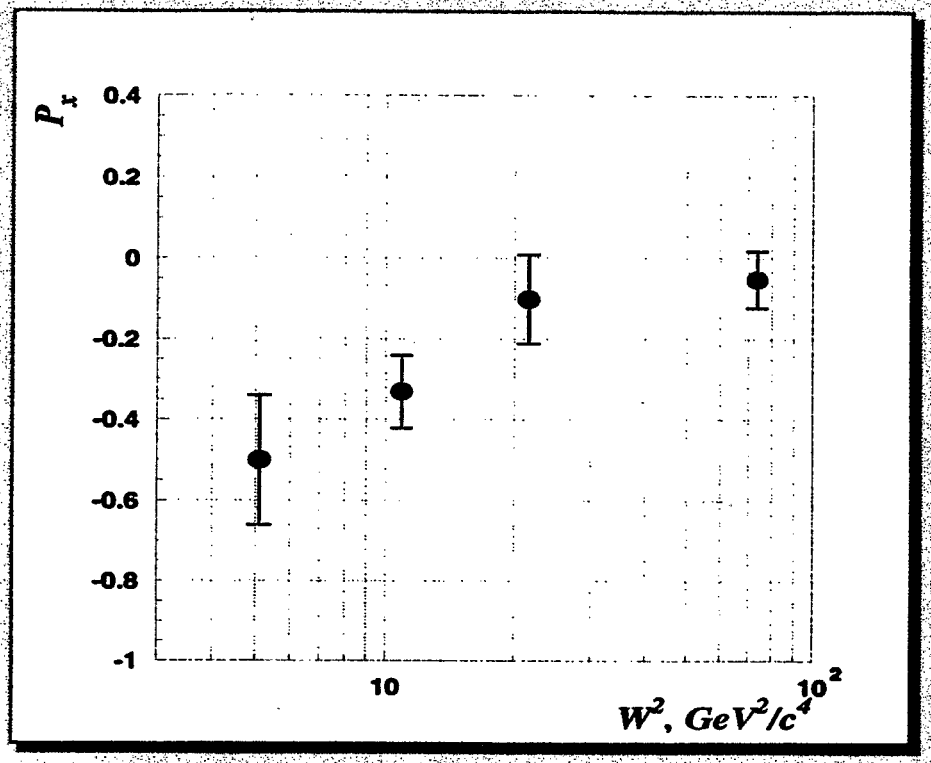
	Target		
P_L^Λ (%)	isoscalar	proton	neutron
A	−6.3	−6.1	−6.6
B	−3.0	−3.1	−2.8

Λproduction at NOMAD



DIS variable distribution in NOMAD ν_μ CC data and MC (green line)

Longitudinal polarization: $x_F < 0$



W^2 dependence:

- smaller $W^2 \Rightarrow$ better chance for Λ to get the s-quark from the *nucleon sea*
- similar dependence on Q^2
- *polarized* strangeness inside the nucleon is favoured

Results

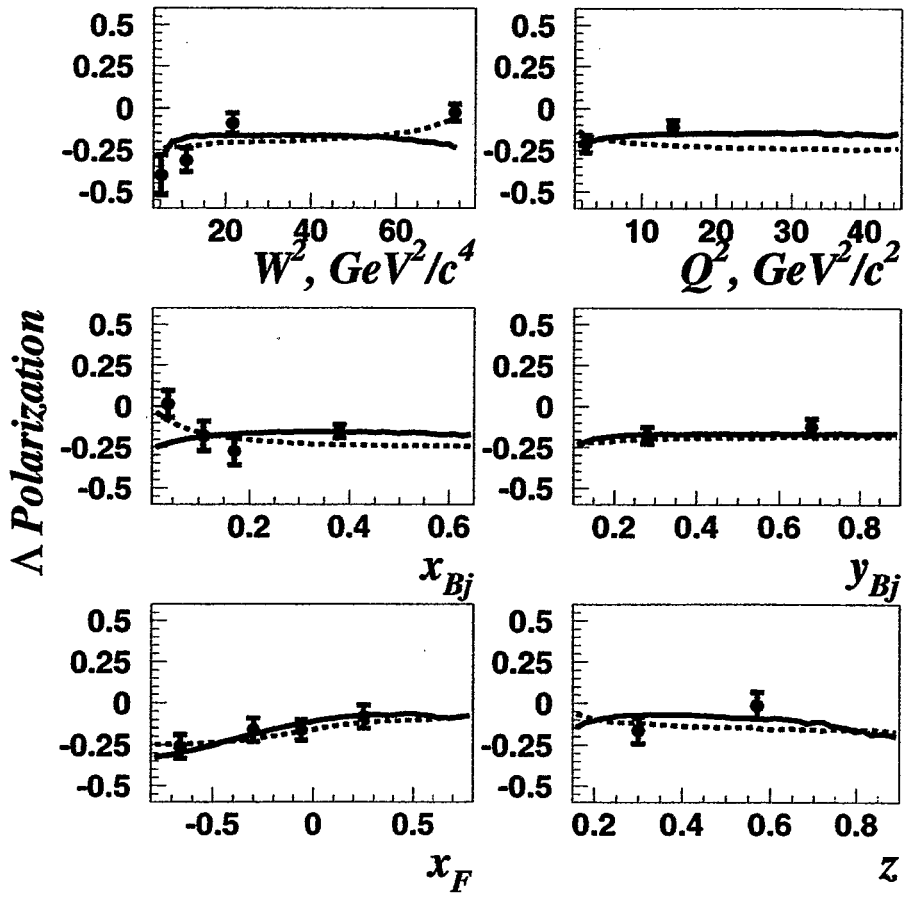


Figure 3: Our model predictions (model A - solid line, model B - dashed line) for polarization of Λ hyperons produced in ν_μ charged current DIS interactions off nuclei as functions of W^2, Q^2, x_{Bj}, y_{Bj}, x_F and z (at $x_F > 0$). The points with error bars are from NOMAD.

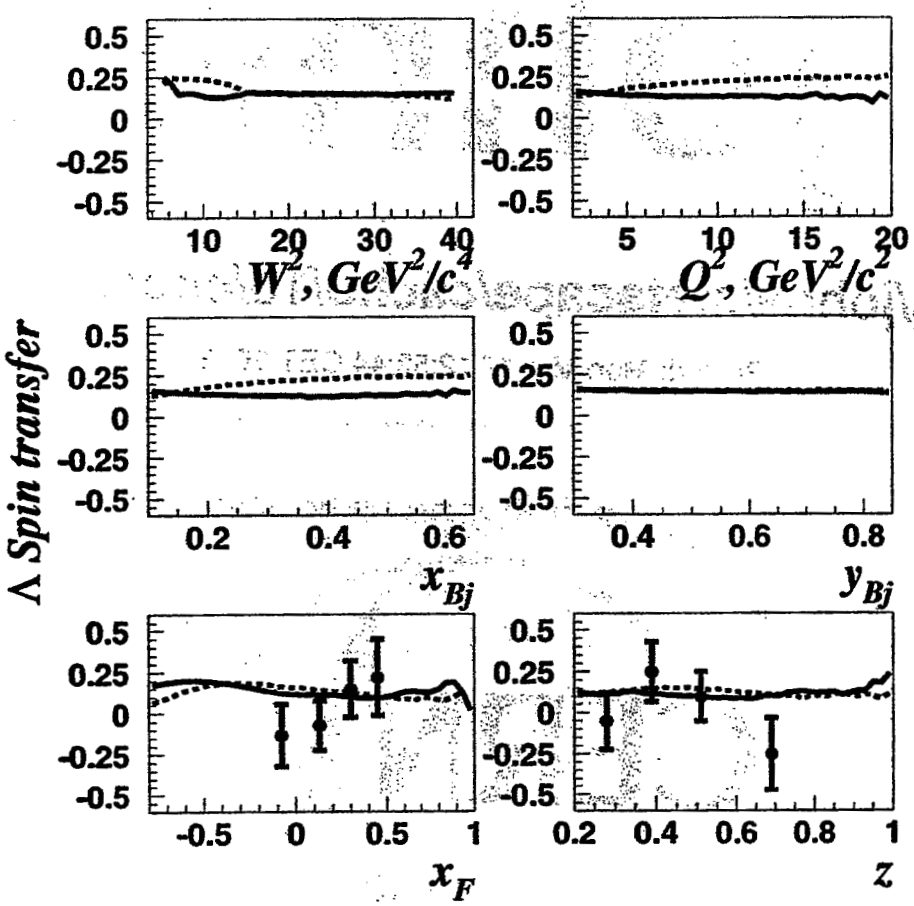


Figure 4: Our model predictions (model A - solid line, model B - dashed line) for the spin transfer of Λ hyperons produced in e^+ DIS interactions off nuclei as functions of W^2, Q^2, x_{Bj}, y_{Bj}, x_F and z (at $x_F > 0$). ($E_e = 27.5$ GeV) The points with error bars are from HERMES

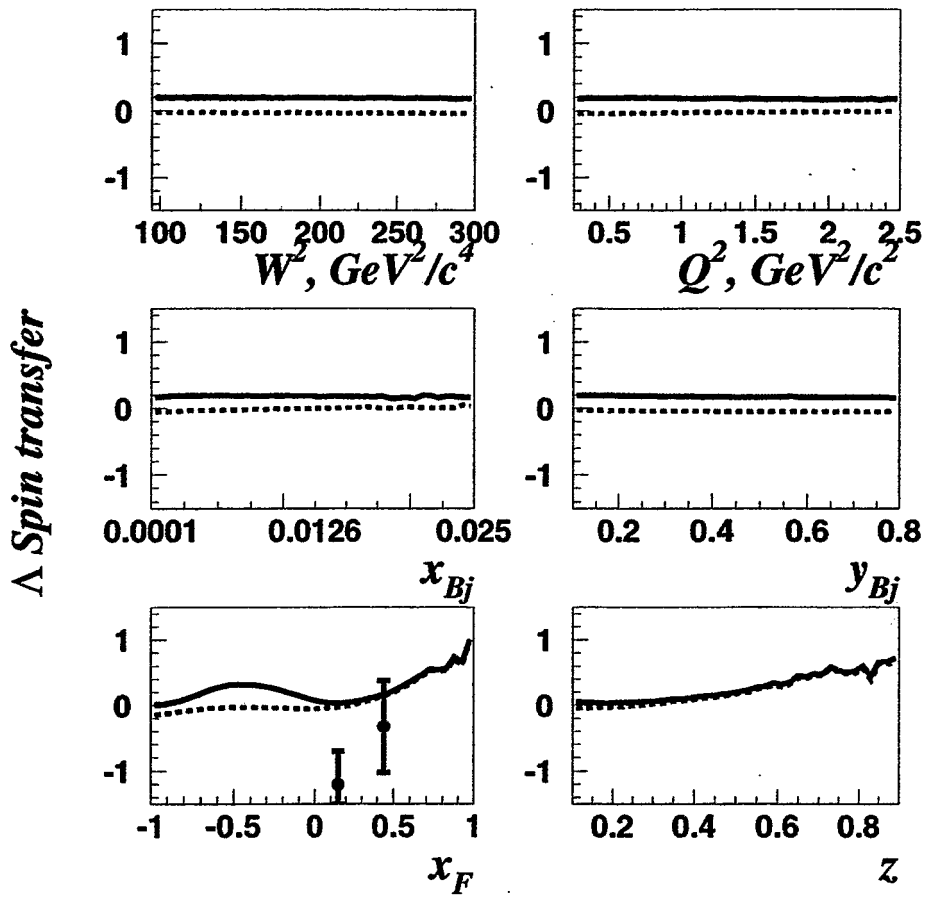


Figure 5: Our model predictions (model A - solid line, model B - dashed line) for the spin transfer of Λ hyperons produced in μ^+ DIS interactions off nuclei as functions of W^2, Q^2, x_{Bj}, y_{Bj}, x_F and z (at $x_F > 0$). ($E_\mu = 470$ GeV)

Λ and $\bar{\Lambda}$ polarization in ν_μ NC DIS

The coordinate system used:

- $\vec{n}_x = \vec{e}_\Lambda$
- $\vec{n}_y = \vec{e}_\Lambda \times \vec{e}_\nu / |\vec{e}_\Lambda \times \vec{e}_\nu|$
- $\vec{n}_z = \vec{n}_x \times \vec{n}_y$

Which variables do we have?:

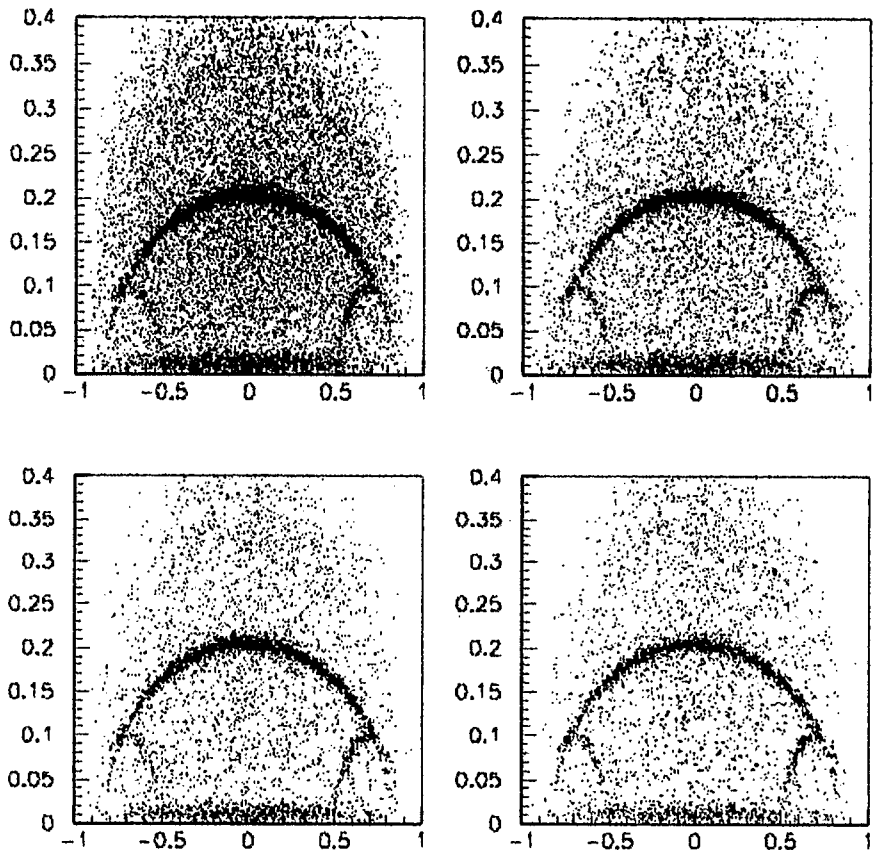
YES x_F, p_T, z
NO W^2, Q^2, x_{Bj}, y_{Bj}, E_ν

Mesurements of the Λ ($\bar{\Lambda}$) polarization is ν NC interactions can provide some additional information w.r.t. the results obtained for ν CC events. For details see **M.L.Mangano *et al.*, "Physics at the front-end of a neutrino factory: A quantitative appraisal", CERN-TH/2001-131, hep-ph/0105155.**

		Λ Polarization		
full sample	2021	-0.17 ± 0.07	-0.19 ± 0.07	-0.13 ± 0.07
$x_F < 0$	1424	-0.24 ± 0.08	-0.26 ± 0.07	-0.12 ± 0.08
$x_F > 0$	597	-0.03 ± 0.14	0.03 ± 0.11	-0.16 ± 0.16

Selection	Entries	$\bar{\Lambda}$ Polarization		
		P_x	P_y	P_z
full sample	212	0.29 ± 0.23	0.14 ± 0.22	-0.30 ± 0.27

Lambda



Armenteros plots
outside the target volume

Z_{V0} > 10 cm, 20 cm,
30 cm, and 40 cm
from the target edge

4 - Future Experiments

- COMPASS @ CERN $\leftarrow$ SMC $\leftarrow$ NMC $\leftarrow$ EMC

  measure ΔG via $\gamma^* g \to c\bar{c}$

  $$0.08 < x < 0.35 : \quad \delta\left(\frac{\Delta G}{G}\right) \sim 0.1 \text{ to } 0.15$$

  also via Q^2 evolution of $g_1^p(x, Q^2)$

  $$\delta\left(\int_0^1 dx\, \Delta G(x)\right) \to \sim 0.35$$

- polarized beams @ RHIC (pRHIC)

  measure ΔG via dijets, γ+jet production

  $$x < 0.1 : \quad \delta\left(\frac{\Delta G}{G}\right) \sim 0.075$$

- polarized photoproduction @ SLAC

  measure ΔG via $\gamma g \to D\bar{D}$ near threshold

First Attempt to Extract ΔG

asymmetry in multi-γ production

$\Delta G \simeq 0 \pm$

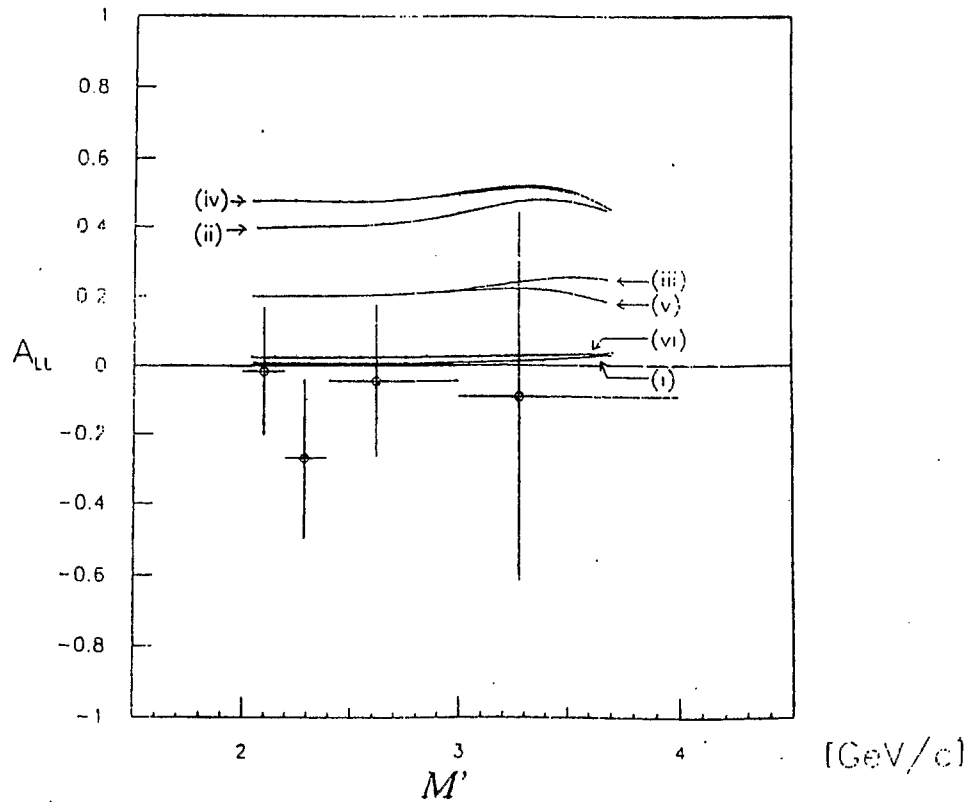


Fig. 3. A_{LL} for inclusive multi-γ pair production ($|p_T'| < 1.0$ GeV/c) and several model calculations ((i)–(vi): see Table 2).

(FNAL: 1994

HERMES Evaluation of ΔG

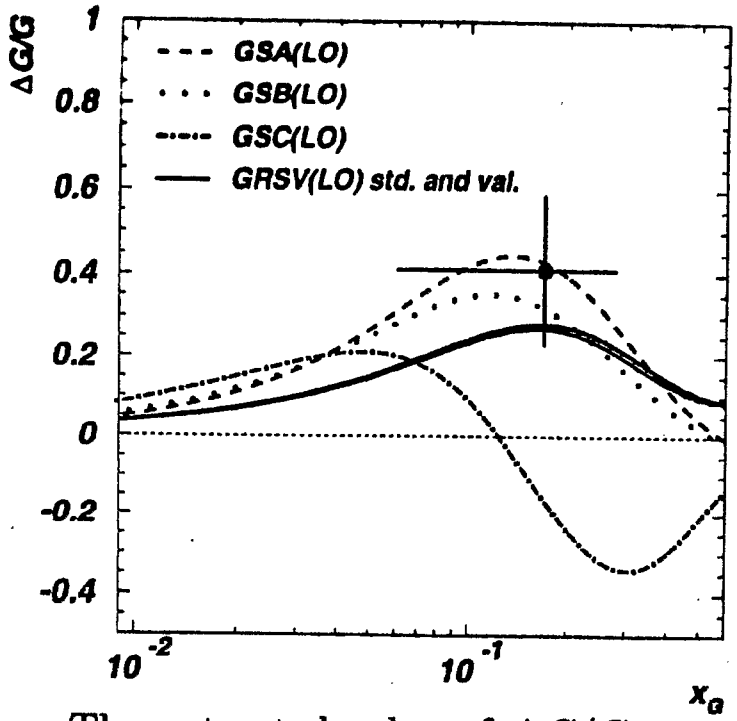


FIG. 4. The extracted value of $\Delta G/G$ compared with phenomenological QCD fits to a subset of the world's data on $g_1^{p,n}(x, Q^2)$. The curves are from Refs. [28,29], evaluated at a scale of 2 $(\mathrm{GeV/c})^2$. The indicated error on $\Delta G/G$ represents statistical and experimental systematic uncertainties only; no theoretical uncertainty is included.

from production of pairs of high-p_T hadrons

$$\frac{\Delta G}{G} = 0.41 \pm 0.18 \pm 0.03 \pm ?$$

stat. exp. syst. theor. syst.

@ $\langle x_G \rangle = 0.17$, $\langle k_T^2 \rangle = 2.1\,\mathrm{GeV}^2$

Projected Future Measurements of ΔG

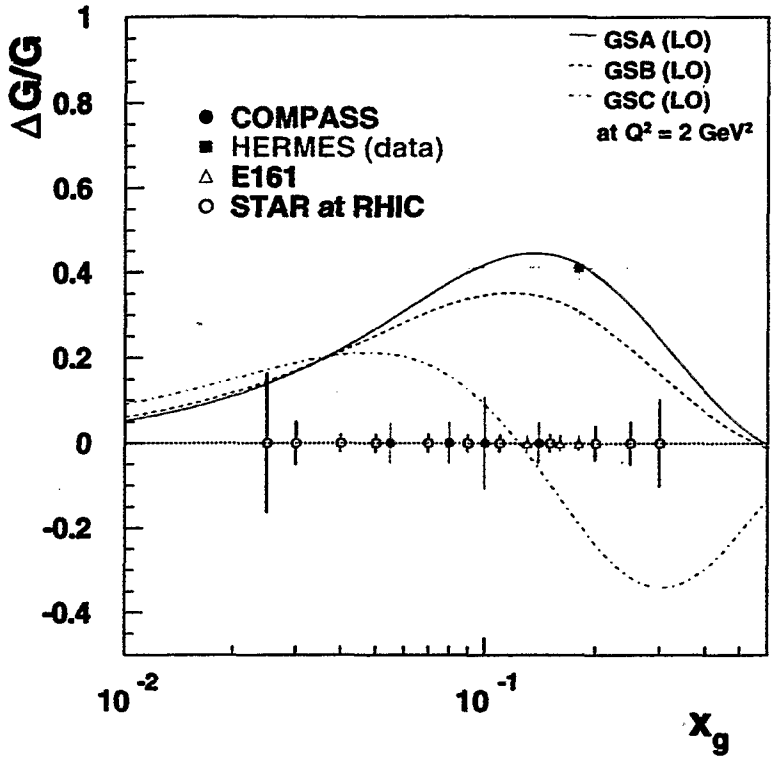


Fig. 3. Comparison of approved experiments for measurement of $\Delta G/G$. Shown are the expected errors, except for HERMES, where the first measurement is shown. The curves show the parameterizations A, B and C of Gehrmann and Sterling [14].

been performed by the HERMES experiment for x_{Bj} values down to 0.02 [7]. With the COMPASS experiment these data will be complemented in a x_{Bj} range down to 0.003 with an improved precision compared to the SMC experiment, which has measured flavor dependent quark polarizations for the first time.

Having the possibility to rotate the polarization of the target from longitudinal to transverse direction allows to determine the transverse structure function $h_1(x, Q^2)$ in COMPASS. In addition to the structure functions f_1 and g_1 the structure function h_1 is required for a complete description of the nucleon. h_1 has not been measured before. The HERMES experiment is performing a measurement of

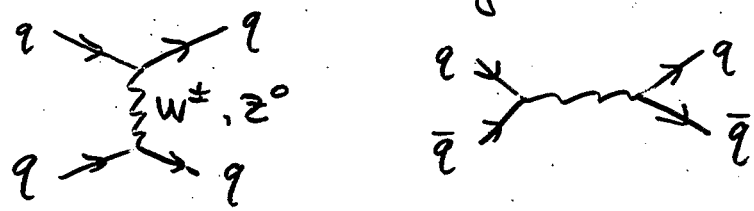
Parity-Violating Asymmetries at RHIC

(J.E. + Moretti + Ross

arise at tree level in

$$q + q \to q + q \,, \quad q + \bar{q} \to q + \bar{q}$$

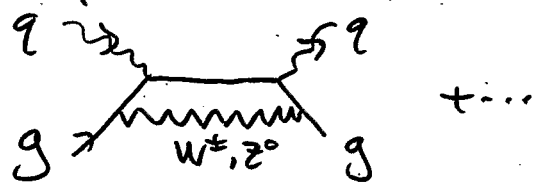
due to $W^{\pm}, Z^{0}$ exchanges:



contribution also possible from

$$q + g \to q + g$$

at one-loop level



$+ \cdots$

corrections $\propto \Delta G$ to asymmetries

$$A_L \, d\sigma \equiv d\sigma_{-} - d\sigma_{+} \,, \quad A_{PV} \equiv d\sigma_{--} - d\sigma_{++}$$

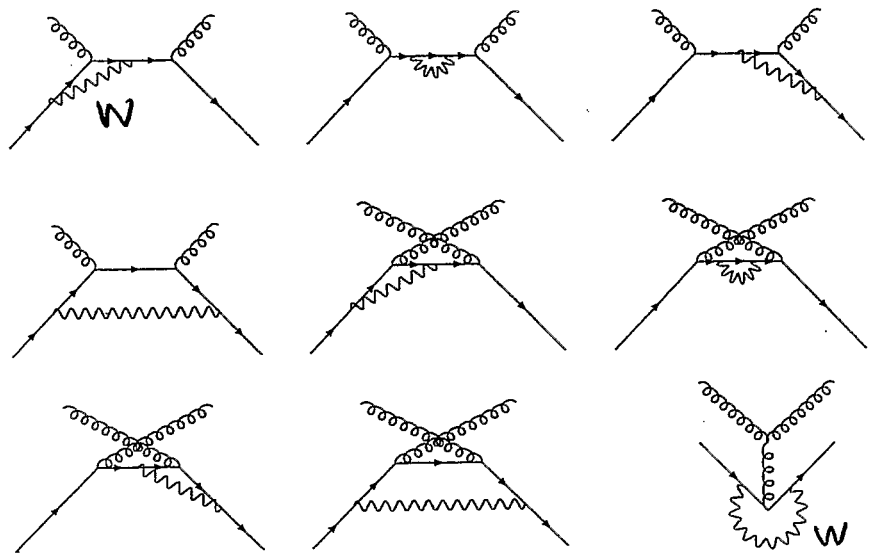
$\uparrow$ $\qquad\qquad\qquad\qquad$ $\uparrow$

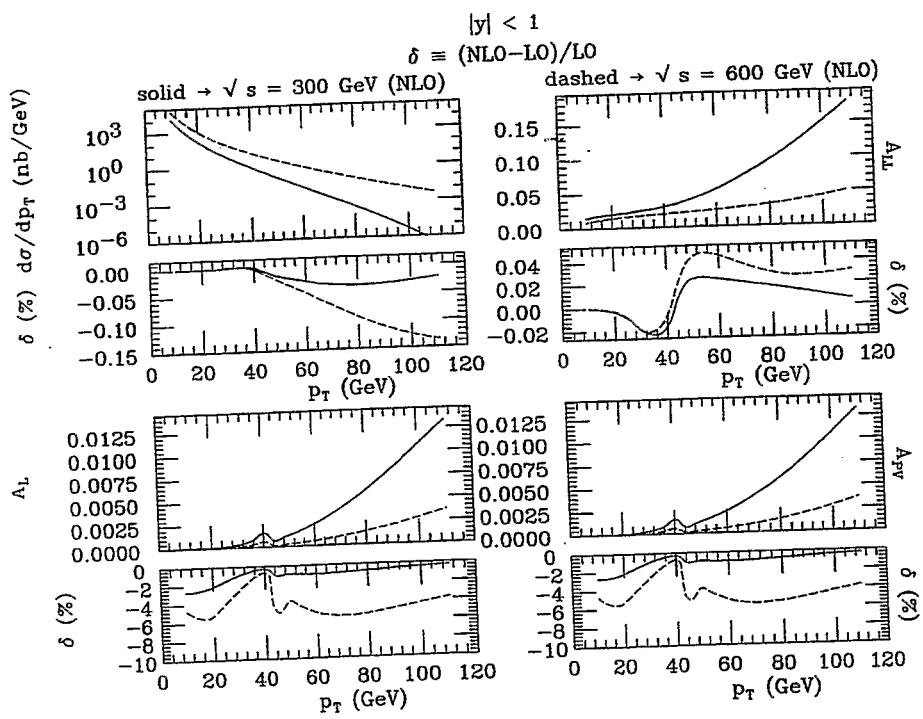
turn out to be rather small

$\Rightarrow$ robust predictions

Corrections to parity-violating asymmetries @ RHIC

$q + g \to q + g$





1-Why Supersymmetry?

Hierarchy Problem:

energy: gravity ~ other forces: $m_P \sim 10^{19}$ GeV

why is $m_W \ll m_P$?

alternatively

why is $G_F \gg G_N$? $\quad \frac{1}{m_W^2} \sim 10^{34} \times \frac{1}{m_P^2}$

or

why is $V_{Coulomb} \gg V_{Newton}$? $\quad e^2 \gg G_N m^2 \sim m^2/m_P^2$

Set by hand?

what about quantum corrections?

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right) \Lambda^2 \gg m_W^2$$

cut off $\Lambda \sim m_P$?

made naturally small by supersymmetry:

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right)(m_B^2 - m_F^2)$$

$$\lesssim m^2_{H,W} \quad \text{if} \quad |m_B^2 - m_F^2| \lesssim 1\ \text{TeV}^2$$

low-energy supersymmetry

CM

Minimal Supersymmetric Model

postulate doubling of particle spectrum

γ	W	Z	g	l	q	$H_{1,2}$
photino			gluino	slepton	squark	Higgs (x2)
$\tilde{\gamma}$	$\tilde{W}$	$\tilde{Z}$	$\tilde{g}$	$\tilde{l}$	$\tilde{q}$	$\tilde{H}$

supersymmetry guarantees equal couplings

sparticle masses unknown: expect $\lesssim 1$ TeV

$\boxed{\text{postulate}}$ universal masses $\equiv$ CMSSM

before renormalization m_0 $\quad \tilde{l}, \tilde{q}, H$

$m_{1/2}$ $\quad \tilde{\gamma}, \tilde{W}, \tilde{Z}, \tilde{g}$

other basic parameters

$\tan\beta$ ratio of Higgs vacuum expect^n values

μ mixing between Higgs fields

Assume conservation of $R = (-1)^{3B+L+2S}$

$\Rightarrow$ lightest sparticle stable $\quad \chi = \tilde{\gamma}/\tilde{Z}/\tilde{H}^0$

relic from Big Bang

(S)Experimental Hints

2 indications from precision (LEP) data

- Higgs boson probably light

  global fit: $m_H \lesssim 200$ GeV

  consistent with prediction of MSSM:

  $m_H \lesssim 130$ GeV

- Measured gauge couplings favour supersymmetric grand unified theories

  minimal non-supersymmetric GUT:

  $$\sin^2\theta_W(M_Z)\Big|_{\overline{MS}} \simeq 0.214 \pm 0.004$$

  experimental value:

  $$\sin^2\theta_W(M_Z)_{\overline{MS}} \simeq 0.232 \pm \nearrow$$

  depends on sparticle masses

Supersymmetric Higgs Bosons

Five particles predicted:

3 neutrals $\quad$ 2 charged

h; H, A $\quad$ $H^{\pm}$

$\downarrow$

lightest resembles Standard Model Higgs

predicted to be relatively light:

$m_h < m_Z$ @ classical (tree) level

$\downarrow$

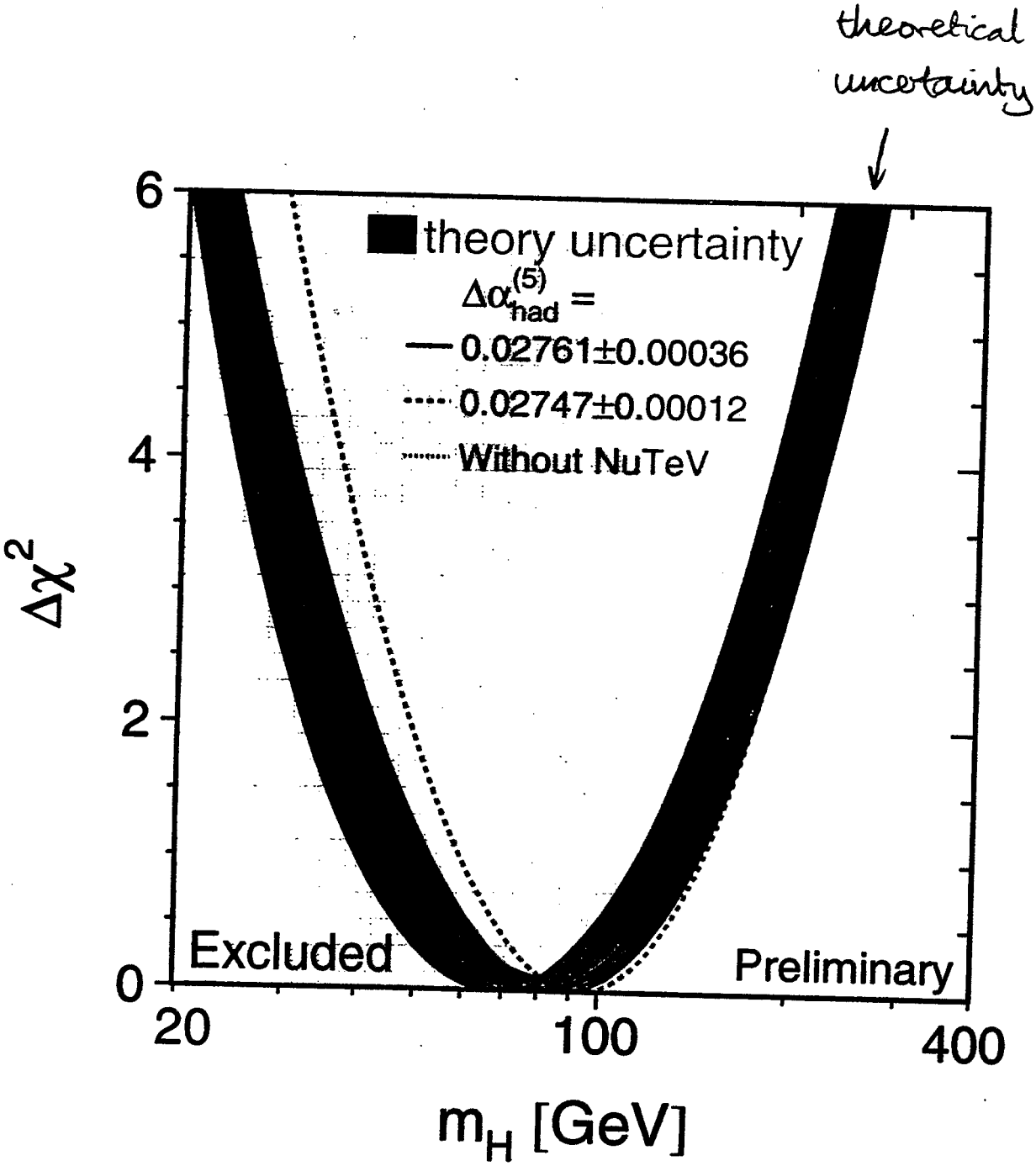
Okada et al)
S.E, Ridolfi, Zwirner)
Haber + Hempfling)

$m_h \lesssim 130\,\text{GeV}$ including quantum corrections

consistent with analysis of electroweak data

more circumstantial evidence for supersymmetry?

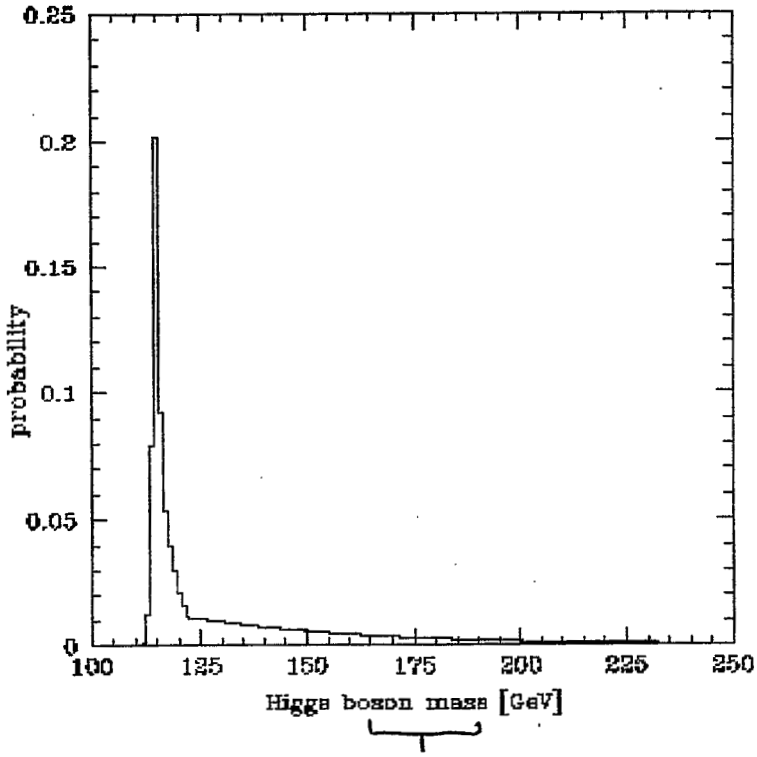
Indirect Information on m_H



Probability Distribution for Higgs Mass

combining precision measurements

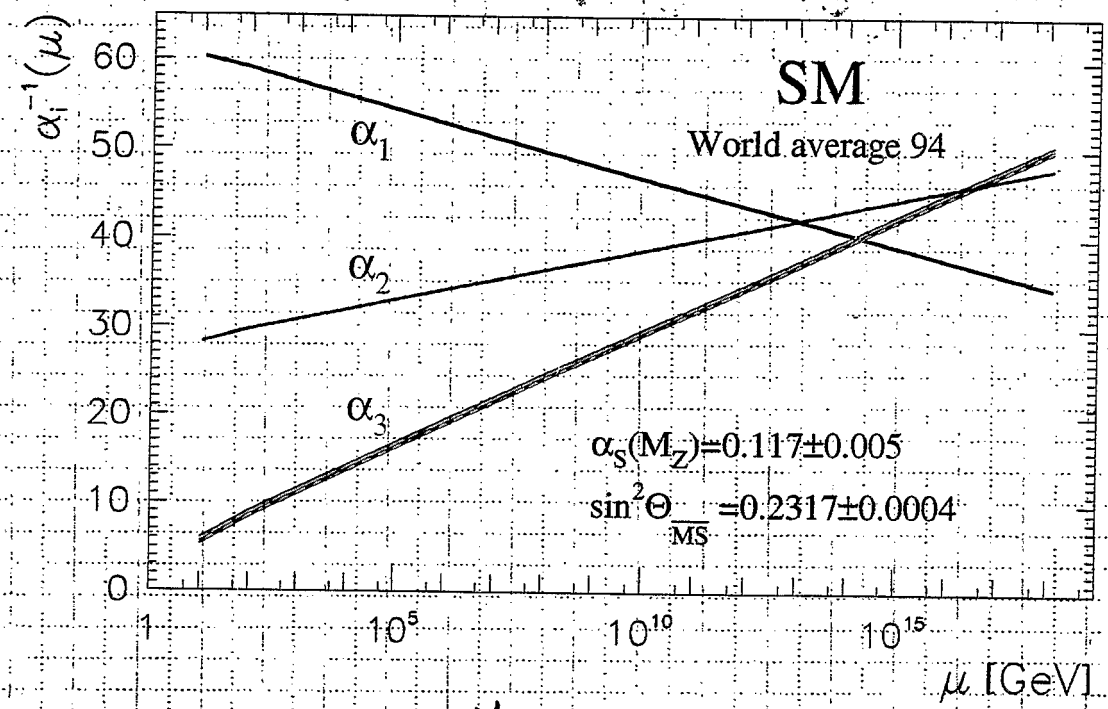
⊕ direct limits



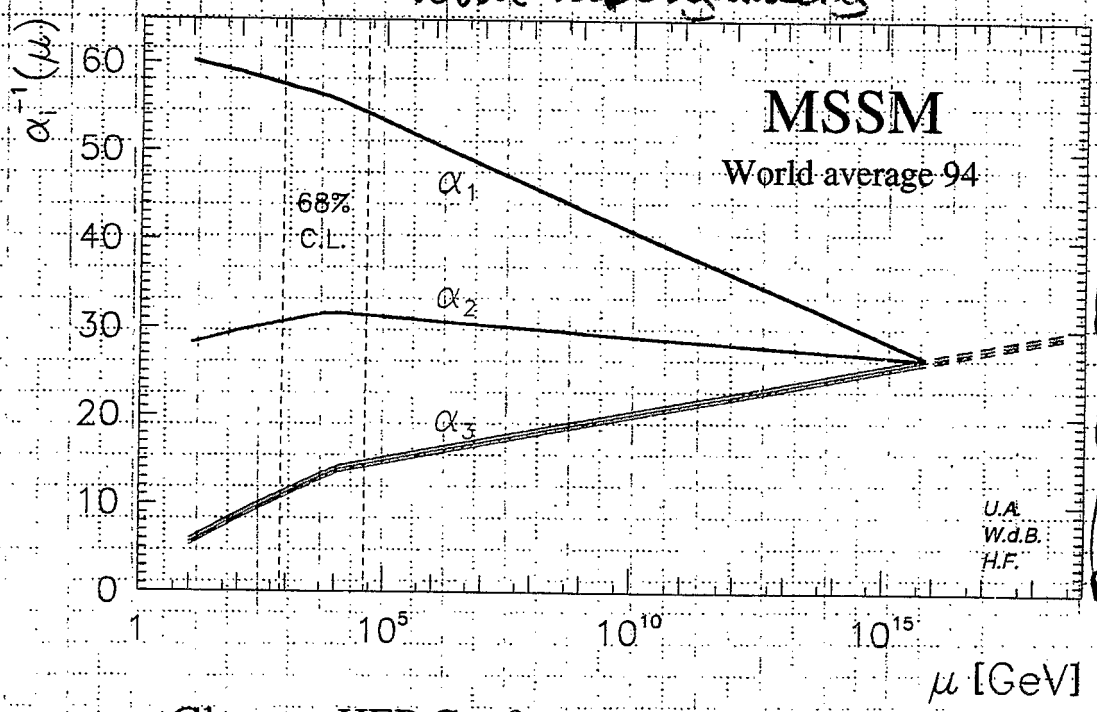
Standard Model

(Erler: hep-ph/0010153

Unification? without supersymmetry



with supersymmetry



1990

(J.E. + Kelley + Nanopou

(Langacke + Luo

(Amaldi de Boer Fürstena

1991

Glasgow HEP Conference 1994 :

$M_S=10^{3.7\pm0.8\pm0.4}$ GeV $\quad M_U=10^{15.9\pm0.2\pm0.1}$ GeV

return to this later!

24 F

F14

3.2 Experimental constraints

no sparticles seen: $m_{\chi^\pm} \gtrsim 104$ GeV

spartner of $W^\pm/H^\pm$ $\rightarrow$

$m_{\tilde{e}} \gtrsim 100$ GeV

also squarks, gluinos, ...

no Higgs seen: $m_H > 114.4$ GeV

sensitive to sparticle masses:

$$\delta m_H^2 \propto \frac{m_t^4}{m_W^2} \ln\left(\tilde{m}^2/m_t^2\right)$$

$b \to s\gamma$ decay:

agreement with Standard Model limits

sparticle loop contributions

$(g-2)_\mu$:

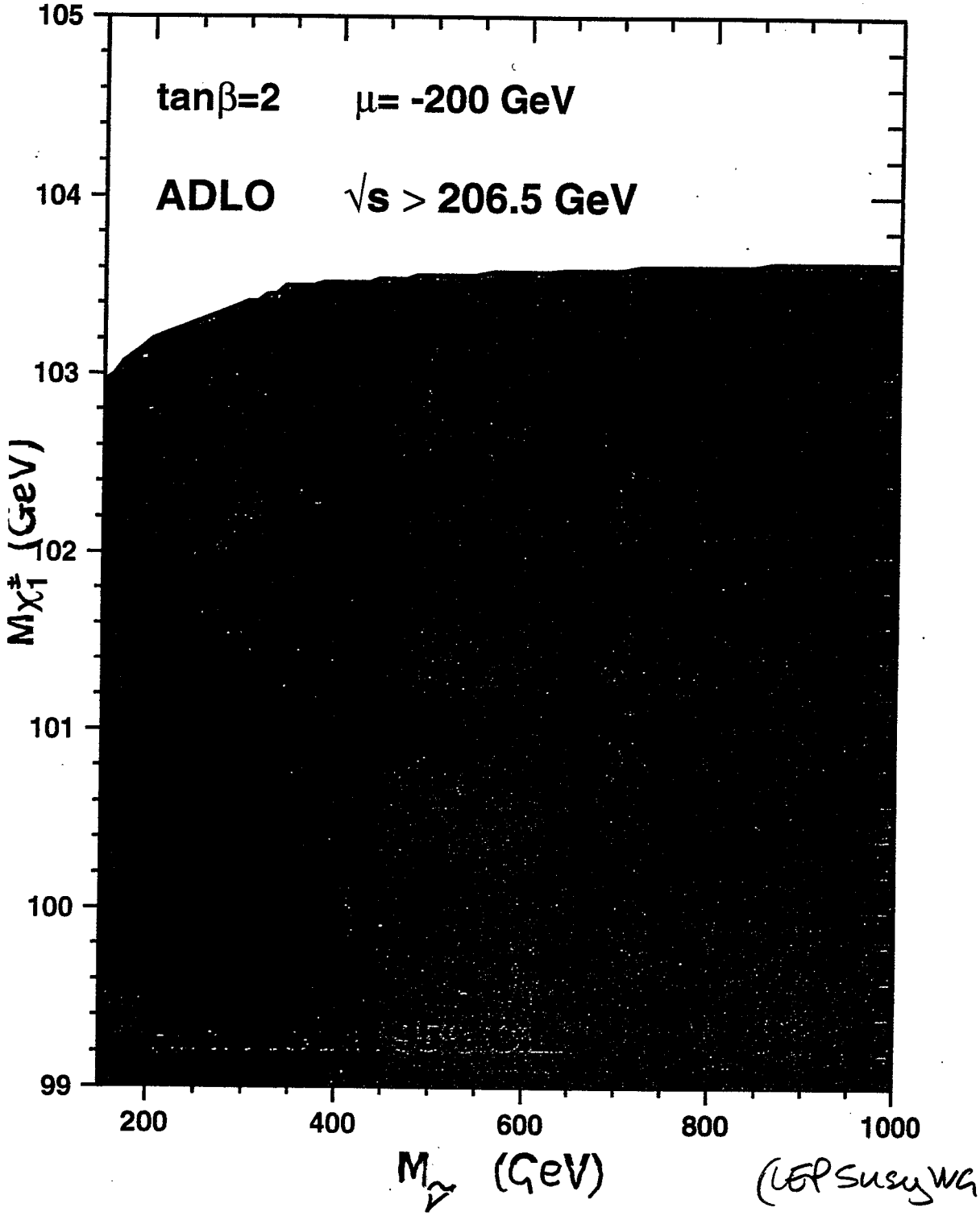
consistent with MSSM:

is discrepancy significant?

cosmological relic density

LEP Constraint on Charginos

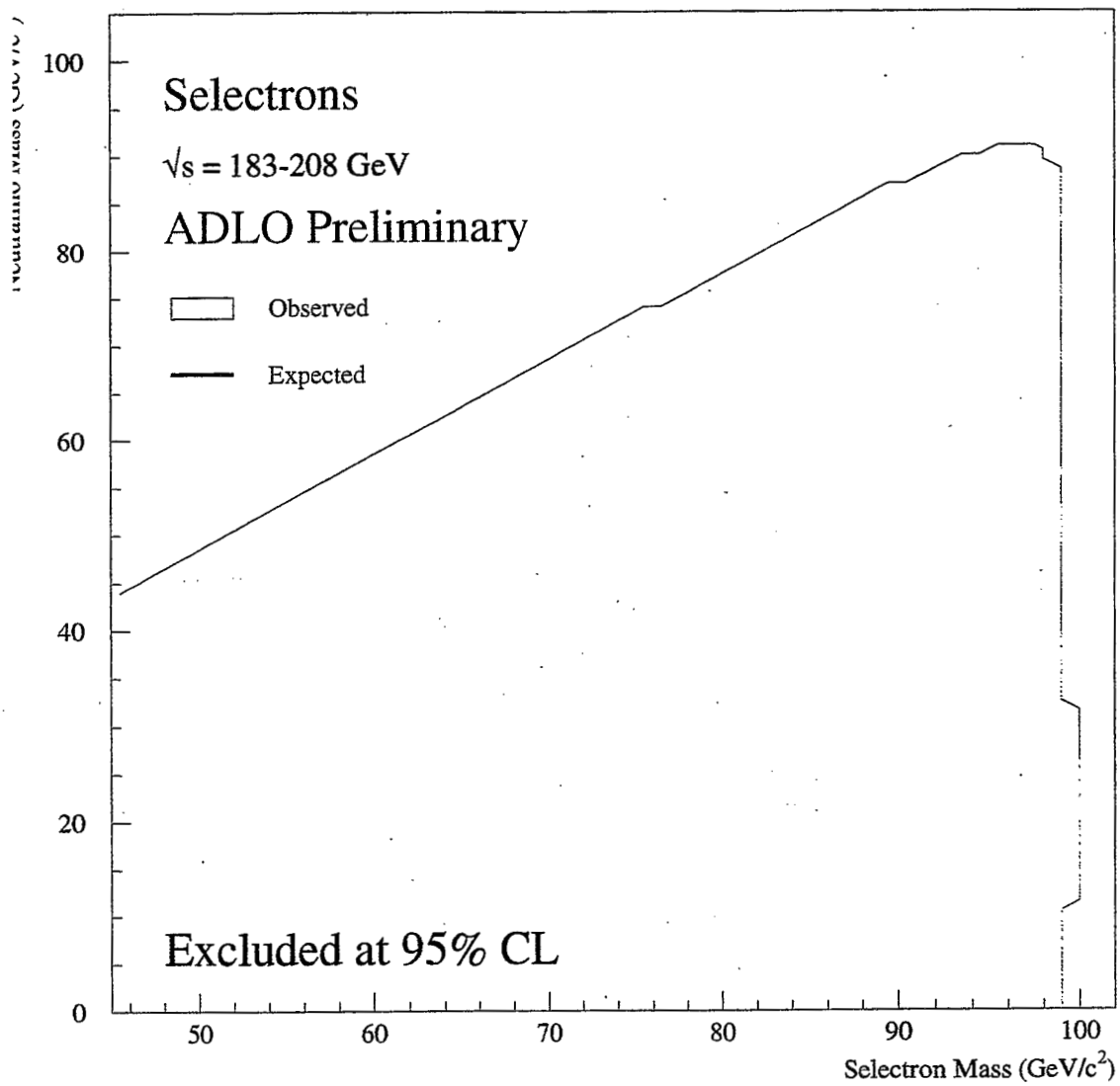
$m_{\chi^\pm} \gtrsim 103$ GeV



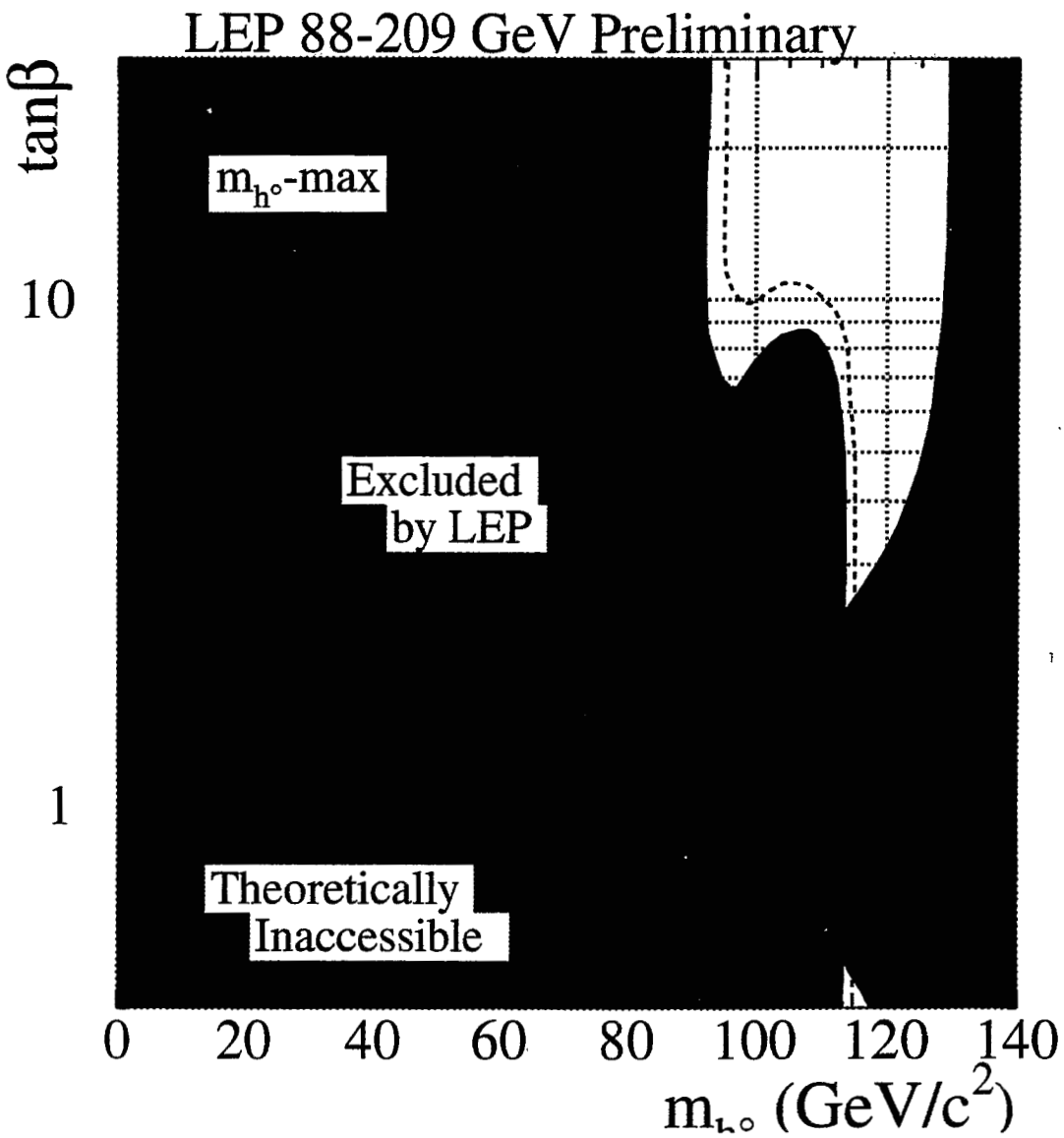
(LEP SUSY WG

LEP Constraint on Sleptons

$m_{\tilde{e}} \gtrsim 100$ GeV



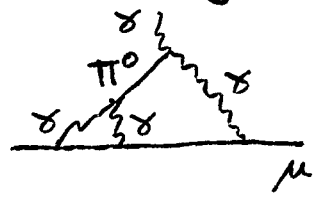
(LEP susy WG)


LEP 88-209 GeV Preliminary
tanβ
10
1
m_{h^o}-max
Excluded
by LEP
Theoretically
Inaccessible
0
20
40
60
80
100
120
140
m_{h^o} (GeV/c^2)

updated

Muon Anomalous Magnetic Moment

after correction of sign in light-by-light scattering:



$$a_\mu^{exp} - a_\mu^{th} \simeq (30 \pm 10) \times 10^{-10}$$ (BNL E821)

main error experimental statistics

largest theoretical error from QCD

$(\pm 7) \times 10^{-10}$

deviation not (very) significant

but naturally explained by supersymmetry

particularly if $\mu > 0$

but $\mu < 0$ not excluded.

overall consistency: a_μ, cosmology, m_h, $b \to s\gamma$, ..

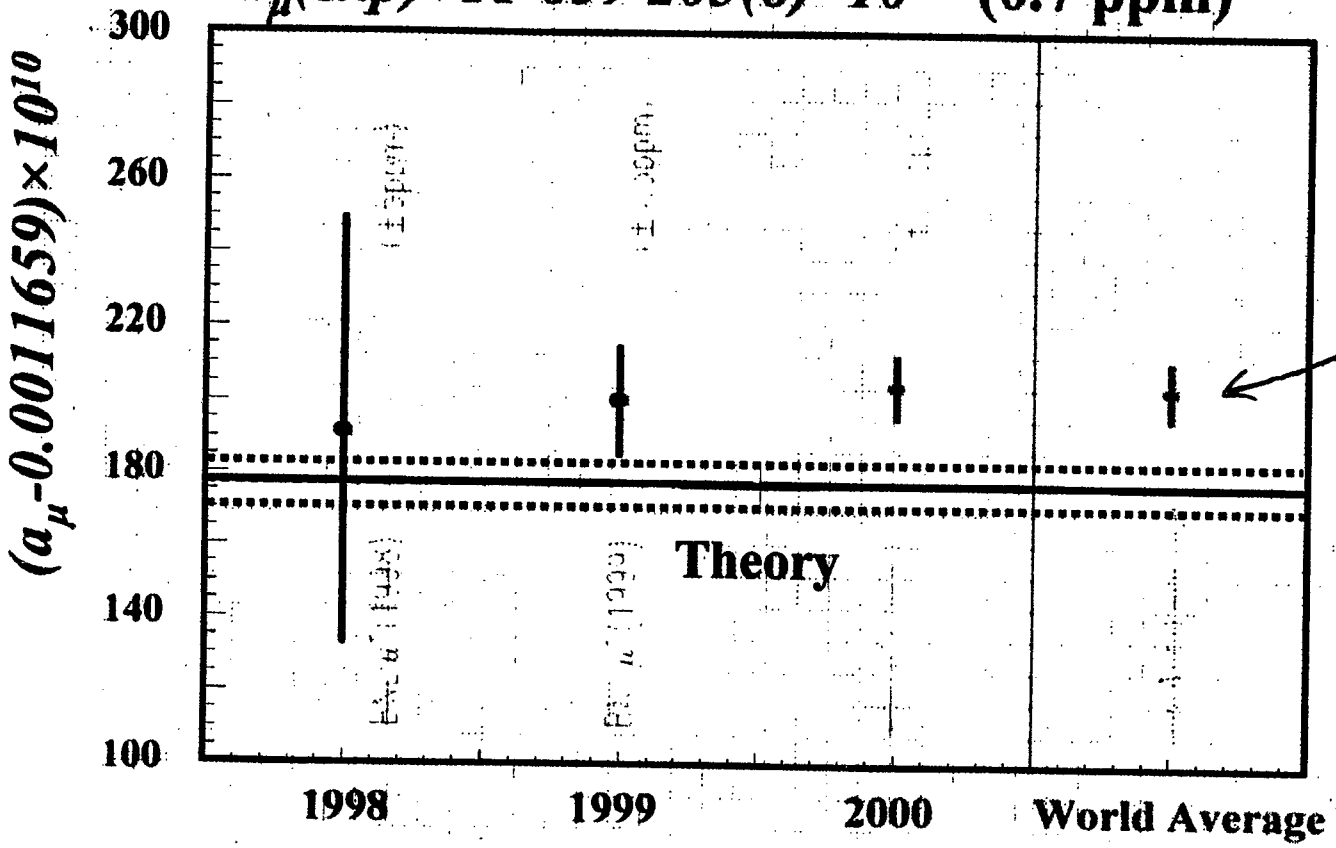
Results

From the Data of 2000:

$a_\mu(exp)=11\ 659\ 204(7)(5)\times 10^{-10}$ (0.7 ppm)

Exp. World Average:

$a_\mu(exp)=11\ 659\ 203(8)\times 10^{-10}$ (0.7 ppm)



3-σ discrepancy with e^+e^- data

would imply new physics @ TeV scale

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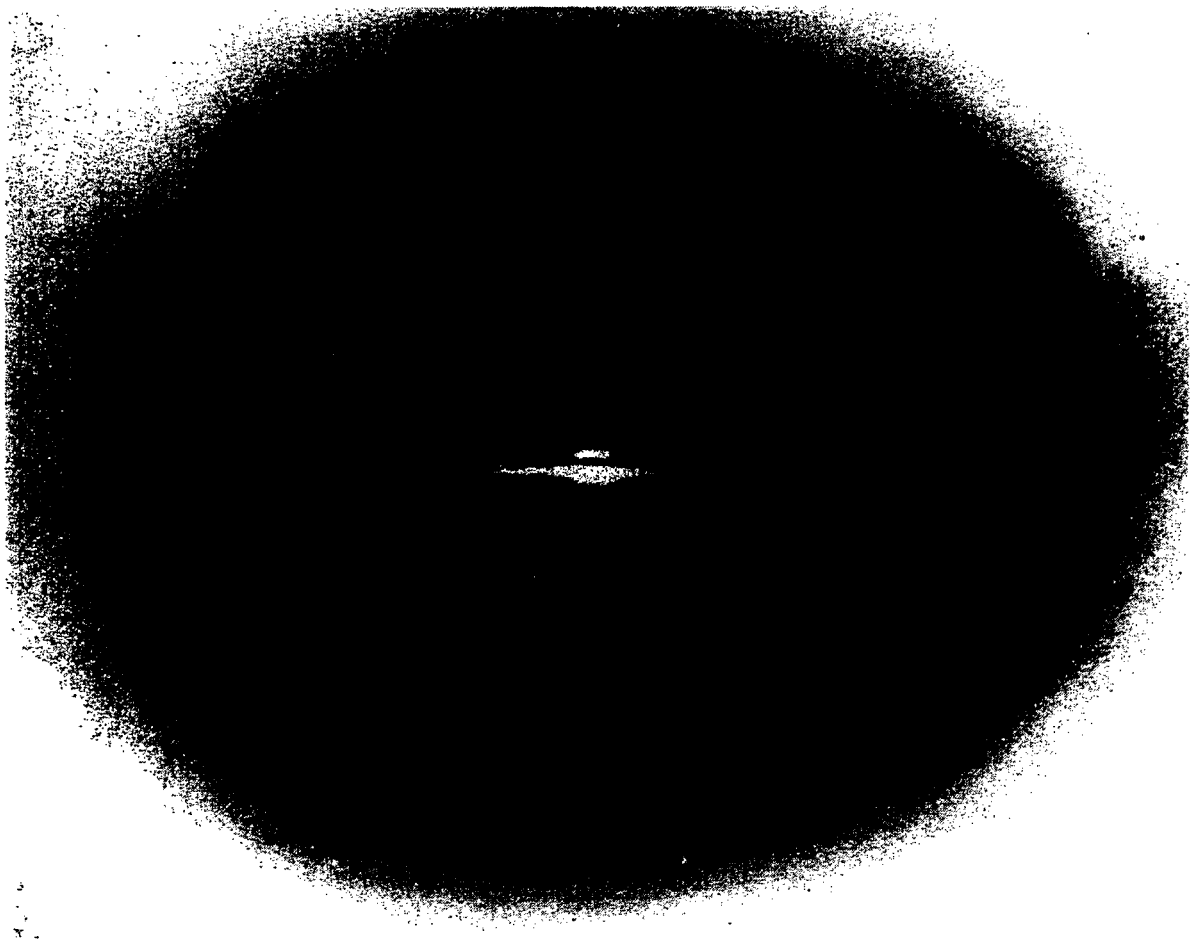


$0.1 < \Omega h^2 < 0.3$

my favourite candidate for Cold Dark Matter

3 Lightest Supersymmetric Particle ?

- Expected to be stable in most models

  $\Rightarrow$ present in Universe as cosmological relic

- Because of multiplicatively-conserved quantum number:

$$R \text{ parity} = \begin{cases} +1 & \text{for all particles} \\ -1 & \text{for all sparticles} \end{cases}$$

(Fayet

- Conservation related to those of baryon, lepton numbers:

$$R = (-1)^{3B+L+2S}$$ ← spin

- Violation possible via spontaneous/explicit $L \times$

$$\langle 0|\tilde{\nu}|0\rangle \neq 0 \; ? \qquad HL \text{ coupling}$$

↑ constraints from laboratory experiments

3 important consequences of R conservation:

1) Sparticles always produced in pairs

   e.g. $pp \to \tilde{q}\tilde{g}X$, $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$

2) Heavier sparticles decay into lighter ones

   e.g. $\tilde{q} \to q\,\tilde{\gamma}$, $\tilde{\mu} \to \mu\,\tilde{\gamma}$

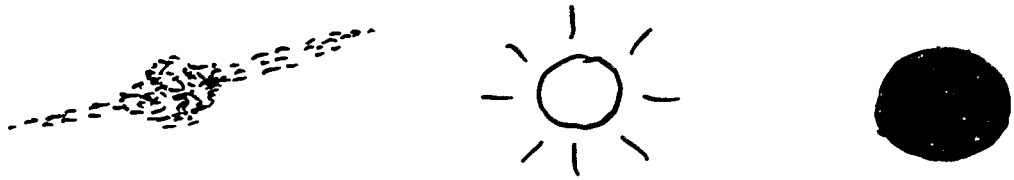
3) Lightest sparticle stable

   no legal decay mode!

Nature of Lightest Supersymmetric Particle

cannot have $\begin{cases} \text{electromagnetic charge} \\ \text{strong interactions} \end{cases}$

If it did, it would dissipate energy, condense into



be detectable as anomalous heavy isotopes

BUT upper limits $\ll$ expected abundance:

$$\frac{n_{heavy}}{n_{normal}} \lesssim 10^{-15} \rightarrow 10^{-30}$$

$\Rightarrow$ relic does not bind to ordinary nuclei

$\Rightarrow$ no strong or electromagnetic interactions

Supersymmetric candidates

Spin:	0	½	1	3/2
	sneutrino	neutralino	—	gravitino
	excluded by LEP, dark matter searches	$\tilde{\gamma}/\tilde{H}/\tilde{Z}$		$\tilde{G}$ generally heavier than

Supersymmetric Relic Density

controlled by annihilation rate

$$\rho_\chi = m_\chi n_\chi \; : \; n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \cdots)}$$

typical annihilation rate $\sigma_{ann} \sim \frac{1}{m^2}$

$\Rightarrow$ relic density increases with mass

$$m_\chi \lesssim O(1)\ \text{TeV}$$

BUT sometimes density reduced by coannihilation: $\sigma_{coann}(\chi \tilde{X} \to \text{ordinary})$

important if $\frac{\Delta m}{m} \sim 0.1$

$\Rightarrow$ possible 'tail' out to large m_χ

AND sometimes rapid annihilation via direct-channel pole: $m_\chi \sim \frac{1}{2} m_{Higgs, Z, \ldots}$

$\Rightarrow$ possible 'funnel' out to large m_χ

can be important @ large $\tan\beta$

After WMAP

Confirmation of Standard Cosmological Model

$$\Omega_{tot} \simeq 1, \quad \Omega_\Lambda \gg \Omega_{CDM} \gg \Omega_b, \Omega_\nu$$

with much higher precision

of LEP and Standard Model

$\Omega_{tot} = 1.02 \pm 0.02$	inflation	$\leftarrow$
$\Omega_{CDM} h^2 = 0.111 \pm 0.009$	constrains susy	$\leftarrow$
$\Omega_b h^2 = 0.0224 \pm 0.0009$	leptogenesis?	$\leftarrow$
$\Omega_\nu h^2 < 0.0076$	$\sum_\nu m_\nu < 0.7$ eV	
$\Omega_\Lambda \simeq 0.73$		

Supersymmetric Parameter Space after WMAP

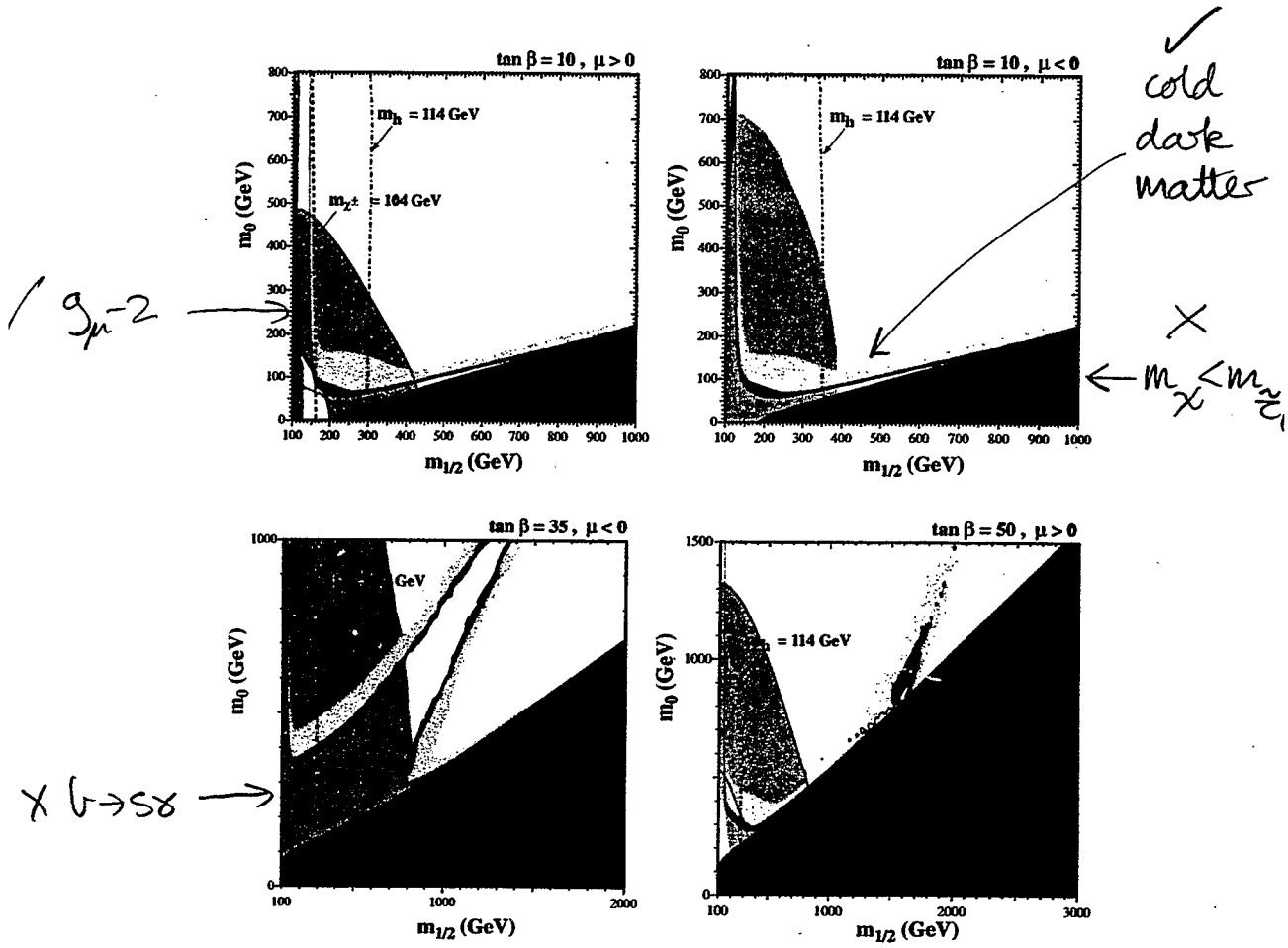


Figure 1: *The* $(m_{1/2}, m_0)$ *planes for (a)* $\tan\beta = 10, \mu > 0$, *(b)* $\tan\beta = 10, \mu < 0$, *(c)* $\tan\beta = 35, \mu < 0$, *and (d)* $\tan\beta = 50, \mu > 0$. *In each panel, the region allowed by the older cosmological constraint* $0.1 \leq \Omega_\chi h^2 \leq 0.3$ *has medium shading, and the region allowed by the newer cosmological constraint* $0.094 \leq \Omega_\chi h^2 \leq 0.129$ *has very dark shading. The disallowed region where* $m_{\tilde{\tau}_1} < m_\chi$ *has dark (red) shading. The regions excluded by* $b \to s\gamma$ *have medium (green) shading, and those in panels (a,d) that are favoured by* $g_\mu - 2$ *at the 2-*σ *level have medium (pink) shading. A dot-dashed line in panel (a) delineates the LEP constraint on the* $\tilde{e}$ *mass and the contours* $m_{\chi^\pm} = 104$ *GeV* ($m_h = 114$ *GeV) are shown as near-vertical black dashed (red dot-dashed) lines in panel (a) (each panel).*

(J.E. + Olive + Santoso + Spanos

Strengthened Upper Limits on Sparticle Masses

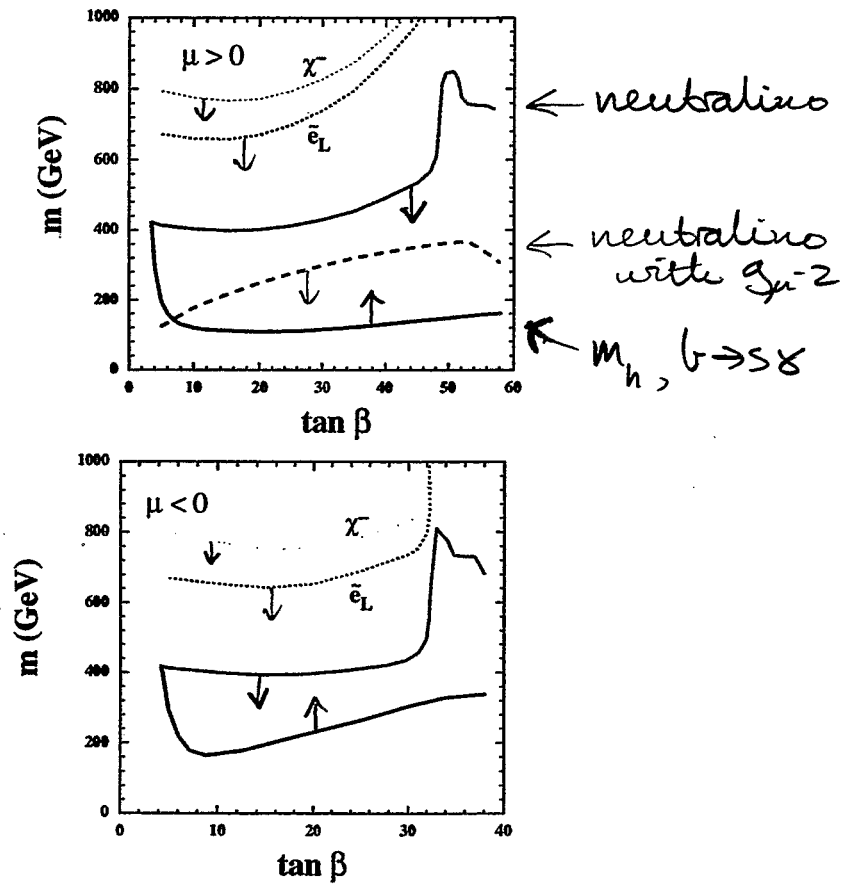


Figure 3: *The ranges of m_χ allowed by cosmology and other constraints, for (a) $\mu > 0$ and (b) $\mu < 0$. Upper limits without (red solid line) and with (blue dashed line) the $g_\mu - 2$ constraint are shown for $\mu > 0$: the lower limits are shown as black solid lines. Note the sharp increases in the upper limits for $\tan\beta \gtrsim 50, \mu > 0$ and $\tan\beta \gtrsim 35, \mu < 0$ due to the rapid-annihilation funnels. Also shown as dotted lines are the $\tilde{e}_L$ and $\chi^\pm$ masses at the tips of the coannihilation tails.*

(J.E. + Olive + Santoso + Spanos

3.4 – Proposed Supersymmetric Benchmarks

(Battaglia + De Roeck + J.E. + Gianotti + Matchev + Olive + Pape + Wilson hep-ph/0106204)

- post-LEP

  sparticle, Higgs ← theoretical uncertainties

- $b \to s\gamma$

- cosmological relic density

  $0.1 \leq \Omega_\chi h^2 \leq 0.3$ ← hard upper limit

- $g_\mu - 2$

  favour $\Delta(g_\mu - 2) \leq 2\sigma$: not required (*)

Choose points that illustrate possibilities

not 'fair' sampling of parameter space

5 in 'bulk' of cosmological region

4 spread along coannihilation 'tail'

2 in 'focus-point' region

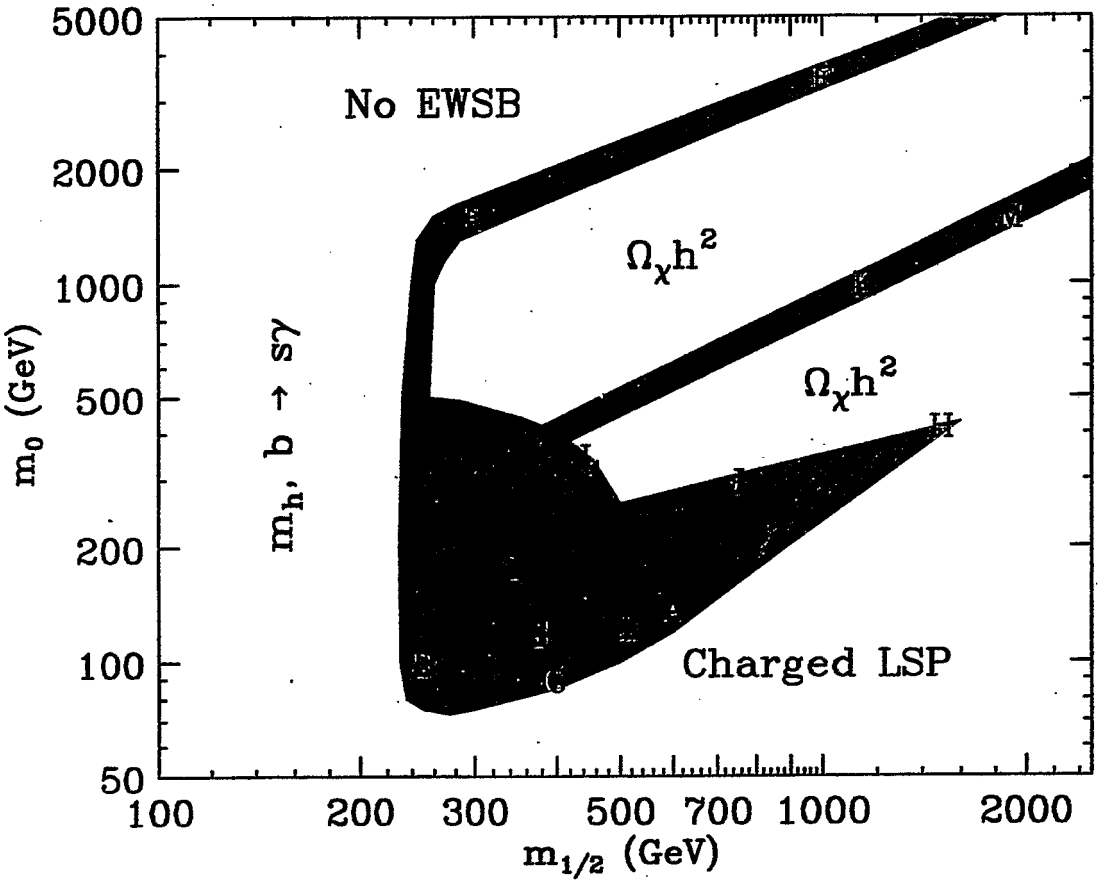
2 in rapid-annihilation 'funnels'

$\tan\beta = 5, 10, 20, 35, 50$

two points with $\mu < 0$ (*)

Benchmark Supersymmetric Scenarios

illustrated range of allowed possibilities



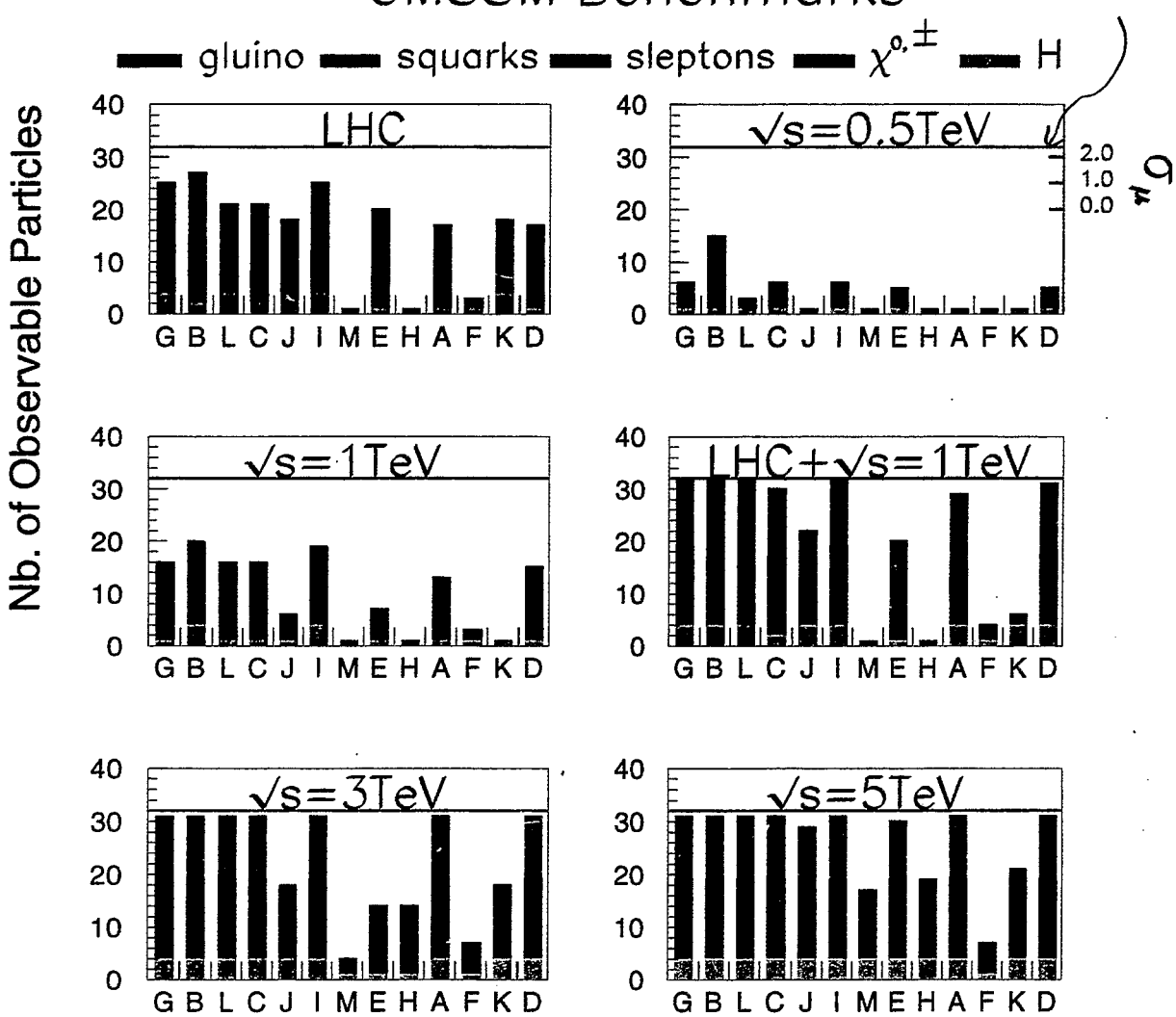
(Battaglia + De Roeck + J.E. + Giusotti + Matchev + Olive + Pape + Wilson

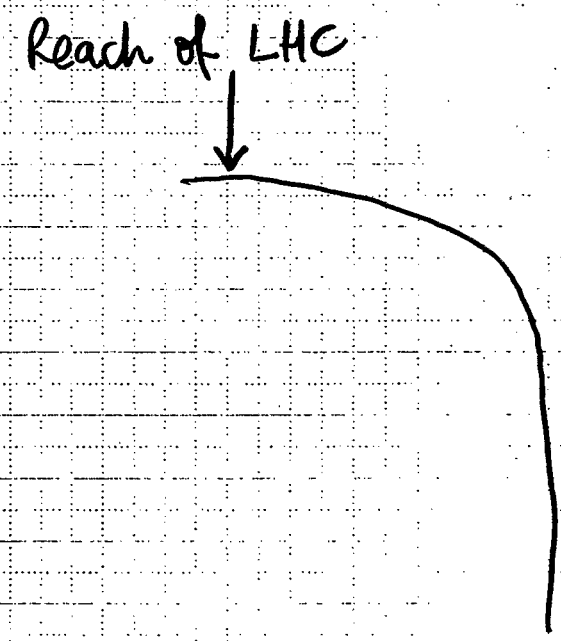
Observability of Supersymmetry

(Battaglia et al.: hep-ph/0106204

with future accelerators

updated




Reach of LHC

COSMIC METALLIC LOOKS

NEW HIGHLIGHTER STICKS AND SPARTICLES

THE BODY SHOP
COLOURINGS

35 - Searches for Dark Matter Particles

focus on neutralinos

- Annihilation in galactic halo (Silk + Srednicki

$$\tilde{\chi}\tilde{\chi} \to l^+ l^-, \bar{q}q \to \underbrace{\bar{p}, e^+, \gamma, (\nu)}_{\text{cosmic rays?}}$$

(Silk + Olive + Srednicki

- Annihilation in Sun or Earth galactic centre?

$\tilde{\chi}$ captured by elastic scattering, ΔE_{recoil}

$$\tilde{\chi}\tilde{\chi} \to \underbrace{\text{"high energy"}\ \nu}_{\text{underground detectors: } \nu \text{ or } \mu} \quad \sim \text{GeV}$$

- Elastic Scattering in Laboratory (Goodman + Witten

$$\tilde{\chi}N \to \tilde{\chi}N \to \text{detectable recoil energy}$$

$$E \sim \text{keV} \times \left(\frac{m_\chi}{4\,\text{GeV}}\right)$$

(- Inelastic Scattering

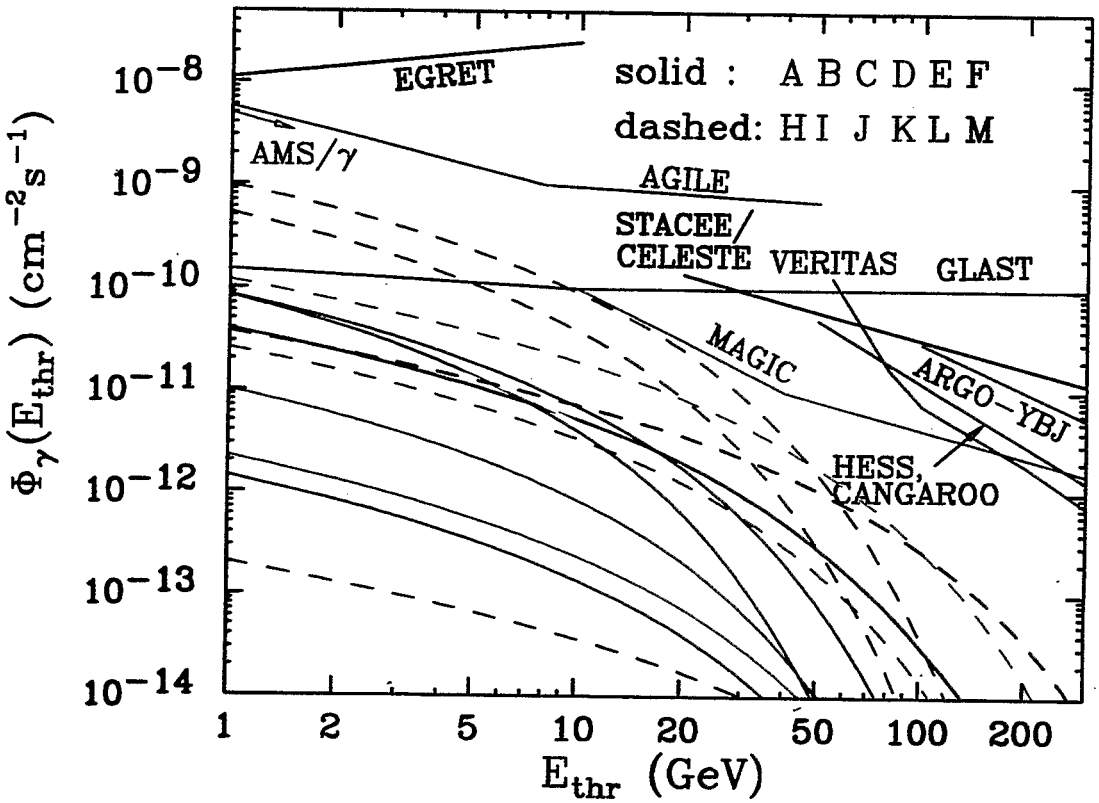
$$\tilde{\chi}N \to \tilde{\chi}(N^* \to N\gamma)$$

de-excitation ⊕ recoil energy: small rate)

Gamma-Ray Spectra

in supersymmetric benchmark scenarios

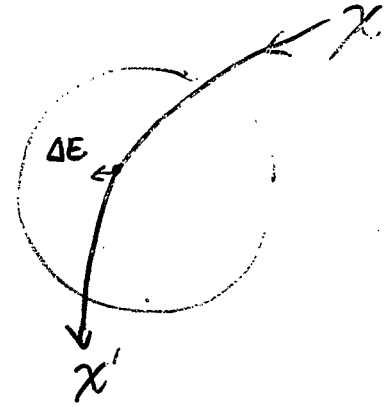
uncertain concentration in galactic centre



(J.E. + Feng + Fornal + Matchev + Olive

Annihilation in Sun (Earth)

- Capture of relic particle due to recoil energy loss

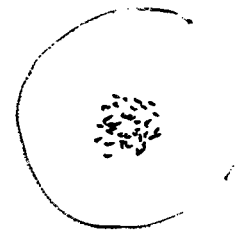


hyperbolic orbit ⇒ elliptic orbit

perihelion < solar radius
(gas) (earth)

- Repeated scattering, energy loss

⇒ quasi-isothermal distribution



- Population control by annihilation

$\chi\chi \to \nu + \cdots$

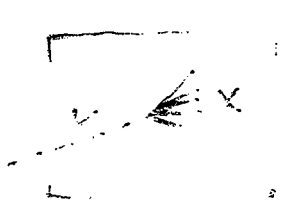
evaporation negligible for $m_\chi >$ few GeV

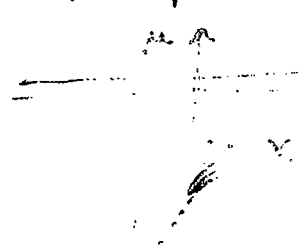
- High-energy solar neutrinos (from core of Earth)

$E_\nu \gtrsim$ GeV

vulnerable to MSW ?!

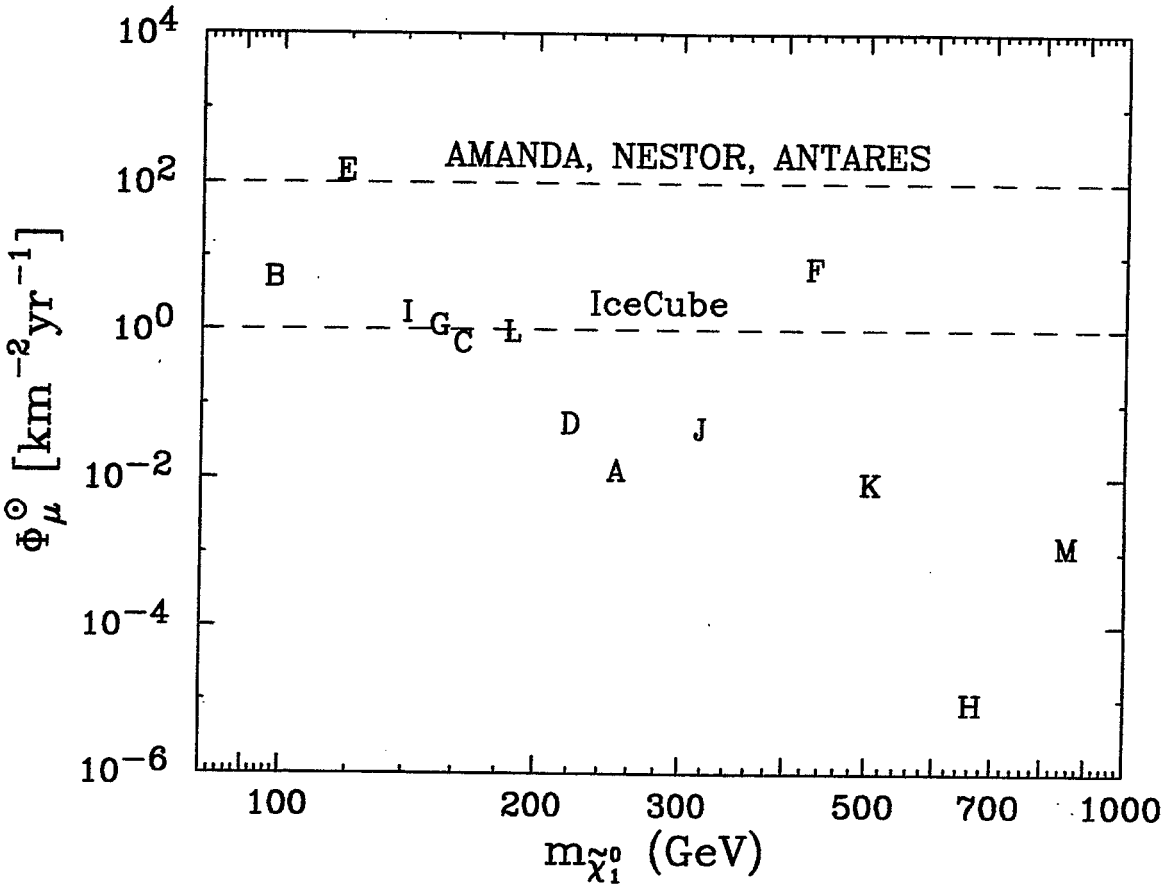
- detect directly or via μ production





$\chi\chi \to \nu \to \mu$

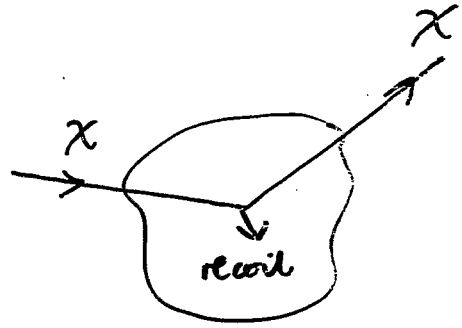
annihilation inside the Sun



(J.E. + Feng + Festh + Matchev + Olive

Direct Detection of Dark Matter

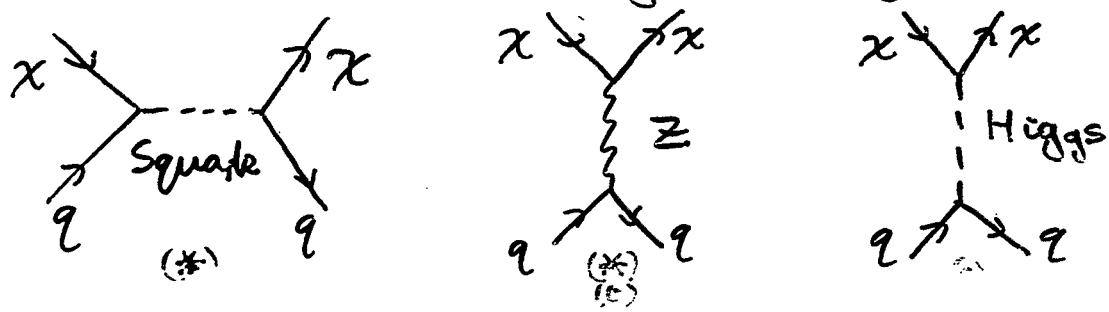
scattering of nucleus in laboratory:



recoil energy $E \sim m_\chi v^2/2$

$\sim$ keV

interaction mediated by exchanges of



two important types of interaction:

<u>spin-dependent</u>(*):

matrix element $\propto$ quark contributions to proton spin: $\mathcal{M} \sim \sum_i \Delta q_i \, c_i$

not coherent: important for small nuclei.

<u>spin-independent</u>:

matrix element $\propto$ quark contributions to proton mass: coherent, important for heavy nuclei

Elastic Neutralino Scattering

(JE + Forshl + Olive
hep-ph/0007113
0106148

low-energy effective lagrangian:

$$\alpha_{2i}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}_i\gamma_\mu\gamma^5 q_i) + \alpha_{3i}(\bar{\chi}\chi)(\bar{q}_i q_i)$$

+ velocity-dependent terms

spin-dependent:

$$\sigma_2 = \frac{32}{\pi} G_F^2 m_r^2 \Lambda^2 J(J+1)$$

reduced mass

$$\Lambda = \frac{1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)$$

$$\sum_i \frac{\alpha_{2i}}{\sqrt{2}G_F}\Delta q_i$$: cont^{ns} to proton spin

$\Delta u = 0.78 \pm 0.02$, $\Delta d = -0.48 \pm 0.02$, $\Delta s = -0.15 \pm 0.0$

spin-independent:

$$\sigma_3 = \frac{4m_r^2}{\pi}\left[Z f_p + (A-Z) f_n\right]^2$$

$$\frac{f_p}{m_p} = \sum_{q=u,d,s} f_{Tq}\frac{\alpha_{3q}}{m_q} + \frac{2}{27} f_{Tq}\sum_{q=c,b,t}\frac{\alpha_{3q}}{m_q}$$

where

$$m_p f_{Tq} = \langle p|m_q\bar{q}q|p\rangle \equiv m_q B_q$$

contributions to proton mass

Spin-independent matrix element

- quark mass ratios from chiral symmetry analysis

$$\frac{m_u}{m_d} = 0.553 \pm 0.043, \quad \frac{m_s}{m_d} = 18.9 \pm 0.8$$

- octet baryon mass splittings:

$$\frac{B_u - B_s}{B_d - B_s} = 1.49 \quad \text{with negligible error}$$

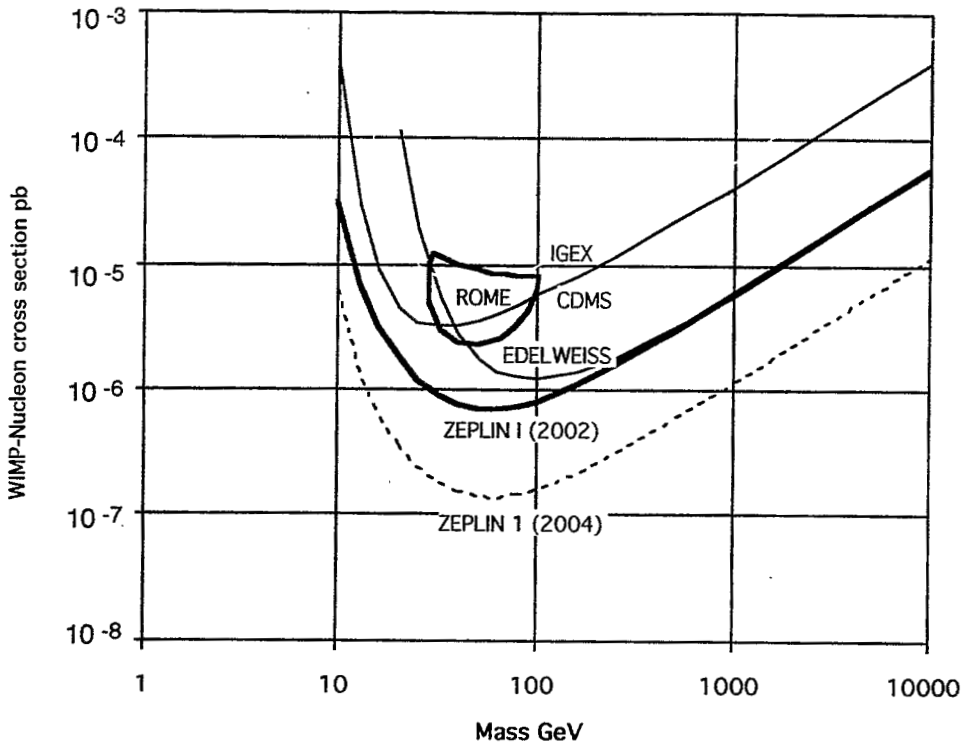
- πN σ-term analysis

$$y = \frac{2B_s}{B_d + B_u} = 0.2 \pm 0.1$$

implies $\dfrac{B_d}{B_u} = 0.73 \pm 0.02$

small uncertainties in elastic scattering cross sections $(p \simeq n)$

Current status of searches for weakly interacting massive particles

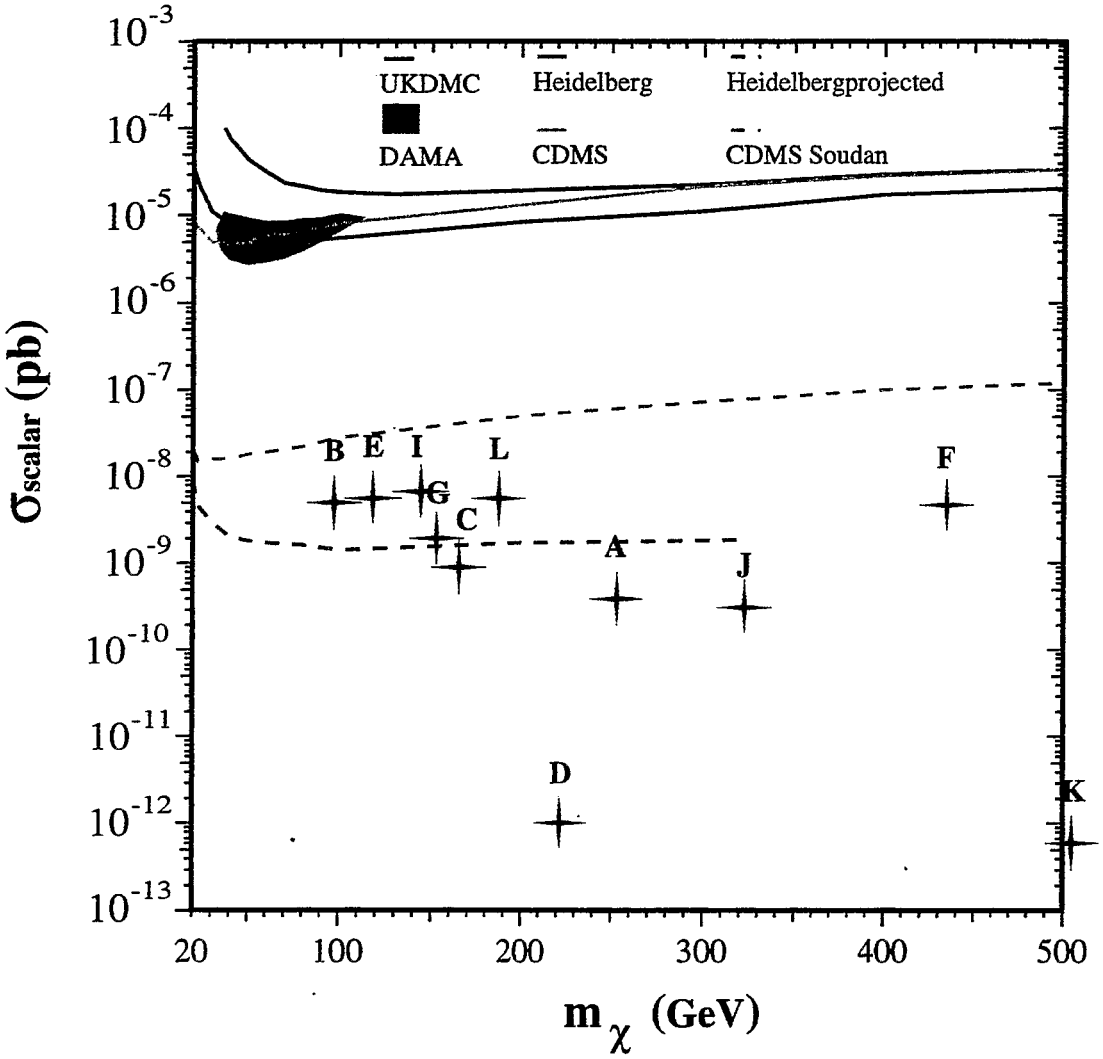


Smitt

prospects for dark matter search

Spin-Independent Elastic Scattering

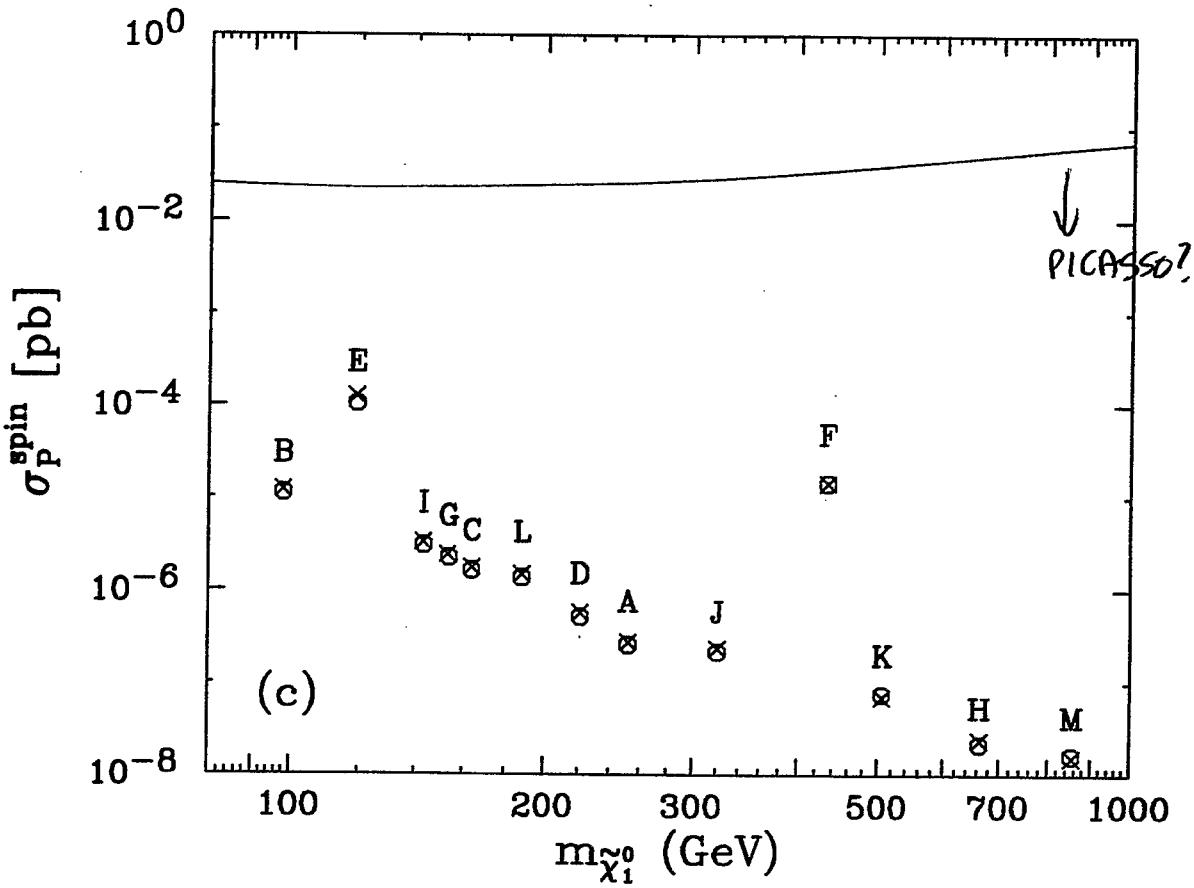
in supersymmetric benchmark scenarios



(J.E. + Feng + Forshl + Matchev + Olive

Spin-Dependent Elastic Scattering

in benchmark scenarios



(J.E. + Feng + Forshll + Matchev + Olive

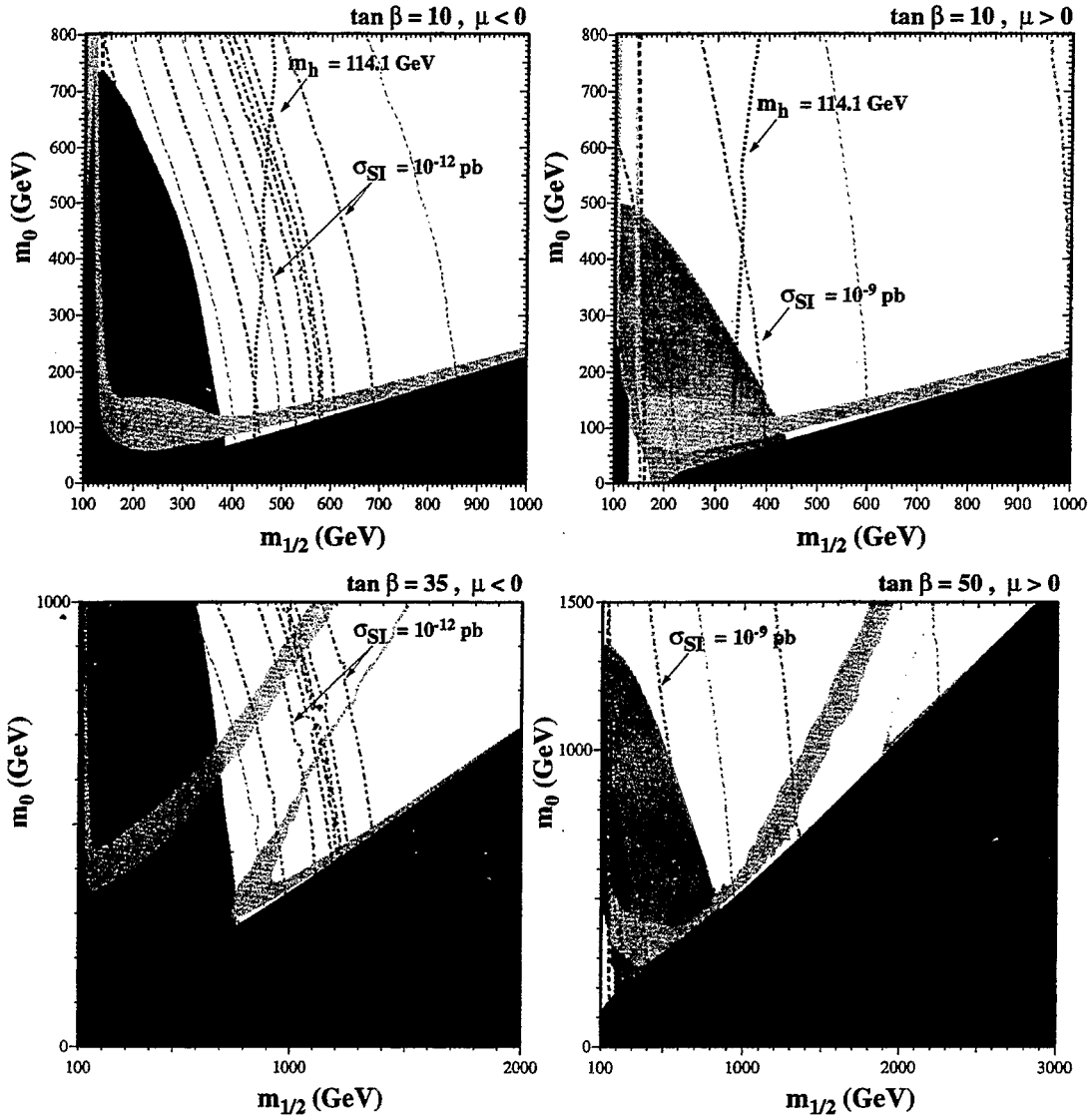


Figure 1: *Spin-independent cross sections in the* $(m_{1/2}, m_0)$ *planes for (a)* $\tan\beta = 10, \mu < 0$, *(b)* $\tan\beta = 10, \mu > 0$, *(c)* $\tan\beta = 35, \mu < 0$ *and (d)* $\tan\beta = 50, \mu > 0$, *assuming* $A_0 = 0, m_t = 175$ *GeV and* $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ *GeV [14]. The double dot-dashed (orange) curves are contours of the spin-independent cross section, differing by factors of 10 (bolder) and interpolating factors of 3 (finer - when shown). For example, in (b), the curves to the right of the one marked* 10^{-9} *pb correspond to* 3×10^{-10} *pb and* 10^{-10} *pb. The near-vertical lines are the LEP limits* $m_{\chi^\pm} = 103.5$ *GeV (dashed and black) [29],* $m_h = 114.1$ *GeV (dotted and red) [9]. In the dark (brick red) shaded regions, the LSP is the charged* $\tilde{\tau}_1$, *so this region is excluded. The light (turquoise) shaded areas are the cosmologically preferred regions with* $0.1 \leq \Omega_\chi h^2 \leq 0.3$ *[14]. The medium (dark green) shaded regions that are most prominent in panels (a) and (c) are excluded by* $b \to s\gamma$ *[18]. The sloping shaded (pink) regions in panels (b) and (d) delineate the* $\pm 2 - \sigma$ *ranges of* $g_\mu - 2$ *[12].*

Spin-Independent Cross Sections

(J.E. + Ferstl + Olive: hep-ph/0111069

Spin-Dependent Cross Sections

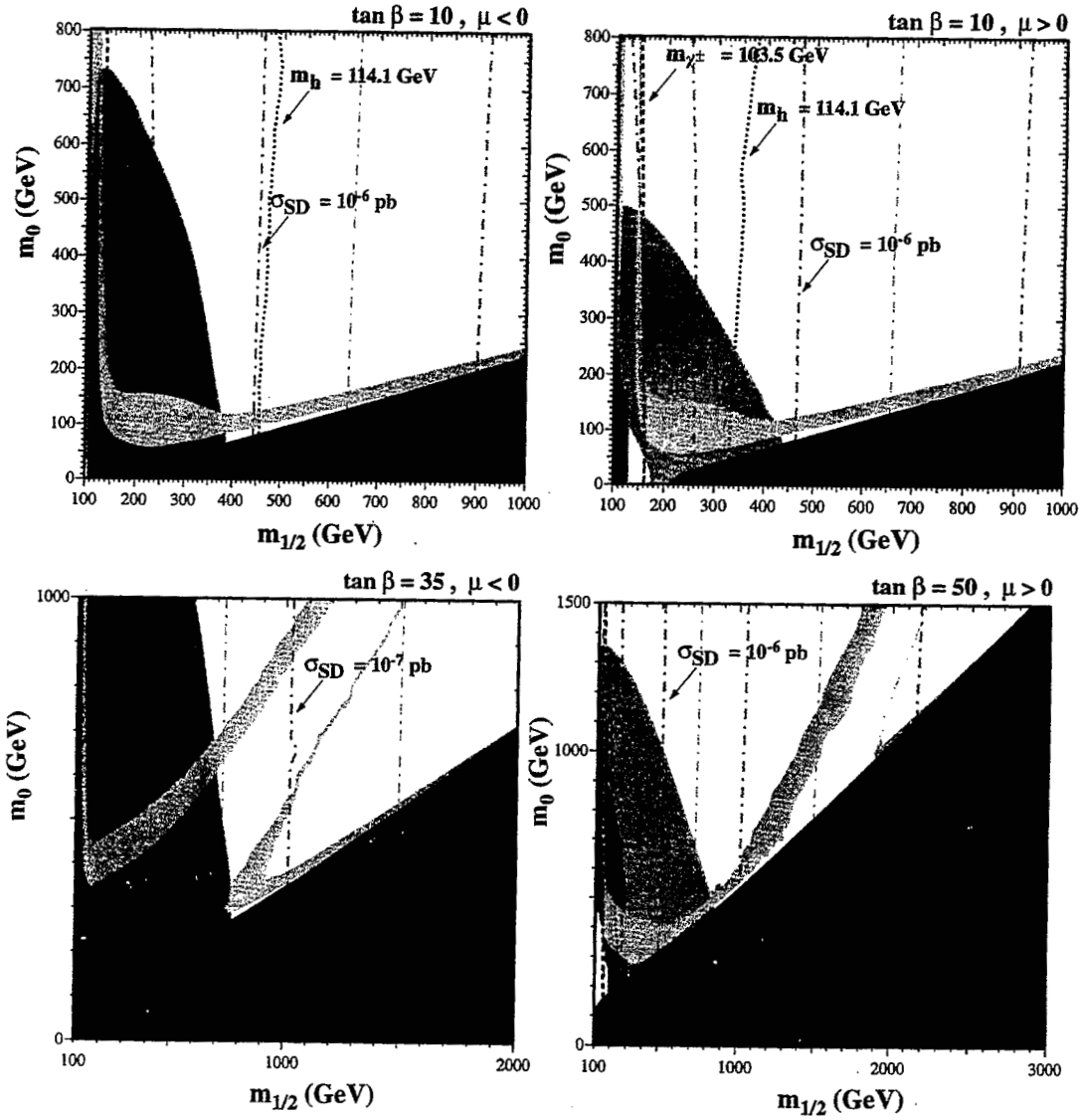
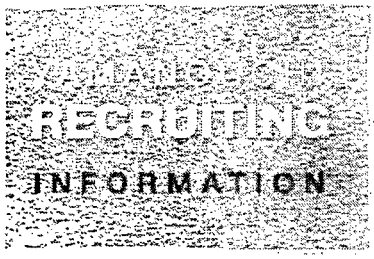


Figure 2: *Spin-dependent cross sections in the* $(m_{1/2}, m_0)$ *planes for (a)* $\tan\beta = 10, \mu < 0$, *(b)* $\tan\beta = 10, \mu > 0$, *(c)* $\tan\beta = 35, \mu < 0$ *and (d)* $\tan\beta = 50, \mu > 0$, *assuming* $A_0 = 0, m_t = 175$ *GeV and* $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ *GeV [14]. The dot-dashed (blue) lines are contours of the spin-dependent cross section, differing by factors of 10 (bolder) and interpolating factors of 3 (finer - when shown). The near-vertical dashed lines are the LEP limits* $m_{\chi^\pm} = 103.5$ *GeV (black) [29],* $m_h = 114.1$ *GeV (red) [9]. In the dark (brick red) shaded regions, the LSP is the charged* $\tilde{\tau}_1$, *so this region is excluded. The light (turquoise) shaded areas are the cosmologically preferred regions with* $0.1 \leq \Omega_\chi h^2 \leq 0.3$ *[15]. The medium (dark green) shaded regions are excluded by* $b \to s\gamma$ *[18].*

(J.E. + Feng + Olive: hep-ph/0111064



経験者採用情報

| 研究開発職 | 生産技術職 |

研究開発職（経験者募集）

1. 創薬研究者

循環器、炎症、糖尿病またはウイルス分野の薬理評価に関する研究

－上記分野に研究経験のある修士了以上の方

勤務地：茨城県つくば市(創薬研究本部)

2. 薬物動態研究者

(1)新薬開発における前臨床薬物動態研究

(2)CTDに対応した承認申請資料(日米欧)の作成

－薬物動態に関する専門知識を有し、新薬承認申請の経験(国内外問わず、米国ＮＤＡ経験者特に歓迎）または薬物代謝酵素／トランスポーターの専門知識・研究経験豊富な薬学系大卒以上の方

勤務地：東京都板橋区(代謝研究所)

3 製剤開発、分析法開発研究者

(1)新規生理活性物質の製剤化開発研究(経口・注射製剤)

(2)前記製剤の試験法開発研究

(3)ＤＤＳ研究

－上記研究経験１０年以上、大卒以上の方

勤務地：静岡県焼津市(創剤研究所)

資格　：上記以外に、英語力堪能で国際感覚のある方

待遇　：当社規定による

応募　：履歴書(写真貼付)、研究経歴書を下記連絡先へ郵送。書類受領後、弊社より詳細を連絡。

連絡先：〒103-8411 東京都中央区日本橋本町2-3-11
山之内製薬株式会社 人事部 仲村、宮野 Tel 03-3244-3066

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Elastic Scattering Cross Sections

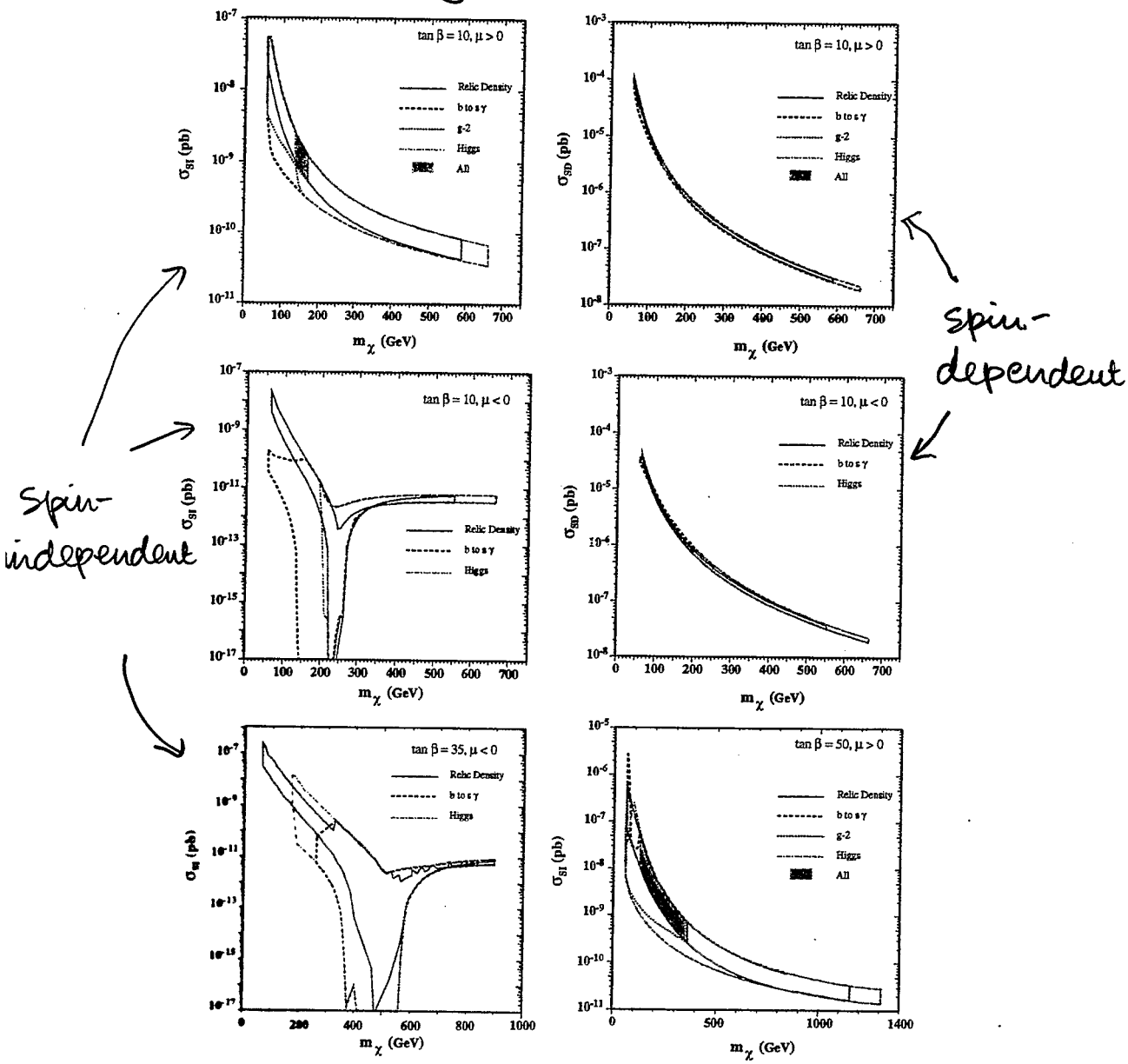

Figure 3. *Allowed ranges of the cross sections for* $\tan\beta = 10$ *and (a, b)* $\mu > 0$, *(c, d)* $\mu < 0$, *for (a, c) spin-independent and (b, d) spin-dependent elastic scattering. Panel (e) shows the spin-independent cross section for* $\tan\beta = 35$ *and* $\mu < 0$, *and panel (f) the spin-independent cross section for* $\tan\beta = 50$ *and* $\mu > 0$. *The solid (blue) lines indicate the relic density constraint [15], the dashed (black) lines the* $b \to s\gamma$ *constraint [18], the dot-dashed (green) lines the* m_h *constraint [9], and the dotted (red) lines the* $g_\mu - 2$ *constraint [12]. The shaded (pale blue) region is allowed by all the constraints.*

(J.E. + Ferstl + Olive: hep-ph/0111064

WMAP

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Ranges for Scattering Cross Sections

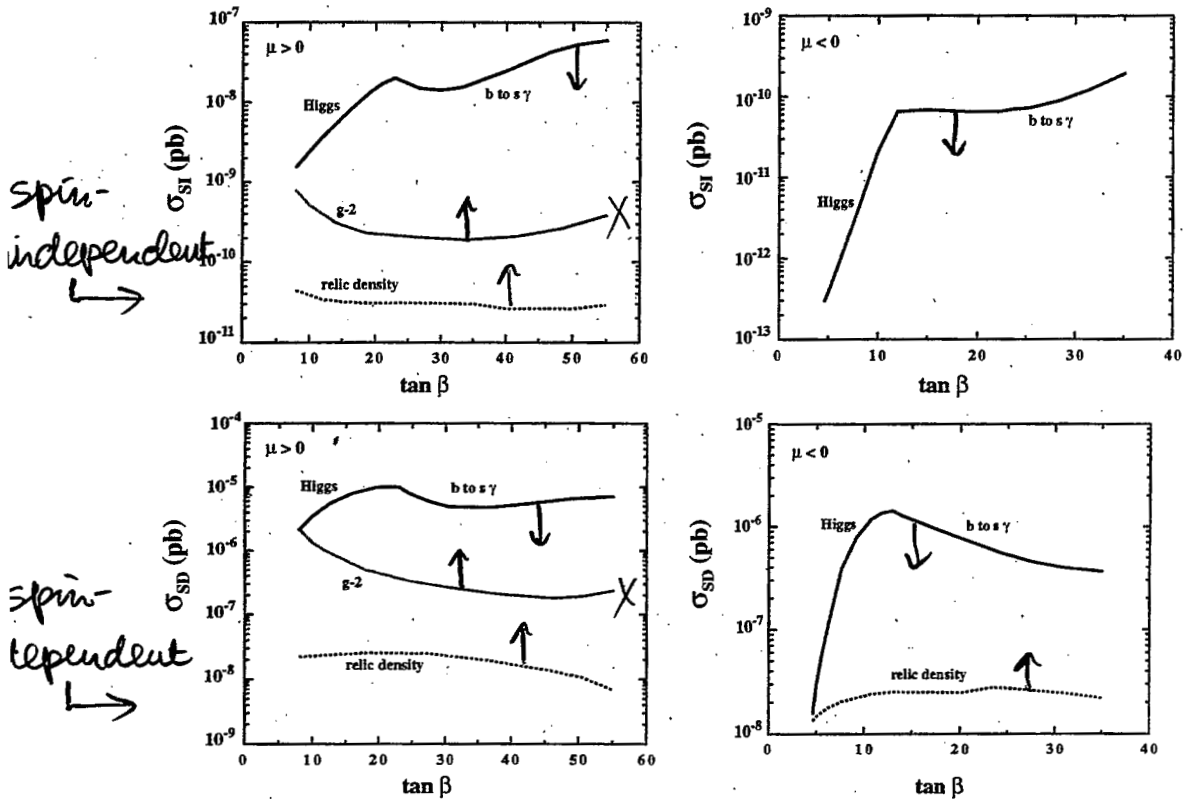

Figure 4: *The allowed ranges of (a, b) the spin-independent cross section and (c, d) the spin-dependent cross section, for (a, c) $\mu > 0$ and (b, d) $\mu < 0$. The darker solid (black) lines show the upper limits on the cross sections obtained from m_h and $b \to s\gamma$, and (where applicable) the lighter solid (red) lines show the lower limits suggested by $g_\mu - 2$ and the dotted (green) lines the lower limits from the relic density.*

(J. E. + Feng + Olive:
hep-ph/0111064

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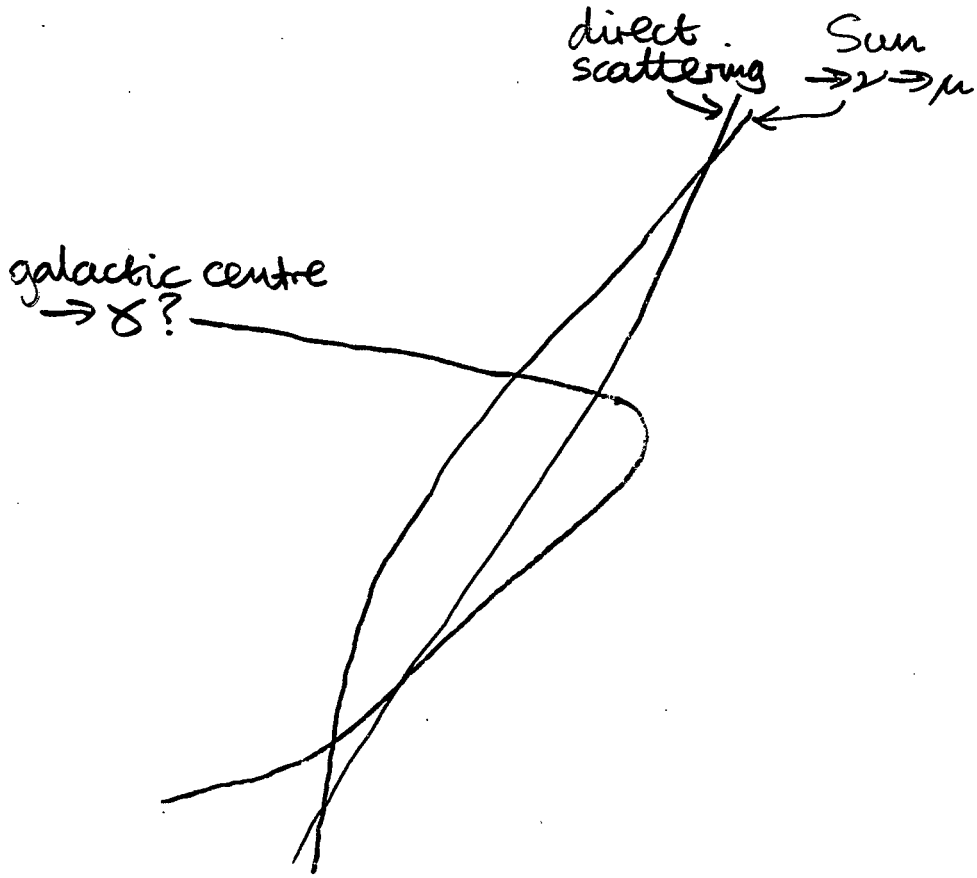

direct scattering
Sun
→ν → μ
galactic centre
→ γ ?

Physics with Precision Measurements of the Nucleon Structure

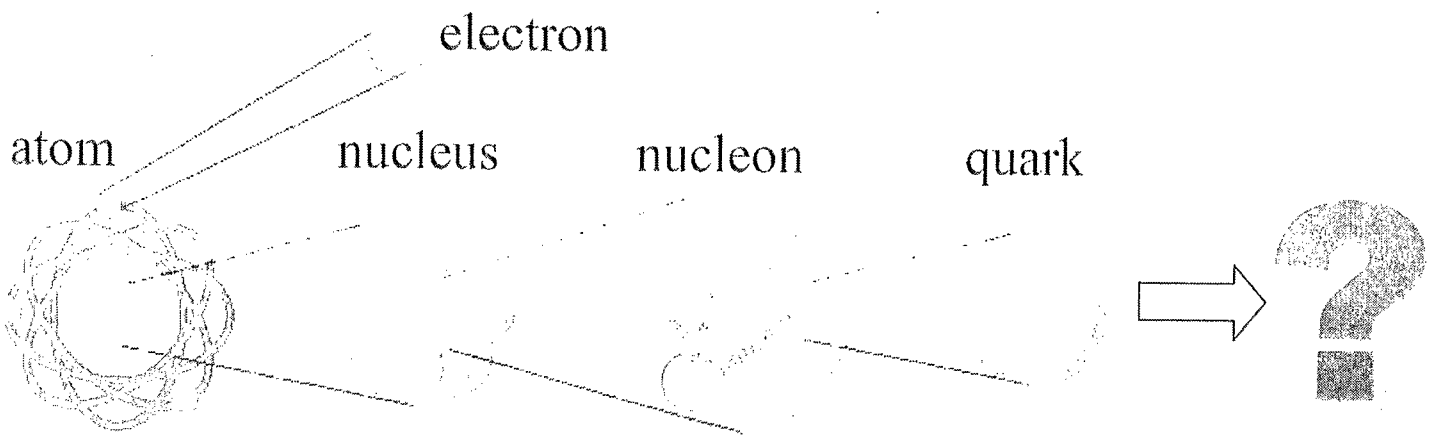
Naohito SAITO
Kyoto University/RIKEN

Outline of Lectures

- Lecture I
  - Motivation of Structure Studies
  - Methodology of Structure Studies
  - Structure Functions and Parton Distribution Functions
  - Scaling and its violation
- Lecture II
  - Polarized extension of structure studies

Particle Physics = Reductionism

- Efforts to understand the complex system (e.g. matter) in terms of simpler elements
  - What is the ultimately elementary particle?
  - No more substructure?

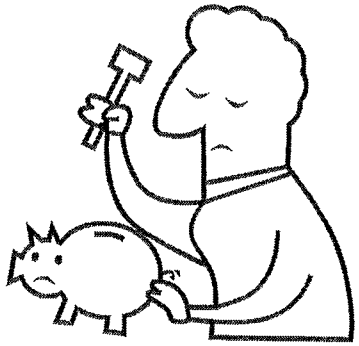


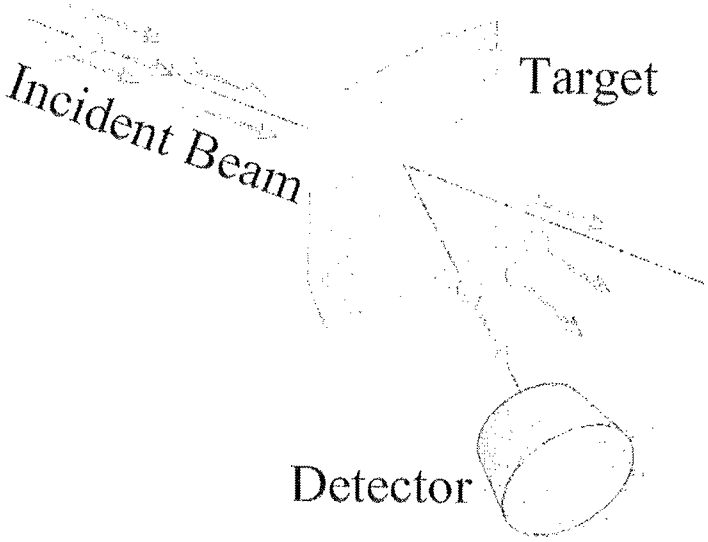
Why Proton Structure Studies?

- Understand the proton in terms of simpler elements = quarks and gluons
  - QCD describes how quarks and gluons interplay in their evolution in Q^2 or energy scale; test of pQCD
  - Q^2 evolution also determines strong coupling constant α_S
- With the knowledge of quark and gluon distributions in the proton
  - proton-proton collider will become quark-quark, gluon-quark, and gluon-gluon colliders
  - it would provide further test of the SM in the quark sector

Structure Studies

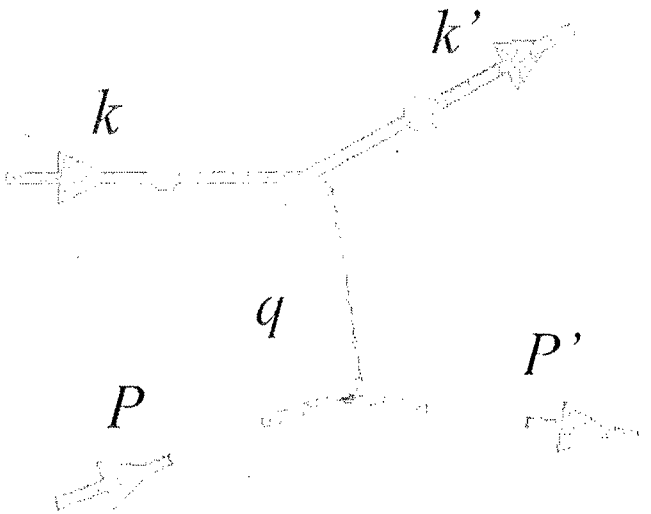
- Classical ways to study structure
  - Break-up
  - Expose to *a light source*





Electron-Proton Elastic Scattering

- Observables
  - Incoming electron 4-momentum k
  - Target proton initial 4-momentum P
  - Scattered electron 4-momentum k'
  - Recoil proton 4-momentum P'



$$P + q = P' \quad (q \equiv k - k')$$

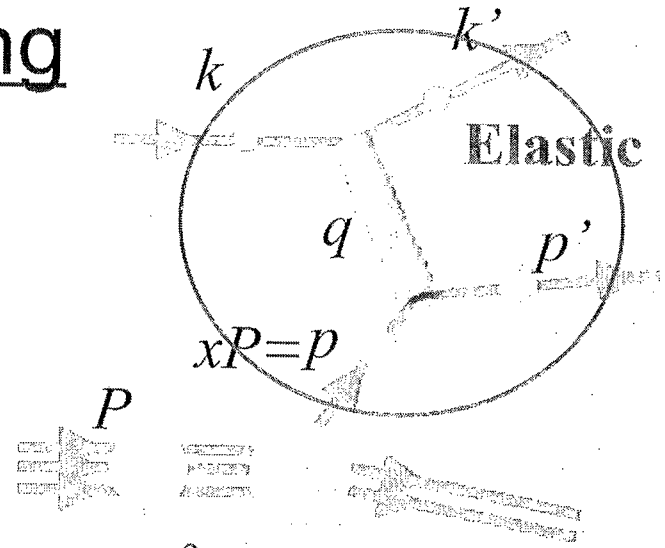
$$\Leftrightarrow P^2 + 2P \cdot q + q^2 = P'^2$$

$$\Leftrightarrow 2P \cdot q = Q^2 \quad (Q^2 = -q^2)$$

$$\frac{Q^2}{2P \cdot q} = 1$$

Electron-Proton Deep Inelastic Scattering

- Observables:
  - Measured variables:
    - Incoming electron 4-momentum k
    - Outgoing electron 4-momentum k'
    - Incoming proton 4-momentum P
  - Unmeasured variables:
    - Incoming parton 4-momentum p
    - Outgoing parton 4-momentum p'



$$p+q=p' \quad (q \equiv k-k')$$

$$\Leftrightarrow p^2+2P\cdot q+q^2=p'^2$$

$$\Leftrightarrow 2p\cdot q=Q^2 \quad (Q^2=-q^2)$$

$$\Rightarrow \frac{Q^2}{2P\cdot q}\neq 1 \text{ unless } P=p$$

$$x \equiv \frac{Q^2}{2P\cdot q}$$

$$\Rightarrow 2xP\cdot q=2p\cdot q$$

$$\Rightarrow p=xP; \frac{Q^2}{2p\cdot q}=1$$

What are being scattered in DIS?

- Cross section for DIS includes unknown functions representing structure of the proton :$F_1(x,Q^2)$ & and $F_2(x,Q^2)$

$$\frac{d^2\sigma}{dQ^2dx}=\frac{4\pi\alpha^2}{Q^4}\frac{E'}{E}\left(F_2(x)\cos^2\frac{\theta}{2}+\frac{Q^2}{2M^2x^2}2xF_1(x)\sin^2\frac{\theta}{2}\right)\frac{1}{x}$$

- Compare with the formula for spin-1/2 vs spin-1/2 scattering cross section

$$\frac{d\sigma}{dQ^2}=\frac{4\pi\alpha^2z^2}{Q^4}\left(\frac{E'}{E}\right)^2\left(\cos^2\frac{\theta}{2}+\frac{Q^2}{2m^2}\sin^2\frac{\theta}{2}\right)$$

- If partons are spin-1/2, angular distribution should follow spin-1/2 pattern

→Ratio of the coefficients in front of the $\cos^2\theta/2$ and $\sin^2\theta/2$ should be identical to above

If spin ½

$$\frac{2xF_1(x)}{F_2(x)}=1$$

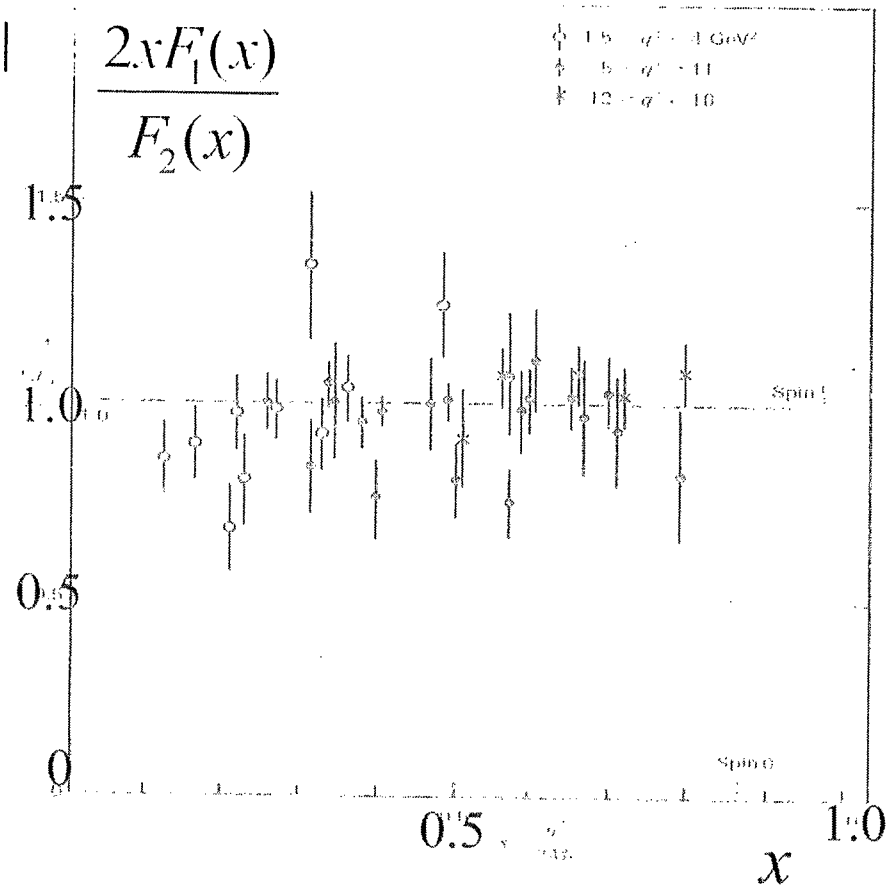
If spin 0

$$\frac{2xF_1(x)}{F_2(x)}=0$$

Experimental Verification of CGR

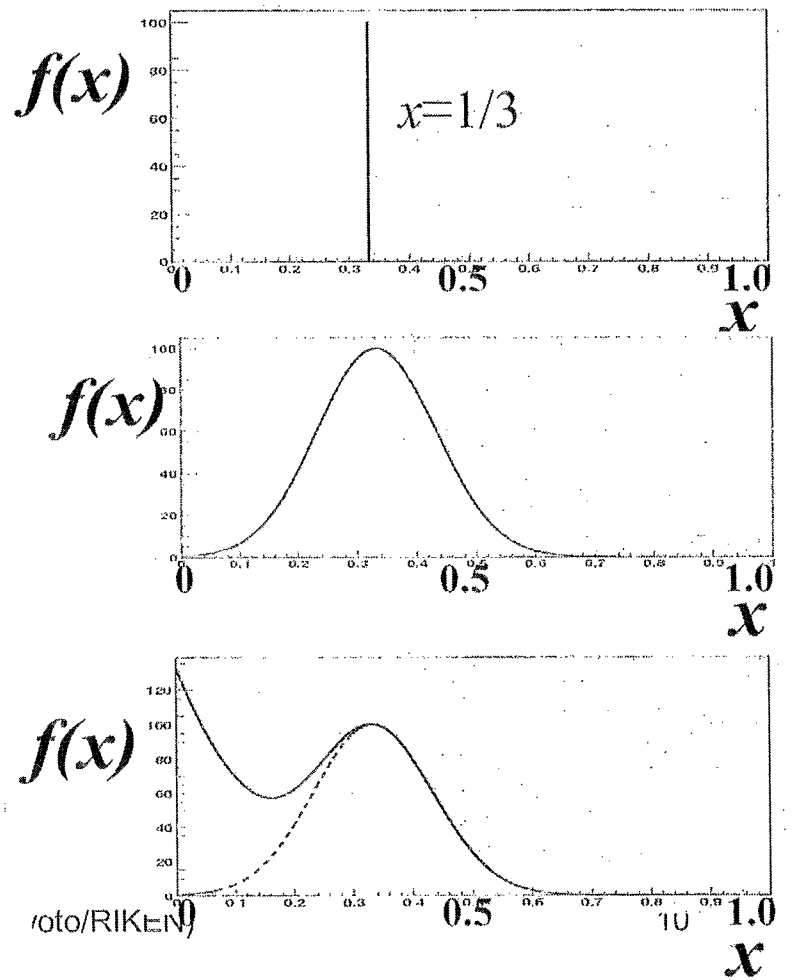
- Early experimental data verified Callan-Gross Relation
  - $0.1 < x < 0.8$
  - $1.5 < Q^2 < 16\ \mathrm{GeV}^2$
- Scattered Partons are spin ½ !

  → Quarks



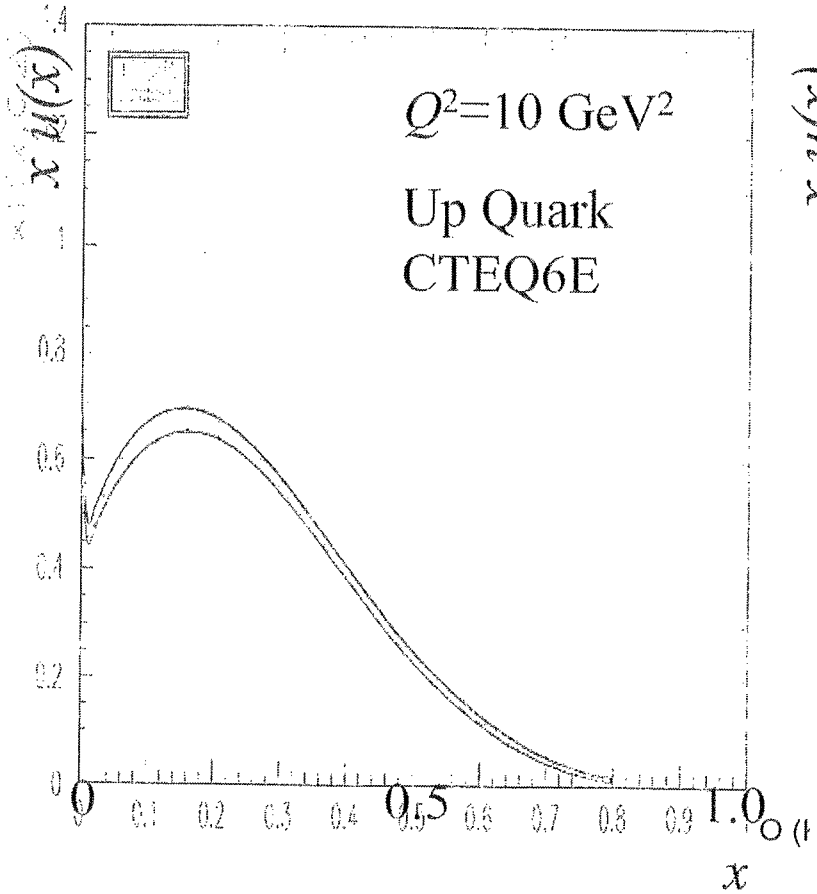
Probability to find a parton with xP = Parton Distribution Function

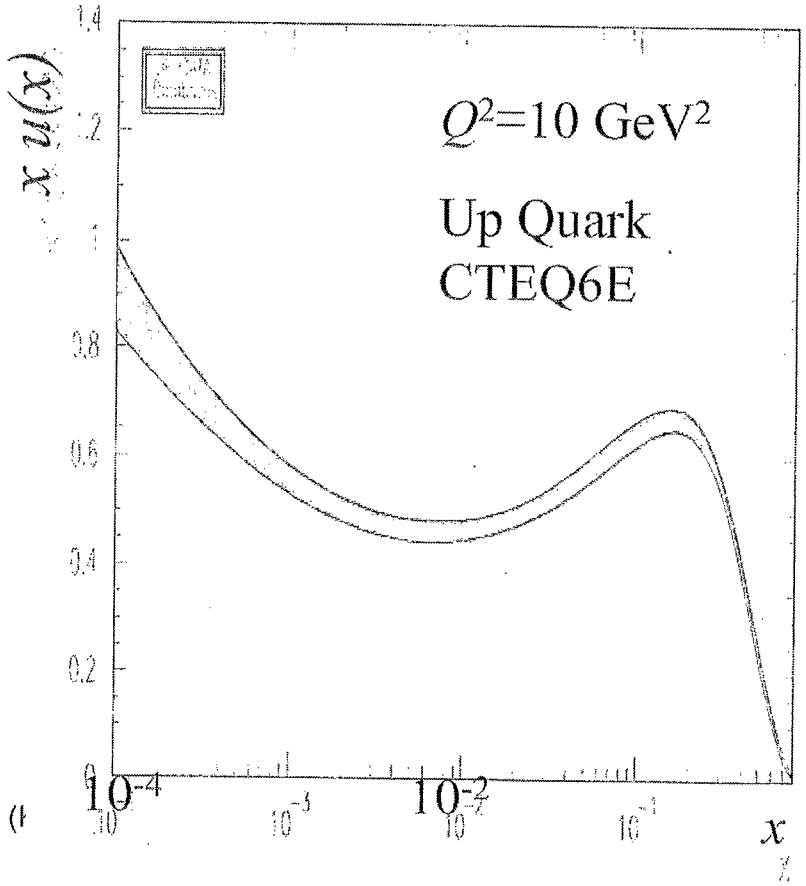
- If quarks are free…
- They are bound
- And there are sea-quarks



Example: Up Quark Distribution

- Obtained through Global QCD Analysis by CTEQ





Normalization of PDFs

- The proton comprises 2 u-quarks, 1 d-quark and 0 s-quark; (no c, b, t …of course)

$$\int_0^1 dx[u(x)-\bar{u}(x)]=2,\ \int_0^1 dx[d(x)-\bar{d}(x)]=1,\ \int_0^1 dx[s(x)-\bar{s}(x)]=0$$

- Momentum Sum Rule

$$\int_0^1 dx\, x \sum_{f=all} f(x)=1$$

- Experimentally…

$$\int_0^1 dx\, x[u(x)+\bar{u}(x)]+\int_0^1 dx\, x[d(x)+\bar{d}(x)]$$

$$+\int_0^1 dx\, x[s(x)+\bar{s}(x)]\approx 0.5$$

•Some neutral object carry a half momentum of the proton! Indeed.

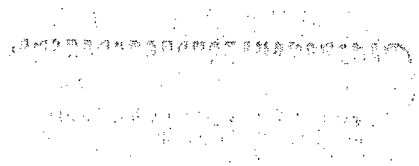
$$\int_0^1 dx\, xg(x)\approx 0.5$$

Q^2 Evolution – changing resolution

- Low Q ~ 200 MeV
  - Proton is still seen as a whole

- Mid Q ~ 1 GeV
  - Quarks are seen

- Higher Q ~ 10 GeV
  - Sea-quarks are seen



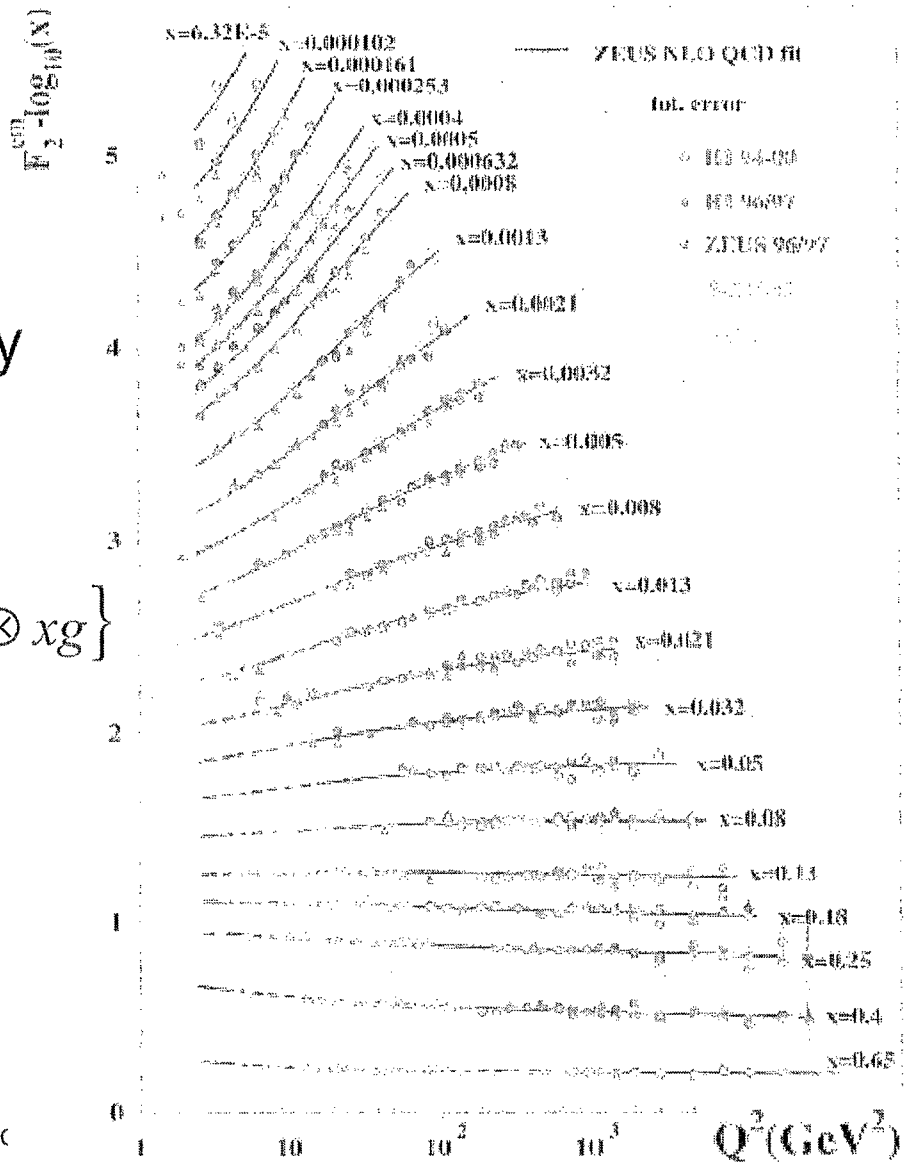
Q^2 Evolution of F_2

- Data well described by NLO QCD: DGLAP evolution

$$\frac{dF_2^{ep}}{d\ln Q^2} = \frac{\alpha_S}{2\pi}\left\{P_{qq} \otimes F_2^{ep} + P_{qg} \otimes xg\right\}$$

- $dF_2/d\ln Q^2 > 0$ at $x << 1$
- $dF_2/d\ln Q^2 < 0$ at $x \sim 1$

- Turn over $\sim x = 0.1$

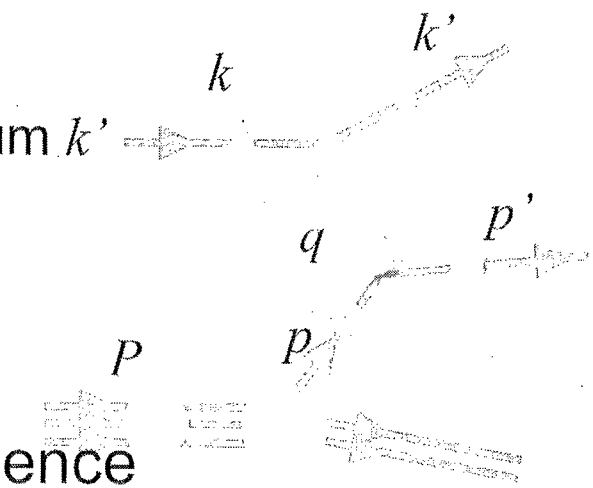


Neutrino-Proton Deep Inelastic Scattering

- Charged Current

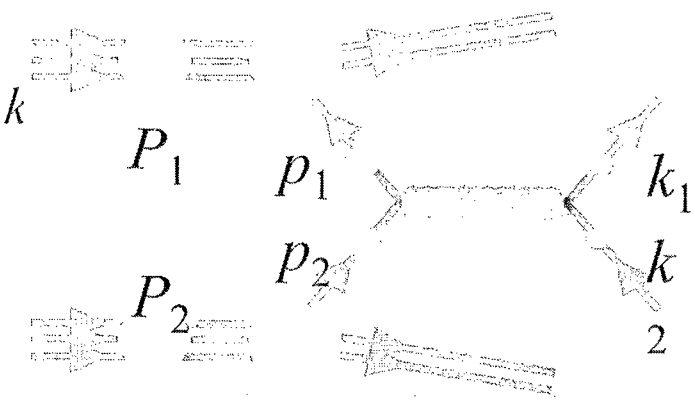
$$\frac{d^2\sigma(\nu p \text{ or } \bar{\nu} p)}{dQ^2 d\nu} = \frac{G^2}{2\pi}\cdot\frac{k'}{k}\left[W_2(Q^2,\nu)\cos^2\frac{\theta}{2} + 2W_1(Q^2,\nu)\sin^2\frac{\theta}{2} \pm W_3(Q^2,\nu)\frac{k+k'}{M}\sin^2\frac{\theta}{2}\right]$$

- Flavor Sensitive – Weak charge strongly correlates with flavor
- Observables:
  - Outgoing charged lepton 4-momentum k'
  - Target proton 4-momentum P
  - Outgoing quark momentum p'
  - Incoming neutrino momentum poorly known k
- Usually subject to nuclear dependence



Drell-Yan Lepton Pair Production

- Observables:
  - 4-momentum of each lepton k_1, k
  - Incident beam proton 4-momentum P_1
  - Target proton 4-momentum P_2



- Reconstruction of Partonic Kinematics

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{1}{3}\cdot\frac{4\pi\alpha^2}{3M^2}\cdot\sum_i e_i^2\{q(x_1)\bar{q}(x_2)+1\leftrightarrow 2\}$$

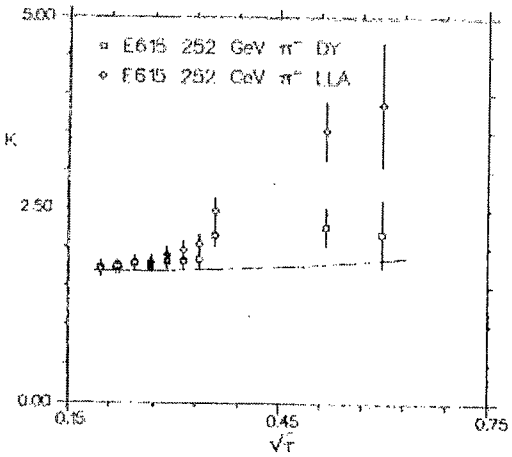
  - $M^2=(k_1+k_2)^2$; $s=(P_1+P_2)^2$; $\tau=M^2/s$
  - If transverse component of (k_1+k_2) is negligible

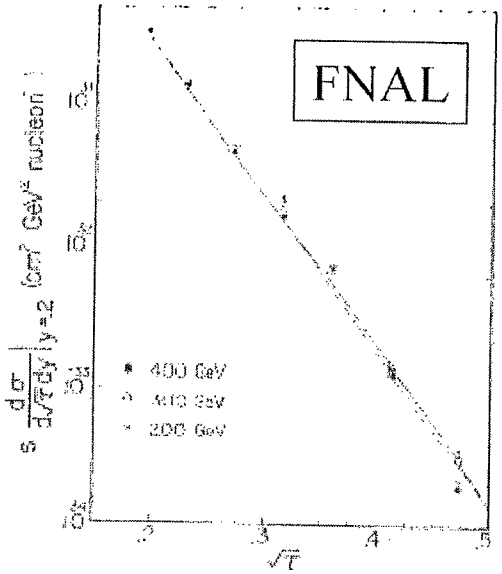
$$\tau = x_1 x_2 ; y = \frac{1}{2}\ln(\frac{x_1}{x_2})$$

$$x_1 = \sqrt{\tau}\exp(y), x_2 = \sqrt{\tau}\exp(-y)$$

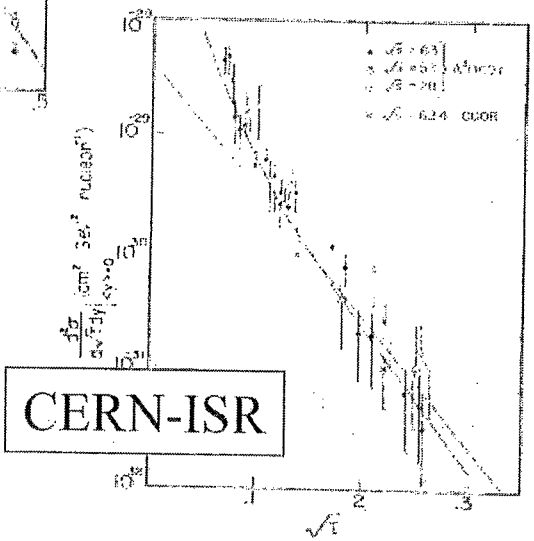
Scaling in Drell-Yan Cross Section

- Cross section scales with $\sqrt{\tau}$ independent of beam energy



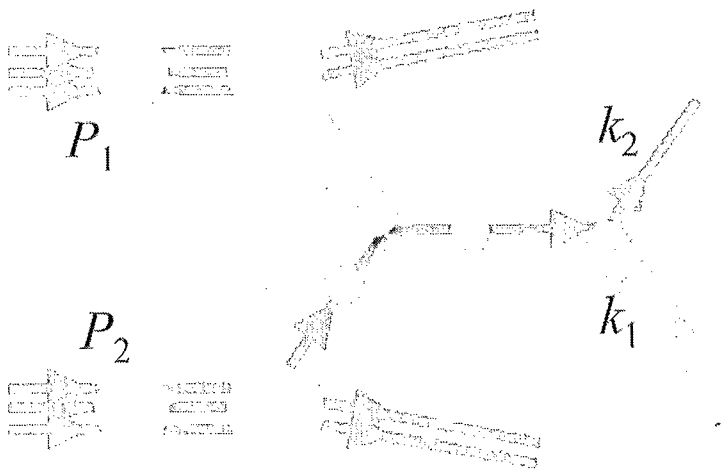


A.S.Ito et al, PRD23(81)604



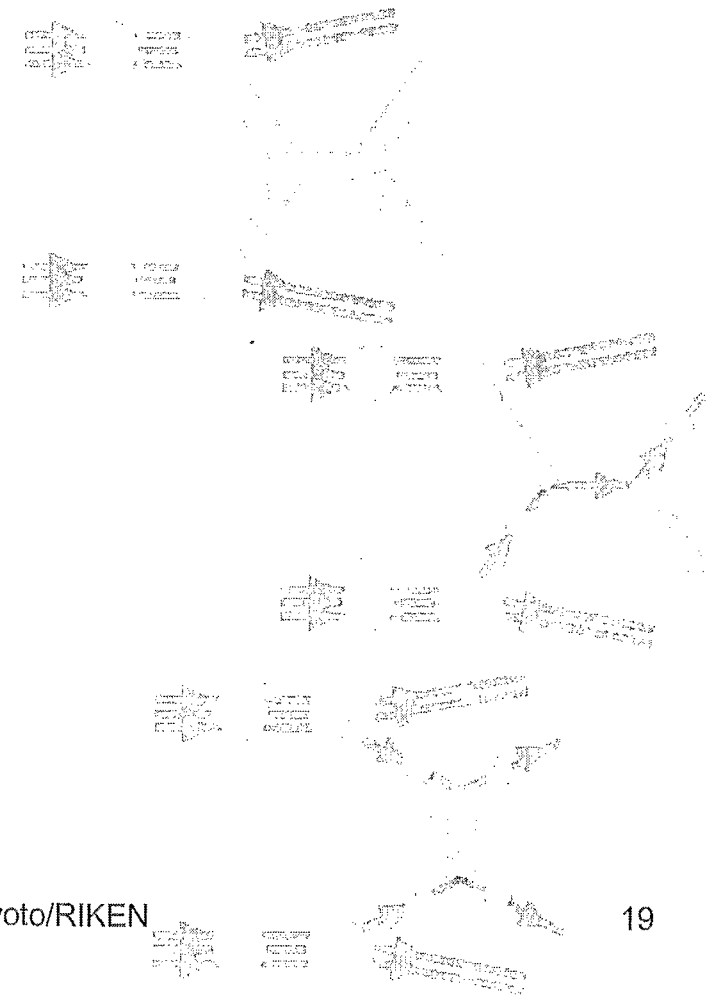
Prompt Photon Production

- Dominated by Gluon Compton
- Observable
  - Incoming Proton 4-momentum P_1
  - Target Proton 4-momentum P_2
  - Outgoing photon 4-momentum k_1
  - Outgoing Jet momentum or Jet Axis k_2 or n_2
- Subject to x_1- x_2 ambiguity
- Good energy resolution can be achieved for photon
- Higher order correction & intrinsic k_T will smear resolution



Two-Jet Production

- Observables:
  - Incoming Proton 4-momentum
  - Target Proton 4-momentum
  - Outgoing jet momentum
- Mixture of gg, gq, qq scattering
- Subject to x_1-x_2 ambiguity
- Higher order correction and Intrinsic k_T will smear resolution



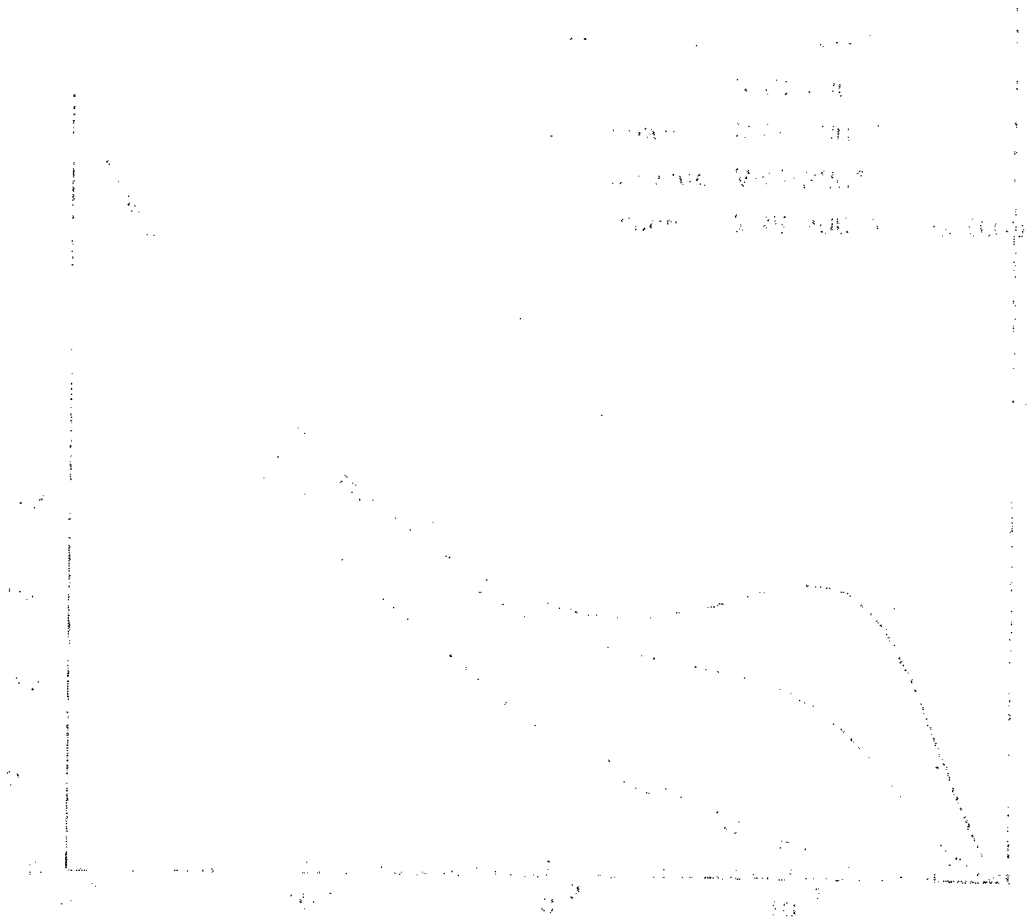
Processes used for Structure Studies

- NC-DIS is the major source; supplemented by hadronic processes

process	$f_1(x)$	$f_2(x)$	comment
NC DIS	$q(x)+\bar{q}(x)$	-	Flavor insensitive
CC DIS	$q(x)-\bar{q}(x)$	-	Flavor sensitive; Nuclear dependence
Drell-Yan	$q(x)$	$\bar{q}(x)$	Co-linear assumption needed for x-reconstruction
Prompt γ	$g(x)$	$q(x)$	Co-linear assumption needed for x-reconstruction
Two jet	$g(x)$ $q(x)$ $q(x)$	$g(x)$ $g(x)$ $q(x)$	Co-linear assumption needed for x-reconstruction largely mixed processes

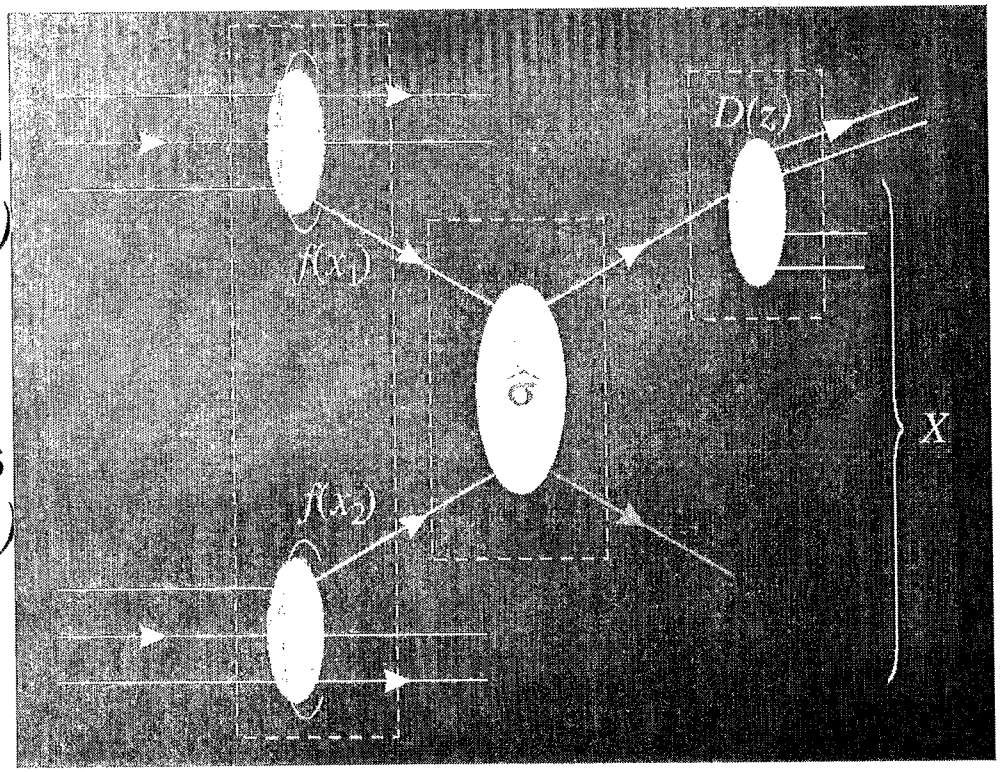
Parton Distributions

- Up, Down, Strange quark distributions and gluon distribution evaluated at Q^2=100 GeV^2



Hadron Production in pp Collisions

- 3 steps to produce hadron
  1) Emit Partons $f(x)$
  2) Partons Scatter σ
  3) PartonFragmens into hadron $D(z)$
- Universality of $f(x)$, σ, $D(z)$, if Factorization Proven

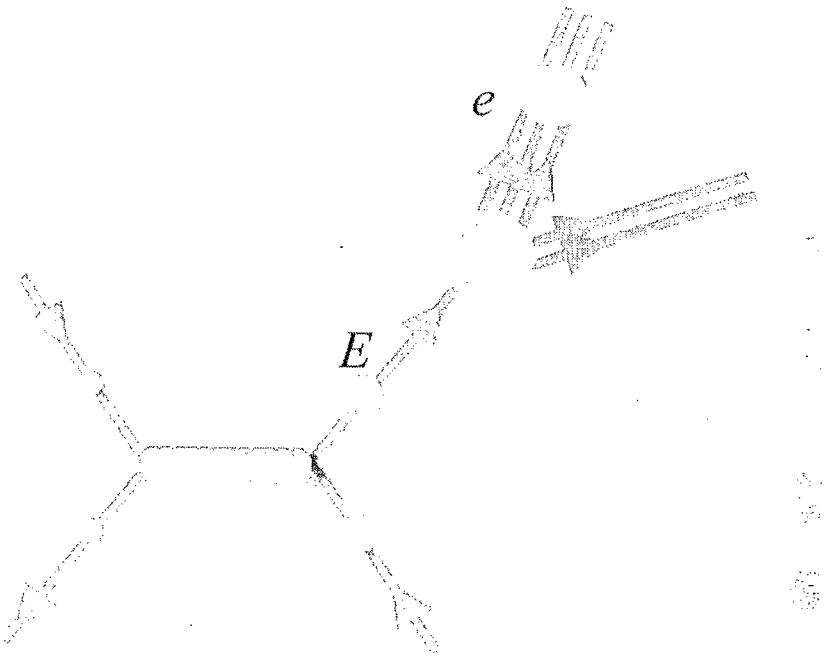


$$E\frac{d^3\sigma}{dp^3} = \sum_{ij}\int f_i(x_1) f_j(x_2)\frac{d\hat{\sigma}}{dt} D(z)\,dP$$

Fragmentation Function : $D(z)$

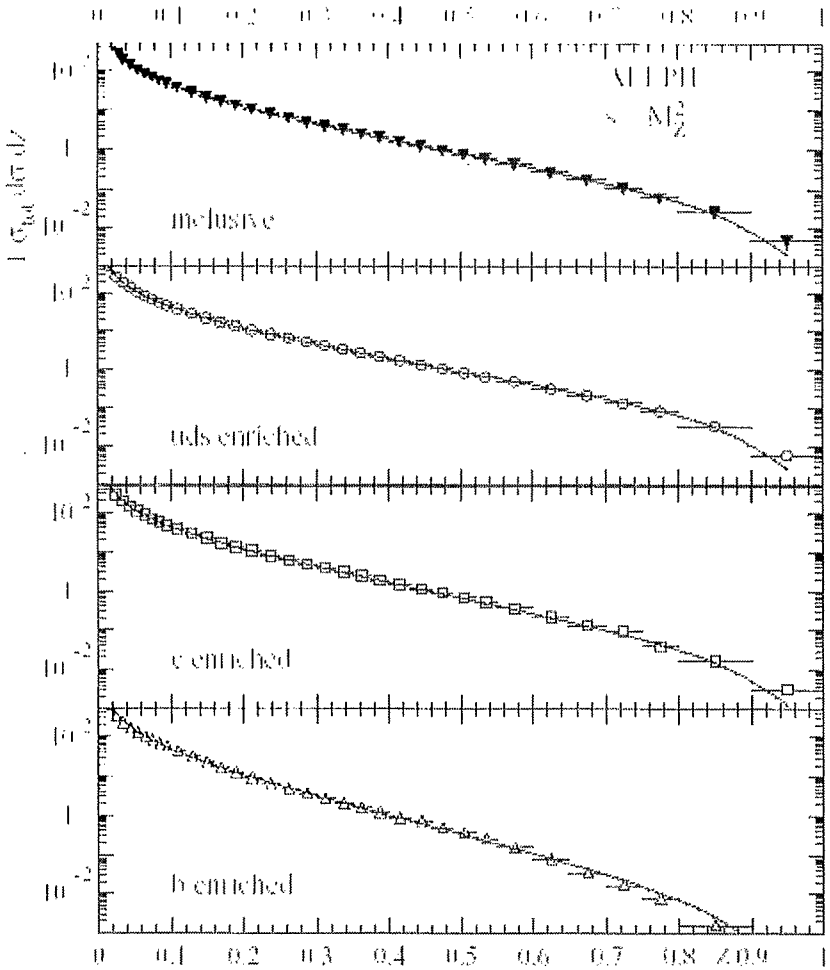
- Probability to have hadron with $e=zE$ from a scattered parton
- e.g. π^+ from u quark $D_{\pi+/u}(z)$

- Can be measured in Two-jet production in e^+e^- experiments
- Already many data points from PETRA, LEP etc. but precision is limited
- BELLE@KEK is producing precision data with ultra high statistics



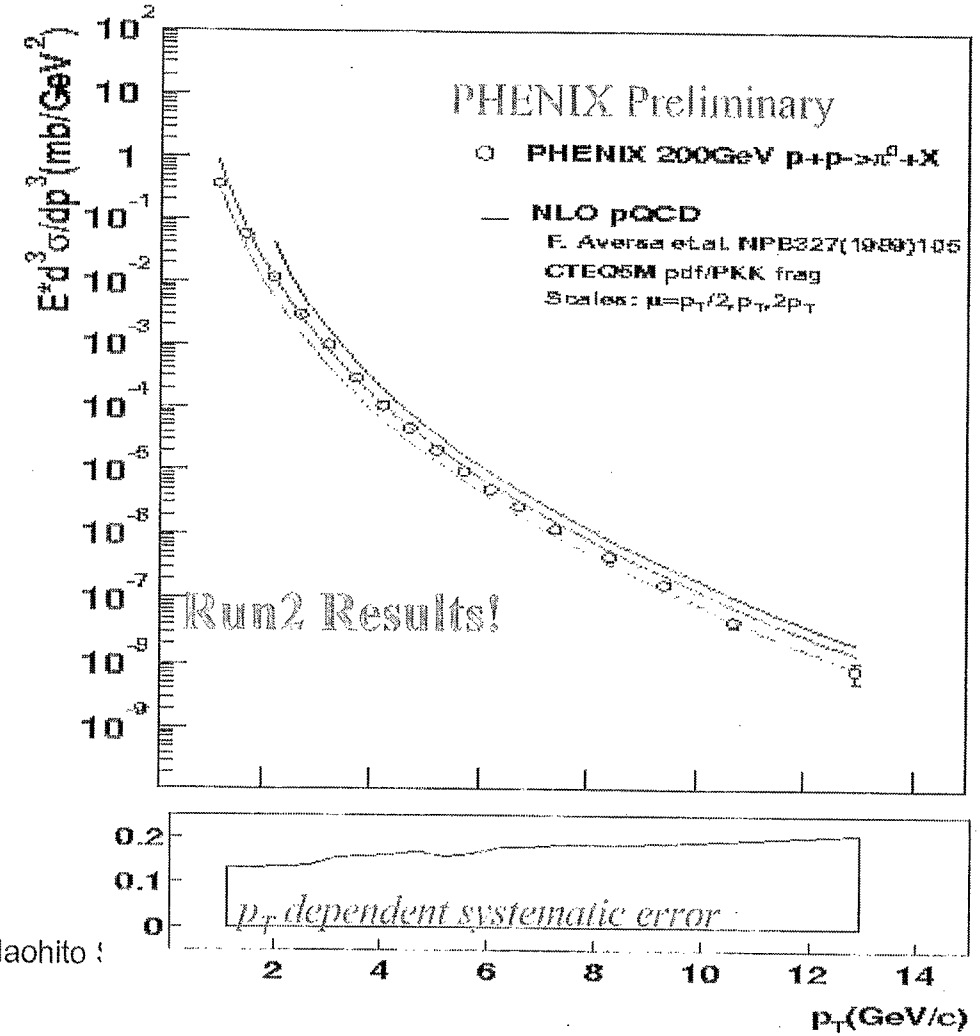
Fragmentation Functions

- Fragmentation functions for charged hadron obtained from LEP experiment



π^0 Production in pp collisions

- Theory explains cross sections for 10^8!



Summary

- Hadron structure studies are important for
  - QCD studies
  - For any physics signals in hadron related processes – hadron colliders
- Quark and gluon distributions and fragmentation functions are extracted

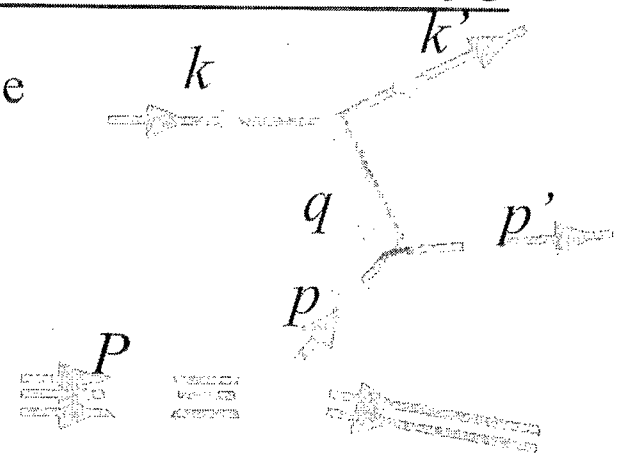
Polarized extension of structure studies

F_1 and F_2 are measured in unpolarized case

$$\frac{d^2\sigma}{dq^2dx}=\frac{4\pi\alpha^2}{q^4}\left[(1-y)\frac{F_2(x,q^2)}{x}+y^2\frac{2xF_1(x,q^2)}{x}\right]$$

Partonic interpretation

$$F_2(x)=x\sum_q e_q^2\left[q(x)+\bar{q}(x)\right]$$



In polarized case, g_1 and g_2 are measured

$$\frac{d^2\sigma^{\uparrow\downarrow}}{dxdy}-\frac{d^2\sigma^{\uparrow\uparrow}}{dxdy}=\frac{8\pi\alpha^2ME}{Q^4}\left[(2y-y^2-\frac{Mxy^2}{E})2xg_1(x,Q^2)-\frac{4M}{E}x^2yg_2(x,Q^2)\right]$$

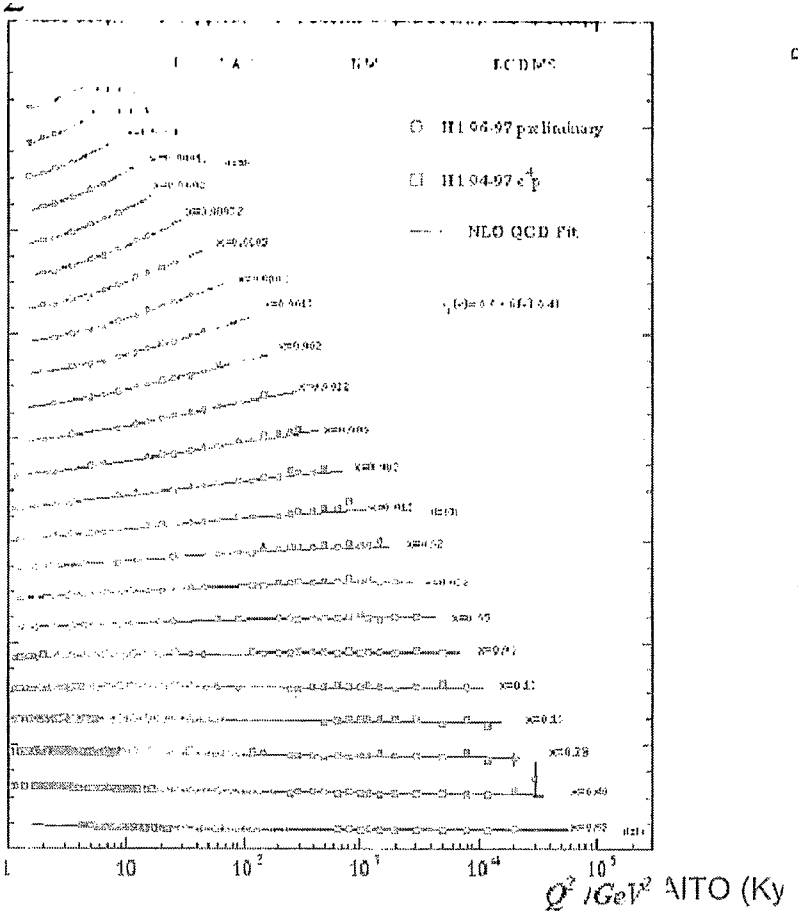
g_2 can be written using g_1 to a good precision

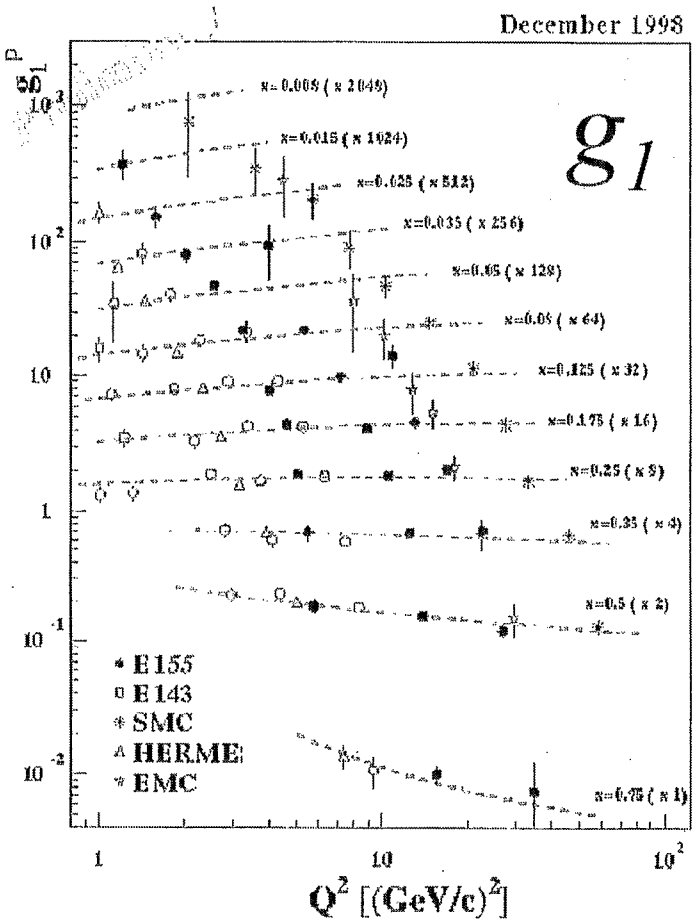
$$g_2(x,Q^2)=-g_1(x,Q^2)+\int_x^1\frac{g_1(y,Q^2)}{y}dy+\bar{g}_2(x,Q^2)$$

Partonic interpretation $\quad g_1(x,Q^2)=\frac{1}{2}\sum_q e_q^2\left[\Delta q(x)+\Delta\bar{q}(x)\right]$

Comparison of Unpolarized and polarized DIS

F_2





"Proton Spin Crisis"

- Proton spin ½ should be understood in terms of quark-spin, gluon-spin and their orbital angular momentum

$$\frac{1}{2}_{proton} = \frac{1}{2}\Delta\Sigma + \Delta g + L_z$$

$$\Delta\Sigma \equiv \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

- If the proton spin is fully carried by the quark-spin $\Delta\Sigma$=1.0

However experimental data were interpreted as

$$\Delta\Sigma \approx 0$$

J. Ashman et al., Phys.Lett.B206:364,1988

From $g_1(x)$ to $\Delta\Sigma$

- Observables: $g_1(x, Q^2)$ for proton and neutron

$$\begin{cases} g_1^p(x,Q^2) = \frac{1}{2}\left\{\frac{4}{9}\Delta U(x,Q^2) + \frac{1}{9}\Delta D(x,Q^2) + \frac{1}{9}\Delta S(x,Q^2)\right\} \\ g_1^n(x,Q^2) = \frac{1}{2}\left\{\frac{1}{9}\Delta U(x,Q^2) + \frac{4}{9}\Delta D(x,Q^2) + \frac{1}{9}\Delta S(x,Q^2)\right\} \end{cases}$$

$\Delta U = \Delta u + \Delta\bar{u}, \Delta D = \Delta d + \Delta\bar{d}$

$\Delta S = \Delta s + \Delta\bar{s}$

- We need to know the 1st moment of $\Delta\Sigma(x)$

$$\Delta\Sigma = \int_0^1 dx\, \Delta\Sigma(\mathrm{x}) = \int_0^1 dx\, \left(\Delta U(x) + \Delta D(x) + \Delta S(x)\right)$$

- Actually we can extract ΔU, ΔD, and ΔS

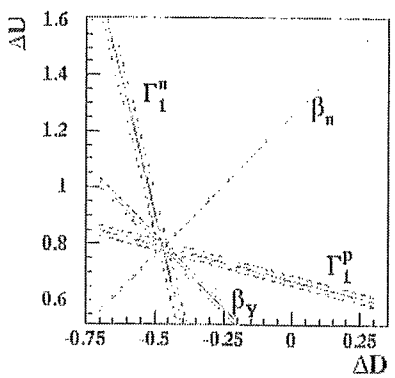
Determination of ΔU,ΔD,and ΔS

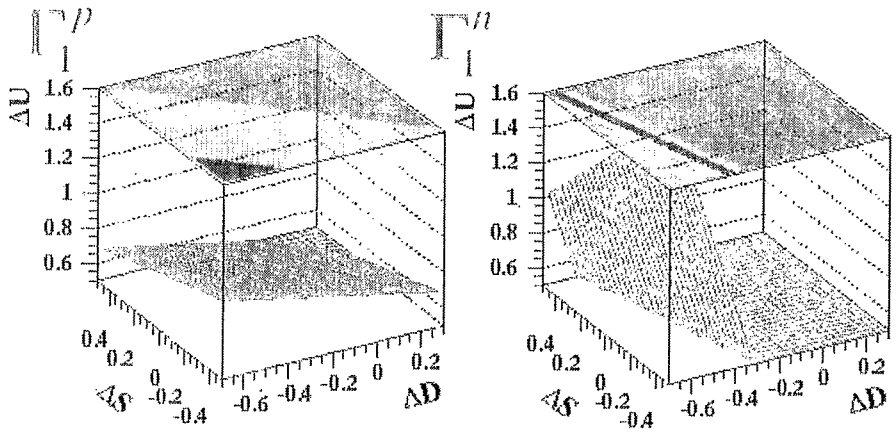
- The 1st moment of $g_1(x)$:Γ_1

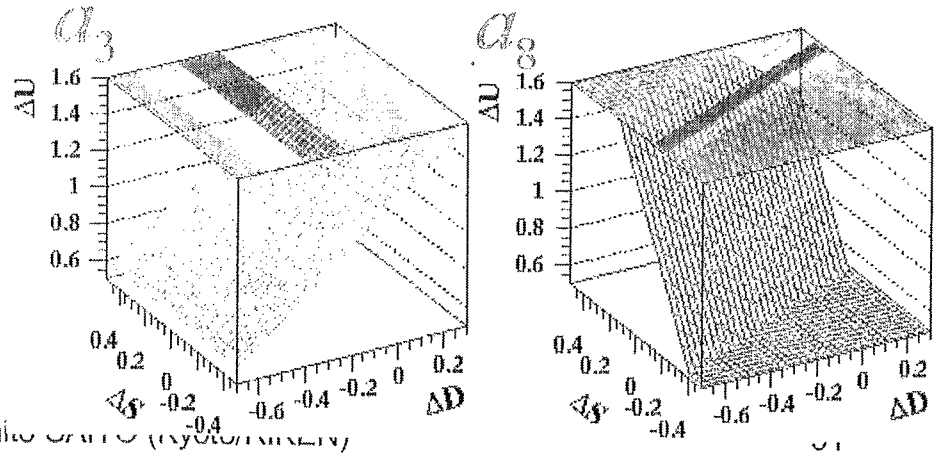
$$\Gamma_1^p = \frac{4}{18}\Delta U + \frac{1}{18}\Delta D + \frac{1}{18}\Delta S$$

- From Octet Baryon beta decay constant
  - Neutron $a_3 = \Delta U - \Delta D$
  - Hyperon

$$a_8 = \Delta U + \Delta D - 2\Delta S$$







Quark spin content in the proton spin

- $\Delta U, \Delta D$, and ΔS are extracted

$$\Delta U = 0.8; \Delta D = -0.4; \Delta S = -0.2$$

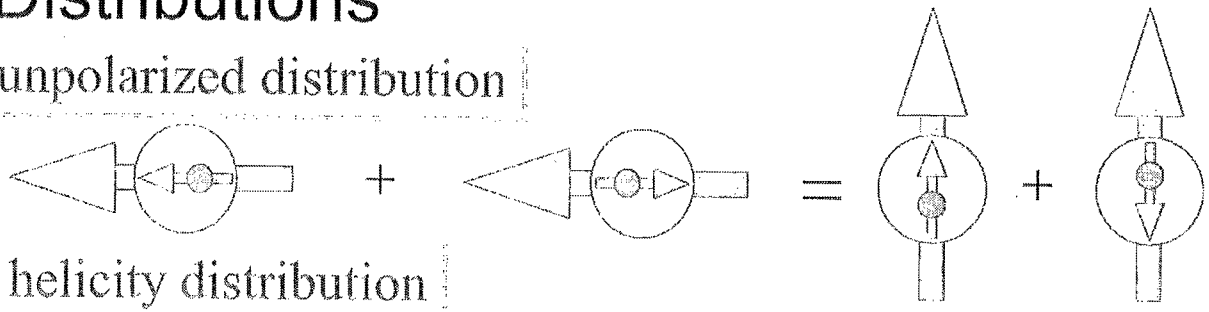
$$\Rightarrow \Delta\Sigma = 0.2$$

- Various approaches:
  - Gluon spin contribution: requires gluon sensitive processes
  - Verify quark contribution: requires flavor sensitive processes
  - Orbital angular momentum: Deeply Virtual Compton Scattering

Quark-Gluon Distributions

- Quark Distributions

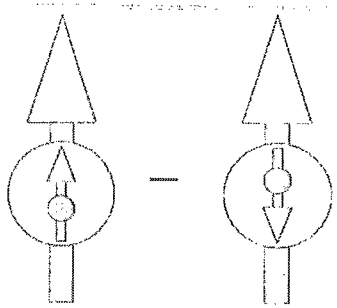
unpolarized distribution

$q(x,Q^2)=$ 

helicity distribution

$\Delta q(x,Q^2)=$

transversity distribution

$\delta q(x,Q^2)=$ 

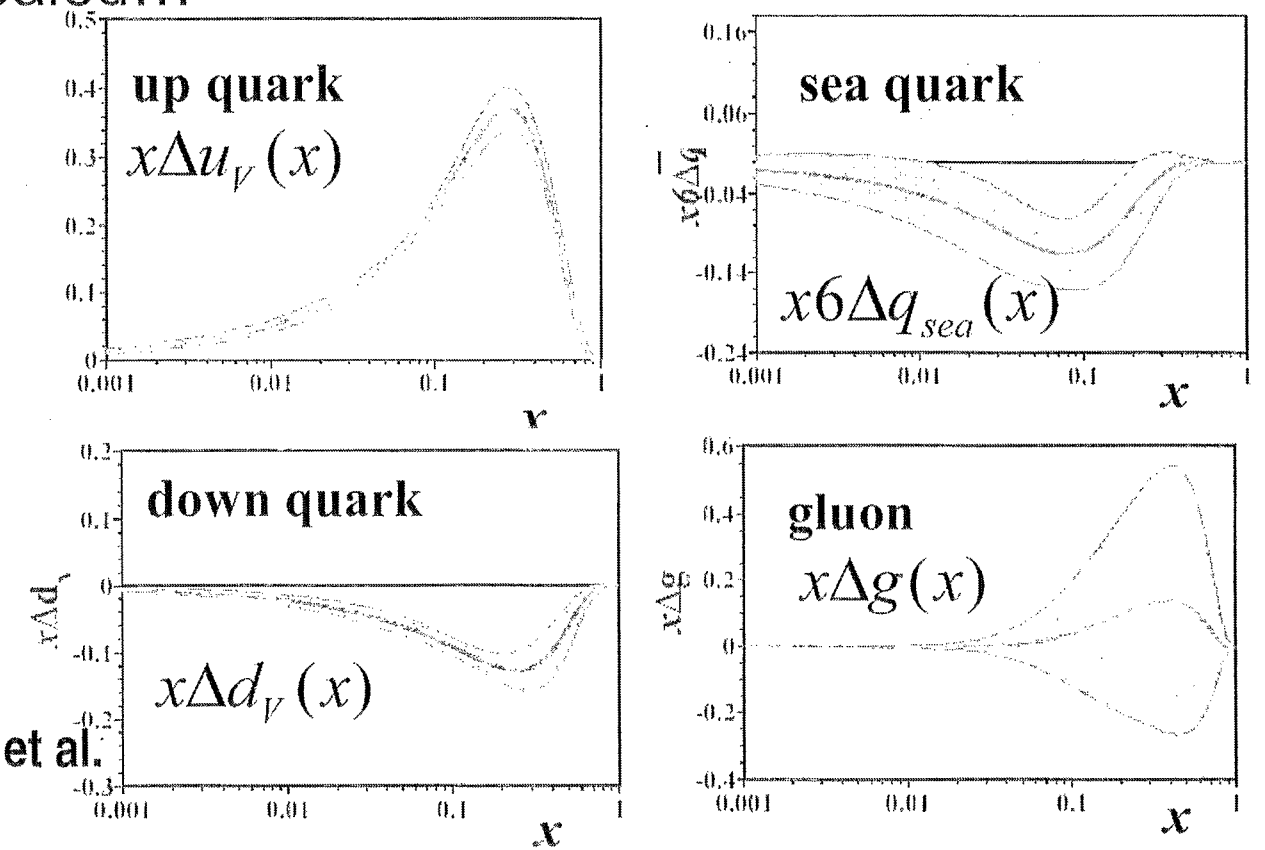
$g(x,Q^2)=$

$\Delta g(x,Q^2)=$

No Transverse Gluon Distribution

Polarized Parton Distributions

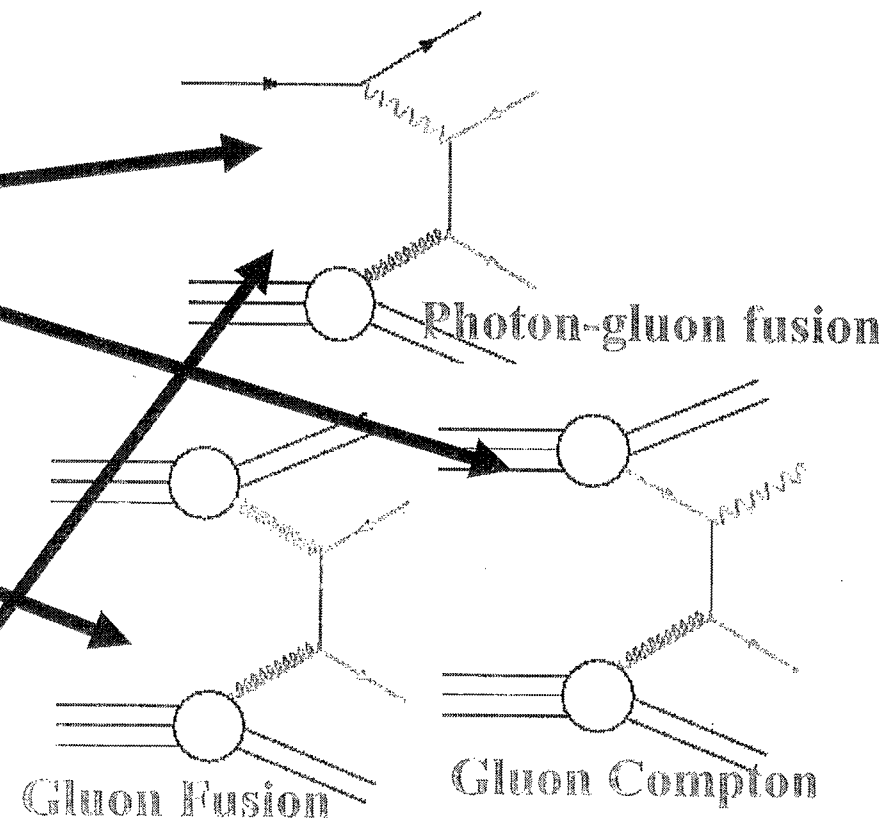
- Detailed analysis of lepton scattering experiments revealed…



M. Hirai et al.

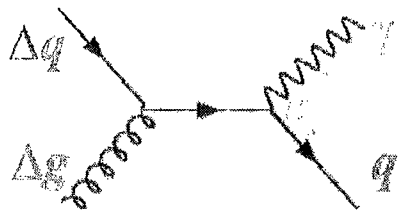
Dig out $\Delta g(x)$ and $\Delta g = \int_0^1 dx \Delta g(x)$

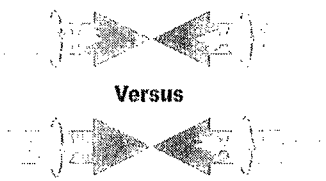
- Current Experiments
  - HERMES
    - High-pT hadron pair
  - RHIC Spin
    - Prompt Photon (+ jet)
    - Jet
    - Inclusive hadron
    - Heavy flavor (charm, bottom, J/ψ …)
  - COMPASS
    - Open Charm
    - High-PT hadron pair



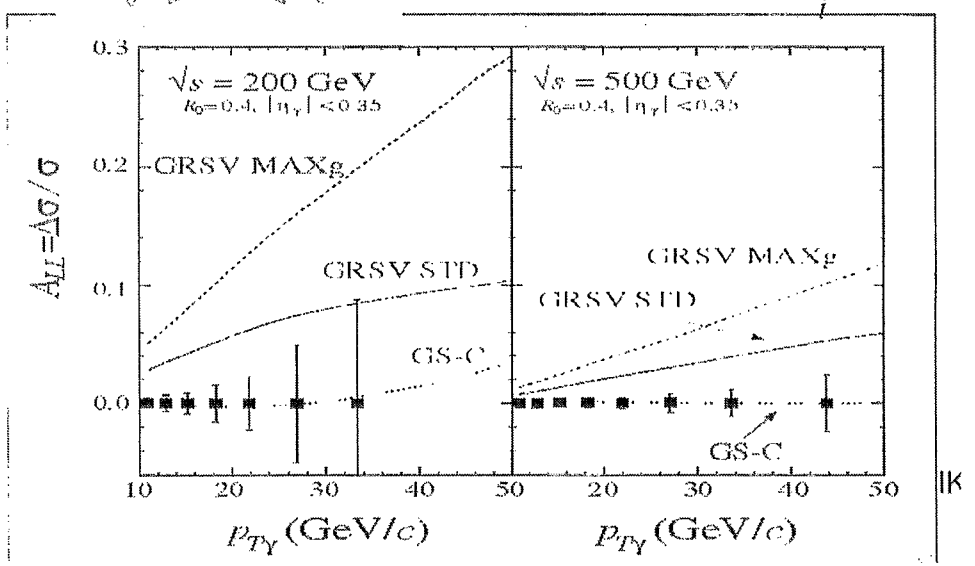
Prompt Photon Production: A_{LL}

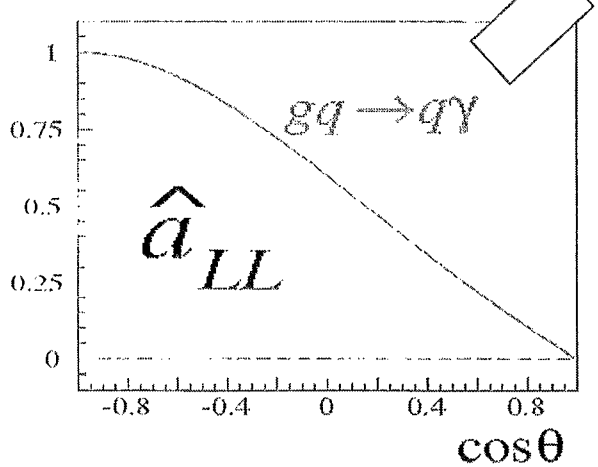
- Gluon Compton Diminates
  - small contamination from annihilation
- Measured quark polarization in polarized DIS Can be used



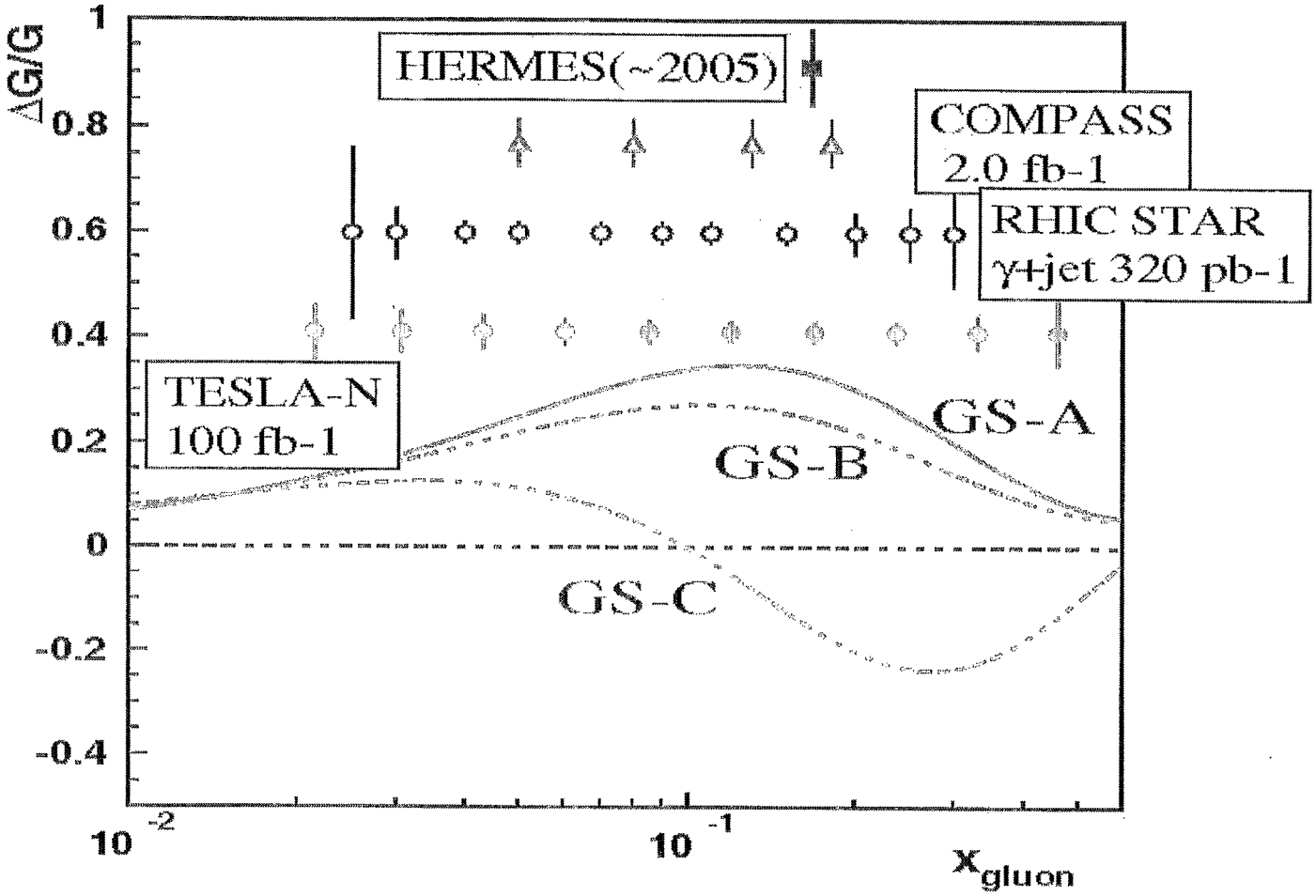


$$A_{LL} = \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\sum_i e_i^2 \Delta q_i(x_2)}{\sum_i e_i^2 q_i(x_2)} \otimes a_{LL}(gq \to q\gamma)$$



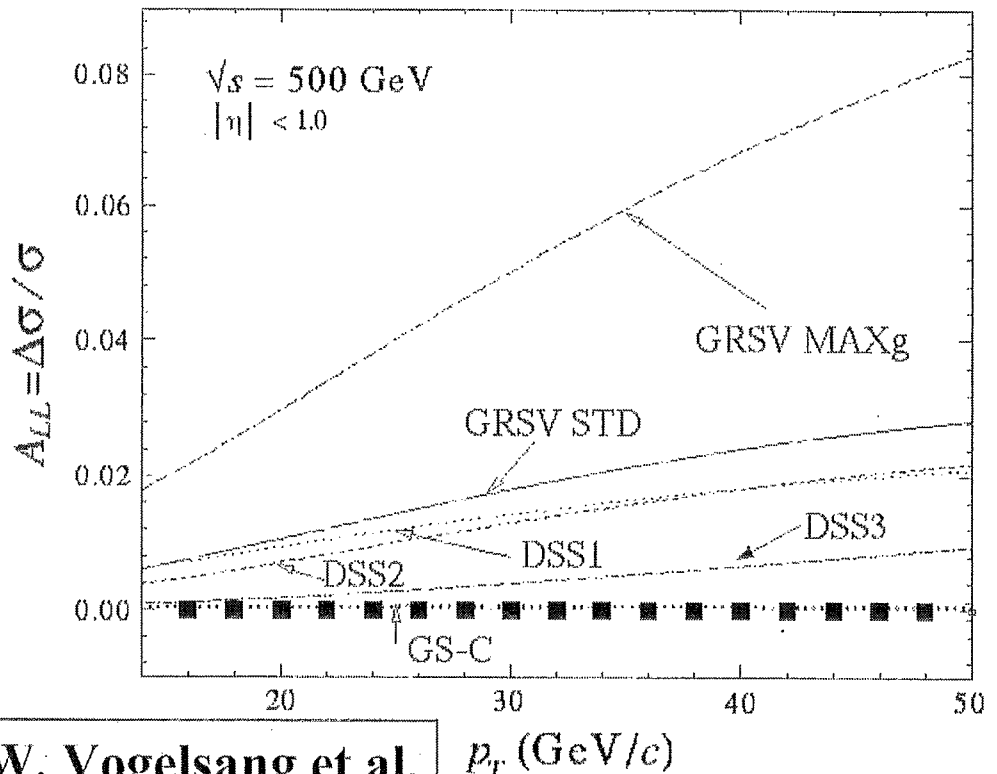


Sensitivity Comparison

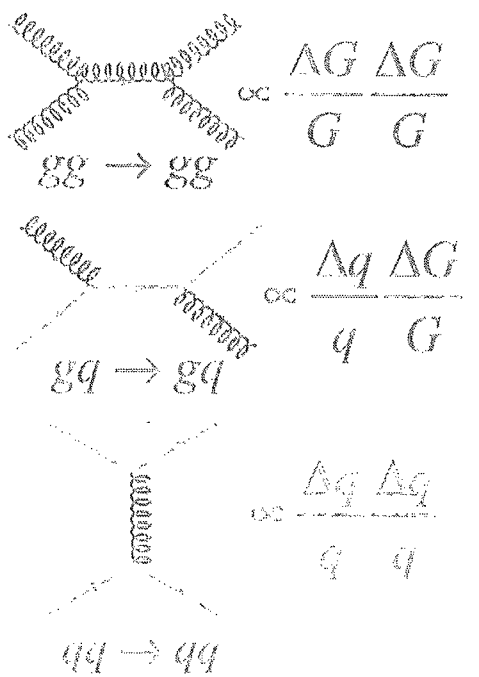


Jet Production

- Mixture of various processes, but very high statistics!

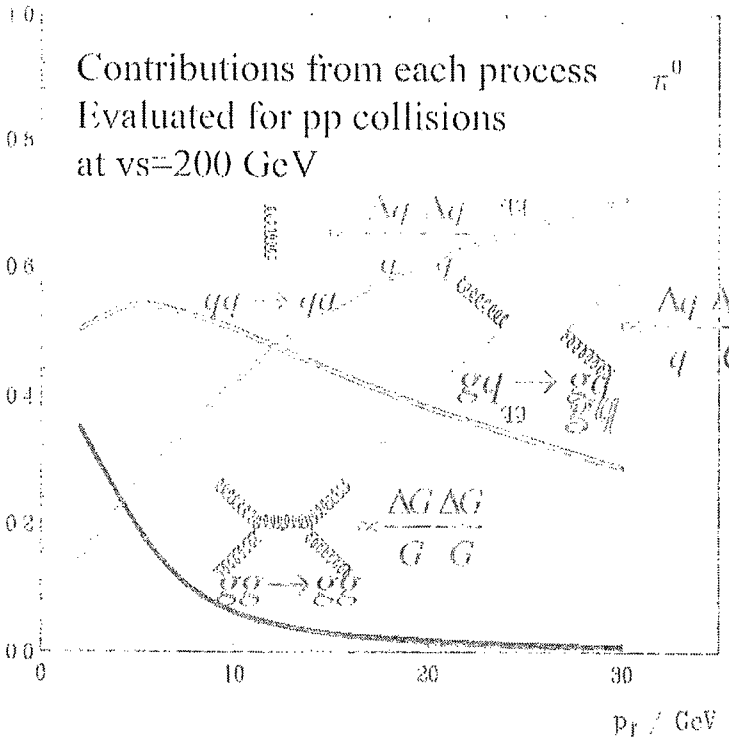


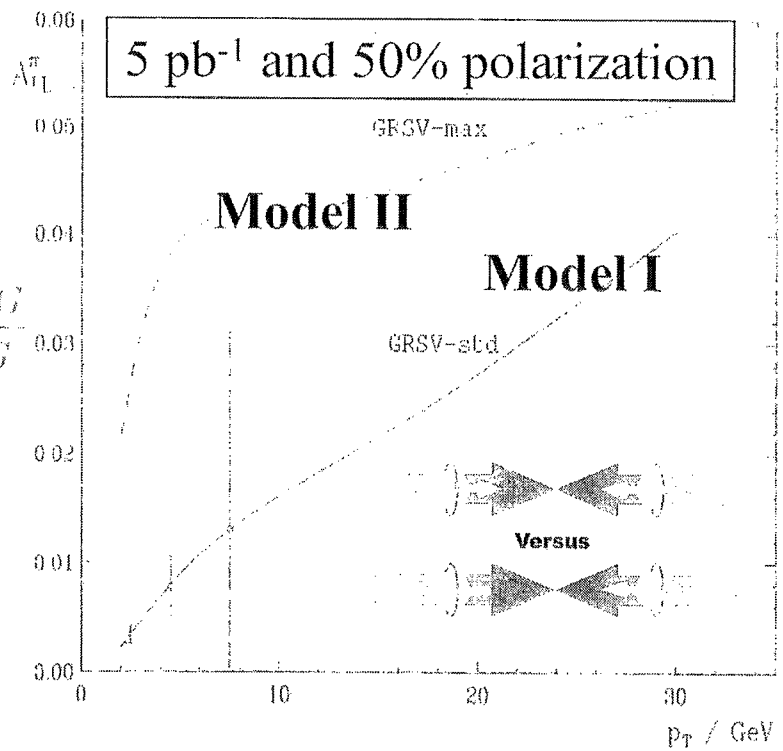
W. Vogelsang et al.



Hadron Production

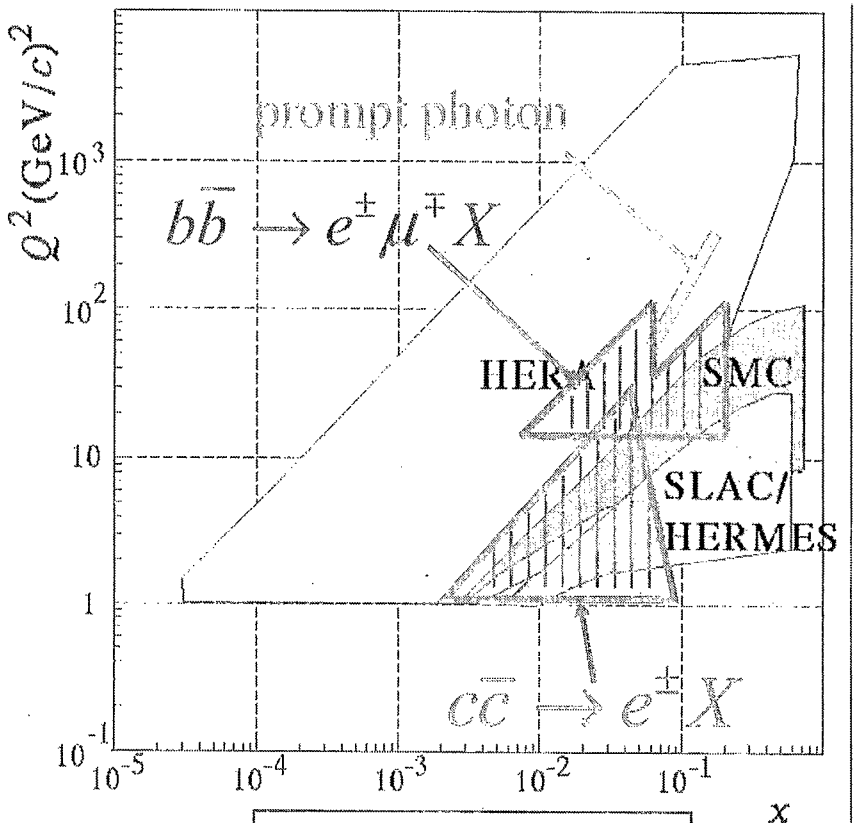
- For example, π^0 production
  - Considered as a result of jet fragmentation
  - Easy to identify
  - Mixture of processes but high statistics





Kinematical Coverage

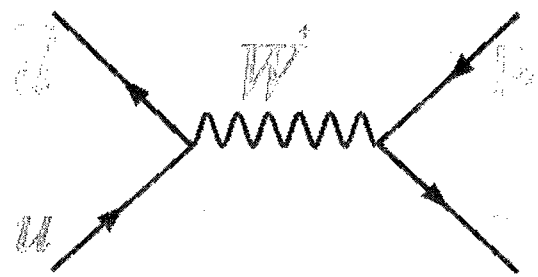
- Δg probed x-Q^2 regions are compared with DIS coverage

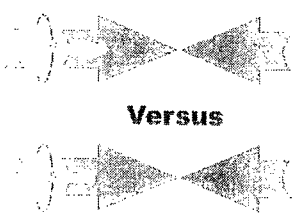


Pp 200 GeV Only!

Quark Polarization

- Two approaches
  - Semi-inclusive DIS: next slide
  - Polarized W production
    - V-A nature ensure quark polarization
    - Weak charge highly correlated with flavor

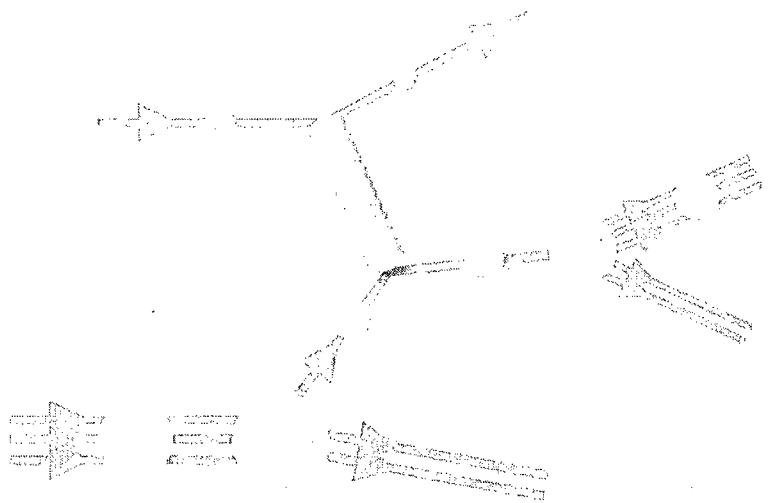




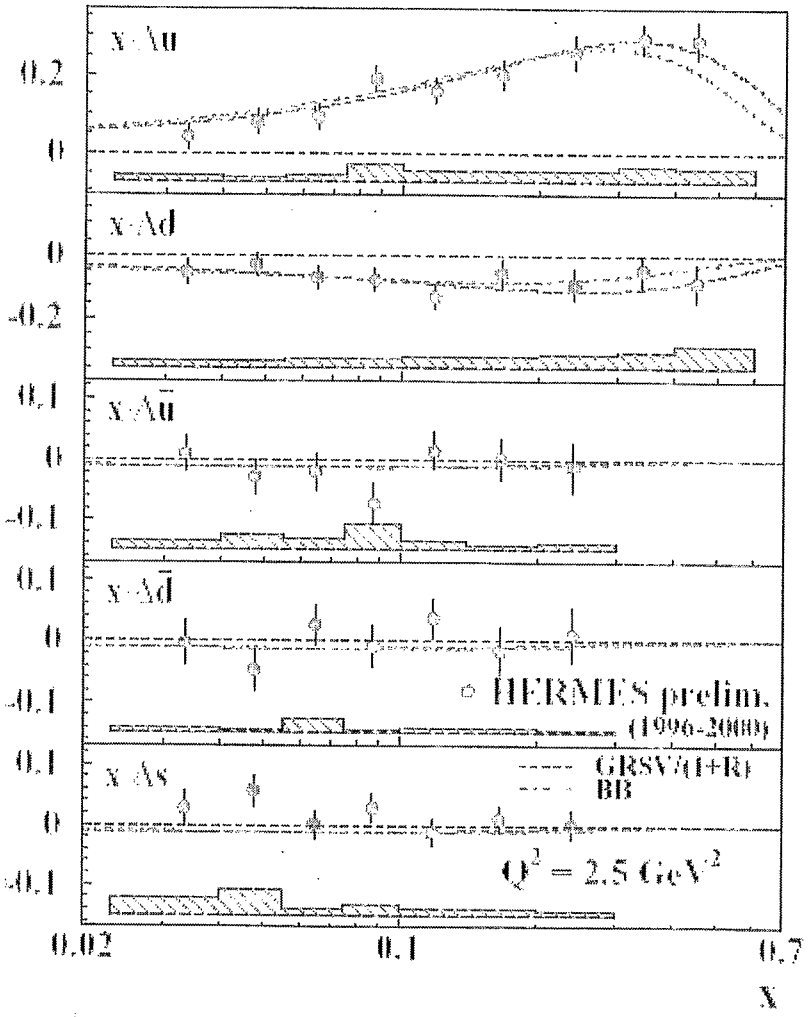
$$A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

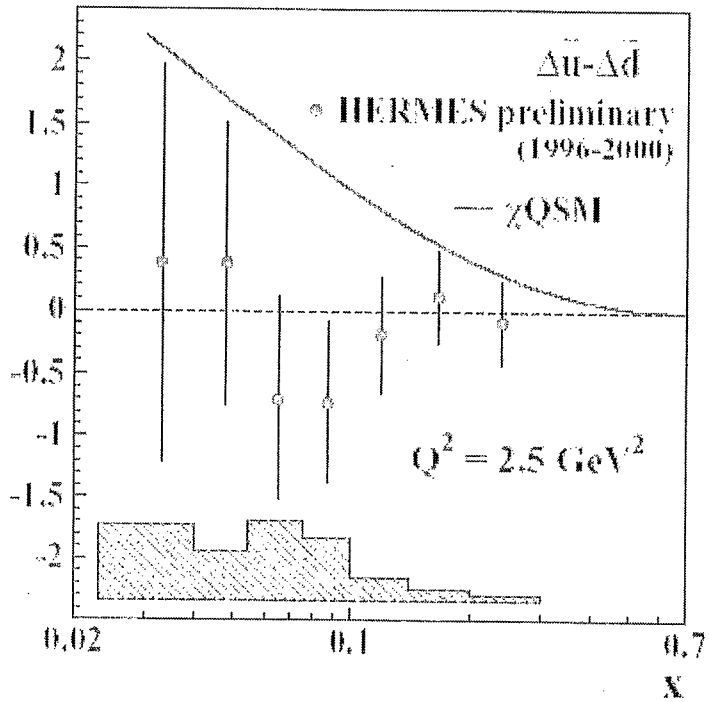
Semi-Inclusive DIS

- Using final state hadron to tag quark flavor
- Detect $\pi^+ \rightarrow u$ probability high
- Detect $\pi^- \rightarrow d$ probability high
- Still maintain x and Q^2 reconstruction
- Need large Q^2 to ensure factorization works
- Subject to precision of fragmentation function $D(z)$



HERMES SI-DIS

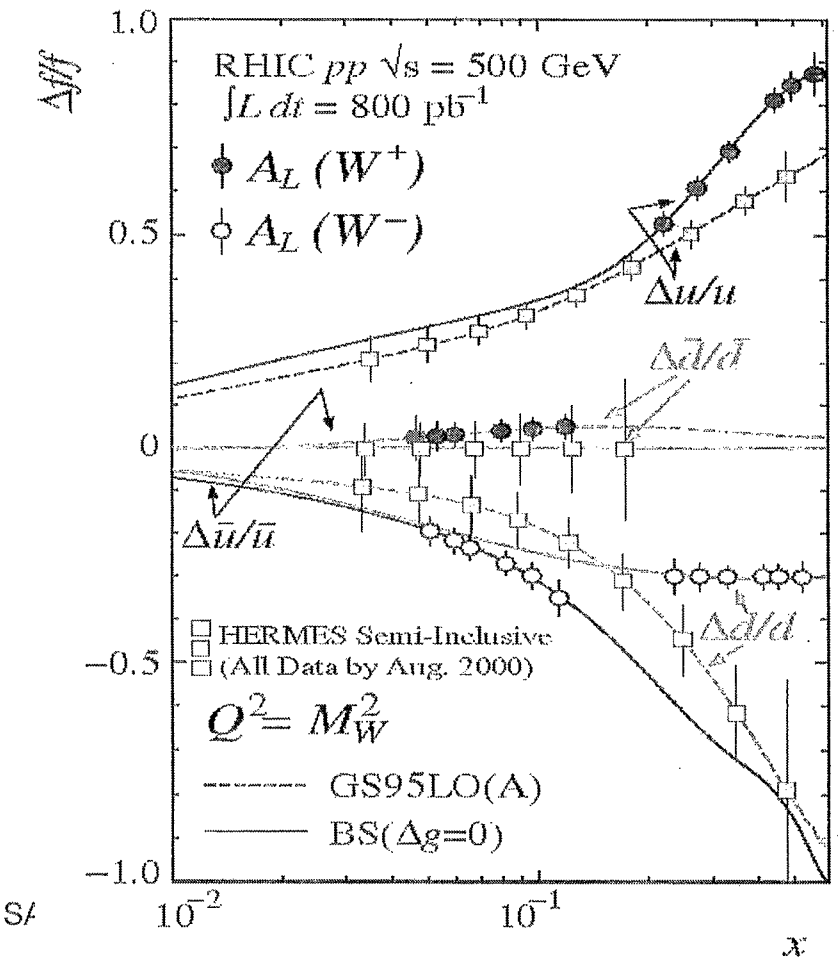




Fragmentation ambiguities are under study

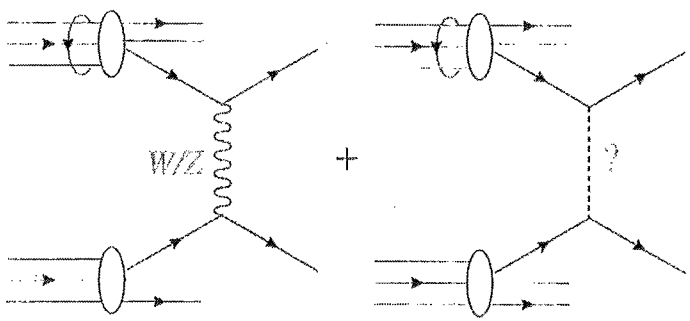
Comparison of Sensitivity for $\Delta q(x)$

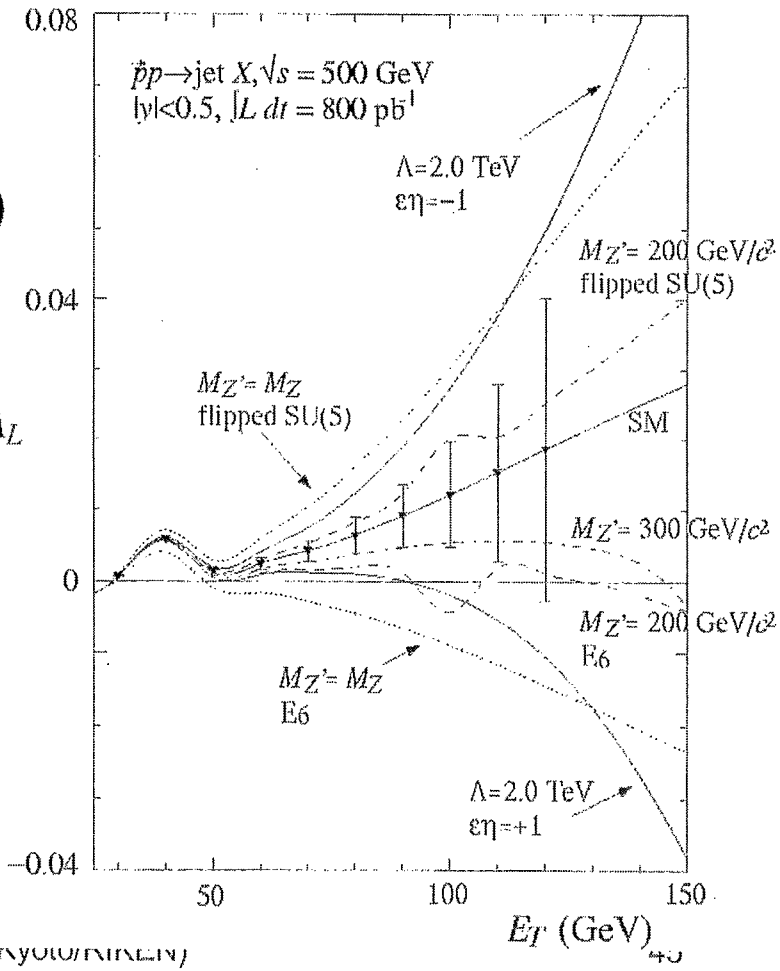
- W is sensitive to each flavors
  - No fragmentation ambiguity
  - x-reconstruction is not superb
- SI-DIS sensitivity is good especially for up quark
  - Subject to fragmentation ambiguity
  - x-reconstruction is superb



Possibility for New Physics Studies (I)

- Anomalous Parity Violation in Jet Production
  - Contact Interaction (Scale Λ)
    - CDF Λ>1.8 TeV
    - D0 Λ>2.4 TeV
    - RHIC Spin Reach Λ~3.3 TeV
  - New Gauge Boson Z′

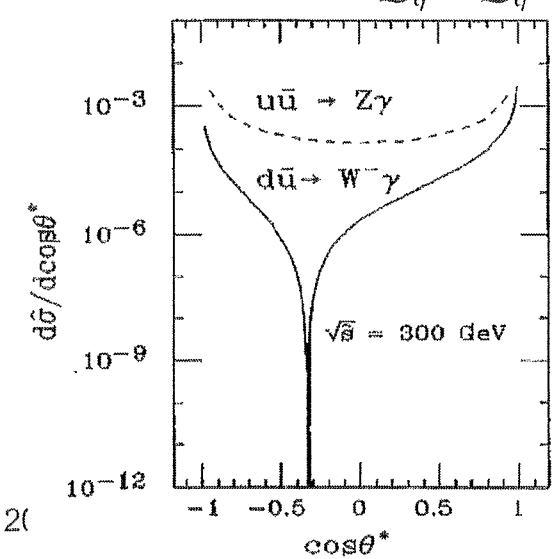




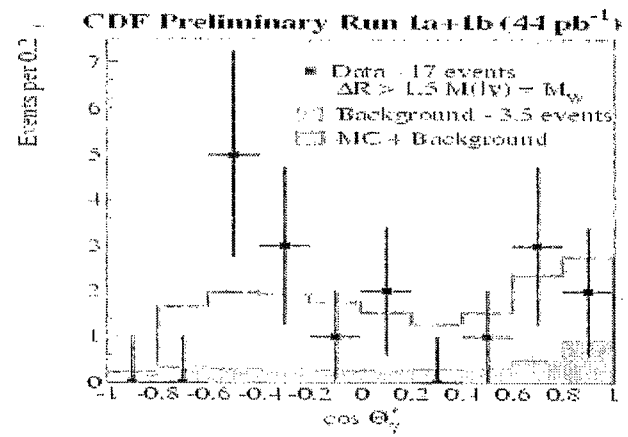
Possibility for New Physics Studies (II)

- Radiation ZERO is the clean signal of $WW\gamma$ coupling event in hadron collisions
  - t and u channel destructively interfere with s channel

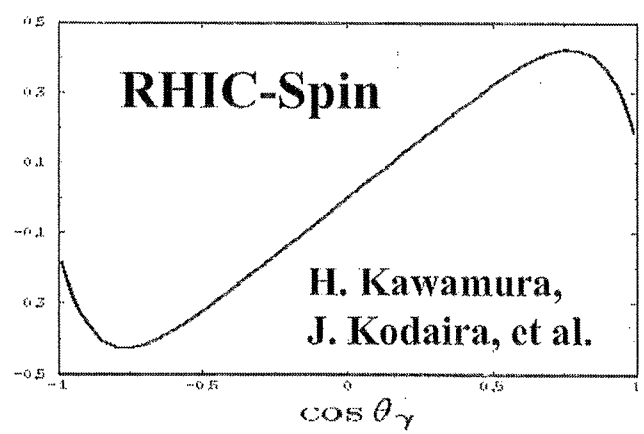
$$\sigma = 0 \,@\, \cos\theta^* = \frac{Q_q + Q_{q'}}{Q_q - Q_{q'}}$$



CDF



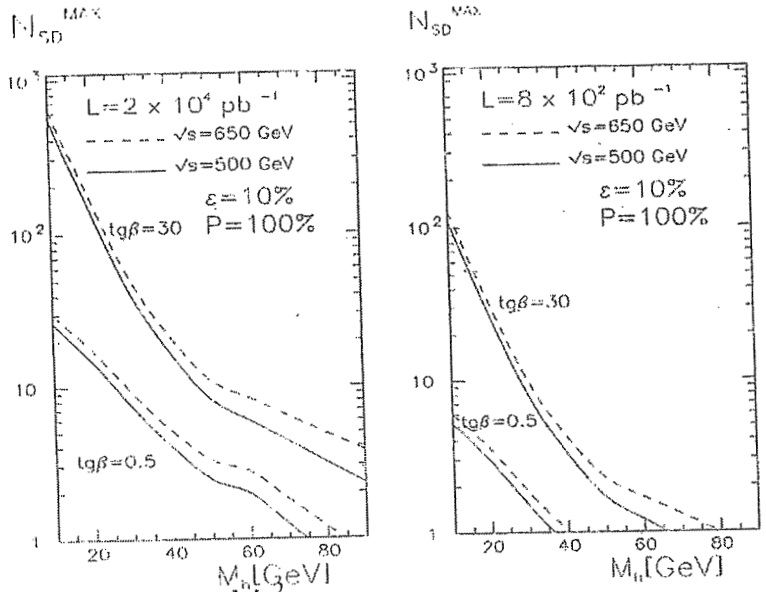
A_{LL}^{PV}

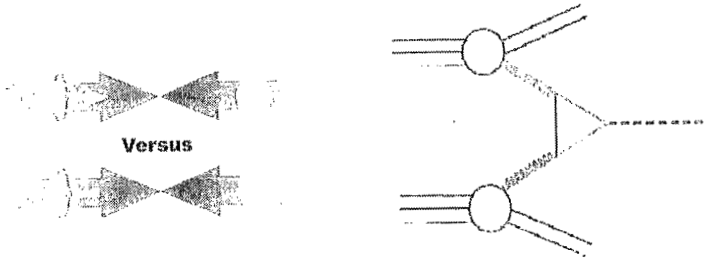


2(hito SAITO (Ky

Possibility for New Physics Studies (III)

- B. Grzadkowski, J.F. Gunion and T.C. Yuan PRL 71 (93) 488
  - Proposed to use polarized gluon-fusion to specify CP state of Higgs
    CP violation in Higgs Sector





$$A_L = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)} \propto \frac{\int dx_1 dx_2\, g(x_1)\Delta g(x_2)\delta(x_1x_2 - \frac{M_h^2}{s})(|M_{++}|^2 - |M_{--}|^2)}{\int dx_1 dx_2\, g(x_1) g(x_2)\delta(x_1x_2 - \frac{M_h^2}{s})(|M_{++}|^2 + |M_{--}|^2)}$$

$$\propto \frac{\Delta g(x_2)}{g(x_2)} \cdot \frac{-4\,\mathrm{Im}(EO^*)}{2(|E|^2+|O|^2)}$$

***E*: gg coupling to a CP even state**

***O*: gg coupling to a CP odd state**

Summary

- Polarized studies are catching up Unpolarized studies; some surprises
- HERMES, COMPASS, and Polarized RHIC are producing new results
- Detailed knowledge of the spin structure of the nucleon would open new possibilities in Particle-Nuclear Physics

List of Participants

Eguchi, Hisato (Niigata University)
Ellis, John (CERN)
En'yo, Hideto (RIKEN/RBRC)
Fukao, Yoshinori (Kyoto University)
Hasegawa, Taiki (Tokyo Institute of Technology)
Hayakawa, Masasi (RIKEN)
Heuser, Johann (RIKEN)
Hirai, Masanori (RIKEN)
Igi, Keiji (Kanagawa University)
Ishii, Noriyoshi (RIKEN)
Itakura, Kazunori (RBRC)
Kajino, Tositaka (National Astronomical Observatory)
Kano, Hiroki (Tokyo Institute of Technology)
Kitazawa, Masakiyo (Kyoto University)
Kiyomichi, Akio (RIKEN)
Koike, Yuji (Niigata University)
Kurita, Kazuyoshi (Rikkyo University)
Maeda, Tatsunari (Hiroshima University)
Matsuura, Taeko (University of Tokyo)
Mawatarai, Kentaro (Kobe University)
Muto, Ryotaro (Kyoto University)
Nagashima, Junji (Niigata University)
Nakamura, Shin (RIKEN)
Naruki, Megumi (Kyoto University)
Nawa, Kanabu (Kyoto University)
Ohnishi, Hiroaki (RIKEN)
Ohta, Shigemi (KEK)
Okada, Hiromi (Kyoto University)
Okada, Kensuke (RIKEN/RBRC)
Osuga, Hroshi (Tokyo Institute of Technology)
Saito, Naohito (Kyoto University)
Sakuma, Fuminori (Kyoto University)
Sekimoto, Miwako (KEK)
Shibata, Toshiaki (Tokyo Institute of Technology)
Sudo, Kazutaka (RIKEN)
Suganuma, Hideo (Tokyo Institute of Technology)
Tabaru, Tsuguchika (RIKEN)
Tada, Tsukasa (RIKEN)
Tanida, Kiyoshi (RIKEN)
Togawa, Manabu (Kyoto University)
Tojo, Junji (RIKEN)
Tsumura, Kyosuke (Kyoto University)
Uehara, Yosuke (University of Tokyo/KEK)
Watanabe, Yasushi (RIKEN/RBRC)
Yazaki, Koichi (Tokyo Woman's Christian University/RIKEN)
Yokkaichi, Satoshi (RIKEN)

Program of the School

March 26 (Wed)	
9:30 - 9:50	Registration
Beginning of School	
9:50 - 10:00	Orientation
10:00 - 11:00	Ellis (1)
11:30 - 12:30	Saito (1)
Lunch	
14:00 - 15:00	Ellis (2)
15:20 - 16:20	Saito (2)
16:40 - 17:40	Ellis (3)
18:00 -	Discussion with refreshments
End of School	

PHOTOS

Additional RIKEN BNL Research Center Proceedings:

Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
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