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Formal Report

RIKEN BNL Research Center

BNL/RIKEN RHIC SPIN PHYSICS SYMPOSIUM

RIKEN BNL Research Center
Fifth Anniversary Celebration

BNL, Upton, New York

April 30, 2002

RBRC Scientific Articles

Volume 6

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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 hard QCD/spin physics, lattice QCD and RHIC (Relativistic Heavy Ion Collider) physics through nurturing of a new generation of young physicists. The Director of RBRC is Professor T. D. Lee.

A Memorandum of Understanding between RIKEN and BNL was signed on April 30, 2002 extending this collaboration and the RIKEN BNL Research Center (RBRC) for another five years.

Since its inception the Center has now matured with both a strong theoretical and experimental group. These consist of Fellows, Postdocs, RBRC Physics/University Fellows and an active group of Consultants/Collaborators. Computing capabilities consist of a 0.6 teraflops parallel processor computer operational since August 1998. It was awarded the Supercomputer 1998 Gordon Bell Prize for price performance. This is expected to be augmented by a ten teraflops QCDOC computer in 2003. The Center also organizes an extensive series of workshops on specific topics in strong interactions with an accompanying series of published proceedings.

Members and participants of RBRC on occasion will develop articles in the nature of a status report, a general review, and/or an overview of special events, such as this one.

N. P. Samios

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Photographer: **Roger R. Stoutenburgh, Information Services Division**
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BNL/RIKEN RHIC Spin Physics Symposium

Date: April 30, 2002
Time: 1:30 – 4:45 p.m.

Place: Berkner Auditorium

	Chairman: T. D. Lee	
1:30 PM	Opening Addresses	
	P. Paul	
	S. Kobayashi	
	A. Arima	
	N. Samios	
	P. Rosen	
2:10 PM	R. Jaffe	QCD Spin Physics: From the Allotropes of Hydrogen to the Polarized Collider at RHIC
2:40 PM	W. MacKay	Polarized Protons in RHIC
3:10 PM	Coffee Break	
	Chairman: H. En'yo	
3:40 PM	K. Kurita	Proton-Carbon CNI Polarimeter for RHIC
4:00 PM	N. Saito	Spin Physics with the First Polarized Proton Collider, RHIC
4:30 PM	S. Ozaki	Concluding Remarks

QCD SPIN PHYSICS: FROM THE ALLOTROPES OF HYDROGEN TO THE POLARIZED COLLIDER AT RHIC

Robert Jaffe

QCD Spin Physics

From the Allotropes of Hydrogen to the

Polarized Collider at RHIC

R.L. Jaffe

QCD

$$\mathcal{L} = -\frac{1}{4}\,\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} + \bar{q}(iD_\mu\gamma^\mu + m)q$$

Why Care?

After all, the Lagrangian is known. . .

- ⋆ 99.95% of the visible mass in the universe is composed of protons and neutrons.
- ⋆ It's the only nontrivial quantum field theory we have yet encountered in Nature.
  - Standard model → perturbative → trivial
  - String theory/quantum gravity as yet unknown
- ⋆ QCD is remarkably challenging.
  - No free parameters
  - Interactions from symmetry (gauge invariance)
  - Just the kind of challenge that awaits string theory when its underlying structure is discovered!
- ⋆ Surprising properties & haunting regularities

A QCD Primer

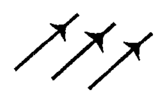
⋆ Quarks: 3 light flavors, 3 heavy flavors

Flavor	Charge	Mass
u	2/3	1–5 MeV
d	−1/3	3–9 MeV
s	−1/3	75–170 MeV

QCD $\approx$ 150 to 250 MeV ⟵ "Natural" Scale of Strong Force

c	2/3	1.15–1.35 GeV
b	−1/3	4.0–4.4 GeV
t	2/3	174.3 ± 5.1 GeV

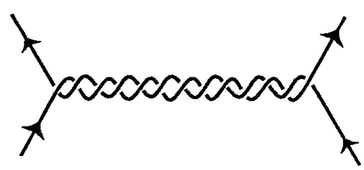
⋆ Color and Quantum Chromodynamics

- Quarks come in three colors: 

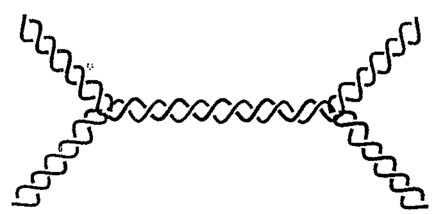
- Color is a charge coupled to eight generalized "photons" ⇒ gluons.

Spin-one

$\alpha_s \Longleftrightarrow \alpha$



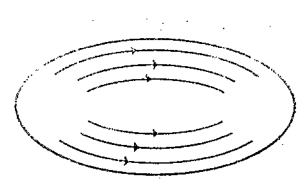
Quark-quark force



Gluon-gluon force

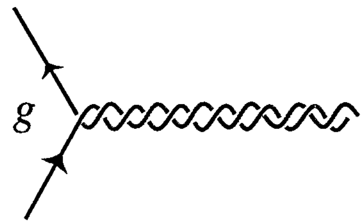
⋆ Color confinement

Quarks are confined in "bags" of "normal vacuum" surrounded by some poorly understood, complex phase of gluon condensate.



Why is QCD so hard??

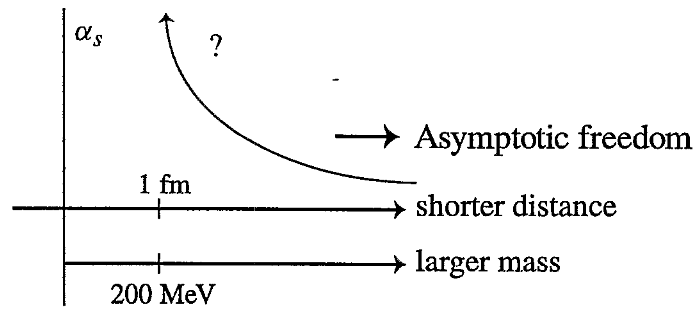
⋆ No scale!



$$\alpha_s \equiv \frac{g^2}{4\pi}$$

⋆ No parameter!

Wait! What about α_s?



⋆ Hadrons form at the scale where α_s grows large.

⋆ That scale, Λ_{QCD}, defines the basic unit of mass for hadrons.

⋆ What about quark masses?

$m_u, m_d \ll \Lambda_{\mathrm{QCD}}$	Negligible
$m_s \approx \Lambda_{\mathrm{QCD}}$	Perplexing
$m_c, m_b, m_t \gg \Lambda_{\mathrm{QCD}}$	Simplifying

The Spin of the Proton

⋆ Who discovered the spin of the proton?

- Hint: Not Uhlenbeck & Goudsmit
- Hint: He won the 1932 Nobel Prize for this discovery.
- Hint: He was a theorist.
- Hint: He wore an $\hbar$ tie pin (!)

⋆ **Werner Heisenberg**

⋆ Actually, the discovery of the spin of the proton is also credited to the experimenter David Dennison, of the University of Michigan, who measured the specific heat of molecular hydrogen in 1927.

Nobel Laureates in Physics, 1901–97

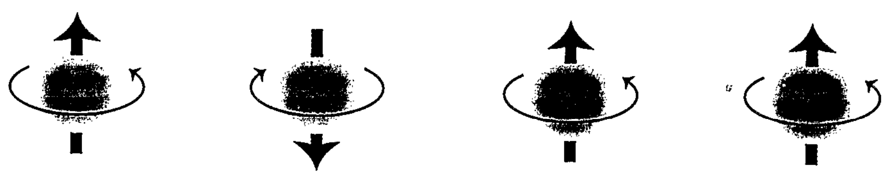
⋆ Physics 1932

- The prize was awarded to

  Heisenberg, Werner
  b. 1901, d. 1976
  Leipzig University

"for the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of **the allotropic forms of hydrogen.**"

Parahydrogen   Orthohydrogen



$s = 0$ $L = 0, 2, 4, \ldots$

$s = 1$ $L = 1, 3, 5, \ldots$

The Proton is Composite

- ⋆ History of surprises began with Otto Stern's 1933 discovery

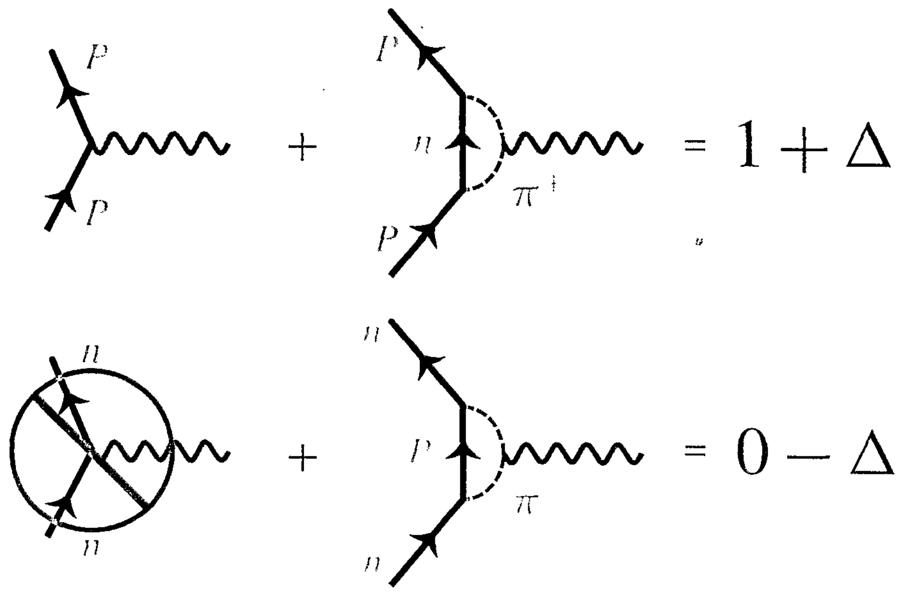
$$\vec{\mu}_p = \frac{e\hbar}{mc} \otimes \; 2.79 \; \vec{s}_p$$

when he expected 1.

- ⋆ So the proton is composite.

- ⋆ First vision: Yukawa's Pion

$\mu_p = 2.79$ $\qquad\qquad$ $\mu_n = -1.91$

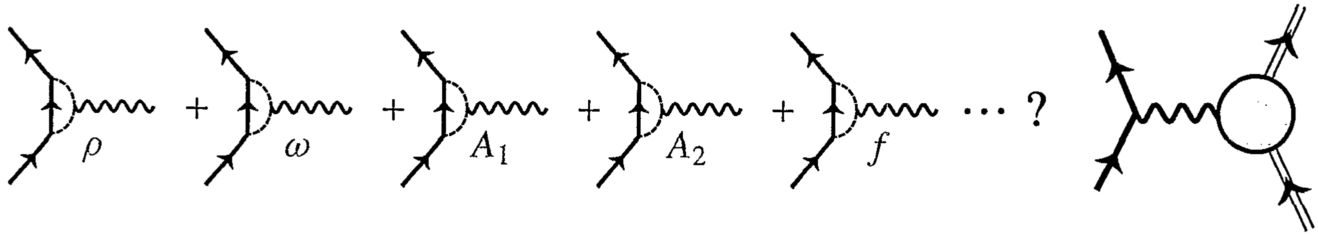


$2.79 = 1 + 1.79$ $\qquad\qquad$ $-1.91 = 0 - 1.91$

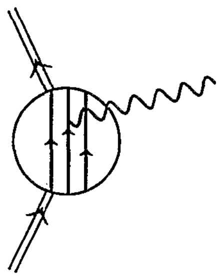
Not Bad!

Quarks

⋆ Then revision!



Meson expansion is out of control $\Rightarrow$ QUARKS



$$\frac{\mu_n}{\mu_p} \cong -\frac{2}{3} \cong -\frac{1.91}{2.79}$$

Successes like μ_n/μ_p led to more detailed model building, to development of QCD, and to predictions of proton and neutron spin content.

⋆ First vision:

$$|p\rangle = |uud\rangle$$
$$|n\rangle = |udd\rangle$$

⋆ Three nonrelativistic quarks in an s-wave bound state

⋆ Additive quark model: Spin of the nucleon is the sum of the quarks' spins.

The quark spin and the nucleon spin

⋆ Quark spin operator:

$$\Delta Q_a s_\mu = \langle Ns|\bar{q}_a \gamma_\mu \gamma_5 q_a|Ns\rangle$$

$$\Delta\Sigma = \Delta U + \Delta D + \Delta S$$

⋆ $\bar{q}\gamma_k\gamma_5 q$ is the generator of the internal rotations of the quark field about the $\hat{e}_k$ direction.

⋆ Nonrelativistic limit:

$$\rightarrow q^\dagger \sigma_k q$$

⋆ But how to measure??

⋆ β-decay, parity-violating coupling measures certain combinations of ΔQ's:

- $F + D = \Delta U - \Delta D$ measured in nucleon β decay.

- $2F = \Delta U - \Delta S$ in hyperon (Λ, Σ, . . .) β decay.

$$F + D = 1.257 \pm 0.003$$
$$3F - D = 0.575 \pm 0.016$$

$$\Delta\Sigma = \Delta U + \Delta D + \Delta S$$
$$= 3F - D + 3\Delta S$$

Three independent quantities,

$$\{\ \Delta U,\ \Delta D,\ \Delta S,\}\quad \text{or}$$

$$\{F,\ D,\ \&\ \Delta\Sigma\ \}$$

But only two can be "measured" via β decay.

Before the "modern era":

$$\Delta\Sigma = 0.60 \pm 0.05 + 3\Delta S$$

- ⋆ Relies on $(u \leftrightarrow d \leftrightarrow s)$ symmetry, but that looks reliable.

- ⋆ The problem lay in waiting:

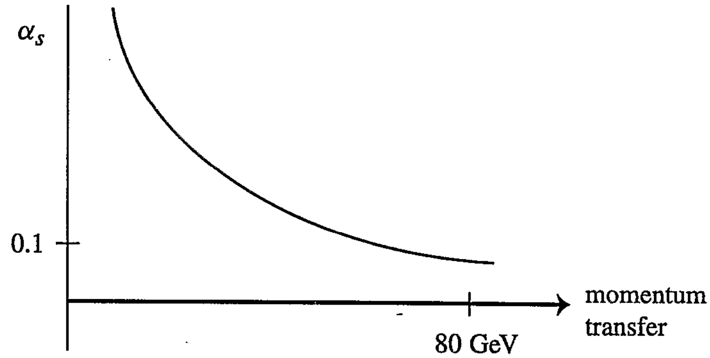
  - If $\Delta\Sigma \approx 1$ then $\Delta s \approx 0.4$!

  - If $\Delta\Sigma \approx 0.6$ then what carries the nucleon spin?

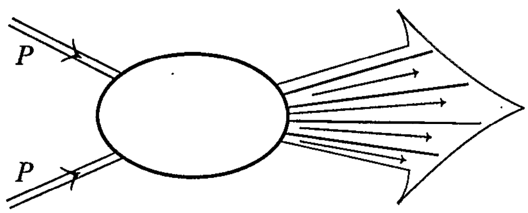
  - What if $\Delta\Sigma$ is very different from unity??

Enter: Deep Inelastic Processes

"Hard" Momentum Transfer Makes QCD Easy!

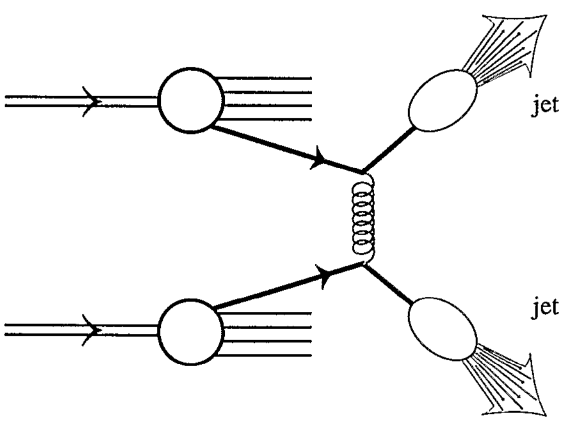


- Hadron-hadron scattering at low momentum transfer (Swiss watches!)



Dozens of reaction products – baryons mesons, strange particles,. . .
nearly uninterpretable

- Hadron-hadron scattering at high momentum transfer



One-gluon exchange
$\Rightarrow$ quark $\Rightarrow$ jet

- Turn QCD on itself!

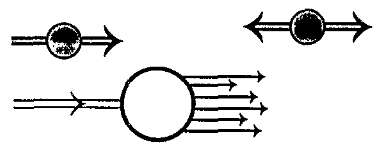
Parton distribution functions

- ⋆ $q(x, Q^2)$ – Probability to find a quark with $p \sim xP_\infty$ in a nucleon with P_∞ when probed at a distance scale $\sim 1/Q$.
- ⋆ Why? Why not $\Psi(\vec{x}, t)$?
- ⋆ Because these exist in RQFT!
  and can be measured!

Spin dependence:

- ⋆ $\Delta U(x) = u^\uparrow(x) - u^\downarrow(x) + \bar{u}^\uparrow(x) - \bar{u}^\downarrow(x)$
- ⋆ And spin components defined earlier are x integrals:

$$\Delta U = \int_0^\infty dx\, \Delta U(x)$$



$g_1(x, Q^2)$

Heuristics and possibility of measuring $\Delta\Sigma$

Generalize to gluon distributions –

- ⋆ $G(x, Q^2)$ momentum distribution of gluons
- ⋆ $\Delta G(x, Q^2)$ gluon spin distribution, with

$$\Delta G = \int_0^\infty dx\, G(x)$$

First information: Deep Inelastic Scattering

$$\vec{e}\ \vec{p} \to e'\ X$$

⋆ SLAC-Yale Collaboration 1970–1985

⋆ EMC & SMC at CERN 1980–1999.

⋆ SLAC redux, Hermes, COMPASS, . . . , 1990–. . .

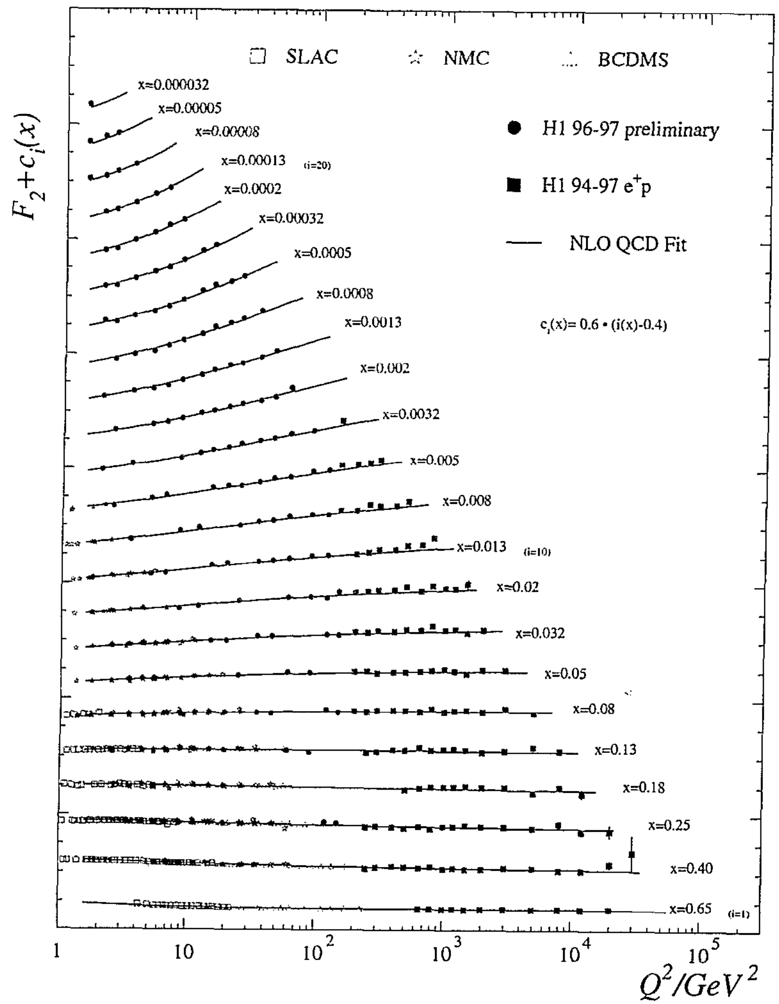
⋆ Gives sum rules for polarized scattering

$$\int_0^\infty dx\, g_1^{\mathrm{ep}}(x,Q^2) = \tfrac{1}{18}\Big(9F - D + 6\Delta s(Q^2)\Big) + \mathcal{O}(\ln Q^2)$$
$$= \tfrac{1}{18}\Big(3F + D + 2\Delta\Sigma(Q^2)\Big) + \mathcal{O}(\ln Q^2)$$
$$\int_0^\infty dx\, g_1^{\mathrm{en}}(x,Q^2) = \tfrac{1}{18}\Big(6F - 4D + 6\Delta s(Q^2)\Big) + \mathcal{O}(\ln Q^2)$$
$$= \tfrac{1}{18}\Big(-2D + 2\Delta\Sigma(Q^2)\Big) + \mathcal{O}(\ln Q^2)$$

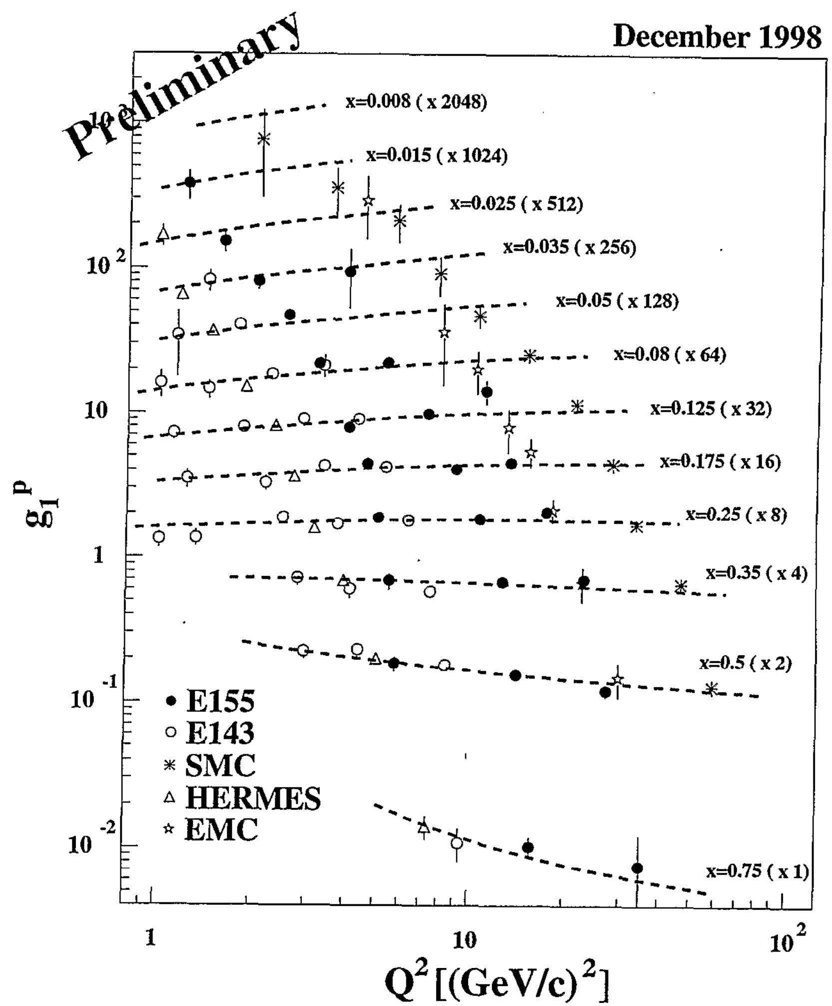
- Experiments conclude:

Only a small fraction of the proton spin
is carried by the spin of the quarks
$(14 \pm 9 \pm 21)\%$

World data on F_1^p



World data on g_1^p



The New Era of QCD Spin Physics

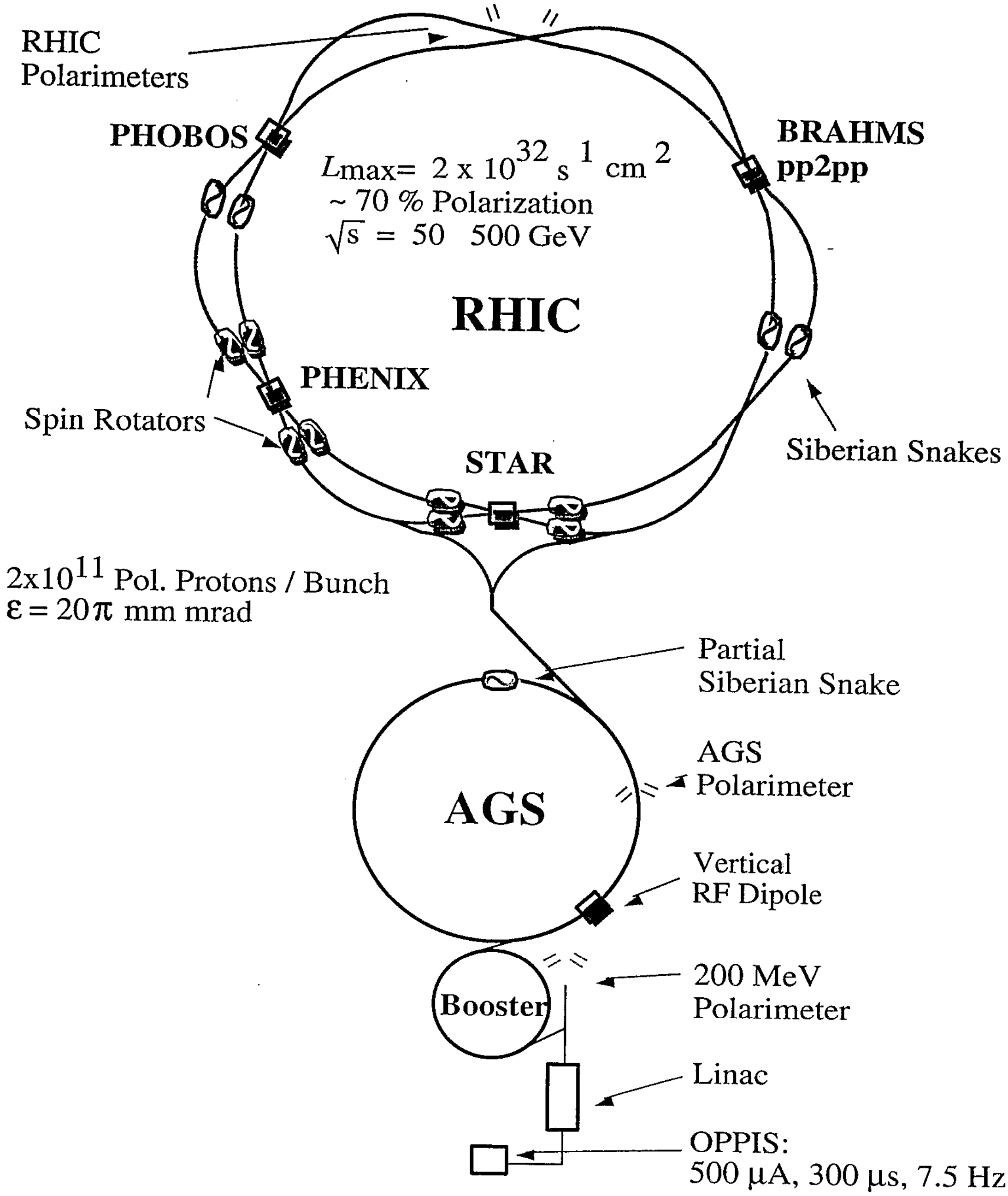
⋆ Dominated by the realization that QCD spin structure is

- Complex, subtle, and interesting
- Open to study with methods of perturbative QCD (pQCD) at high momentum transfer

⋆ Defined by the advent of new facilities

- Dominated by the Polarized Collider at RHIC
- Complemented by muon scattering in COMPASS at CERN
- And the continuing electron scattering program at HERMES at DESY

Polarized Proton Collisions at BNL



The New Era of QCD Spin Physics II

⋆ What is the spin substructure of the nucleon?

Experiment $\otimes$ Theory

★ What is the role of gluons? $\overrightarrow{\text{RHIC}}$

They carry half the nucleon's momentum.

Gluon spin and the axial anomaly are deeply linked.

- What is the role of antiquarks? $\overrightarrow{\text{RHIC}}$

- What about orbital angular momentum?

- What other spin information lurks in the nucleon?

  Transversity! $\overrightarrow{\text{RHIC}}$

  Correlated spin $\times$ transverse momentum distributions. $\overrightarrow{\text{RHIC}}$

★ Does pQCD, factorization, etc. apply without modification to polarization processes?

- New tests of pQCD in polarized hadron collider physics $\overrightarrow{\text{RHIC}}$

- First test the foundations, then explore new regime. $\overrightarrow{\text{RHIC}}$

I. What does carry the nucleon's spin?
and
How can we learn about it?

What does quantum field theory tell us?

$$\frac{1}{2} = \int_0^1 dx \Big[\tfrac{1}{2}\Delta\Sigma(x,Q^2) + \Delta G(x,Q^2) + \mathcal{L}_Q(x,Q^2) + \mathcal{L}_G(x,Q^2) \Big]$$

Manohar & Jaffe
Bashinsky & Jaffe, Hagler & Schafer
Harindranath & Kundu

Theorists

$\mathcal{L}_Q(x,Q^2)$ and $\mathcal{L}_G(x,Q^2)$ are quark and gluon orbital angular momentum about the $\hat{P}$ axis in the infinite momentum frame. Probably not experimentally measurable.

Challenge to Lattice QCD

$\Delta G(x,Q^2)$ is measurable

Prime objective for $\overrightarrow{\text{RHIC}}$ (see Saito's talk)

Total gluon spin contribution will be measured experimentally and

Presents important challenge to Lattice QCD

II. Considerations on ΔG

⋆ No reason for ΔG to be small

⋆ Operator for ΔG is extremely interesting:

$$\Delta G(Q^2) = \frac{1}{2P^+}\int d\xi^- \epsilon(\xi^-)\langle PS|\overbrace{F^{+\lambda}(0)}^{\text{gluon field}}\underbrace{\mathcal{I}(0,x^-)}_{\text{Wilson link}}\overbrace{\tilde{F}^{+}_{\lambda}(\xi^-)}^{\text{dual gluon field}}\Big|_{Q^2}|PS\rangle$$

where

$$\epsilon(x) = \begin{cases} 1, & \text{for } x > 0 \\ -1, & \text{for } x < 0 \end{cases}$$

⋆ So in general gauges, the operator corresponding to gluon spin is nonlocal!

⋆ However, in $A^+ = 0$ gauges it reduces to local operator

$$\Delta G \stackrel{A^+=0}{\longrightarrow} \frac{1}{P^+}\langle PS|A^1F^{+2} - A^2F^{+1}|PS\rangle$$

More considerations on ΔG

⋆ Gluon spin in light-cone gauge:

$$\Delta G \stackrel{A^+=0}{\longrightarrow} \frac{1}{P^+}\langle PS|A^1F^{+2} - A^2F^{+1}|PS\rangle$$

⋆ Identical to generator M_G^{+12} obtained from symmetry analysis, which confirms parton analysis

⋆ Also identical to anomalous (Kogut-Susskind) current in $A^+ = 0$ gauge, which explains mistaken identification of ΔG with anomalous current

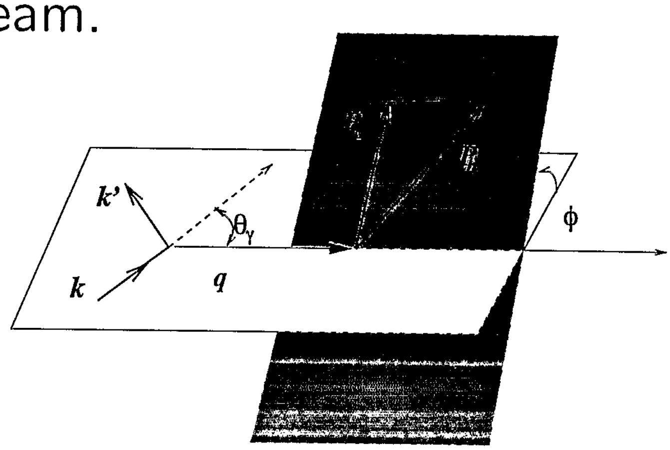
⋆ Calculation of ΔG on lattice is an important challenge.

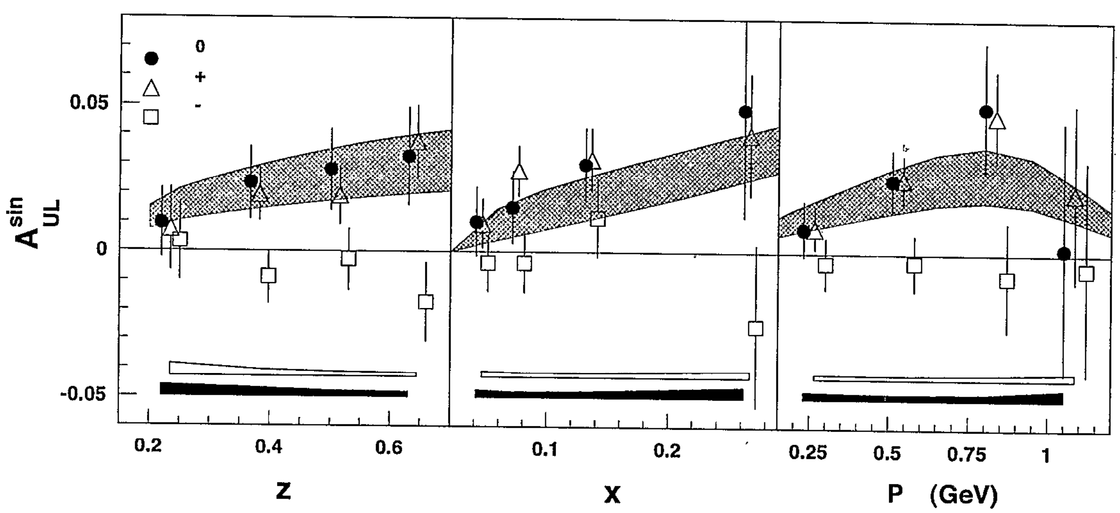
⋆ We likely have not heard the end of ΔG and the anomaly.

III. Do Standard pQCD Tools Work for Transverse Spin?

Unexpected large asymmetries:

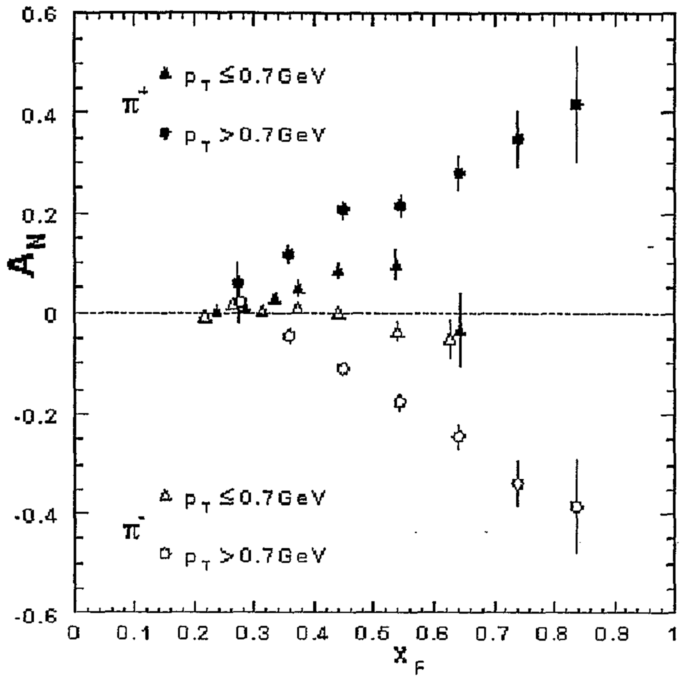
⋆ Azimuthal asymmetry observed at HERMES in $e\vec{p} \to e'\pi X$ with target polarization parallel to lepton beam.





Note approximate with u-quark dominance. Should be approx. $\pi^+ : \pi^0 : \pi^- :: 1 : 1 : 0$. Data show $\pi^+ \sim \pi^0 \gg \pi^-$

⋆ Classic $\vec{k} \times \vec{p} \cdot \vec{s}_\perp$ asymmetry in $\vec{p}_\perp\ p \to \pi\ X$



E704 at Fermilab

⋆ In QCD both these asymmetries are twist-three effects, expected to vanish like $p_\perp/\sqrt{s}$. Nevertheless, both are strikingly large.

⋆ Higher-twist effects in totally inclusive experiments (e.g., g_2 and twist-four corrections to DIS) are very small.

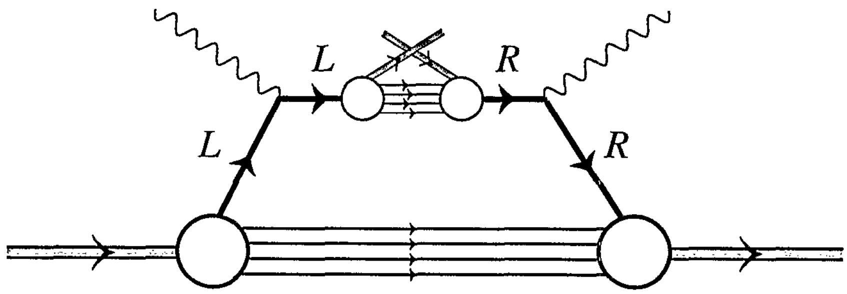
⋆ Difference here is processes involve

[parton distribution] $\otimes$ [parton fragmentation]

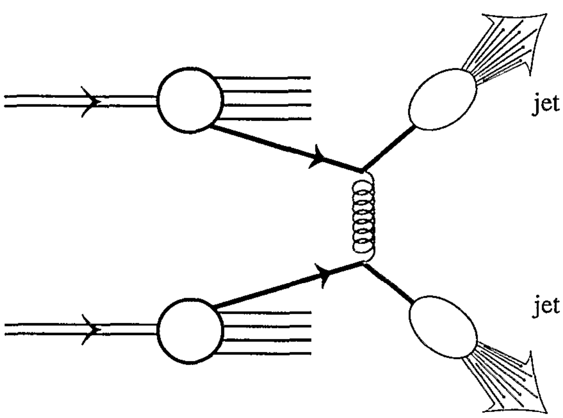
Factorization with Two Soft Processes?

Theorists have raised questions about factorization in DIS processes with observed hadrons.

⋆ Single particle inclusive lepto-production:
initial quark distribution × quark fragmentation function



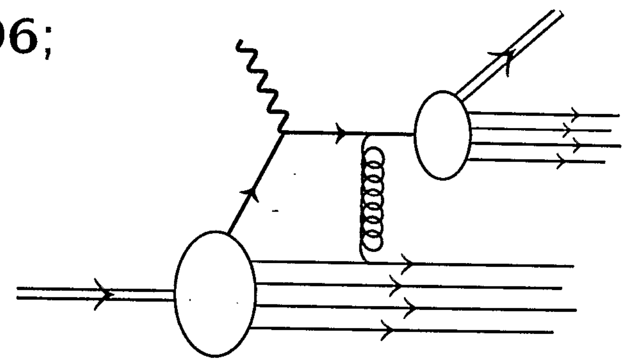
⋆ Hadron-hadron scattering at
high momentum transfer
Initial quark distribution × initial quark distribution



One-gluon exchange
⇒ quark ⇒ jet

Does pQCD Apply? Recent theory activity:

- ⋆ Brodsky, Hwang, and Schmidt **hep-ph/0201296**;
  Collins **hep-ph/0204004**



- ⋆ Need to reinterpret factorization in light of important final state interactions.

Wonderful tests at $\overrightarrow{\text{RHIC}}$

- ⋆ $\mathcal{A}_{TT}/\mathcal{A}_{LL} \ll 1$ Because there is no gluon-transverse spin in the deep inelastic domain.

N. Saito & R. Jaffe

- ⋆ Interference fragmentation function (free of factorization ambiguities) measures transversity at $\overrightarrow{\text{RHIC}}$

- ⋆ Complete study of single spin asymmetry, $\mathcal{A}_N$ at $\overrightarrow{\text{RHIC}}$

Conclusions

⋆ QCD is rich and complex and we are made of it!

⋆ Precise studies of quark/gluon composition of nucleons surprise us:

- Spin fraction of quarks is small.
- Nucleon contains polarized strange quarks.
- Complex structure ⇔ Simple quark models?

⋆ Challenges to theorists!

- Specific matrix elements for lattice QCD
- Does pQCD work for transverse spin? for distribution × fragmentation?
- What does carry the spin of the nucleon?

⋆ Future measurements at $\overrightarrow{\mathrm{RHIC}}$

- Test of pQCD
- Polarized gluon and antiquark distributions
- Transverse polarization distributions

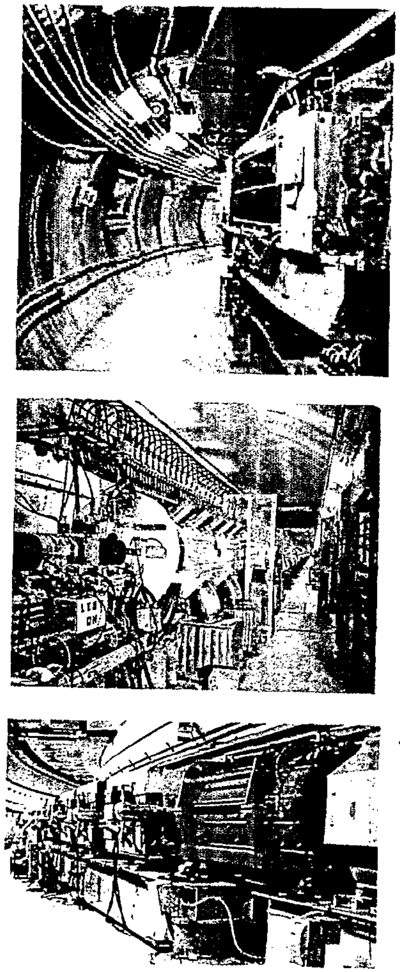
POLARIZED PROTONS IN RHIC

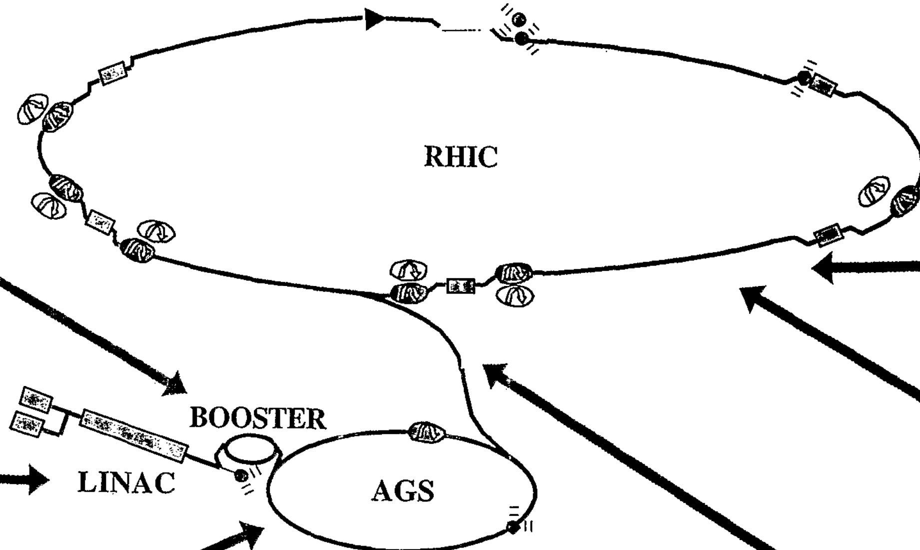
Waldo MacKay

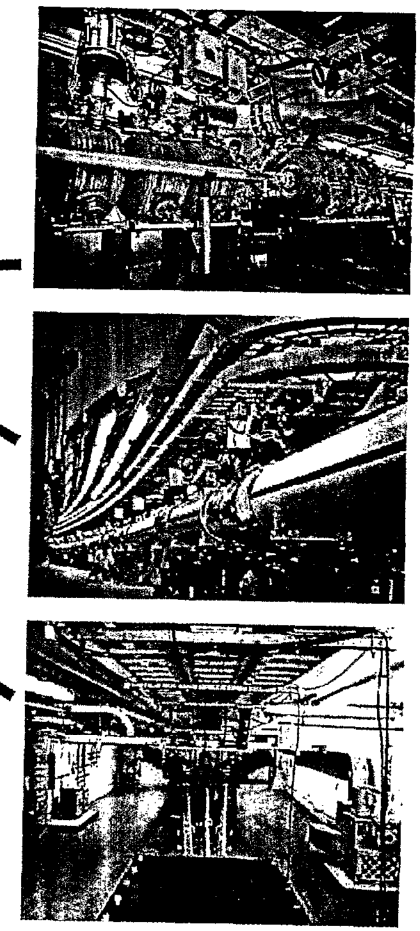
Polarized Protons in RHIC

- Layout of the RHIC and injectors.
- RIKEN contributions to RHIC Spin program.
- Intro to accelerator physics.
  - Spin dynamics.
  - Depolarizing resonances.
- Hardware: Siberian snakes and rotators.
- 35 1st polarized proton run.
- Future plans.
- Summary: successes of RIKEN/BNL Collaboration.

Accelerator Complex







LINAC: Linear Accelerator
AGS: Alternating Gradient Synchrotron
RHIC: Relativistic Heavy Ion Collider

RIKEN Contributions to RHIC Spin

- Superconducting Helical Siberian Snakes
- Superconducting Helical Spin Rotators (PHENIX and STAR)

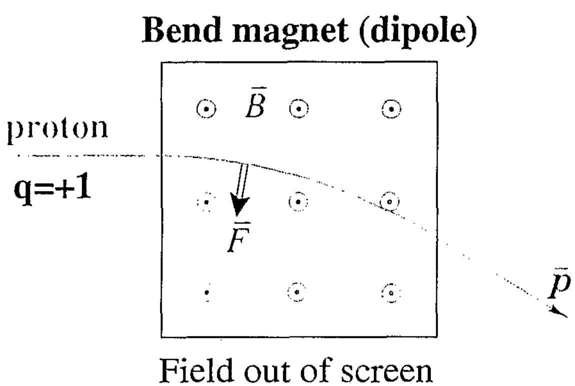
Total of 48 helical dipoles

- Special probe for magnetic measurements of helical dipoles
- Power supplies and quench circuits for Snakes and Rotators
- Polarimeters (Subject of following talk by Dr. K. Kurita)

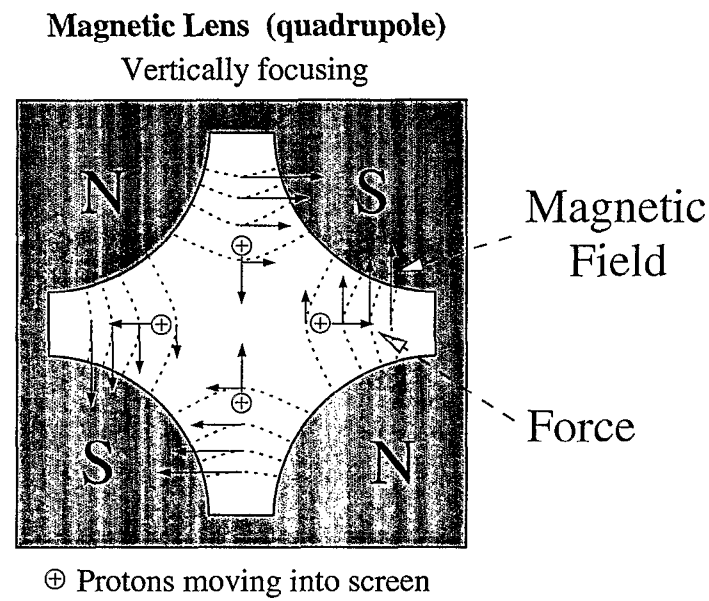
Domo Arigato Gazaimashita.

Particle Trajectories in Magnetic Fields

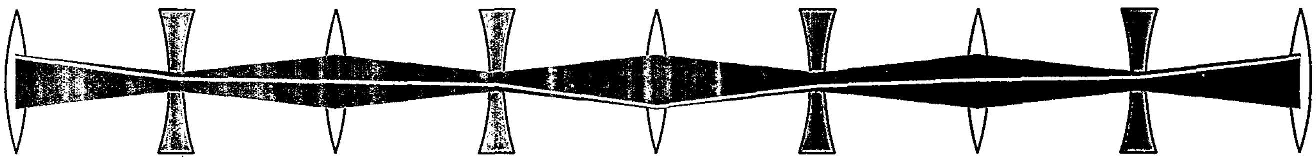
Dipole magnets bend the beam around the ring.



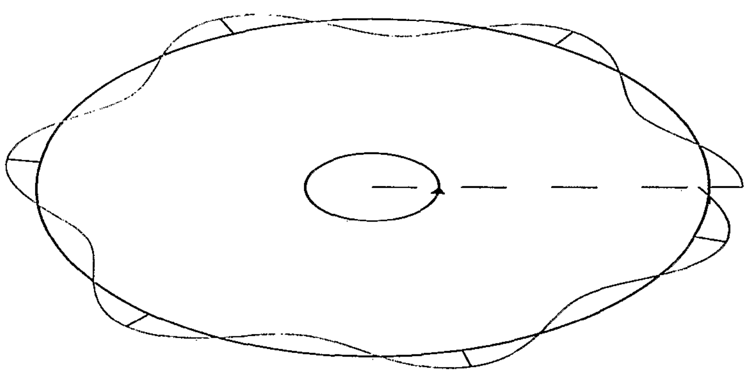
Quadrupole magnets focus the beam for stability.



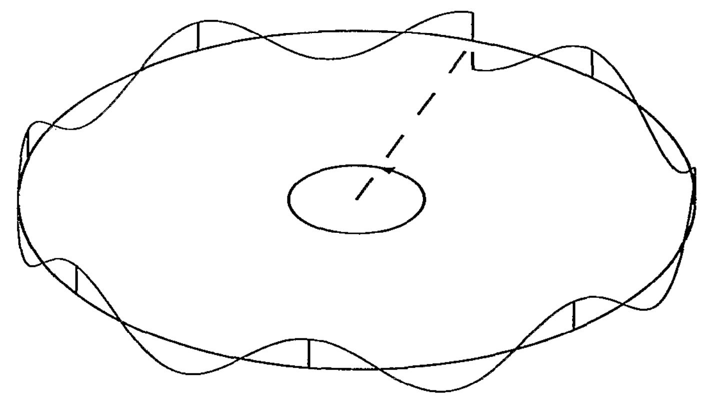
Transport and Betatron Oscillations



Alternate focusing and defocusing lenses for stability.



Horizontal Betatron Oscillation
with tune: $\nu_h = 6.3$,
i.e., 6.3 oscillations per turn.



Vertical Betatron Oscillation
with tune: $\nu_y = 7.5$,
i.e., 7.5 oscillations per turn.

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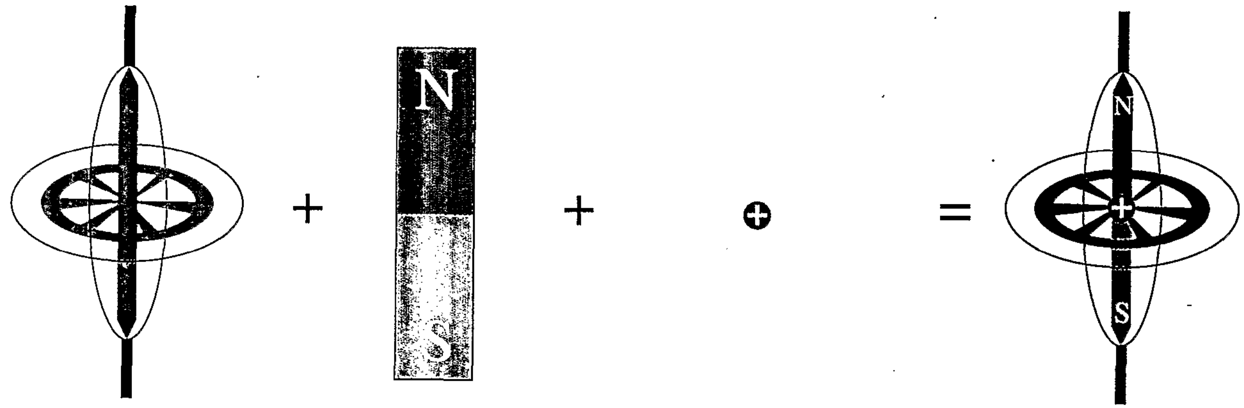
Simple Model of Proton



Gyroscope + Bar magnet + Charge = "proton"

Spin

Magnetic Dipole Moment

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Polarization: Average spin of the ensemble of protons.

Thomas—Frenkel (BMT) Equation

In the local rest frame of the proton, the spin precession of the proton obeys the Thomas-Frenkel equation:

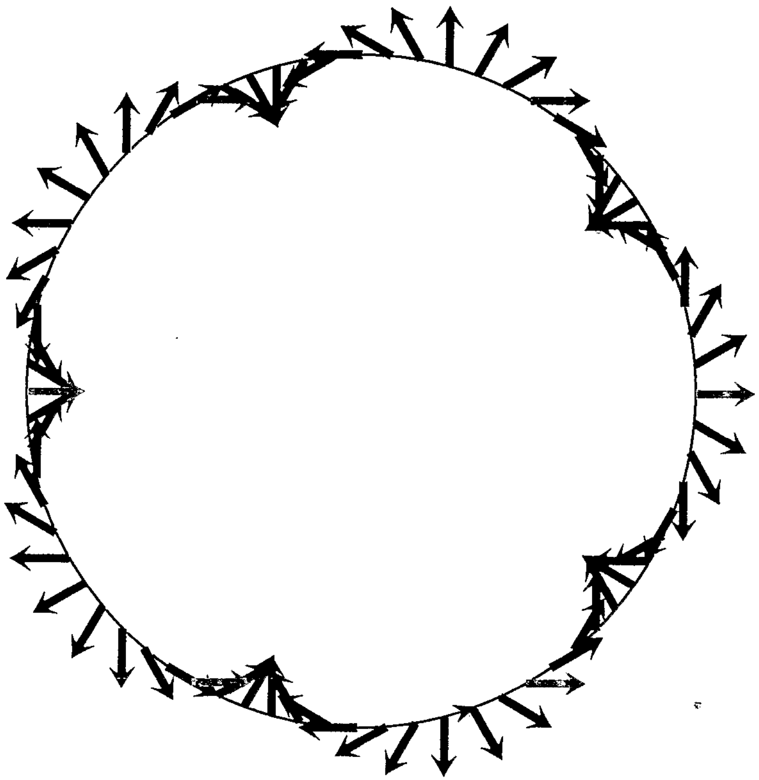
$$\text{Torque}: \quad \frac{d\vec{S}^*}{dt} = \frac{q}{\gamma m}\vec{S}^* \times \left[(1+G\gamma)\vec{B}_\perp + (1+G)\vec{B}_\parallel\right] \qquad \text{TF}$$

$$\text{Force}: \quad \frac{d\vec{p}}{dt} = \frac{q}{\gamma m}\vec{p} \times \vec{B}_\perp \qquad \text{Lorentz}$$

(This is a mixed description: t, and $\vec{B}$ in the lab frame, but spin $\vec{S}^*$ in local rest frame of the proton.)

$$G = \frac{g-2}{2} = 1.7928, \qquad \gamma = \frac{\text{Energy}}{mc^2}.$$

Spin Precession in a Ring



Example with 6 precessions of spin in one turn:

$$G\gamma + 1 = 6.$$

Spin tune: number of precessions per turn relative to beam's direction.
So we subtract one:

$$\nu_{\text{spin}} = G\gamma \quad \propto \quad \text{energy},$$

i.e., 5 in this example.

Depolarizing Resonances

Resonance Condition:

$$\nu_{\text{spin}} = N + N_{\text{v}}\nu_{\text{v}},$$

where N and N_{v} are integers.

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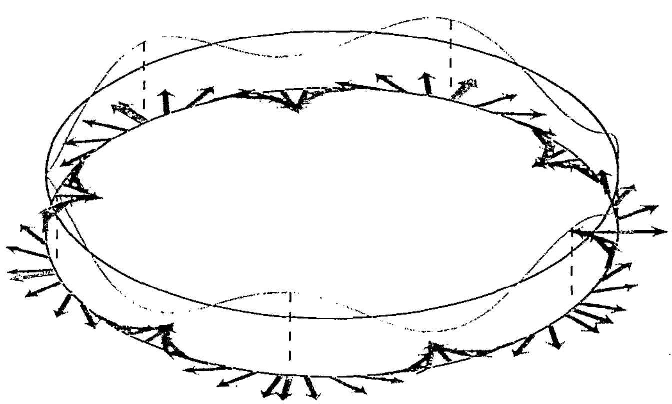
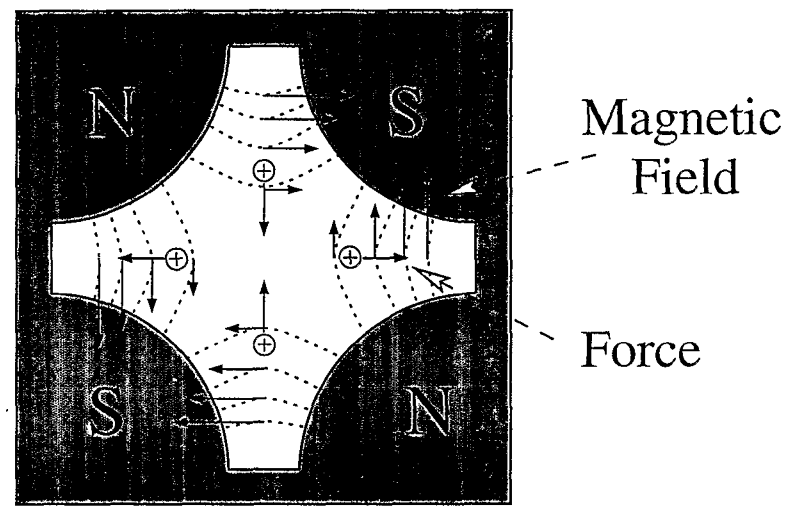
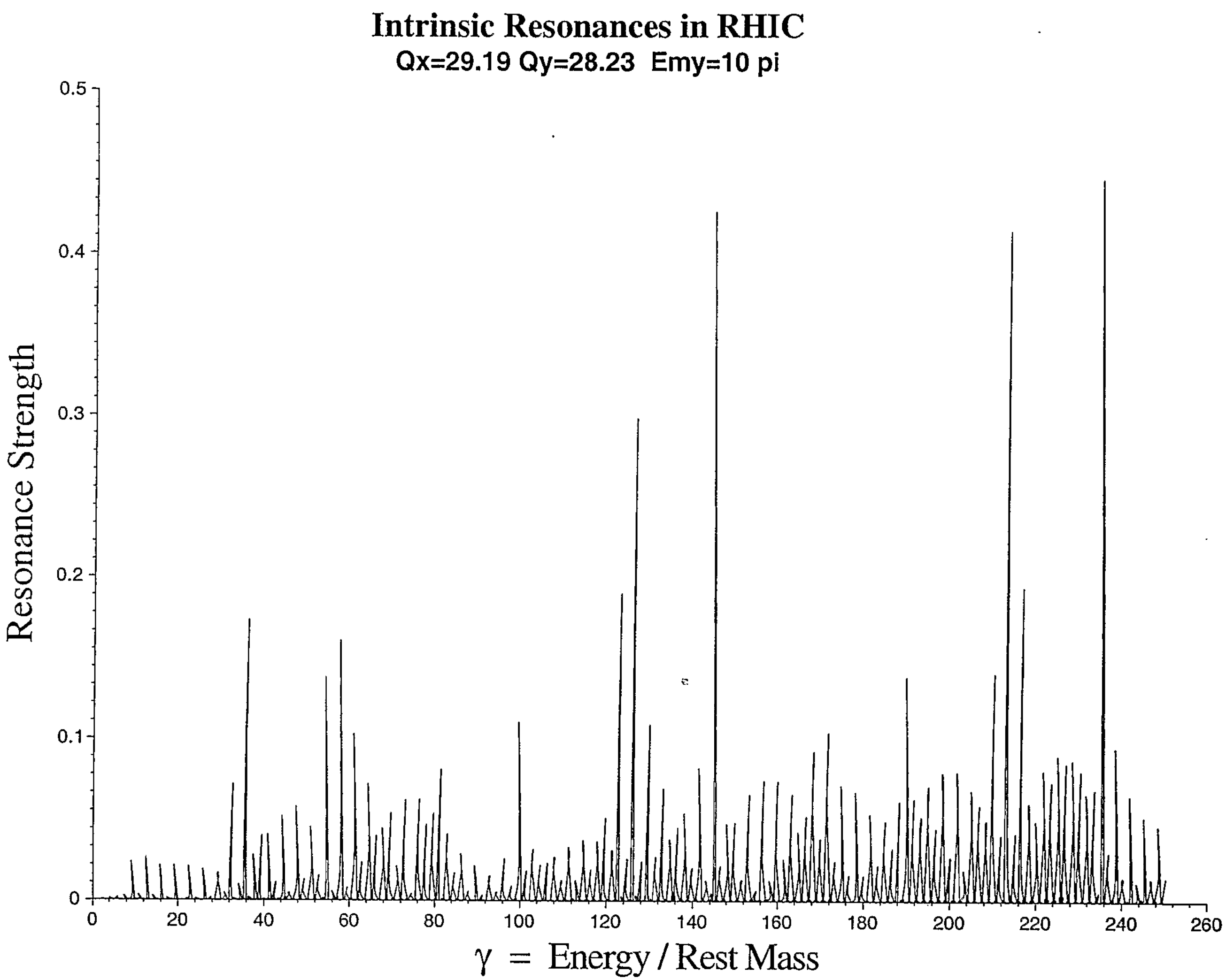


Magnetic Lens (quadrupole)
Vertically focusing



⊕ Protons moving into screen

Depolarizing Resonances



Will depolarize beam during acceleration.

Solution: Snakes

Snake Charming

- 2 snakes: spin is up in one half of the ring, and down in the other half.
- Spin tune: $\nu_{\text{spin}} = \frac{1}{2}$
  (It's energy independent.)
- "The unwanted precession which happens to the spin in one half of the ring is unwound in the other half."

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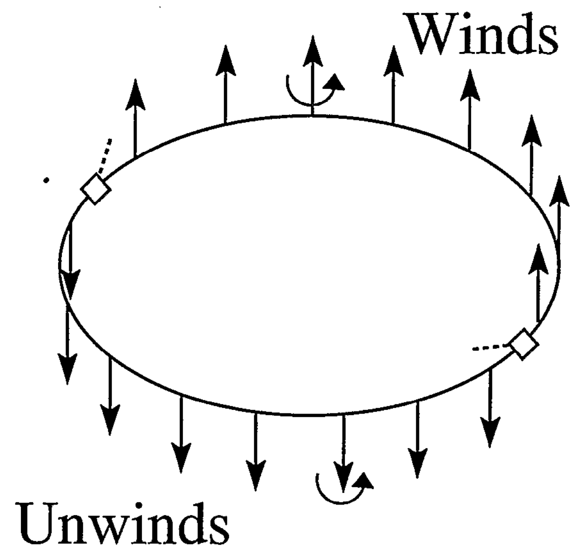
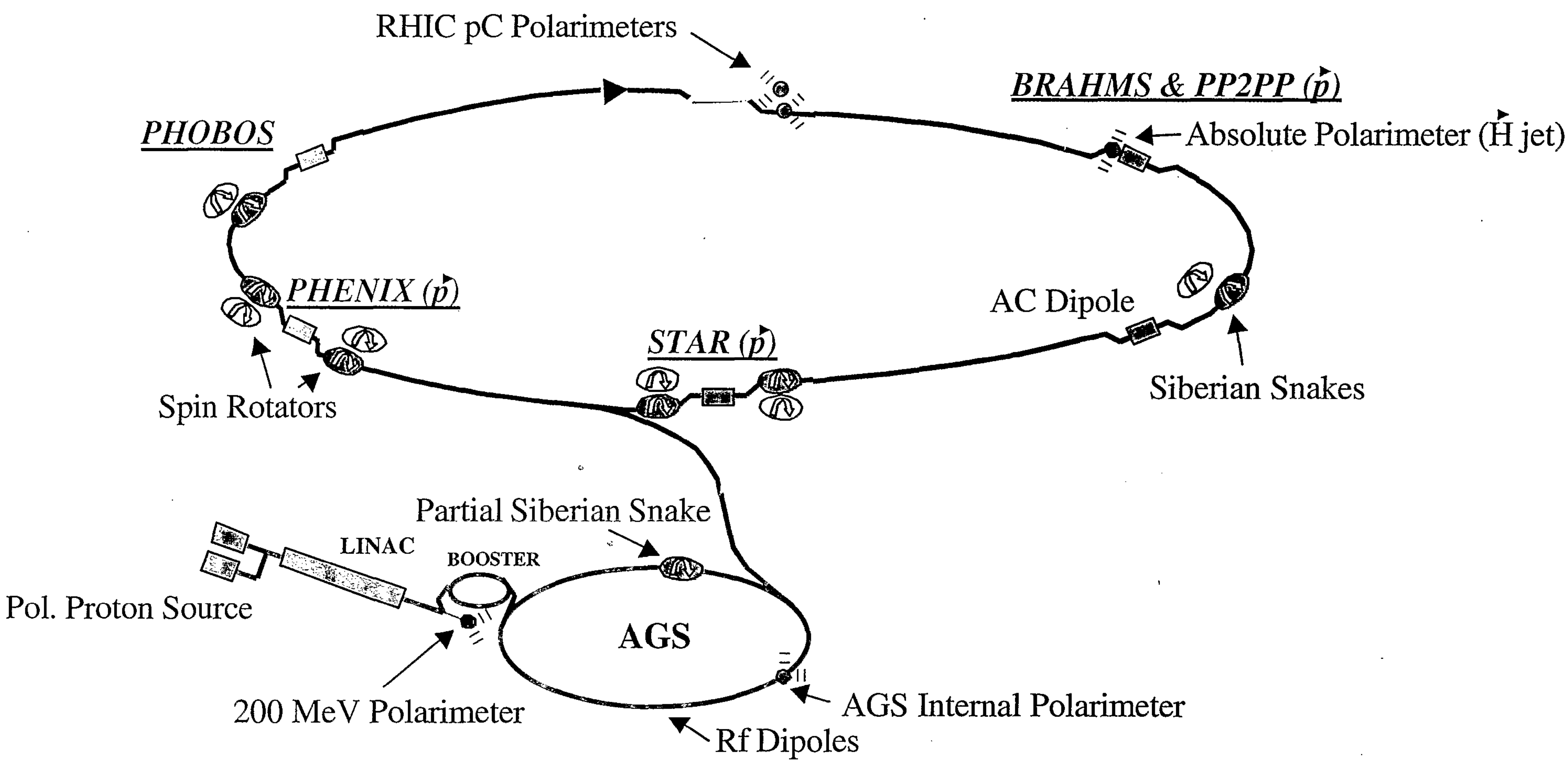
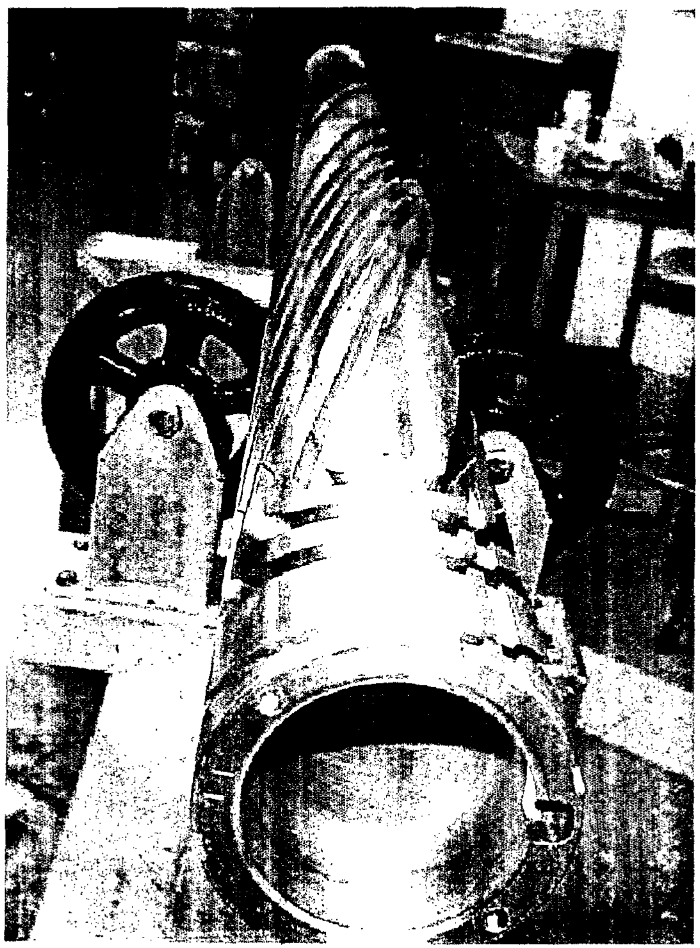
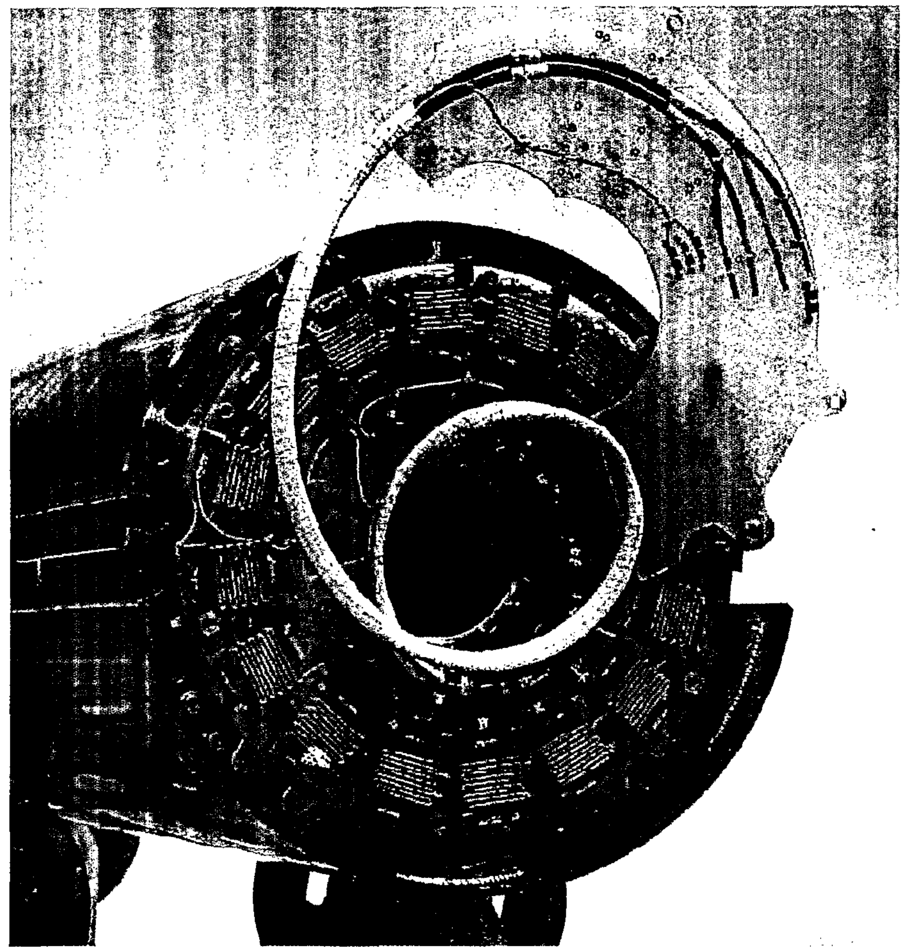


Accelerator Complex for Protons

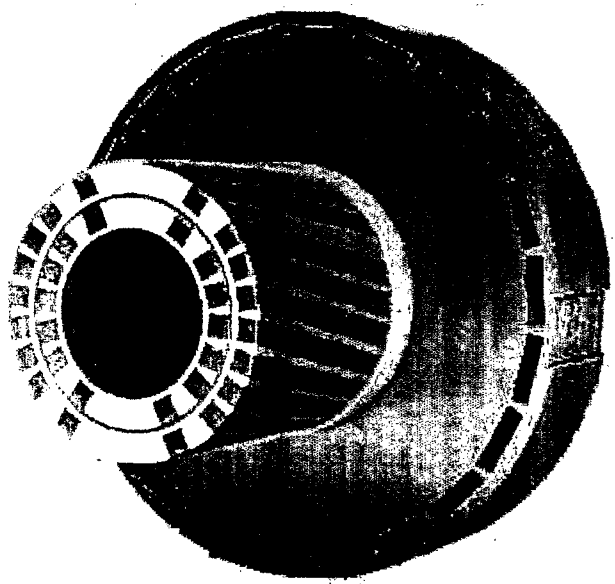


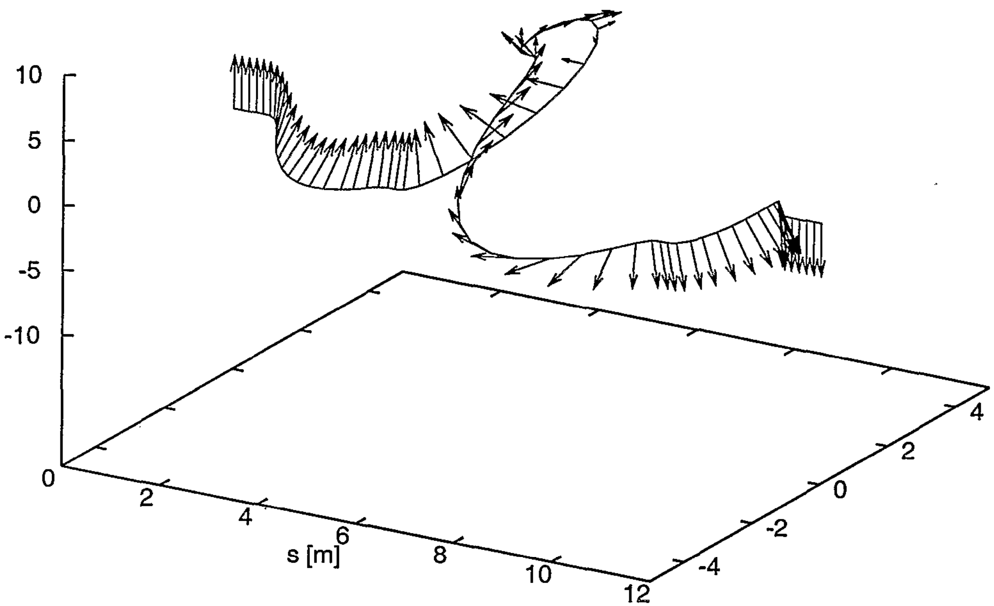
Helical Dipoles



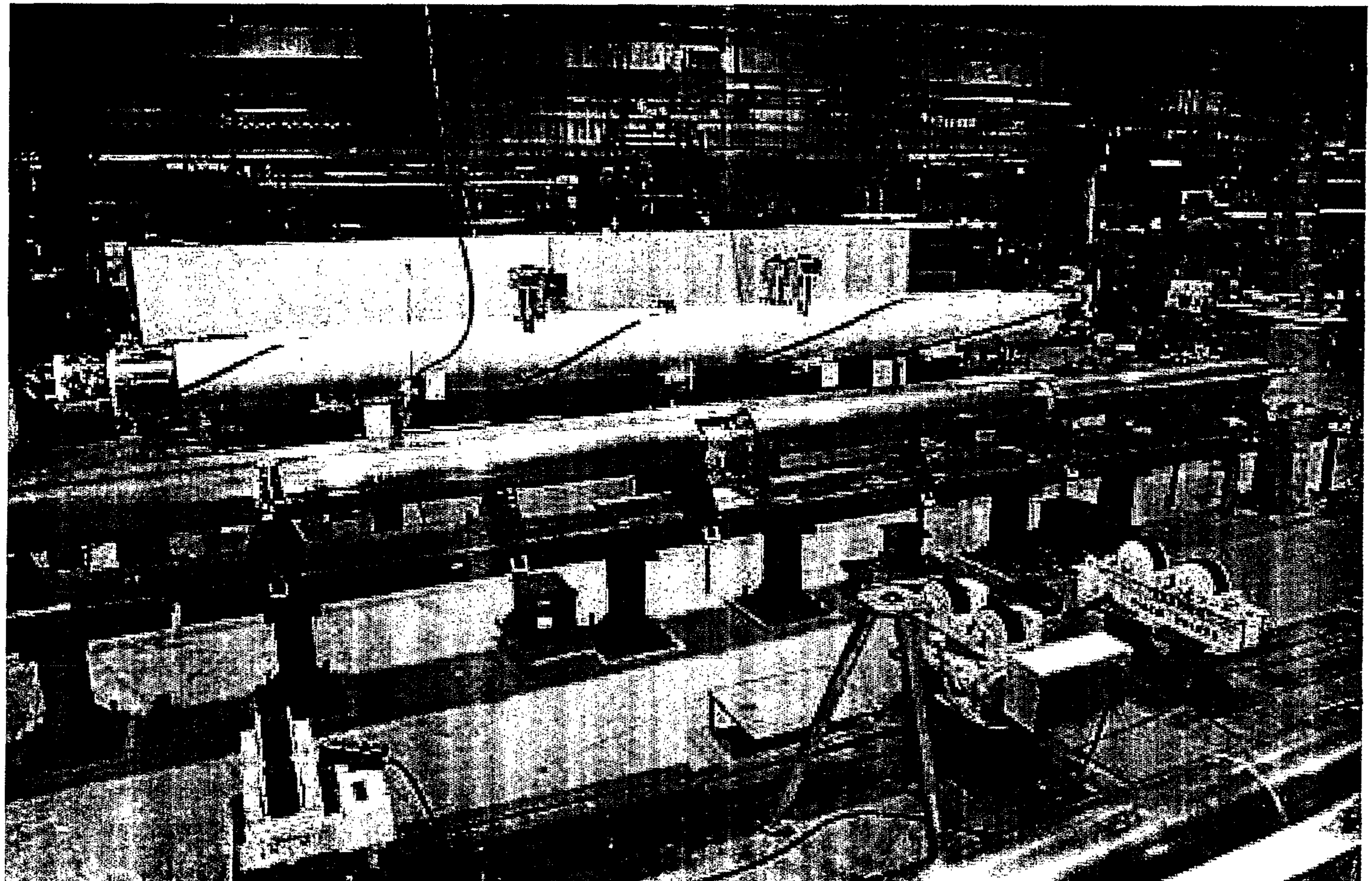


Trajectory and Spin through Snakes

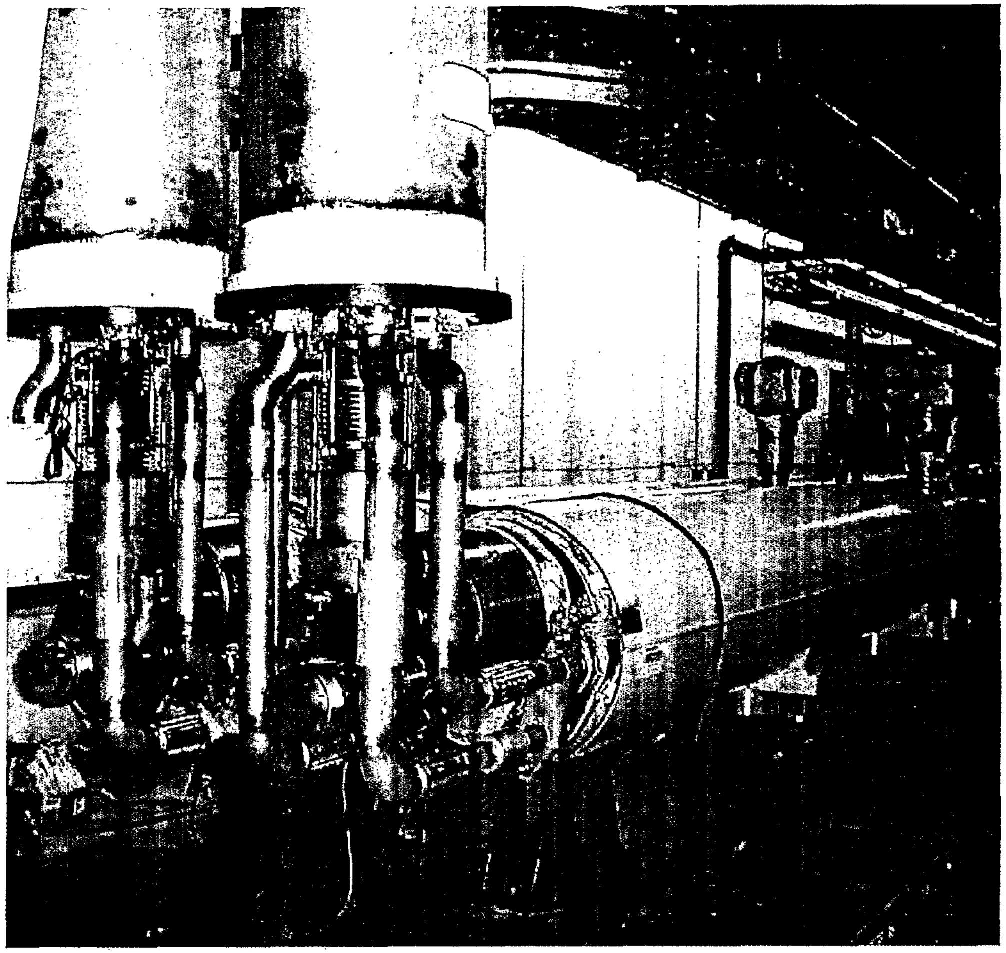




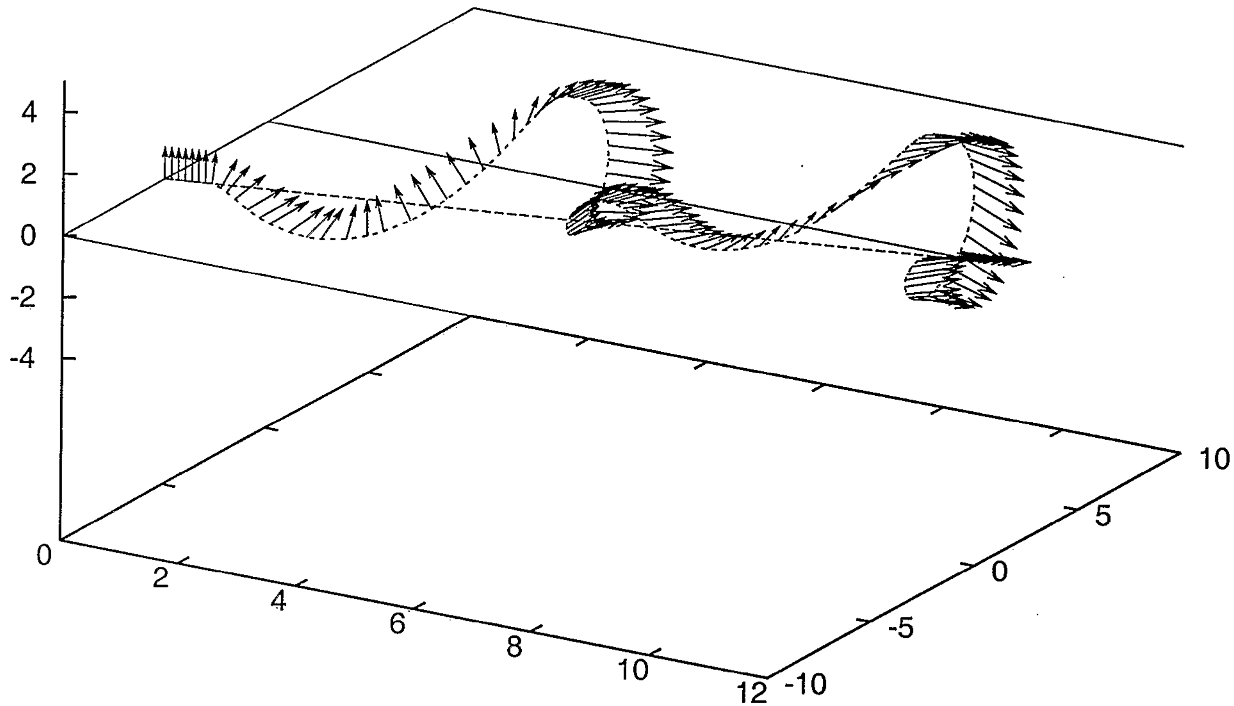
Construction of Cold Masses

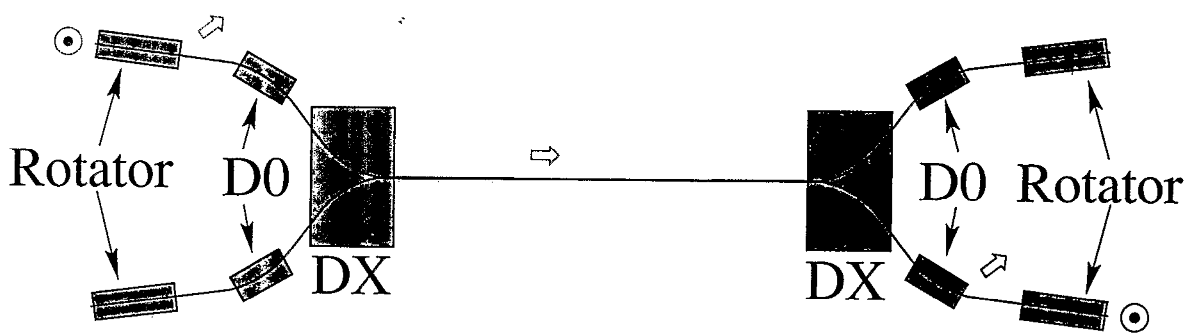


Installation of Rotators



Helical Spin Rotators



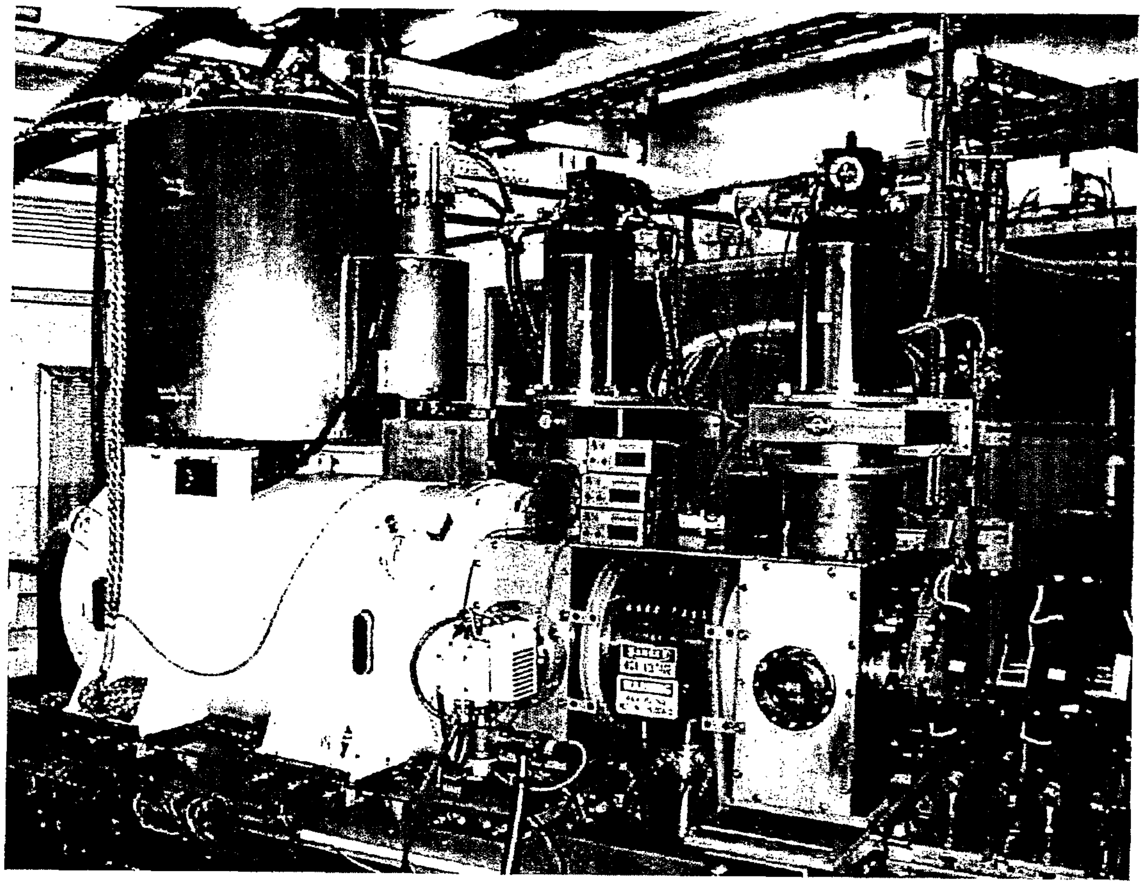


Performance of 1st Run

Parameter	Design	1st Run
C.M. Energy [GeV]	500	200
L_{peak} [$\times 10^{30}$ cm^{-2}s^{-1}]	200	1.5
Polarization	70%	25%
Polarization direction	Vert. & Long.†	Vert.
Protons/bunch [$\times 10^{11}$]	2	0.8
bunches/ring	112	55
β^* [m]	1†	3
Emittance $\pi\epsilon^N_{95\%}$ [π μm]	20	25

† STAR and PHENIX only.

High Intensity Polarized H^- Source



KEK OPPIS*
upgraded at TRIUMF

70 → 80% Polarization

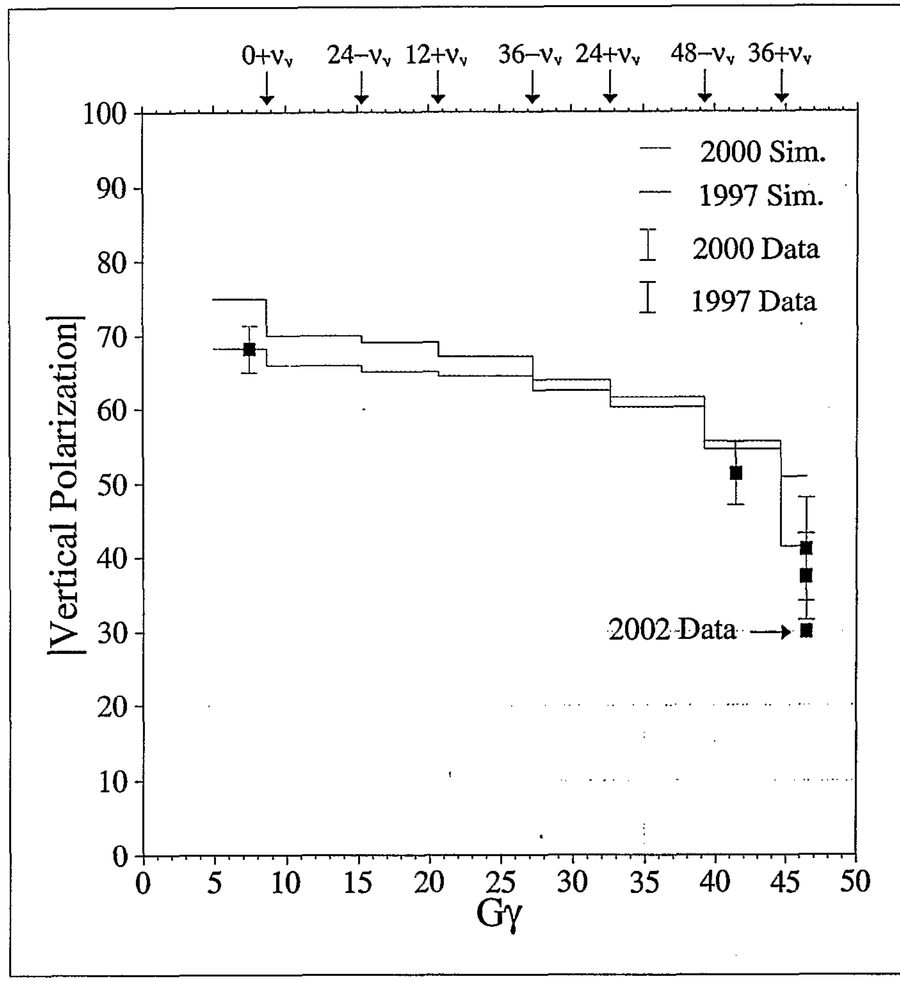
15×10^{11} protons/pulse
at source

6×10^{11} protons/pulse
at end of LINAC

*Optically Pumped Polarized Ion Source

Comments on Injector Performance

- Source: Worked beautifully.
- Booster: No depolarization.
- AGS: Polarization loss larger in FY02 due to lower ramp rate and higher bunch intensity
  - Failed main magnet power supply. (Repair by Fall'02.)
- AGS: New partial superconducting helical snake should give polariation $\sim 70\%$.



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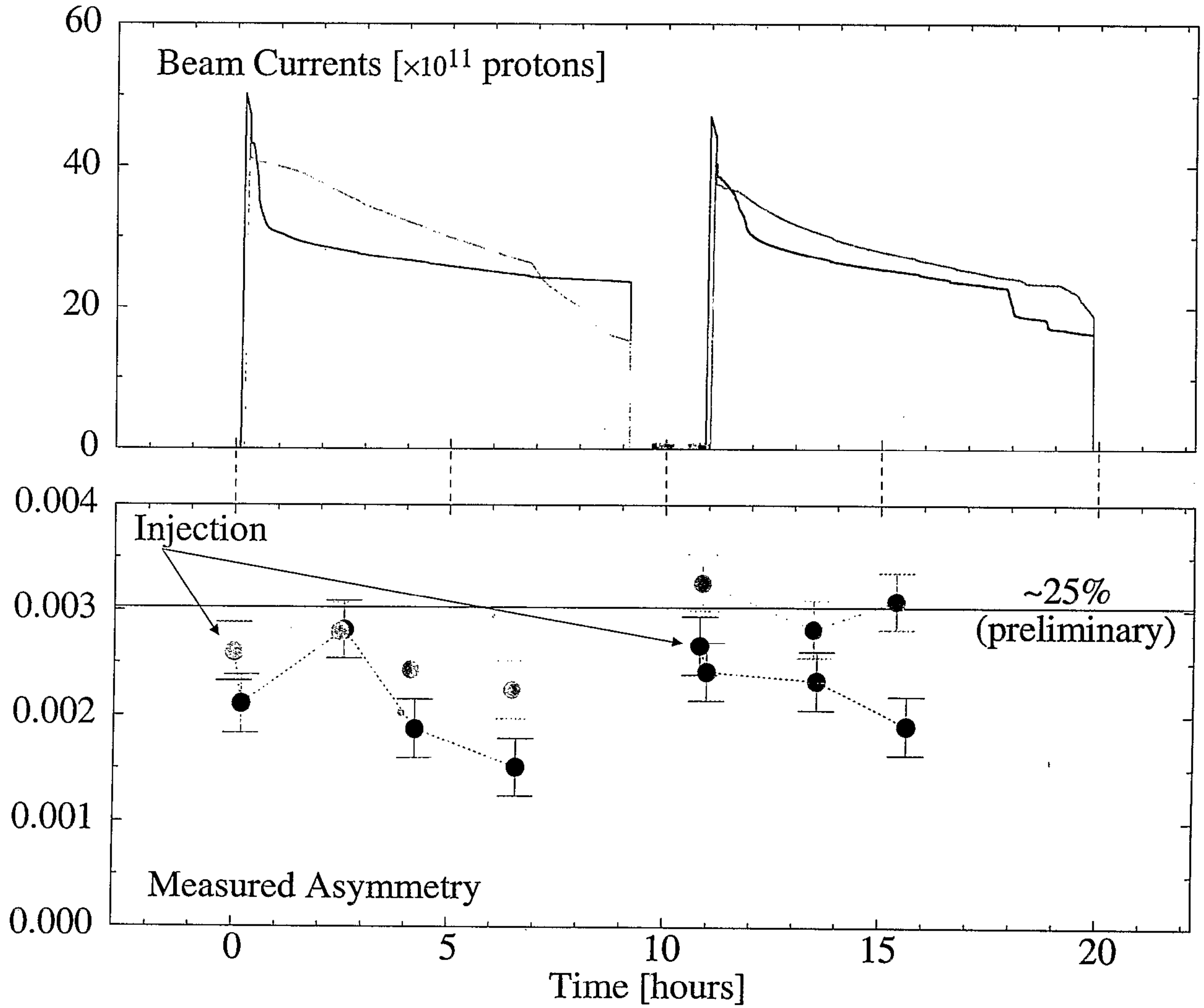
RHIC Beam Polarization



Future Plans

Preparations for Next Run

- Next time: spin rotators at STAR and PHENIX
  for longintudinal polarization.
- New CNI† polarimeter in AGS
  to improve tuning AGS for higher polarization.

Beyond Next Run

- Polarimeter using Polarized Hydrogen Jet target
  for absolute calibration of CNI polarimeters in RHIC.
- New Superconducting Helical Partial Snake in AGS
  to improve polarization transmission.

†CNI: Coulomb Nuclear Interference.

Summary

Successes from RIKEN/BNL Collaboration

- First superconducting helical snakes. (Work very well!)
- Polarized protons accelerated to highest energy.
- First collider with polarized protons! $\sqrt{s} = 200$ GeV
- CNI polarimeters work beautifully. (See next talk by Dr. Kurita.)

PROTON-CARBON CNI POLARIMETER FOR RHIC

Kazuyoshi Kurita

Proton-Carbon CNI Polarimeter for RHIC

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RHIC Spin Physics Celebration

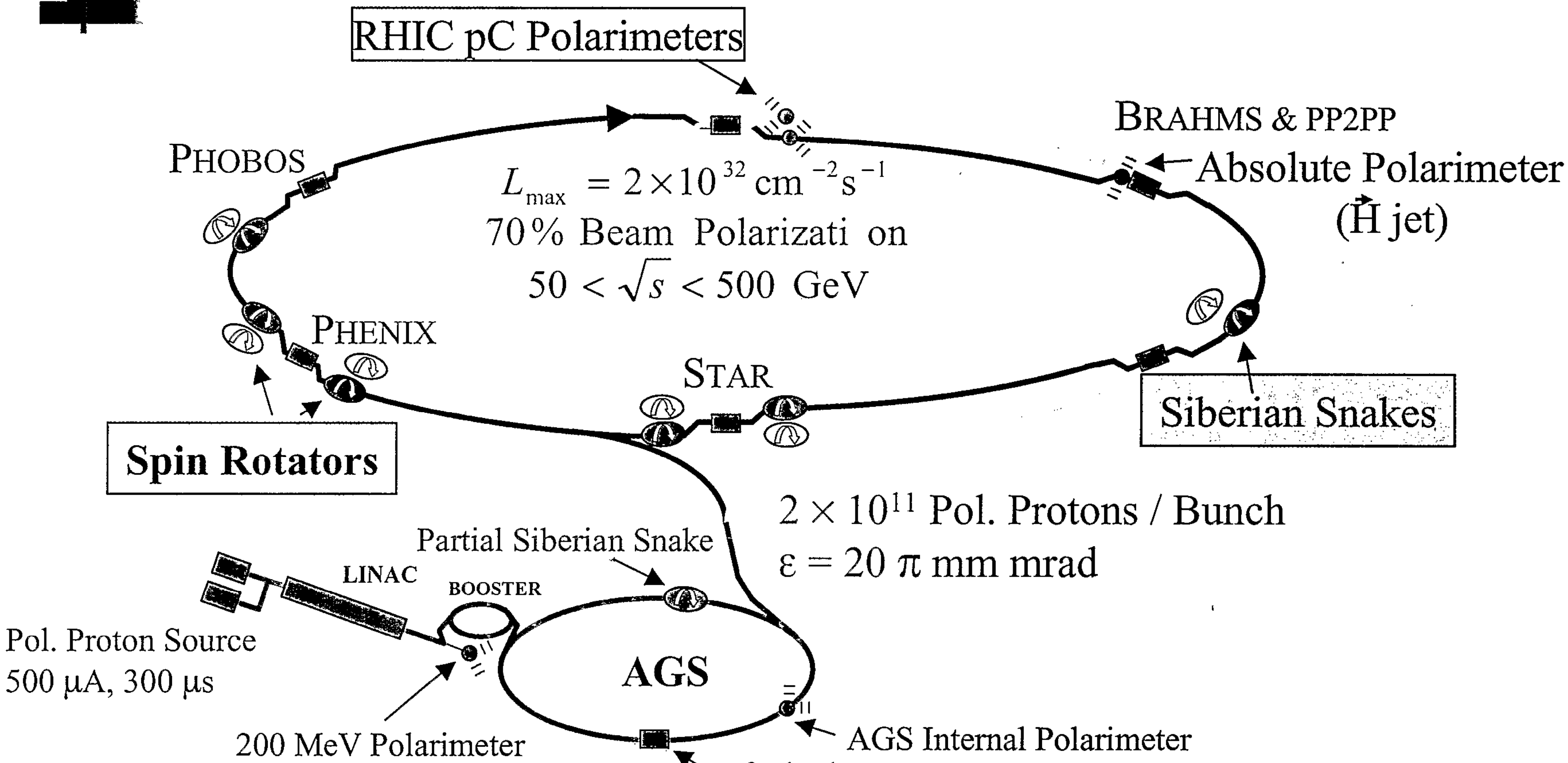
Kazu Kurita

Rikkyo University

Outline

- *1, Introduction*
- *2, BNL-AGS Experiment 950*
- *3, RHIC spin commissioning*
- *4, Towards absolute polarization*
- *5, Summary*

RHIC Spin Program

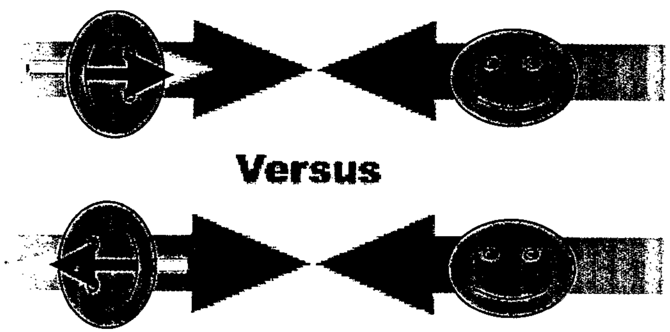


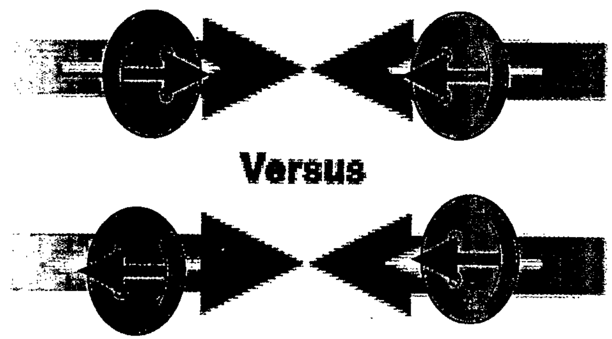
Illustrated by Thomas Roser

Kazu Kurita

Importance of RHIC Polarimetry

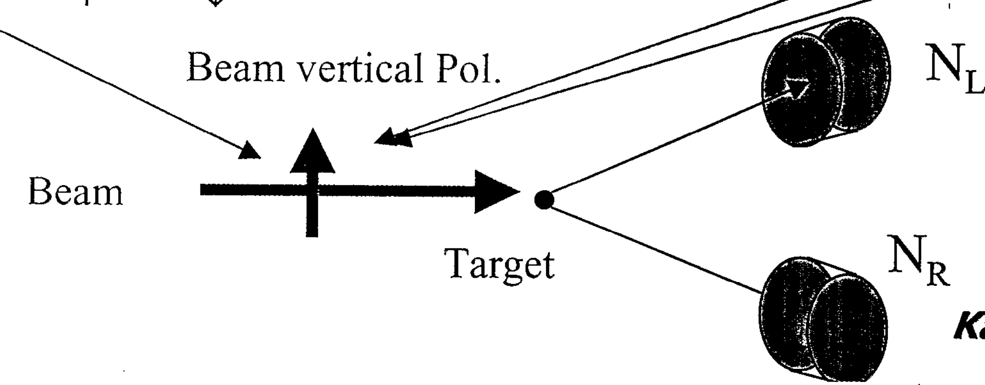
Single Spin Asymmetry	Double Spin Asymmetry





$$A_L = \frac{1}{p_B}\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$A_{LL} = \frac{1}{p_{B_1} p_{B_2}}\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}$$



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Our effort for RHIC polarimeter

- Nov,'97 inclusive pion asymmetry study in AGS-E925 with carbon target
- Apr,'98 Carbon detection test in IUCF-CE75
- Jan,'99 Kyoto Tandem test for E950 Si detector
- Mar,'99 AGS-E950 to study pC CNI in the AGS ring AGS-E925 with hydrogen target
- Aug,'00 Si detector calibration at BNL-Tandem
- Sep,'00 commissioning of RHIC pC CNI polarimeter
- Dec,'01 first spin physics run

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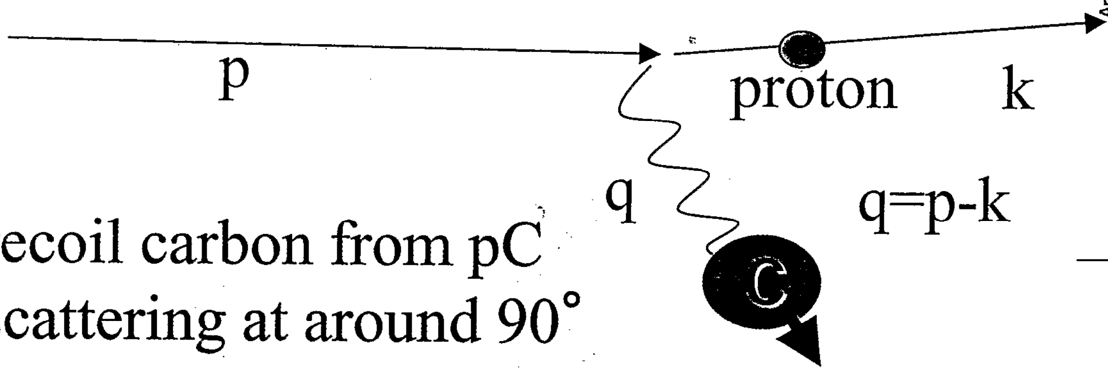
Proton-Carbon CNI Region

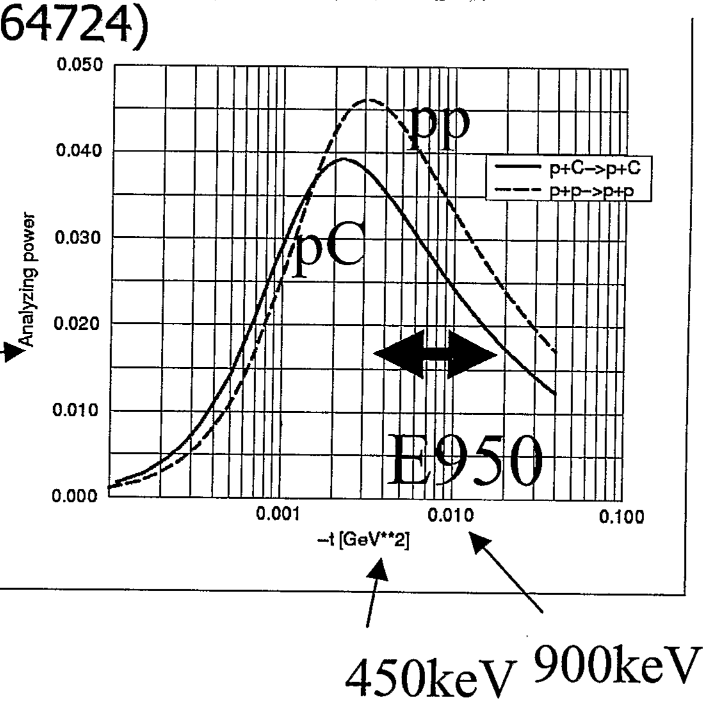
CNI reaction was suggested for RHIC polarimetry during RBRC theory workshop in summer 1997.
(T.L. Trueman and E. Leader, BNL-64724)

Coulomb Nuclear Interference Region
(very forward elastic scattering)

$10^{-3} < -t = q^2 \leq 10^{-2}$ (GeV/c)^2



recoil carbon from pC scattering at around 90°



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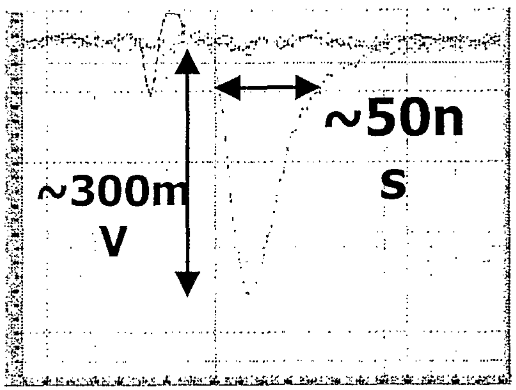
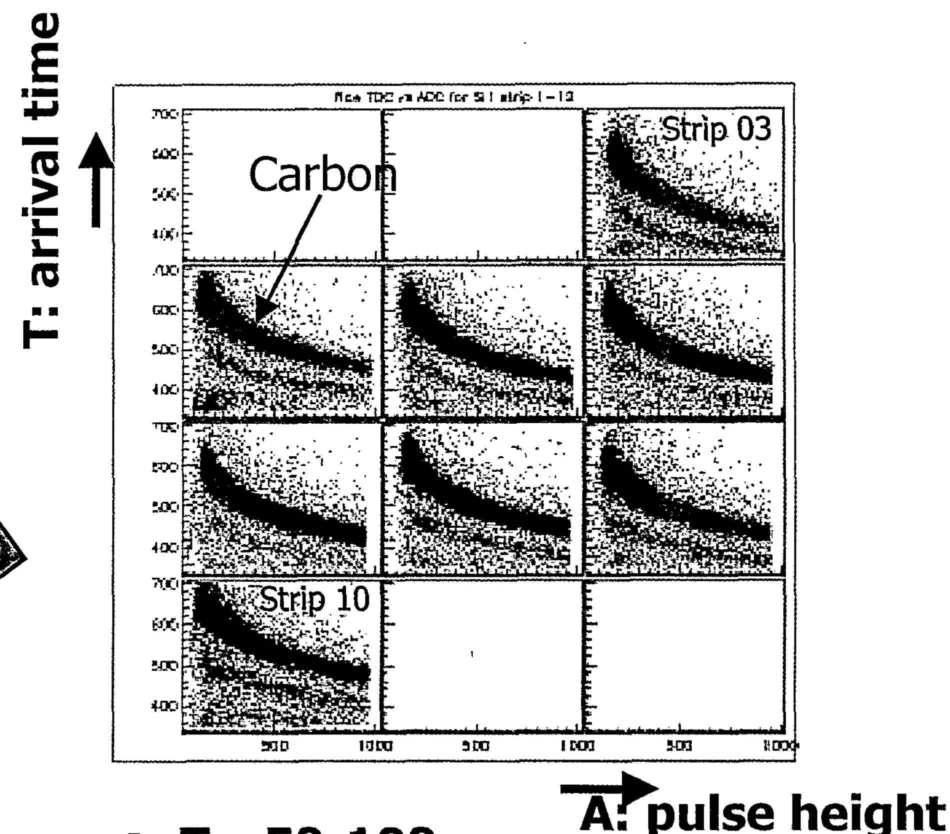
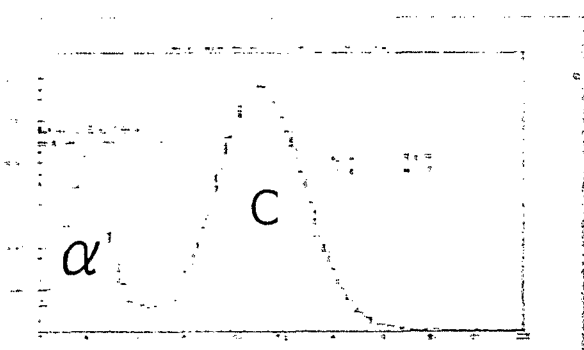
Recoil Carbon detection with Si



Si signal after Shaping



range · T= 50-100ns
A = 40-400mV



Mass distribution

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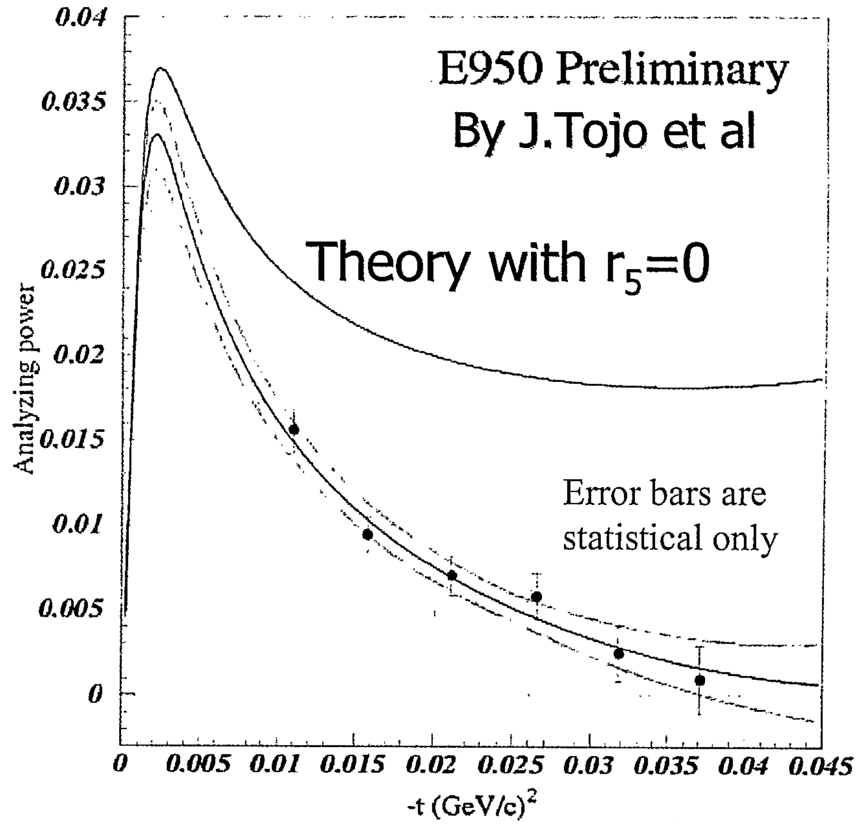
E950 Result

- *t dependence of An is qualitatively consistent with theory*
- *Data is inconsistent with r_5=0 theory*
- *Beam energy dependence of An may be larger than expected*



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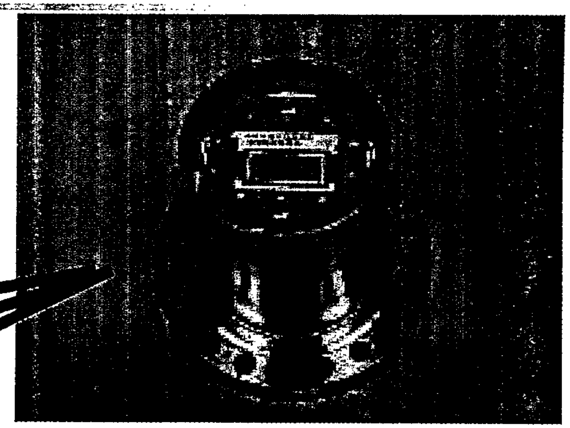
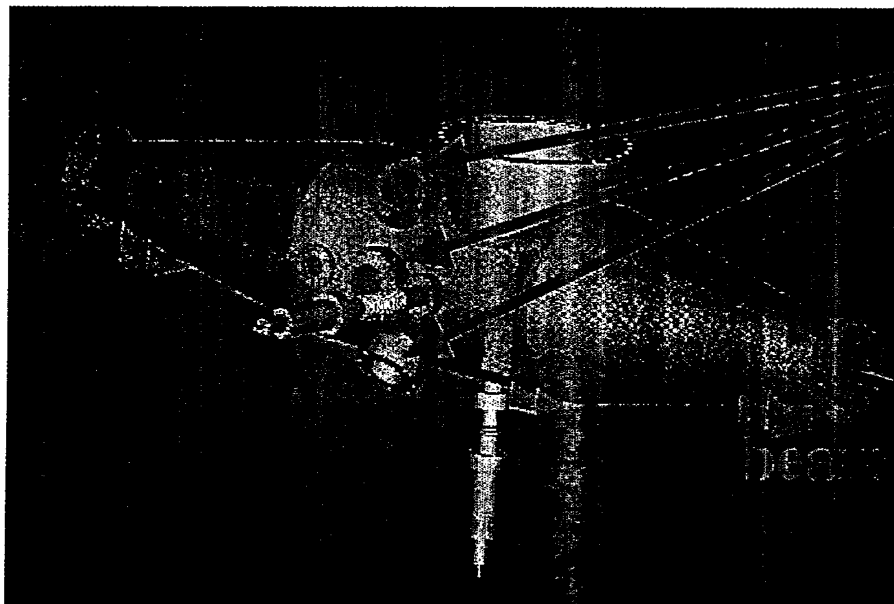
3, RHIC Polarimeter Design

Detector ports



Micro ribbon C target(5um/cm2 thick)



Target control

Detector ports and targets arrangement

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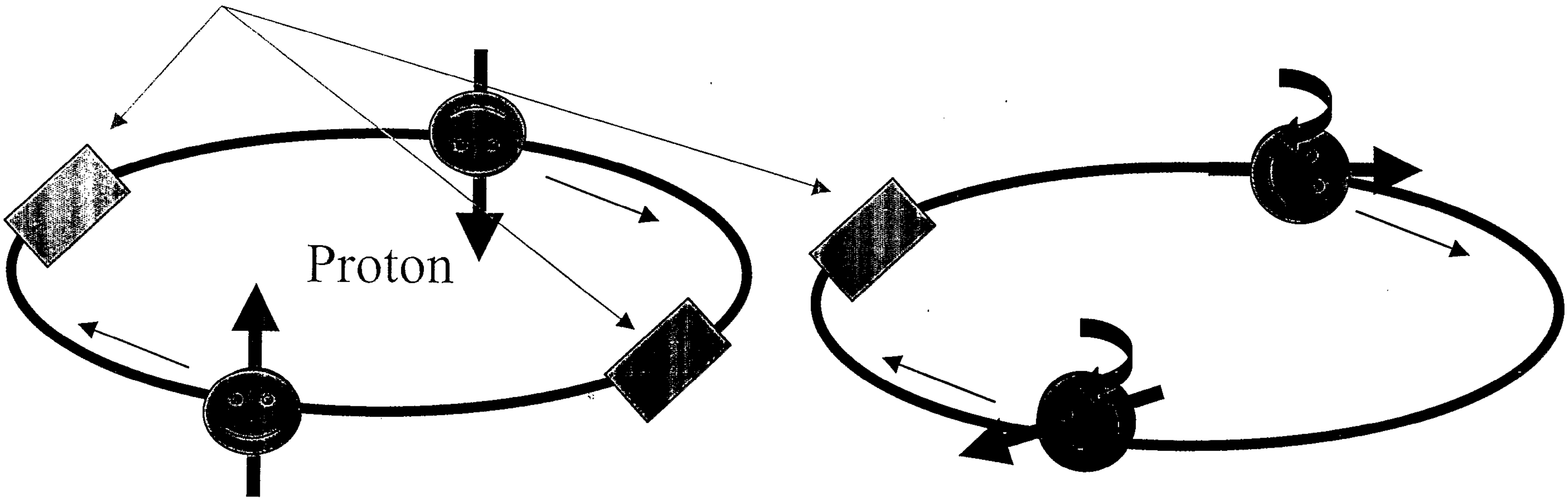
Polarized Proton Acceleration with Siberian Snake Magnets

Helical Dipole Magnets "Siberian Snake"



Two snake operation
Spin direction is vertical
P_{beam}<250GeV/c

One Snake Operation
Spin direction is horizontal
P_{beam}<100 GeV/c

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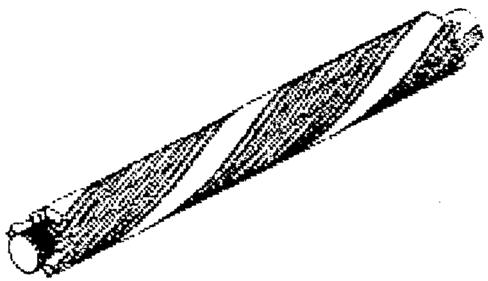
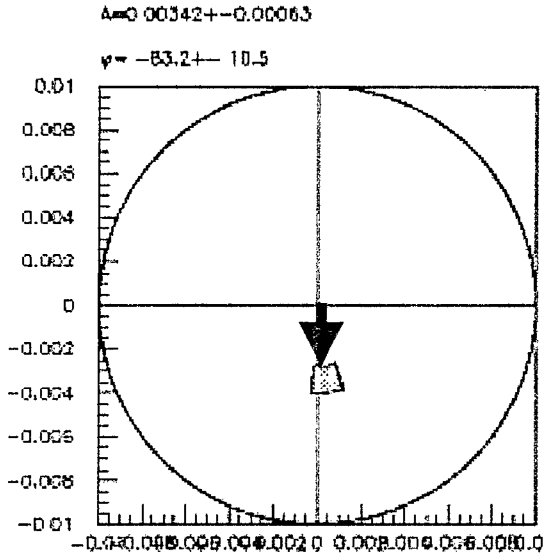
Spin Celebration@ RBRC

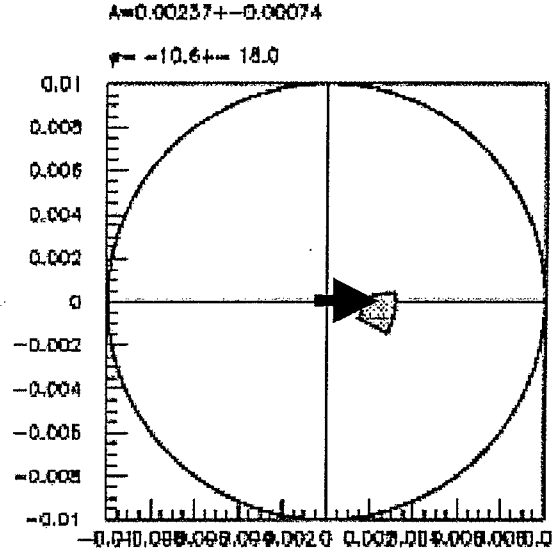
Sep., 2000

Polarization with Snake magnet ON/OFF





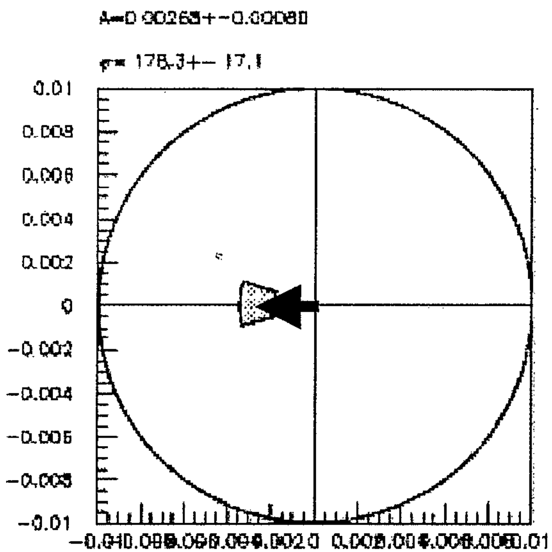
Gγ=46.5 Injection energy
Snake OFF Vertical polarization



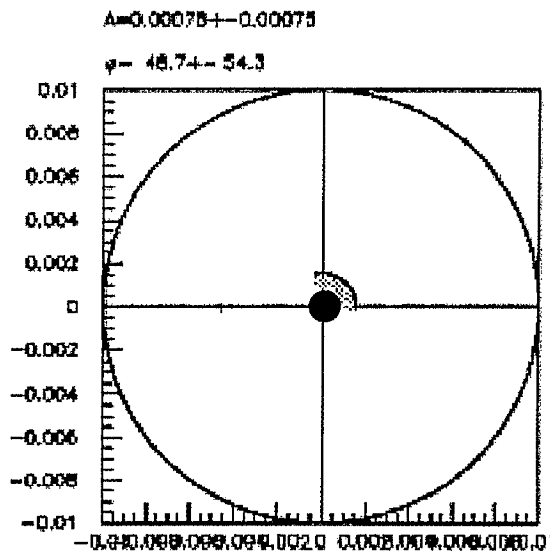
Gγ=46.5 Injection energy
Snake ON Horizontal polarization

G=1.79285

g :Lorentz factor



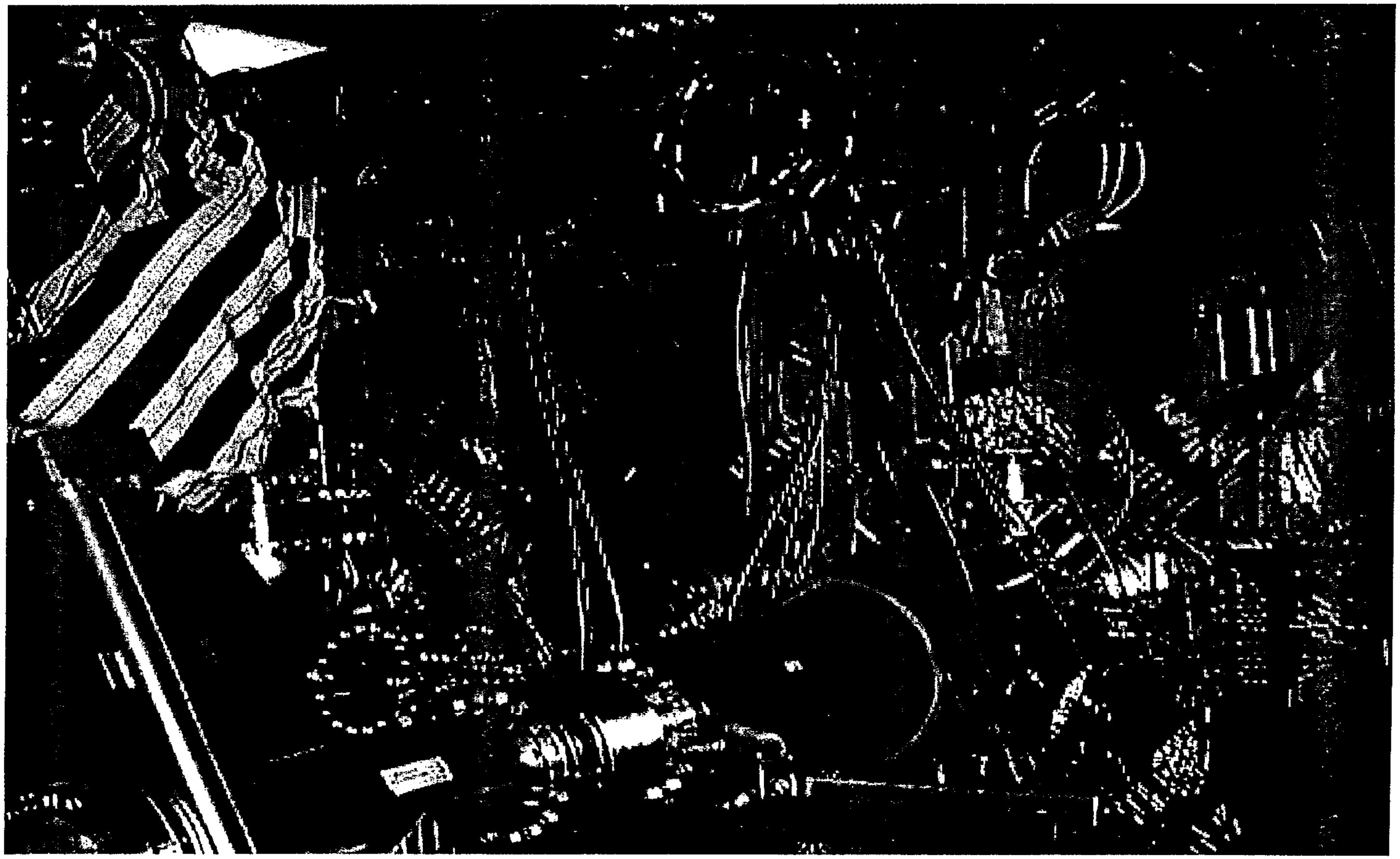
Gγ=48 Acceleration with Snake ON
Horizontal polarization



Gγ=48 Acceleration with Snake OFF
Polarization lost

Polarization was kept up to ~30GeV

Y2001 RHIC pC CNI Polarimeter Setup



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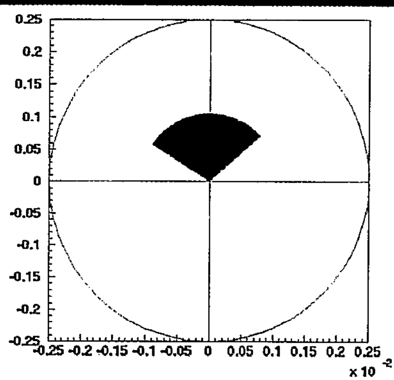
Improvement from Y■■■■

- Y■■■commissioning
  - One Sanke
  - One Polarimeter
  - Four Si detectors
  - CAMAC FERA DAQ
  - Two hours for 2M events
  - Six bunch mode
  - Lost Pol. at ■■GeV

- Y■■■■pol. acceleration
  - Two Snakes in each rings
  - Two Polarimeters
  - Six Si detectors each
  - Dead-time less WFD
  - One minutes for ■■M events
  - ■■bunch mode
  - **No depol. till ■■■GeV**
  - Calibration with embeded Am

Pol vector in Polar Coordinate

■■■■年
31.5GeV



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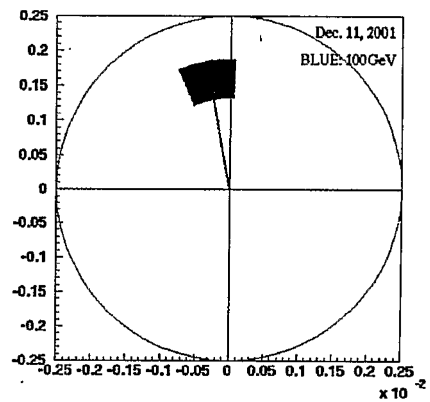
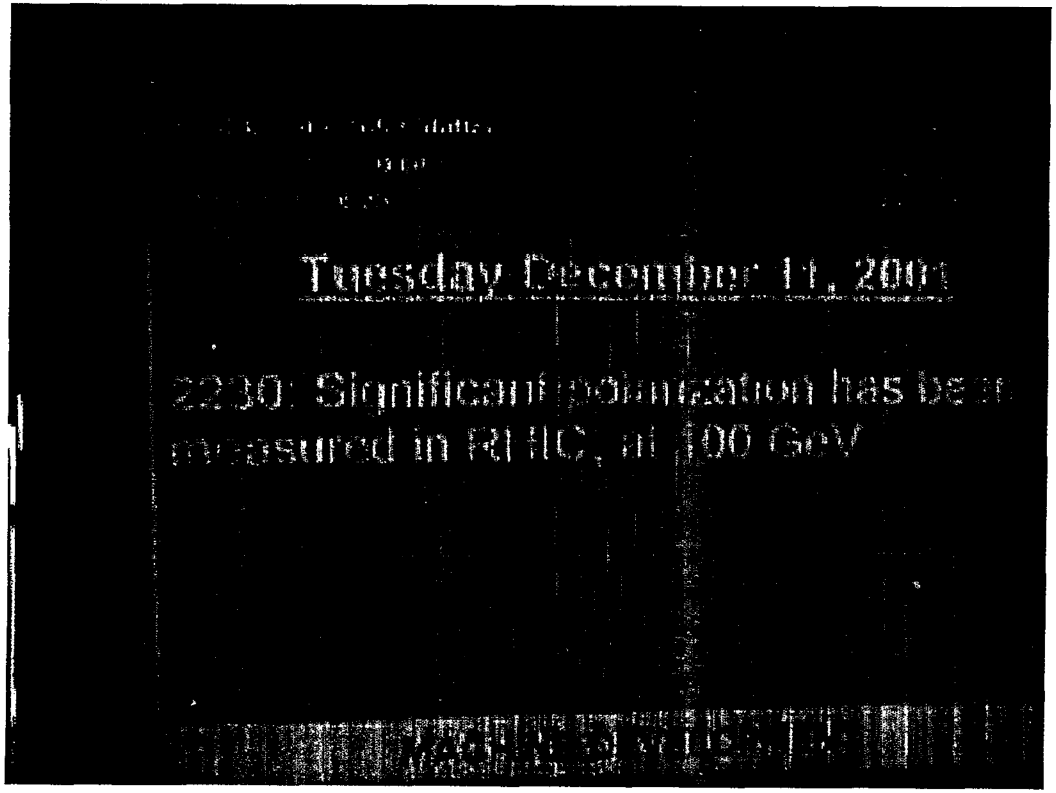


■■■1年
100GeV

rita

The first asymmetry measurement at 100GeV



- Cheers!

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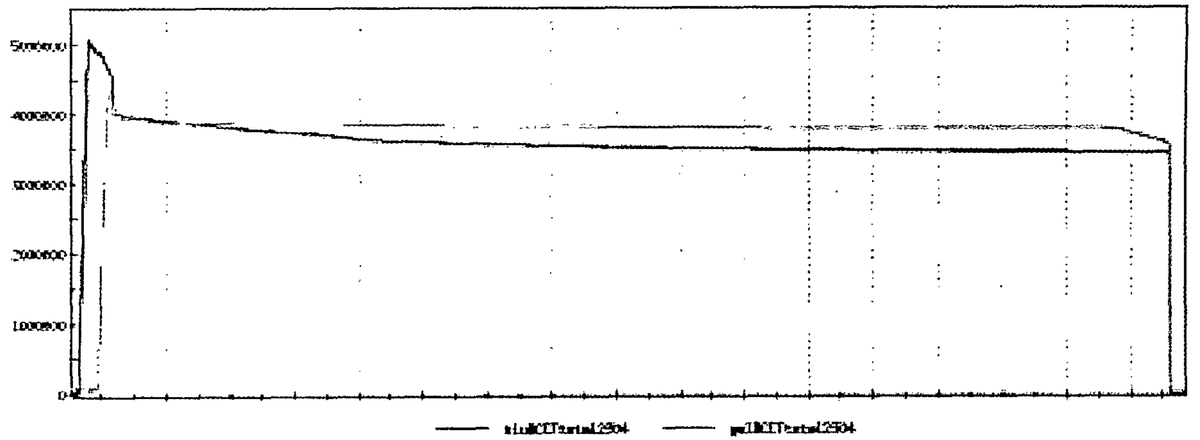
Beam Current and Polarization

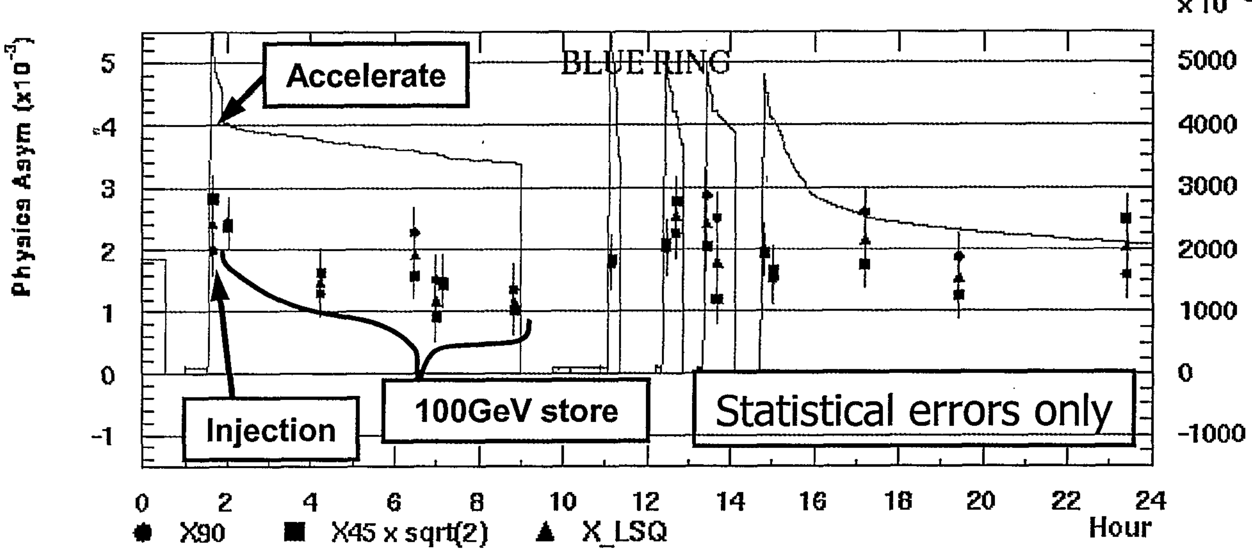
Beam currents [$\times 10^6$ ions]
About [illegible] in both rings

Integrated luminosity
PHENIX 0.18 [illegible]
STAR



Polarization History

- Measurements stable
- Polarization [illegible]%
- Systematic error ~25%
- Small (if at all) pol. loss during store



Summary

- Carbon recoil detection technique was established in AGS and RHIC for pC CNI polarimetry
- Precise absolute calibration will be done using pp CNI scattering with polarized gas jet target

Kazu Kurita

SPIN PHYSICS WITH THE FIRST POLARIZED PROTON COLLIDER, RHIC

Naohito Saito

SPIN PHYSICS WITH THE FIRST POLARIZED *pp* COLLIDER RHIC

Special Symposium of RHIC Spin Physics
April 30, 2002

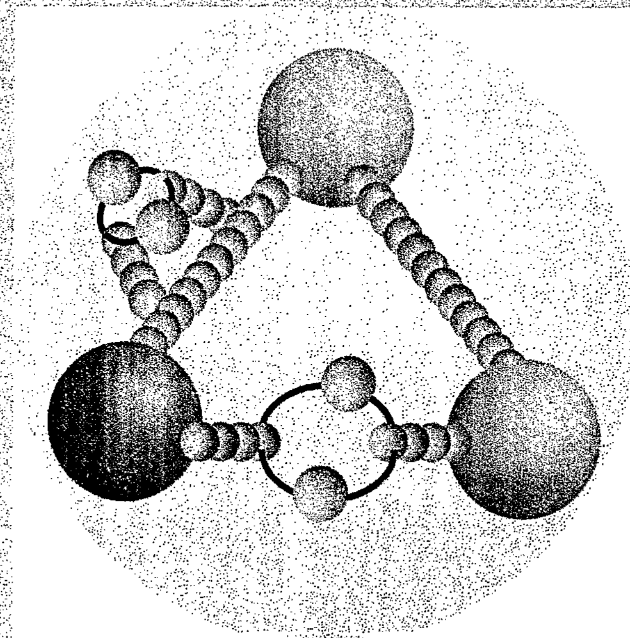
Naohito Saito

Kyoto University/ RIKEN / RBRC

Proton and its Properties

RHIC

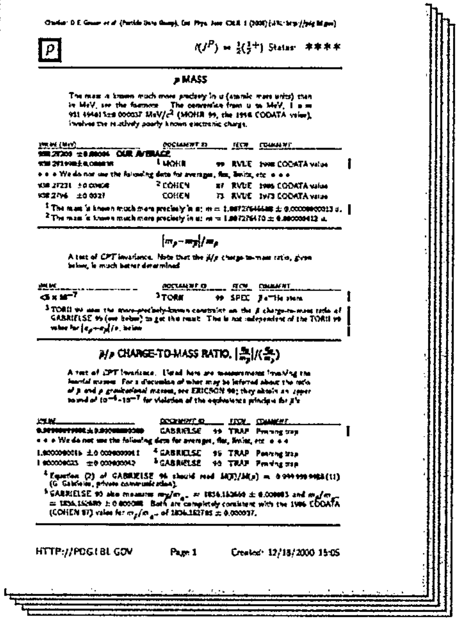
- Proton is the most fundamental building block of all matter as well as a complex mixture of quarks and gluons
  - *up* quark + *up* quark + *down* quark glued together with *gluon*, with infinite number of quark-anti-quark pairs
- Spin is one of the fundamental properties of the Proton



	proton	*up*	*down*	*gluon*	*sea-quark*	other contribution
Electric charge (e)	+1	+2/3 x 2	-1/3	0	0	none
Mass (MeV/c^2)	938.272	~5	~9	0	~170	dynamic contribution
Spin ($\hbar$)	1/2	~0.4	~-0.2	?	~-0.05	orbital motion

Why Spin Physics?

- "Spin" is a fundamental observable.


$J^P = \frac{1}{2}(\frac{1}{2}^+)$ Status: ****

p MASS

p/p̄ CHARGE-TO-MASS RATIO

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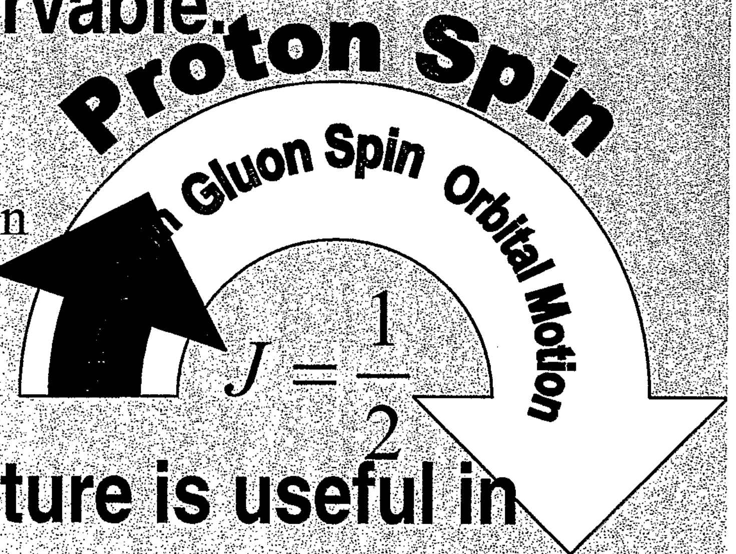
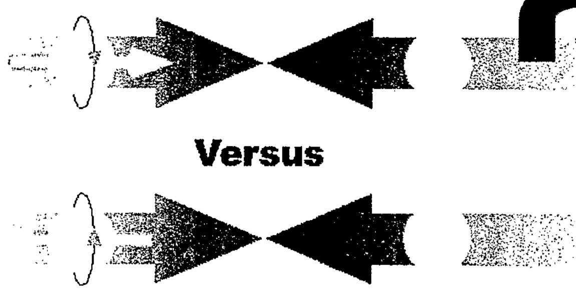
$$\Delta\Sigma = 0.1 \sim 0.3$$

Total fraction of the proton spin carried by the quark spin; Scheme dependent.



- *Axial vector* nature is useful in symmetry tests
  - Parity
  - Time Reversal

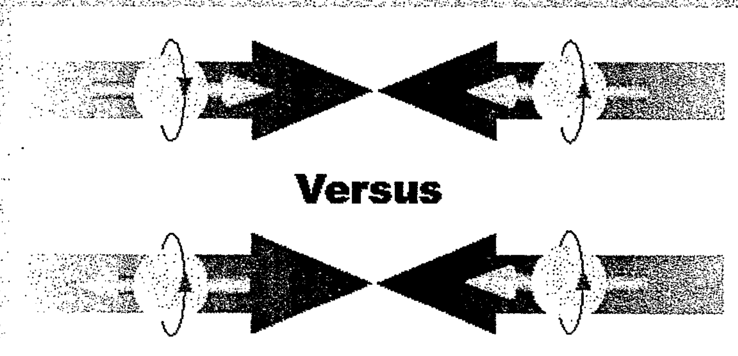


		$\mathcal{P}$	$\mathcal{T}$
position	x	$-x$	x
momentum	p	$-p$	$-p$
spin	σ	σ	$-\sigma$

Spin Physics at RHIC

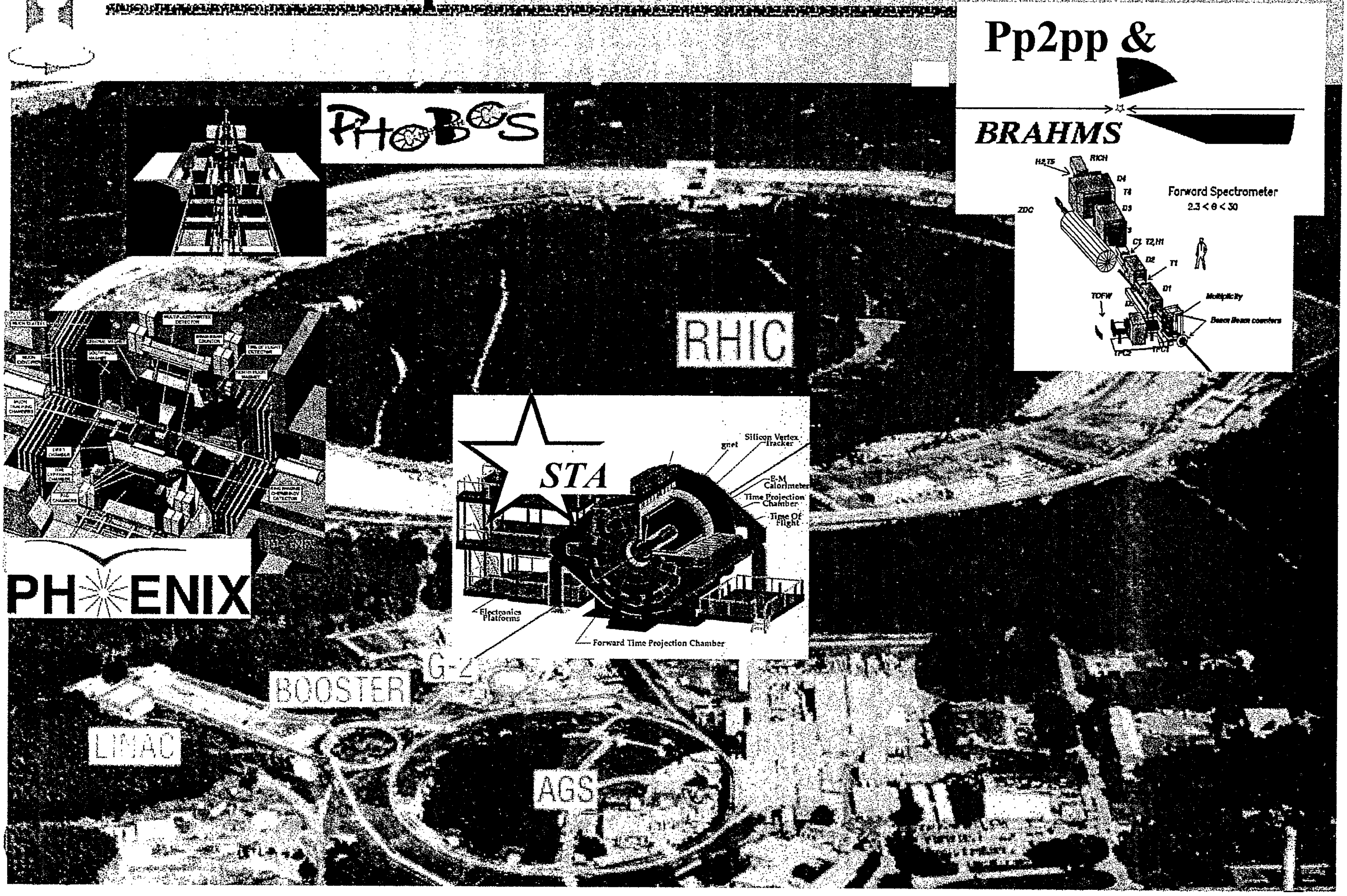
RHIC

Measure Spin Asymmetries in *pp* collision to pin down



- Spin Structure of the Nucleon
  - Proton Spin Sum Rule
  - Transversity Distributions
- Spin Dependence of Fundamental Interactions
  - Parity Violating Interaction
  - T Violation → CP Violation (CPT = 1)
- Spin Dependence of Fragmentation
  - e.g. Lambda fragmentation function
- Spin Dependence in *pp* elastic scattering

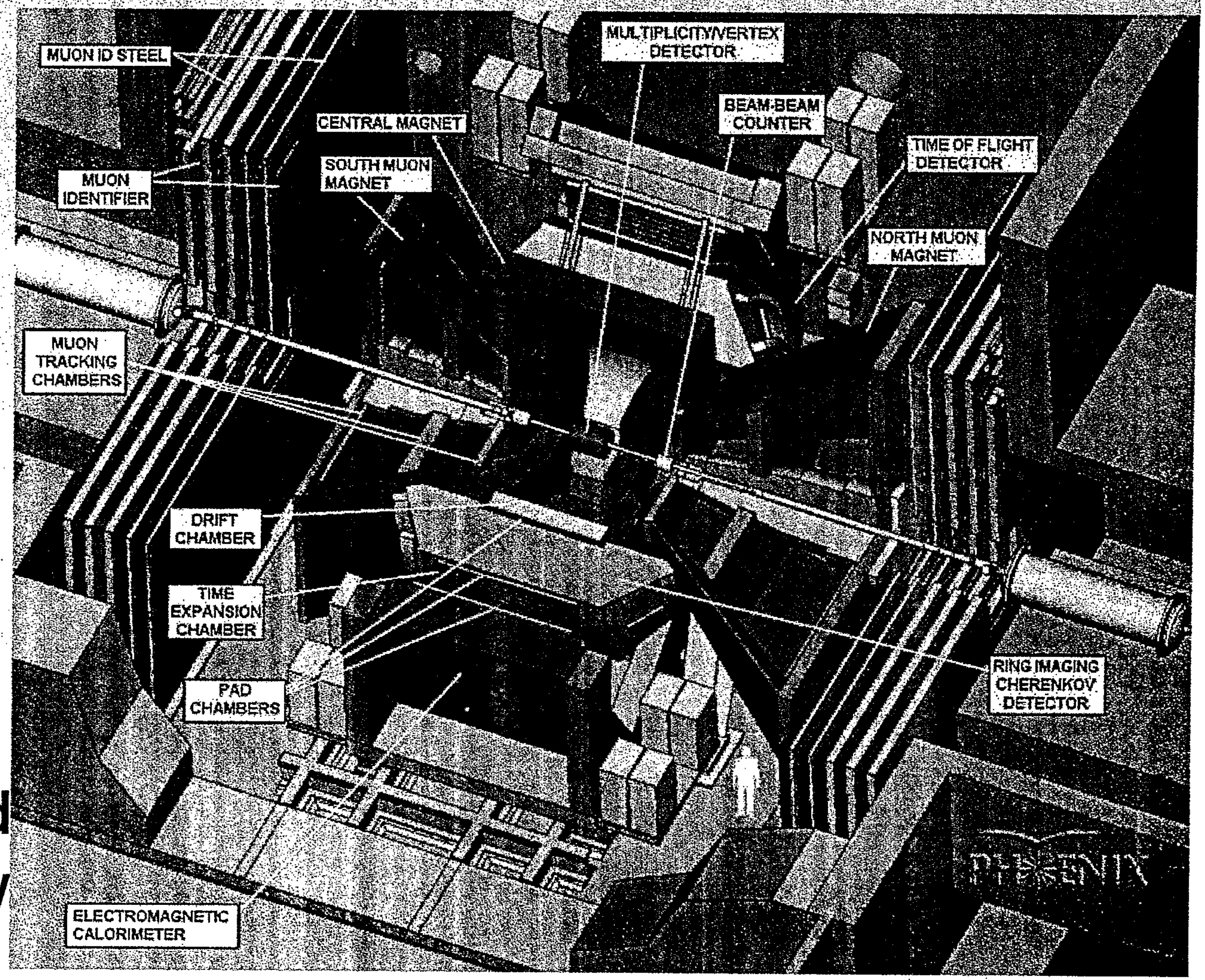
RHIC's Experiments



PHENIX Detector System

RHIC

- Inner Detectors:
  - BBC
  - MVD
  - NTC
- Central Arms
  - EMCal
  - Tracking
  - PID
    - RICH
    - TOF
- Muon Arms
  - South Completed
  - North to be ready for next run



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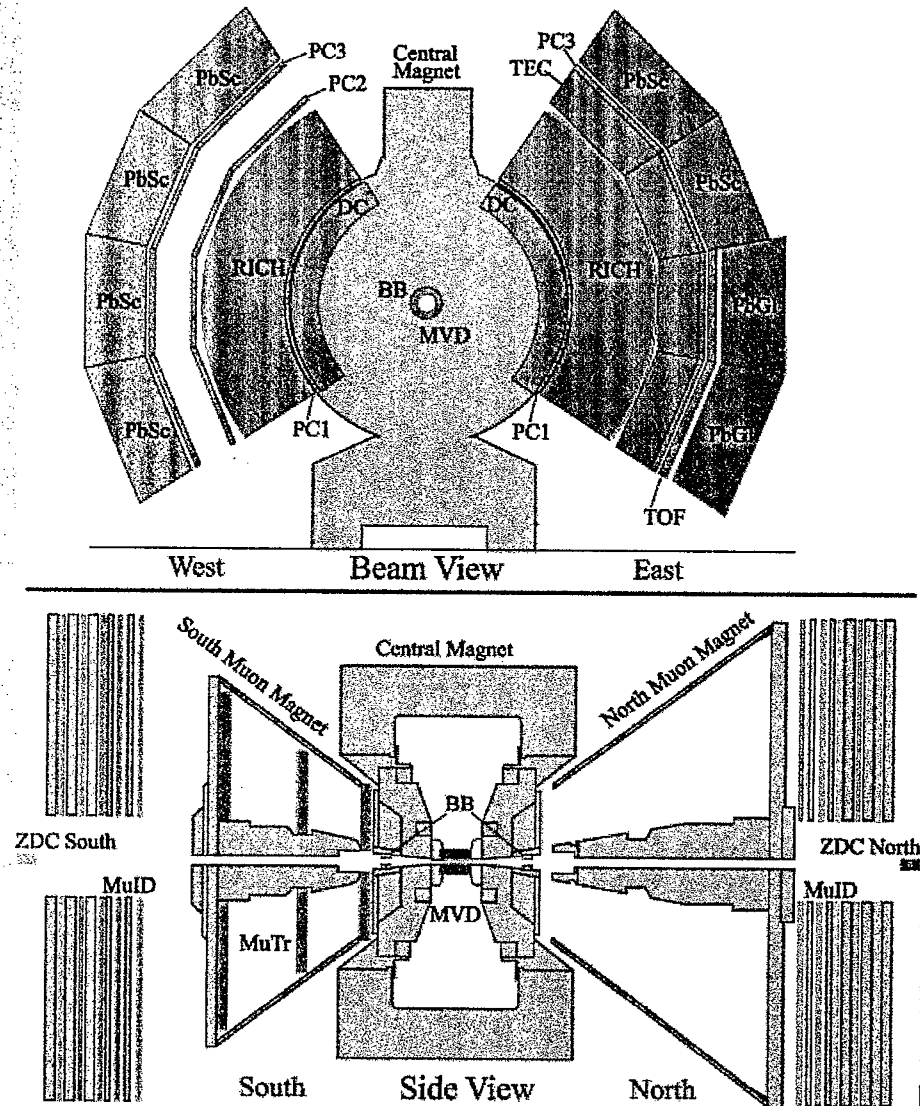
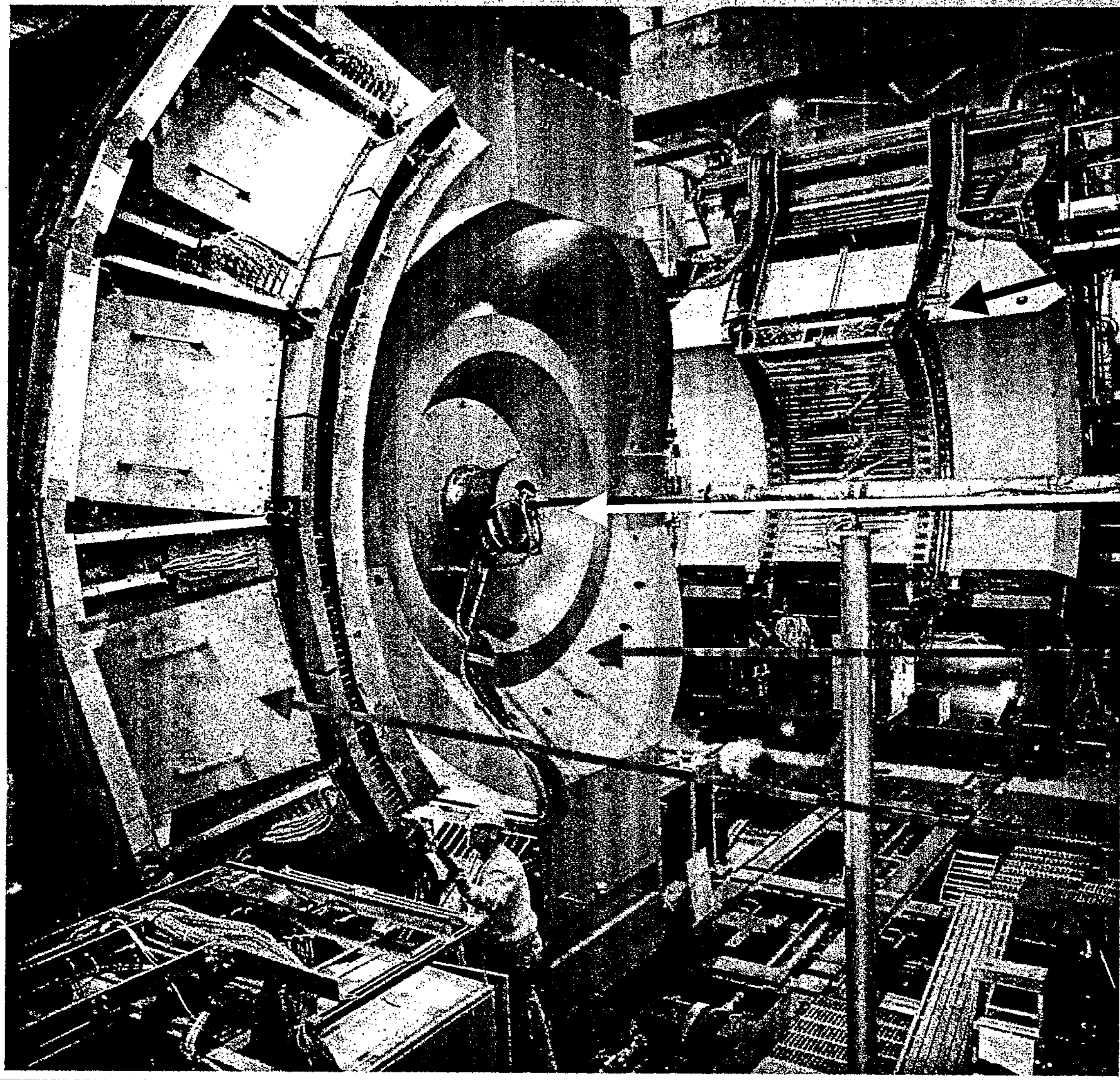
PHENIX Run2 Configuration

- Fully equipped Central Arms
  - EMCal
  - Trk Chambers
  - RICH
- Newly installed Muon Arm
  - Muon Tracker
  - Muon Identifier
- New Counter
  - NTC
- EMC-RICH Trigger

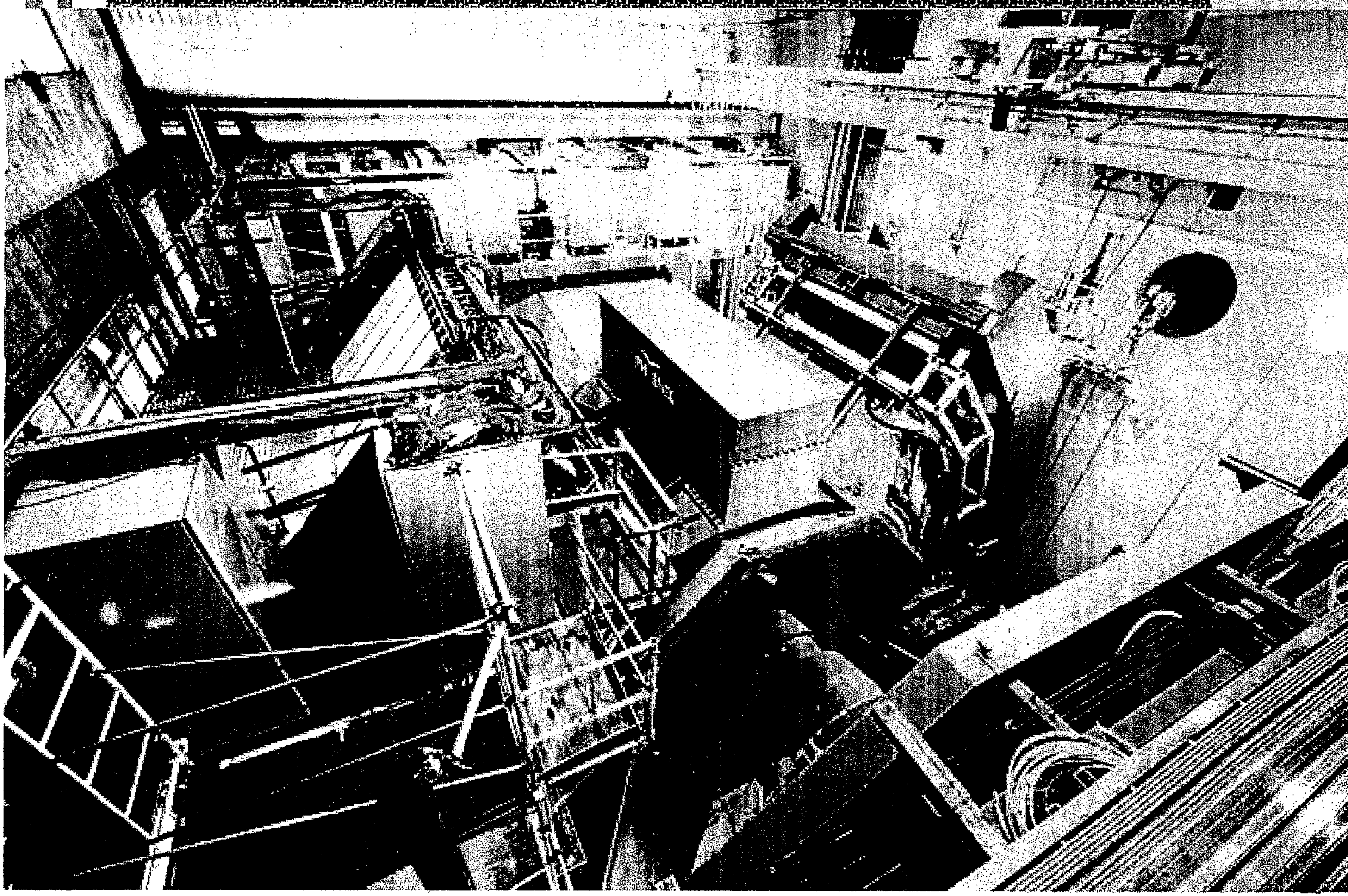


PHENIX Central Spectrometer

RHIC



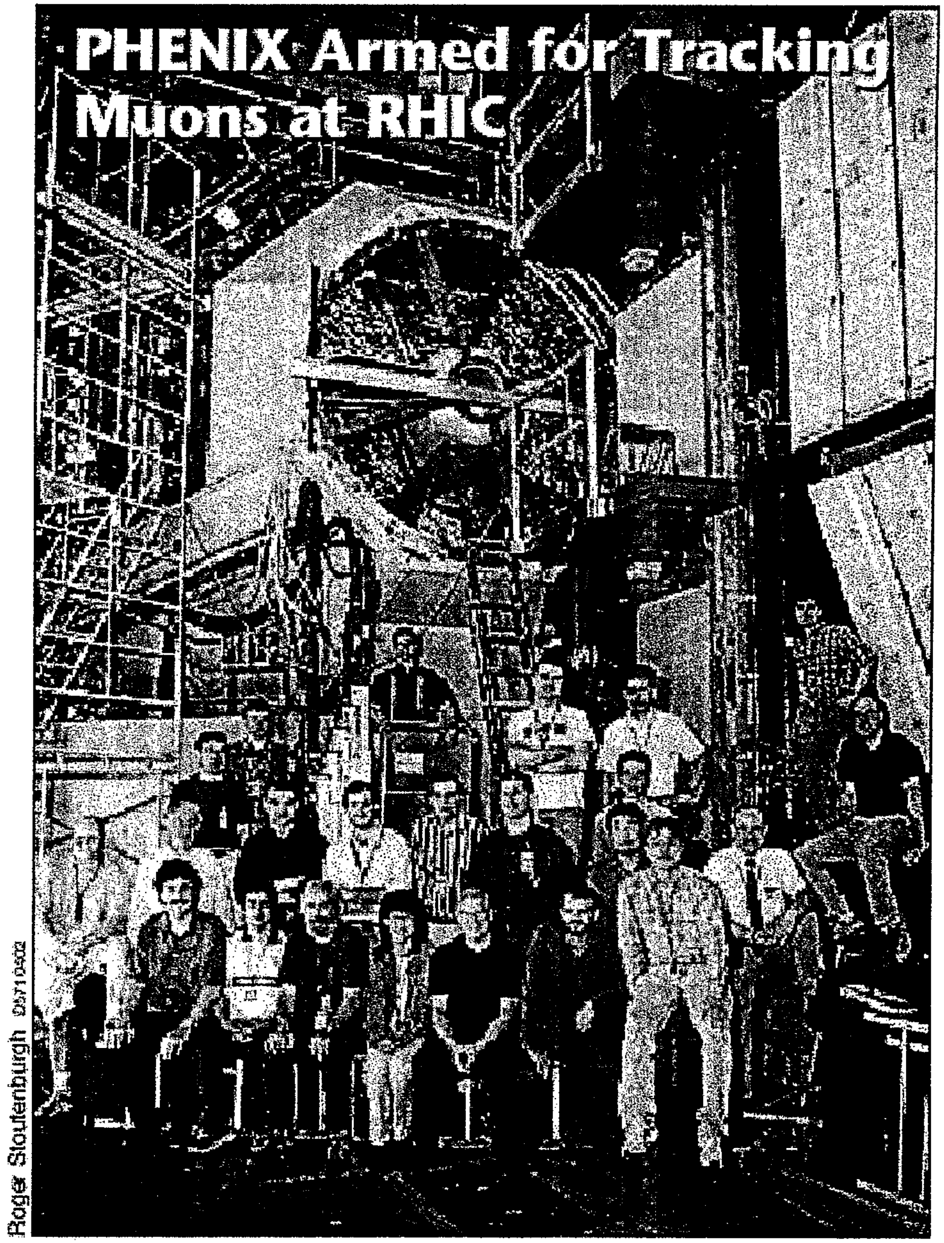
PHENIX Run-2 Installation



PHENIX Muon Arms

RHIC

- South Muon Arm Completed and Commissioned in Run-2
- North Muon Arm is to be completed for Run-3
- Muon Arms are Crucial for both HI and Spin Physics
  - J/ψ production
  - W production



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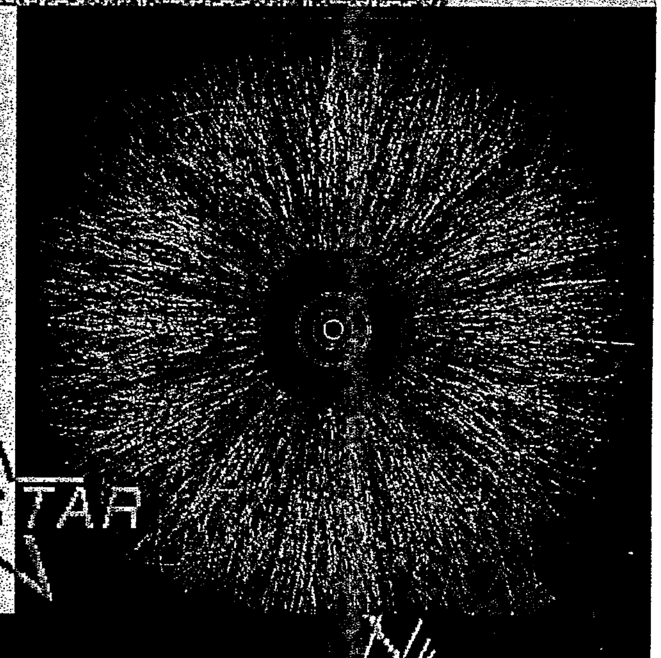
RHIC Achievements

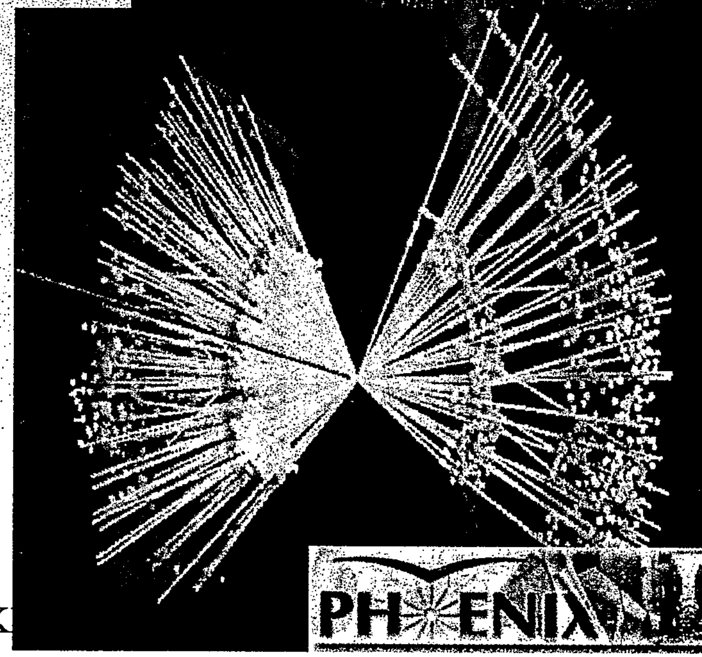
Run-1

- First Collision of Gold beams at 56 and 130 GeV/A last year
- 10% of Designed Luminosity achieved
- Successful Physics Run
- Successful Spin Commissioning!



Run-2

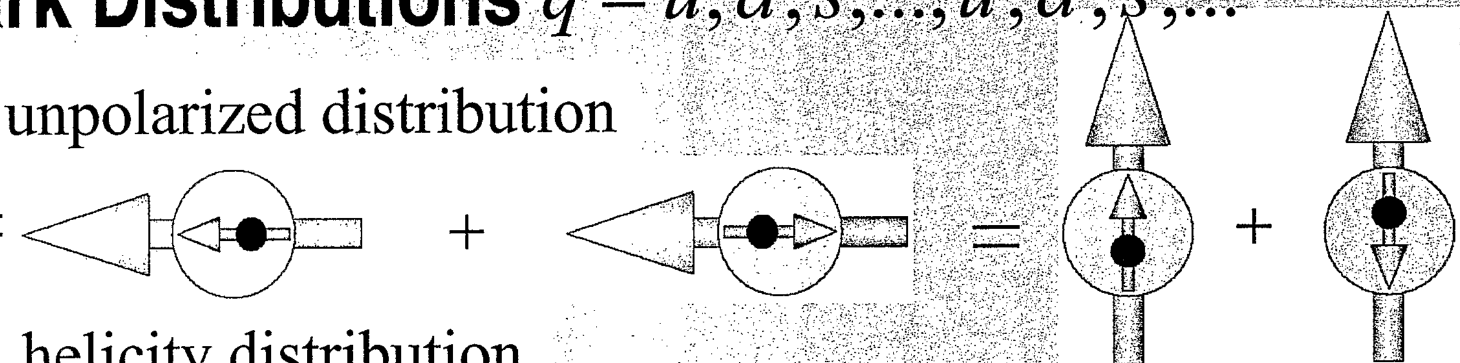
- First Collision of Gold beams at 200 GeV/A !!!
  - 42 μb^{-1} delivered & 24 μb^{-1} recorded
  - 170 M events processed
- First Collision of Polarized Proton Beams at 200 GeV!!!
  - 3.7 G events processed
  - 0.15 pb^{-1} recorded



Quark and Gluon Distributions

Quark Distributions $q = u, d, s, \ldots, \bar{u}, \bar{d}, \bar{s}, \ldots$

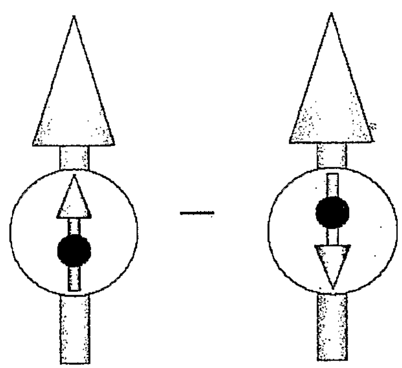
unpolarized distribution

$q(x,Q^2) =$ 

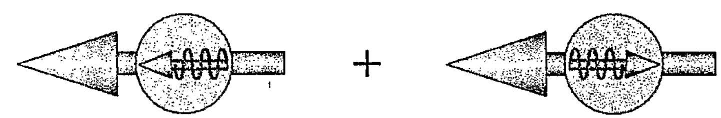
helicity distribution

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

transversity distribution

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

Gluon Distributions

$g(x,Q^2) =$ 

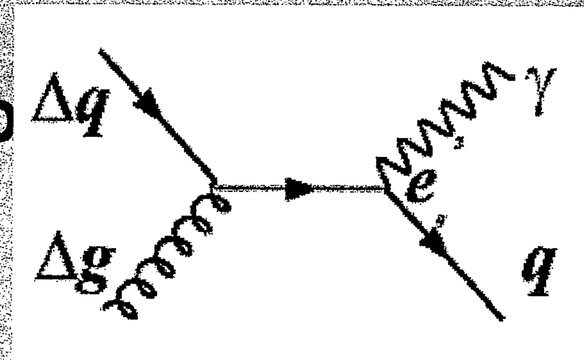
$\Delta g(x,Q^2) =$ 

No Transverse Gluon Distribution

Prompt Photon Production

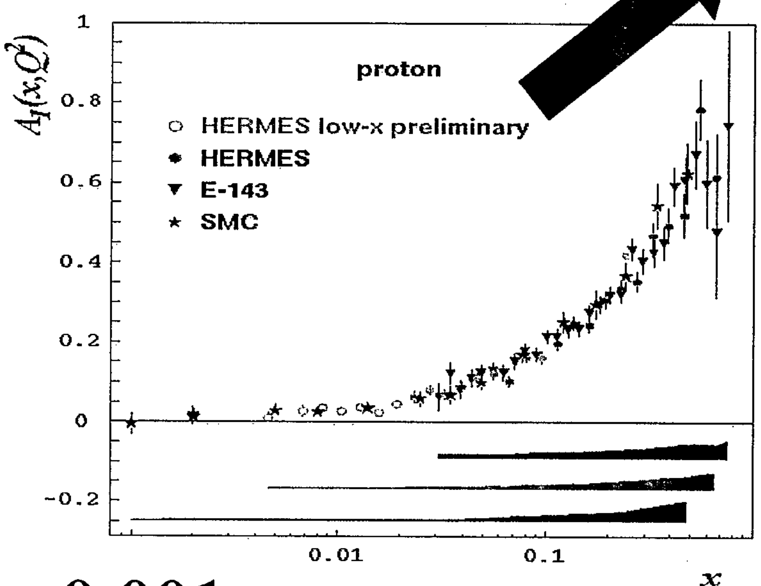
Gluon Compton Dominates

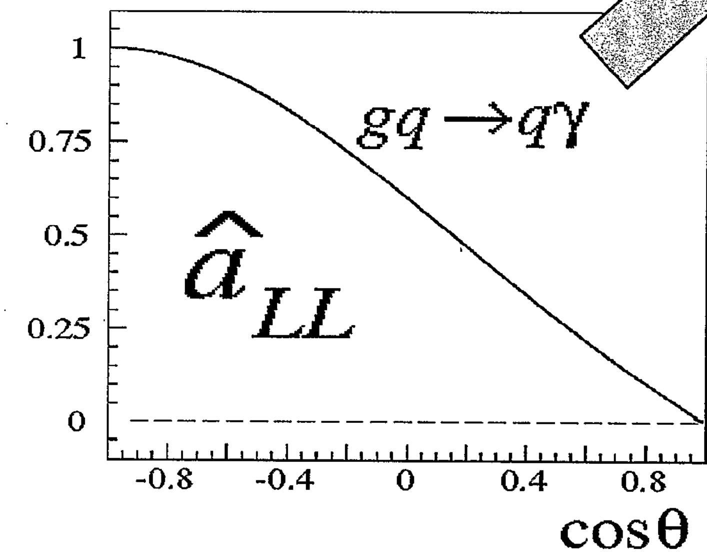
- Small Contamination from Annihilatio[n]
- No fragmentation contribution in LO



Versus

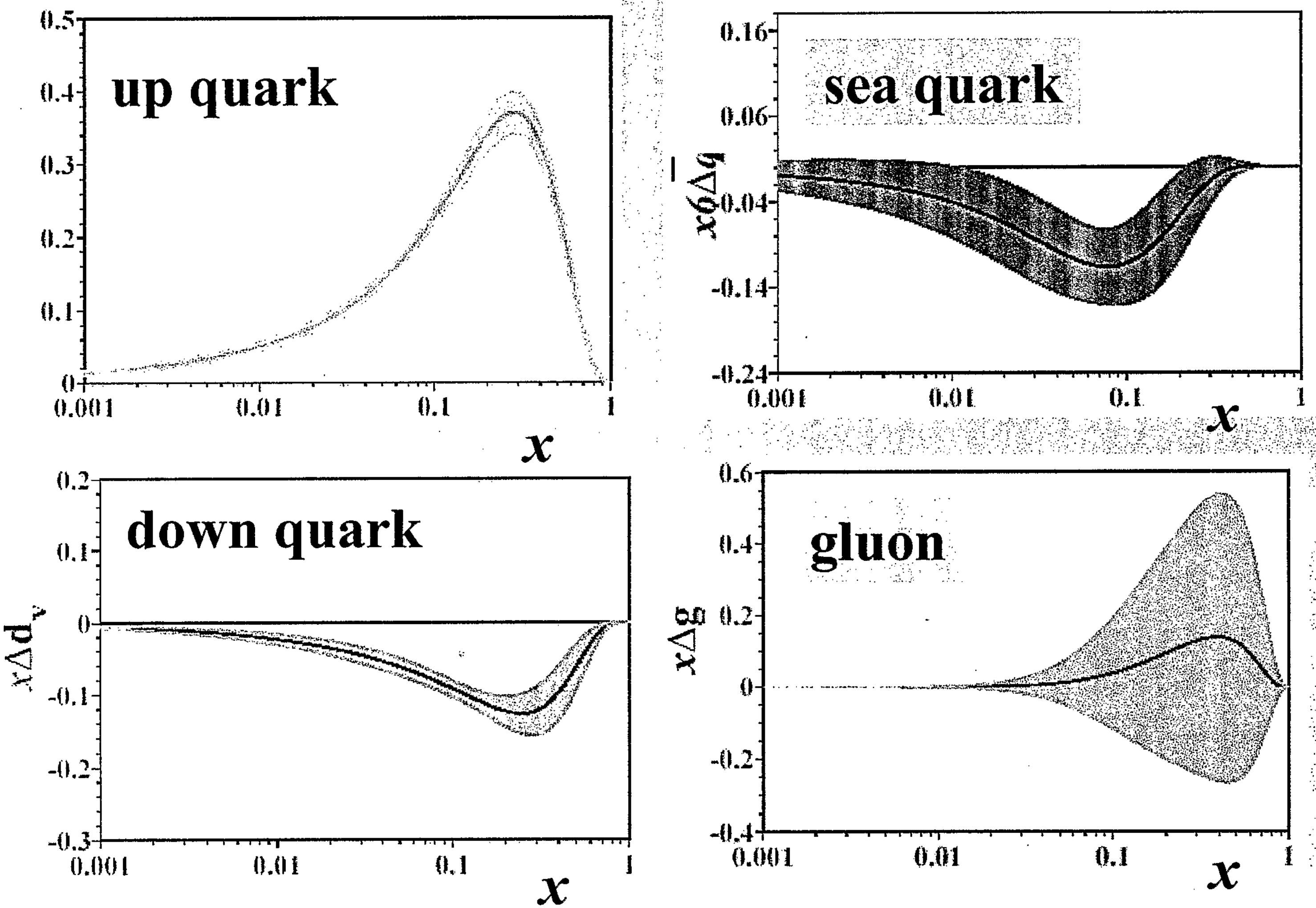
$$A_{LL} = \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\sum_i e_i^2 \Delta q_i(x_2)}{\sum_i e_i^2 q_i(x_2)} \otimes a_{LL}(gq \to q\gamma)$$





Polarized Quark and Gluon Distributions

- Detailed analysis of lepton scattering experiments revealed...



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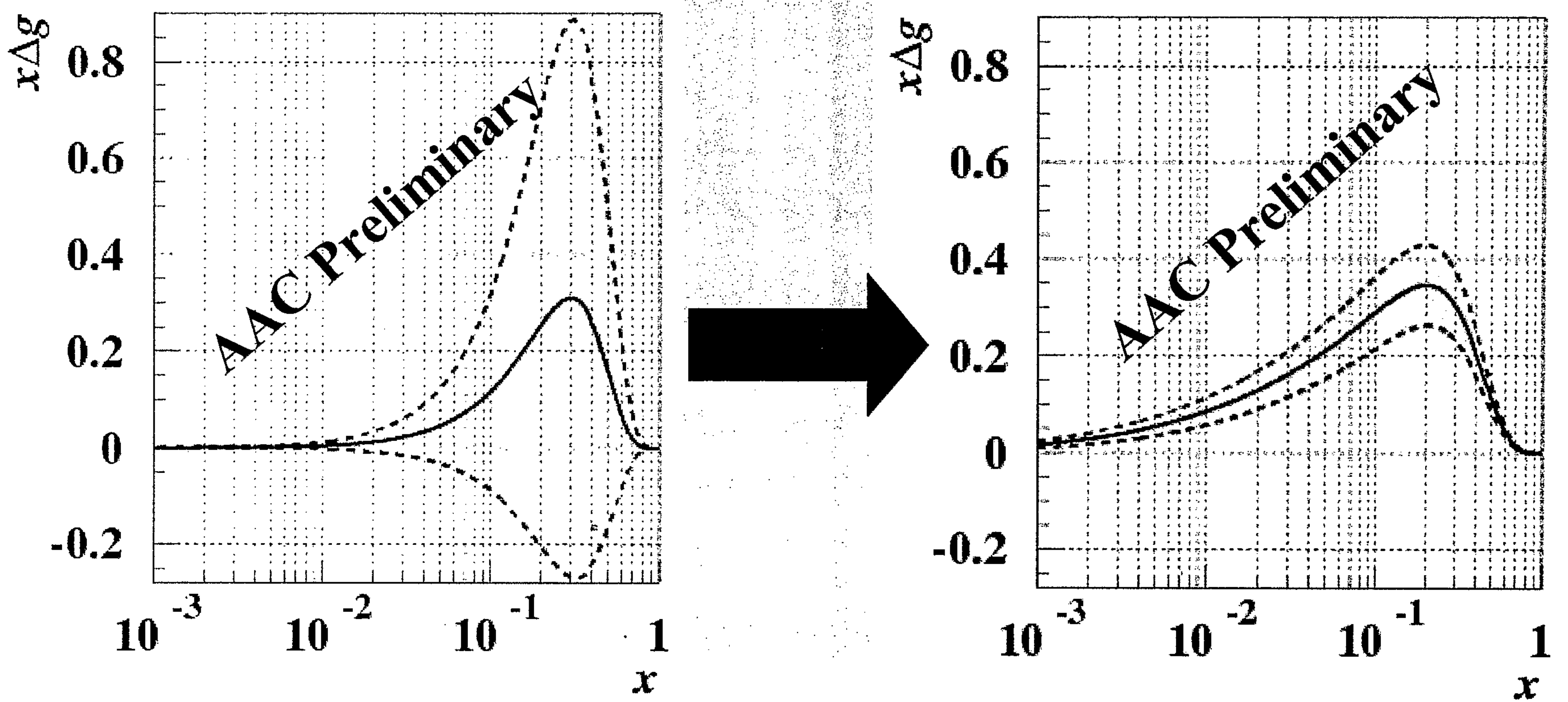
Impact of RHIC Spin Δg Measurement

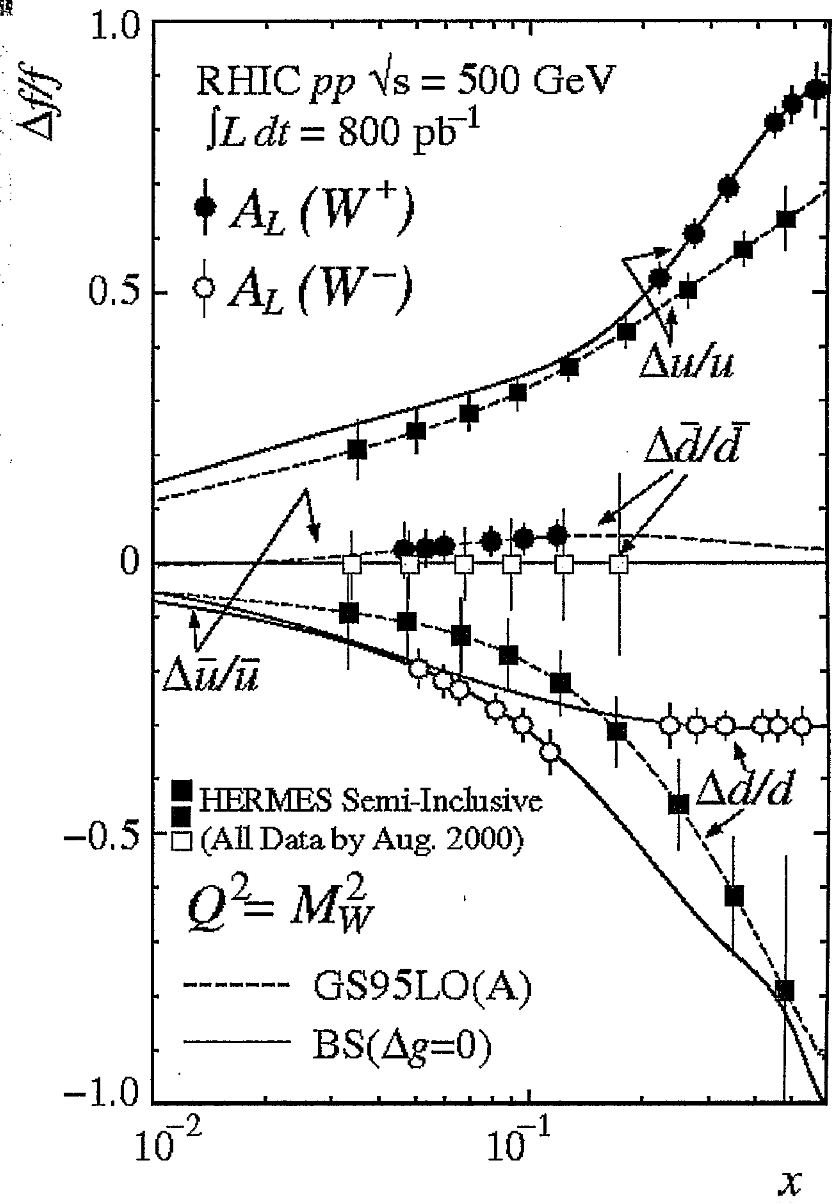
- If we include PHENIX Prompt Photon Data in Global QCD Analysis…



M. Hirai *et al.*

Sea-quark measurement with W

- W production is the best tool to pin down spin-flavor structure of the nucleon
  - V-A process fixes spin of quarks
  - Charged current ~flavor
- Comparison with DESY-HERMES; Semi-inclusive DIS
  - W has no fragmentation ambiguity



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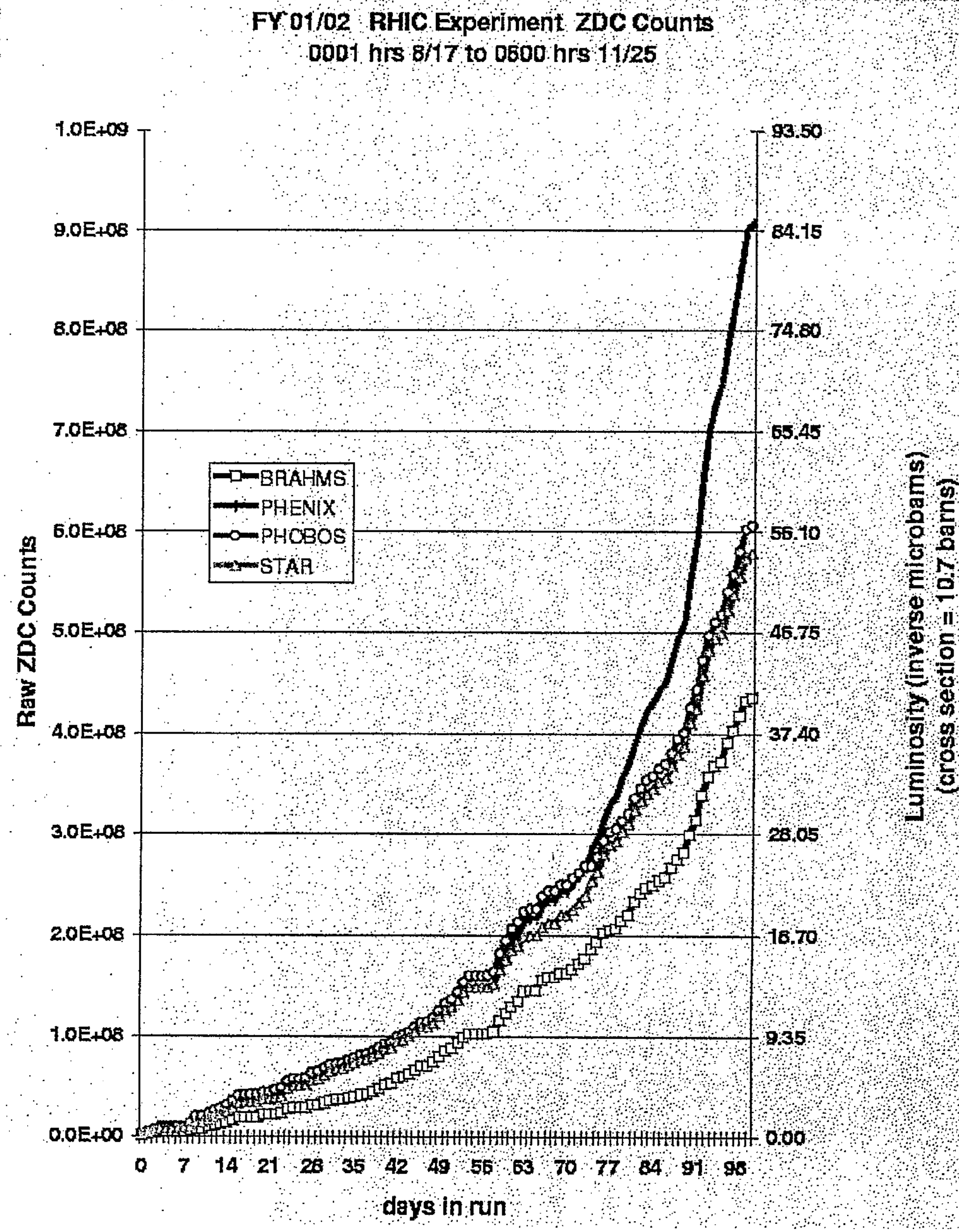
RHIC Au-Au Luminosity

- Last Two weeks were most productive
- PHENIX has received 42 μb^{-1} within useful vertex region and 24 μb^{-1} has been recorded



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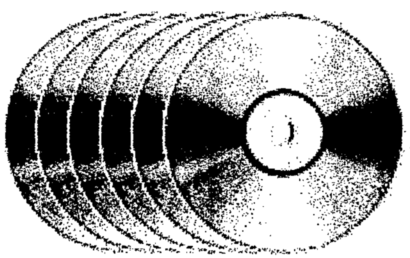
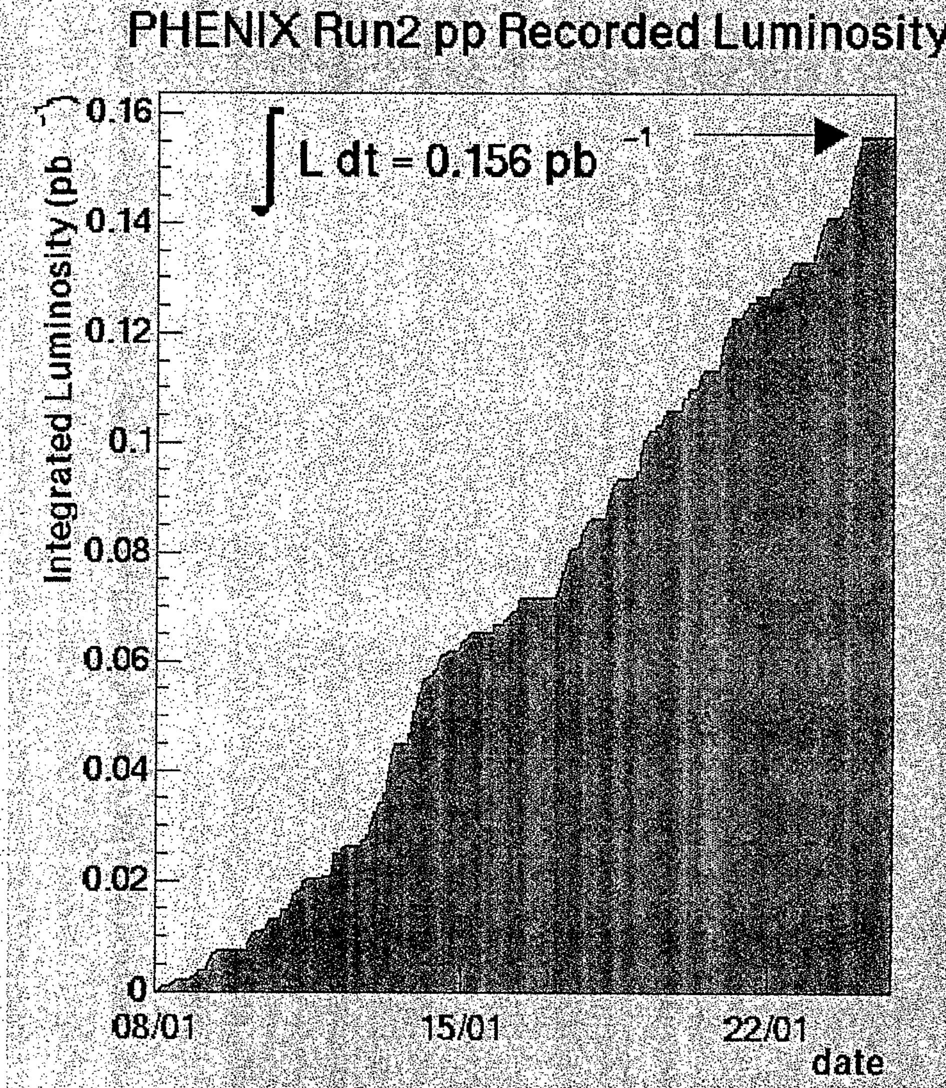
PHENIX Run2 pp

- Delivered peak luminosity at PHENIX
  ~ $1 \times 10^{30} cm^{-2} s^{-1}$

- Data Band Width
  ~ 60 MB/s = 6 CD's/min





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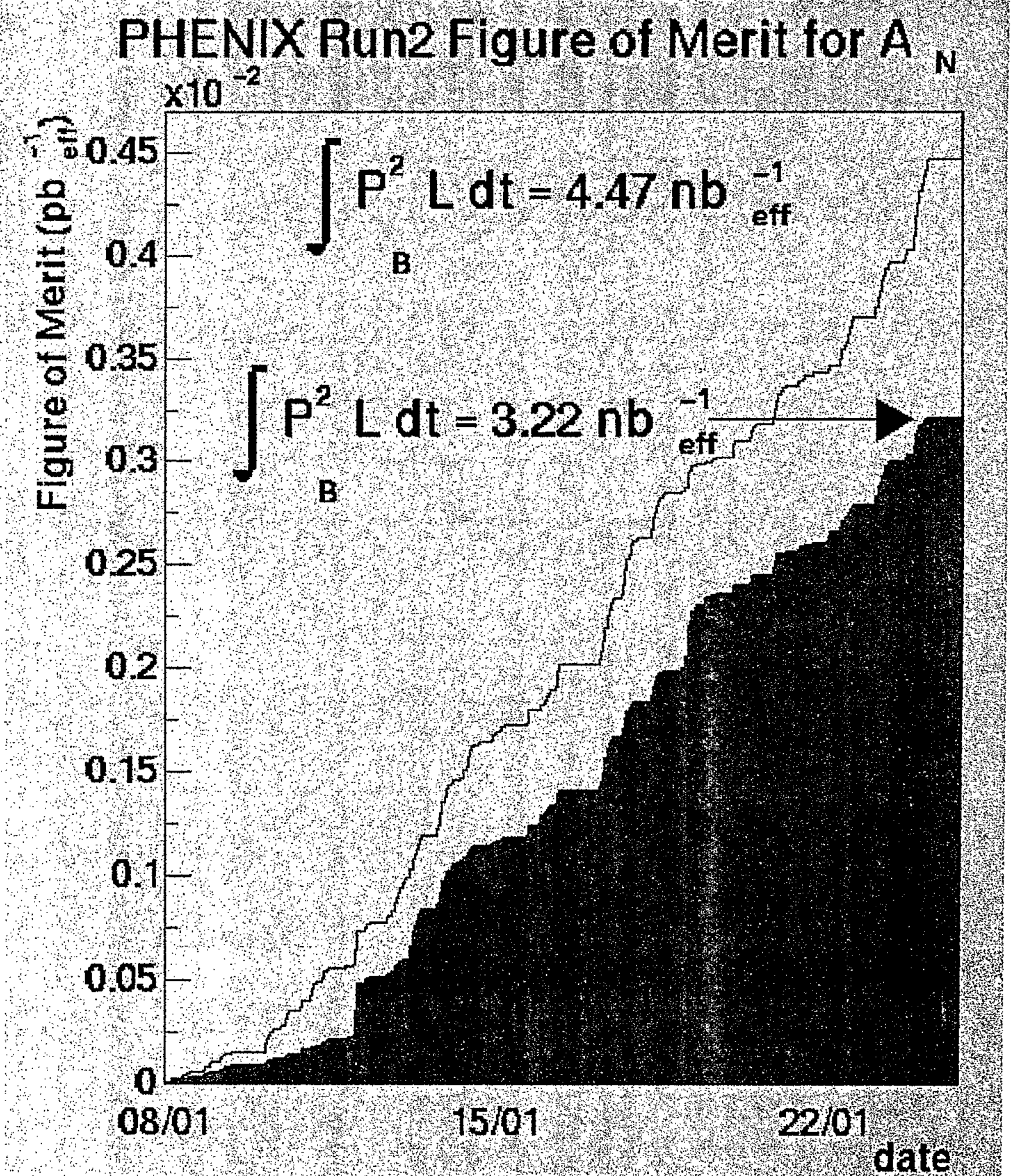
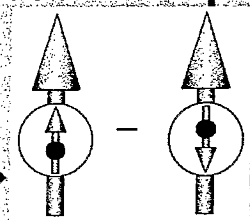
PHENIX Run 2 Spin

- Beam Polarized Transversely
- Yellow > Blue
  - $\langle P_{yellow} \rangle = 17\%$
  - $\langle P_{blue} \rangle = 14\%$
    - Assumption: Analyzing Power is E-indep.
- Enough Statistics for first A_N physics

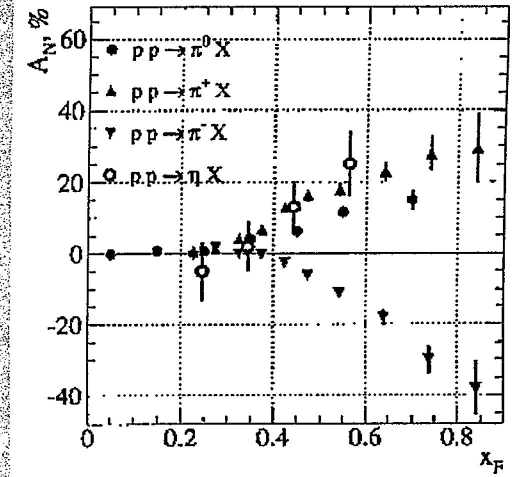


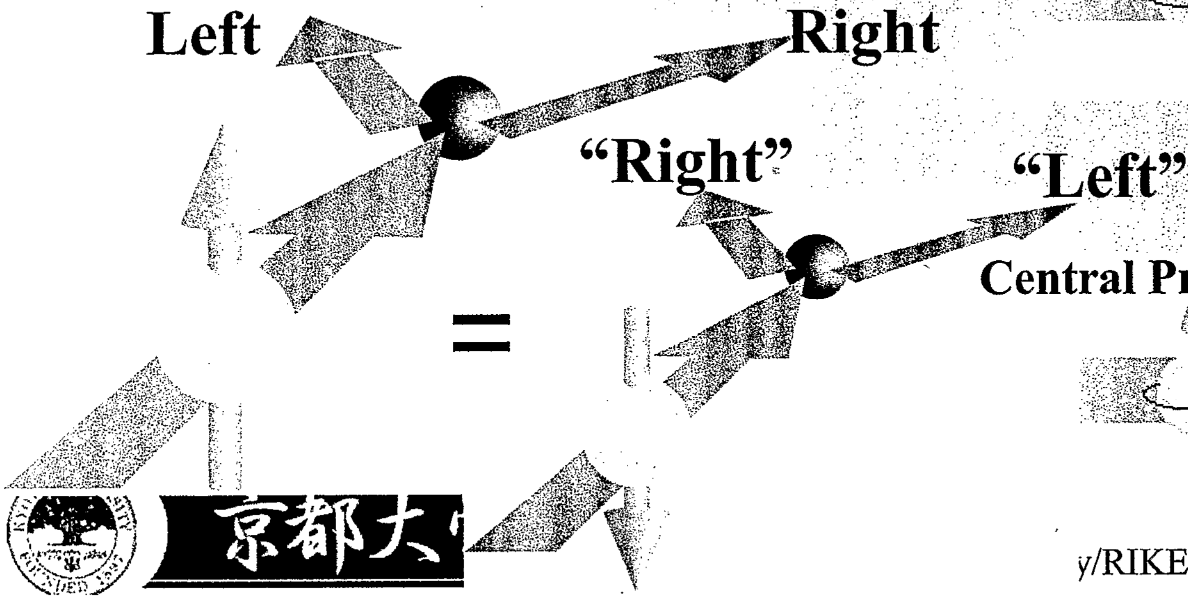
Single Transverse Spin Asymmetry A_N

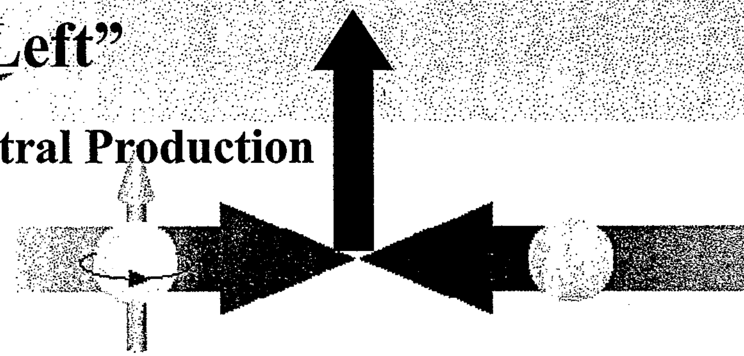
- Large LEFT-RIGHT asymmetries have been observed up to maximum energies available
- Possible origins are:
  - Transverse spin dependence in initial state →



  - Transverse spin dependence in final state → Collins-Heppelman Effect
- However always suppressed by p_T^{-1} according to pQCD : Higher-twist Effect
  - Hi p_T data is crucial in understanding this effect







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y/RIKEN/ RBRC)

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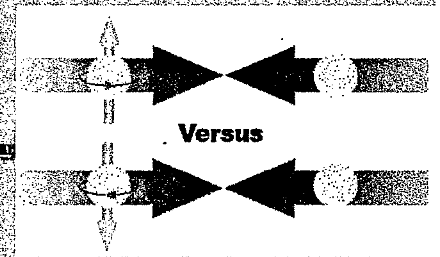
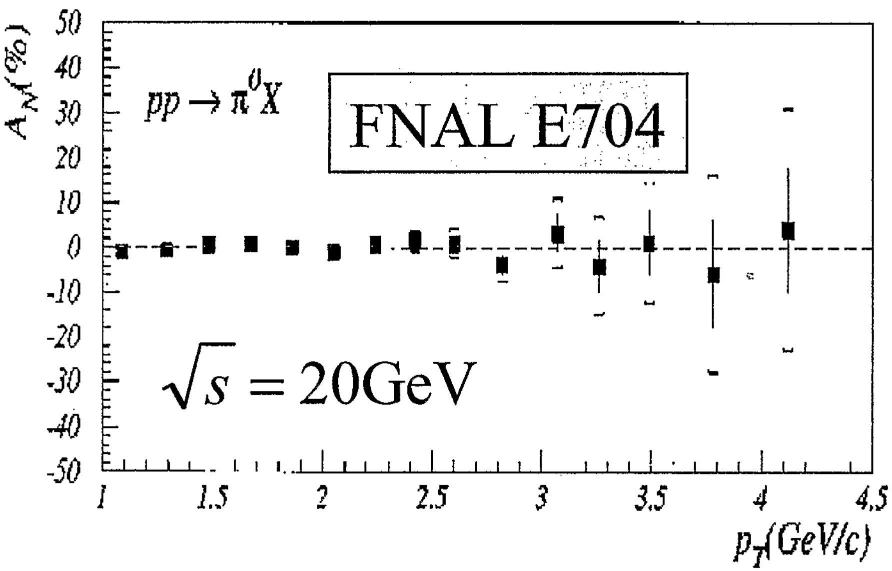
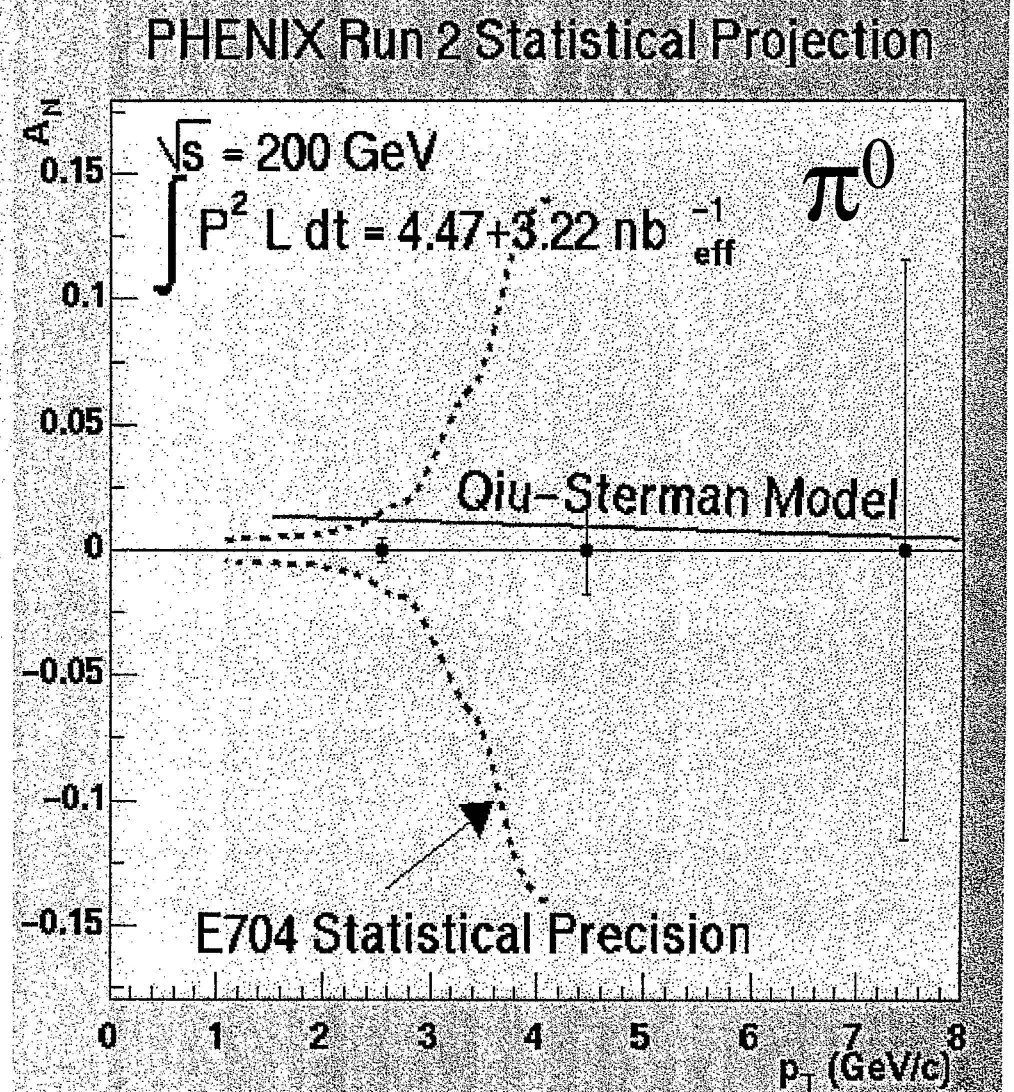
PHENIX Run-2 Projection For $A_N(\pi^0)$



- Will Reach Highest p_T
- Statistical Significance = E704 x 10 !!
- Complementary to STAR Measurement at Forward region





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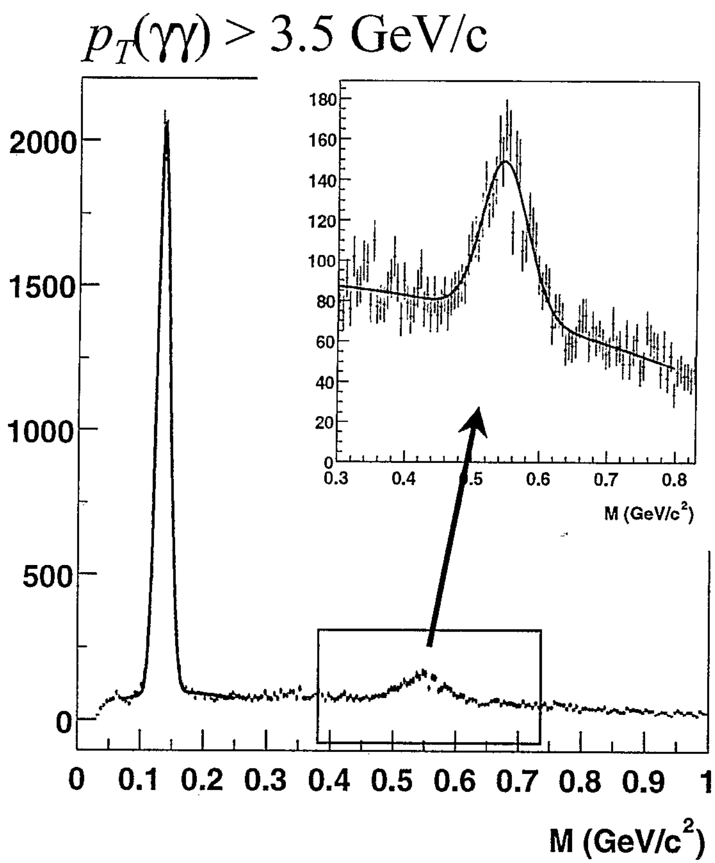
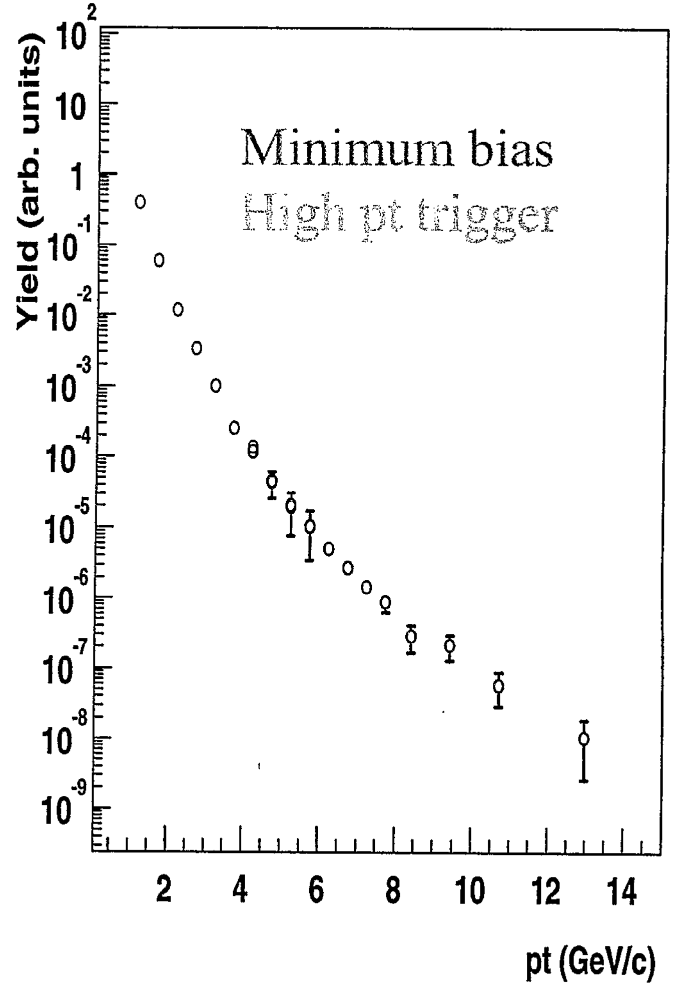
PHENIX EMCal Performance in Run-2

RHIC

- Excellent γ reconstruction!
  - Both π^0 and η are clearly seen
  - Statistics extend to > 10 GeV/*c*





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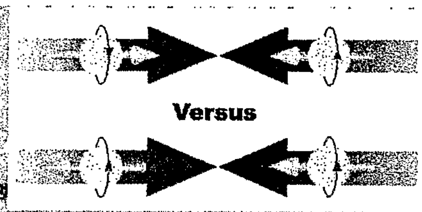
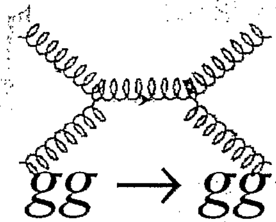
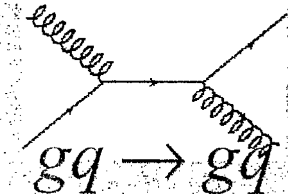
PHENIX Spin Goal for Next Run



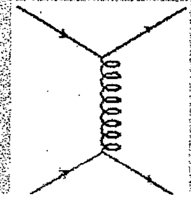
- Hi Statistics Pion Data! Sensitive to $\Delta g(x)$!



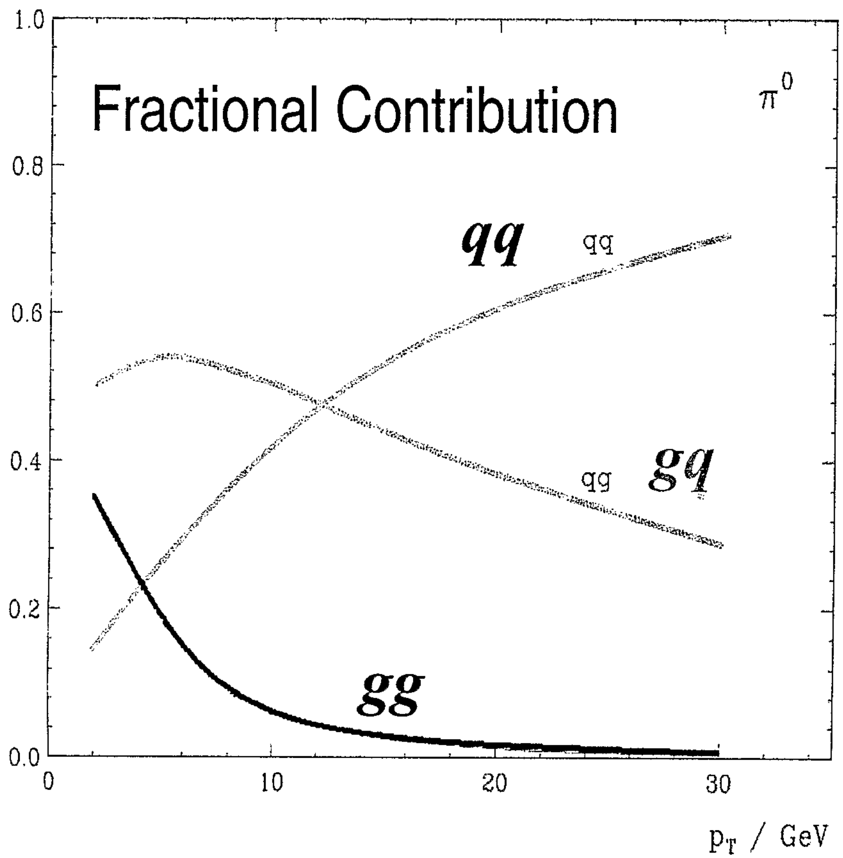
$gg \rightarrow gg \quad \propto \frac{\Delta G}{G}\frac{\Delta G}{G}$

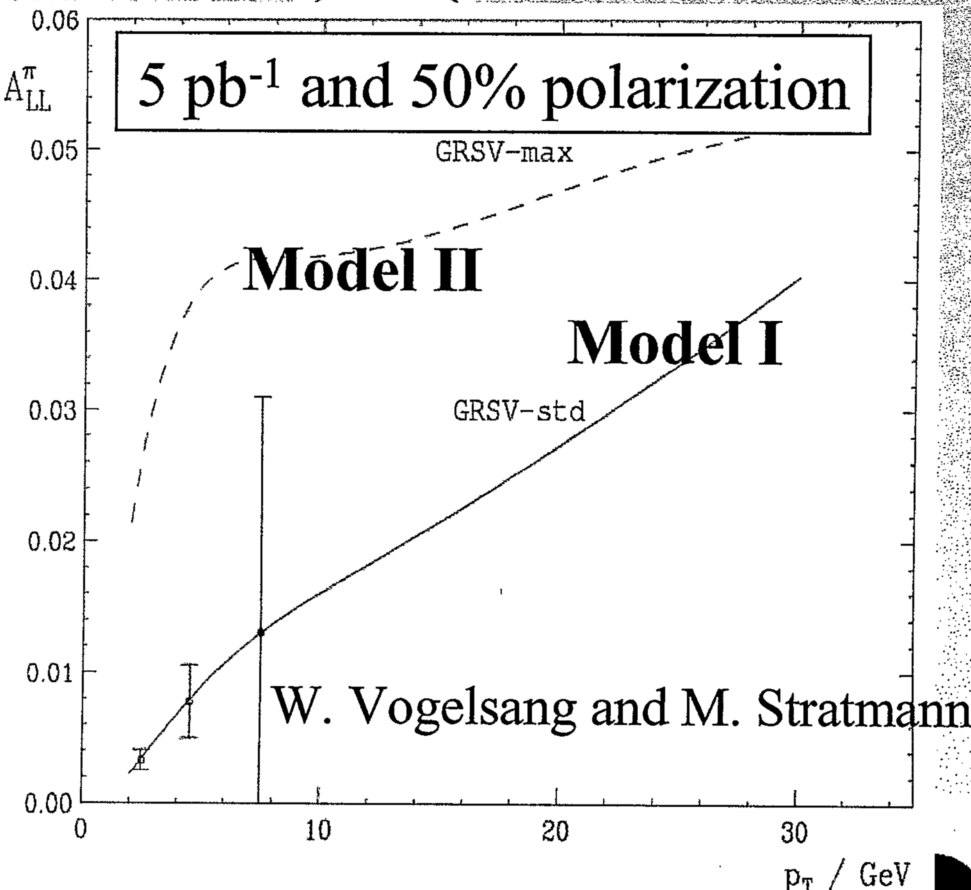


$gq \rightarrow gq \quad \propto \frac{\Delta q}{q}\frac{\Delta G}{G}$



$\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$





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RHIC Spin Plan (under discussion)

Year	CM Energy	Weeks	Int. Lum.	Remarks
2002	200 GeV	5	7 pb^{-1}	Gluon pol. with pions / TT*
2003	200 GeV	8	160 pb^{-1}	Gluon pol. with direct γ , jets/ TT
	500 GeV	2	90 pb^{-1}	PV W production, u-quark pol.
2004	200 GeV	8	160 pb^{-1}	Gluon pol. with γ + jet/ TT
	500 GeV	2	120 pb^{-1}	First ubar,dbar pol. meas..
2005	500 GeV	8	480 pb^{-1}	Gluon pol. with γ+jet, γ,jet+jet, heavy flavor, ubar, dbar pol.
	200 GeV	2	48 pb^{-1}	Gluon pol. with γ, γ+jet, heavy flavor/TT
2006	500 GeV	5	300 pb^{-1}	More statistics
	200 GeV	5	120 pb^{-1}	
2007	200 GeV	10	210 pb^{-1}	

*** TT Transverse Spin Physics**

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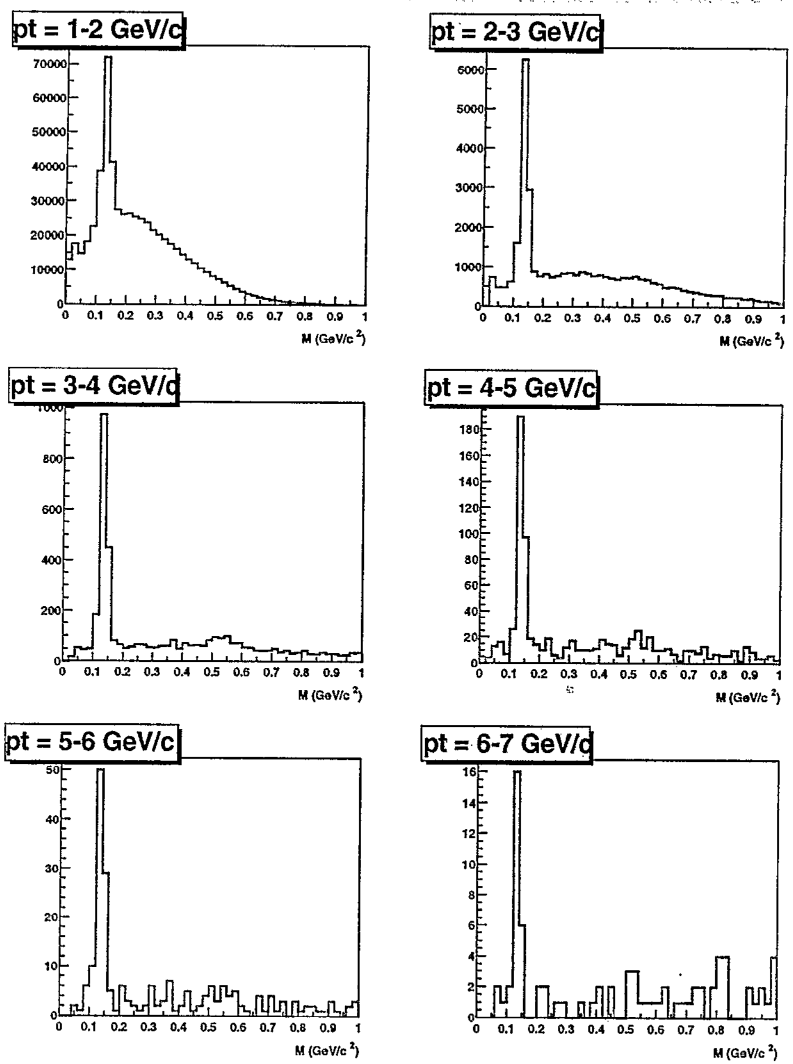
Summary

- First Spin Physics Run was SUCCESSFUL
  - Many accomplishments by C-AD, STAR, and PHENIX
- Polarization at AGS has to be improved!!
- More excitements are coming!

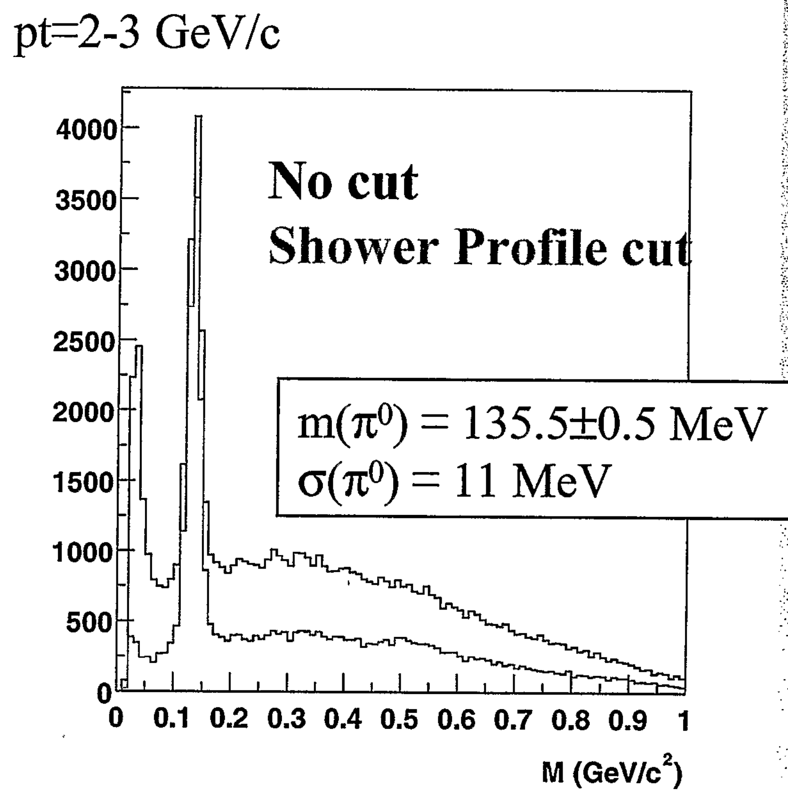
- Thanks:
  - Strong Supports from US-DOE, NSF and MEXT-Japan
  - Superb Supporting Staff at BNL and RIKEN
  - Keen Senior Scientists: Dr. Arima, Prof. Lee, Dr. Samios, Dr. Ozaki, and Prof. Masaike
  - Hard-working Young and Semi-young Colleague
  - My special personal thanks:
    - Bob, Gerry and Ishihara-san

EMC Performance

Semi-Offline Analysis of EMC



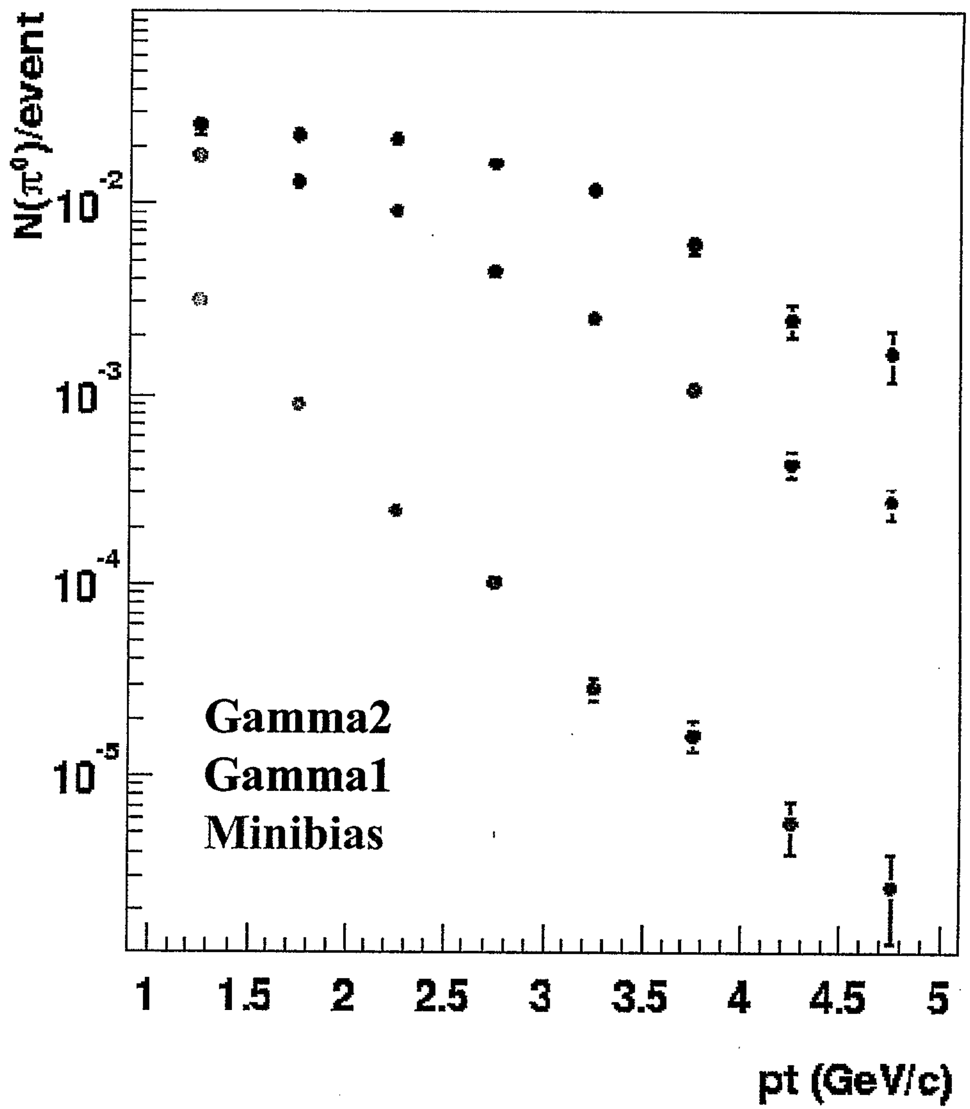
By Alexander Bazilevsky



EMC Trigger Performance

RHIC

- Our brand new trigger system just work fine!!!
- Hi-p_T sample enhanced by factor 20-200!
- Trigger team led by Matthias Perdekamp



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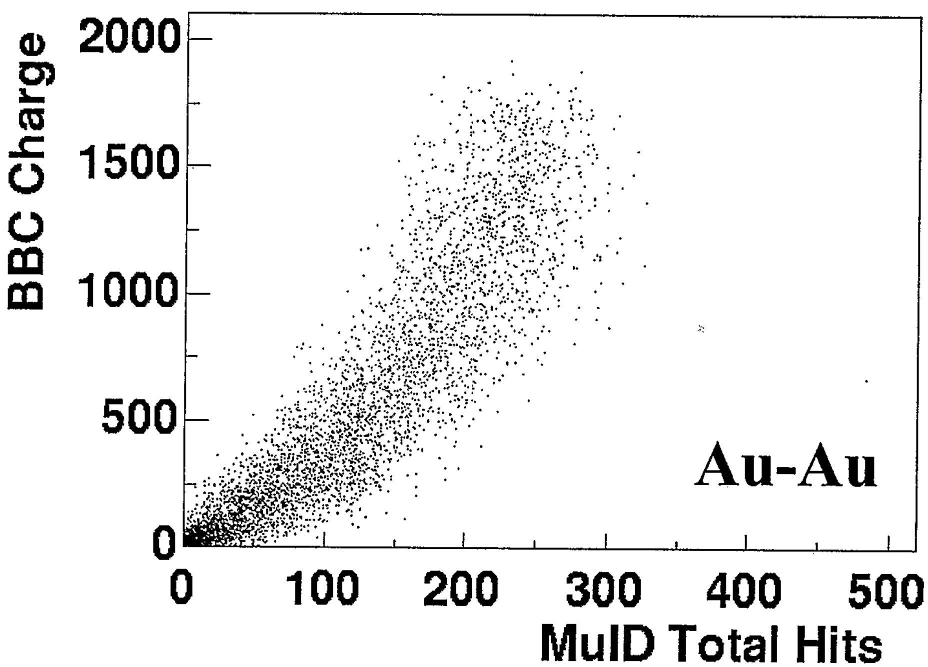
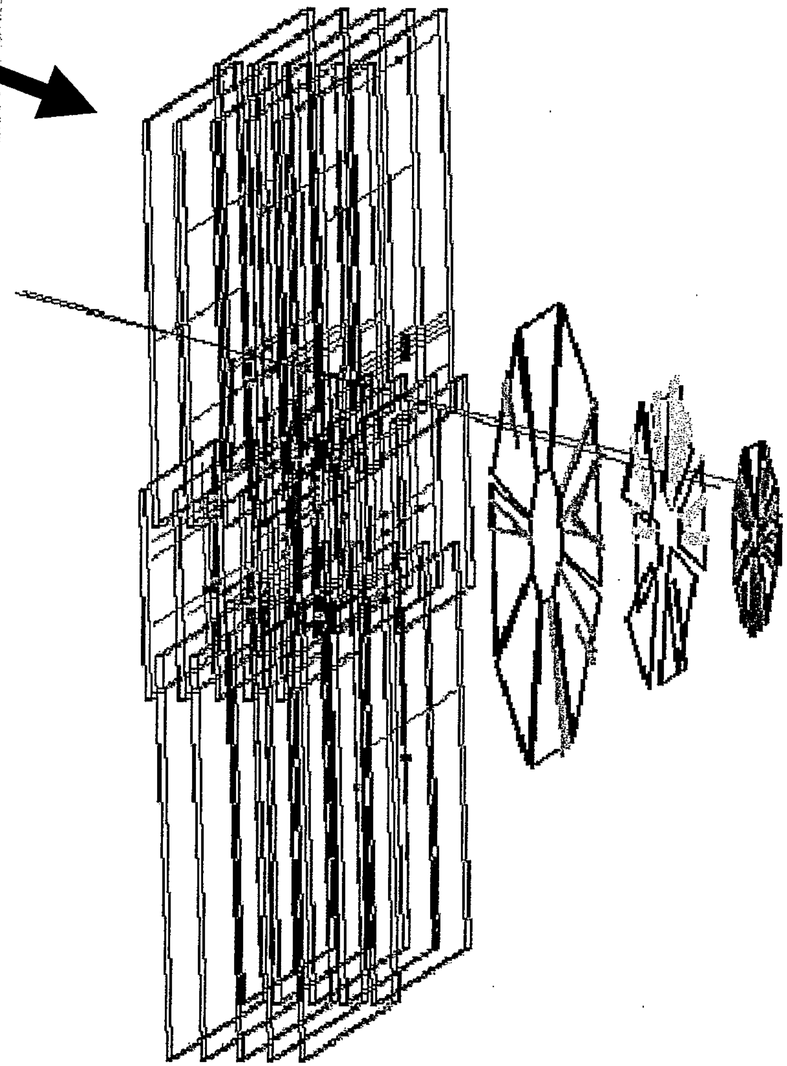
Muon Arm Performance

- Muon Track Candidate
- MuID Hits Correlated with BBC





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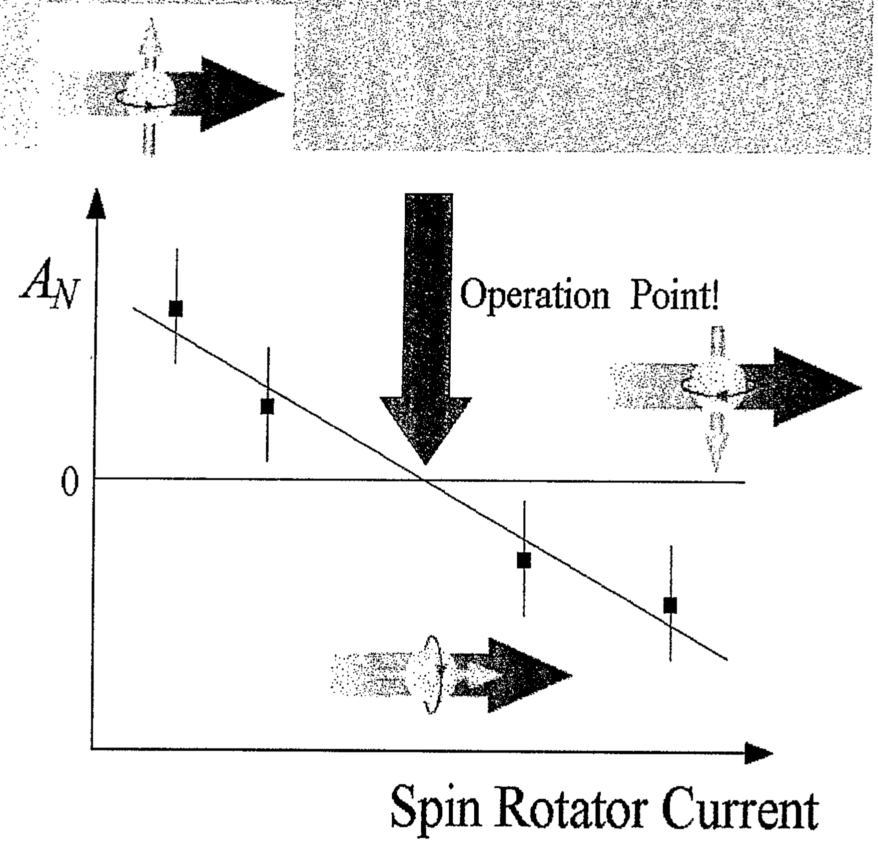
Motivation of Local Polarimeter

Confirm Spin Dynamics in RHIC Ring

- Especially for the operation with ***SPIN ROTATORS***
  - Spin Dynamics between Spin Rotators is completely transparent to the rest of accelerator "by design"
- Very important to be ready for Run3, where we use Spin Rotators



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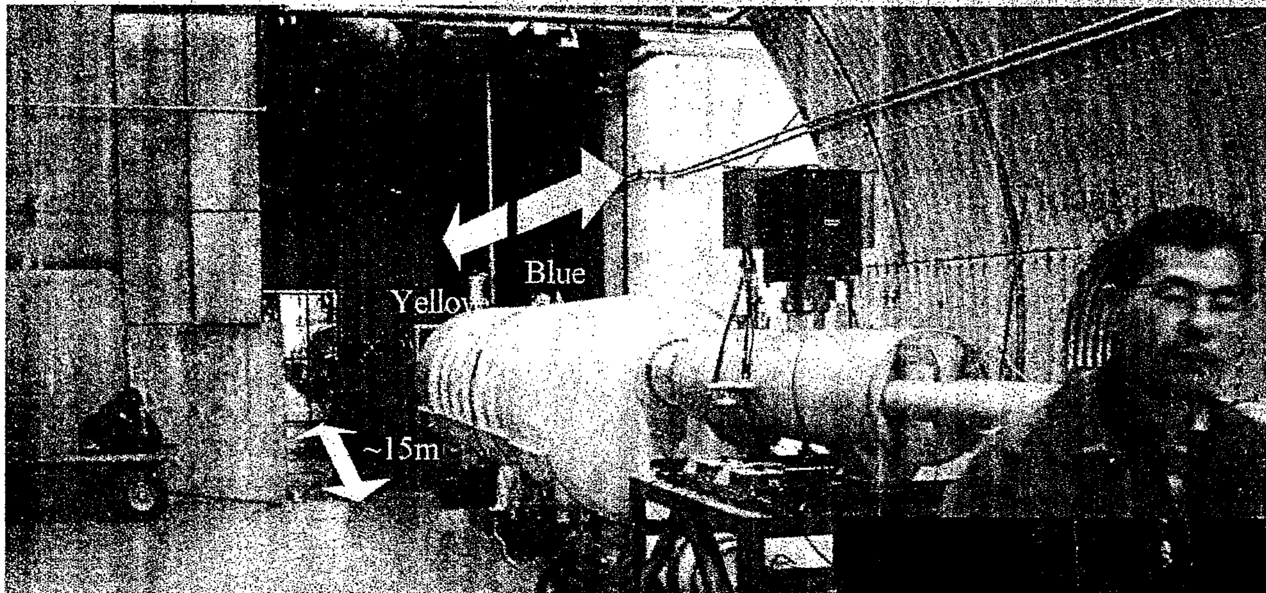
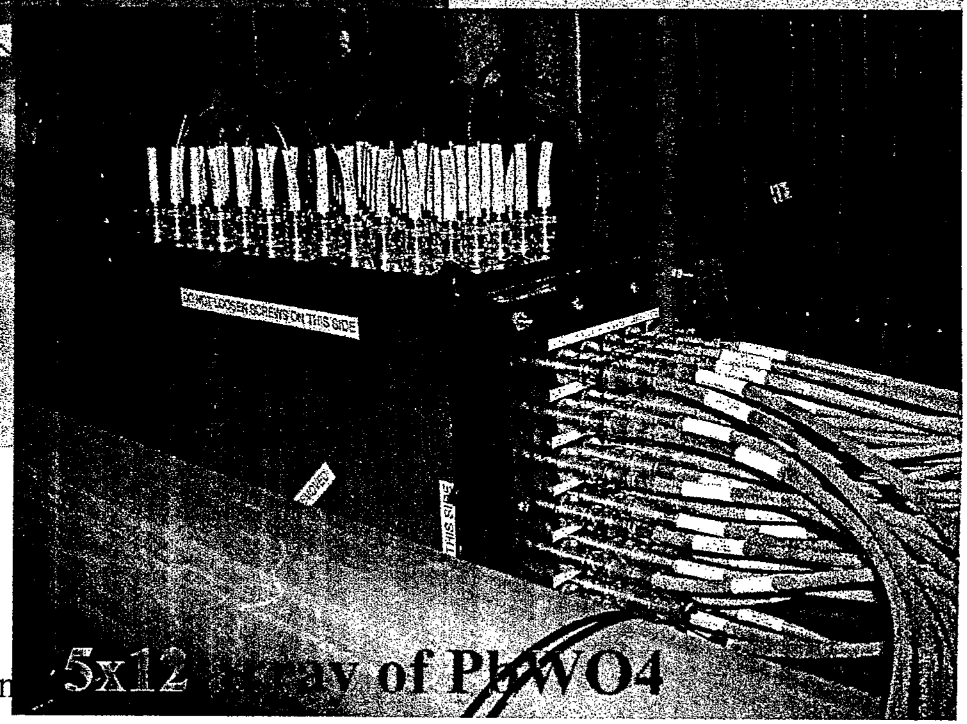
Local Polarimeter Test at IP12

RHIC



Brendan, Abhay Yoshi, Manabu, Yuji, Kiyoshi, Yasushi, Yousef, Gerry, Ken, Sasha, Naohito

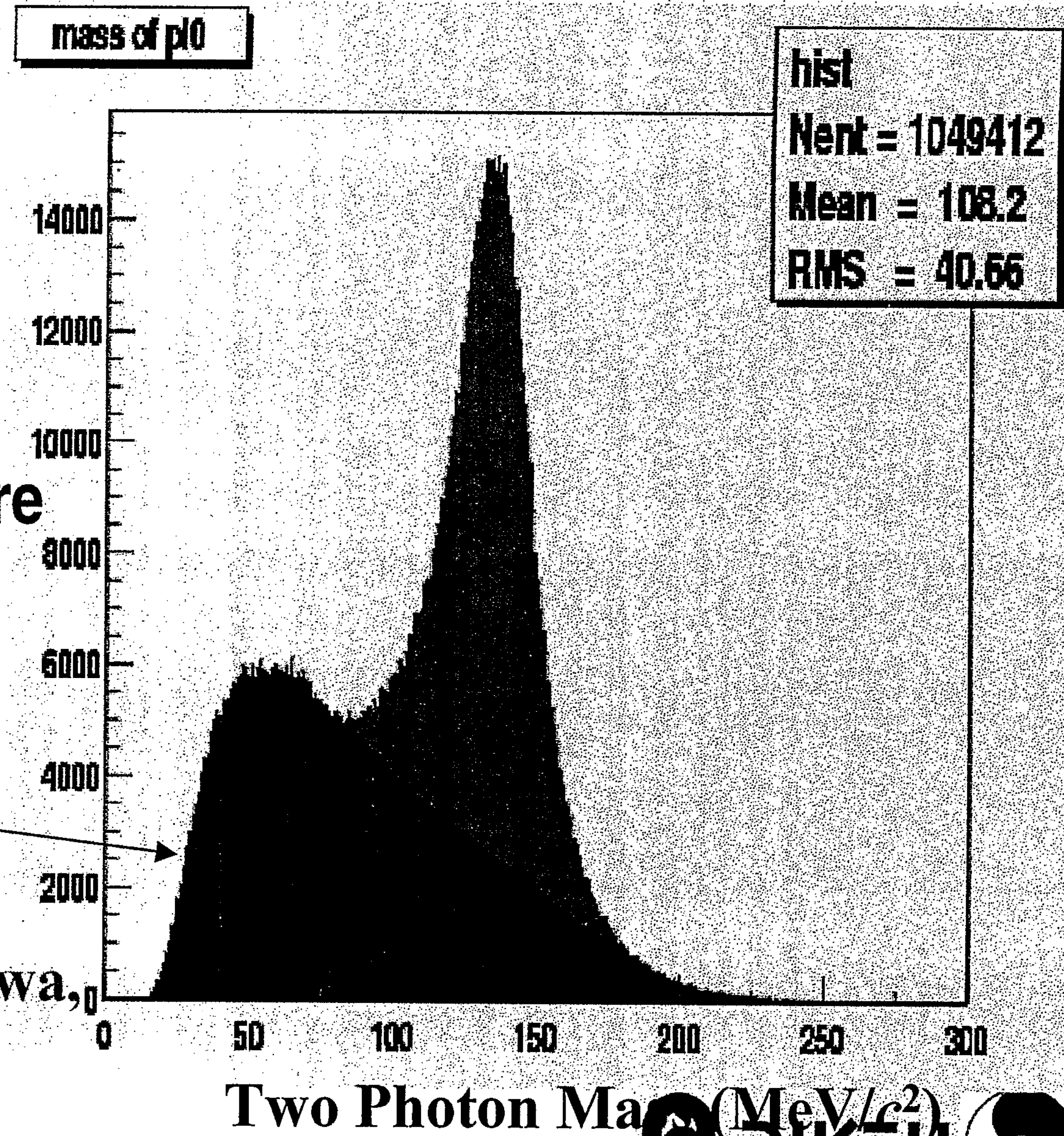
(Kyoto Un



5x12 array of PbWO4

Local Polarimeter Offline Plot

- Invariant mass distribution of two photon candidates
- Calibration is being refined
- Systematic studies are underway



Combinatorial Background

Yoshi Fukao, Manabu Togawa, Alexander Bazilevsky

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CONCLUDING REMARKS
RETROSPECTIVE ON THE RHIC PROJECT AND RHIC SPIN PHYSICS PROGRAM

Satoshi Ozaki

Concluding Remarks
Retrospective
on
The RHIC Project and RHIC Spin Physics Program

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BNL/RIKEN RHIC Spin Physics Celebration

April 30, 2002

Brookhaven National Laboratory

Brookhaven Science Associates

April 1991: Fest for Start of the RHIC Construction

RHIC Idea conceived as part of the NSAC Long Range Plan in 1983

Funding for construction began to flow starting Oct. 1990

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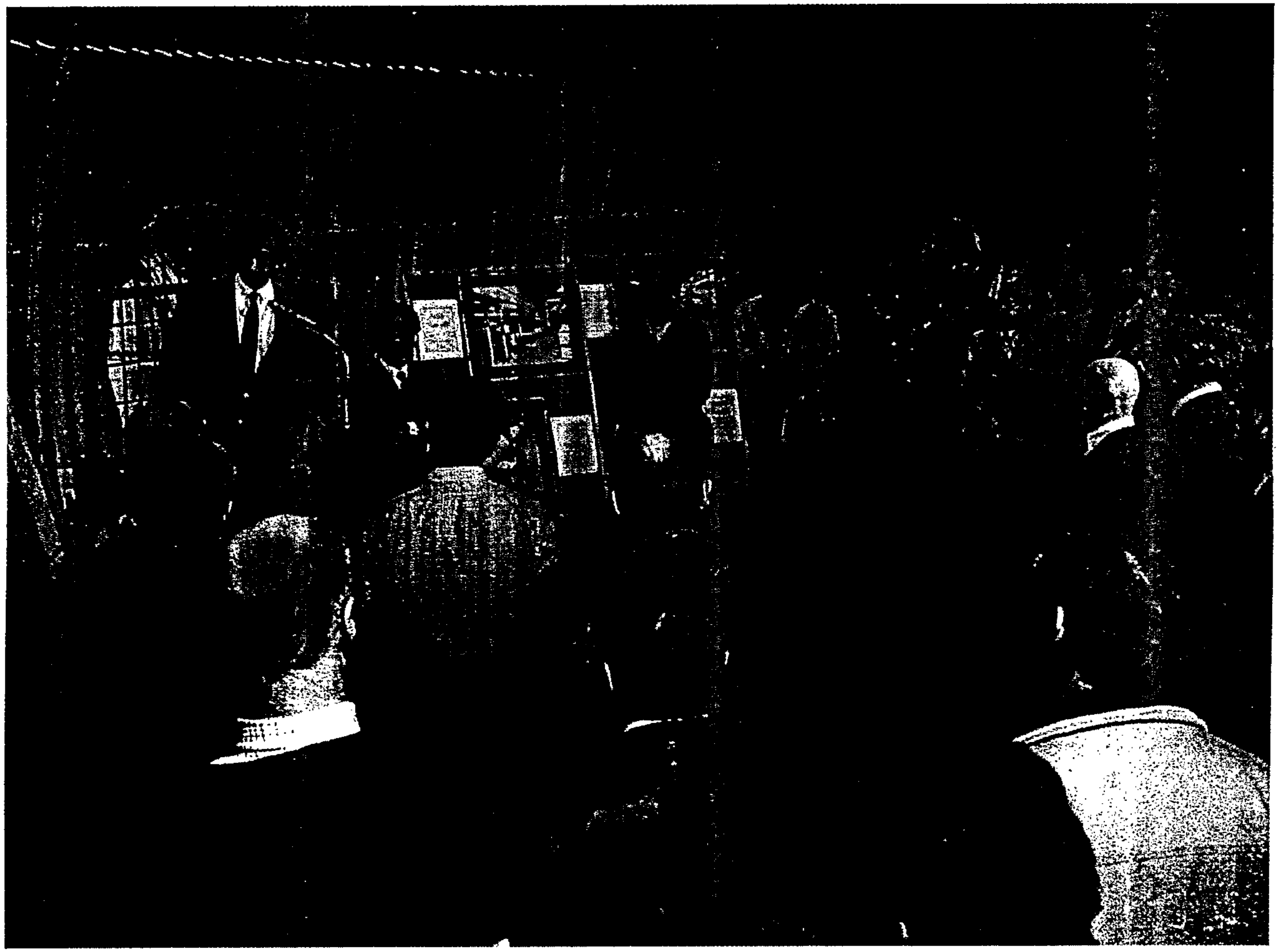
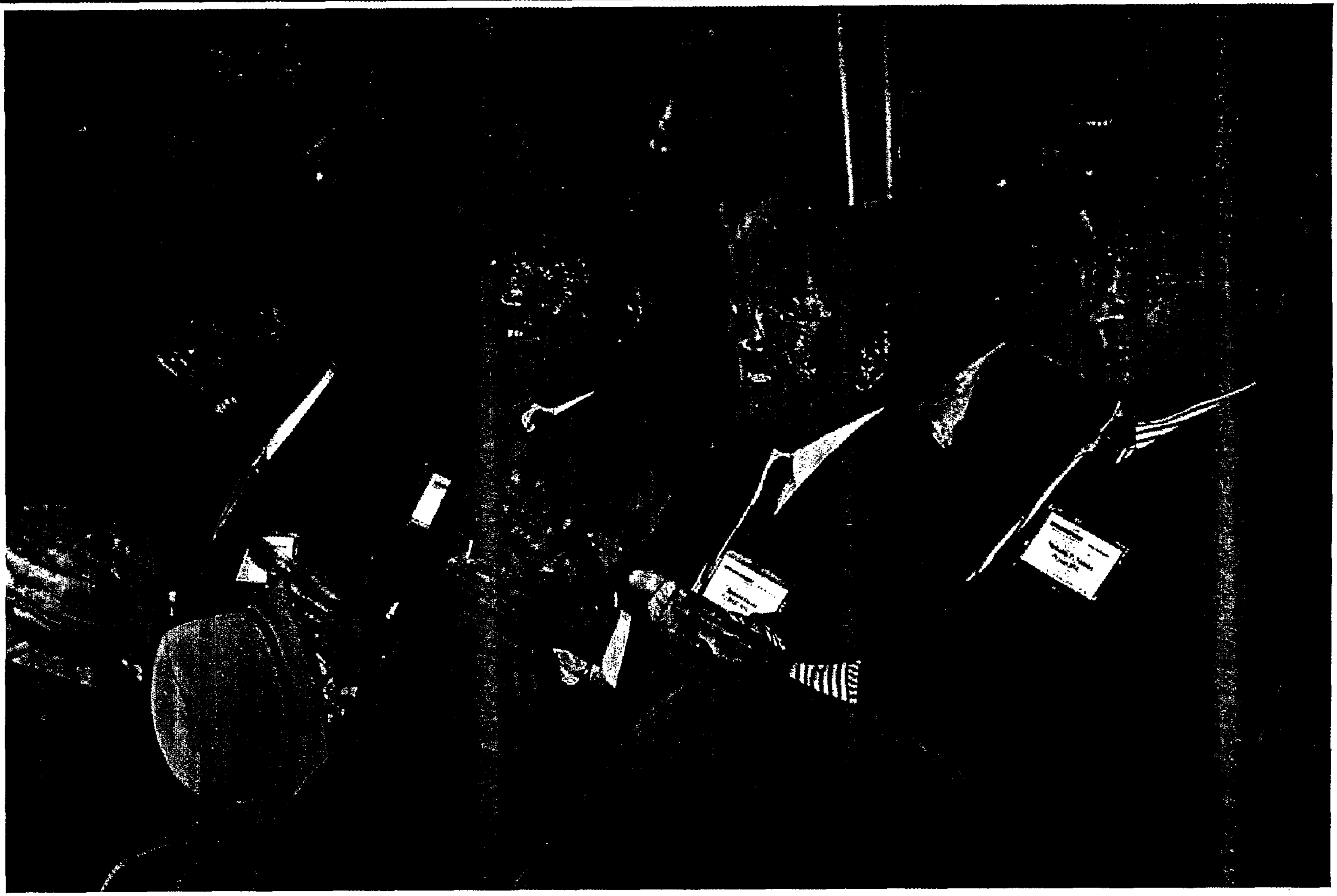
March 1997: The Au Beam through the 1st Sextant

The success of the 1st Sextant test helped keep our momentum high



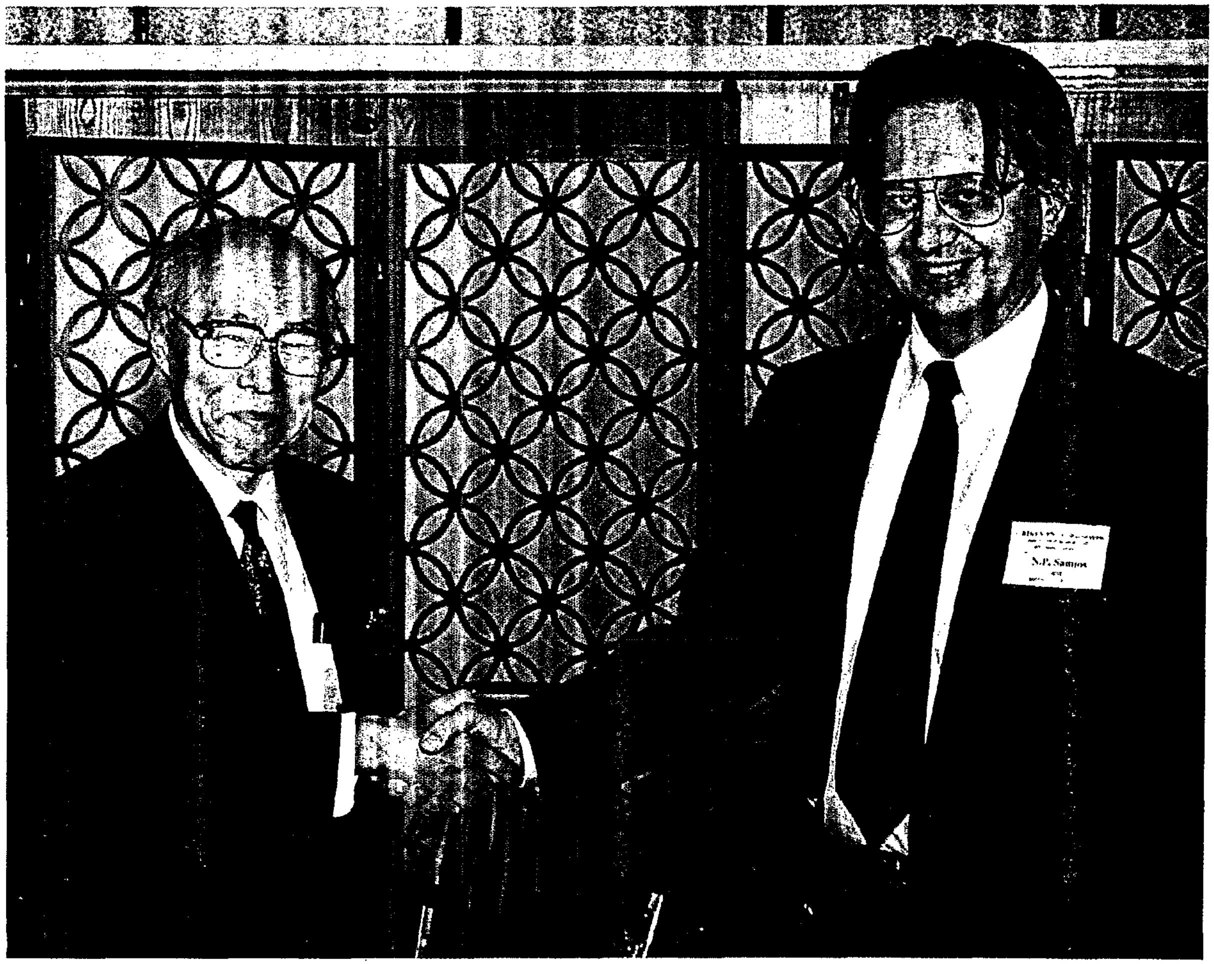
October 1999: All are Happy at the RHIC Dedication



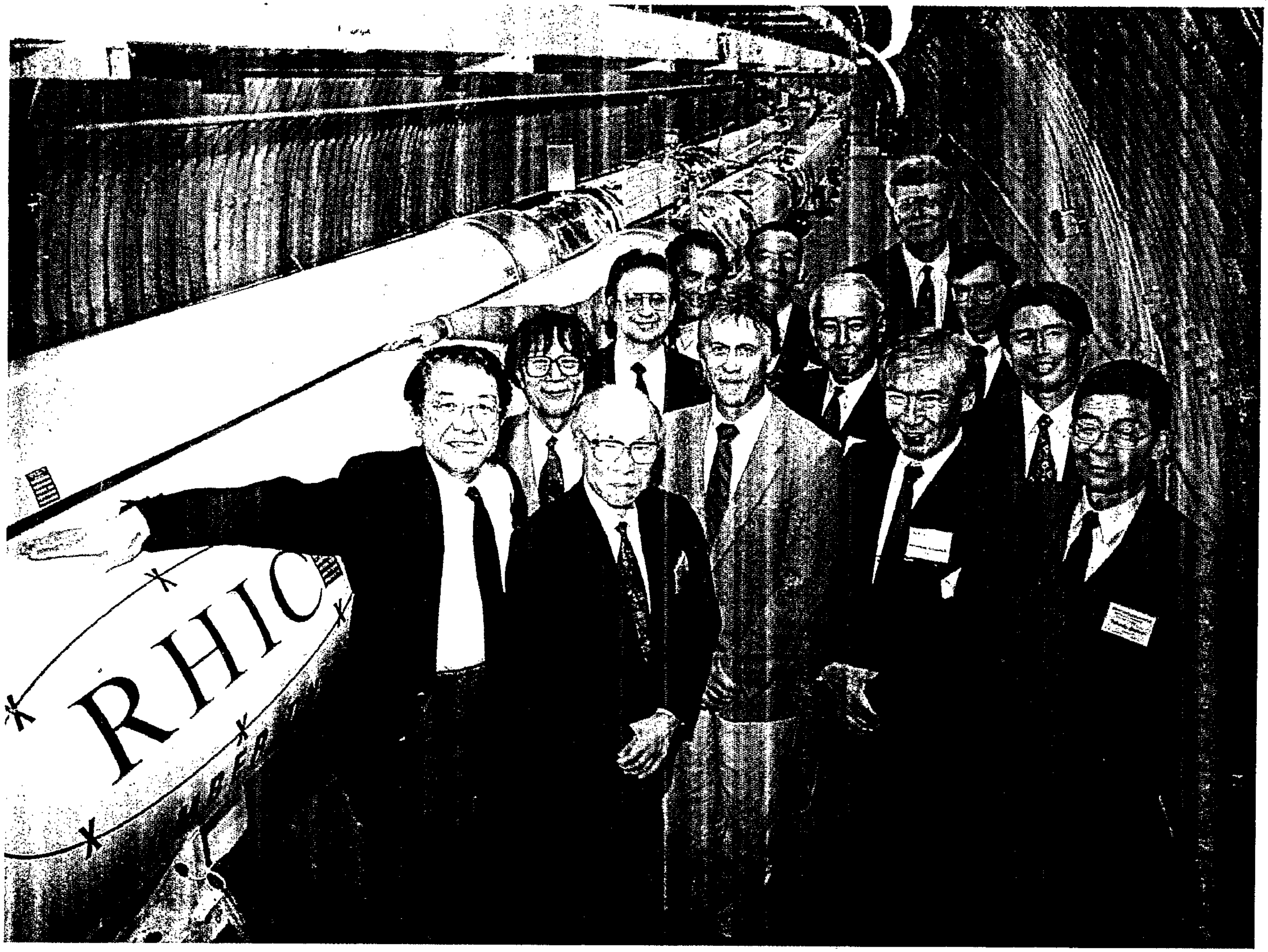
September 1995: The beginning of the collaboration

Initial MOU to cover the Spin Physics Collaboration was signed in 1995

Initial contact to invite RIKEN scientists to join RHIC program took place in 1992



September 1995: RIKEN team in the tunnel



April 30, 1997: Signing of MOU revised for RBRC

1997 MOU included provisions to establish RBRC at BNL

The DOE-STA protocol was signed on May 3, 1996, placing the RIKEN-BNL collaboration under a formal Gov.-Gov. framework

September 1997: Hanging of the RBRC Shingle

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September 1997: Japan/US Culinary Exchange

Brookhaven Science Associates

BROOKHAVEN NATIONAL LABORATORY

Conclusions

- Message from the Symposium
  - The spin physics program at RHIC has opened an important new frontier of science
  - It would not have been possible to achieve this success without a wise investment of the US-DOE and strategic contribution from RIKEN and the Japanese Government.

- We came a long way to reach accomplishments which we celebrate today.
- RHIC is well on the way in producing exciting physics results in the Relativistic Heavy Ion physics arena.
- RHIC is ready to make a strong leap forward in the Spin Physics arena.

- Achievements presented today are the fruits of
  - extensive efforts of many people, not only at BNL but also at RIKEN and elsewhere in the world
  - strong support of the scientific community
  - good understanding of the funding agencies
  - And, especially, a strong leadership.

PHOTOGRAPHS OF CELEBRATION EVENTS

APPENDIX

Visit to BNL by the Minister of Education, Culture, Sports, Science and Technology

Date: **April. 30, 2002**

Time: **8:00 a.m. –11:00 a.m.**

Visitors

TOYAMA Atsuko (Mrs.)	Minister of Education, Culture, Sports, Science and Technology
IMAMURA Tsutomu (Mr.)	Director-General, Research Promotion Bureau Ministry of Education, Culture, Sports, Science and Technology
OSANAI Masaru (Mr.)	Director, International Science and Technology Affairs Division Science and Technology Policy Bureau Ministry of Education, Culture, Sports, Science and Technology
ASADA Kazunobu (Mr.)	Secretary to the Minister of Education, Culture, Sports, Science and Technol
FUKAI Hiroshi (Mr.)	Secretary to the Minister of Education, Culture, Sports, Science and Technol
INOUE Keiji (Mr.)	Deputy Director, International Affairs Division, Minister's Secretariat Ministry of Education, Culture, Sports, Science and Technology
ARAKI Hideo (Mr.)	Assistant Police Inspector, Metropolitan Police Department

Agenda

6:00 a.m. Ministers party departs Hotel, Manhattan

8:00 a.m. Breakfast at Three Village Inn
Minister Tohyama, Prof. Arima, J. Marburger, S. Takeda, S. Ozaki

8:00 a.m. Breakfast at Danford's
P. Paul, S. Kobayashi, T.D. Lee, (T. Imamura?)

8:50 a.m. Depart from Breakfast site

9:30 a.m. Arrival at BNL. Proceed to Building 460
Signing of the MOU in Laboratory Directors office
Attendees:
Dr. S. Kobayashi, Minister Toyama, Prof. A. Arima,
Dr. P. Paul, Dr. J. Marburger, Prof. T.D. Lee, Dr. H. En-yo
Drs. P. Rosen, D. Kovar, M. Gunn, F. Crescenzo
Drs. I. Tanihata, T. Kirk, N.P. Samios, S. Ozaki
Minister's entourage from MEXT (6), entourage from NYC (2), JSPS (2)
Visitors from RIKEN (3), C. Shimoyamada, A. Taketani
BNL Public Affairs, Press if any, Photographer and video person

Activities:

9:30 Introduction of Minister by S. Ozaki to US members
Greeting by S. Kobayashi and introduction of Japanese members
Greeting by P. Paul, and Introduction of members on US side

9:40 Signing of MOU and Implementing Agreement by S. Kobayashi and P. Paul
Photo Sessions

9:50 Address by Minister
Address by J. Marburger

10:00 a.m. Depart Director's Office for Tour
BNL Attendees: P. Paul, T. Kirk, N.P. Samios, *at al*

10:00 a.m. Tours of RHIC for Minister and RIKEN parties — Tour Leader: S. Ozaki

10:05 Arrive at PHENIX Counting House
Poster presentation by Japanese Researchers (in Japanese)

10:20 PHENIX Experimental Halls

10:35 RHIC Tunnel,

10:55 Depart from PHENIX Counting House

11:00 a.m. Departure from BNL for Yale University, New Haven, CT

Spin Program Celebration

Date: **April. 30, 2002**
Time: **9:30 a.m. –9:00 p.m.**

9:30 AM Japanese Delegation arrival at BNL. Proceed to Building 460
Signing of the MOU in Laboratory Directors office
Attendees:
Dr. S. Kobayashi, Minister Toyama, Prof. A. Arima,
Dr. P. Paul, Dr. J. Marburger, Prof. T.D. Lee, Dr. H. En-yo
Drs. P. Rosen, D. Kovar, M. Gunn, F. Crescenzo
Drs. I. Tanihata, T. Kirk, N.P. Samios, S. Ozaki
Minister's entourage from MEXT (6), entourage from NYC (2), JSPS (2)
Visitors from RIKEN (3), C. Shimoyamada, A. Taketani
BNL Public Affairs, Press if any, Photographer and video person

10:00 AM Depart Director's Office for Tour — Tour Leader: S. Ozaki
BNL Attendees: P. Paul, T. Kirk, N.P. Samios,

10:00 AM Tours of RHIC for others — Tour Leader: T. Kirk
10:05 Arrive at PHENIX Counting House
10:05 PHENIX Experimental Halls
10:20 RHIC Tunnel to see spin rotators,
10:35 Poster presentation of PHENIX and Physics Results
11:00 Depart from PHENIX Counting House

11:20 AM RBRC QCD supercomputer: Bldg: 515 — Tour Leader: T.D. Lee

12:00 PM Lunch at Berkner Hall Room A/B/C
Opening Greeting: P. Paul and Marvin Gunn, Manager, DOE/CH

1:30 PM Special Symposium
Chairman: T. D. Lee

1:30 PM		Opening Addresses	
		P. Paul	
		S. Kobayashi	
		A. Arima	
		N. Samios	
		P. Rosen	
2:10 PM	30	R. Jaffe	QCD Spin Physics: From the Allotropes of Hyd Polarized Collider at RHIC
2:40 PM	30	W. MacKay	Polarized Protons in RHIC
3:10 PM	30	Coffee Break	
		Chairman: H. En'yo	
3:40 PM	20	K. Kurita	Proton-Carbon CNI Polarimeter for RHIC
4:00 PM	30	N. Saito	Spin Physics with the First Polarized Proton Col
4:30 PM	15	S. Ozaki	Concluding Remark

6:30 PM Dinner at Three Village Inn (by Invitation only)

Other RBRC Scientific Articles Proceedings Volumes: