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Theory Studies for RHIC-Spin

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Organizer

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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 eight 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 has increased to include ten theorists and one experimentalist in the current academic year, 2001-2002. Beginning this year there is a new RIKEN Spin Program at RBRC with four Researchers and three Research Associates.

In addition, the Center 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 thirty-eight 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.

T. D. Lee
August 2, 2001

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

CONTENTS

THEORY STUDIES FOR RHIC-SPIN

– INTRODUCTION AND OVERVIEW –

Polarized pp collider physics at RHIC is one of the most exciting developments at the crossroads of nuclear and particle physics in recent years. RHIC-Spin will provide, with unprecedented detail and accuracy, a wealth of information on the spin structure of the nucleon and on spin phenomena in QCD at high energies, as well as on unpolarized pp cross sections.
Very recently, polarized protons have been collided for the first time. Despite the fact that many technical difficulties had to be overcome, the first, just completed, RHIC-Spin run has been a great success, and first results are expected to be made public within the next few months.
A solid theoretical framework will be crucial for interpreting and learning from the expected data, as well as for making predictions for future measurements. The aim of this workshop was to attract several spin theorists to the center, in order to collaborate on RHIC-Spin with both experimentalists and theorists at RBRC. The focus in this workshop was not so much on having a large number of participants, but rather on having a small number of visitors at the center for an extended period of time, typically 4-7 weeks. Stays of such a duration are expected to facilitate the exchange and development of new ideas and to stimulate close and enduring collaborations.
Jianwei Qiu (Iowa State) and Mauro Anselmino (Torino) have been leading for years in developing approaches for understanding and predicting transverse single-spin asymmetries in QCD. Their presence at the center this spring was very timely, since A_N in pion production has been one of the first measurements at RHIC-Spin. This led to very interesting and fruitful "spin discussions" during their stay, from which both theorists and experimentalists benefited. Qiu and myself have started to collaborate on extending previous work on A_N by Qiu and Sterman, based on a QCD collinear-factorization theorem at non-leading twist (for details, see Qiu's contribution in these proceedings). Our new calculation, done in collaboration with also C. Kouvaris (MIT) who visited RBRC for a week during Qiu's stay, will apply also to the central-rapidity region, which is currently relevant for the RHIC experiments. We expect to publish our results within the next few months.
The production of Λ baryons in polarized pp collisions is another interesting topic at RHIC-Spin. Among other things, it will allow to study spin effects in fragmentation. The topic is all the more exciting, since strikingly large Λ polarization was observed in unpolarized fixed-target pp experiments. Anselmino and Umberto d'Alesio (Cagliari) have been working on spin phenomena in Λ production and presented and continued their work during their stay here (see their contributions in these proceedings). In particular, they performed new calculations aiming at a better quantitative understanding not only of spin asymmetries in Λ production, but also of the production cross section itself.
A major focus of polarized-pp measurements at RHIC will be on measuring the spin-dependent gluon density, Δg. A channel for doing this is the spin asymmetry in heavy-flavor production. These proceedings contain a summary of Marco Stratmann's (Regensburg) important work (done in collaboration with I. Bojak (Adelaide)) on the calculation of the next-to-leading order QCD corrections to the spin-dependent cross section. Their results will be invaluable for reliably extracting Δg from future data. Stratmann also discussed his work with experimentalists at

RBRC, and first steps toward a Monte-Carlo implementation of the results were taken. This is expected to result in a long-term collaboration between Stratmann and RBRC experimentalists. Stratmann also presented a talk on the spin structure of the *photon* (see these proceedings), which is a very interesting topic for the EIC. In addition, during Stratmann's stay, we made progress on the calculation of the first-order QCD corrections to the partonic hard scattering cross sections relevant for the double-spin asymmetry A_{LL}^{π} for inclusive-pion production at large p_T. These calculations, once completed, will be very important for RHIC-Spin since pion production is another promising channel for measuring Δg. Finally, while Stratmann was here, we also prepared and published a paper (with J. Soffer (Marseille)) examining the possibilities for measuring transversity at RHIC through transverse double-spin asymmetries in jet and prompt-photon production.

Jiro Kodaira (Hiroshima), during his stay at RBRC, has continued work on interesting new aspects of the spin dependence of the Drell-Yan process. Many interesting discussions on theoretical issues emerged from this. Together with his student H. Yokya, who visited RBRC for two weeks during Kodaira's presence at the Center, they have considered new observables and begun with the calculation of next-to-leading order QCD corrections to the associated cross sections. Interesting results are expected to emerge from this. One application is to study the impact of QCD soft-gluon resummation on the spin asymmetries for the Drell-Yan process. The (relative) simplicity of this reaction makes it an ideal testing ground for such studies. Kodaira also presented exciting new work on B-meson light-cone distribution amplitudes in heavy quark effective theory (see these proceedings).

The workshop has been a great success. I am grateful to all participants for coming to the Center, and for their dedicated efforts relating to RHIC-Spin. It has been – and will be in the future – a pleasure to collaborate with the participants. Significant advances have been made. As always, the level of support provided by Prof. T.D. Lee and his RIKEN-BNL Research Center for this workshop has been magnificent, and I am very grateful for it. I also thank Brookhaven National Laboratory and the U.S. Department of Energy for providing the facilities to hold this workshop. Finally, sincere thanks go to Pamela Esposito for her invaluable help in organizing and running the workshop.

Werner Vogelsang RBRC, April 2002

What do we learn from Λ polarization in SIDIS?

Mauro Anselmino

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Λ hyperons show naturally their polarization through the angular distribution of their weak decays, $\Lambda \to p\,\pi$: this makes them special particles, which may give access to new information.

We consider here the production of Λ's in semi-inclusive deep inelastic scattering (SIDIS), $\ell N \to \ell \Lambda X$. and discuss the leading order and leading twist expressions of polarization, considering the new knowledge which can be obtained and the novel tests of available information which can be performed.

The independent observables depend on elementary dynamics, distribution and fragmentation functions, both polarized and unpolarized. First access to separate q and $\bar{q}$ unpolarized and polarized fragmentation function is possible. Weak interaction contributions are also taken into account.

The transverse polarization of Λ's produced off transversely polarized protons could offer a good access to the so far unmeasured transversity distribution; transverse polarization from unpolarized initial states could offer a direct information on new polarizing fragmentation functions which might explain the longstanding problem of Λ transverse polarization in unpolarized processes.

The usefulness of studying the separate dependence on different kinematical variables and of combining RHIC pp data with DIS data is stressed.

What do we learn from Λ polarization in SIDI

- Independent observables in

  $\ell(\lambda) + N(\mu) \longrightarrow \ell' + H(h) + X$

  λ, μ, h = helicities

  and partonic expressions

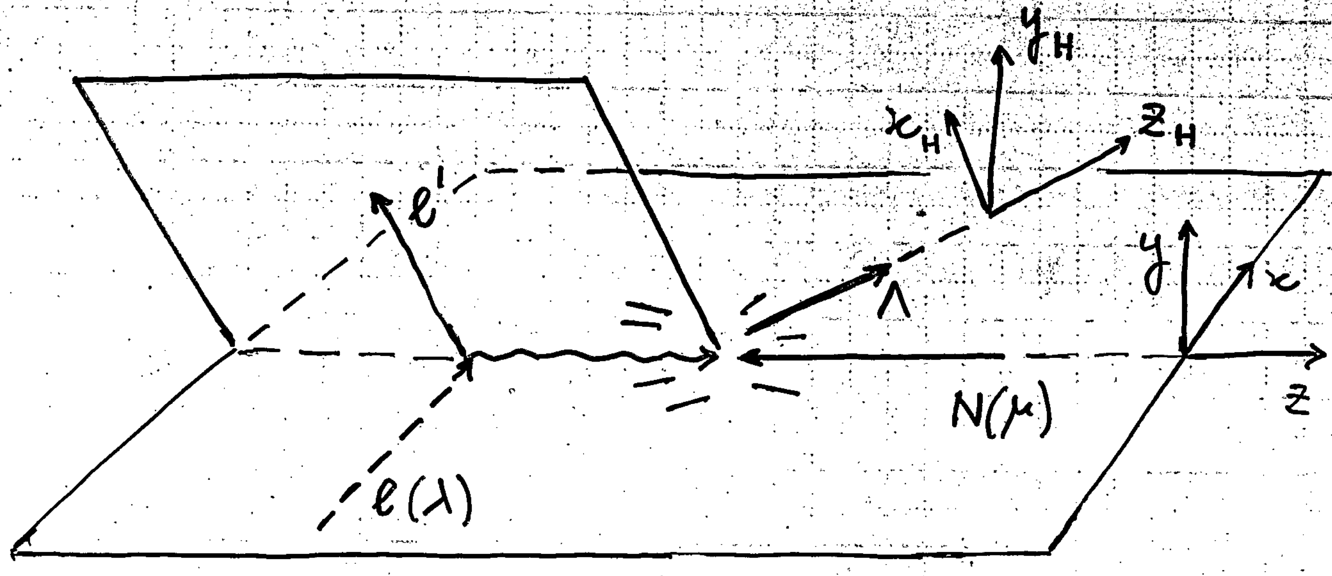
- Ways of getting new information

- Electro-weak contributions

- Transverse polarization from transversely polarized protons: access to h_1

- Transverse polarization in unpolarized SIDIS

Mauro Anselmino
BNL - March 6, 2000

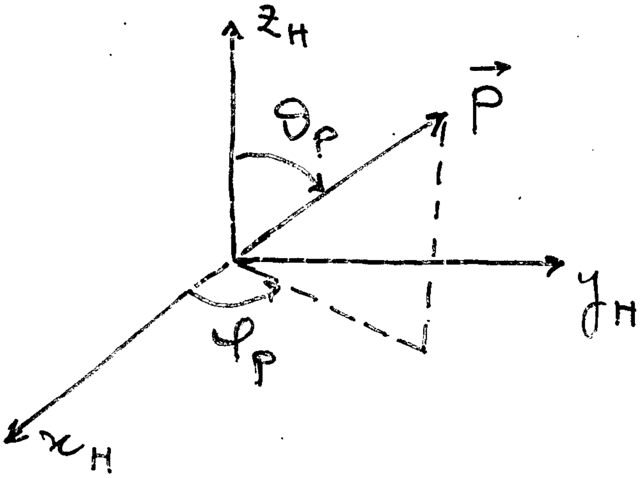


$\Lambda \to p\pi$ in helicity rest frame

Angular distribution of decay:

$$W(\theta_p, \varphi_p) = \frac{1}{4\pi}\left[1 + \alpha\, \vec{P} \cdot \hat{p}\right]$$

$$\alpha = 0.642 \pm 0.013 \implies P_{x_H}, P_{y_H}, P_{z_H}$$



$$\ell(\lambda) + N(\mu) \longrightarrow H(h) + \ell' + X$$

λ, μ, h = helicities

$$d\sigma^{Hh}_{\lambda\mu} \equiv \frac{d\sigma^{Hh}_{\lambda\mu}}{dx\, dy\, dz}$$

x, y, z = usual DIS variables

$$\left[x = \frac{Q^2}{2p\cdot q} \quad y = \frac{Q^2}{xs} \quad z = \frac{P_h \cdot P}{p\cdot q} \right]$$

Definitions:

$$d\sigma^{H}_{\lambda\mu} = d\sigma^{H+}_{\lambda\mu} + d\sigma^{H-}_{\lambda\mu}$$

(cross-section for producing H from a given initial helicity state)

$$P^{H}_{\lambda\mu} = \frac{d\sigma^{H+}_{\lambda\mu} - d\sigma^{H-}_{\lambda\mu}}{d\sigma^{H}_{\lambda\mu}}$$

(longitudinal polarization of H, produced from given initial helicity state)

Parity: $d\sigma^{Hh}_{\lambda\mu} = d\sigma^{H-h}_{-\lambda-\mu} \Rightarrow$ 4 indep. observab.

Unpolarized cross-section

$$d\sigma^H = \frac{1}{4}\left[d\sigma^H_{++} + d\sigma^H_{--} + d\sigma^H_{+-} + d\sigma^H_{-+}\right]$$

$$= \frac{1}{2}\left[d\sigma^H_{++} + d\sigma^H_{+-}\right] \equiv d\sigma^H_{00}$$

Usual double-spin asymmetry

$$\Delta d\sigma^H \equiv d\sigma^H_{++} - d\sigma^H_{+-} \implies A^H_{\parallel} = \frac{\Delta d\sigma^H}{2\, d\sigma^H}$$

Spin-transfer from lepton

$$d\sigma^{H+}_{+0} - d\sigma^{H-}_{+0} = P^H_{+0}\, d\sigma^H = -P^H_{-0}\, d\sigma^H$$

Spin-transfer from nucleon

$$d\sigma^{H+}_{0+} - d\sigma^{H-}_{0+} = P^H_{0+}\, d\sigma^H = -P^H_{0-}\, d\sigma^H$$

Other quantities are related to these:

$$P^H_{++} = \frac{1}{1+A_{\parallel}}\left(P^H_{+0} + P^H_{0+}\right)$$

$$P^H_{+-} = \frac{1}{1-A_{\parallel}}\left(P^H_{+0} - P^H_{0+}\right)$$

LO pQCD

$$\frac{d\sigma^{Hh}_{\lambda\mu}}{dx\,dy\,dz} = \sum_{q,\lambda_q} e_q^2\, q^{\mu}_{\lambda_q}(x)\, \frac{d\hat{\sigma}_{\lambda\lambda_q}}{dy}\, D^{Hh}_{q_{\lambda_q}}(z)$$

2 independent partonic cross-sections

$$\frac{d\hat{\sigma}_{++}}{dy} = \frac{d\hat{\sigma}_{--}}{dy} = \frac{4\pi\alpha^2}{sxy^2}$$

$$\frac{d\hat{\sigma}_{+-}}{dy} = \frac{d\hat{\sigma}_{-+}}{dy} = \frac{4\pi\alpha^2}{sxy^2}(1-y)^2$$

(flavour independent)

$\Rightarrow$ 4 kinds of distribution/fragmentation functions

$$q(x) = q_+^+ + q_+^-$$

$$\Delta q(x) = q_+^+ - q_+^-$$

$$D(z) = D_{q_+}^{H+} + D_{q_+}^{H-}$$

$$\Delta D(z) = D_{q_+}^{H+} - D_{q_+}^{H-}$$

$$\frac{d\sigma^H}{dx\,dy\,dz} = \frac{2\pi\alpha^2}{sx}\,\frac{1+(1-y)^2}{y^2}\sum_q e_q^2\, q(x)\, D_q^H(z)$$

$$A_{LL}^H = \underbrace{\frac{y(2-y)}{1+(1-y)^2}}_{\equiv \hat{A}_{LL}}\;\frac{\sum_q e_q^2\,\Delta q(x)\, D_q^H(z)}{\sum_q e_q^2\, q(x)\, D_q^H(z)}$$

$$P_{+0}^H = \hat{A}_{LL}(y)\;\frac{\sum_q e_q^2\, q(x)\,\Delta D_q^H(z)}{\sum_q e_q^2\, q(x)\, D_q^H(z)}$$

$$P_{0+}^H = \frac{\sum_q e_q^2\,\Delta q(x)\,\Delta D_q^H(z)}{\sum_q e_q^2\, q(x)\, D_q^H(z)}$$

$\Rightarrow$ P gives new information on D and ΔD

[$\sum_q \Rightarrow u, \bar{u}, d, \bar{d}, s, \bar{s}, \ldots$

Q^2 dependence from QCD evolution]

What do we know about D_q^Λ, ΔD_q^Λ ?

Unpol. Λ

From fits to $e^+e^- \to \Lambda, \bar{\Lambda} + X$

$$\Rightarrow \quad \sum_q \left(D_q^\Lambda + D_{\bar{q}}^\Lambda \right)$$

Flavour decomposition based on assumptions:

$$D_u^\Lambda = D_d^\Lambda \overset{?}{=} D_s^\Lambda$$

Pol. Λ

From fit to $P(\Lambda)$ in e^+e^-

$$\Rightarrow \quad \sum_q \left(\Delta D_q^\Lambda - \Delta D_{\bar{q}}^\Lambda \right)$$

Some sets available

de Florian, Stratmann, Vogelsang

Indumathi, Mani, Rastogi

Boros, Londergan, Thomas

Special combinations

Define $d\tilde{\sigma}^H \equiv \dfrac{d\sigma^H}{dx\,dy\,dz}\,[d\hat{\sigma}]^{-1} = \sum_q e_q^2\, q\, D_q^H$

Assume charge conjugation + isospin invariance $\Rightarrow D_q^{\Lambda} = D_{\bar{q}}^{\bar{\Lambda}}\ ;\ D_d^{\Lambda} = D_u^{\Lambda}$

Unpolarized cross-sections

$$d\tilde{\sigma}^{\Lambda+\bar{\Lambda}}\Big|_p - d\tilde{\sigma}^{\Lambda+\bar{\Lambda}}\Big|_n = \frac{1}{3}\left[u+\bar{u}-d-\bar{d}\right] D_u^{\Lambda+\bar{\Lambda}}$$

$$d\tilde{\sigma}^{\Lambda-\bar{\Lambda}}\Big|_p - d\tilde{\sigma}^{\Lambda-\bar{\Lambda}}\Big|_n = \frac{1}{3}\left[u_v-d_v\right] D_u^{\Lambda-\bar{\Lambda}}$$

$$\Rightarrow\ D_u^{\Lambda\pm\bar{\Lambda}},\ D_u^{\Lambda},\ D_u^{\bar{\Lambda}}$$

$$d\tilde{\sigma}^{\Lambda+\bar{\Lambda}}\Big|_p + d\tilde{\sigma}^{\Lambda+\bar{\Lambda}}\Big|_n = \frac{5}{9}\left[u+\bar{u}+d+\bar{d}\right] D_u^{\Lambda+\bar{\Lambda}} + \frac{2}{9}\left[s+\bar{s}\right] D_s^{\Lambda+\bar{\Lambda}}$$

$$d\tilde{\sigma}^{\Lambda-\bar{\Lambda}}\Big|_p - d\tilde{\sigma}^{\Lambda-\bar{\Lambda}}\Big|_n = \frac{5}{9}\left[u_v+d_v\right] D_u^{\Lambda-\bar{\Lambda}} + \frac{2}{9}\left[s-\bar{s}\right] D_s^{\Lambda-\bar{\Lambda}}$$

$$\Rightarrow\ \left[s+\bar{s}\right] D_s^{\Lambda+\bar{\Lambda}},\quad \left[s-\bar{s}\right] D_s^{\Lambda-\bar{\Lambda}}$$

[M.A., Boglione, D'Alesio, Leader, Murgia]

polarized cross-sections

$$\Delta d\tilde{\sigma}^{\Lambda+\bar{\Lambda}}\Big|_p - \Delta d\tilde{\sigma}^{\Lambda+\bar{\Lambda}}\Big|_n = \frac{1}{3}\left[\Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d}\right] \times D_u^{\Lambda+\bar{\Lambda}}$$

$$\Delta d\tilde{\sigma}^{\Lambda-\bar{\Lambda}}\Big|_p - \Delta d\tilde{\sigma}^{\Lambda-\bar{\Lambda}}\Big|_n = \frac{1}{3}\left[\Delta u_v - \Delta d_v\right] D_u^{\Lambda-\bar{\Lambda}}$$

$(\Delta q_v \equiv \Delta q - \Delta\bar{q})$

Other combinations of $\Delta d\tilde{\sigma}^{\Lambda\pm\bar{\Lambda}}\Big|_{p,n}$ give information on

$$\Delta S_1(x,z) \equiv \left[\Delta s(x) + \Delta\bar{s}(x)\right] D_s^{\Lambda+\bar{\Lambda}}(z)$$

$$\Delta S_2(x,z) \equiv \left[\Delta s(x) - \Delta\bar{s}(x)\right] D_s^{\Lambda-\bar{\Lambda}}(z)$$

$\Rightarrow$ one could learn about Δs and $\Delta\bar{s}$

(is $\Delta s(x) = \Delta\bar{s}(x)$?)

Λ polarization from pol. ℓ and unpol. N

$$d\tilde{\sigma}_{+0}^{\Lambda_+ - \Lambda_- + \bar{\Lambda}_+ - \bar{\Lambda}_-}\Big|_p - d\tilde{\sigma}_{+0}^{\Lambda_+ - \Lambda_- + \bar{\Lambda}_+ - \bar{\Lambda}_-}\Big|_n$$

$$= \frac{1}{3}\left[u(x) + \bar{u}(x) - d(x) - \bar{d}(x)\right] \Delta D_u^{\Lambda+\bar{\Lambda}}(z)$$

$$d\tilde{\sigma}_{+0}^{\Lambda_+ - \Lambda_- - \bar{\Lambda}_+ + \bar{\Lambda}_-}\Big|_p - d\tilde{\sigma}_{+0}^{\Lambda_+ - \Lambda_- - \bar{\Lambda}_+ + \bar{\Lambda}_-}\Big|_n$$

$$= \frac{1}{3}\left[u_v(x) - d_v(x)\right] \Delta D_u^{\Lambda-\bar{\Lambda}}(z)$$

$$\Longrightarrow \quad \Delta D_u^{\Lambda} \quad \text{and} \quad \Delta D_u^{\bar{\Lambda}}$$

Other combinations give information on

$$S_3(x,z) \equiv \left[s(x) + \bar{s}(x)\right] \Delta D_s^{\Lambda+\bar{\Lambda}}(z)$$

$$S_4(x,z) \equiv \underbrace{\left[s(x) - \bar{s}(x)\right]}_{=0\ ?} \Delta D_s^{\Lambda-\bar{\Lambda}}(z)$$

Λ polarization from unpol. ℓ and pol. N

$$d\tilde{\sigma}_{0+}^{\Lambda_+ - \Lambda_- + \bar{\Lambda}_+ - \bar{\Lambda}_-}\Big|_p - d\tilde{\sigma}_{0+}^{\Lambda_+ - \Lambda_- + \bar{\Lambda}_+ - \bar{\Lambda}_-}\Big|_n$$

$$= \frac{1}{3}\left[\Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d}\right] \Delta D_u^{\Lambda + \bar{\Lambda}}$$

$$d\tilde{\sigma}_{0+}^{\Lambda_+ - \Lambda_- - \bar{\Lambda}_+ + \bar{\Lambda}_-}\Big|_p - d\tilde{\sigma}_{0+}^{\Lambda_+ - \Lambda_- - \bar{\Lambda}_+ + \bar{\Lambda}_-}\Big|_n$$

$$= \frac{1}{3}\left[\Delta u_v - \Delta d_v\right] \Delta D_u^{\Lambda - \bar{\Lambda}}$$

Similarly, one gets information on

$$\Delta S_3 \equiv \left[\Delta s + \Delta\bar{s}\right] \Delta D_s^{\Lambda + \bar{\Lambda}}$$

$$\Delta S_4 \equiv \left[\Delta s - \Delta\bar{s}\right] \Delta D_s^{\Lambda - \bar{\Lambda}}$$

Notice that

$$\frac{\Delta S_3}{S_3} = \frac{\Delta s + \Delta\bar{s}}{s + \bar{s}} \qquad \frac{\Delta S_4}{S_4} = \frac{\Delta s - \Delta\bar{s}}{s - \bar{s}}$$

RHS depend only on x in LO

Electro-weak effects in $\ell p \to \ell \Lambda X$

Now $d\hat{\sigma}_{++} \neq d\hat{\sigma}_{--}$; $d\hat{\sigma}_{+-} \neq d\hat{\sigma}_{-+}$

$$P^{\Lambda}_{\pm 0} = \frac{\sum_q q(x)\left[d\hat{\sigma}^q_{\pm +} - d\hat{\sigma}^q_{\pm -}\right] \Delta D^{\Lambda}_q(z)}{\sum_q q(x)\left[d\hat{\sigma}^q_{\pm +} + d\hat{\sigma}^q_{\pm -}\right] D^{\Lambda}_q(z)}$$

$$P^{\Lambda}_{0 \pm} = \frac{\sum\left[q_{\pm}(d\hat{\sigma}^q_{++} + d\hat{\sigma}^q_{-+}) - q_{\mp}(d\hat{\sigma}^q_{+-} + d\hat{\sigma}^q_{--})\right] \Delta D^{\Lambda}_q}{\sum\left[q_{\pm}(d\hat{\sigma}^q_{++} + d\hat{\sigma}^q_{-+}) + q_{\mp}(d\hat{\sigma}^q_{+-} + d\hat{\sigma}^q_{--})\right] D^{\Lambda}_q}$$

$$P^{\Lambda}_{\pm\pm} = \frac{\sum\left[q_{\pm}\, d\hat{\sigma}^q_{\pm +} - q_{\mp}\, d\hat{\sigma}^q_{\pm -}\right] \Delta D^{\Lambda}_q}{\sum\left[q_{\pm}\, d\hat{\sigma}^q_{\pm +} + q_{\mp}\, d\hat{\sigma}^q_{\pm -}\right] D^{\Lambda}_q}$$

$\Longrightarrow$ different combinations of polarized distributions, fragmentations and dynamics.

$$P^{\Lambda}_{00} = \frac{\sum q\left[d\hat{\sigma}^q_{++} + d\hat{\sigma}^q_{-+} - d\hat{\sigma}^q_{+-} - d\hat{\sigma}^q_{--}\right] \Delta D^{\Lambda}_q}{4 \sum q\, d\hat{\sigma}^q\, D^{\Lambda}_q}$$

[purely parity violating effect;
$\simeq 1\%$ for $Q^2 > 4000\ \mathrm{GeV}^2$ at HERA]

[$q_+ \equiv q^+_+$ $q_- \equiv q^+_-$]

Λ polarization in CC DIS

$(\ell p \to \nu \Lambda X)$

neutrino couplings select helicity and flavour

$$\ell^- p \to \nu \Lambda X \Longrightarrow \begin{cases} \ell^- u_i \to \nu d_j \\ \ell^- \bar{d}_j \to \nu \bar{u}_i \end{cases}$$

$$\ell^+ p \to \bar{\nu} \Lambda X \Longrightarrow \begin{cases} \ell^+ d_j \to \bar{\nu} u_i \\ \ell^+ \bar{u}_i \to \bar{\nu} \bar{d}_j \end{cases}$$

$$u_i = u, c \qquad d_j = d, s$$

$$\frac{d\hat{\sigma}_{--}^{\ell^- u_i}}{dy} = \frac{d\hat{\sigma}_{++}^{\ell^+ \bar{u}_i}}{dy} = \frac{\pi \alpha^2}{x s} \frac{|V_{ij}|^2}{\sin^4 \theta_W} \left[\frac{1}{y + M_W^2/sx} \right]^2$$

$$\frac{d\hat{\sigma}_{+-}^{\ell^+ d_j}}{dy} = \frac{d\hat{\sigma}_{-+}^{\ell^- \bar{d}_j}}{dy} = \frac{\pi \alpha^2}{x s} \frac{|V_{ij}|^2}{\sin^4 \theta_W} \left[\frac{1-y}{y + M_W^2/sx} \right]^2$$

Some LO expressions:

$$P^{(\pm)}_{[\ell\nu]} = \frac{(1-y)^2[\bar{d}_\pm + R\bar{s}_\pm]\,\Delta D^\Lambda_{\bar{u}} - u_\mp[\Delta D^\Lambda_d + R\,\Delta D^\Lambda_s]}{(1-y)^2[\bar{d}_\pm + R\bar{s}_\pm]\,D^\Lambda_{\bar{u}} + u_\mp[D^\Lambda_d + R\,D^\Lambda_s]}$$

(longitudinally polarized protons)

$$P^{(0)}_{[\ell\nu]} = \frac{(1-y)^2[\bar{d} + R\,\bar{s}]\,\Delta D^\Lambda_{\bar{u}} - u[\Delta D^\Lambda_d + R\,\Delta D^\Lambda_s]}{(1-y)^2[\bar{d} + R]\,D^\Lambda_{\bar{u}} + u[D^\Lambda_d + R\,D^\Lambda_s]}$$

(unpolarized protons; similarly for $[\ell\bar{\nu}]$)

[Ma, Schmidt, Soffer; Boer, Jakob, Mulders;
M.A., Boglione, D'Alesio, Murgia;
Kotzinian, Bravar, von Harrach; ....]

Neglecting terms $\sim \bar{q}\cdot D^\Lambda_{\bar{q}}$

$$P^{(\pm)}_{[\ell\nu]} \simeq P^{(0)}_{[\ell\nu]} \simeq - \frac{\Delta D^\Lambda_d + R\,\Delta D^\Lambda_s}{D^\Lambda_d + R\,D^\Lambda_s}$$

$$P^{(\pm)}_{[\ell\bar{\nu}]} \simeq P^{(0)}_{[\ell\bar{\nu}]} \simeq - \frac{\Delta D^\Lambda_u}{D^\Lambda_u}$$

$R = \mathrm{tg}^2\theta_c = 0.056$

Transverse Λ polarization (P_y) from unpolarized ℓ and transversely polarized (S_y) p (γ^* exchange)

$$P_y^{[0\,S_y]} = \frac{\sum e_q^2\, h_{1q}(x)\, \Delta_T D_q^\Lambda(z)}{\sum e_q^2\, q(x)\, D_q^\Lambda(z)}\, \hat{D}_{NN}(y)$$

$h_{1q} = \Delta_T q = \delta q$ = transversity distrib.

$\Delta_T D$ = transversity fragmentation

$$\hat{D}_{NN} = \frac{d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\uparrow} - d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\downarrow}}{d\hat{\sigma}} = \frac{2(1-y)}{1+(1-y)^2}$$

$\Longrightarrow$ access to h_{1q} ?

At large x and z

$$P_y^{[0\,S_y]} \simeq \frac{4 h_{1u} + h_{1d}}{4u+d}\, \frac{\Delta_T D_u^\Lambda}{D_u^\Lambda}\, \frac{2(1-y)}{1+(1-y)^2}$$

$\Rightarrow$ Information on $\Delta_T D$ needed

D_{NN} in $pp^\uparrow \to \Lambda^\uparrow X$

$\sim f_{a/p} \otimes h_{1b} \otimes \hat{D}_{NN} \otimes \Delta_T D_c^\Lambda$

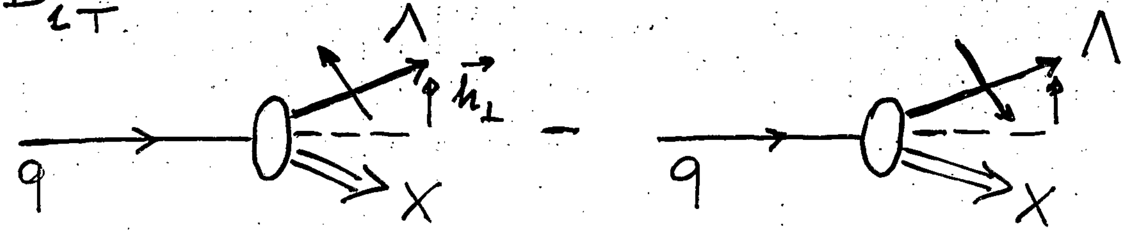
Transverse Λ pol. in unpolarized DIS

$\ell p \to \ell \Lambda^{\uparrow} X$ [similar to $pp \to \Lambda^{\uparrow} X$]

Access to polarizing frag. functions

$$\Delta^N D_{\Lambda^{\uparrow}/q}(z, \vec{k}_\perp) = \hat{D}_q^{\Lambda^{\uparrow}}(z, \vec{k}_\perp) - \hat{D}_q^{\Lambda^{\downarrow}}(z, \vec{k}_\perp)$$

$$\sim D_{1T}^{\perp}$$



[Mulders, Tangerman;
M.A., Boer, D'Alesio, Murgia]

$$P_N^{\Lambda} = \frac{\sum_q e_q^2 \, q(x) \, \Delta^N D_{\Lambda^{\uparrow}/q}(z, k_\perp)}{\sum_q e_q^2 \, q(x) \, \hat{D}_q^{\Lambda}(z, k_\perp)}$$

$\ell p \to \ell \Lambda^{\uparrow} X$ (NOMAD)

$$P_N^{\Lambda} \simeq \frac{\Delta^N D_{\Lambda^{\uparrow}/u}}{D_u^{\Lambda}}$$

Conclusions

$$\left.\begin{array}{l} \ell N \to \ell \Lambda^{\uparrow} X \\ \ell N \to \nu \Lambda^{\uparrow} X \end{array}\right\} \Longrightarrow P(\Lambda)$$

$P(\Lambda)$ depends on parton densities, dynamics and quark fragmentation

Tests of existing knowledge + access to new independent information

Measure of h_1 ?

Mechanism for Λ transverse polar. in unpolarized processes ?

Some data available (HERMES, NOMAD, SLAC), more to come (HERMES with transverse polarization, COMPASS, RHIC...)

<u>Combined data to get more information</u>

TRANSVERSE Λ POLARIZATION IN INCLUSIVE PROCESSES

U. D'ALESIO

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Transverse hyperon polarization in high-energy, unpolarized hadron collisions is a long-standing challenge for theoretical models of hadronic reactions. The straightforward application of perturbative QCD and collinear factorization in the study of these observables is not successful. Therefore, we have proposed a new approach to this problem based on perturbative QCD and its factorization theorems, and which includes polarization and intrinsic transverse momentum, $\boldsymbol{k}_\perp$, effects. It requires the introduction of a new type of leading twist fragmentation function (FF), one which is polarization and $\boldsymbol{k}_\perp$- dependent, the so-called polarizing FF.

We show how the main features of the transverse Λ polarization in unpolarized hadronic reactions can be reproduced within this scheme by fitting available experimental pp data at large p_T.

The problem of the low values (compared to the data) of the unpolarized cross-sections calculated in our approach is discussed.

In the same framework we investigate the transverse polarization of Λ's and $\bar{\Lambda}$'s produced in unpolarized semi-inclusive DIS. Analytical expressions for both neutral and charged current exchange are given. We present the general formalism and a qualitative analysis displaying generic features of the Λ and $\bar{\Lambda}$ polarization for specific scenarios. Different kinematical situations are considered, corresponding to experiments currently able to study Λ production in semi-inclusive DIS.

Another important issue related to the transverse Λ polarization is the study of the double transverse spin asymmetries in $p^\uparrow p \to \Lambda^\uparrow X$ and $\ell p^\uparrow \to \ell' \Lambda^\uparrow X$ from which one can gain information on the transversity distribution function, h_1.

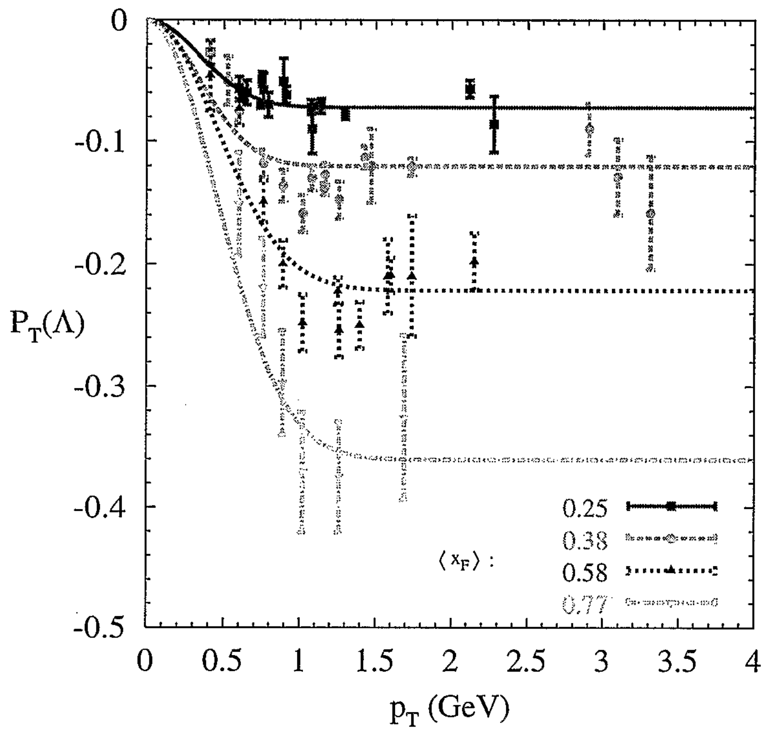
TRANSVERSE Λ POLARIZATION IN INCLUSIVE PROCESSES

Outline:

- Transverse Λ polarization in *unpolarized* hadron collisions, $p\,p(A) \to \Lambda^\uparrow X$:
  The *polarizing fragmentation function* (PFF), a new spin- and $\boldsymbol{k}_\perp$- dependent FF;
- General approach and properties of spin- and $\boldsymbol{k}_\perp$- dependent FF;
- Applications: study of transverse Λ polarization in *unpolarized* (NC, CC) semi-inclusive DIS: $\ell\, p \to \ell'\, \Lambda^\uparrow\, X$ [$\ell \equiv \ell^\pm, \nu$];
- $p^\uparrow\, p \to \Lambda^\uparrow X$ and $\ell\, p^\uparrow \to \ell' \Lambda^\uparrow X$: access to h_1;
- Conclusions and outlook;

Ref.s : M. Anselmino, D. Boer, UD, F. Murgia, PRD63 (2001) 054029; hep-ph/0109186

pA - data: main features



A partial collection of experimental data for $P_T(\Lambda)$ in $p\,p(Be) \to \Lambda^{\uparrow} X$ vs. p_T and for different bins of x_F. The curves are just to guide the eye.

$|P_T(\Lambda)|$:

- is LARGE;
- increases up to $p_T \sim 1$ GeV, where it flattens up to the highest measured p_T;
- in this plateau regime increases linearly with x_F;
- is almost energy-independent;

$P_T(\bar{\Lambda})$ is compatible with zero;

A generalized pQCD approach to Single Spin Asymmetries

1) Extension of usual pQCD formalism (based on factorization theorems) for (semi)inclusive hadronic processes, $A\,B \;\to\; C\,X$, at large energies and (moderately) large p_T

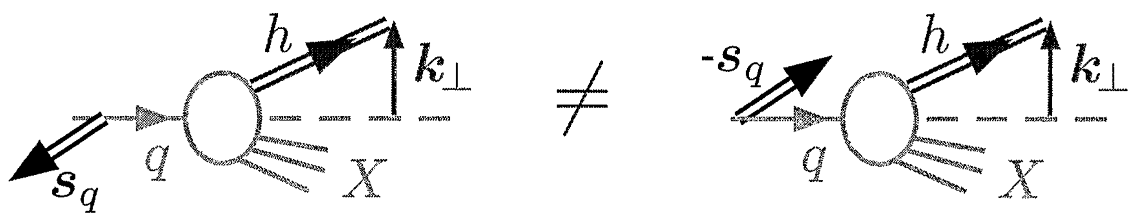
2) Inclusion of spin and intrinsic (partonic) transverse momentum, $\boldsymbol{k}_\perp$, effects

3) New, nonperturbative, twist-two, spin and $\boldsymbol{k}_\perp$-dependent partonic distribution/fragmentation functions are introduced

4) Soft, nonperturbative dynamics generates correlations between the hadron(parton) transverse spin and the parton(hadron) transverse momentum, which imply an azimuthal asymmetry in the $\boldsymbol{k}_\perp$ probability distribution. This in turn originates the asymmetries observed at the hadronic level

Twist-two, spin and $k_\perp$- dependent fragmentation functions

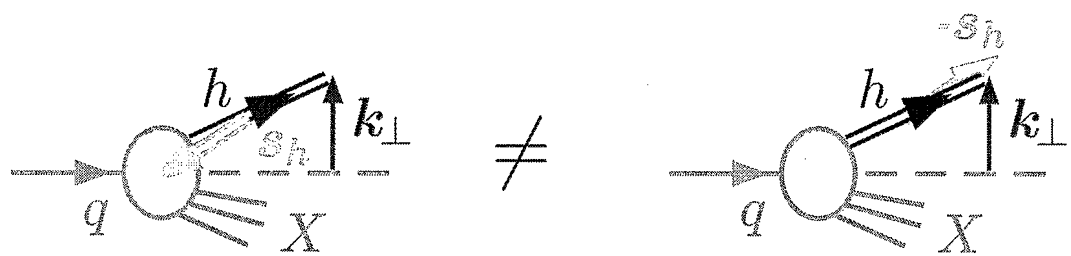
$$\mathbf{q} \to \mathbf{h} + \mathbf{X}$$



$\Delta^N D_{h/q^\uparrow}(z, k_\perp)$

T-odd,

chiral-odd



$\Delta^N D_{h^\uparrow/q}(z, k_\perp)$

T-odd,

chiral-even

FINAL STATE INTERACTIONS!

- $\Delta^N f_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) = \hat{f}_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) - \hat{f}_{q/p^\downarrow}(x, \boldsymbol{k}_\perp)$ [Sivers (90)]
- $\Delta^N f_{q^\uparrow/p}(x, \boldsymbol{k}_\perp) = \hat{f}_{q^\uparrow/p}(x, \boldsymbol{k}_\perp) - \hat{f}_{q^\downarrow/p}(x, \boldsymbol{k}_\perp)$
- $\Delta^N D_{h^\uparrow/q}(z, \boldsymbol{k}_\perp) = \hat{D}_{h^\uparrow/q}(z, \boldsymbol{k}_\perp) - \hat{D}_{h^\downarrow/q}(z, \boldsymbol{k}_\perp)$
- $\Delta^N D_{h/q^\uparrow}(z, \boldsymbol{k}_\perp) = \hat{D}_{h/q^\uparrow}(z, \boldsymbol{k}_\perp) - \hat{D}_{h/q^\downarrow}(z, \boldsymbol{k}_\perp)$ [Collins (93)]

Note: $\hat{f}_{q/p^\downarrow}(x, \boldsymbol{k}_\perp) = \hat{f}_{q/p^\uparrow}(x, -\boldsymbol{k}_\perp)$ and so on

General formalism and applications

P.J. Mulders, R.D. Tangerman, NPB**461** (96); D. Boer, P.J. Mulders, PRD**57** (98); D. Boer, PRD**60** (99), D. Boer *et al.*, NPB**564** (00);

M. Anselmino *et al.*, PLB**362** (95); M. Anselmino, F.Murgia, PLB**442** (98);

M. Anselmino *et al.*, PRD**60** (99); M. Anselmino *et al.*, EPJC**13** (00);

M. Anselmino, F.Murgia, PLB**483** (00);

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$$p\,p(A) \to \Lambda^\uparrow X \qquad P_T(\Lambda) = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

At leading twist and leading order in $\boldsymbol{k}_\perp$ the numerator in $P_T(\Lambda)$ reads

$$d\sigma^{pp\to\Lambda^\uparrow X} - d\sigma^{pp\to\Lambda^\downarrow X} \sim \sum_{abcd} \int dx_a dx_b$$

$$\times\Big\{ \int d^2\boldsymbol{k}_{\perp c}\, f_{a/p}(x_a)\, f_{b/p}(x_b)\, \frac{d\hat\sigma}{dt}(x_a, x_b; \boldsymbol{k}_{\perp c})\, \Delta^N D_{\Lambda^\uparrow/c}(z, \boldsymbol{k}_{\perp c})$$

$$+ \int d^2\boldsymbol{k}_{\perp a}\, \Delta^N f_{a^\uparrow/p}(x_a, \boldsymbol{k}_{\perp a})\, f_{b/p}(x_b)\, \Delta_{NN}\hat\sigma(x_a, x_b; \boldsymbol{k}_{\perp a})\, \Delta_T D_{\Lambda/c}(z)$$

$$+ \int d^2\boldsymbol{k}_{\perp b}\, f_{a/p}(x_a)\, \Delta^N f_{b^\uparrow/p}(x_b, \boldsymbol{k}_{\perp b})\, \Delta'_{NN}\hat\sigma(x_a, x_b; \boldsymbol{k}_{\perp b})\, \Delta_T D_{\Lambda/c}(z) \Big\}$$

[current fragmentation region, large p_T]

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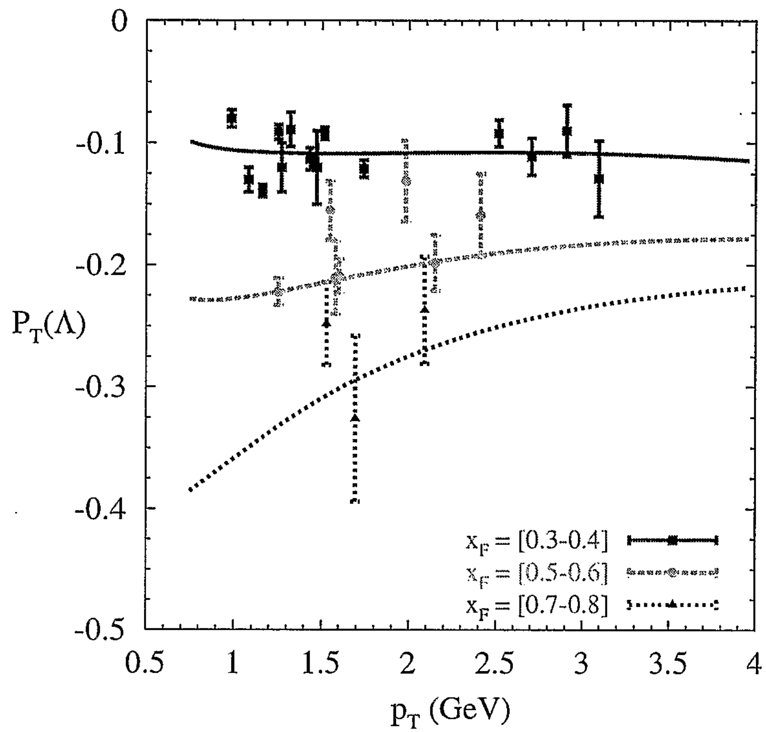
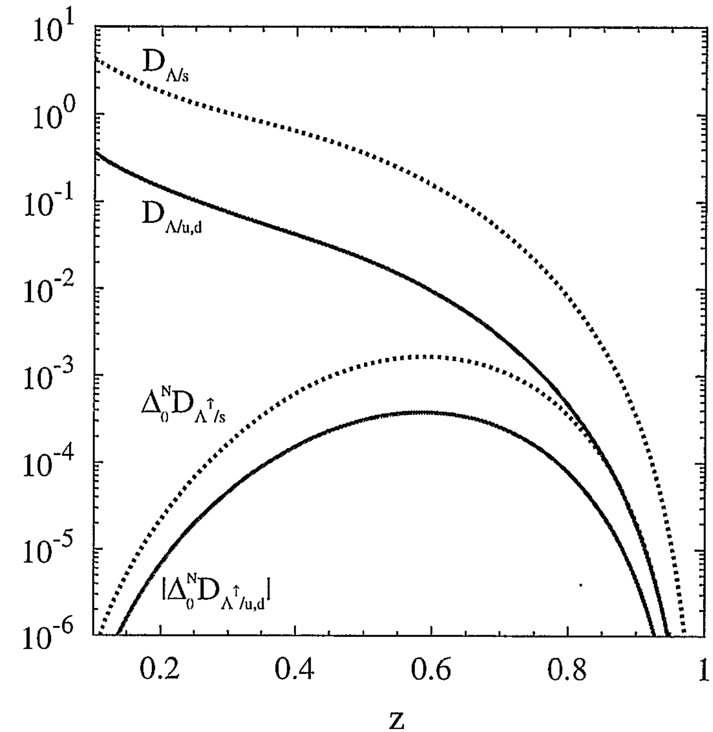
$$P_T^\Lambda(x_F, p_T) = \frac{d\sigma^{p\,p\to\Lambda^\uparrow X} - d\sigma^{p\,p\to\Lambda^\downarrow X}}{d\sigma^{p\,p\to\Lambda^\uparrow X} + d\sigma^{p\,p\to\Lambda^\downarrow X}}$$

$$= \frac{\sum \int dx_a\, dx_b \int d^2\boldsymbol{k}_{\perp c}\, f_{a/p}(x_a)\, f_{b/p}(x_b)\, d\hat{\sigma}(x_a, x_b; \boldsymbol{k}_{\perp c})\, \Delta^N D_{\Lambda^\uparrow/c}(z, \boldsymbol{k}_{\perp c})}{\sum \int dx_a\, dx_b \int d^2\boldsymbol{k}_{\perp c}\, f_{a/p}(x_a)\, f_{b/p}(x_b)\, d\hat{\sigma}(x_a, x_b; \boldsymbol{k}_{\perp c})\, D_{\Lambda/c}(z, \boldsymbol{k}_{\perp c})}$$

$$\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp) \equiv D_{\Lambda^\uparrow/q} - D_{\Lambda^\downarrow/q}\ \left[D_{1T}^\perp\right] = \Delta^N D_{\Lambda^\uparrow/q}(z, |\boldsymbol{k}_\perp|)\sin\phi$$

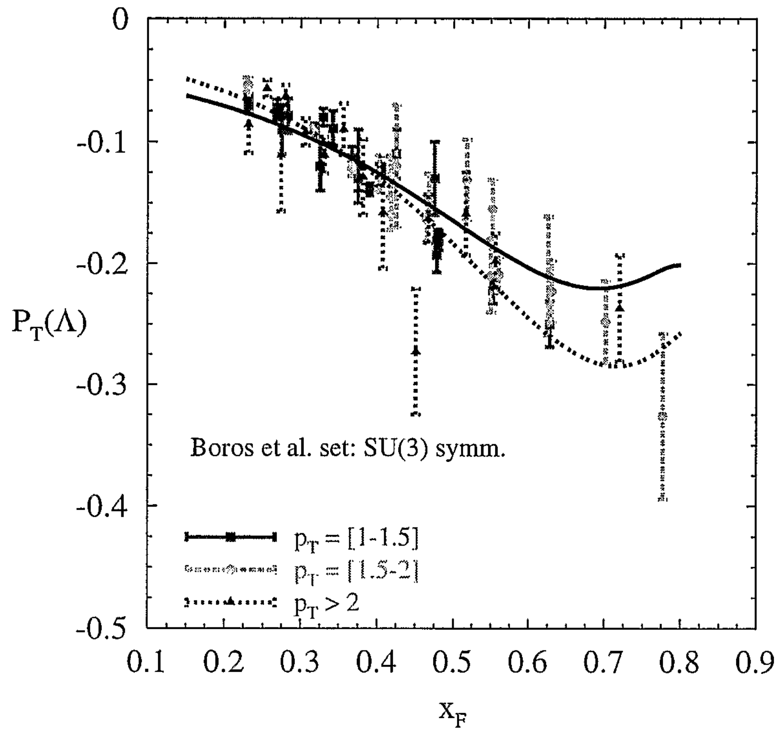
- Λ polarization entirely generated in the fragm. process, $q \to \Lambda^\uparrow + X$;
- Effective, inclusive Λ PFF (consistent with available sets of unpol. FF);
- $\int d^2\boldsymbol{k}_\perp F(\boldsymbol{k}_\perp) \Rightarrow F(k_\perp^0)$, where $k_\perp^0(z) \sim K z^a (1-z)^b$;
- Fit to exp. data $\Rightarrow$ parameterizations for $k_\perp^0(z)$ and $\Delta^N D_{\Lambda^\uparrow/q_v}(z, k_\perp^0)$; e.g. $k_\perp^0(z) = 0.66 z^{0.32}(1-z)^{0.5}$
- intrinsic $k_\perp$ in the initial state might give a proper spin-independent enhancing factor (10-100) to explain the large unpolarized cross-sections (as for γ and π)

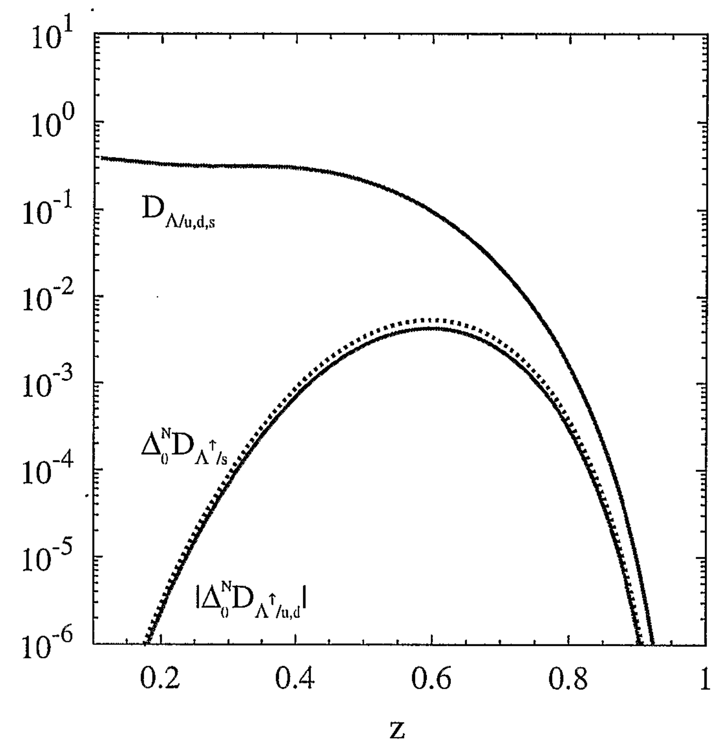




Best fit, obtained with a $SU(3)$ symmetry broken FF set (see plot on the right), to $P_T(\Lambda)$ data from $p-Be$ reactions, vs. p_T and for various x_F bins, at the NN c.m. energy $\sqrt{s} = 30$ GeV.

$|\Delta_0^N D_{\Lambda^\uparrow/u,d}|$ and $\Delta_0^N D_{\Lambda^\uparrow/s}$, as given by our best fit parameters, compared to the Indumathi *et al.* unpolarized FF, $D_{\Lambda/u,d}$ and $D_{\Lambda/s}$. Notice that $\Delta_0^N D_{\Lambda^\uparrow/u,d}$ is negative.





Best fit, obtained with a $SU(3)$ symmetric FF set (see plot on the right), to $P_T(\Lambda)$ data from $p-Be$ reactions, vs. x_F and for various p_T bins, at $\sqrt{s} = 30$ GeV. The two theoretical curves correspond to $p_T = 1.5$ GeV (dotted) and $p_T = 3$ GeV (solid).

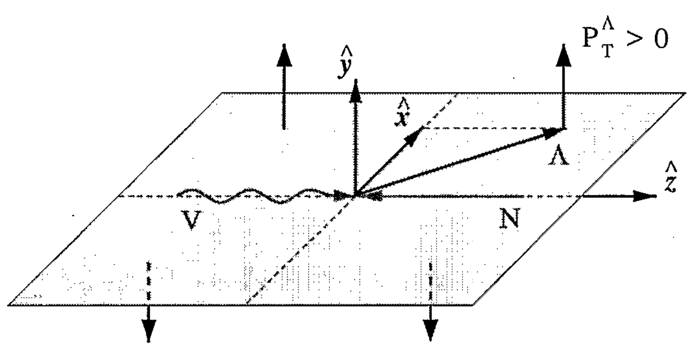
$|\Delta_0^N D_{\Lambda^\uparrow/u,d}|$ and $\Delta_0^N D_{\Lambda^\uparrow/s}$, as given by our best fit parameters, compared to the Boros *et al.* unpolarized FF, $D_{\Lambda/u,d} = D_{\Lambda/s}$. Notice that $\Delta_0^N D_{\Lambda^\uparrow/u,d}$ is negative.

$P_T^\Lambda(x, y, z_h, \boldsymbol{p}_T)$ in unpolarized semi-inclusive DIS $(x_F > 0)$

$$P_T = \frac{d\sigma^{\Lambda^\uparrow} - d\sigma^{\Lambda^\downarrow}}{d\sigma^{\Lambda^\uparrow} + d\sigma^{\Lambda^\downarrow}}\,, \qquad d\sigma^{\Lambda^{\uparrow(\downarrow)}} = \sum f_{q/p}(x)\, \frac{d\hat\sigma^{\ell q}}{dy} D_{\Lambda^{\uparrow(\downarrow)}/q}(z_h, \boldsymbol{p}_T)$$

$$z_h = p \cdot p_h / p \cdot q$$

$$D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp) = \tfrac{1}{2} D_{\Lambda/q}(z, k_\perp) + \tfrac{1}{2} \Delta^N D_{\Lambda^\uparrow/q}(z, k_\perp) \sin\phi$$



SIDIS kinematical representation in the virtual boson - proton c.m. reference frame: $\hat{z}$-axis along the virt. boson direction; $\hat{x}$-axis along the hadron $\boldsymbol{p}_T \equiv \boldsymbol{k}_\perp$; $\hat{y} = \hat{z} \times \hat{x}$ and $\phi = \pi/2$.

The arrows show positive P_T^Λ.

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$D_{\Lambda/q}(z, k_\perp)$ and $\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp)$: gaussian parameterizations

- Define: $D_{\Lambda/q}(z, k_\perp) = \frac{d(z)}{M^2}\,\exp\left[-\frac{k_\perp^2}{M^2 f(z)}\right]$;

$$\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp) = \frac{\delta(z)}{M^2}\,\frac{k_\perp}{M}\,\exp\left[-\frac{k_\perp^2}{M^2 \varphi(z)}\right]\,\sin\phi;$$

  where ϕ is the angle between the spin and $\boldsymbol{k}_\perp$ of Λ

- Require:

▶ $\int d^2k_\perp \left[k_\perp^2\right] D_{\Lambda/q}(z, k_\perp) = \left[\langle k_\perp^2(z)\rangle\right] D_{\Lambda/q}(z) \qquad \Rightarrow \quad$ fix $d(z), f(z)$;

▶ $|\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp)| \,/\, D_{\Lambda/q}(z, k_\perp) \leq 1,\ \forall\, z$ and $\boldsymbol{k}_\perp$; $\quad \varphi(z) = r f(z)$

$$\Rightarrow \quad r < 1 \qquad \frac{|\delta(z)|}{d(z)} \leq \left[\frac{2e}{f(z)}\,\frac{1-r}{r}\right]^{1/2}$$

To obey the positivity constraint in a most natural and simple way:

$$\frac{\delta(z)}{M^3} = \left[N_q \, \frac{z^\alpha (1-z)^\beta}{\alpha^\alpha \beta^\beta / (\alpha+\beta)^{(\alpha+\beta)}}\right] \, \frac{D_{\Lambda/q}(z)}{\pi[\langle k_\perp^2(z)\rangle]^{3/2}} \, [2e(1-r)/r]^{1/2} \quad (1)$$

with $\alpha, \beta > 0$, $|N_q| \leq 1$.

Qualitative analysis of pp data:

- $P^\Lambda < 0$ AND $P^{\bar{\Lambda}} \simeq 0$ $\quad\Rightarrow\quad$ $N_{u,d} < 0,\ N_s > 0$
- increasing of $|P^\Lambda|$ with x_F $\quad\Rightarrow\quad$ large α, $\beta \simeq O(1)$
- large values of $|P^\Lambda|$ $\quad\Rightarrow\quad$ $r \simeq O(1)$ (similar Gaussian shapes)

$\alpha = 6,\ \beta = 1,\ r = 0.7,\ \sqrt{\langle k_\perp^2(z)\rangle} = 0.61 z^{0.27}(1-z)^{0.2}$ (from pions)

Scenarios:

1. $N_{u,d} = -0.8$, $N_s = 1$ (same weight for up and strange quarks)
2. $N_{u,d} = -0.3$, $N_s = 1$ (à la Burkardt and Jaffe)

Analytical results

- $\nu\, p \to \ell^- \,\Lambda^\uparrow X \qquad P_T^\Lambda = \dfrac{(d+R\,s)\,\Delta^N D_{\Lambda^\uparrow/u} + \bar{u}\,(\Delta^N D_{\Lambda^\uparrow/\bar{d}} + R\,\Delta^N D_{\Lambda^\uparrow/\bar{s}})\,(1-y)^2}{(d+R\,s)\,D_{\Lambda/u} + \bar{u}\,(D_{\Lambda/\bar{d}} + R\,D_{\Lambda/\bar{s}})\,(1-y)^2}$

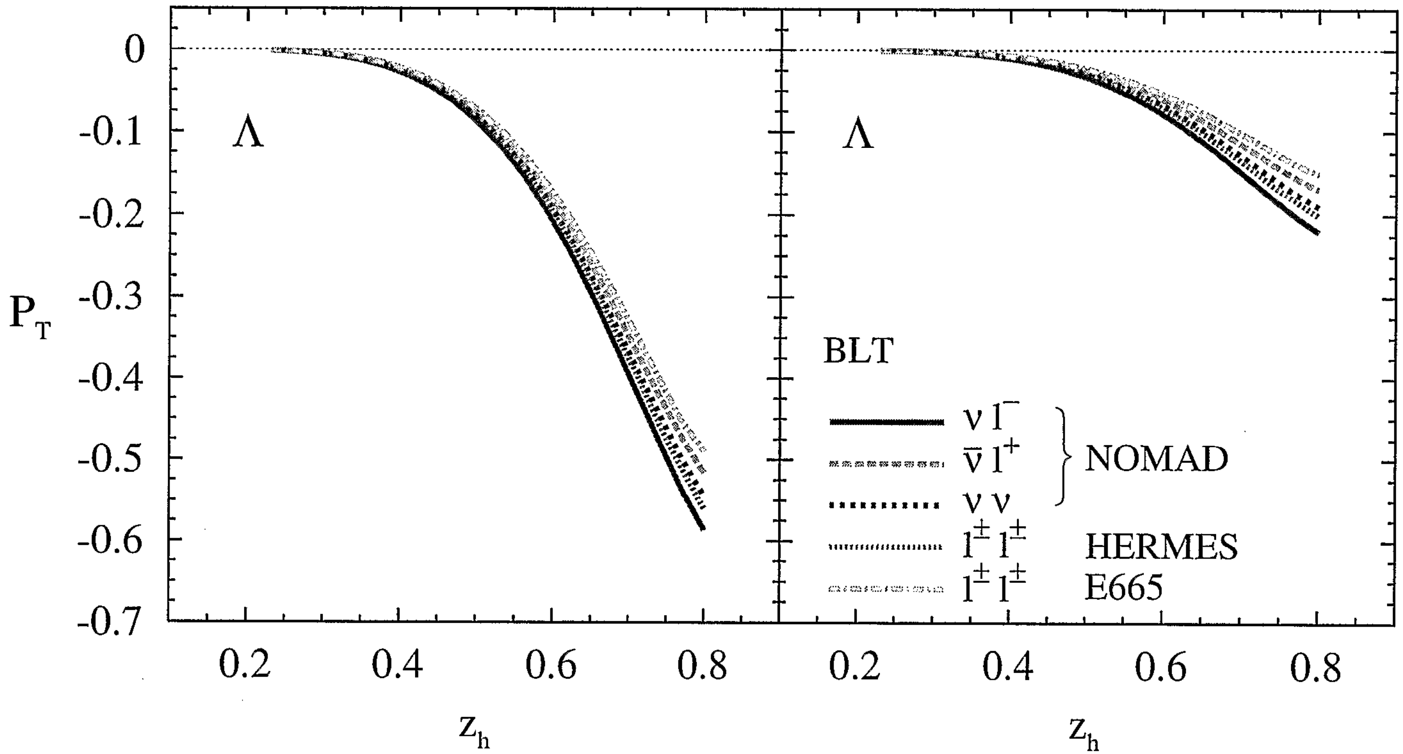
- $\bar{\nu}\, p \to \ell^+ \,\Lambda^\uparrow X \qquad P_T^\Lambda = \dfrac{(1-y)^2 u\,(\Delta^N D_{\Lambda^\uparrow/u} + R\,\Delta^N D_{\Lambda^\uparrow/s}) + (\bar{d}+R\,\bar{s})\,\Delta^N D_{\Lambda^\uparrow/\bar{u}}}{(1-y)^2 u\,(D_{\Lambda/u} + R\,D_{\Lambda/s}) + (\bar{d}+R\,\bar{s})\,D_{\Lambda/\bar{u}}}$

- $\nu\, p \to \nu\,\Lambda^\uparrow X \qquad P_T^\Lambda \simeq \dfrac{(K u+d)\,\Delta^N D_{\Lambda^\uparrow/u} + s\,\Delta^N D_{\Lambda^\uparrow/s}}{(K u+d)\,D_{\Lambda/u} + s\,D_{\Lambda/s}}$

- $\ell\, p \to \ell'\,\Lambda^\uparrow X \qquad P_T^\Lambda \simeq \dfrac{(4u+d)\,\Delta^N D_{\Lambda^\uparrow/u} + s\,\Delta^N D_{\Lambda^\uparrow/s}}{(4u+d)\,D_{\Lambda/u} + s\,D_{\Lambda/s}}$

where $R = \tan^2\theta_c \simeq 0.056$ and $K \simeq 0.555$.

For $z_h > 0.2$ we have $D_{\Lambda/\bar{q}} \ll D_{\Lambda/q}$ and $\Delta^N D_{\Lambda^\uparrow/\bar{q}} \simeq 0$ ($= 0$ in our model)

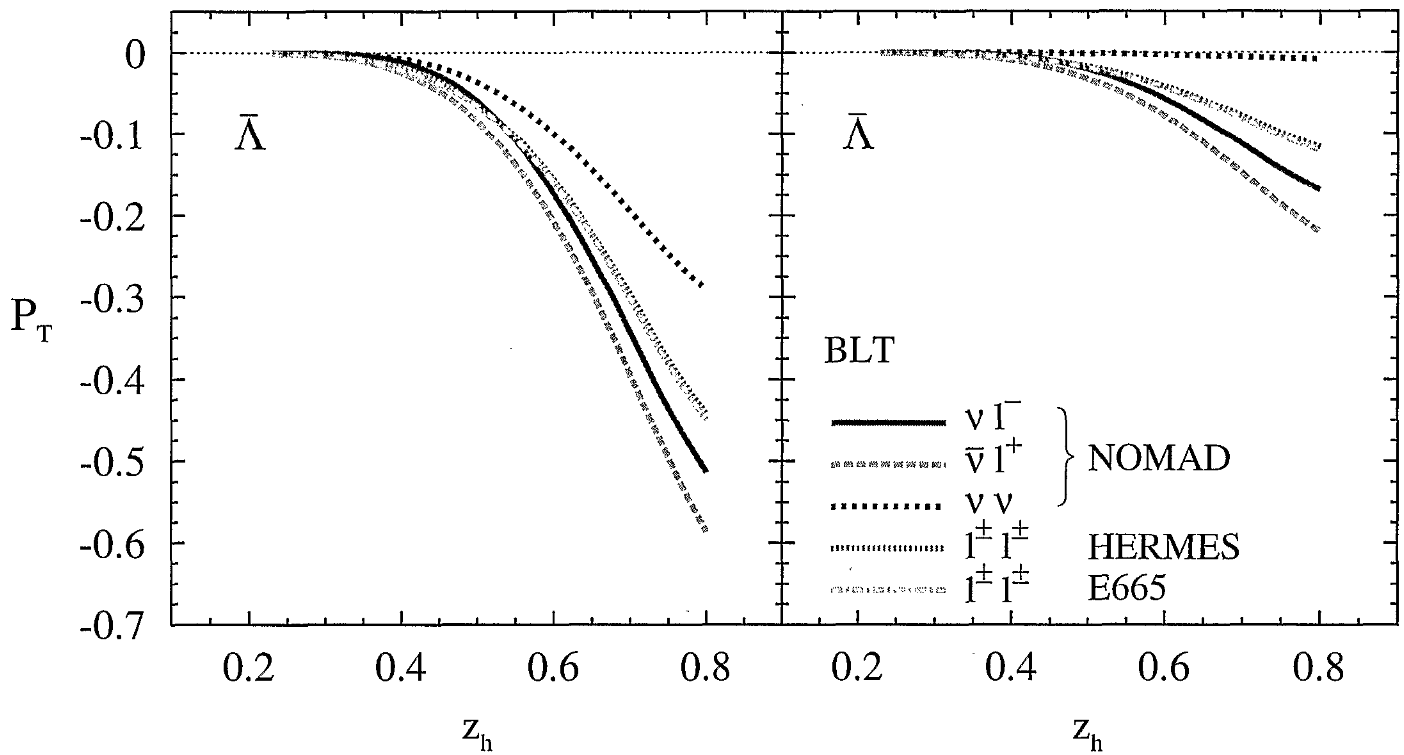


$P_T(\Lambda)$ vs. z_h, integrated over p_T, with a $SU(3)$ symmetric set for the unpolarized FF and with scenario 1 (on the left) and scenario 2 (on the right) for the polarizing FF, for different semi-inclusive DIS processes.

HERMES: $0.023 \leq x \leq 0.4$, $y \leq 0.85$, $1 \leq Q^2 \leq 10$ GeV^2, $E_\Lambda \geq 4.5$ GeV

NOMAD: $\langle x \rangle = 0.22$, $\langle y \rangle = 0.48$, $\langle Q^2 \rangle \simeq 9$ GeV^2

E665: $10^{-3} \leq x \leq 10^{-1}$, $0.1 \leq y \leq 0.8$, $1 \leq Q^2 \leq 2.5$ GeV^2



$P_T(\bar{\Lambda})$ vs. z_h, integrated over p_T, with a $SU(3)$ symmetric set for the unpolarized FF and with scenario 1 (on the left) and scenario 2 (on the right) for the polarizing FF, for different semi-inclusive DIS processes.

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Transversity: h_1 from $p^\uparrow p \to \Lambda^\uparrow X$

$$D_{NN} \equiv \frac{d\sigma^{p^\uparrow p \to \Lambda^\uparrow X} - d\sigma^{p^\uparrow p \to \Lambda^\downarrow X}}{d\sigma^{p^\uparrow p \to \Lambda^\uparrow X} + d\sigma^{p^\uparrow p \to \Lambda^\downarrow X}} = \frac{\Delta_{NN}\sigma}{2\sigma_{\rm unp}} \qquad (2)$$

In collinear partonic configuration, at LO

$$\Delta_{NN}\sigma \sim \sum_{abcd} \int dx_a dx_b \, h_{1a/p}(x_a) \, f_{b/p}(x_b) \, \Delta_{NN}\hat\sigma(x_a, x_b) \, \Delta_T D_{\Lambda/c}(z)$$

$$\Delta_{NN}\hat\sigma \equiv \frac{d\hat\sigma^{a^\uparrow b \to c^\uparrow d}}{d\hat t} - \frac{d\hat\sigma^{a^\uparrow b \to c^\downarrow d}}{d\hat t}$$

$$h_{1a/p} \equiv \Delta_T f_{a/p} \equiv f_{a^\uparrow/p^\uparrow} - f_{a^\downarrow/p^\uparrow} \qquad \Delta_T D_{\Lambda/c} \equiv D_{\Lambda^\uparrow/c^\uparrow} - D_{\Lambda^\downarrow/c^\uparrow}$$

[D. de Florian, J. Soffer, M. Stratmann, W. Vogelsang, PLB(1998)]

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Transversity: h_1 from $\ell\, p^{\uparrow} \to \ell' \Lambda^{\uparrow}\, X \quad (x_F > 0)$

$$P_T = \frac{\sum_q e_q^2\, h_{1q/p}(x)\, \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 f_{q/p}(x) D_{\Lambda/q}(z)}\, \frac{2(1-y)}{1+(1-y)^2} \tag{3}$$

Factorization in variables (test)

$x = Q^2/2p\cdot q \quad y = p\cdot q/p\cdot \ell \quad z = p\cdot p_h/p\cdot q$

$h_{1q/p}$ QCD dynamics $\Delta_T D_{\Lambda/q}$

[M. Anselmino, M. Boglione, F. Murgia, PLB(2000)]

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Conclusions and outlook

- ⇑ PFF $\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp)$ + $\boldsymbol{k}_\perp$- extended pQCD factorization scheme: good description of transverse Λ, $\bar{\Lambda}$ polarization in $p\,A \to \Lambda^\uparrow\,X$;
- ⇓ Unpolarized cross-sections underestimated (data sub-set): $\boldsymbol{k}_\perp$ in the pdf's may give the enhancing (10-100) spin-independent factor (γ, π)
- ⇑ Study of P_T^Λ in unpolarized semi-inclusive DIS ($x_F > 0$): importance of a comparison of different processes (CC vs. NC) to test $\Delta^N D_{\Lambda^\uparrow/q}(z, \boldsymbol{k}_\perp)$;
- ⇑ More data from semi-inclusive DIS to test the z and $\boldsymbol{k}_\perp$ dependence of PFF and from pp reactions at large p_T (RICH);
- ⇑ Importance of $p^\uparrow p \to \Lambda^\uparrow X$ (and $\ell p^\uparrow \to \ell' \Lambda^\uparrow X$) to shed light on h_1.
- ⇑ Similar approach (spin- and $\boldsymbol{k}_\perp$- dependent functions) applied to other Transverse Single Spin Asymmetries: a whole new phenomenology.

B Meson Light-Cone Distribution Amplitudes in Heavy Quark Effective Theory

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Abstract

We discuss the B meson light-cone distribution amplitudes in the heavy-quark limit which are relevant for the QCD factorization approach for the exclusive B meson decays. After giving a brief review on the factorization and the heavy quark effective theory, we derive exact relations between two- and three-particle distribution amplitudes from the QCD equations of motion and heavy-quark symmetry constraint. As solution of these relations, we give representations for the quark-antiquark distribution amplitudes in terms of independent dynamical degrees of freedom. In particular, we find that the Wandzura-Wilczek-type contributions are determined uniquely in analytic form in terms of $\bar{\Lambda}$, a fundamental mass parameter of heavy-quark effective theory. We also comment on the similarity between the B meson light-cone distribution amplitudes and the polarized structure function $g_2(g_T)$.

B Meson Light-Cone Distribution Amplitudes in Heavy Quark Effective Theory

J.Kodaira (Hiroshima)

Phys. Lett. B523 111(2001)
hep-ph/0112146
hep-ph/0112174

"CONTENTS"

in collaboraiton with

H. Kawamura (DESY), C.- F. Qiao (Hiroshima)
K. Tanaka (Juntendo)

♣ Light-Cone Distribution Amplitudes (DAs)

1. Light-Cone DAs

High-Energy QCD Processes and pQCD:
its Importance

Key Word : Factorization Theorem

$\downarrow$

$$\text{Perturbative Parts } (Q^2, \mu_F^2) \otimes \text{Non-Perturbative Parts } (\mu_F^2)$$

$$Q^2 = \text{typical large scale}$$

$$\mu_F = \text{factorization scale}$$

- Perturbative Parts (Old Point of View)

  Perturbation OK $\rightarrow$ Lowest enough (?!)

- Non-Perturbative Parts (Present Point of view)

  Factorization $\rightarrow$ Well Defined Object

  – Universal objects
    We can fix by some experiments
    $\downarrow$
    new prediction for
    other experiments

  – Simple objects
    We have possibility to ask *e.g.*
    $\downarrow$
    Lattice

Examples of Processes for which Factorization holds

- Deep Inelastic Scattering

  Parton (Quark) Distribution Function

$$
\begin{aligned}
W(P\cdot Q\,,\,Q^2) \;\simeq\; & \int d^4z e^{-iq\cdot z} C(z) \\
& \otimes \langle H(P)|\bar{\psi}(z)\Gamma[z,0]\psi(0)|H(P)\rangle \\
& \to z^2 \simeq 0
\end{aligned}
$$

  Γ : generic Dirac Matrix and $Q^2 = -q^2$

  $[z,0]$ is the Link Operator

$$
[z,y] = \mathrm{P}\exp\left(ig\int_0^1 dt(z-y)_\mu A^\mu(tz+(1-t)y)\right)
$$

- $\pi\gamma$ Transition Form Factor

  Light-Cone DAs

$$
\begin{aligned}
F(Q^2) \;\simeq\; & \int d^4z e^{-iq\cdot z} C(z) \\
& \otimes \langle 0|\bar{\psi}(z)\Gamma[z,0]\psi(0)|H(P)\rangle \\
& \to z^2 \simeq 0
\end{aligned}
$$

  Note that

$$
\mathcal{O}(z^2) = \mathcal{O}(1/Q^2)
$$

- Hadron's Electro-magnetic Form Factor
- Hadron Semi-inclusive Production
- ...

2. B Meson Exclusive Decay

Key Word

- CKM Matrix and CP
- Heavy Quark

- Exclusive Semileptonic Decay

$$e.g. \qquad B \to D l \bar{\nu}$$

Isgur & Wise Function

$$\langle D(v')|\bar{c}\Gamma b|\bar{B}(v)\rangle \sim \xi(v \cdot v')$$

- General Framework for $B \to M_1\, M_2$

Fundamental Scale
$M_W \gg m_b \gg \Lambda_{\rm QCD}$
QCD Effects $\geq m_b$ Well-known

$$A(B \to M_1\, M_2) = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle M_1 M_2 | \mathcal{O}_i | B\rangle(\mu)$$

$\mathcal{O}_i$: Weak Effective Hamiltonian (4 − Fermi)
$C_i(\mu)$: Wilson Coefficient
λ_i : Kinematical (CKM) Factor

Question

Can We Estimate $\langle M_1 M_2 | \mathcal{O}_i | B\rangle$?

Old Unjustified Approach

- Naive Factorization Approach
- Hard Scattering (pQCD) Approach

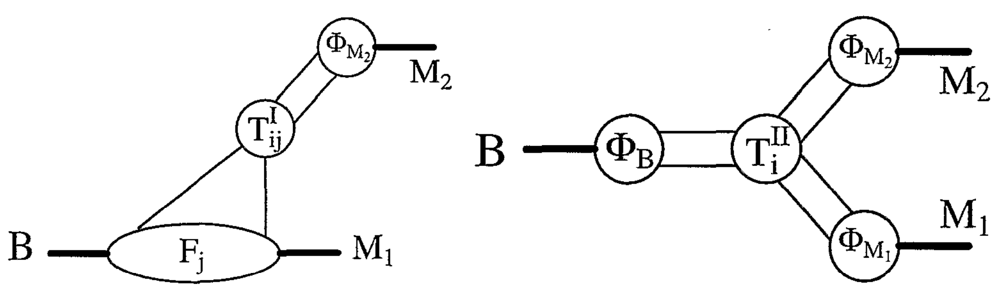
QCD Factorization by

Beneke, Buchalla, Neubert and Sachrajda ('00)
in the Leading Order in $\frac{\Lambda_{\rm QCD}}{m_b}$

$$
\begin{aligned}
&\langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle \\
&\quad = \sum_j F_j^{B\to M_1}(m_2^2) \int_0^1 du\, T_{ij}^I(u) \Phi_{M_2}(u) \\
&\qquad\qquad + (M_1 \leftrightarrow M_2) \\
&\quad + \int_0^1 d\xi du dv\, T_i^{II}(\xi, u, v) \Phi_B(\xi) \Phi_{M_1}(v) \Phi_{M_2}(u)
\end{aligned}
$$

$T^{I,II}$: Hard Part Caluclable in Perturbation
Φ : Light − Cone Distribution Amplitudes
$F_j^{B\to M_1}$: $B \to M_1$Form Factor

Note: when M_1 is Heavy, there is Only First Term



For $B \to \rho\gamma$,$B \to K^* l^+ l^-$ etc

Similar Factorization Holds
Beneke, Feldmann & Seidel ('01)
Bosch & Buchalla ('01)

3. Light-Cone DAs for Light Mesons

Systematic Model-Independent Formalism
Based on
QCD Equations of Motion and (Conformal) Symmetry

For Pseudoscalar Mesons

Lepage & Brodsky ('80) , Chernyak & Zhitnitsky ('84)
Braun & Filyanov ('89) , Ball ('99)

For Vector Mesons

Ball, Braun, Koike & Tanaka ('98)

e.g. for π on
at $z^2 = 0$ up to Twist 3

$$\langle \pi(p)|\bar{q}_\alpha(z)[z,0]q_\beta(0)|0\rangle$$
$$= \frac{if_\pi}{4}\int_0^1 du e^{iup\cdot z}\left[\not{p}\gamma_5\phi(u) - \mu_\pi\gamma_5\left(\phi_p(u) - \sigma_{\mu\nu}p^\mu z^\nu \frac{\phi_\sigma(u)}{6}\right)\right]_{\beta\alpha}$$

where $\quad \mu_\pi = m_\pi^2/(m_q + m_{\bar{q}})$

Light-Cone DAs

- Light Mesons : Well-known
- Heavy (B) Meson : Un-known

1. Heavy Quark Effective Theory (*e.g.* Georgi '90)

Hadron with "Heavy Quark" *e.g.* $\bar{B} = \bar{q}b$

$$m_b \gg \Lambda_{\rm QCD}$$

We can write

$$\begin{aligned} p_b^\mu &= m_b v^\mu + k^\mu \\ \text{with } v^2 &= 1 \ , \ k^\mu = \mathcal{O}(\Lambda_{\rm QCD}) \end{aligned}$$

It is Natural to Write

$$b(x) = e^{-im_b v\cdot x} \left[h_b(x) + H_b(x)\right]$$

h_b and H_b coresspond to Upper (large) and Lower (small) Component Fields

$$P_+ h_b = h_b \ , \ P_- h_b = 0 \ , \ P_+ H_b = 0 \ , \ P_- H_b = H_b$$

$$\text{with} \qquad P_\pm = \frac{1 \pm \not{v}}{2}$$

Lagrangian will be,

$$\mathcal{L}_b = \bar{b}\,(i\,\not{D} - m_b)\,b = \bar{h}_b\, iv\cdot D\, h_b + \mathcal{O}(1/m_b)$$

Physics for h_b

- Massless Deg. of Freedom
- Mass Independent $\to$ Flavor Symmetry
- No Dirac Matrix $\to$ Spin Symmetry

2. B Meson Light-Cone DAs (*e.g.* Grozin & Neubert '97)

$$\langle 0|\bar{q}(z)\Gamma[z,0]h_b(0)|\bar{B}(p)\rangle$$
$$= -\frac{if_B M}{2}\mathrm{Tr}\left[\gamma_5\Gamma\frac{1+\not{v}}{2}\left\{\tilde{\phi}_+(t)+\frac{\tilde{\phi}_-(t)-\tilde{\phi}_+(t)}{2t}\not{z}\right\}\right]$$

where f_B : decay constant, M : B meson mass and

$$z^2=0\ ,\ t=v\cdot z\ ,\ v^2=1\ ,\ p^\mu=mv^\mu$$

Comment:

- Definition of Decay Constant

$$\langle 0|\bar{q}(0)\gamma^\mu\gamma_5 h_b(0)|\bar{B}\rangle \equiv if_B M v^\mu$$

So,

$$\phi_+(0)=\phi_-(0)=1$$

- HQET

$$\not{v}h_b=h_b\rightarrow \text{Only Two DAs}$$

- Meaning of $\tilde{\phi}_+$ and $\tilde{\phi}_-$

Take a Frame: $z_-\neq 0$ and $v_\perp=0$

$$\langle 0|\bar{q}(z)\Gamma[z,0]h_b(0)|\bar{B}(p)\rangle$$
$$= -\frac{if_B M}{2}\mathrm{Tr}\left[\gamma_5\Gamma\frac{1+\not{v}}{2}\left\{\tilde{\phi}_+(t)v_+\gamma_-+\tilde{\phi}_-(t)v_-\gamma_+\right\}\right]$$

If B is moving fast in $+$ direction ($v_+\gg v_-$),

$$\tilde{\phi}_+(t):\text{leading Twist}\quad ,\quad \tilde{\phi}_-(t):\text{sub}-\text{leading Twist}$$

$$\text{BUT}\qquad v_+=v_-$$

♣ QCD Equations of Motion

1. Some Formulae

   Derivative of Wilson line

$$
\begin{aligned}
\frac{\partial}{\partial x_\mu}[ux, vx] &= iguA^\mu(ux)[ux, vx] - igv[ux, vx]A^\mu(vx) \\
&\quad + \int_v^u dtt[ux, tx]igG^{\mu\nu}(tx)x_\nu[tx, vx]
\end{aligned}
$$

   Translation (total derivative) of Wilson line

$$
\begin{aligned}
\partial^\mu[ux, vx] &\equiv \frac{\partial}{\partial y_\mu}[ux + y, vx + y]\big|_{y=0} \\
&= igA^\mu(ux)[ux, vx] - ig[ux, vx]A^\mu(vx) \\
&\quad + \int_v^u dt[ux, tx]igG^{\mu\nu}(tx)x_\nu[tx, vx]
\end{aligned}
$$

2. Operator Identities (EXACT !!)

   For arbitrary strings of Dirac matrices Γ

   Suppress Wison Link Operator

$$
\begin{aligned}
\frac{\partial}{\partial z^\mu}\bar{q}(z)\Gamma h_b(0) &= \bar{q}(z)\overleftarrow{D}_\mu\,\Gamma h_b(0) \\
&\quad + \int_0^1 du\,u\,\bar{q}(z)\,igG_{\mu\alpha}(uz)z^\alpha\Gamma h_b(0) \\
\partial_\mu[\bar{q}(z)\Gamma h_b(0)] &= \bar{q}(z)\overleftarrow{D}_\mu\,\Gamma h_b(0) + \bar{q}(z)\Gamma D_\mu h_b(0) \\
&\quad + \int_0^1 du\,\bar{q}(z)\,igG_{\mu\alpha}(uz)z^\alpha\Gamma h_b(0)
\end{aligned}
$$

   If the first term will be eliminated,

$$
\begin{aligned}
&\frac{\partial}{\partial z^\mu}\bar{q}(z)\Gamma h_b(0) - \partial_\mu[\bar{q}(z)\Gamma h_b(0)] \\
&= -\bar{q}(z)\Gamma D_\mu h_b(0) + \int_0^1 du(u-1)\bar{q}(z)\,igG_{\mu\alpha}(uz)z^\alpha\Gamma h_b(0)
\end{aligned}
$$

3. QCD Equations of Motion

$$\bar{q} \overleftarrow{\not{D}} = (v \cdot D)\, h_b = 0$$

Therefore

- $\Gamma \to \gamma^\mu \Gamma$ in the first eq.

$$\frac{\partial}{\partial z^\mu} \bar{q}(z) \gamma^\mu \Gamma h_b(0) = \int_0^1 du\, u\, \bar{q}(z)\, igG_{\mu\alpha}(uz) z^\alpha \gamma^\mu \Gamma h_b(0)$$

- Cotract the third eq. with v^μ

$$v^\mu \frac{\partial}{\partial z^\mu} \bar{q}(z) \Gamma h_b(0) - v^\mu \partial_\mu [\bar{q}(z) \Gamma h_b(0)] = \int_0^1 du\, (u-1)\, \bar{q}(z)\, igv^\mu G_{\mu\alpha}(uz) z^\alpha \Gamma h_b(0)$$

4. Parametrization of Matrix Elements

- Left-hand Side: Already Known

Note:

$$i\partial^\mu \left(\bar{q} \Gamma h_b \right) = [\bar{q} \Gamma h_b\, , \, \hat{P}^\mu] - m_b v^\mu \bar{q} \Gamma h_b$$

- Three Fock Component

Most General compatible with Lorentz and HQET

$$\langle 0 | \bar{q}(z)\, gG_{\mu\nu}(uz)\, z^\nu\, \Gamma\, h_v(0) | \bar{B}(p) \rangle = \frac{1}{2} f_B M\, \mathrm{Tr} \left[\gamma_5\, \Gamma\, \frac{1+\not{v}}{2} \Big\{ (v_\mu\, \not{z} - t\, \gamma_\mu) \left(\tilde{\Psi}_A(t,u) - \tilde{\Psi}_V(t,u) \right) - i\, \sigma_{\mu\nu} z^\nu\, \tilde{\Psi}_V(t,u) + \frac{z_\mu}{t} (\not{z} - t)\, \tilde{X}_A(t,u) \Big\} \right]$$

♣ Equations to be Solved

1. 1st Identity: $\bar{q}\overleftarrow{\not{D}} = 0$

$$\frac{d\tilde{\phi}_-(t)}{dt} - \frac{1}{t}\left(\tilde{\phi}_+(t) - \tilde{\phi}_-(t)\right) = 2t\int_0^1 du\, u\,(\tilde{\Psi}_A(t,u) - \tilde{\Psi}_V(t,u)) \quad (1)$$

$$\frac{d\tilde{\phi}_+(t)}{dt} - \frac{d\tilde{\phi}_-(t)}{dt} - \frac{1}{t}\left(\tilde{\phi}_+(t) - \tilde{\phi}_-(t)\right) + 4t\frac{\partial\tilde{\phi}_+(t)}{\partial z^2} = 2t\int_0^1 du\, u\,(\tilde{\Psi}_A(t,u) + 2\,\tilde{\Psi}_V(t,u) + \tilde{X}_A(t,u)) \quad (2)$$

where

$$\frac{\partial\tilde{\phi}_+(t)}{\partial z^2} \equiv \left.\frac{\partial\tilde{\phi}_+(t,x^2)}{\partial x^2}\right|_{x^2\to 0}$$

2. 2nd Identity: $(v\cdot D)\,h_b = 0$

$$\frac{d\tilde{\phi}_+(t)}{dt} - \frac{1}{2t}\left(\tilde{\phi}_+(t) - \tilde{\phi}_-(t)\right) + i\bar{\Lambda}\tilde{\phi}_+(t) + 2t\frac{\partial\tilde{\phi}_+(t)}{\partial z^2} = t\int_0^1 du\,(u-1)\,(\tilde{\Psi}_A(t,u) + \tilde{X}_A(t,u)) \quad (3)$$

$$\frac{d\tilde{\phi}_+(t)}{dt} - \frac{d\tilde{\phi}_-(t)}{dt} + \left(i\bar{\Lambda} - \frac{1}{t}\right)\left(\tilde{\phi}_+(t) - \tilde{\phi}_-(t)\right) + 2t\left(\frac{\partial\tilde{\phi}_+(t)}{\partial z^2} - \frac{\partial\tilde{\phi}_-(t)}{\partial z^2}\right) = 2t\int_0^1 du\,(u-1)\,(\tilde{\Psi}_A(t,u) + \tilde{X}_A(t,u)) \quad (4)$$

where

$$\bar{\Lambda} = M - m_b = \frac{iv\cdot\partial\langle 0|\bar{q}\Gamma h_v|\bar{B}(p)\rangle}{\langle 0|\bar{q}\Gamma h_v|\bar{B}(p)\rangle}$$

"effective mass" of meson states in the HQET

3. t Dependence

From (1)

$$\frac{d\tilde{\phi}_-(t)}{dt} - \frac{1}{t}\left(\tilde{\phi}_+(t) - \tilde{\phi}_-(t)\right) = 2t\int_0^1 du\, u\,(\tilde{\Psi}_A(t,u) - \tilde{\Psi}_V(t,u))$$

Eliminate $\partial\tilde{\phi}_+(t)\,/\,\partial z^2$ from (2) & (3)

$$\frac{d\tilde{\phi}_+(t)}{dt} + \frac{d\tilde{\phi}_-(t)}{dt} + 2i\bar{\Lambda}\tilde{\phi}_+(t) = -2t\int_0^1 du\,\left(\tilde{\Psi}_A(t,u) + \tilde{X}_A(t,u) + 2u\,\tilde{\Psi}_V(t,u)\right)$$

To Sove These, Go to the Momentum Space

$$\begin{aligned}\tilde{\phi}_\pm(t) &= \int d\omega\; e^{-i\omega t}\phi_\pm(\omega)\\ \tilde{F}(t,u) &= \int d\omega d\xi\; e^{-i(\omega+\xi u)t}F(\omega,\xi)\;,(F = \{\Psi_V, \Psi_A, X_A\})\end{aligned}$$

In the Frame $z_\perp \neq 0$

ωv^+ : Light-Cone Projection k^+ of $\bar{q}$

ωv^+ , ξv^+ : Light-Cone Projection of $\bar{q}$, g

Note:

$\partial\tilde{\phi}_+(t)\,/\,\partial z^2$ Contains Information on $k_\perp$ Distributions

$$\begin{aligned}\omega\frac{d\phi_-(\omega)}{d\omega} &+ \phi_+(\omega) = I(\omega)\\ (\omega - 2\bar{\Lambda})\,\phi_+(\omega) &+ \omega\phi_-(\omega) = J(\omega)\end{aligned}$$

where $I(\omega)$, $J(\omega)$: Functions of Ψ_V, Ψ_A, X_A

4. Wandzure-Wilczek Approximation and Solution

Wandzure-Wilczek Approximation

Neglect Higher Fock States

Under WW Approximation, $I(\omega) = J(\omega) = 0$

Equation Can be Solved !!

From 1st Eq, (Beneke & Feldmann '01)

$$\phi_-^{(WW)}(\omega) = \int_\omega^\infty d\rho \, \frac{\phi_+^{(WW)}(\rho)}{\rho}$$

Explicit Analytic Solution

$$\begin{aligned} \phi_+^{(WW)}(\omega) &= \frac{\omega}{2\bar{\Lambda}^2}\theta(2\bar{\Lambda} - \omega) \\ \phi_-^{(WW)}(\omega) &= \frac{2\bar{\Lambda} - \omega}{2\bar{\Lambda}^2}\theta(2\bar{\Lambda} - \omega) \end{aligned}$$

Note:

Equations Can be Formaly Solved
if Ψ_V, Ψ_A, X_A are Given

♣ Summary

QCD Factoization for Exclusive B Meson Decays

$\Downarrow$

B Meson Light-Cone DAs for $m_b \to \infty$

- Heavy-quark Symmetry
- QCD (HQET) Equations of Motion

$\Downarrow$

Exact Analytic Solution for Quark-antiquark DAs

- Explicit Analytic Solution for WW-part in terms of $\bar{\Lambda}$
- Integral Sol. for Three-particle Contributions

Some Interesting Features:

- Both Leading and Higher Twist ϕ_+, ϕ_- Receive Three-particle Contributions
- $\phi_+^{(WW)}(\omega) \sim \omega$, $\phi_-^{(WW)}(\omega) \sim \text{const}$ as $\omega \to 0$

Some Remarks:

- Sharp Behavior at $\omega = 2\bar{\Lambda}$: "Distributions"
- Dominance of WW $\phi_\pm(\omega) \approx \phi_\pm^{(WW)}(\omega)$ is Expected
- Light-Cone DAs for Vector Meson B^* are also Determined thanks to Heavy-Quark Spin Symmetry

Our Solution: Powerful!

- Building up B Meson Light-Cone DAs
- Phenomenological Applications (exclusive B decays, ...)

All Relevant QCD Constraints are Satisfied!

SINGLE TRANSVERSE-SPIN ASYMMETRIES

A_N AT RHIC

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February 22, 2002

Table of Contents:

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*Some related references: J.Q. and G. Sterman, Phys. Rev. Lett. 67, 2264 (1991); Nucl. Phys. B378, 52 (1992); Phys. Rev. D59, 014004 (1999); D. Boer and J.Q., Phys. Rev. D65, 034008 (2002); C. Kouvaris, J.Q., and W. Vogelsang, in preparation.

1. INTRODUCTION

- Single Spin Process at RHIC:

$$A(p, \vec{s}) + B(p') \Longrightarrow C(\ell) + X$$

  - only one initial-state hadron is polarized
  - observed particle $C(\ell)$ is unpolarized, and can be any high transverse momentum particle π, p, γ, or lepton
  - cross section: $\sigma(\ell, \vec{s})$

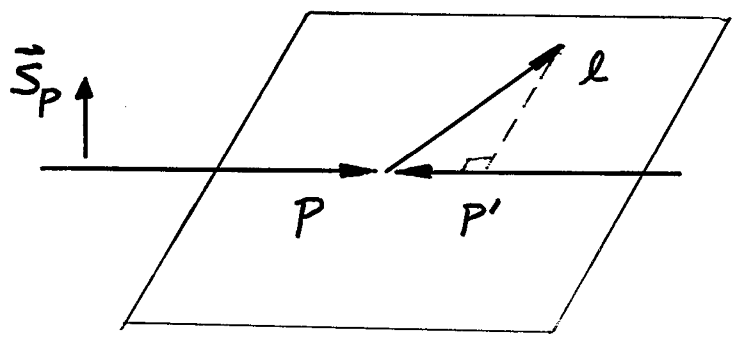
- Single Spin Asymmetry – definition:
  - Spin-avg X-section: $\sigma(\ell) = \frac{1}{2}[\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})]$
  - Spin-dep X-section:
    $$\Delta\sigma(\ell, \vec{s}) = \frac{1}{2}[\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})]$$
  - Single-spin asymmetry:
    $$A(\ell, \vec{s}) \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$
  - Single longitudinal-spin asymmetry: A_L
    particle spin $\vec{s}$ is parallel to its momentum $\vec{p}$
  - Single transverse-spin asymmetry: A_N
    particle spin $\vec{s}$ is perpendicular to its momentum $\vec{p}$

Even though X-section $\sigma(\ell, \vec{s})$ is finite, single spin asymmetry can vanish due to fundamental symmetries of interactions

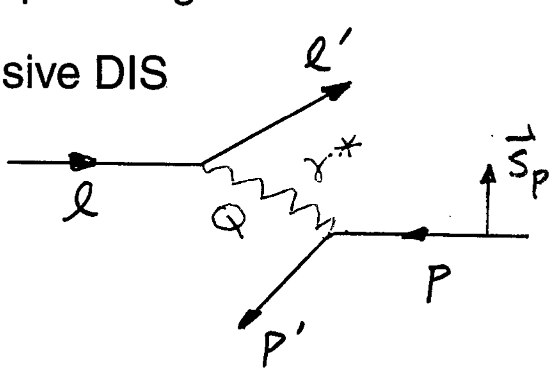
- Parity and time-reversal invariance
  $\Rightarrow A_N = 0$ for inclusive DIS
  - Inclusive DIS X-section:
  $$\sigma(\vec{s}_T) \propto L^{\mu\nu}\, W_{\mu\nu}(\vec{s}_T)$$
  - Hadronic tensor:
  $$W_{\mu\nu}(\vec{s}_T) \propto \langle P, \vec{s}_T |\, j^\dagger_\mu(0)\, j_\nu(y)\, | P, \vec{s}_T \rangle$$
  - Parity and time-reversal invariance:
  $$\begin{aligned} &\langle P, \vec{s}_T |\, j^\dagger_\mu(0)\, j_\nu(y)\, | P, \vec{s}_T \rangle \\ &\qquad = \langle P, -\vec{s}_T |\, j^\dagger_\nu(0)\, j_\mu(y)\, | P, -\vec{s}_T \rangle \end{aligned}$$
  $$\Rightarrow\ W_{\mu\nu}(\vec{s}_T) = W_{\nu\mu}(-\vec{s}_T)$$
  - Spin-dependent X-section:
  $$\begin{aligned} \Delta\sigma(\vec{s}_T) &\propto L^{\mu\nu}\, \left[W_{\mu\nu}(\vec{s}_T) - W_{\mu\nu}(-\vec{s}_T)\right] \\ &= L^{\mu\nu}\, \left[W_{\mu\nu}(\vec{s}_T) - W_{\nu\mu}(\vec{s}_T)\right] = 0 \end{aligned}$$
  because $L^{\mu\nu}$ is symmetric for a unpolarized lepton
  - Above result is valid for any two-current correlators

- Parity conserved interactions $\Rightarrow A_L = 0$

- Single spin asymmetries correspond to T-odd triple product: $A_N \propto i\,\vec{s}_p \cdot (\vec{p} \times \vec{\ell})$
  - $\vec{p}$ is beam particle's three momentum
  - $\vec{\ell}$ is momentum of observed particle
  - the phase "i" is required by time-reversal invariance
  - covariant form: $A_N \propto i\epsilon^{\mu\nu\alpha\beta}\, p_\mu s_\nu \ell_\alpha p'_\beta$

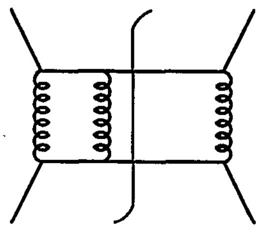


- Nonvanishing A_N requires a phase, a spin flip, and enough vectors to fix a scattering plan
  - Inclusive DIS does not have enough vectors
    Note: q and p can only fix a line
- Following examples can generate nonvanishing A_N:
  - Single hadron (or photon) at high ℓ_T
  - Drell-Yan lepton angular distribution
  - Semi-inclusive DIS
  - ...

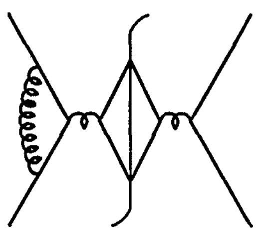


2. A_N FOR SINGLE HADRON PRODUCTION

- pQCD was first used to study single transverse-spin asymmetry by Kane, Pumplin, and Repko in 1978



+ c.c.

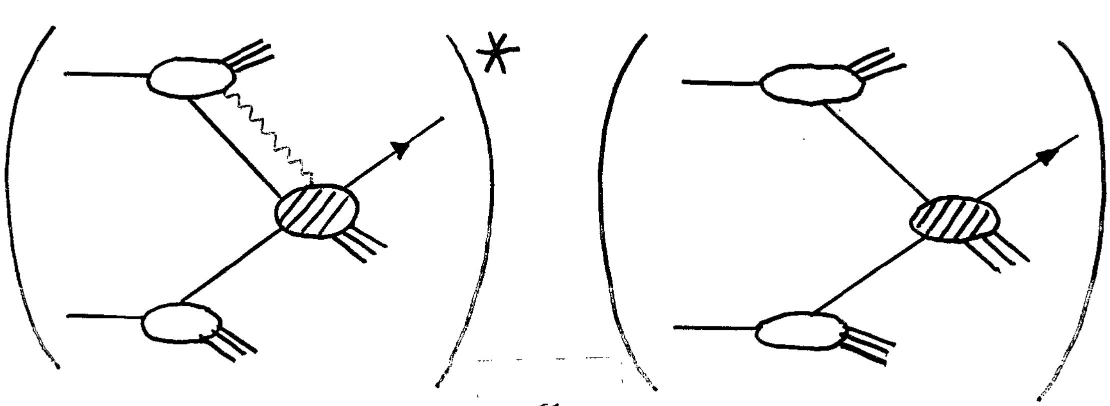


+ c.c.

  - imaginary part of the loop provides the phase
  - quark mass provides the needed spin flip
  - $A_N \propto \frac{m_q}{\ell_T} \langle p, \vec{s}_T | \bar{\psi} \Gamma \psi | p, \vec{s}_T \rangle$ where $\Gamma = \gamma^+ \gamma_5 \gamma_T, ...$

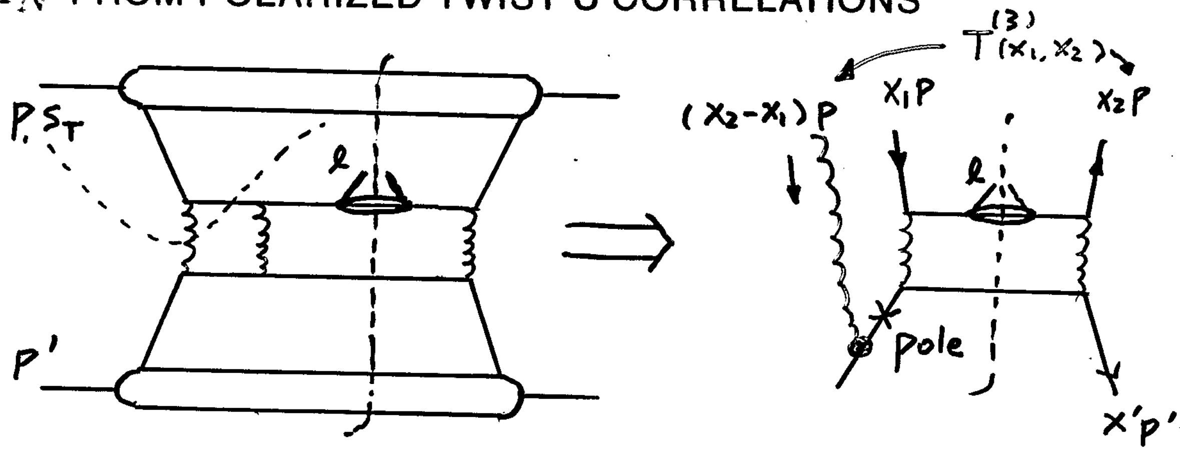
- The fact that $A_N \propto m_q$ indicates that A_N is a twist-3 effect in QCD perturbation theory

- QCD dynamics is much richer than the parton model
  - twist-3 arises from "intrinsic" k_T
    $\Rightarrow \; A_N \propto T_{k_T} \sim \langle p, \vec{s}_T | \bar{\psi} \Gamma \partial_T \psi | p, \vec{s}_T \rangle$
  - twist-3 from interference between a quark state and a quark-gluon state
    $\Rightarrow \; A_N \propto T_{A_T} \sim \langle p, \vec{s}_T | \bar{\psi} \Gamma A_T \psi | p, \vec{s}_T \rangle$



+ c.c.

A_N FROM POLARIZED TWIST-3 CORRELATIONS



- Unpinched pole $\Rightarrow\ i\delta(x_1 - x_2)$
- Color gauge invariance combines T_{k_T} and T_{A_T} to

$$T_{D_T}(x_1, x_2) \quad \propto \quad \langle p, \vec{s}_T | \bar{\psi}\Gamma D_T \psi | p, \vec{s}_T \rangle$$

$$T_F(x_1, x_2) \quad \propto \quad \langle p, \vec{s}_T | \bar{\psi}\Gamma F_T^+ \psi | p, \vec{s}_T \rangle$$

- $A_N \neq 0$ requires
  - $T(x_1, x_2, \vec{s}_T) \neq 0$ when $x_1 = x_2$
  - $T(x_1, x_2, \vec{s}_T) \neq T(x_1, x_2, -\vec{s}_T)$
  - Combination of $T(x_1, x_2, \vec{s}_T)$ and partonic part is real

  $\Rightarrow\ A_N \propto T_F(x_1, x_2)$ with $x_1 = x_2$, and

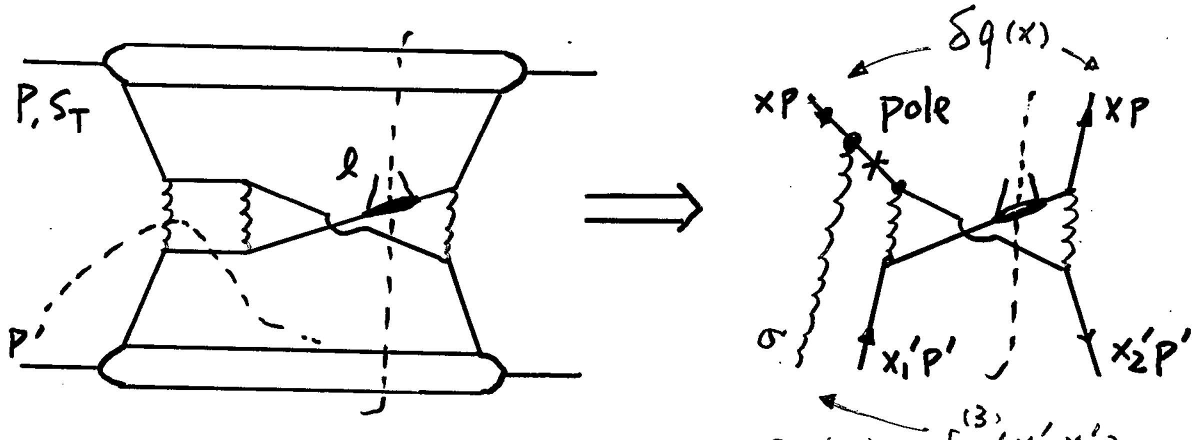
$$T_F(x_1, x_2) = \int \frac{dy_1^- dy_2^-}{4\pi} \mathrm{e}^{ix_1 P^+ y_1^- + i(x_2 - x_1)P^+ y_2^-}$$

$$\times \langle P, \vec{s}_T | \bar{\psi}_a(0)\gamma^+ \left[\epsilon^{s_T \sigma n \bar{n}} F_\sigma^{\ +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- Three field operator does not have the probability interpretation of normal parton distributions

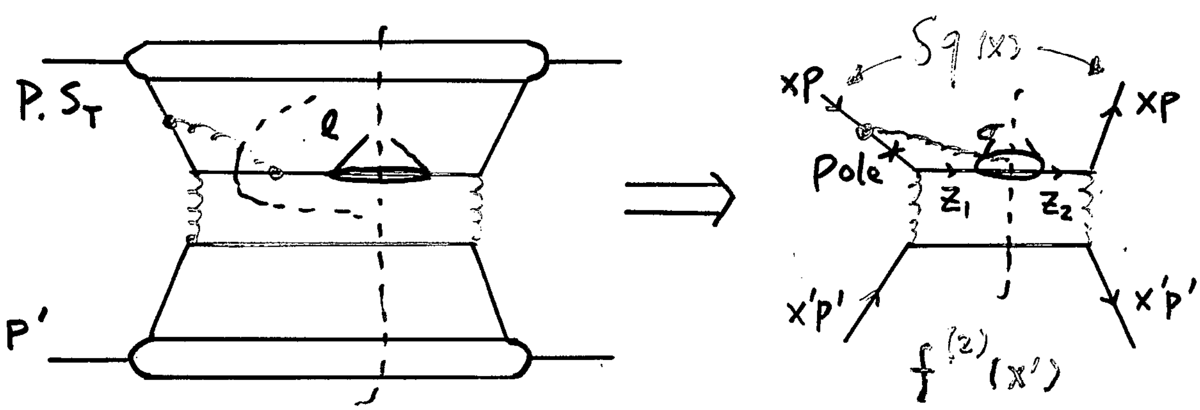
A_N FROM TWIST-2 TRANSVERSITY DISTRIBUTION

- Twist-3 initial-state unpolarized correlation[a]



  - even γ's in operator definition of $\delta q(x)$
    $\Rightarrow$ much smaller number of diagrams
  - double suppression from $\delta q(x)$ and chiral-odd twist-3 correlation function
  - contribution to A_N is a factor of 5-10 smaller than that from polarized initial-state T_F

- Twist-3 unpolarized fragmentation function



  - Expect to be of similar size, and much smaller than that from polarized initial-state T_F

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[a] Y. Kanazawa and Y. Koike, Phys. Lett. B490 (2000) 99

- Generalized factorization formula for hadronic single transverse-spin asymmetries

$$\begin{aligned}\Delta\sigma_{AB\to h}(\vec{s}_T) = & \sum_{abc} T^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes f_{b/B}(x') \\ & \otimes \hat{\sigma}_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z) \\ & + \sum_{abc} \delta q^{(2)}_{a/A}(x, \vec{s}_T) \\ & \otimes \Big\{ f_{b/B}(x') \otimes \hat{\sigma}'_{ab\to c}(\vec{s}_T) \otimes D^{(3)}_{c\to h}(z_1, z_2) \\ & + f^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}''_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z) \Big\}\end{aligned}$$

- $\hat{\sigma}$, $\hat{\sigma}'$, and $\hat{\sigma}''$ are perturbatively calculable

- T,P–invariance $\longrightarrow$ at least one function has TWO x's

- Chiral-odd $\delta q(x)$ requires chiral-odd $f^{(3)}_{b/B}$ and $D^{(3)}_{c\to h}$
  $\Rightarrow$ first term is larger than the other two

- Can generalize $\otimes$ to convolution in k_T for both initial-state and final-state interactions
  - Initial-state $k_T \Rightarrow$ Sivers effect

    D. Sivers, Phys. Rev. D43 (91) 261;

    M. Anselmino et al., Phys. Lett. B362 (95) 164; ...
  - Final-state $k_T \Rightarrow$ Collins effect

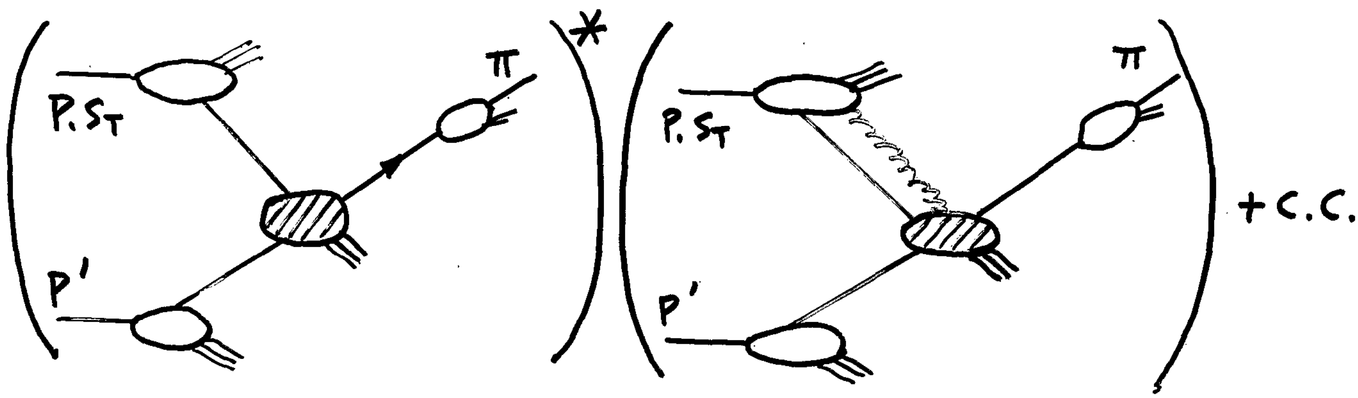
    J. Collins, Nucl. Phys. B396 (93) 161;

    R.L. Jaffe, et al., Phys. Rev. Lett. 80 (1998) 1166; ...

LEADING CONTRIBUTION TO THE ASYMMETRY OF PION PRODUCTION

- Minimal approach (collinear factorization):

$$\Delta\sigma_{AB\to h}(\vec{s}_T) \approx \sum_{abc} T^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes f_{b/B}(x')$$
$$\otimes\, \hat{\sigma}_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z)$$



- Keep only quark fragmentation
  - observed momentum: $\ell_T^2 \propto x x' z^2 S$
  - parton distributions are steeply falling as $x \to 1$ e.g., $f_q(x) \propto (1-x)^\alpha$ with $\alpha > 3-4$
  - quark fragmentation function falls slower as $z \to 1$ e.g., $D_{q\to\pi}(z) \propto (1-z)^{n_q}$ with $n_q \sim 2$

    $\Rightarrow$

    X-section is dominated by small $x \sim x'$ and large z

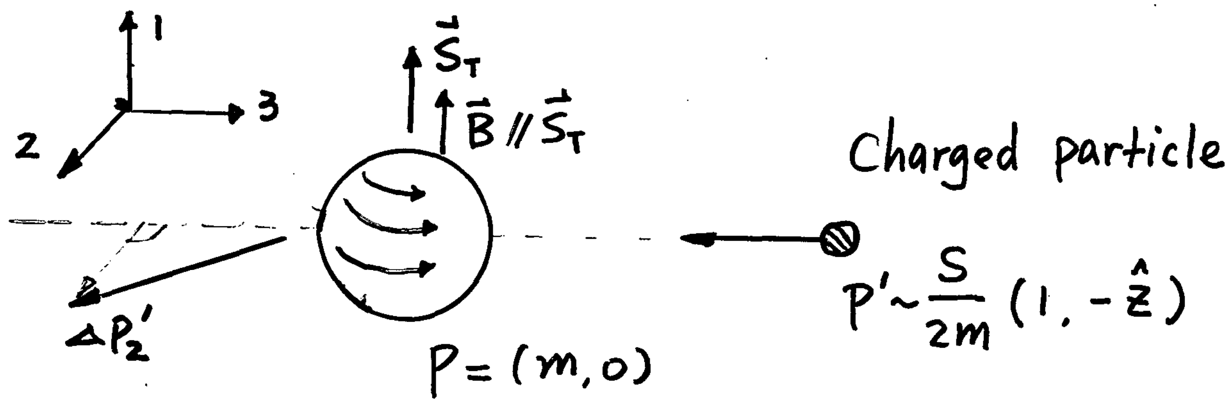
- Need gluon fragmentation contribution at low ℓ_T and large S

WHAT $T_F(x,x)$ TELLS US?

$$T_F(x,x) \propto \langle P, \vec{s}_T | \bar{\psi}_a(0)\gamma^+ \left[\int dy_2^- \, \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- a classical (Abelian) analog:

  rest frame of $(p, \vec{s}_T)$



  - change of transverse momentum

$$\frac{d}{dt} p_2' = e(\vec{v}' \times \vec{B})_2 = -e v_3 B_1 = e v_3 F_{23}$$

  - in the c.m. frame

$$(m, \vec{0}) \to \bar{n} = (1, 0, 0_T), \quad (1, -\hat{z}) \to n = (0, 1, 0_T)$$

$$\Longrightarrow \quad \frac{d}{dt} p_2' = e \, \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}$$

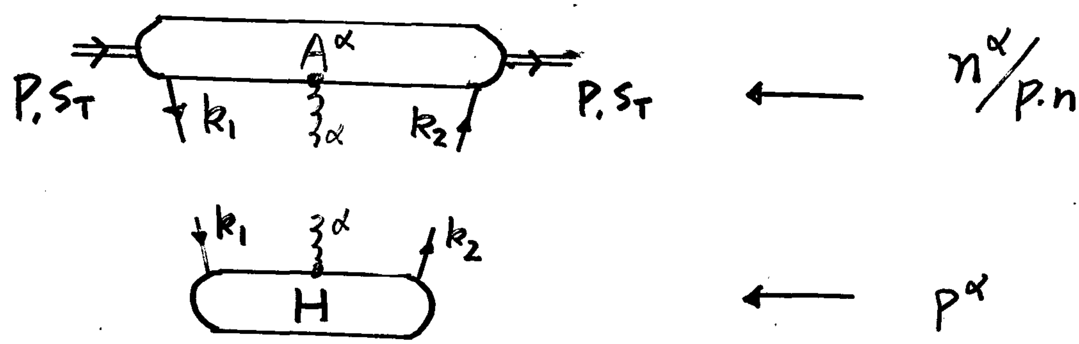
  - total change: $\Delta p_2' = e \int dy^- \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}(y^-)$

- Color field strength $F^{+\sigma}$ alone is not gauge invariant

- T_F represents a fundamental quantum correlation between quark and gluon inside a hadron

Technical steps to calculate the asymmetries

— in a color covariant gauge



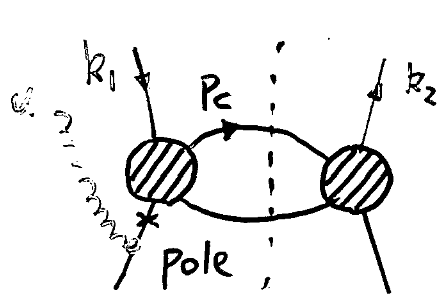
- gluon field: $A^\alpha \to n \cdot A = A^+$
- expand $H(k_1, k_2)$ to linear in k_T

$$H(k_1,k_2) \to H(x_1 p, x_2 p) + \frac{\partial H}{\partial k_{2_\sigma}}(k_{2_T} - k_{1_T})^\sigma + \ldots$$

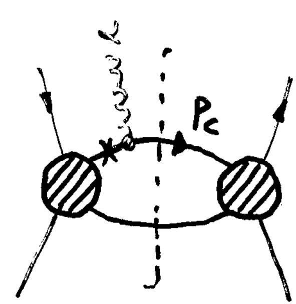
- convert $(k_{2_T} - k_{1_T})^\sigma A^+ \to \partial^\sigma A^+ \to F^{\sigma +}$
- factorized formula:

$$\Delta\sigma(\vec{s}_T) = \int dx_1 dx_2\, T_F(x_1, x_2) \left[i\epsilon^{\sigma s_T n \bar{n}} \frac{\partial H}{\partial k_{2_\sigma}} \right]_{k_{2_T}=0}$$

- either x_1 or x_2 is fixed by the pole in partonic part.

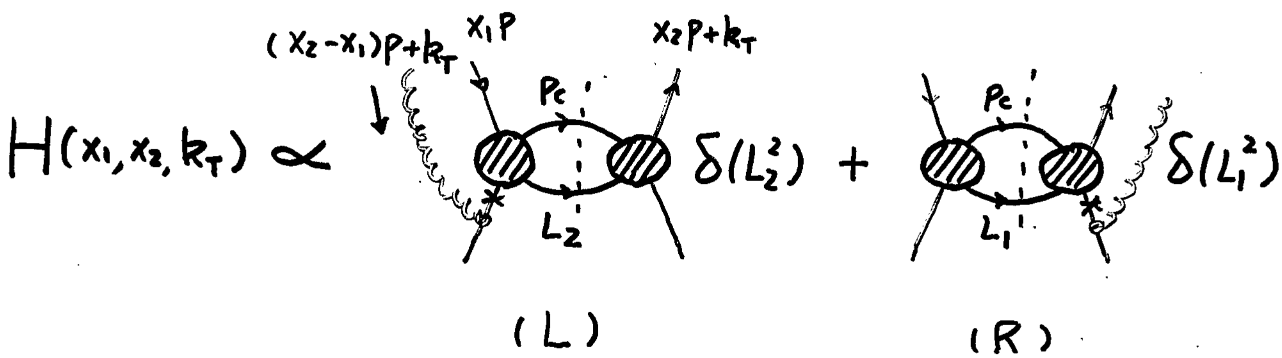


Initial-state



Final-state

Contribution from initial-state interaction



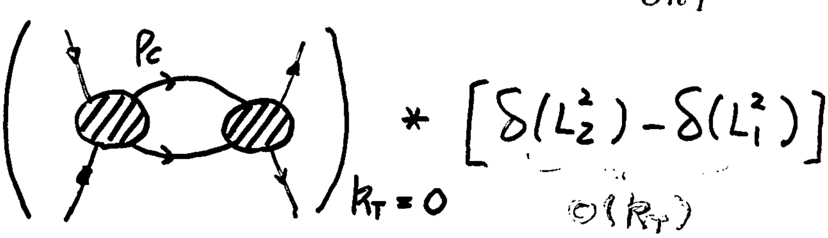
- Soft-gluon pole gives the needed phase:

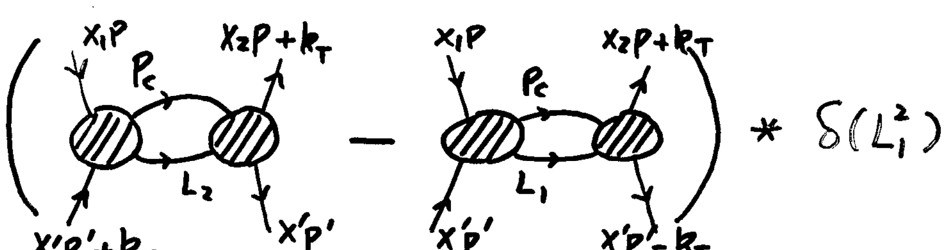
$$\frac{1}{x_2 - x_1 + i\epsilon} \rightarrow -i\pi\delta(x_2 - x_1)$$

- Two type contributions to partonic $\frac{\partial H}{\partial k_T}$:

$L_2 = x_2 P + x'p' - P_c + k_T$

$L_1 = x_1 P + x'p' - P_c$





  - phase space δ-functions $\Rightarrow$ derivative term

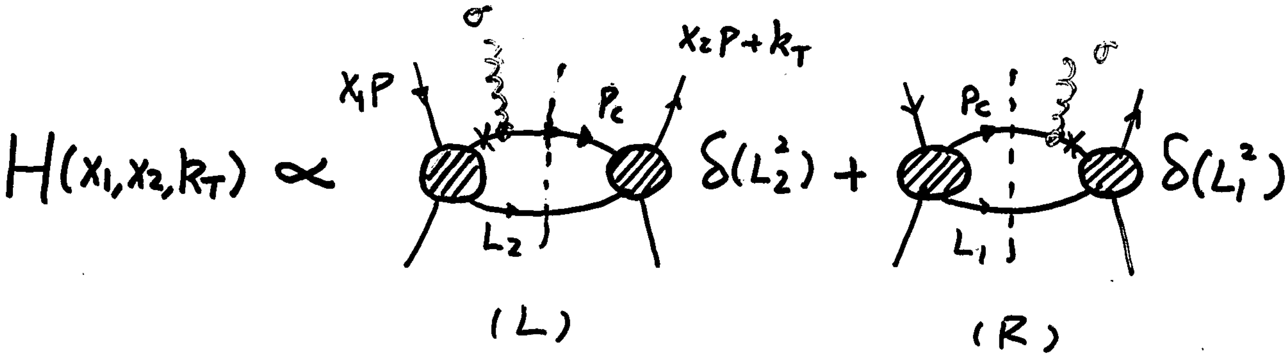
    $\delta(L_2^2) - \delta(L_1^2) \approx \delta'(L_1^2)(-2p_c \cdot k_T) \Rightarrow x\frac{d}{dx}T_F(x, x)$

  - non-derivative term

    $(L) - (R) \propto \frac{2p_c \cdot k_T}{\hat{u}} \Rightarrow T_F(x, x)$

- in forward region, $x\frac{d}{dx}T_F(x, x) \gg T_F(x, x)$
  because $T_F(x, x) \propto (1 - x)^{\alpha}$ as $x \rightarrow 1$.

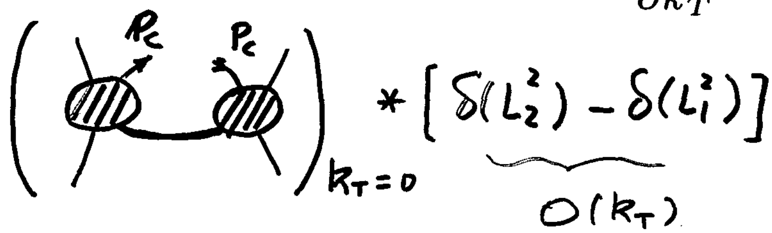
CONTRIBUTION FROM FINAL-STATE INTERACTION

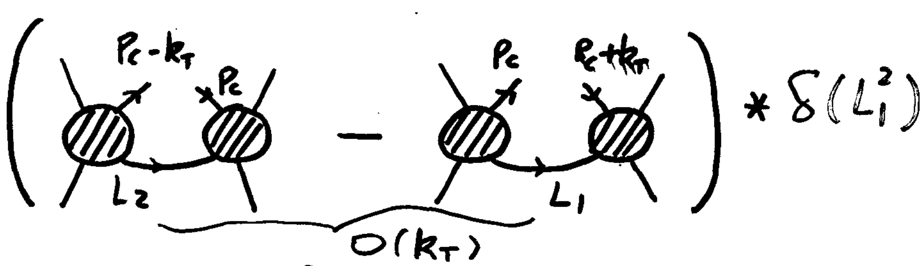


- Soft-gluon pole gives the needed phase:

$$\frac{-1}{x_2 - x_1 + \frac{p_c \cdot k_T}{p_c \cdot p} - i\epsilon} \to -i\pi\delta(x_2 - x_1 + \frac{p_c \cdot k_T}{p_c \cdot p})$$

- Two type contributions to partonic $\frac{\partial H}{\partial k_T}$:





  - phase space δ-functions $\Rightarrow$ derivative term

    $\delta(L_2^2) - \delta(L_1^2) \approx \delta'(L_1^2)(-2p_c \cdot k_T) \Rightarrow x\frac{d}{dx}T_F(x,x)$

  - non-derivative term

    $(L) - (R) \propto \left[\frac{2p_c \cdot k_T}{\hat{u}} + \frac{2p_c \cdot k_T}{\hat{t}}\right] \Rightarrow T_F(x,x)$

- most contribution to $A_N \propto \ell_T/u$

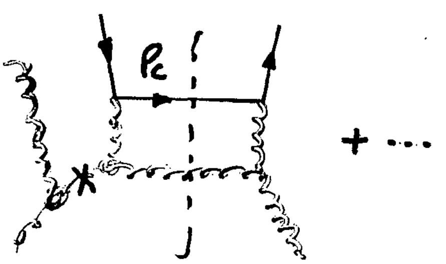
- part of final-state effect $\propto \ell_T/t \sim 1/\ell_T$

  $\Rightarrow A_N$ does not fall as fast as $1/\ell_T$ as ℓ_T increases.

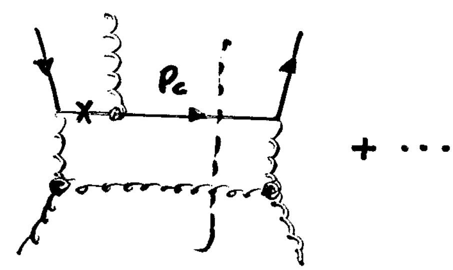
Leading $(\partial/\partial x)T_F(x,x)$ contribution to the asymmetries

$$E\frac{d\Delta\sigma}{d^3\ell} \propto \epsilon^{\ell_T s_T n \bar{n}}\, D_{c\to\pi}(z) \otimes \left[-x\frac{\partial}{\partial x}T_F(x,x)\right]$$
$$\otimes \frac{1}{-\hat{u}}\left[G(x')\otimes\Delta\hat{\sigma}_{qg\to c} + \sum_{q'} q'(x')\otimes\Delta\hat{\sigma}_{qq'\to c}\right]$$

- $\Delta\hat{\sigma}_{qg\to c}$ and $\Delta\hat{\sigma}_{qq'\to c}$ are perturbatively calculable
- Example, $qg \to qg$ scattering



I-S



F-S

- initial-state:

$$\frac{1}{2(N_C^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1-N_C^2\frac{\hat{u}^2}{\hat{t}^2}\right]$$

- final state:

$$\frac{1}{2N_C^2(N_C^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1+2N_C^2\frac{\hat{s}\hat{u}}{\hat{t}^2}\right]$$

- unpolarized:

$$\frac{N_C^2-1}{2N_C^2}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1-\frac{2N_C^2}{N_C^2-1}\frac{\hat{s}\hat{u}}{\hat{t}^2}\right]$$

- extra gluon interaction leads to a different color factor

MODEL FOR QUARK-GLUON CORRELATION $T_F(x, x)$

- Twist-3 correlation $T_F(x, x)$:

$$T_F(x, x) = \int \frac{dy_1^-}{4\pi} e^{ixP^+ y_1^-}$$

$$\times \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \left[\int dy_2^- \, \epsilon^{s_T \sigma n \bar{n}} \, F_\sigma^{\ +}(y_2^-) \right] \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- Twist-2 quark distribution:

$$q(x) = \int \frac{dy_1^-}{4\pi} e^{ixP^+ y_1^-} \langle P, \vec{s}_T | \bar{\psi}_a(0) \gamma^+ \psi_a(y_1^-) | P, \vec{s}_T \rangle$$

- Model for $T_F(x, x)$ of quark flavor a:

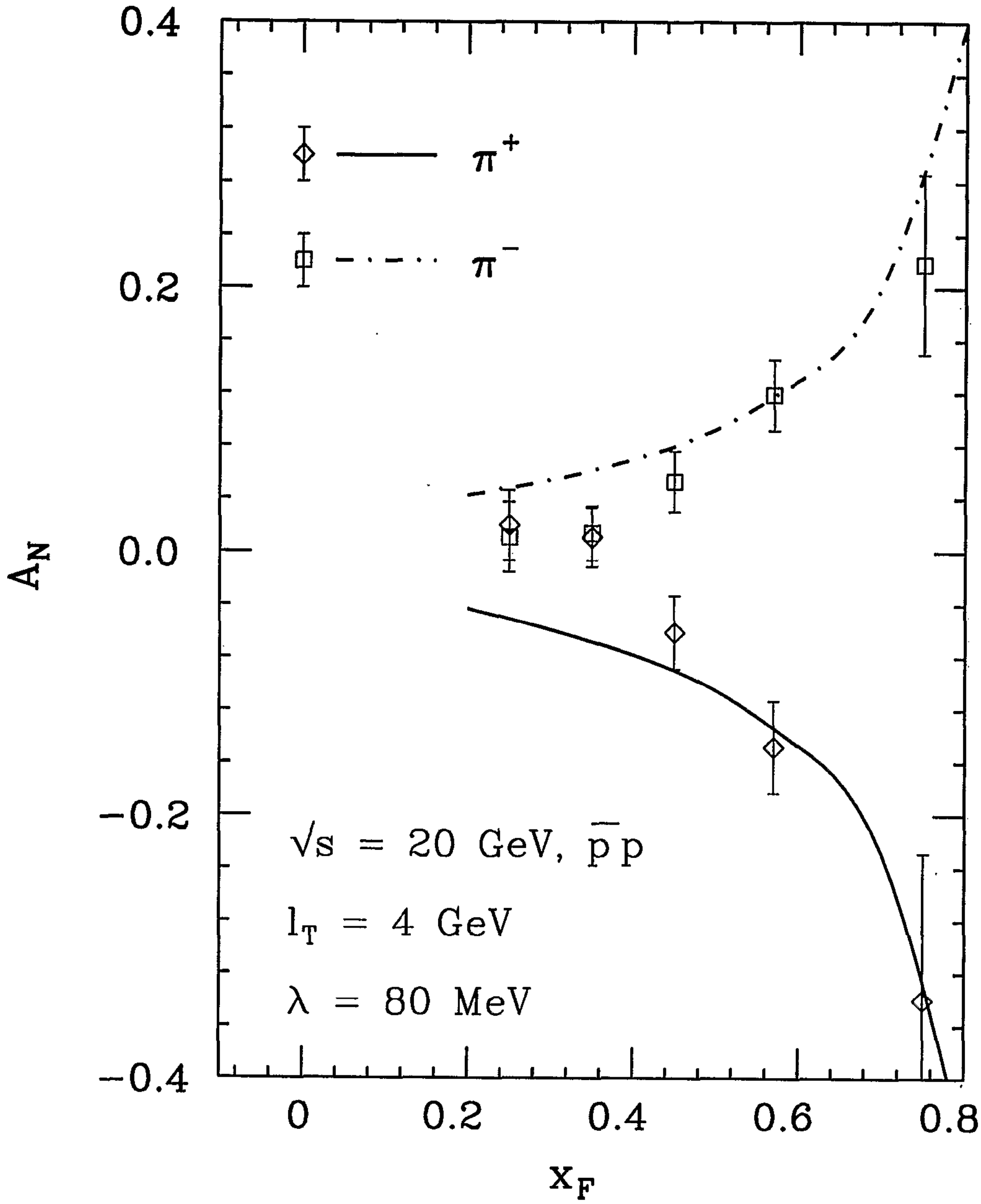
$$T_{F_a}(x, x) \equiv \kappa_a \, \lambda \, q_a(x)$$

  with $\kappa_u = +1$ and $k_d = -1$ for proton

- Fitting parameter $\lambda \sim O(\Lambda_{\text{QCD}})$

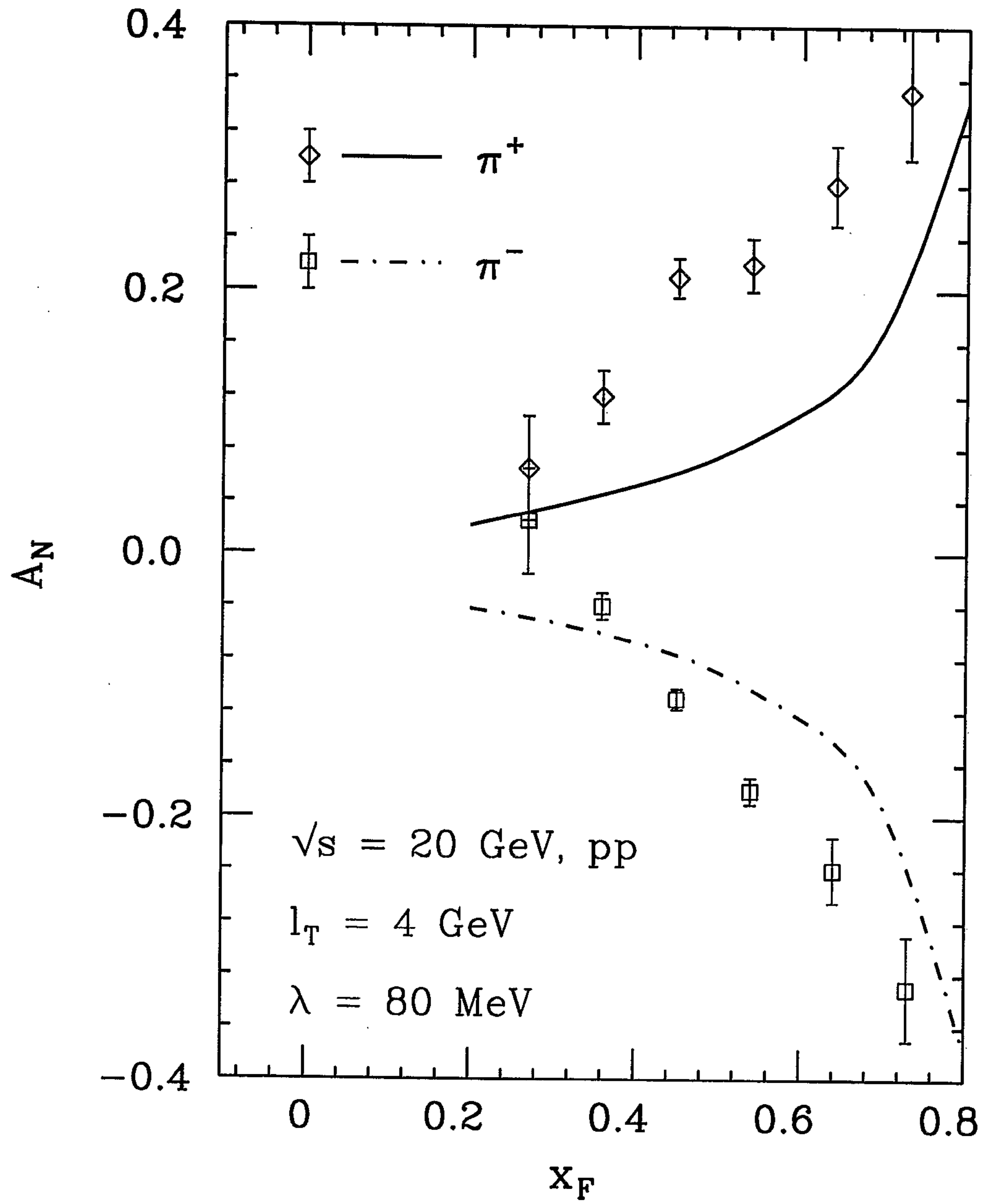
- Predictive power of the factorization approach:
  - extract $T_F(x, x)$ from one observable, say π^+ or π^-
  - use it to predict other observable, say π^0
  - $(\partial/\partial x) T_F(x, x)$ leads to enhancement of the asymmetries in forward region
  - same partonic parts can be used for calculating the asymmetries in production of other types of single hadron, say in k, or p production

COMPARE AN APPLE WITH AN ORANGE (I)



Fermilab data with ℓ_T up to 1.5 GeV

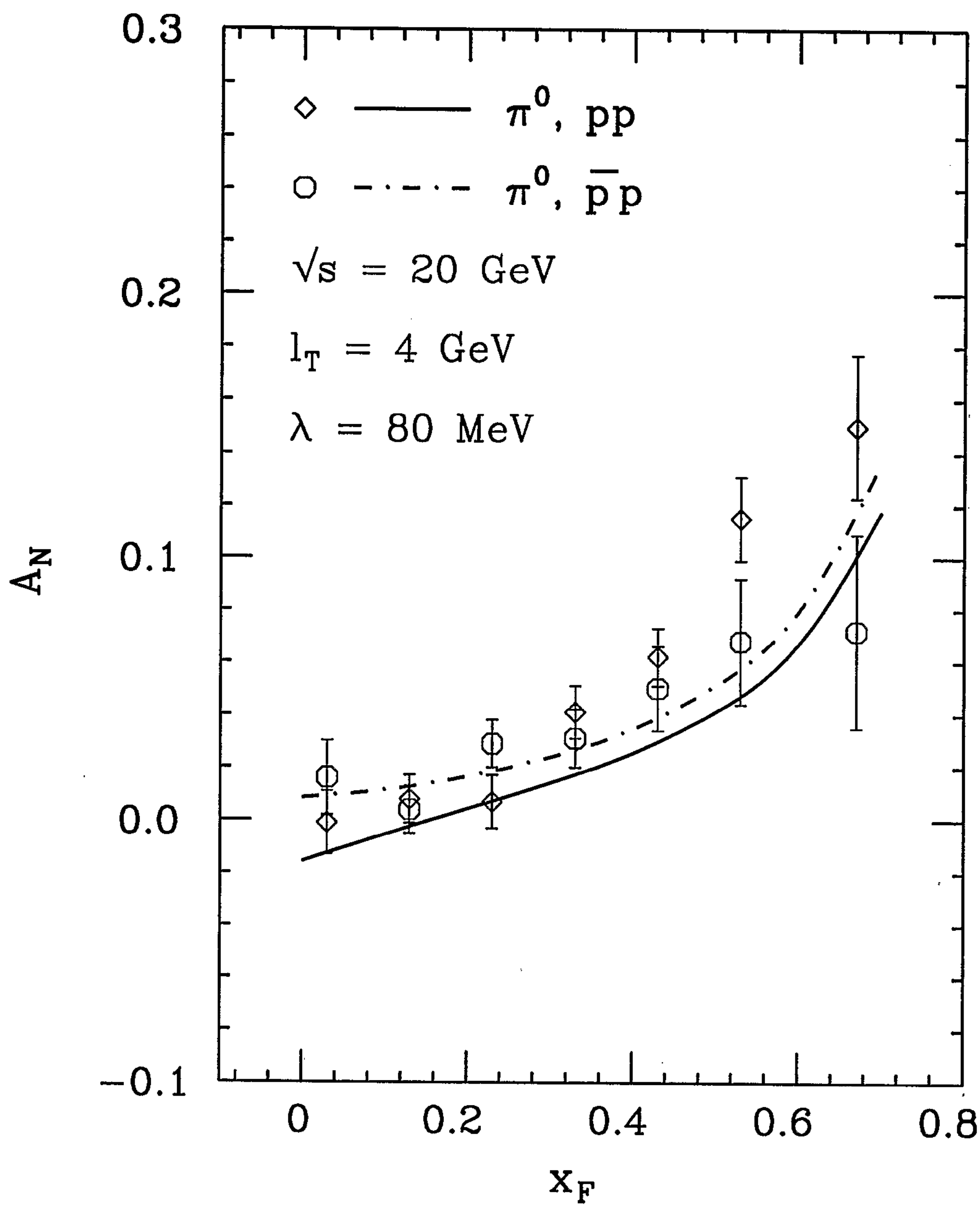
COMPARE AN APPLE WITH AN ORANGE (II)



Fermilab data with ℓ_T up to 1.5 GeV

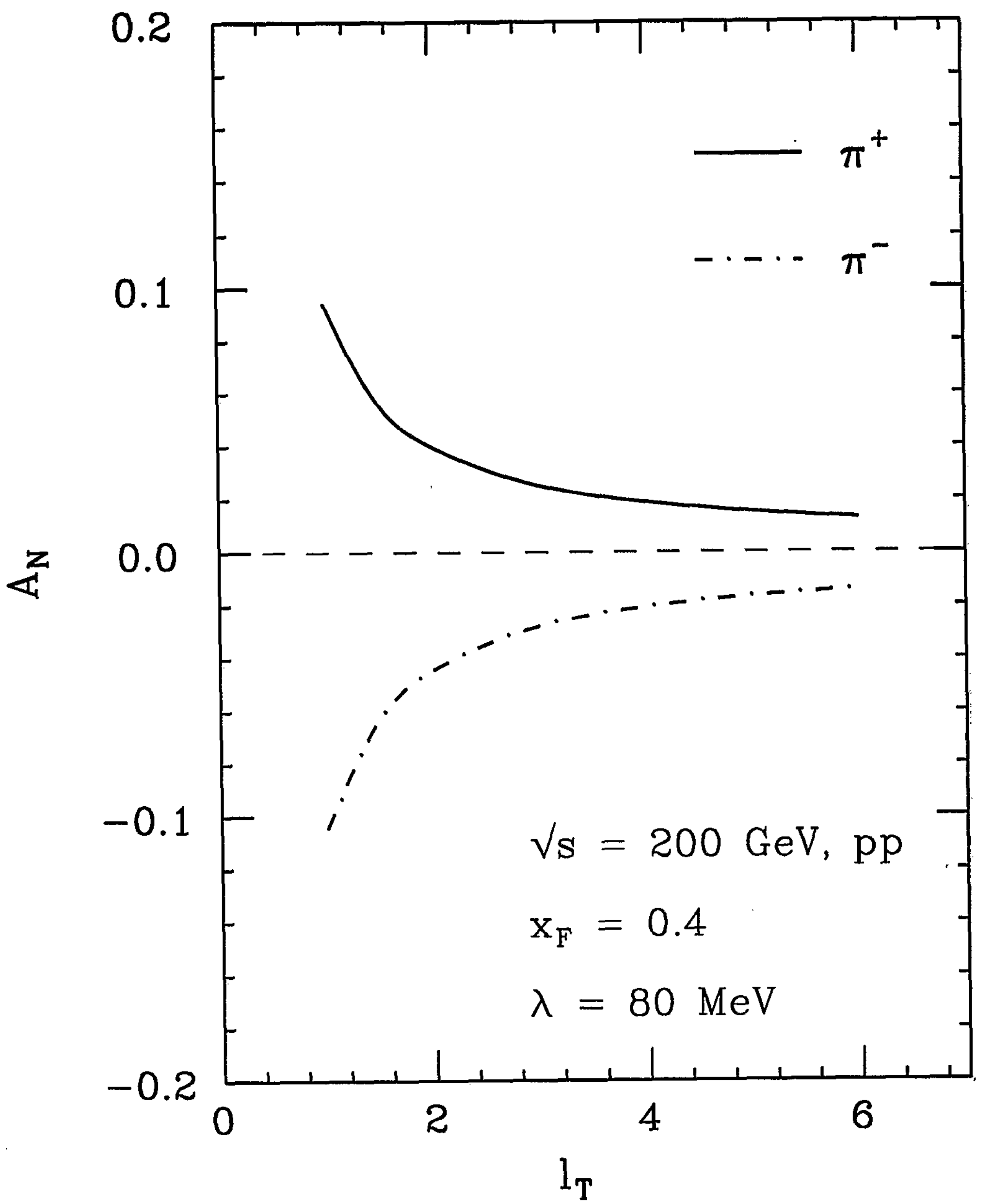
Theory curves fit data better if evaluated at a lower ℓ_T

COMPARE AN APPLE WITH AN ORANGE (III)



Fermilab data with ℓ_T up to 1.5 GeV

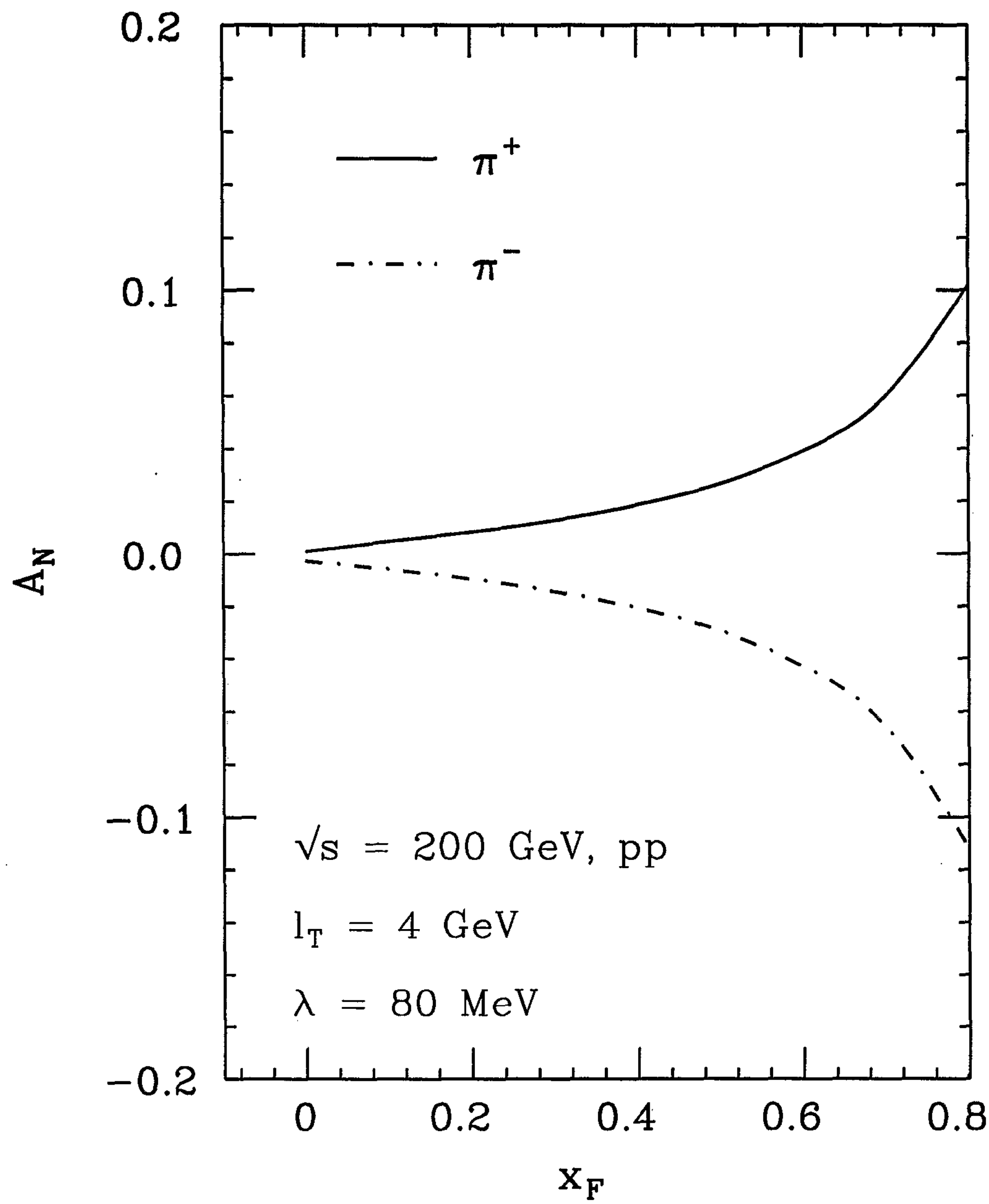
A_N AT RHIC ENERGY (I)



Derivative term only for partonic hard part

Non-drivative term are getting calculated by Kouvaris, Qiu, and Vogelsang

A_N AT RHIC ENERGY (II)



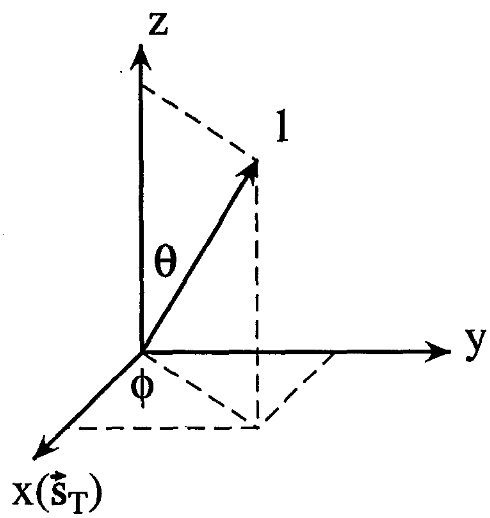
Derivative term only for partonic hard part

4. A_N FOR DRELL-YAN MASSIVE DILEPTON[a]

- Process:

$$A(p,\vec{s}) + B(p') \Rightarrow \gamma^*(Q)[\rightarrow \ell\bar{\ell}] + X$$

- Frame:



- Single transverse-spin asymmetry in $\frac{d\sigma}{dQ^2 d\Omega}$

$$A_N = \sqrt{4\pi\alpha_s}\left[\frac{\sin 2\theta \sin\phi}{1+\cos^2\theta}\right]\frac{1}{Q} \times \frac{\sum_q e_q^2 \int dx\, T_q(x,x)\,\bar{q}(Q^2/xS)}{\sum_q e_q^2 \int dx\, q(x)\,\bar{q}(Q^2/xS)}$$

- No derivative term at the tree level!
- In principle, there is no free parameter!
- A_N is very small and is estimated to be 2-4%

---

[a] D. Boer and J.Q., Phys. Rev. D65 (2002) 034008, and references therein.

5. SUMMARY AND OUTLOOK

- Single transverse-spin asymmetry is a unique tool to explore nonperturbative physics beyond parton distributions
- QCD factorization approach allows to quantify the size of high order corrections, because of infrared safe partonic hard parts
- QCD factorization approach provides a systematic way to calculate the asymmetries in different processes
- Single transverse spin asymmetry in single hadron production is an excellent observable to test the QCD factorization
- Data on the asymmetries provide nonperturbative information on quark-gluon correlation
- Theoretical calculation with derivative term only are consistent with Fermilab data
- A full leading order calculation will soon be available.
- Drell-Yan single transverse-spin asymmetry is a clean probe. But, the asymmetry is small

Heavy Flavor Production in Polarized pp Collisions

Marco Stratmann

Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany

Due to the dominance of the gluon-gluon-fusion mechanism, heavy flavor production in polarized pp collisions is one of the most promising tools to extract the polarized gluon density Δg in the future. However, for a reliable determination of Δg the knowledge of the next-to-leading order (NLO) QCD corrections is indispensable. Such a calculation was completed very recently[1], and we sketch the general outline and some important technical details. We discuss the behaviour of the total partonic cross sections, in particular near threshold and at high energies. It is demonstrated that the dependence on unphysical factorization and renormalization scales, μ_f and μ_r, respectively, is largely reduced when going from the LO to the NLO of QCD. The unknown precise value of the heavy quark mass appears to be the major uncertainty in the calculation of heavy flavor cross sections. Theoretical estimates of heavy quark rates and spin asymmetries must include a simulation of the heavy quark decay into experimentally observed particles, usually leptons, as well as the detector acceptance which can be rather limited. This important 'matching' between experiment and theory can be achieved by taking the probability that a heavy quark in a given (p_T, η)-bin is actually detected from a Monte-Carlo generator, e.g., from PYTHIA. First results for the single-inclusive charm spin asymmetry including such a 'model' for the PHENIX acceptance are presented. Finally, we present a general technique based on Mellin-moments[2] for implementing in a fast way, and without any approximations, higher-order calculations of partonic cross sections into global analyses of parton distribution functions. A case study for such an analysis is presented using a set of fictitious data for the transverse momentum distribution of 'prompt' photons in polarized pp collisions.

[1] Work done in collaboration with I. Bojak; hep-ph/0112276.
[2] Work done in collaboration with W. Vogelsang; Phys. Rev. **D64** (2001) 114007.

Heavy Flavor Production in Polarized pp Collisions

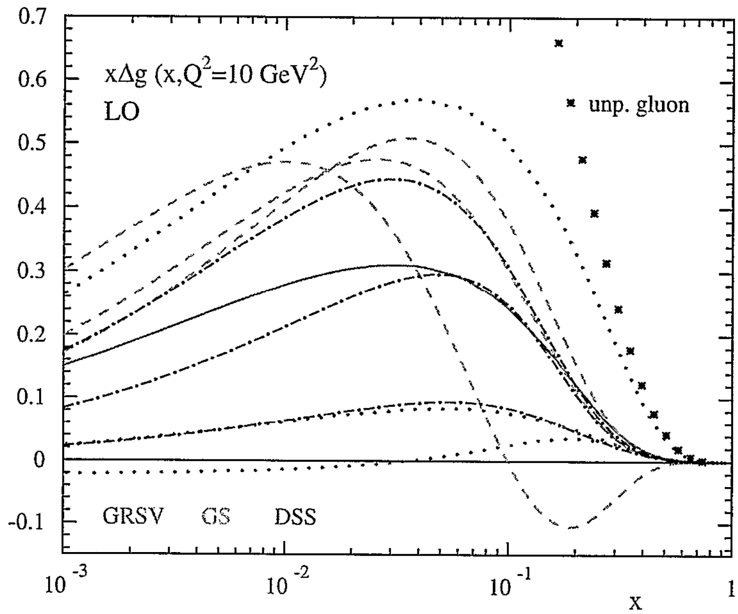
Marco Stratmann

(Regensburg)

- **Motivation**: Hunting down Δg
- **Open heavy flavor production in NLO QCD**:
  - Why NLO?
  - Sketch of NLO calculation (method, problems)
  - Some results
- **Matching theory and experiment**:
  - Heavy quark decay & detection ('efficiency')
  - Extraction of Δg ('global analysis')
- **Detour**: Do we understand *unpolarized* HQ data?
- **Summary & Outlook**

Motivation: hunting down Δg

What do we know from QCD analyses of DIS data?



$\rightsquigarrow$ $\Delta g(x, Q^2)$ only weakly constrained by DIS data alone

- lever-arm in Q^2 too small to study scaling violations
- no sum rule which *directly* relates quarks and gluons
  unpol.: mom. sum; pol.: spin sum contains *unknown* $L_z^{q,g}$)

$\rightsquigarrow$ need

- DIS data at *higher* energies ($\rightarrow$ EIC, pol. HERA, ... ??)

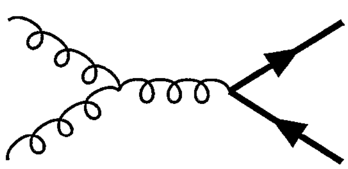
and/or

- direct information on Δg from *other* processes $\rightarrow$ RHIC

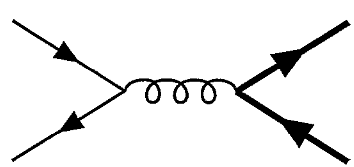
$\Uparrow$

best candidates: processes dominated by Δg in LO

e.g. HQ prod.:



vs.



dominant at small/med. p_T takes over at large p_T

General problem of all QCD analyses so far:

lesson from *unpolarized* fits: CTEQ, GRV, MRST

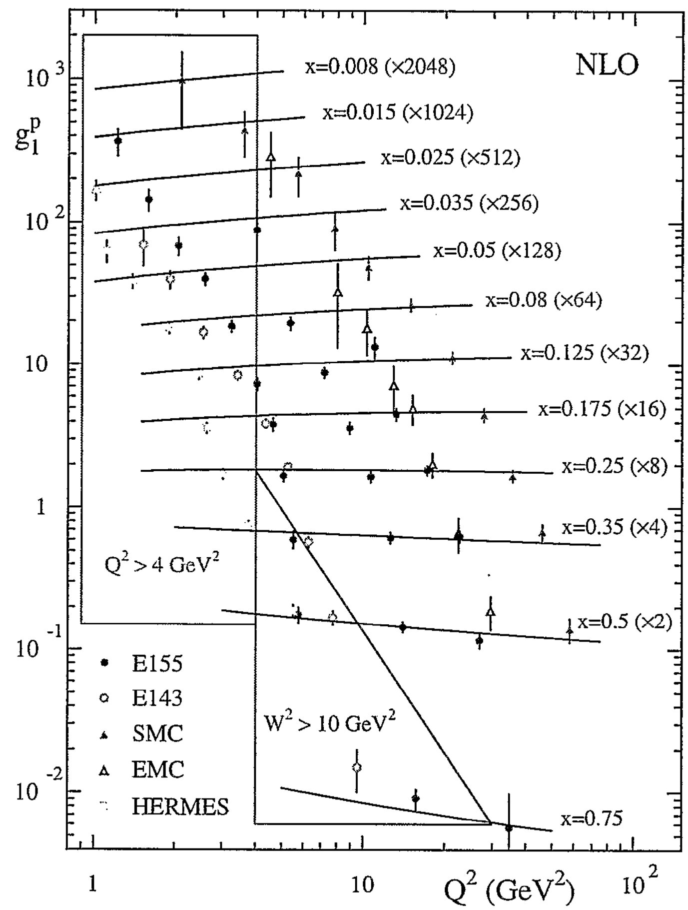
leading twist descr. of F_2 *fails* for low Q^2 and/or high x

$\rightsquigarrow$ impose cuts ($Q^2 \gtrsim 4$, $W^2 \gtrsim 10$ GeV^2) to obtain only the *universal* (twist-2) part of PDF's

we cannot afford similar cuts for g_1:

would loose 'all' data

$\rightsquigarrow$ usually only $Q^2 \gtrsim 1$, $W^2 \gtrsim 4$ GeV^2



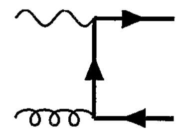
$\Rightarrow$ current PDF's *may* suffer from higher twist contrib.

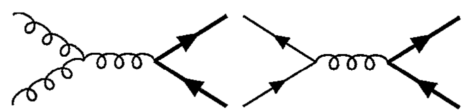
$\Rightarrow$ PDF's have to pass 'consistency check':

measurements at higher ('safer') scales $\leftrightarrow$ RHIC

• Open heavy flavor production in NLO QCD

We are interested in the NLO QCD corrections to:

photoproduction: 

hadroproduction: 

Why NLO? Several reasons ...

▷ experience from unpolarized calculations

Smith, van Neerven, Beenakker et al., Nason et al.

- large corrections near threshold, $S \to 4m^2$
- large corrections for $S \to \infty$

▷ behaviour of perturbation series

- dependence on unphysical scales $\mu_{f,r}$ expected to be reduced

▷ genuine NLO features

- new processes: $g(\gamma)q \to Q\bar{Q}q$ $\leftrightarrow$ may dilute sensitivity to Δg
- angular correlations are trivial in LO ('back-to-back')
- more realistic p_T spectra

▷ features of polarized cross sections

- LO $\Delta\sigma$ can oscillate $\leftrightarrow$ large corrections in vicinity of zero?

Sketch of NLO calculation: together with I. Bojak

Current status:

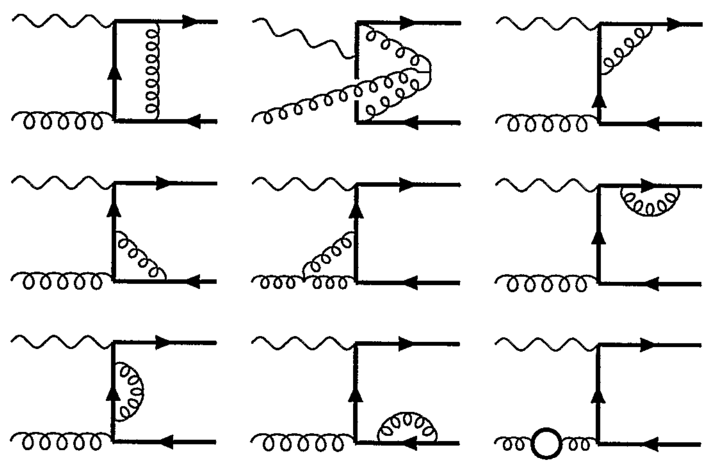
▷ photoproduction: ✓ (PLB433(1998)411; NPB540(1999)345)

▷ hadroproduction: ✓ (1^{st} results in hep-ph/0112276)

Step I: photoproduction

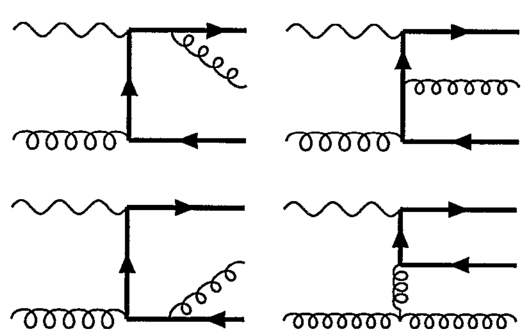
1-loop corrections

to $\gamma g \to Q\bar{Q}$



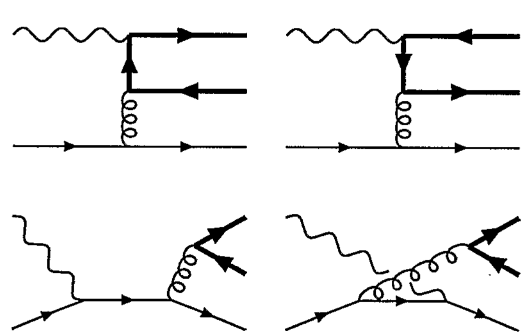
'real' corrections

to $\gamma g \to Q\bar{Q}$



new NLO process

$\gamma q \to Q\bar{Q}q$

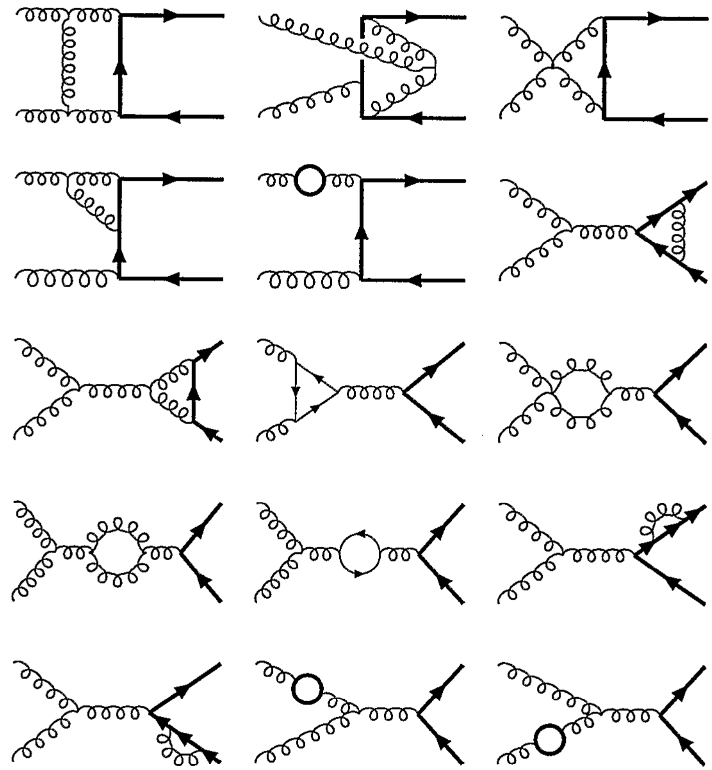


Step II: hadroproduction

very similar, only lots and lots of diagrams ...

1-loop corrections

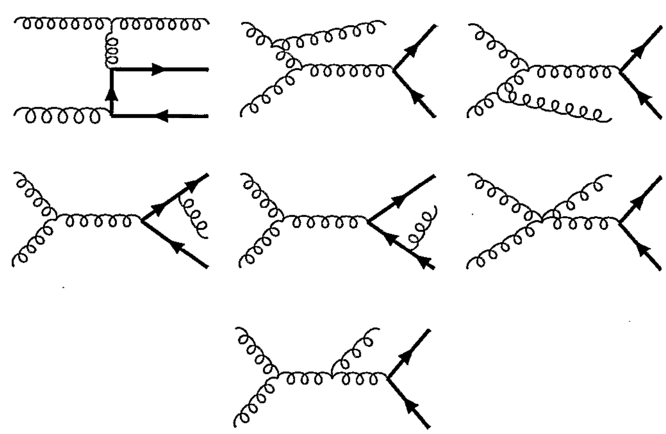
to $gg \to Q\bar{Q}$



$+\ \gamma g$ graphs with $\gamma \to g$

'real' corrections

to $gg \to Q\bar{Q}$



$+\ \gamma g$ graphs with $\gamma \to g$

PLUS NLO corrections ('real' + '1-loop') to $q\bar{q} \to Q\bar{Q}$

new genuine NLO process $gq \to Q\bar{Q}q$

General method/treatment of singularities:

- project onto helicities $\lambda_{1,2} = \pm$ of *incoming* partons using γ_5 and $\epsilon_{\mu\nu\rho\sigma}$

$$\rightsquigarrow \quad \frac{\Delta\hat{\sigma}}{\hat{\sigma}} \equiv \frac{1}{2}\left[|M(++)|^2 \mp |M(+-)|^2\right]$$

  are calculated simultaneously $\rightarrow$ important check $\checkmark$

- cannot use 'crossing', e.g., $q\bar{q} \to Q\bar{Q}g \not\leftrightarrow g\bar{q} \to Q\bar{Q}\bar{q}$

- obtain usual bunch of singularities in $(\Delta)\hat{\sigma}$

  $\rightsquigarrow$ work in $n = 4 + \varepsilon$ dimensions (*dim. regularization*)

Then

IR singularities

cancel in sum of 1-loop and 'real' contributions

UV singularities

have to be removed by renormalization (mass, α_s)

use $\overline{\text{MS}}_Q$ scheme: heavy quark loops decouple

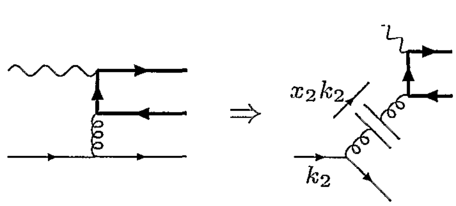
$1/\varepsilon^2$ singularities

when collinear and IR sing. coincide; cancel as for IR

collinear (mass) singularities

have to be removed by factorization

e.g.



$\sim \int dx_2 P_{gq}(x_2)\, d\Delta\hat{\sigma}^{LO}_{\gamma g}(x_2, s, t)$

- 1-loop virtual corrections: $[(\gamma)gg \to Q\bar{Q},\ q\bar{q} \to Q\bar{Q}]$

$2 \to 2$ kinematics; only interfer. with Born contributes:

$$d\Delta\hat{\sigma}_{\text{virt}} \sim \ldots \sum (\Delta M_{\text{virt}}\, \Delta M^*_{\text{Born}} + c.c.)\ \delta(s+t+u)$$

$$\updownarrow$$

tensor loop-integrals $\sim \int d^n q\, \frac{q^\mu [q^\nu [q^\rho]]}{L_1 L_2 [L_3 [L_4]]}$

handle with (mod.) Passarino-Veltman decomposition

$\leadsto$ set of n-dim. scalar integrals: A_0, B_0, C_0, D_0

[✓ all integrals agree with results in Beenakker et al.]

final step: renormalization $\leadsto$ UV finite

- 'real' corrections: $[(\gamma)gg \to Q\bar{Q},\ q\bar{q} \to Q\bar{Q}]$

full $2 \to 3$ kinematics (involved due to HQ mass)

use *phase space slicing*: (as in unpol. HQ calc., Smith et al.)

split into hard / soft part: only collinear $1/\varepsilon \to$ factorization; cancels IR, $1/\varepsilon^2$ poles in $d\Delta\hat{\sigma}_{\text{virt}}$

$$\uparrow$$

$$\int_0^{s_4^{\max}} ds_4 = \underbrace{\int_0^{\Delta} ds_4}_{\substack{\text{soft} \\ 2\to 2}} + \underbrace{\int_\Delta^{s_4^{\max}} ds_4}_{\substack{\text{hard} \\ 2\to 3}}$$

kinematics

The 'Δ-method' is easy and transparent

but $\ln^i(\Delta/m^2)$ (i=1,2) have to cancel *numerically*

$2 \to 3$ phase space integration:

$$d\Delta\hat{\sigma}_{\text{real}} \sim \ldots \int d\theta_1 d\theta_2 \sin^{1-\varepsilon}\theta_1 \sin^{\varepsilon}\theta_2 \, |\Delta M_{\text{real}}|^2$$

we want to calculate *single-inclusive* HQ distributions:

$$\text{e.g. } \underset{\text{observed}}{gg \to Q} \; \underset{\text{integrated out}}{(\bar{Q}g)}$$

calculation requires extensive *partial fractioning* to get

$$I^{(k,l)} = \int \frac{d\theta_1 \; \sin^{1-\varepsilon}\theta_1 \; d\theta_2 \; \sin^{\varepsilon}\theta_2}{(a + b\cos\theta_1)^k (A + B\cos\theta_1 + C\sin\theta_1\cos\theta_2)^l}$$

some $I^{(k,l)}$ are tough: ✓ agree with Beenakker et al.

$I^{(k,l)}$ with $a^2 = b^2$ and/or $A^2 = B^2 + C^2$ can diverge $\rightsquigarrow \frac{1}{\varepsilon}$

- subtlety in pol. calculation: γ_5 in n dimensions

γ_5 (and $\epsilon_{\mu\nu\rho\sigma}$) are 4-dim. $\rightsquigarrow$ use HVBM *prescrip.* in n dim.

price to pay: $(n-4)$-dim. scalar products ('hats') $\widehat{p \cdot k}$

$\rightsquigarrow$ special care in phase space integrations required!!

rewrite $\mathrm{dPS}_3(\theta_1, \theta_2) \to \mathrm{dPS}_3(\theta_1, \theta_2) \times \mathcal{I}(\hat{k}^2)$

$\mathcal{I}(\hat{k}^2) \sim \mathcal{O}(\varepsilon) \rightsquigarrow$ contribute if they pick up $1/\varepsilon$!!

add. compl. due to *artificial helicity viol.*: $\Delta P^n_{qq} \neq P^n_{qq}$

$\to$ add. factorization (Vogelsang)

- final step: factorization; sum soft and virtual $\rightsquigarrow$ finite

- genuine NLO processes: $(\gamma)gq \to Q\bar{Q}q$

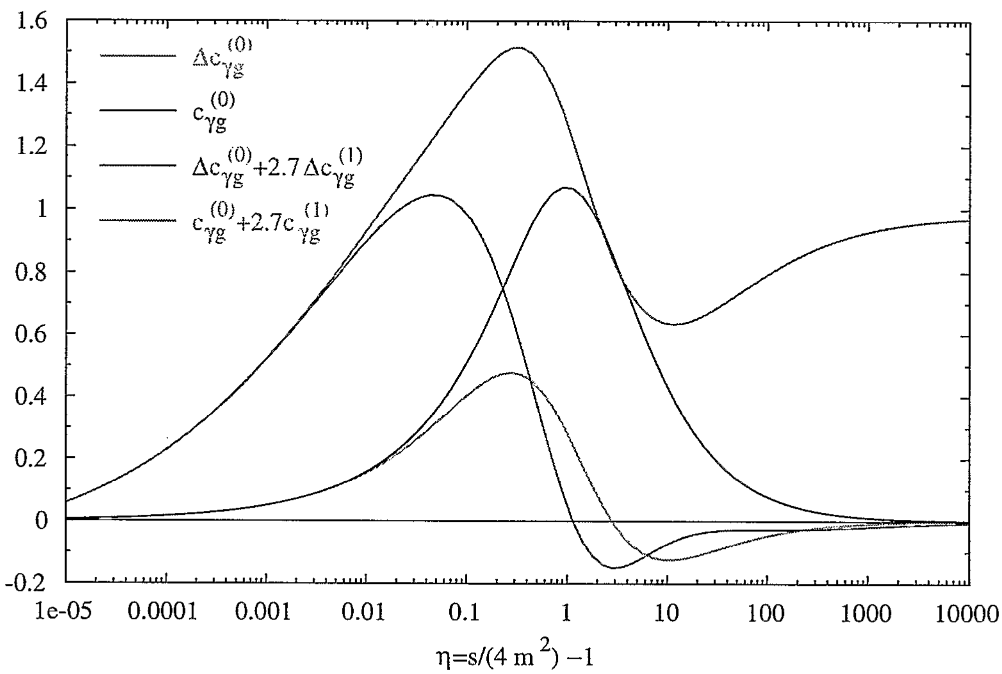
straightforward, only collinear poles

Some results:

total *partonic* γg photoproduction cross section:

'scales' in $\eta = s/(4m^2) - 1$: [here: $\mu_f = \mu_r$]

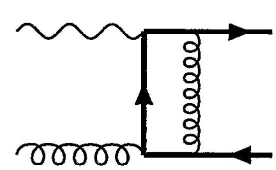
$$\Delta\hat{\sigma}_{\gamma g} = \frac{e_Q^2 \alpha \alpha_s}{m^2} \left[\Delta c_{\gamma g}^{(0)} + 4\pi\alpha_s \left(\Delta c_{\gamma g}^{(1)} + \Delta \bar{c}_{\gamma g}^{(1)} \ln \frac{\mu_f^2}{m^2} \right) \right]$$



$\rightsquigarrow$ large enhancements w.r.t. LO:

threshold: η, $\beta = \sqrt{1 - 4m^2/s} \to 0$

(1) 'Coulomb' singularity:



phase space $\sim \beta$

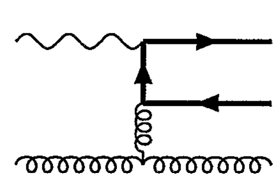
LO ME $\sim 1 \to 0$; NLO ME $\sim 1/\beta \to$ const

(2) 'soft gluons' $\sim \beta \ln^2 8\beta^2 \leftarrow$ can be resummed

high energy: $\eta \to \infty$, $\beta \to 1$

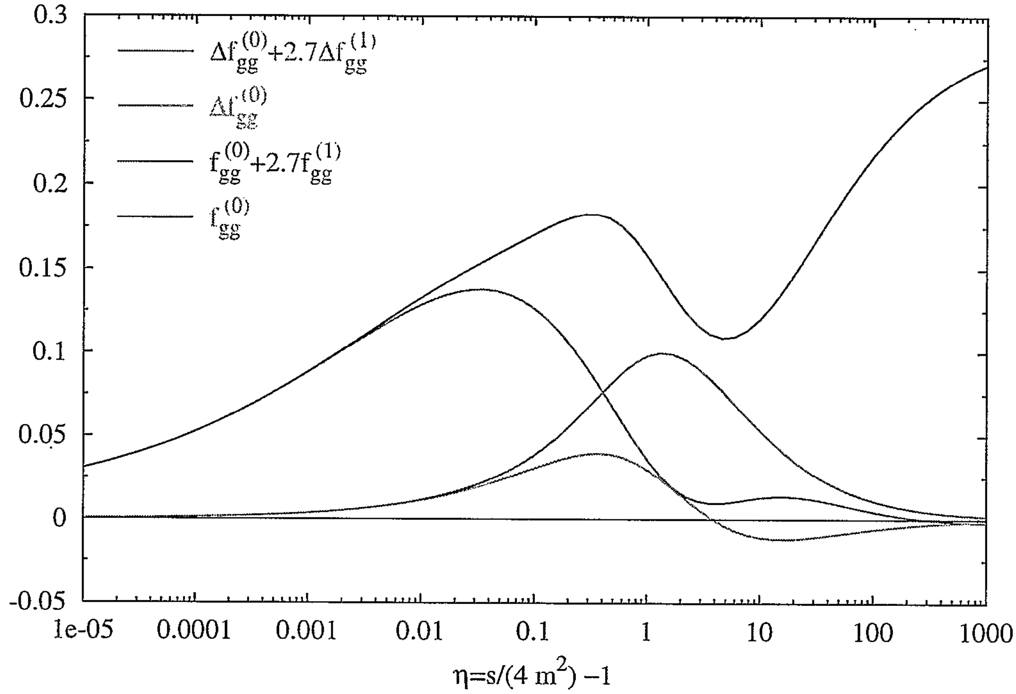
't-channel gluon exchange'

cancels in $\Delta\hat{\sigma}$

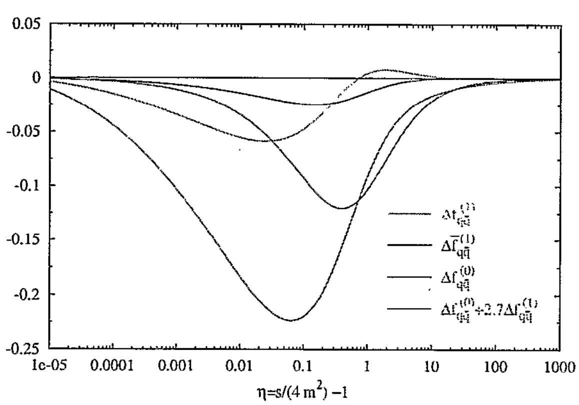


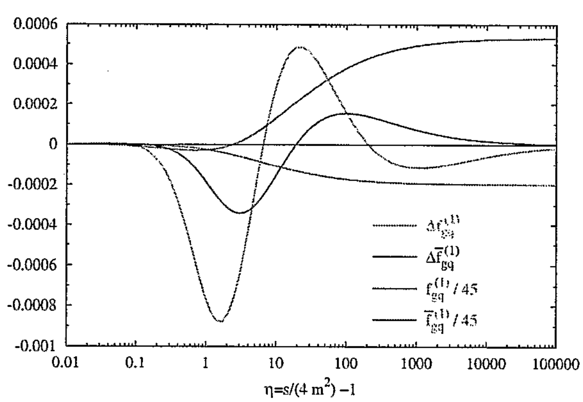
... and similarly for the ...

total *partonic* gg hadroproduction cross section:



total *partonic* $q\bar{q}$ and gq hadroproduction cross sections:





as expected for $q\bar{q}$ - annihilation: $\Delta\widehat{\sigma}_{q\bar{q}} = -\widehat{\sigma}_{q\bar{q}}$

(but only *after* correcting for $\Delta P_{qq}^n \neq P_{qq}^n$!)

total hadronic cross section:

physical cross section is convolution of partons and $\Delta\hat{\sigma}_{ff'}$:

$$s = x_1 x_2 S$$

$$\updownarrow$$

$$\Delta\sigma = \sum_{f,f'} \int_{\frac{4m^2}{S}}^{1} dx_1 \int_{\frac{4m^2}{x_1 S}}^{1} dx_2 \, \Delta f(x_1,\mu_f^2)\Delta f'(x_2,\mu_f^2)\Delta\hat{\sigma}_{ff'}(s,m^2,\mu_r^2,\mu_f^2)$$

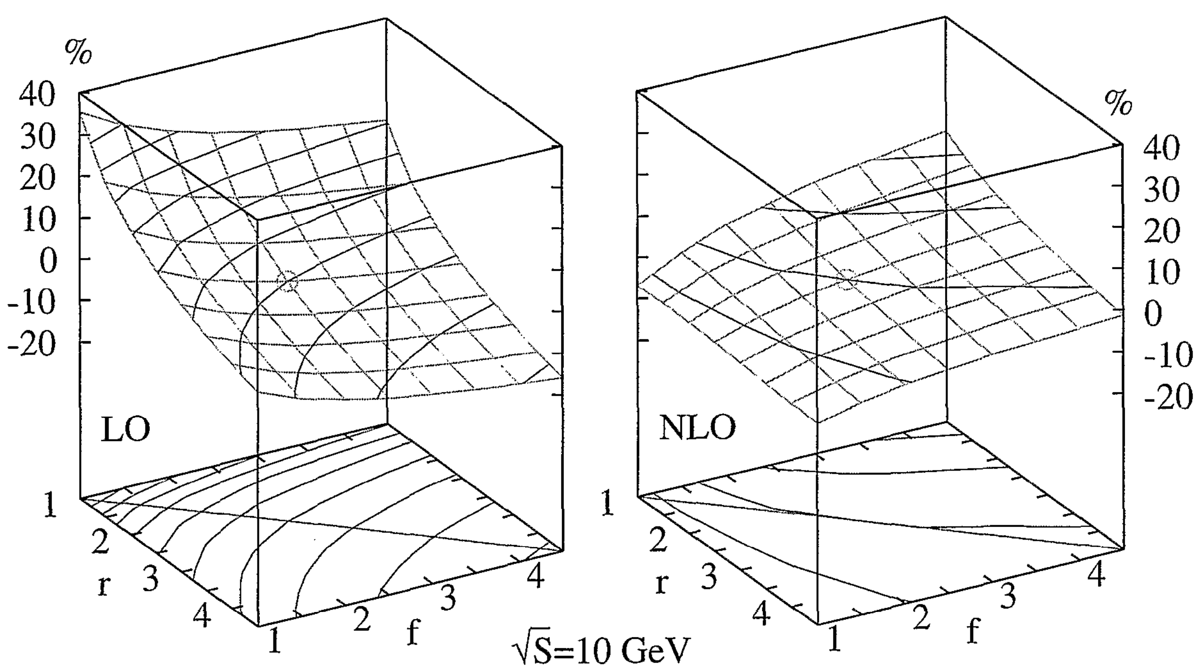
$$\updownarrow$$

$$\gamma p\text{:} \; = \delta(1-x_2)$$

$\leadsto$ η dependence of $\Delta\hat{\sigma}_{ff'}$ is smeared out

scale dependence of total *charm photo*production $\Delta\sigma$

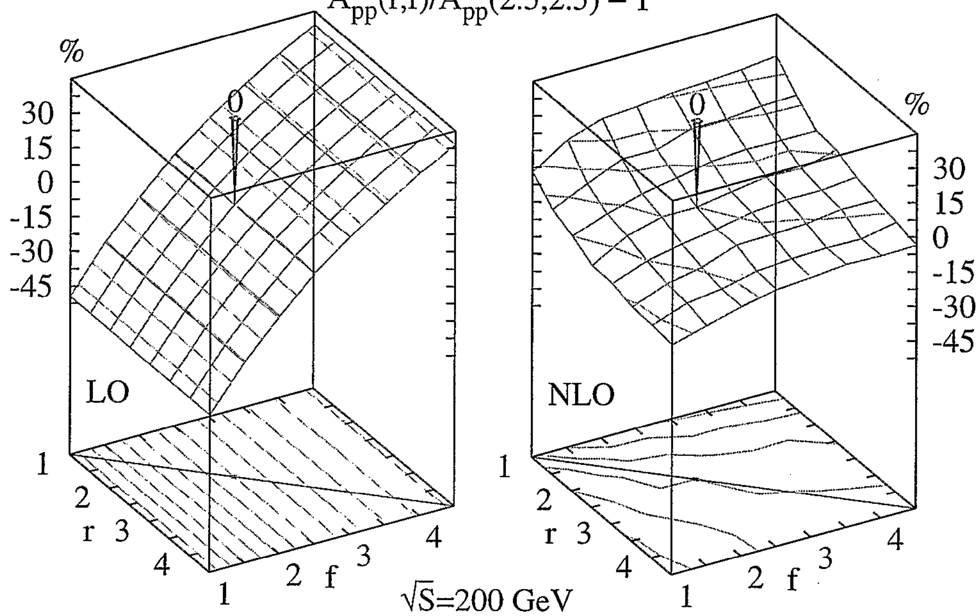
$r = \mu_r^2/m_c^2$ and $f = \mu_f^2/m_c^2$ using GRSV, $m_c = 1.5$ GeV



COMPASS

$\leadsto$ dependence on unphys. scales *largely reduced* in NLO scale dep. of total pp spin asymmetry $A^Q = \mathrm{d}\Delta\sigma^Q/\mathrm{d}\sigma^Q$:

$A^c_{pp}(r,f)/A^c_{pp}(2.5,2.5) - 1$

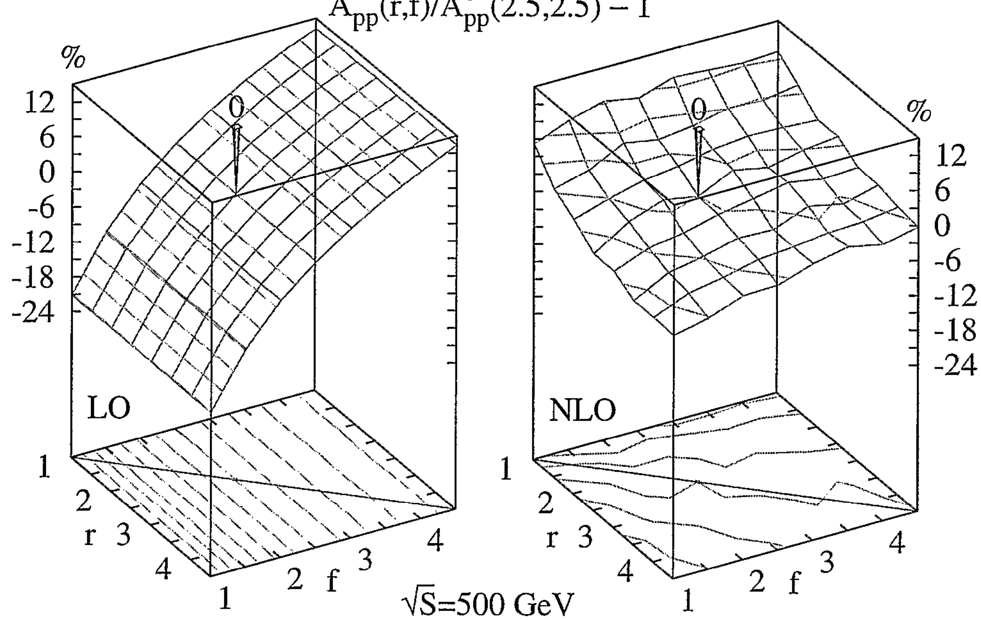


$\sqrt{S}$=200 GeV

$r=\mu_r^2/m_c^2$, $f=\mu_f^2/m_c^2$, m_c=1.4 GeV

RHIC

$A^b_{pp}(r,f)/A^b_{pp}(2.5,2.5) - 1$

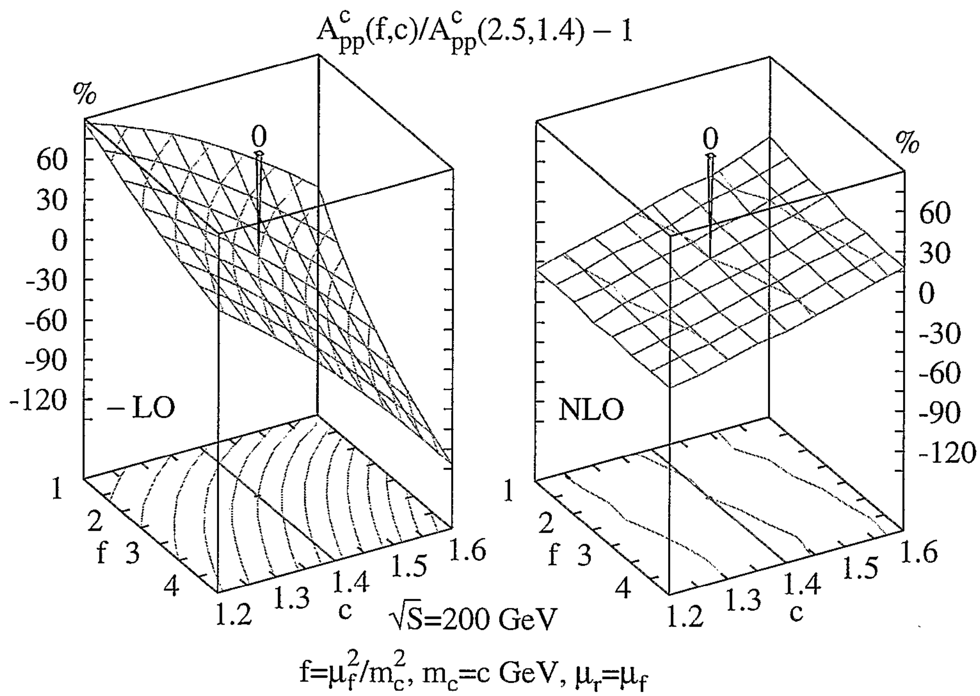


$\sqrt{S}$=500 GeV

$r=\mu_r^2/m_b^2$, $f=\mu_f^2/m_b^2$, m_b=4.5 GeV

RHIC

mass dependence of total pp spin asymmetry:



$\rightsquigarrow$ m_Q is *dominant uncertainty*; better for b production

analytical/numerical checks on our NLO results:

photoproduction

✓ NLO unpolarized — Smith, van Neerven; Ellis, Nason

✓ NLO polarized (abelian part: $\gamma\gamma \to Q\bar{Q}g$) — Contogouris et al.; Jikia, Tkabladze

✓ NLO polarized (seem to agree) — Contogouris, Merebashvili, Grispos

hadroproduction

✓ NLO unpolarized — Beenakker et al.; Nason et al
(agree; num. irrel. typo in HQ-loop of Beenakker et al.)

- <u>Matching theory and experiment</u>

Heavy quark decay & detection:

<u>aim</u>: study *and* optimize sensitivity to Δg for various heavy flavor observables

$\rightsquigarrow$ need *realistic* error estimates for rates and A^Q

<u>problem</u>: calc. assuming a 4π-detector, 100% efficiency, and 'parton = hadron level' are of limited use

- c, b usually not seen directly;
  c, b decays can have 'multi-body' kinematics
- detector coverage often limited
- non-trivial relation of exp. and theor. variables, e.g., p_T distr. of decay μ's vs. p_T^Q

<u>experimental situation</u>:

hermes: charm production near threshold

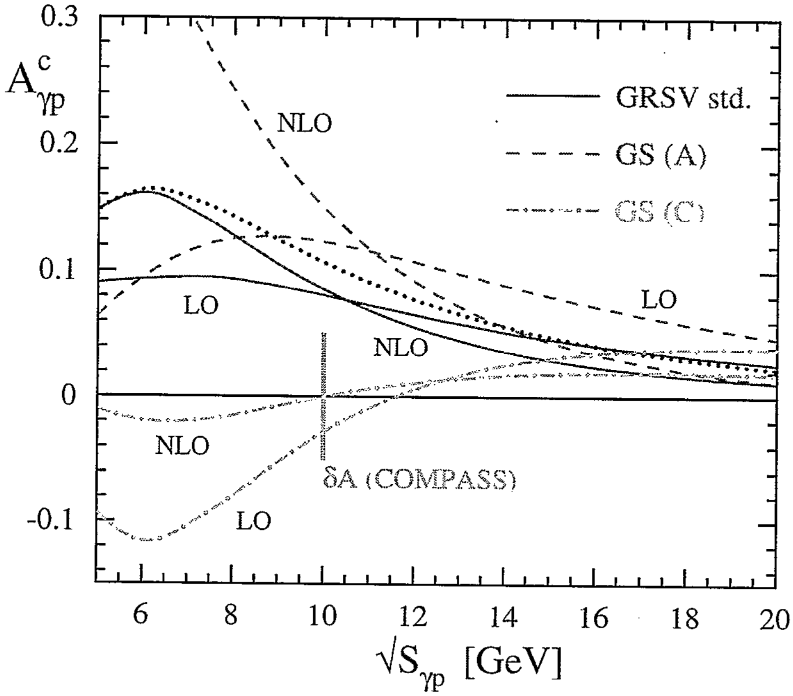
COMPASS: 'only' total charm prod. at $\sqrt{S} = 10\,\text{GeV}$
error estimate given in proposal

RHIC: differential distributions for c and b; different $\sqrt{S}$, channels/strategies to detect heavy quarks

<u>need</u>:

- unpol. *and* pol. NLO parton level MC
- include HQ decay in theor. estimates
- close collab. between theory and experiment

(I) photoproduction of charm @ COMPASS :



✓ some sensitivity to Δg

✓ reduced scale dependence in NLO

✓ 'background' from NLO γq process small

✓ 'background' from *resolved* γ's (e.g., $gg \to c\bar{c}$) small:

Vogelsang, MS

$\sqrt{S_{\gamma p}}$ [GeV]	GRSV Δg direct [nb]	GRSV Δg resolved [nb]	large Δg direct [nb]	large Δg resolved [nb]	GSC Δg direct [nb]	GSC Δg resolved [nb]
10	10.2	-0.72	23.0	-0.63	-3.48	-0.70
20	13.9	-0.29	23.2	0.33	19.6	-0.70
100	-4.76	2.09	-9.71	4.00	0.58	2.27

× NLO corrections are sizable

× sizable dependence on m_{charm}

× can extract Δg 'only' for single $\langle x \rangle \sim \mathcal{O}(0.1 \div 0.2)$

(II) hadroproduction of heavy quarks @ RHIC :

- heavy quark tagging at PHENIX via $e^\pm$ and/or $\mu^\pm$

lepton detection is limited to

$$\begin{array}{lcc} e^\pm & : & |\eta_{e^\pm}| \leq 0.35 \\ \mu^\pm & : & 1.2 \leq |\eta_{\mu^\pm}| \leq 2.4 \end{array}$$

$\rightsquigarrow$ *crucial* to include simulation of HQ-decay in all theory estimates for spin asymmetries

idea: use PYTHIA to generate *'efficiencies'*

suitable bins in (p_T^e, η_e)

$\updownarrow$

$$\varepsilon_{\rm eff}^{c,b} \equiv \frac{\#[c,b \text{ in } (p_T,\eta)\text{–bin} \to e^\pm \text{ in 'acceptance'}]}{\#[c,b \text{ in } (p_T,\eta)\text{–bin}]}$$

essential: $\varepsilon_{\rm eff}^{c,b}$ *independent* of c, b production

$\rightsquigarrow$ $\varepsilon_{\rm eff}^{c,b}$ give the probability that c, b's in a given (p_T, η)-bin are detected at PHENIX

very recently: 1$^{\rm st}$ results for 'single electron tag' $\varepsilon_{\rm eff}^{c,b}$

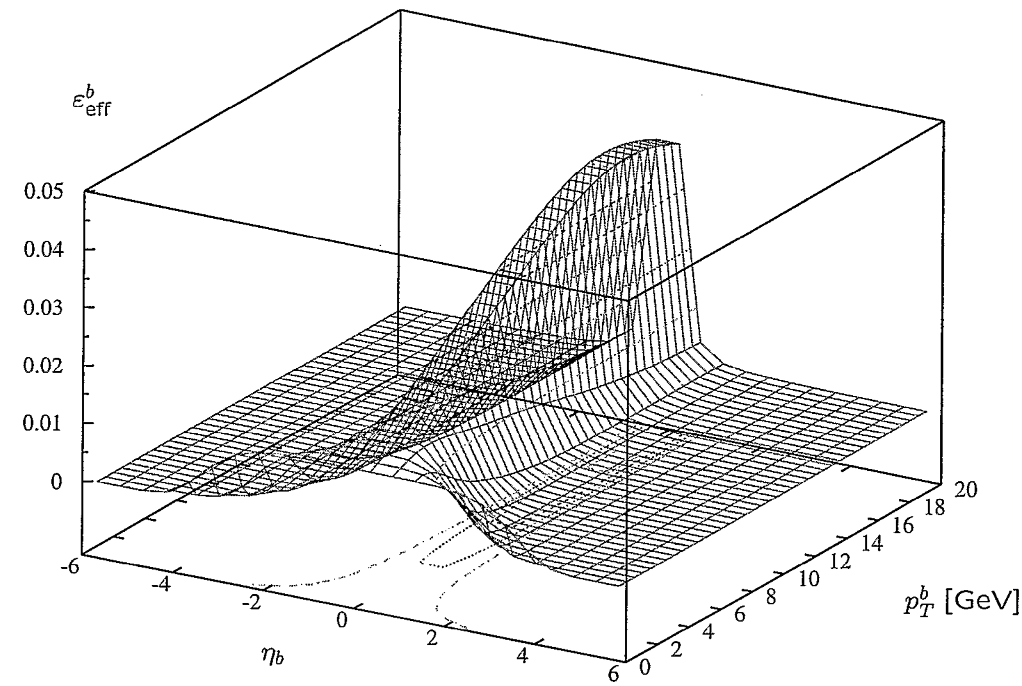
Grosse Perdekamp, Xie, ...

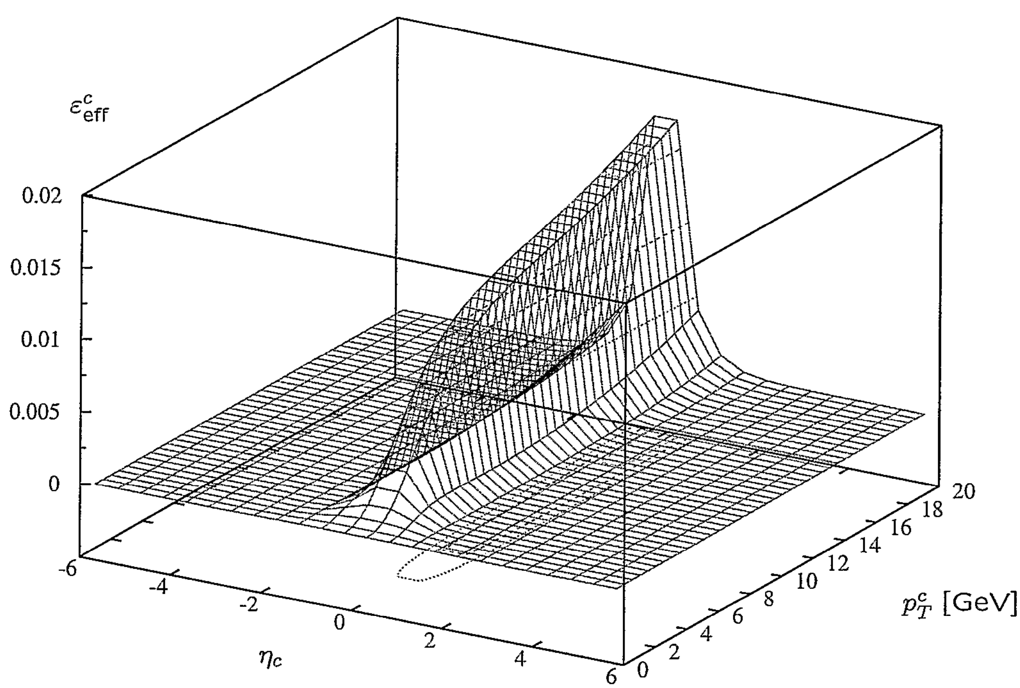
✓ ready to use for single incl. spin asymmetries in NLO

- other promising tags: 'μe coincidences'

× work in progress; spin asymmetries in NLO require MC

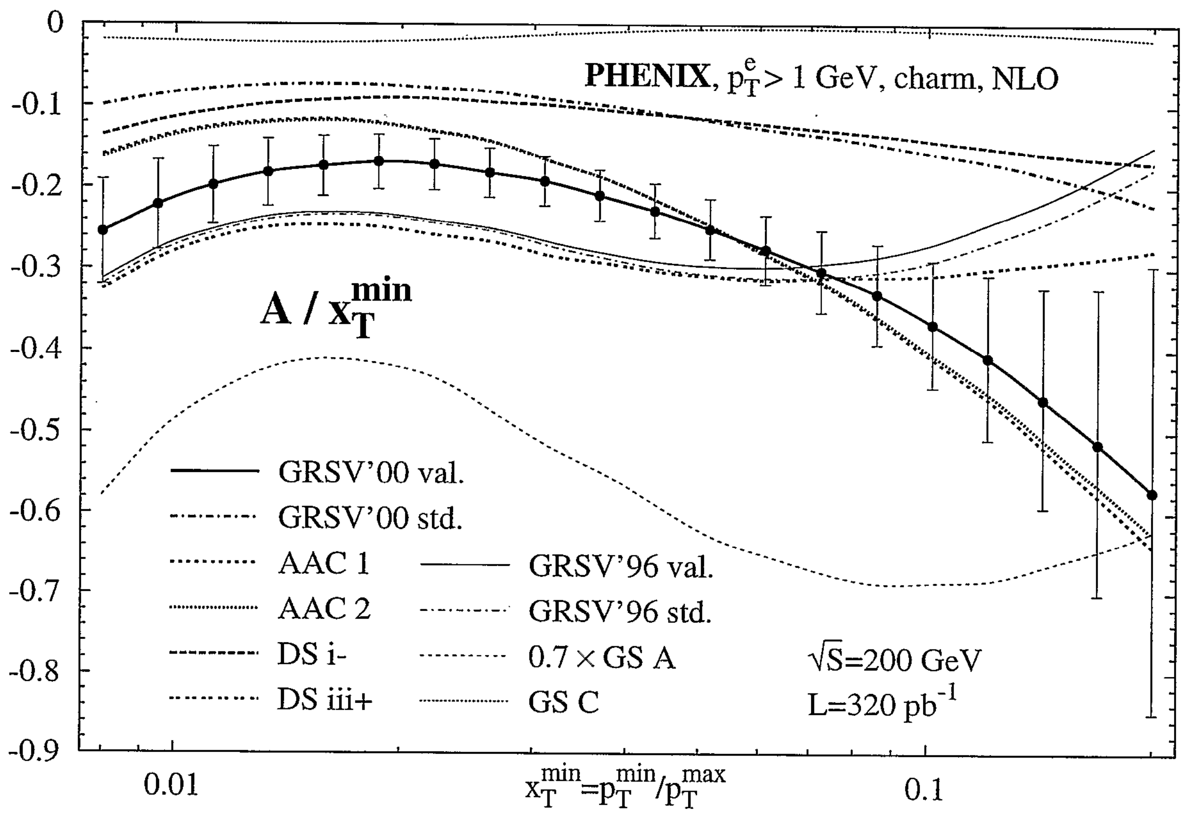
• some typical results for the 'single electron tag' $\varepsilon_{\text{eff}}^{c,b}$

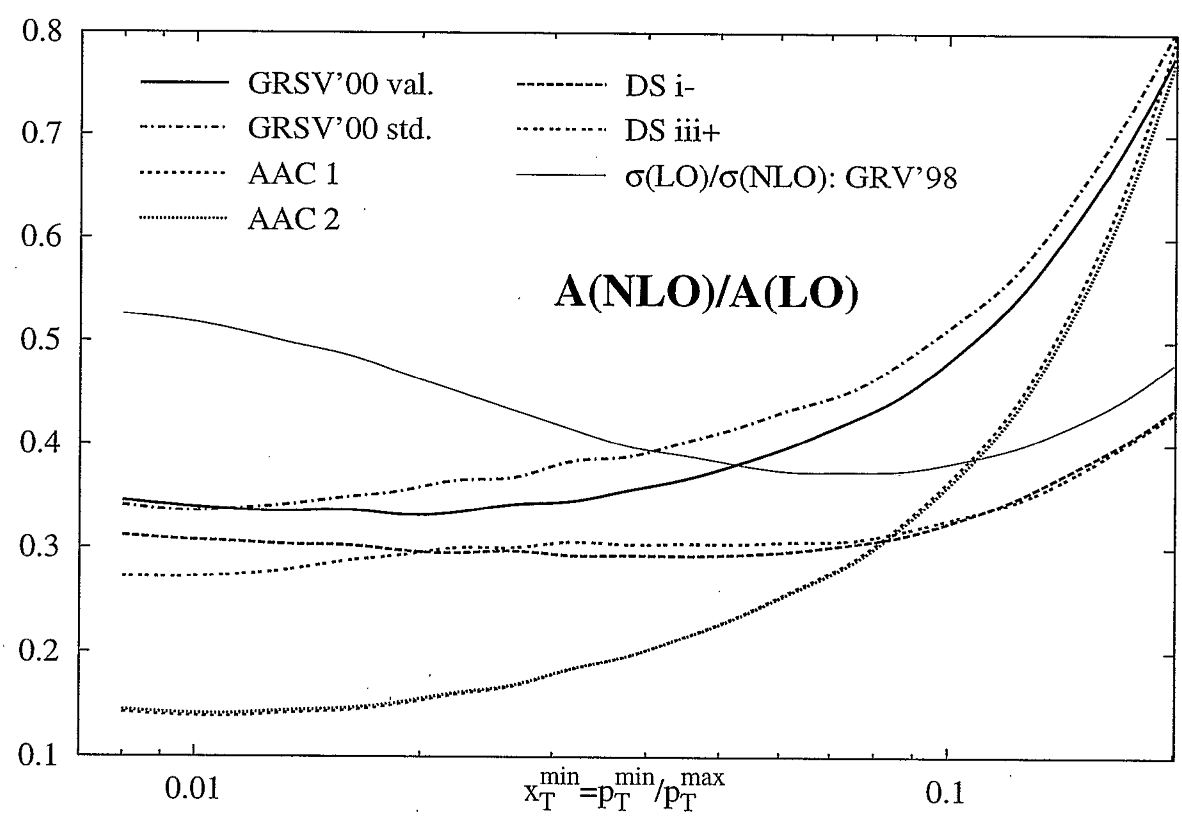




[required: $c, b \to e + X$, $p_T^e > 1$ GeV, and $|\eta_e| \leq 0.35$]

... and for the 'single-inclusive charm' spin asymmetry:





more results will be available soon ...

Extraction of Δg ('global analysis'):

✓ modern evol. codes operate on grids $\rightsquigarrow$ very fast

× NLO calc. of jets, prompt-γ, HQ, ... are based on multi-dim. MC's $\rightsquigarrow$ *much too slow for global fitting*

⇒ need a *reliable* and *fast* work-around, e.g.:

- use LO with fudge K-factor (done in some unp. fits)
  × K-factor may crit. depend on unknown PDF's (pol. PDF's and $\Delta\hat{\sigma}$'s can oscillate!)

- pre-calculate major part of NLO cross sections ('grids')
  ✓ almost as fast as DIS fits

'Double Mellin transform' technique: Kosower; Vogelsang, MS

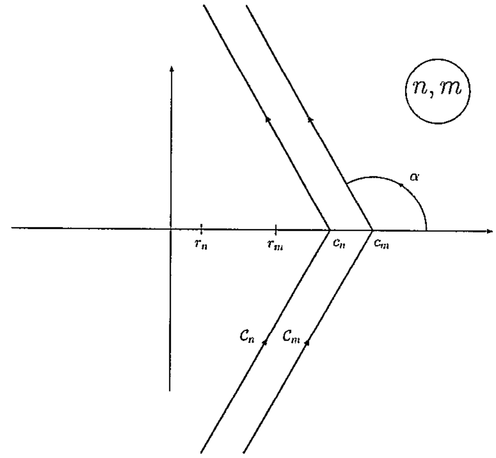
idea: get rid of slow 'double convolutions'

$$d\sigma \simeq \sum_{i,j} \int dx_1\, dx_2\, \underset{\uparrow \atop \int_{\mathcal{C}_n} dn\, x_1^{-n}\, f_i^n}{f_i(x_1)}\; \underset{\uparrow \atop \int_{\mathcal{C}_m} dm\, x_2^{-m}\, f_j^m}{f_j(x_2)}\; \hat{\sigma}_{ij}(x_1, x_2)$$

$$= \sum_{i,j} \int_{\mathcal{C}_n} dn \int_{\mathcal{C}_m} dm\, f_i^n\, f_j^m \left[\underbrace{\int dx_1\, dx_2\, x_1^{-n}\, x_2^{-m}\, \hat{\sigma}_{ij}(x_1, x_2)}_{\equiv\, \tilde{\sigma}_{ij}^{n,m}} \right]$$

then: pre-calculate $\tilde{\sigma}_{ij}^{n,m}$ on a suitable $n \times m$ grid for all subprocesses *and* data pts. *once* before the fit inverse transformation $\int_{\mathcal{C}_n} dn \int_{\mathcal{C}_m} dm$: done on $n \times m$ grids

$\mathcal{C}_n, \mathcal{C}_m$: contours in complex n, m plane to the right of all poles



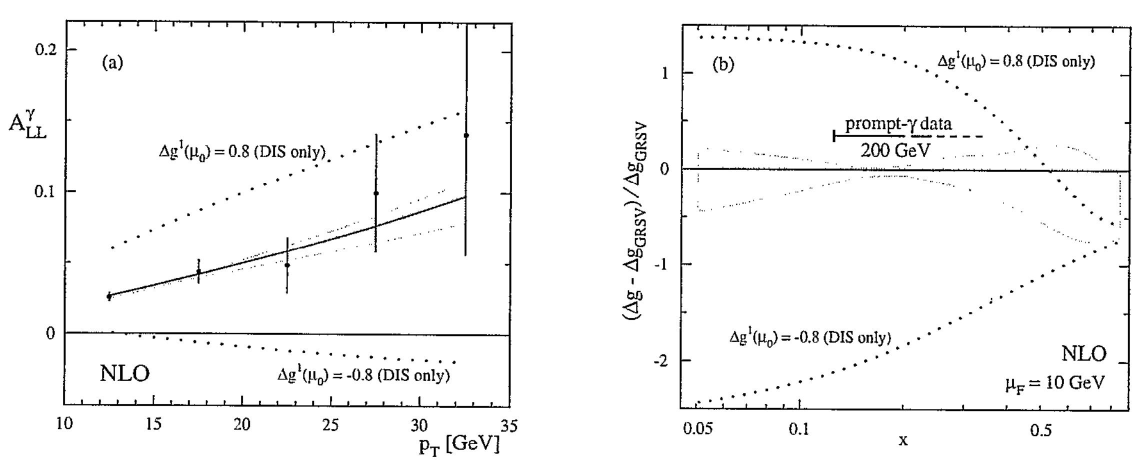
· no new poles beyond those already present in $f^{n,m}$

case study with projected prompt-γ data: Vogelsang, MS

· 64×64 grid gives excellent num. stability

· 1000 calc. of full NLO cross section take $10 \div 15$ sec.!

NLO fits (DIS+γ) with random start values for Δg give:
['data' pts. based on GRSV Δg and Gaussian 1σ-errors]



$\rightsquigarrow$ strong constraint on Δg around $x \simeq 0.15$

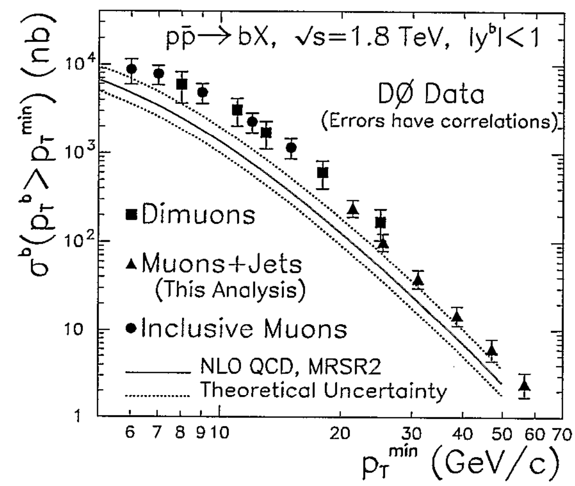
Mellin technique applicable to *all* NLO processes

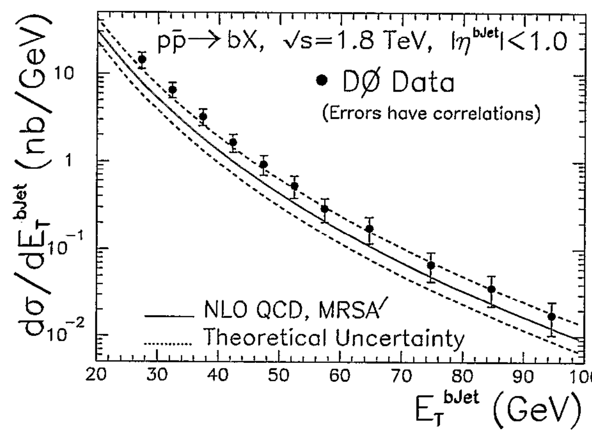
- Detour: do we understand *unpolarized* HQ data?

prior to Δg meas. one *must* check the unpol. 'status':

$\Rightarrow$ incl. b-rate from QCD too small in $p\bar{p}$, ep, and $\gamma\gamma$!

latest DØ results: **(I)** 'central' b's: $|y^b| < 1$, $p_T^b > p_T^{\text{min}}$

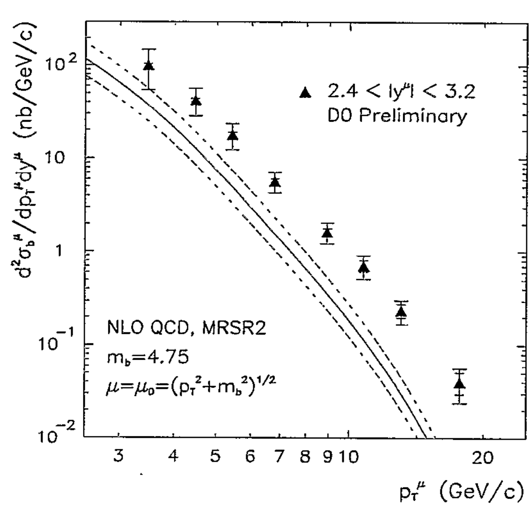


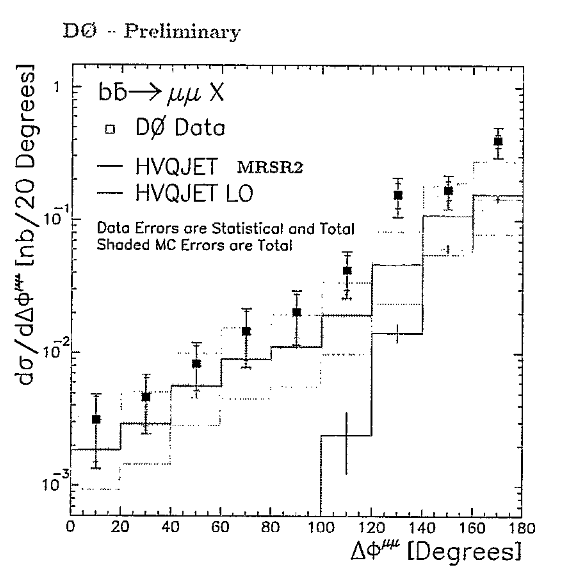


$\rightsquigarrow$ b-jets $\approx \checkmark$; otherwise data/theory $\approx 2 \div 2.5$

(II) 'forward' b's

(III) ang. corr. in $b\bar{b} \to \mu\mu$





$\rightsquigarrow$ data/theory $\simeq 4$ data/theory $\simeq 1.8$

attempts to understand the discrepancy:

several possibilities have been discussed:

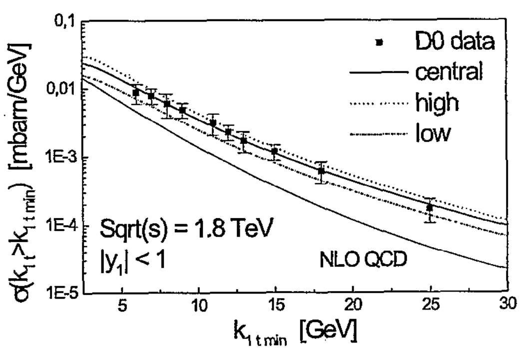
exp. problems, NNLO corrections, modified gluon density, 'intrinsic k_T', resum $\ln p_T/m$, ...

recently studied/proposed:

- 'BFKL' effects

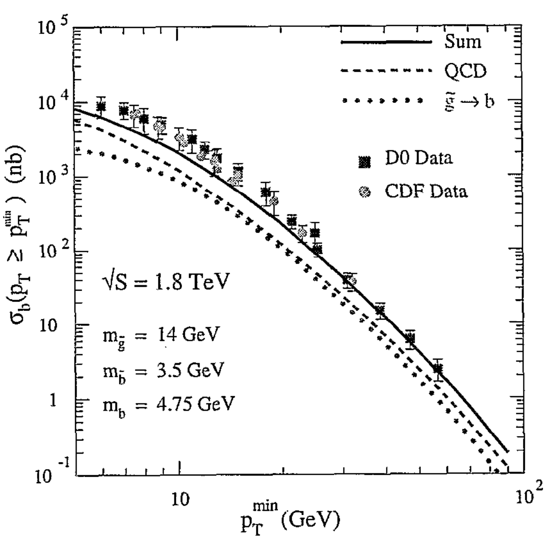
  Hägler, Kirschner, Schäfer, Szymanowski, Teryaev

  - uses: NLL BFKL vtx.; unintegrated gluon; k_T factorization
  - tests: $b\bar{b}$ correlations



- 'SUSY' effects

  Berger, Harris, Kaplan, Sullivan, Tait, Wagner



  - idea: $gg, q\bar{q} \to \tilde{g}\tilde{g}$, then $\tilde{g} \to b\tilde{\bar{b}}$
  - claim: consistent with all MSSM constraints
  - tests: bb, $\overline{bb}$ pairs; slower running of α_s

$\rightsquigarrow$ upcoming run II should improve exp. status

a RHIC measurement would be helpful as well

• Summary & Outlook

HAVE

✓ NLO polarized single incl. hadroproduction of HQ's

✓ started close collaboration with RBRC on HQ's

✓ fast tool for NLO global QCD analyses of PDF's

HAVE TO

- develop polarized NLO parton level MC for HQ's
- improve understanding of unpol. HQ production
- study other HQ observables (jets, ang. corr.)
- study impact of uncertainties on unpol. PDF's on Δg
- keep an eye on light gluinos:
  RHIC $\rightarrow$ 'gluino factory'? just kidding ...
  seriously: spin effects, bb vs. $b\bar{b}$ pairs, ...

Probing the spin structure of the photon at the EIC[†]

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Nothing is known experimentally about the parton content of circularly polarized photons, defined by $\Delta f^{\gamma}(x,Q^2) \equiv f_+^{\gamma+}(x,Q^2) - f_-^{\gamma+}(x,Q^2)$, where $f_+^{\gamma+}$ ($f_-^{\gamma+}$) denotes the density of a parton f with helicity '+' ('−') in a photon with helicity '+'. The present round of spin experiments, HERMES, COMPASS, and RHIC, is not sensitive to these distributions either. The Δf^{γ} contain information different from that included in the unpolarized ones, f^{γ}, and their measurement is vital for a *complete* understanding of the partonic structure of photons. It has been demonstrated [1] that measurements of the structure function g_1^{γ} and of di-jet spin asymmetries at a future polarized linear e^+e^- collider can provide valuable information about Δf^{γ}. Also HERA, after an upgrade to polarization for both the electron and the proton beam, could be in the position to shed some light on the Δf^{γ}, the preferred tool being the study of "resolved"-photon contributions to the spin asymmetry for (di-)jet photoproduction [2]. This presentation extends the previous HERA studies to the case of the EIC with a c.m.s. energy of $\sqrt{S_{\rm ep}} = 100$ GeV. Again we will exploit the predictions of two very different models for the Δf^{γ} [3], and study the sensitivity of (di)-jet production to these unknown quantities. For the "maximal scenario" we saturate the positivity bound $|\Delta f^{\gamma}(x,Q^2)| \leq f^{\gamma}(x,Q^2)$ at a low input scale $\mu \simeq 0.6\,\text{GeV}$, using the GRV f^{γ} densities. The "minimal scenario" is defined by a vanishing hadronic input at the scale μ.

The generic expression for polarized resolved photoproduction of two jets with laboratory system rapidities η_1, η_2 and transverse momentum p_T reads in LO

$$\frac{d^3\Delta\sigma}{dp_T d\eta_1 d\eta_2} = 2p_T \sum_{f^e,f^p} x_e \Delta f^e(x_e,\mu_f^2) x_p \Delta f^p(x_p,\mu_f^2) \frac{d\Delta\hat{\sigma}}{d\hat{t}} , \tag{1}$$

where $x_e \equiv p_T/(2E_e)\,(e^{-\eta_1}+e^{-\eta_2})$ and $x_p \equiv p_T/(2E_p)\,(e^{\eta_1}+e^{\eta_2})$. The Δf^p and Δf^e in (1) denote the spin-dependent parton densities of the proton and electron, i.e., photon, respectively, see [2]. The key advantage of *di*-jet as compared to single-inclusive jet production is that a measurement of *both* jet rapidities allows for fully reconstructing the kinematics of the underlying hard subprocess and thus for determining $x_{\gamma} = x_e/y$ on an experimental basis, with y being the fraction of the electron's energy taken by the photon. In this way it becomes possible to "scan" the x-shape of Δf^{γ}. However, unfolding the Δf^{γ} from a jet-measurement would in general be a very involved task, since many subprocesses and combinations of parton densities contribute to the cross section. It was shown [4] that the ratios of the dominant unpolarized

[†]Talk presented by Marco Stratmann

LO subprocesses are roughly constant w.r.t. the c.m.s. scattering angle, such that the jet cross section factorizes approximately into some "effective parton densities" times a single partonic cross section. In the polarized case the situation is somewhat less clear, but the approximation still works surprisingly well at a level of $5-10\%$ accuracy. The appropriate effective densities are given by [2] $\Delta f_{\rm eff}^{\gamma} = \sum_q (\Delta q^{\gamma} + \Delta \bar{q}^{\gamma}) + \frac{11}{4}\Delta g^{\gamma}$ (see also ref. [5]) such that the polarized double resolved jet cross section can be expressed as $\Delta\sigma^{2-\rm jet} \simeq \Delta f_{\rm eff}^{\gamma} \otimes \Delta f_{\rm eff}^{p} \otimes \Delta\hat{\sigma}_{qq'\to qq'}$. It is only for large p_T that deviations from the exact results become more pronounced.

In general the lower energy of the EIC, as compared to HERA, has both advantages and disadvantages: spin asymmetries are generally expected to be larger at the EIC since – for a given jet transverse momentum – the parton densities are probed at somewhat higher x. On the other hand, event rates will be lower, with ensuing larger statistical uncertainties (assuming similar integrated luminosities for HERA and the EIC). Also, the resolved photon component we are interested in here generally becomes the less important, the smaller the energy of the interaction is. Nevertheless, our results show the trend that the advantages of having lower energies outweigh the disadvantages, so that the EIC appears superior to HERA concerning the potential for determining the Δf^{γ}. This is in particular true if one keeps in mind that we have assumed only a rather modest luminosity for our simulation concerning the EIC.

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eic workshop

BNL 3/1/2002

Probing the Spin Structure of the Photon at the EIC*

Marco Stratmann

(Regensburg)

- Why do we need PDF's of *polarized* photons?
- NLO QCD framework and models for Δf^γ
- Accessing Δf^γ at the EIC:
  - promising processes: one-jet incl., di-jets
  - estimates of spin asymmetries and stat. errors
  - pros and cons of other experiments:
    polarized HERA, TESLA, THERA
- Summary

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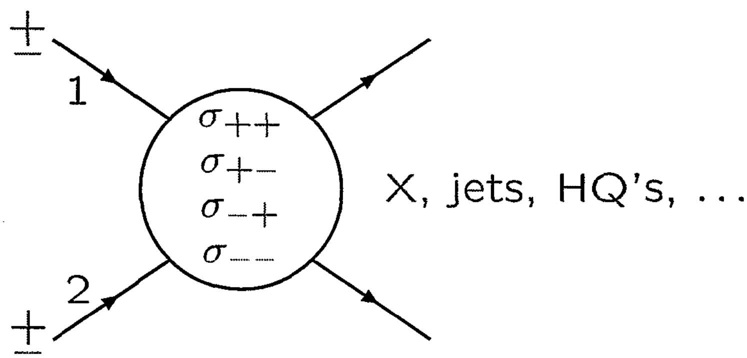
* in collaboration with Werner Vogelsang (RIKEN-BNL)

• Why do we need *polarized* PDF's?

⋆ helicity - *averaged* PDF's only contain *half* of the information about the parton content of nucleons and photons (similar: fragmentation functions)

generic process with long. pol. beams (helicities $+$ or $-$):



only *two* indep. helicity config.: $\sigma_{++} = \sigma_{--}$, $\sigma_{+-} = \sigma_{-+}$

$\rightsquigarrow \frac{1}{2}(\sigma_{++} + \sigma_{+-}) \equiv \sigma$ (usual unpol. cross section)

$$\frac{1}{2}(\sigma_{++} - \sigma_{+-}) \equiv \Delta\sigma = \Delta f_1 \otimes \Delta f_2 \otimes \Delta\hat{\sigma}$$

$\boxed{f_+^{1+} - f_-^{1+}}$ $\boxed{\frac{1}{2}(\hat{\sigma}_{++} - \hat{\sigma}_{+-})}$

where '1', '2' $= p, e^{\pm}, \gamma$

$\Rightarrow$ basic 'building blocks' are f_+ and f_- (or f and Δf)

experimentally relevant:

'spin asymmetry' $\boxed{A \equiv \frac{d\Delta\sigma}{d\sigma} = \frac{N_{++} - N_{+-}}{N_{++} + N_{+-}}}$

ratio of 'counting rates'

$\star$ different Q^2-evolution for $\Delta f \rightsquigarrow$ important QCD test

$\star$ current knowledge

	unpolarized	helicity-dependent
proton $(\Delta)f^p$	$\checkmark$	$(\checkmark) \to$ RHIC!
photon $(\Delta)f^\gamma$	$(\checkmark)$	$\times$
fragmentation $(\Delta)D_f^h$	$(\checkmark)$	$(((\checkmark)))$ for $\vec{\Lambda}$

$\rightsquigarrow$ need at least *some* info about Δf^γ from experiment

$\star$ Δf^γ not accessible with present experiments

$\rightsquigarrow$ what about future facilities?

candidates: (need *two* pol. beams for non-zero twist-2 asym.!)

$\vec{e}\vec{e}$: linear collider (e.g. TESLA)

$\vec{e}\vec{p}$: EIC or pol. HERA ($\vec{p}$-beam?) or ...

$\star$ understanding of 'background' from resolved-γ's:

- photoproduction @ COMPASS or HERMES
  resolved contr. *expected* to be small ($\lesssim 5 \div 10\%$)

- precision measurements @ linear colliders
  (tiny) part of QCD background

$\star$ other aspects (not considered here, more work needed)

- linear polarization — Jaffe, Manohar; Artru, Mekhfi
  feature: only gluons contribute, counterpart of 'transversity'

- spin-1 target — Hoodbhoy, Jaffe, Manohar; Artru, Mekhfi
  feature: add. str. fct. b_1 (not accessible in $\Delta\sigma$)

• QCD framework and models for Δf^γ

Q^2-evolution of Δf^γ: LO: Irving, Newland; Hassan, Pilling; Xu
NLO: Vogelsang, MS

very similar to unpol. case: $P_{ij} \to \Delta P_{ij}$, $k_i \to \Delta k_i$

calculated up to NLO

$$\frac{\mathrm{d}\Delta q_i^\gamma}{\mathrm{d}\ln Q^2} = \underbrace{\Delta k_i}_{\substack{\text{inhom. piece}\\ \gamma\to i}} + \left(\Delta P_i \otimes \Delta q_i^\gamma\right) \qquad i = (\mathrm{NS}, \mathrm{S})$$

well-known solution: $\Delta q_i^\gamma = \Delta q_{i,\mathrm{pl}}^\gamma + \Delta q_{i,\mathrm{hadr}}^\gamma$

pointlike part: depends only on Q_0 $\Delta q_{i,\mathrm{pl}}^\gamma(Q_0^2) = 0$

hadronic part: *non*-pert. input required

Δq_i^γ 'counts' as $\mathcal{O}(\alpha/\alpha_s)$ in LO

$\rightsquigarrow$ 'direct' and 'resolved' photon contributions are on equal footing (e.g. photoprod. at HERA)

DIS structure function g_1^γ: (counterpart of unpol. F_2^γ)

$$g_1^\gamma(x,Q^2) = g_1^{\text{"proton"}}(x,Q^2) + \frac{3\alpha}{4\pi}\sum_q e_q^4\, \Delta C_\gamma(x)$$

contributes in NLO: $\gamma^*\gamma \to q\bar{q}$

realistic models for Δf^γ:

Glück, Vogelsang; Glück, Vogelsang, MS

no data yet $\rightsquigarrow$ have to fully rely on *models* to study processes sensitive to Δf^γ

models should be realistic $\rightsquigarrow$ any constraints on Δf^γ ?
... yes!

· 'positivity':

guarantees that

$$\boxed{|\Delta\sigma| \leq \sigma}$$

to all orders in perturbation theory

$$\leftrightarrow |\Delta f^\gamma| = |f_+^{\gamma+} - f_-^{\gamma+}| \leq f_+^{\gamma+} + f_-^{\gamma+} = f^\gamma \quad \text{(exact in LO)}$$

[but Δf^γ *not* pos. def. $\rightsquigarrow$ no γ - 'mom. sum rule' a la
Frankfurt, Gurvich; Schuler, Sjöstrand]

· 'current conservation':

Narison, Shore, Veneziano; Bass; Bass, Brodsky

implies that

$$\boxed{\int_0^1 dx\, g_{1,\mathrm{pl}}^\gamma(x, Q^2) = 0}$$

to all orders in perturbation theory

automatically fulfilled in LO and NLO ($\overline{\mathrm{MS}}$ and DIS_γ):
1^{st} moments of $\Delta k_{q,g}$ and ΔC_γ all vanish!

$\Rightarrow$ only 'positivity' is useful for practical purposes
sufficient to give *upper bounds* for spin asymmetries

To study the sensitivity to Δf^γ at future experiments it is sufficient to construct two *extreme* models:

$$|\Delta f^\gamma| \;\leq\; f^\gamma$$

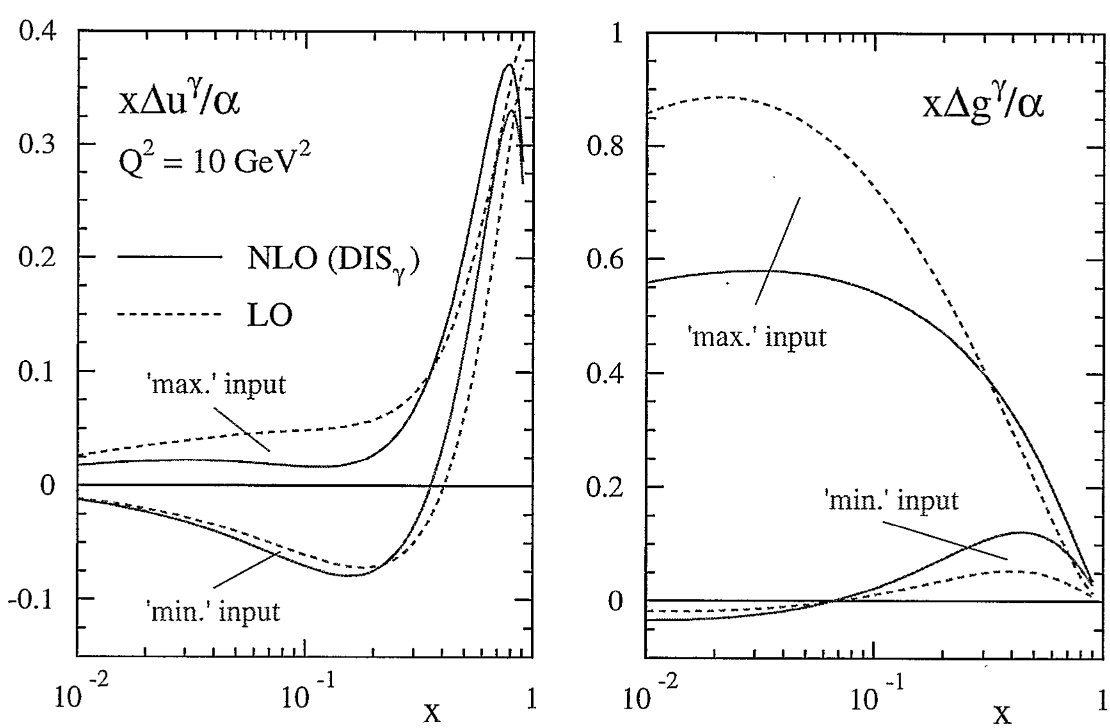
$$\swarrow \qquad\qquad \searrow$$

'max.' input | 'min.' input

$$\boxed{\Delta f^\gamma(x, Q_0^2) = f^\gamma_{\mathrm{GRV}}(x, Q_0^2)} \qquad \boxed{\Delta f^\gamma(x, Q_0^2) = 0}$$

$$Q_0 \sim 0.6\ \mathrm{GeV}$$

pure VMD input at Q_0 | pointlike for all Q



$\rightsquigarrow$ expect sizable (perhaps even sign) differences in spin asymmetries sensitive to our Δf^γ models

• Prospects of measuring Δf^γ in the future

several future colliders are currently under scrutiny:

(I) polarized $\vec{e}\vec{p}$ collider

EIC (was eRHIC & EPIC)	$\sqrt{S} = 100\,\text{GeV}$ $\mathcal{L} = \mathcal{O}(200\,\text{pb}^{-1})$ can use existing RHIC $\vec{p}$ beam
pol. HERA (several workshops in the past)	$\sqrt{S} \simeq 300\,\text{GeV}$ $\mathcal{L} = \mathcal{O}(100 \div 500\,\text{pb}^{-1})$ future option for HERA
THERA (recent initiative)	$\sqrt{S} \simeq 1000\,\text{GeV}$ $\mathcal{L} = \mathcal{O}(10\,\text{pb}^{-1})$?? remote option: TESLA $\otimes$ HERA polarization for e and p ??

(II) linear $\vec{e}\vec{e}$ collider

e.g., TESLA (series of workshops)	$\sqrt{S} \simeq 500\,\text{GeV}$ $\mathcal{L} = \mathcal{O}(100\,\text{fb}^{-1})$ $\gamma\gamma$ - mode ?? (backscat. laser photons) polarized beams planned

Let's study the potential of each machine w.r.t. Δf^γ

• Δf^γ @ future polarized $\vec{e}\vec{p}$ colliders

Δf^γ accessible via *resolved contr.* in photoproduction

general problem: suppression of unwanted direct-γ part

promising processes: Vogelsang, MS

· $\boxed{\vec{e}\vec{p} \to \text{jet} + \text{X}}$ (similar for $\text{h}^\pm + \text{X}$)

× only indirect direct/resolved 'separation' via

$$\begin{array}{lccc} (\Delta)\sigma_{\text{dir}} & \text{dominant} & \eta_{\text{lab}} < 0 & (\leftrightarrow x_\gamma \to 1) \\ (\Delta)\sigma_{\text{res}} & \text{for} & \eta_{\text{lab}} > 0 & (\leftrightarrow x_\gamma \ll 1) \end{array}$$

[positive η: proton direction]

✓ stable under NLO corrections de Florian, Frixione

· $\boxed{\vec{e}\vec{p} \to \text{jet}_1 + \text{jet}_2 + \text{X}}$

✓ reconstruction of x_γ possible:

define direct and resolved samples via x_γ-cut

old idea: Forshaw, Roberts

✓ LO QCD ≈ MC Butterworth, Goodman, WV, MS

extraction of Δf^γ from $\Delta\sigma/\sigma$:

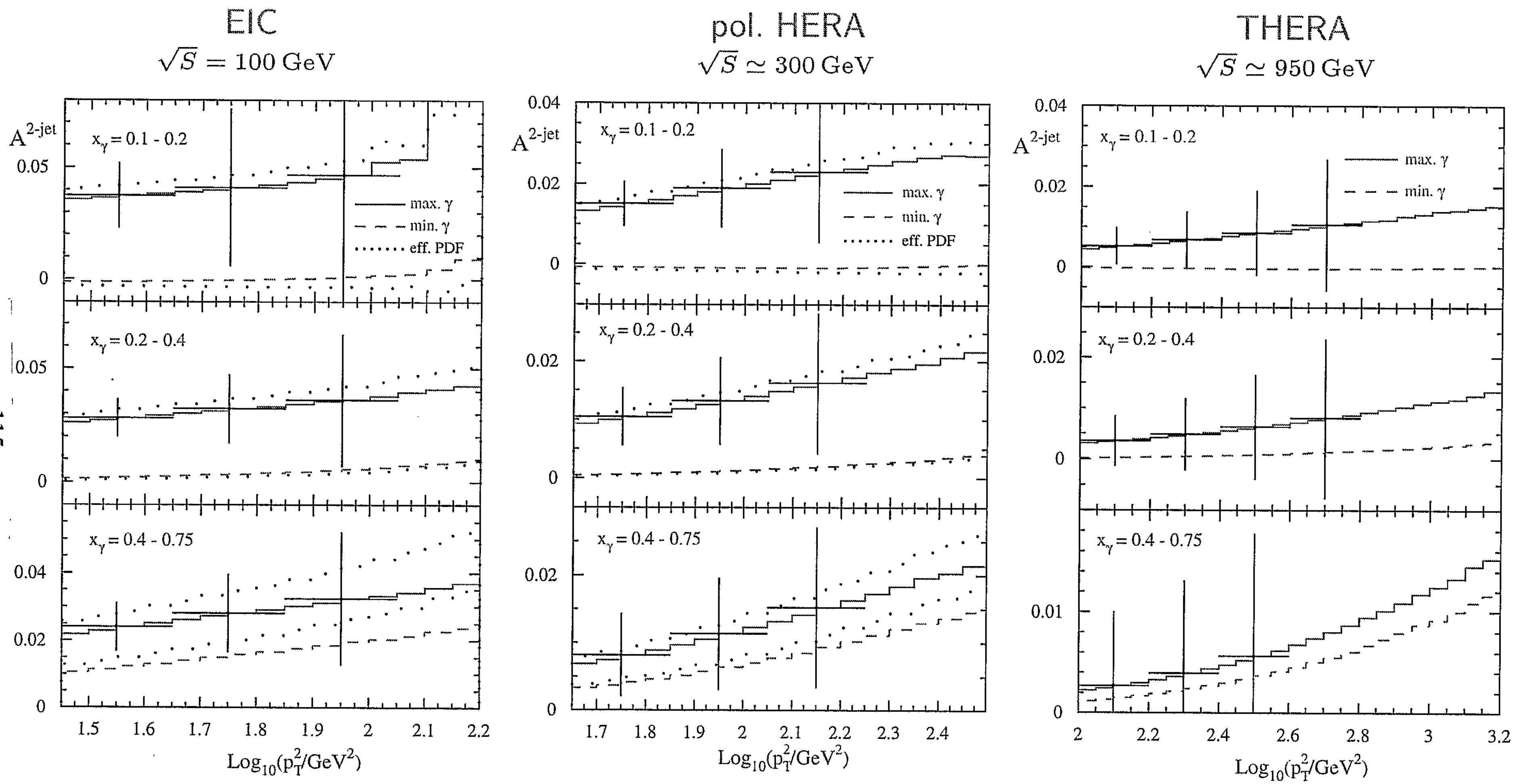
· $\Delta\sigma/\sigma$ is complicated function of $\Delta f^{\gamma,p}$ and $(\Delta)\hat{\sigma}_{ij}$

idea: *effective* PDF's unpol.: Combridge, Maxwell

$\sigma_{\text{res}} \simeq f^\gamma_{\text{eff}} \otimes f^p_{\text{eff}} \otimes \hat{\sigma}_{qq' \to qq'}$ with $\boxed{f_{\text{eff}} = \sum(q+\bar{q}) + \frac{9}{4}g}$

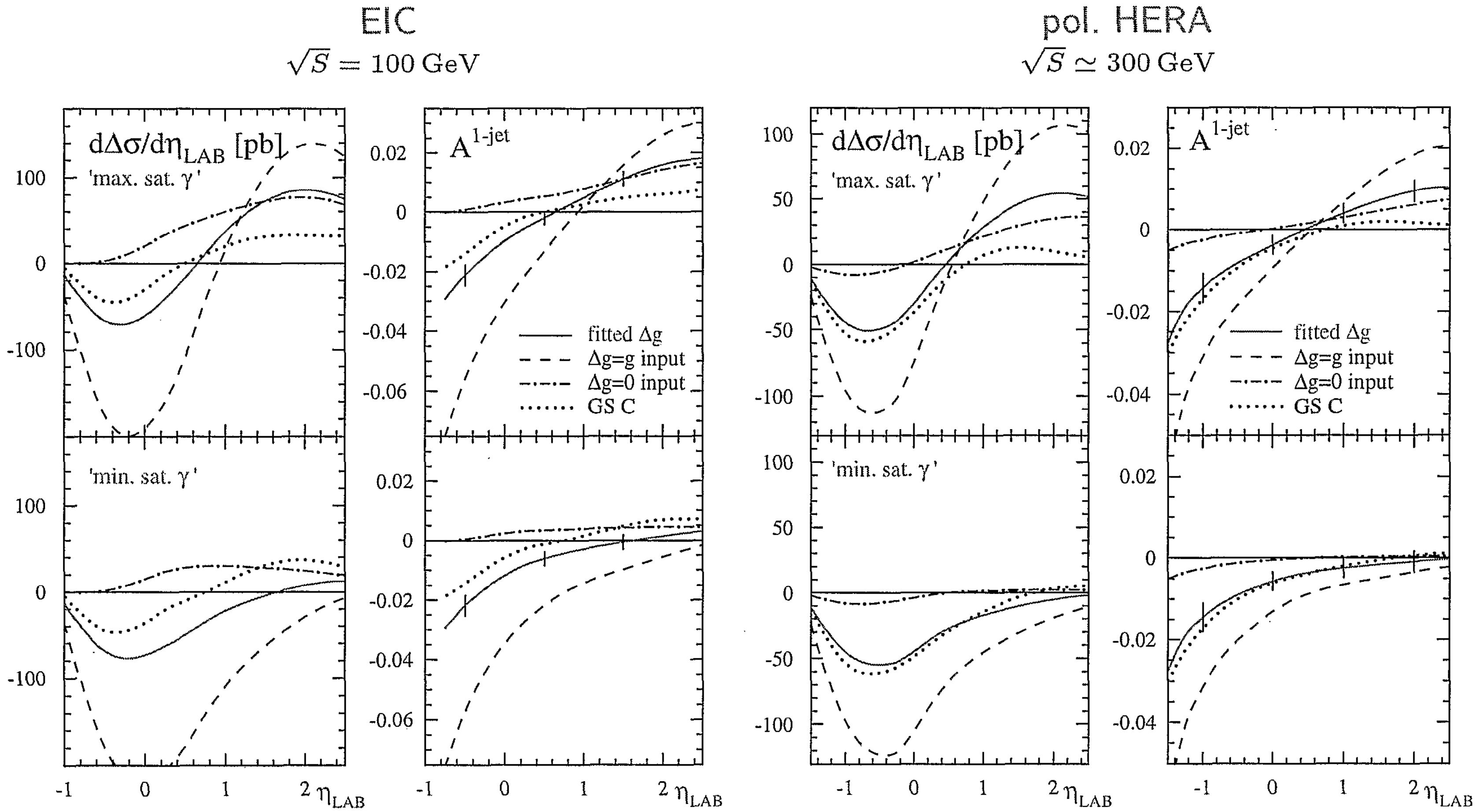
· works fine in *pol. case* with $\ldots + \frac{11}{4}\Delta g$ WV, MS

• Di-jets @ $\vec{e}\vec{p}$ machines: overview & comparison



<u>param. used</u>: LO; Δf^p: GRSV; $\mu = p_T$; 'errors': $\mathcal{L} = 200\,\mathrm{pb}^{-1}$, $P_e = P_p = 0.7$; WW: $0.2 \leq y \leq 0.85$, $Q^2_{\mathrm{max}} = 4\ (1)\ \mathrm{GeV}^2$ (EIC)
$|\Delta\eta| \equiv |\eta_1 - \eta_2| \leq 1$, $0 < \frac{\eta_1+\eta_2}{2} < 2$ (EIC, pol. HERA) and $-1.5 < \frac{\eta_1+\eta_2}{2} < 1.5$ (THERA)

• 1-jet inclusive @ $\vec{e}\vec{p}$ machines: overview & comparison

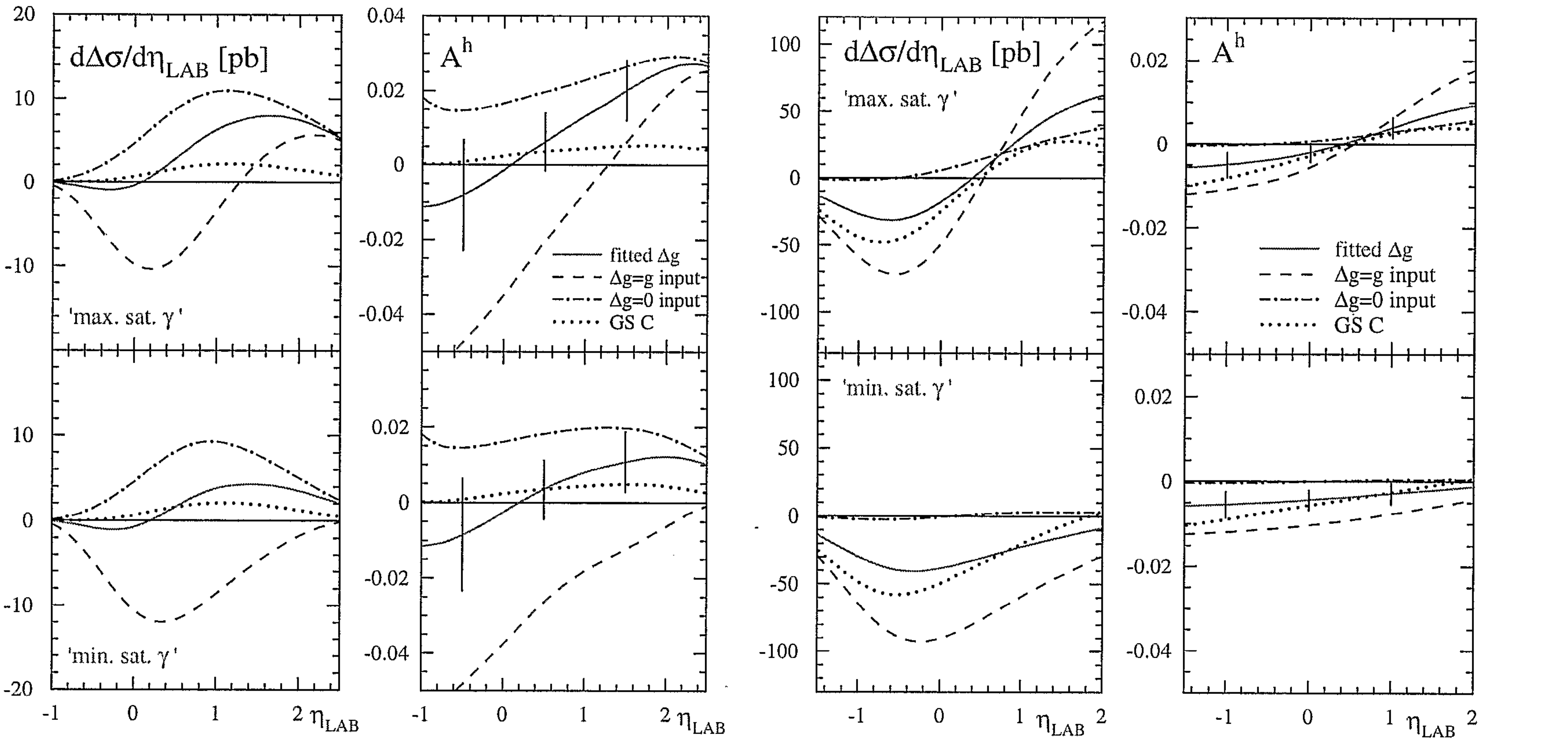


<u>param. used</u>: LO; Δf^p: GRSV; $\mu = p_T$; 'errors': $\mathcal{L} = 100\,\mathrm{pb}^{-1}$, $P_e = P_p = 0.7$
WW: $0.2 \leq y \leq 0.85$, $Q^2_{\max} = 4\ (1)\ \mathrm{GeV}^2$ (EIC); $p_T^{\min} = 8\ (5)\ \mathrm{GeV}$ (EIC)

• 1-hadron inclusive @ $\vec{e}\vec{p}$ machines: overview & comparison

EIC $\qquad\qquad$ pol. HERA

$\sqrt{S} = 100\,\mathrm{GeV}$ $\qquad\qquad$ $\sqrt{S} \simeq 300\,\mathrm{GeV}$



<u>param. used</u>: LO; $h = \pi^{\pm} + K^{\pm}$; Δf^p: GRSV; $\mu = p_T$; 'errors': $\mathcal{L} = 100\ (200)\ \mathrm{pb}^{-1}$ (EIC), $P_e = P_p = 0.7$, $\varepsilon^h_{\mathrm{eff}} = 0.8$
WW: $0.2 \leq y \leq 0.85$, $Q^2_{\max} = 4\ (1)\ \mathrm{GeV}^2$ (EIC); $p_T^{\min} = 3\ (4)\ \mathrm{GeV}$ (EIC)

• Δf^{γ} @ a future linear $\vec{e}\vec{e}$ collider

many advantages compared to $\vec{e}\vec{p}$:

+ no Δf^{p} involved $\rightsquigarrow$ clean signature for Δf^{γ}
+ $\gamma^{*}\gamma$ DIS possible $\rightsquigarrow$ g_1^{γ} accessible
+ $\gamma\gamma$-collider option under scrutiny (TESLA)

  interesting since

  (roughly) $$A^{e^+e^-}_{\text{process}} \sim \underset{\substack{\nearrow \\ \text{should be large}}}{A_{\gamma-\text{flux}}} \times \underset{\substack{\nearrow \\ \text{wanted}}}{A_{f^{\gamma}}} \times \underset{\substack{\uparrow \\ \text{QCD}}}{A_{\hat{\sigma}}}$$

'classical' γ-source: EPA

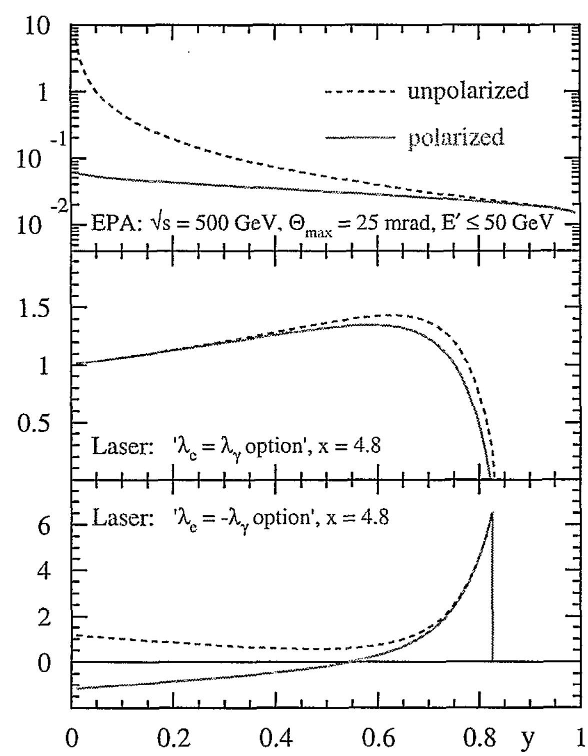
· $A^{\text{EPA}}_{\gamma-\text{flux}} \ll 1$ for most y

alt. source: laser photon

(see: Ginzburg, Kotkin, Serbo, Telnov, Panfil)

· $A^{\text{laser}}_{\gamma-\text{flux}} \simeq 1$ for *all* y

· approx. mono-energetic γ-spectrum $\rightsquigarrow$ better $x_{\gamma}^{\text{meas}} \leftrightarrow x_{\gamma}^{\text{true}}$ in DIS



promising processes:

· $\gamma^{*}\gamma$ DIS: $g_1^{\gamma}/F_1^{\gamma}$ probes mainly $\Delta u^{\gamma}/u^{\gamma}$

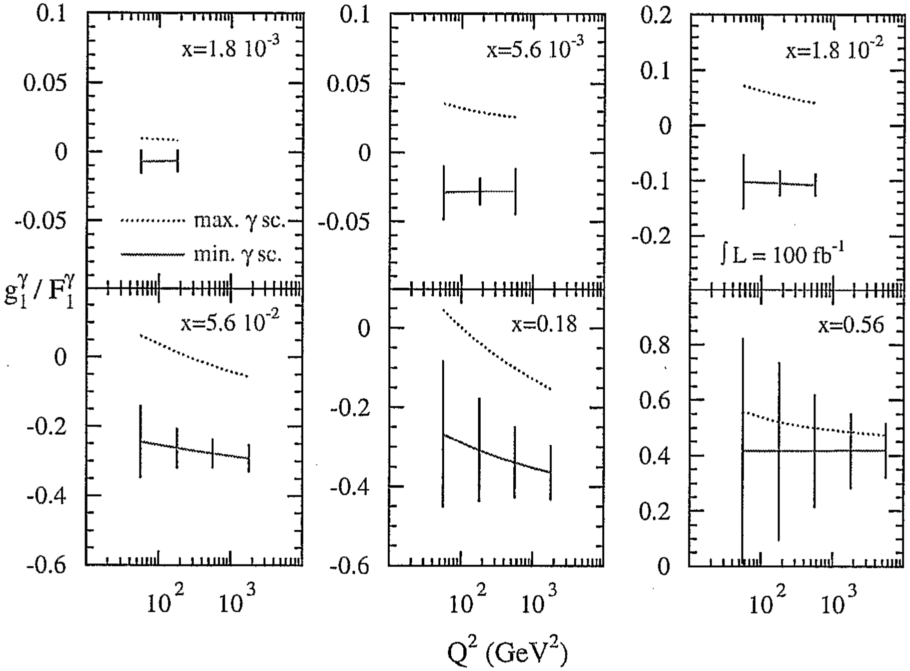
· di-jets: select 'double resolved' part via x_{γ}-cut (a la OPAL) probes mainly $\Delta g^{\gamma}/g^{\gamma}$

• Δf^{γ} @ TESLA: $g_1^{\gamma}/F_1^{\gamma}$ and di-jets

DIS: $g_1^{\gamma}/F_1^{\gamma}$

$$\sqrt{S} = 500\,\mathrm{GeV}$$

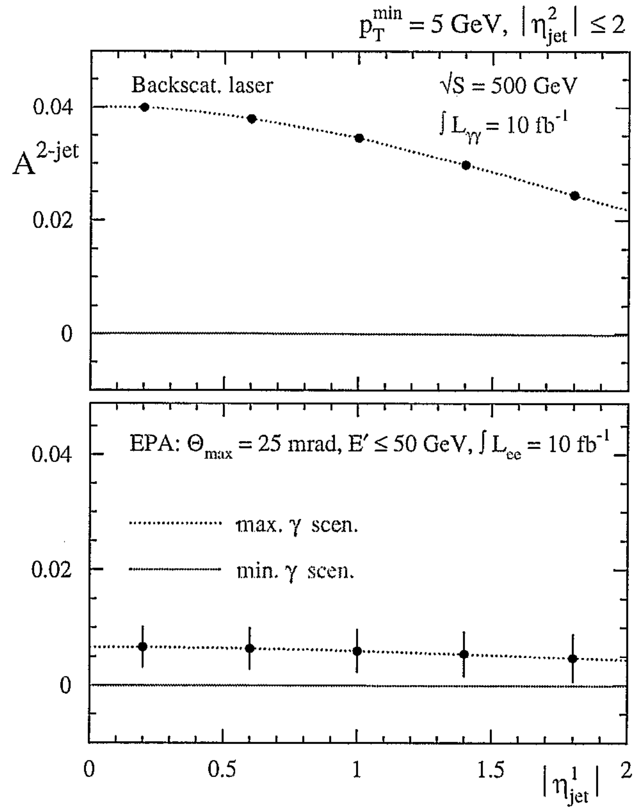
target photon: backscat. laser



errors would be larger for a WW (EPA) γ-target

(more studies needed here)

di-jets



double resolved contribution:

$$x_{\gamma}^{\pm} \leq 0.80$$

• Summary & comparison of results

collider	$\sqrt{S}$ [GeV]	promising processes	required lumi. $[\mathrm{pb}^{-1}]$	mainly sensitive to	remarks
EIC	100	1-jet incl.	100	Δg^γ	dir. vs res.
		di-jets	200	$\Delta f^\gamma_{\mathrm{eff}}$	✓
pol. HERA	300	1-jet incl.	100	Δg^γ	dir. vs res.
		(1-had. incl.)	200	compl. combi.	small $p_T^{\min}$ req.
		di-jets	200	$\Delta f^\gamma_{\mathrm{eff}}$	✓
THERA	950	((di-jets))	$\gg$200	$\Delta f^\gamma_{\mathrm{eff}}$	large stat. errors
lin. collider		g_1^γ	100000	Δu^γ	only in $\gamma\gamma$-mode ?
TESLA	500	di-jets	10000	$\Delta f^\gamma_{\mathrm{eff}}$	better in $\gamma\gamma$-mode

· higher energies are *not* always helpful ($\rightarrow$ THERA): small asymmetries; large stat. errors

· $\gamma\gamma$-mode for next linear collider helpful (probably mandatory for g_1^γ measurement)

best process: di-jets (best enhancement of resolved contr.; access to x_γ; eff. PDF approx. works well)

best machine to pin down Δf^γ: EIC in $\vec{e}\vec{p}$ and TESLA ($\vec{\gamma}\vec{\gamma}$-mode)

[of course, pol. HERA would be also nice]

Theory Studies for RHIC-Spin

A RIKEN BNL Research Center Workshop
Spring 2002

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Theory Studies for RHIC-Spin

Spring 2002

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

Speakers:

M. Anselmino
U. D'Alesio
J. Kodiara
J. Qiu
M. Stratmann

Organizer: W. Vogelsang