Fundamental Open Questions in Spin Physics

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We will address to the following questions:

- What is the proton spin good for?
- What contributes to the proton spin?
- What needs to be measured next?
- What are the prospects?

Outline

- Some intringing and unexpected observations
- Guided tour on parton distributions functions
  - Unavoidable digression on unpolarized PDF
  - Δq, $\Delta\bar{q}$: Flavor separation from SIDIS $eN \rightarrow ehX$ and prospects
  - Gluon Polarization $\Delta g(x)$ in the nucleon: Present status and prospects
- Quark Transversity $\delta q(x, Q^2)$ and A_{TT} asymmetries
- New degrees of freedom in QCD
  - QCD mechanisms for single spin asymmetries A_N (Sivers versus Collins)
  - More TMD dependence
  - Generalized parton distributions and orbital angular momentum
- Outlook

Recall what we know from pp $\rightarrow$ pp since 1979

This was the motivation for a successful Siberian Snake Program

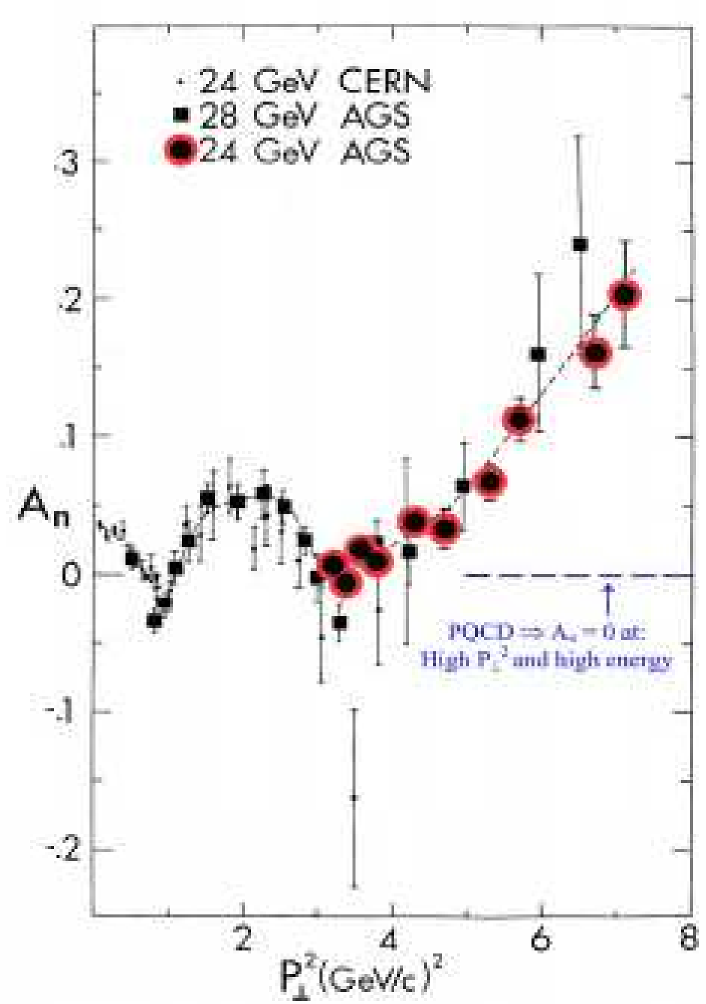
AGS A_n DATA

PERTURBATIVE QCD $\Rightarrow$
$A_n = 0$ at HIGH $P_\perp^2$ and HIGH ENERGY

$A_n \neq 0 \Rightarrow$
PROBLEM WITH PQCD?

NO MODEL CAN EXPLAIN ALL
HIGH-$P_\perp^2$ SPIN EFFECTS (A_n & A_{nn})

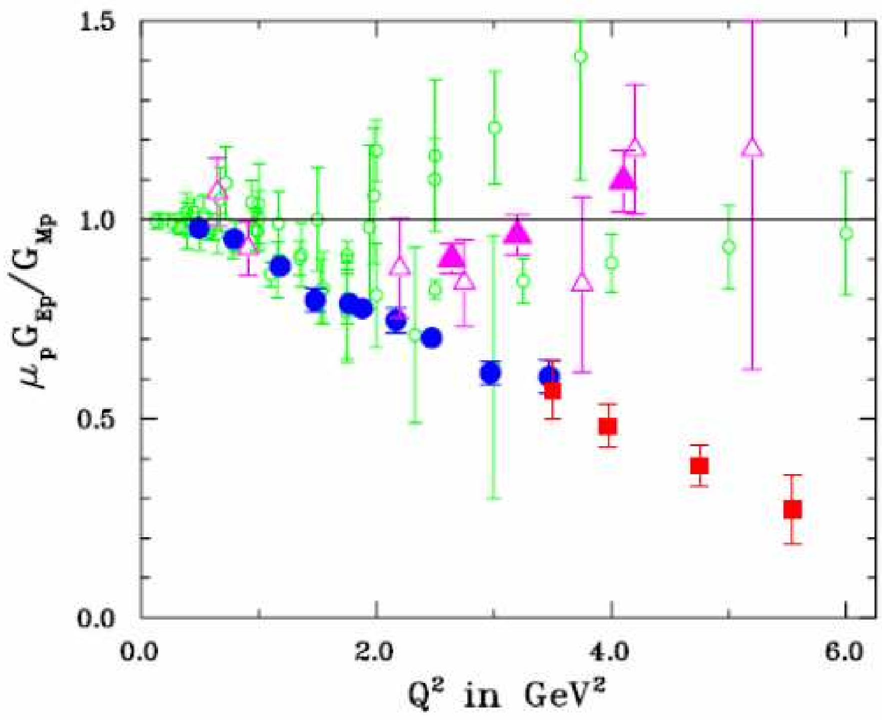
GOAL at J-PARC
MEASURE A_n (and A_{nn})
up to $P_\perp^2 = 12$ (GeV/c)^2



Recall what we learnt recently from ep→ep

A simple reaction which was believed to be totally understood

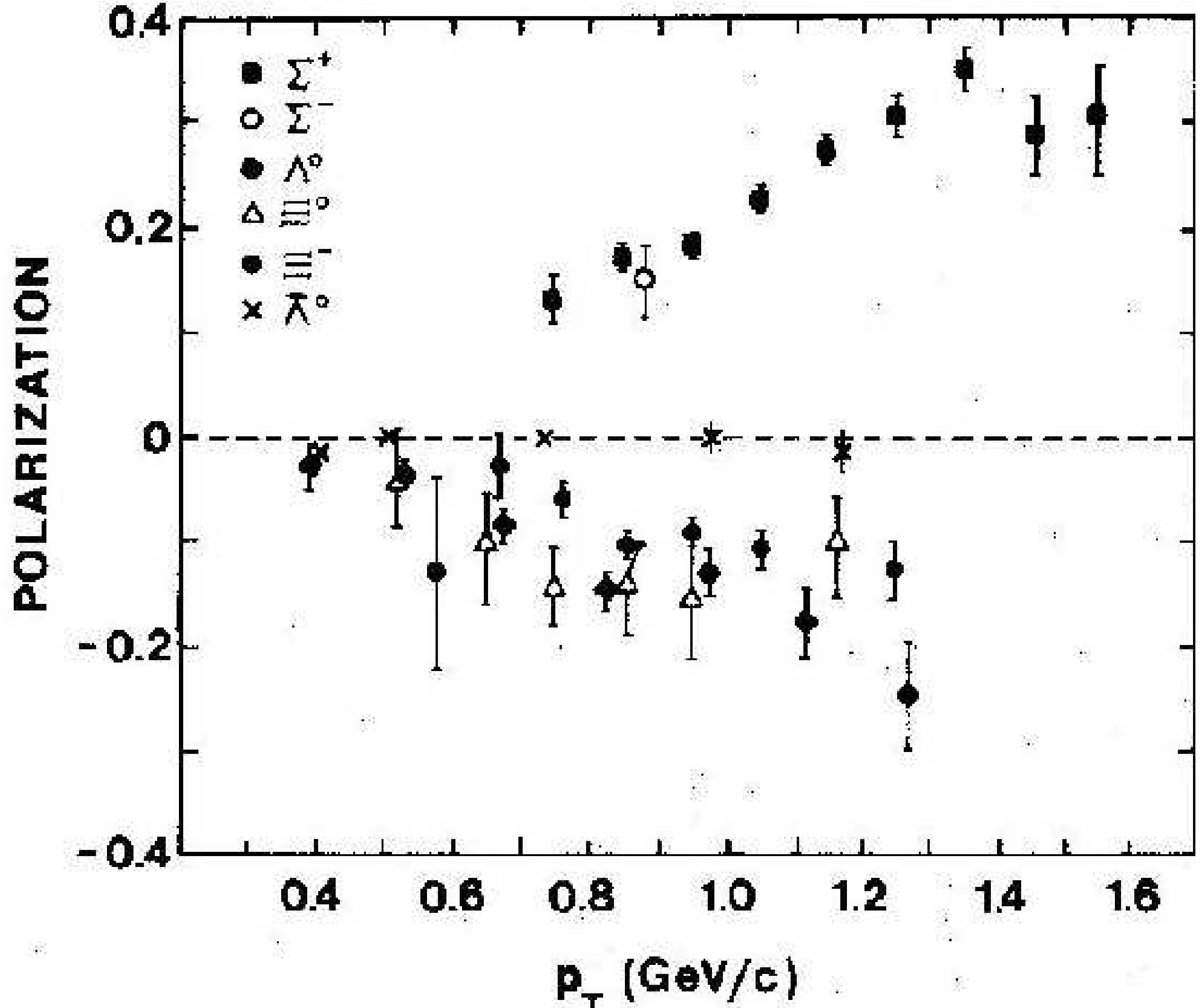
Data From GEp(I) and GEp(II) Experiments



(Jones *et al.*, Phys. Rev. Lett. 84, 1398 (2000); Gayou *et al.*, Phys. Rev. Lett. 88, 092301 (2002); and Punjabi *et al.*, Phys. Rev. C 71, 055202 (2005))

New surprises: Large A_N in hyperon inclusive production at FNAL in 1976

Many more puzzling single spin asymmetry data since then



Some specific goals

1) - To understand the nucleon spin structure in terms of quarks and gluons.

2) - To test the SPIN SECTOR of pQCD (Several spin asymmetries calculated to NLO)

Basic information comes from Deep Inelastic Scattering (DIS)

$$lN \to l' X \quad \text{or} \quad l(\uparrow)N(\uparrow) \to l' X$$

We recall that ($q = u, d, s, ...$)

$$\text{unpolarized DIS} \Rightarrow F_2^{p,n}(x, Q^2) = \sum_q e_q^2 [xq(x, Q^2) + x\bar{q}(x, Q^2)] \,,$$

$$\text{long. polarized DIS} \Rightarrow g_1^{p,n}(x, Q^2) = 1/2 \sum_q e_q^2 [\Delta q(x, Q^2) + \Delta\bar{q}(x, Q^2)] \,,$$

the $q(x, Q^2)$'s (same for antiquarks) are defined as $q = q_+ + q_-$, where $q_\pm$ are the quark distributions in a polarized proton with helicity parallel $(+)$ or antiparallel $(-)$ to that of the proton. Similarly $\Delta q(x, Q^2)$'s (same for antiquarks) are defined as $\Delta q = q_+ - q_-$.

Idem for the gluon distributions defined as $G = G_+ + G_-$ and $\Delta G = G_+ - G_-$.

In DIS they only enter in the QCD Q^2 evolution of the quark distributions.

DGLAP evolution equations

The gluon distribution contributes to the scaling violations predicted by QCD

$$\frac{d}{d\ell n Q^2}\begin{pmatrix} q(x,Q^2) \\ G(x,Q^2) \end{pmatrix} = \begin{pmatrix} P_{qq}(\alpha_s,x) & P_{qG}(\alpha_s,x) \\ P_{Gq}(\alpha_s,x) & P_{GG}(\alpha_s,x) \end{pmatrix} \bigotimes \begin{pmatrix} q(x,Q^2) \\ G(x,Q^2) \end{pmatrix}$$

where $\otimes$ denotes a convolution and the P_{ij} are known "'splitting functions"'.
We have similar coupled equations for Δq and ΔG, with ΔP_{ij}.
There has been a considerable experimental activity in measuring the unpolarized and polarized structure functions $F_2^{p,n}$ and $g_1^{p,n}$ (See below).

Nucleon helicity sum rule

We have the following sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G(Q^2) + L_q(Q^2) + L_g(Q^2)$$

where $\Delta\Sigma = \sum_q \int_0^1 [\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)]dx$ is twice the quark (+ antiquark) spin contribution to the nucleon spin.

- ΔG, $L_{q,g}$ contributions of gluon and orbital angular momentum of quark and gluon.

- So far $\Delta\Sigma \sim 0.3$ and ΔG small and still badly known.

- $L_{q,g}$ might be relevant contributions?

- Is there a "‘dark spin"’ problem?

Short digression on the quantum statistical approach

Collaboration with Claude Bourrely and Franco Buccella

- A Statistical Approach for Polarized Parton Distributions
  Euro. Phys. J. C23, 487 (2002)
- Recent Tests for the Statistical Parton Distributions
  Mod. Phys. Letters A18, 771 (2003)
- The Statistical Parton Distributions: status and prospects
  Euro. Phys. J. C41,327 (2005)
- The extension to the transverse momemtum of the statistical parton distributions
  Mod. Phys. Letters A21, 143 (2006)
- Strangeness asymmetry of the nucleon in the statistical parton model
  Phys. Lett. B648, 39 (2007)
- How is transversity related to helicity for quarks and antiquarks in a proton?
  Mod. Phys. Letters A24, 1889 (2009)
- New tests of the quantum statistical approach of the parton distributions
  (in preparation)

Basic procedure for PDF

$[\exp[(x - X_{0p})/\bar{x}] \pm 1]^{-1}$, simple description, at input scale Q_0^2, with *plus* sign for quarks and antiquarks, corresponds to Fermi-Dirac distribution and *minus* sign for gluons, corresponds to Bose-Einstein distribution. X_{0p} is a constant which plays the role of the *thermodynamical potential* of the parton *p* and $\bar{x}$ is the *universal temperature*, same for all partons.

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From chiral structure of QCD, two important properties, relate quark and antiquark and restrict gluon distribution:

- Potential of a quark q^h of helicity *h* is opposite to the potential of the corresponding antiquark $\bar{q}^{-h}$ of helicity *-h*, $X_{0q}^h = -X_{0\bar{q}}^{-h}$.

- Potential of the gluon G is zero, $X_{0G} = 0$.

The PDF at $Q_0^2 = 4$GeV^2 (9 parameters only)

For light quarks $q = u, d$ of helicity $h = \pm$, we take

$$xq^{(h)}(x, Q_0^2) = \frac{A X_{0q}^{h} x^{b}}{\exp[(x - X_{0q}^{h})/\bar{x}] + 1} + \frac{\tilde{A} x^{\tilde{b}}}{\exp(x/\bar{x}) + 1} \ ,$$

consequently for antiquarks of helicity $h = \mp$

$$x\bar{q}^{(-h)}(x, Q_0^2) = \frac{\bar{A} (X_{0q}^{h})^{-1} x^{2b}}{\exp[(x + X_{0q}^{h})/\bar{x}] + 1} + \frac{\tilde{A} x^{\tilde{b}}}{\exp(x/\bar{x}) + 1} \ .$$

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For strange quarks and antiquarks, s and $\bar{s}$, given our poor knowledge on both unpolarized and polarized distributions, we first took in 2002 $xs(x, Q_0^2) = x\bar{s}(x, Q_0^2) = \frac{1}{4}[x\bar{u}(x, Q_0^2) + x\bar{d}(x, Q_0^2)]$ and $x\Delta s(x, Q_0^2) = x\Delta\bar{s}(x, Q_0^2) = \frac{1}{3}[x\Delta\bar{d}(x, Q_0^2) - x\Delta\bar{u}(x, Q_0^2)]$. Given the strange quark asymmetry, this was improved in Phys. Lett. B648, 39 (2007).

For gluons we use a Bose-Einstein expression given by $xG(x, Q_0^2) = \frac{A_G x^{b_G}}{\exp(x/\bar{x}) - 1}$, with a vanishing potential and the same temperature $\bar{x}$. We also need to specify the polarized gluon distribution and we take the particular choice $x\Delta G(x, Q_0^2) = 0$.

- $\bar{d}(x) > \bar{u}(x)$, flavor symmetry breaking expected from Pauli exclusion principle. Was already confirmed by violation of the Gottfried sum rule (NMC).
- $\Delta\bar{u}(x) > 0$ and $\Delta\bar{d}(x) < 0$, a PREDICTION confirmed by polarized DIS (see below) and will be more precisely checked at RHIC-BNL from $W^{\pm}$ production.

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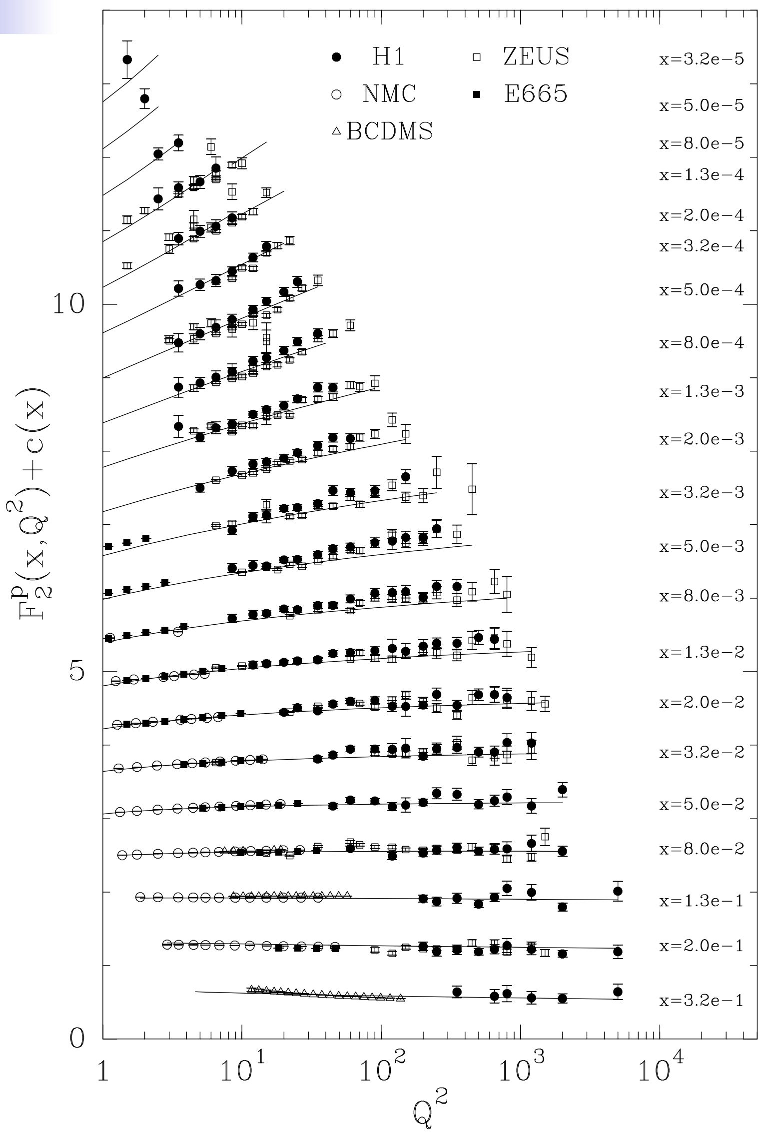
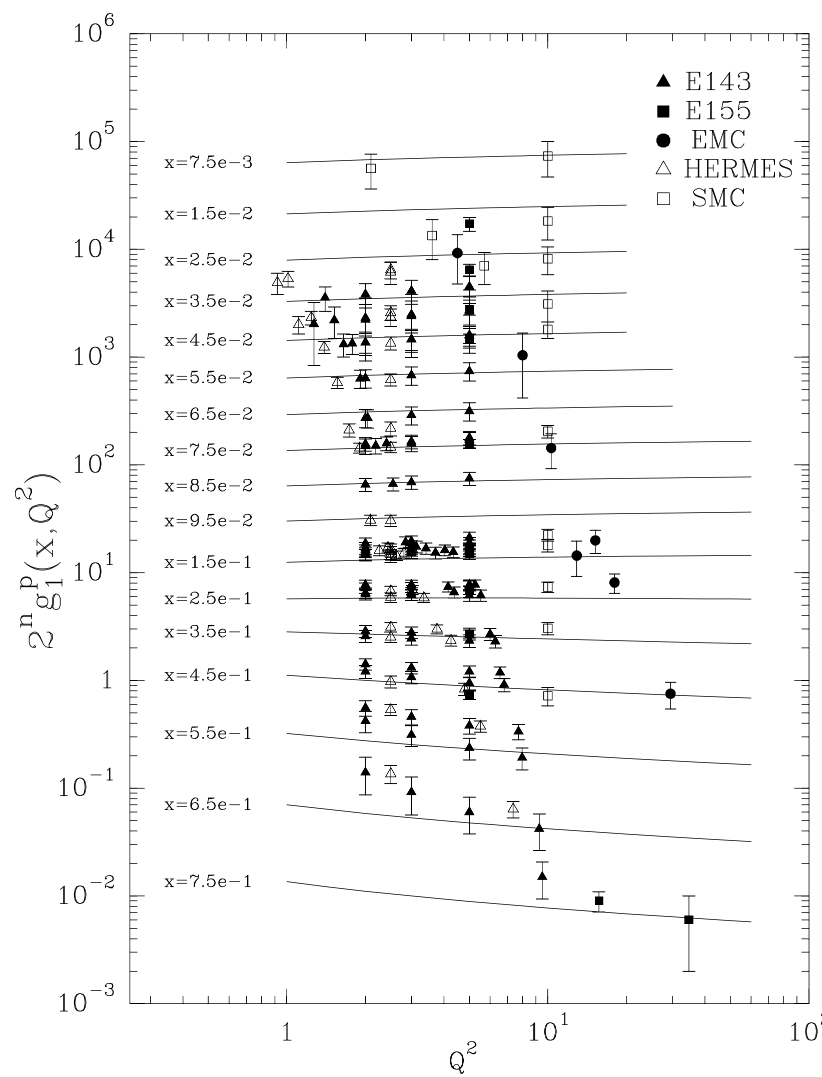
- Note that since $u^{-}(x) \sim d^{-}(x)$, it follows that $\bar{u}^{+}(x) \sim \bar{d}^{+}(x)$, (see next slide) so we have $\Delta\bar{u}(x) - \Delta\bar{d}(x) \sim \bar{d}(x) - \bar{u}(x)$, i.e. the flavor symmetry breaking is almost the same for unpolarized and polarized distributions ($\bar{u}$ and $\bar{d}$ polarizations contribute to about 10% to the Bjorken sum rule).

Recall what we know from unpolarized F_2^p and polarized g_1^p DIS

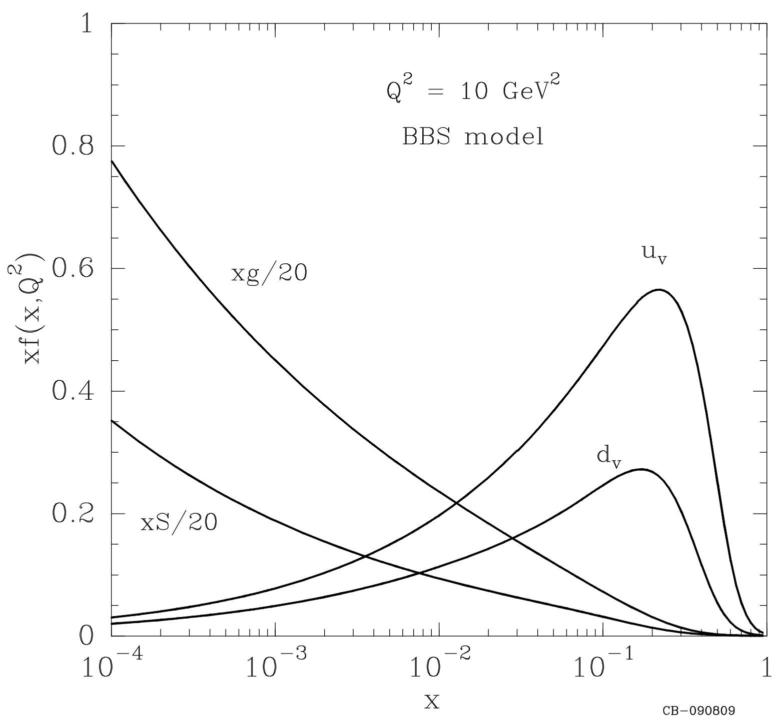


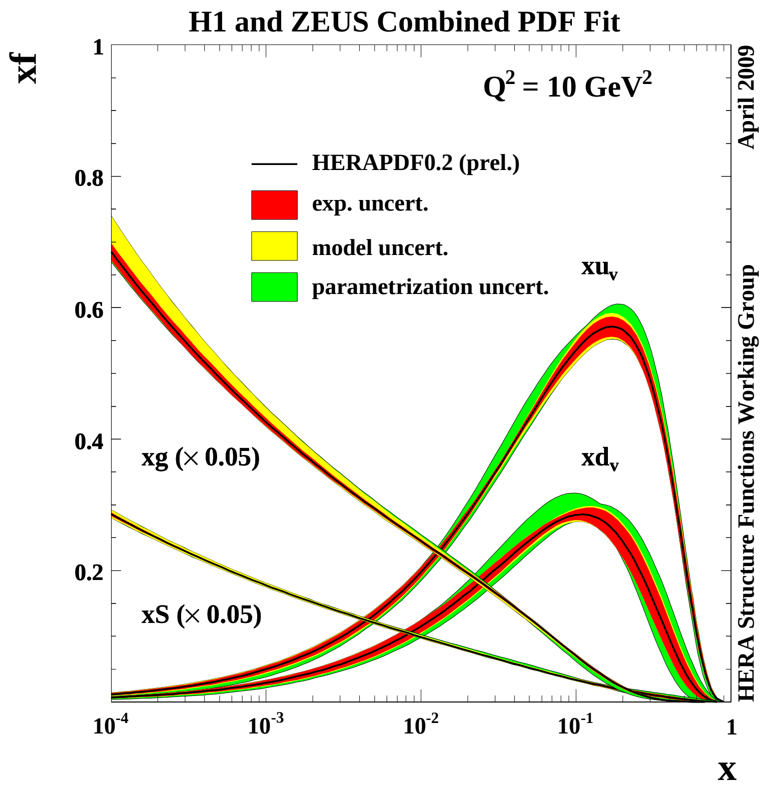


Flavor separation for unpolarized quark distributions

- Easier for u and d, thanks to the high precision of the data on $F_2^{p,n}$ and neutrino DIS.
- Have found long ago that $\bar{u} < \bar{d}$ from the violation of Gottfried sum rule
  Confirmed recently from dilepton production but need to be clarified at high x
  We are still unclear whether $s < \bar{s}$ or $s > \bar{s}$.

A global view of the unpolarized parton distributions

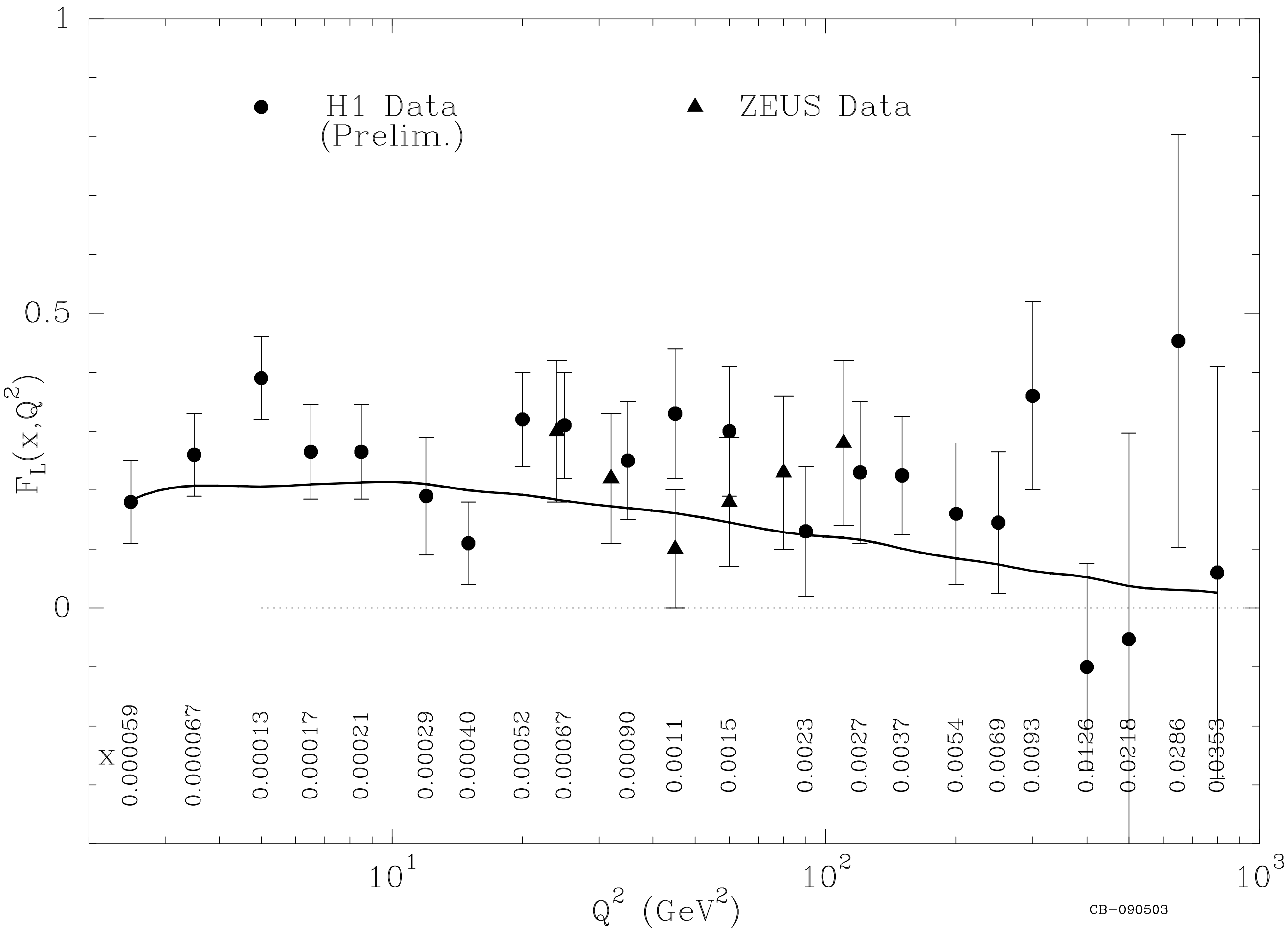




Need to know more about the sea quarks

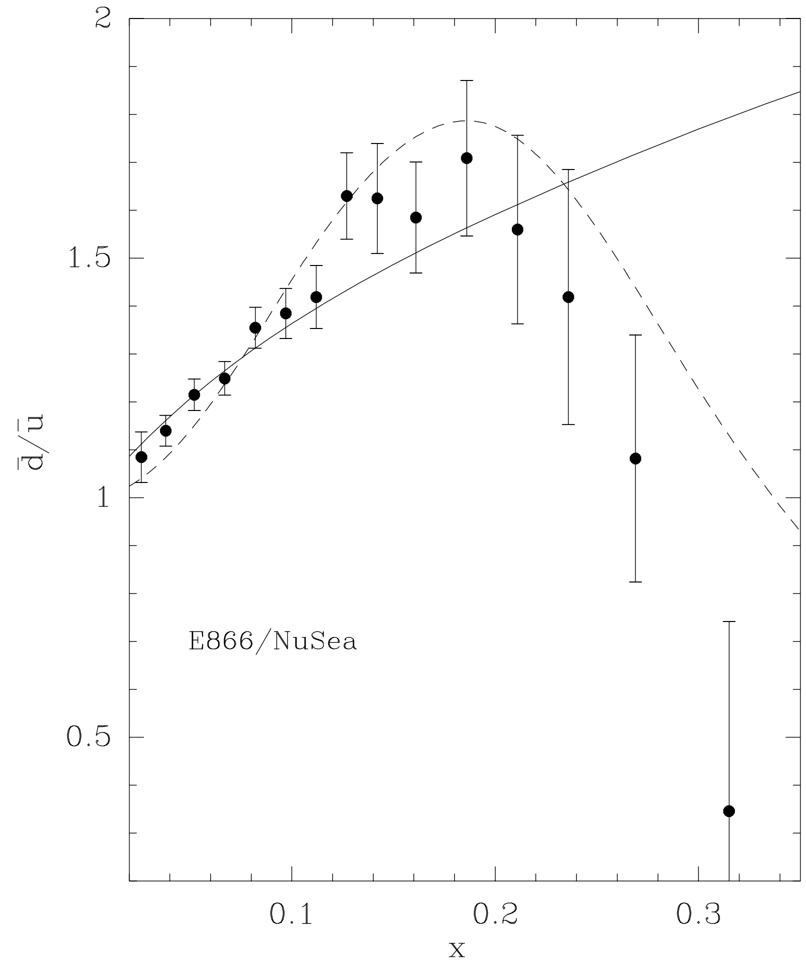
The longitudinal structure function F_L

Using some approximations $xG(x,Q^2) \simeq 8.3/\alpha_s F_L(0.4x, Q^2)$



The important issue of $\bar{d}/\bar{u}$ at large x ?

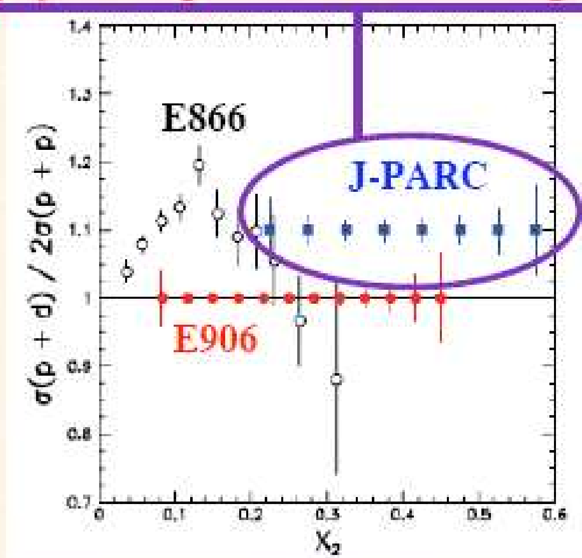
From Drell-Yan process at $Q^2 = 54\text{GeV}^2$



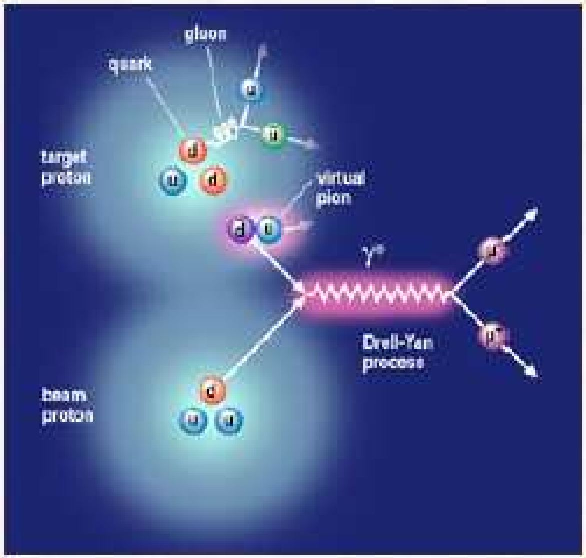
Prospects for this important issue at FNAL and J-PARC

Flavor asymmetric antiquark distributions: $\bar{u} / \bar{d}$

Theoretical studies are needed for physics importance in this *x* region.



J-PARC proposal (P24), M. Bai *et al.* (2007)

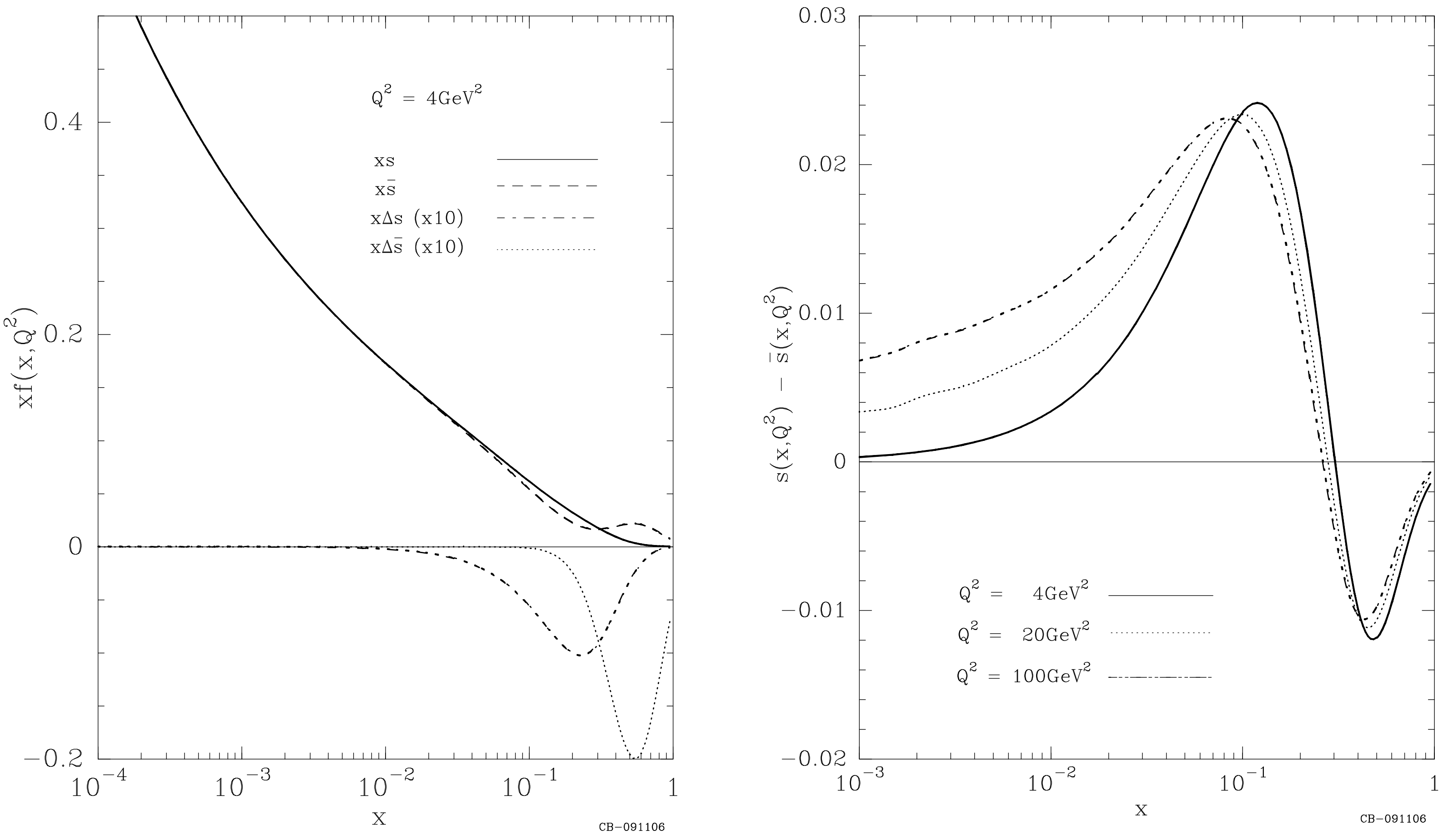


http://www.acuonline.edu/academics/cas/physics/research/e906.html

This project is suitable for probing "peripheral structure" of the nucleon.

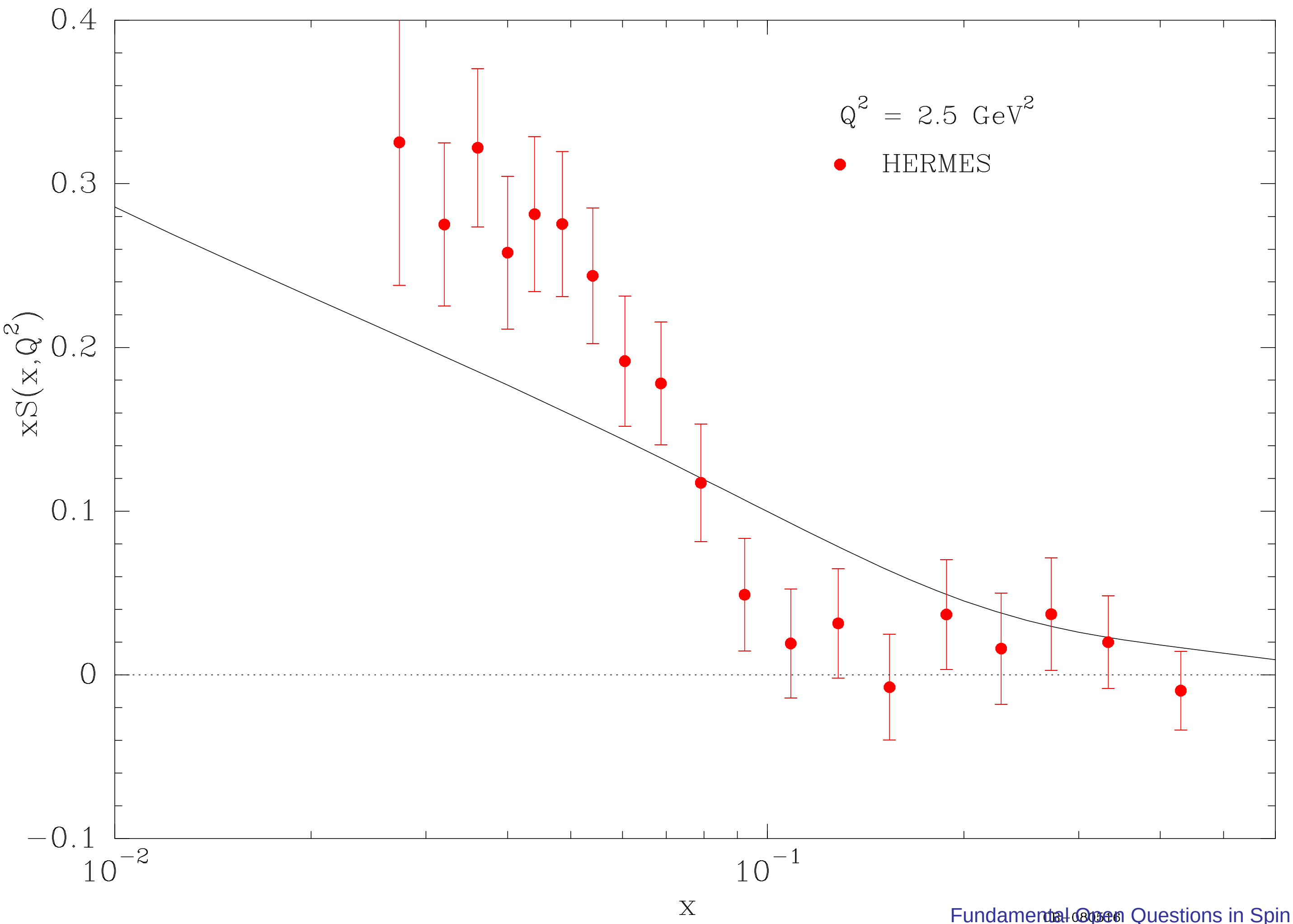
Refs. SK, Phys. Rep. 303 (1998) 183;
G. T. Garvey and J.-C. Peng, Prog. Part. Nucl. Phys. 47 (2001) 203.

The strange quark and antiquark distributions



This requires four new parameters $X_{0s}^{\pm}, b_s, \tilde{A}_s$ to fit the CCFR and NuTeV neutrino data for dimuon production

The $xS(x) = xs(x) + x\bar{s}(x)$ distribution from Hermes



Large uncertainties on $xs(x) - x\bar{s}(x)$

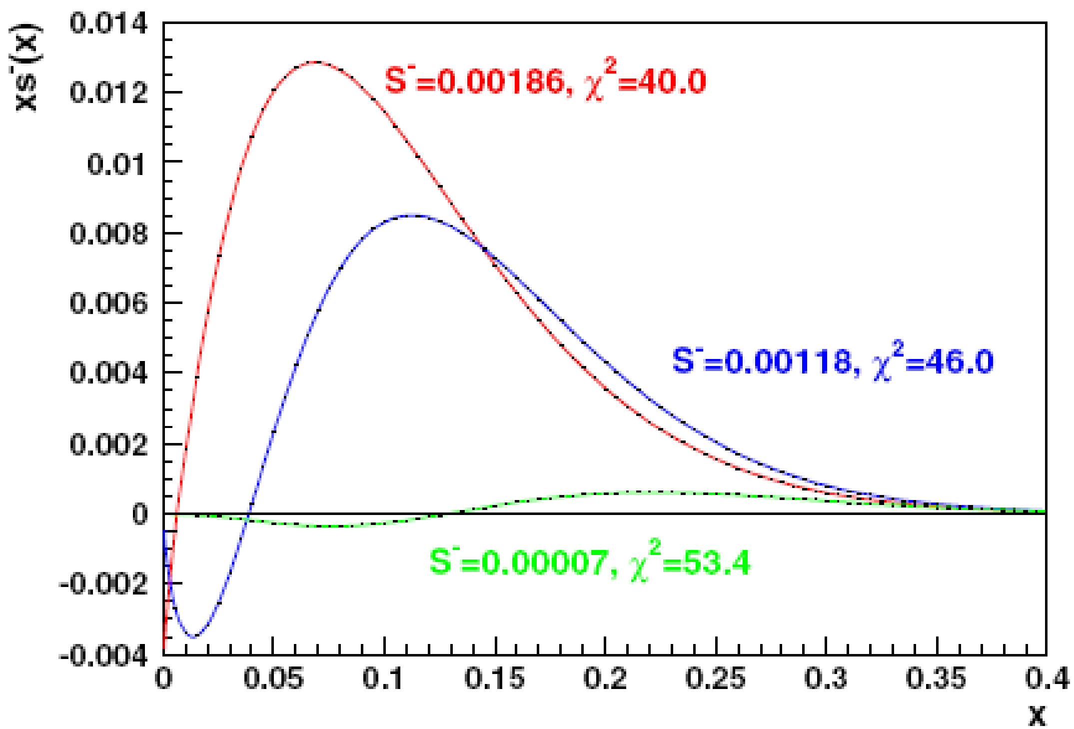


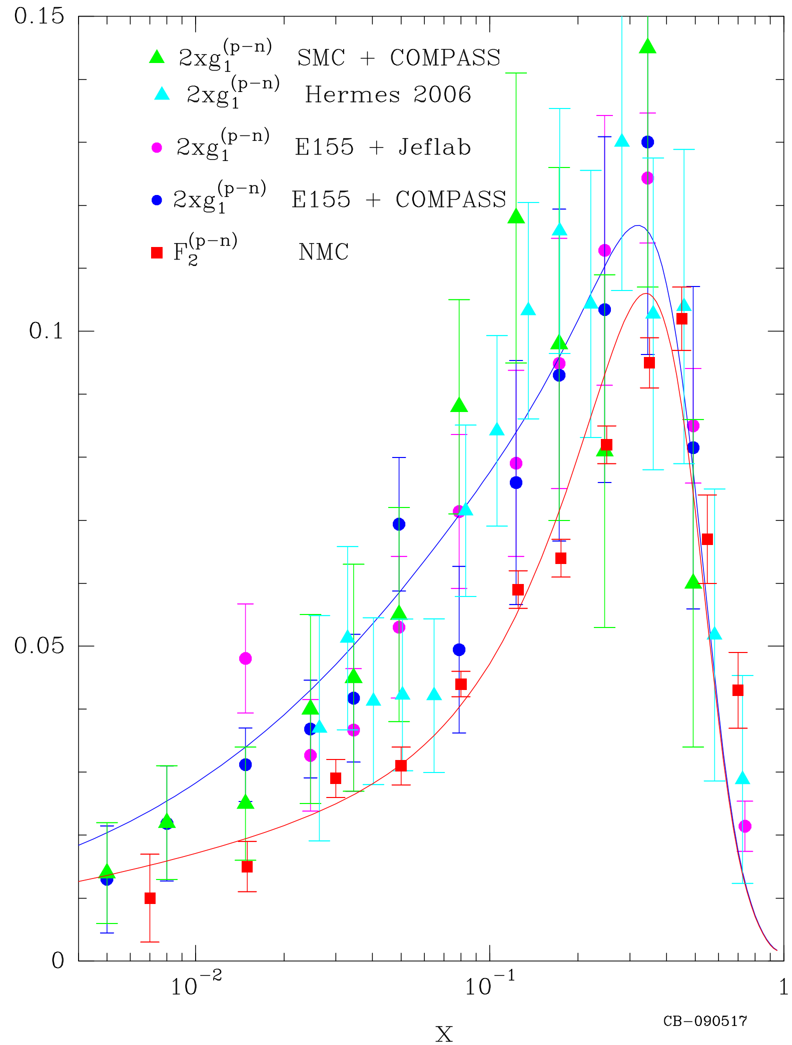
FIG. 4 (color online). xs^- for x_0 of 0.01, 0.05, and 0.15. χ^2's are labeled for an effective DOF of 38.8.

D. Mason *et al.*, NuTeV Collaboration, Phys. Rev. Lett. 99, 192001 (2007).

Positive strange asymmetry S^- from charm production.

An interesting observation at $Q^2 = 4GeV^2$: unpolarized and polarized are related

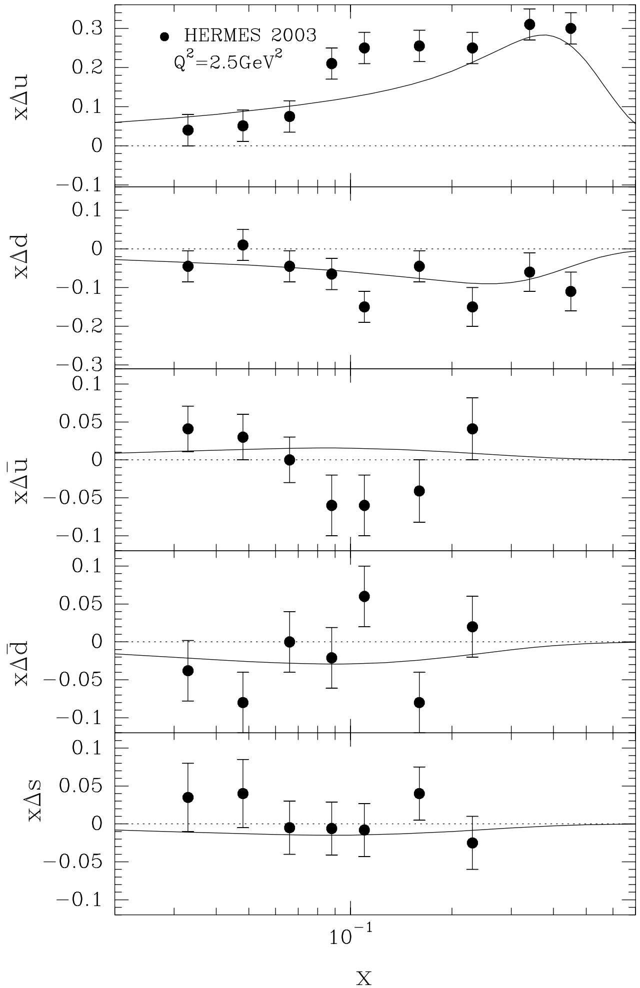
$F_2^{p-n} \simeq 2xg_1^{p-n} \;\Rightarrow\; u^+$ dominates and $u^- \simeq d^-$

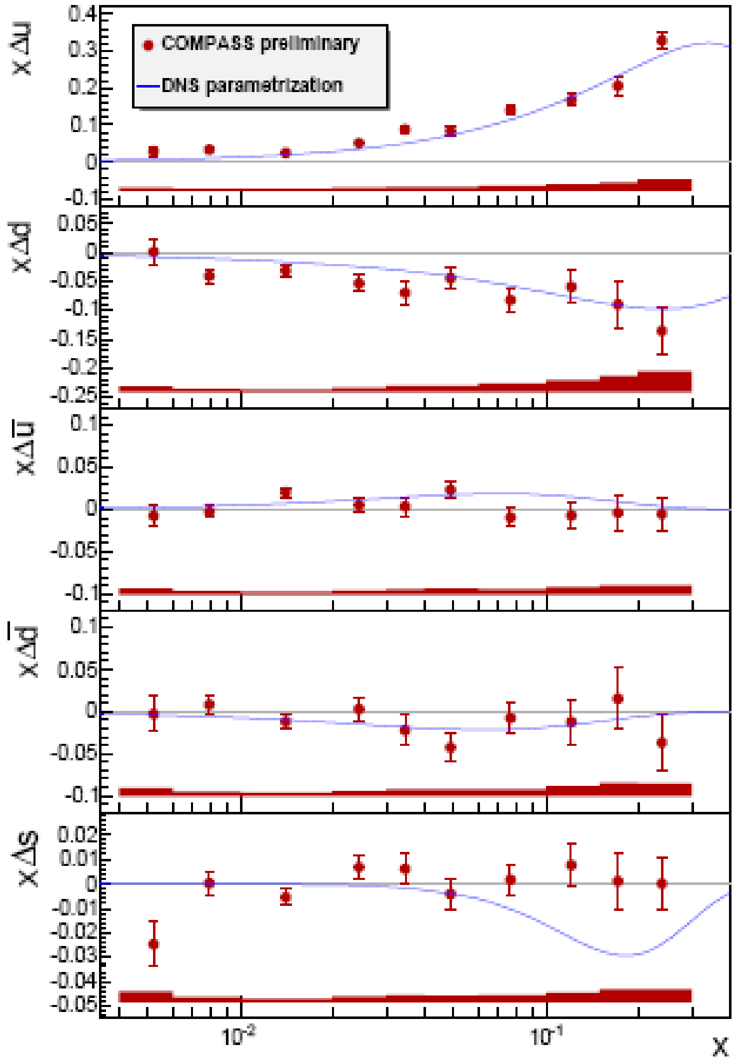


Flavor separation for quark helicity distributions

- One possibility is semi-inclusive DIS (Hermes, Compass), supplemented by JLab at high x.
- Another one is Δq and $\Delta \bar{q}$ flavor separation from $W^{\pm}$ production at RHIC.

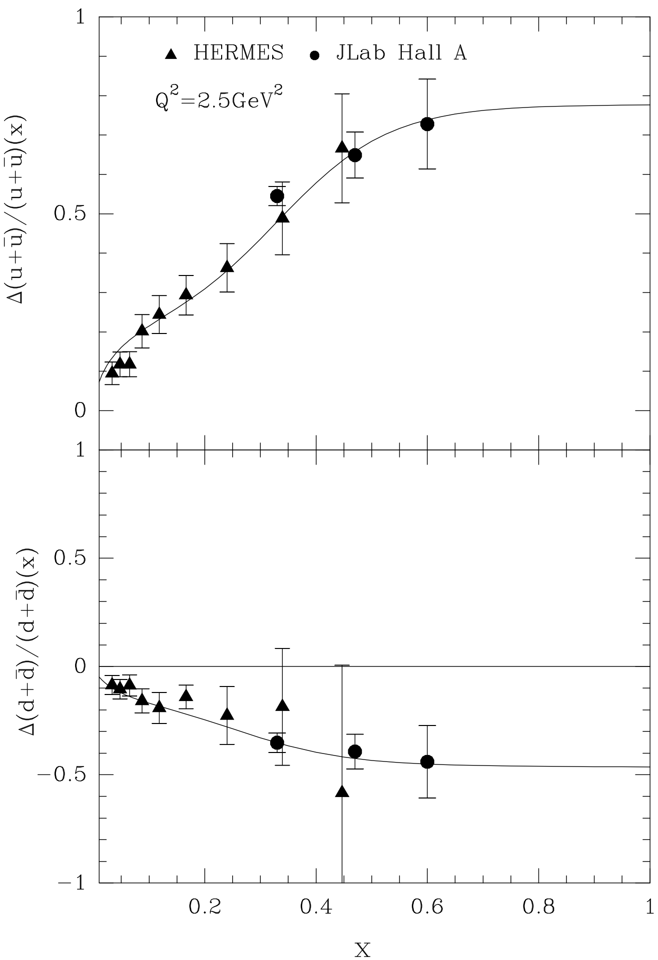
Polarized quarks distributions vs x at DESY and CERN: flavor separation from SIDIS





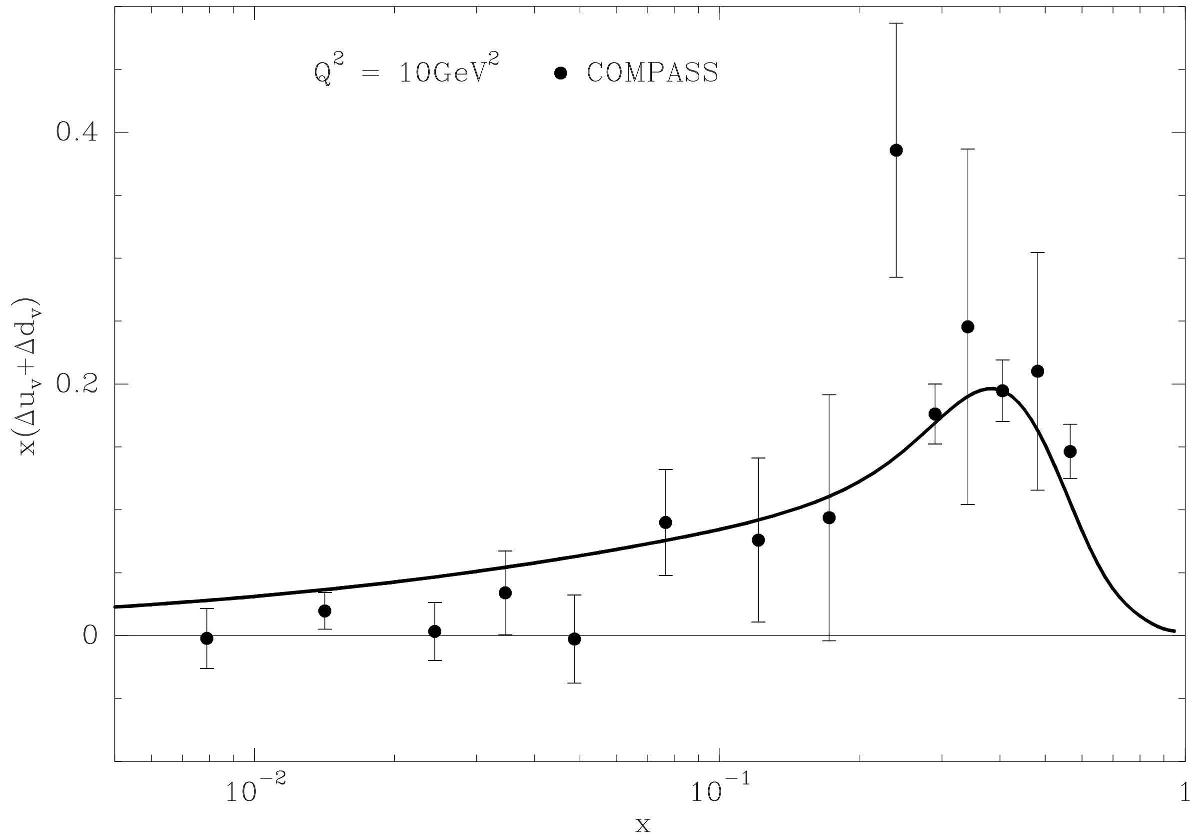
Polarized quarks distributions versus x at JLab

A key question: what is the behavior for $x \to 1$?

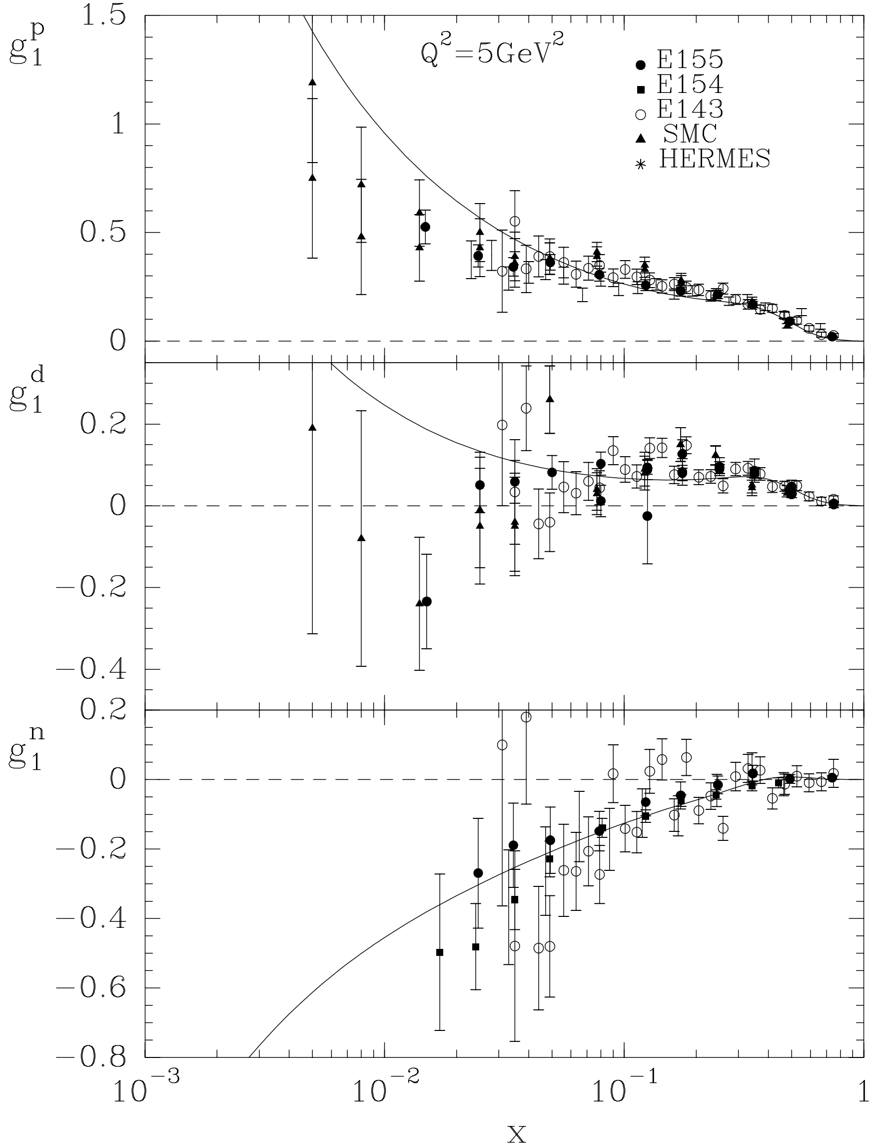


The valence quark helicity distributions versus x

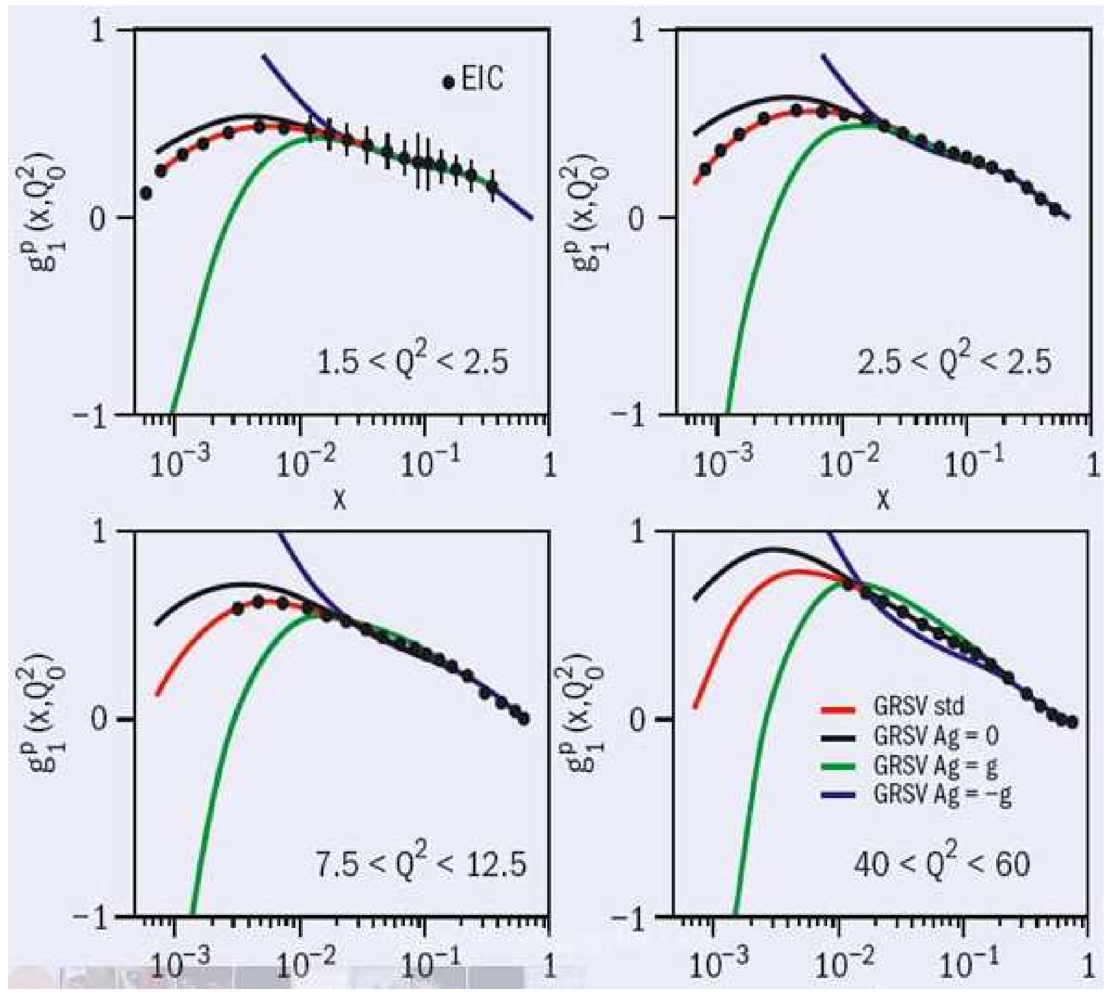
From semi-inclusive DIS $\mu d \to \mu h^{\pm} X$ can determine the valence quark helicity distributions. Combined with g_1^d it leads to $\Delta\bar{u} + \Delta\bar{d} = 0.0 \pm 0.04 \pm 0.03$
i.e. a highly non-symmetric polarized sea



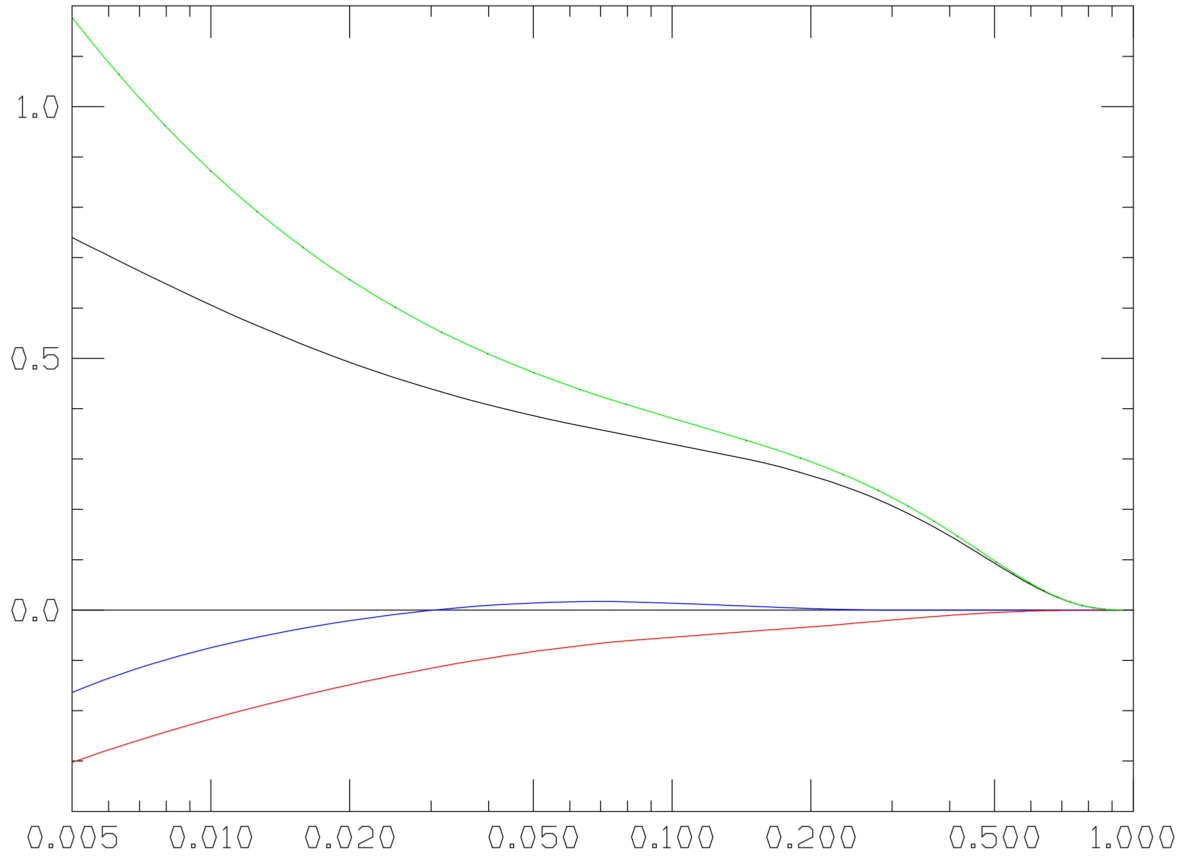
Antiquarks dominate the very low x region, in particular strange sea quarks



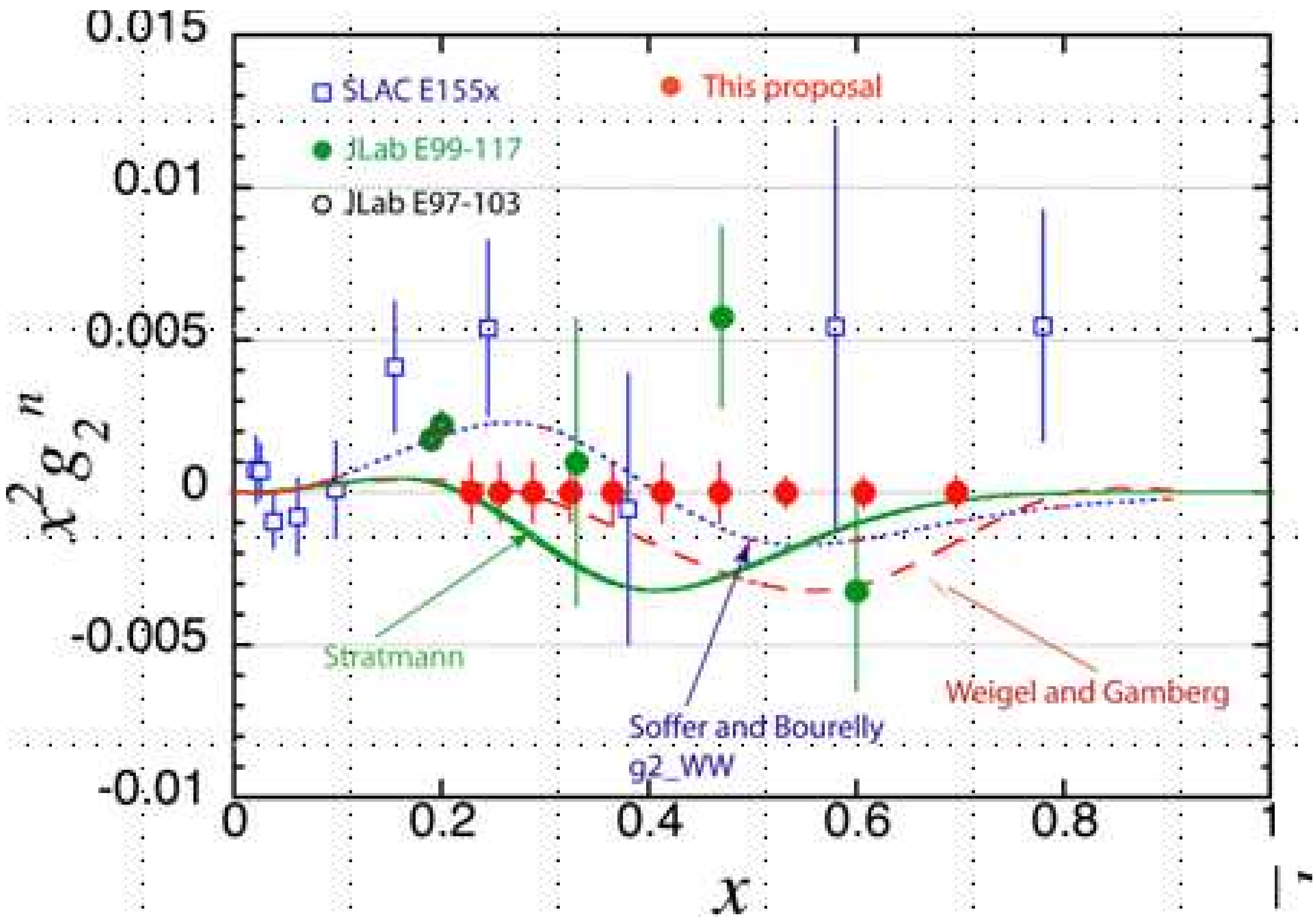
Sensitivity to ΔG of the very low x region of $g_1^p(x)$



Antiquarks dominate the very low x region of $g_1^p(x)$(prediction from DSSV)



The $g_2^{p,n}$ structure functions versus x : test of higher twists contributions



Predictions at leading twist assuming Wandzura-Wilczek sum rule

Δq and $\Delta\bar{q}$ flavor separation from $W^\pm$ production at RHIC

Consider the parity-violating helicity asymmetry $A_L^{PV}(W)$

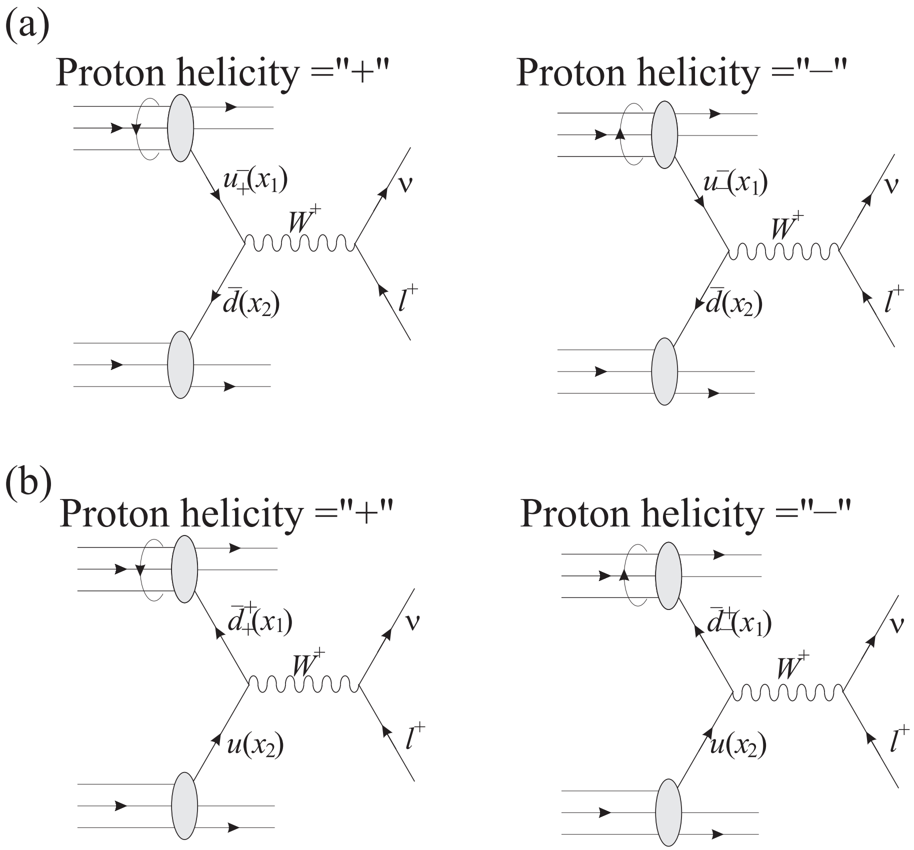
$$A_L^{PV}(y) = \frac{\Delta d\sigma/dy}{d\sigma/dy} = \frac{d\sigma_-^W/dy - d\sigma_+^W/dy}{d\sigma_-^W/dy + d\sigma_+^W/dy} \ ,$$

where $\pm$ stands for the helicity of one polarized proton beam. For W^+, at the lowest order of the Drell-Yan production mechanism, it reads

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

where $x_a = \sqrt{\tau}e^y$, $x_b = \sqrt{\tau}e^{-y}$ and $\tau = M_W^2/s$. The general trend of $A_L^{PV}(y)$ can be easily understood and, for example at $\sqrt{s} = 500$GeV near $y = +1$, $A_L^{PV}(W^+) \sim \Delta u/u$ and $A_L^{PV}(W^-) \sim \Delta d/d$, evaluated at $x = 0.435$. Similarly for near $y = -1$, $A_L^{PV}(W^+) \sim -\Delta\bar{d}/\bar{d}$ and $A_L^{PV}(W^-) \sim -\Delta\bar{u}/\bar{u}$, evaluated at $x = 0.059$.
Since one selects the leptonic decay $W \to e\nu$, effectively one measures
A$_L^{PV}(y_e) = \Delta d\sigma/dy_e/d\sigma/dy_e$

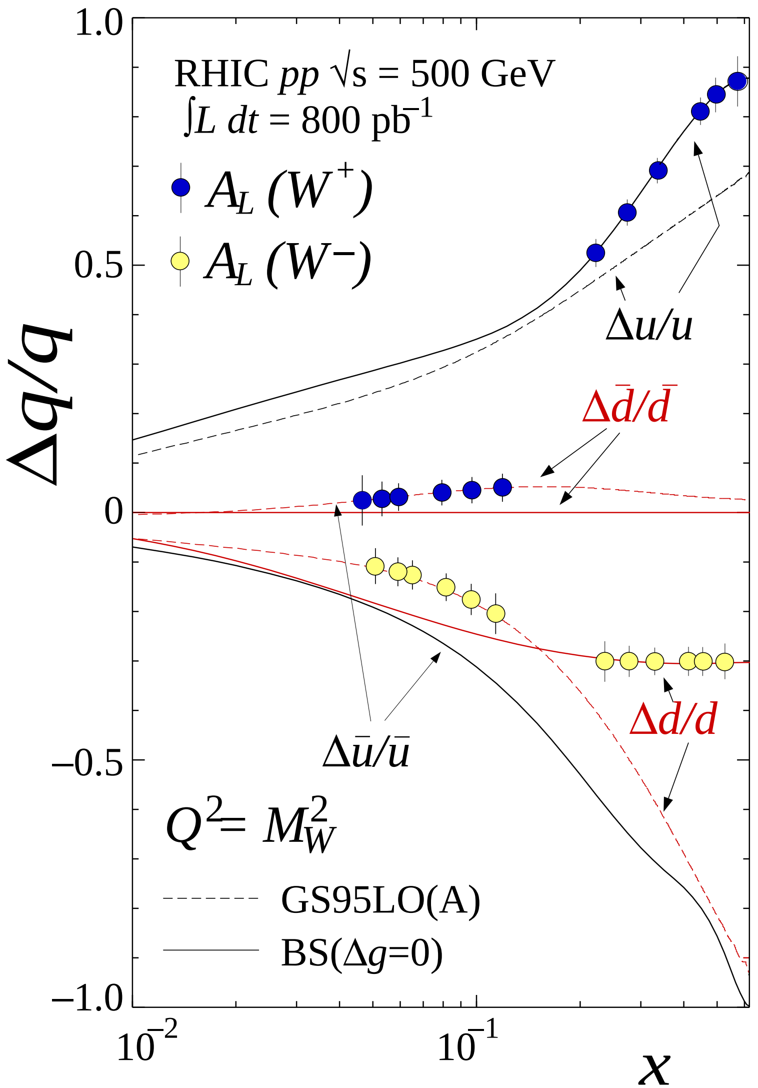
W^+ production in polarized pp collisions



C. Bourrely and J. S., Phys. Lett. B314, 132 (1993)

Flavor separation from $W^{\pm}$ production at RHIC for PDF at $Q^2 \sim 6500\text{GeV}^2$

Expected sensitivity for near future of RHIC running at 500GeV



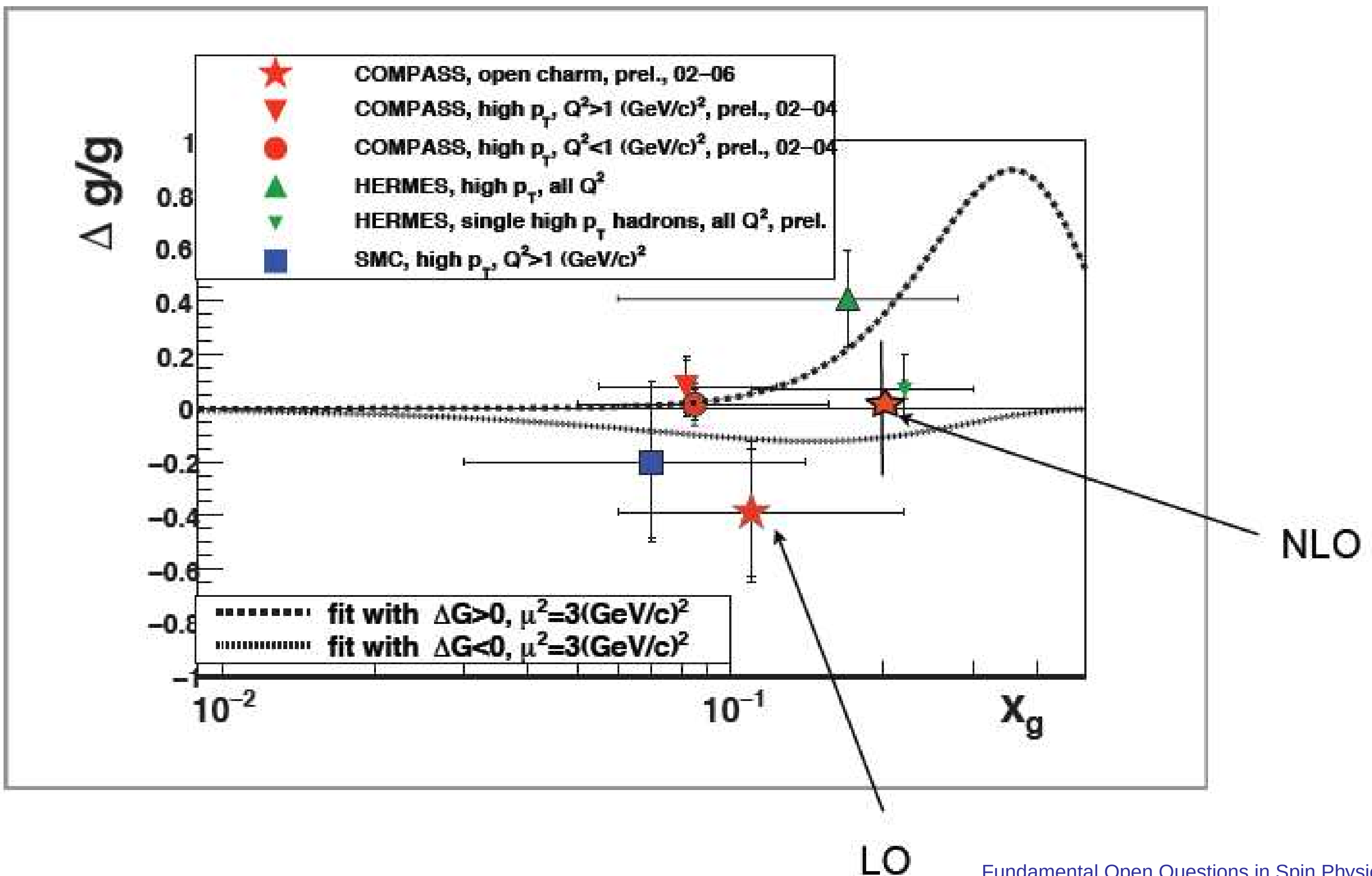
Gluon Polarization $\Delta g(x)$ in the nucleon

- From polarized DIS only, the Q^2 evolution does NOT allow the determination of $\Delta g(x)$, because of lack of accuracy and limited Q^2 range.
- From DIS with high-p_T hadron pairs in the final state from $\gamma^* g \rightarrow q\bar{q}$.
- In DIS open charm is another option

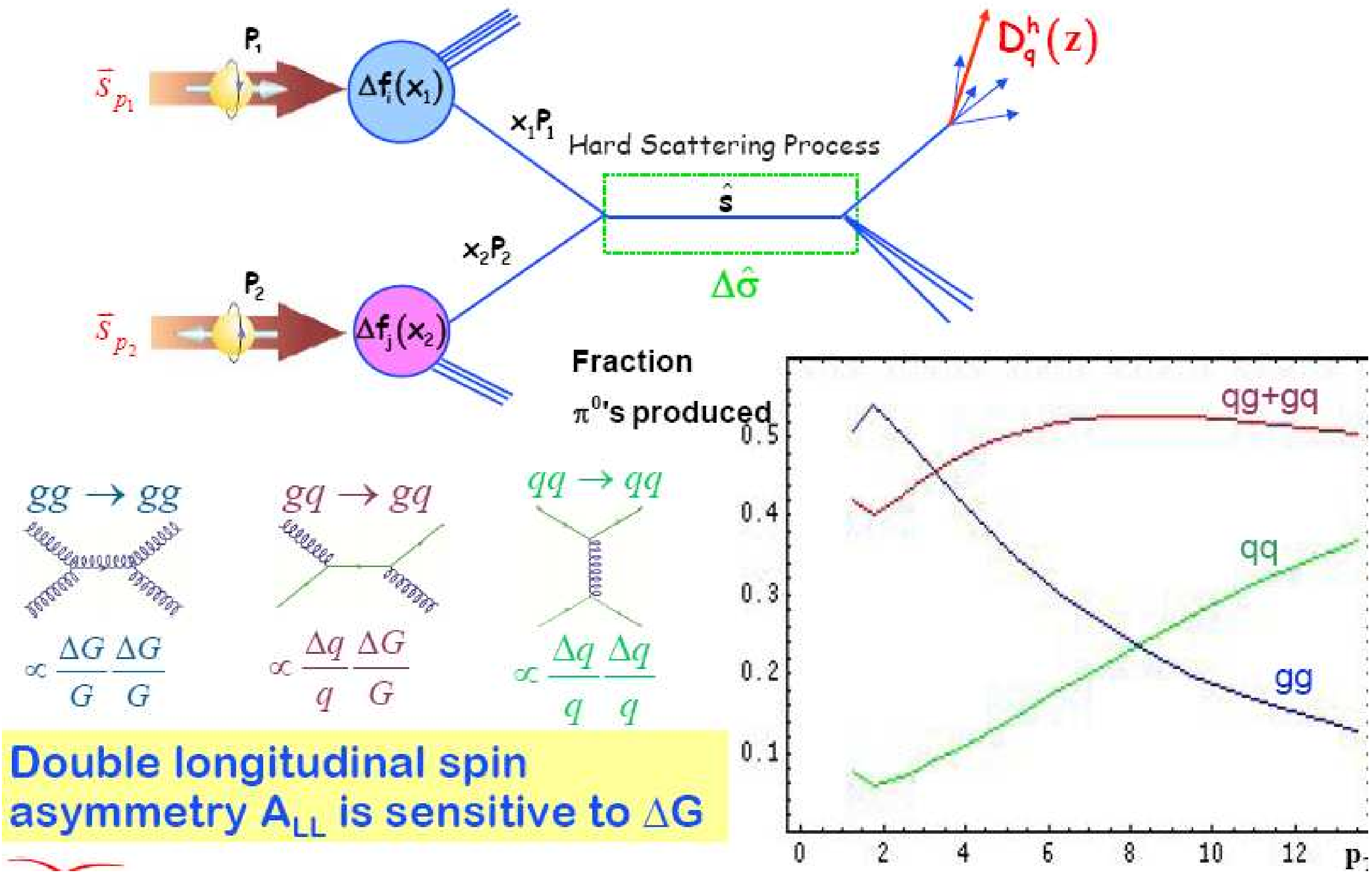
It is also crucial to measure it at RHIC

Present knowledge of Gluon Polarization from DIS

Photon-gluon fusion: Open charm - At NLO get zero



The gluon polarization at RHIC

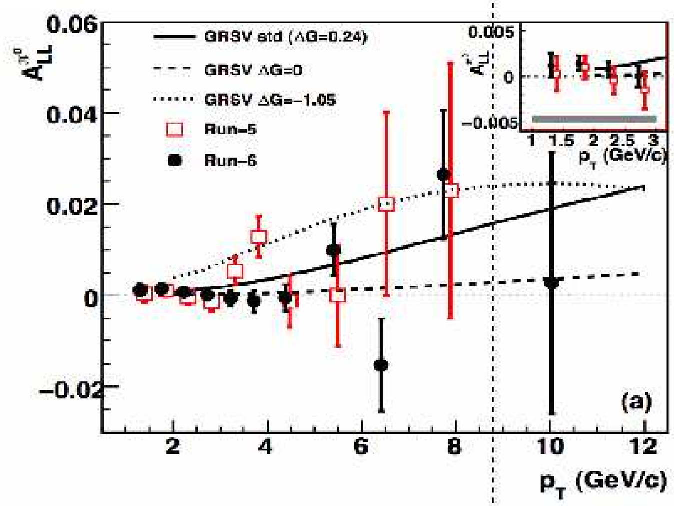


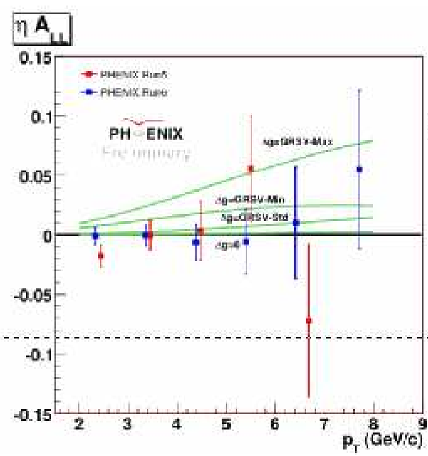
Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

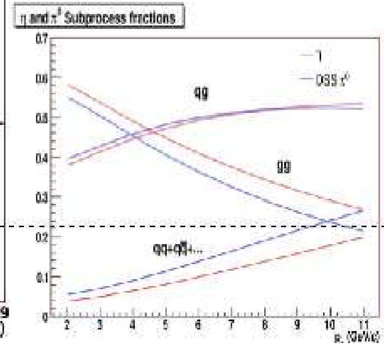
The gluon polarization at RHIC from PHENIX

π^0 and η asymmetry results from PHENIX

- ❑ π^0 A_{LL} at 200 GeV
  - high statistics measurement
  - 2005: PRD76, 051106
  - 2006: Submitted to PRL (arXiv:0810.0694)





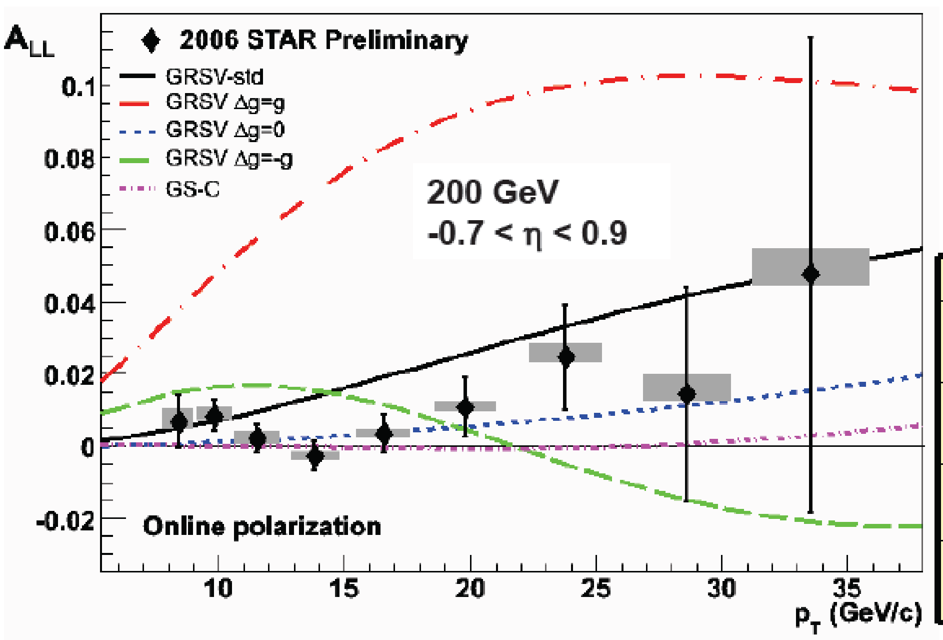


- ❑ η at 200 GeV
  - Analysis similar to π^0
  - Fractional sub process differ somewhat
  - Independent confirmation of ΔG

Jet production at RHIC from STAR

Sensitivity to Δg only in the medium p_T region, dominated by $gq \to gq$. Low p_T region dominated by gg collisions

2006 inclusive A_{LL}^{jet}



GRSV curves with cone radius 0.7 and $-0.7 < \eta < 0.9$

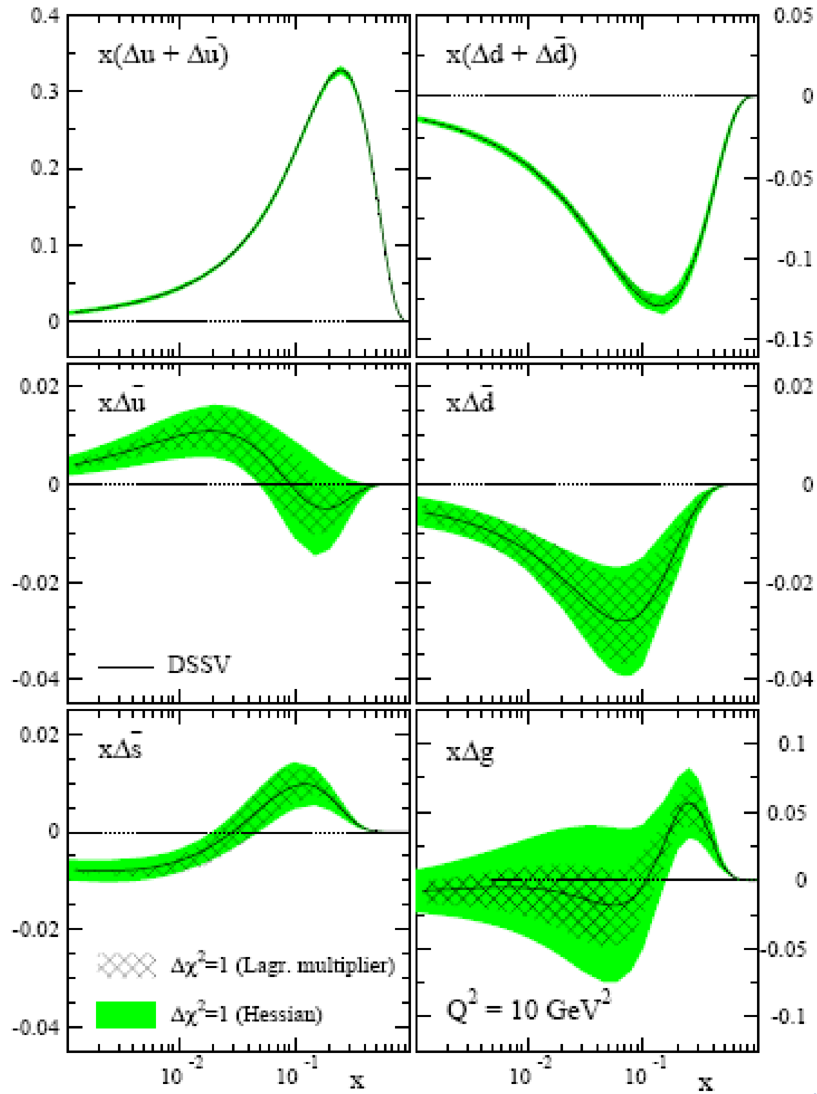
A_{LL} systematics	$(\times 10^{-3})$
Reconstruction + Trigger Bias	[-1,+3] (p_T dep)
Non-longitudinal Polarization	~ 0.03 (p_T dep)
Relative Luminosity	0.94
Backgrounds	1st bin ~ 0.5 Else ~ 0.1

p_T systematic	±6.7%

- Using jet patch trigger ($\Delta\eta\times\Delta\phi$ = 1×1 patch of towers) only

❖ ***Statistical uncertainties are 3-4 times smaller than 2005 in high p_T region (p_T>13 GeV/c)***

Present knowledge of polarized PDF from a recent global fit with 26 parameters !!(DSSV)



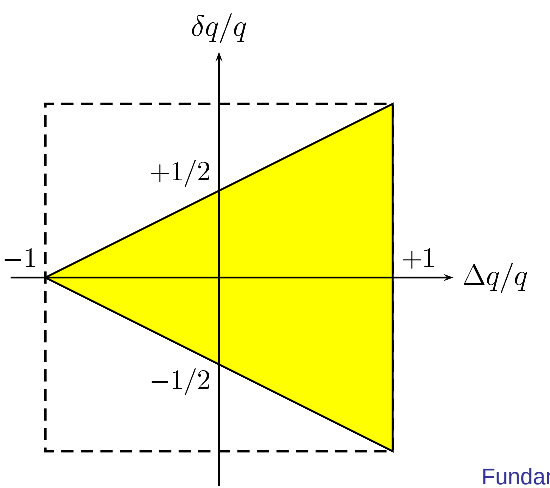
Quark Transversity Distribution $\delta q(x,Q^2)$

It was first mentioned by Ralston and Soper in 1979, in $pp \to \mu^+\mu^- X$ with transversely polarized protons, but forgotten until 1990, where it was realized that it completes the description of the quark distribution in a nucleon as a density matrix

$$\mathcal{Q}(x,Q^2) = q(x,Q^2) I \otimes I + \Delta q(x,Q^2)\sigma_3 \otimes \sigma_3 + \delta q(x,Q^2)(\sigma_+ \otimes \sigma_- + \sigma_- \otimes \sigma_+)$$

This new distribution function $\delta q(x,Q^2)$ is chiral odd, leading twist and decouples from DIS. Only recently, it has been extracted indirectly, for the first time.
There is a positivity bound (J.S., PRL 74,1292,1995) survives up to NLO corrections

$$q(x,Q^2) + \Delta q(x,Q^2) \geq 2|\delta q(x,Q^2)|$$



Quark Transversity Distribution $\delta q(x, Q^2)$

Current status on transversity

Anselmino et al, arXiv:0812.4366

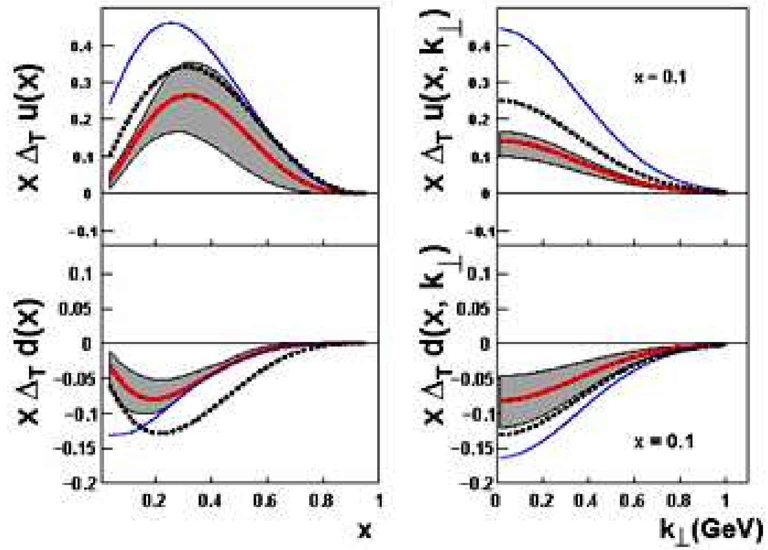
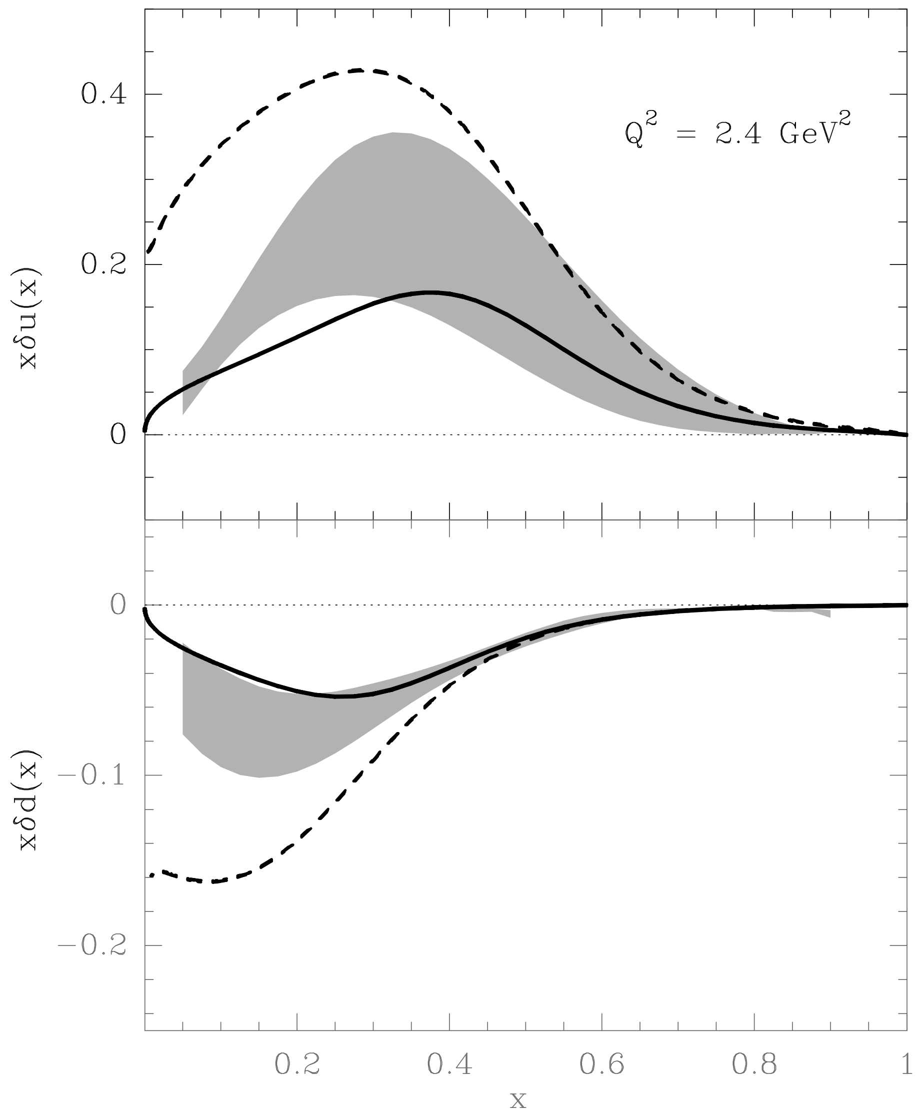


Figure 7. Comparison of the extracted transversity (solid line) with the helicity distribution (dashed line) at $Q^2 = 2.4$ GeV^2. The Soffer bound [46] (blue solid line) is also shown.

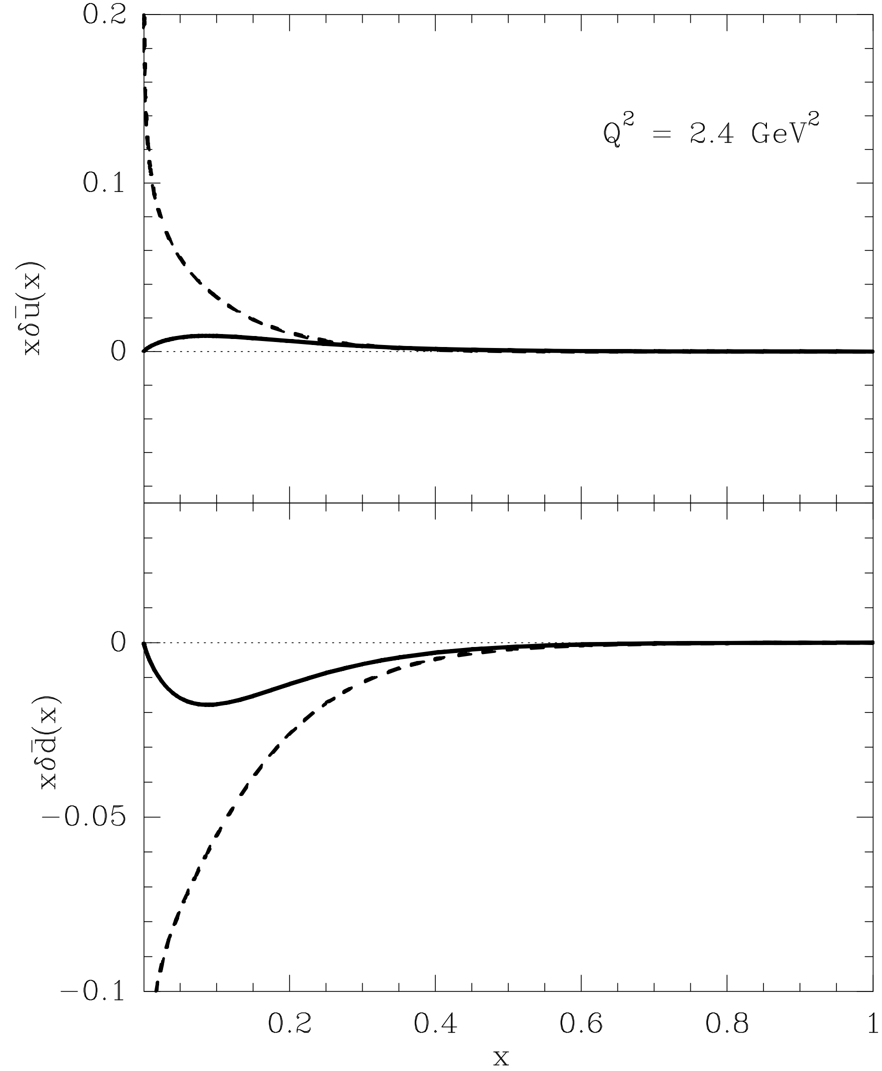
- Global analysis combining Collins effect measurements in SIDIS from HERMES and COMPASS with measurements of the Collins fragmentation function by BELLE

A Simple Model for Quark Transversity

Distribution: $\delta q(x, Q^2) = 0.6 \Delta q(x, Q^2)$

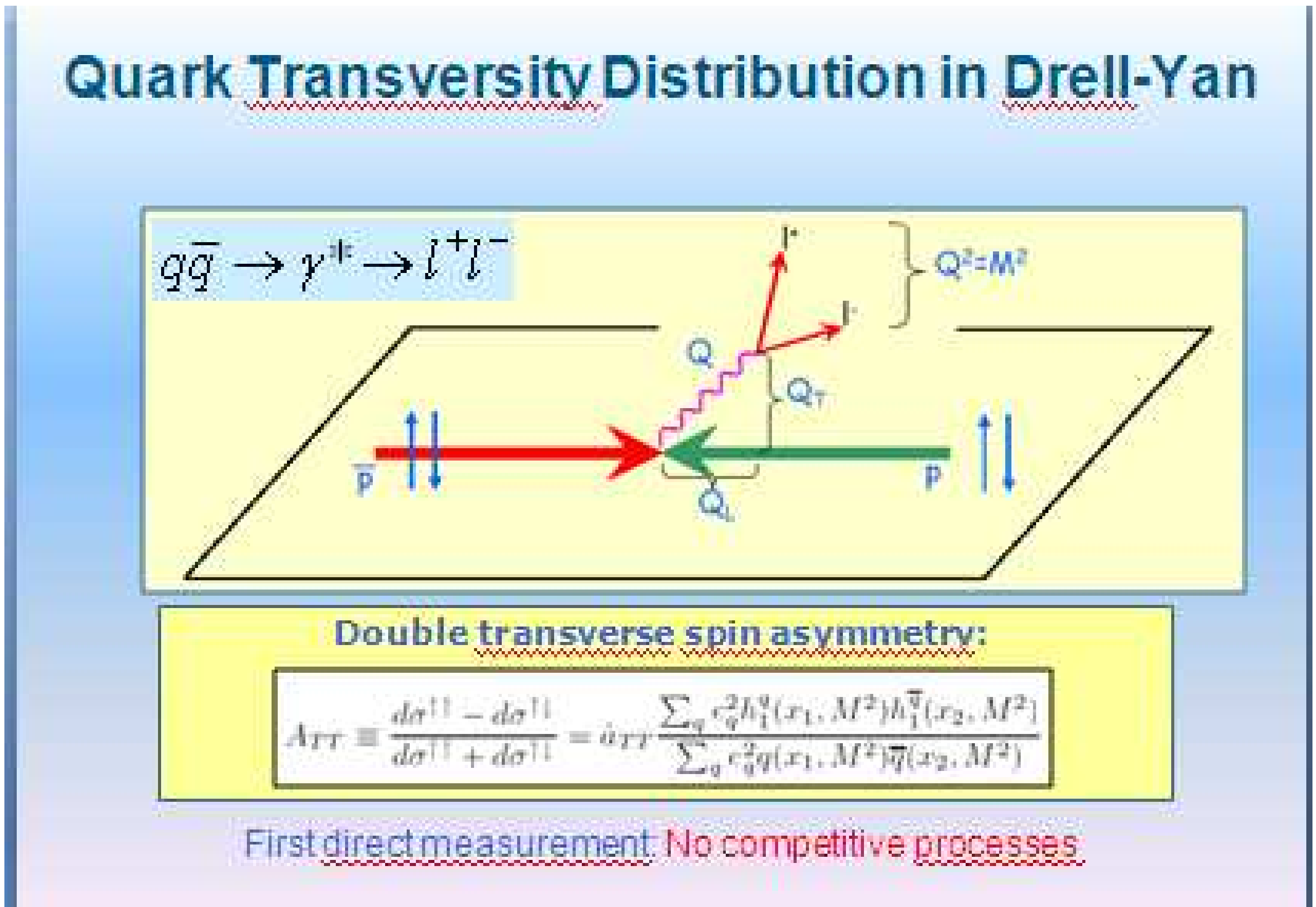


A Simple Model for Antiquark Transversity Distribution: $\delta\bar{q}(x,Q^2) = 0.6\Delta\bar{q}(x,Q^2)$

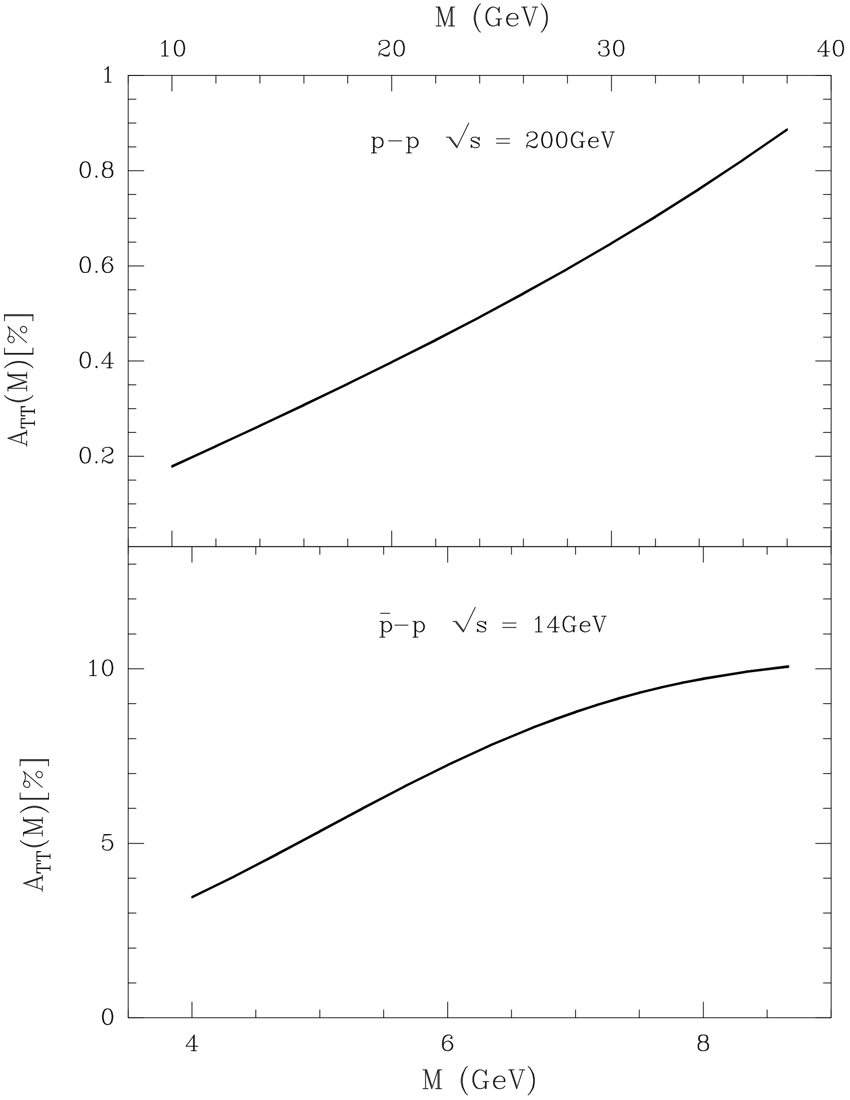


A_{TT} in the PAX experiment $\bar{p}p \to l^+l^-X$ at COSY

A new challenge: how to make polarized $\bar{p}$?



Predicted A_{TT} for Drell-Yan in pp and $\bar{p}p$



Single spin asymmetries A_N in QCD

What is a single spin asymmetry (SSA)?

Consider the collision of a proton of momentum $\overrightarrow{p}$, carrying a transverse spin $\overrightarrow{s_T}$ and producing an outgoing hadron with transverse momentum $\overrightarrow{k_T}$. The SSA defined as

$$A_N = \frac{d\sigma(\overrightarrow{s_T}) - d\sigma(-\overrightarrow{s_T})}{d\sigma(\overrightarrow{s_T}) + d\sigma(-\overrightarrow{s_T})}$$

is zero, unless the cross section contains a term $\overrightarrow{s_T} \cdot (\overrightarrow{p} \times \overrightarrow{k_T})$

Two QCD mechanisms

- Introduce Transverse Momentum Dependence (TMD)
  - TMD parton distributions $\Rightarrow$ Sivers effect 1990
  - TMD fragmentation distributions $\Rightarrow$ Collins effect 1993
- Consider higher twist operators
  - In collinear approach introduce quark-gluon correlators (Efremov-Teryaev 1982 Qiu-Sterman 1991)

Single spin asymmetries in SIDIS

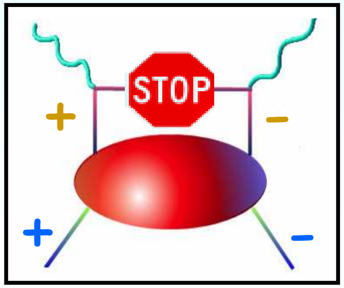
Transversity

$$\delta q(x,Q^2) = q^{\uparrow} - q^{\downarrow}$$

Difference of probabilities to find quarks with spin aligned or anti-aligned to the nucleon transverse spin

Chiral-odd

requires spin flip of the quark



Not measurable in inclusive DIS

Unmeasured for long time!

Sivers function

$$f_{1T}^{\perp q}(x, p_T^2)$$

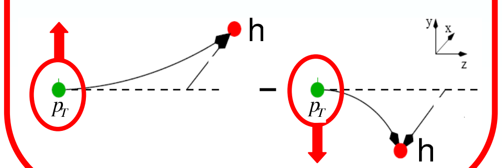
Chiral-even T- odd

Probability to find unpolarized quarks with transverse momentum p_T in a transversely pol. nucleon.

describes spin-orbit correlation in the nucleon

Requires **non-zero orbital angular momentum!**

azimuthal asymmetries in the direction of the outgoing hadrons.



Collins function

$$H_1^{\perp}(z, k_T^2)$$

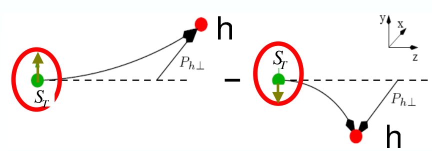
Chiral-odd T- odd

Correlation between transverse spin of the fragmenting quark and transverse momentum of the produced hadron

describes spin-orbit correlation in fragmentation

Analyzer of fragmenting quark's transv. polarization

azimuthal asymmetries in the direction of the outgoing hadrons.



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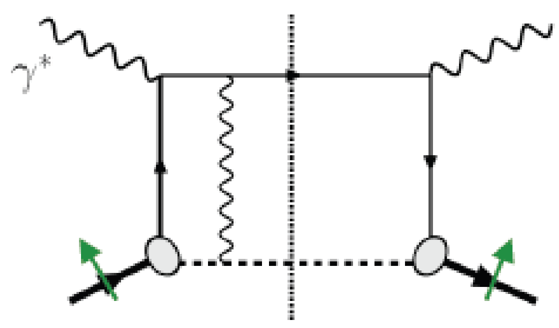
Process-dependence of Sivers functions

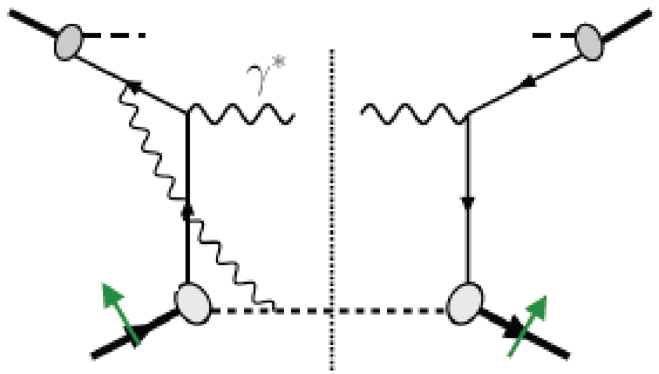
Crucial role of gauge links in TMDs

$$f_{\mathrm{DY}}^{\mathrm{Sivers}}(x, k_\perp) = - f_{\mathrm{DIS}}^{\mathrm{Sivers}}(x, k_\perp)$$

DIS: "attractive"



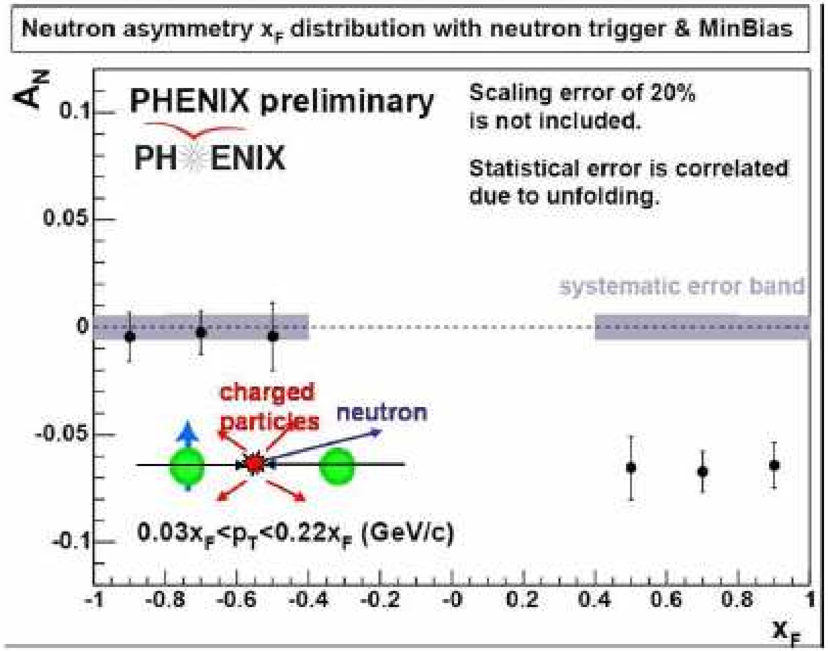
DY: "repulsive"



- hugely important in QCD -- tests a lot of what we know about description of hard processes

Another puzzling SSA

A_N at $\sqrt{s} = 200GeV$, small angles in neutron inclu. production

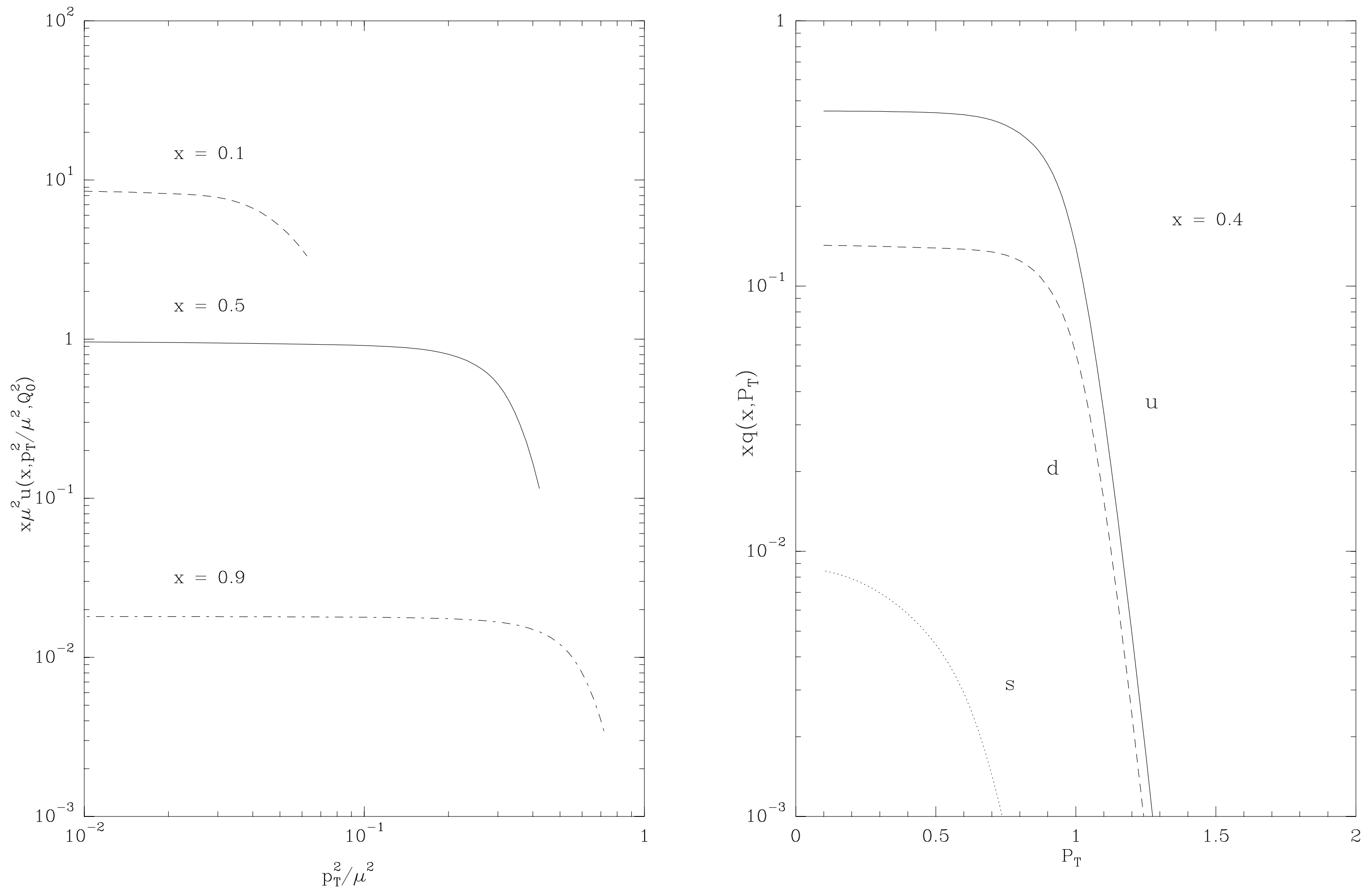


Large and no x_F dependence. $A_N(x_F < 0) = 0$

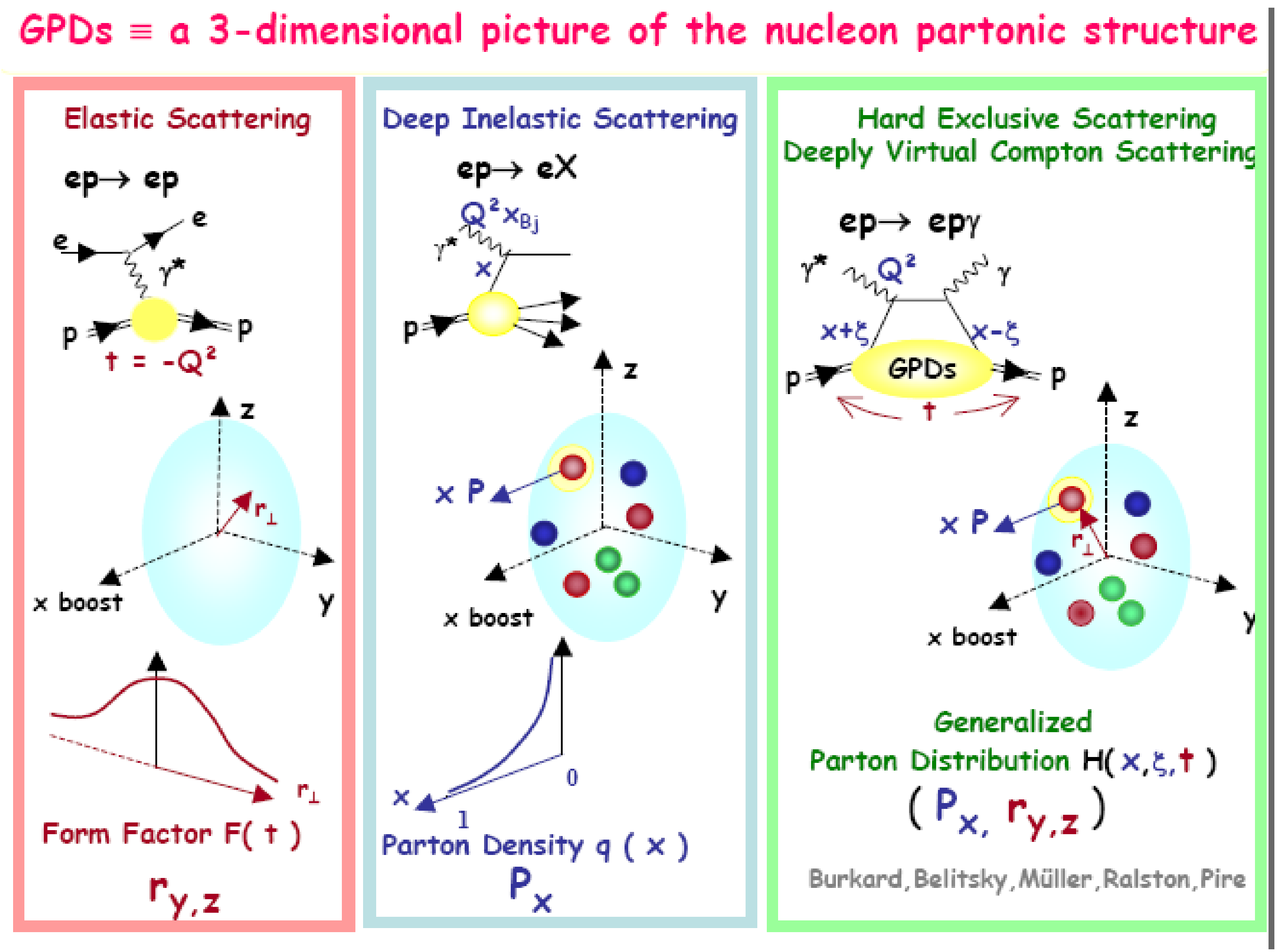
Cross section not yet release.

Perhaps a new challenge for theory

TMD dependence of the statistical quark distributions



Generalized parton distributions: don't break the proton



Generalized parton distributions:

$$2J_{quark} = \Delta\Sigma + 2L_q$$

Experimental effort at first stage: Plan to fully explore this physics

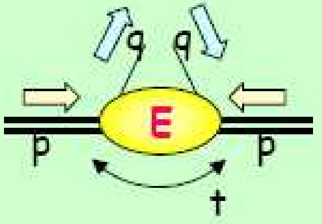
'Holy Grails' of the GPD quest

- Contribution to the nucleon spin puzzle

  E related to the angular momentum

  $2J_q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$

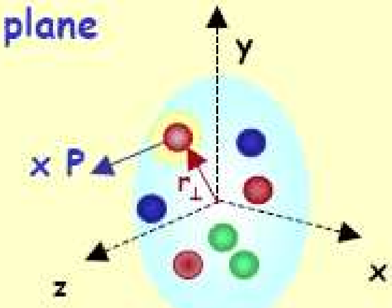
  $\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$



- GPD= a 3-dimensional picture of the partonic nucleon structure or spatial parton distribution in the transverse plane

  $H(x,\ \xi=0,\ t) \rightarrow H(x,\ r_{x,y})$

  probability interpretation
  Burkardt



Outlook

- Rapid theoretical progress and new calculations are made in QCD spin physics
- Many experimental results are coming out and we are entering an area of precision
- Spin physics generates new tools, new concepts, new challenges
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- All this will provide a detailed understanding of the nucleon spin structure
- Perhaps some surprises are round the corner !!
- We might also rely on some help from

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SERENDIPITY :

The art to find something unforseen by looking for another matter

Thank you !