Fundamental Open Questions in Spin Physics

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We will address to the following questions:

- What is particle 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 $eN \to ehX$ and prospects
  - Gluon Polarization $\Delta g(x)$ in the nucleon: Present status and prospects
- Quark Transversity $\delta q(x, Q^2)$ and double transverse spin asymmetries A_{TT}
- New degrees of freedom in QCD
  - QCD mechanisms for single spin asymmetries A_N (Sivers versus Collins)
  - 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

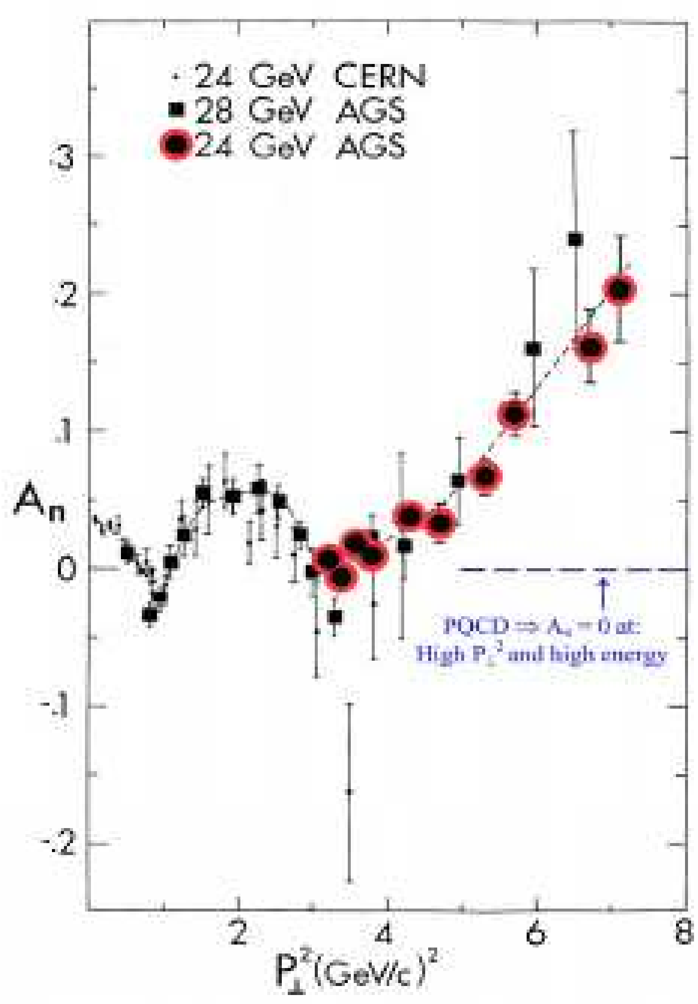
AGS A_n DATA

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})

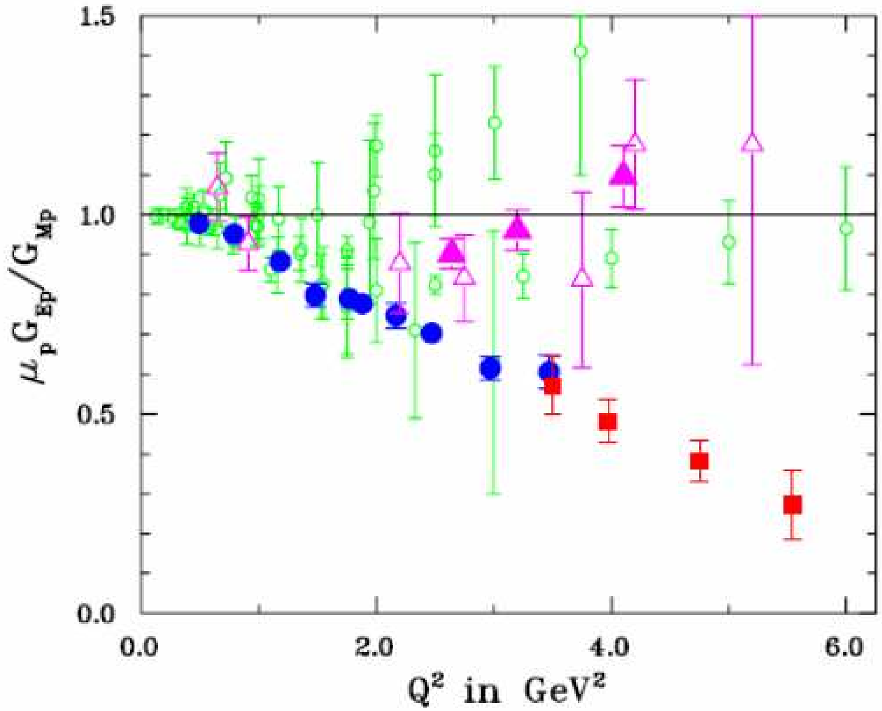
GOAL at J-PARC
MEASURE A_n (and A_{nn})
up to $P_\perp^2 = 12$ (GeV/c)^2



Recall what we learnt recently from ep→ep

A simple reaction which was believed to be totally understood

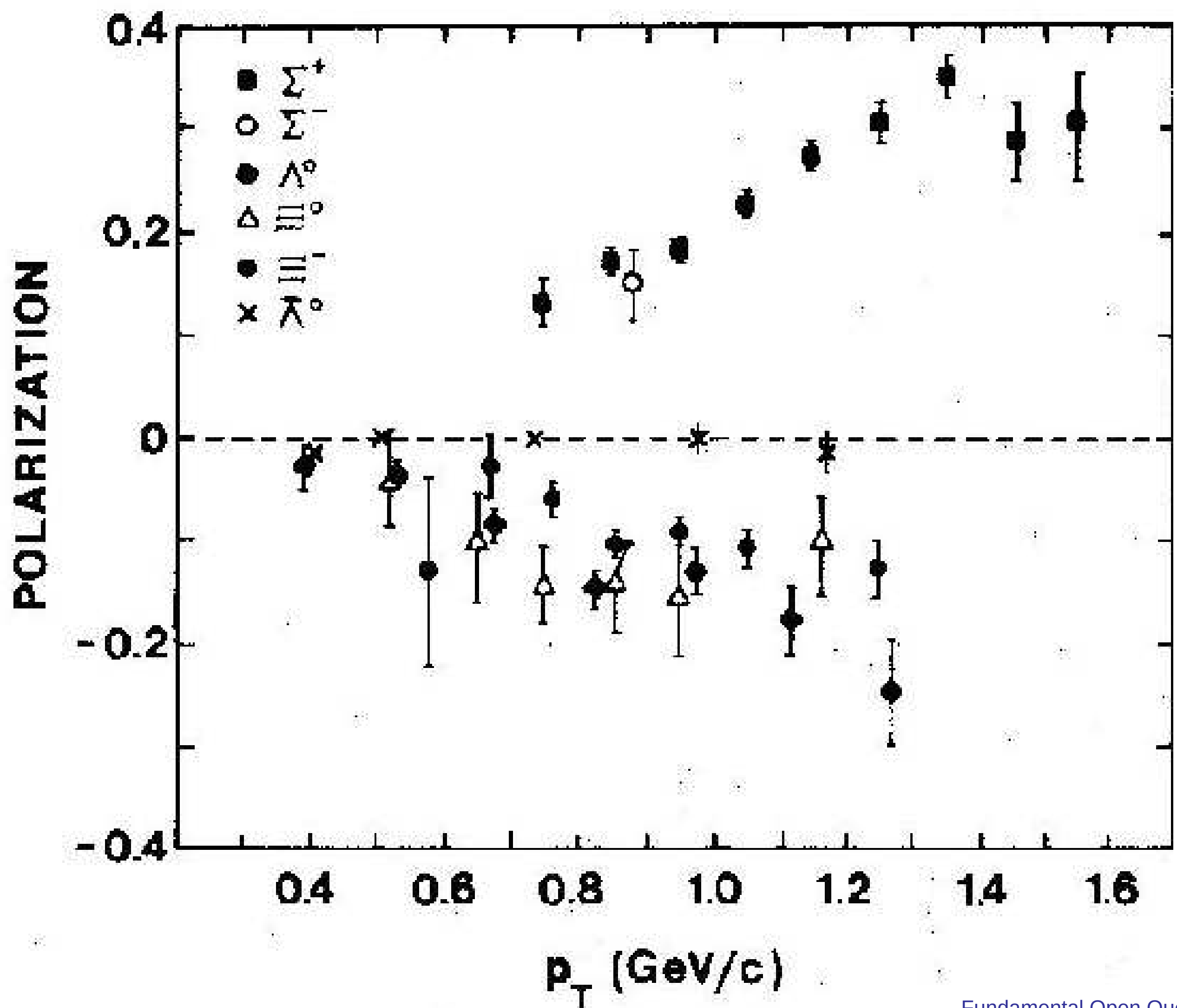
Data From GEp(I) and GEp(II) Experiments



(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



6th Int. Spin Symposium - Marseille 1984

6th Int. Spin Symposium - Marseille 1984

200 physiciens à Marseille donnent une nouvelle vision de l'univers

Vers la connaissance des effets du "spin" des chercheurs bouleversent les théories "acceptées" sur les structures de la matière

Les protons (1) et les électrons (2) particules principales de notre univers, tourneraient comme une toupie sous les effets du spin, comme son nom l'indique en anglais (tourner). Un "Spin" dont les propriétés pourraient bien changer une nouvelle fois notre vision de l'univers.

En ce sens, on comprend que le seul "spin" ait réuni 200 physiciens parmi les plus connus au monde dans leur spécialité, dont le professeur O. Chamberlain, Prix Nobel de Physique, pour sa découverte de l'anti-proton en 1955.

A l'heure du bilan de ce 6e symposium qui se déroulait à la faculté de la Timone et pour la première fois en France, M. Allan Krish professeur à l'université du Michighan communiquait **"en 1970, les physiciens pensaient que les propriétés du spin n'étaient pas importantes dans l'interaction des particules.**

Il précisait **"nous avons découvert que les forces qui dépendent du spin sont très fortes. Les expériences de spin nous donnent une information inattendue sur la nature des forces fondamentales. Elles suggèrent que la théorie qui est généralement acceptée pourrait avoir des difficultés très sérieuses"**. Une nouvelle évolution des connaissances sur la structure de la matière qui ne rencontre pas l'adhésion de tous, si l'on en croit les chercheurs en présence qui notaient **"les expériences sur les propriétés du spin sont difficiles, à la fois d'un point de vue technologique et conceptuel. Elles demandent un effort supplémentaire. Certains pensent que le spin n'est pas important, afin de ne pas avoir à fournir cet effort"**. Dans ces travaux qui s'inscrivent effectivement dans une évolution de la vision du monde, certains ne souhaiteraient pas voir fausser des théories "acceptées", pour ne pas dire acquises. Au contraire, pour les physiciens réunis à Marseille ces expériences doivent être considérées **"comme une leçon importante pour tous. "En effet" nous ne devrons pas accepter les hypothèses sans qu'elles soient confortées par une évidence expérimentale certaine"**, insistait le Pr. Krish. Grâce ou à cause des effets du spin dont l'initiateur est M. Abragam, professeur au collège de France, la physique atomique aurait donc de bonnes chances de franchir un nouveau pas. Aujourd'hui, on évoque la possibilité de mieux faire marcher les réacteurs thermo-nucléaires.

Dans cette nouvelle conquête de l'univers, un nouveau pas vers la paix ?

Viviane KARSENTY.

(1) Proton : noyau de l'atome d'hydrogène, corpuscule chargé d'électricité positive.
(2) Électron : corpuscule chargé d'électricité négative. Le nombre des protons égal à celui des électrons planétaires définit le numéro atomique de l'élément chimique.

(DE GAUCHE A DROITE)
M. Thirion directeur de laboratoire au Centre d'études nucléaires de Saclay il travaille également au centre de physique théorique de Marseille. M. Allan Krish professeur à l'université du Michighan. M. Soffer, maître de recherches au Cnrs de Marseille il est organisateur de symposium considéré comme un "modèle d'organisation", hier il était également notre interprète. A droite, M. Chamberlain, Prix Nobel de Physique et professeur à l'université de Barkley.

La Marseillaise » - Mercredi 19 septembre 1984 —— Page

6th Int. Spin Symposium - Marseille 1984

6th Int. Spin Symposium - Marseille 1984

Le Meridional   Vendredi 27 septembre 1984

La ville au quotidien

200 savants du monde entier ont joué à la toupie pour mieux connaître la matière

● Avoir le « spin » ou ne pas l'avoir, telle est l'une des grandes questions qui agitent les plus hautes sphères de la physique contemporaine. Mais, au fait, qu'est-ce que le « spin » ?

« C'est un peu comme si l'on observait La Canebière à plusieurs années-lumière, les piétons et les automobilistes étant des particules de matière animées chacune d'une logique propre », déclarait dernièrement M. Jacques Soffer, maître de recherches au C.N.R.S., lors de la réception donnée à l'Hôtel de ville en l'honneur des 200 participants au 6e symposium de spin-physique qui vient de se dérouler à la Faculté de pharmacie.

Une manifestation qui n'a pas grande signification pour l'homme de la rue, mais qui s'avère de la première importance pour les physiciens [illegible]

[illegible] spécialistes préfèrent en ignorer l'existence, elle n'en demeure pas moins un puissant facteur de remise en question d'un certain nombre de théories jusqu'alors jugées fondamentales. Ce qui est tout à fait typique de la démarche scientifique dans la mesure où une théorie émise peut être considérée comme exacte jusqu'à ce que l'expérience démontre le contraire, comme l'ont souligné, lors d'une conférence de presse de clôture, les têtes d'affiche de ce symposium, MM. Owen Chamberlain, Prix Nobel de physique pour sa découverte de l'antiproton et professeur à l'université de Berkley aux U.S.A., Alan Krisch, professeur à l'université du Michigan et président du Comité international de Parrainage du Symposium ; et Thirion, du Laboratoire « Saturne » à Saclay.

6th Int. Spin Symposium - Marseille 1984

Some specific goals

- To understand the nucleon spin structure in terms of quarks and gluons.
- To test the SPIN SECTOR of pQCD (Several spin asymmetries calculated to NLO)

Basic information comes from Deep Inelastic Scattering (DIS)

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

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

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

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.

Nucleon helicity sum rule

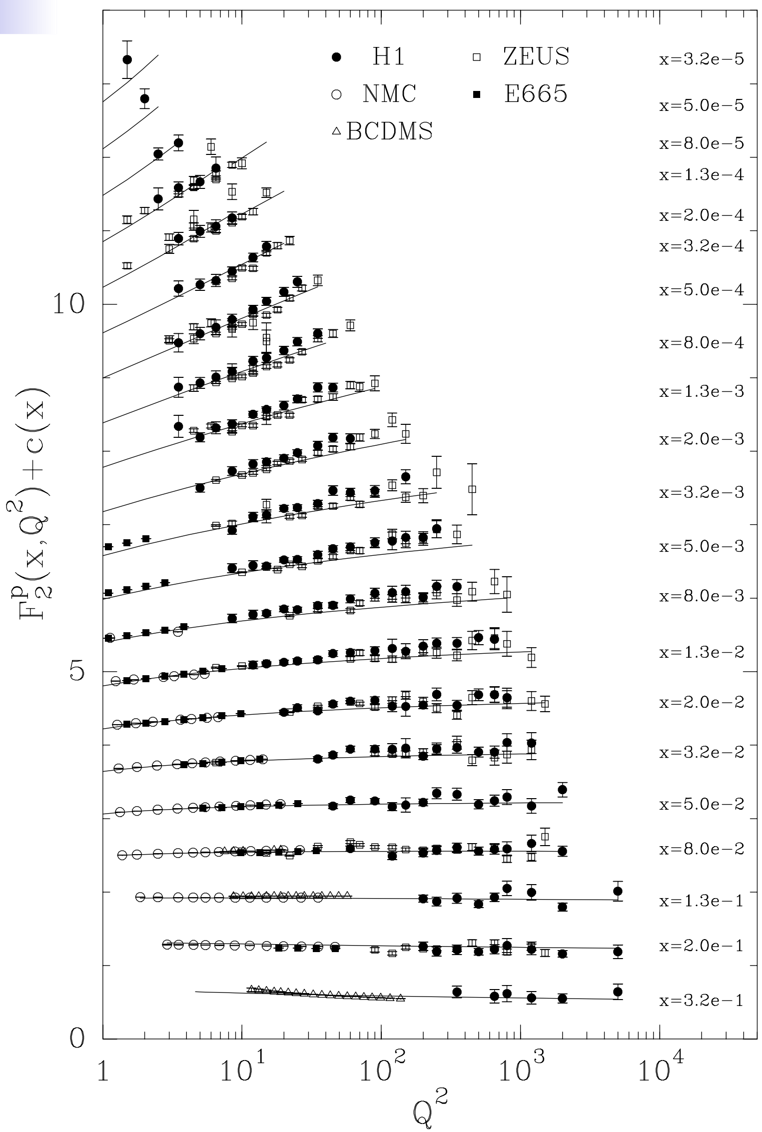
We have the following sum rule

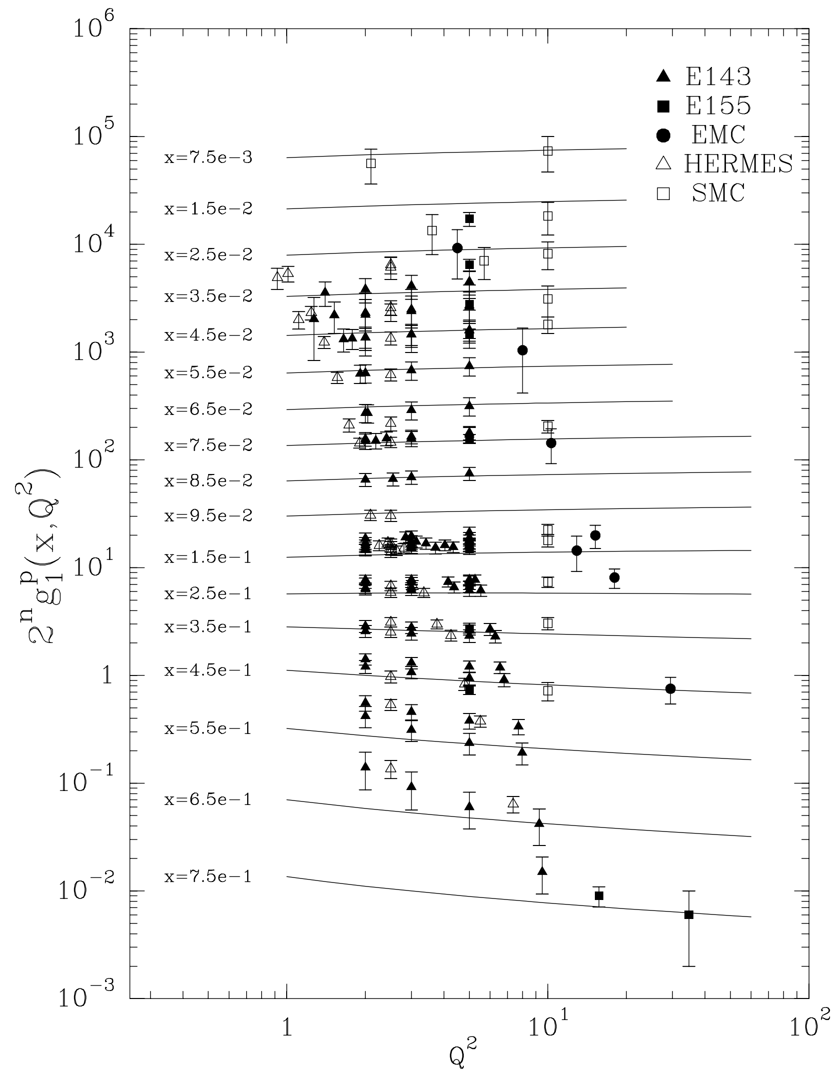
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G(Q^2) + L_q(Q^2) + L_g(Q^2)$$

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?

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

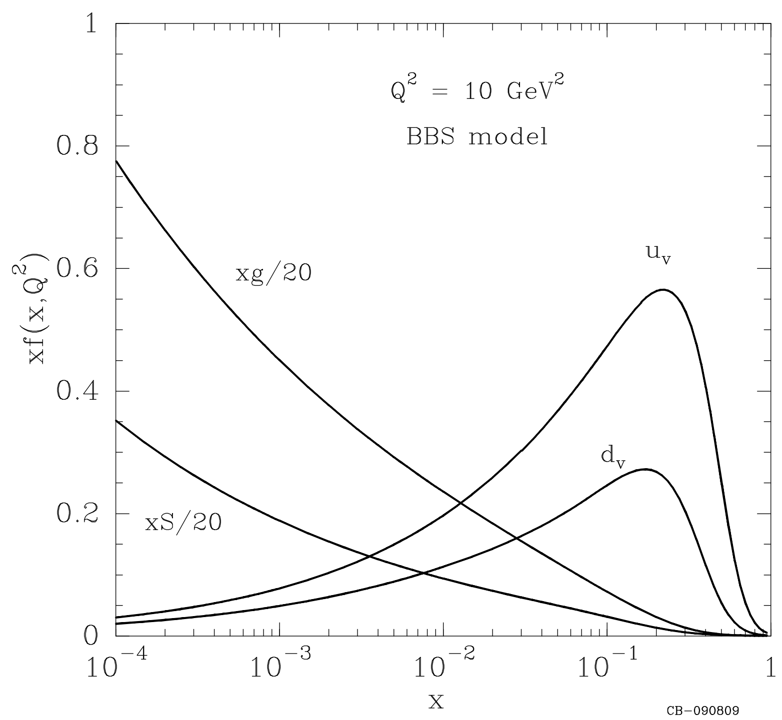


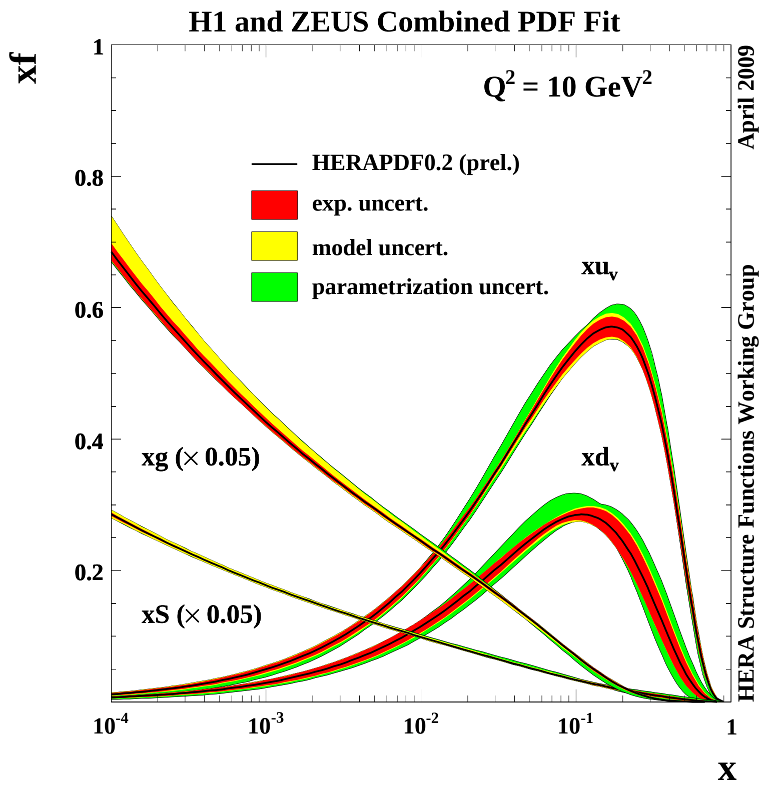


Flavor separation for unpolarized quark distributions

- 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

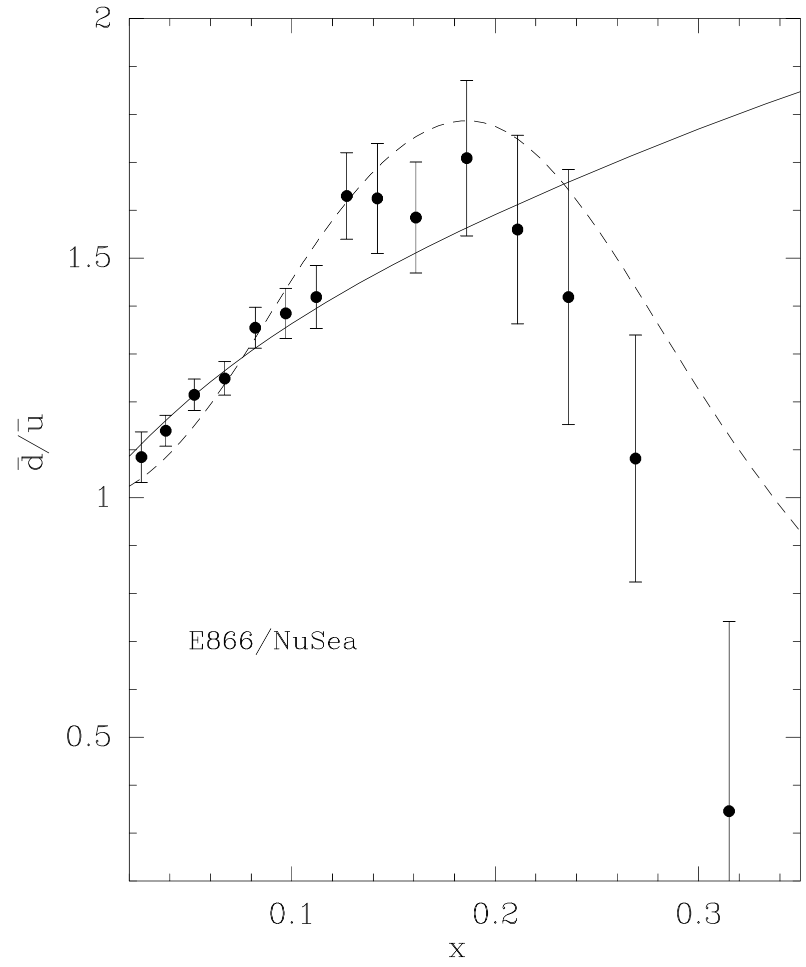




Need to know more about the sea quarks

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

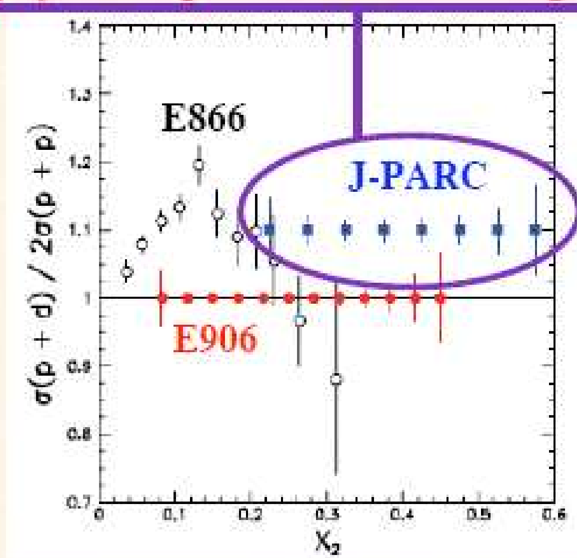
From Drell-Yan process at $Q^2 = 54$GeV^2



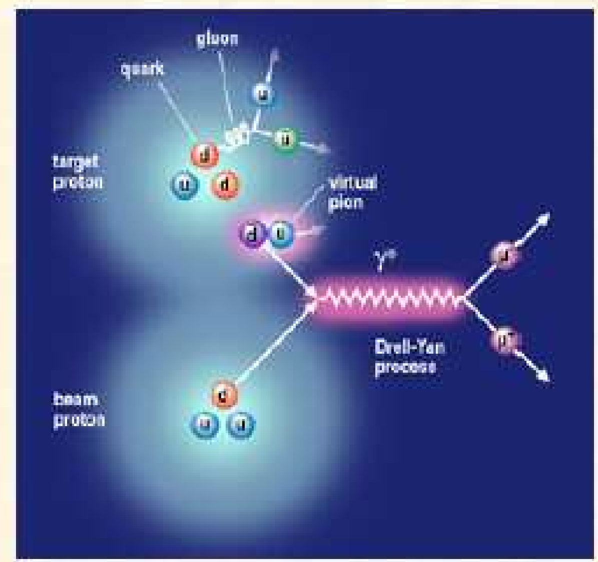
Prospects for this important issue at FNAL and J-PARC

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.

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

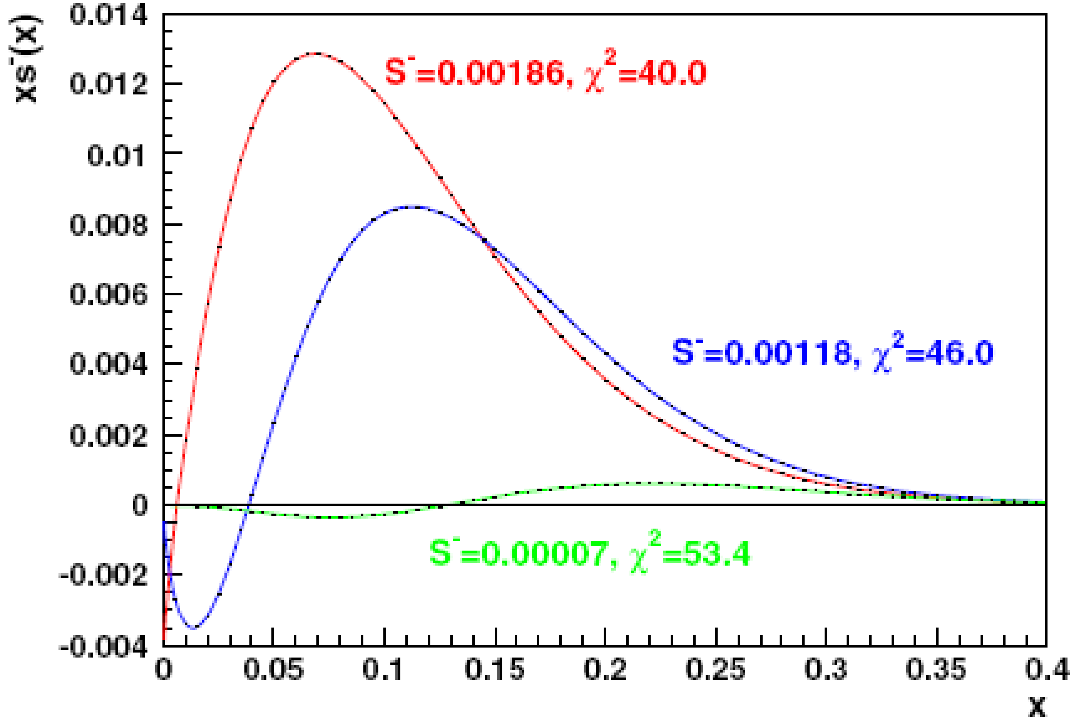


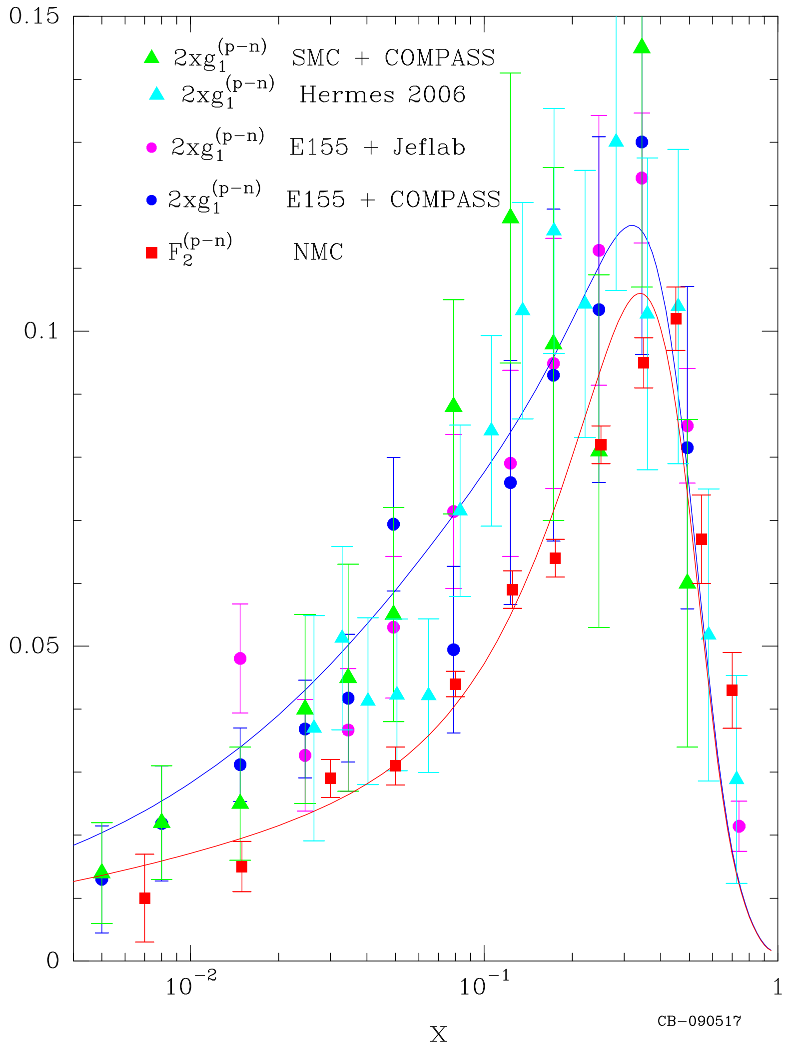
FIG. 4 (color online). xs^- for x_0 of 0.01, 0.05, and 0.15. χ^2's are labeled for an effective DOF of 38.8.

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

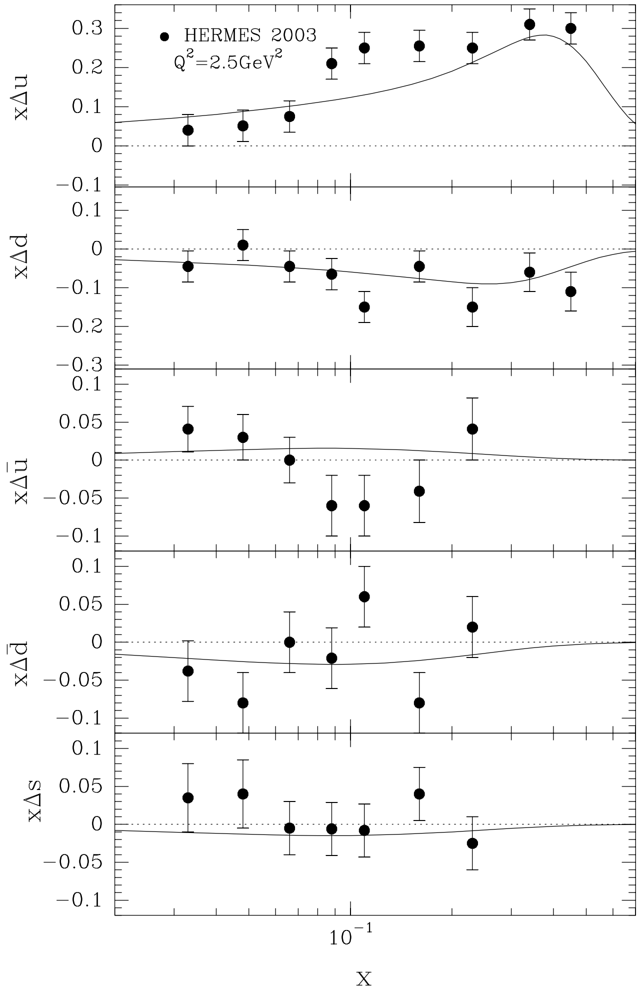
$F_2^{p-n} \simeq 2xg_1^{p-n} \;\Rightarrow\; u^+$ dominates and $u^- \simeq d^-$

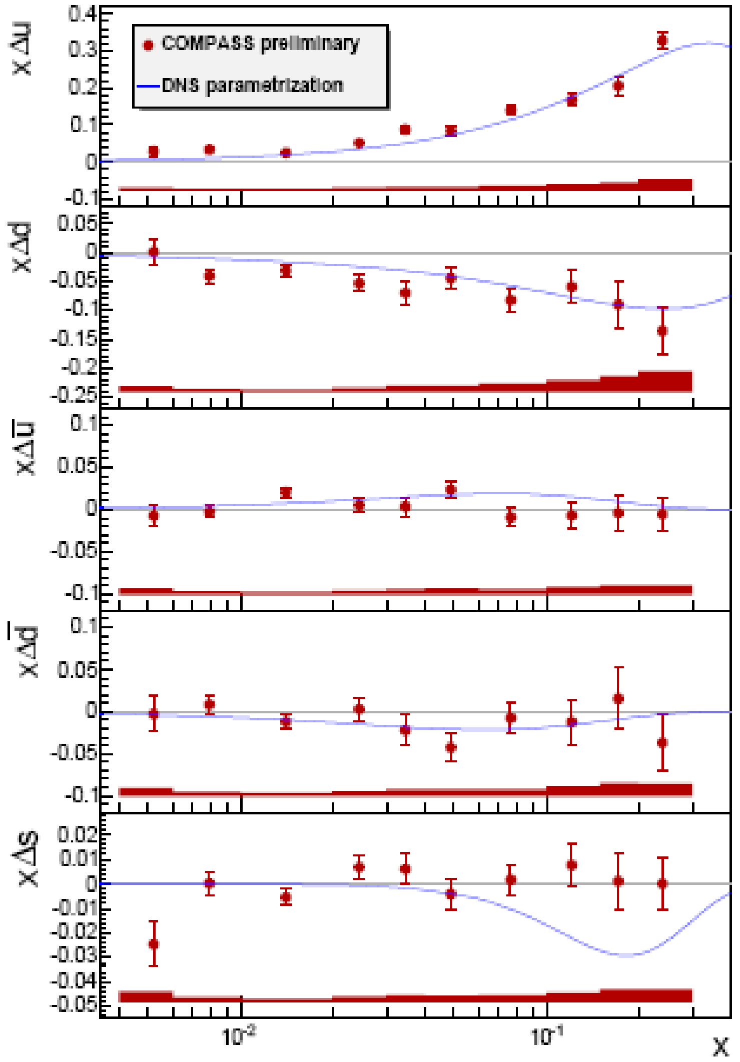


Flavor separation for quark helicity distributions

- 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.

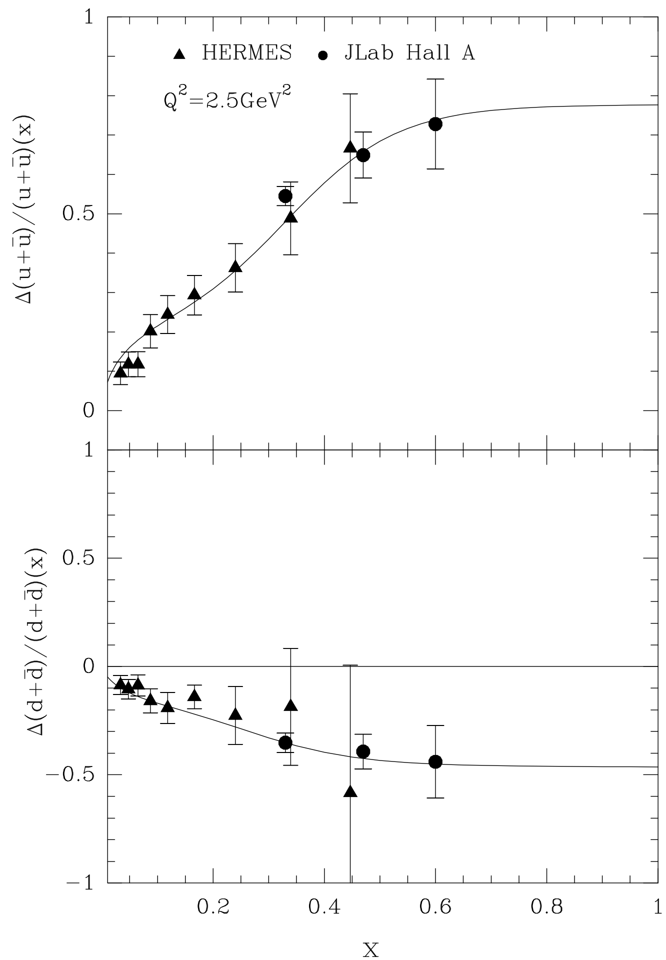
Polarized quarks distributions vs x at DESY and CERN: flavor separation from SIDIS





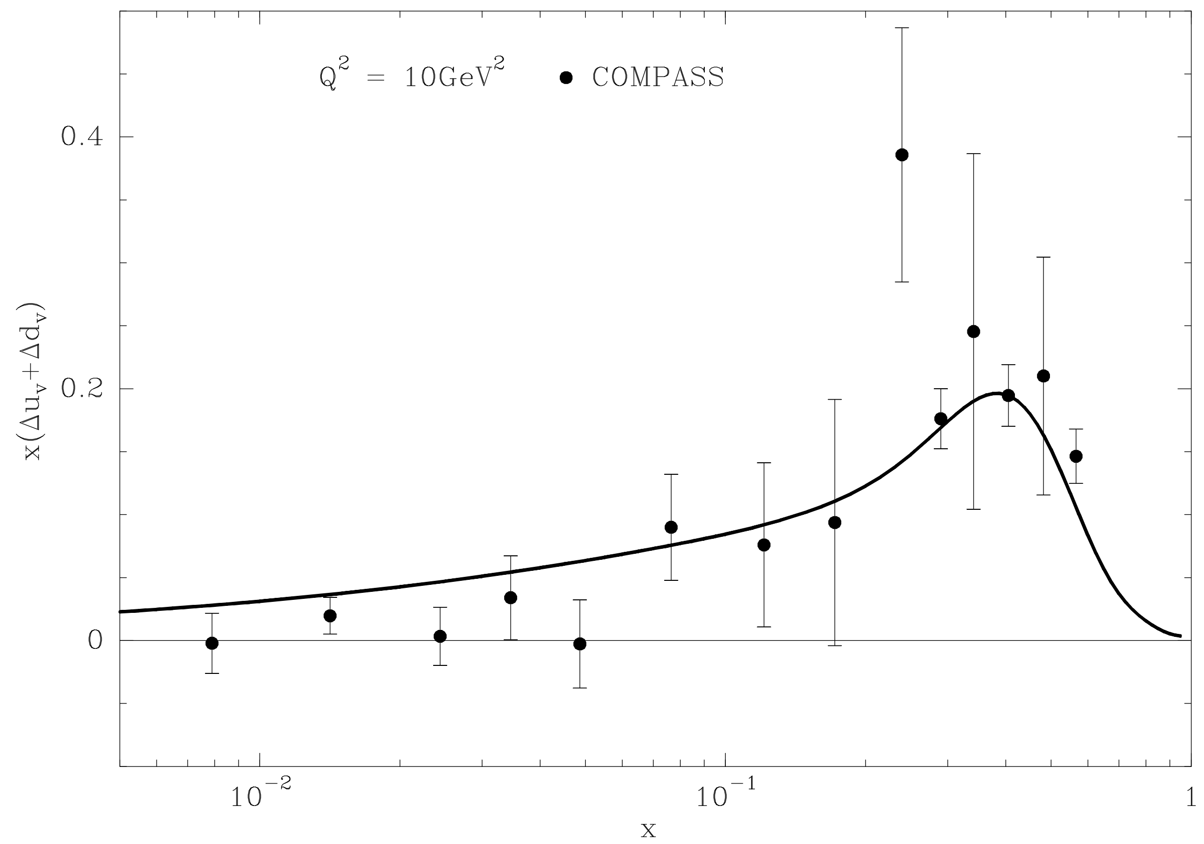
Polarized quarks distributions versus x at JLab

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

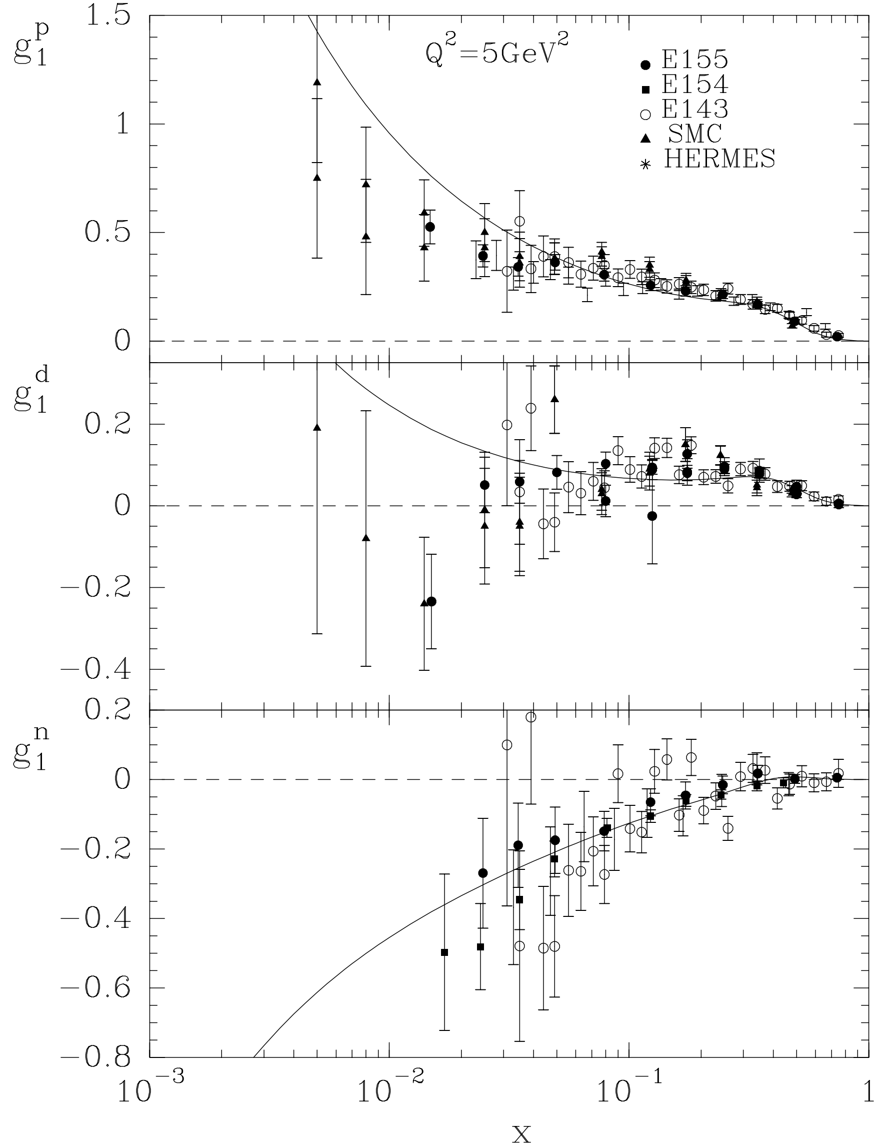


The valence quark helicity distributions versus x

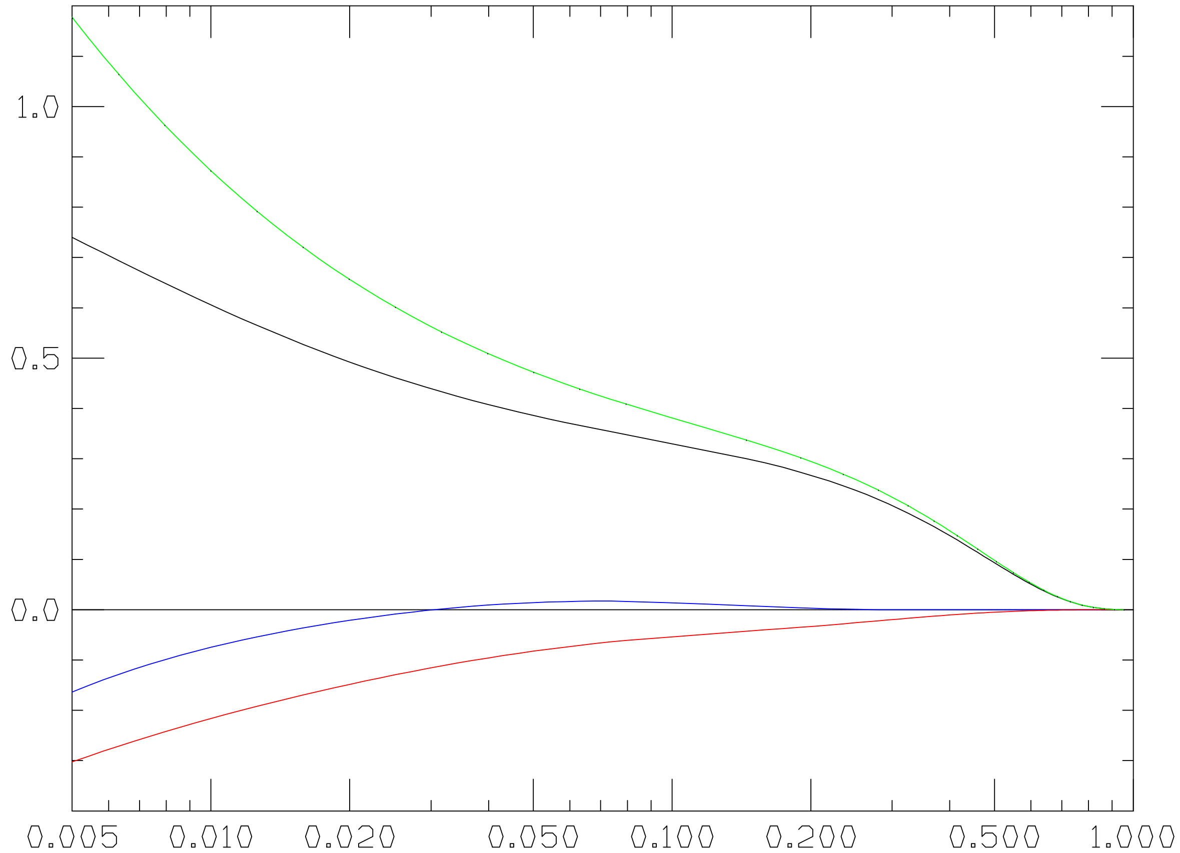
From semi-inclusive DIS $\mu d \to \mu h^{\pm} X$ can determine the valence quark helicity distributions. Combined with g_1^d it leads to $\Delta\bar{u} + \Delta\bar{d} = 0.0 \pm 0.04 \pm 0.03$
i.e. a highly non-symmetric polarized sea



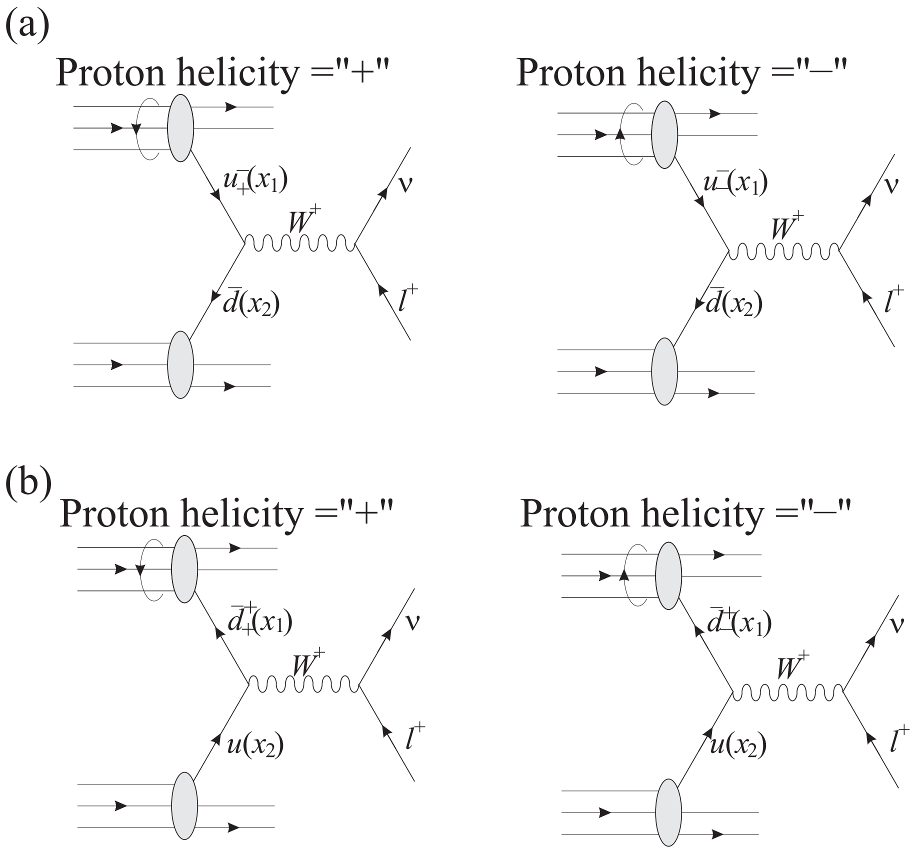
Antiquarks dominate the very low x region, in particular strange sea quarks



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



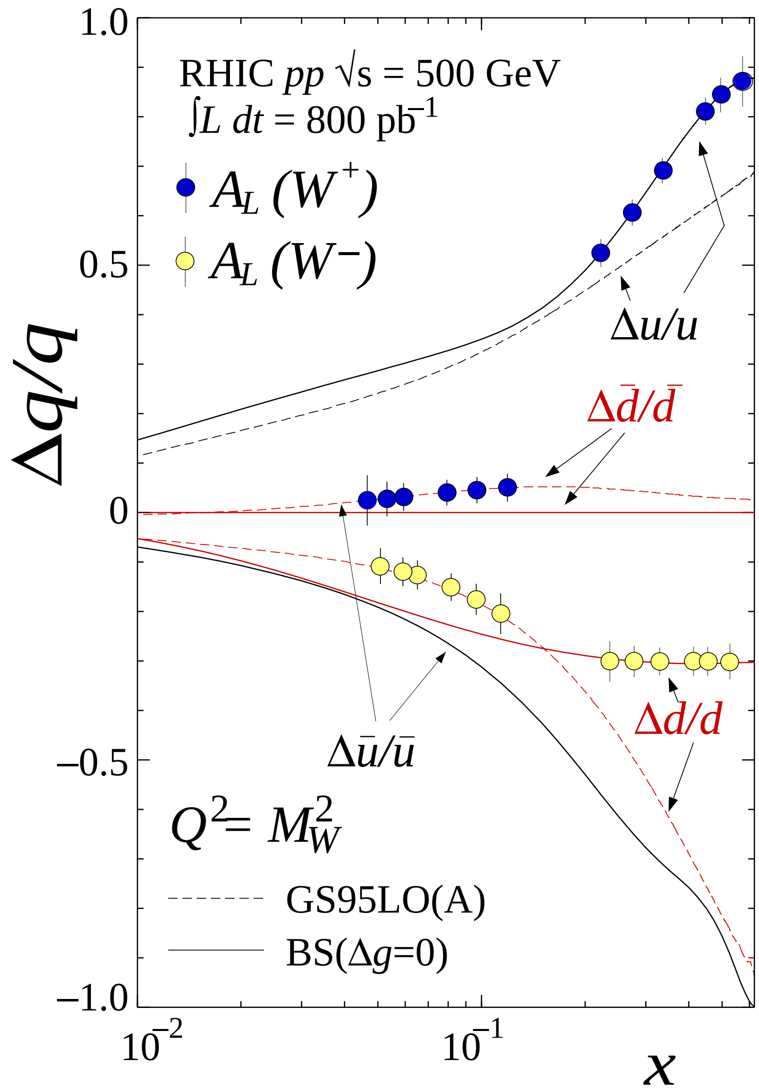
W^+ production in polarized pp collisions



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



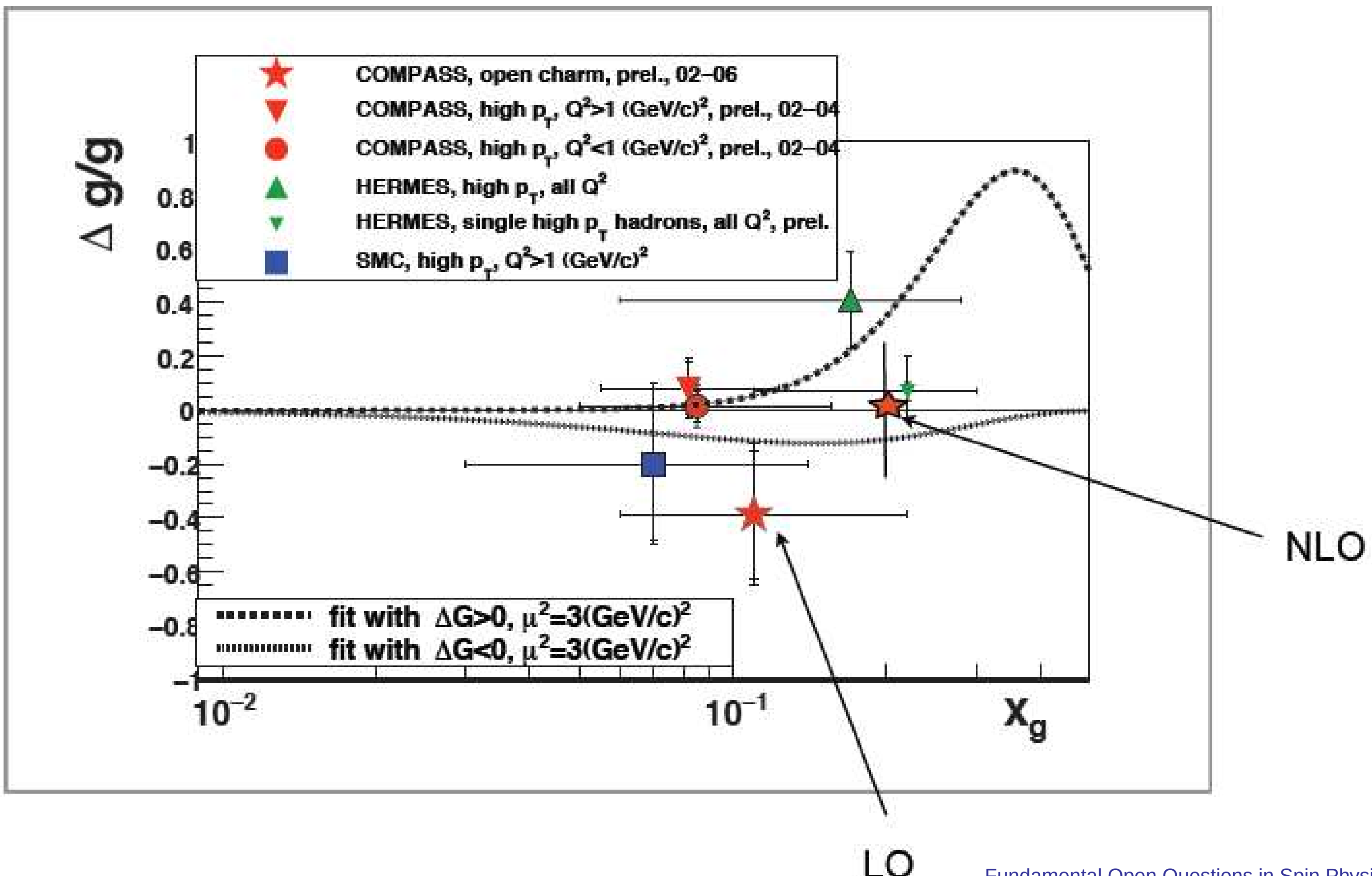
Gluon Polarization $\Delta g(x)$ in the nucleon

- 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

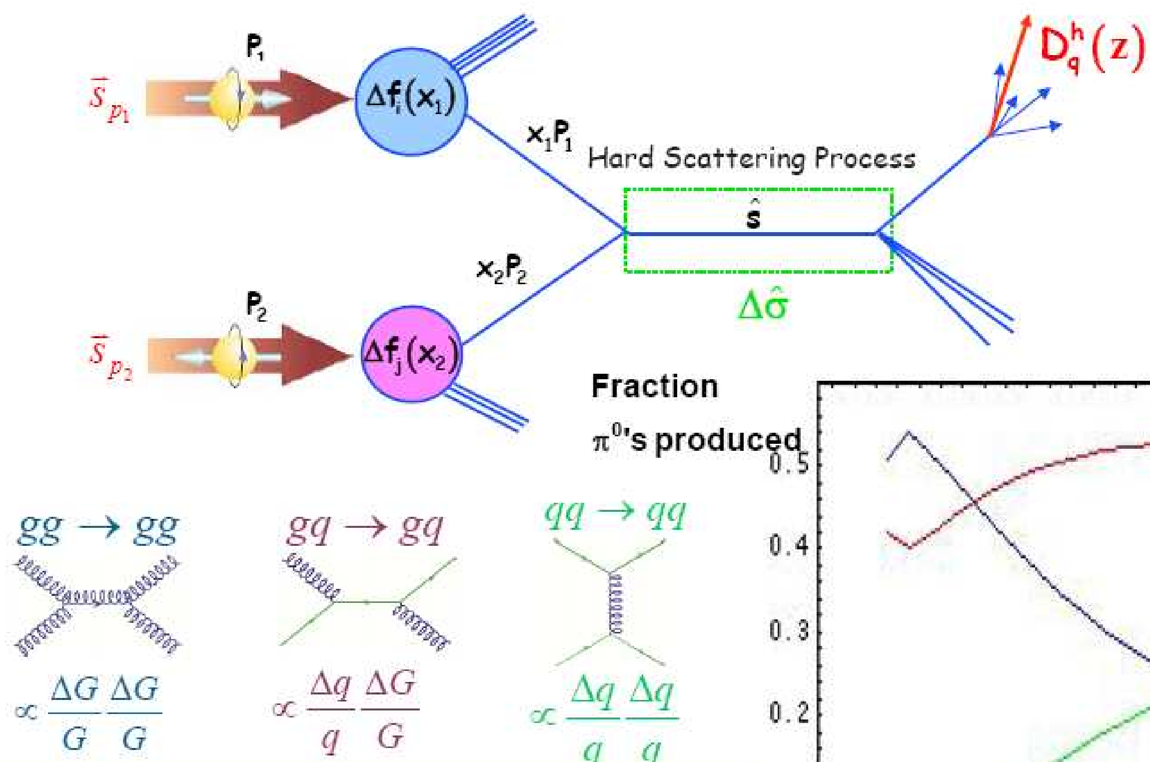
It is also crucial to measure it at RHIC

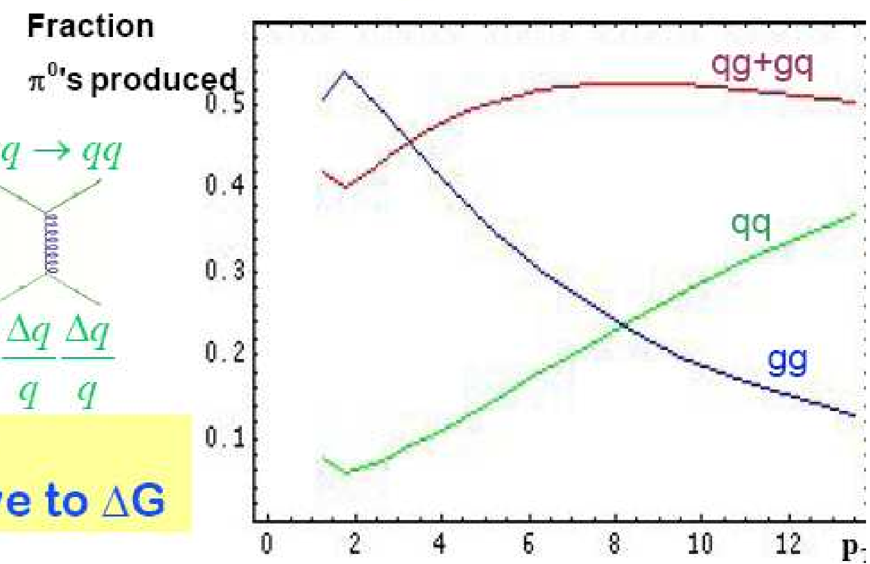
Present knowledge of Gluon Polarization from DIS

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



The gluon polarization at RHIC



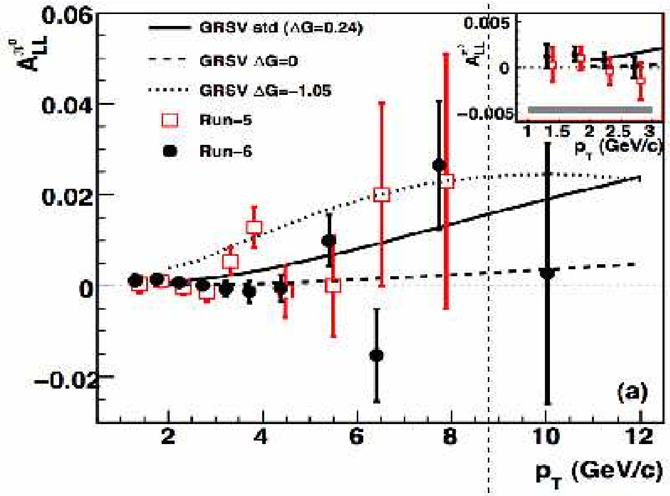


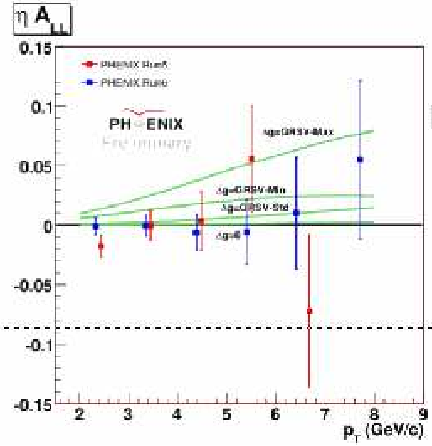
Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

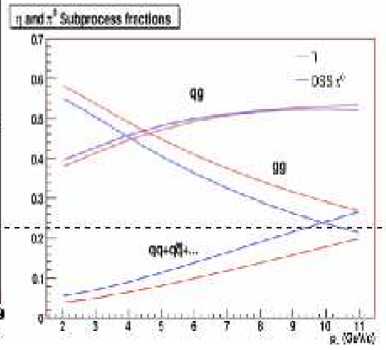
The gluon polarization at RHIC from PHENIX

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)

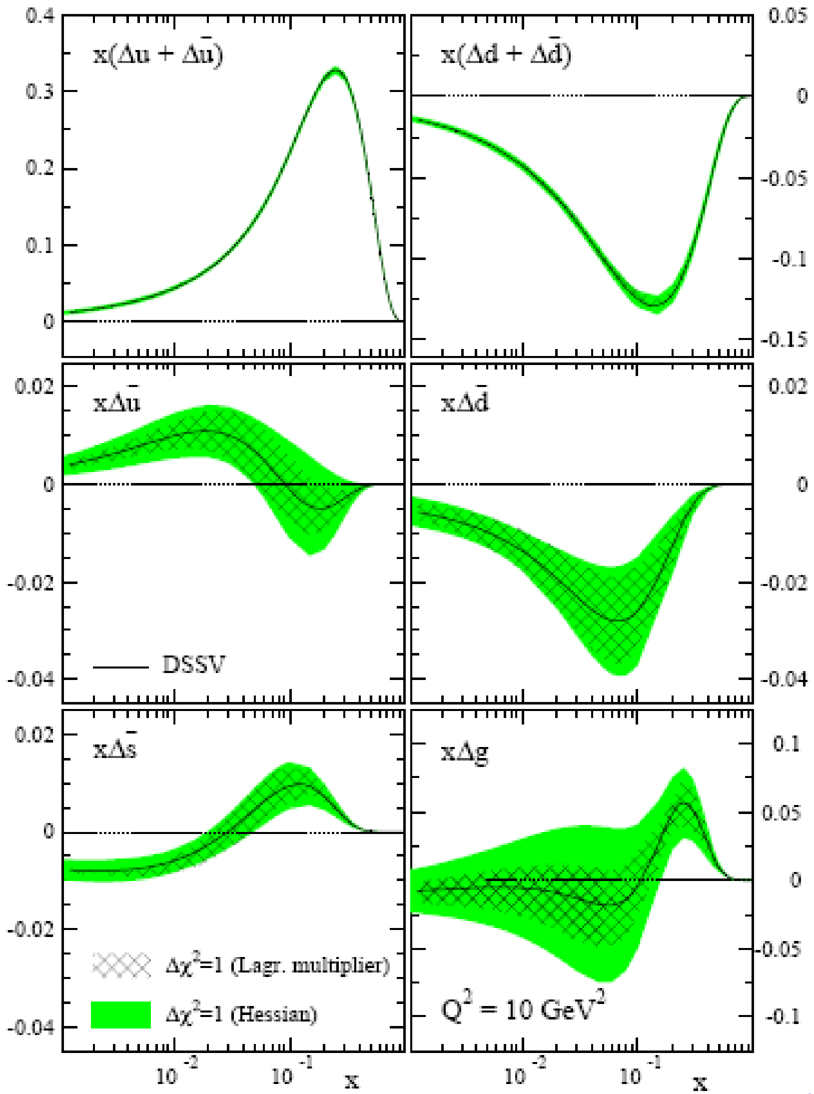






- ❑ η at 200 GeV
  - Analysis similar to π^0
  - Fractional sub process differ somewhat
  - Independent confirmation of ΔG

Present knowledge of polarized PDF from a recent global fit (DSSV)



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

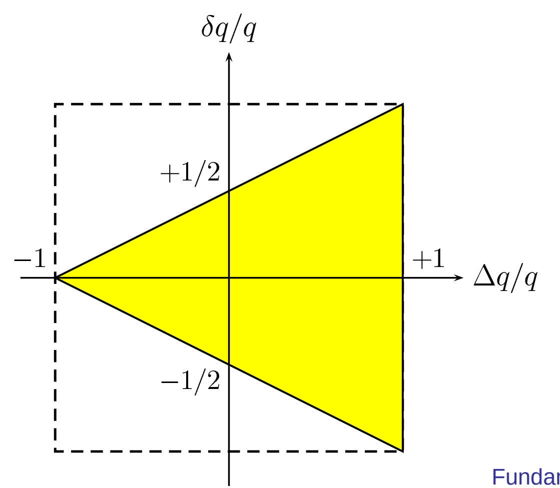
It was first mentioned by Ralston and Soper in 1979, in $pp \to \mu^+\mu^- X$ with transversely polarized protons, but forgotten until 1990, where it was realized that it completes the description of the quark distribution in a nucleon as a density matrix

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

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

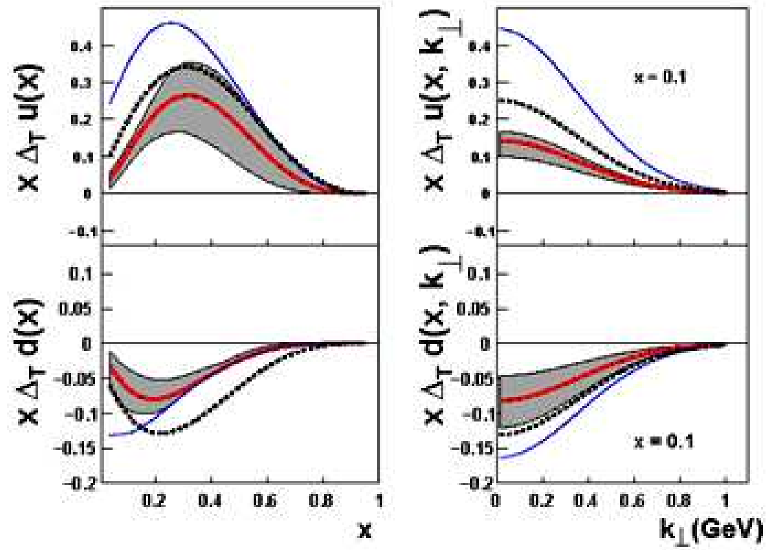
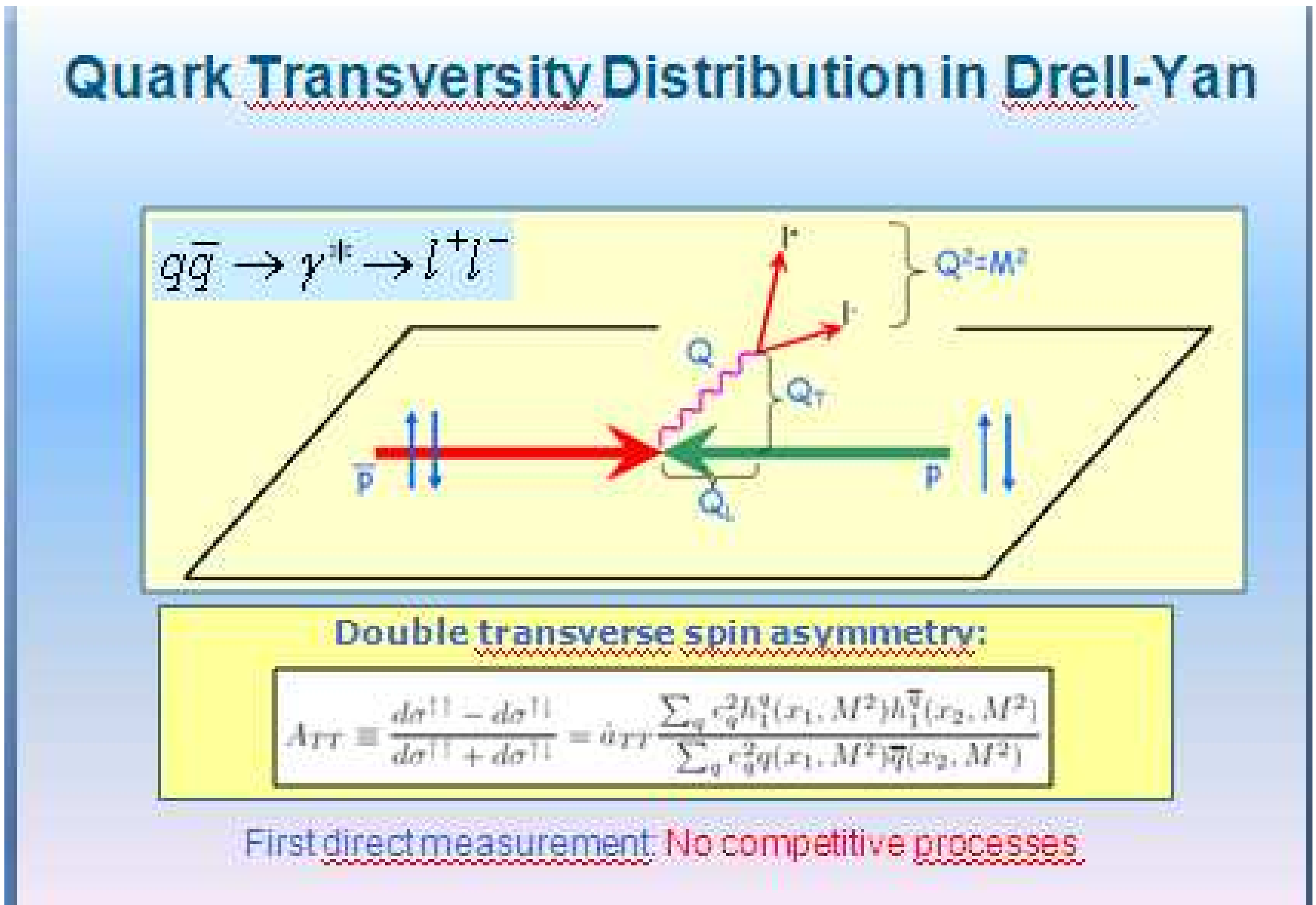


Figure 7. Comparison of the extracted transversity (solid line) with the helicity distribution (dashed line) at $Q^2 = 2.4$ GeV^2. The Soffer bound [46] (blue solid line) is also shown.

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

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

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



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 $\overrightarrow{s_T} \cdot (\overrightarrow{p} \times \overrightarrow{k_T})$

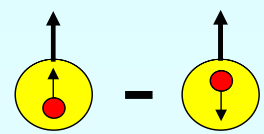
Two QCD mechanisms

- 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

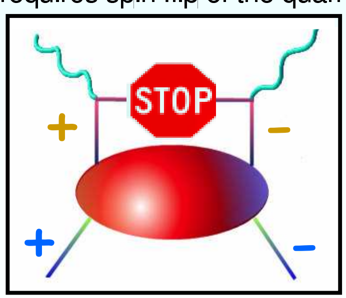
$$\delta q(x,Q^2) = q^{\uparrow} - q^{\downarrow}$$



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

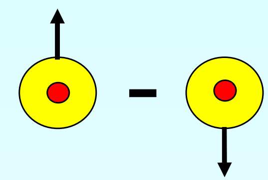


Not measurable in inclusive DIS

Unmeasured for long time!

Sivers function

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



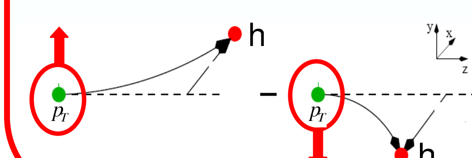
Chiral-even T- odd

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

describes spin-orbit correlation in the nucleon

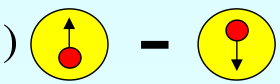
Requires **non-zero orbital angular momentum!**

azimuthal asymmetries in the direction of the outgoing hadrons.



Collins function

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



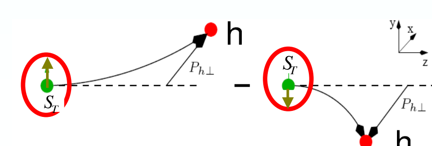
Chiral-odd T- odd

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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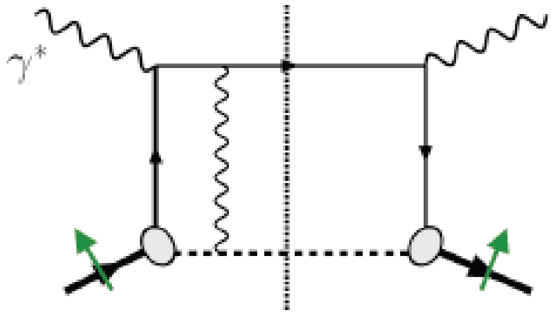
Process-dependence of Sivers functions

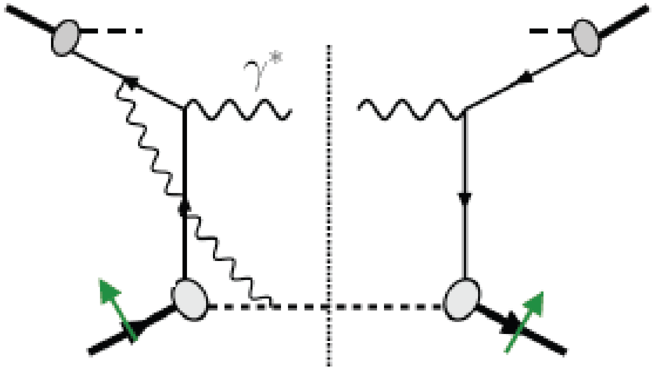
Crucial role of gauge links in TMDs

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

DIS: "attractive"



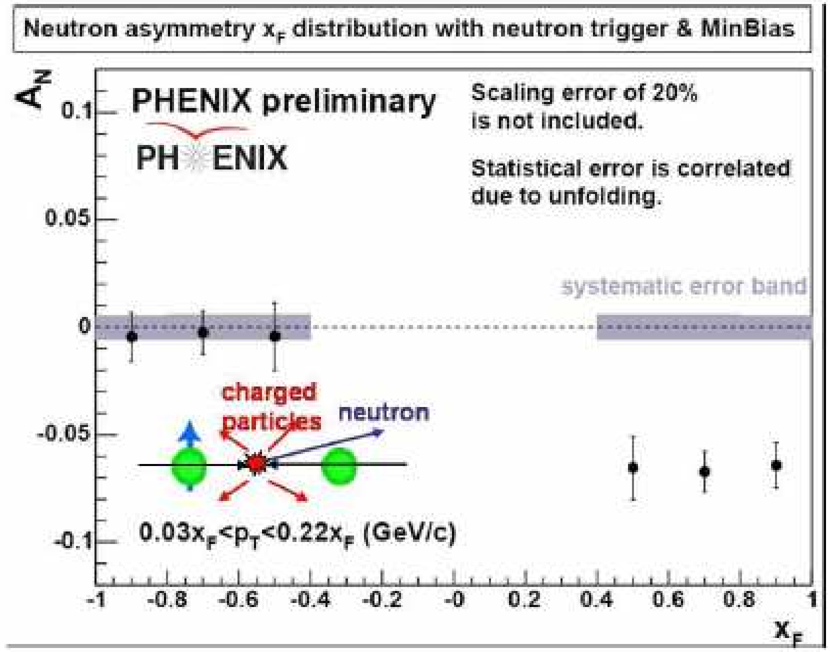
DY: "repulsive"



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

Another puzzling SSA

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

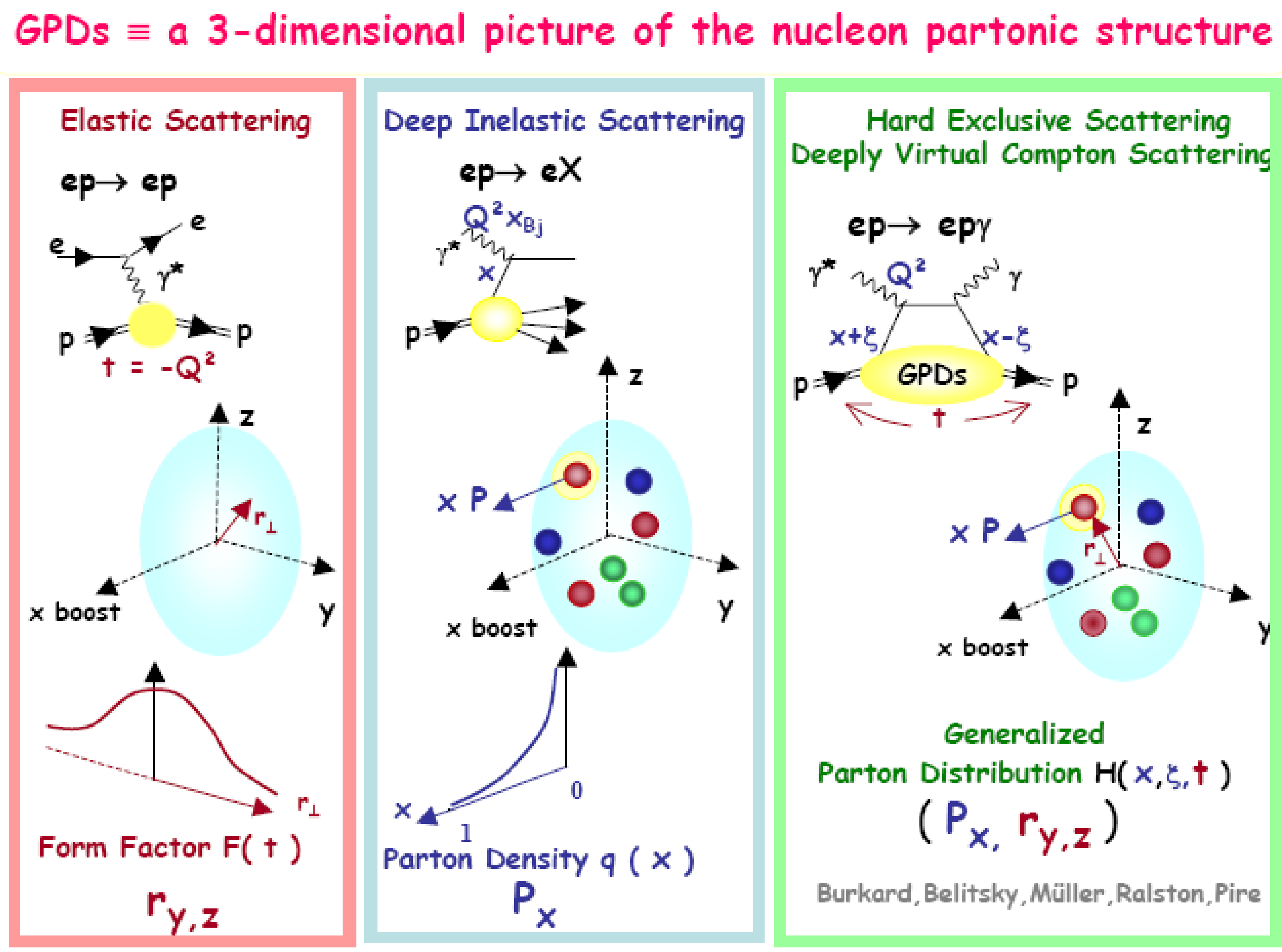


Large and no x_F dependence. $A_N(x_F < 0) = 0$

Cross section not yet release.

Perhaps a new challenge for theory

Generalized parton distributions



Generalized parton distributions

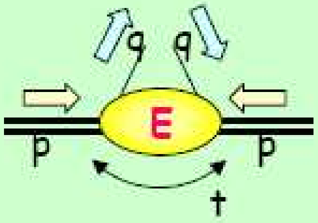
'Holy Grails' of the GPD quest

- Contribution to the nucleon spin puzzle

  E related to the angular momentum

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

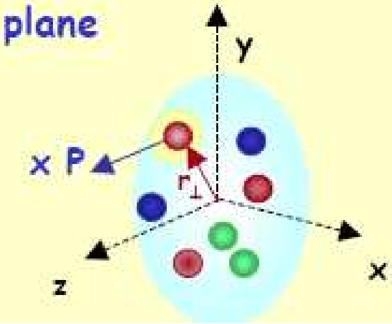
  $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$



- 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
- 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 !