The Nucleon Spin Structure and QCD Spin Physics

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We will address to the following questions:

- What is known?
- What is missing?
- What needs to be measured next?
- What are the prospects?

Outline

- Main Goals
- Digression on parton distributions functions
  - Δq, $\Delta\bar{q}$ and flavor separation
  - 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}
- Single spin asymmetries (SSA) in QCD
  - QCD mechanisms (Sivers versus Collins)
  - An interesting case: A_N in π^0 production
- Conclusions

Main 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)

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

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).

Digression on polarized PDF (C. Bourrely, F. Buccella, J. S.)

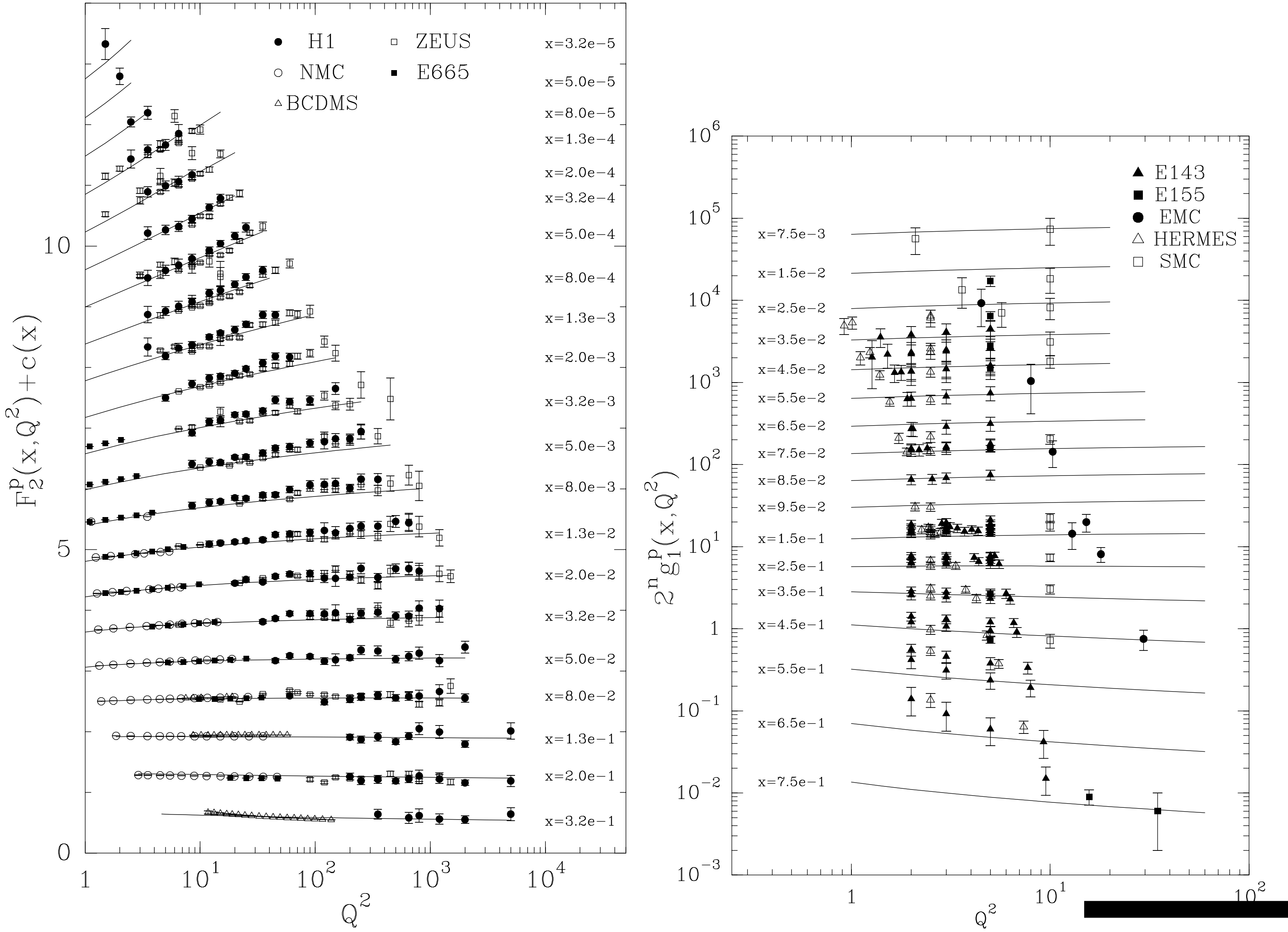
- A Statistical Approach for Polarized Parton Distributions
  Euro. Phys. J. C23, 487 (2002)
- Recent Tests for the Statistical Parton Distributions
  Mod. Phys. Letters A 18, 771 (2003)
- The Statistical Parton Distributions: status and prospects
  Euro. Phys. J. C41, 327 (2005)
- The extension to the transverse momentum dependence of the statistical parton distributions
  Mod. Phys. Letters A 21, 143 (2006)
- Strangeness asymmetry of the nucleon in the statistical parton model
  Phys. Letters B 648, 39 (2007)
- New tests and predictions from the statistical parton distributions
  (in preparation)

Digression on polarized PDF (C. Bourrely, F. Buccella, J. S.)

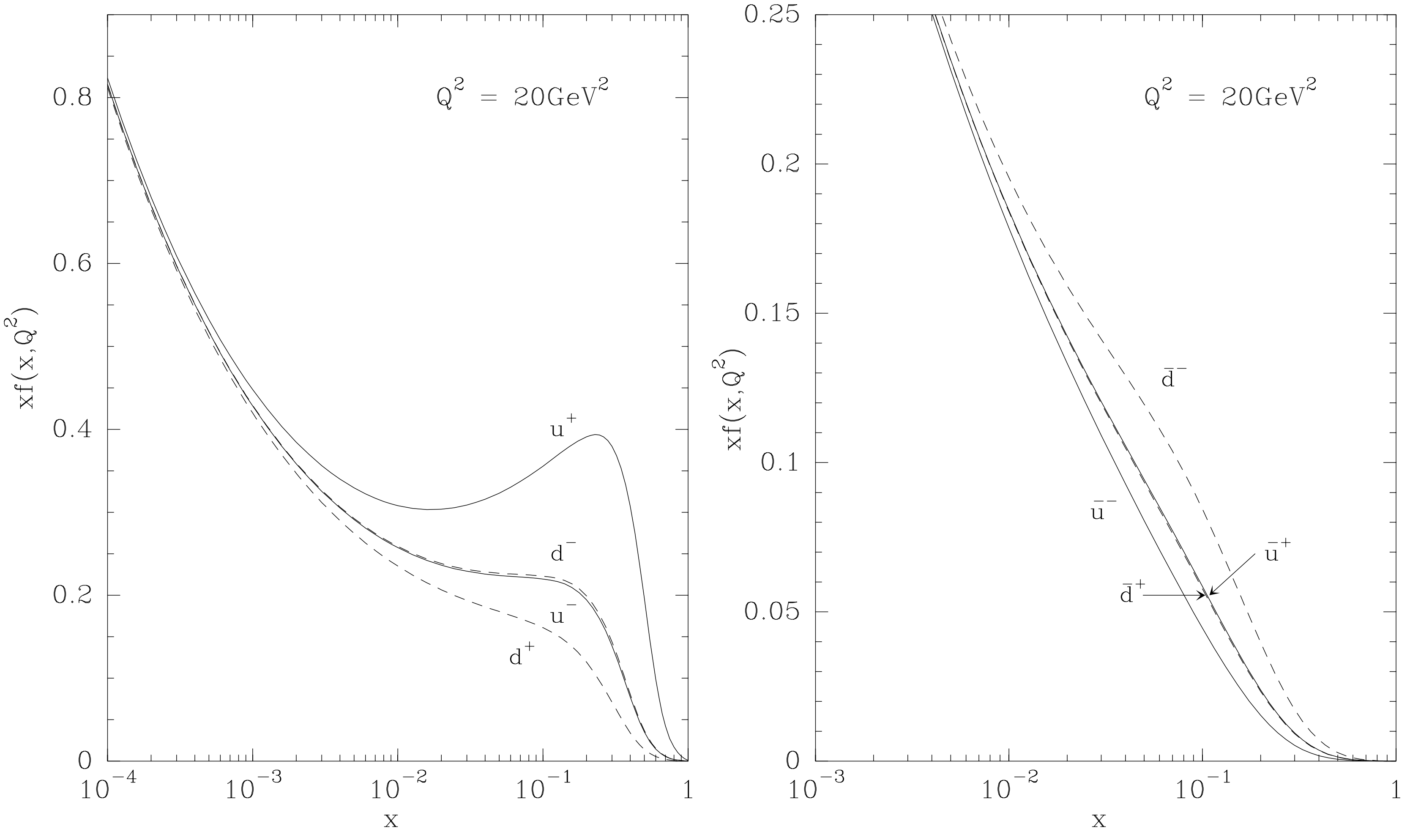
A new set of PDF is constructed in the framework of a statistical approach of the nucleon, which has the following characteristic features:

- The building blocks are the helicity dependent distributions $q_{\pm}$ and $\bar{q}_{\pm}$.
- The chiral properties of QCD lead to strong relations between q and $\bar{q}$.
  e.g. $\Delta u > 0 \Rightarrow \Delta \bar{u} > 0$, $\Delta d < 0 \Rightarrow \Delta \bar{d} < 0$
- All unpolarized and polarized distributions depend upon eight free parameters, determined in 2002, from an NLO fit of the data.
- New tests against experimental (unpolarized and polarized) data are very satisfactory, in particular in hadronic reactions (more to come from RHIC).

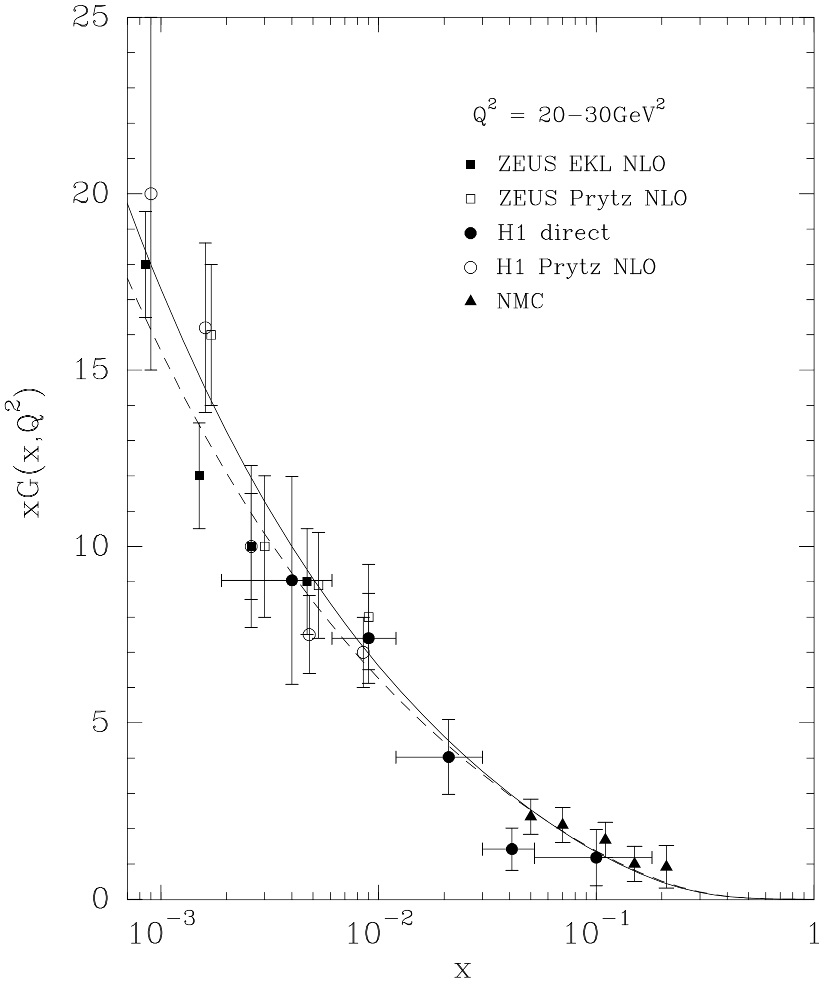
Recall what we know from unpolarized and polarized DIS



Predictions for different quark helicity components



The gluon distribution

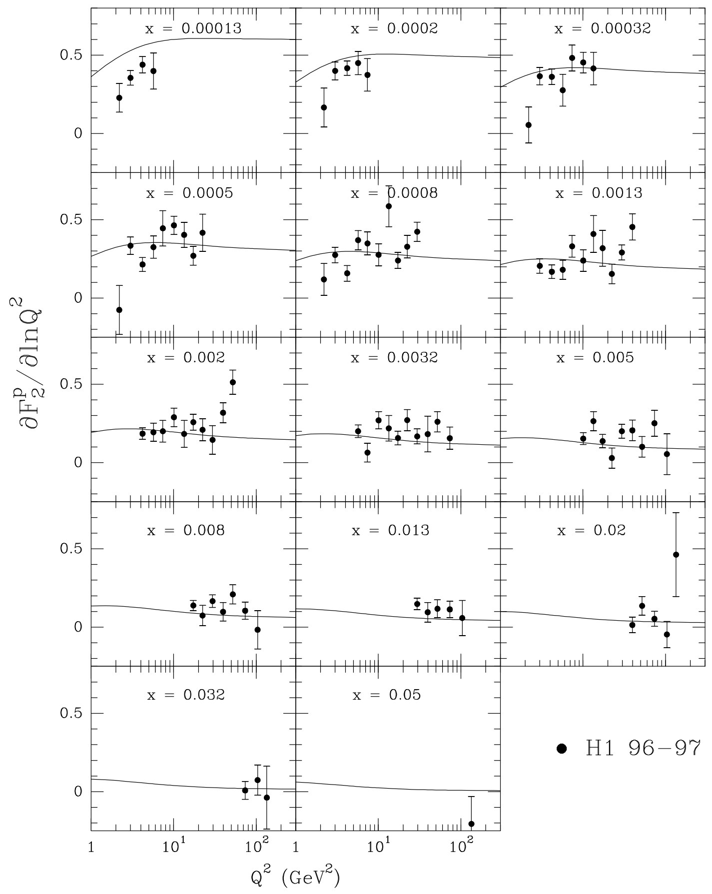


Note the scale difference mainly in the low x region

Accurate determination of $G(x)$ at HERA

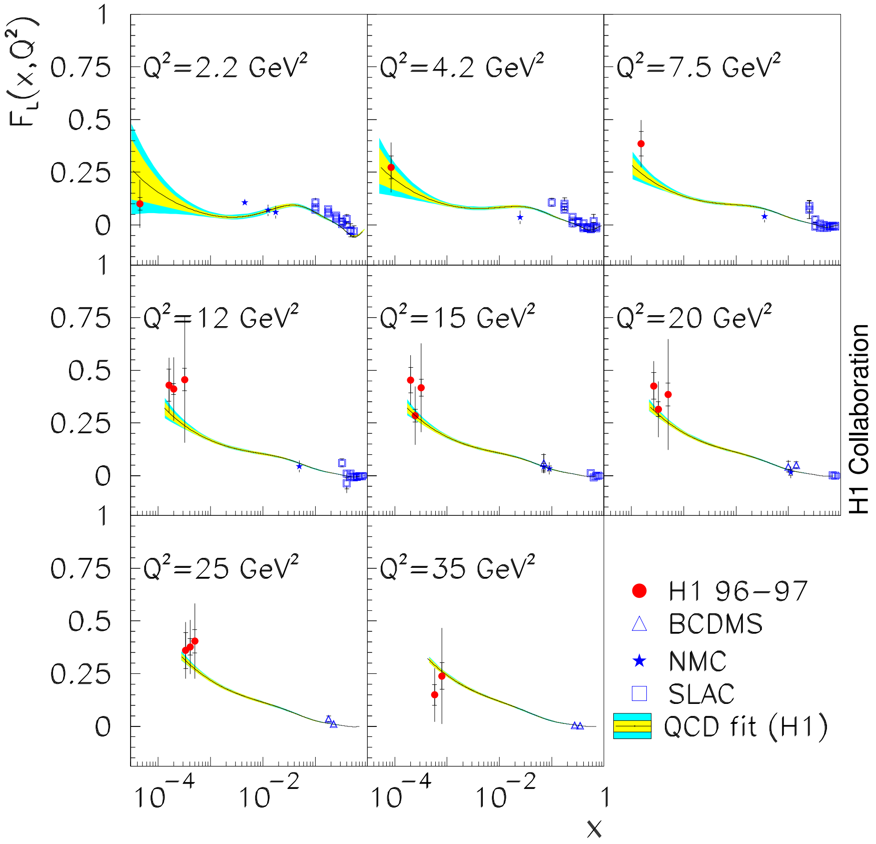
Two ways to determine the gluon distribution: measure F_L or $dF_2/dlnQ^2$

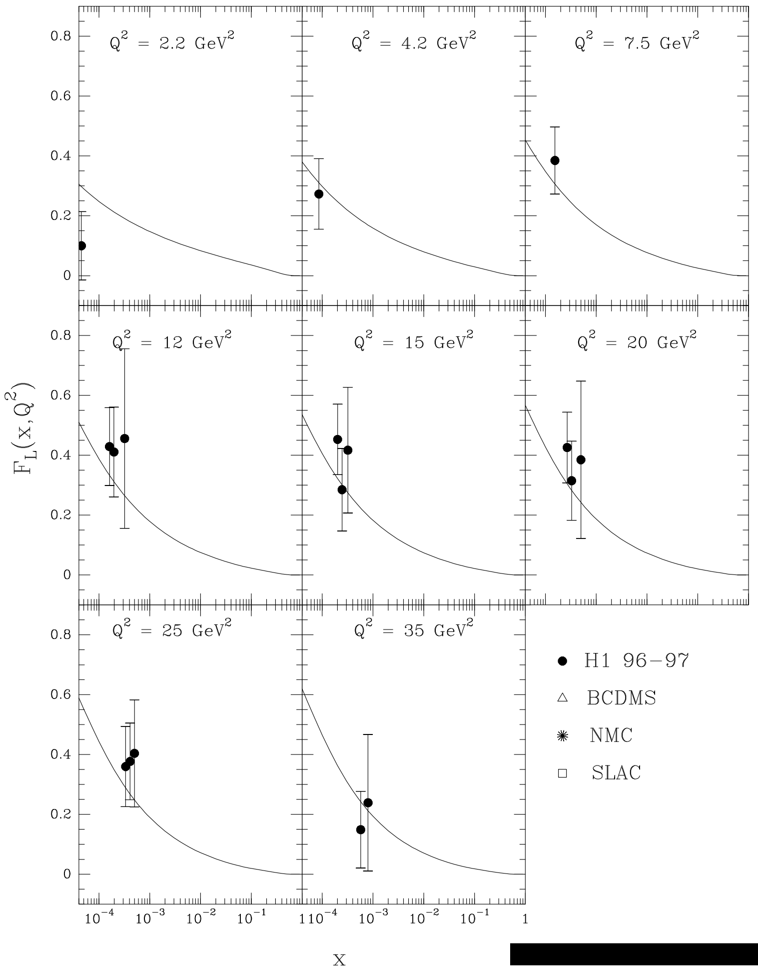
At LO $dF_2/dlnQ^2 \sim \alpha_s G(2x) + ...$



Accurate determination of $G(x)$ at HERA

Two ways to determine the gluon distribution: measure F_L or $dF_2/dlnQ^2$
F_L is the last measurement at HERA

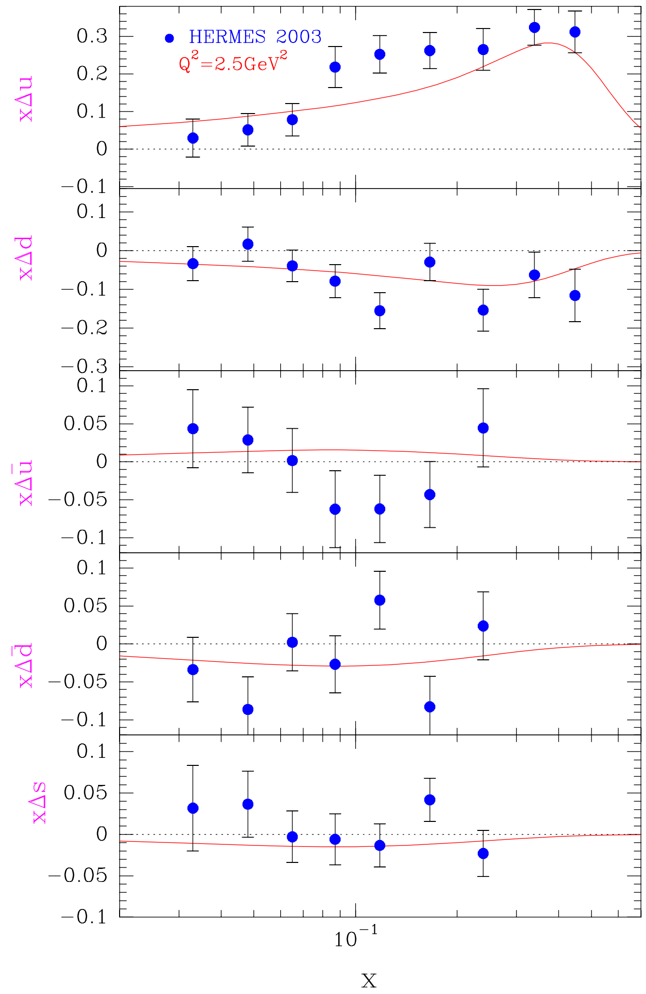




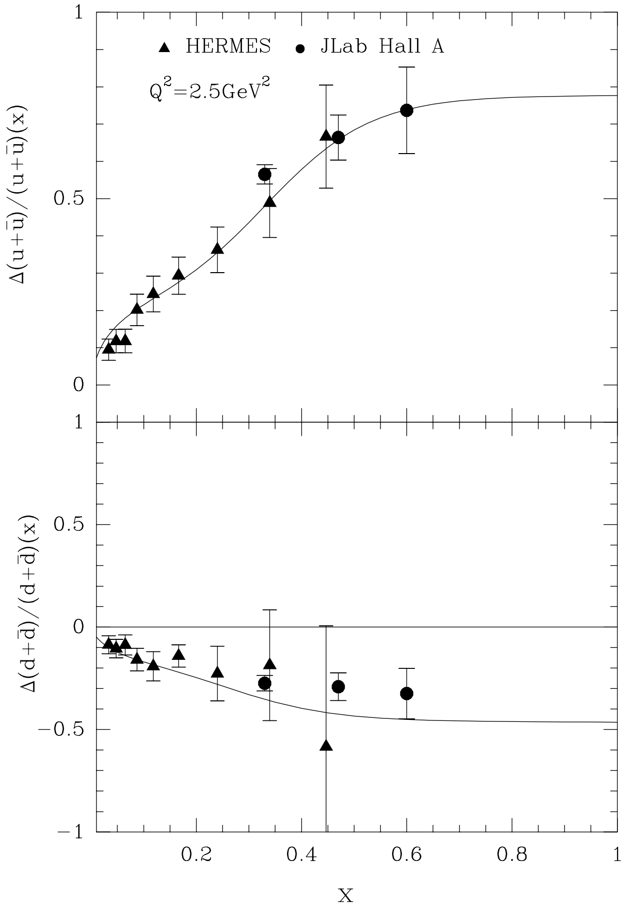
Flavor separation

- **Quark unpolarized distributions**
  Easier for u and d, thanks to the high precision of the data on $F_2^{p,n}$ and neutrino DIS. Have found not long ago that $\bar{u} < \bar{d}$ from dilepton production and we are still unclear if $s < \bar{s}$ or $s > \bar{s}$.
- **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.

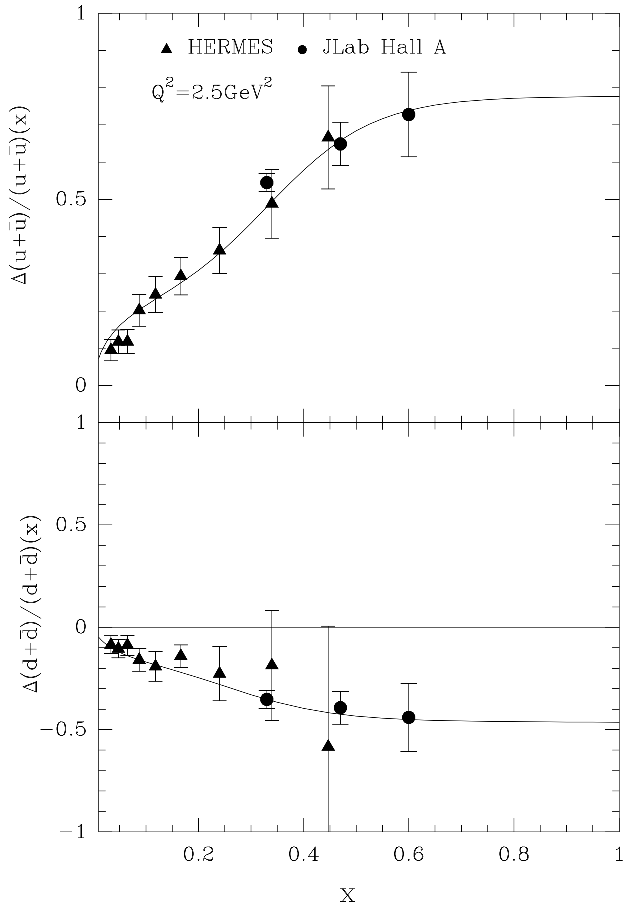
Δq and $\Delta \bar{q}$ flavor separation from SIDIS $eN \to ehX$



Flavor separation at high x from JLab

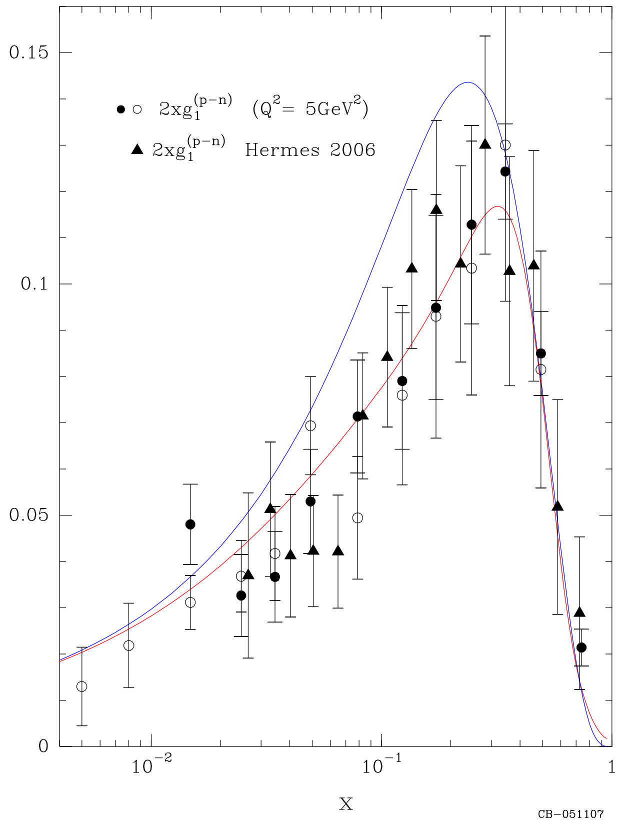


Before data correction



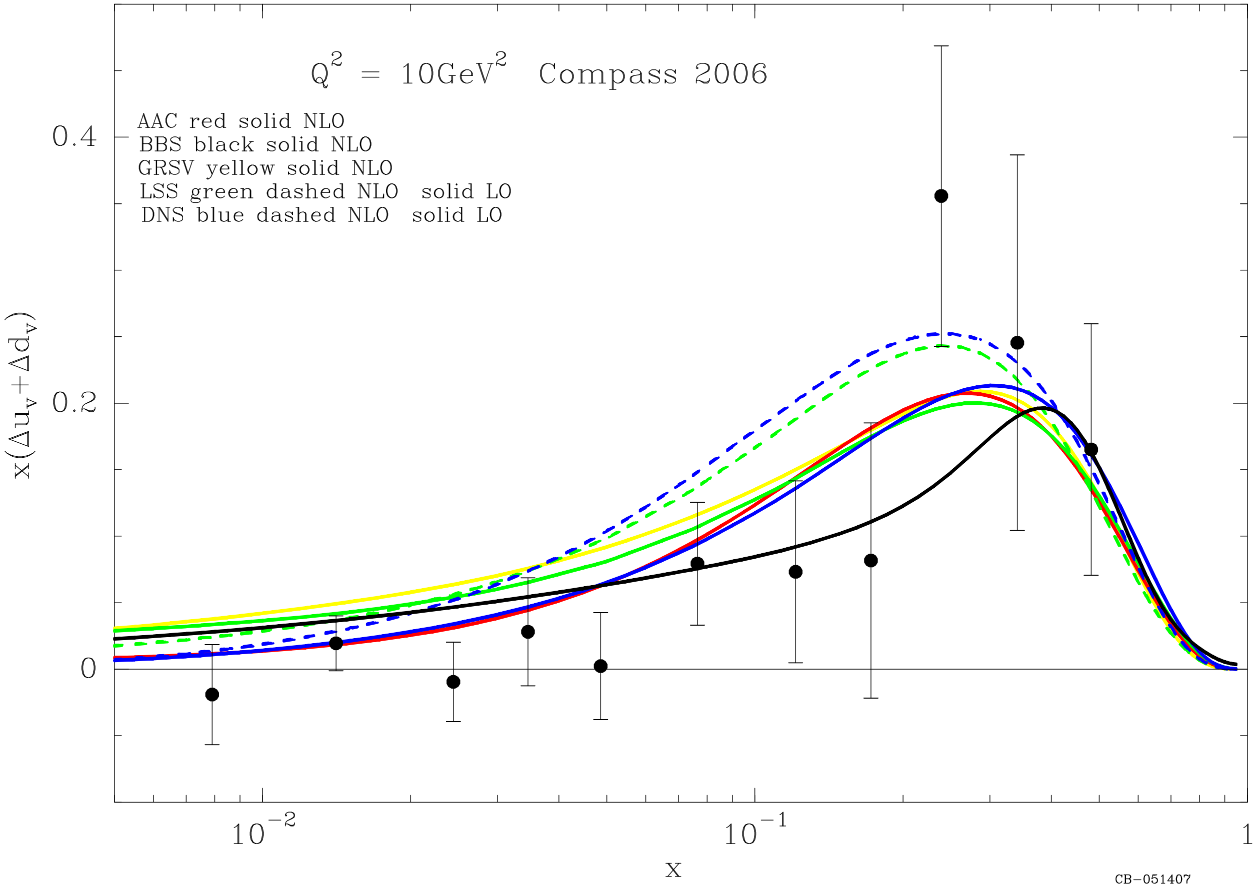
After data correction

Very recent tests from DIS (COMPASS)



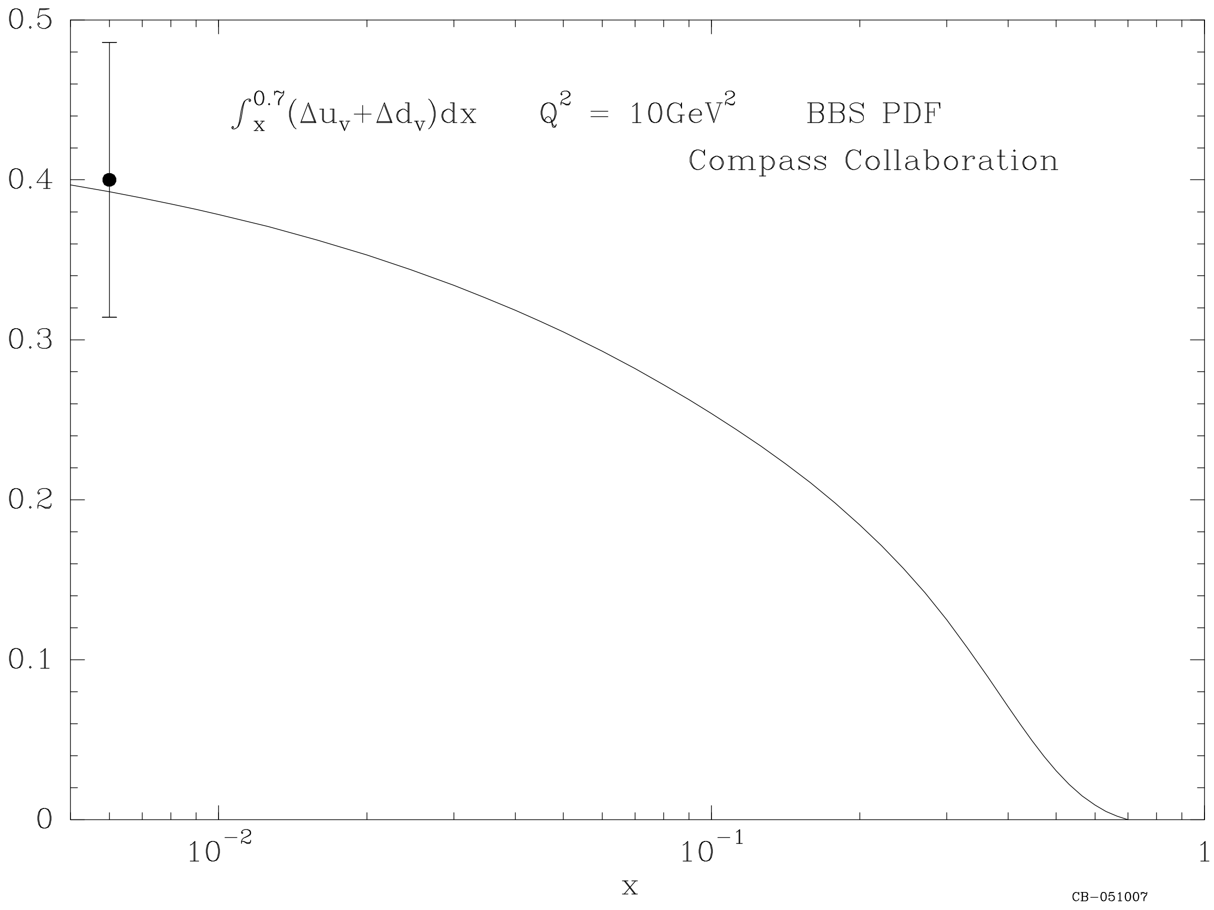
Non-Singlet part of $g_1^p - g_1^n$: red BBS $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$ and blue AAC $\Delta\bar{u} = \Delta\bar{d}$

Very recent tests from DIS (COMPASS)



Comparison of various parametrizations with the data

Very recent tests from DIS (COMPASS)



A flavor symmetric $\Delta\bar{q}$ leads to a much higher value ~ 0.6

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

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

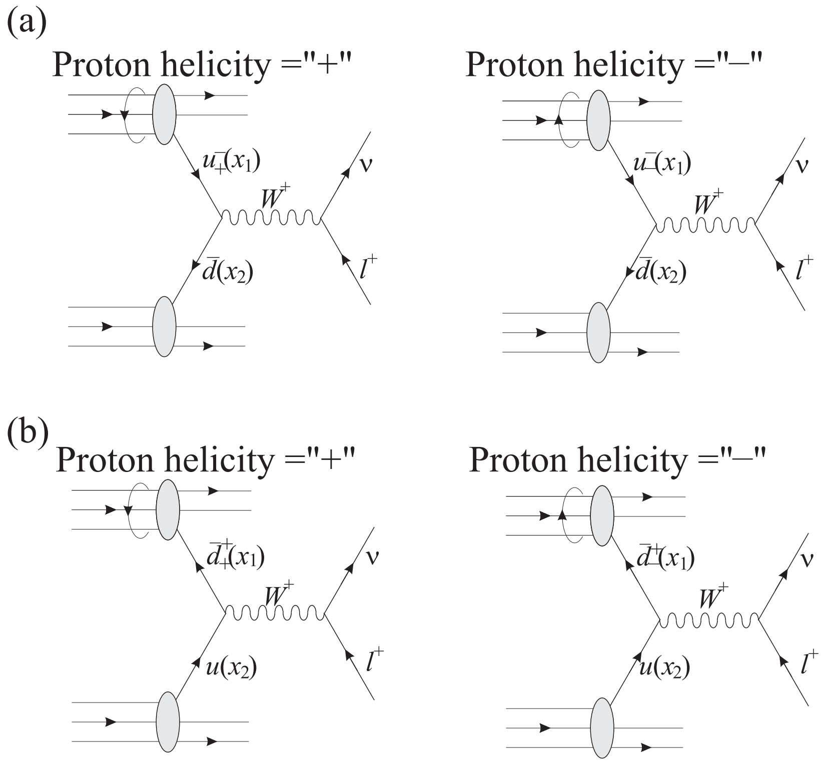
$$A_L^{PV}(y) = \frac{\Delta d\sigma/dy}{d\sigma/dy} = \frac{d\sigma_-^W/dy - d\sigma_+^W/dy}{d\sigma_-^W/dy + d\sigma_+^W/dy},$$

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 $\tau = M_W^2/s$.

W^+ production in polarized pp collisions



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

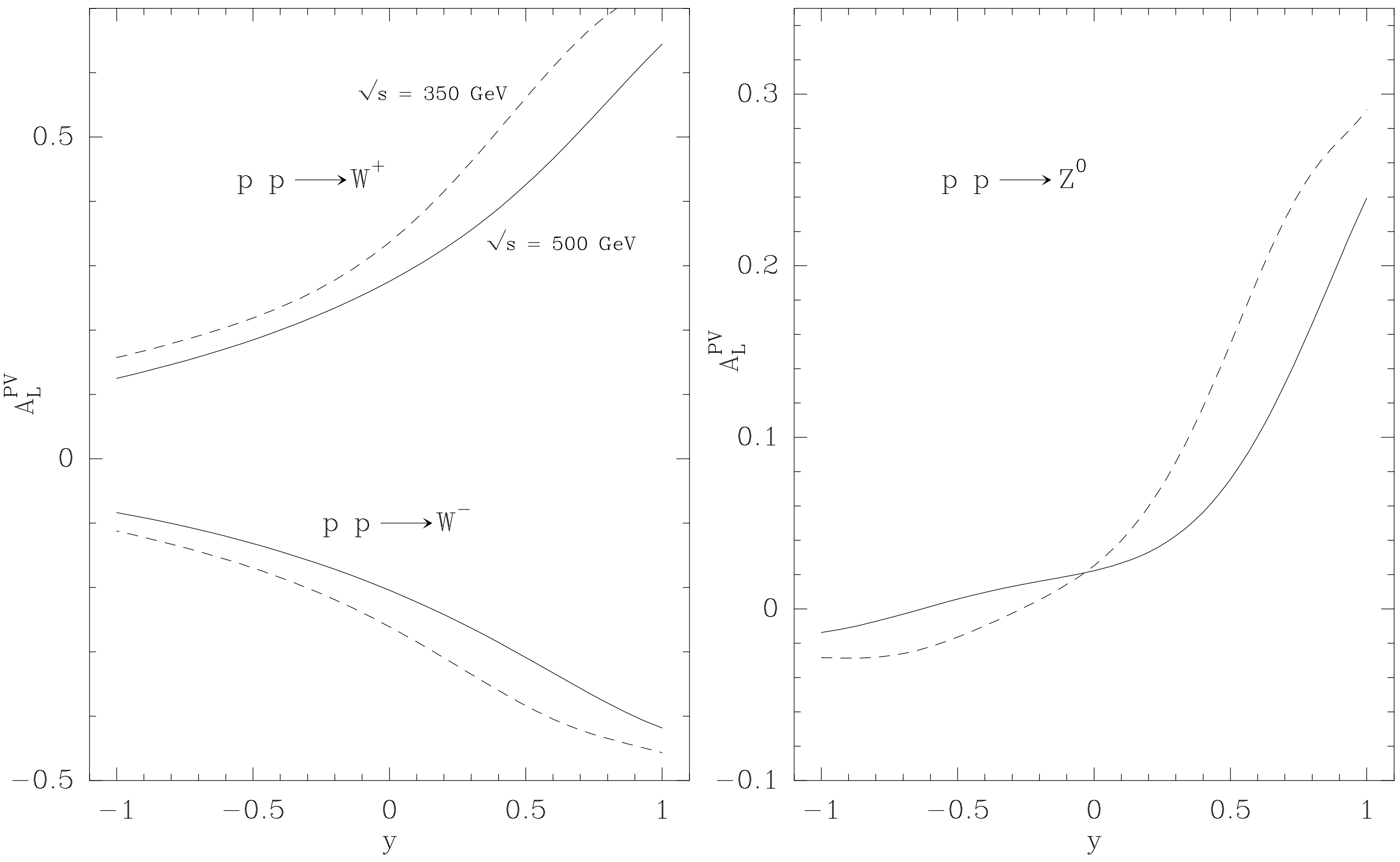
Polarized quarks flavor separation

For W^- production one interchanges u and d. 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 $x = 0.059$.

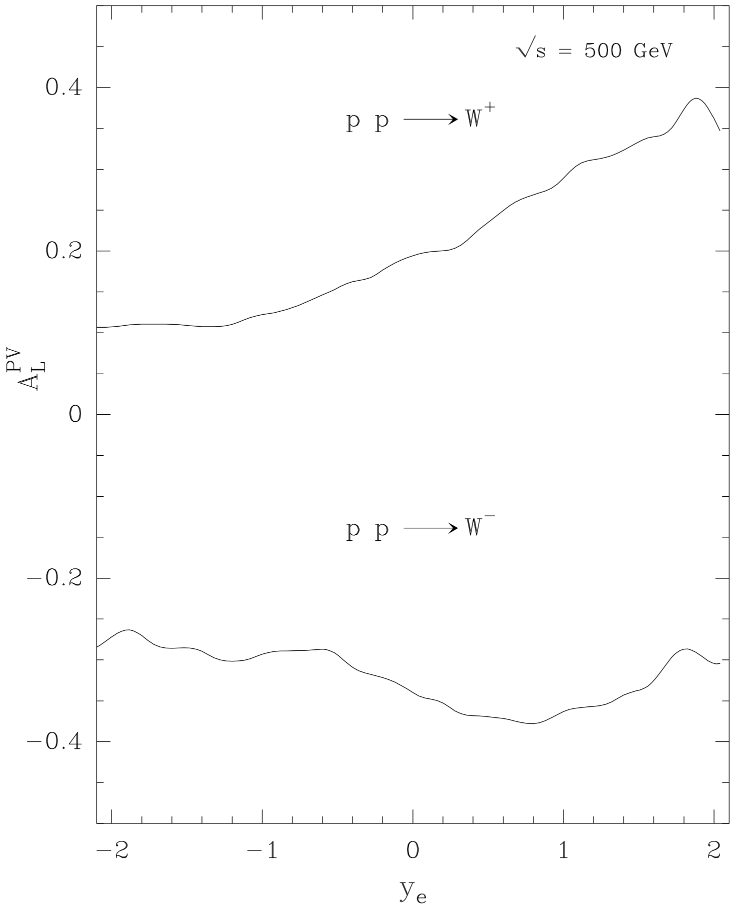
Since one selects the leptonic decay $W \rightarrow e\nu$, one measures

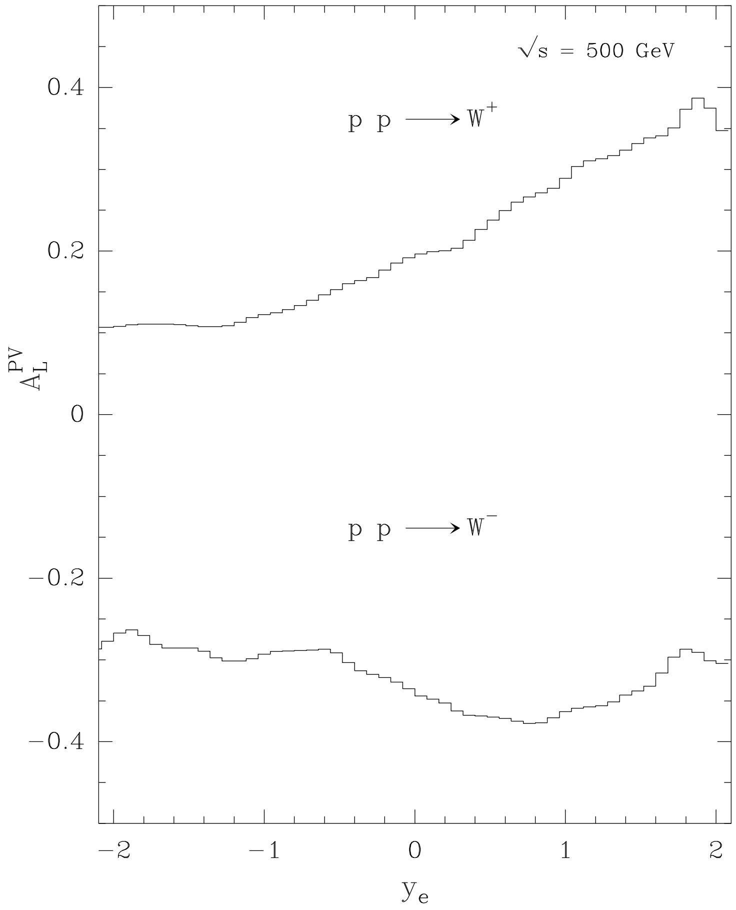
$$A_L^{PV}(y_e) = \frac{\Delta d\sigma/dy_e}{d\sigma/dy_e} = \frac{d\sigma_-^W/dy_e - d\sigma_+^W/dy_e}{d\sigma_-^W/dy_e + d\sigma_+^W/dy_e} ,$$

Parity-violating asymmetries

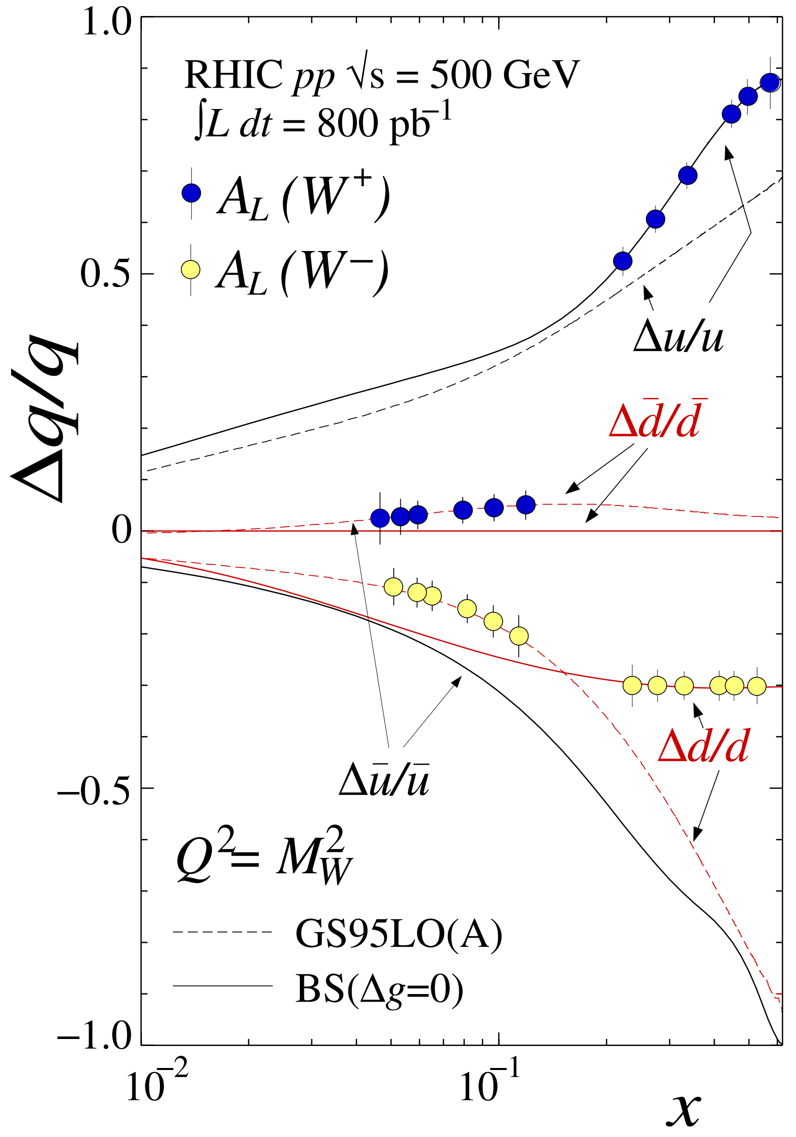


Parity-violating asymmetries(using RhicBos, thanks to P. Nadolski)





Expected sensitivity for the polarized PDF



Nucleon spin 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 $\Delta\Sigma \sim 0.2$ and ΔG badly known.
- $L_{q,g}$ might be relevant contributions?

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

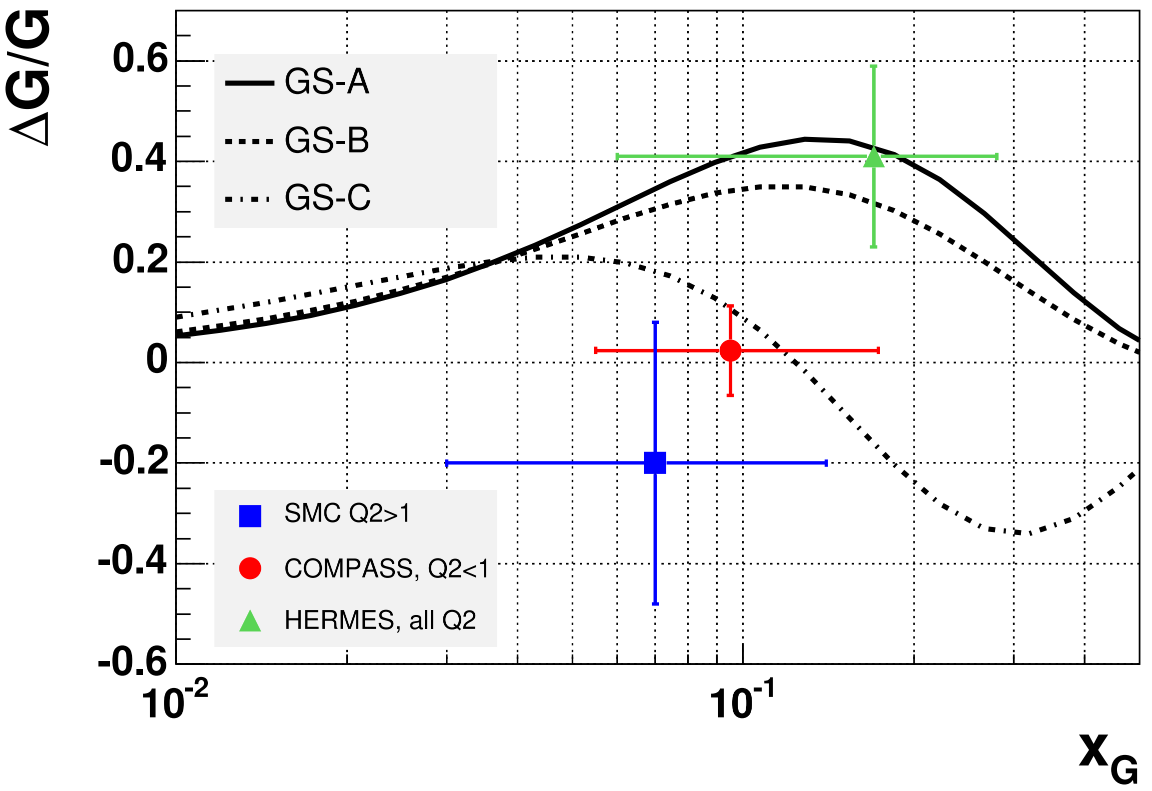
- From polarized DIS only, the Q^2 evolution does NOT allow the determination of $\Delta g(x)$, because of lack of accuracy and limited Q^2 range.
- From DIS with high-p_T hadron pairs in the final state, one has at $x = 0.095$ and $Q^2 < 1$GeV^2 ($\gamma^* g \rightarrow q\bar{q}$)

$$\Delta g(x)/g(x) = 0.024 \pm 0.089(stat) \pm 0.057(syst)$$

- Hermes has a positive result 0.40 ± 0.20

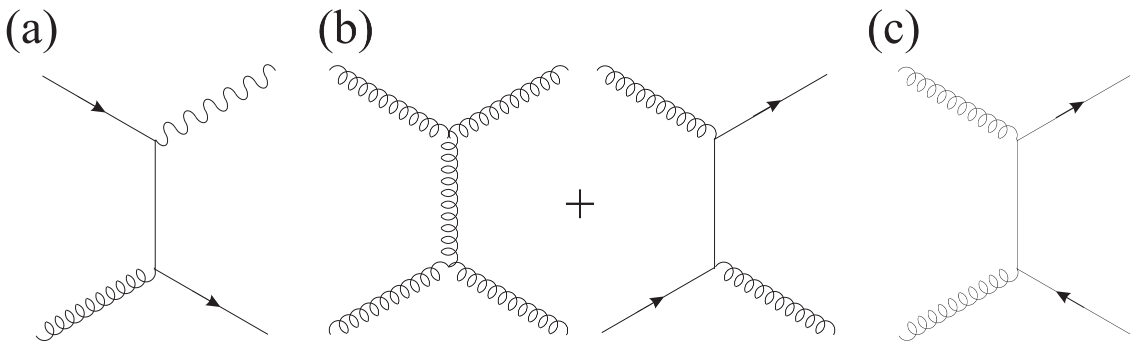
It is crucial to measure it at RHIC

Present knowledge of Gluon Polarization (PLB 633, 25, 2006)



Lowest-order diagrams with initial gluons

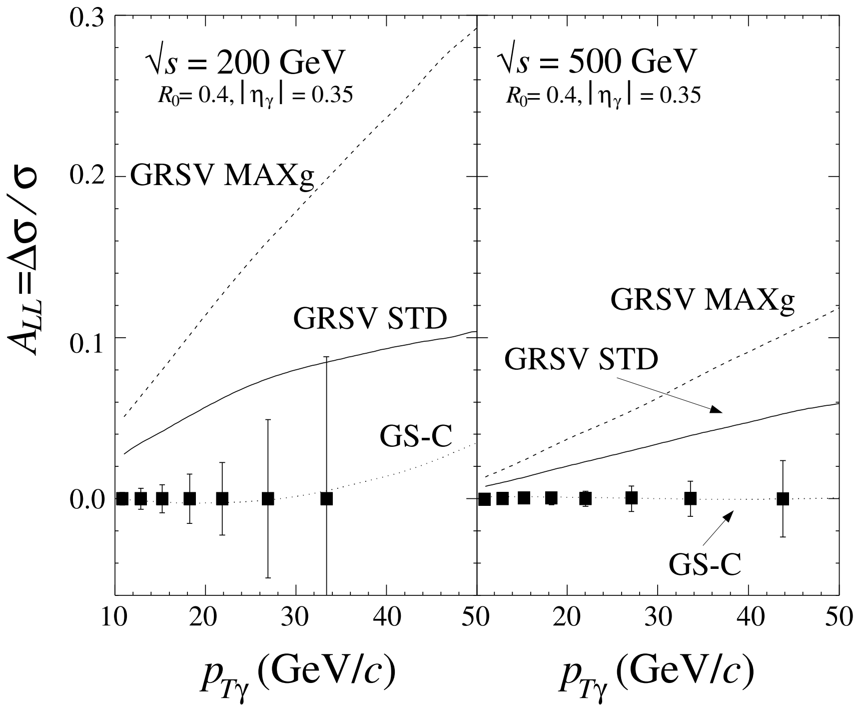
How to check this first "‘indication"’ that Δg is small?



- High-p_T photon production (a)
- Jets production (b)
- Heavy-flavor production (c)

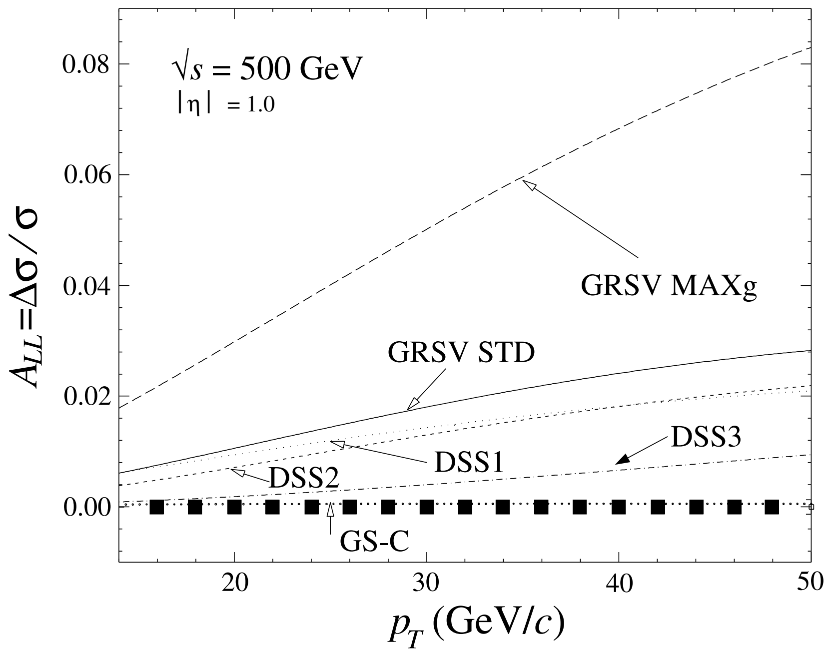
Prompt photon production at RHIC

$$A_{LL} \approx \frac{\Delta g(x_1)}{g(x_1)} \cdot \left[\frac{\sum_q e_q^2 \left[\Delta q(x_2) + \Delta \bar{q}(x_2)\right]}{\sum_q e_q^2 \left[q(x_2) + \bar{q}(x_2)\right]} \right] \cdot \hat{a}_{LL}(gq \to \gamma q) + (1 \leftrightarrow 2)$$

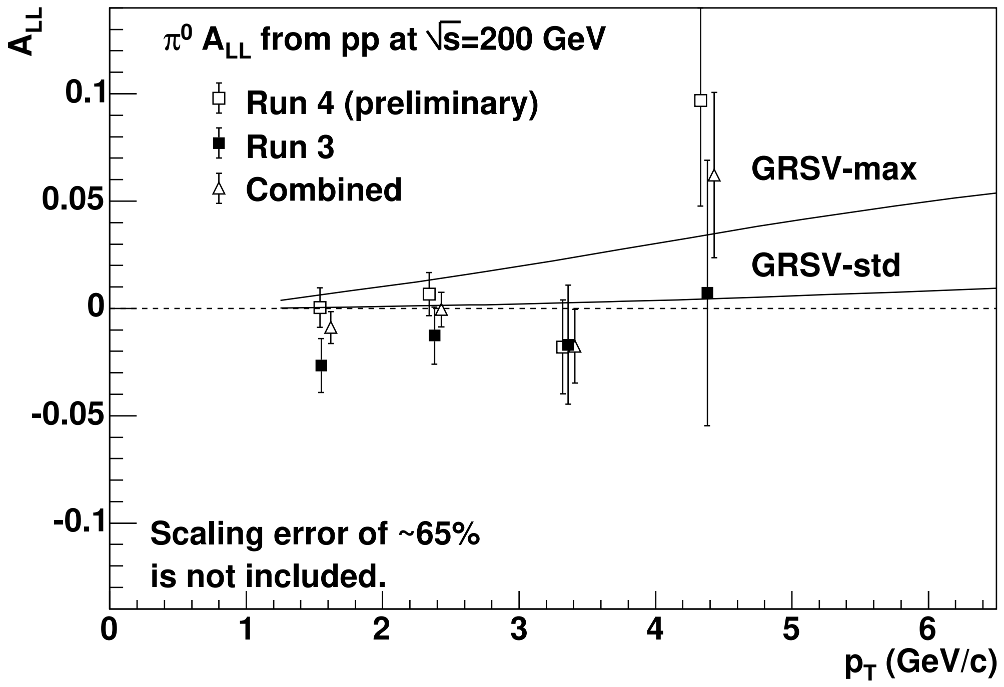


Jet production at RHIC

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



Data on π^0 production at RHIC at low p_T



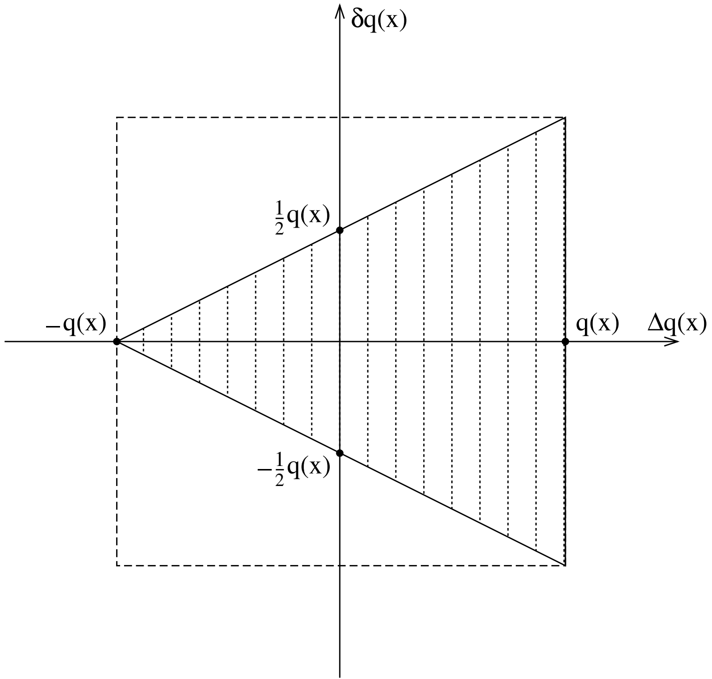
Quark Transversity Distribution $\delta q(x, Q^2)$

It was first mentioned by Ralston and Soper in 1979, in $pp \to \mu^+\mu^-$ 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

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

This new distribution function $\delta q(x, Q^2)$ is chiral odd, leading twist and decouples from DIS, was never measured. Only a positivity bound (J.S., PRL 74,1292,1995) survives up to NLO corrections

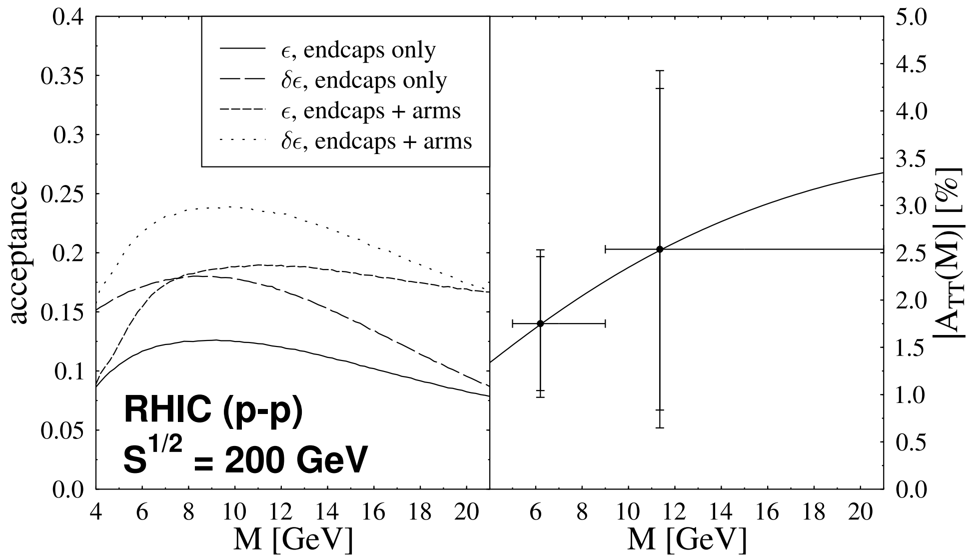
$$q(x, Q^2) + \Delta q(x, Q^2) \geq 2|\delta q(x, Q^2)|$$



A_{TT} in Drell-Yan dimuon production

It can be measured by the double transverse spin asymmetry in Drell-Yan dimuon production

$$A_{TT} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)} = \hat{a}_{TT} \frac{\sum_q e_q^2 \delta q(x_1, M^2)\delta\bar{q}(x_2, M^2) + (1 \leftrightarrow 2)}{\sum_q e_q^2 q(x_1, M^2)\bar{q}(x_2, M^2) + (1 \leftrightarrow 2)}.$$



A_{TT} for Z production

$$A_{TT}(Z) = \frac{\sum_q (b_q^2 - a_q^2)\delta q(x_1, M^2)\delta\bar{q}(x_2, M^2) + (1 \leftrightarrow 2)}{\sum_q (b_q^2 + a_q^2) q(x_1, M^2)\bar{q}(x_2, M^2) + (1 \leftrightarrow 2)}$$

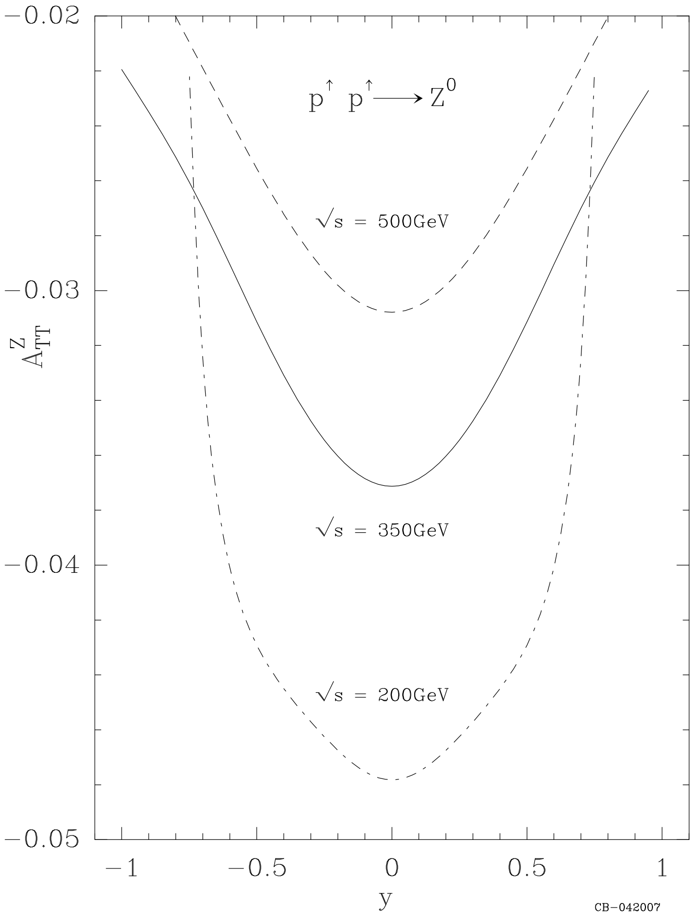
For W production, since W coupling is V-A i.e. $a_q = b_q$

we expect $A_{TT} = 0$ Must check this

However single spin asymmetry $A_N(W^{\pm})$ allows the flavor separation of Sivers functions for u ,$\bar{u}$, d and $\bar{d}$.

(I. Schmidt and J.S. Phys. Lett. B 563, 179 (2003))

A_{TT} for Z production



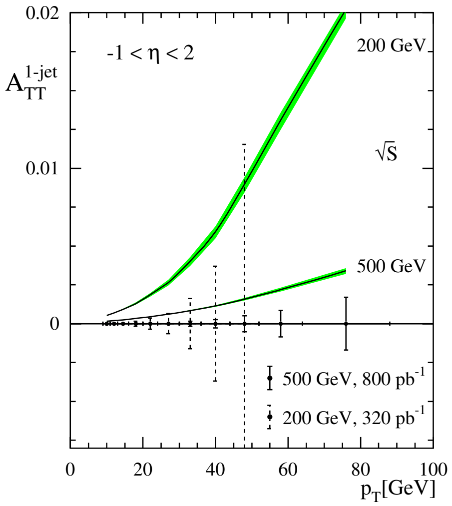
Assume $\delta\bar{u} < 0$ and $\delta\bar{d} > 0$

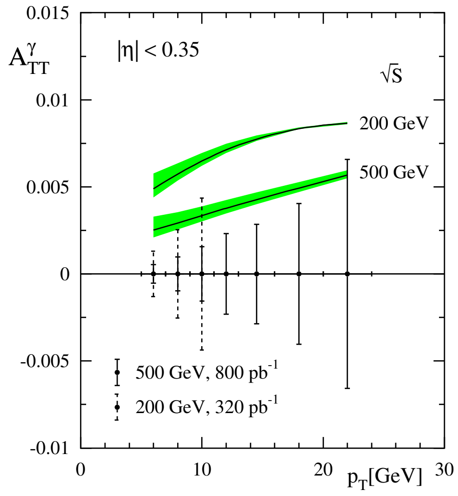
Upper bounds on A_{TT} in Jet and prompt photon productions

Sensitivity to δq only in the high p_T region, dominated by $qq \to qq$, because no transversity for the gluons. Use positivity bound. Expect $|A_{TT}| << |A_{LL}|$

It is important to verify this theoretical expectation

(J.S., M.Stratmann and W.Vogelsang, Phys. Rev. D65, 114024 (2002))





Single spin asymmetries A_N

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 $\overrightarrow{s_T} \cdot (\overrightarrow{p} \times \overrightarrow{k_T})$
It can be shown that this requires the existence of an helicity flip and final state interactions, which generate a phase difference between the flip and the non-flip amplitudes, to avoid violation of time reversal invariance.
In the naive parton model one expects very small SSA, because of the double suppression $\alpha_s m_q/Q$.
Actually a large SSA has been discovered 30 years ago (We should celebrate!!!) at FNAL with a 300 GeV proton beam in $pBe \to \overrightarrow{\Lambda} X$ (G.Bunce et al., PRL 36, 1113 (1976)) and many more SSA have been observed later. In particular large SSA in $p^{\uparrow} p \to \pi X$ and $\bar{p}^{\uparrow} p \to \pi X$ observed at FNAL by E704 in 1990 (see below).

What positivity can bring into this game?

Recently, new general positivity bounds were derived (J.S.,PRL 91,092005,2003), among the spin observables in a single particle inclusive reaction, where the two initial particles carry a spin-1/2,

$$A(1/2) + B(1/2) \to C + X.$$

In particular for $y = 0$ one has

$$1 + A_{TT} \geq 2|A_N|$$

for any value of $\sqrt{s}$ and p_T. From the previous results $A_{TT} \sim 0$ for $pp \to \gamma X$ and $pp \to jetX$, we get a strong bound e.g. $|A_N| \leq 1/2$.

Single spin asymmetries in QCD

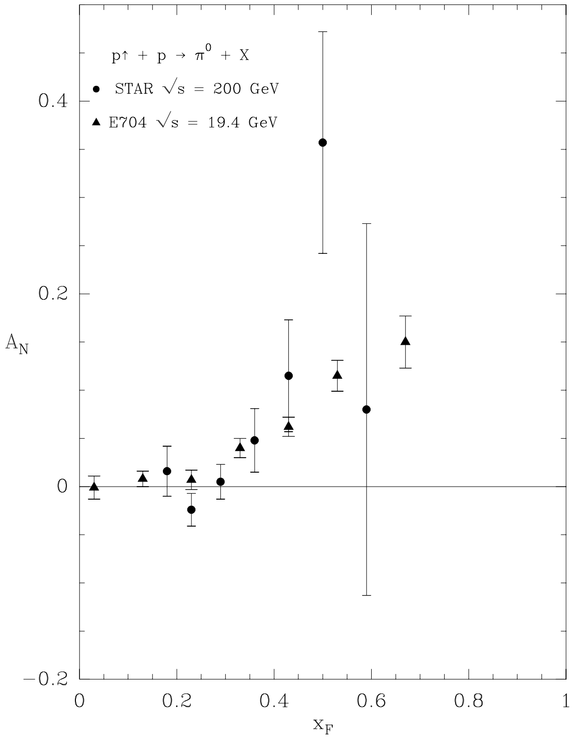
Two QCD mechanisms

- 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)

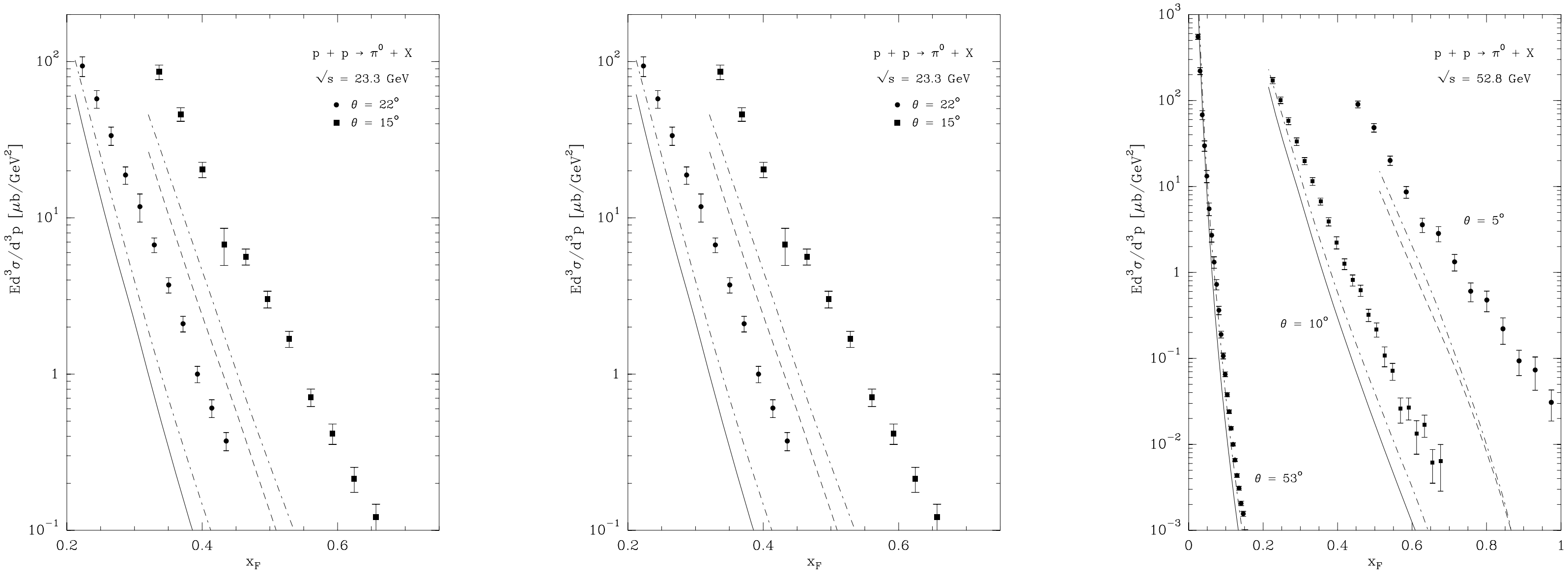
The gauge-invariance properties of the TMD PDF have been first clarified (S. Brodsky, D.S. Hwang, I. Schmidt, Phys. Lett.B 530,99 (2002)) for DIS and Drell-Yan processes. In general both Sivers and Collins effects contribute to a specific reaction, although there are some cases in which only one of them contributes. For example in SIDIS, the Collins effect is the only mechanism that can lead to asymmetries A_{UT} and A_{UL}. On the other hand, it does not appear in some electroweak interaction processes, where there is only the Sivers effect. In direct photon production in pp collisions, which is dominated by $qg \rightarrow q\gamma$, the SSA is sensitive to both the quark and the gluon Sivers functions, according to x_F of the photon. (I. Schmidt, J. S. and J. J. Yang, Phys. Lett.B 612, 258 (2005)).

An interesting case: A_N in π^0 production

Do we understand this asymmetry, given the fact that STAR is at very small angle 2.6° and E704 at 9°to 64°?



An interesting case: A_N in π^0 production

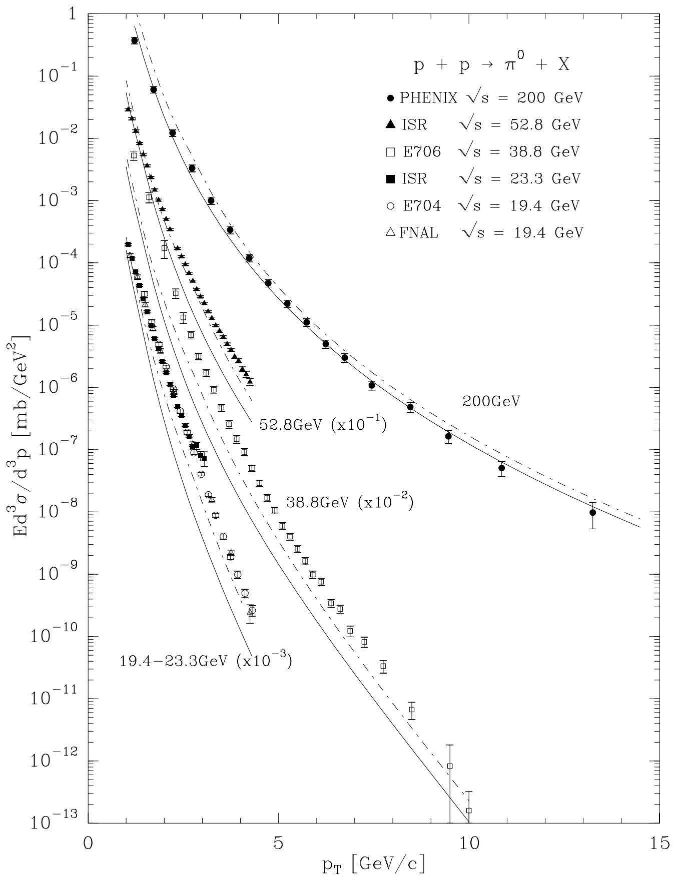


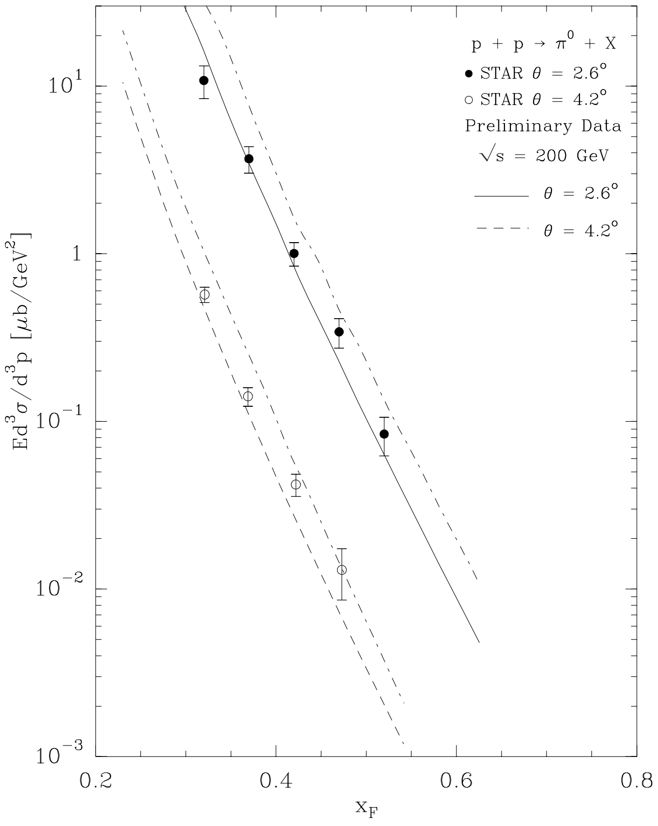
The pQCD calculation underestimates the cross section at low energies and small angles. This is not the case at 90° and at small angles at high energy, which is the STAR kinematic range.

Don’t try to "explain" the asymmetry, ignoring the unpolarized cross section (C. Bourrely and J. S., EPJC 36,371 (2004))

Need also to consider resummation effects (see W. Vogelsang et al.)

An interesting case: A_N in π^0 production





Conclusions

- 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
- All this will provide a detailed understanding of the nucleon spin structure
- May be some surprises are round the corner!

KEEP GOING ALL THIS GOOD WORK