Lecture 3: Partonic Structure of the Nucleon

Nucleon Structure: A Hard Problem

- The nucleon is an excitation of 3 quarks in the **QCD vacuum**. Understanding the vacuum structure and its properties, such as color confinement, is essential.
- Light quarks (up and down) are nearly massless, responsible for a small fraction of nucleon mass. **Chiral symmetry** and its spontaneous breaking is essential to understand many of its properties.
- Understanding the role of **the gluons** is a key. The gluons excited from the presence of the valence quarks generate many of the fundamental properties of the nucleon, including spin and mass.

Solving the nucleon structure is at least as difficult as solving ^{208}Pb !!!

How to make progress?

- **Make the most realistic lattice QCD calculation possible with best available algorithms, the limited computation resource, and the graduate students one can support**
  - convince the funding agency that lattice QCD is about to make an important impact (or already has).
- **Find ideas connecting data, the fundamental theory, and "intuition"**
  - Wave function is not the right language.

Some Good Theoretical Ideas

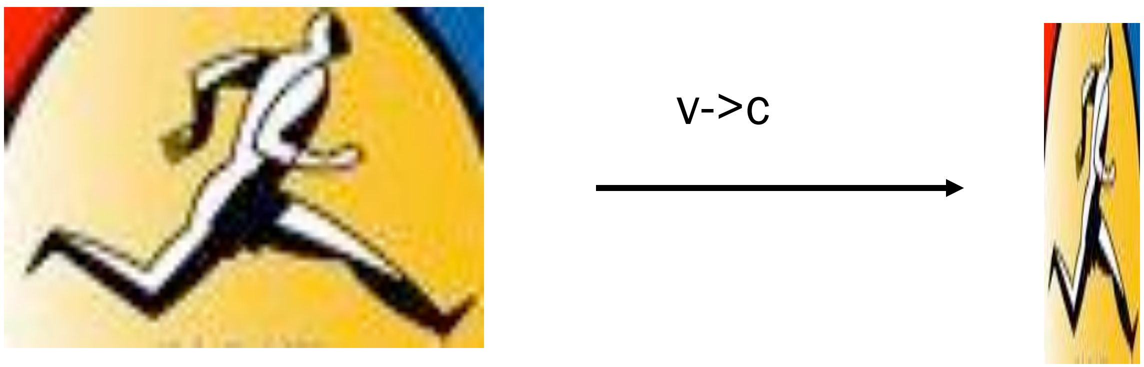
- **Strange quarks can be directly probed!** (Kaplan & Manohar,…)
- **Pion cloud physics can be studied in a systematic expansion** (Weinberg, Gasser & Leutwyler, Bernard, Meissner, Holstein, …)
- **$N_c = 3$ is a large number!** ('t Hooft, Witten, Dashen, Jenkins, Manohar, Goity, Lebed, …)
- **Generalized parton distributions** (Ji, Radyushkin, Muller, Burkardt, Diehl, Vanderhargen, …)

The list continues

- **Transverse momentum dependent parton distributions** (Sivers, Collins, Mulders, Brodsky, Ji,…)
- **Hard exclusive processes can be factorized & soft and collinear effective field theory** (Brodsky, Lepage, Radyushkin, Bauer, Fleming, Steward,…)
- **Two-photon exchange can be important in elastic electron-nucleon scattering** (Carlson, Vanderhaegen, …)
- …

Nucleons in terms of partons

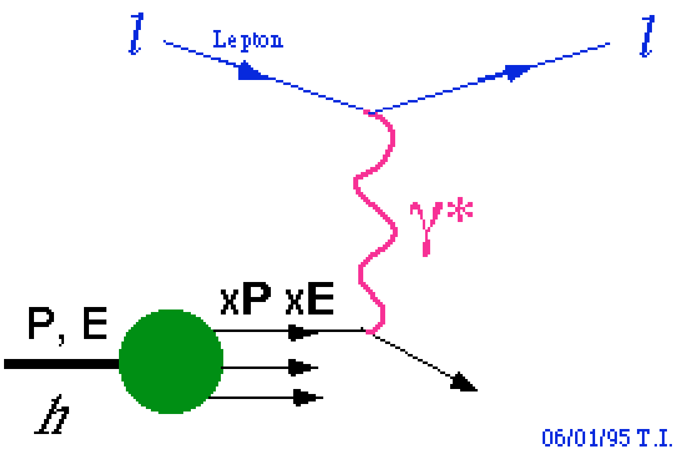
- **The Set-up: the nucleon moving at the speed of light (infinite momentum frame, IFM)**

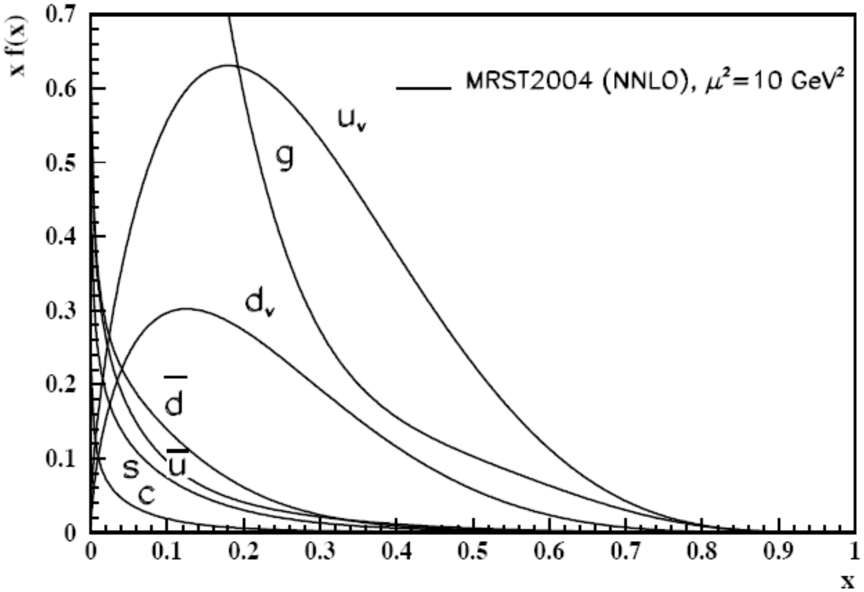


  - The spatial profile collapses into 2D
  - The interactions between the underlying constituents are time-dilated and appears to be free: partons!

Feynman parton distributions

- Parton's longitudinal momentum k^z can be described by the momentum fraction $x = k^z/P^z$
- Parton distributions in x can be measured in deep-inelastic scattering & other hard processes





The nucleon mass

- **The overall scale set by Λ_{QCD}**

$$M_{\text{planck}} \exp(-8\pi^2 / g^2 \beta_0)$$

A perfectly natural mass scale! (F. Wilczek)

- **However, gluons are massless and light quarks have small masses**
  1. **Einstein: energy generates mass!**

     $M = E/c^2$

- **Quark and gluon energy generates the mass**

The QCD energy

- **One can calculate the proton mass through the expectation value of the QCD hamiltonian,**

$$H_{\rm QCD} = H_q + H_m + H_g + H_a .$$

$$H_q = \int d^3\vec{x}\ \bar{\psi}(-i\mathbf{D}\cdot\alpha)\psi,$$ Quark energy

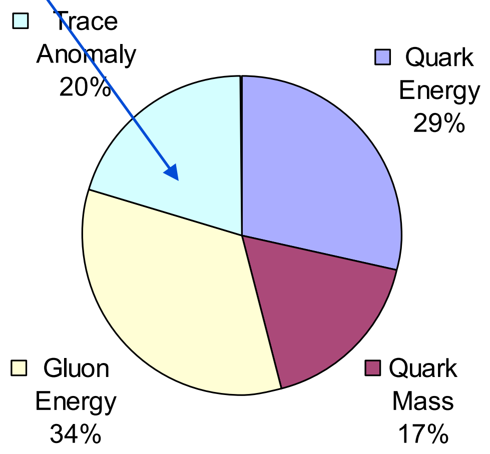
$$H_m = \int d^3\vec{x}\ \bar{\psi}m\psi,$$ Quark mass

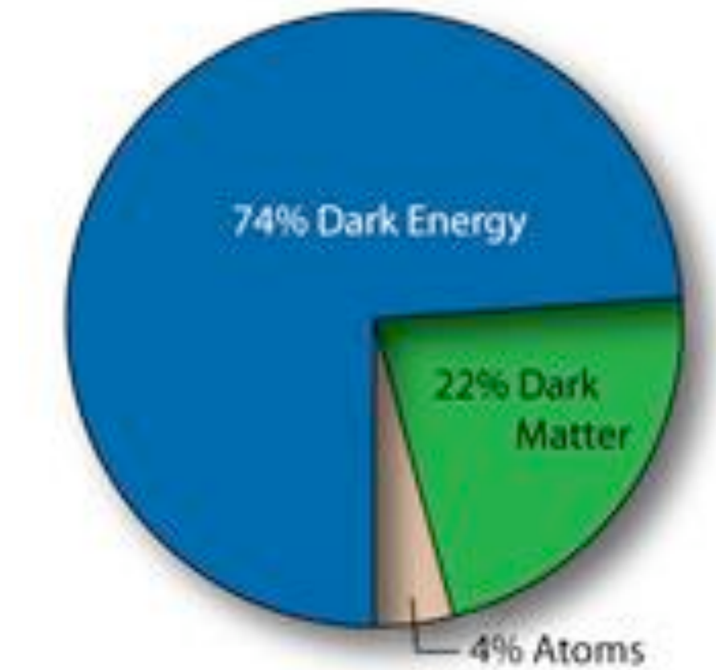
$$H_g = \int d^3\vec{x}\ \frac{1}{2}(\mathbf{E}^2+\mathbf{B}^2),$$ Gluon energy

$$H_a = \int d^3\vec{x}\ \frac{9\alpha_s}{16\pi}(\mathbf{E}^2-\mathbf{B}^2).$$ Trace anomaly or vacuum energy

The proton mass budget

Vacuum energy

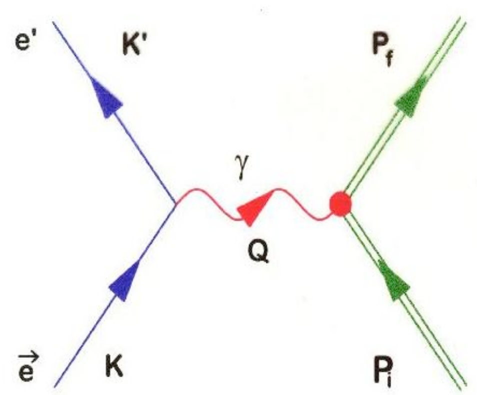




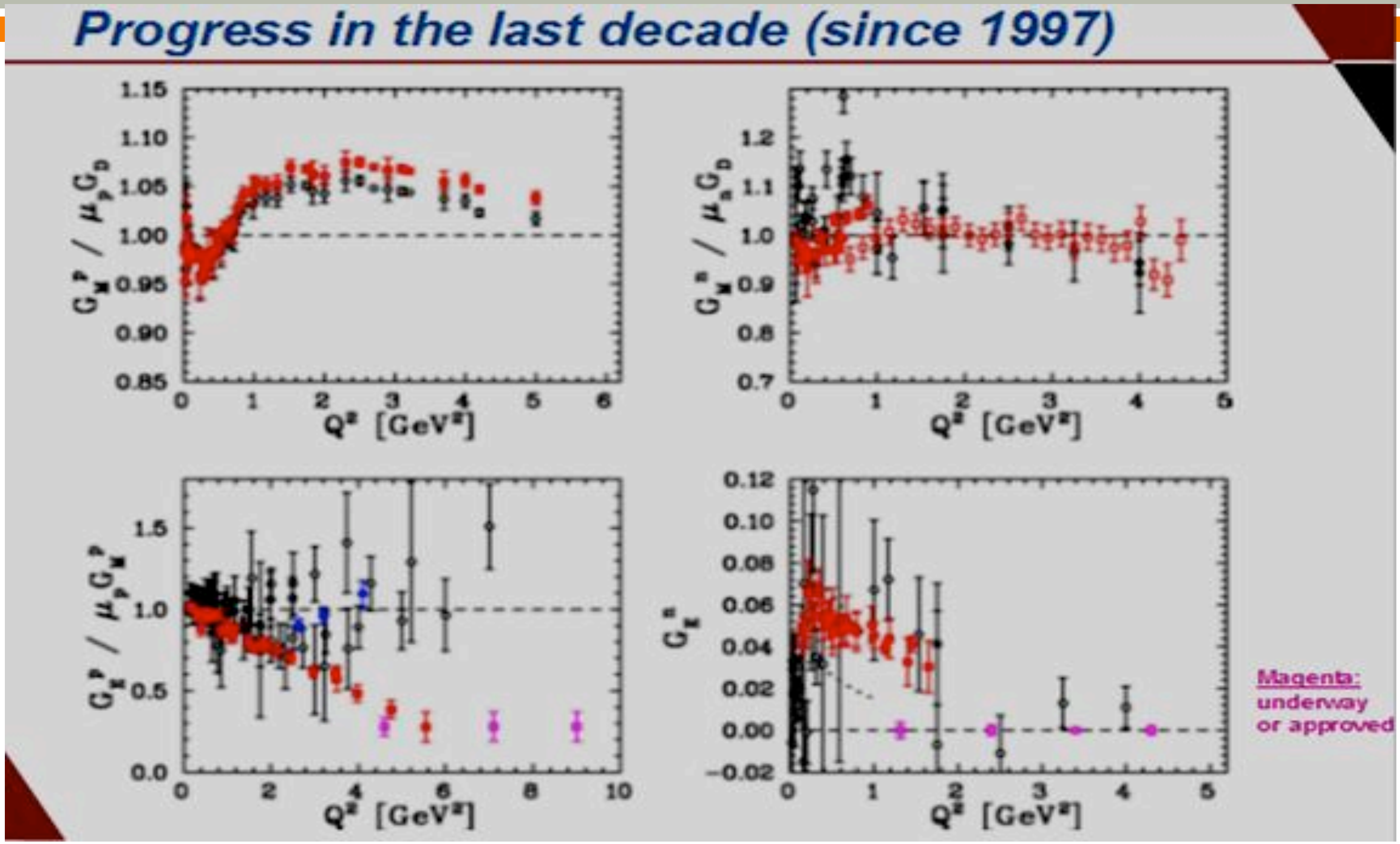
X. Ji, PRL, Phys.Rev.Lett.74:1071-1074,1995

Parton distribution in the transverse plane

- **Partons can be localized in the transverse plane (D. Soper, 1972)**
- **Parton densities in the transverse plane are related to the Fourier transformation of the Dirac form factor F_1 measured in elastic scattering (Burkardt, 2002)**



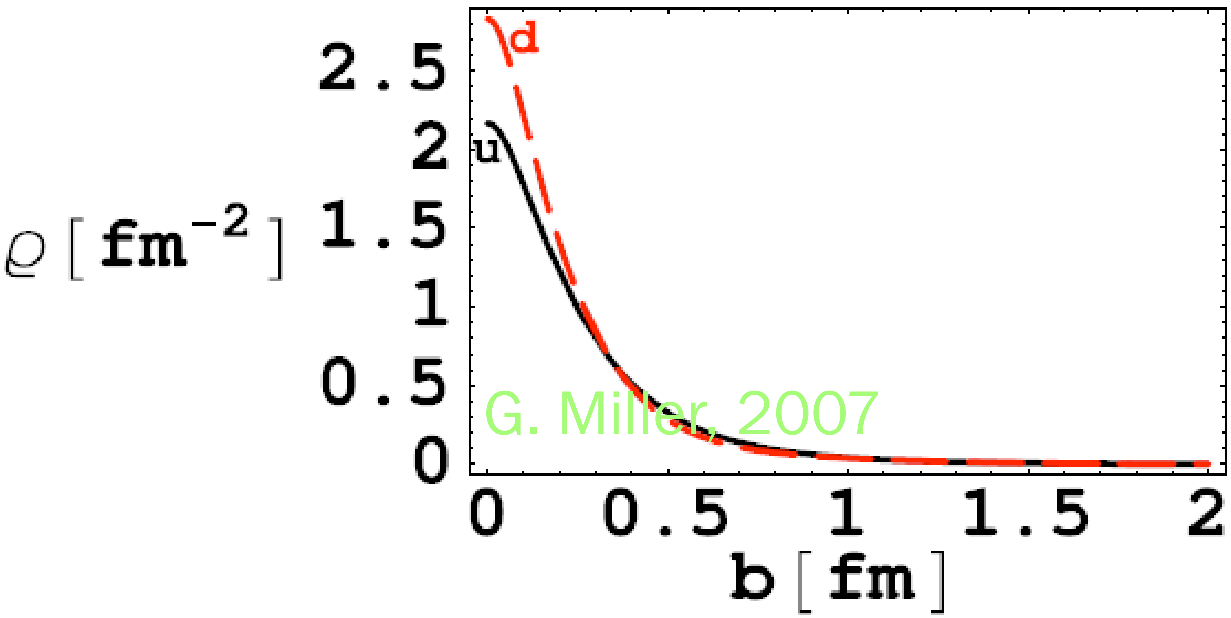
Measurement in form factors



proton

neutron

Partons in transverse plane

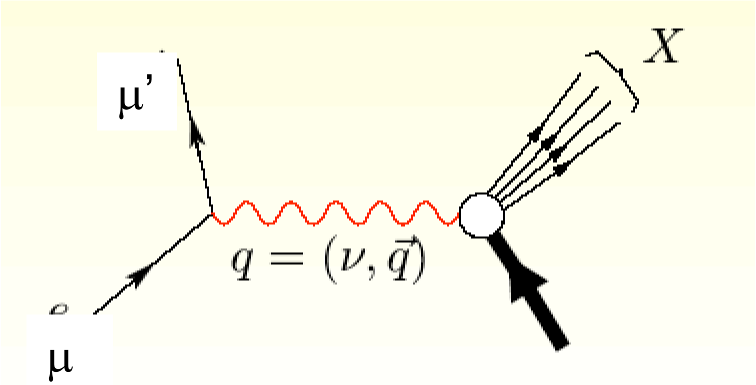


Generalized parton distribution

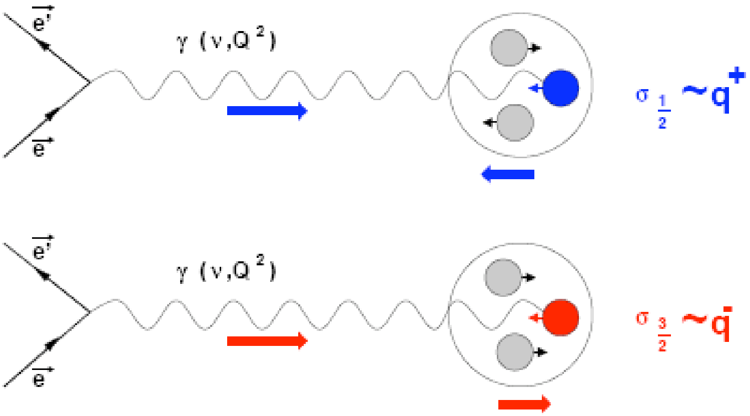
- **In its simplest incarnation, it is a distribution of partons joint in longitudinal momentum x and transverse coordinate b!**
  - Give a more detailed description of partons than Feynman distributions and form factors alone.
- **A key to understand the spin structure of the proton.**
  - The spin of the proton in the simple quark model comes entirely from spin of the un-paired quark.
  - The EMC experiment shows that the actual situation is much more complicated.

EMC exp at CERN (1988)

- Polarized muon + proton deep-inelastic scattering



- It measures the spin density of the quarks

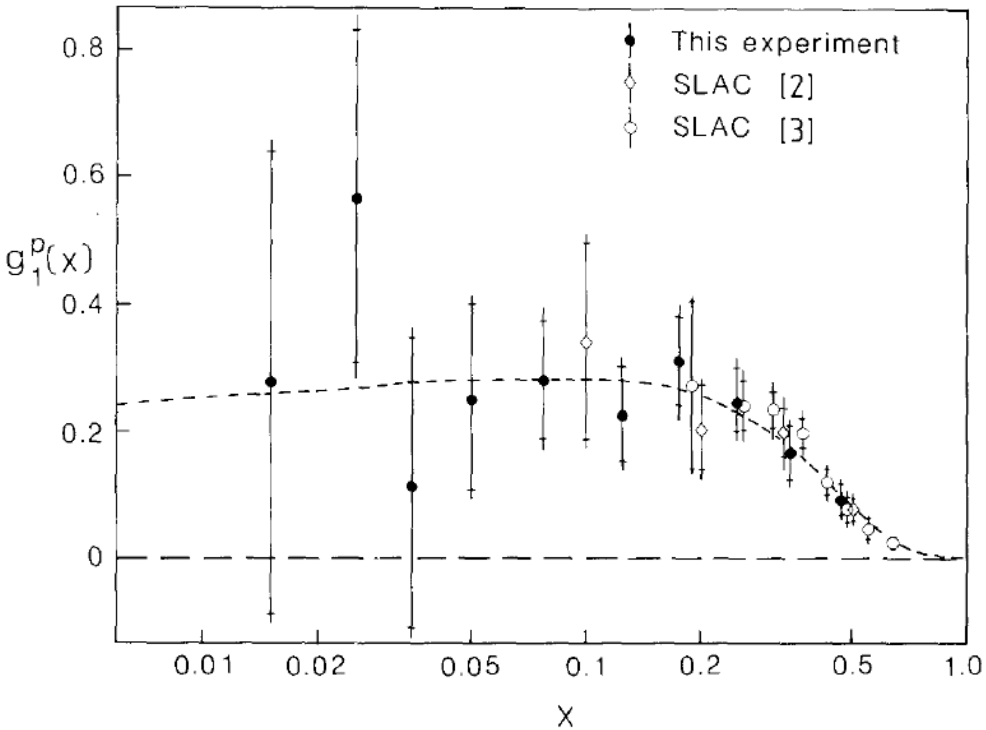


$g(x) \sim \sum e^2(q_+(x)-q_-(x))$

$\Delta q(x)$

The result

Phys.Lett.B206:364,1988



$$\langle S_z \rangle_{\text{quarks}} = \tfrac{1}{2}(\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s})$$

$$= \tfrac{1}{2}\sqrt{\tfrac{3}{2}}\, a_0 = +0.060 \pm 0.047 \pm 0.069 \,.$$

No. of citations: 1500 !

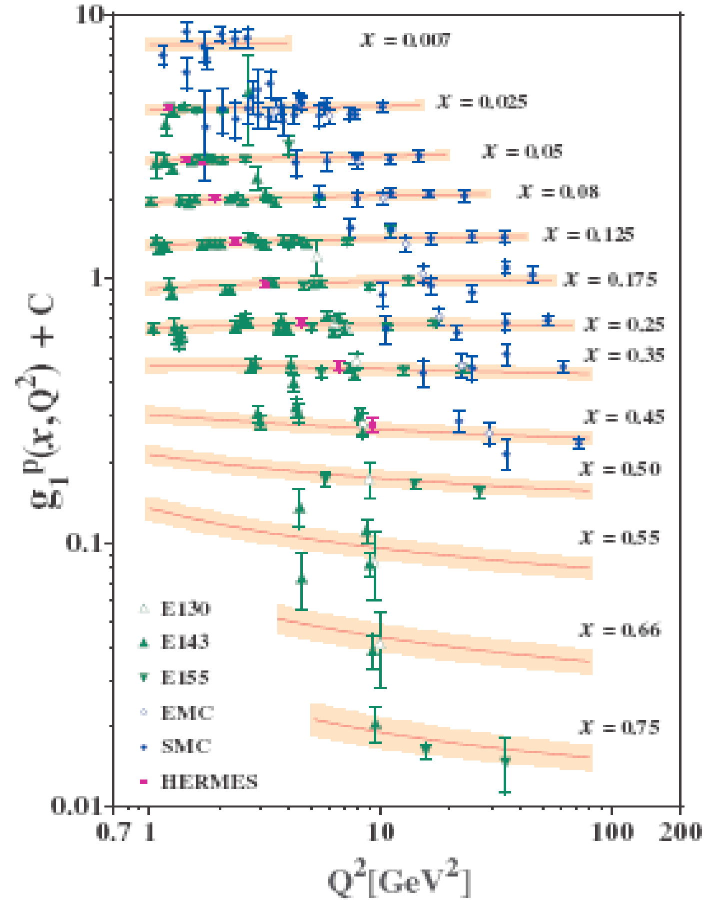
Something wrong with the exp?

- **Impressive follow-ups**
  - SLAC Exp: E142,E143,E155,E156
  - SMC
  - HERMES
  - COMPASS
- **The EMC result is correct!**

  Global fits of data with NLO QCD formalism yield

  $\langle S_z \rangle_{quarks} = 0.25 \pm 0.10$

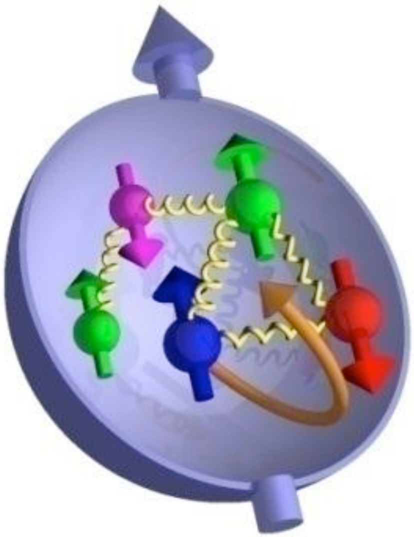
  At Q = 1 GeV



Spin of the proton in QCD

- The spin of the proton must be generated from the angular momentum of the internal quarks and gluons!
- The quarks have both spin **S** and orbital angular momentum (OAM) **L**, giving a total **Jq**
- The gluons must also carry angular momentum **Jg**

$$J = 1/2 = J_q(\mu) + J_g(\mu)$$



Quark OAM

- **The quark orbital motion, rxp, is suspected to be significant in proton**
  - Quarks are essentially massless, and therefore are ultra relativistic. For relativistic particles in a bound state, Dirac equation yields a substantial lower component wave function, which is a p-wave
  - Large anomalous magnetic moment of the proton also point to the large orbital motion.
  - ....
- **But how to measure it ?**

We must know some information about momentum and position simultaneously !

Wigner distribution

- For 1-D quantum system, it is defined as

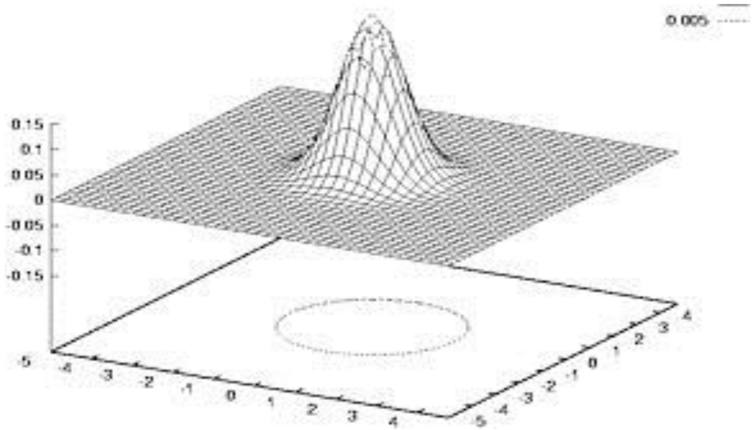
$$W(x,p) = \int \psi^*(x-\eta/2)\psi(x+\eta/2)e^{ip\eta}d\eta \ ,$$

  - When integrated over x (p), one gets the momentum (probability) density.
  - Not positive definite in general (not strict density), but is in classical limit!
  - Any dynamical variable can be calculated as

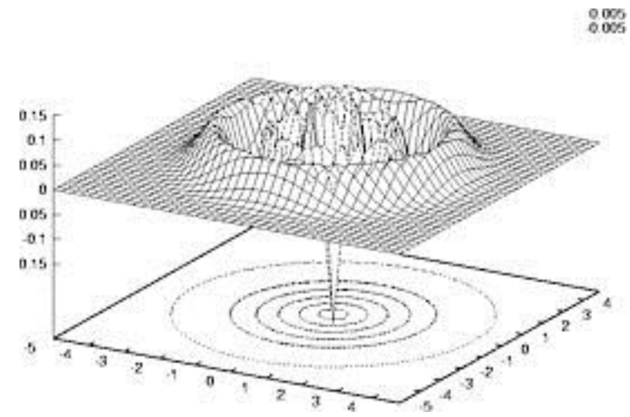
$$\langle O(x,p)\rangle = \int dxdp\, O(x,p)W(x,p)$$

Harmonic oscillator & squeezed light

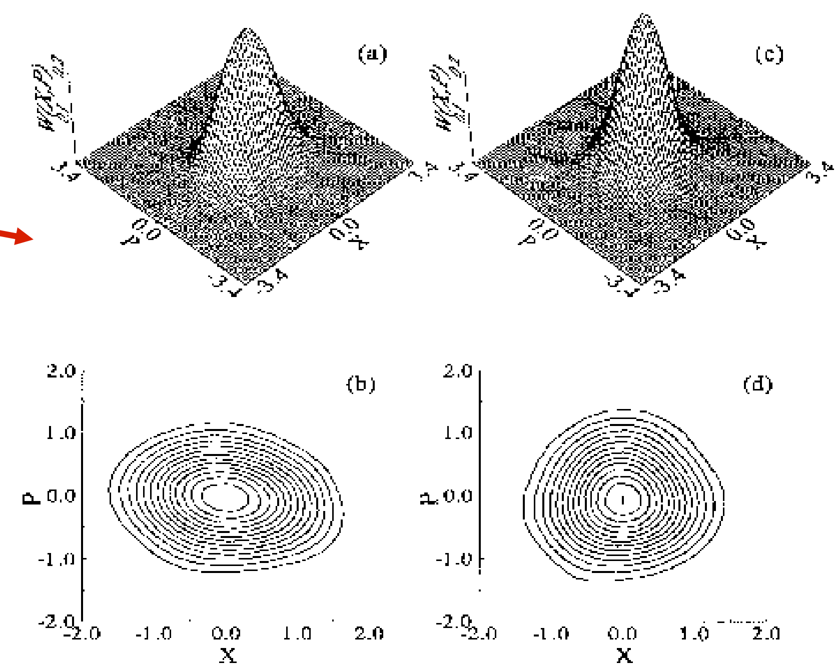
n=0



n=5



Wiger distribution of squeezed light!



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Measurement of the Wigner Distribution and the Density Matrix of a Light Mode Using Optical Homodyne Tomography: Application to Squeezed States and the Vacuum

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(Received 16 November 1992)

GPD and AM sum rule

- **Knowing GPD, one can reconstruct the angular momentum of partons (Ji, Phys.Rev.Lett.78:610-613,1997)**

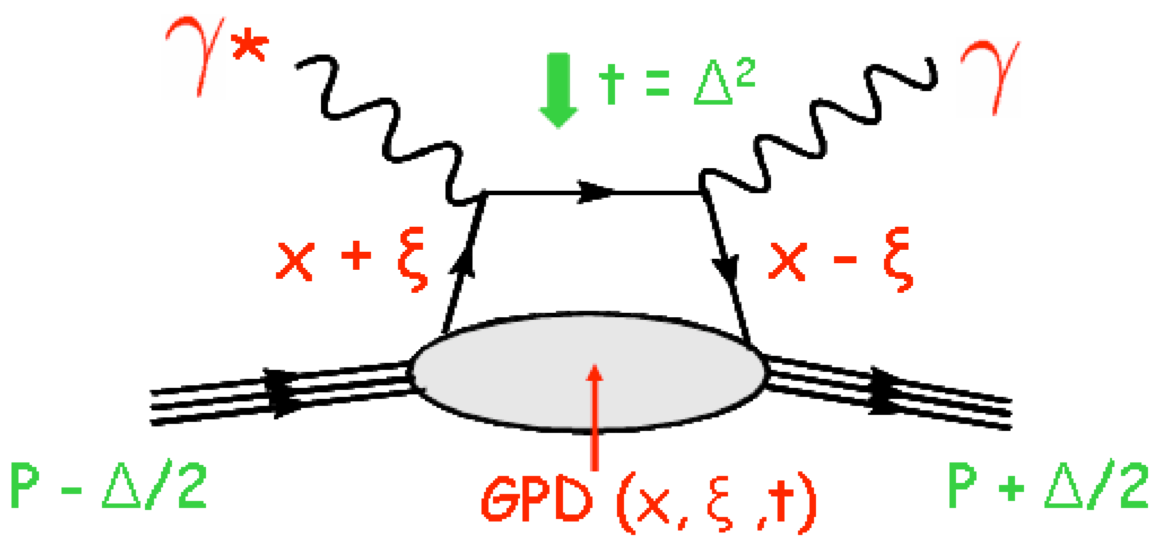
$$J_q = \lim_{t\to 0}\frac{1}{2}\int dx\, x[H_q(x,t,\xi)+E_q(x,t,\xi)]$$

  - x: parton momentum fraction
  - ξ: skewed parton momentum fraction
  - t: t-channel momentum transfer

Deep exclusive processes

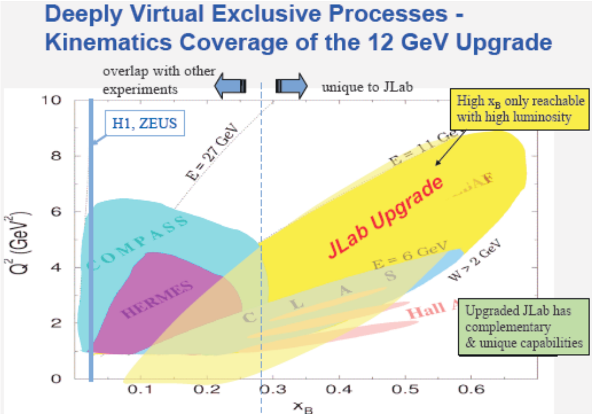
- A process in which the proton is probed like the elastic scattering. However, the partons are probed more exclusively

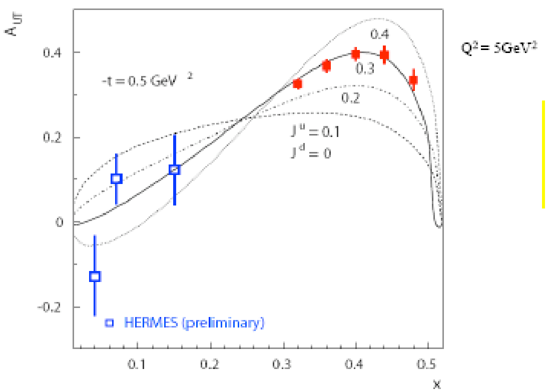
Deeply virtual Compton scattering



Experimental Impact

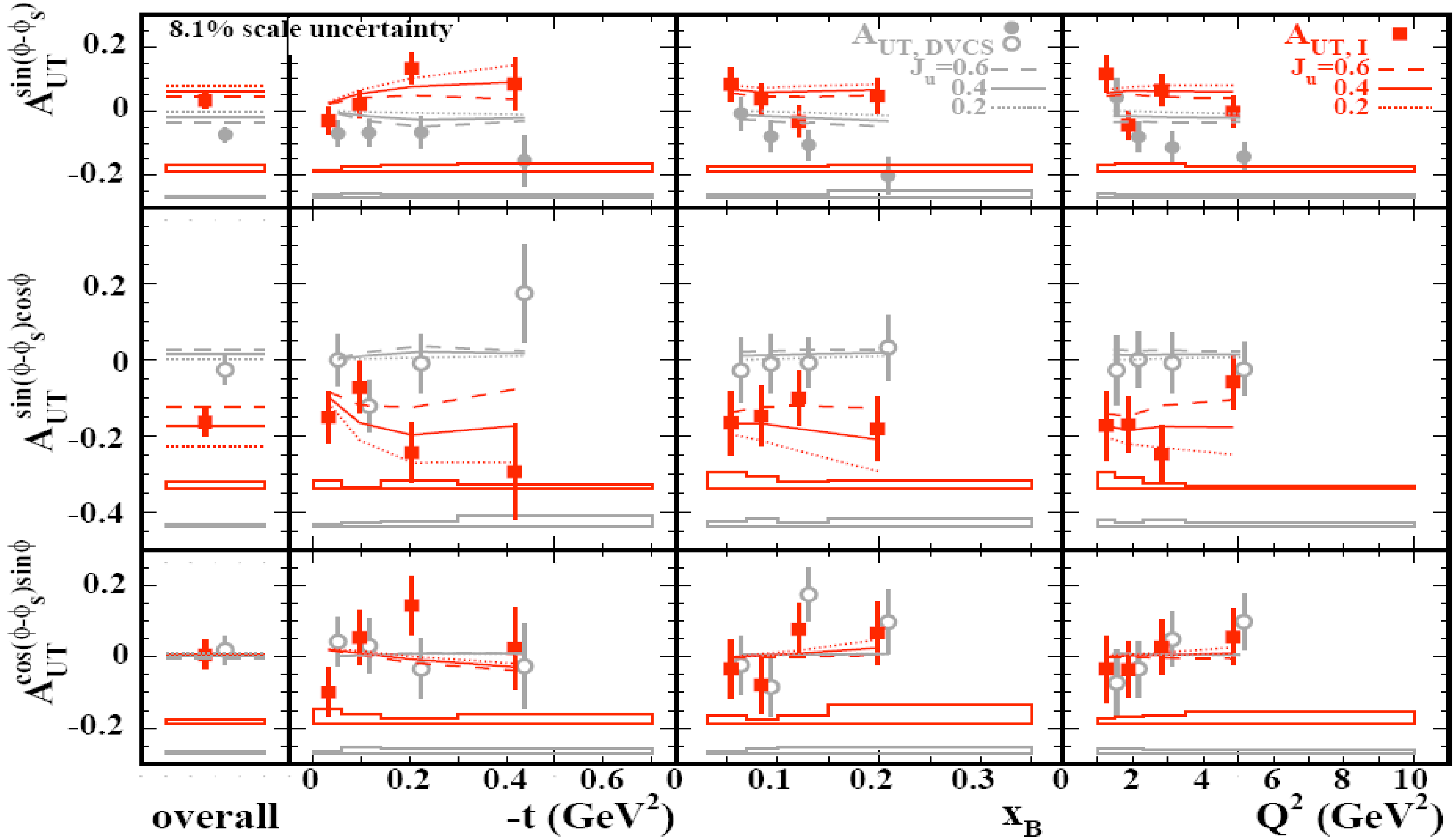
- Early measurements were made at ZEUS & H1
- More extensive measurements at HERMES and JLab
- Extensive and exciting program at Jlab 12 GeV upgrade,



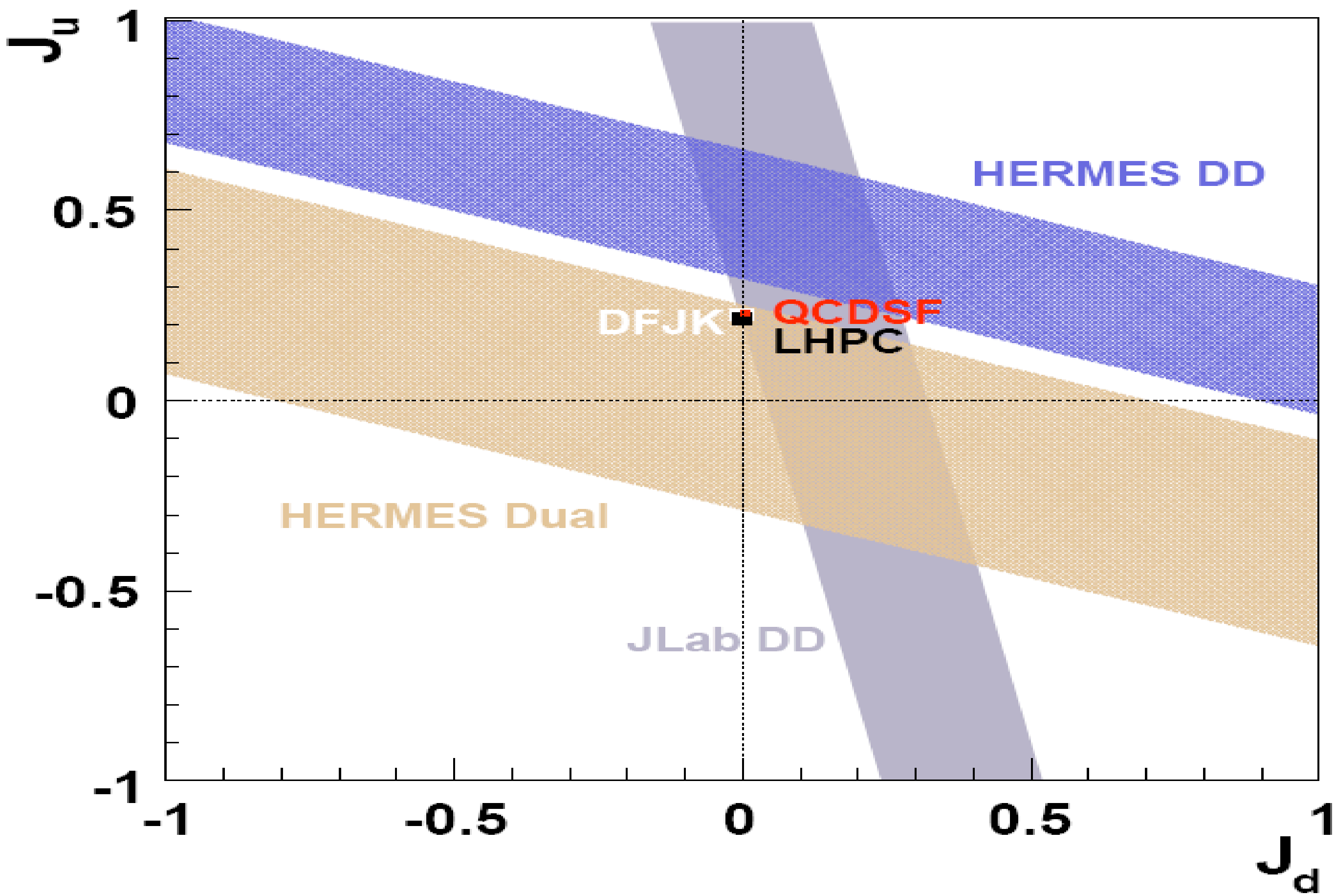


- One of the important motivations for a future electron-ion collider (EIC, recommend in LRP)

Example of data



Up and down quark AM in the proton



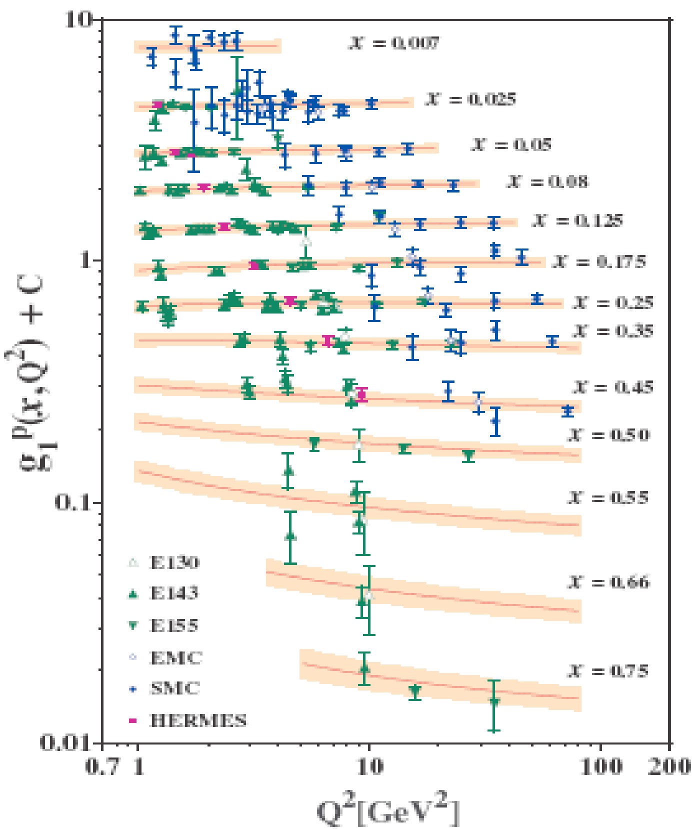
Large gluon polarization?

- Thought to be large because of the possible role of axial anomaly $-(\alpha_s/2\pi)\Delta g$ (Altarelli & Ross, 1988)
  - 2-4 units of hbar!
- Of course, the gluon contribute the proton spin directly.

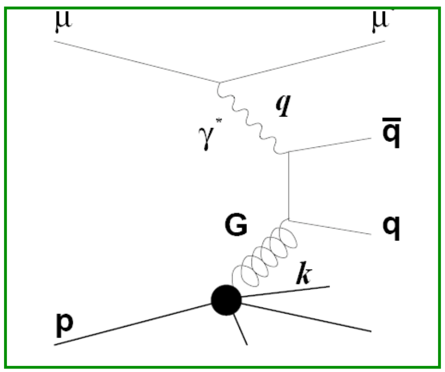
  $1/2 = \Delta g + \ldots$
- One of the main motivations for RHIC spin and COMPASS expts.
- Surprisingly-rapid progress, but the error bars remain large.

Measurements from DIS

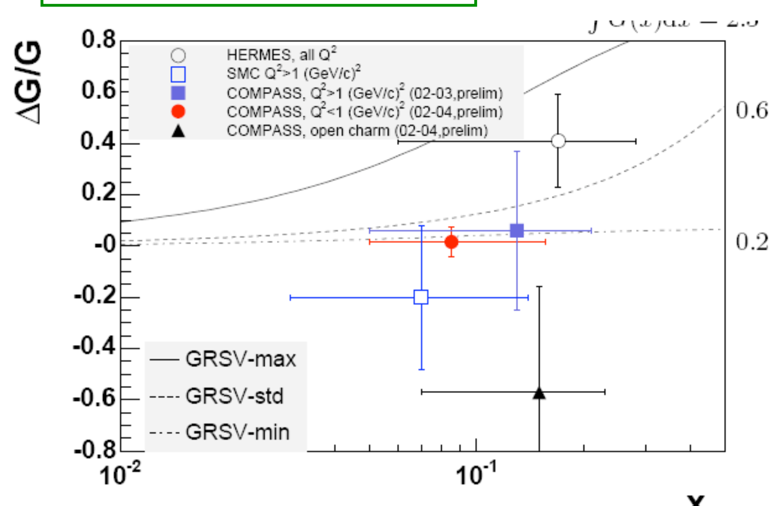
- **Q-evolution in inclusive spin structure function $g_1(x)$**



- **Two leading-hadron production in semi-inclusive DIS**



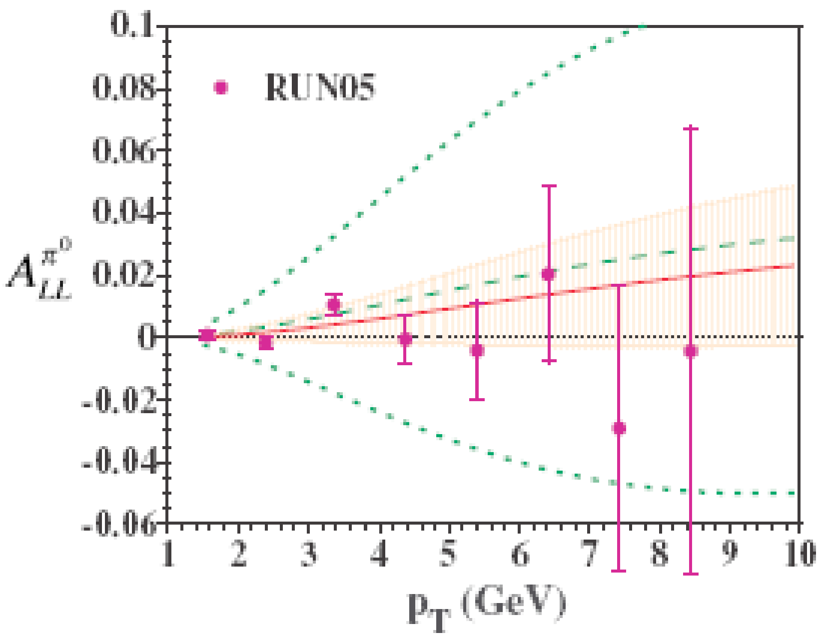
SMC
HEMRES
COMPASS



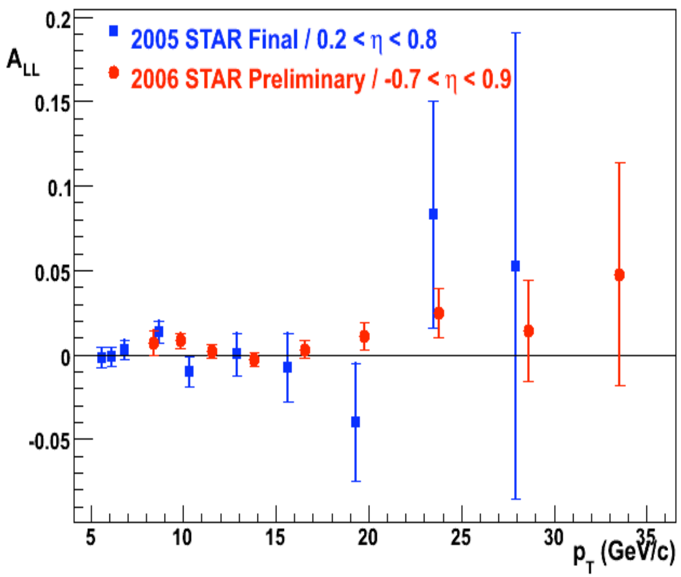
$\Delta G/G$ is small or has a node around $x_g \approx 0.1$

Measurement from Polarized RHIC

- π production in polarized PP collision at RHIC



- Two jet production in polarized PP collision at RHIC

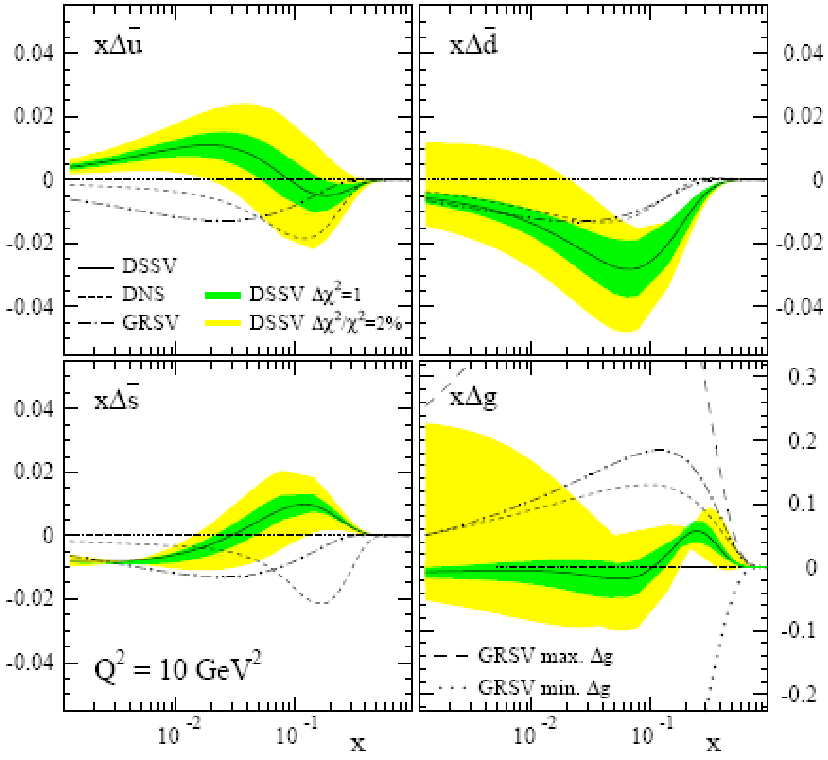


(NLO) Global fit of Pol. Parton Distribution

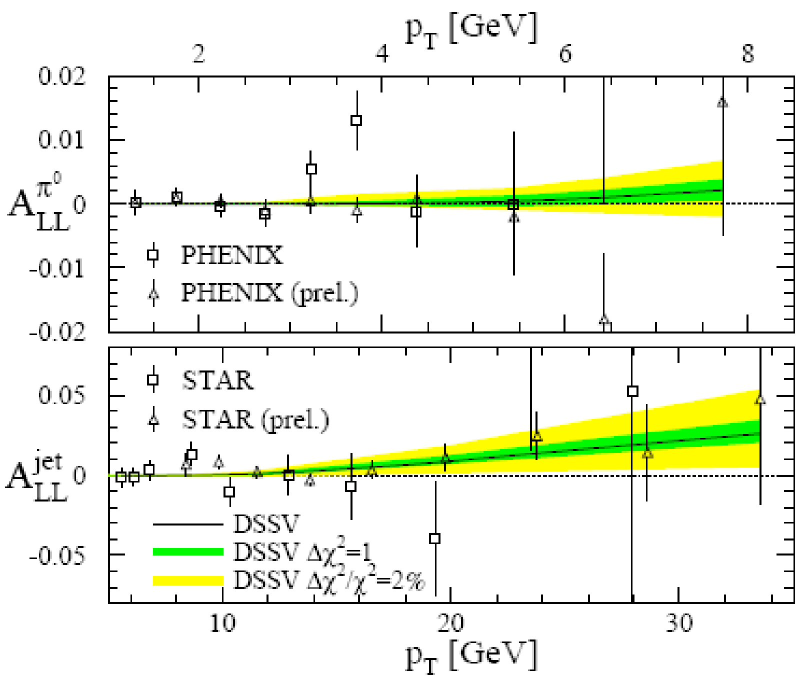
- **Many efforts in the past have been made**
  - Gluck, Reya, Stratmann, Vogelsang (2001)
  - Blumlein and Bottcher (2003)
  - Leader, Sidorov, Stamenov (2006)
  - Hirai, Kumano, Saito (2006)
  - .....
- **One of the most recent is the NLO fit by de Florian, Sassot, Stratmann and Vogelsang (hep-ph/0804.0422) in which pp collision jet data are first included. (Technically challenging!)**

DSSV PDF

Polarized sea distributions



RHIC spin asymmetries



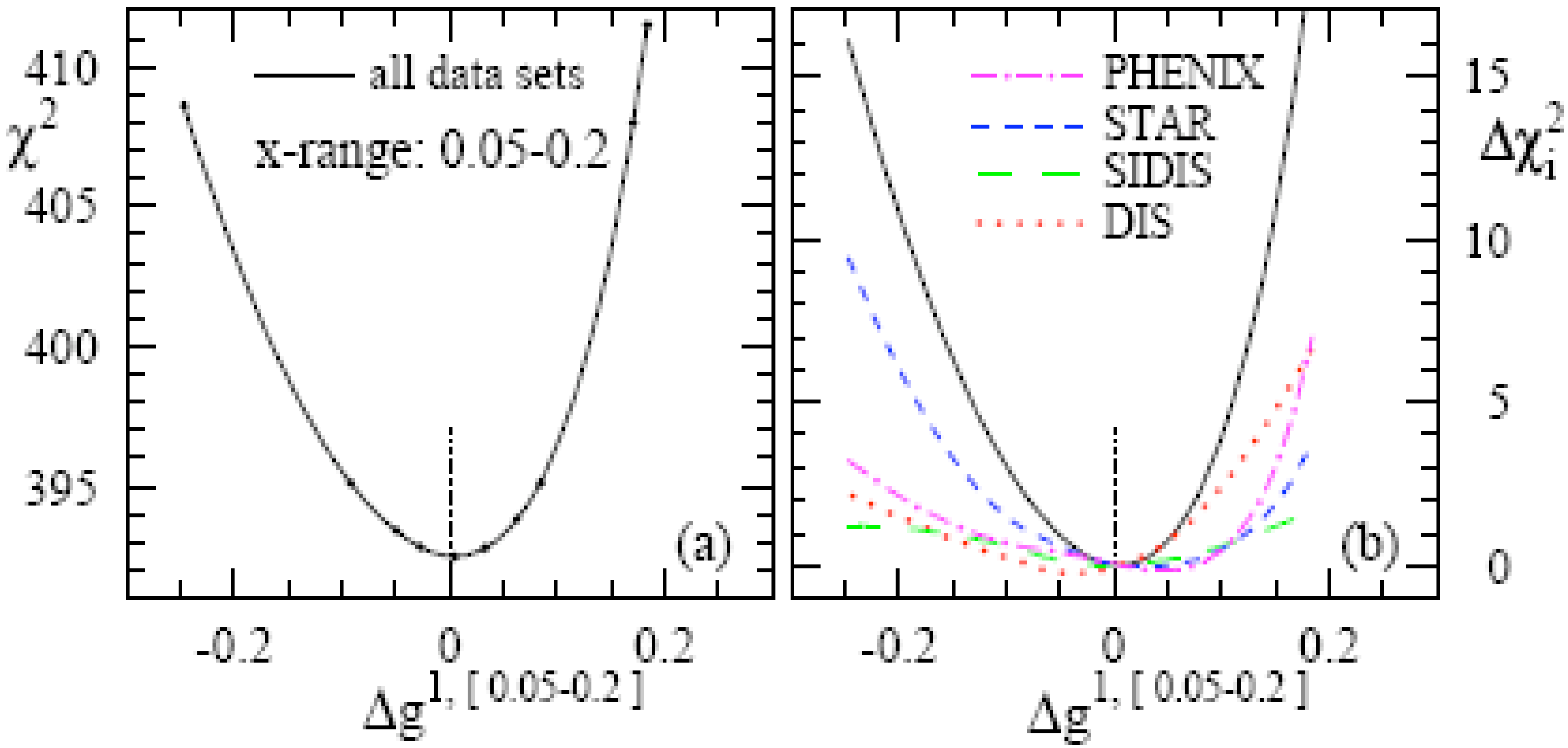
DSSV spin content

TABLE II: First moments $\Delta f_j^{1,[x_{\min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

	$x_{\min} = 0$ best fit	$x_{\min} = 0.001$ $\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

- The gluon pol. is small, but the uncertainty is large. Future data will improve this

Gluon polarization and chi-squared

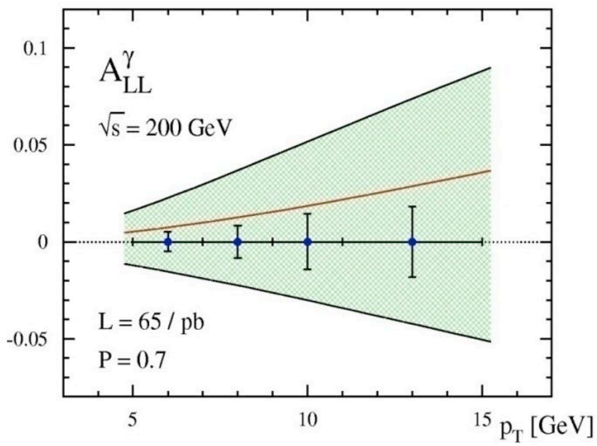


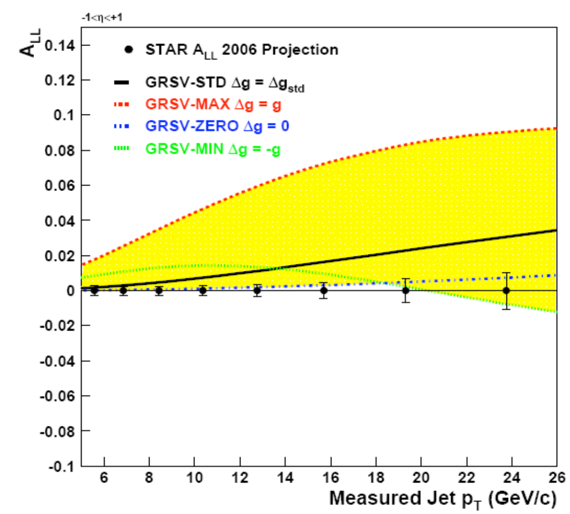
Conclusion?

- **The gluon helicity contribution to the proton spin is not overwhelming!**
- However, it can make a significant contribution compared to ½, the data is becoming more constraining.
- Need better data..
- How to measure the total gluon contribution!

Looking to the future

- **RHIC**
  - Direct photon production
  - Higher precision in jet and pion





- **Electron-ion Collider!**

Lattice QCD

- Only way we know how to solve QCD non-perturbatively with controllable precision.
- As computer power improves and algorithms get better, lattice computation finally becomes the benchmark for hadronic physics.
- What can one calculate
  - Mass/spectroscopy
  - Form factors, couplings,
  - Parton distributions/GPDs
  - Low-energy constants, polarizabilities…
- Let the professionals do the work.