Future Challenges of Spin Physics

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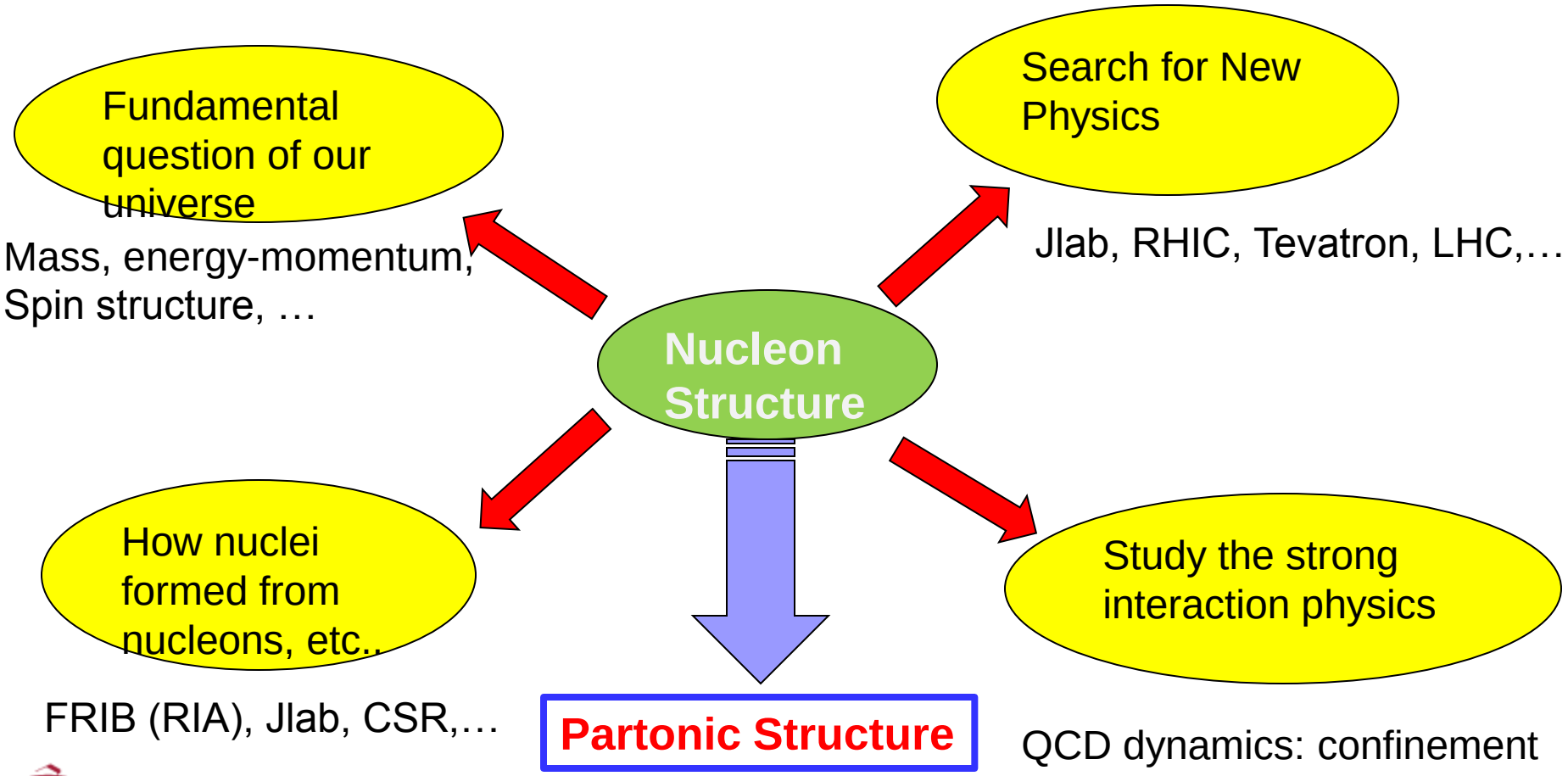
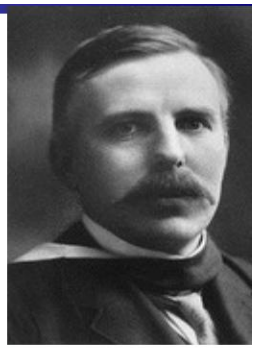
Exploring nucleon is of fundamental in Science



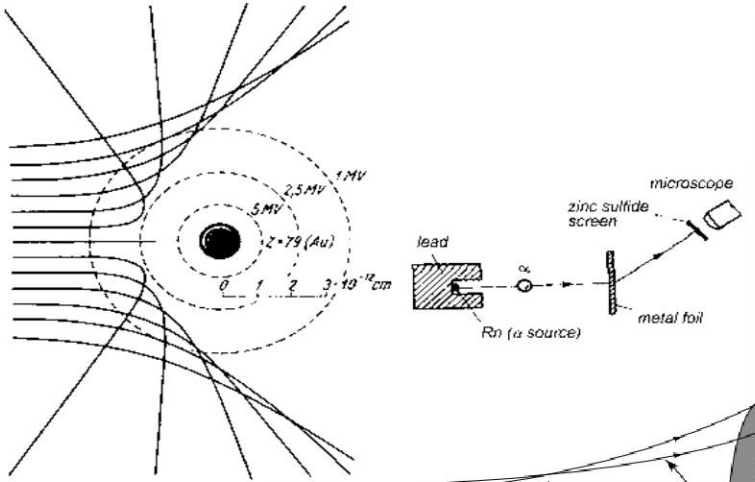
Exploring the nucleon: Of fundamental importance in science

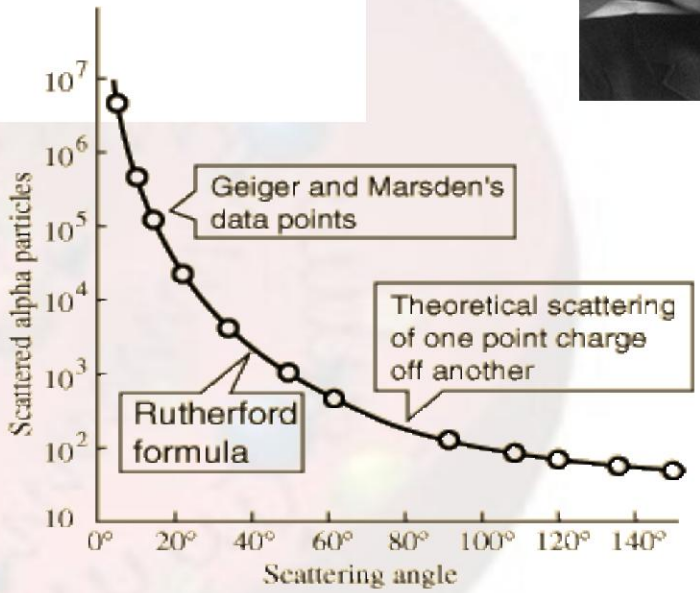
Rutherford Scattering

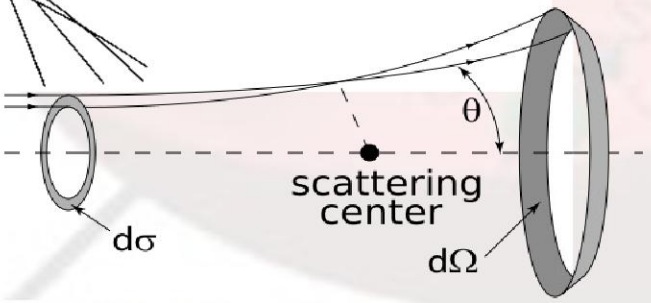


The Scattering of α and β Particles by Matter and the Structure of the Atom

E. Rutherford, F.R.S.*
Philosophical Magazine
Series 6, vol. 21
May 1911, p. 669-688

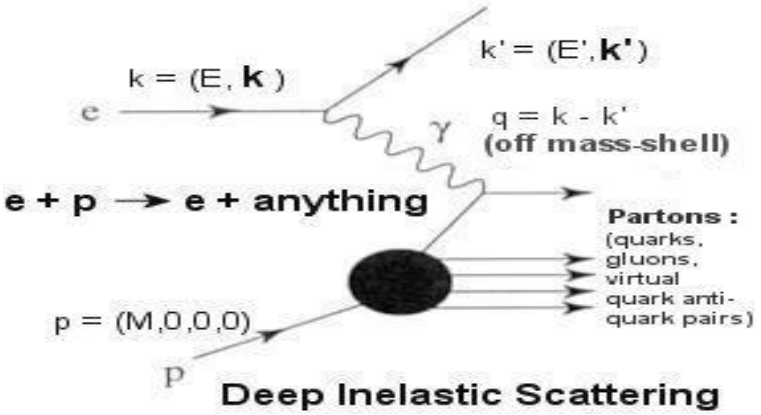




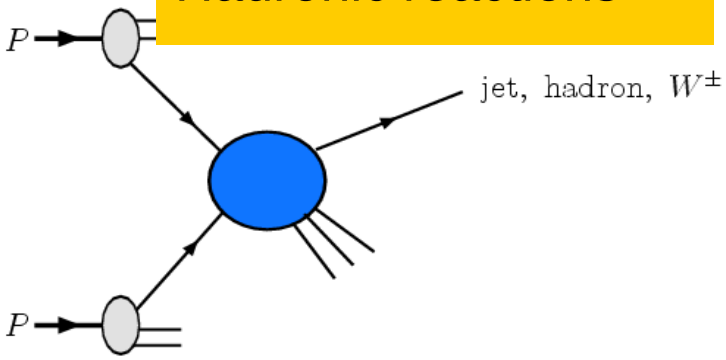


$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha\hbar c}{2mv_0^2}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

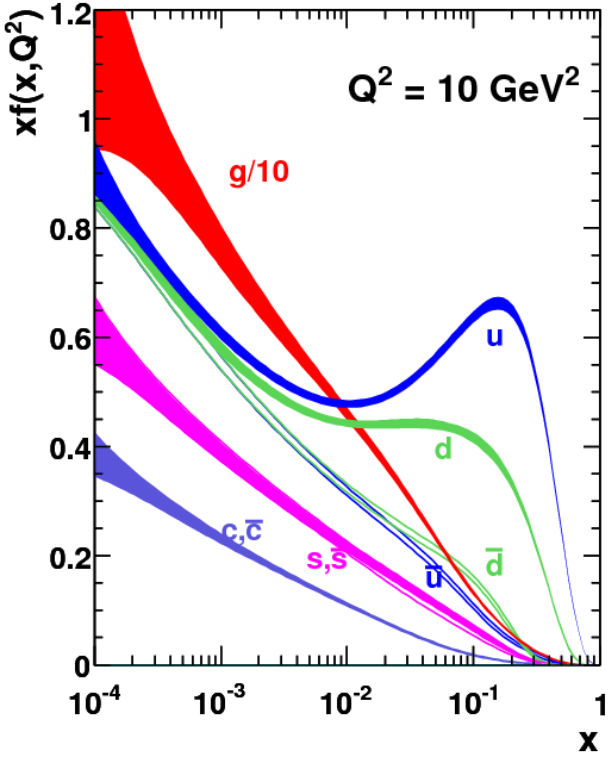
Rutherford Probe: Feynman Parton Picture



Hadronic reactions

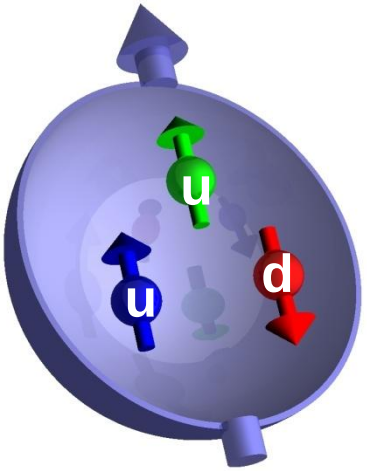


- Inclusive cross sections probe the momentum (longitudinal) distributions of partons inside nucleon

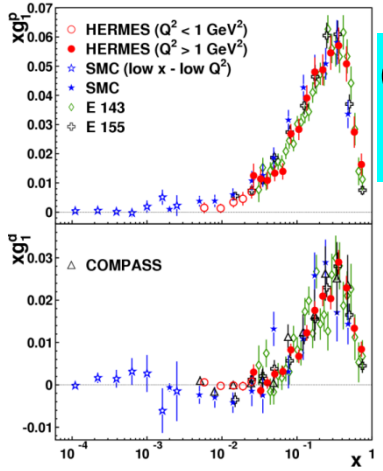


- Proton Spin physics has long history, starting from the quark model in 60's, and has been focus in hadronic physics for decades
- In the simple Quark Model, the three quarks are in the s-orbital, its spin ($\frac{1}{2}$) should be carried by the three quarks
- European Muon Collaboration: 1988

  "Spin Crisis"--- proton spin carried by quark spin is rather small

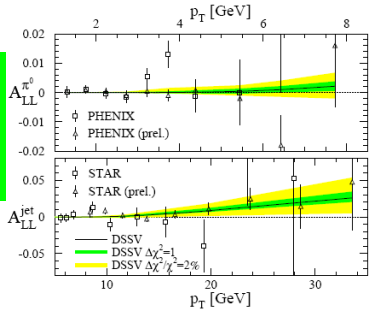


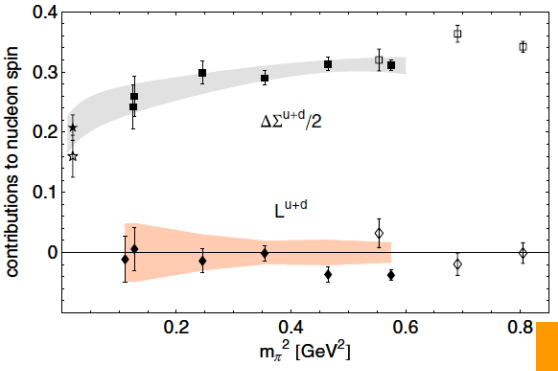
Proton Spin Sum Rule

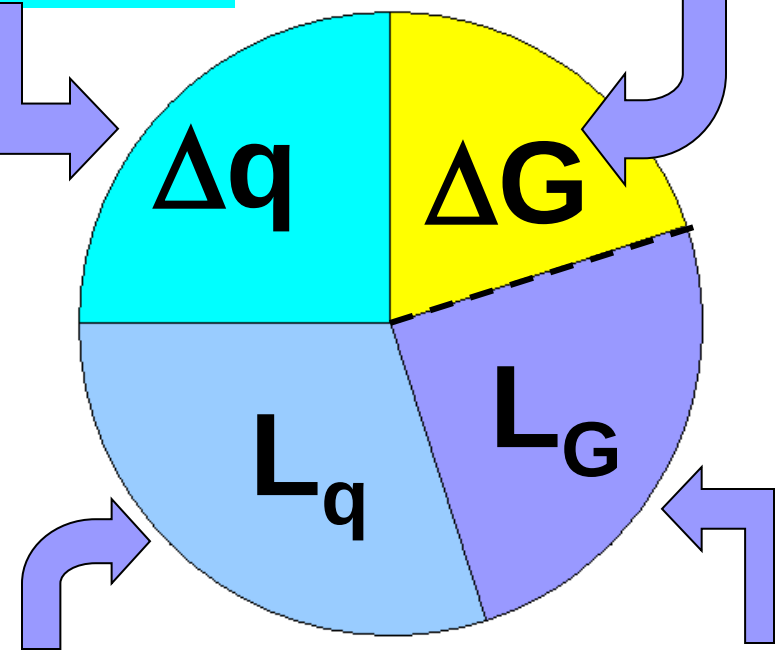


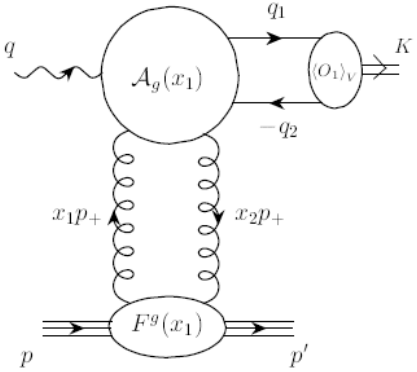
Quark spin ~30%
DIS, and pp coll.

Gluon spin~ 0-70%
RHIC, EIC, …









Deeply Virtual Compton Scattering,
Exclusive Meson Production in DIS,
Transverse spin phenomena

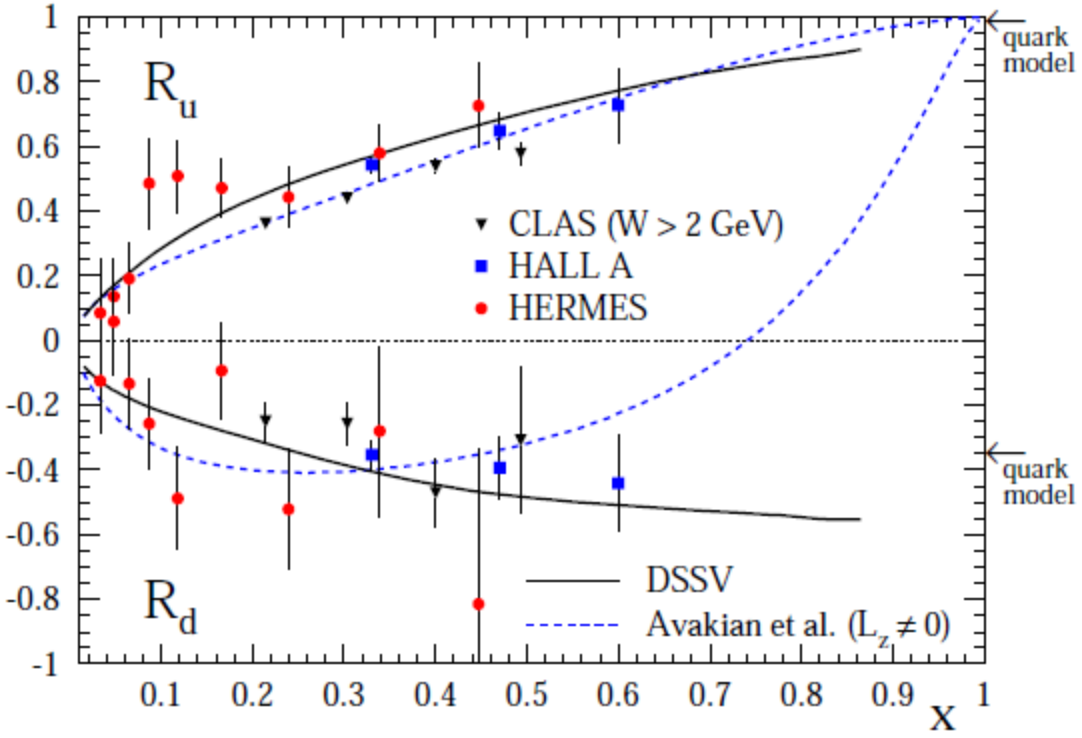
Future challenges

- Get the numbers
  - Spin sum rule
- Understand the physics
  - QCD dynamics
- Involve both exp. and theory developments, and the collaboration among them

Quark spin: Future Challenges

- Have been well determined from polarized DIS experiments
  - Total quark spin contribution is about 30%
- Questions remains
  - Quark polarization at $x \rightarrow 1$?
    - Nontrivial QCD dynamics
  - Sea quark polarizations?
    - a potential contribution to the proton spin (-6% from the current global analysis)

Quark orbital angular momentum contribution at large-x

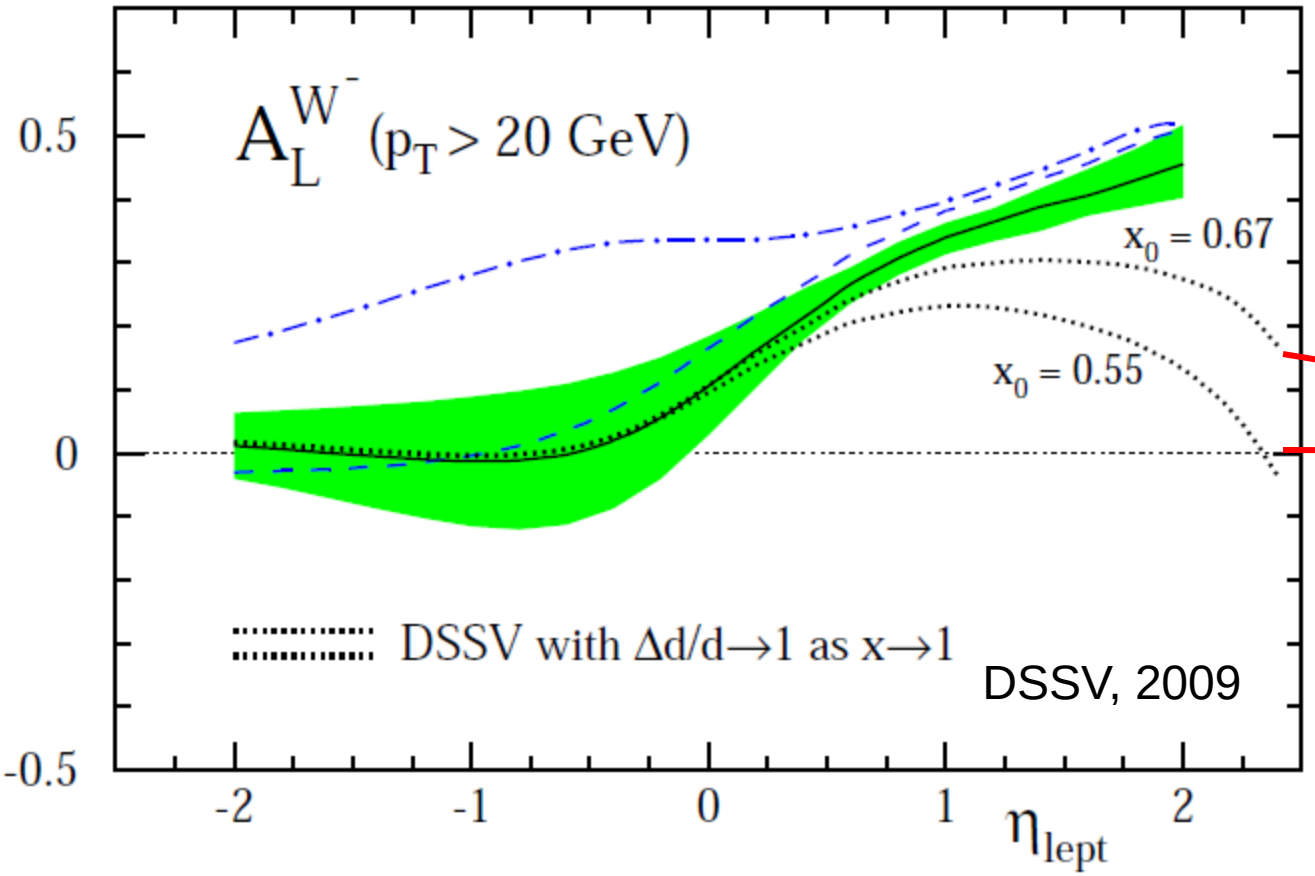


Power counting rule
Brodsky-Burkardt-Schmidt 95
$q^-/q^+ \sim (1-x)^2$

Quark-orbital-angular Momentum contribution
Avakian-Brodsky-Deur-Yuan,07
$q^-/q^+ \sim (1-x)^2 \log^2(1-x)$

It will be interested to see how this compares with the future data from RHIC and JLab

Constrain large-x valence quark polarization from W asymmetry

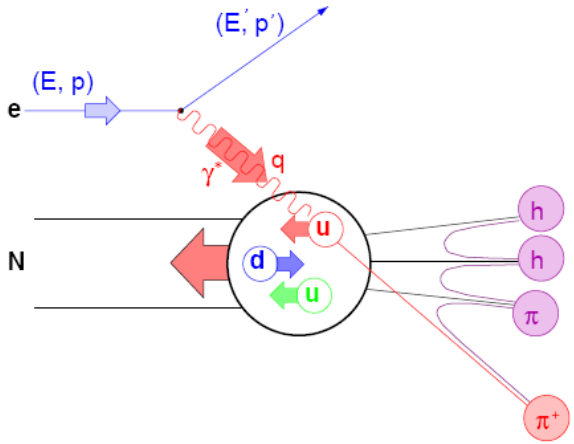


Power counting predictions

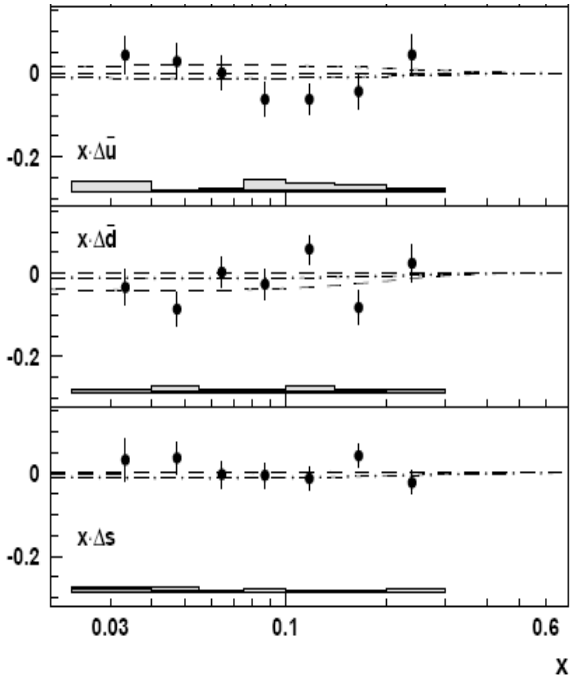
Sea quark polarization

- One can measure the sea quark contribution to the spin of the proton through fragmentation of the polarized quark into mesons

Semi-inclusive DIS

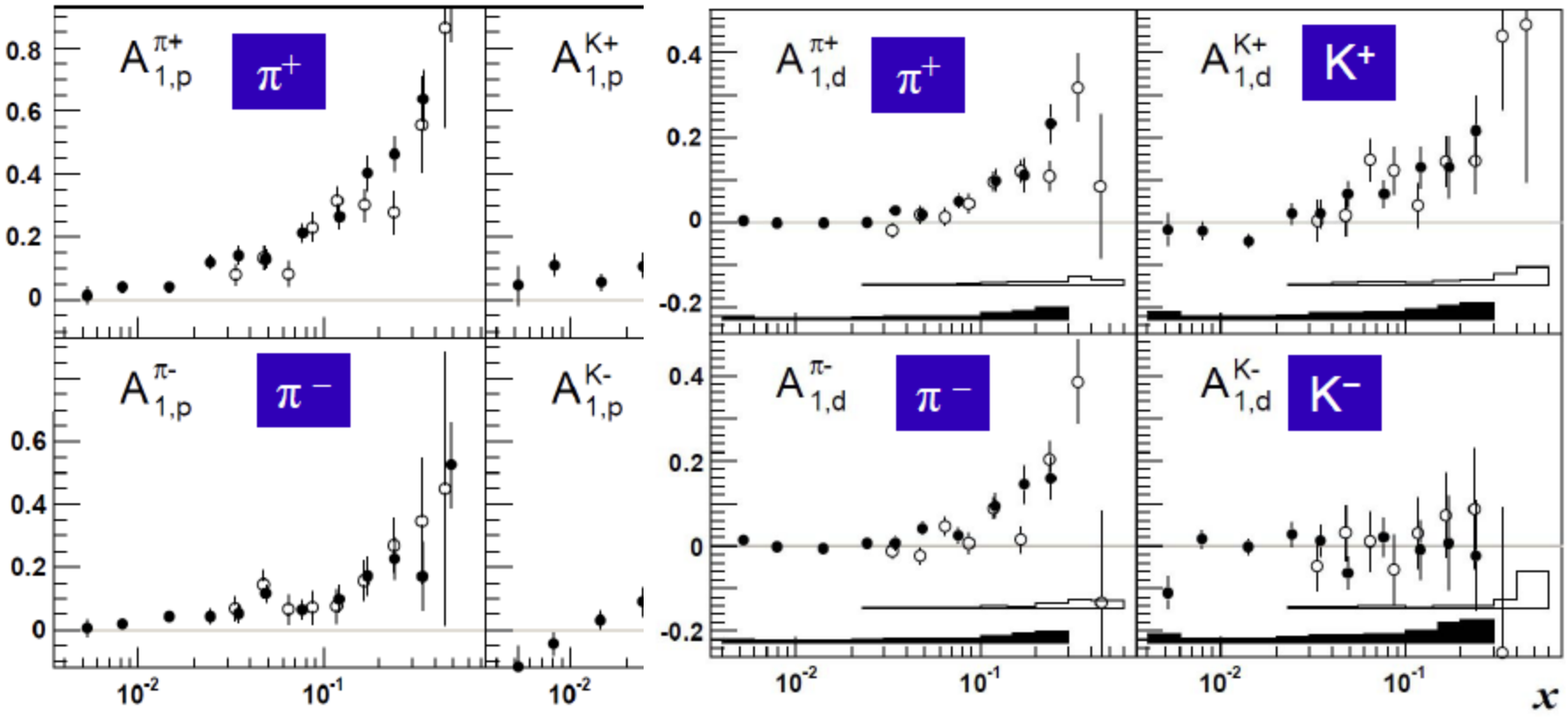


HERMES, 2004



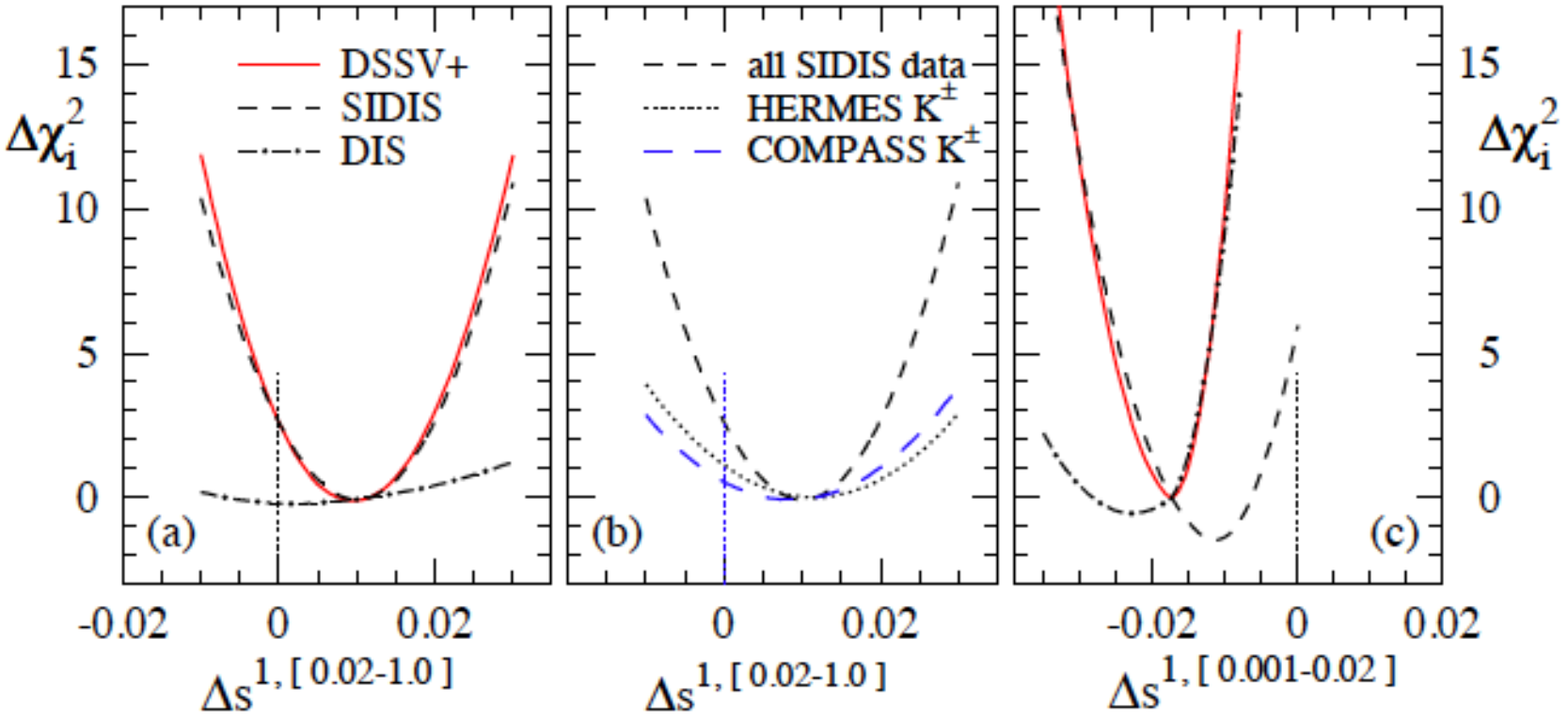
- Major topic at EIC

COMPASS and HERMES



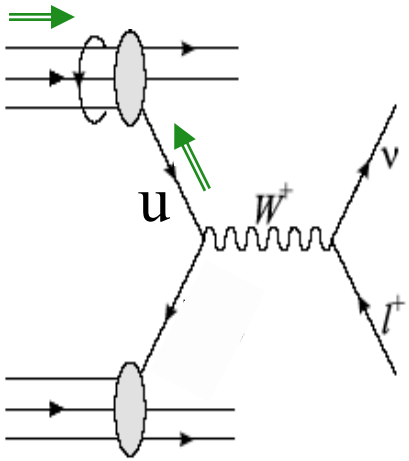
Schill, talk at High Pt Physics at BNL

DSSV+ fit



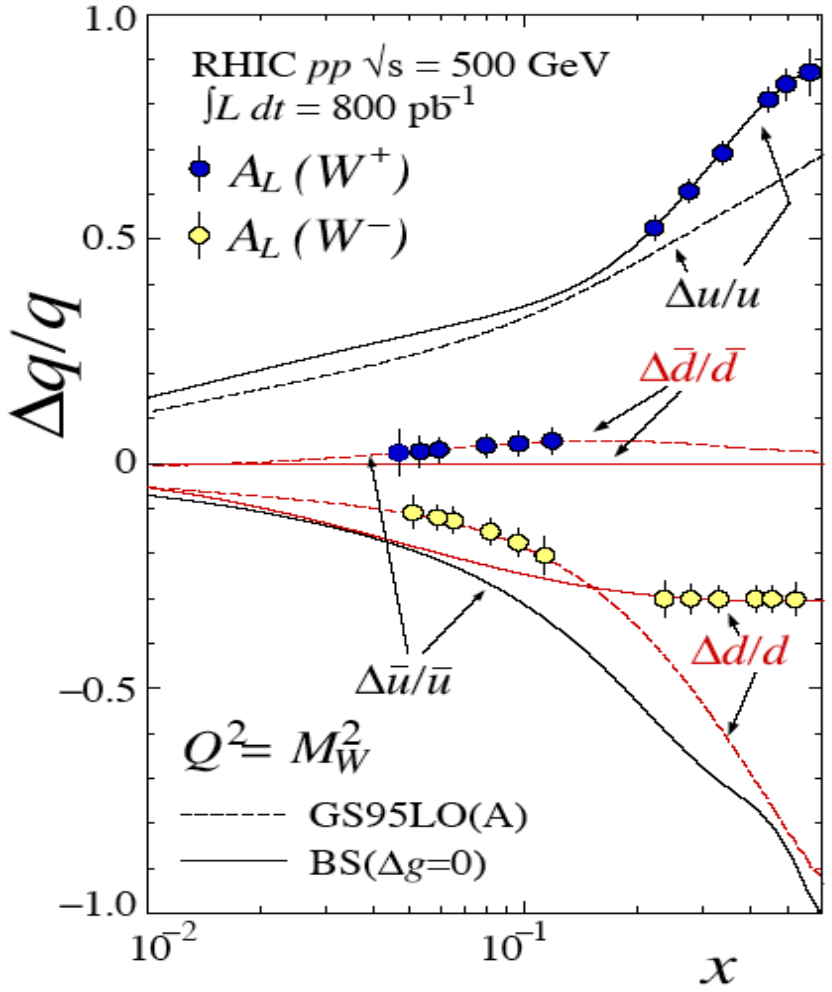
With improved knowledge of the fragmentation functions, the future SIDIS will play even more important role in this game

RHIC spin

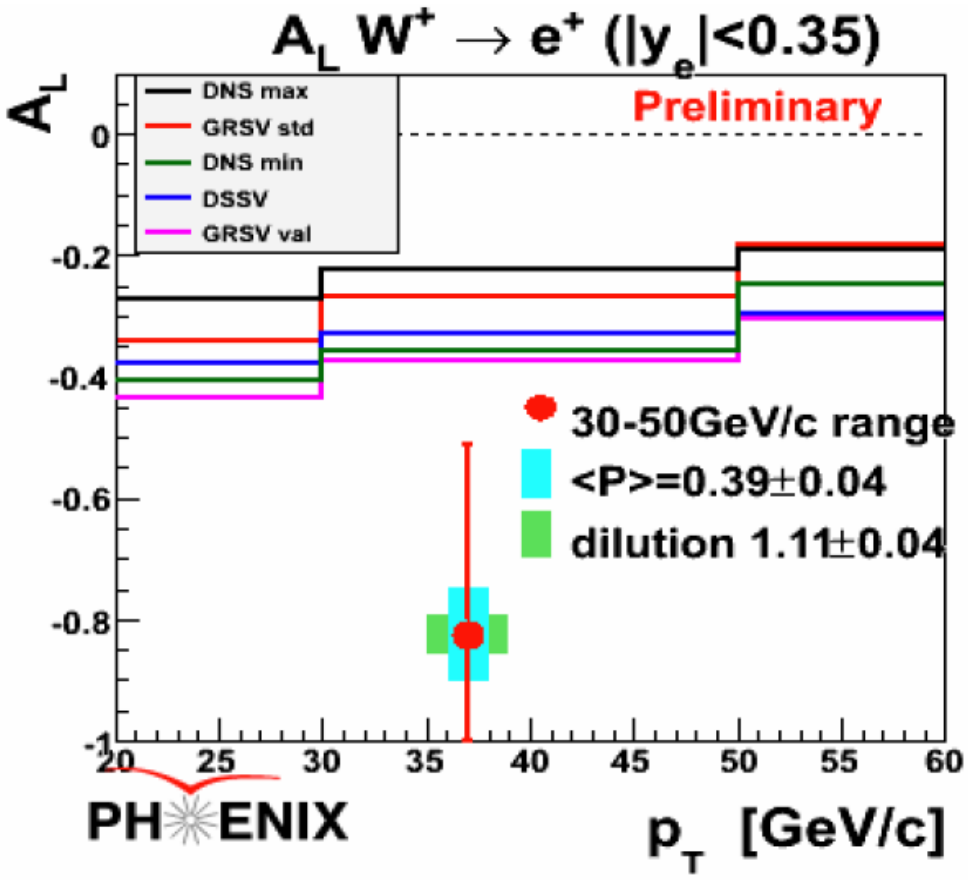


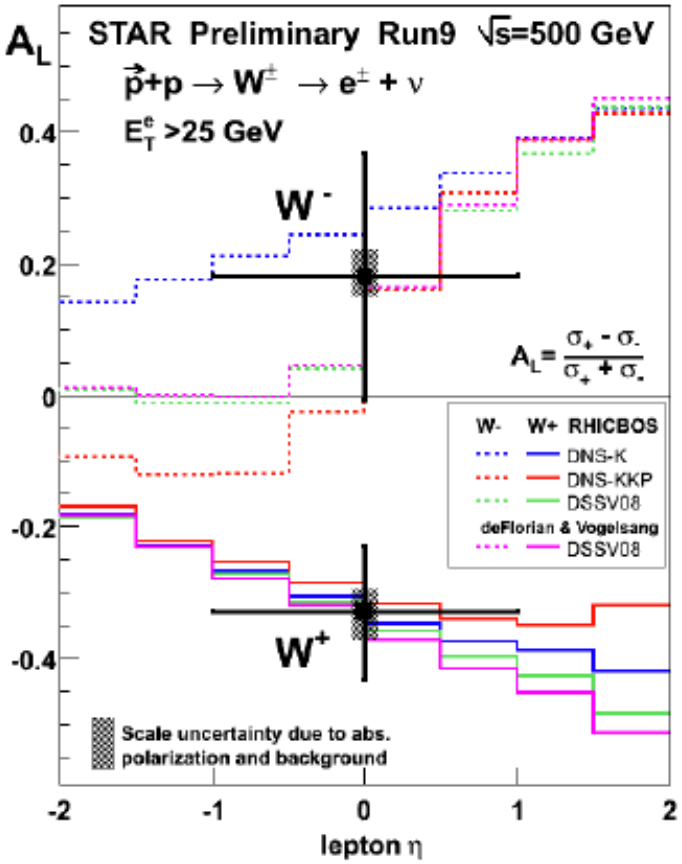
unpol.

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

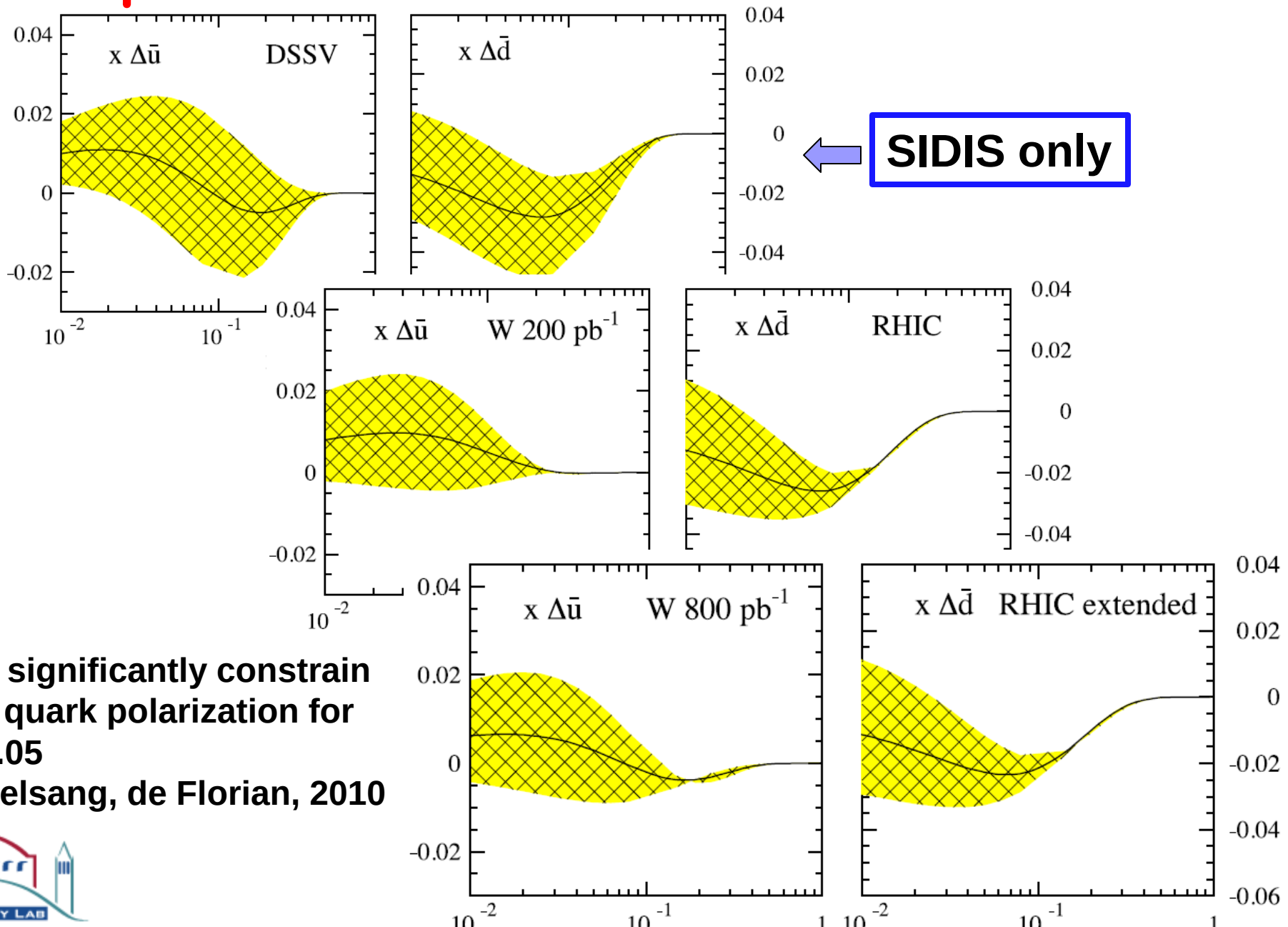


First results





Impact from W measurements



Will significantly constrain sea quark polarization for x<0.05

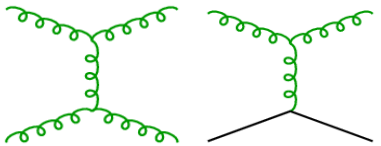
Vogelsang, de Florian, 2010

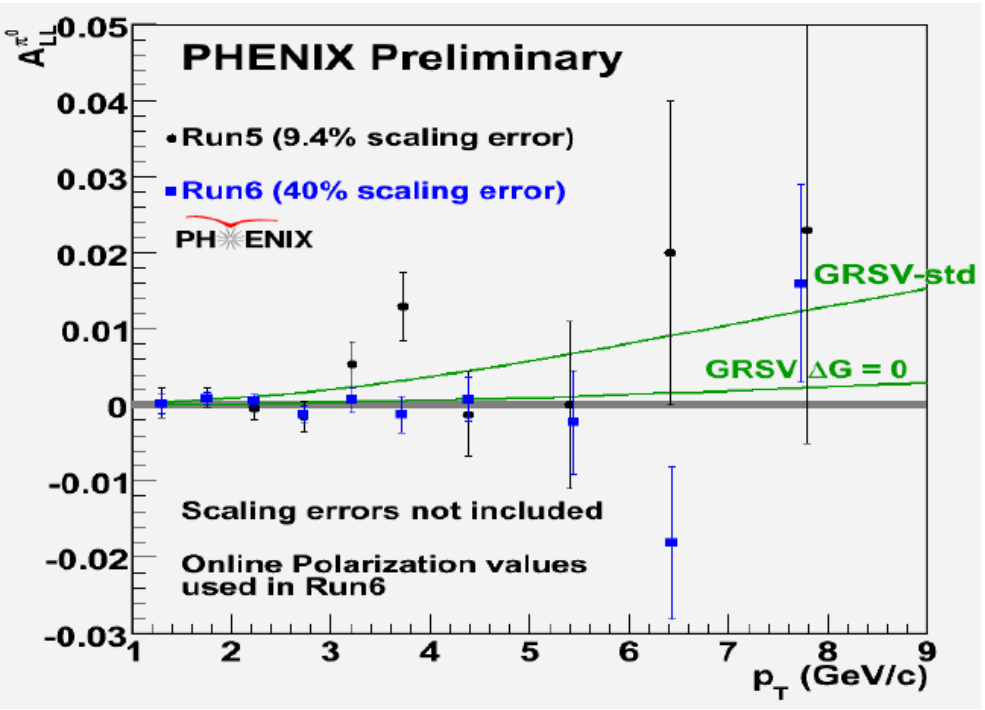
GLUON SPIN (HELICITY)

Exciting results from RHIC

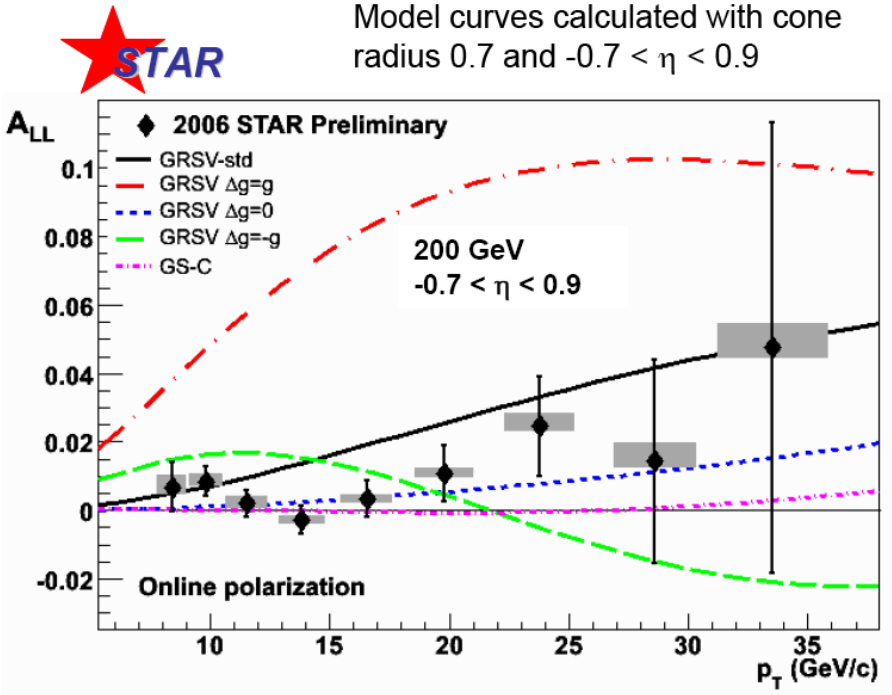
Double longitudinal spin asymmetry

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta\sigma}{\sigma}$$





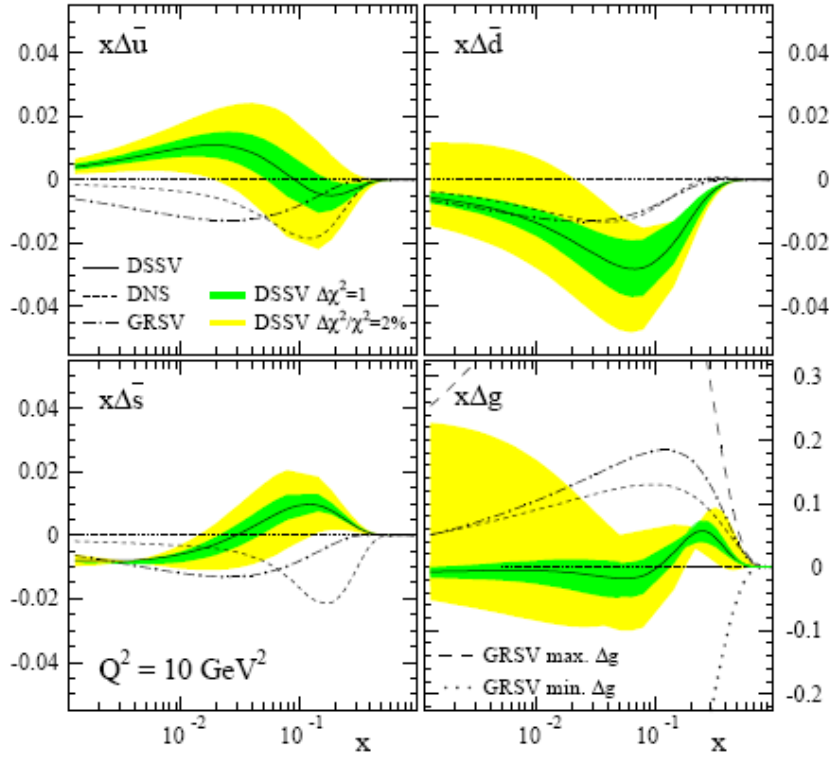
Model curves calculated with cone radius 0.7 and $-0.7 < \eta < 0.9$



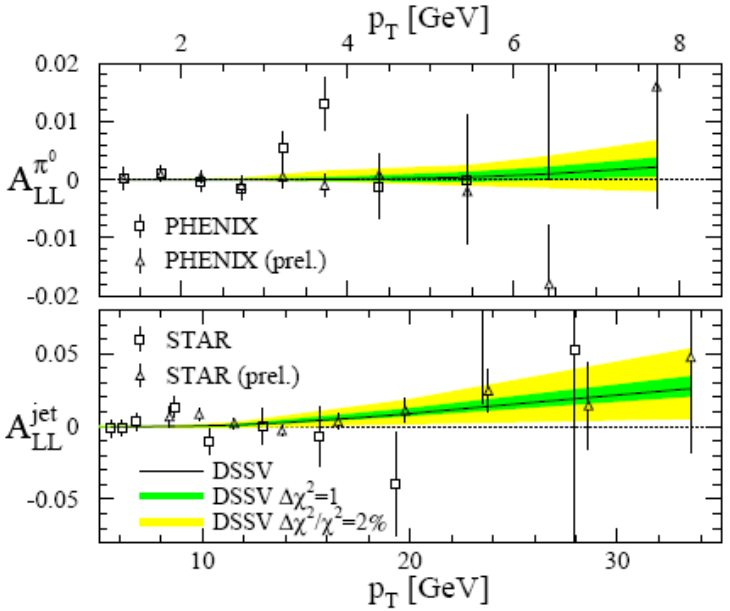
arXiv:0710.2048 [hep-ex]

Global fit constrains the gluon spin from the RHIC data

Polarized sea and gluon distributions



RHIC spin asymmetries



de Florian, Sassot, Stratmann and Vogelsang (0804.0422)

DSSV spin content

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

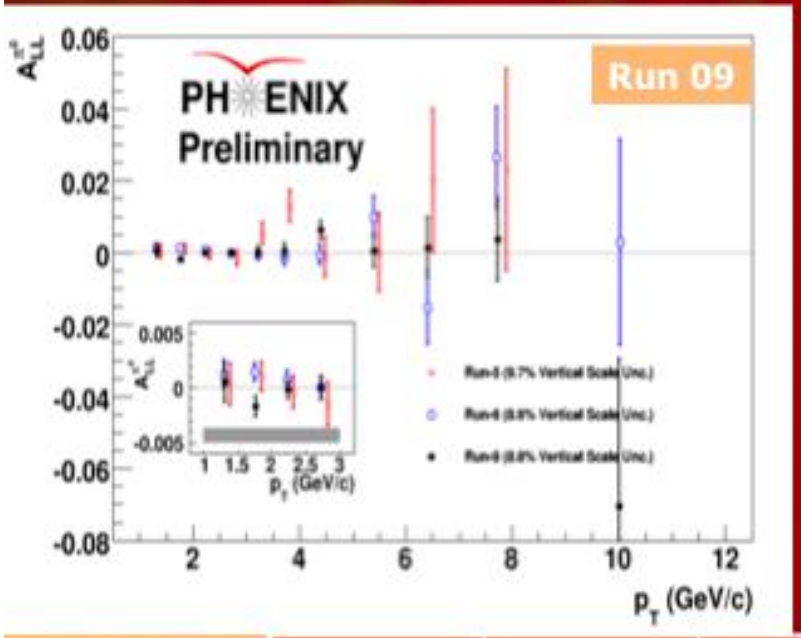
	$x_{\min} = 0$	$x_{\min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-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	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

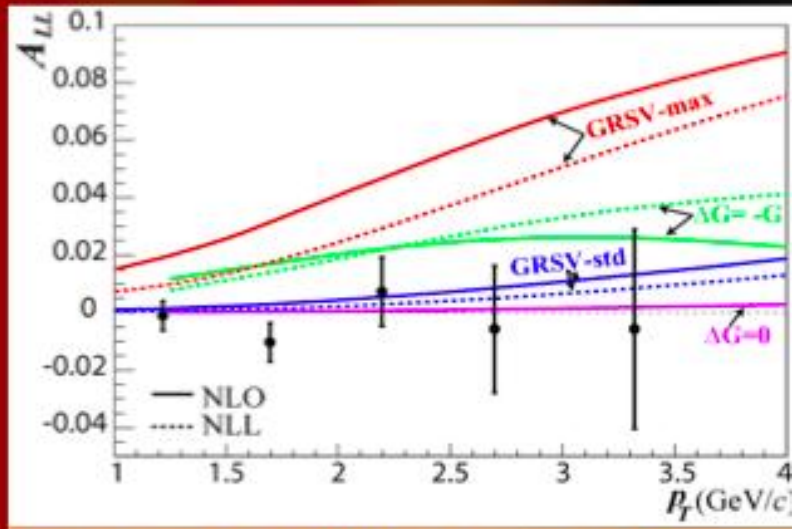
- Gluon pol. is small, but the uncertainty is large. Future data will improve this
- Before RHIC, ΔG in order of 1~2

Latest results from RHIC

PHENIX

Neutral Pion A_{LL}





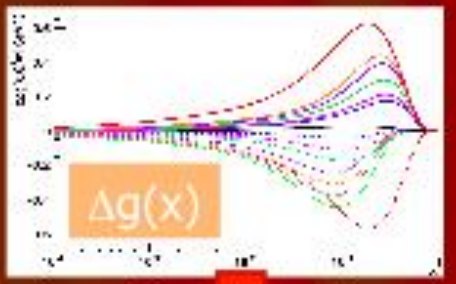
Phys. Rev. D 79, 012003 : $\sqrt{s}$ = 62.4 GeV

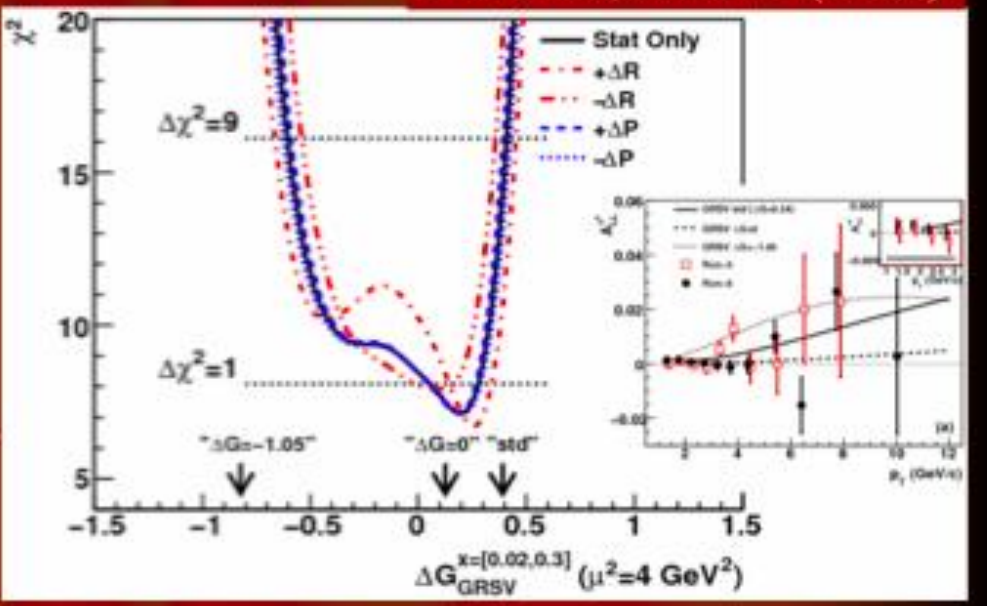
Year	$<P_B>$ (%)	$<P_Y>$ (%)	$L_{analyzed}$ (pb^{-1})	FOM (P^4L)
2005	50	49	2.5	0.15
2006	56	57	6.5	0.66
2009	57	57	14	1.5

Constraining ΔG Using A_{LL}

- Generate $\Delta g(x)$ for varying ΔG in GRSV fit, generate A_{LL} for each $\Delta g(x)$, calculate χ^2 for each expectation curve

PRL 103, 012003 (2009)

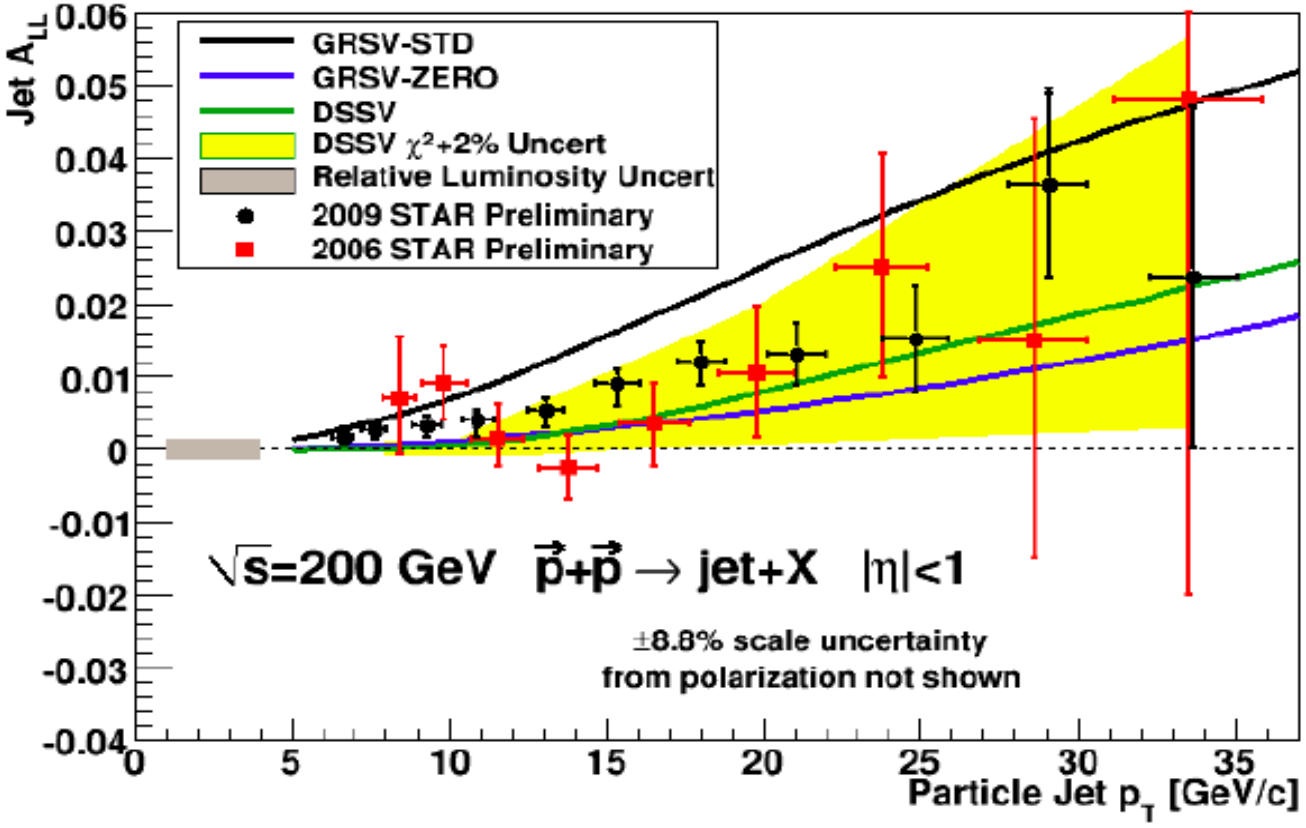




Considering only the statistical uncertainty :

$$\Delta G^{[0.02,0.3]}_{\mathrm{GRSV}} = 0.2 \pm 0.1\ (1\sigma)\ \text{and}\ 0.2^{+0.2}_{-0.8}\ (3\sigma)$$

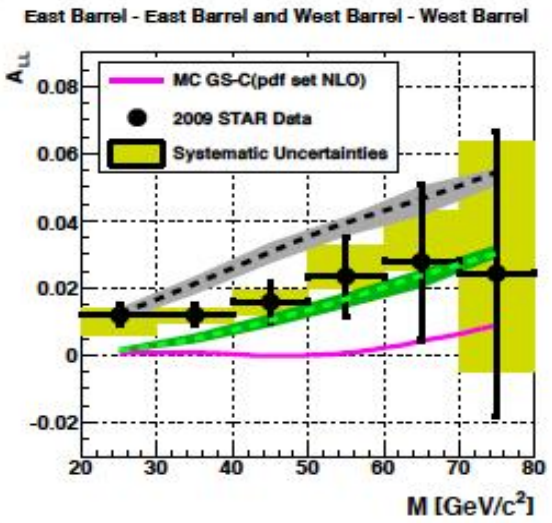
2006 vs 2009

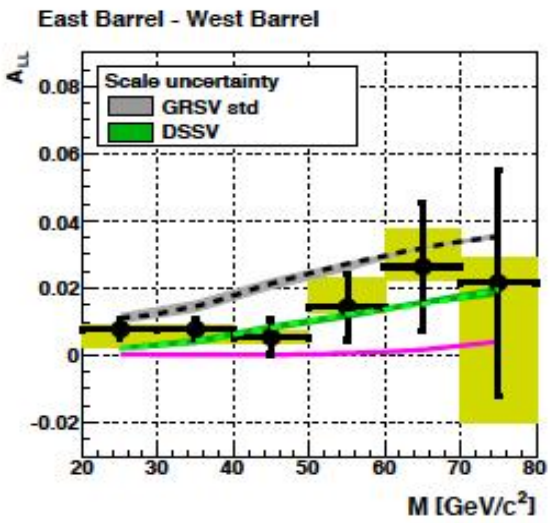


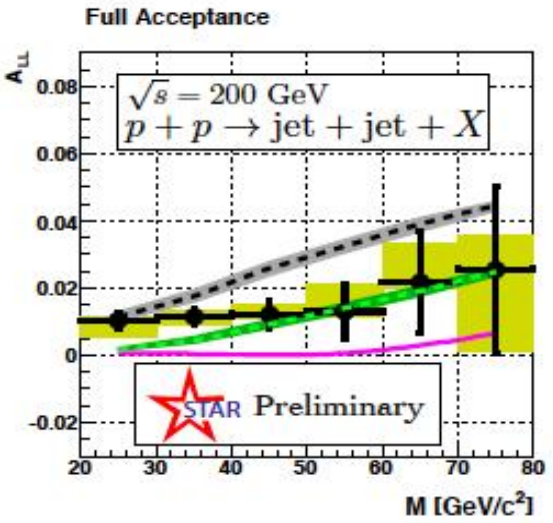
- 2009 STAR data is a factor of 3 (high-p_T) to >4 (low-p_T) more precise than 2006 STAR data
- Results fall between predictions from DSSV and GRSV-STD
- Precision sufficient to merit finer binning in pseudorapidity

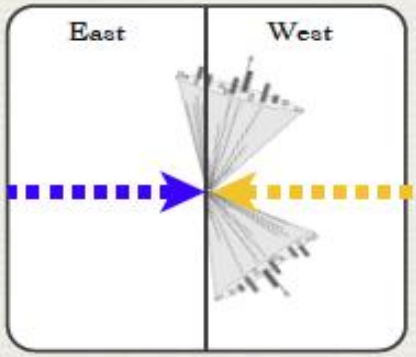
Di-Jet Asymmetry: STAR

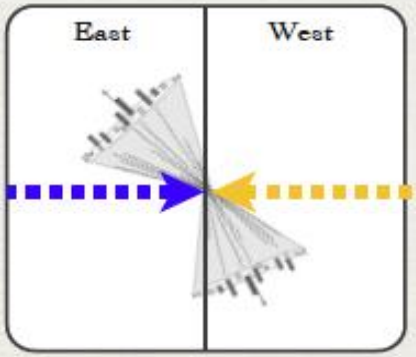
Run 9 Asymmetry











- It seems the new data push ΔG to higher value
  - Between DSSV and GRSV-Std
- Hope the data from both experiments will converge and provide further constraints
- What happens for a finite ΔG

Recall the DGLAP evolution

- LO $\Delta\Sigma$ dos not evolve, while ΔG evolves logarithmically

$$t = \ln Q^2/\Lambda^2_{\rm QCD}$$

$$\frac{d}{dt}\begin{pmatrix}\Delta\Sigma\\ \Delta g\end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{pmatrix}0 & 0\\ \frac{3}{2}C_F & \frac{\beta_0}{2}\end{pmatrix}\begin{pmatrix}\Delta\Sigma\\ \Delta g\end{pmatrix}$$

Altarelli-Parisi

$$\frac{d}{dt}\begin{pmatrix}L_q\\ L_g\end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{pmatrix}-\frac{4}{3}C_F & \frac{n_f}{3}\\ \frac{4}{3}C_F & -\frac{n_f}{3}\end{pmatrix}\begin{pmatrix}L_q\\ L_g\end{pmatrix}$$

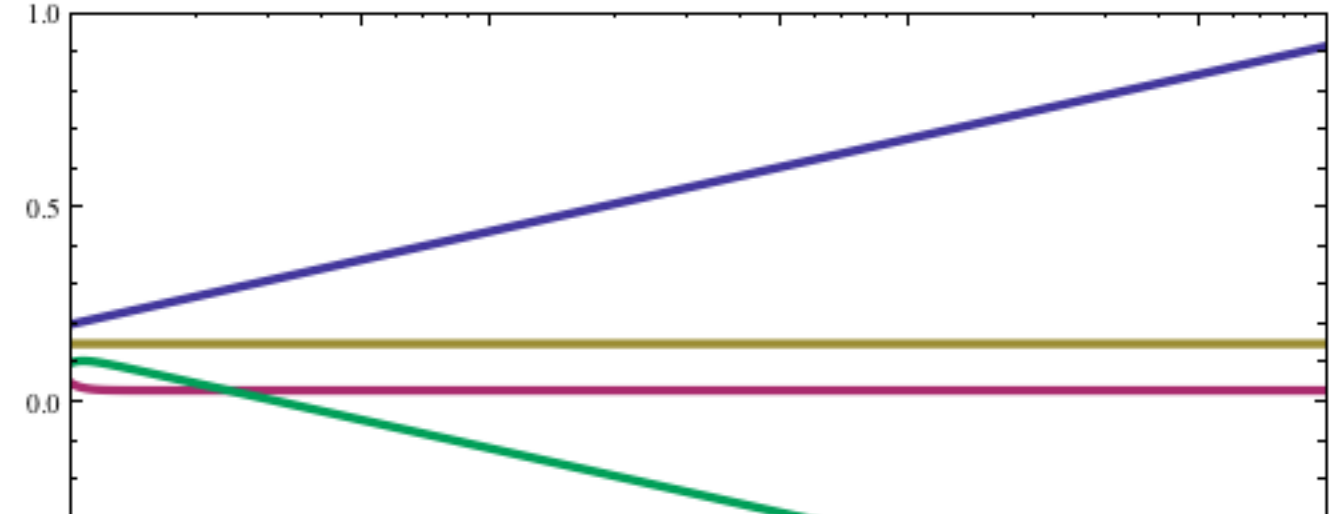
$$+\frac{\alpha_s(t)}{2\pi}\begin{pmatrix}-\frac{2}{3}C_F & \frac{n_f}{3}\\ -\frac{5}{6}C_F & -\frac{11}{2}\end{pmatrix}\begin{pmatrix}\Delta\Sigma\\ \Delta g\end{pmatrix}$$

Ji-Hoodbhoy-Lu
Hagler-Schafer

Q^2 dependence

$$\Delta\Sigma(t) = \text{const},$$

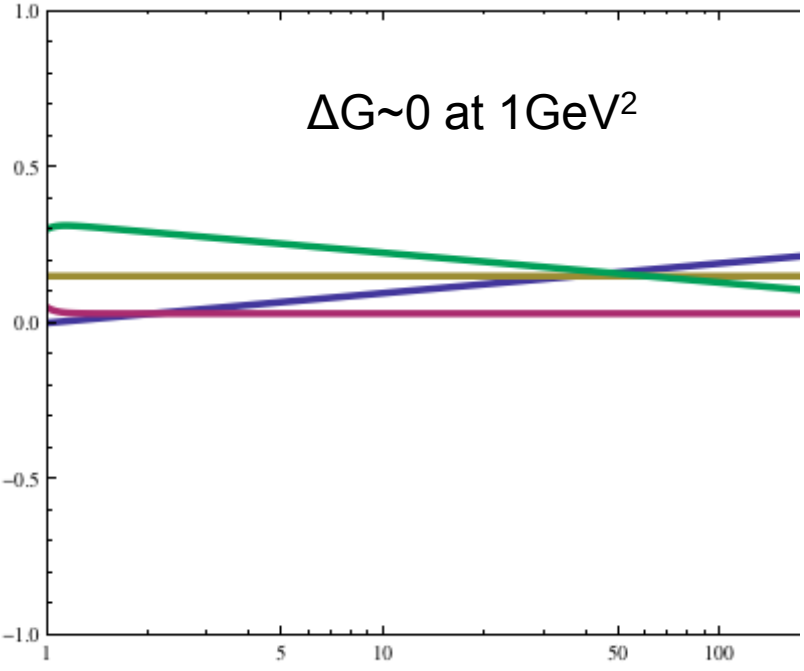
$$\Delta g(t) = -\frac{4\Delta\Sigma}{\beta_0} + \frac{t}{t_0}\left(\Delta g_0 + \frac{4\Delta\Sigma}{\beta_0}\right)$$



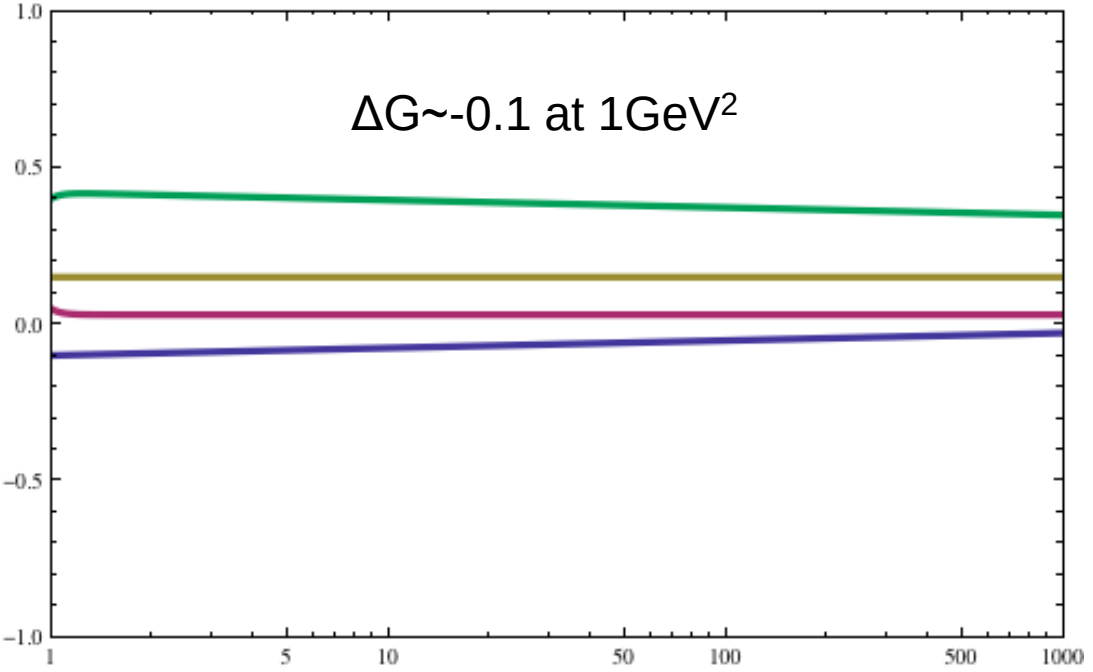
ΔG

ΔΣ/2~0.15

Lq



ΔG~0 at $1GeV^2$



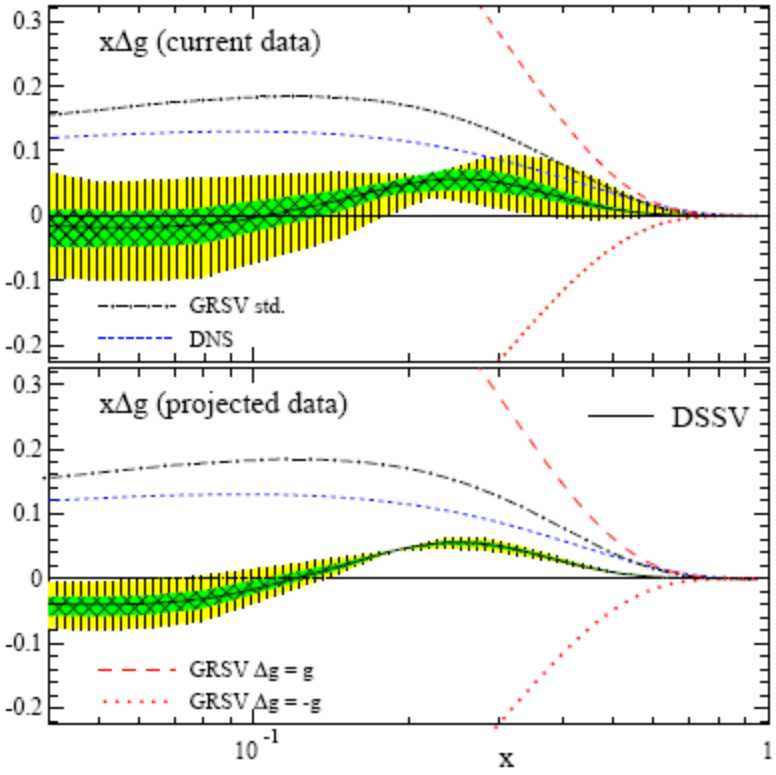
ΔG~-0.1 at $1GeV^2$

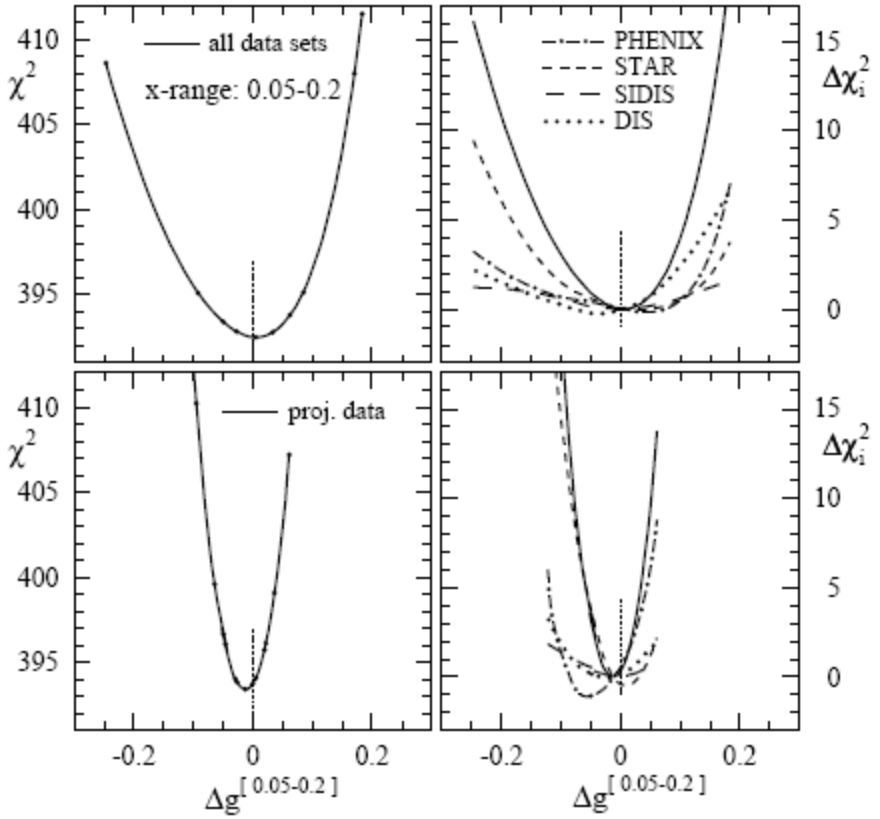
Future challenges

- Experimentally, we want to extend to wide range of x
- Theoretically, understand the dynamics: evolution
  - small-x: ~x^{α}, or, Ln(x), or other behavor
  - Resummation, BFKL for unpolarized, what about the polarized case?

    Bass-Landshoff, Ball-Forte-Ridolfi,Bartles-Ermolaev-Ryskin, …

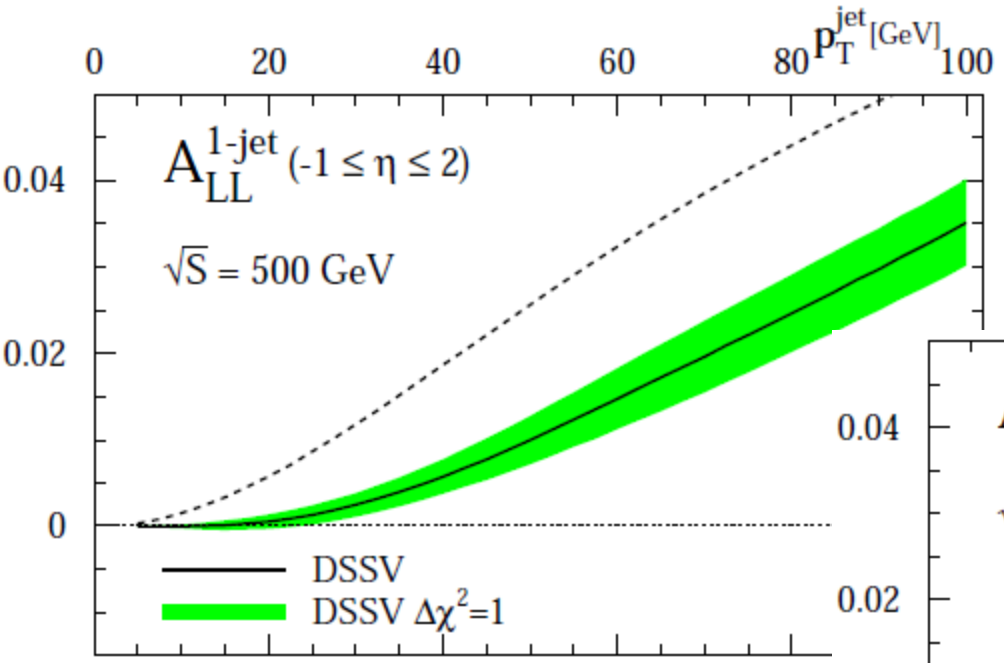
Future improvement

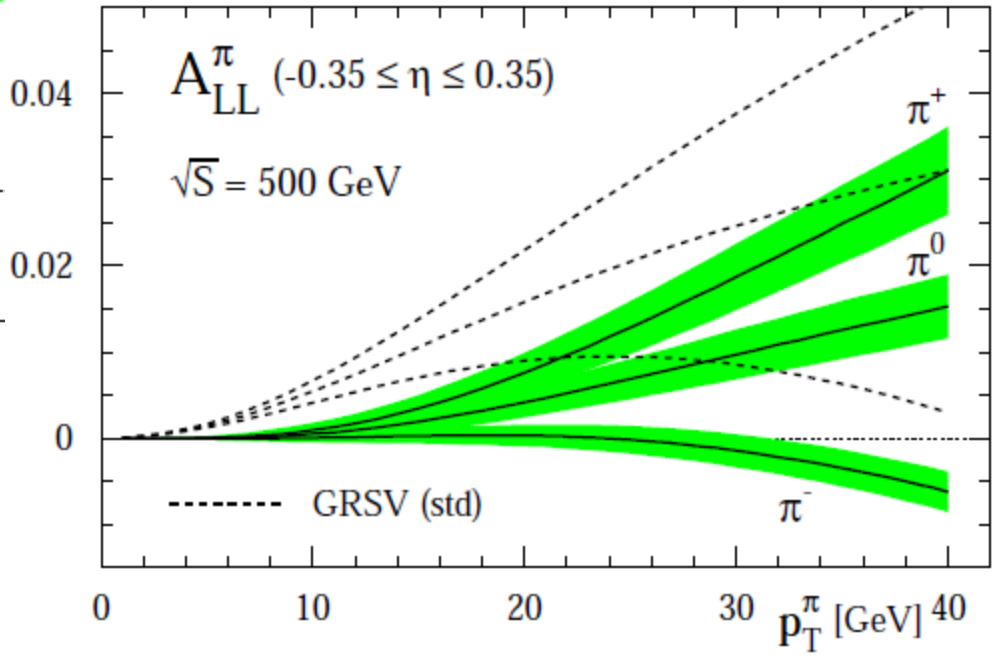




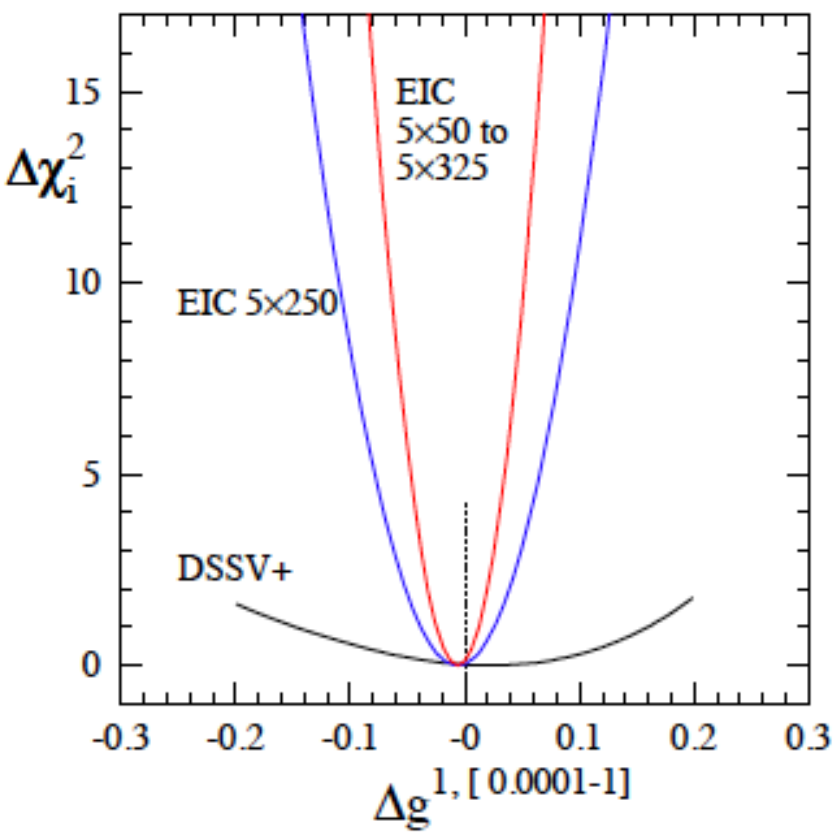
RHIC data errors scale down a factor of 4 expected from next long pp run
At 200GeV (50 pb^{-1} with 60% polarization) RHIC Spin plan 2008

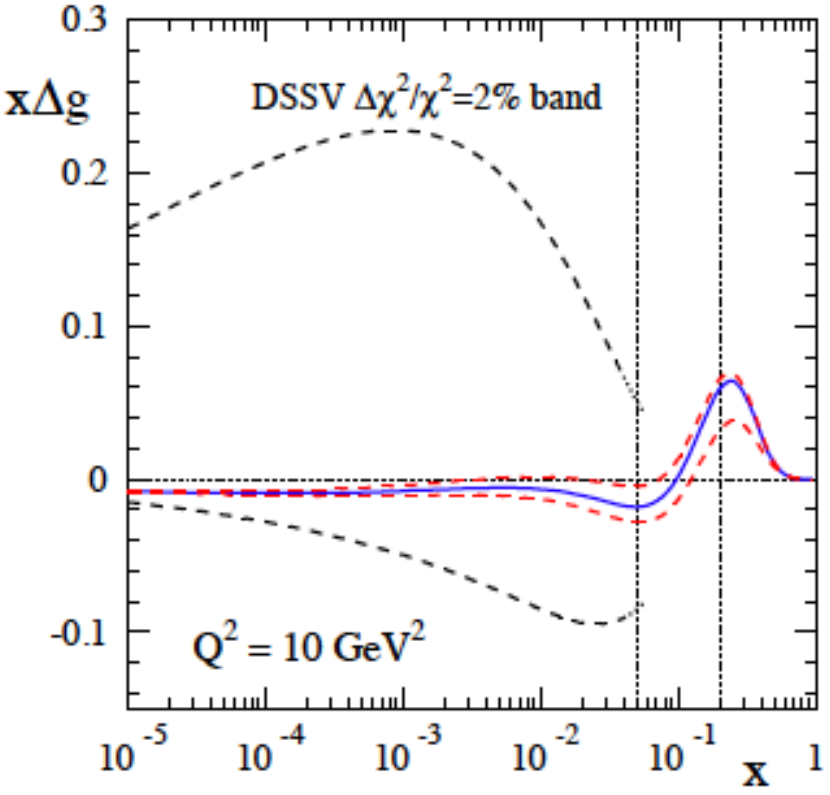
500GeV Impact





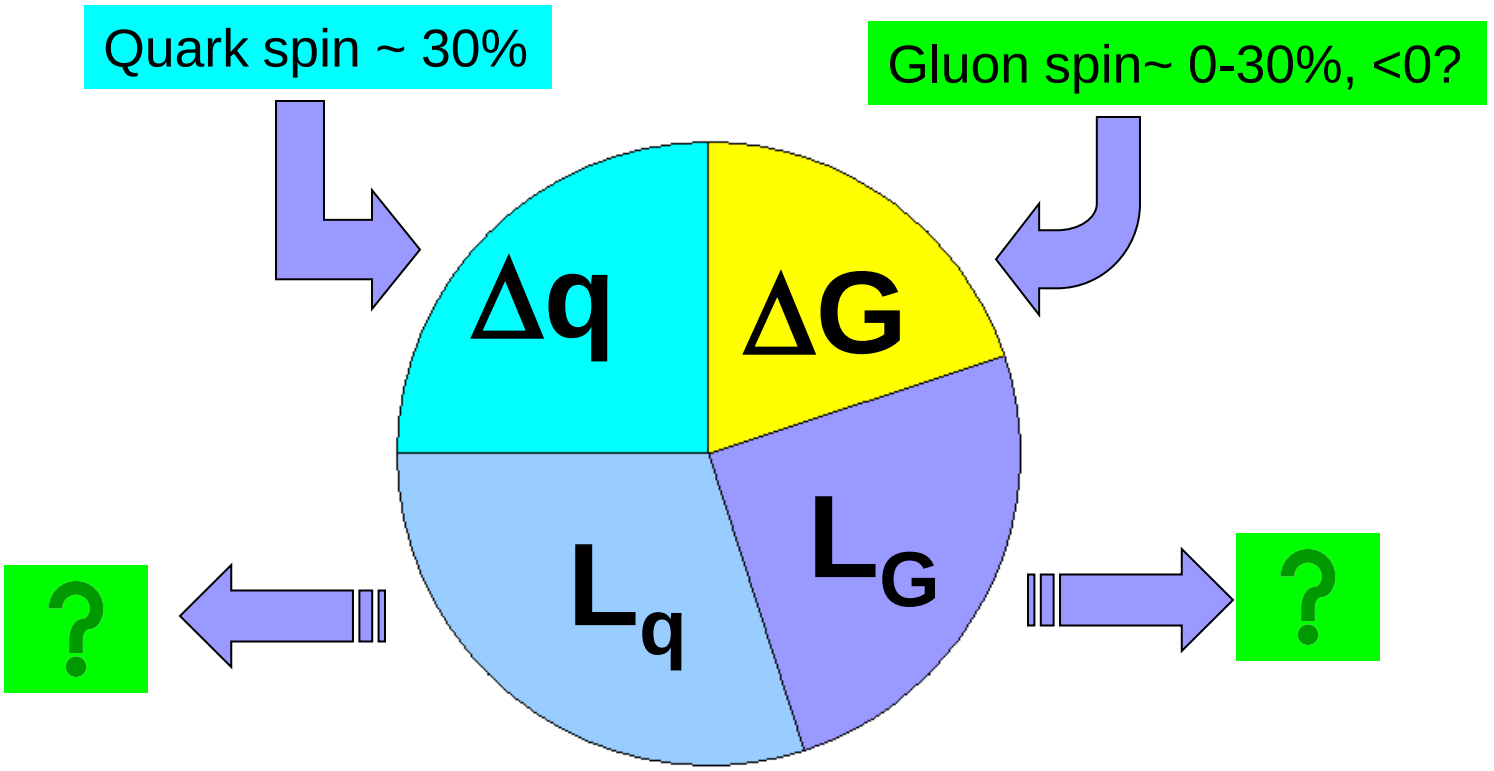
EIC Impact





Stratmann, et al., EIC-Write-up

Where are we now for the spin puzzle



Hunting for L_q:

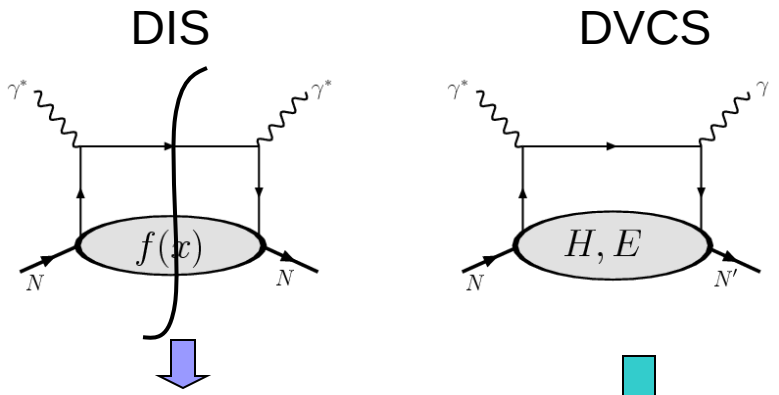
Generalised Parton Distributions (GPDs)

$$\int (H + E)\, x\, dx = J_q = 1/2\, \Delta\Sigma + L_z$$

Ji,96

$\Delta\Sigma$ → 25%(DIS)

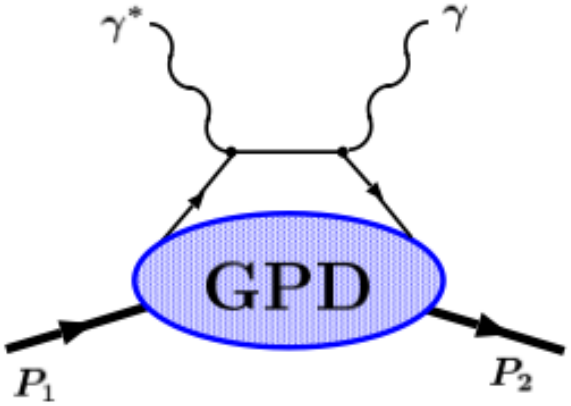
- A new type of parton "distributions" contains much more information
  - Can be measured in deeply virtual compton scattering and other hard exclusive processes
  - **Related to form factors and parton distributions**
- Comprehensive programs at JLab,HERMES,COMPASS

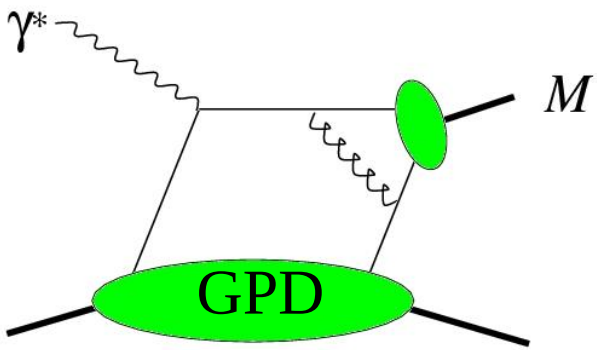


Mueller et al., 94; Ji, 96; Radyushkin, 96

Access the GPDs

- Deeply virtual Compton Scattering (DVCS) and deeply virtual exclusive meson production (DVEM)





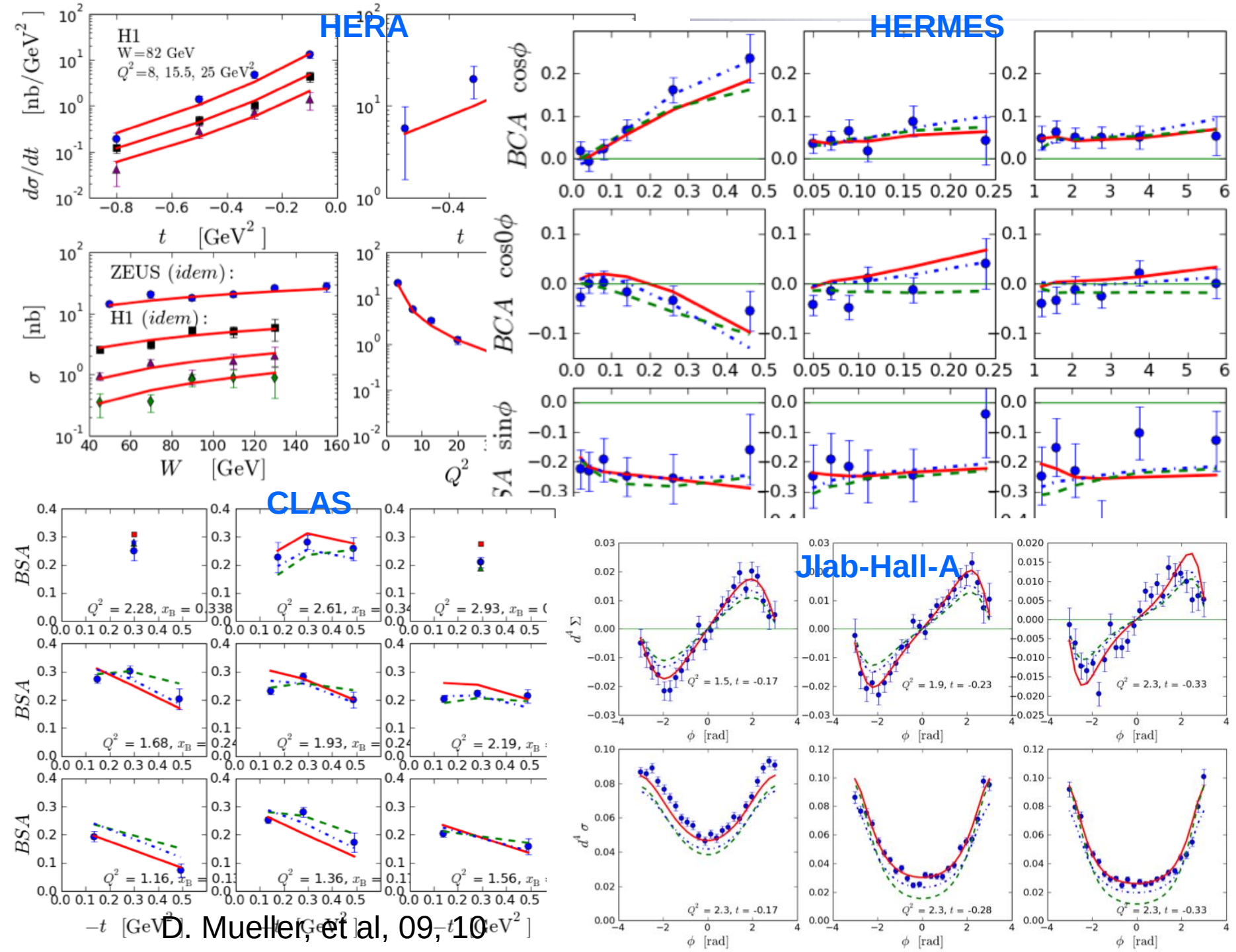
In the Bjorken limit: $Q^2 >> (-t), \Lambda^2_{QCD}, M^2$

Extract the GPDs

- The theoretical framework has been well established
  - Perturbative QCD corrections at NLO, some at NNLO
- However, GPDs depend on x, ξ, t, it is much more difficult than PDFs (only depends on x)
  - There will be model dependence at the beginning

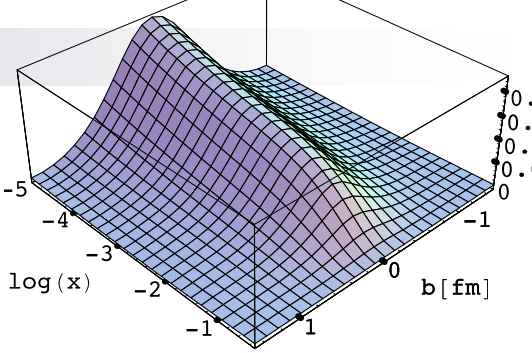
Great efforts have been made

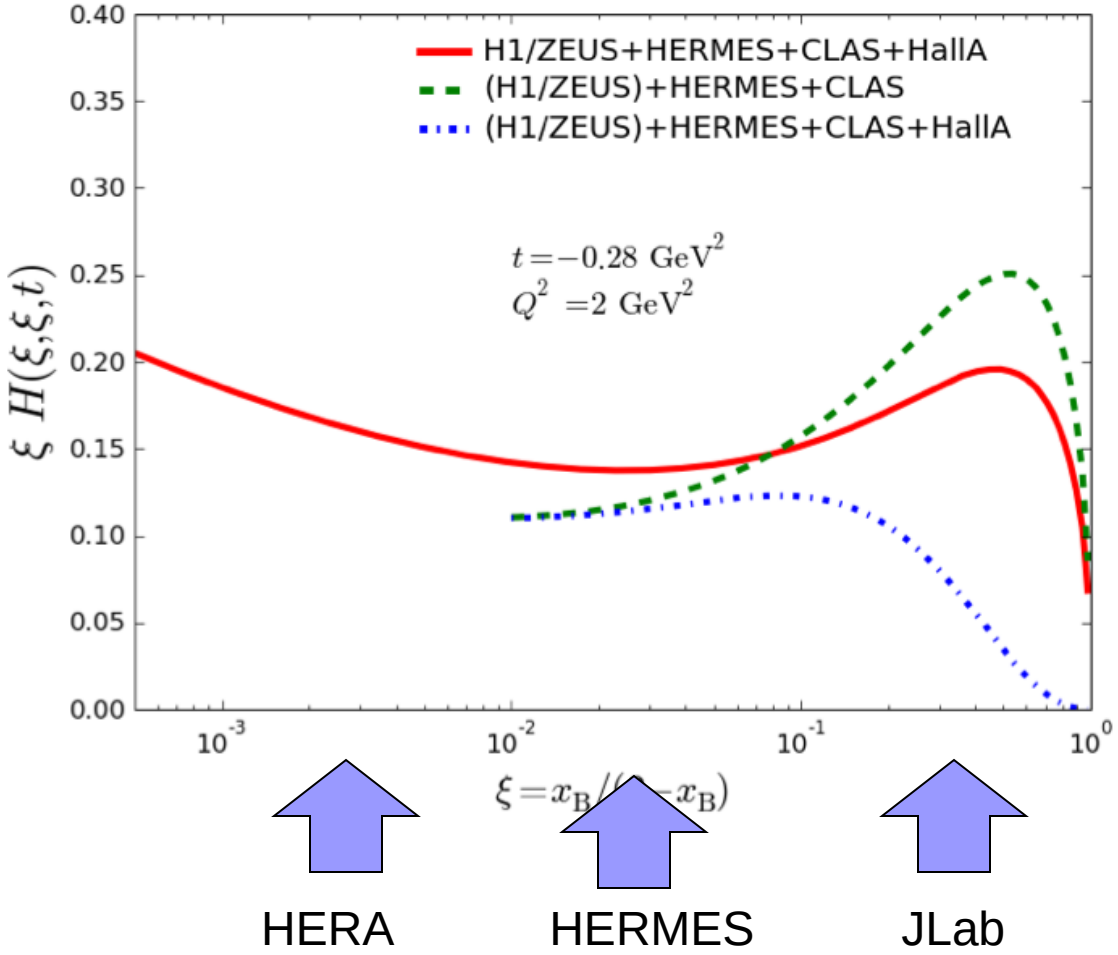
- Several groups have been working on extraction of the GPDs
- We do have a glimpse of the GPDs
- Decisive answer shall be possible with future JLab 12 GeV and COMPASS, and the planed EIC



D. Mueller, et al, 09, 10

One example: H(x,x,t)





D. Mueller, et al, 09, 10

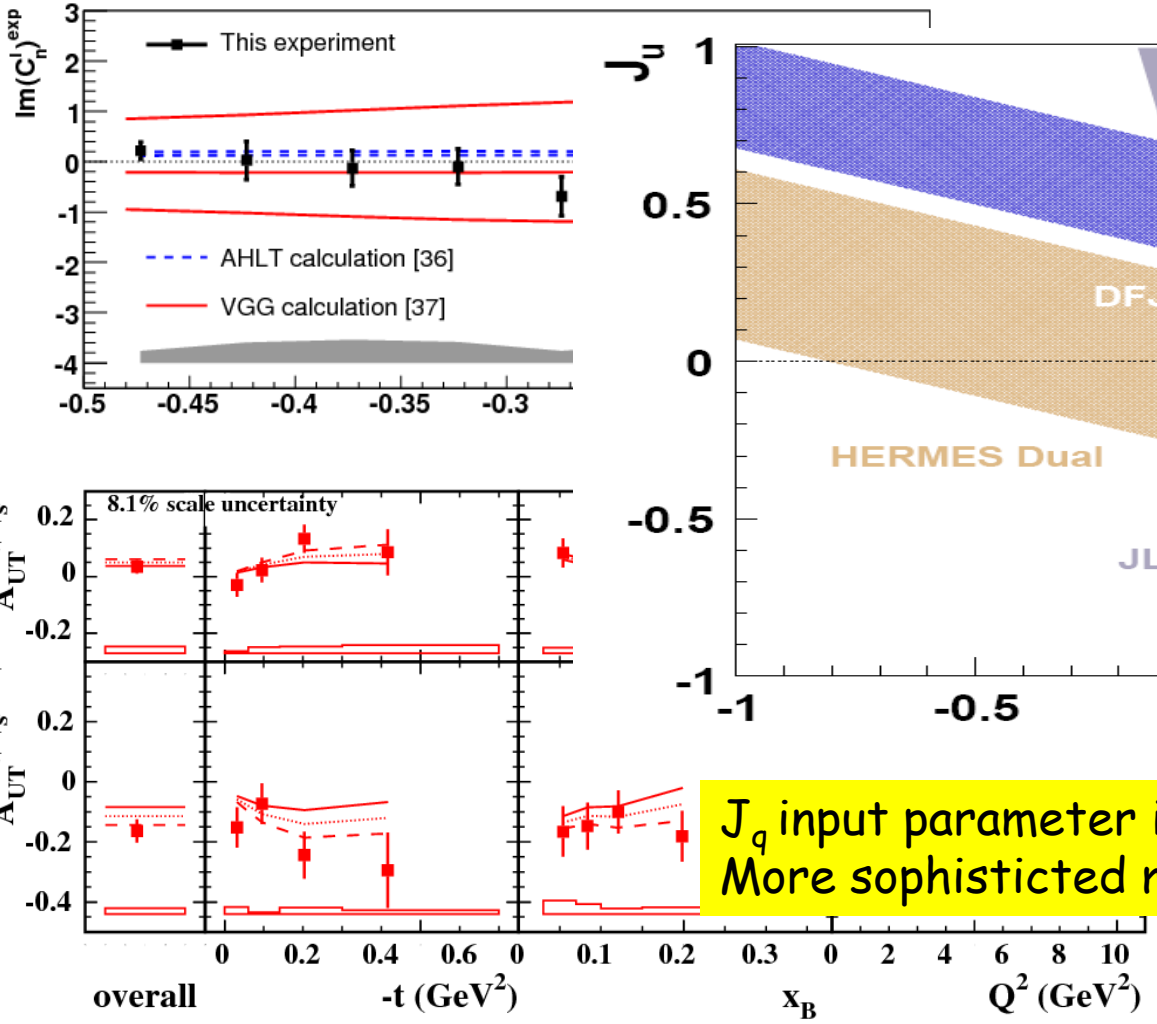
Small-x range constrained by HERA, uncertainties at large-x shall be very much reduced with Jlab 12 GeV COMPASS, and the planed EIC

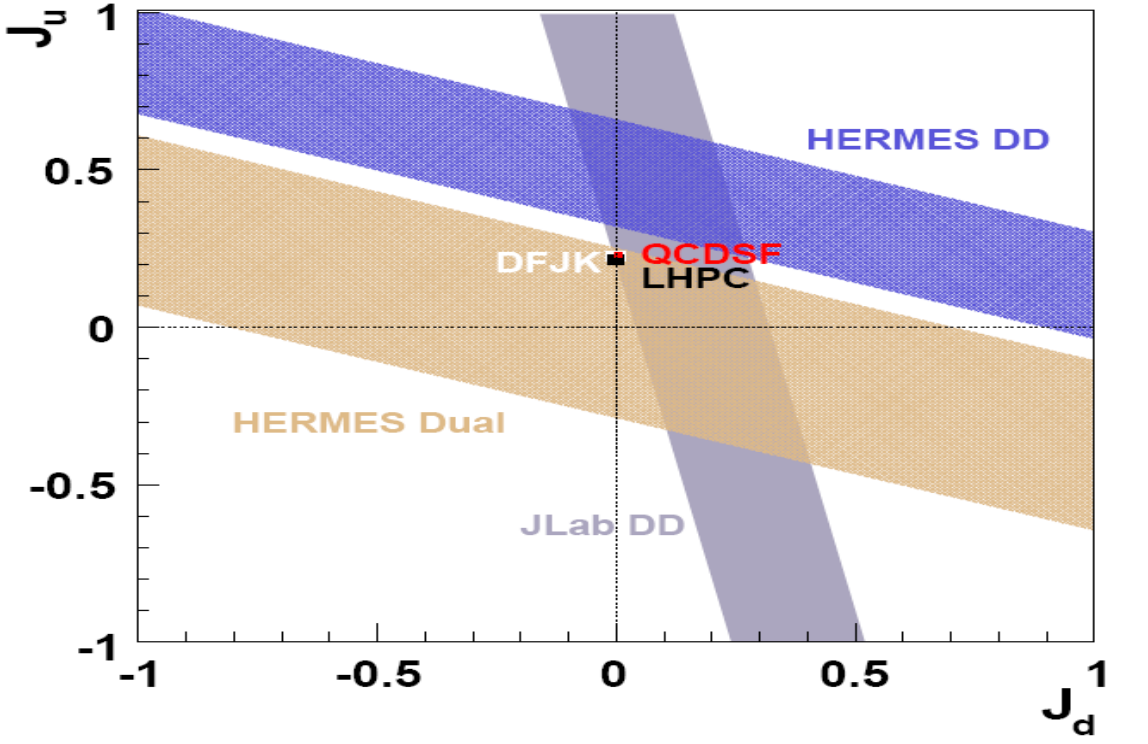
Of course, there are also other GPDs, in particular, the GPD E

Future challenges

- With vast data available in the future, theory has to build a solid way to
  - Understand the experimental data
  - Model-dependent fit
- Model-independently extract orbital angular momentum from the exp. Data as much as possible
- Gluon GPD→OAM is a real challenge!
  - Kroll, Metz, Mueller et al.,…

DVCS with transversely polarized target from HERMES & Jlab



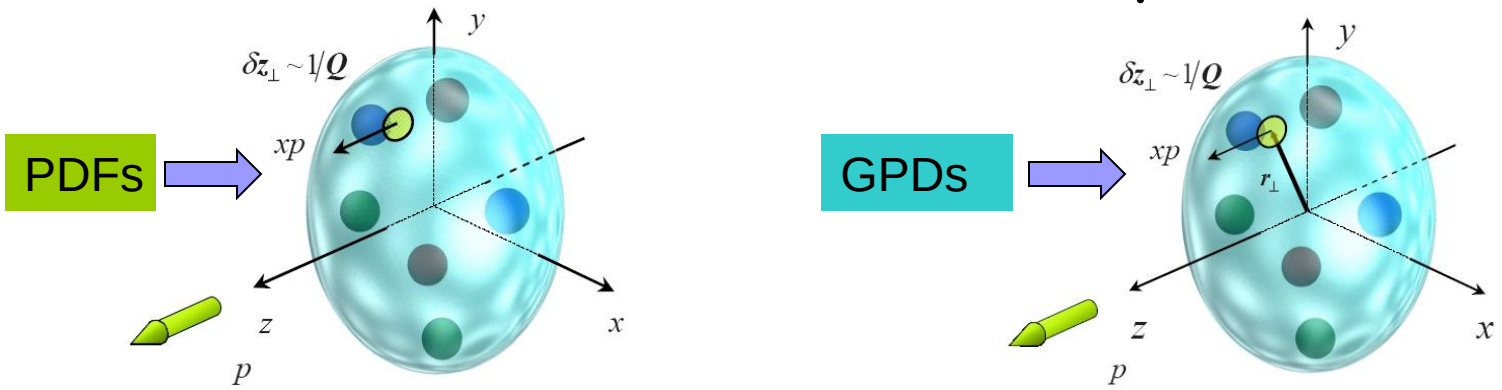


J_q input parameter in the GPD ansatz, need More sophisticted model for GPDs

Jlab Hall A, 0709.0450; HERMES, 0802.2499

Hadron tomography via GPDs

- GPDs: fully correlated parton distributions in both momentum and coordinate space

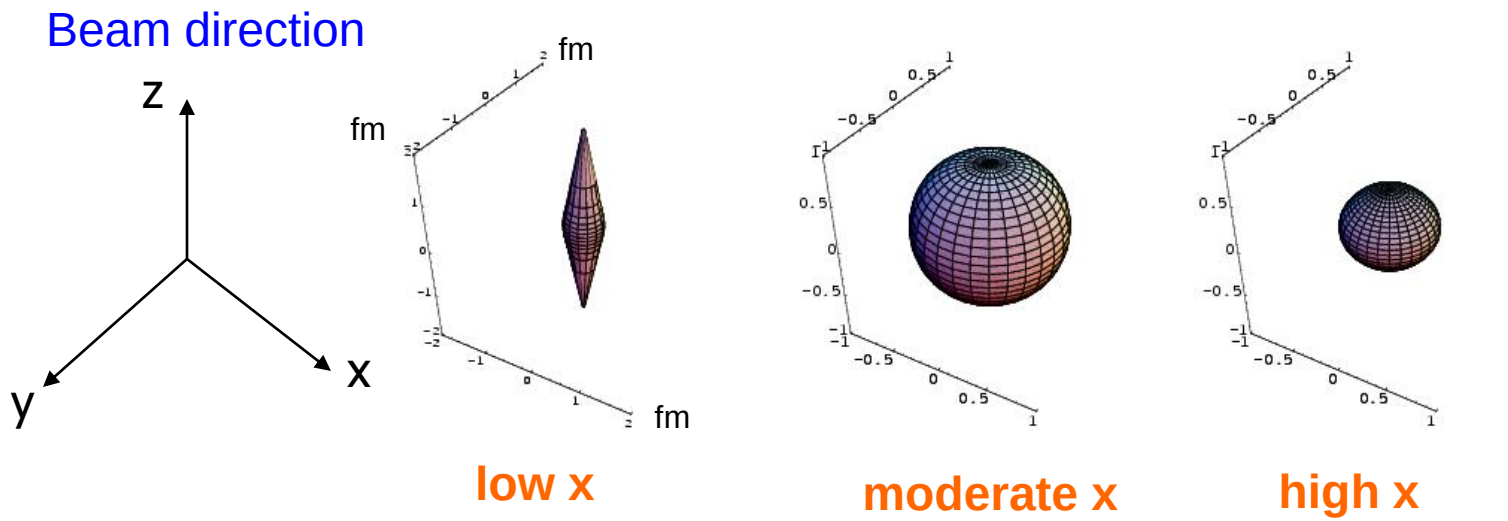


- From the Fourier transform of the momentum transform, we will obtain the partons' 3-d image in nucleon

Burkardt 00,02;
Belitsky-Ji-Yuan, PRD04

3D image of quarks at fixed-x

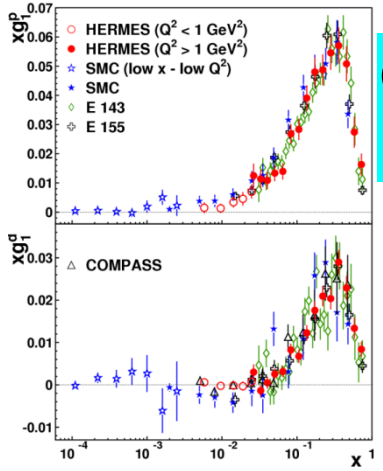
- GPDs can be used to picture quarks in the proton (Belitsky-Ji-Yuan, PRD 04)
  - Fourier transform of the GPDs (respect to the momentum transfer) is a function of position $\vec{r}$ and Feynman momentum x: $f(\vec{r},x)$
  - One can plot this distribution as a 3D function at fixed x



Momentum Distribution in 3-D

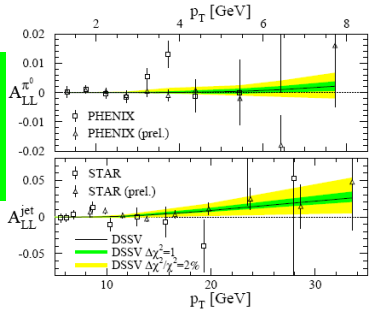
- Transverse momentum dependent parton distributions
- Great progress in the last few years
  - Connections to other phenomena
    - Quark-gluon correlation (twist-3) effects
    - Generalized Parton Distributions
  - QCD dynamics: Factorization, Universality, …
  - **Still in developing…**
- Single Transverse Spin Asymmetry

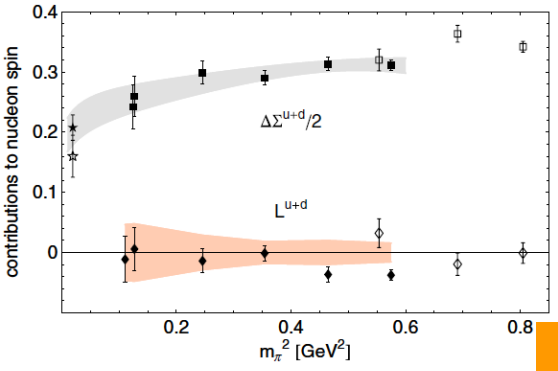
Proton Spin Sum Rule

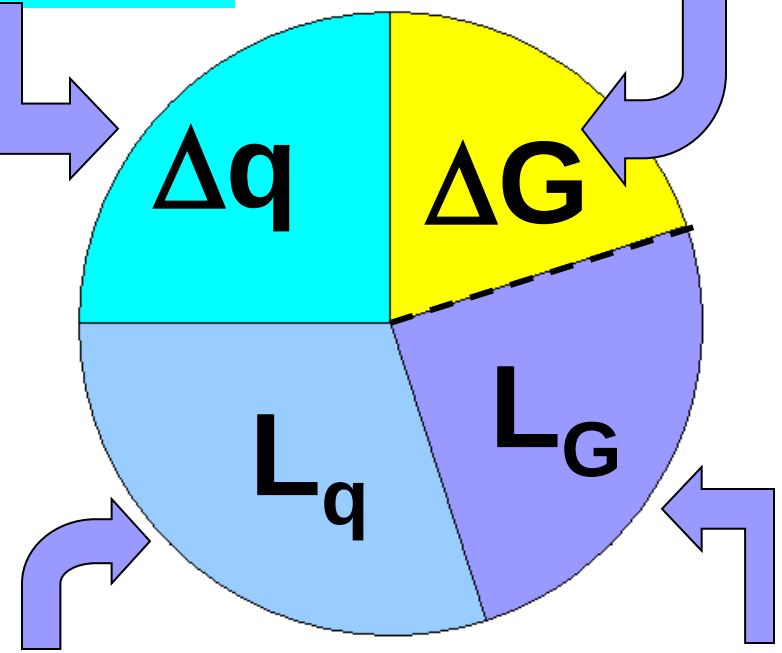


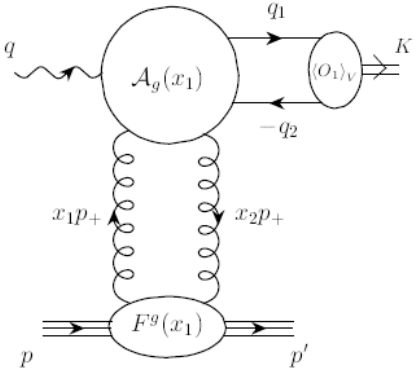
Quark spin ~30%
DIS, and pp coll.

Gluon spin~ 0-70%
RHIC, EIC, …









Deeply Virtual Compton Scattering,
Exclusive Meson Production in DIS,
Transverse spin phenomena

Challenge Sum Rule

RBRC has been very success to bring experimentalists and theorists together. Hope this will continue