New Results on Nucleon Spin and 3D Structure Measurements

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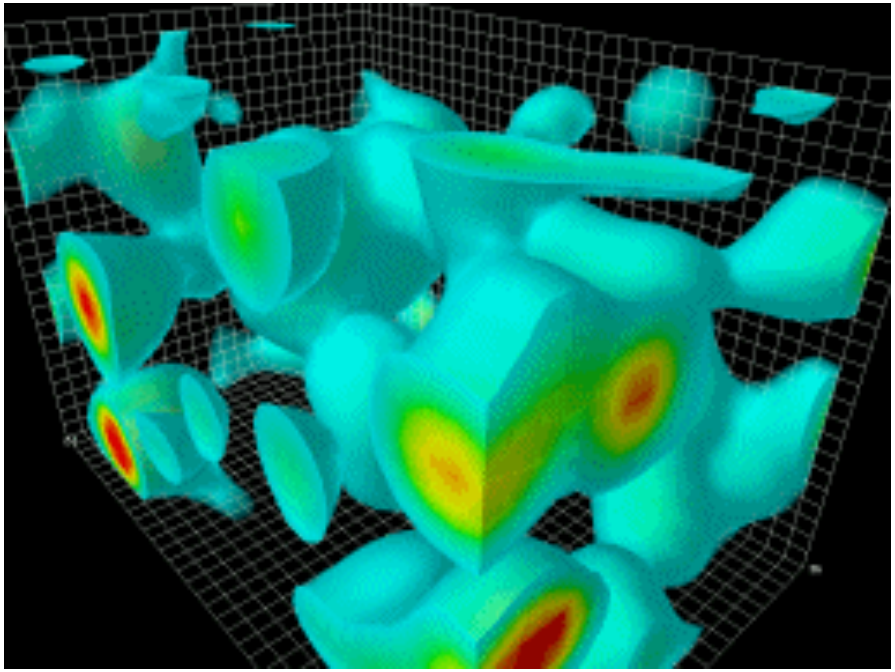
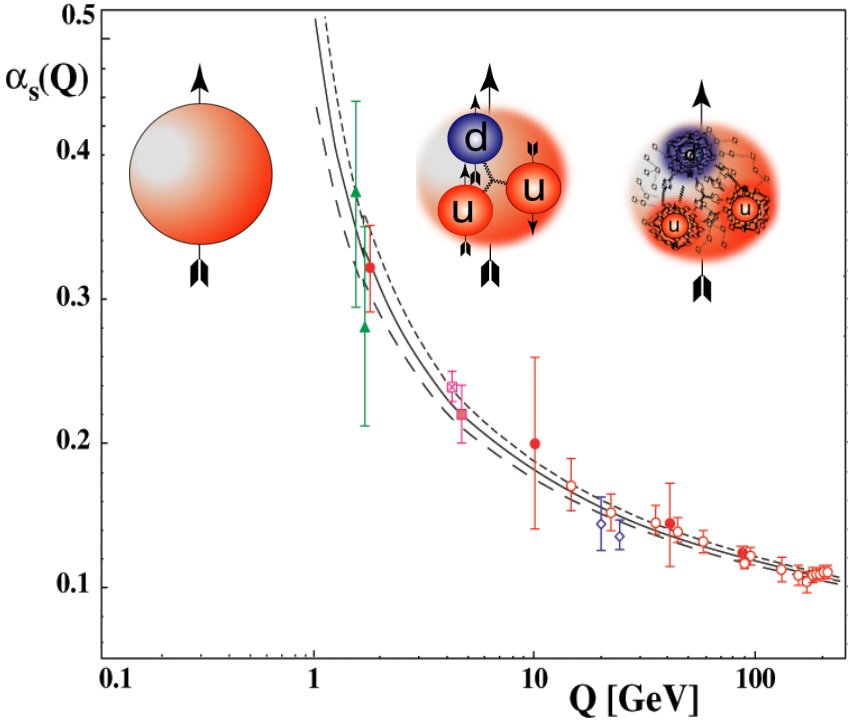
Duke UNIVERSITY

昆山杜克大学 DUKE KUNSHAN UNIVERSITY

QCD: still unsolved in non-perturbative region



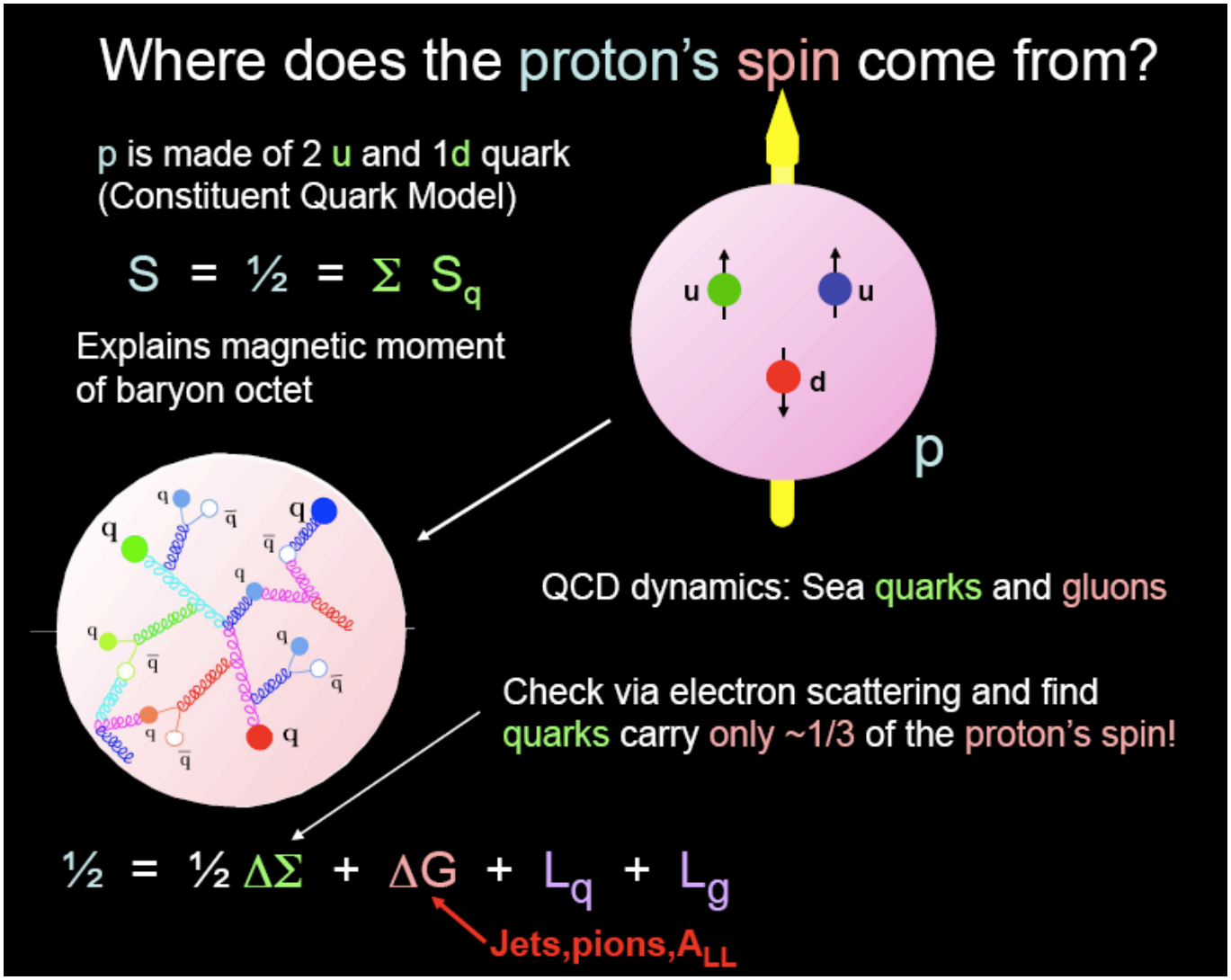


Gauge bosons: gluons (8)

- ***2004 Nobel prize for ``asymptotic freedom''***
- ***non-perturbative regime QCD ?????***
- ***One of the top 10 challenges for physics!***
- ***QCD: Important for discovering new physics beyond SM***
- ***Nucleon structure is one of the most active areas: spin puzzle, ...***

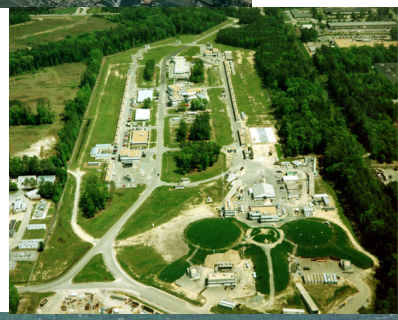
Spin structure of the nucleon

- 1980s: "Proton spin crisis" (original EMC result from CERN)



Impressive experimental progress in QCD spin physics in the last 30 years

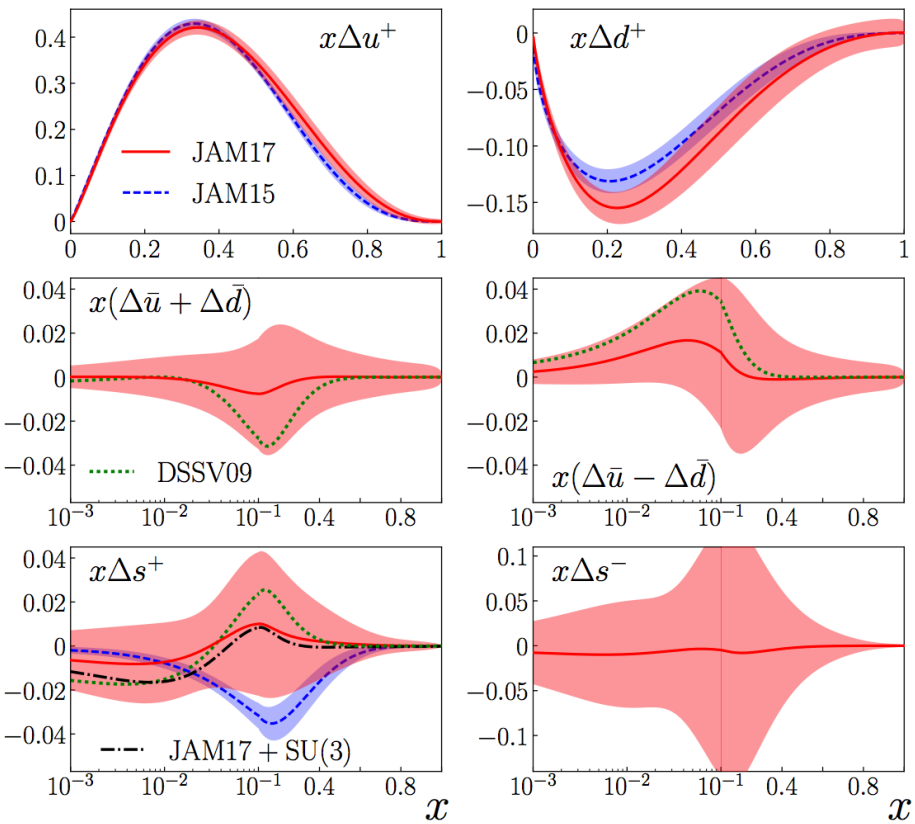
- **Inclusive spin-dependent DIS**
  - CERN: EMC, SMC, COMPASS
  - SLAC: E80, E142, E143, E154, E155
  - DESY: HERMES
  - JLab: Hall A, B and C
- **Semi-inclusive DIS**
  - SMC, COMPASS
  - HERMES, JLab
- **Polarized pp collisions**
  - BNL: PHENIX & STAR
  - FNAL: POL. DY
- **Polarized e+e- collisions**
  - KEK: Belle

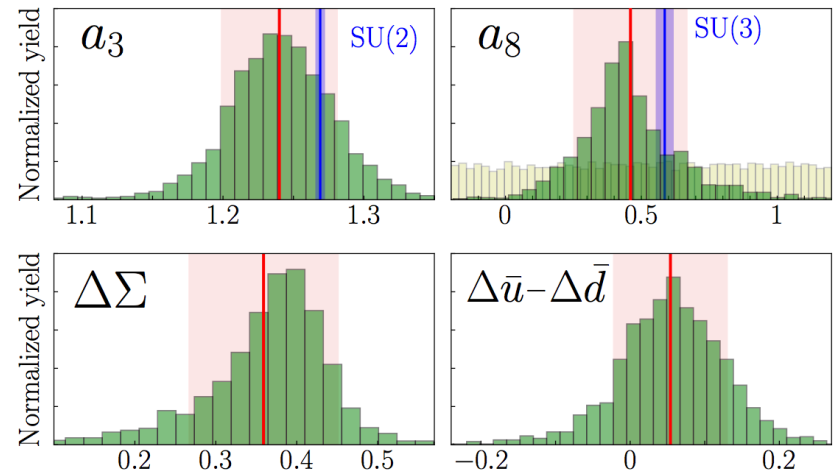


Z. Meziani

Global Analysis: Polarized PDF

Global analysis of spin-dependent parton





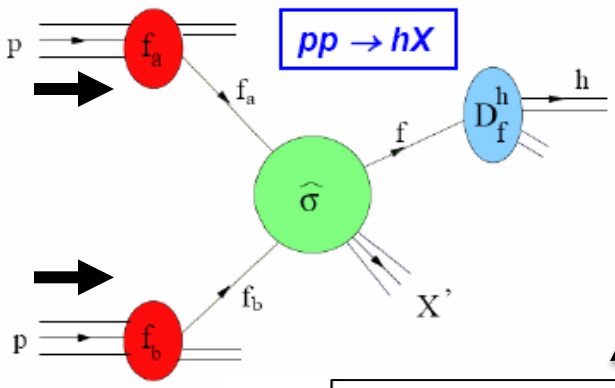
$$\Delta\Sigma = 0.36(9)$$

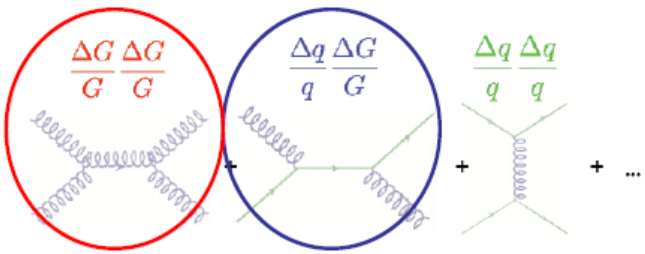
$$\Delta s^+ = -0.03(10)$$

$$(\mu^2 = 1\ \mathrm{GeV}^2)$$

J.J. Ethier *et al.* (JAM Collaboration), Phys. Rev. Lett. 119, 132001 (2017).

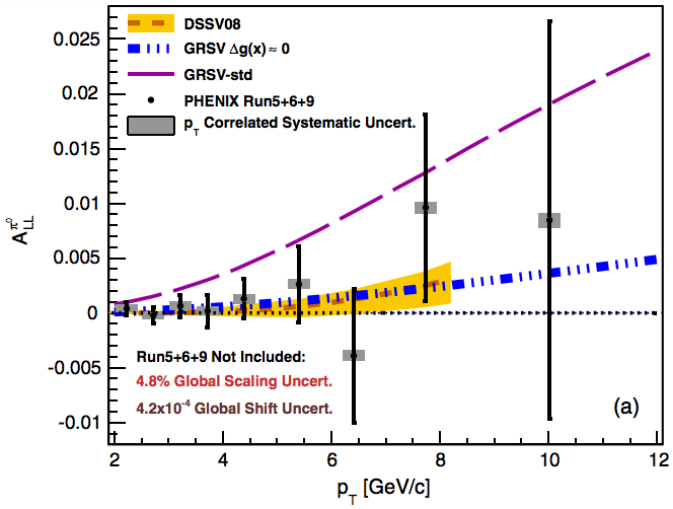
Measurement of the gluon polarization Δg at RHIC



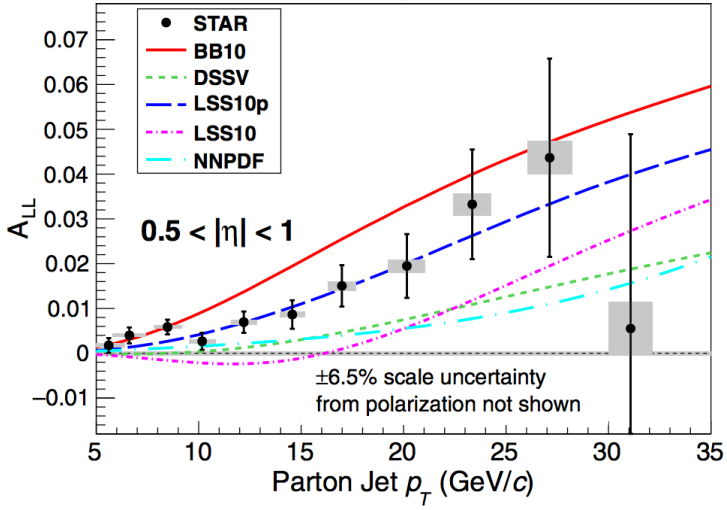


Dominates at low p_T

Dominates at high p_T



Phys. Rev. D 90 (2014) 012007



Phys. Rev. Lett. 115 (2015) 092002

D. de Florian *et al*,
PRL 113 (2014) 012001

E. Nocera et al,
NPB 887 (2014) 276

Surrow et al on sea quark spin from W production at RHIC

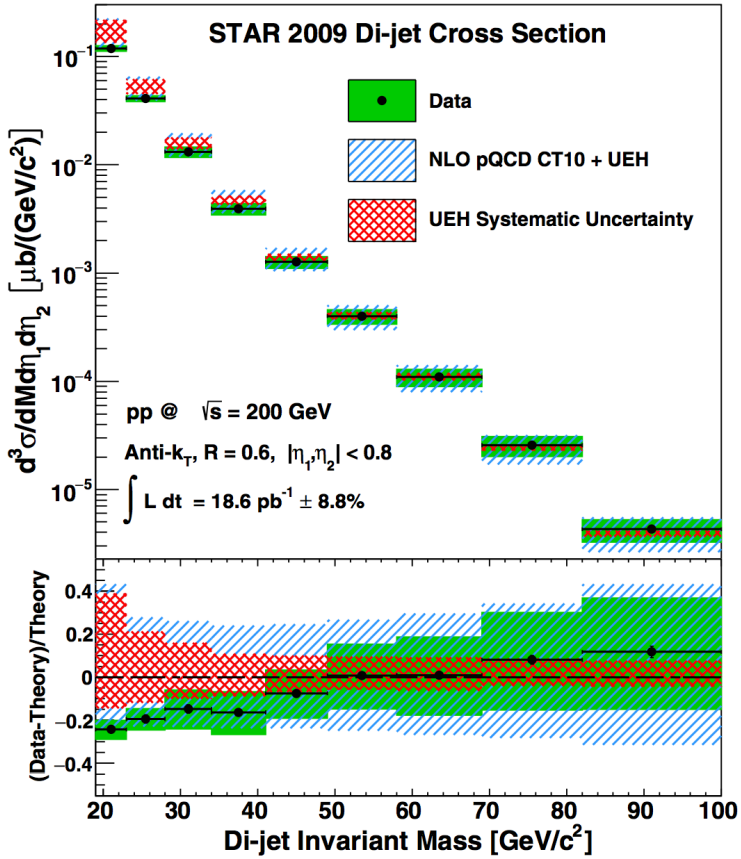
$\int_{0.05}^{1} dx\Delta g(x,Q^2=10GeV^2) = 0.20^{+.06}_{-.07}$ DSSV++

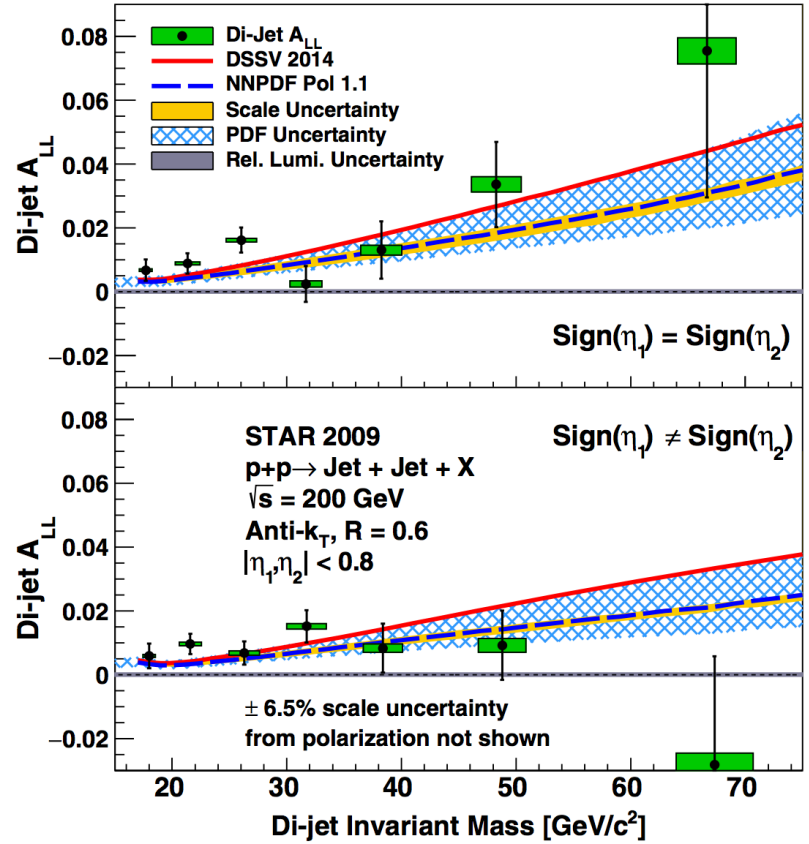
$\int_{0.05}^{0.2} dx\Delta g(x,Q^2=10GeV^2) = 0.17+-0.06$ NNPDFpol1.1

$\int_{0.001}^{0.8} dx\Delta g(x,Q^2 = 1\ GeV^2) = 0.5+-0.4$ JAM15

Longitudinal DSA for Dijet in pp Collisions

First measurement of A_{LL} for midrapidity dijet in polarized pp collisions



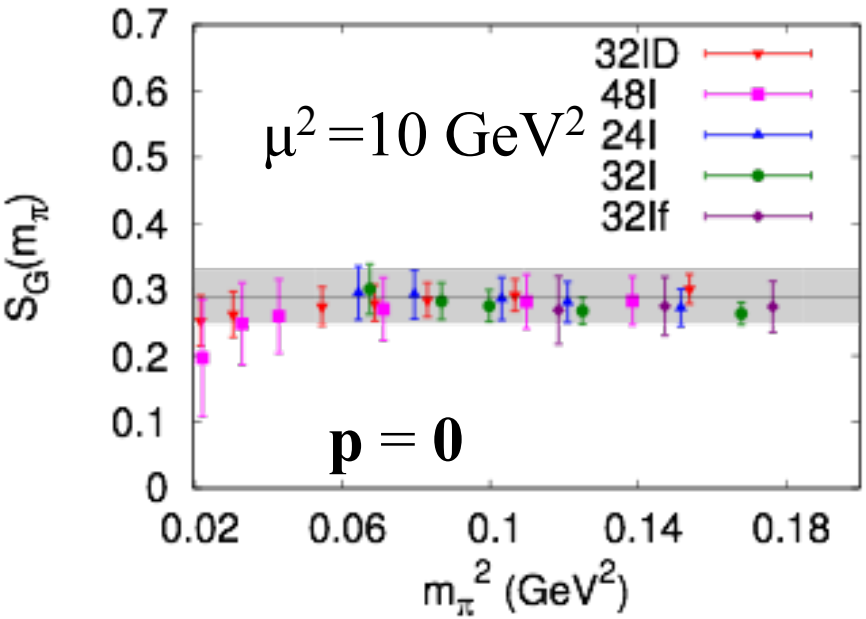


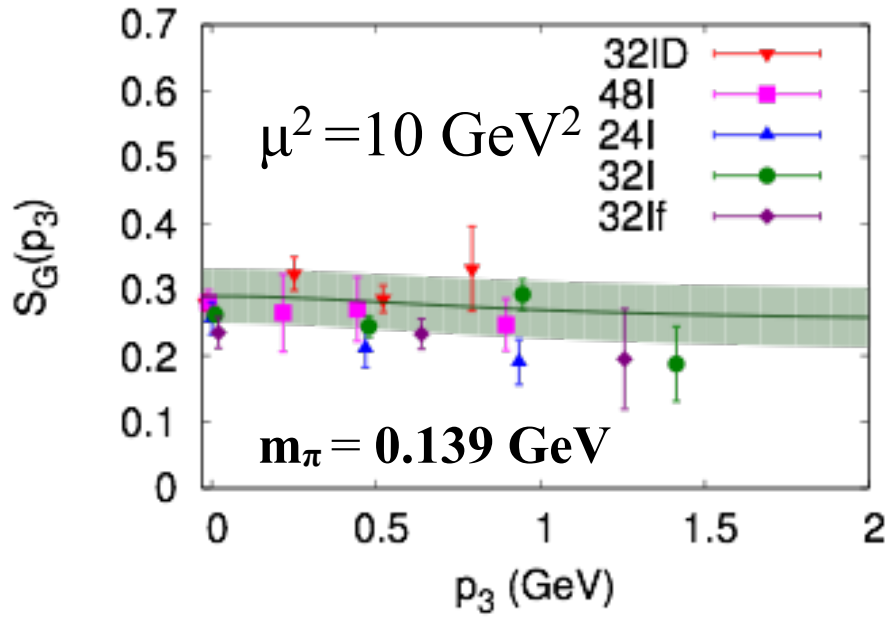
Support analyses that find $\Delta g \sim 0.2$ for the region of x>0.05

L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. D 95, 071103(R) (2017).

Gluon Spin From Lattice QCD

First lattice QCD calculation of the gluon spin in the nucleon





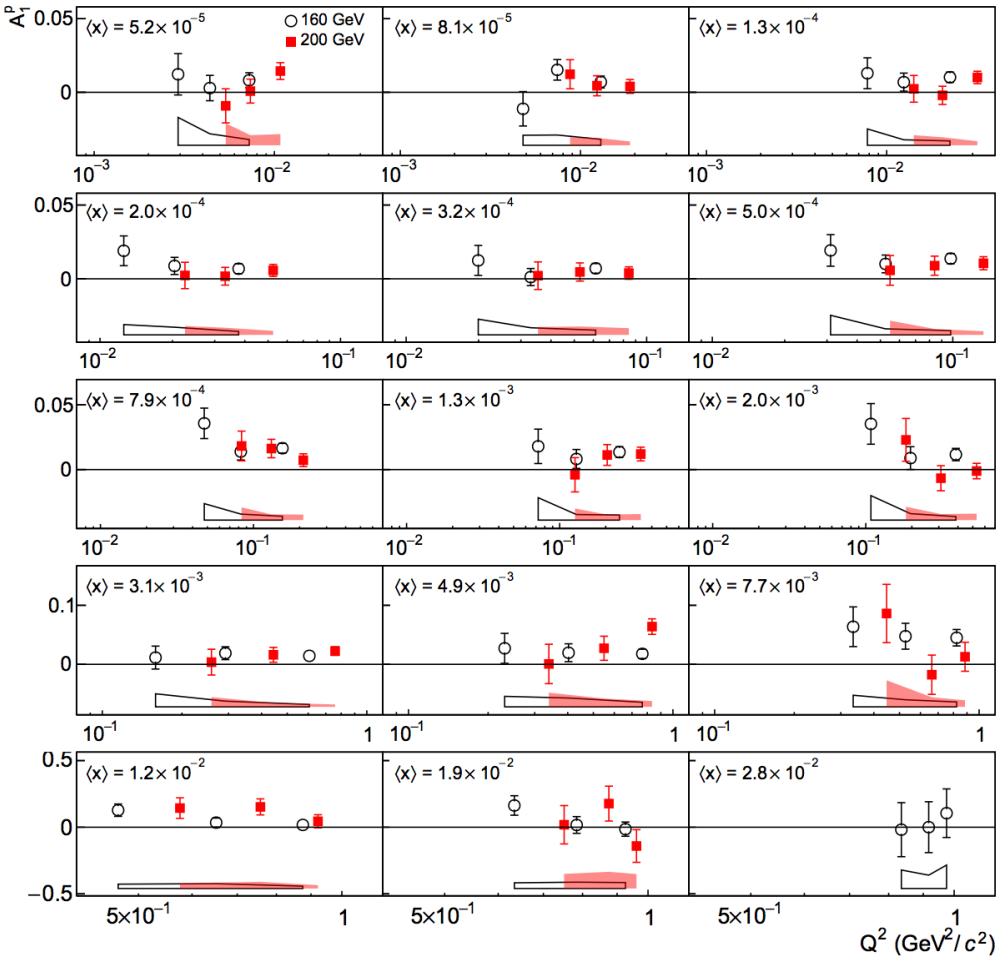
$$\Delta G \approx S_g\,(|\mathbf{p}|\to\infty): \quad 0.251(47)(16) \qquad (\mu^2 = 10\ \mathrm{GeV}^2)$$

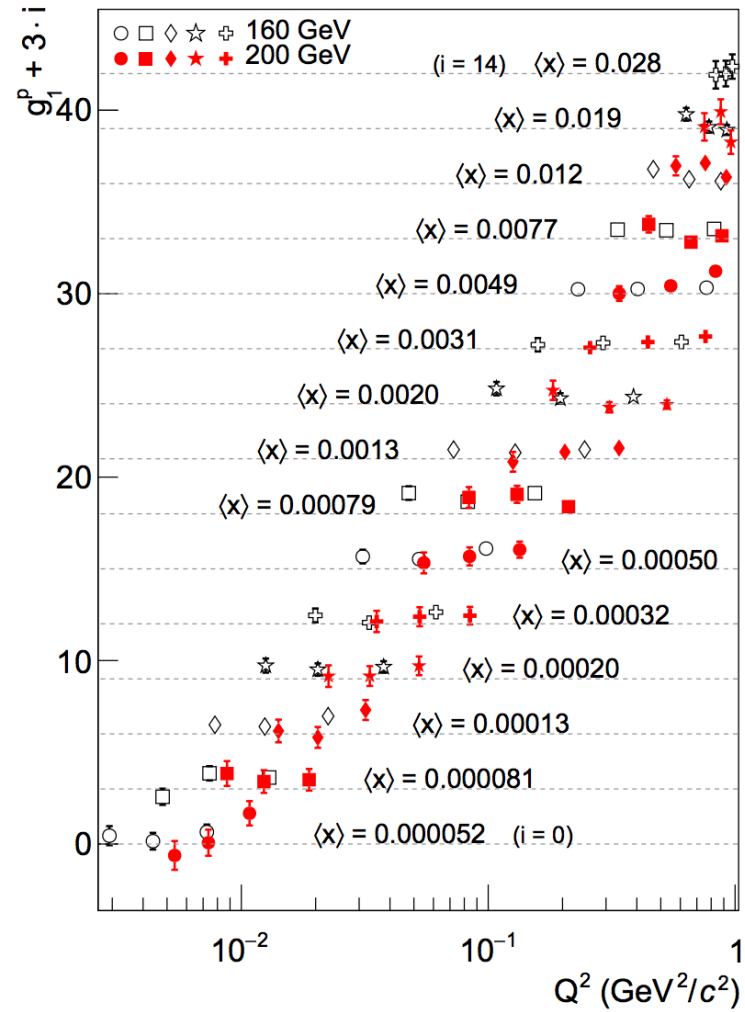
50(9)(3)% of the total proton spin

Y.-B. Yang *et al.* (χQCD Collaboration), Phys. Rev. Lett. 118, 102001 (2017).

Proton Spin Structure Function at Small-*x*

Spin effects are found at such small-x (down to 4×10^{-5}) for the first time



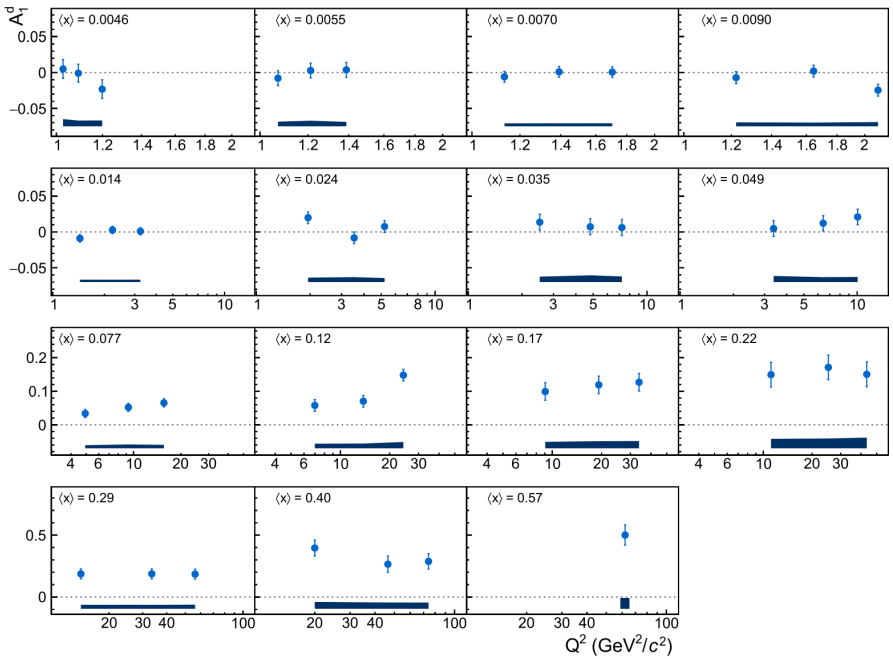


M. Aghasyan *et al.* (COMPASS Collaboration), arXiv:1710.01014 [hep-ex].

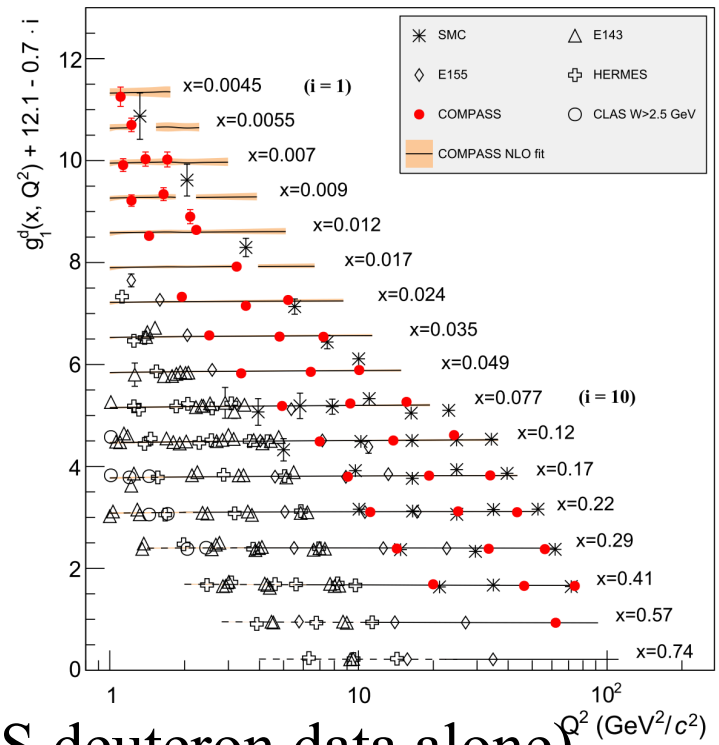
Deuteron Spin Structure Function

Final COMPASS results:

Longitudinal spin asymmetry



Spin-dependent structure function



Flavor singlet axial charge (COMPASS deuteron data alone)

$$a_0(Q^2 = 3\,(\mathrm{GeV}/c)^2) = 0.32 \pm 0.02_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}} \pm 0.05_{\mathrm{evol}} \qquad \text{(NLO)}$$

C. Adolph *et al.* (COMPASS Collaboration), Phys. Lett. B 769, 34 (2017).

GDH Sum Rule

- GDH sum rule

$$I_N^{GDH} = \int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} \left(\sigma_{\frac{3}{2}}(\nu) - \sigma_{\frac{1}{2}}(\nu) \right) = 2\pi^2 \alpha \frac{\kappa^2}{M^2}$$

$$I^{GDH} = \int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} \left(\sigma_P(\nu) - \sigma_A(\nu) \right) = 4\pi^2 \alpha \frac{\kappa^2}{M^2} S$$

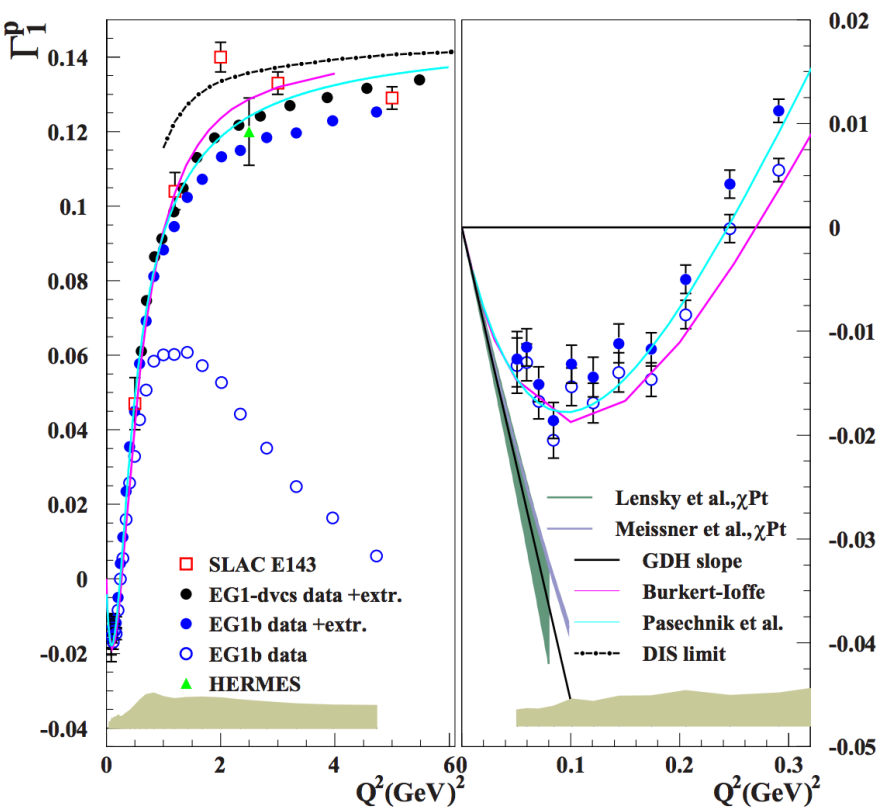
- Generalized GDH sum rule

$$I_{TT}(Q^2) = \frac{M^2}{4\pi^2 \alpha} \int_{\nu_{th}}^{\infty} \frac{K(\nu, Q^2) \sigma_{TT}(\nu, Q^2)}{\nu^2} d\nu$$

$$= \frac{2M^2}{Q^2} \int_0^{x_{th}} \left[g_1(x, Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x, Q^2) \right] dx$$

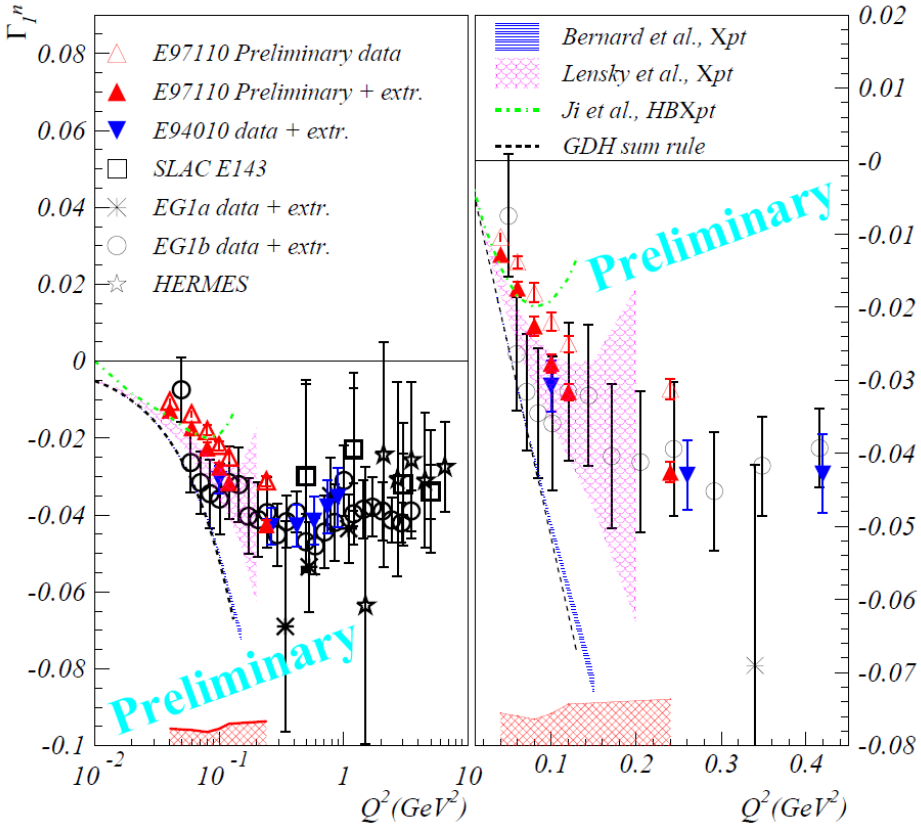
Generalized GDH Sum Rule for Nucleons

Proton:



R. G. Fersch *et al.* (CLAS Collaboration), Phys. Rev. C 96, 065208 (2017).

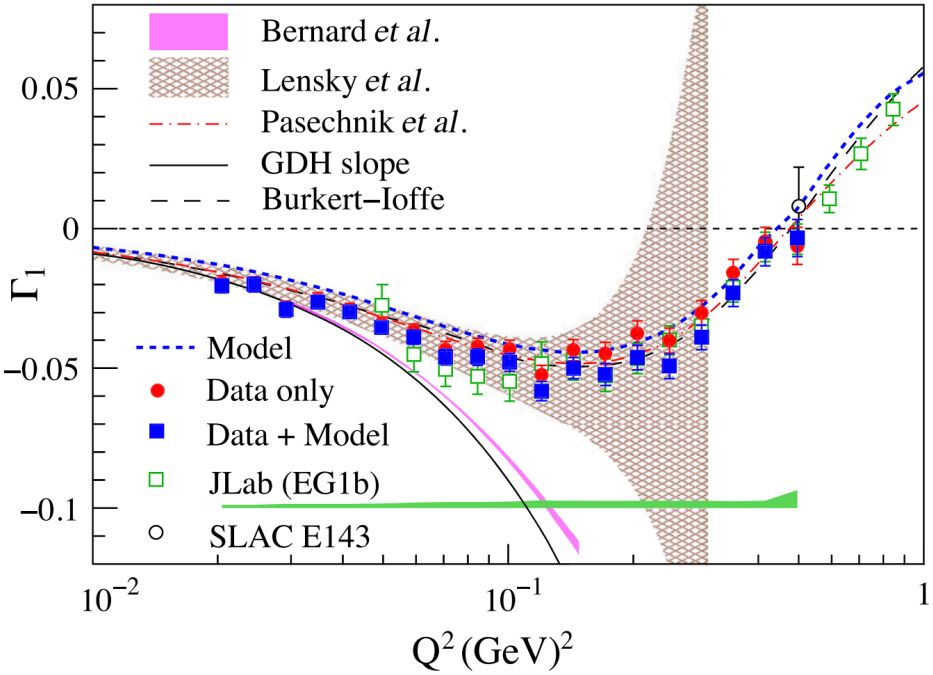
Neutron:

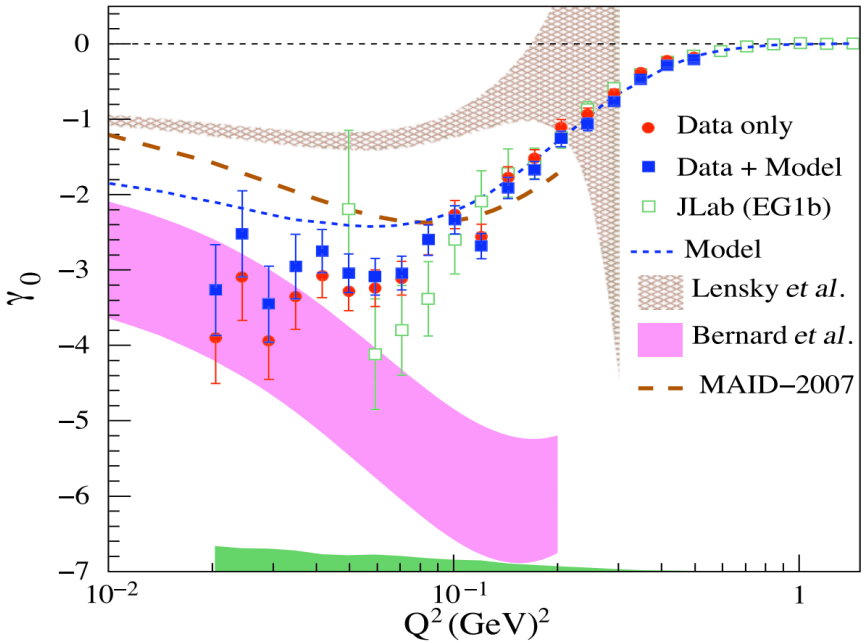


Provided by V. Sulkosky (Preliminary result of E97110)

Deuteron Spin Structure Function at Low-Q^2

Deuteron generalized GDH sum, the moment Γ_1, and the spin polarizability γ_0 are determined down to $Q^2 \sim 0.02$ GeV^2 for the first time





$$\Gamma_1(Q^2) = \int_0^{x_0} g_1(x, Q^2)dx = \frac{Q^2}{2M^2} I_1(Q^2)$$

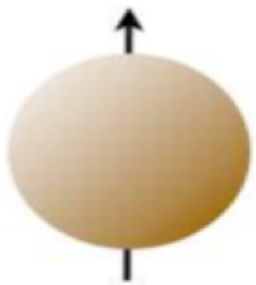
$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left(g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right) dx$$

$$I^{GDH} = \int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} \left(\sigma_P(\nu) - \sigma_A(\nu) \right) = 4\pi^2 \alpha \frac{\kappa^2}{M^2} S$$

K.P. Adhikari *et al.* (CLAS Collaboration), Phys. Rev. Lett. 120, 062501 (2018).

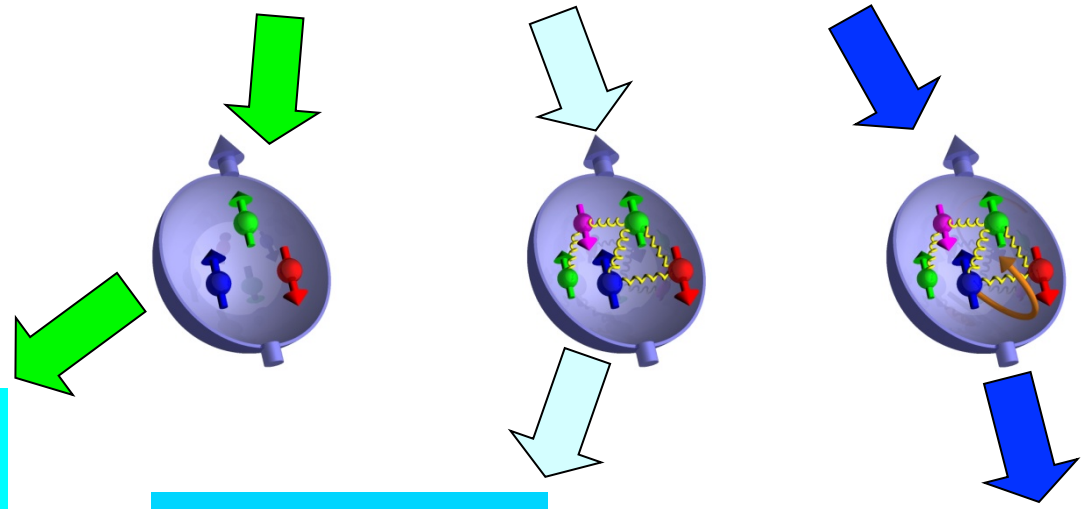
The incomplete nucleon: spin puzzle

Jaffe-Manohar, 90
Ji, 96



Proton Spin

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



Quark helicity
Best known

$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

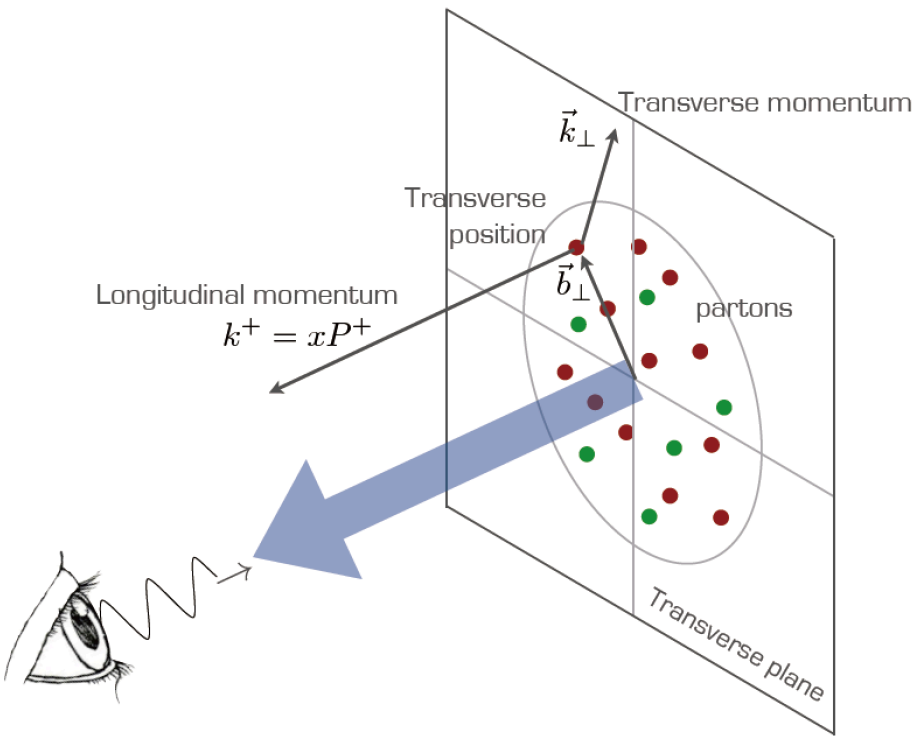
$$\sim 20\%(\mathrm{STAR\ Data})$$

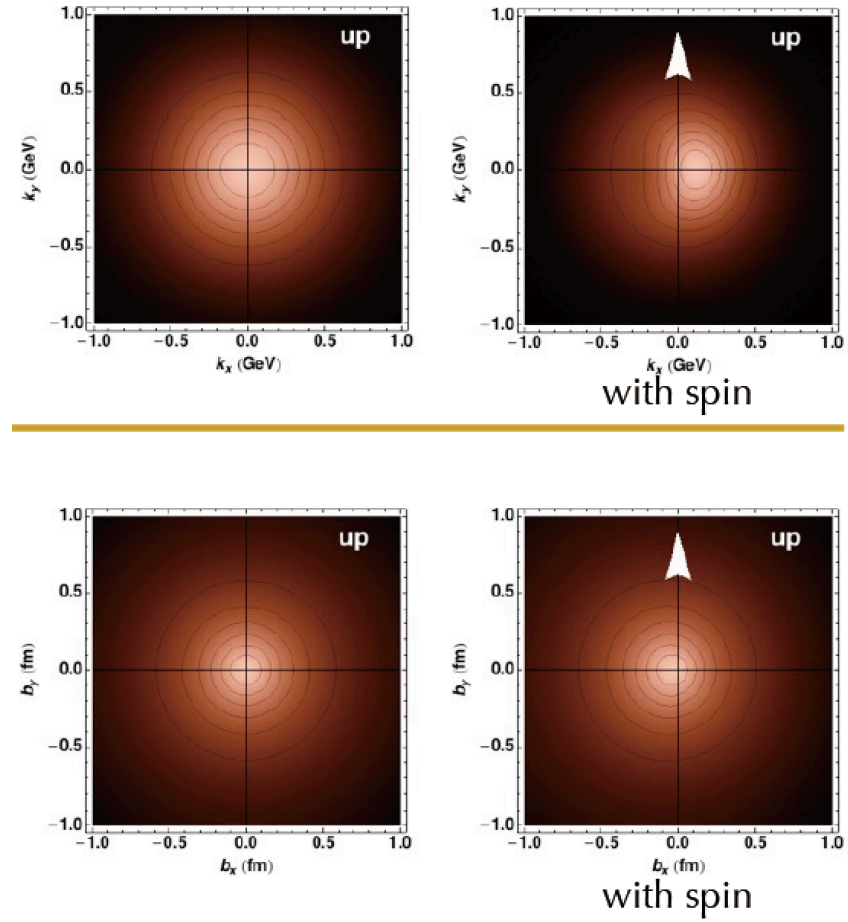
Maybe even more from Lattice

Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

Orbital motion - Nucleon Structure from 1D to 3D





Generalized parton distribution (GPD)

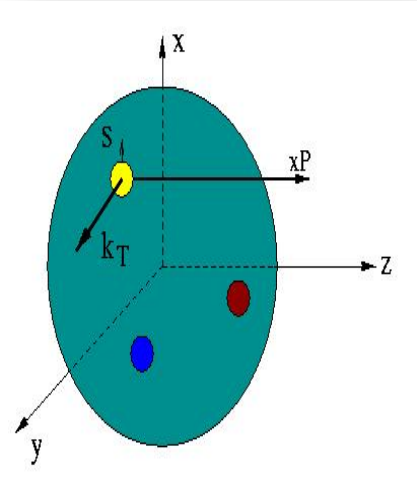
Transverse momentum dependent parton distribution (TMD)

[Bacchetta's talk (2016)]

Unified View of Nucleon Structure

$W_p^u(x,k_T,\boldsymbol{r_T})$ Wigner distributions

5D Dist.

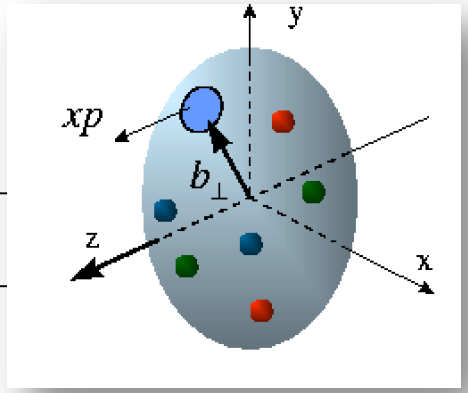


$d^2\boldsymbol{r_T}$

d^2k_T

TMD PDFs
$f_1^u(x,k_T)$, ..
$h_1^u(x,k_T)$

GPDs/IPDs

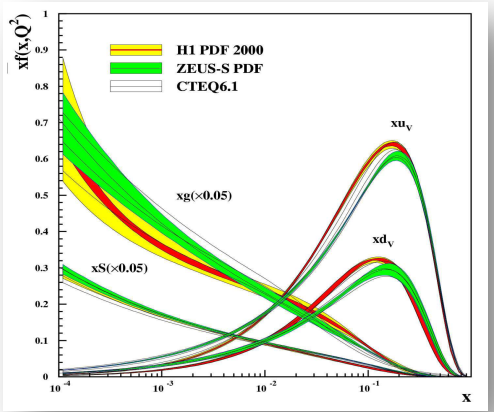


3D imaging

d^2k_T

d^2r_T

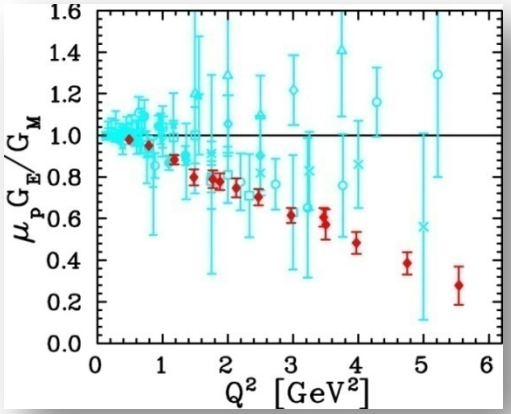
dx &
Fourier Transformation



PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

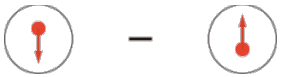
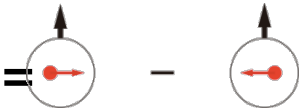
Form
Factors
$G_E(Q^2)$,
$G_M(Q^2)$



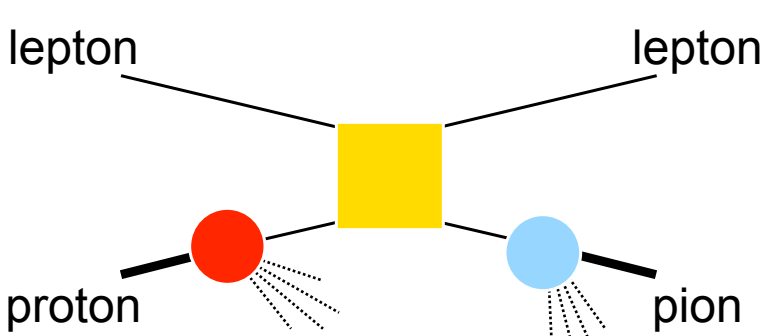
H. Gao

Leading Twist TMDs

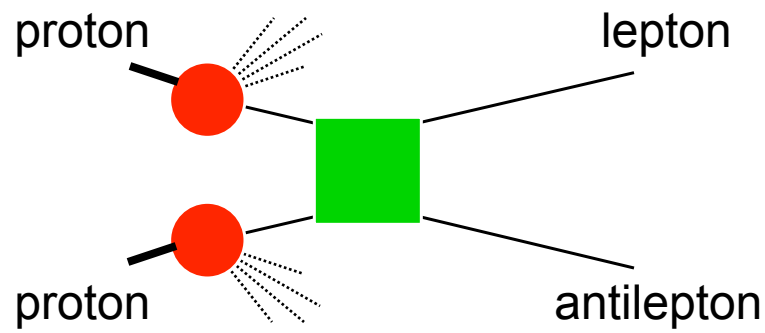
→ Nucleon Spin
→ Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 =$ 		$h_1^{\perp} =$  Boer-Mulder
	L		$g_1 =$  Helicity	$h_{1L}^{\perp} =$ 
	T	$f_{1T}^{\perp} =$  Sivers	$g_{1T}^{\perp} =$ 	$h_{1T} =$  Transversity $h_{1T}^{\perp} =$  Pretzelosity

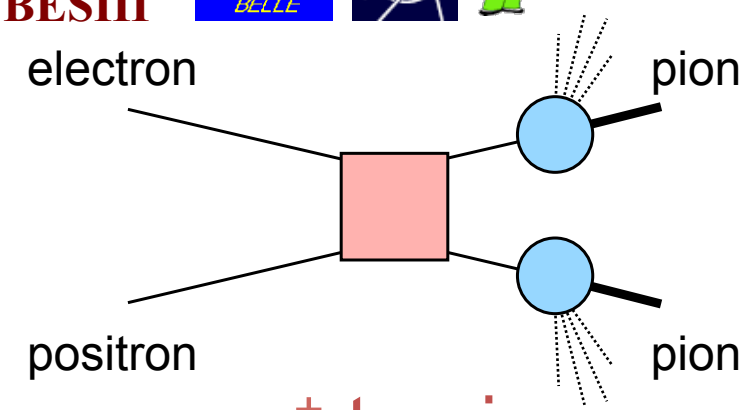
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

$$f_{1T}^{\perp q}(\mathrm{SIDIS}) = -f_{1T}^{\perp q}(\mathrm{DY})$$

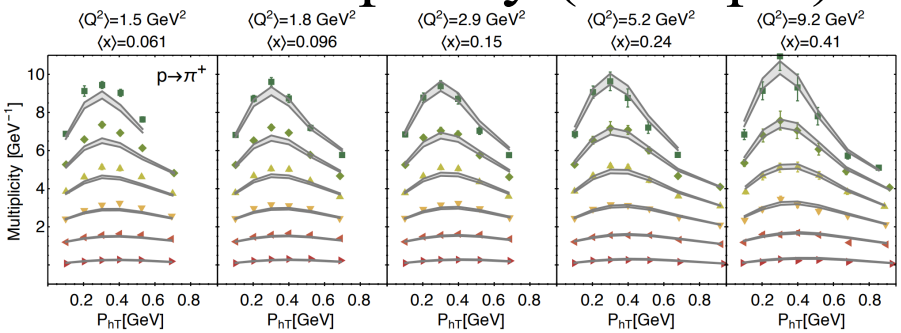
$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

Drell-Yan Programs

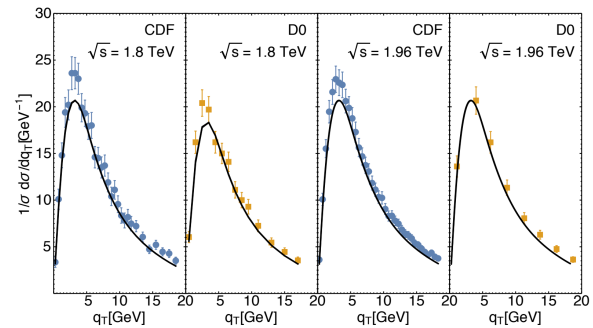
Global Analysis: Unpolarized TMD

Global analysis of semi-inclusive DIS, Drell-Yan and Z production data with TMD evolution

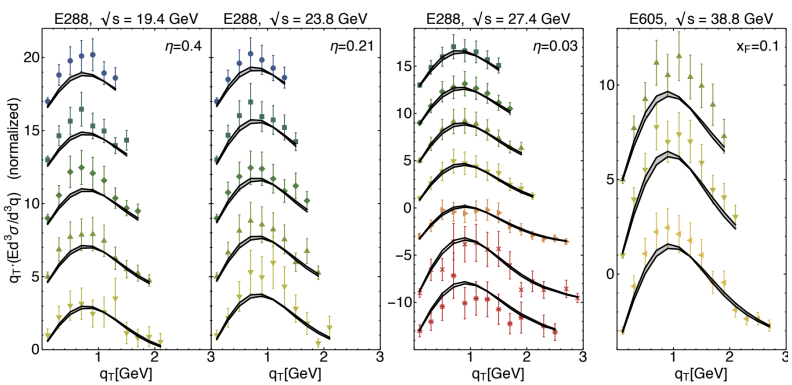
SIDIS multiplicity (example)



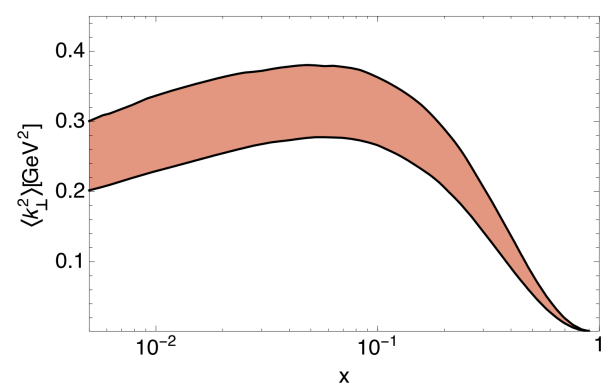
Z production



Drell-Yan cross section

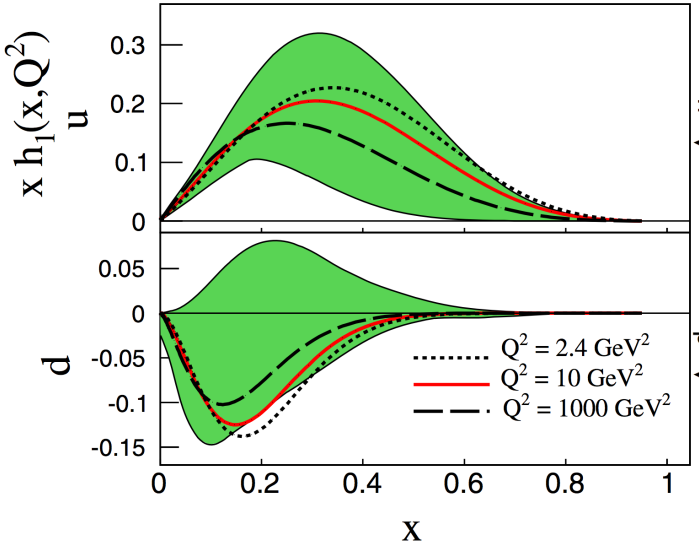


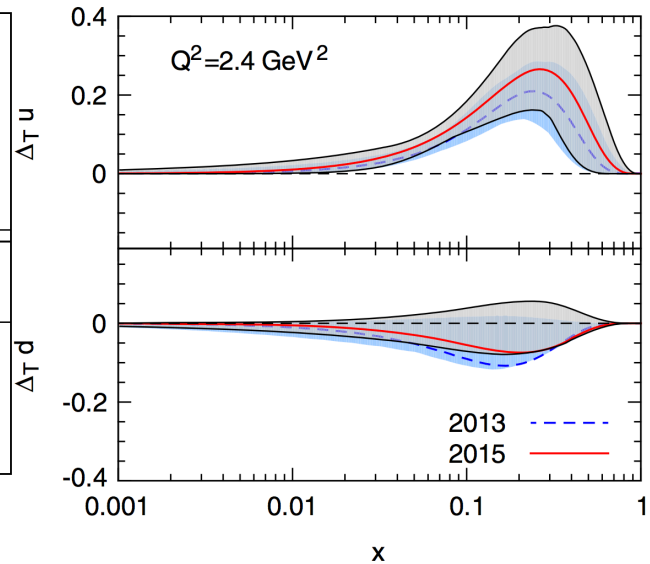
Transverse momentum distribution

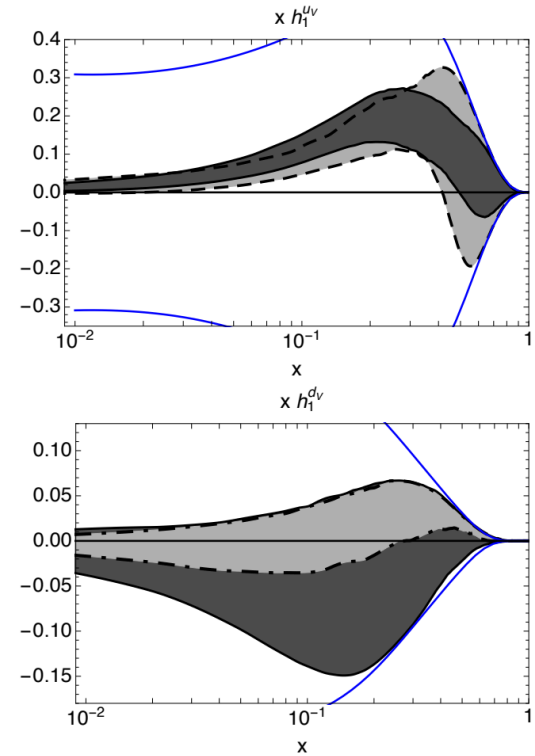


A. Bacchetta *et al.*, J. High Energy Phys. 06 (2017) 081.

Global Analysis: Transversity







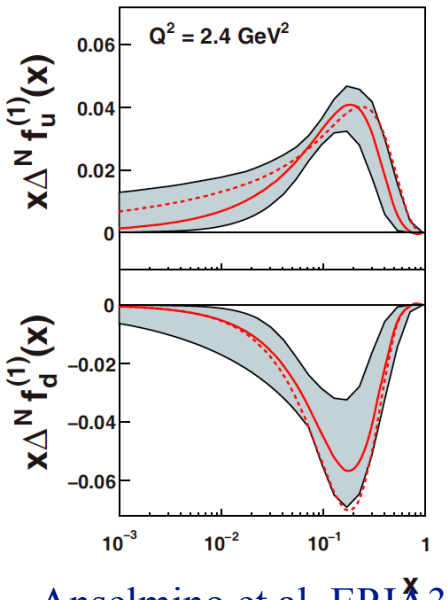
Z.-B. Kang et al., Phys. Rev. D 93, 014009 (2016).

M. Anselmino et al., Phys. Rev. D 92, 114023 (2015).

M. Radici and A. Bacchetta, arXiv: 1802.05212[hep-ph]

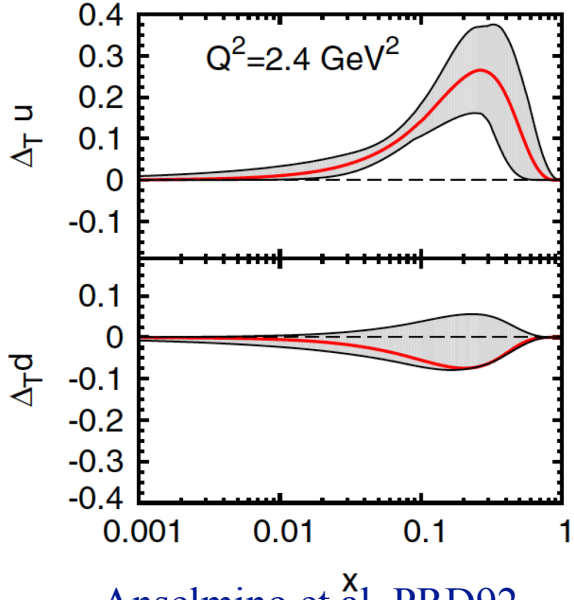
Global Analysis: Polarized TMDs

Sivers



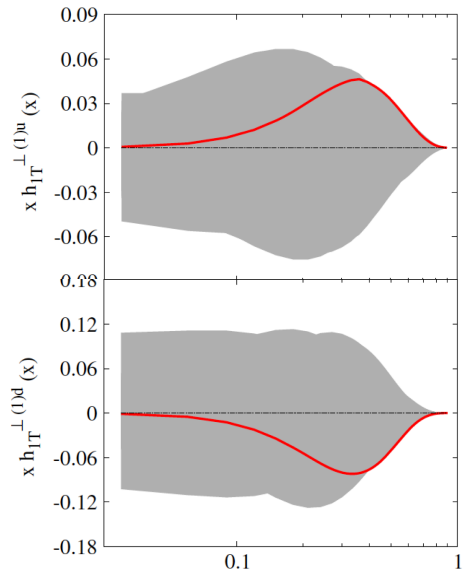
Anselmino et al, EPJA39, 89 (2009)

Transversity



Anselmino et al, PRD92, 114023 (2015)

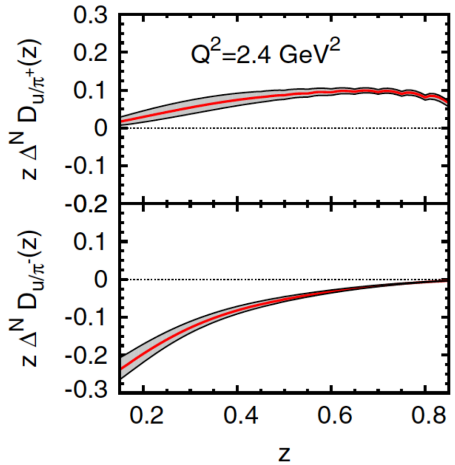
Pretzelosity

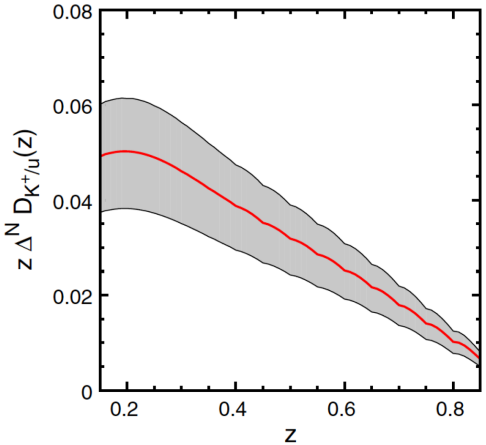


Lefky et al, PRD91, 034010 (2015)

Collins fragmentation

Anselmino et al, PRD92, 114023 (2015)
PRD93, 034025 (2016)

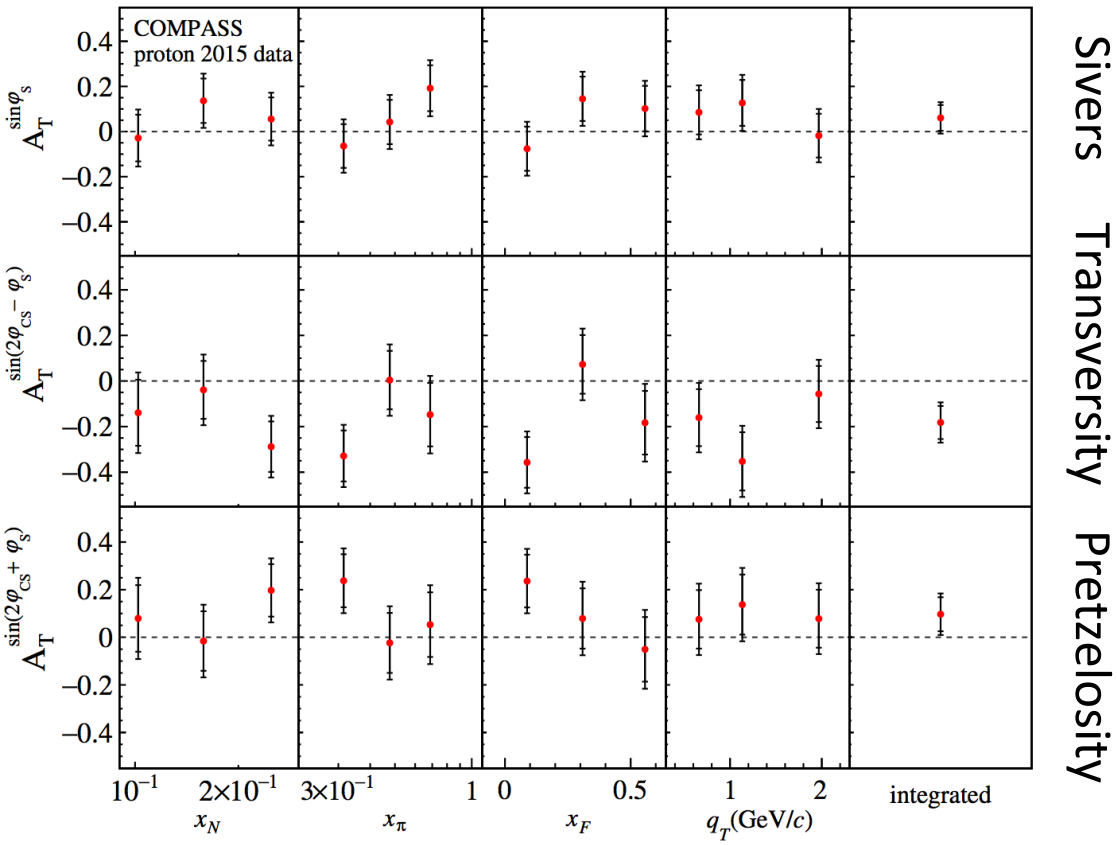




Transverse Spin Asymmetry in Drell-Yan

First measurement of transverse spin dependent azimuthal asymmetry in DY

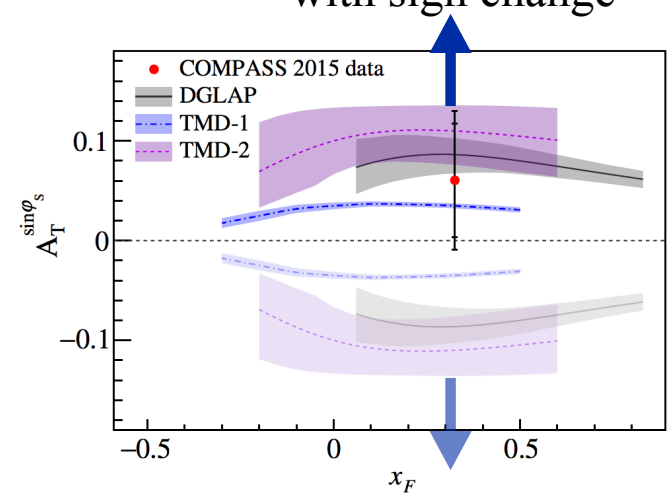
190 GeV/c π^- beam, transversely polarized NH_3 target



Sign change test

$$f_{1T,\mathrm{DY}}^{\perp} = -f_{1T,\mathrm{SIDIS}}^{\perp}$$

with sign change

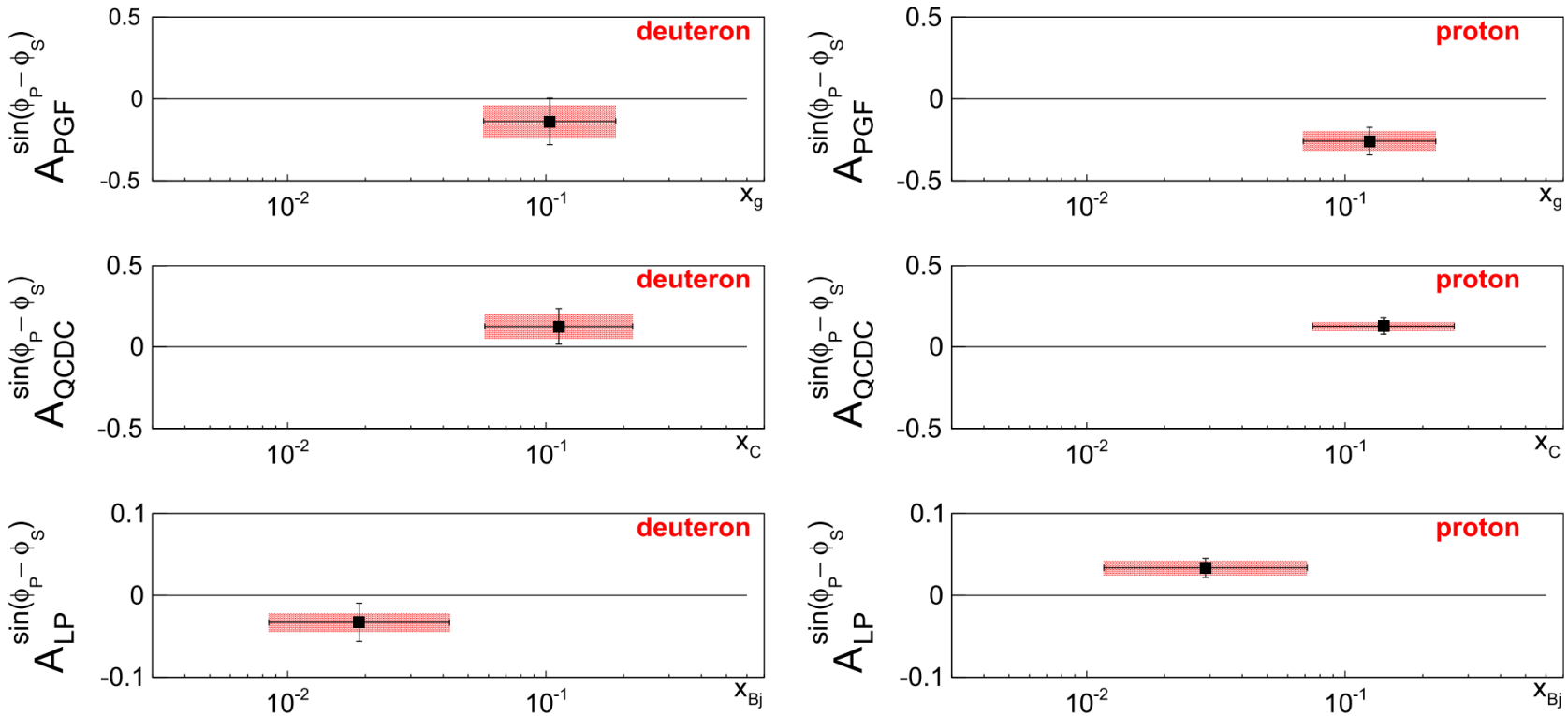


without sign change

M. Aghasyan *et al.* (COMPASS Collaboration), Phys. Rev. Lett. 119, 112002 (2017).

Sivers Asymmetry for Gluon

First measurement of the Sivers asymmetry for gluon in SIDIS



$$A_{PGF}^{Siv,d} = -0.14 \pm 0.15(\text{stat.}) \pm 0.10(\text{syst.})$$

$$\langle x_g \rangle = 0.13$$

$$A_{PGF}^{Siv,p} = -0.26 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$$

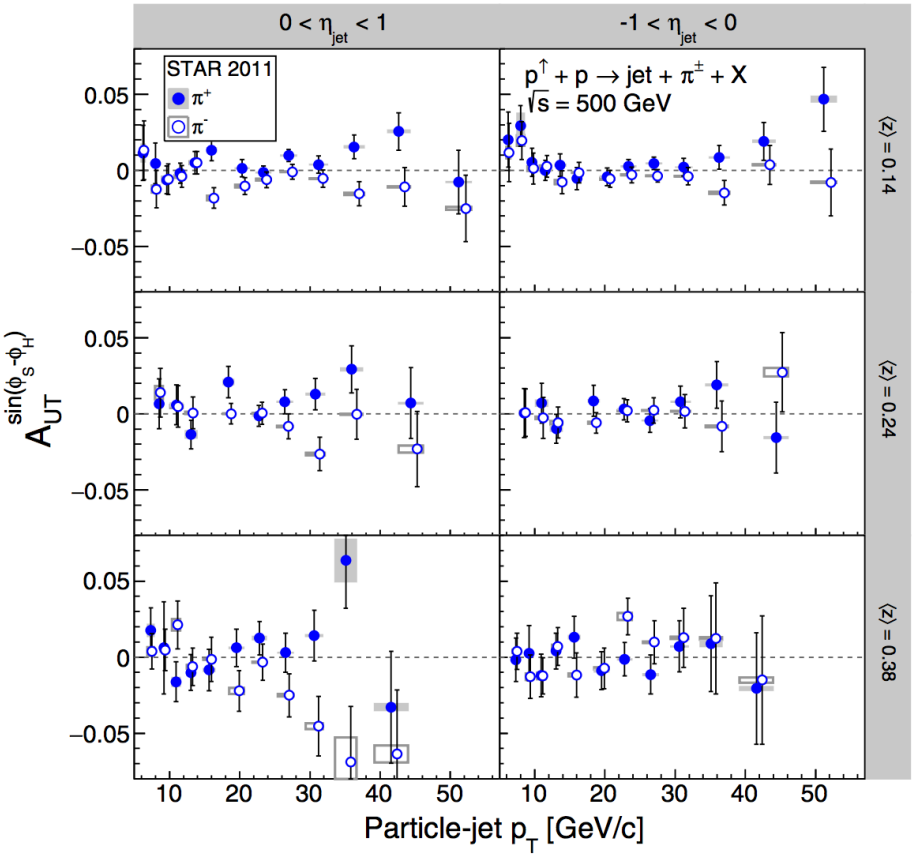
$$\langle x_g \rangle = 0.15$$

C. Adolph *et al.* (COMPASS Collaboration), Phys. Lett. B 772, 854 (2017).

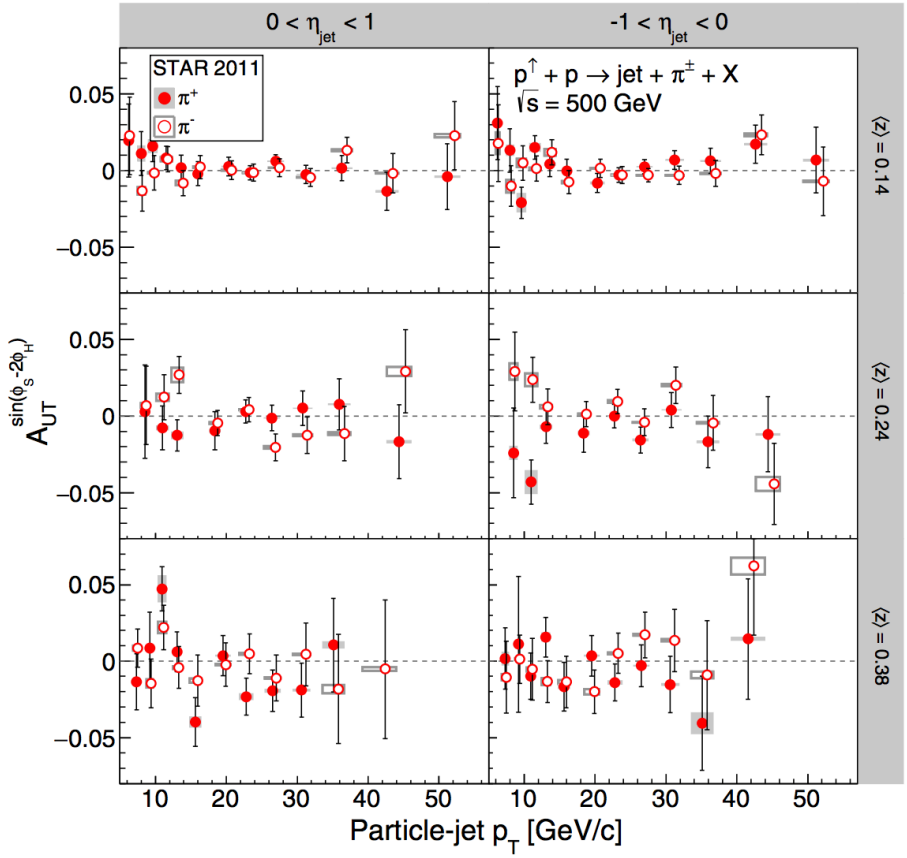
Collins Asymmetry in pp Collisions

First measurement of the Collins-like asymmetry, sensitive to linearly polarized gluon, from pp collisions

Collins asymmetry



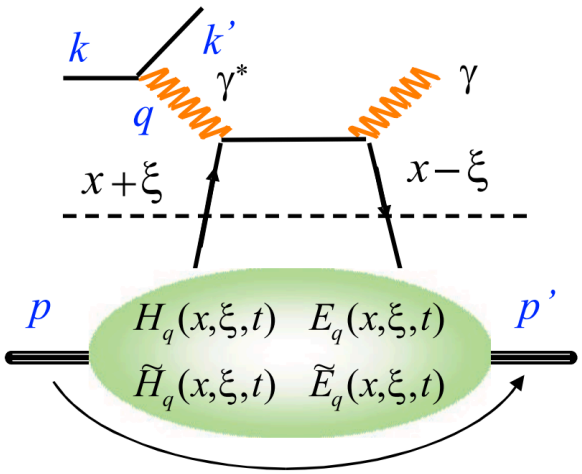
Collins-like asymmetry



L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. D 97, 032004 (2018).

Access GPDs through Hard Processes

Deeply Virtual Compton Scattering (DVCS)



$t=(p'-p)^2$

Interference with Bethe-Heitler (BH) process gives access to real and imaginary part of DVCS amplitude

$$d\sigma \propto |\mathcal{T}|^2 = |\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2 + \mathcal{I}$$

$$\mathcal{I} \propto \frac{-e_\ell}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\}$$

e.g.:

$$c_{1,\rm unpol.}^{\mathcal{I}} \propto \left[F_1\,\mathfrak{Re}\,\mathcal{H} - \frac{t}{4M_p^2}F_2\,\mathfrak{Re}\,\mathcal{E} + \frac{x_{\rm B}}{2-x_{\rm B}}(F_1+F_2)\,\mathfrak{Re}\,\tilde{\mathcal{H}}\right]$$

Access different GPDs

$$d\sigma_{LU} = \sin\phi\cdot\mathcal{I}m\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

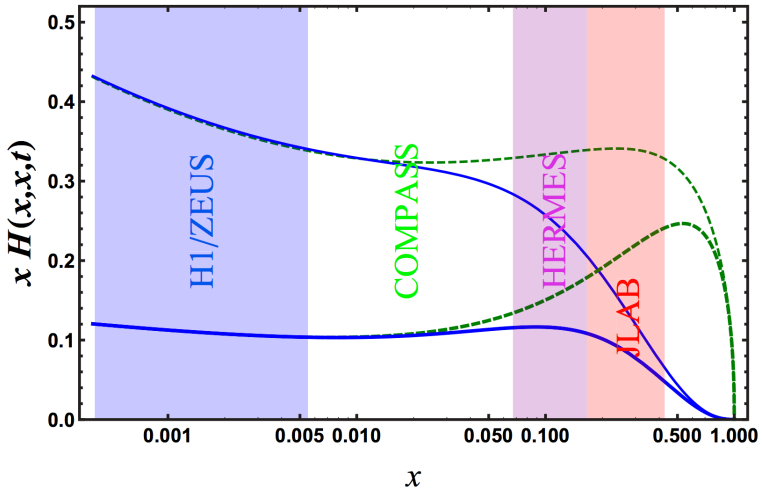
$$d\sigma_{UL} = \sin\phi\cdot\mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_BkF_2\tilde{\mathcal{E}}\ldots\}d\phi$$

$$d\sigma_{LL} = (A + B\cos\phi)\cdot\mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\ldots\}d\phi$$

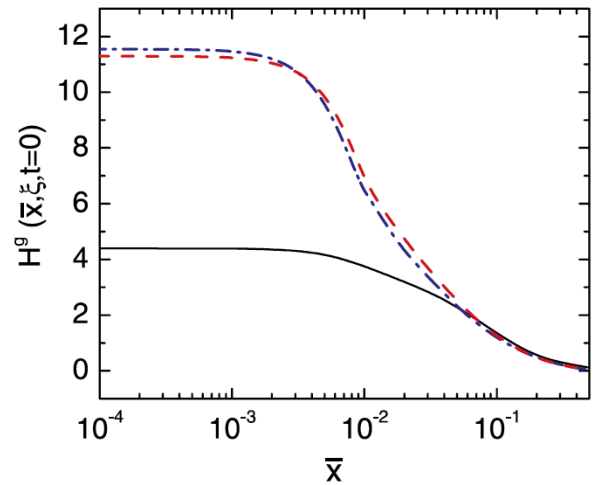
$$d\sigma_{UT} = \cos\phi\cdot\mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$$

Alternative processes: deeply virtual meson production (DVMP), double DVCS, timelike Compton scattering (TCS)…

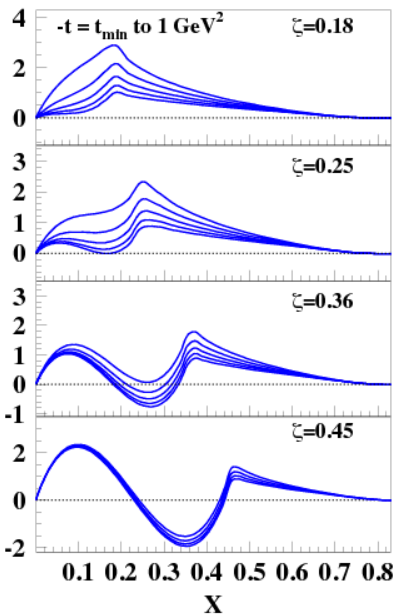
Global Analysis of GPDs

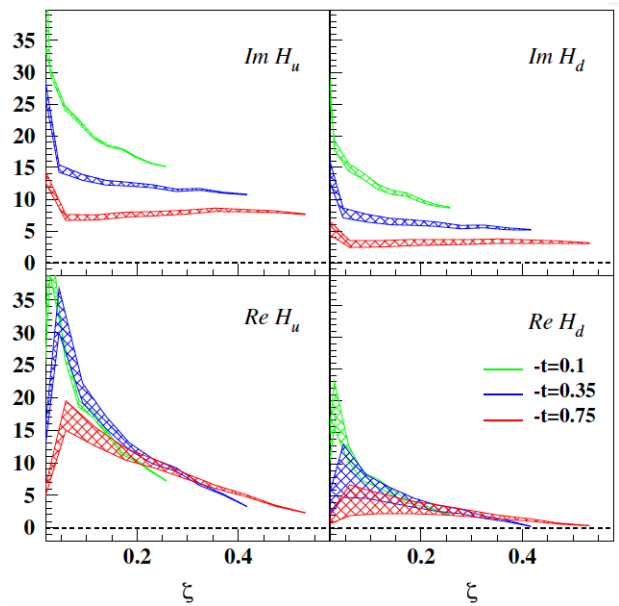


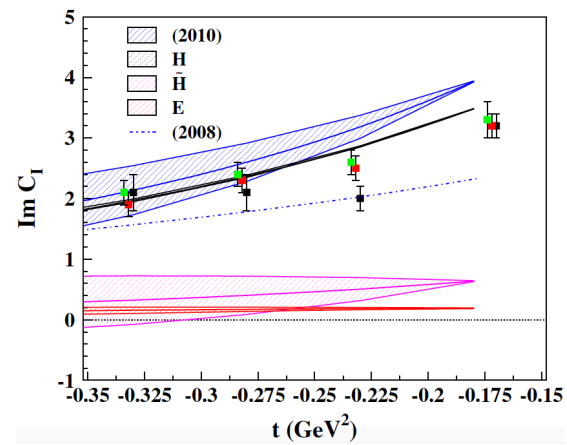
Kumerički and Müller NP B841, 1(2010)



Goloskokov and Kroll, EPJ C53, 367(2008)

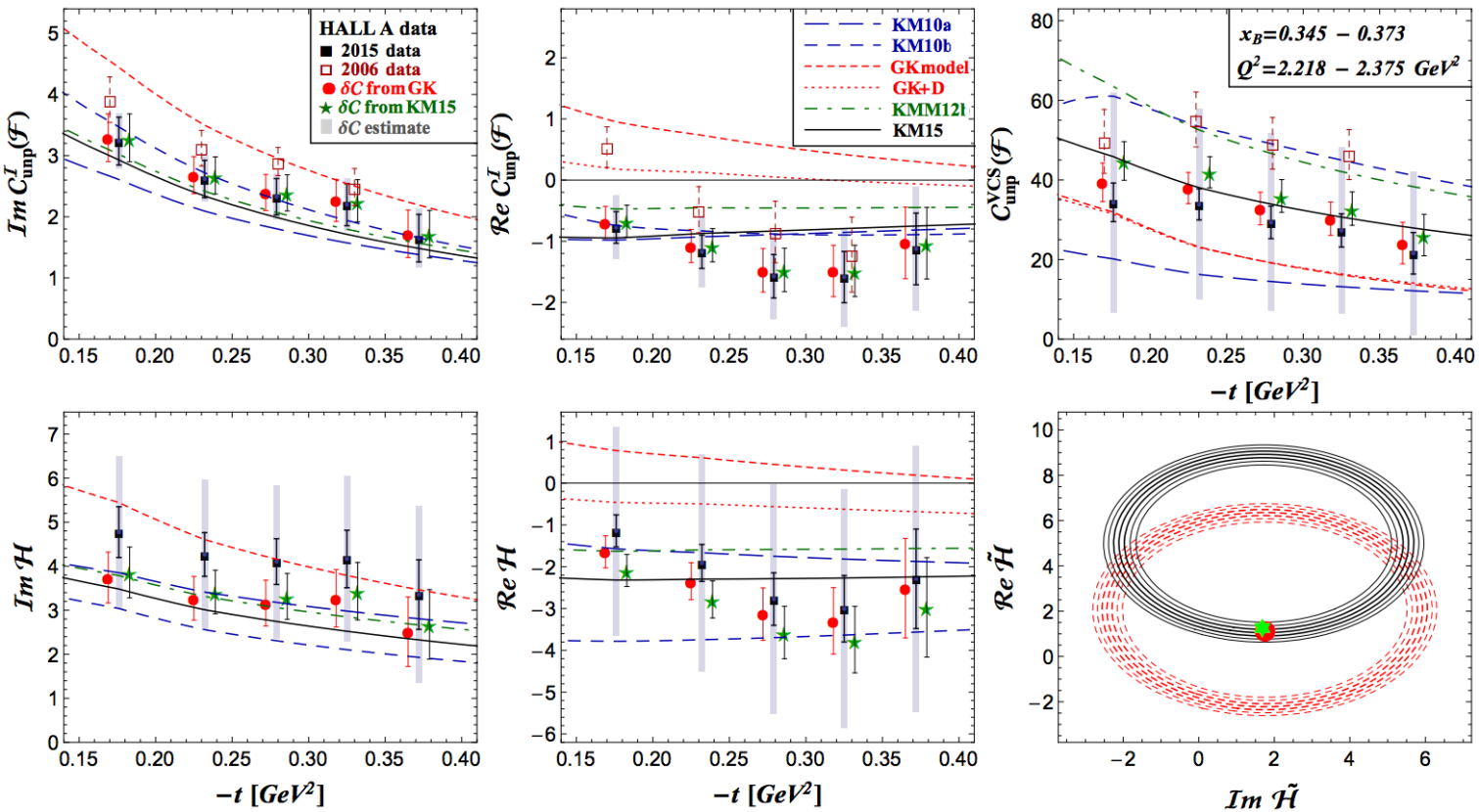






Goldstein et al., PR D84, 034007(2011)

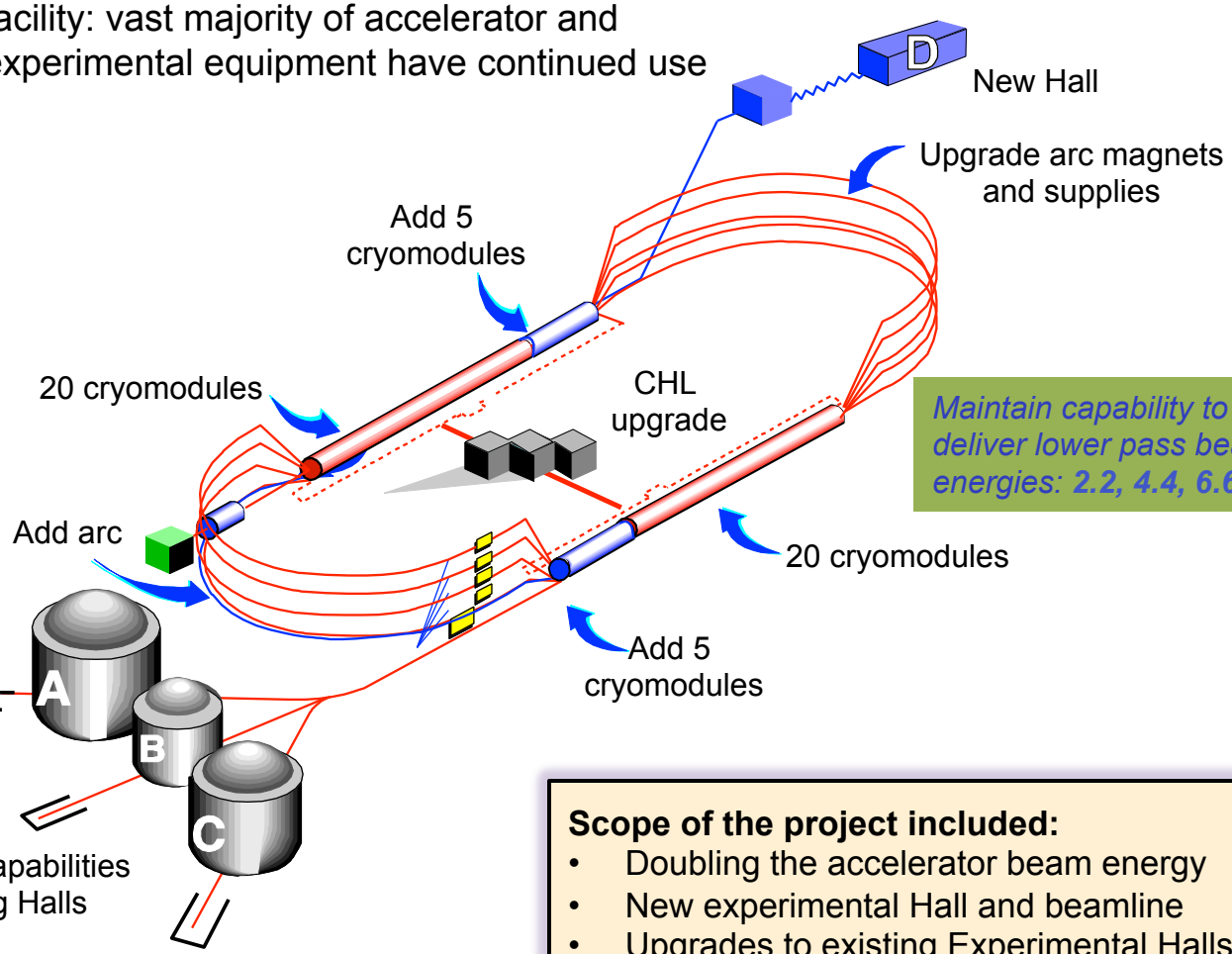
Global Fits of GPDs



K. Kumericki *et al.*, EPJ Web Conf. 112 (2016) 01012.

12 GeV Upgrade Project

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan. **Completed**

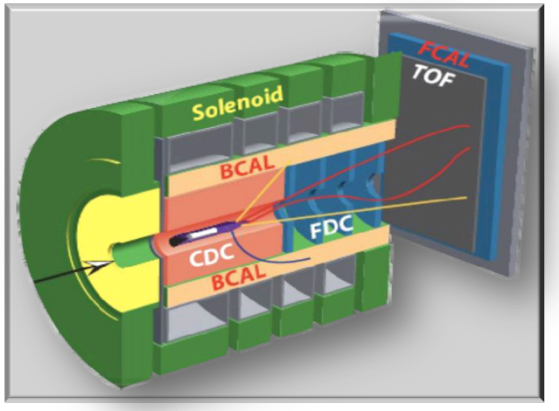
*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

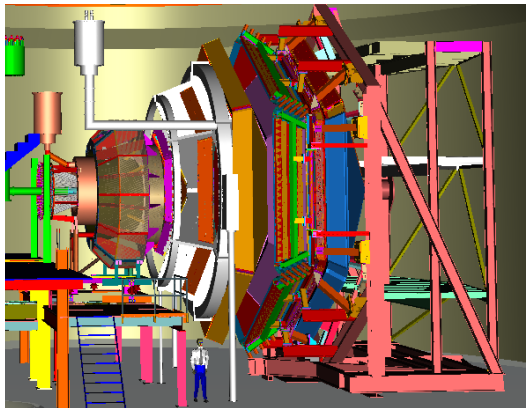
Scope of the project included:

- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

12 GeV Upgrade Physics Instrumentation

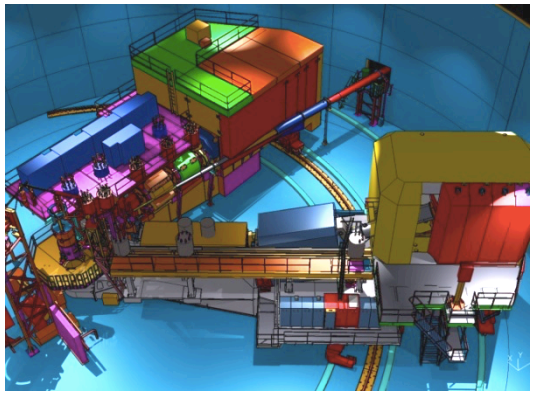
GLUEx (Hall D): **exploring origin of confinement by studying hybrid mesons**

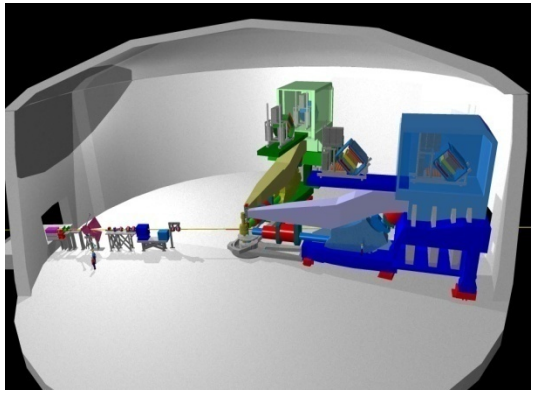




CLAS12 (Hall B): **understanding nucleon structure via generalized parton distributions**

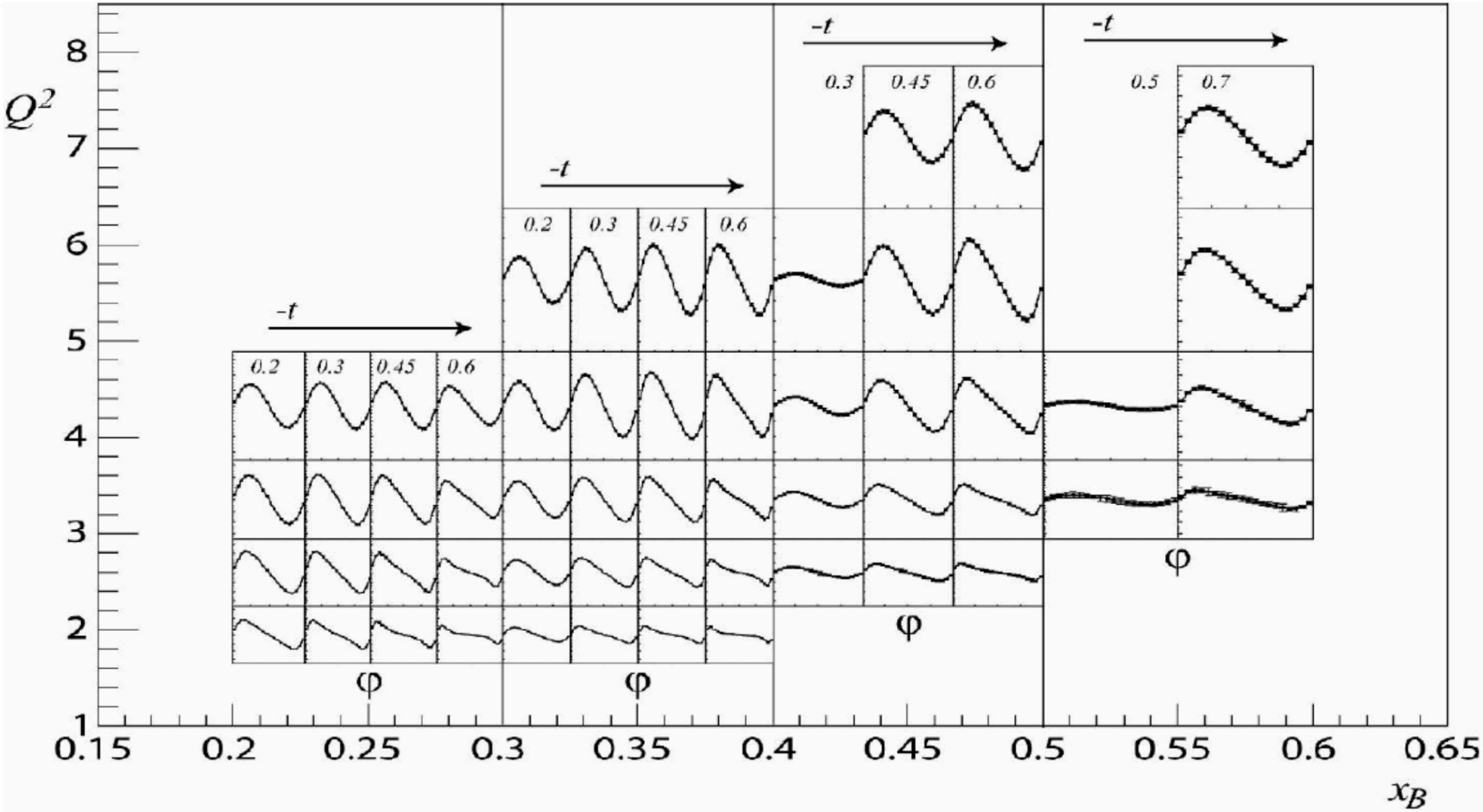
SHMS (Hall C): **precision determination of valence quark properties in nucleons and nuclei**





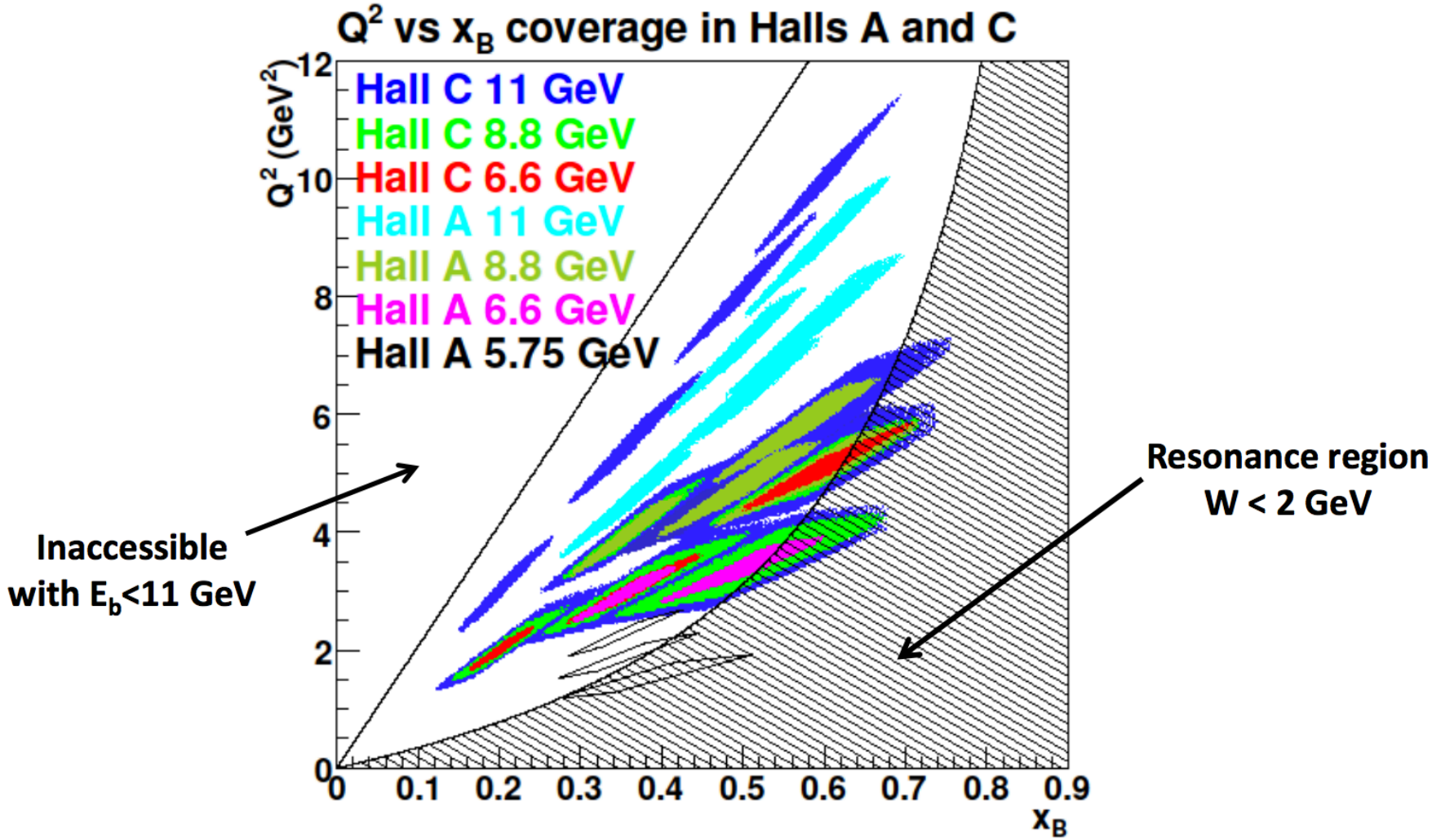
Hall A: **nucleon form factors,**
& future new experiments like Moller & SOLID

Hall B E12-06-119 Experiment



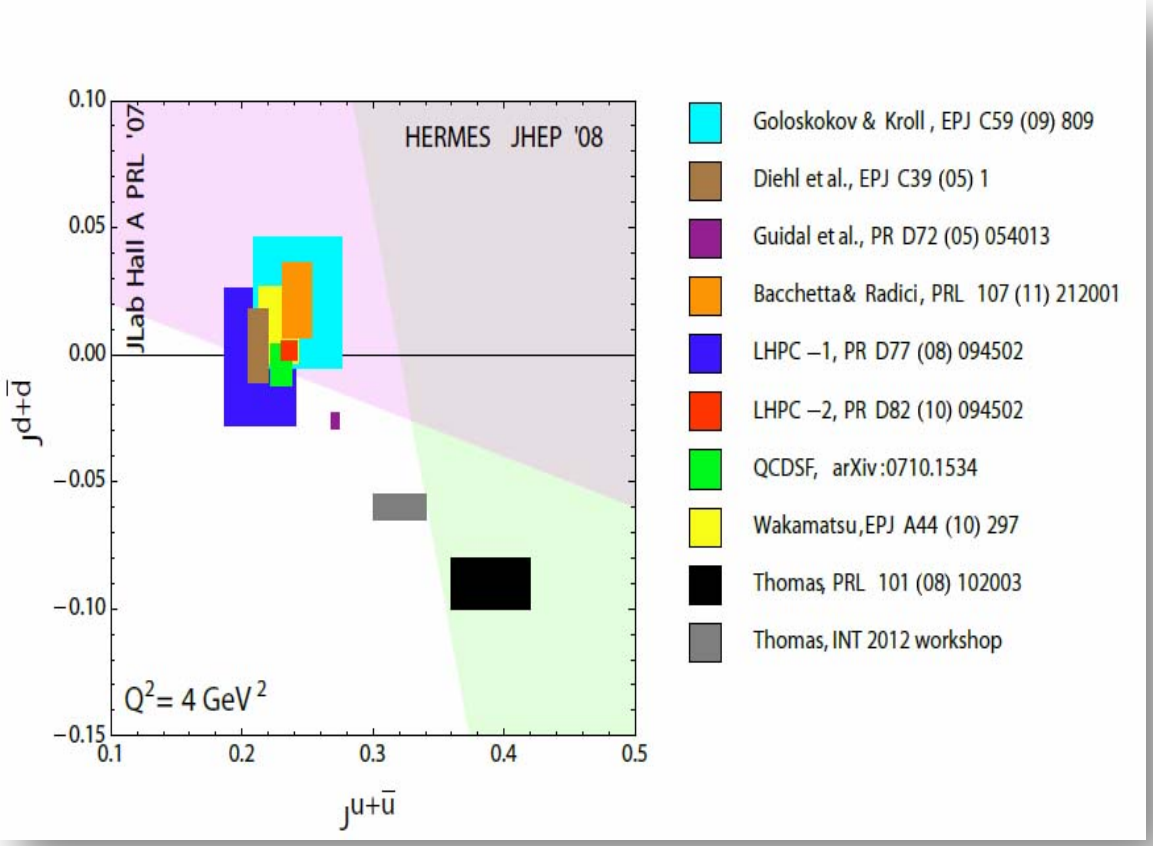
Extensive DVCS experiments at 12-GeV JLab: E12-06-114 (unpolarized proton @ Hall A), E12-06-119 (unpolarized proton; long. Pol. proton @ Hall B), E12-11-003 (unpolarized neutron @ Hall B), E12-12-010 (trans. polarized proton @ Hall B), E12-13-010 (unpolarized proton @ Hall C)

Hall C E12-13-010 Experiment



Quark Angular Momentum

Ji's sum rule: $$J^q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,t)+E^q(x,\xi,t)] = \frac{1}{2}\Delta\Sigma + L^q$$

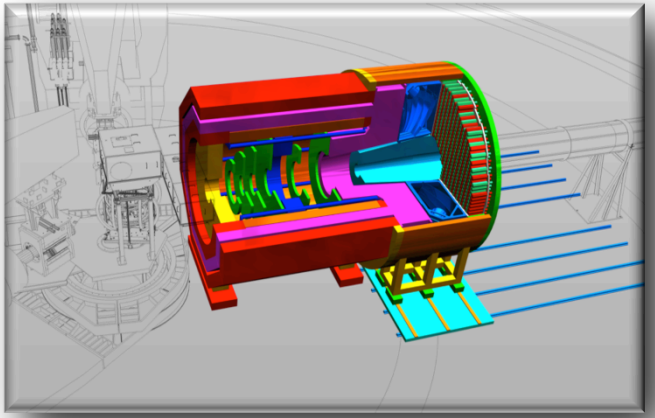


→ **Access to quark orbital angular momentum with GPDs**

Solenoidal Large Intensity Device (SoLID) Physics

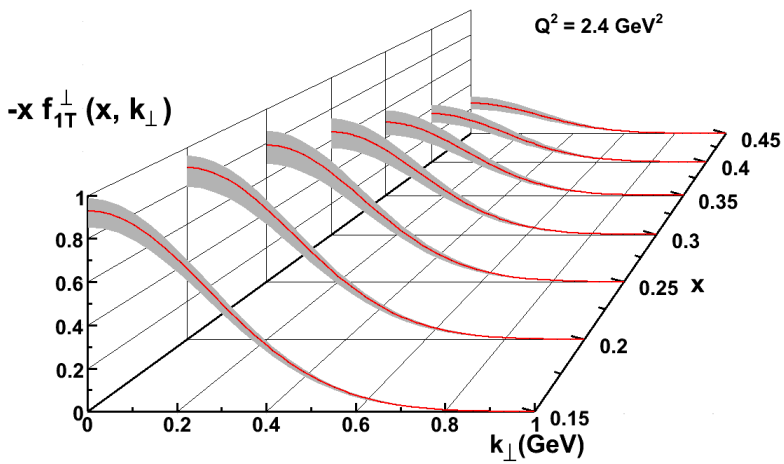
SoLID provides unique capability:

- ✓ high luminosity ($10^{37\text{-}39}$)
- ✓ large acceptance with full ϕ coverage

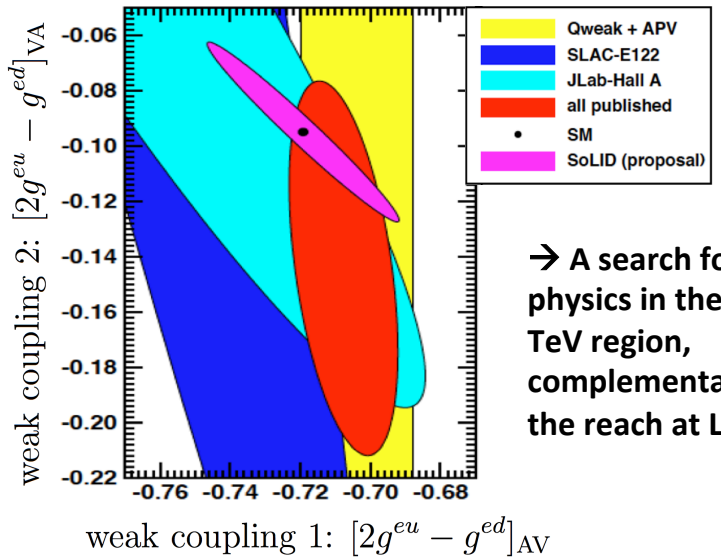


→ multi-purpose program to maximize the 12-GeV science potential

1) Precision in 3D momentum space imaging of the nucleon

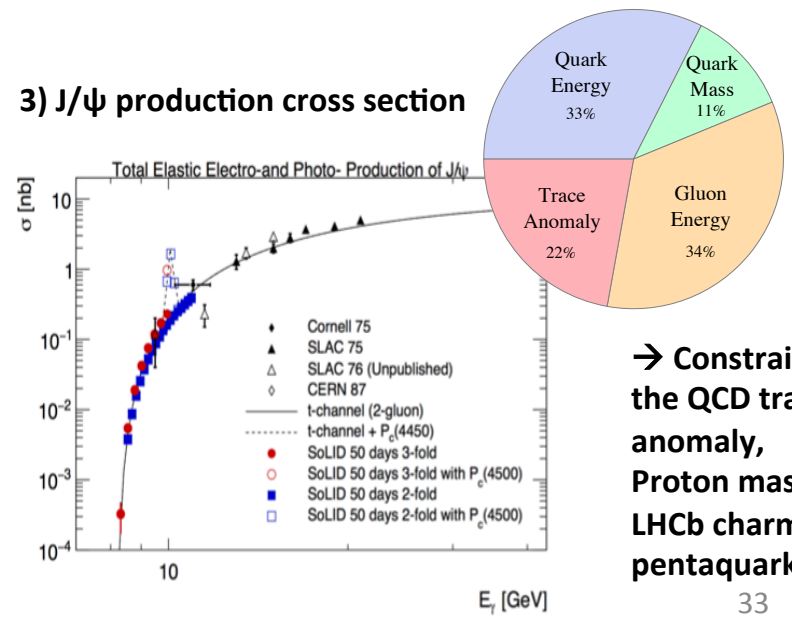


2) Precise determination of the electroweak couplings



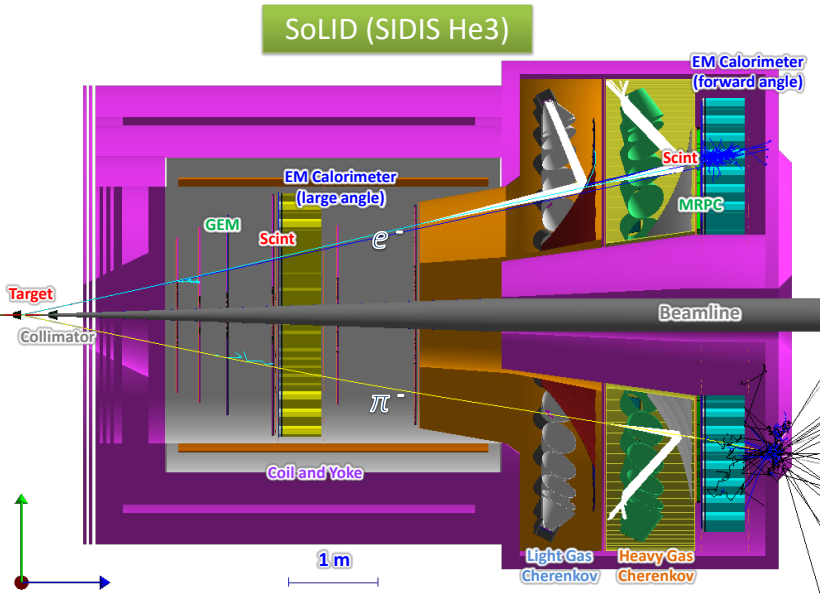
→ **A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.**

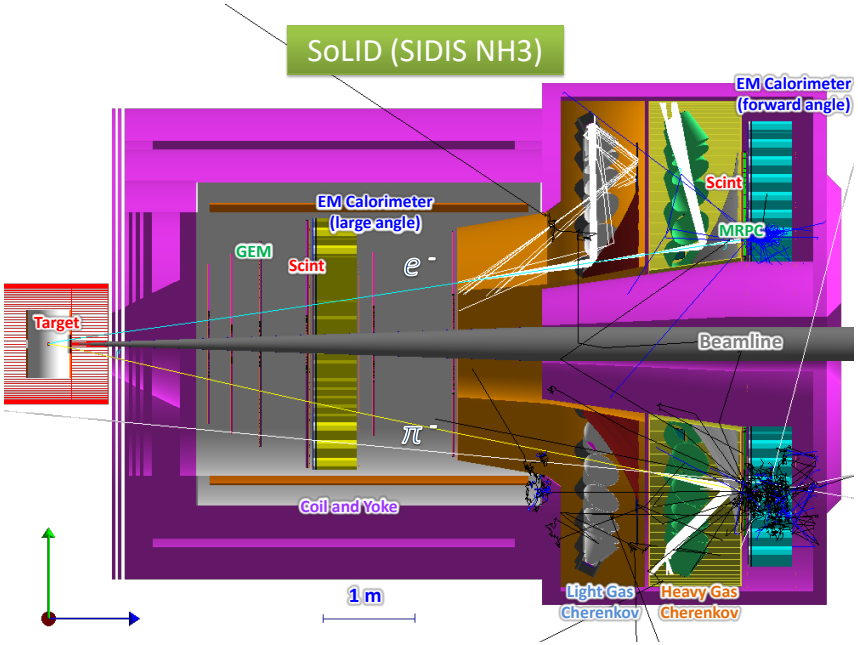
3) J/ψ production cross section



→ **Constrain the QCD trace anomaly, Proton mass , LHCb charmed pentaquark**

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV





E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

Three run group experiments approved: TMDs, GPDs, and

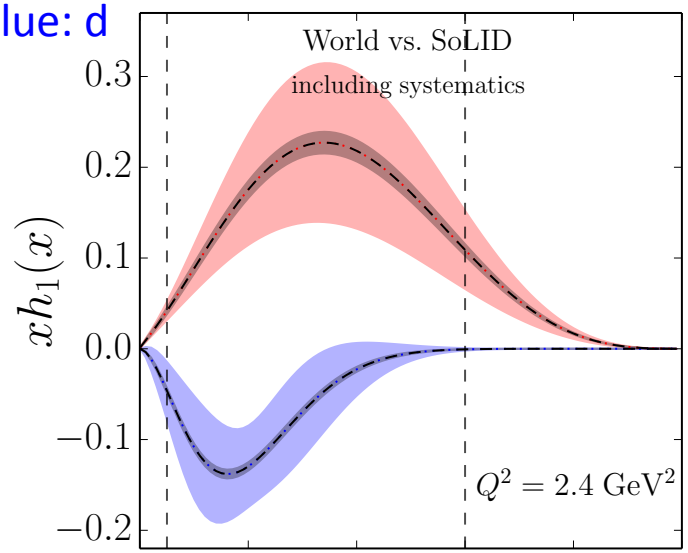
much more

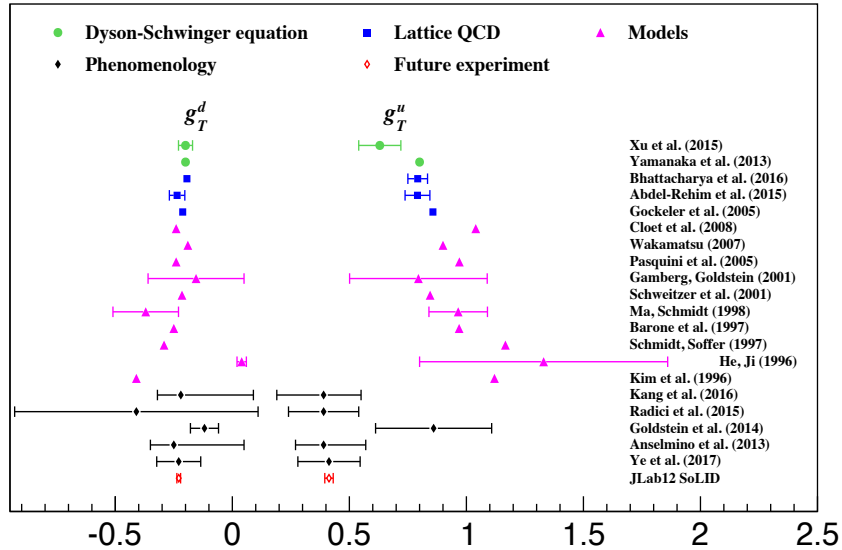
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

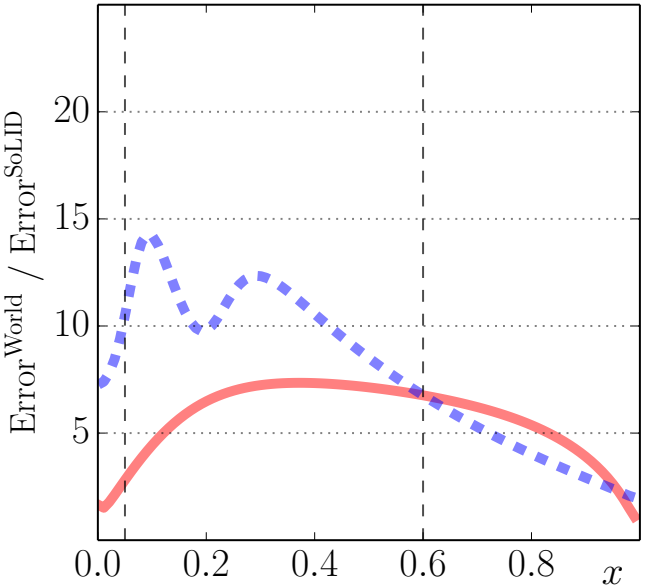
SoLID Impact on Transversity and Tensor Charges

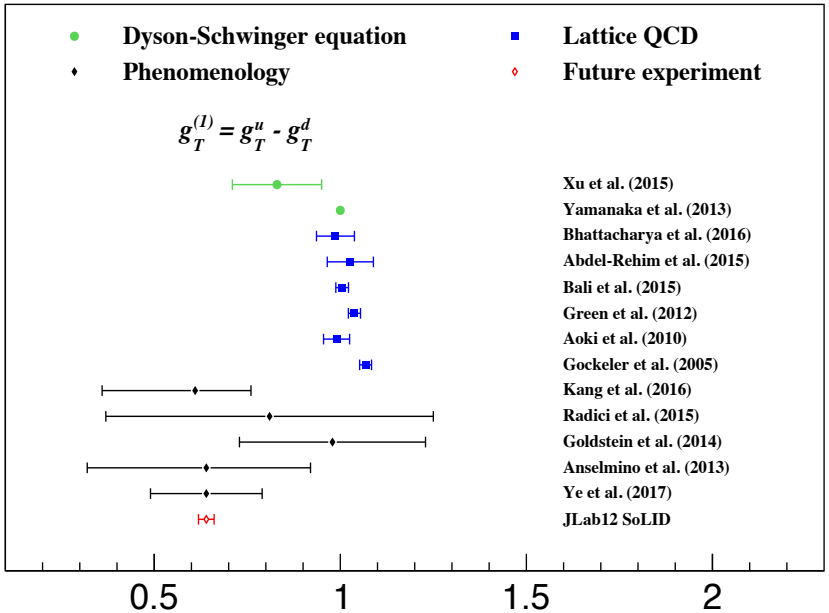
Red: u

blue: d









Z. Ye et al., PLB 767, 91 (2017)

Summary

- Spin remains important and puzzling for nucleon
- Three-dimensional imaging of nucleon will help solve this remaining puzzle, and uncover the rich dynamics of QCD
- Major progresses have been made in spin and three-dimensional structure of the nucleon worldwide
- Awaiting new results on nucleon spin, TMDs and GPDs, especially those planned at 12-GeV JLab

Thanks to J.-P Chen, R. Ent, C. Keppel, T.-B. Liu, Z.-E. Meziani, C. Peng, A. Prokudin, N. Sato, P. Souder, V. Sulkosky, Z. Ye, X.F. Yan, and Z. Zhao, and others

(Apology - not all results are included due to the time limit)

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