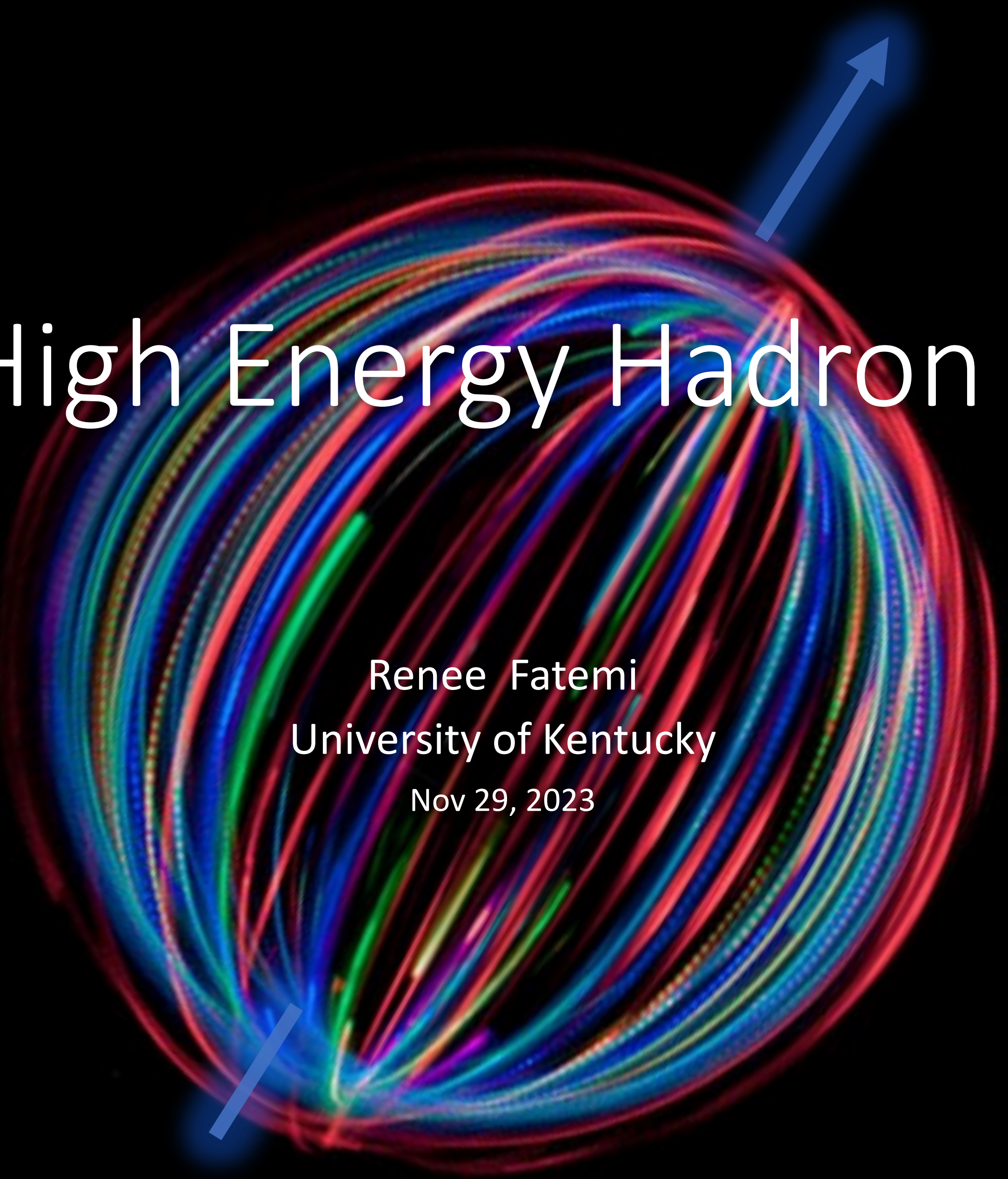
Spin in High Energy Hadron Physics



Renee Fatemi
University of Kentucky

Nov 29, 2023

6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan

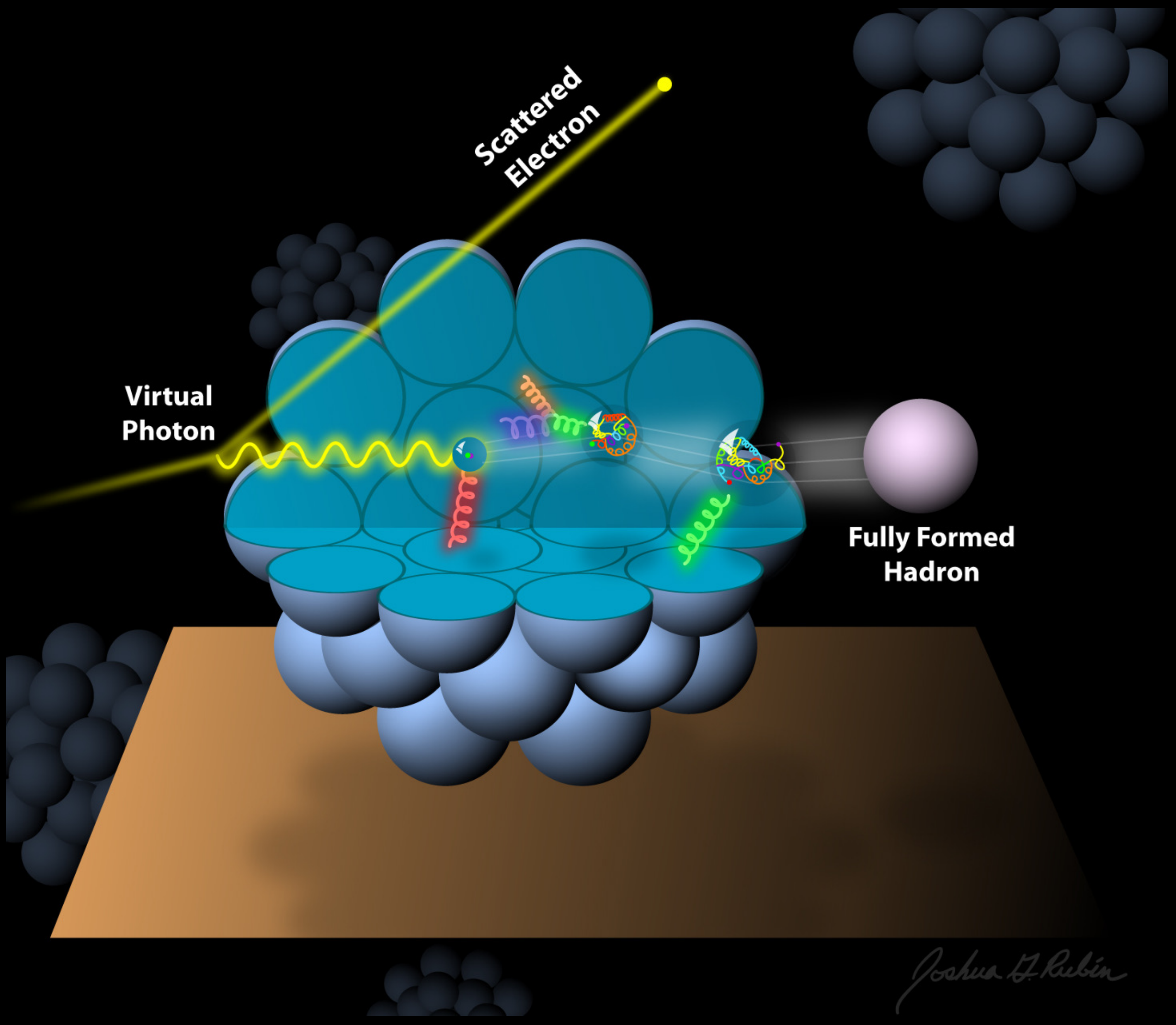
What is “high” energy?

- High enough that it is possible to probe the internal structure of the hadron

- High enough that it is possible to break apart the hadron and enable the study the hadronization process

- Regime where energy scales are high enough that factorization theorems can be applied.

- First step : polarized beams and targets!



Polarized Targets

DIFFUSION DE PROTONS POLARISES DE 20 MeV PAR UNE CIBLE DE PROTONS POLARISES ET MESURE PRELIMINAIRE DU PARAMETRE C_{nn}

A. ABRAGAM, M. BORGHINI, P. CATILLON, J. COUSTHAM,
P. ROUBEAU et J. THIRION
Centre d'Etudes Nucléaires de Saclay, France

Reçu le 15 Octobre 1962

First polarized targets were made of lanthanum magnesium nitrate and operated at Saclay in 1962 (*Phys.Lett. 2, 310*). Lawrence Berkeley Lab soon followed in 1963 (*Phys.Lett. 7, 293*).

These targets used the ”solid-effect”:

1. Find a material with lots of protons
2. Dope it with extra paramagnetic centers, i.e. electrons
3. Cool it down to ~1K and immerse high magnetic field

$$P_{TE} = \tanh\left[\frac{\mu B}{kT}\right]$$

B = 2.5T and T = 1K

P_{e^-}= 92%

P_p= 0.25%

4. Drive e^-p spin transition with microwave RF
5. Electron relaxes quickly and is off to pair again
6. Measure polarization using Nuclear Magnetic Resonance (NMR) techniques at proton spin flip frequency.

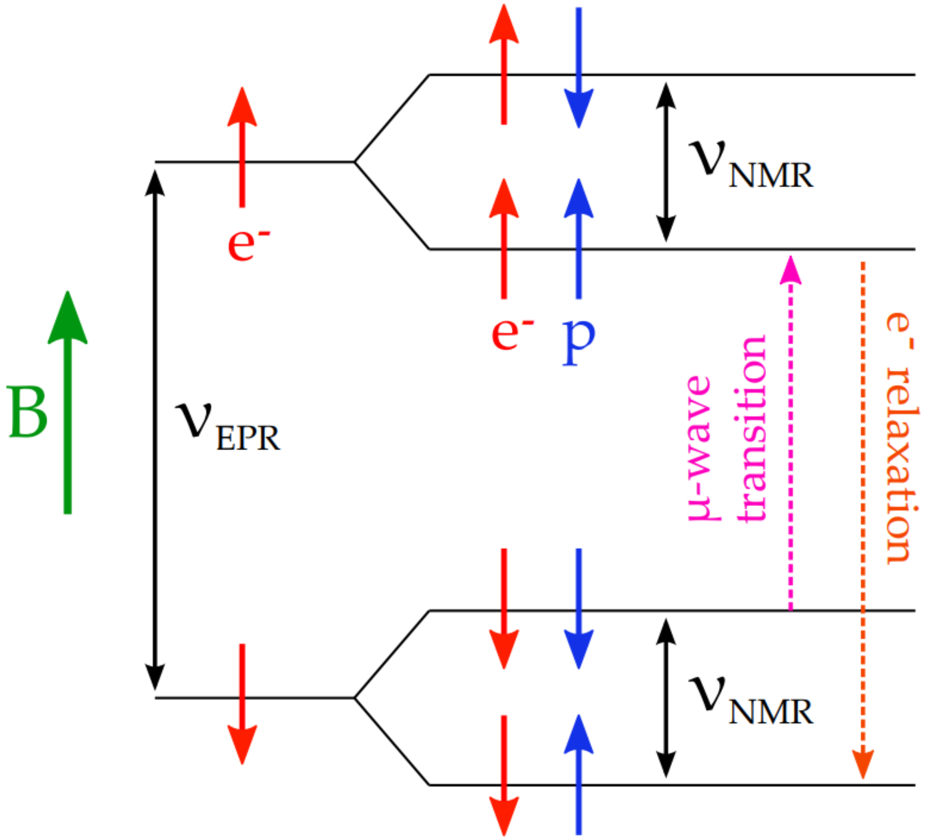


Figure by James Maxwell

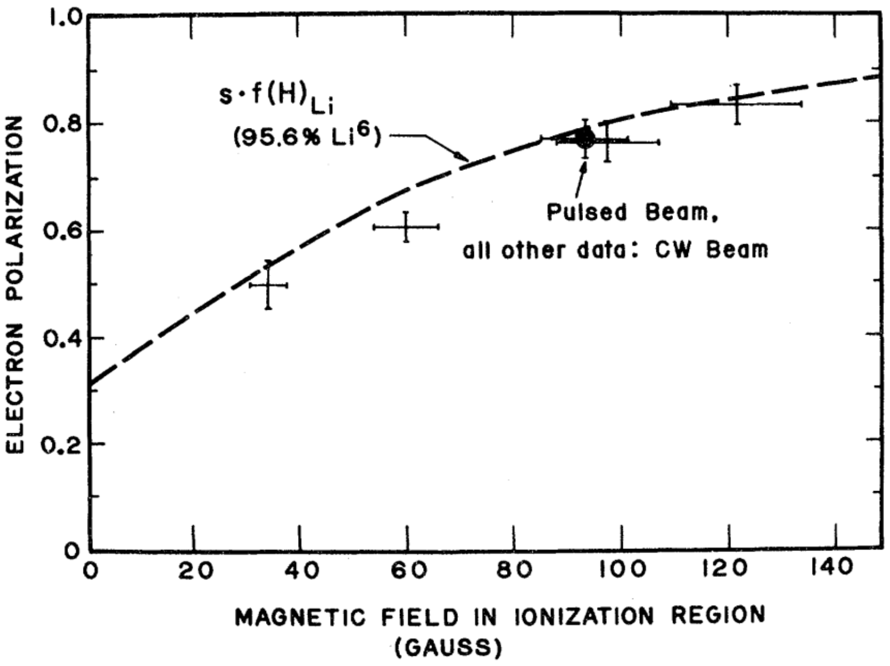
High Energy Polarized Beams

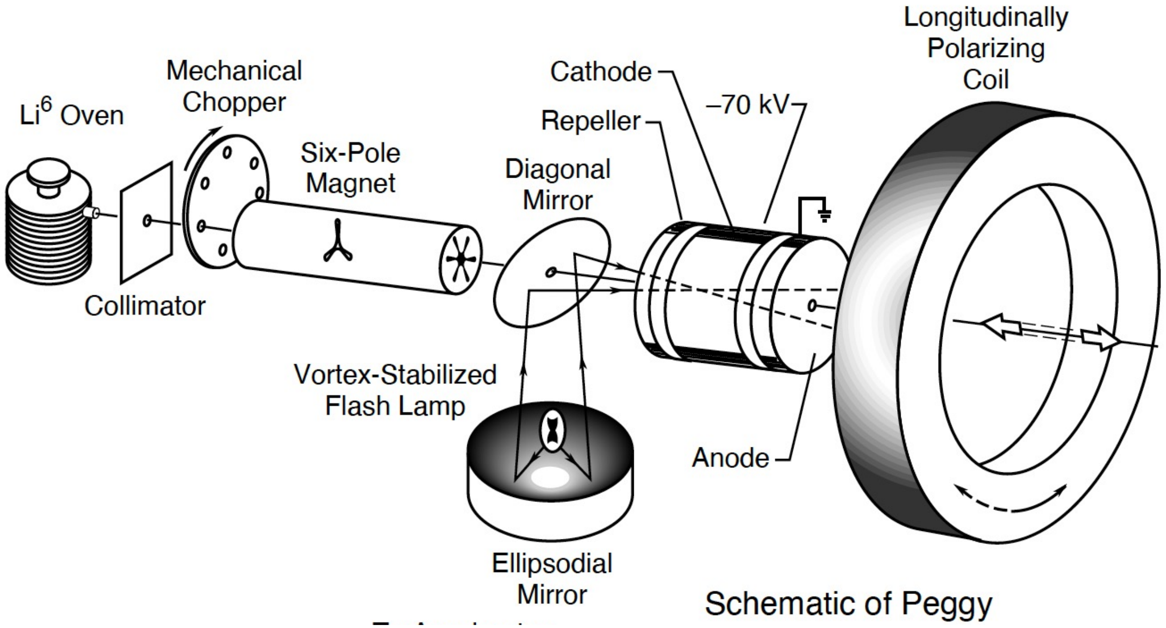
PHYSICAL REVIEW A VOLUME 5, NUMBER 1 JANUARY 1972

Polarized Electrons from Photoionization of Polarized Alkali Atoms*

V. W. Hughes, R. L. Long, Jr.,† M. S. Lubell, M. Posner,‡ and W. Raith
Yale University, New Haven, Connecticut 06520
(Received 30 June 1971)

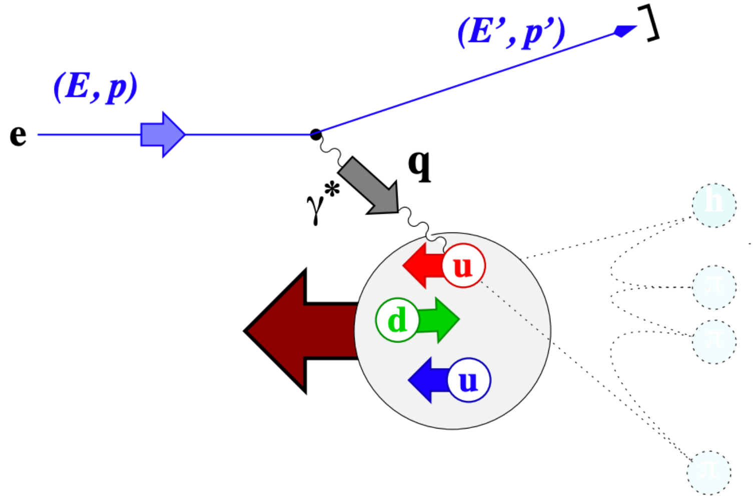
The process of photoionization of polarized alkali atoms in an atomic beam has been studied for potassium and lithium. Depolarization processes associated with photoionization of alkali molecules and optically excited atoms were discovered. After eliminating these depolarization mechanisms, the measured photoelectron polarization agreed within an accuracy of 3% with the predicted polarization based on the current theory for this electric dipole process. Using a polarized Li^6 atomic beam and a pulsed uv light source, we have produced an intense and highly polarized electron beam with 2×10^8 electrons in 1.5 μsec and with a polarization of 0.78, which is a suitable prototype injector source for a high-energy electron accelerator.





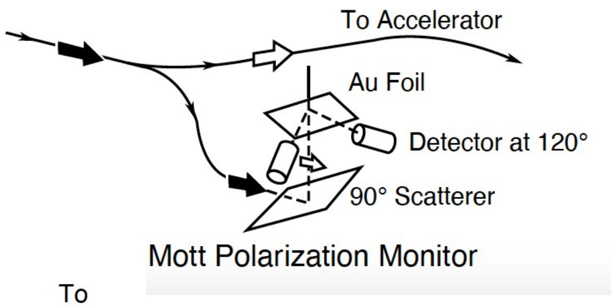
Schematic of Peggy

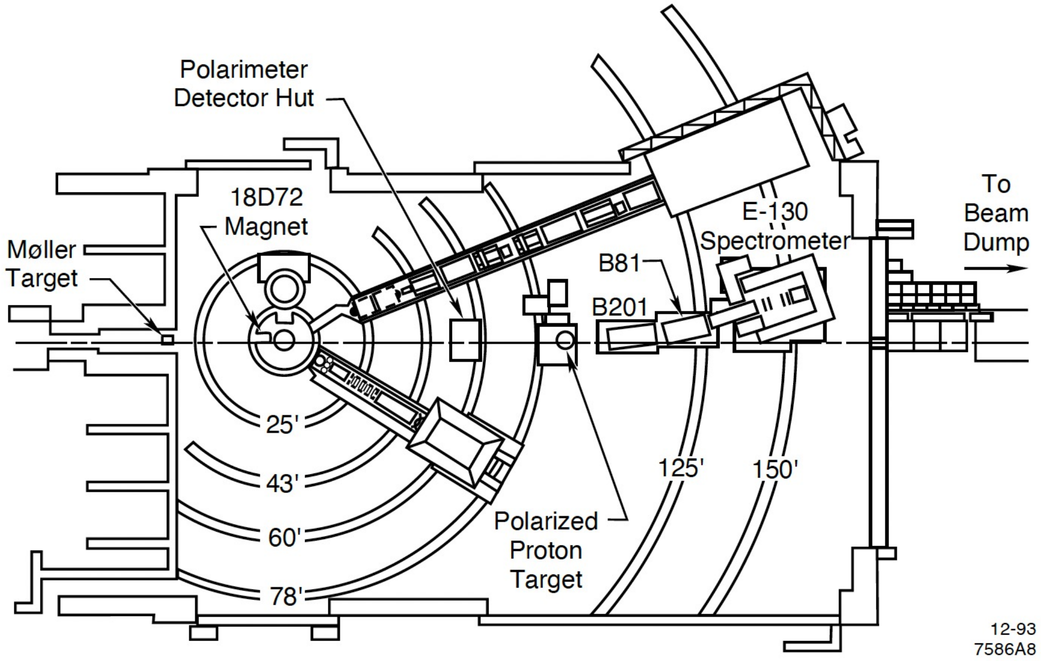
SLAC : First $\vec{e} + \vec{p}$ DIS experiments



E-80 and E-130

- Electron beams with energy 6-22 GeV and 50-80% polarization
- Butanol targets with ~60% proton polarization
- Electrons were detected in spectrometers located at End Station A.
- Mott and Moller polarimeters developed to measure beam polarizations at source and ESA

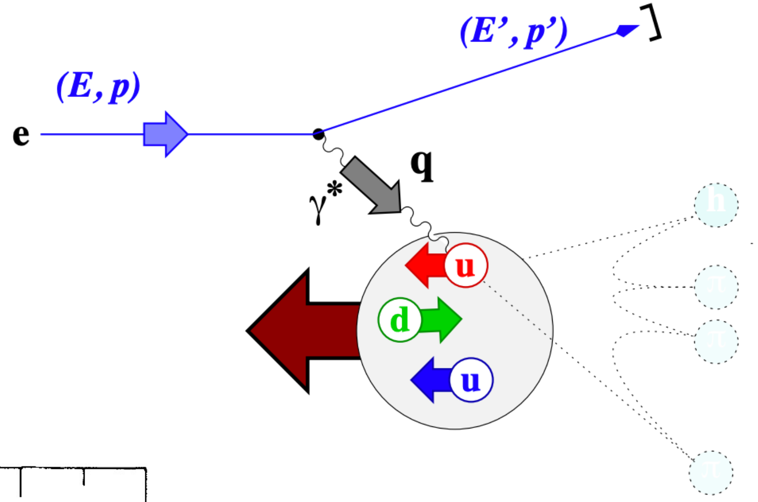




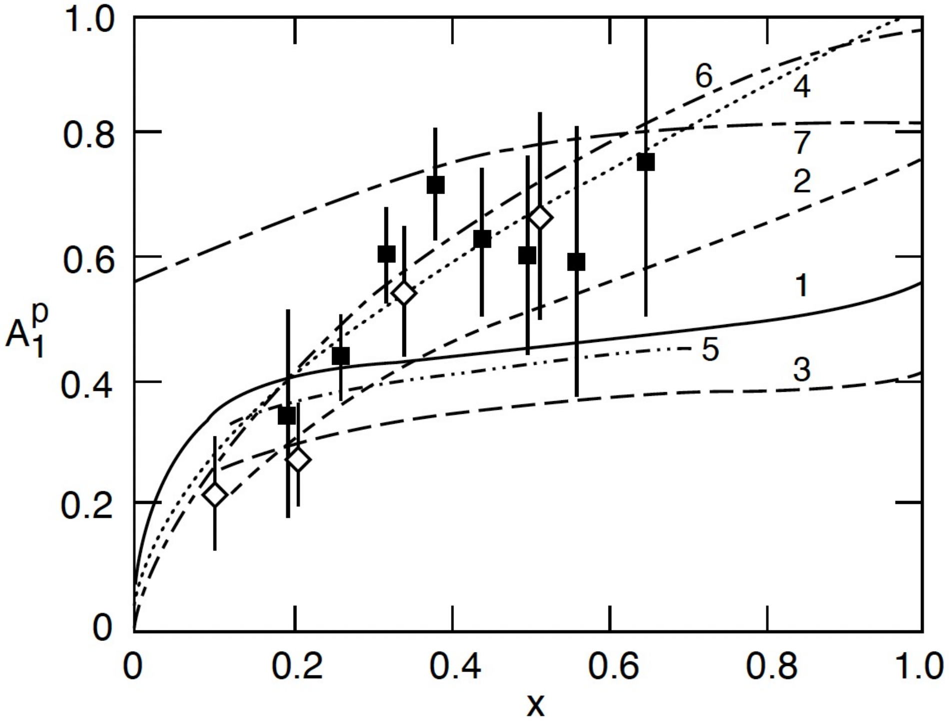
$$A_{||} = \frac{N^A - N^{\bar{A}}}{N^A + N^{\bar{A}}}$$

Allows for the first time the measurement of electron scattering rates, as a function of energy and scattering angle, when beam and target helicities are aligned (A) vs anti-aligned ($\bar{A}$)!

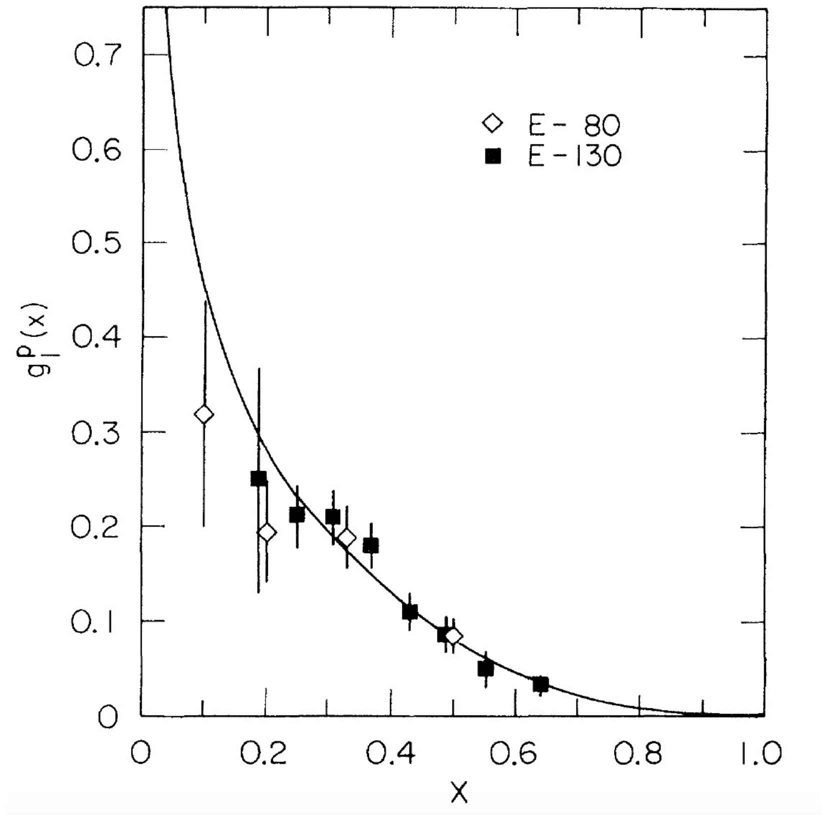
SLAC : First $\vec{e} + \vec{p}$ DIS experiments



$$A_{||} = D(A_1 + \eta A_2) \approx DA_1$$



$$g_1 \approx F_1 A_1$$



Quark Parton Model :

$$g_1(x) = \frac{1}{2} \sum_{q+\bar{q}} e_q^2 \Delta f_q(x)$$

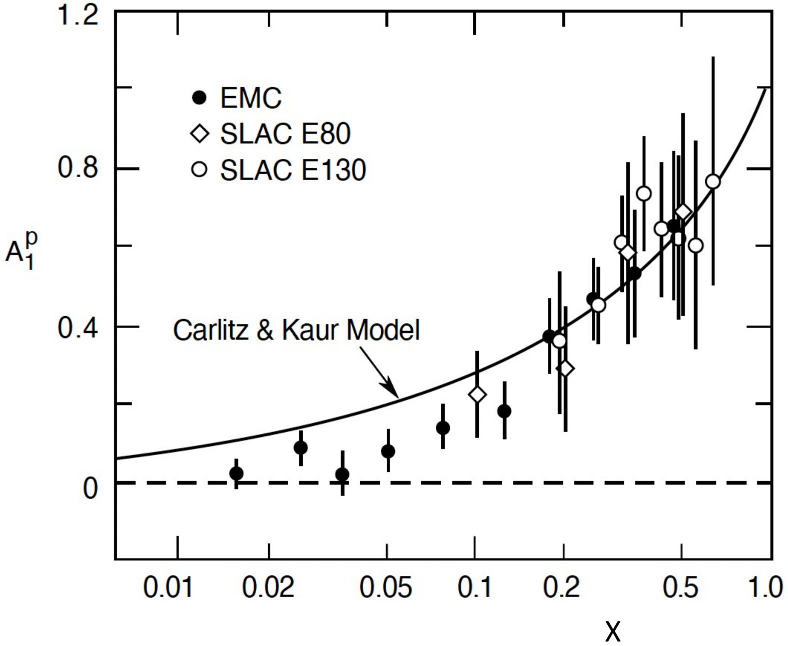
$$\Delta f(x) = f(x)^+ - f(x)^-$$

x = momentum fraction carried by struck quark

E-80 Phys. Rev. Lett. 37 (1976) 1261
E-130 Phys. Rev. Lett. 51 (1983) 1135

CERN : First $\vec{\mu} + \vec{p}$ DIS experiments

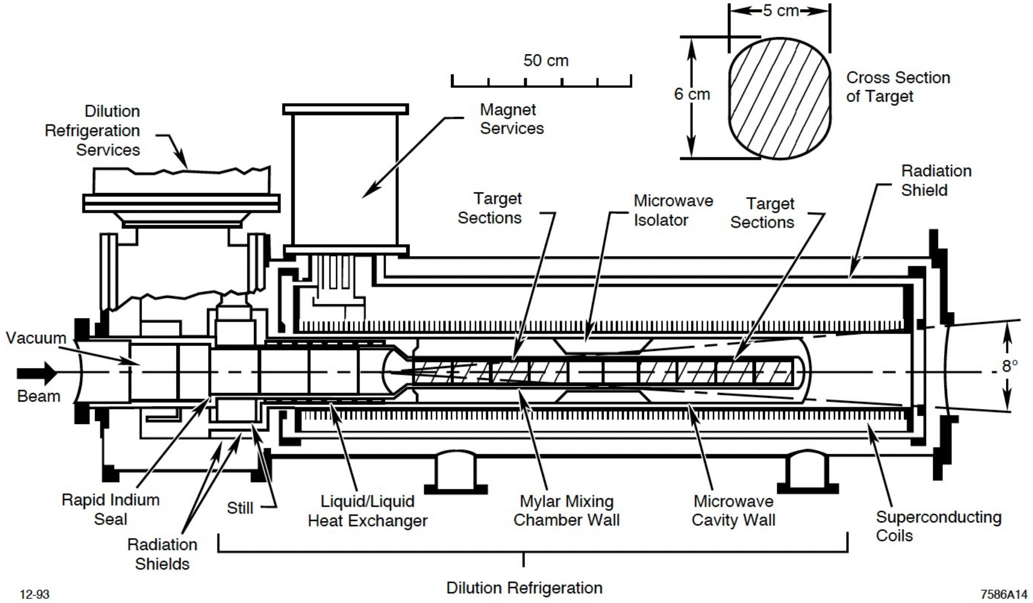
Phys. Lett. B206 (1988) 364

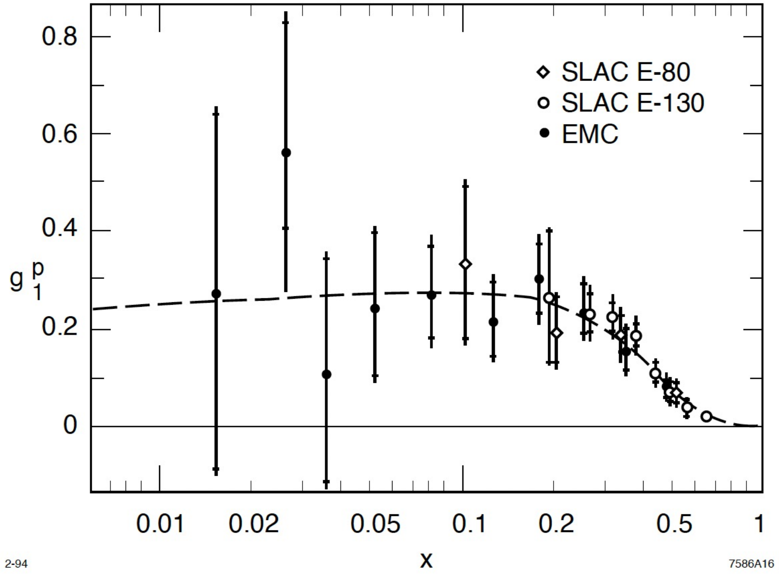


European Muon Collaboration (EMC)

- Muon beams with energy 100-200 GeV → pushes to higher Q^2 and lower x.
- Muon polarization comes from parity violating pion decays ~80%
- Intensity of muon beam was low and large transverse width
- Need a large target to maximize statistics -> 2m long ammonia target
- Target split in half and polarized in opposite directions to remove need to normalize to incoming beam luminosity
- Muons were detected in downstream spectrometers

Nucl. Phys. B328 (1989) 1





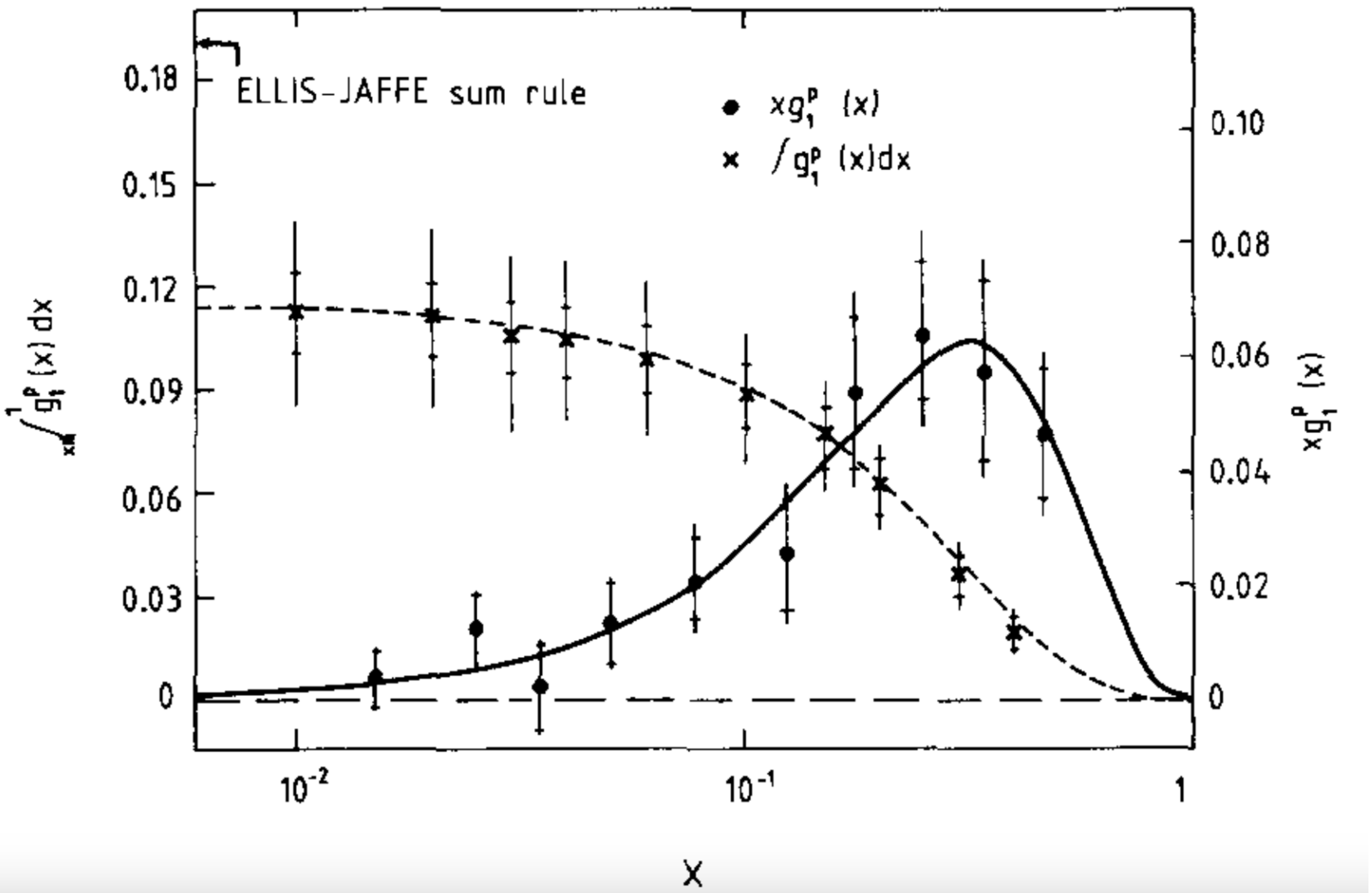
The plot that launched the "spin-crisis"

The Ellis-Jaffe Sum Rule predicts a value for the integral of $g_1(x)$ over all x assuming:

1) No gluon contribution to the spin of the proton
2) No strange sea contribution to spin of the proton.

Conclusion was that quarks carry very little of the spin of the proton -> $14 \pm 9 \pm 21\%$!

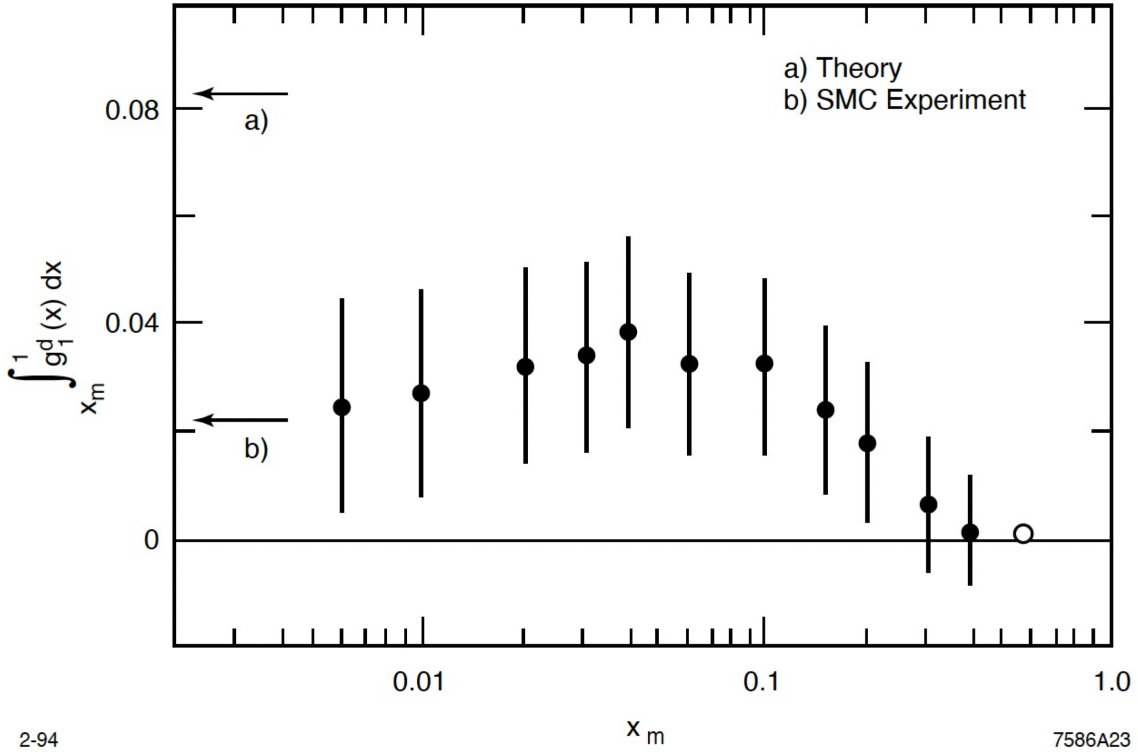
This generated a lot of discussion in the high energy physics community.



CERN: Spin Muon Collaboration

SMC

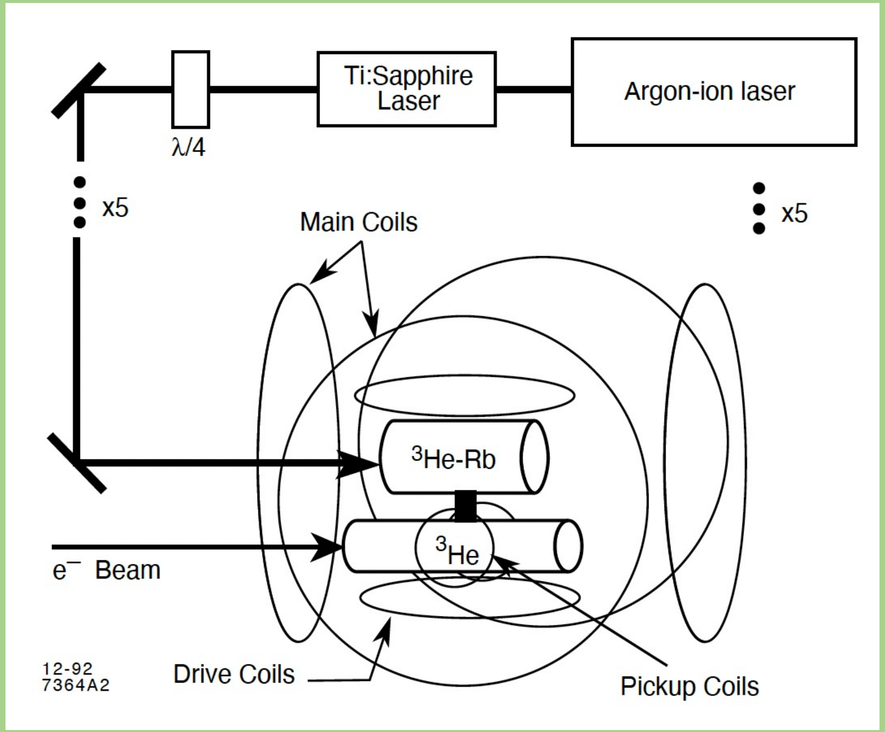
- Dedicated spin structure experiment utilizing polarized muons
- Measured muon beam polarization directly
- Switched to butanol targets for faster polarization reversal.
- Ran with proton and deuteron targets
- Confirmed EMC findings

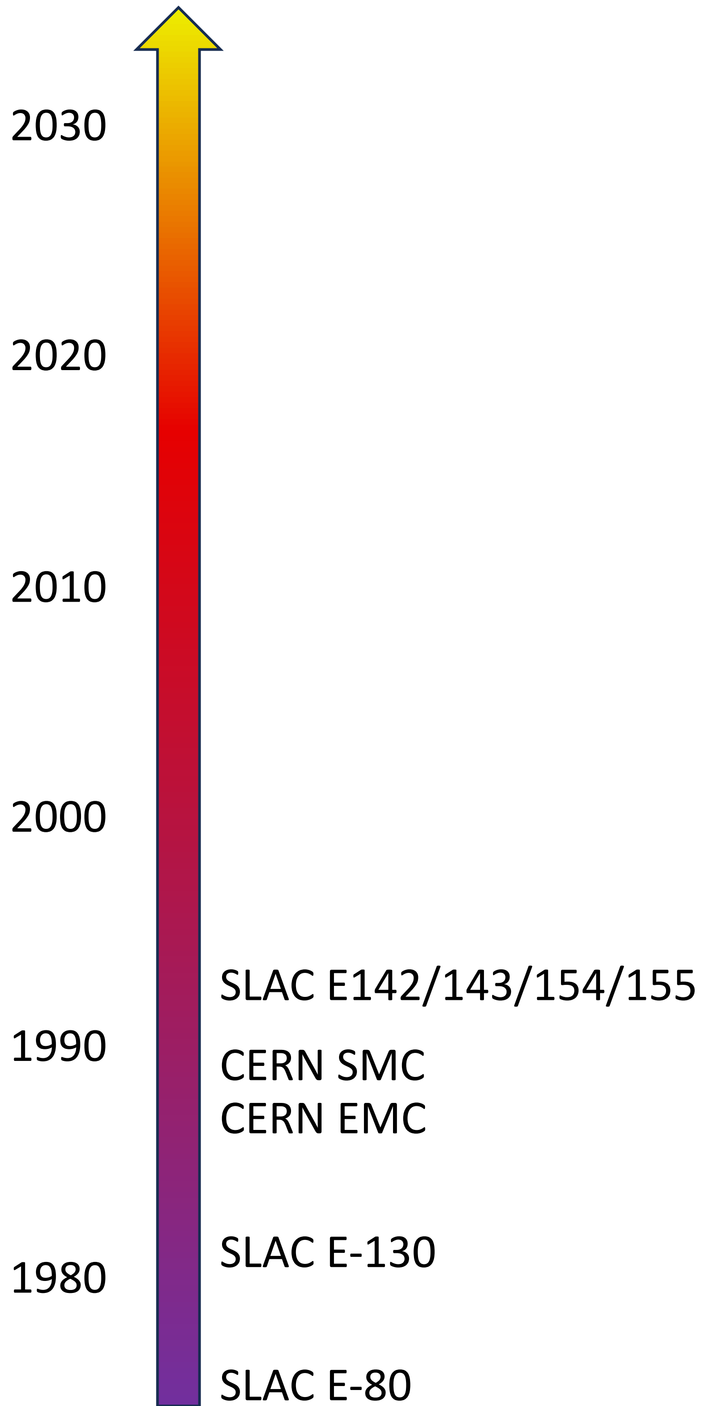


Phys. Rev. B 302 (1993) 553

SLAC E142+E143

- The ESA program quickly followed suit by developing and running with the first polarized gas ^3He target in E142
- $^{15}ND_3$ and ^6LiD solid targets were used for E143/155 later in the decade




2030
2020
2010
2000
SLAC E142/143/154/155
1990
CERN SMC
CERN EMC
SLAC E-130
1980
SLAC E-80

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SLAC E142/143/154/155

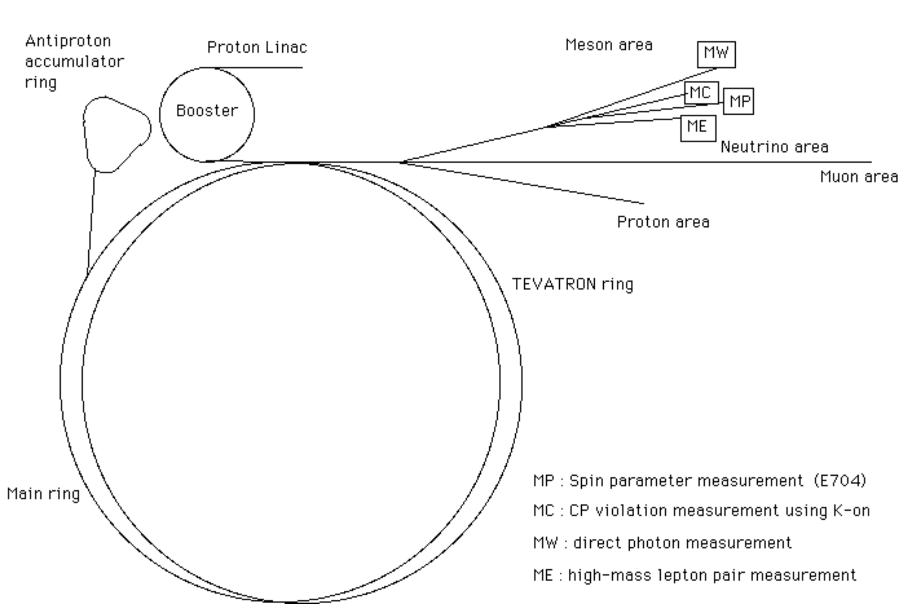
FNAL E581/704

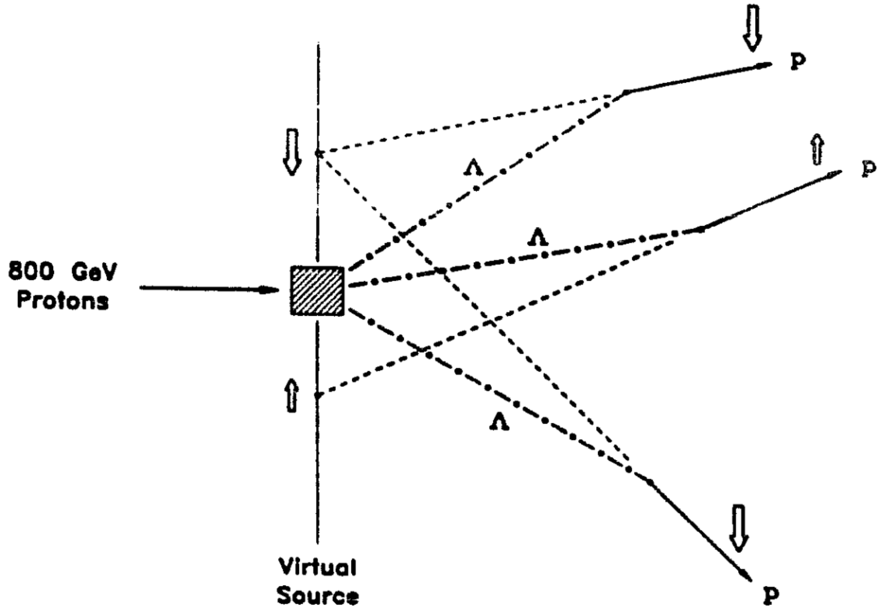
CERN SMC

CERN EMC

SLAC E-130

SLAC E-80





Fermilab Spin Physics Facility

- 800 GeV protons from the Tevatron impinge a beryllium target
- $\Lambda + \overline{\Lambda}$ are produced and decay into protons ($\bar{p}$) + π^- (π^+)
- Proton spin is tagged via momentum and position reconstruction from hodoscopes in the beamline.
- Proton polarization flipped with spin rotators
- Result is 200 GeV protons beams with 45% polarization

PRL 61 (1988) 1918
PLB 264 (1991) 462-466

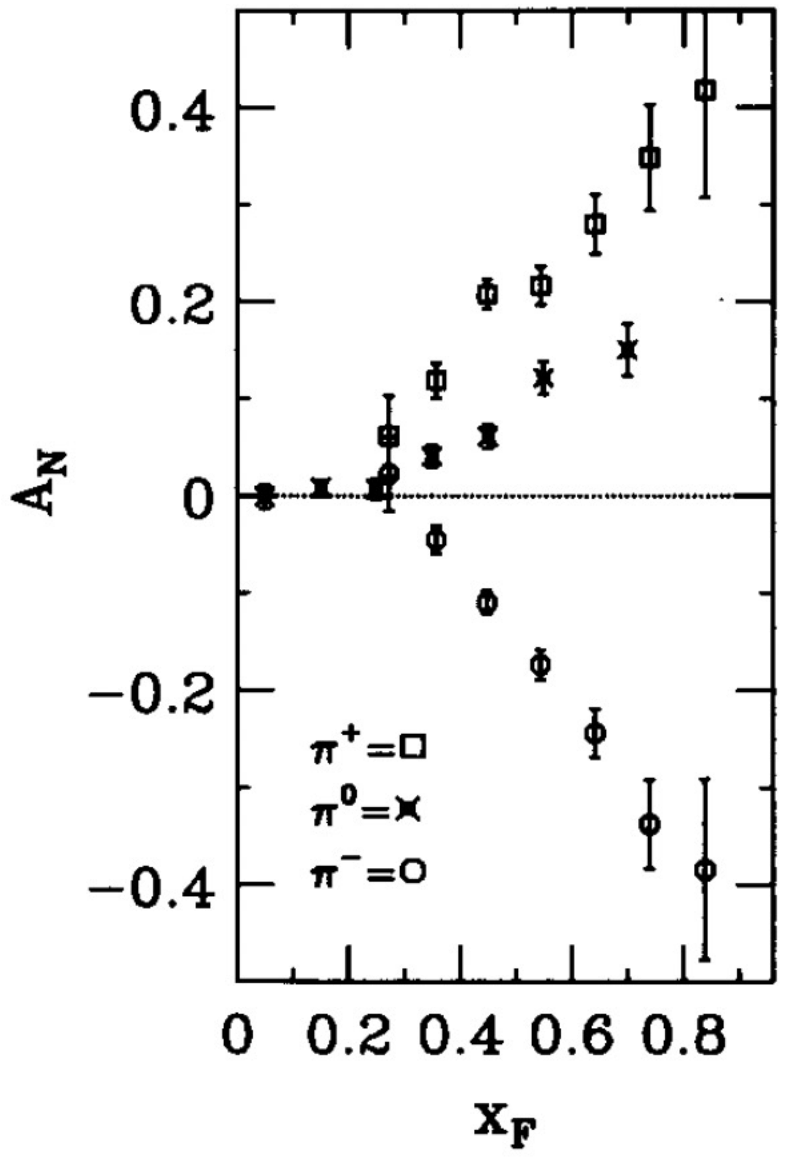
FNAL E851/E704

200 GeV polarized proton beam incident on liquid hydrogen target.
Neutral pions reconstructed with lead glass calorimeter
Charged pions identified with gas Cerenkov detector.
Pion p_T = 0.2 - 2 GeV

$$A_N = \frac{1}{P_B \cos\theta} \frac{N_{\uparrow}(\theta) - N_{\downarrow}(\theta)}{N_{\uparrow}(\theta) + N_{\downarrow}(\theta)}$$

Large asymmetries cannot be explained with the parton model.
PRL 41 (1978) 1689

Published in 1988 – same year as EMC result!

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FNAL E581/704
CERN SMC
CERN EMC
SLAC E-130
SLAC E-80
The quark helicity distribution is small – how small? Is it zero?
Where does the remainder of the proton spin reside? Gluon helicity? Strange quarks? Partonic orbital angular momentum?
What is the mechanism behind large meson transverse single spin asymmetries?
Can this newly minted theory of Quantum Chromodynamics explain this phenomena?

2030

2020

2010

2000

CERN COMPASS

JLAB HALLS A,B,C
DESY HERMES
SLAC E142/143/154/155

1990

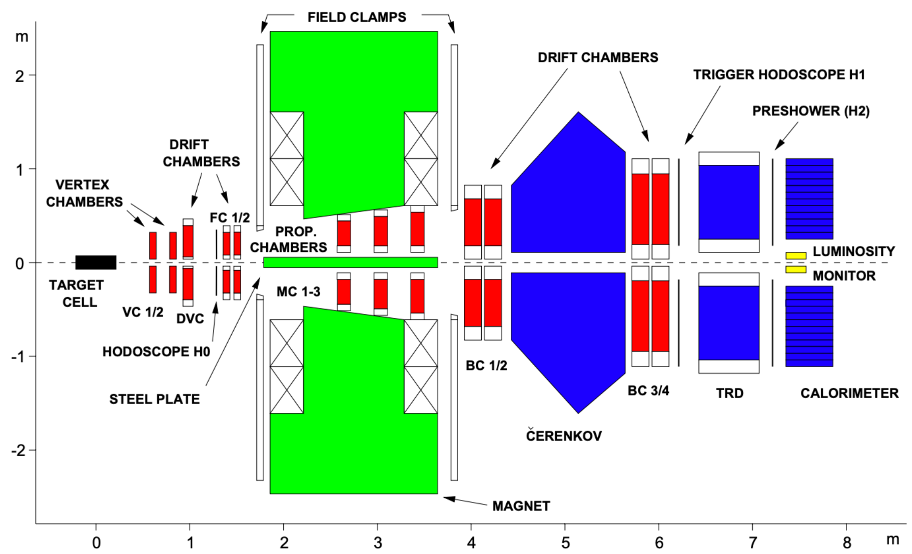
FNAL E581/704
CERN SMC
CERN EMC

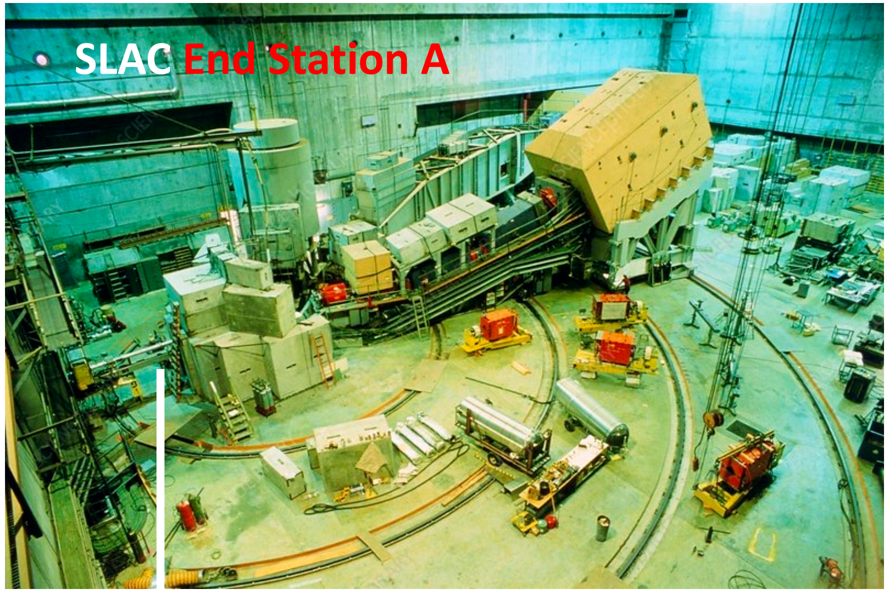
1980

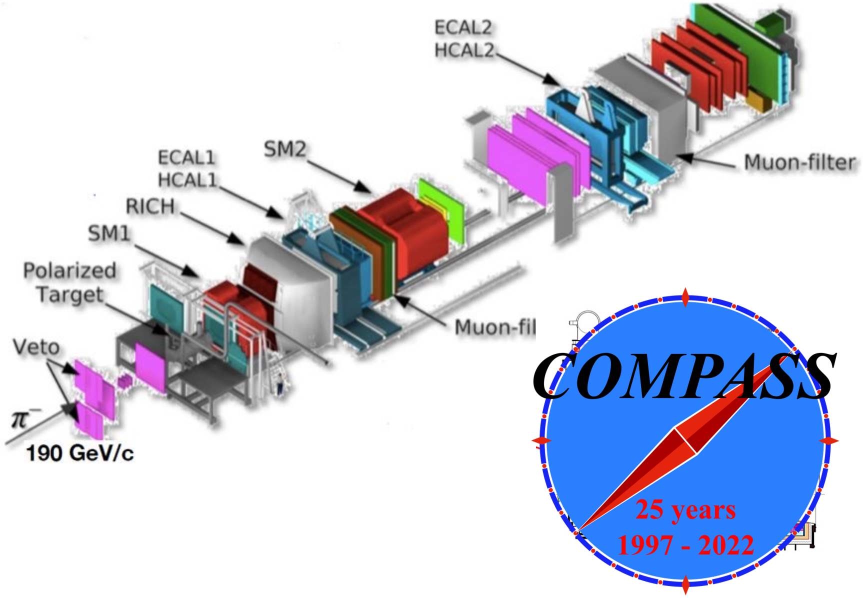
SLAC E-130

SLAC E-80

The HERMES spectrometer

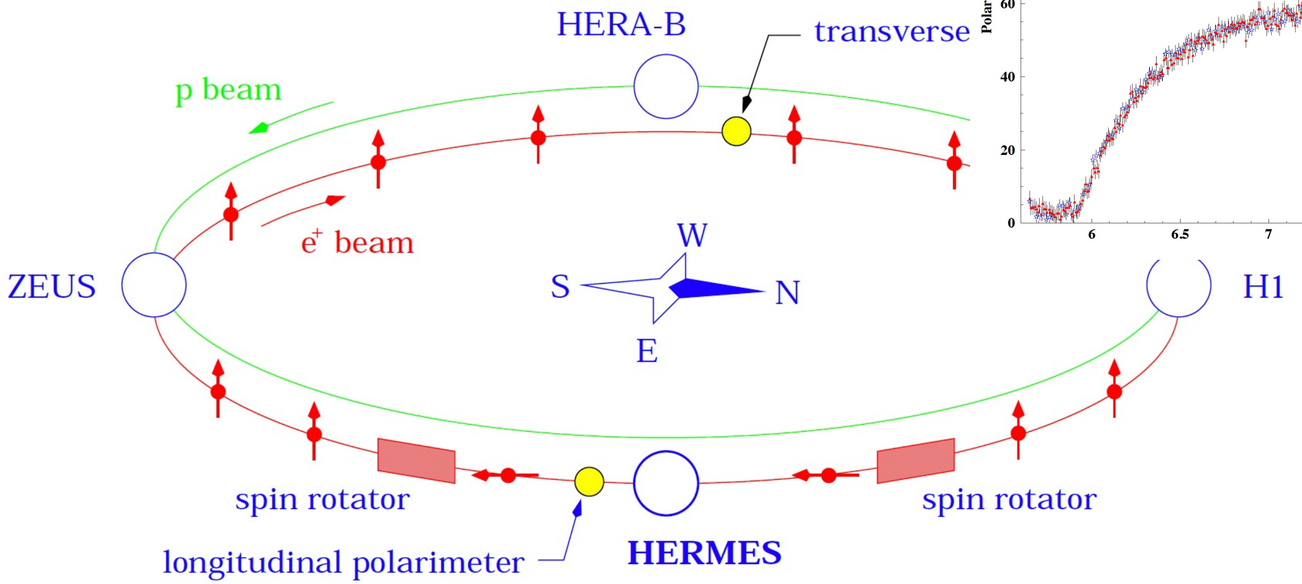


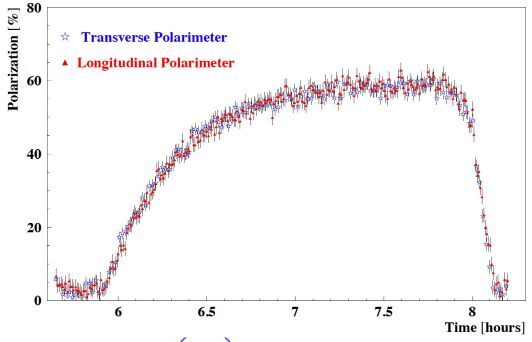


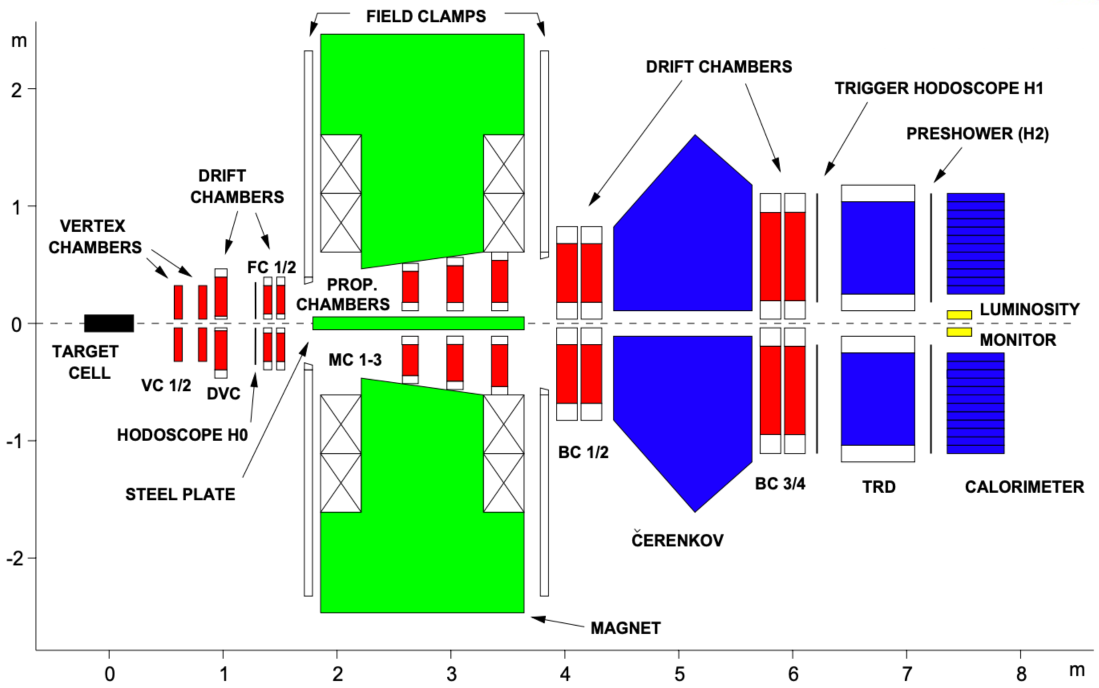


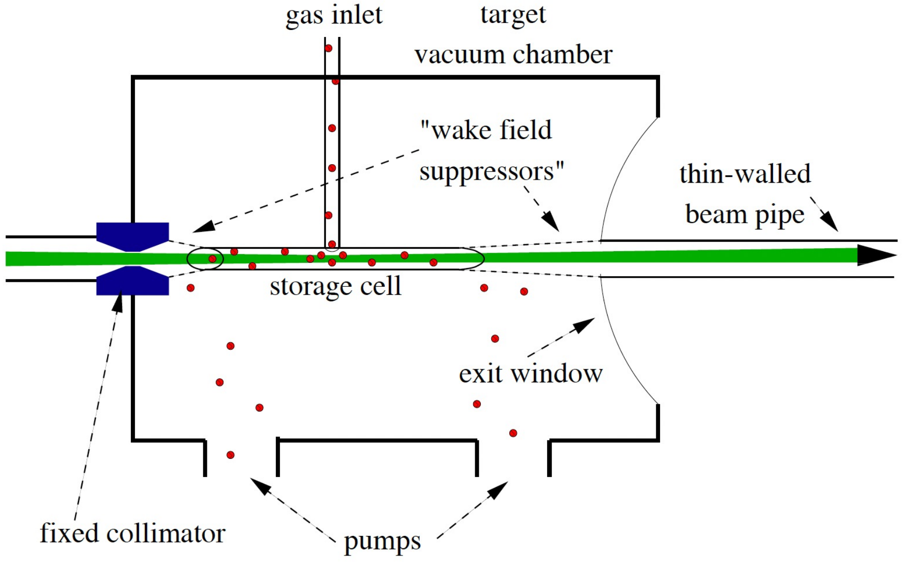
DESY: Hermes

- 27.6 GeV 30 mA e^+ beam
- <pol> ~50% Sokolov-Ternov effect
- Polarized H, D and ^{3}He gas targets
- High (1%) resolution spectrometer with PID.

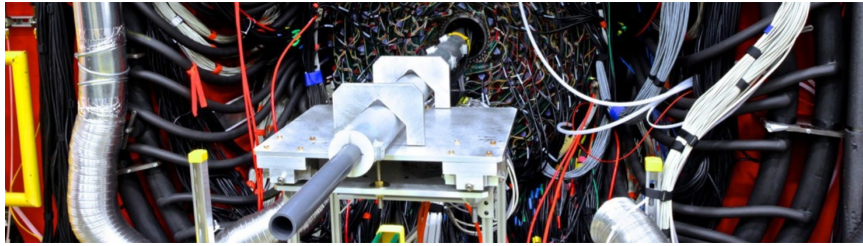






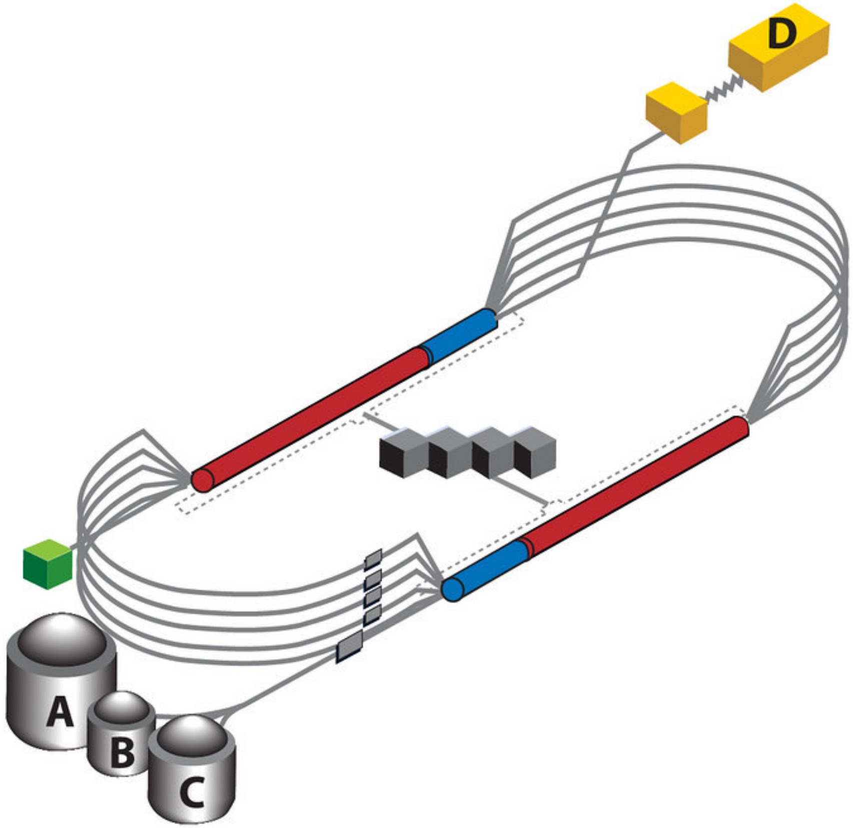


Jefferson Lab: Halls A, B, C and D



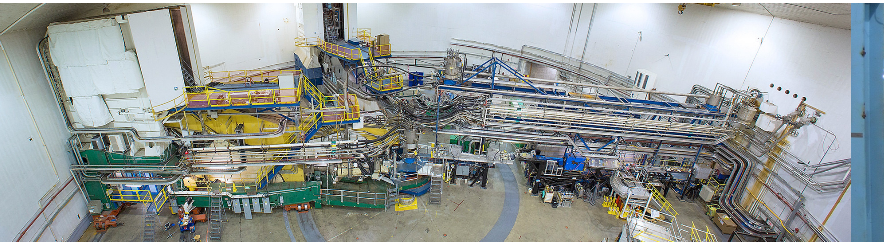
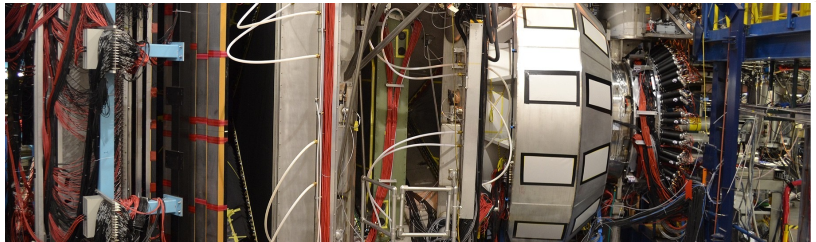
6 GeV Era   1995- 2012

- Energies from 0.4-6 GeV
- Strained layer GaAr source provides beam polarizations upward of 80%
- Continuous-wave beam with currents of nA – 100 uA delivered simultaneously to three halls.
- Solid and gas polarized targets combined with high currents provide highest luminosities in ep scattering

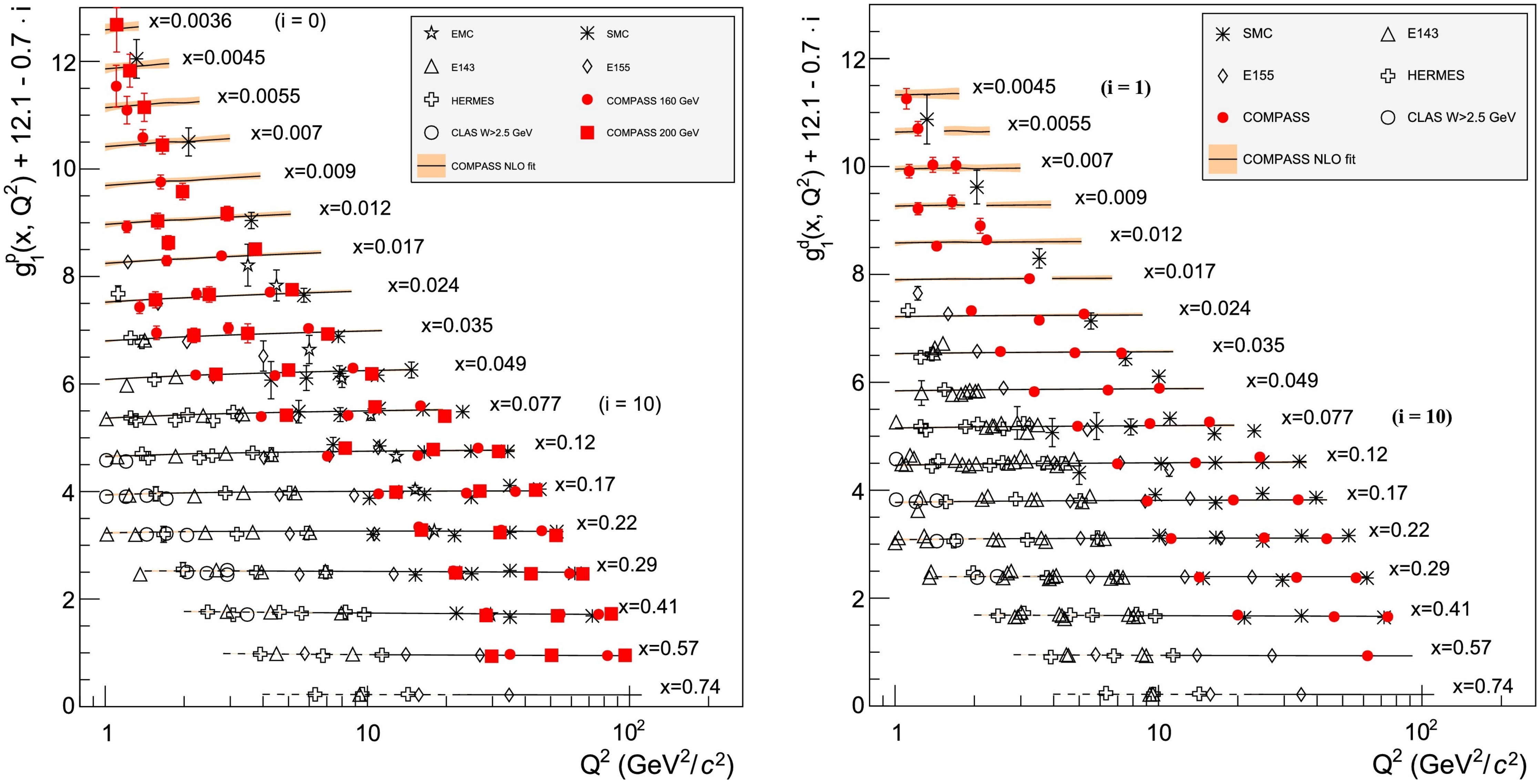


12 GeV Era   2017- present

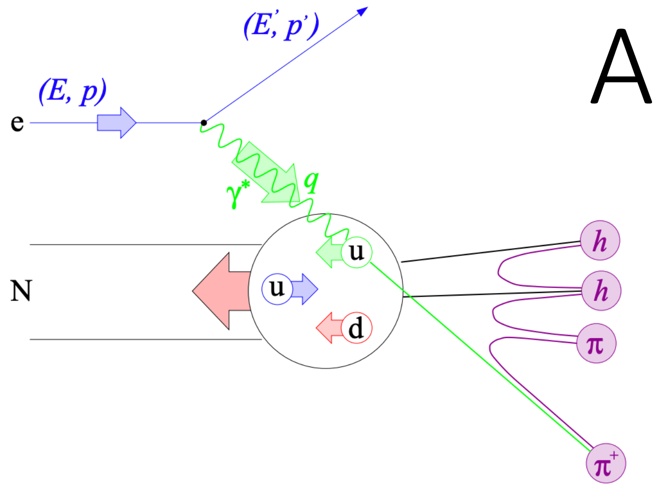
- New experimental Hall D and linearly polarized photon beamline
- Up to 11 GeV for Halls A-C and 12 GeV for Hall D
- Detector upgrades to existing Halls B and C

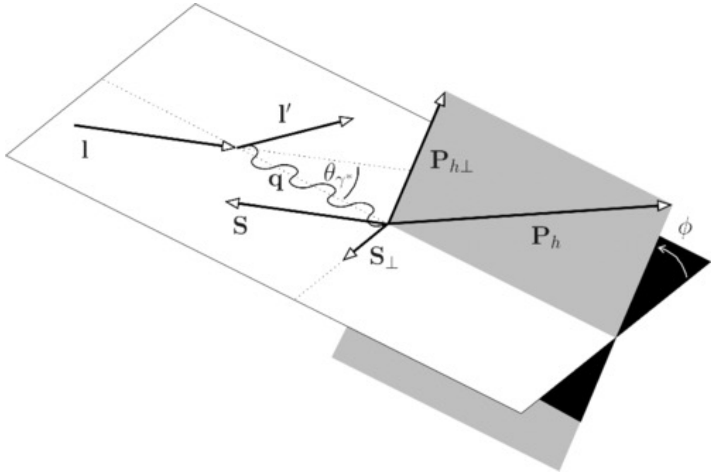

Four experimental programs & 25 years later

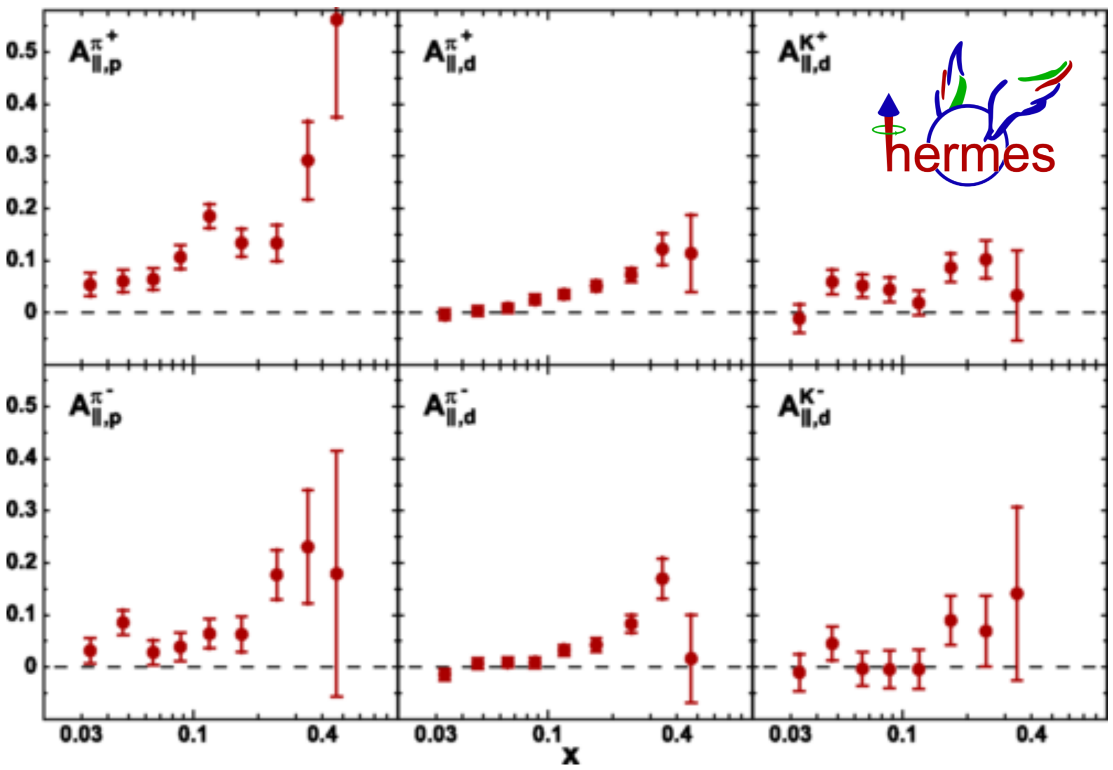


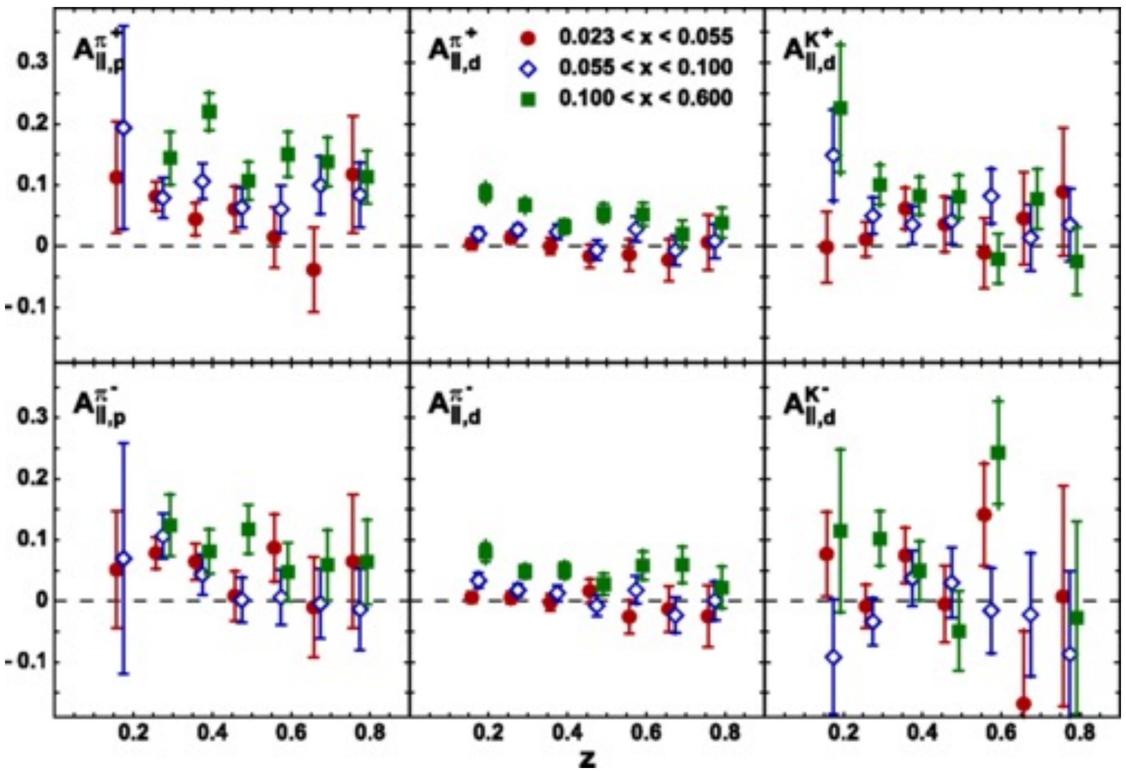
Also, semi-inclusive DIS



Allows for flavor tagging and extraction of information about individual quark helicity distributions. Requires information about associated fragmentation functions.





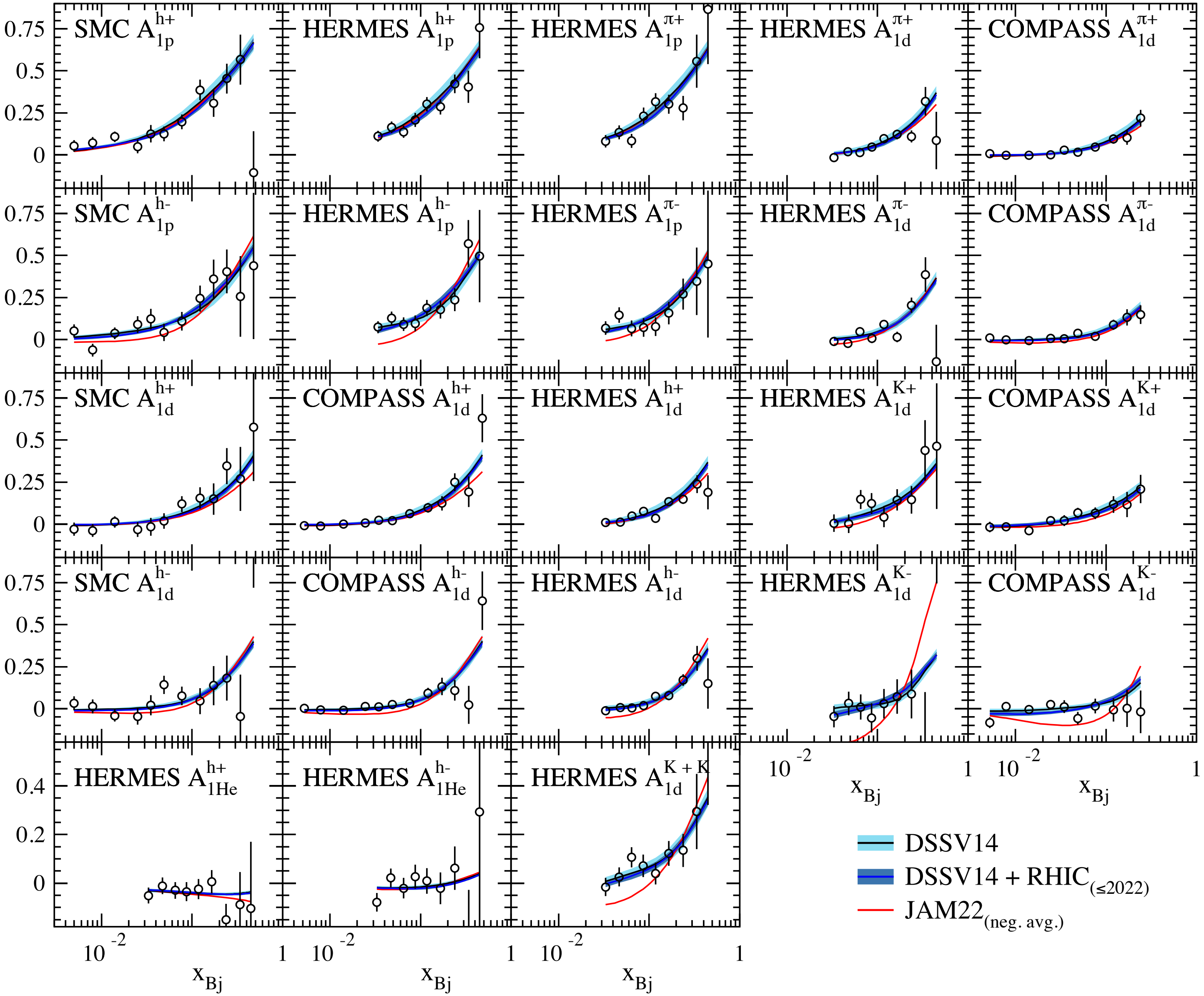


Phys. Rev. D 99, 112001

Global QCD Analysis : inclusive + SIDIS

Need NLO theoretical framework to interpret data and extract the helicity distributions,

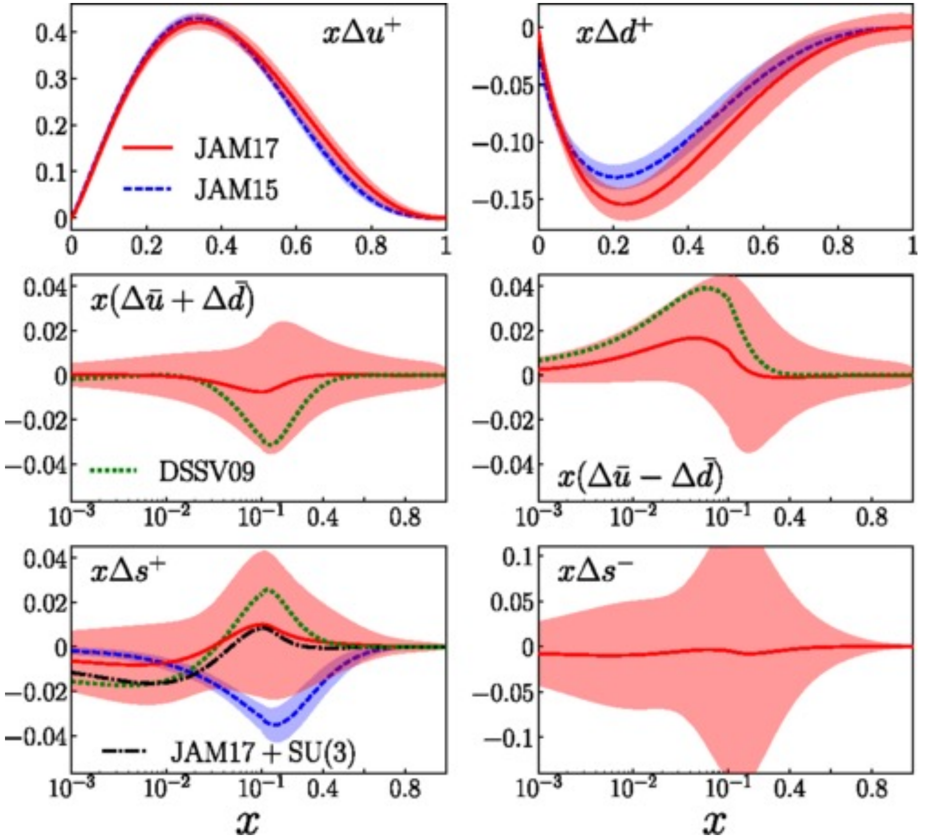
- **DSSV**
  PRL 101 (2008) 072001
  PRD 80 (2009) 034030
  PRL 113 (2014) 012001
  PRD 100 (2019) 114027
- **JAM**
  PRD 93 (2016) 074005
  PRL 119 (2017) 132001
  PRD 104 (2021) L031501
- **NNPDF** **only inclusive*
  NPB 874 (2013) 36
  NPB 887 (2014) 276
  arXiv : 1510.04248
  arXiv : 1702.05077

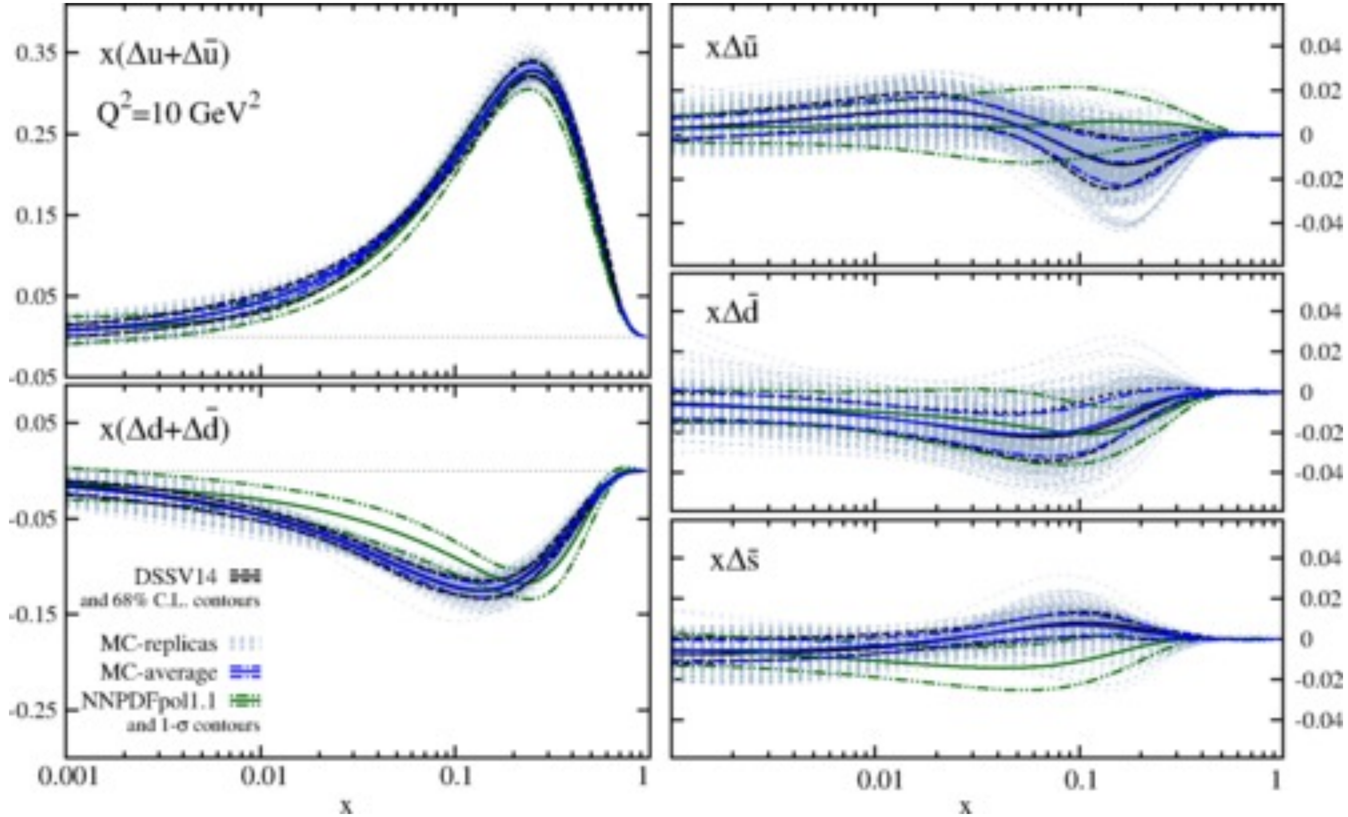


Global Analysis : Helicity Distributions

Total Quark Contribution to proton $\Delta\Sigma = \int dx[\Delta q + \Delta\bar{q}]$ ~ 0.25

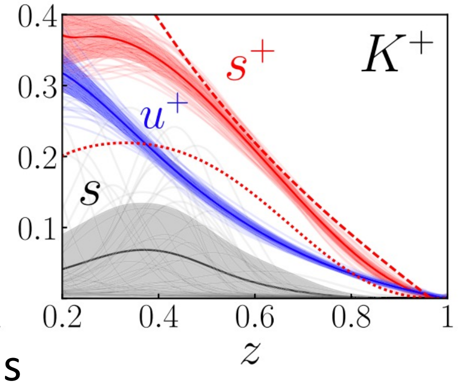
- Precision is driven by existing DIS + SIDS data
- Evolves slowly with Q^2 -> lots of room for additional contributions from strange quarks, gluons, orbital angular momentum….





Total strange quark contribution is small!

Shape of Δs highly impacted by SIDIS data and associated fragmentation functions



RELATIVISTIC HEAVY ION COLLIDER
… world's 1st high energy $\vec{p}\vec{p}$ collider

2030

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BNL RHIC
CERN COMPASS

JLAB HALLS A,B,C
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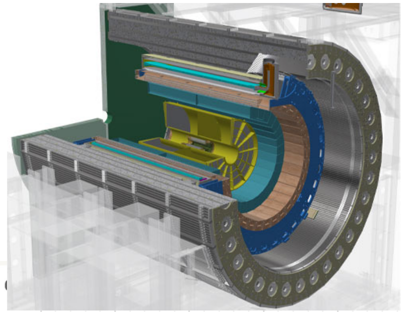
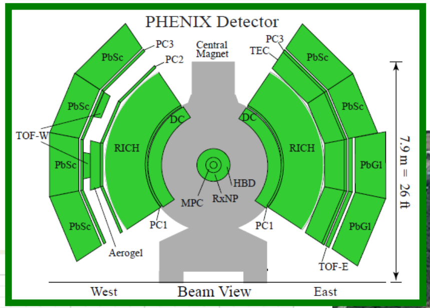
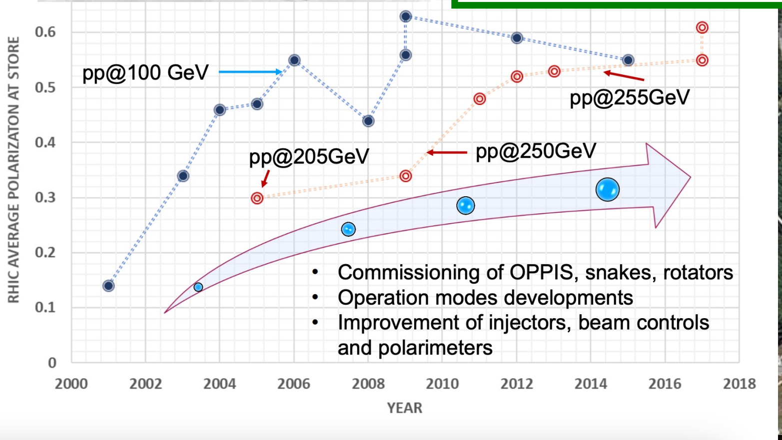
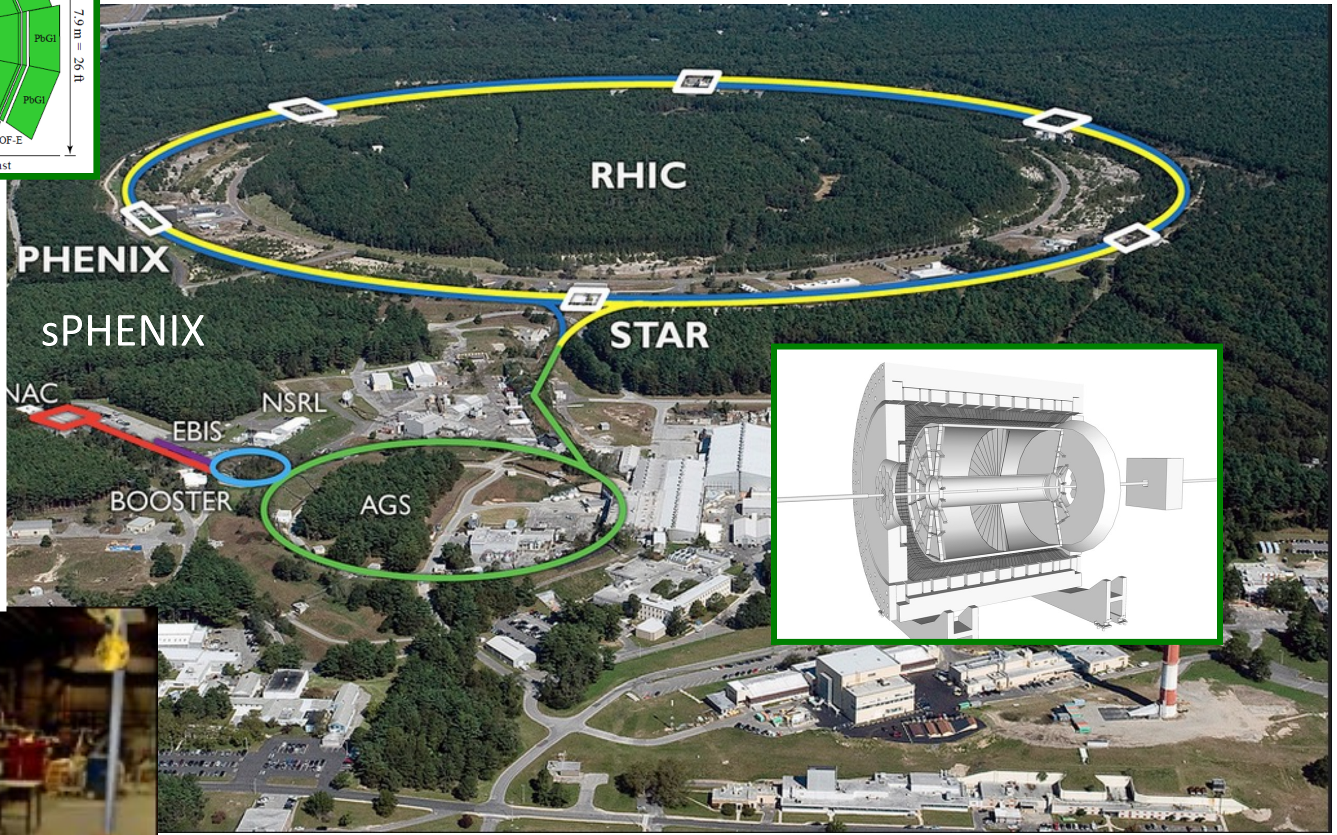
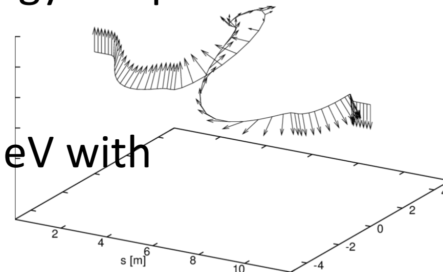








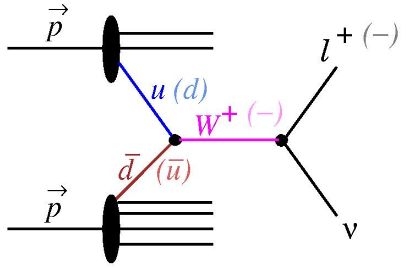
Siberian snakes rotate proton spin vector by π, preserving spin tune through energy ramp.
Derbenev and Kondratanko in 1970.

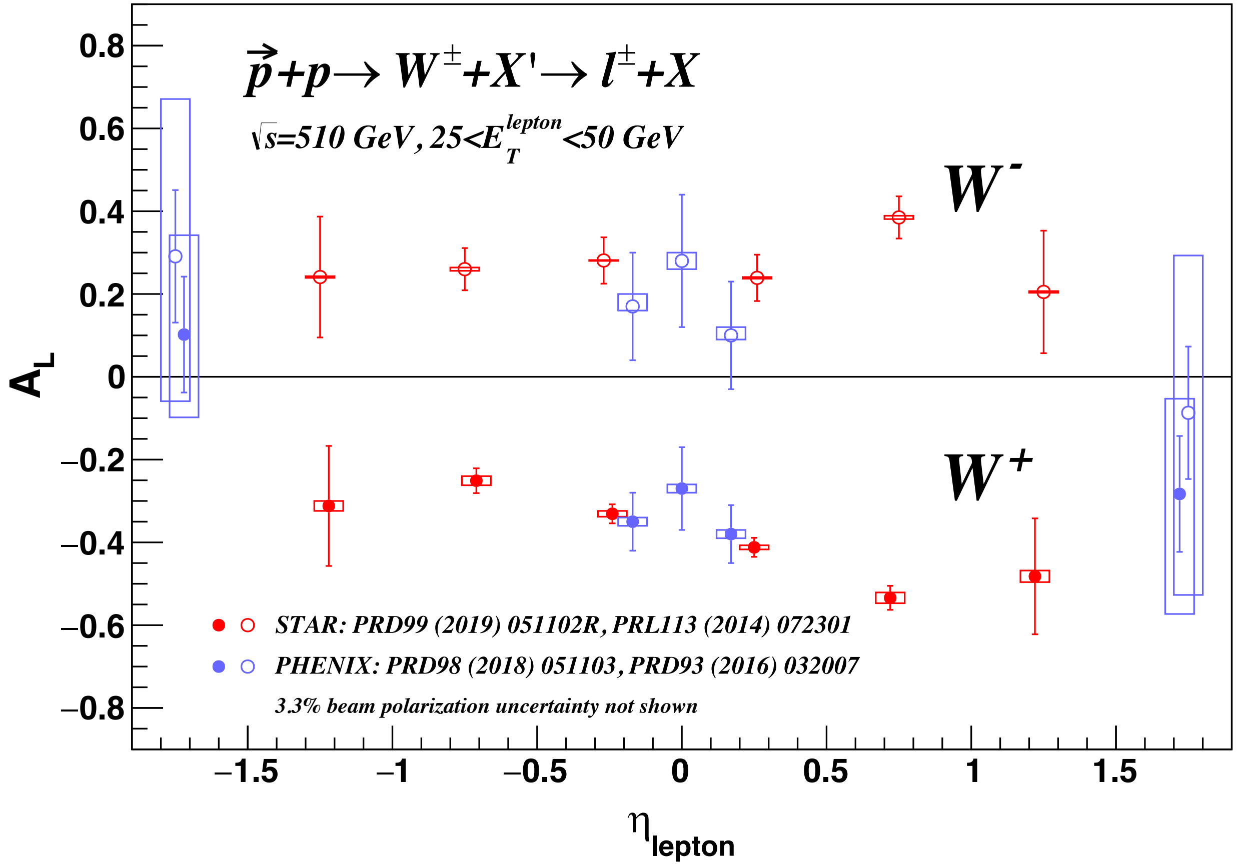


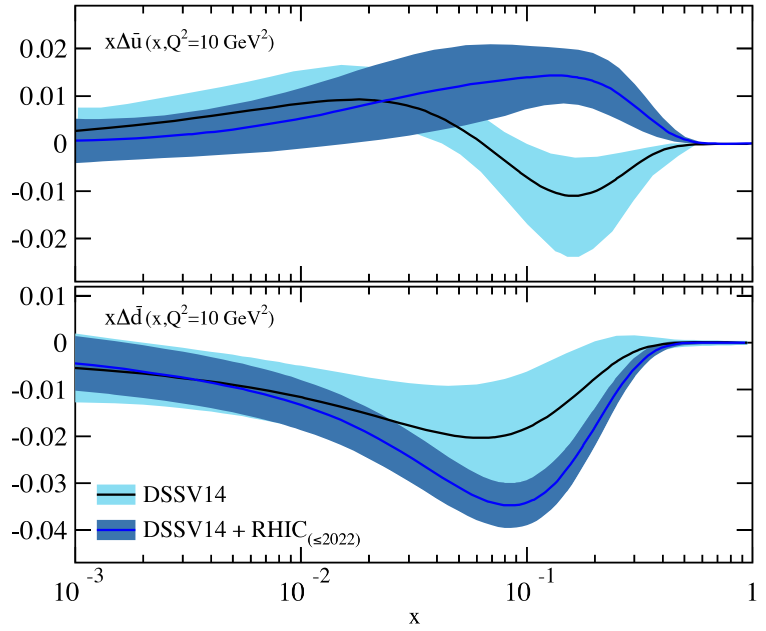
Beam energies range from 30-250 GeV with average polarization of 50-65%

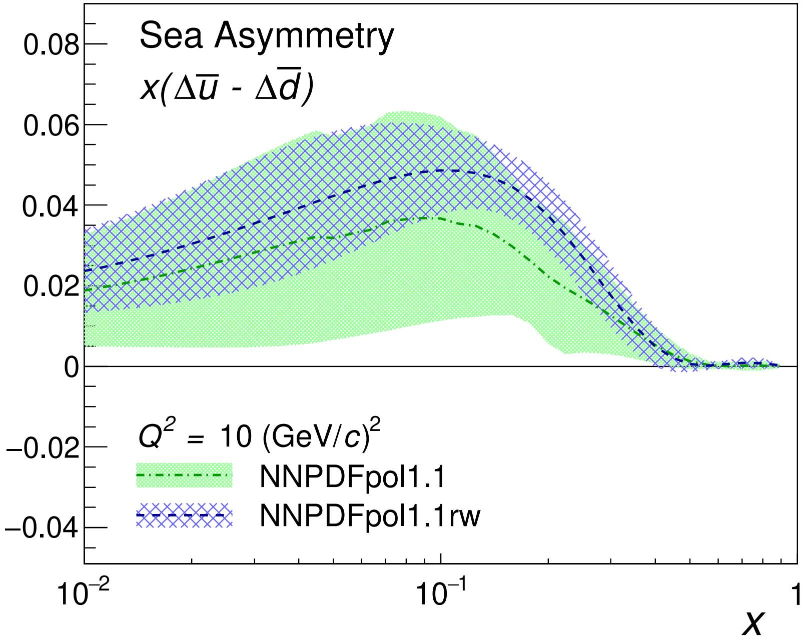
Accessing polarized sea with $W^{+/-}$

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





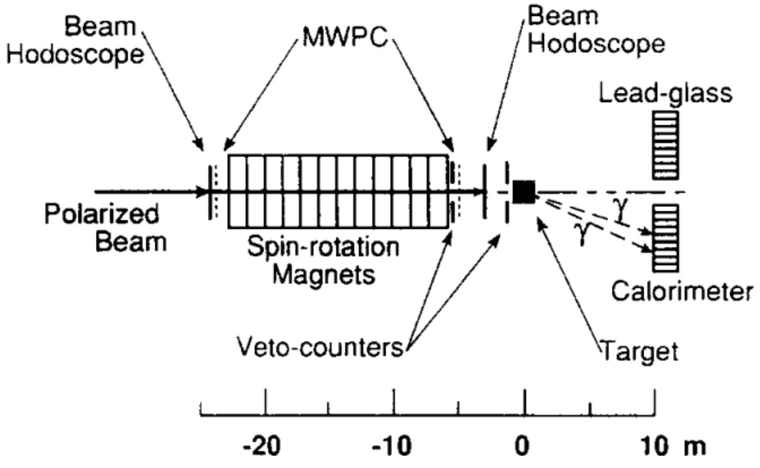


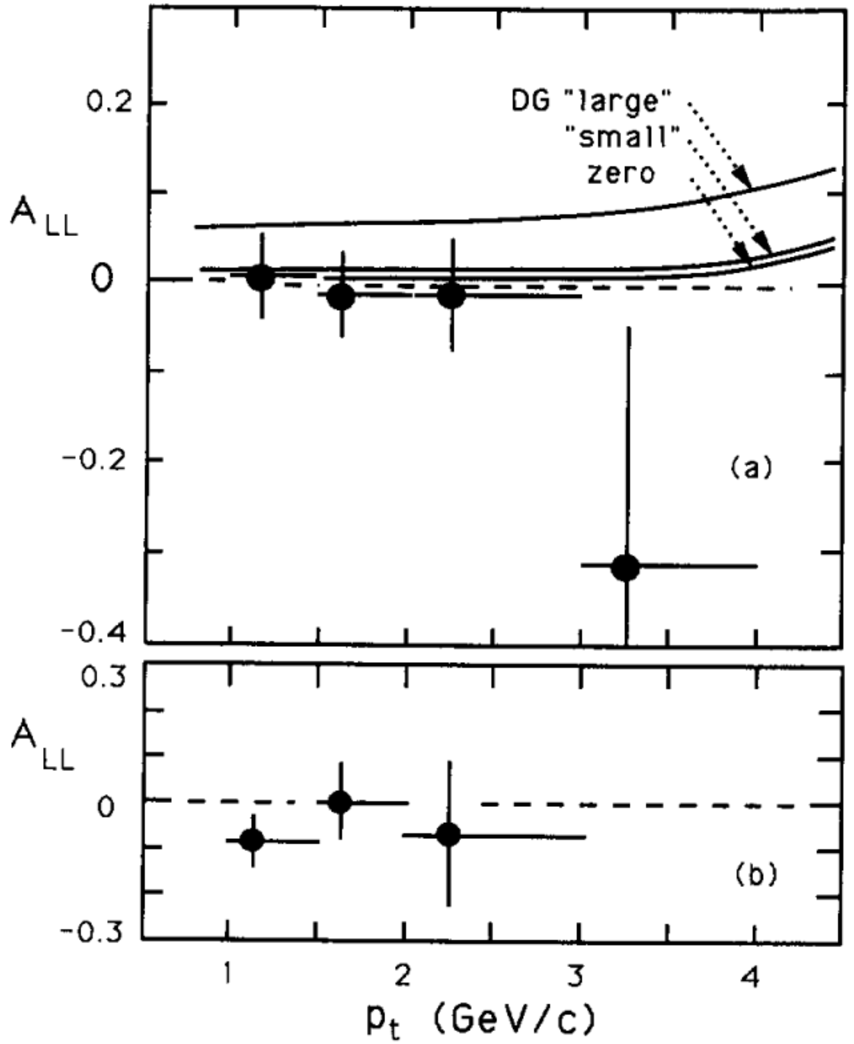


First measurement of A_{LL} in high energy $\vec{p}\vec{p}$ collisions

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{f_A f_B f_C} \Delta f_A \Delta f_B \times \Delta\sigma_{AB\to CX} \times D_C}{\sum_{f_A f_B f_C} f_A f_B \times \sigma_{AB\to CX} \times D_C}$$

- Lepton-proton scattering only sensitive to gluons at NLO
- But pp collision have gluon scattering at leading order
- Inclusive pion production is sensitive to both quark and gluon helicity distributions.
- E581/E704 Collaboration used beam from FNAL Spin Physics Facility and polarized pentanol target <pol> = 75-80%
- Theory curves provided by G. Ramsey and D. Sivers

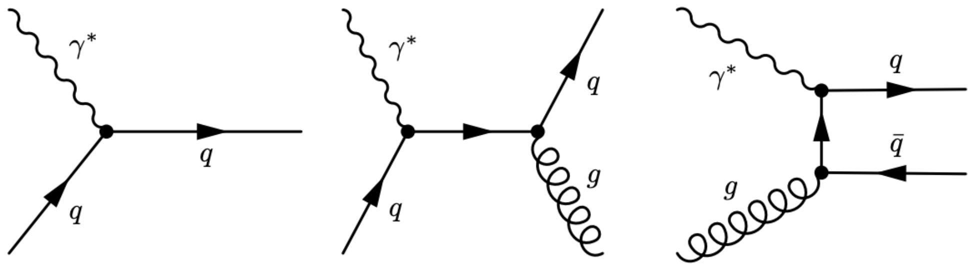


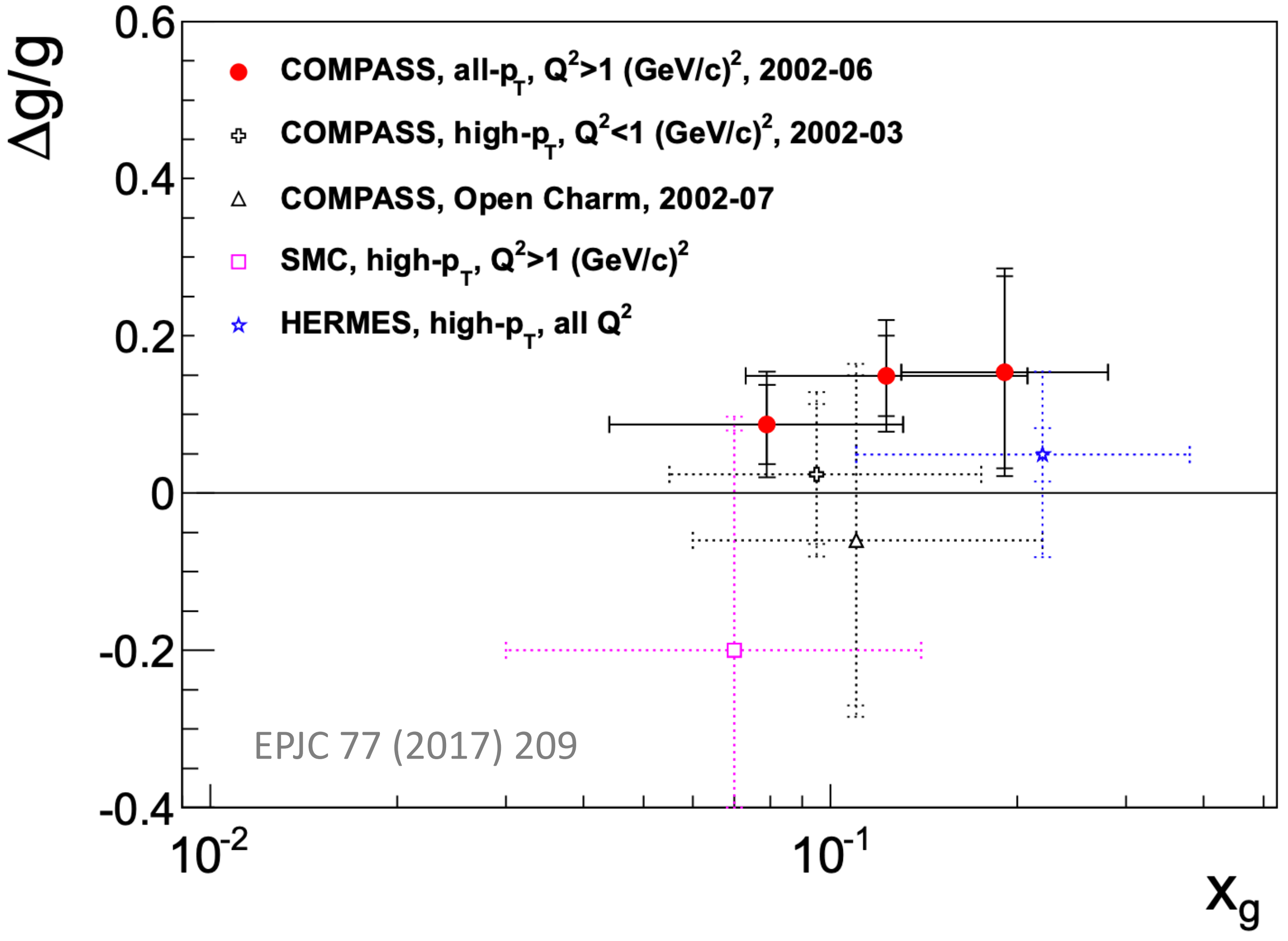


PLB 261 (1991), 197-200

Gluon Helicity in DIS lepton-proton scattering

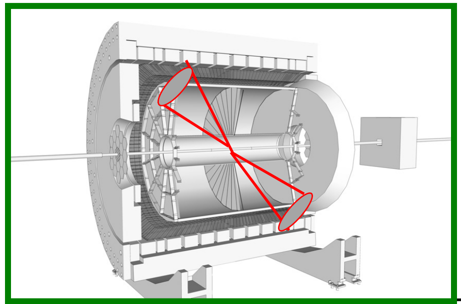
Longitudinal asymmetries of high –pT hadron pairs and open charm allowed traditional DIS experiments to enhance sensitivities to gluon helicity distributions.



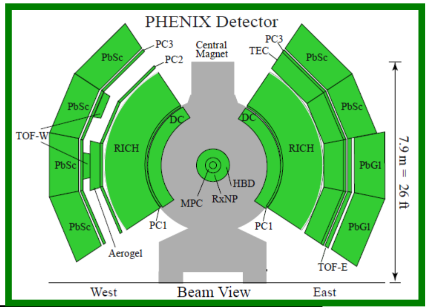


Extraction of Δ g/g is model dependent, but dependence is weak. Results very consistent with those from FNAL E704.

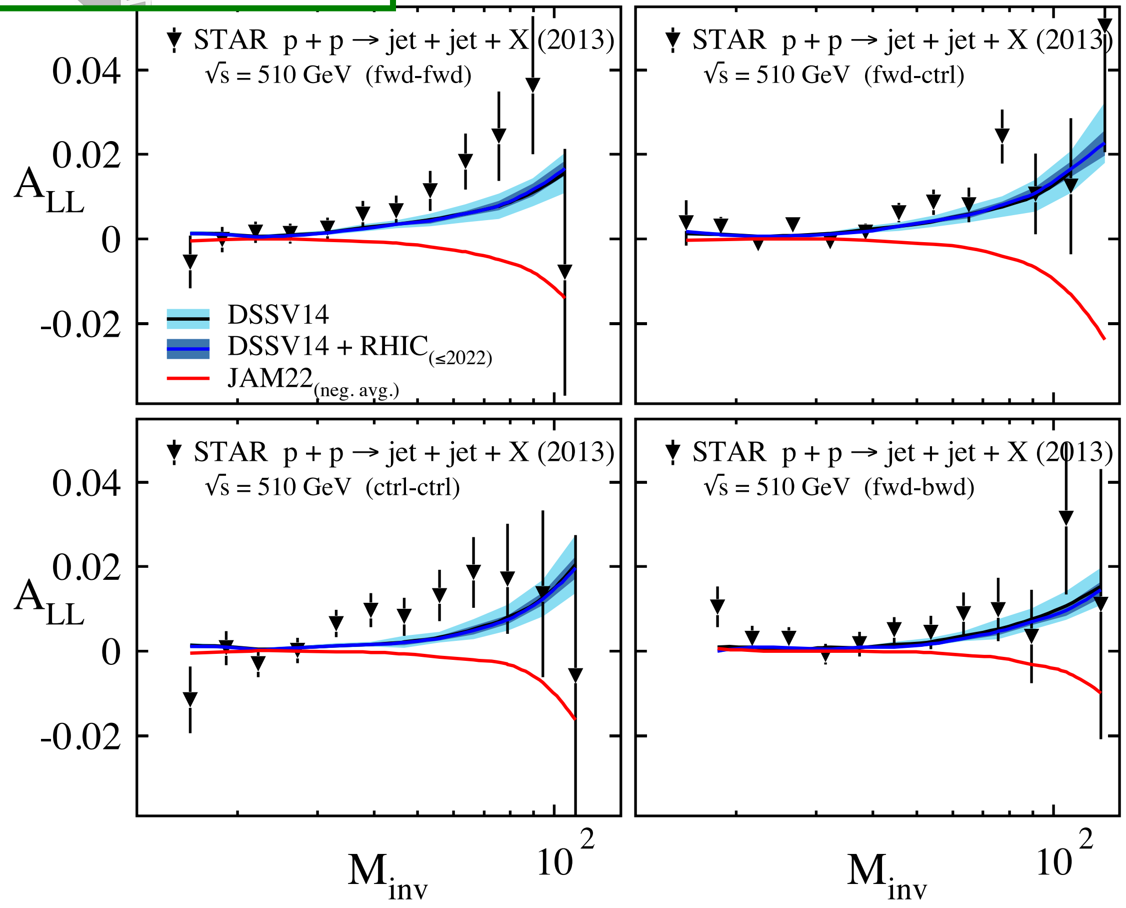
ΔG in $\vec{p}\vec{p}$ collisions @ RHIC

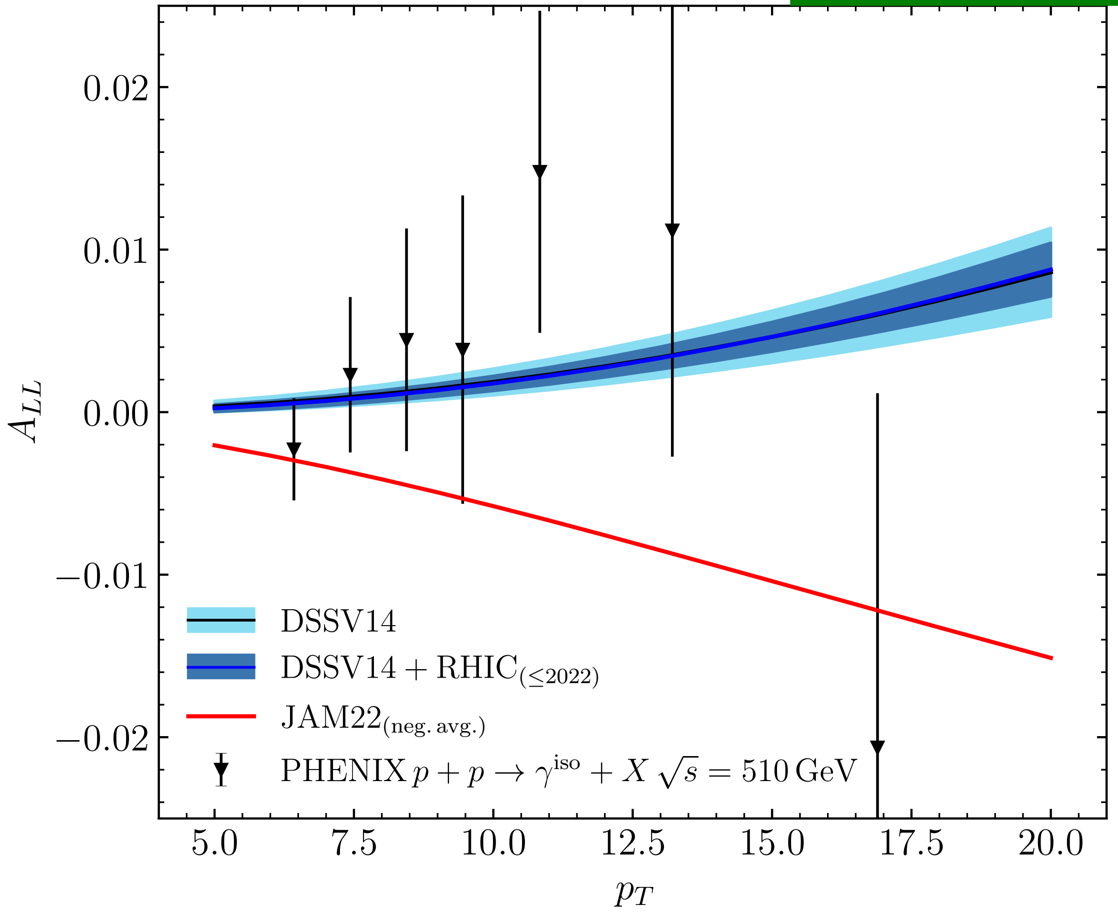


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{f_A f_B f_C} \Delta f_A \Delta f_B \times \Delta\sigma_{AB\to CX} \times D_C}{\sum_{f_A f_B f_C} f_A f_B \times \sigma_{AB\to CX} \times D_C}$$



Phys.Rev. D 100 (2019) 052005

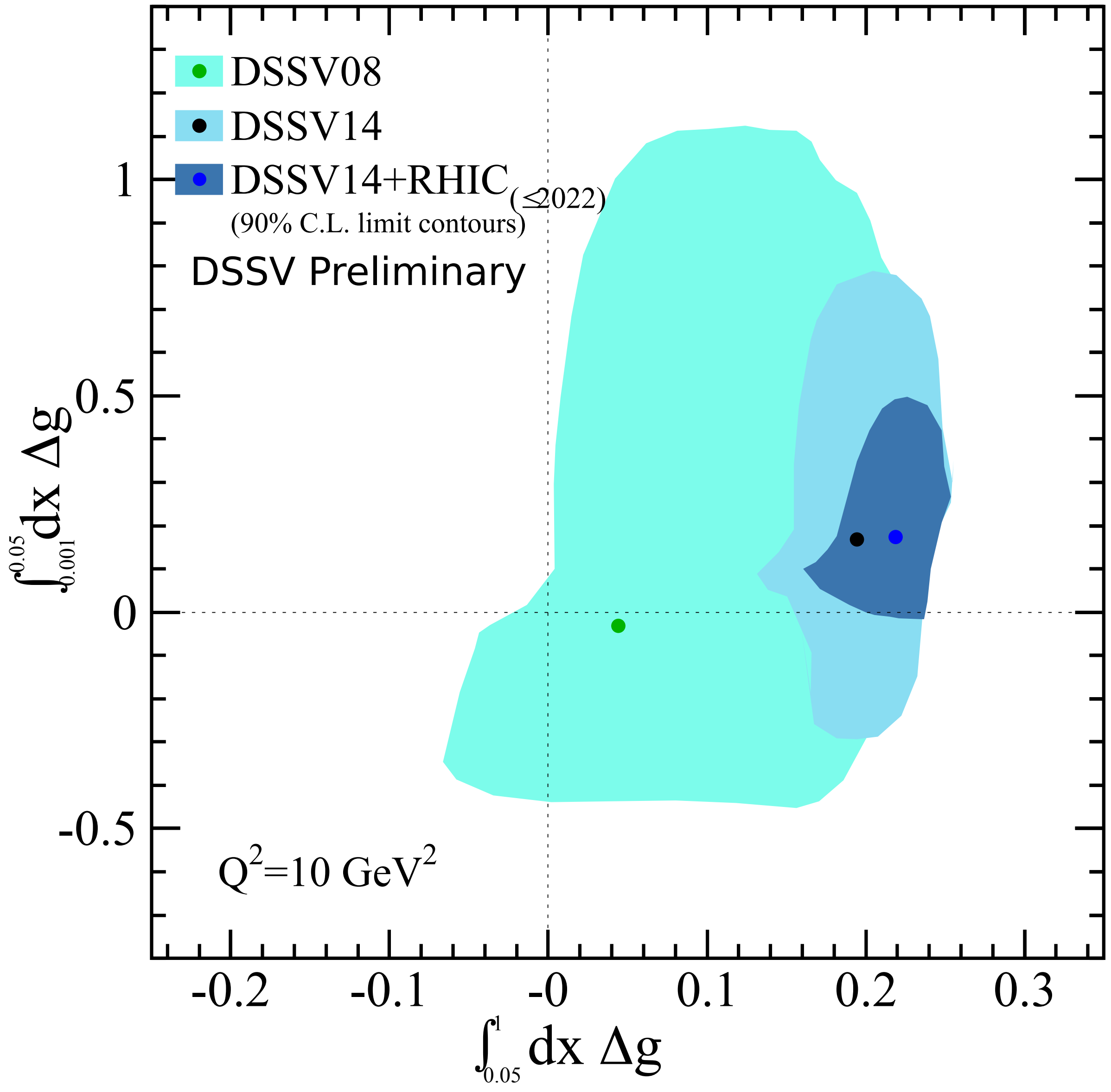


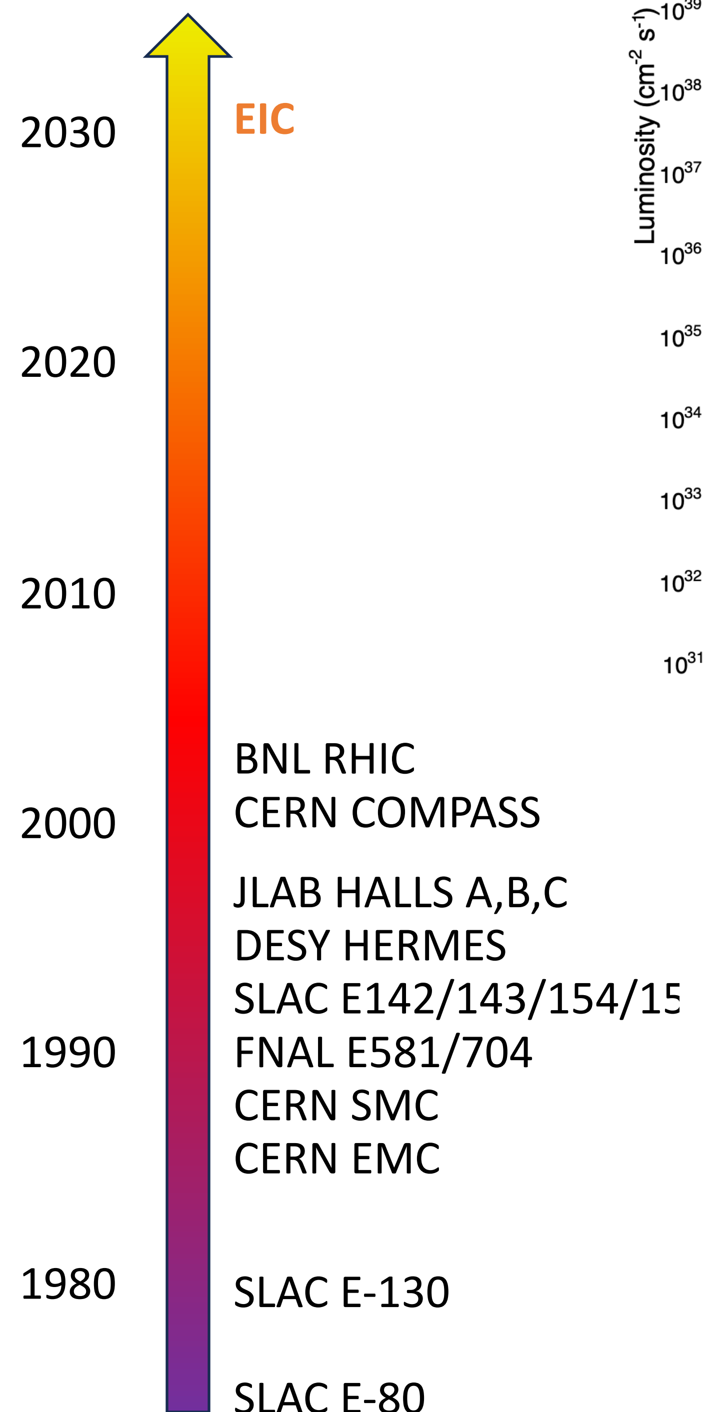


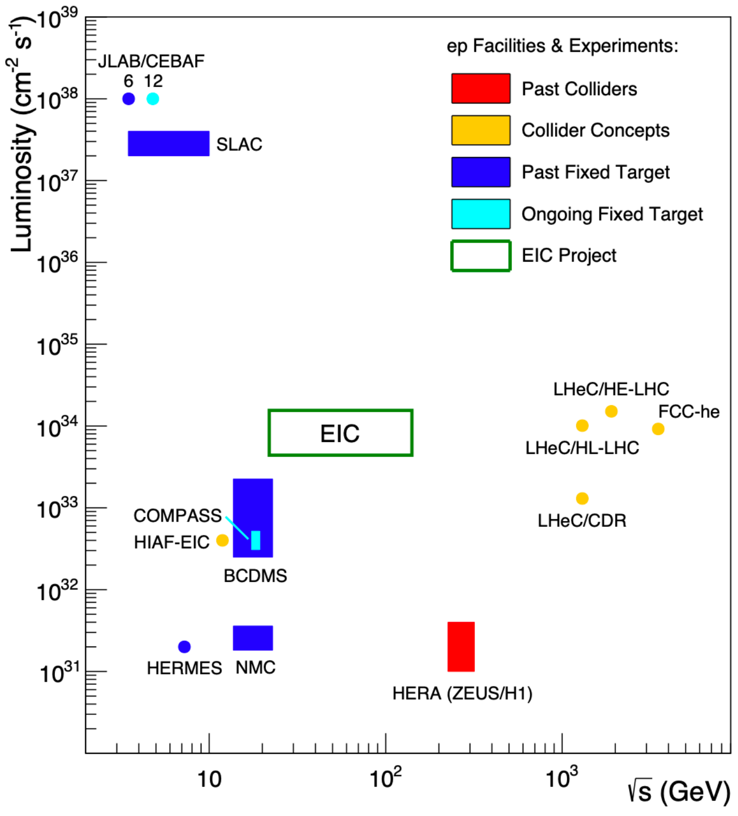
PRL 130 (2023) 251901

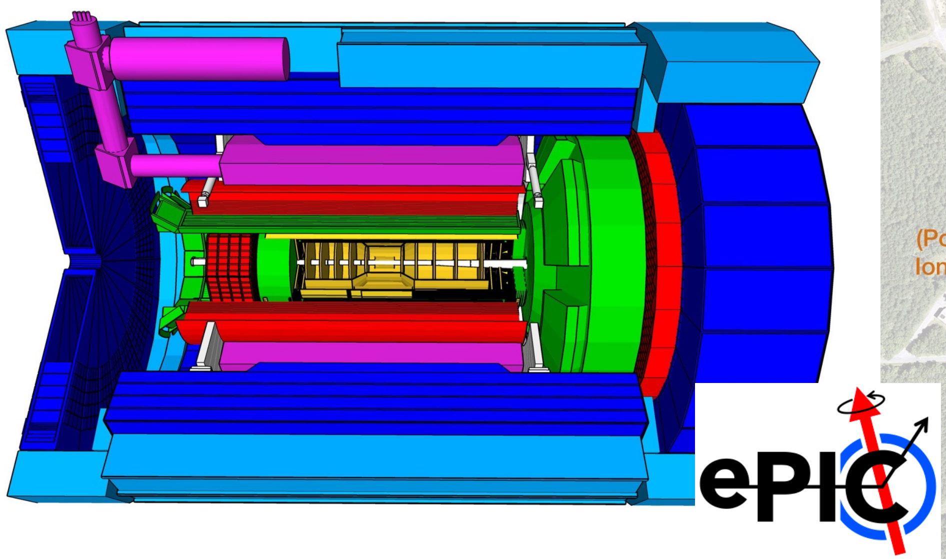
Global QCD Analyses : ΔG

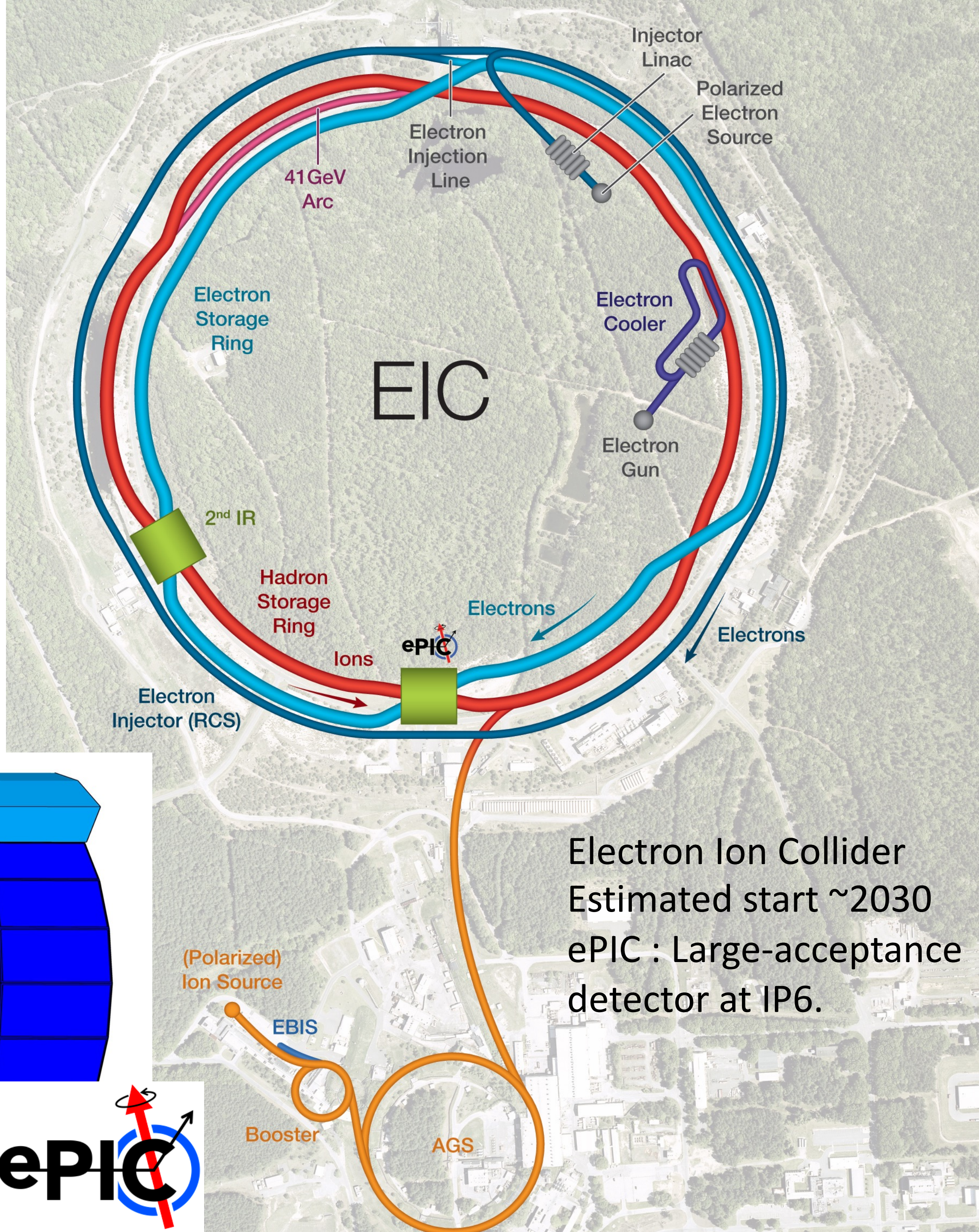
- Inclusive DIS fixed target data do not cover a wide enough kinematic range to really constrain the gluon helicity distribution.
- Inclusive jet and pion A_{LL} results from RHIC have steadily narrowed the contribution from gluon for x > 0.05.
- Dijet and prompt photon A_{LL} show clearly that ΔG is positive.
- Large uncertainties remain for the low-x gluons
- High x gluons appear to contribute 40% to a high energy proton's spin.





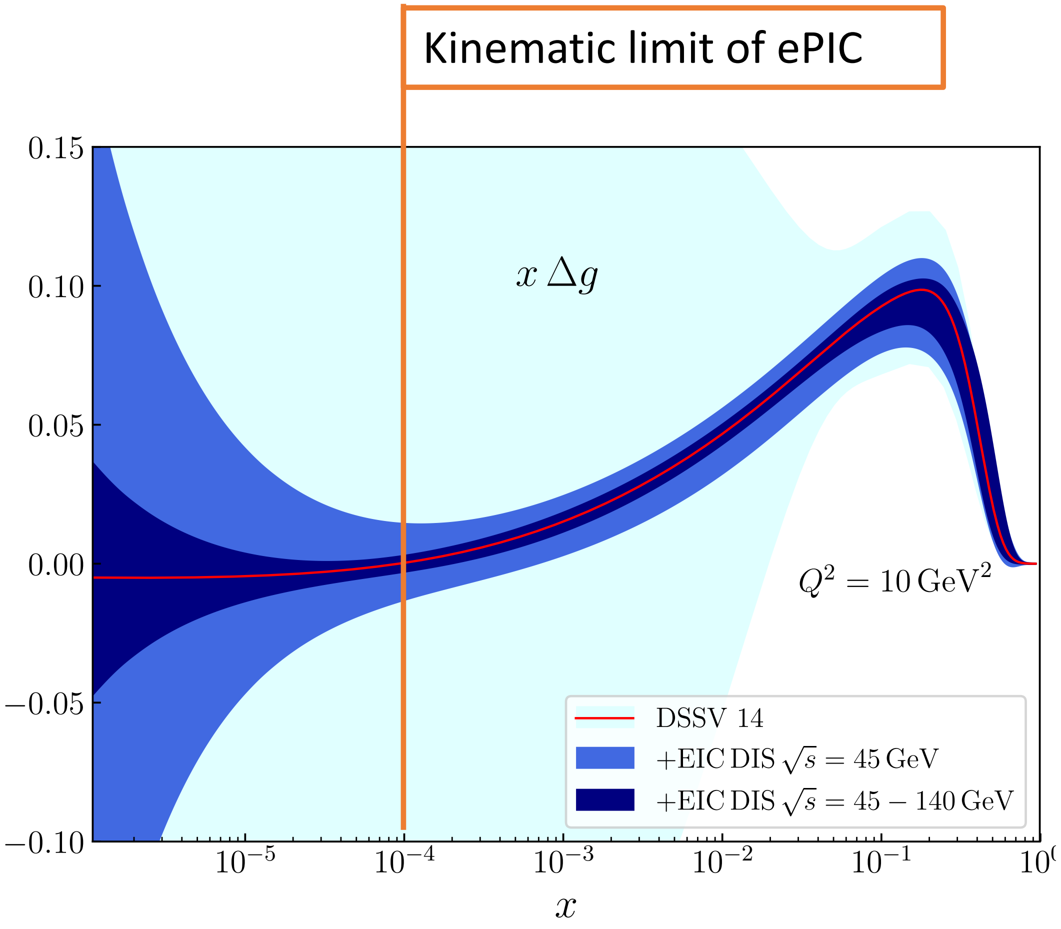






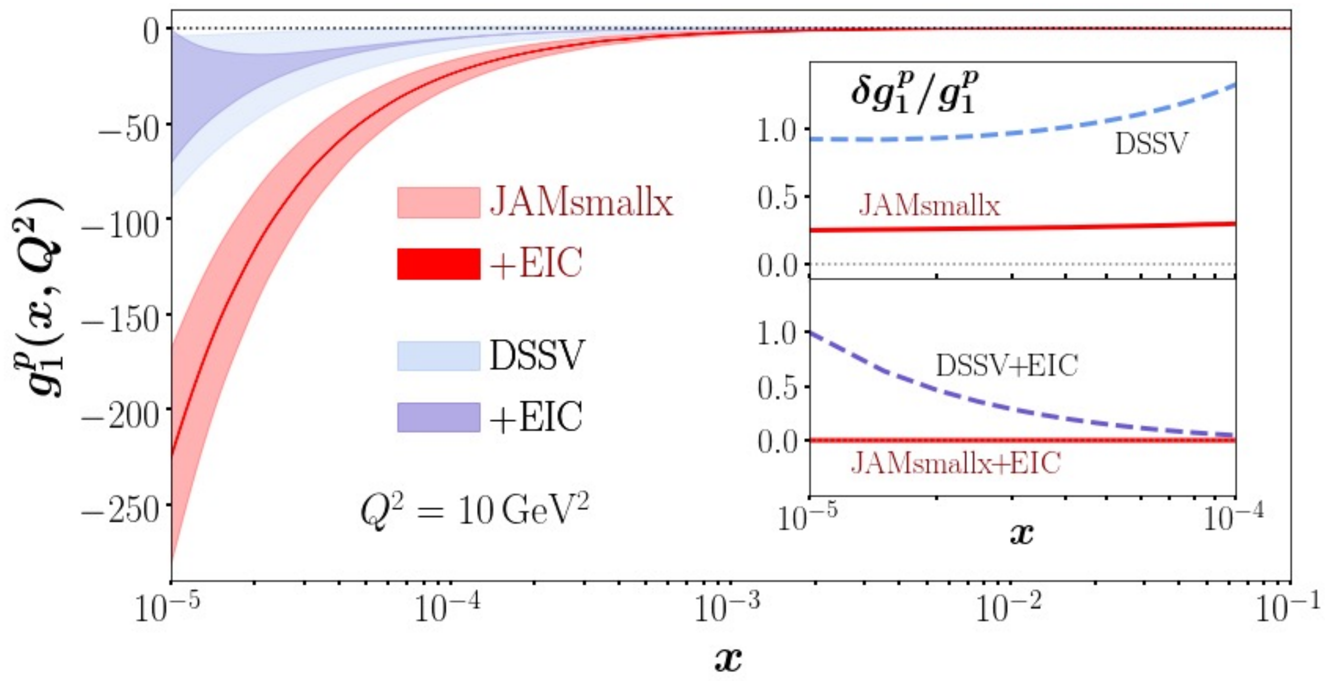
Electron Ion Collider
Estimated start ~2030
ePIC : Large-acceptance detector at IP6.

EIC constraints on $\Delta g(x)$



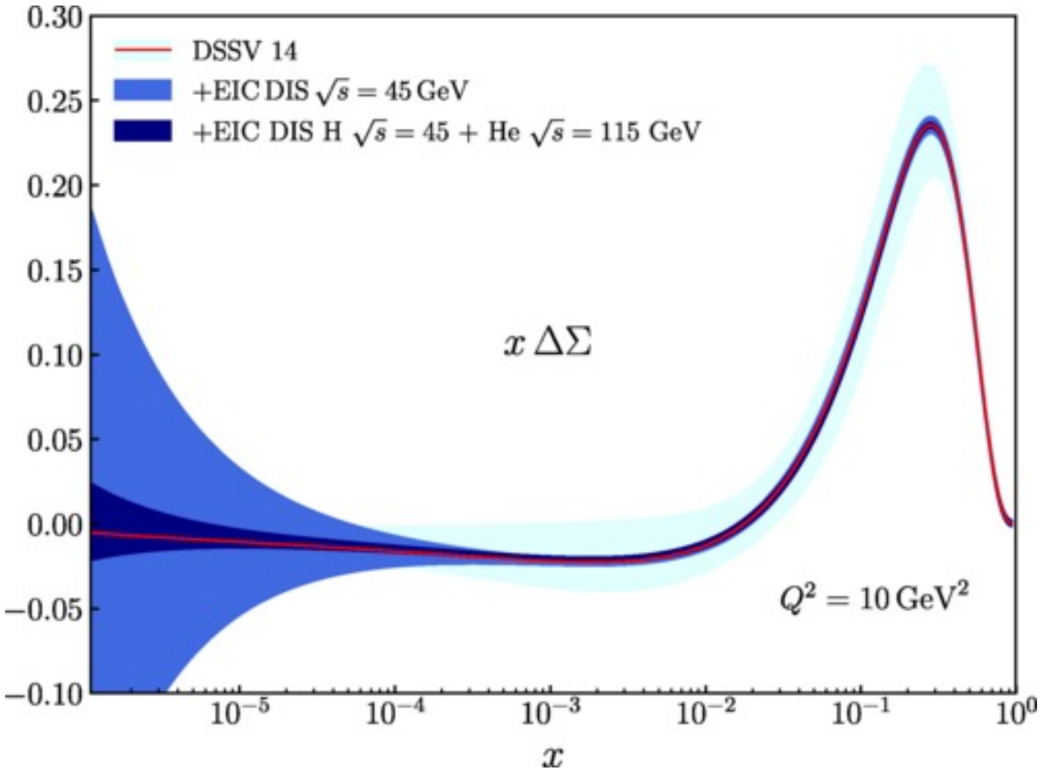
PRD 102 (2020) 094018

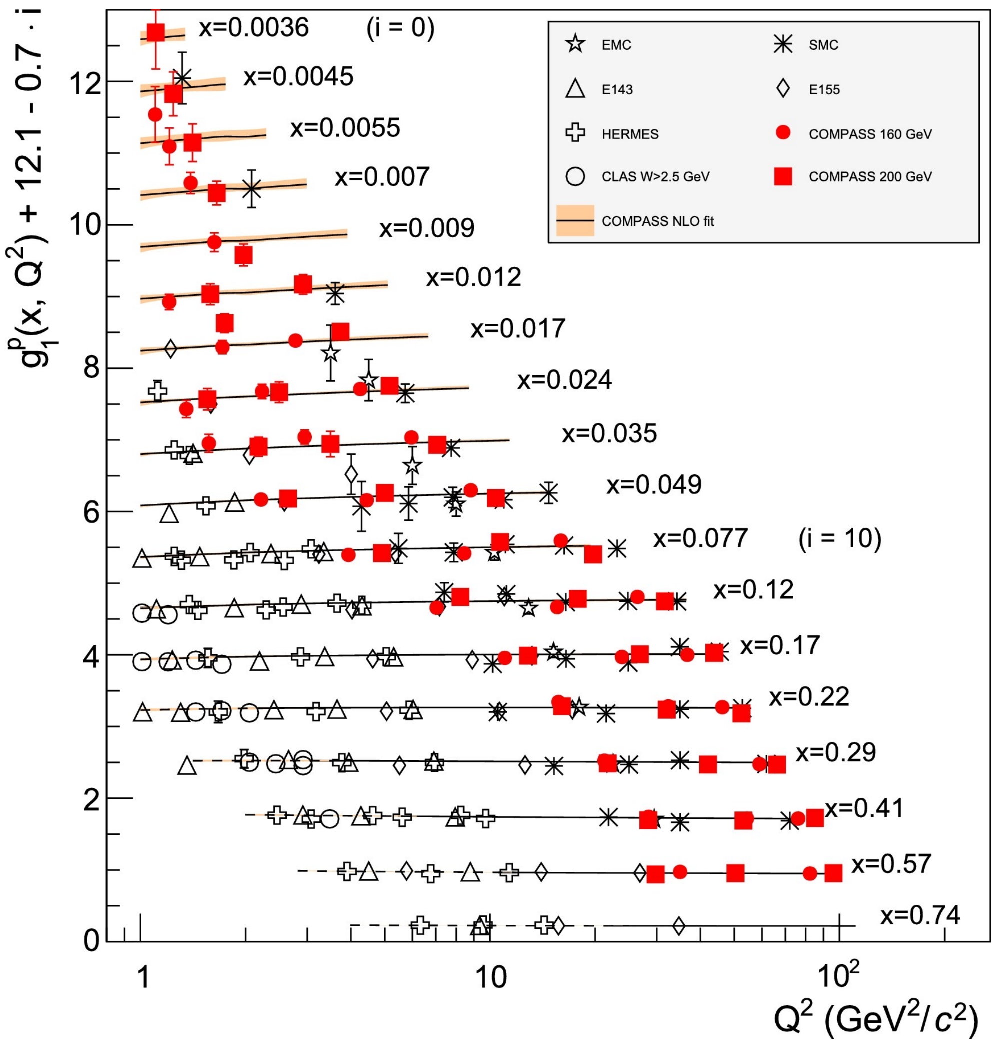
Curves x < 10^{-4} rely are constrained by evolution equations. ***DSSV*** and ***JAMsmallx*** use Q^2 and x evolution respectively.



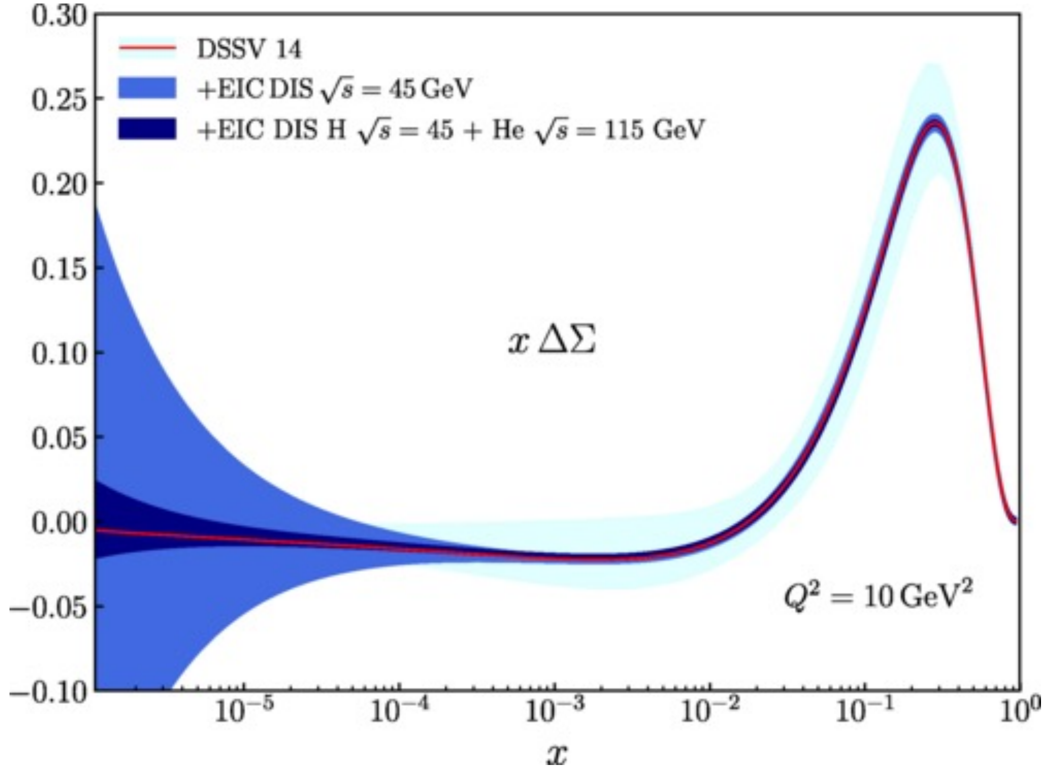
PRD 104 (2021) L031501

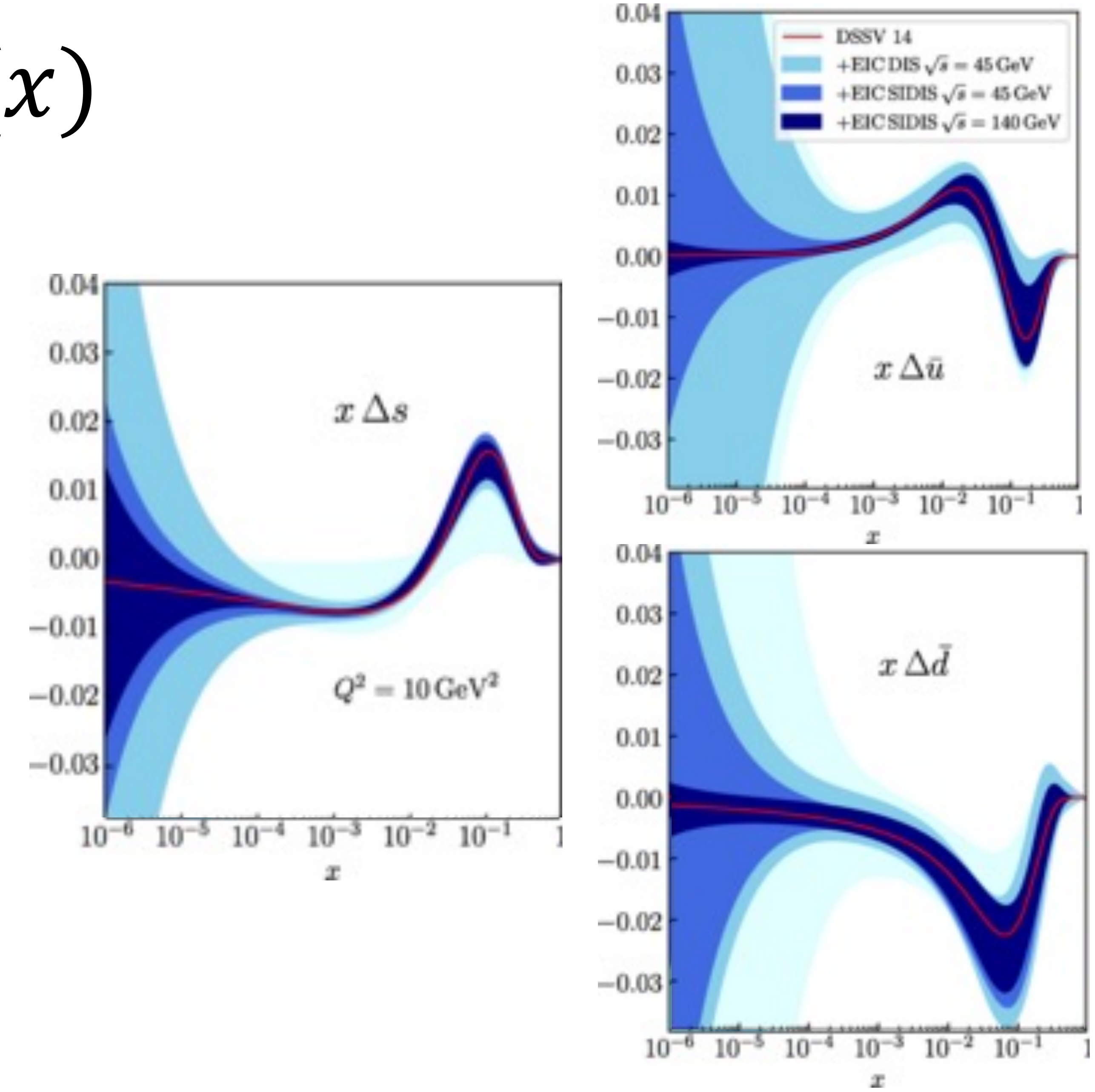
EIC constraints on $\Delta q(x)$





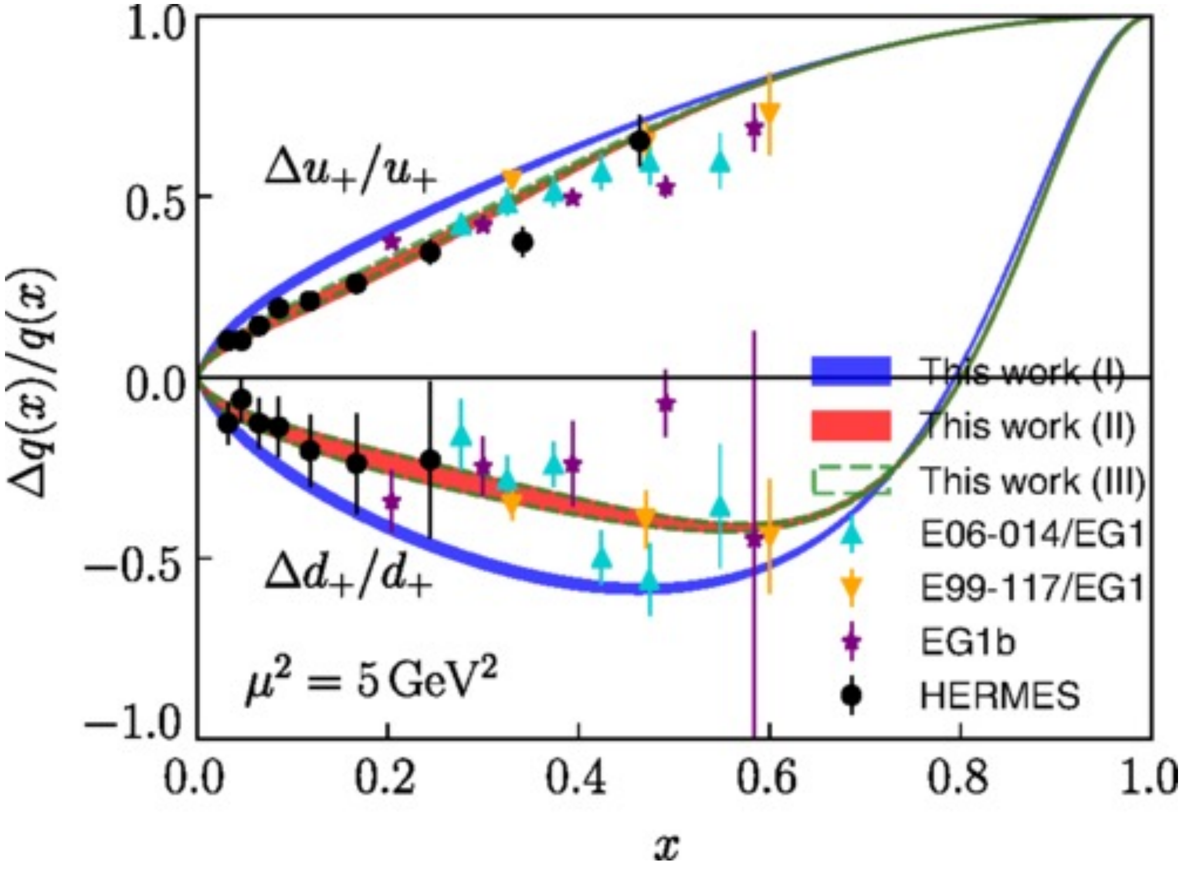
EIC constraints on $\Delta q(x)$



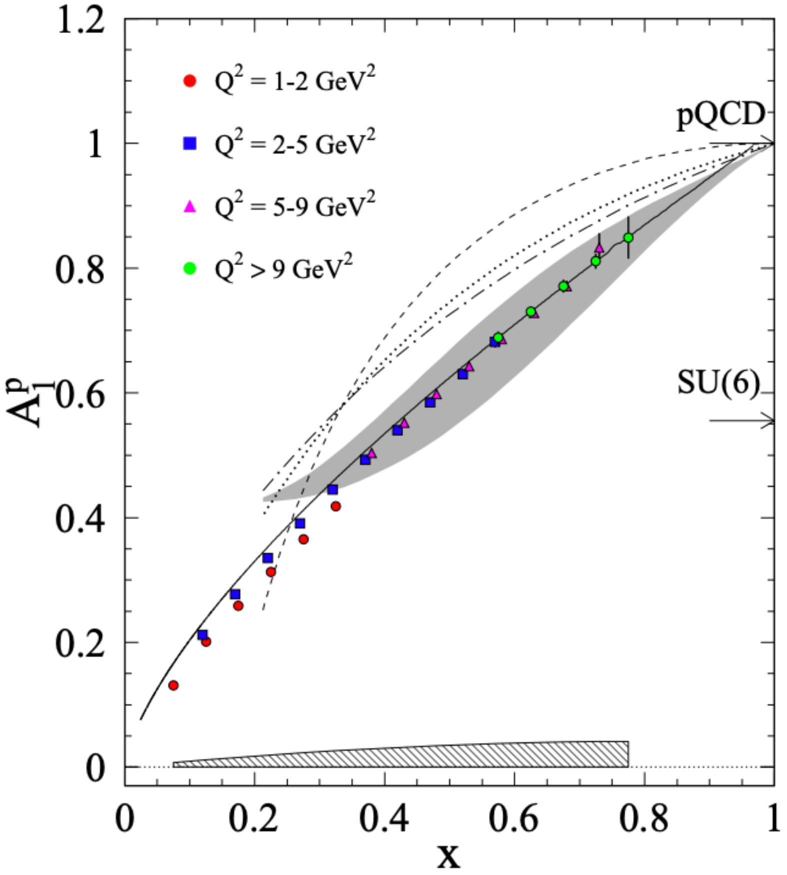


High x @ JLAB

High -x is testing ground for QCD models. One example uses gauge-gravity correspondence, light-front holography and the generalized Veneziano model to predict a sign change for Δd at x = 0.8 +/- 0.03!



Phys. Rev. Lett. 124 (2020) 082003

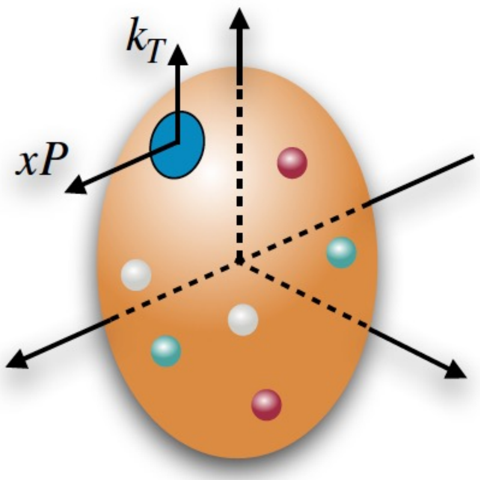


JLAB Proposal 12-06-109 for Hall-B

EIC
2030
2020
2010
2000
1990
1980
BNL RHIC
CERN COMPASS
JLAB HALLS A,B,C
DESY HERMES
SLAC E142/143/154/155
FNAL E581/704
CERN SMC
CERN EMC
SLAC E-130
SLAC E-80
The quark helicity distribution is small – how small? Is it zero?
Where does the remainder of the proton spin reside? Gluon helicity? Strange quarks? Partonic orbital angular momentum?
What is the mechanism behind large meson transverse single spin asymmetries?
Can this newly minted theory of Quantum Chromodynamics explain this phenomena?

Transverse Polarization Observables

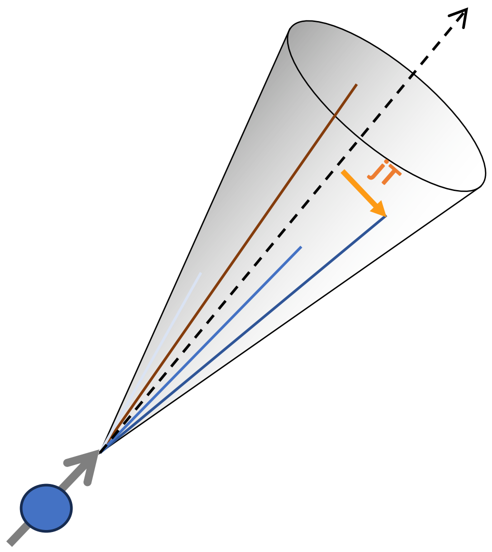
- Around the start of the Hermes experiment (1995) work by Kotzinian, Boer, Mulders, Tangerman and later Bacchetta et al. *JHEP 02 (2007) 093* expressed SIDIS cross-sections in terms of transverse momentum distributions (TMDs).



- TMDs are characterized by two scales, the scale of the hard interaction **Q** and the scale of the transverse momentum $\Lambda_{QCD} \sim k_T \ll$ **Q**.

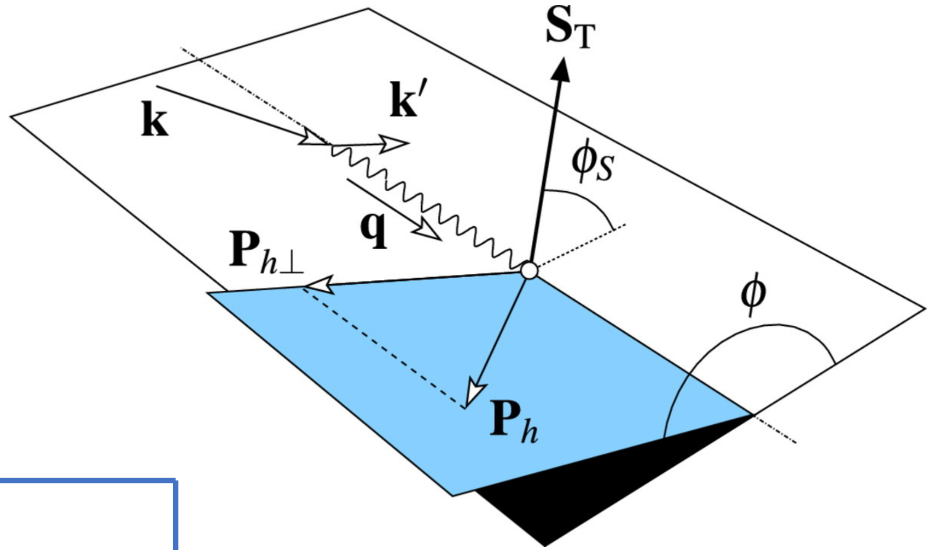
- **TMDPDFs** : parton distribution functions that characterize the correlations between the partonic spin, partonic momentum (**x, k_T**) and the spin of the parent hadron, at a hard interaction scale **Q.**

- **TMDFFs** : fragmentation functions that characterize the correlations between the spin of a fragmenting parton and the spin and momentum (**z, j_T**) of the emerging hadrons, at a hard interaction scale **Q**.



- The introduction of transverse momentum has deep implications for pQCD – requiring new factorization proofs and evolution equations.

TMDs in SIDIS



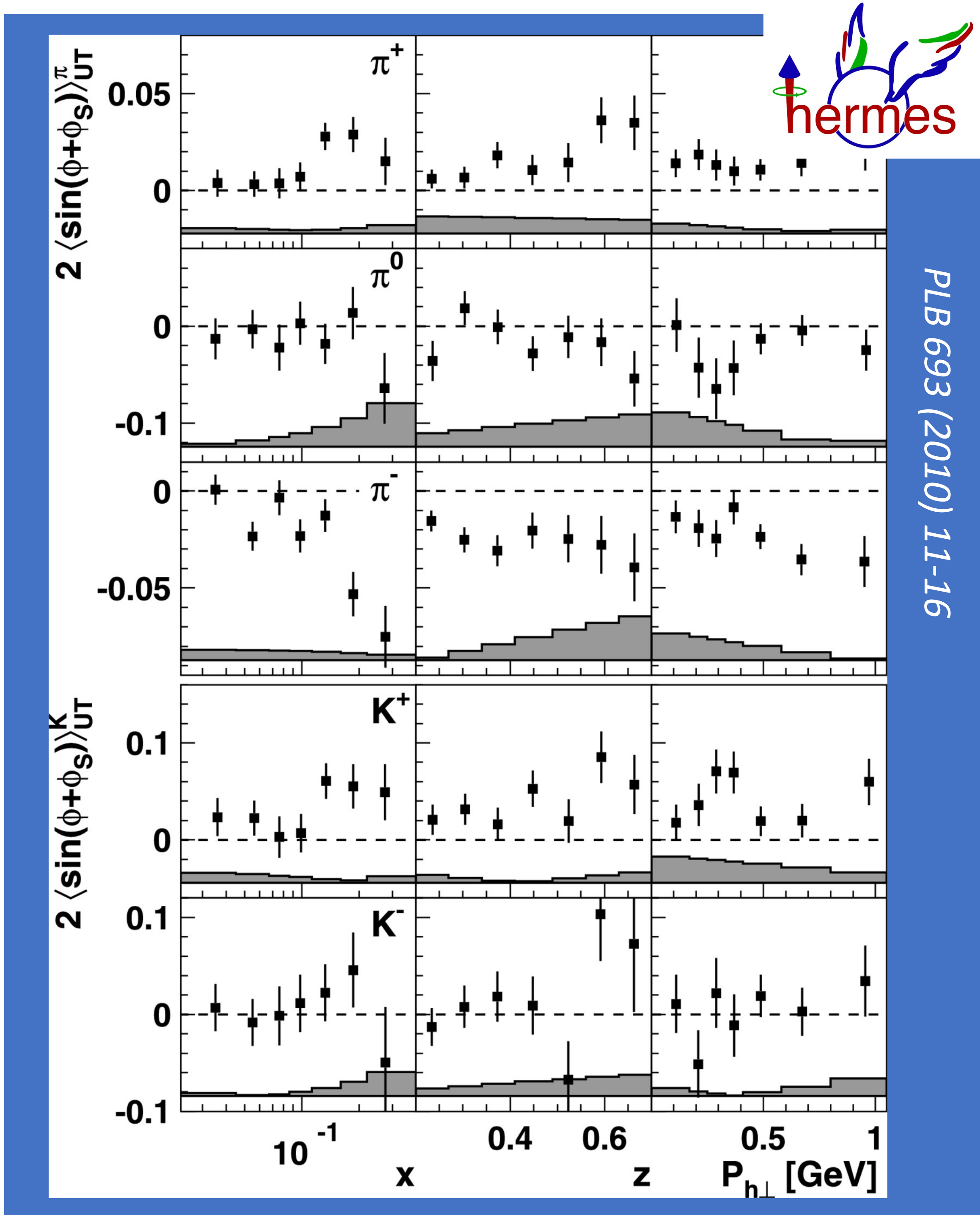
$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{ F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&\quad + S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&\quad + S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Bigg\}
\end{aligned}
$$

$$A_{\text{COLLINS}} \propto \frac{h_1^q(x,k_T)\otimes H_1^{\perp,q}(z,j_T^2)}{f_1^q(x,k_T)\otimes D_1^q(z,j_T^2)}$$

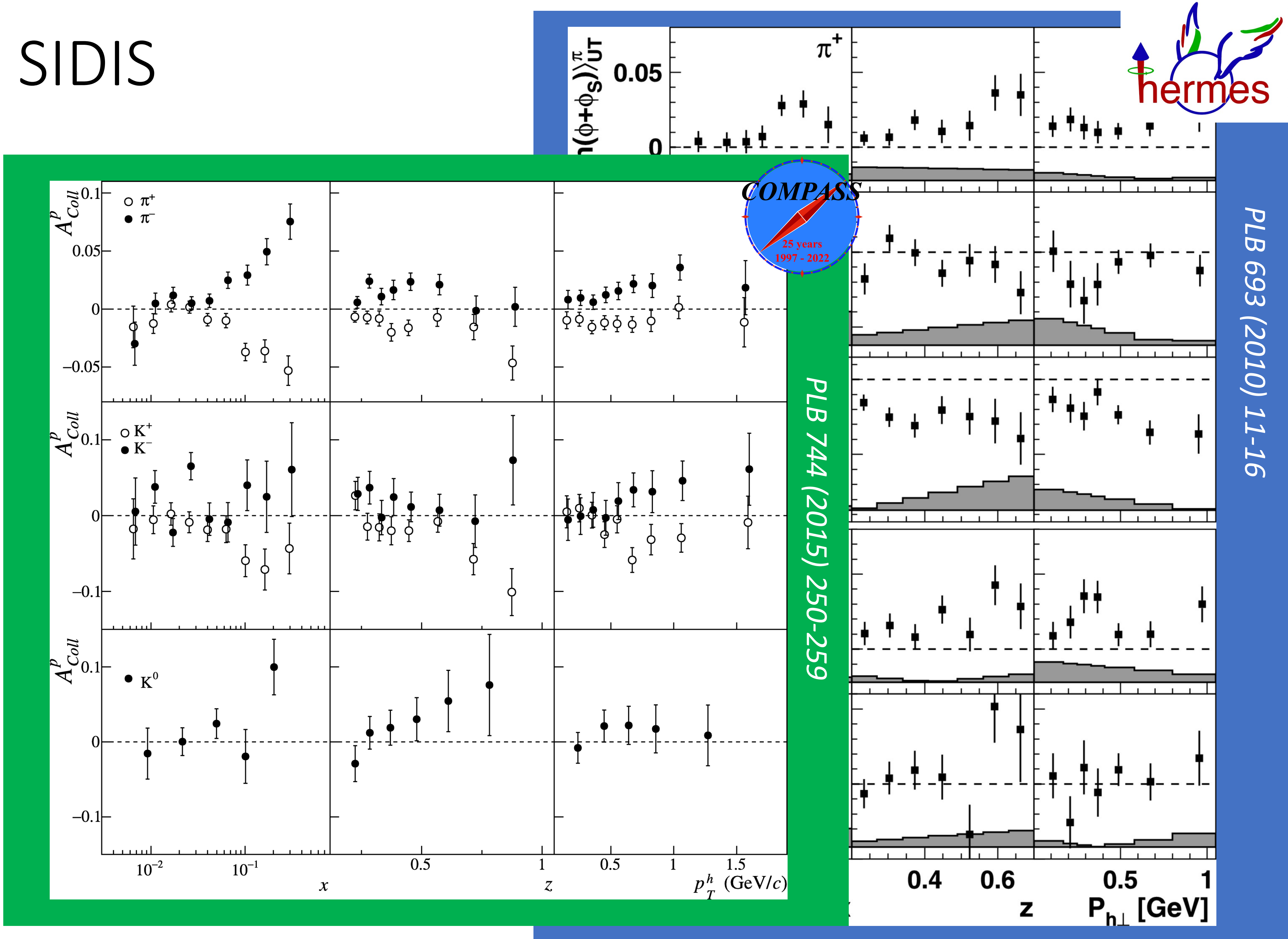
$h_1^q(x,k_T)$ Probability for quark to be transversely polarized inside a proton with transverse spin.

$H_1^{\perp,q}(z,j_T^2)$ Correlations between quark transverse spin and azimuthal modulations in the fragmentation.

Collins in SIDIS

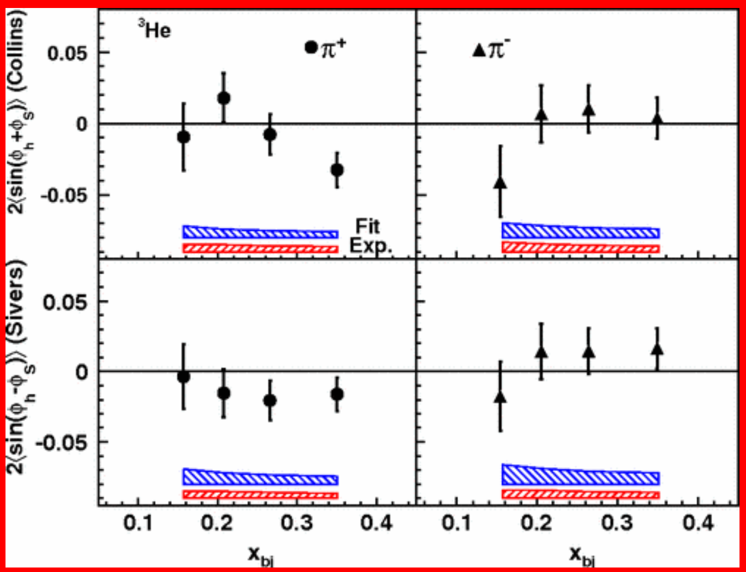


Collins in SIDIS

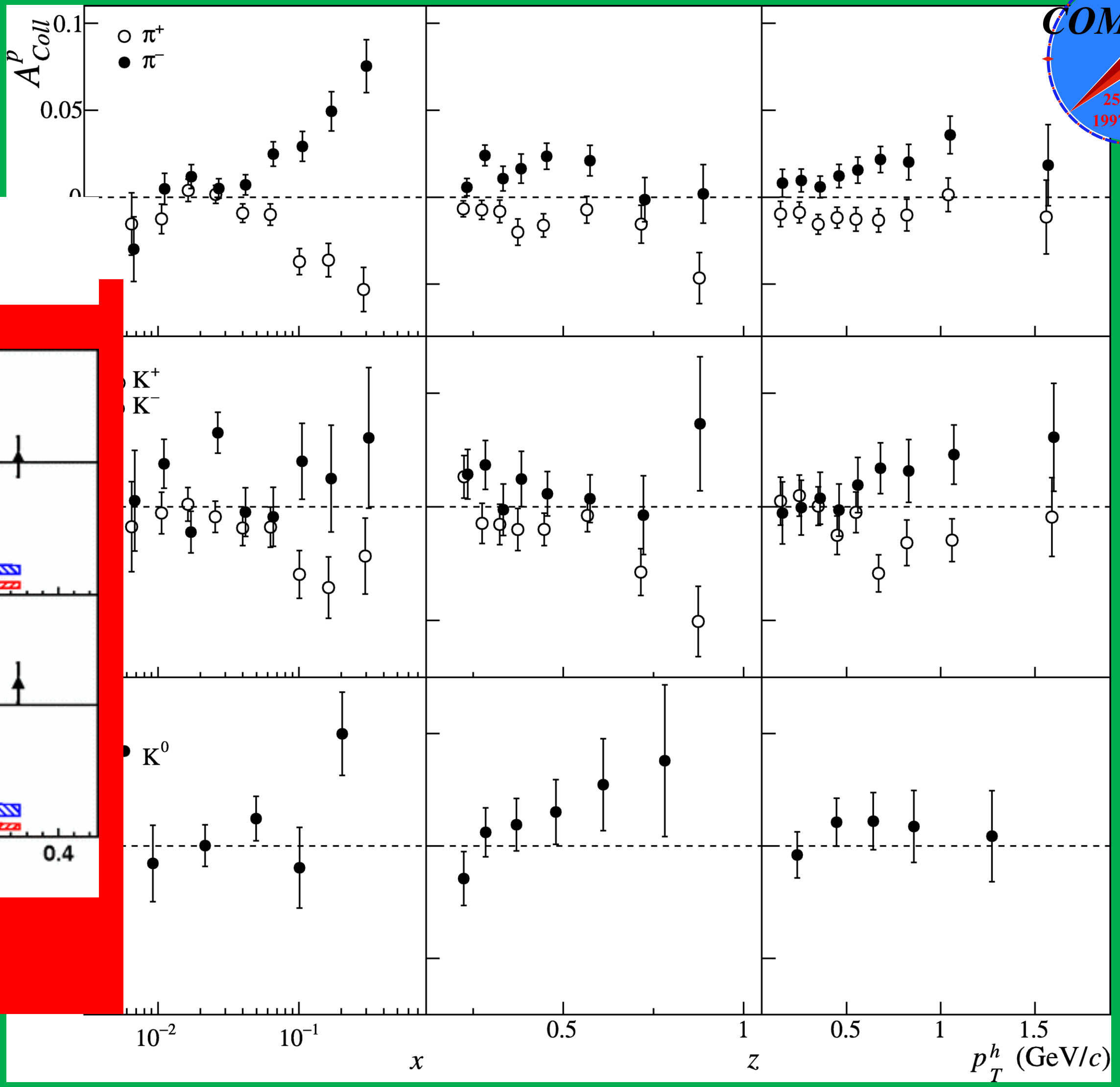


Collins in SIDIS

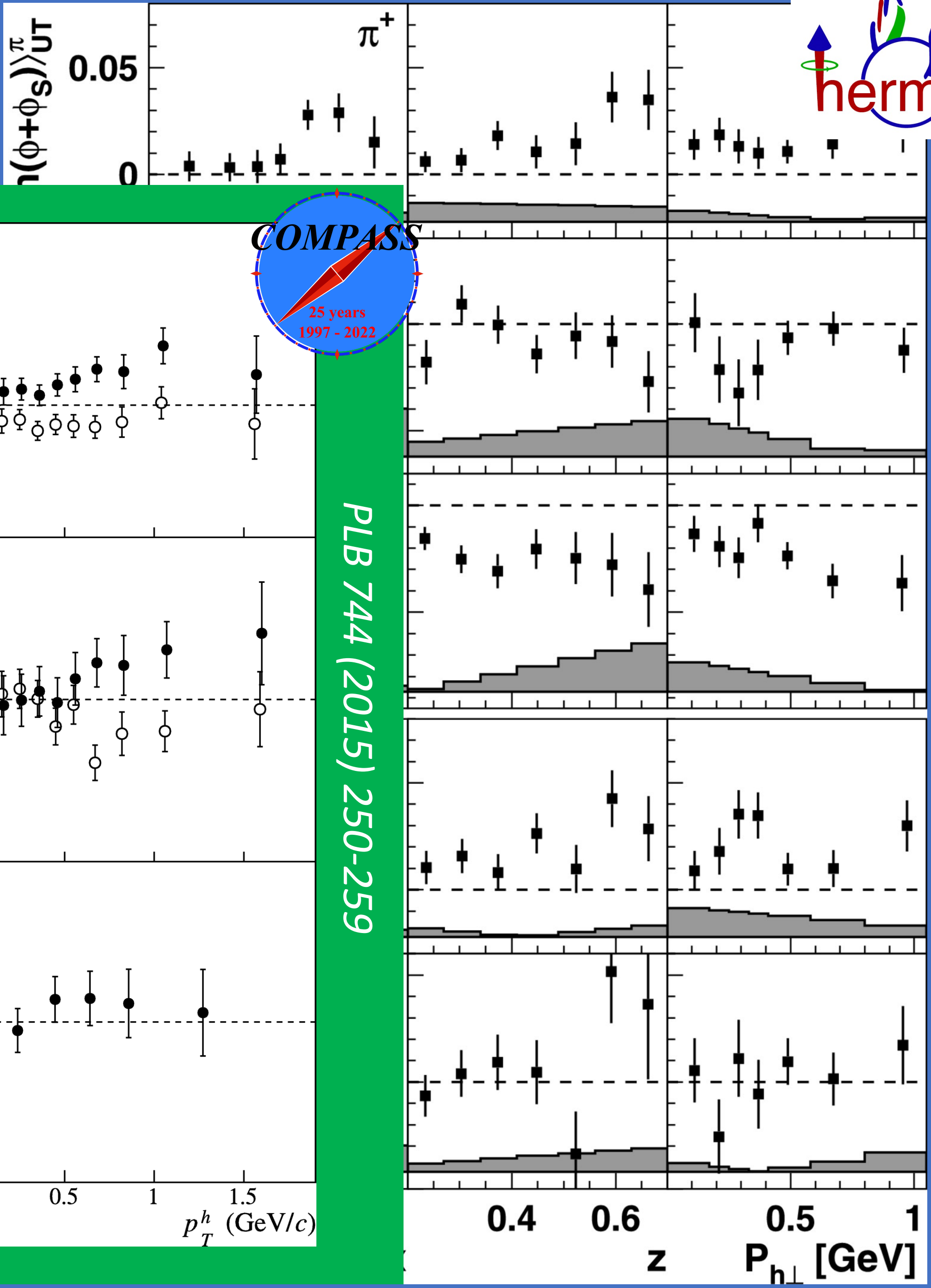
Jefferson Lab Hall-A



PRL 107 (2011) 072003

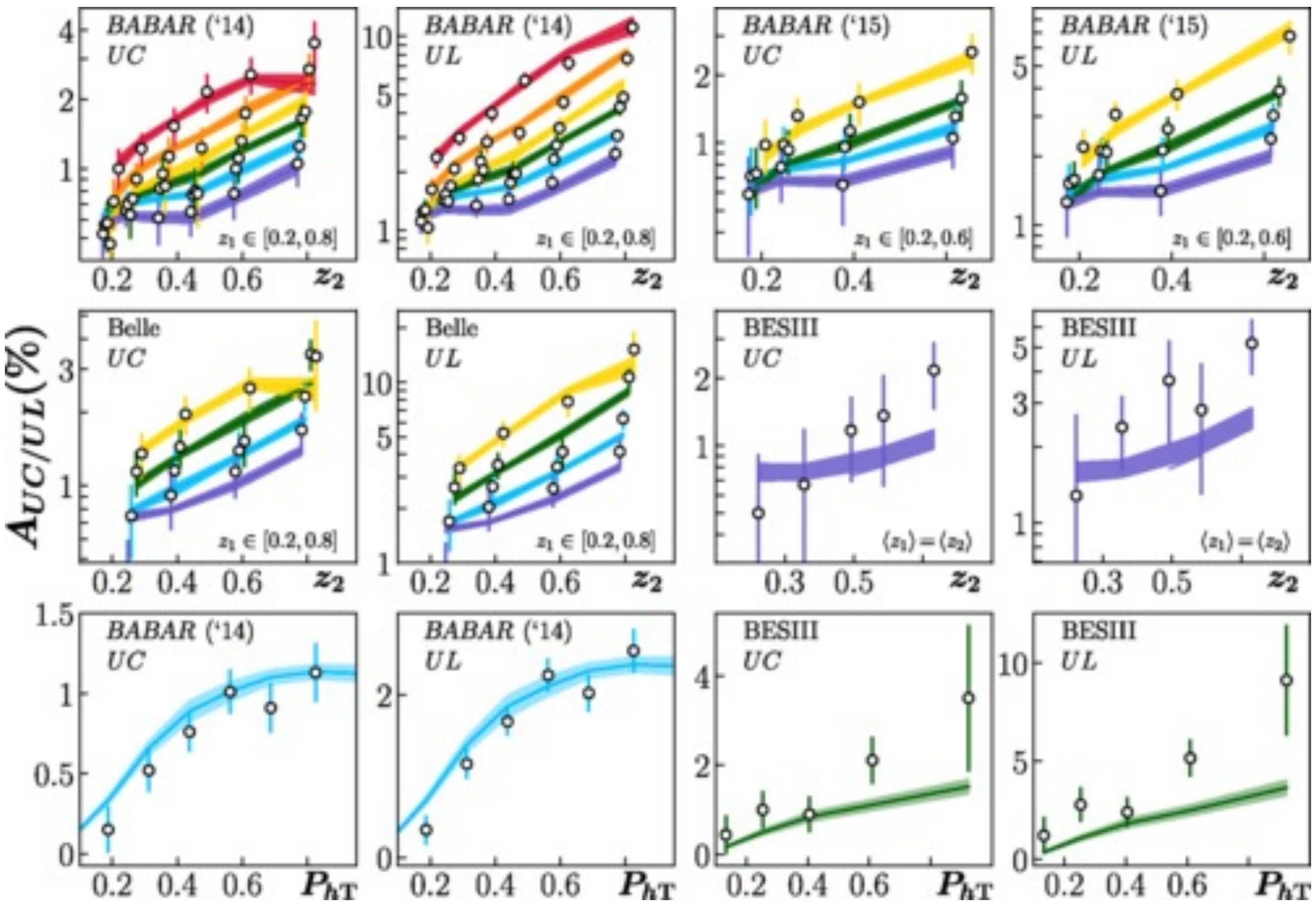


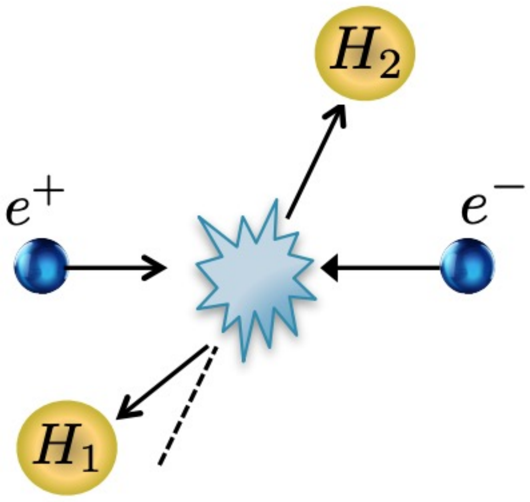
PLB 744 (2015) 250-259



PLB 693 (2010) 11-16

Collins Functions in e^+e^- collisions



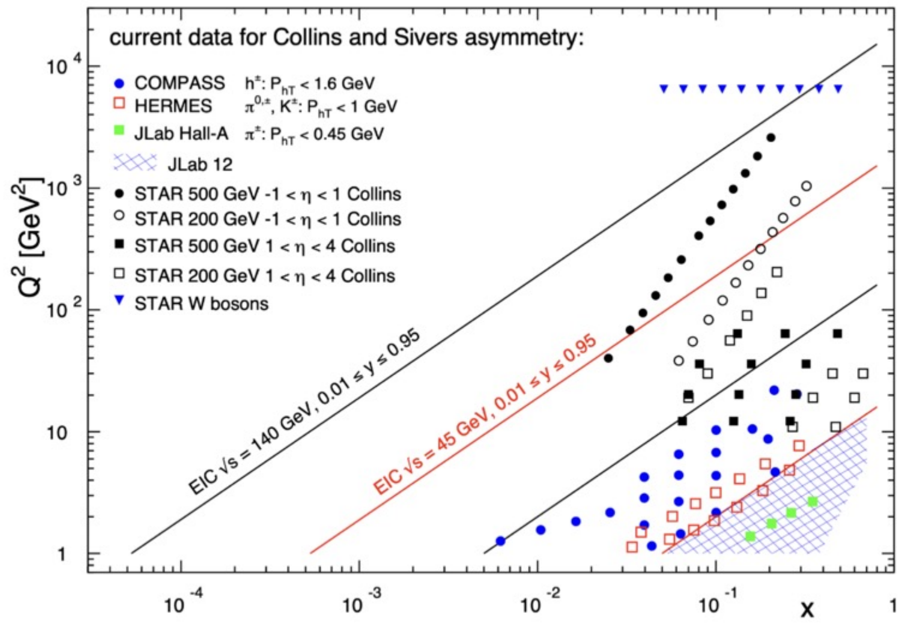


$$A_{12}^{UC} = \left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle \frac{\pi\langle k_{tC}^2\rangle}{4M^2} \left[\frac{H_1^{fav}\bar{H}_2^{\prime fav} + H_1^{dis}\bar{H}_2^{\prime dis}}{D_1^{fav}\bar{D}_2^{fav} + D_1^{dis}\bar{D}_2^{dis}} - \frac{(H_1^{fav} + H_1^{dis})(\bar{H}_2^{\prime fav} + \bar{H}_2^{\prime dis})}{(D_1^{fav} + D_1^{dis})(\bar{D}_2^{fav} + \bar{D}_2^{dis})} \right].$$

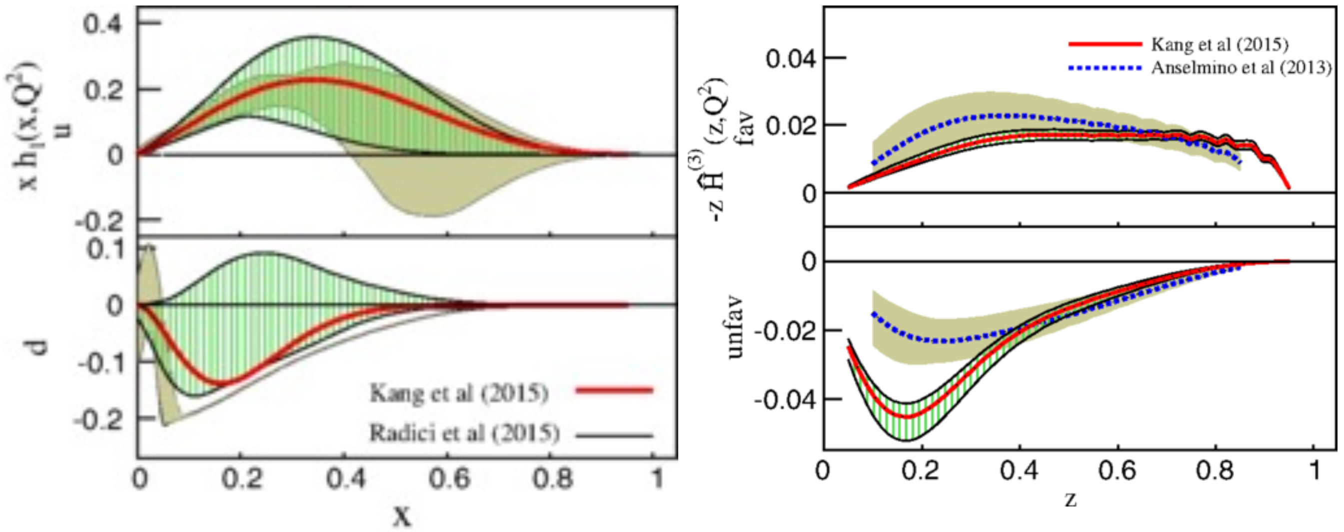
$$A_{12}^{UL} = \left\langle \frac{\sin^2\theta}{1+\cos^2\theta} \right\rangle \frac{\pi\langle k_{tC}^2\rangle}{4M^2} \left[\frac{H_1^{fav}\bar{H}_2^{\prime fav} + H_1^{dis}\bar{H}_2^{\prime dis}}{D_1^{fav}\bar{D}_2^{fav} + D_1^{dis}\bar{D}_2^{dis}} - \frac{H_1^{fav}\bar{H}_2^{\prime dis} + H_1^{dis}\bar{H}_2^{\prime fav}}{D_1^{fav}\bar{D}_2^{dis} + D_1^{dis}\bar{D}_2^{fav}} \right],$$

Global TMD Analysis

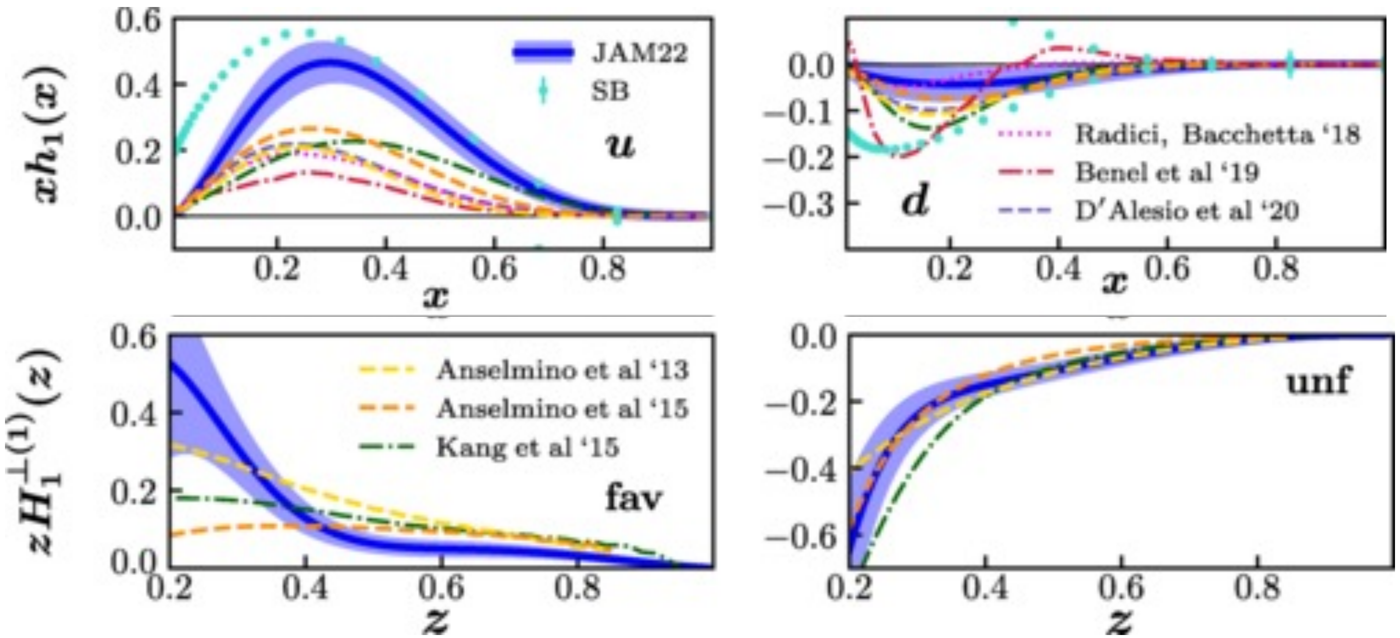
- Requires the development of methodology to handle differences in hard scale Q^2.
- Unlike collinear observables, evolution contains a non-perturbative component that cannot be calculated from first principles.



PRD 93 014009 (2015)



PRD 106 (2022) 034014

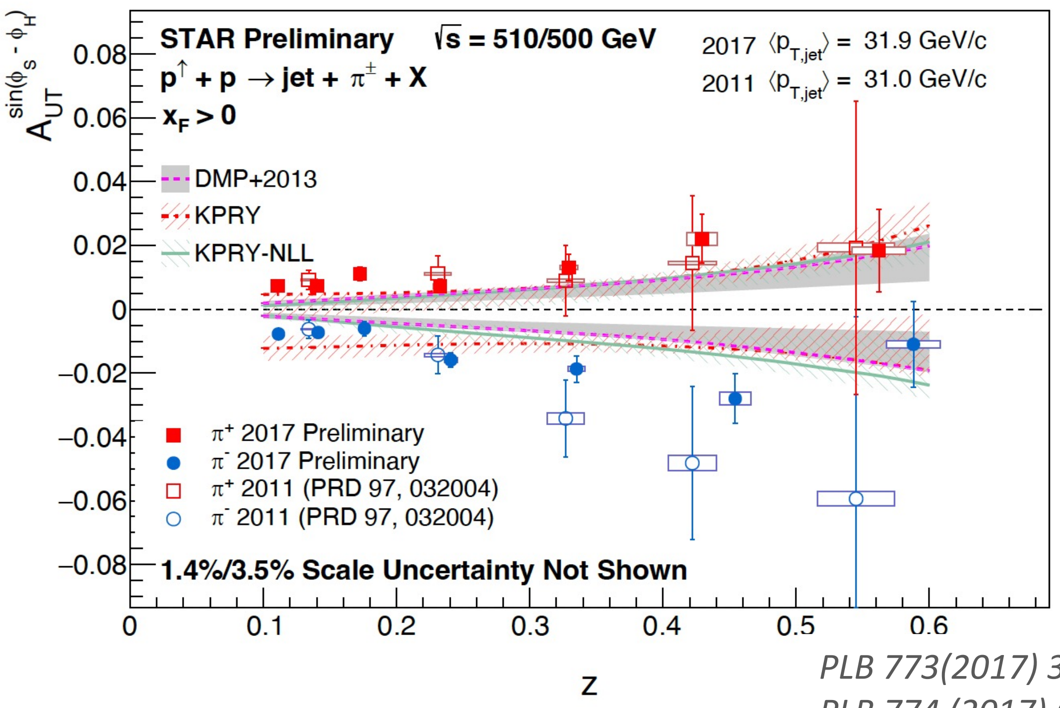


Collins in $p^{\uparrow}p$ collisions @ RHIC

$$A_{UT}^{\sin(\varphi_S-\varphi_H)} \propto \frac{\sum_{a,b,c} h_1^a(x_1,\mu)\ f_b(x_2,\mu)\ \sigma_{ab\to c}^{\text{Collins}}\ H_{1,h/c}^{\perp}(z_h,j_T;Q)}{\sum_{a,b,c} f_a(x_1,\mu)\ f_b(x_2,\mu)\ \sigma_{ab\to c}^{\text{unpol}}\ D_{h/c}(z_h,j_T;Q)}$$

Sensitive to collinear transversity and TMD Collins function! In contrast to SIDIS measurements hadron j_T is independent of initial state transverse momentum.

PRL 100 (2008) 032003
JHEP 11 (2017) 068

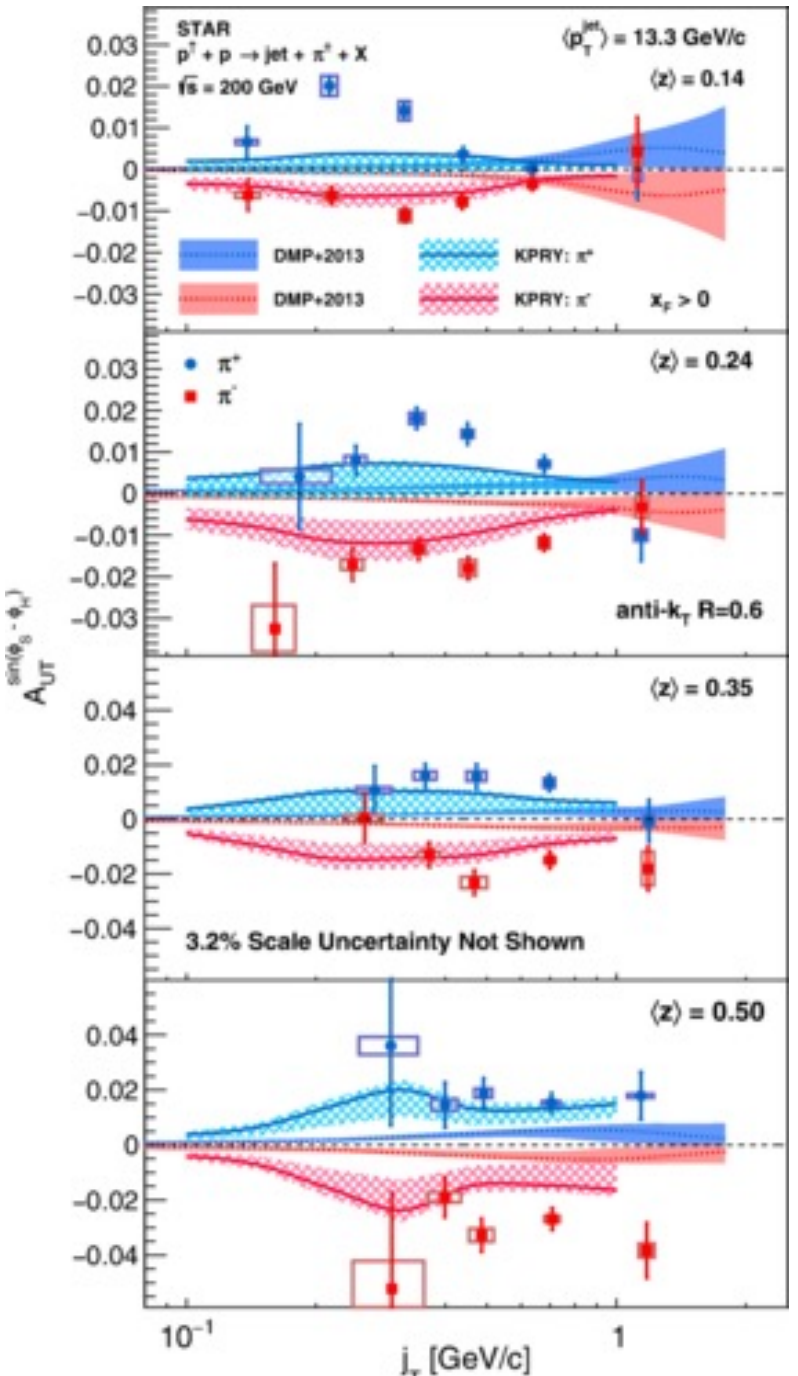


PLB 773(2017) 300
PLB 774 (2017) 635

Asymmetries increase as a function of z.

Multi-dimensional binning shows correlations between z and j_T.

Phys.Rev.D 106, 072010



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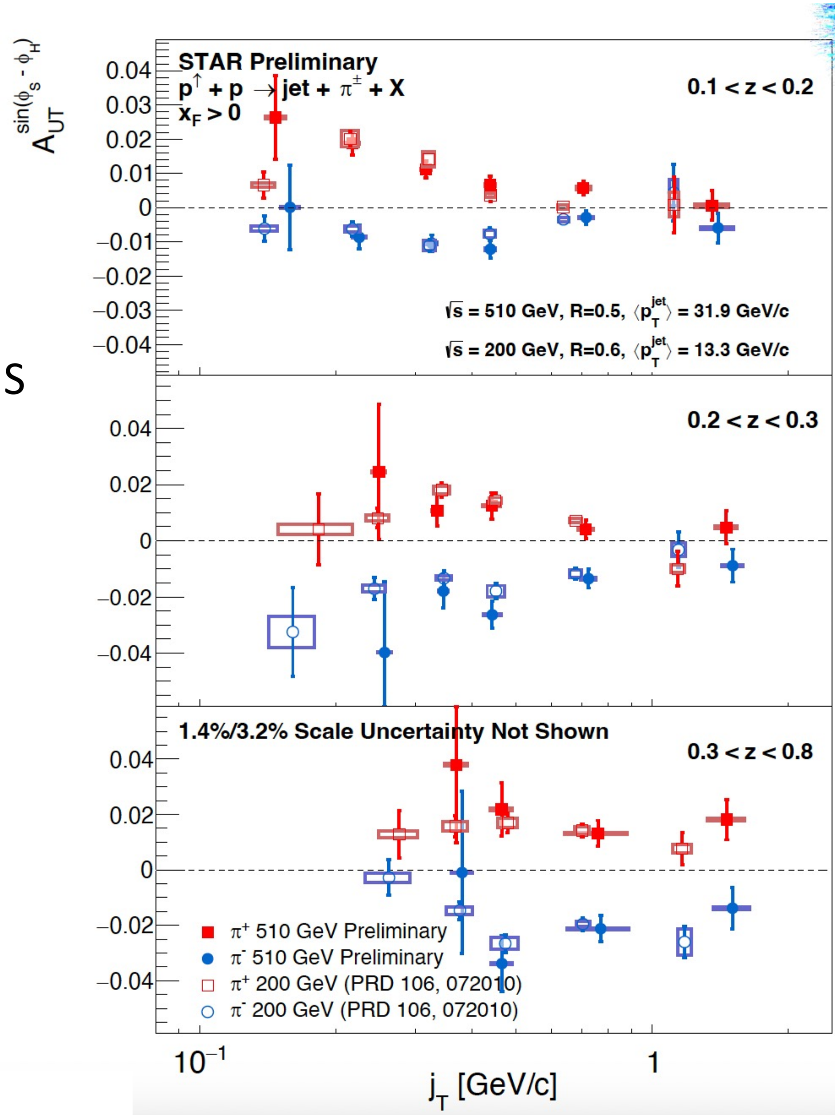
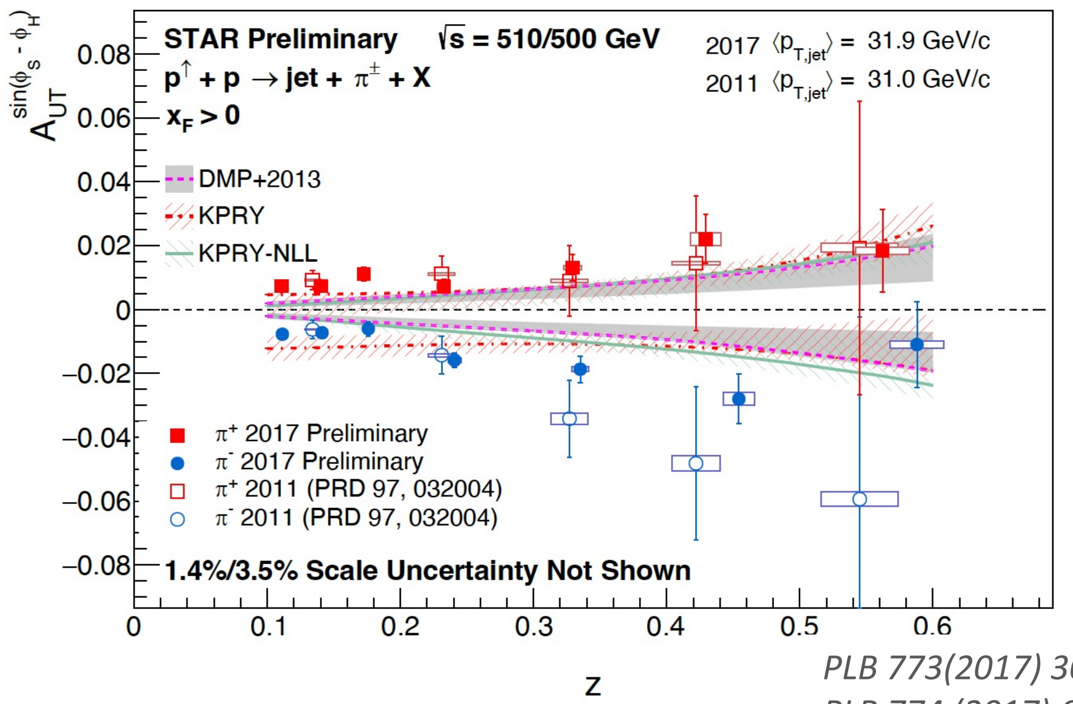
Sensitive to **collinear transversity** and TMD Collins function! In contrast to SIDIS measurements hadron j_T is independent of initial state transverse momentum.



JHEP 11 (2017) 068

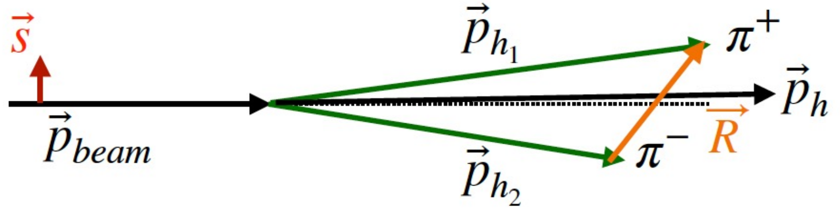


PLB 773(2017) 300
PLB 774 (2017) 635

Asymmetries at 200 and 500 GeV are very consistent. Evolution effects may be small?

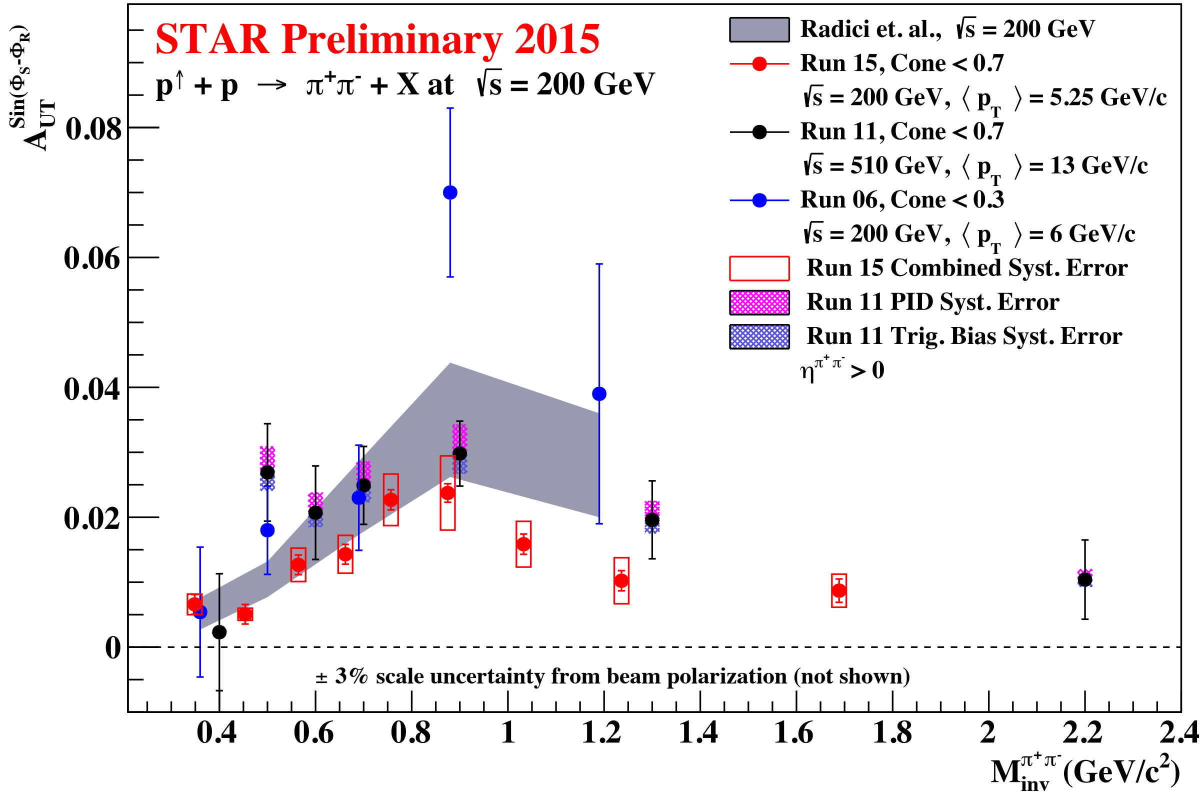
Size of factorization breaking effects unknown.

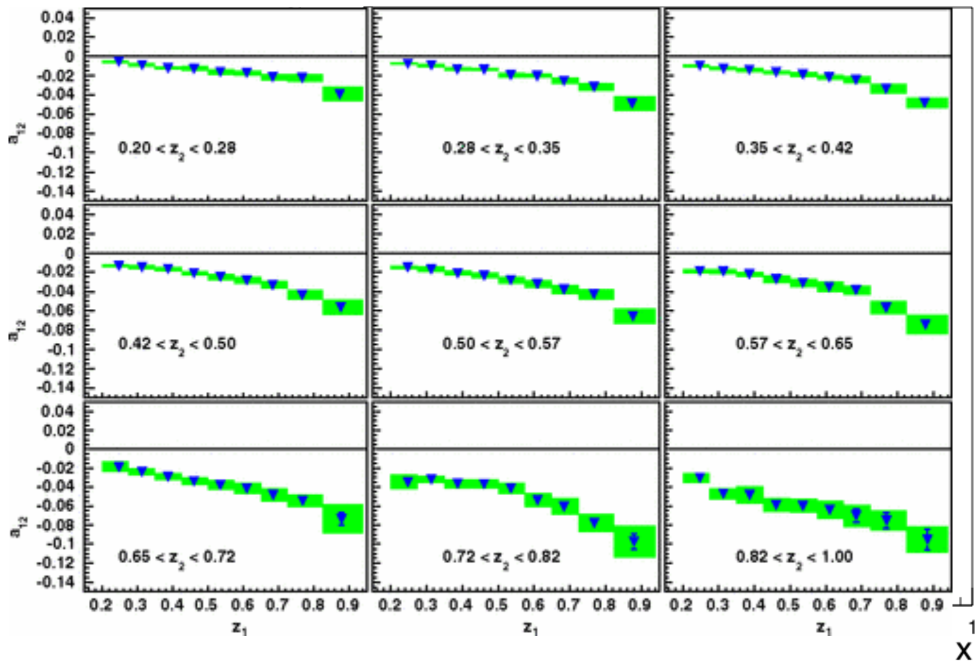
Di-hadrons in $p^{\uparrow}p$ @RHIC



$$A_{UT} = \frac{d\sigma_{UT}}{d\sigma_{UU}} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \frac{\sum_{i,j,k} h_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) H_1^{\sphericalangle h_1 h_2/k}(z, M_h^2)}{\sum_{i,j,k} f_1^{i/p_a}(x_a) f_1^{j/p_b}(x_b) D_1^{h_1 h_2/k}(z, M_h^2)}$$

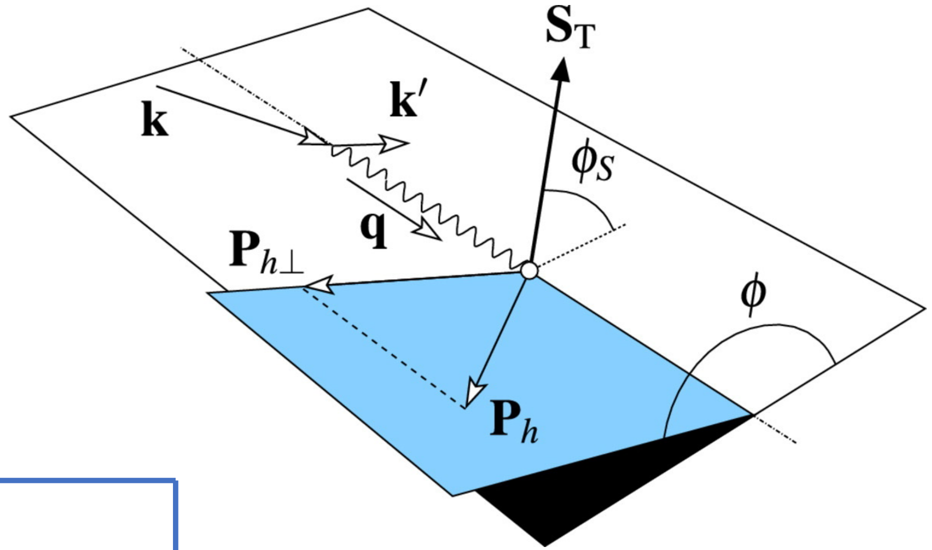
Probes same x –region as HERMES, COMPASS and JLAB, but at higher Q^2.





PRL 107 (2011) 072004

TMDs in SIDIS



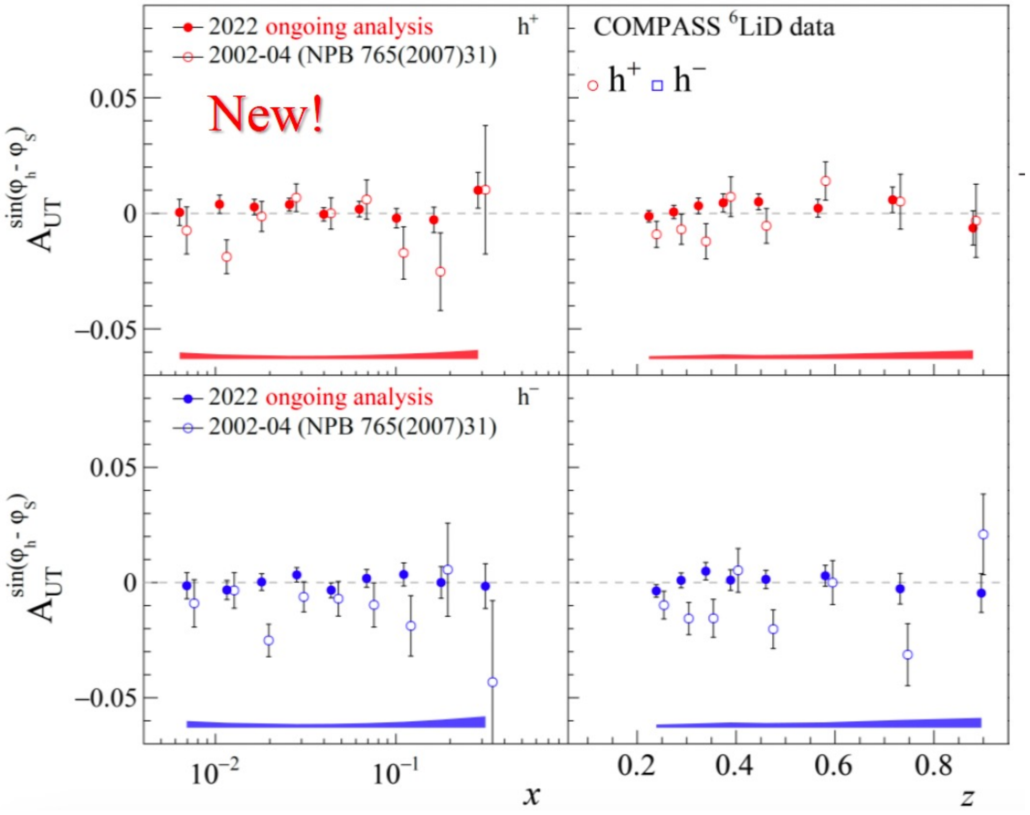
$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{ F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&+ S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&+ S_T\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\quad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

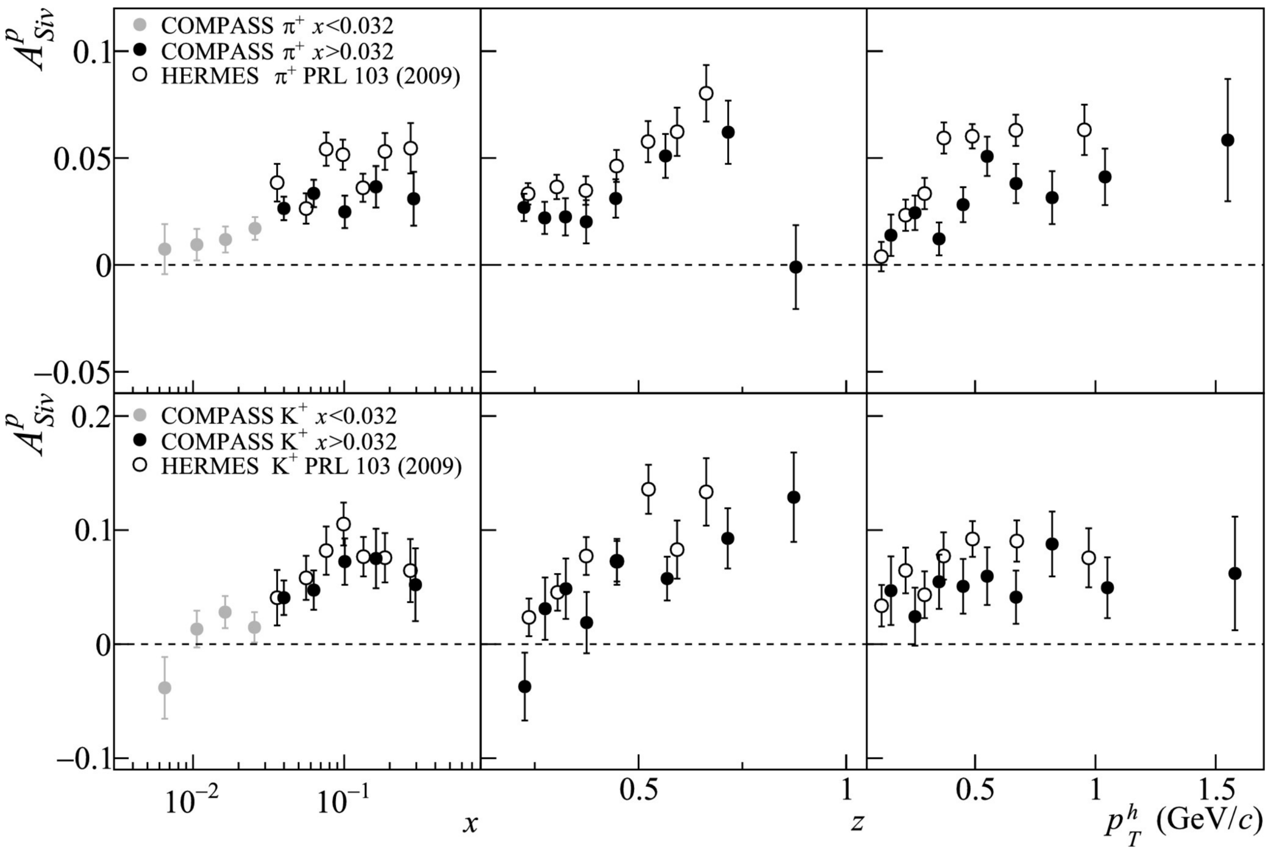
$$A_{\mathrm{SIVERS}} \propto \frac{f_{1T}^{\perp,q}(x,k_T)\otimes D_1^q(z,j_T^2)}{f_1^q(x,k_T)\otimes D_1^q(z,j_T^2)}$$

$f_{1T}^{\perp,q}(x,k_T)$ — correlation between the quark k_T and proton momentum and transverse spin.

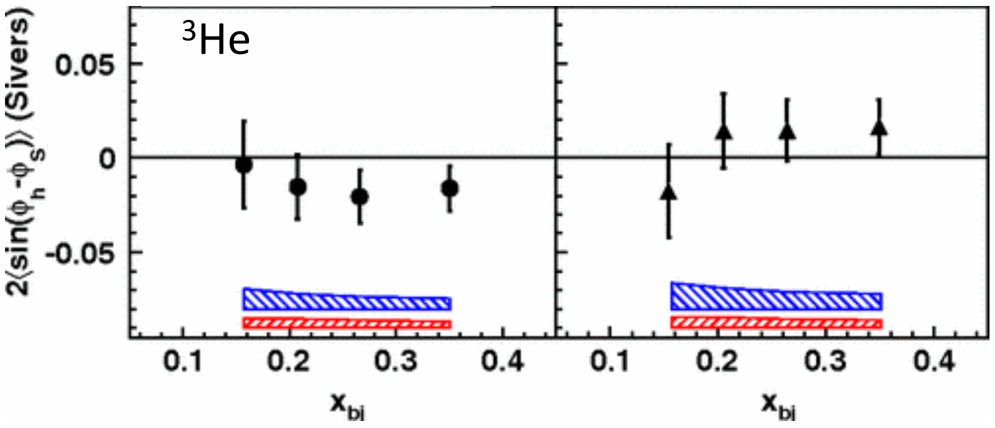
$D_1^q(z,j_T^2)$ — Probability for a quark to fragment into a hadron with z and j_T

Sivers in SIDIS



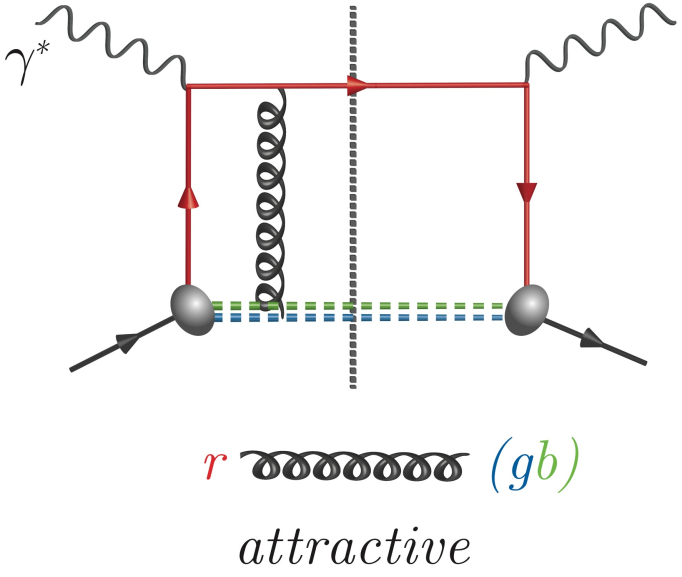


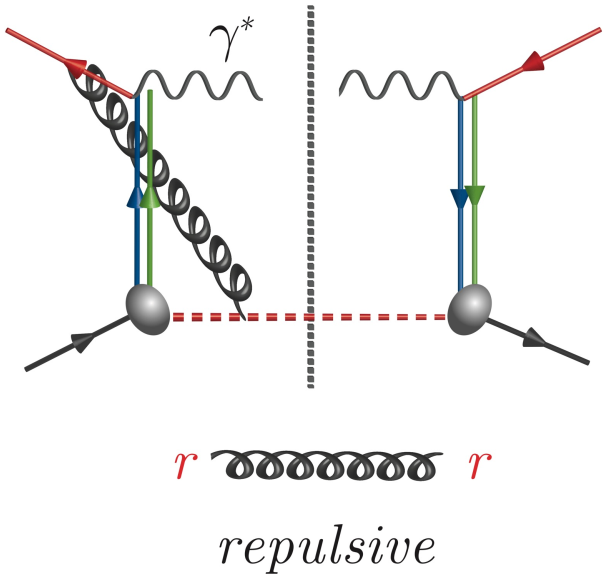
Jefferson Lab PRL 107 (2011) 072003



PRL 103 (2009) 152002, PLB 744 (2015) 250-259

Sivers as a window into QCD color interactions





SIDIS

Final-state interaction

Opposite colors attract

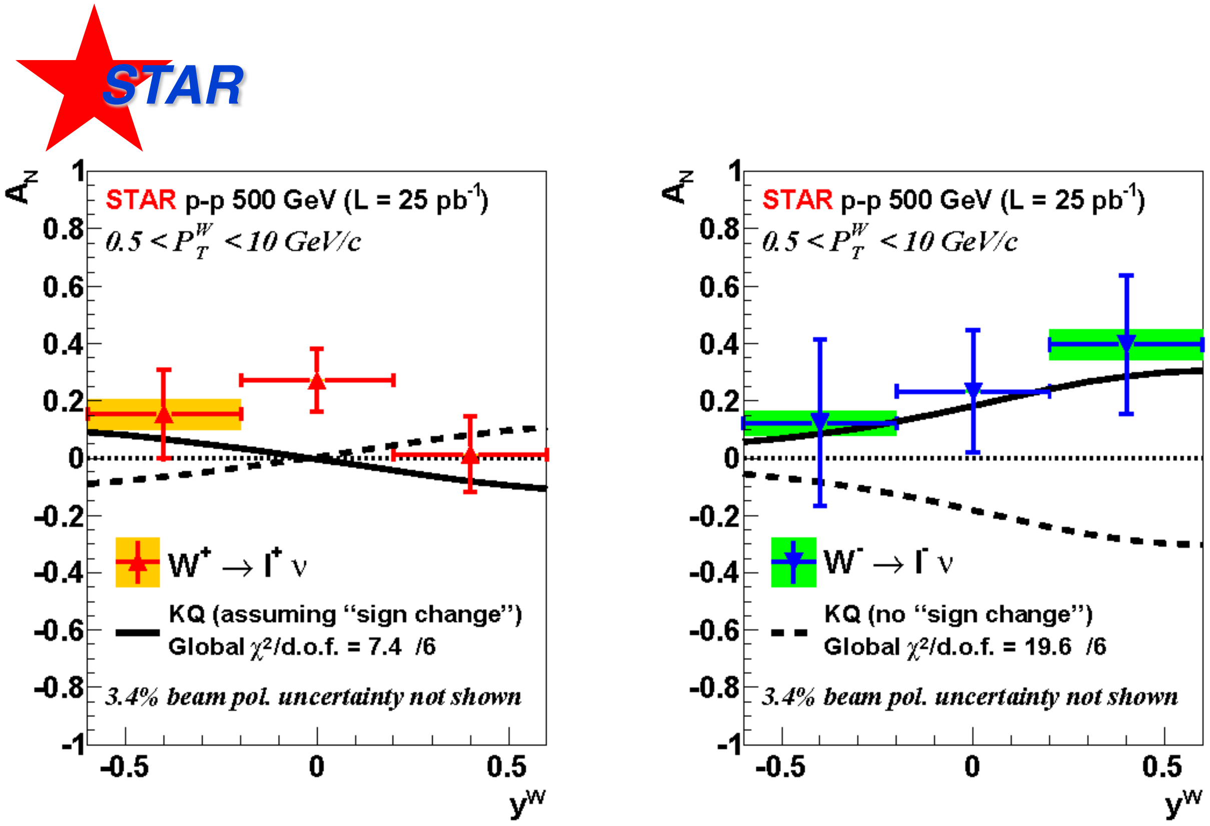
Drell-Yan, W or Z

Initial-state interaction

Like colors repel

Sivers in $p^{\uparrow}p$ and $p^{\uparrow}\pi$

Exploratory STAR measurement of A_N for W in 2011 favored **sign change** if evolution effects are modest.



Sivers in $p^{\uparrow}p$ and $p^{\uparrow}\pi$

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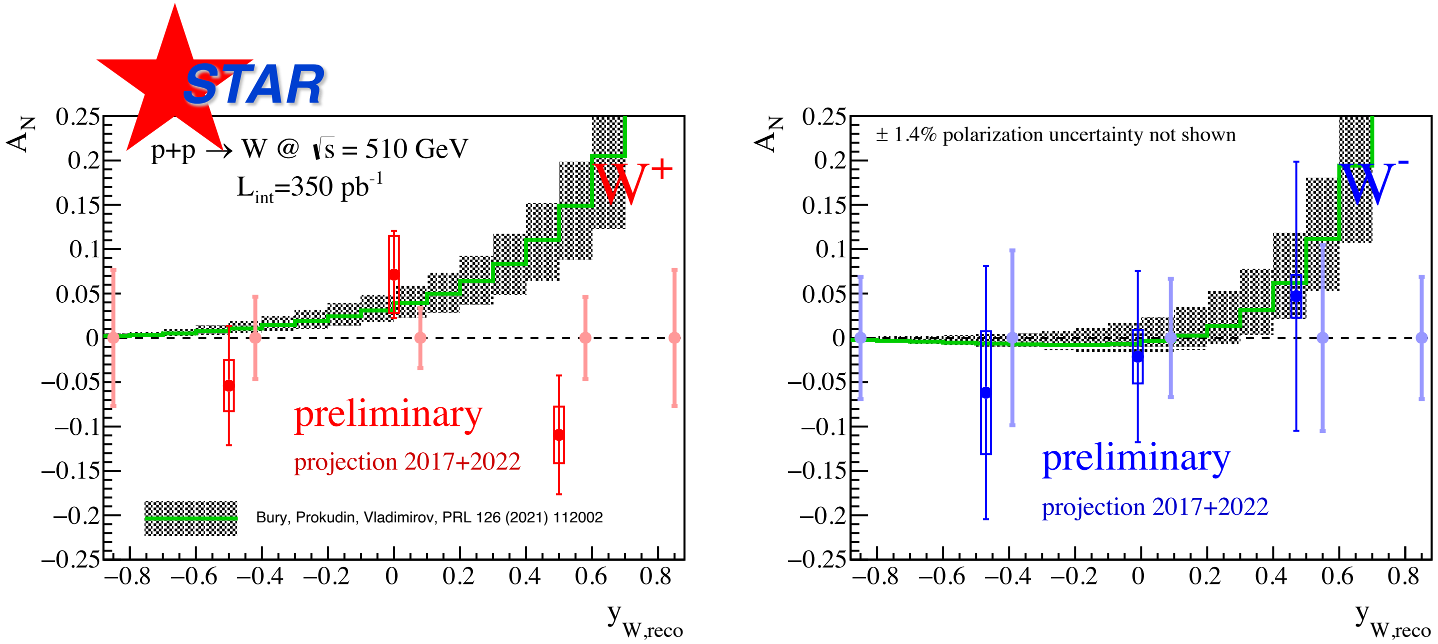
14x more data in 2017 produced systematically smaller asymmetries – need precision and extended tracking in Run 22 to provide definitive test of sign change.



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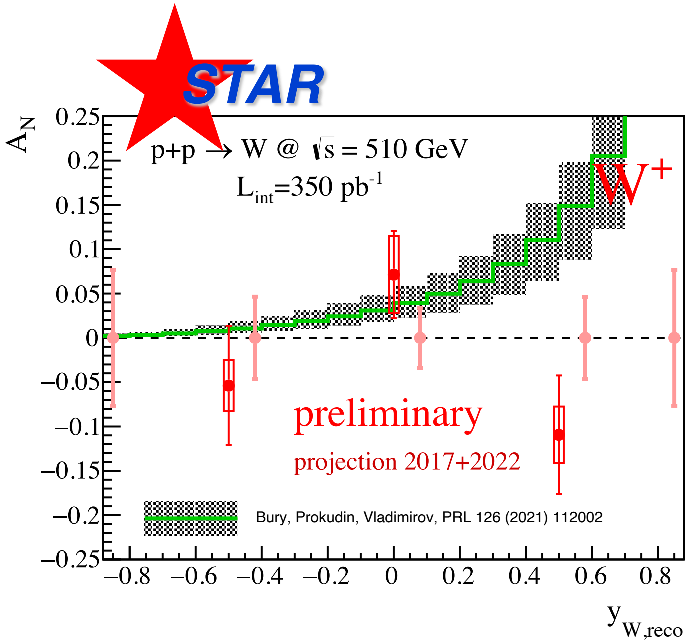

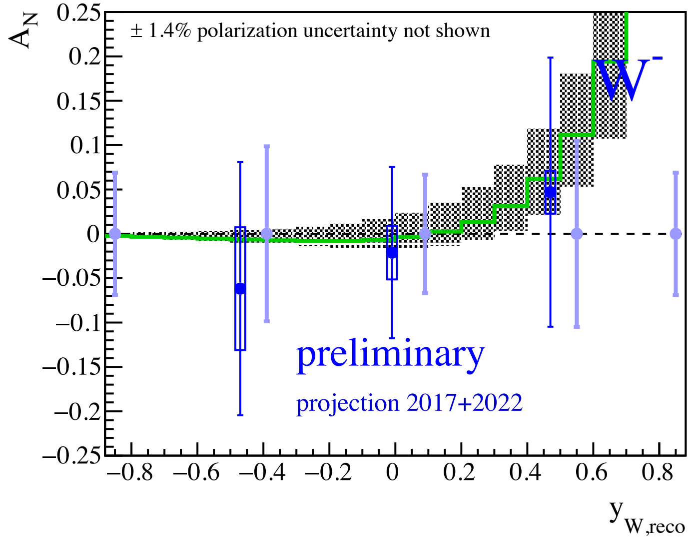

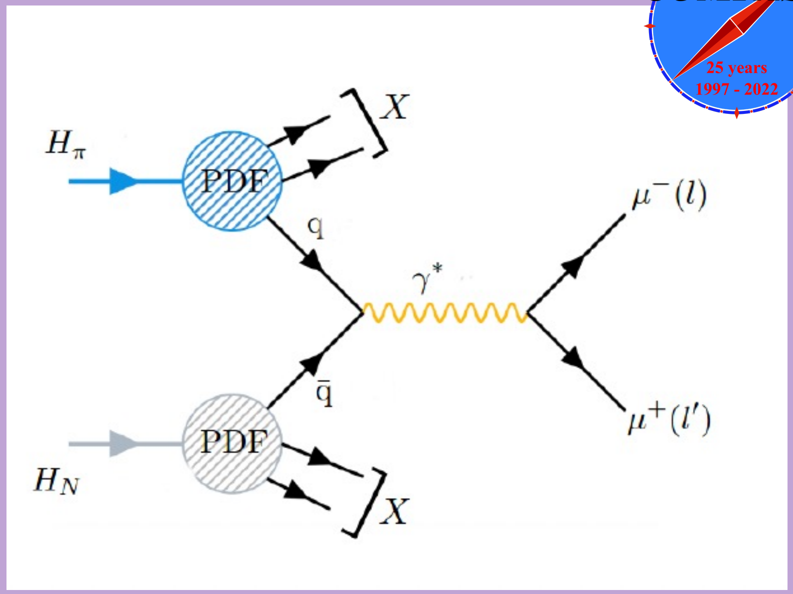

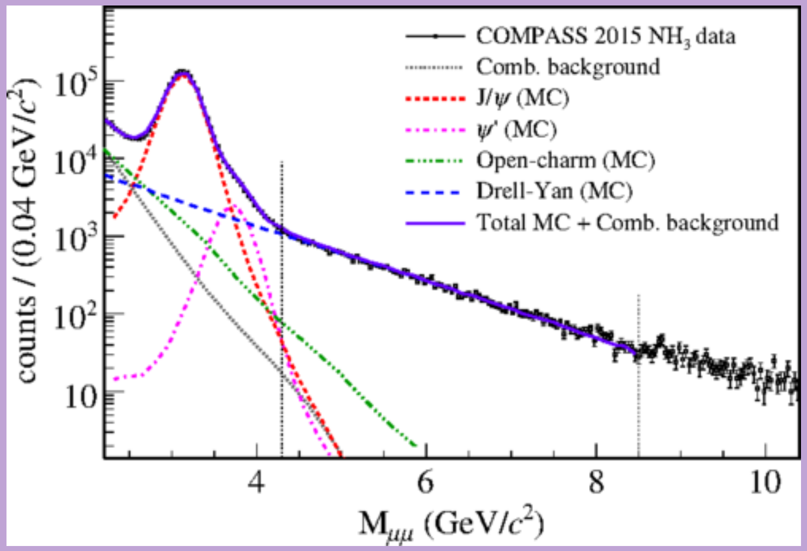

Sivers in $p^{\uparrow}p$ and $p^{\uparrow}\pi$

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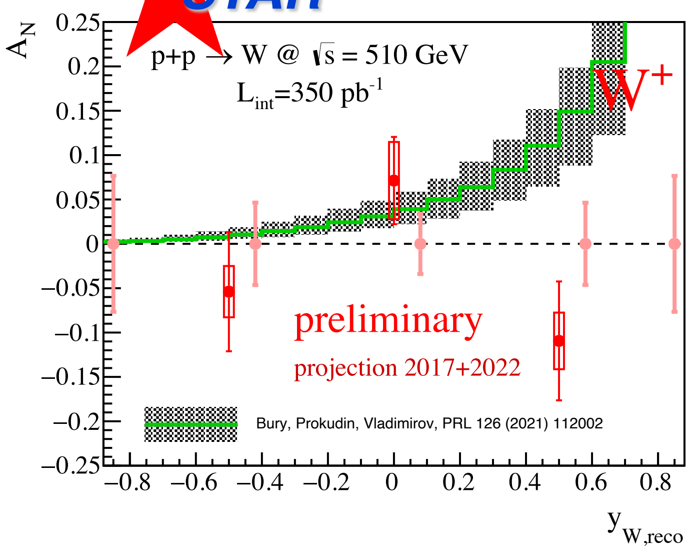
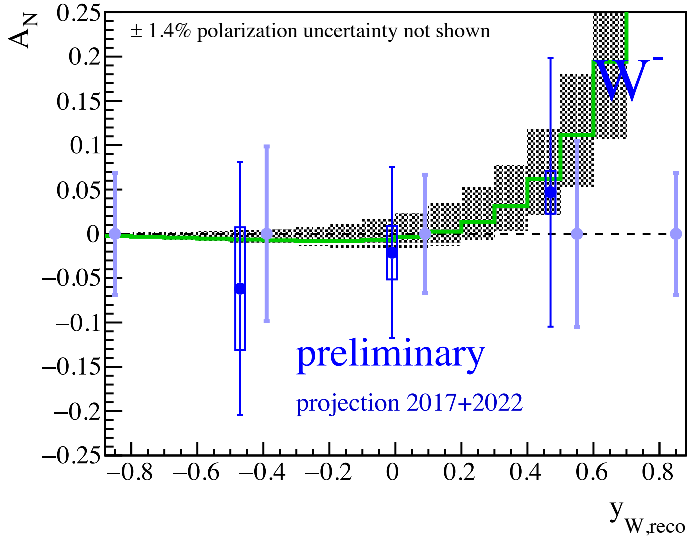
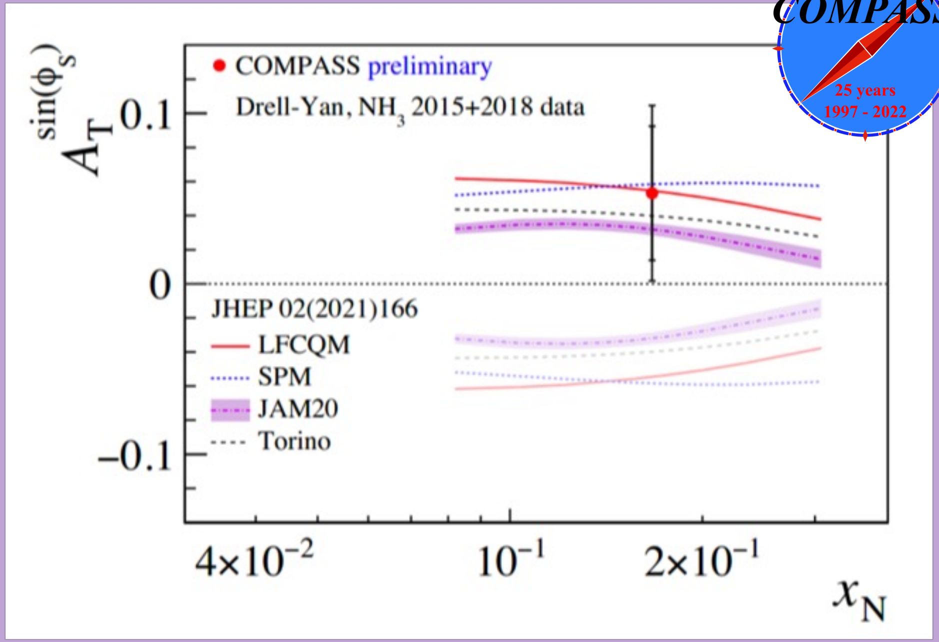
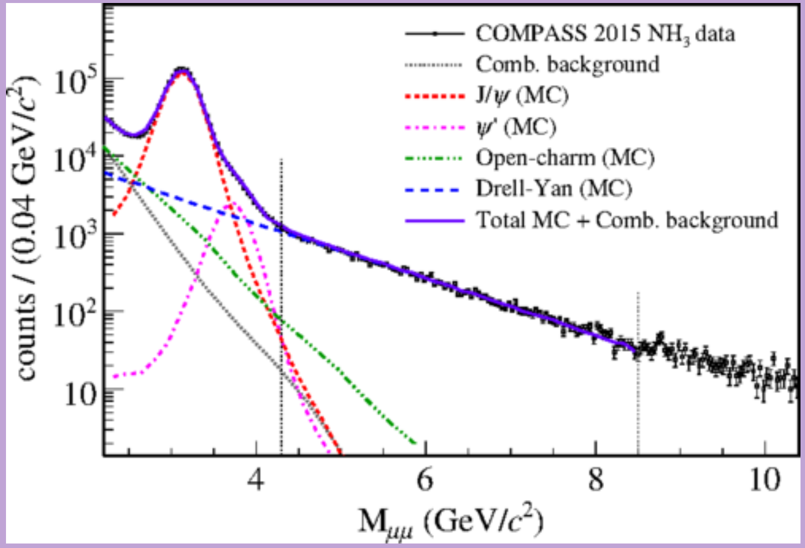






COMPASS favors sign change!



2030 — EIC

FNAL SPINQUEST

2020 — 12 GeV Upgrade

2010

BNL RHIC
CERN COMPASS

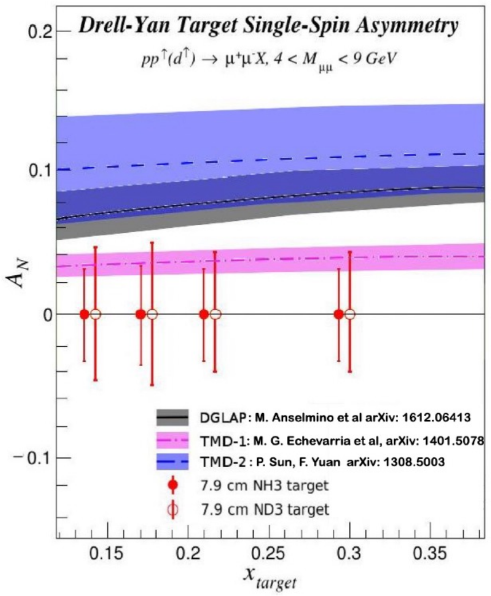
2000

JLAB HALLS A,B,C
DESY HERMES
SLAC E142/143/154/155
FNAL E581/704
CERN SMC

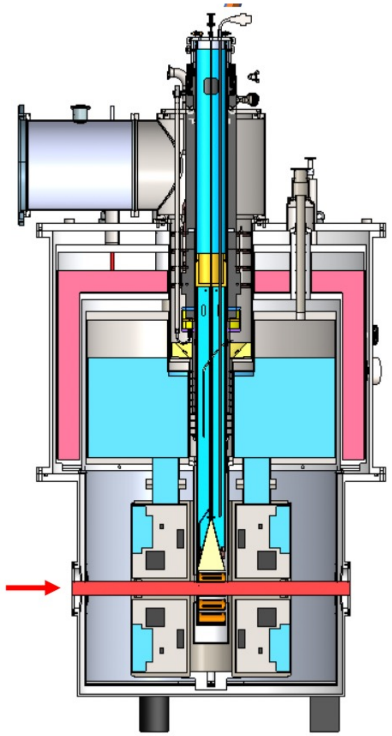
1990 — CERN EMC

1980 — SLAC E-130

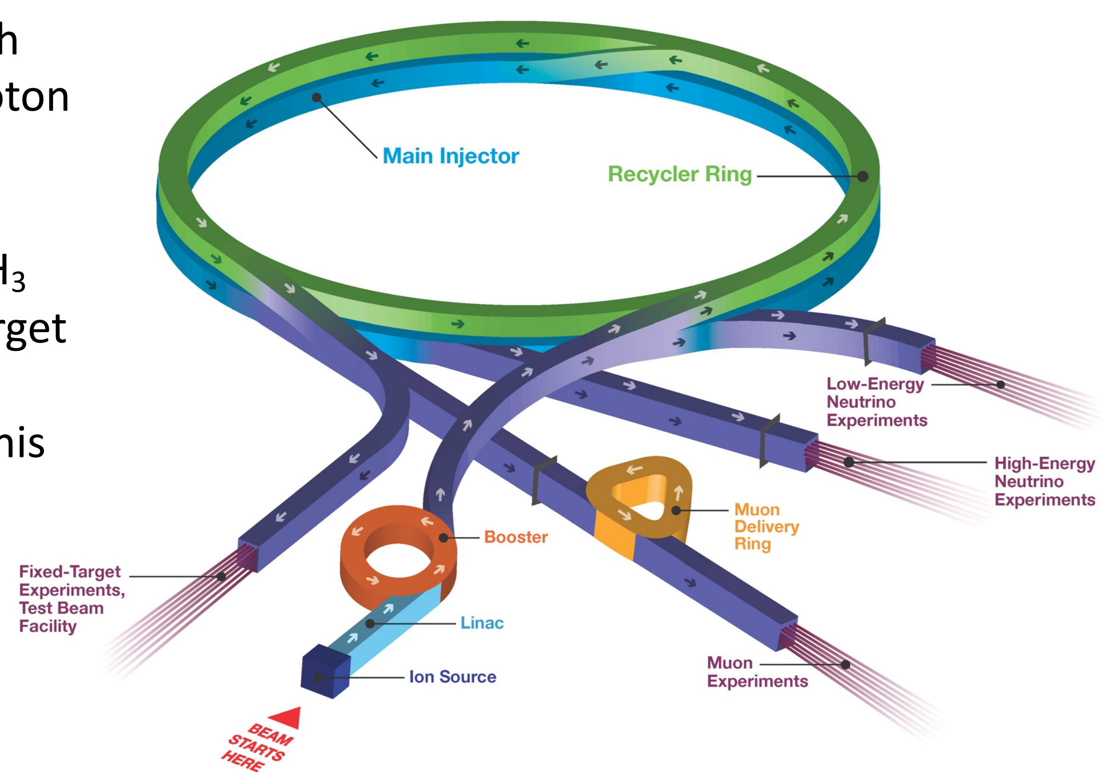
SLAC E-80

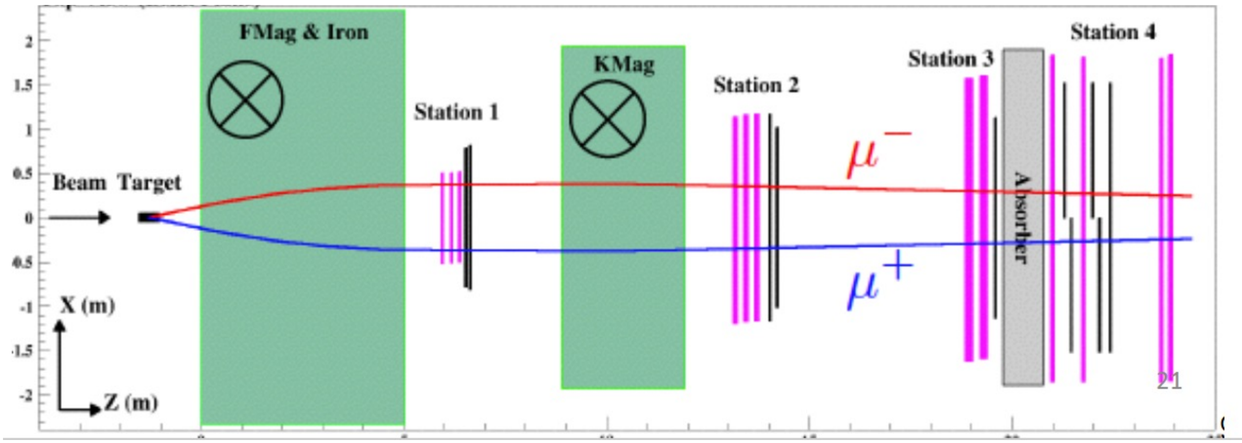


120 GeV high intensity proton beam
8 cm long polarized NH_3 and ND3 target @ 1K
First beam this month!

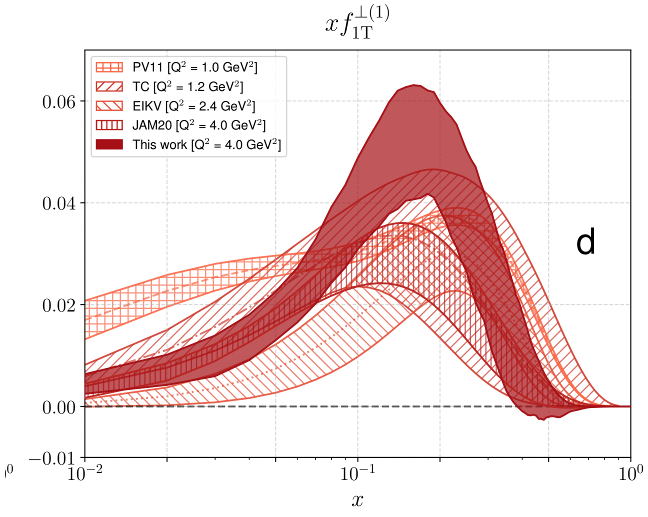


Fermilab Accelerator Complex

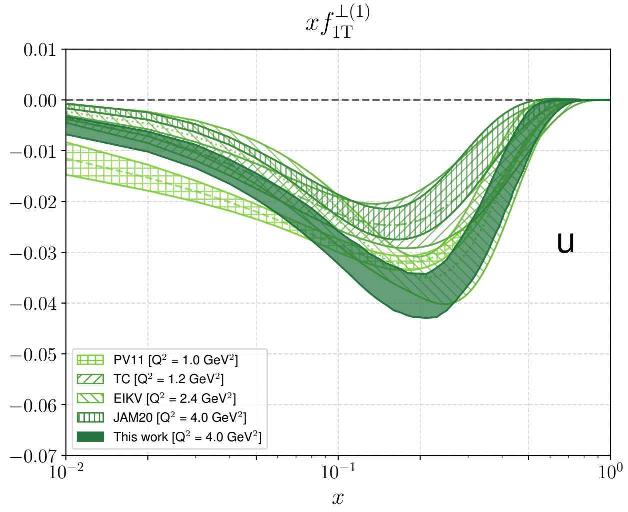




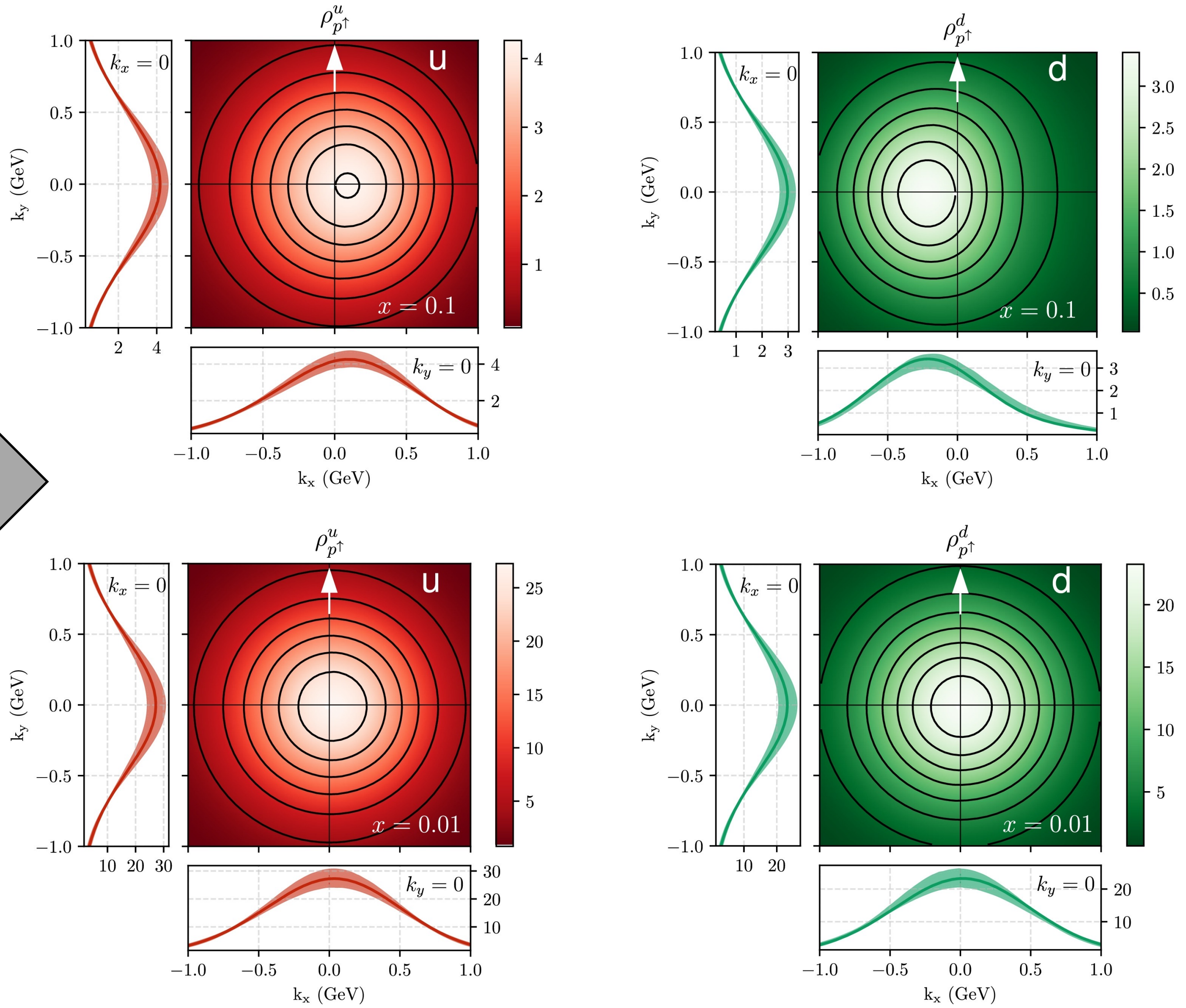
Global QCD Analyses : Sivers TMD



$$\int d^2\boldsymbol{k}_T \, \frac{k_T^2}{2M^2} \, f_{1T}^{\perp a}(x, k_T^2; Q^2)$$

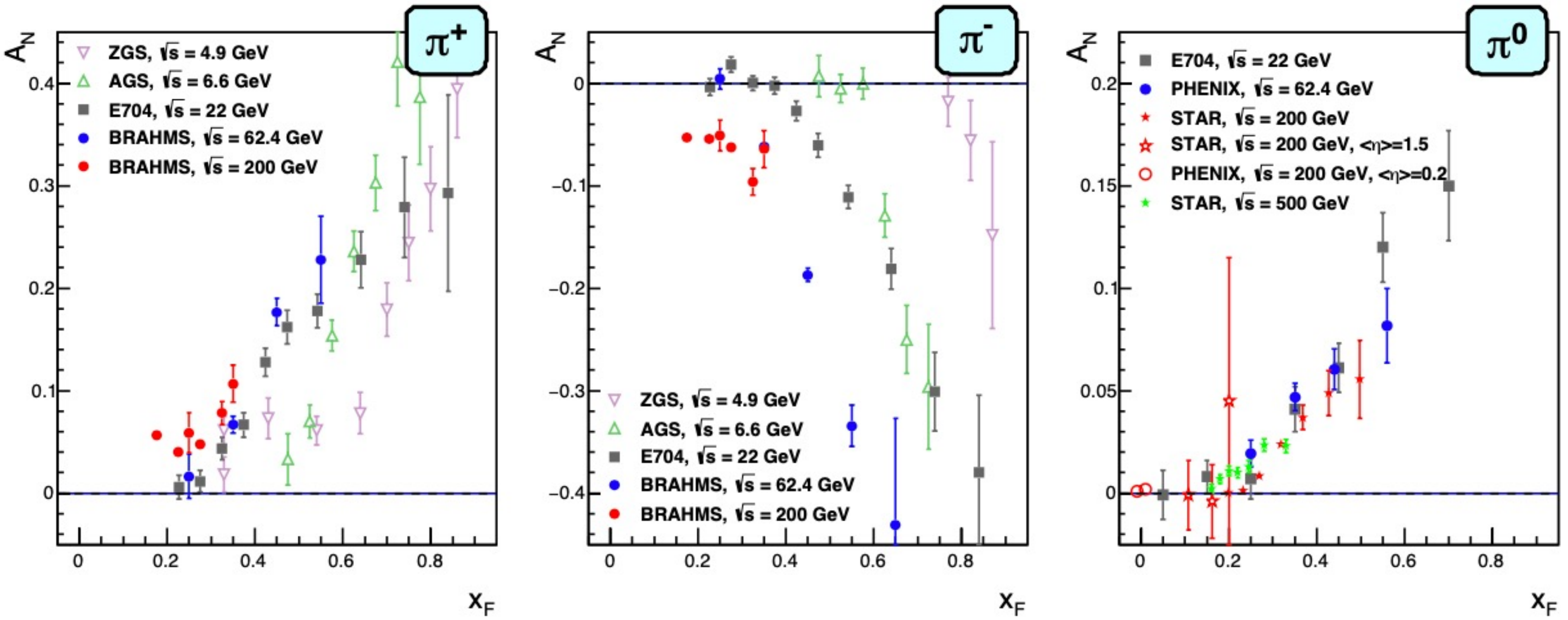


3D



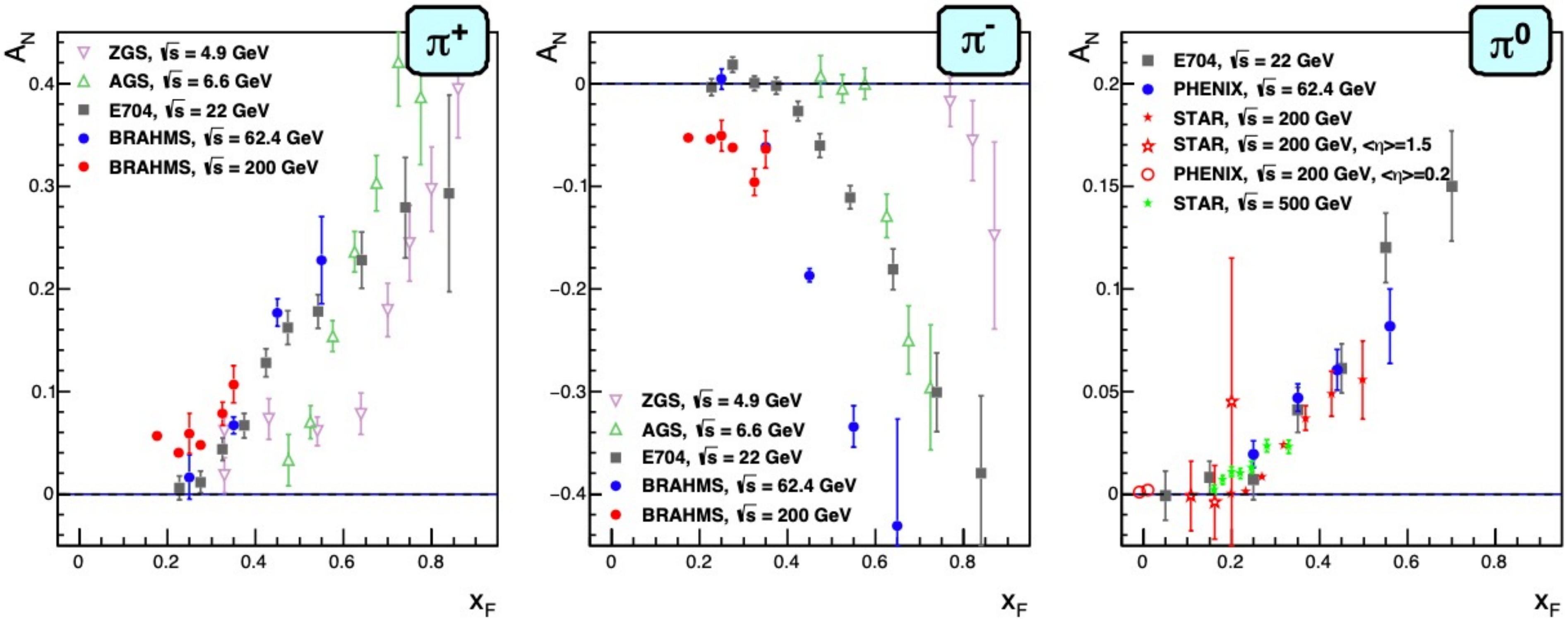
PLB 827 (2022) 136961

How do TMDs connect to large A_N?



Large asymmetries for $p^{\uparrow}p \rightarrow \pi + X$ are reproduced by STAR, PHENIX and BRAHAMs @ RHIC. They persist up to $\sqrt{s} = 500$ GeV.

How do TMDs connect to large A_N?



$p^{\uparrow}p \rightarrow \pi + X$ cannot be described by TMD framework – only one hard scale $\boldsymbol{\Lambda_{QCD}} \ll \boldsymbol{Q}$ available. Instead use collinear twist-3 (CT3) framework to encapsulate multi-parton interactions.

How do TMD connect to CT3?

$$\pi F_{FT}(x,x) = \int d^2\vec{k}_T \, \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2) \equiv f_{1T}^{\perp(1)}(x)$$

Nucl. Phys B667 (2003) 201

Qiu-Sterman CT3 matrix element

TMD Sivers Function

1st moment of Sivers

$$H_1^{\perp(1)}(z) \equiv z^2 \int d^2\vec{p}_\perp \, \frac{p_\perp^2}{2M_h^2} H_1^{\perp}(z, z^2 p_\perp^2)$$

PRD 93 (2016) 014009

"Collins" CT3 matrix element

TMD Collins Function

A_N for π, γ, jet

SIDIS, DY, W/Z, e+e-

PRD 102 (2020) 054002

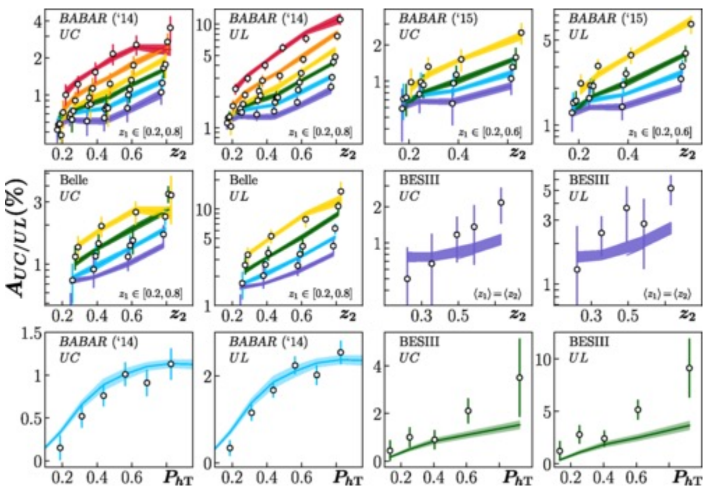
Origin of single transverse-spin asymmetries in high-energy collisions

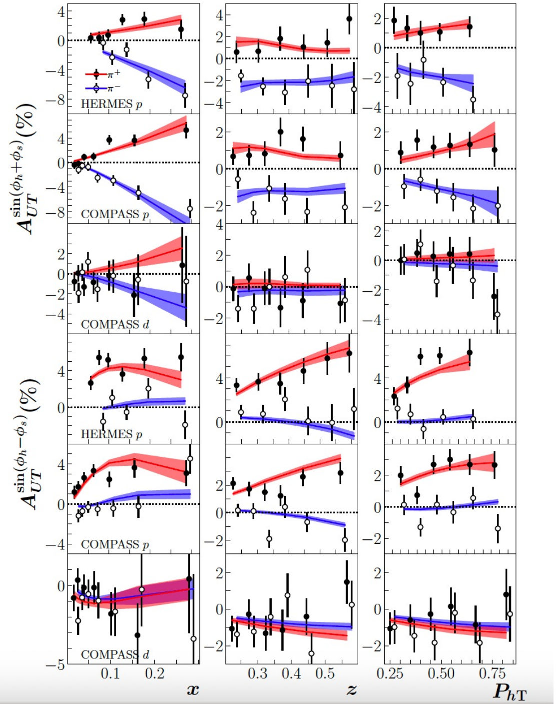
Justin Cammarota,[1,2,*] Leonard Gamberg,[3,†] Zhong-Bo Kang,[4,5,6,‡] Joshua A. Miller,[2,§] Daniel Pitonyak,[2,¶] Alexei Prokudin,[3,7,**] Ted C. Rogers,[7,8,††] and Nobuo Sato[7,‡‡]

In this paper we perform the first simultaneous QCD global analysis of data from semi-inclusive deep inelastic scattering, Drell-Yan, e^+e^- annihilation into hadron pairs, and proton-proton collisions. Consequently, we are able to extract a universal set of non-perturbative functions that describes the observed asymmetries in these reactions. The outcome of our analysis indicates single transverse-spin asymmetries in high-energy collisions have a common origin. Furthermore, we achieve the first phenomenological agreement with lattice QCD on the up and down quark tensor charges.

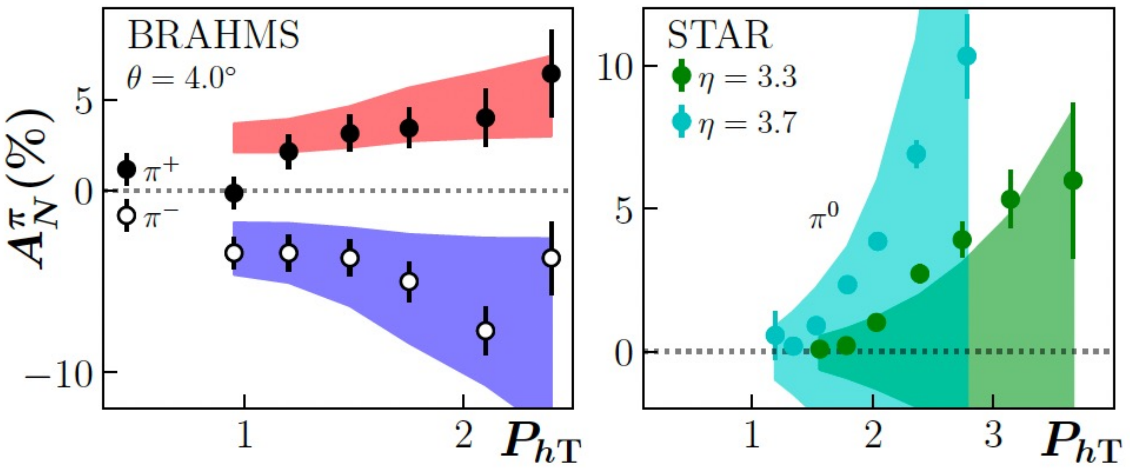
1) Extract non-perturbative functions from TMD observables

2) Use them to predict A_N for π, γ, jet



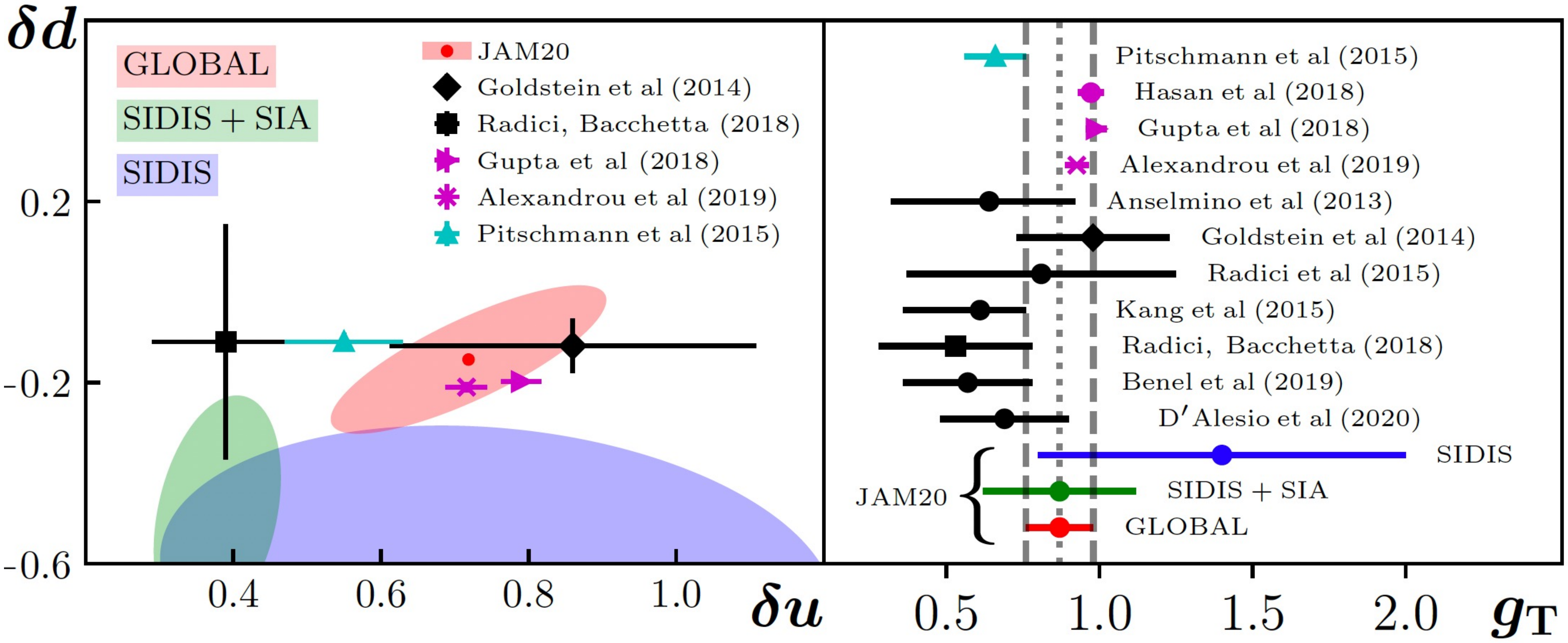


e⁺e⁻ and SIDIS



Asymmetries dominated by $h_1^q(x) \otimes H_1^{\perp,q}(z)$ term.
Large uncertainties due to extrapolation past where regime where data provides constraints.

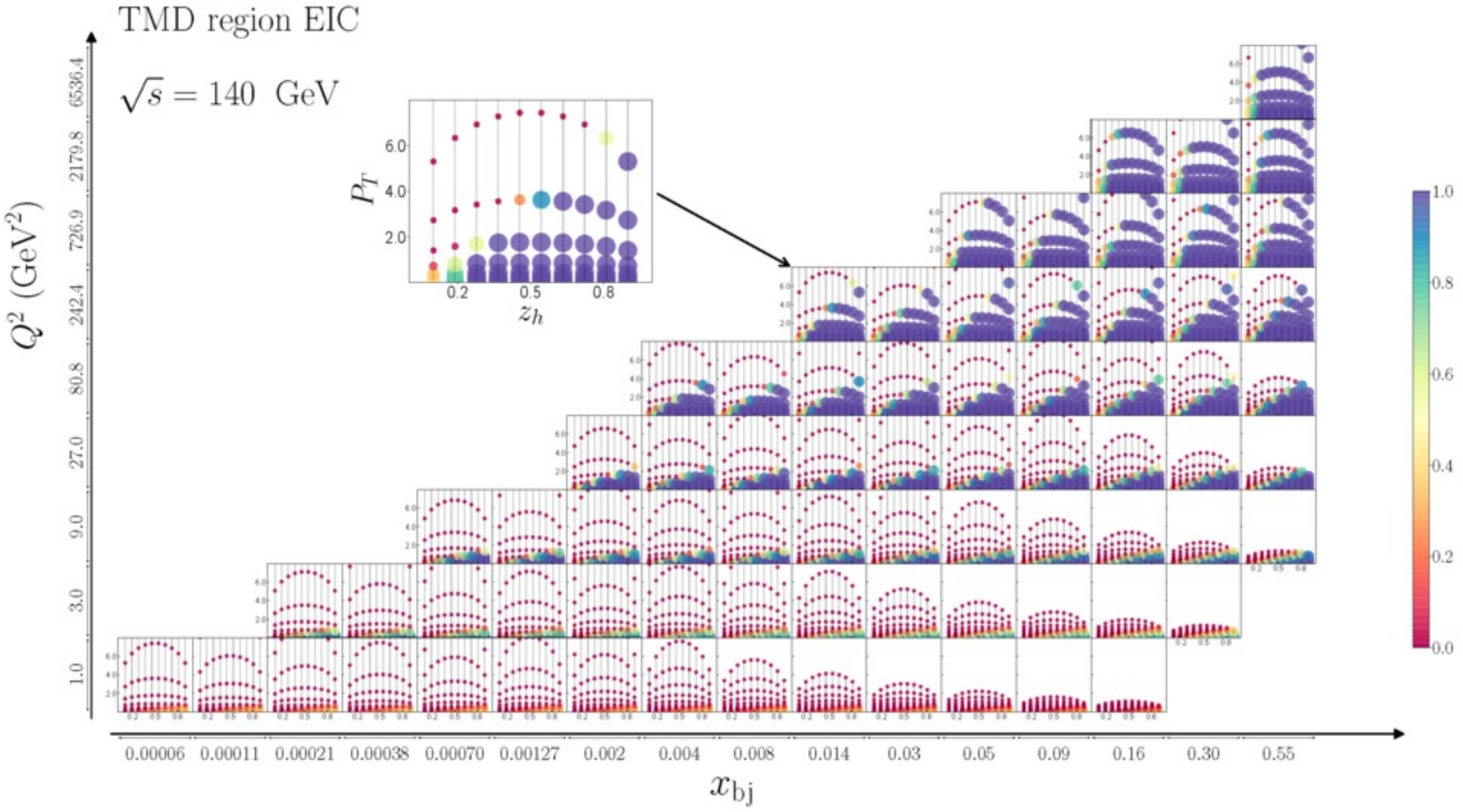
Now include A_N



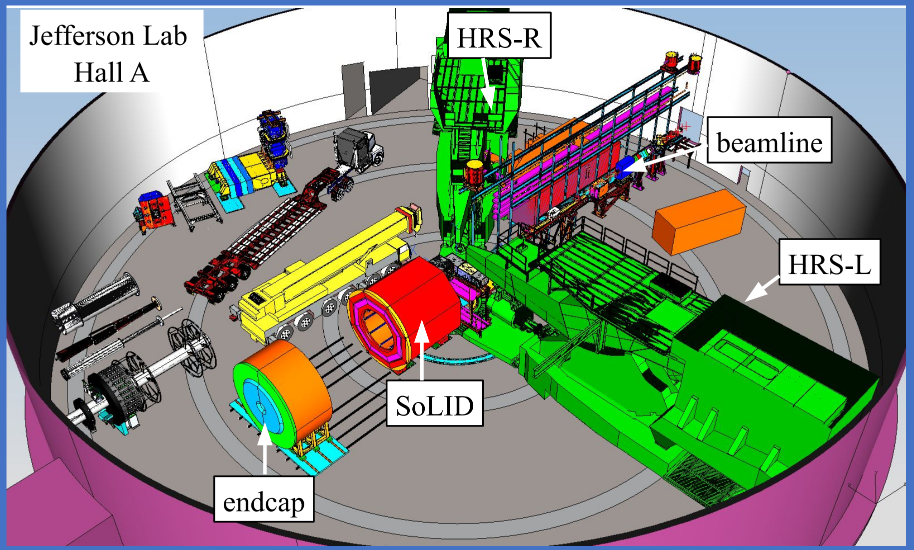
$\delta q = \int_0^1 dx\left[h_1^q(x) - h_1^{\bar{q}}(x)\right]$

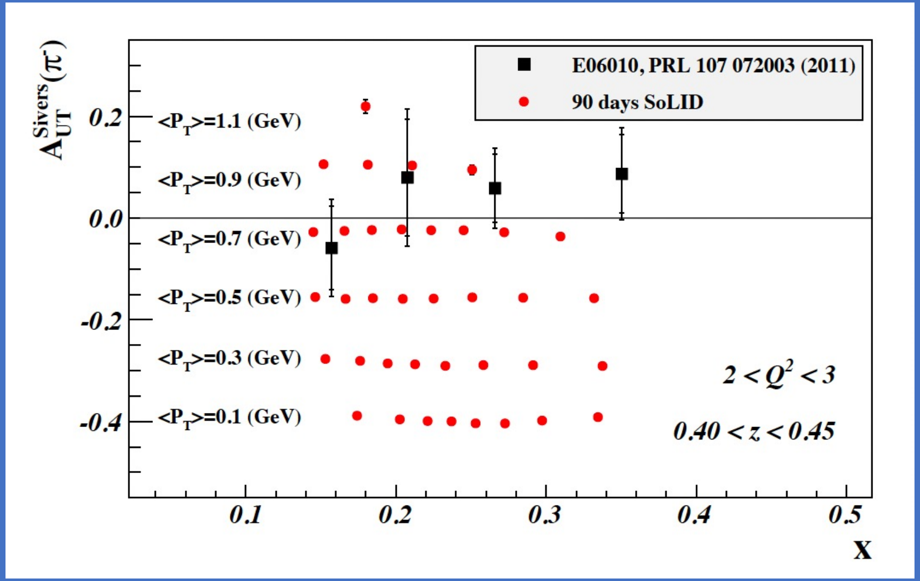
$g_T = \delta u - \delta d$

Future TMD measurements



Low-x at the EIC

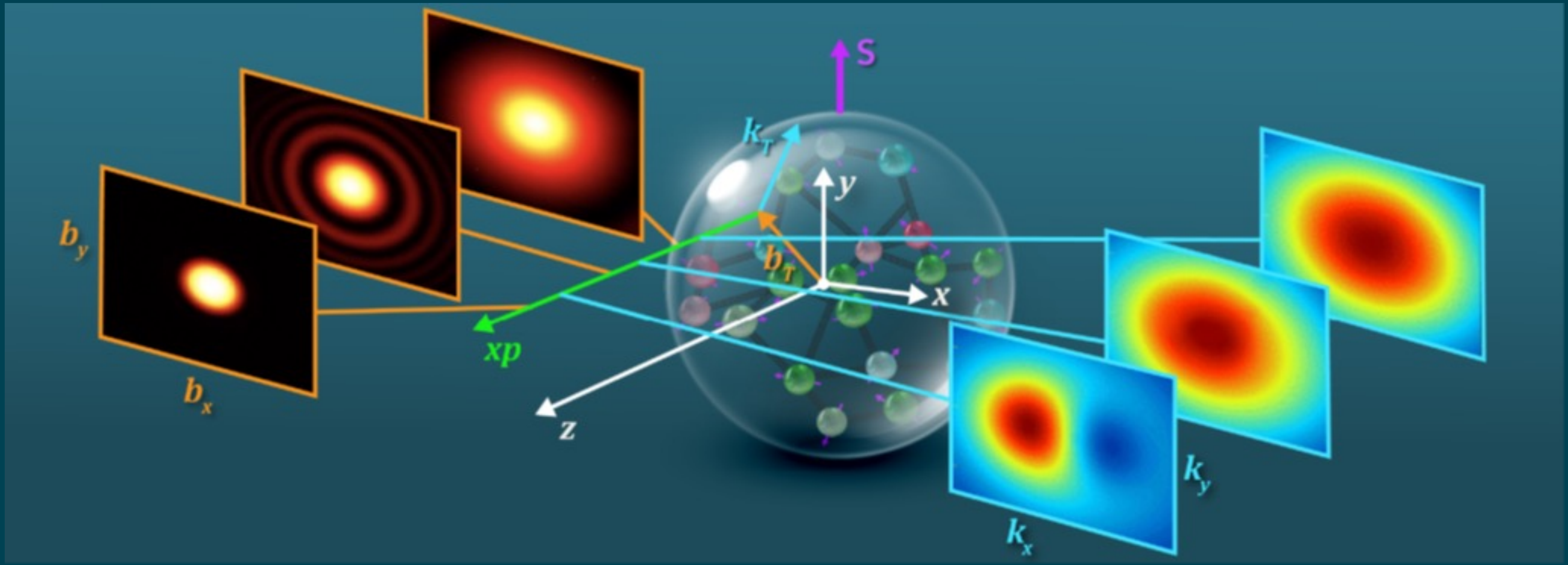




High-x at the JLAB 12 GeV

3D Imaging

GPD

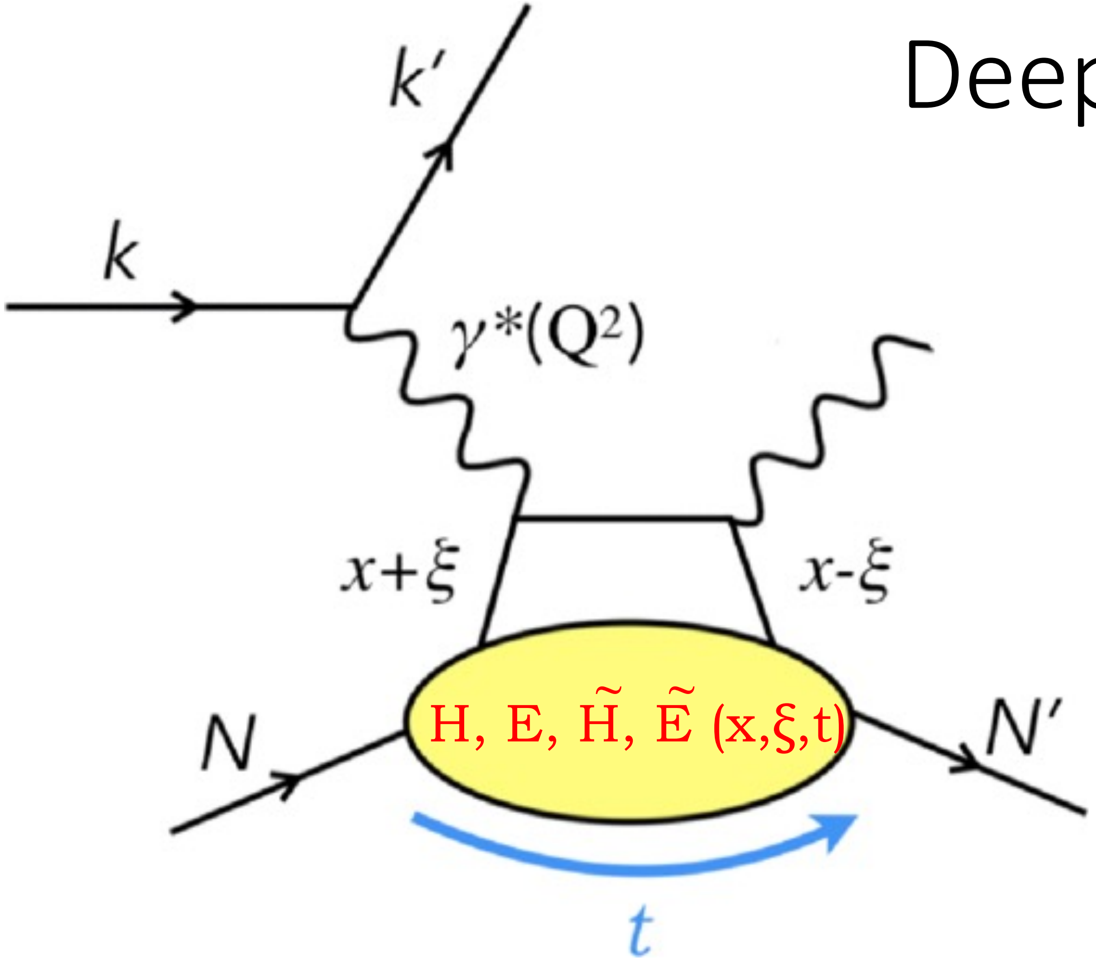


TMD

- 2D in parameter space +1 in momentum space
- Collinear factorization
- Gives access to parton helicity and OAM
- Cleanest probe is Deeply Virtual Compton Scattering
- Multiple channels, including Deeply Virtual Meson Production are necessary for full reconstruction.

- 3D in momentum space
- Non-trivial factorization
- Origin of spin-orbit correlations is orbital angular momentum.

Deeply Virtual Compton Scattering

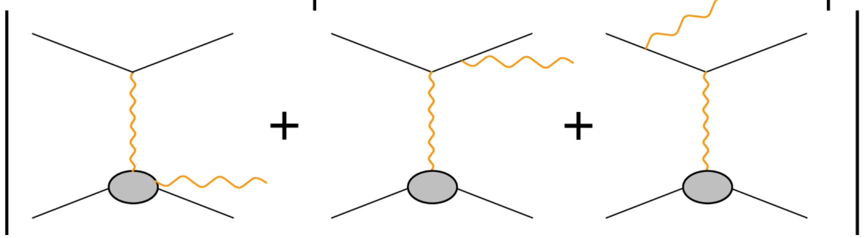


x   parton longitudinal momentum fraction

2ξ   change in x of interacting parton

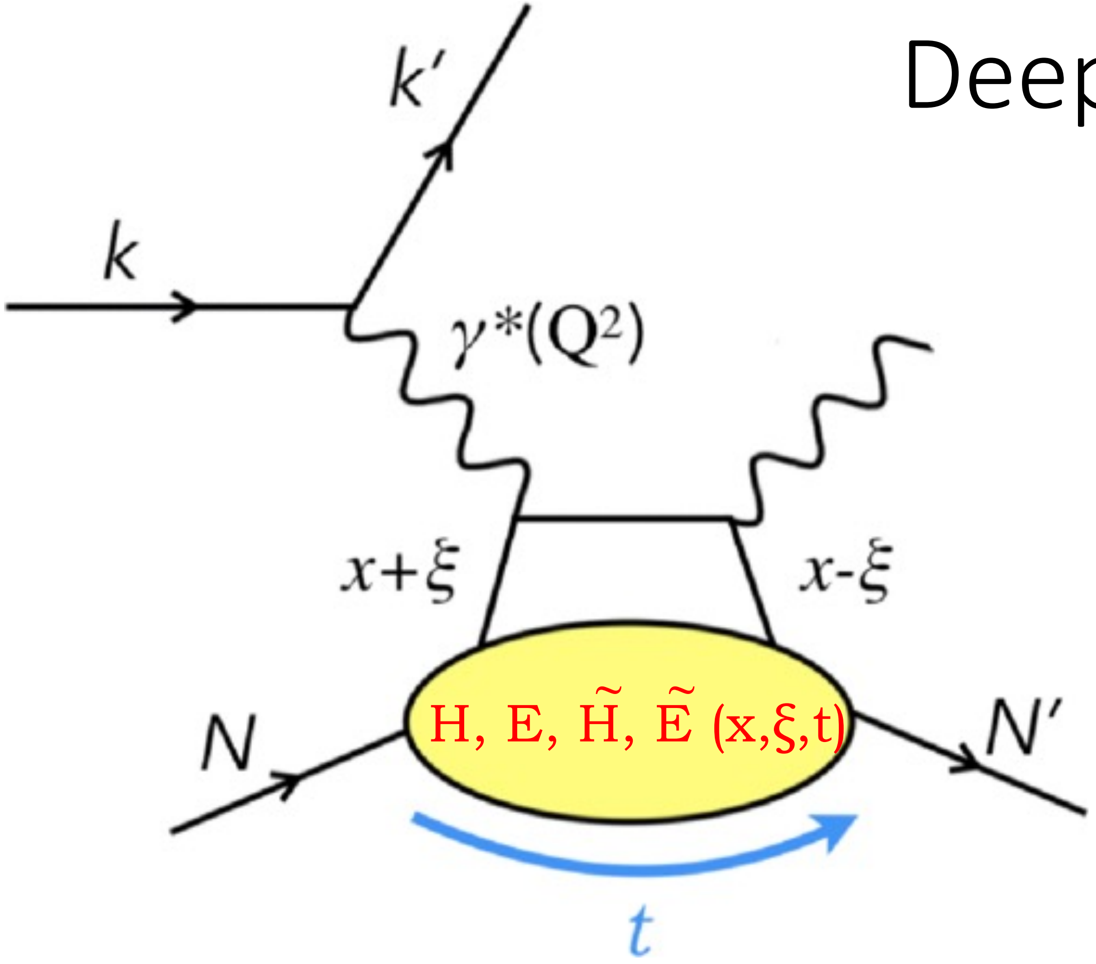
$t = \Delta^2 = (p-p')^2$ Fourier transform in t of GPDs at $\xi = 0$ gives impact parameter $b_\perp$ distribution

$\sigma(eN \longrightarrow eN\gamma) =$



$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

Deeply Virtual Compton Scattering



3D QUARK NUMBER DENSITY & HELICITY

$$q(x, \mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} H(x,0,-\Delta_\perp^2)$$

$$\Delta q(x, \mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} \widetilde{H}(x,0,-\Delta_\perp^2)$$

M. Burkardt, PRD 62, 71503 (2000)

QUARK ANGULAR MOMENTUM : Ji Sum Rule

$$\frac{1}{2}\int_{-1}^{1} xdx(H(x,\xi,t=0)+E(x,\xi,t=0)) = J = \frac{1}{2}\Delta\Sigma + \Delta L$$

X. Ji, Phy.Rev.Lett.78 (1997)

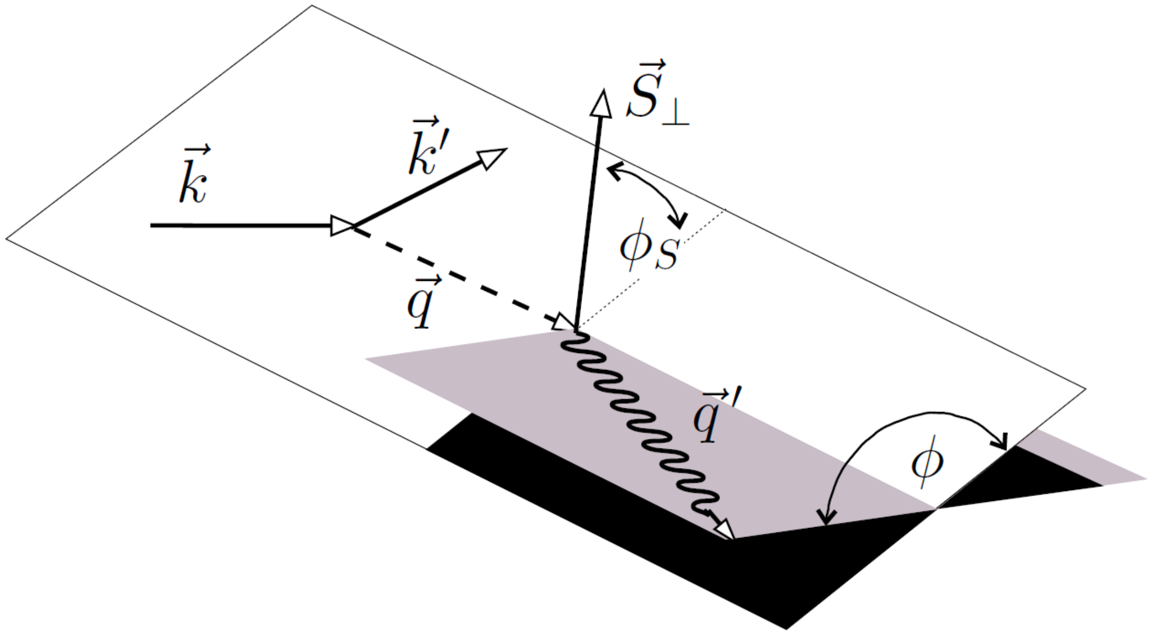
GPD Extraction

DVCS cross-section is parameterized in terms of Compton form factors (CFF). *Nucl.Phys. B629 (2002) 32*

CFF are complex functions
- imaginary component accesses GPDs along the diagonal of $x = \pm\xi$
- real component accesses convolution of GPD with initial parton momentum.

Various spin asymmetries, measured as a function of ϕ are sensitive to different CFF.

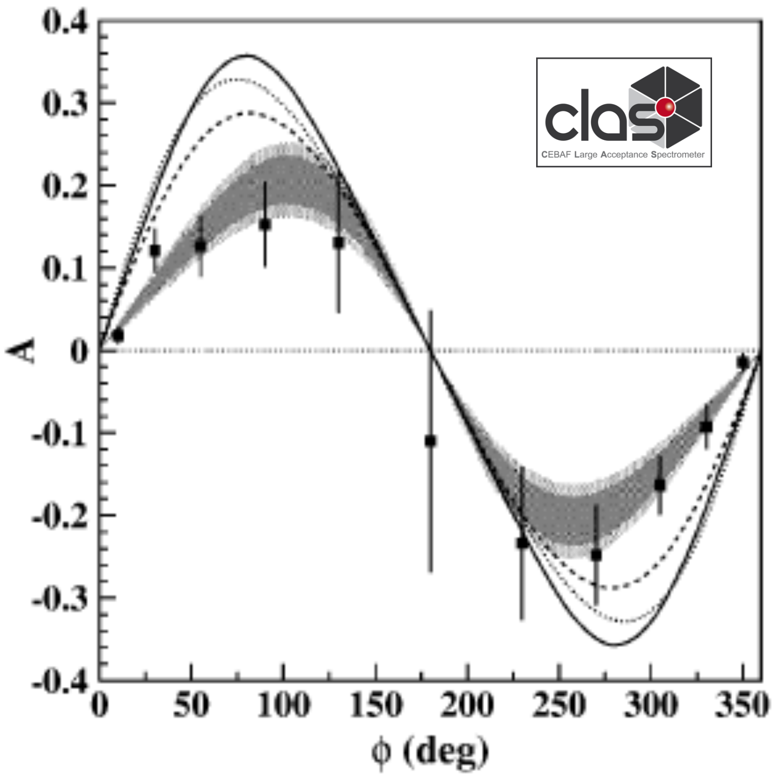
Full extraction of GPDs will requires a global analysis.

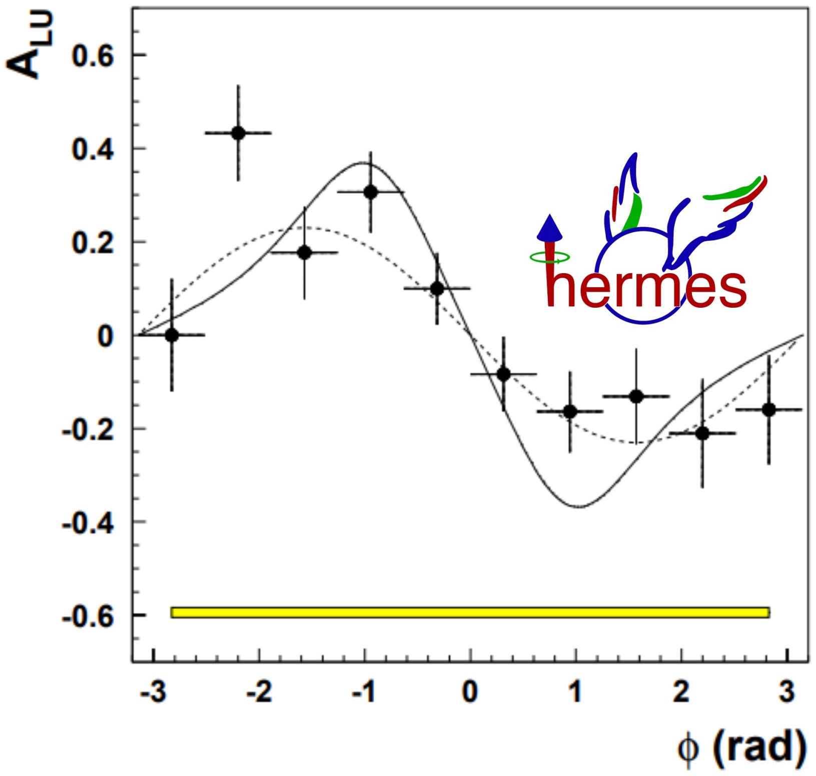


CFF	$\mathcal{Im}$	$\mathcal{Re}$
$\mathcal{H}$	A_{LU}	A_{LL} A_{LT} σ
$\widetilde{\mathcal{H}}$	A_{UL}	A_{LL} A_{LT} σ
$\mathcal{E}$	A_{UT}	A_{LL} A_{LT} σ

First DVCS Measurements

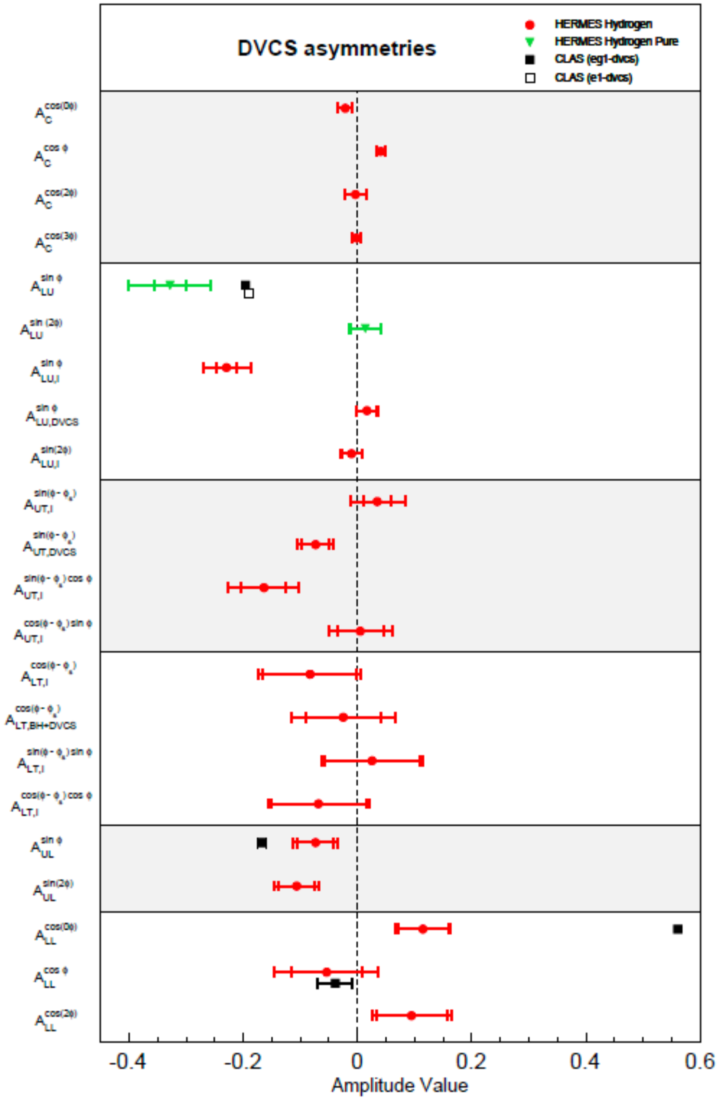
… published back-to-back in PRL 87 (2001)

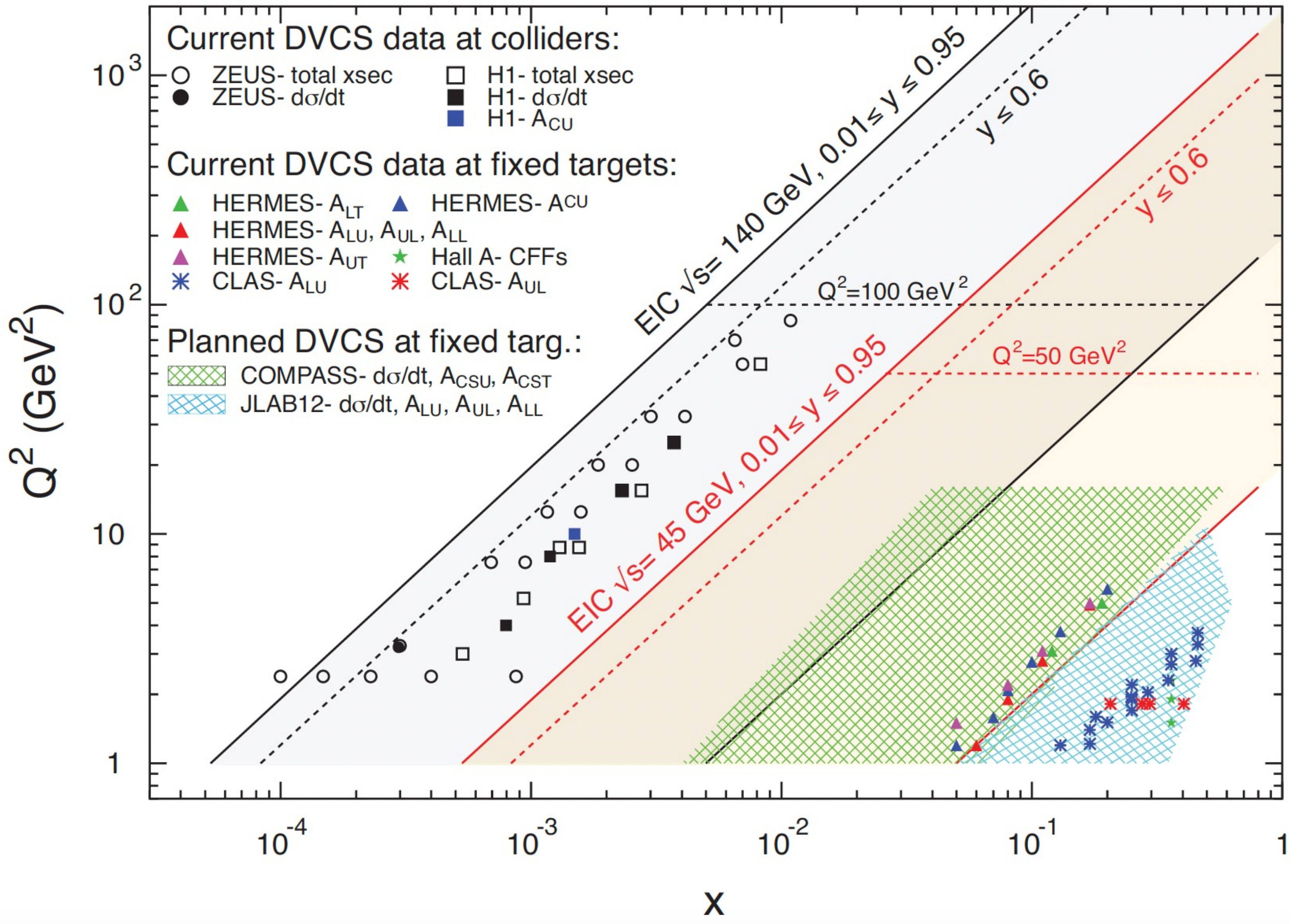




Beam Spin Asymmetries – polarized beam + unpolarized target – sensitive to $H, E, \tilde{H}$

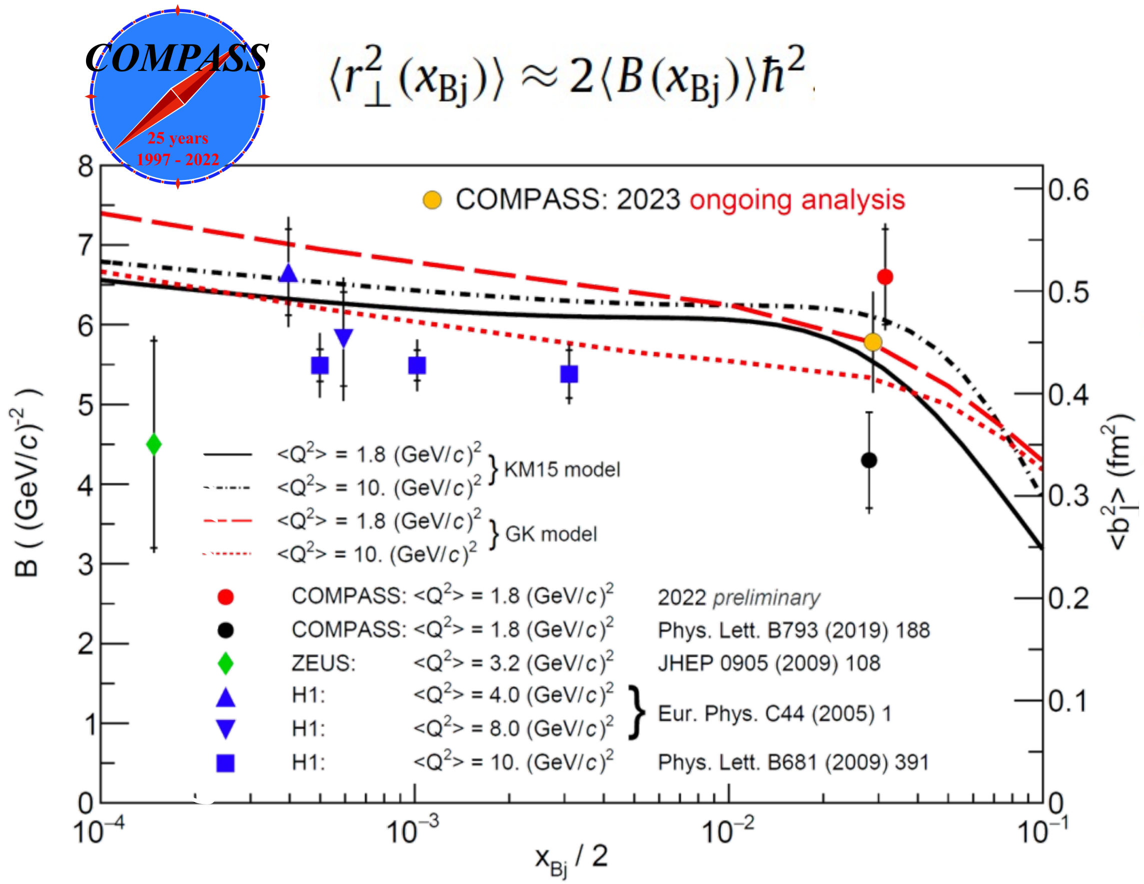
Current and Future DVCS Experiments

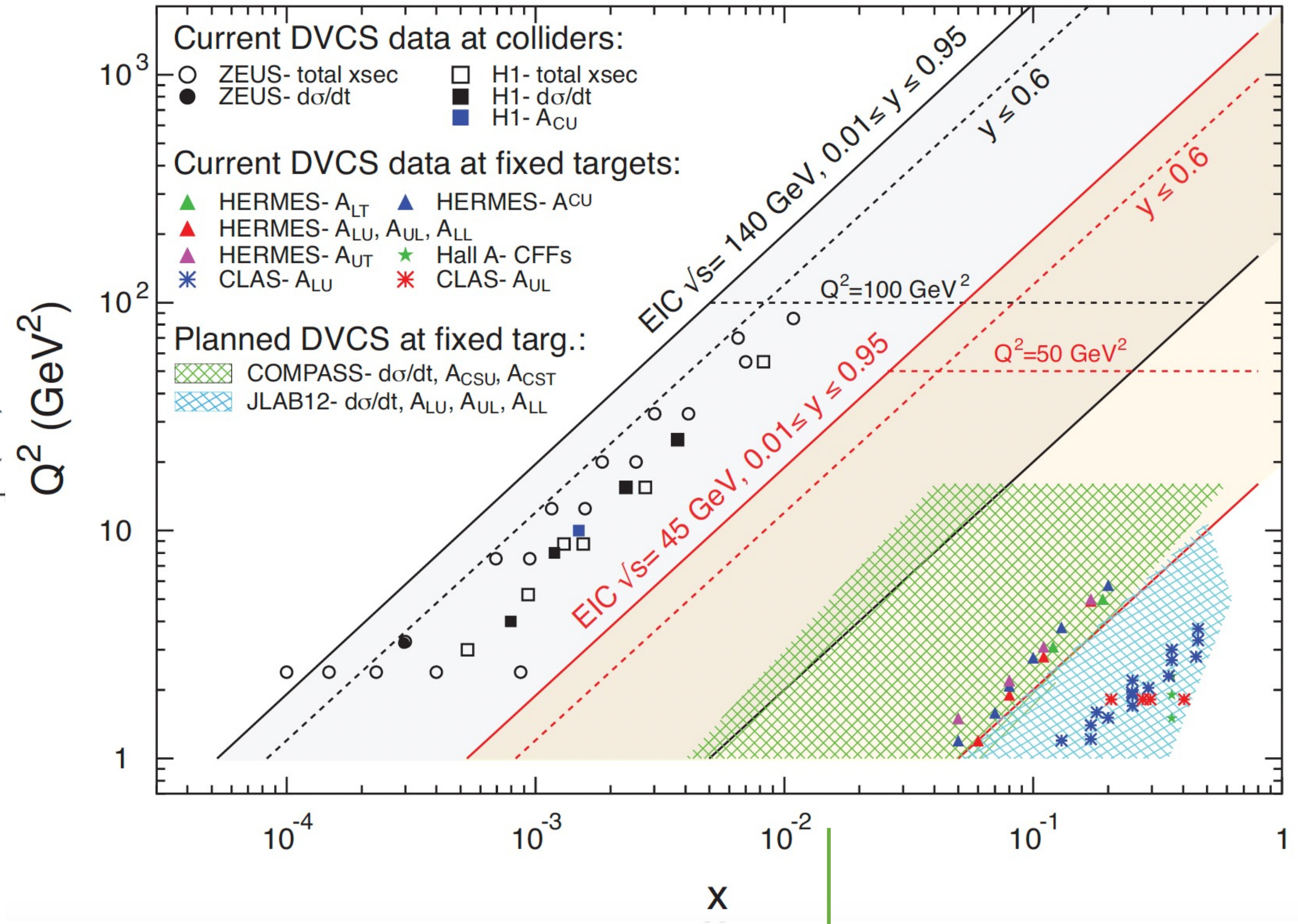




from Silvia Niccolai, SPIN 2023

Current and Future DVCS Experiments



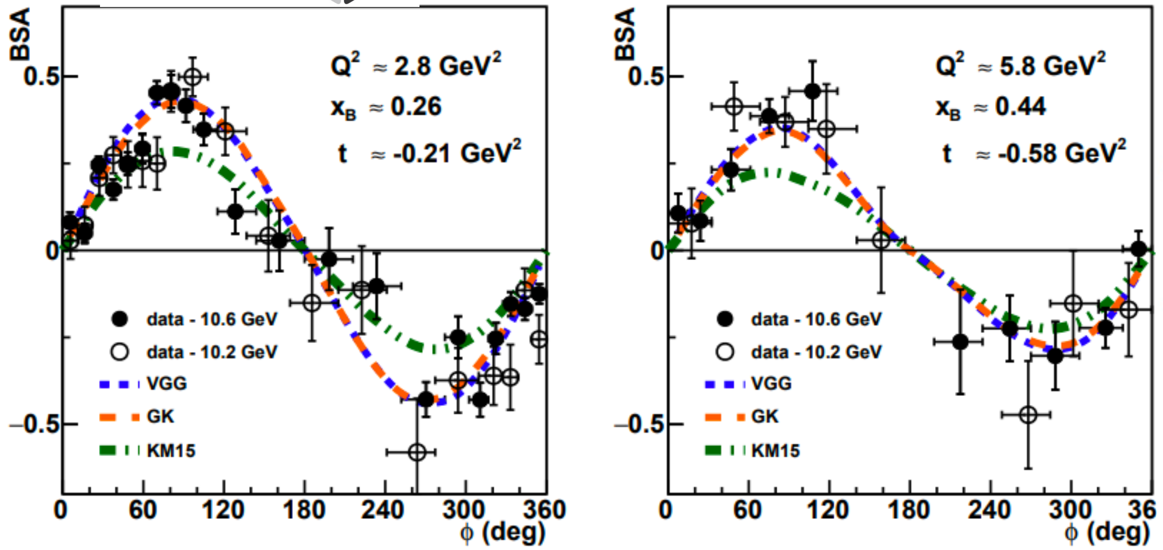


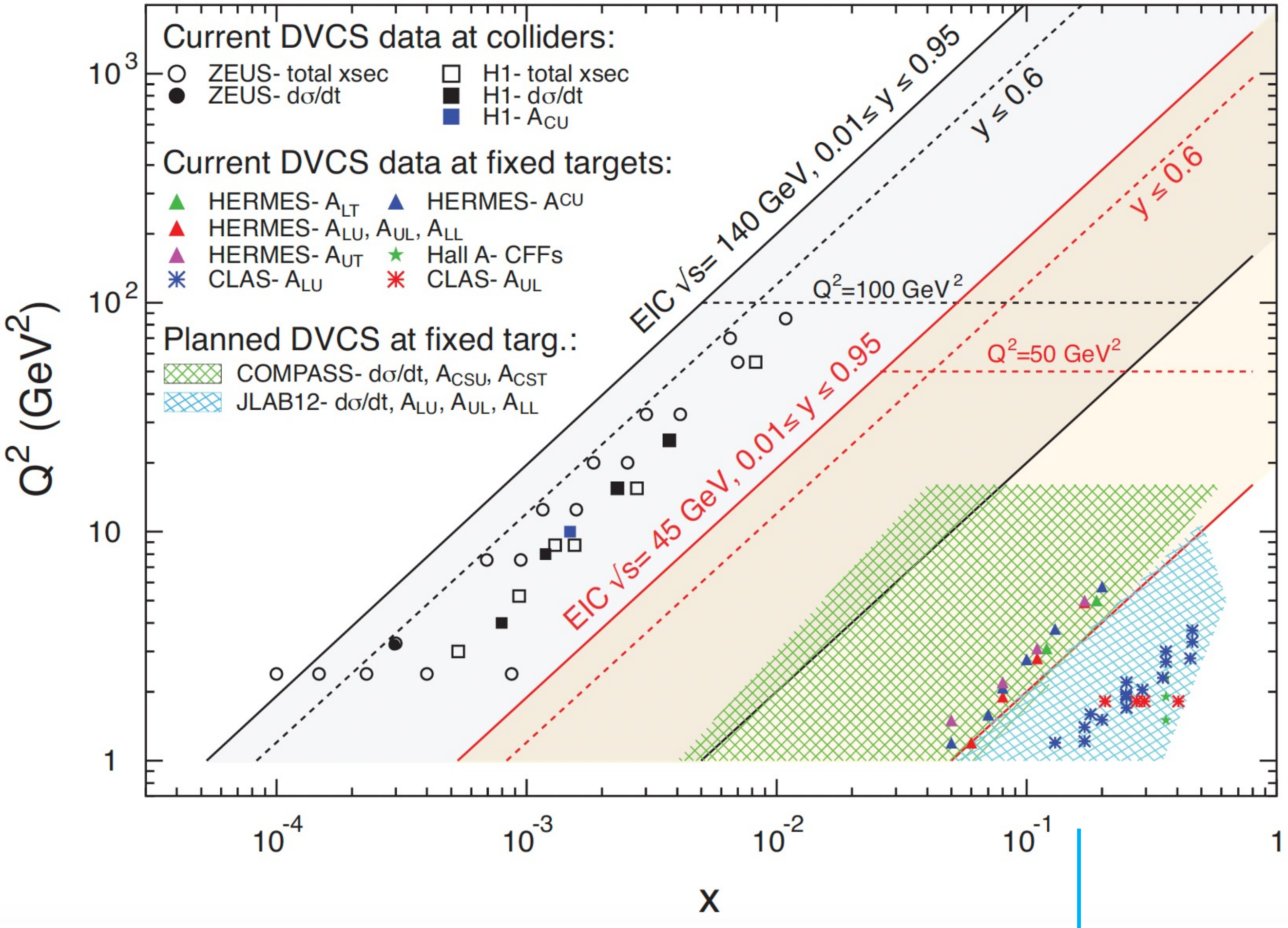
Assumes :

- Dominance of Im($\mathcal{H}$)
- Negligible effects from nonzero skew

Current and Future DVCS Experiments

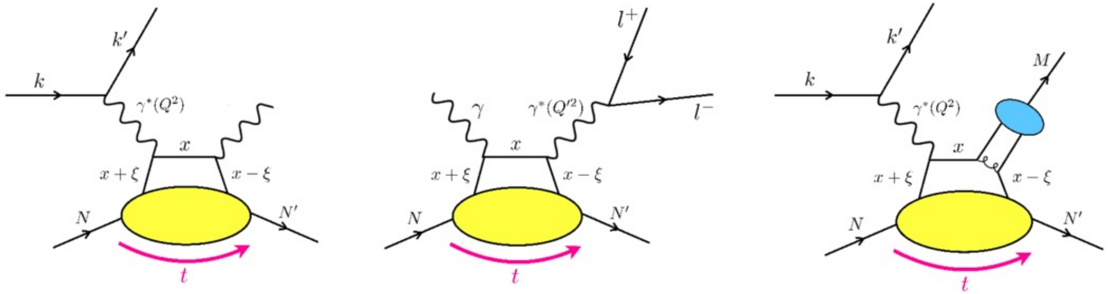
PRL 130 (2023)



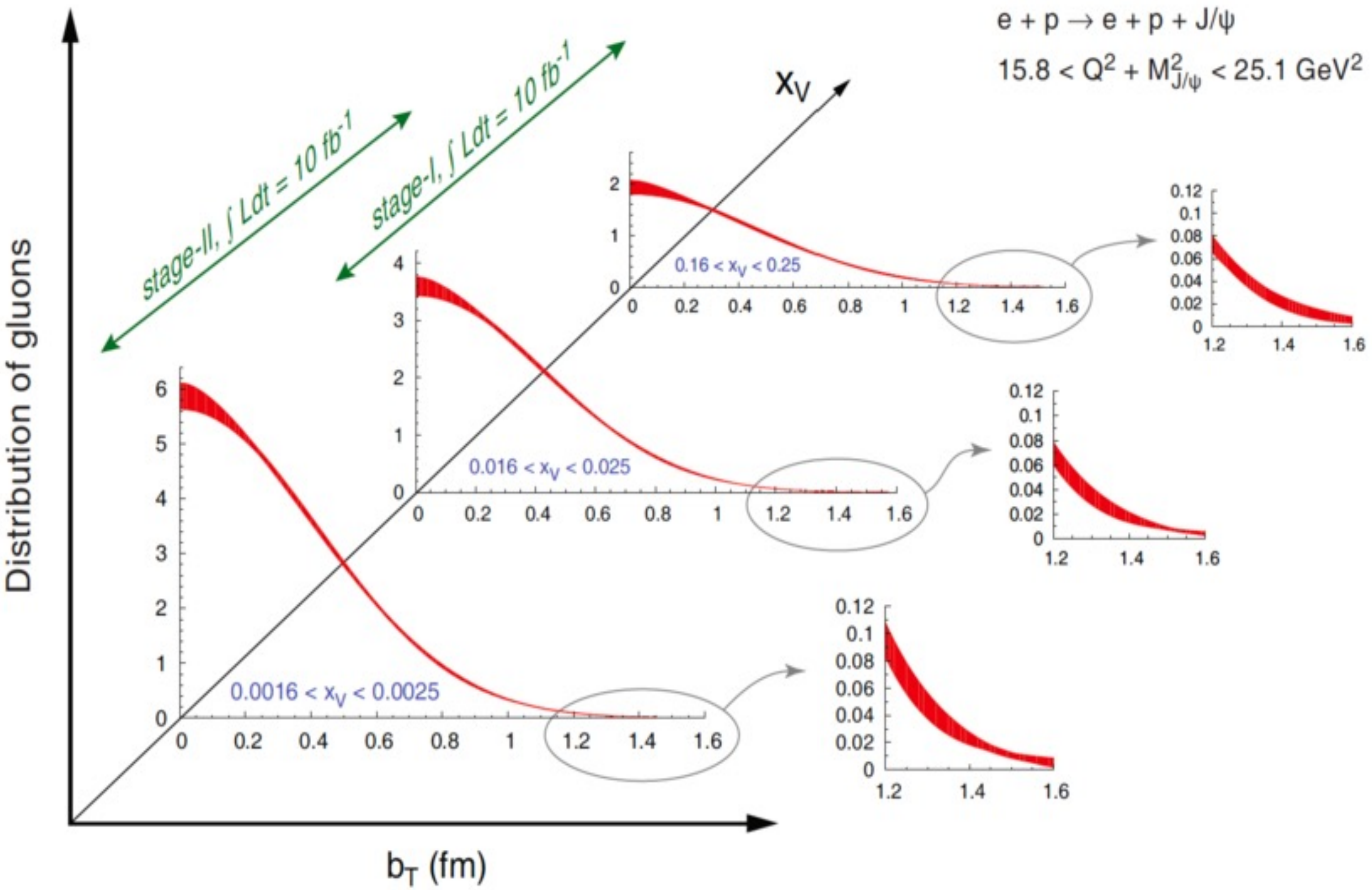


- 86% polarized 10.6 GeV beam
- Unpolarized LH_2 target

GPDs at the EIC



- Will access a unique kinematic space that is sensitive to gluons and sea quarks.
- GPD program is one of the most experimentally demanding at the EIC.
- Requires multi-dimensional binning over broad range of center-of-mass energies.
- Requires precision calorimetry to reconstruct scattered electron and photon.
- Requires careful design of the interaction region to allow for reconstruction of protons scattered at small forward angles.



Lets Take Stock

The quark helicity distribution is small – how small? Is it zero?

25% of the proton spin originates with the quarks (Q^2=10 GeV^2)
Note this is consistent with original EMC result $14 \pm 9 \pm 21\%$!
The up (down) quarks like to (anti) align with the spin of the proton.

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The strange quark helicity distribution in the proton is small, while the gluon is $\sim 40 \pm 10\%$ for x > 0.05 (Q^2=10 GeV^2). The error grows quickly to > 100% when lower x is included.

Where does the remainder of the proton spin reside? Gluon helicity? Strange quarks? Partonic orbital angular momentum?

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To date, only quantitative estimate of OAM comes from the remainder of the gluon and quark helicity distributions. Sivers asymmetries reflect significant flavor dependent OAM in the proton. GPDs provide access to quark OAM and gluon total angular momentum.

Lets Take Stock

The quark helicity distribution is small – how small? Is it zero?

25% of the proton spin originates with the quarks (@ Q^2=10 GeV^2)
Note this is consistent with original EMC result $14 \pm 9 \pm 21\%$!
The up (down) quarks like to (anti) align with the spin of the proton.

Where does the remainder of the proton spin reside? Gluon helicity? Strange quarks? Partonic orbital angular momentum?

The strange quark helicity distribution in the proton is small, while the gluon is $\sim 40 \pm 10\%$ for x > 0.05 (Q^2=10 GeV^2). The error grows quickly to > 100% when lower x is included.

To date, only quantitative estimate of OAM comes from the remainder of the gluon and quark helicity distributions. Sivers asymmetries reflect significant flavor dependent OAM in the proton. GPDs provide access to quark OAM and gluon total angular momentum.

What is the mechanism behind large meson transverse single spin asymmetries?

Multi-parton interactions! Depending on the observable, these interactions can be described either by transverse momentum or collinear higher twist distribution functions. TMDs, together with GPDs, are starting to give a 3D picture of how the quarks and gluons live inside the proton.

Where to next?

EIC

2030

FNAL SPINQUEST

2020

12 GeV Upgrade

2010

BNL RHIC

CERN COMPASS

2000

JLAB HALLS A,B,C

DESY HERMES

SLAC E142/143/154/155

1990

FNAL E581/704

CERN SMC

CERN EMC

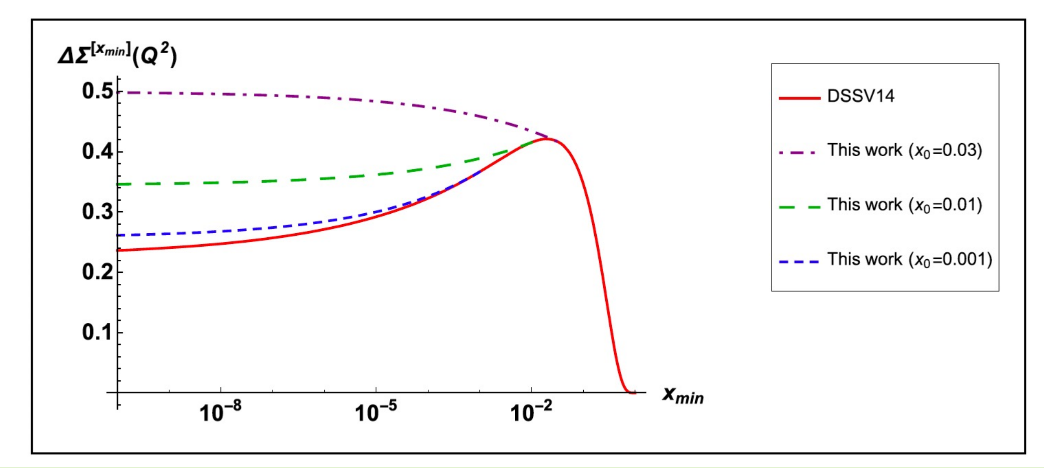
1980

SLAC E-130

SLAC E-80

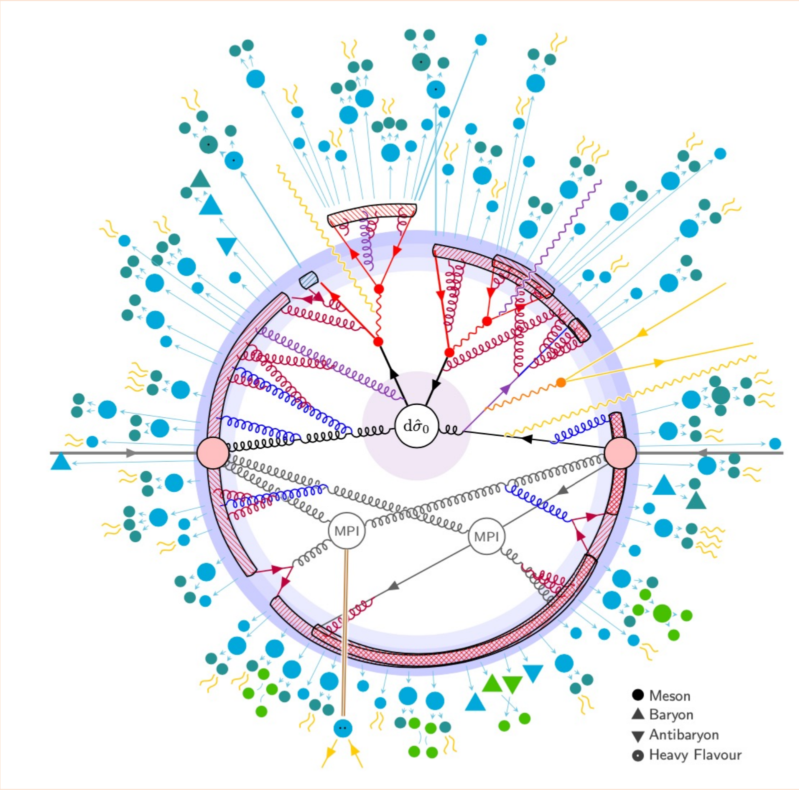
Where to next?

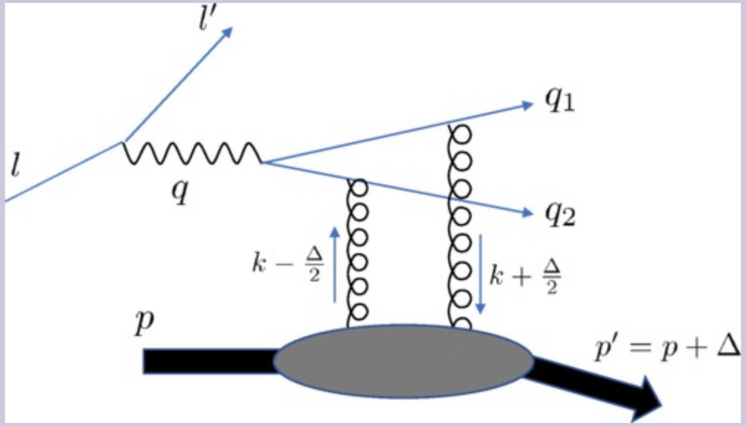
… a personal view



How does low-x evolution of $\Delta q, \Delta g$ change our picture of the proton? Test of the *polarized dipole amplitude* picture will be interesting! (*JHEP 01, 72*)

Using jets to study the spin dependence of the hadronization process, at RHIC and EIC. What can EEC teach us about the spin dependence in hadronization?
(2310.15159)

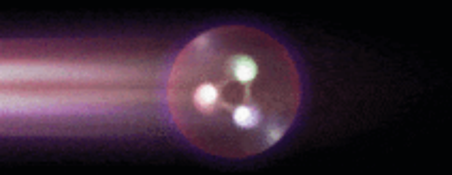




Various ways, in addition to GPDs, to probe orbital angular momentum. For example, exclusive dijet double spin asymmetries (*PRL 128, 182002*)

Postcard credit : CERN

Thank you!



RESOURCES

Emlyn Hughes' SLAC Summer School Lectures
Ed Kinney's SLAC Summer Institute slides
COMPASS slides from Barbara Badelek and Bakur Parsamyan
Mai Bai's CNFS Summer School slides

Ralf Seidl's EINN 2023 slides
Ishara Fernando's SPIN 2023 slides
Silvia Niccolai's SPIN 2023 slides
TMD Handbook arXiv : 2304.03302