Experimental Studies of Transverse Momentum Dependent Parton Distributions

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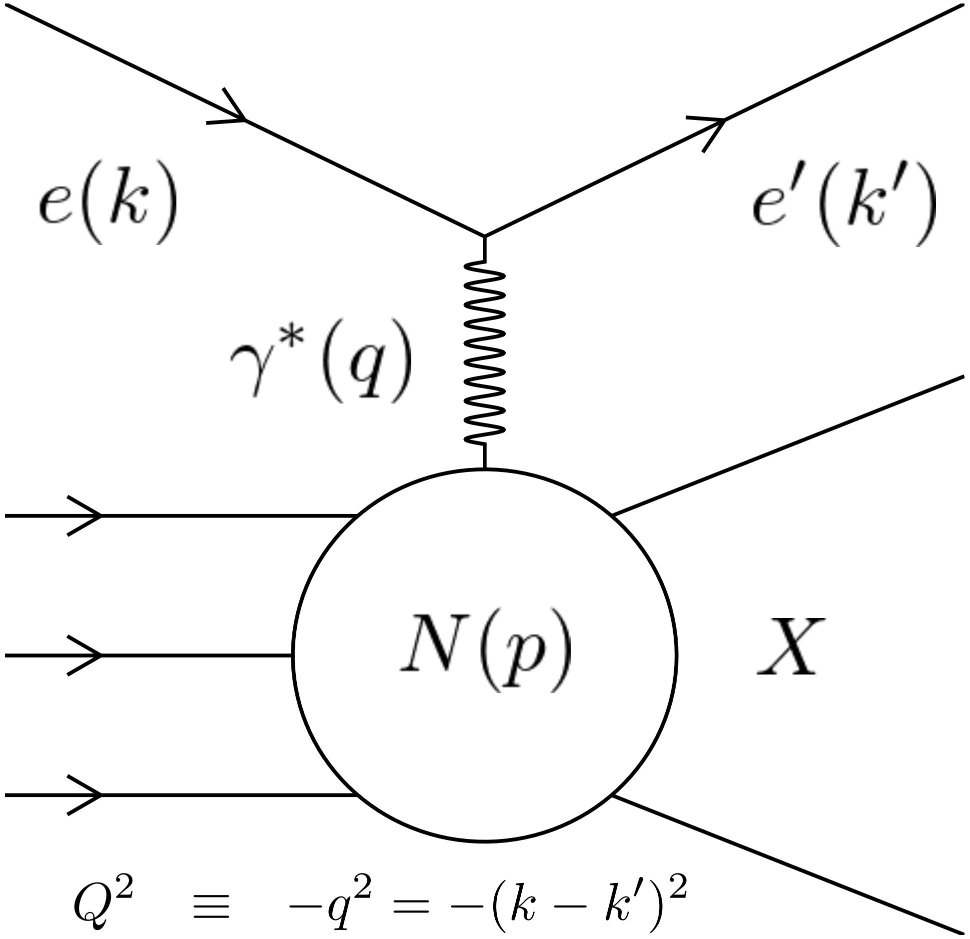
Outline

- Introduction: historical overview of lepton scattering for hadron structure
- Semi-Inclusive DIS and the TMD formalism for interpretation of SIDIS data
- Key results from previous experiments
- Selected highlights of the 12 GeV TMD/SIDIS program at CEBAF
- Future EIC
- Conclusions

Acknowledgements

- **Supported by the US Department of Energy, Office of Science, Office of Nuclear Physics, Award ID DE-SC0014230**
- This talk is a brief summary of a **huge** and growing field of research involving hundreds (if not thousands) of scientists; and I have necessarily left out a large number of recent and not-so-recent published results and ongoing efforts, both experimental and theoretical, given the time limit.
- I have intentionally chosen to emphasize/highlight the upcoming results of the JLab 12 GeV program, as it is currently underway and many experiments will take data and publish results over the next five years
- Special thanks to:
  - HERMES and COMPASS Collaborations
  - CLAS12, SBS, and SoLID Collaborations
  - The large group of outstanding theorists/phenomenologists working in this field, to develop the framework for global TMD extraction, Monte Carlo generators needed for analysis of upcoming data from JLab 12, future EIC, and elsewhere

Lepton-Nucleon Scattering in QED



$$Q^2 \equiv -q^2 = -(k-k')^2$$

Feynman diagram for electron-nucleon scattering in the one-photon-exchange (Born) approximation

$$\alpha_{em} = \frac{e^2}{4\pi\epsilon_0\hbar c} = \frac{1}{137.035999139(31)} \text{ (PDG)}$$

Why lepton scattering?

- Charged leptons (e.g., electrons) interact with the charged constituents of hadrons/nuclei predominantly via electromagnetic (EM) interaction (but also weak interaction).
- Electrons are point-like
- EM interaction is "weak"→low-order QED perturbation theory works well→"clean" theoretical interpretation
- EM interaction is well-described by the exchange of a single virtual photon of four-momentum q plus perturbatively calculable $\mathcal{O}(\alpha_{em})$ radiative corrections.
- One-photon-exchange approximation is analogous to impulse approximation in classical mechanics, Born approximation in non-relativistic QM
- The availability of high-quality electron beams w/ well-defined properties (energy, intensity, polarization, duty cycle, etc.) makes electron scattering a precision probe of nuclear structure

Electron-Nucleon Scattering: Kinematic Variables

Kinematic quantity definition	Description
$k^\mu \equiv (E_e, \boldsymbol{k}_e)$	Incident electron four-momentum
$k'^\mu \equiv (E'_e, \boldsymbol{k}'_e)$	Scattered electron four-momentum
$p^\mu \equiv (E_N, \boldsymbol{p}_N) \overset{lab}{\Longrightarrow} (M_N, \boldsymbol{0})$	Initial nucleon four-momentum
$q \equiv k - k' = (E_e - E'_e, \boldsymbol{k_e} - \boldsymbol{k'_e}) \equiv (\omega, \boldsymbol{q})$ $Q^2 \equiv -q^2 = -(k-k')^2 = 2k \cdot k' > 0$ $Q^2 = 2E_e E'_e(1 - \cos\theta_e) = 4E_e E'_e \sin^2\frac{\theta_e}{2}$	Four-momentum transfer: four-vector and Q^2 definition (note: electron mass neglected, $m_e \ll E_e, E'_e$)
$\nu \equiv \frac{p \cdot q}{M_N} \overset{lab}{\Longrightarrow} E_e - E'_e \equiv \omega$	Electron energy loss in the lab (nucleon rest) frame
$x \equiv \frac{Q^2}{2p \cdot q} \overset{lab}{\Longrightarrow} \frac{Q^2}{2M_N\nu}$	Bjorken "x" scaling variable ($0 \leq x \leq 1$)
$y \equiv \frac{p \cdot q}{p \cdot k} \overset{lab}{\Longrightarrow} \frac{\nu}{E_e}$	Electron fractional energy loss in lab (nucleon rest) frame
$W^2 \equiv (p+q)^2 = M_N^2 + 2M_N\nu - Q^2 = M_N^2 + Q^2\frac{1-x}{x}$	Virtual photon-nucleon invariant mass

R. Hofstadter
Nobel Prize 1961

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

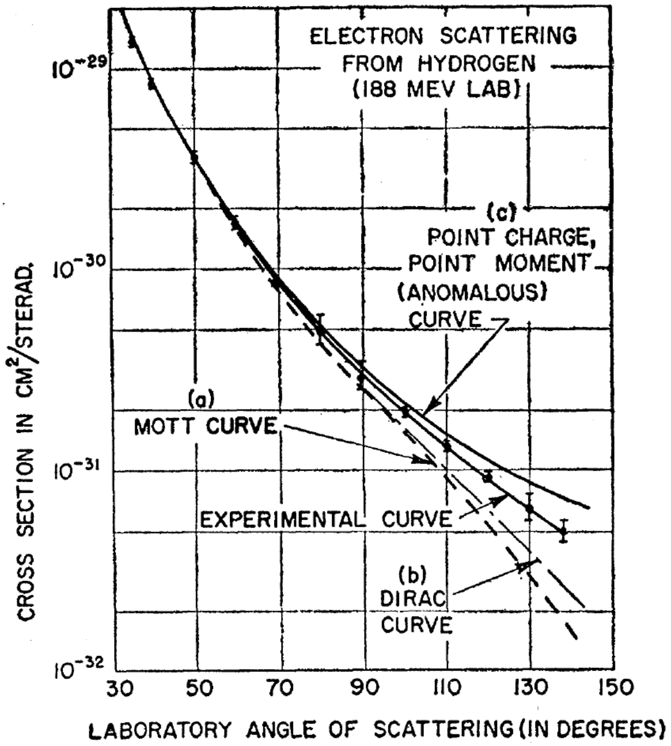
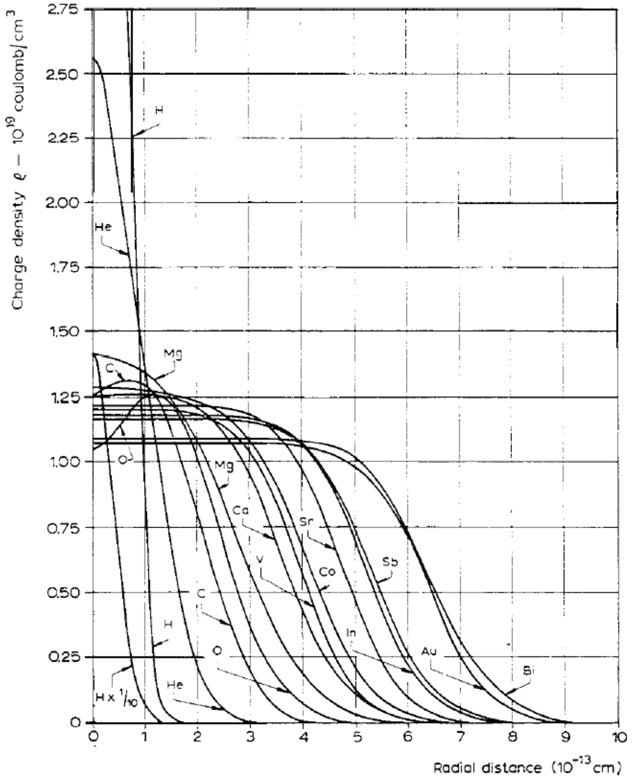


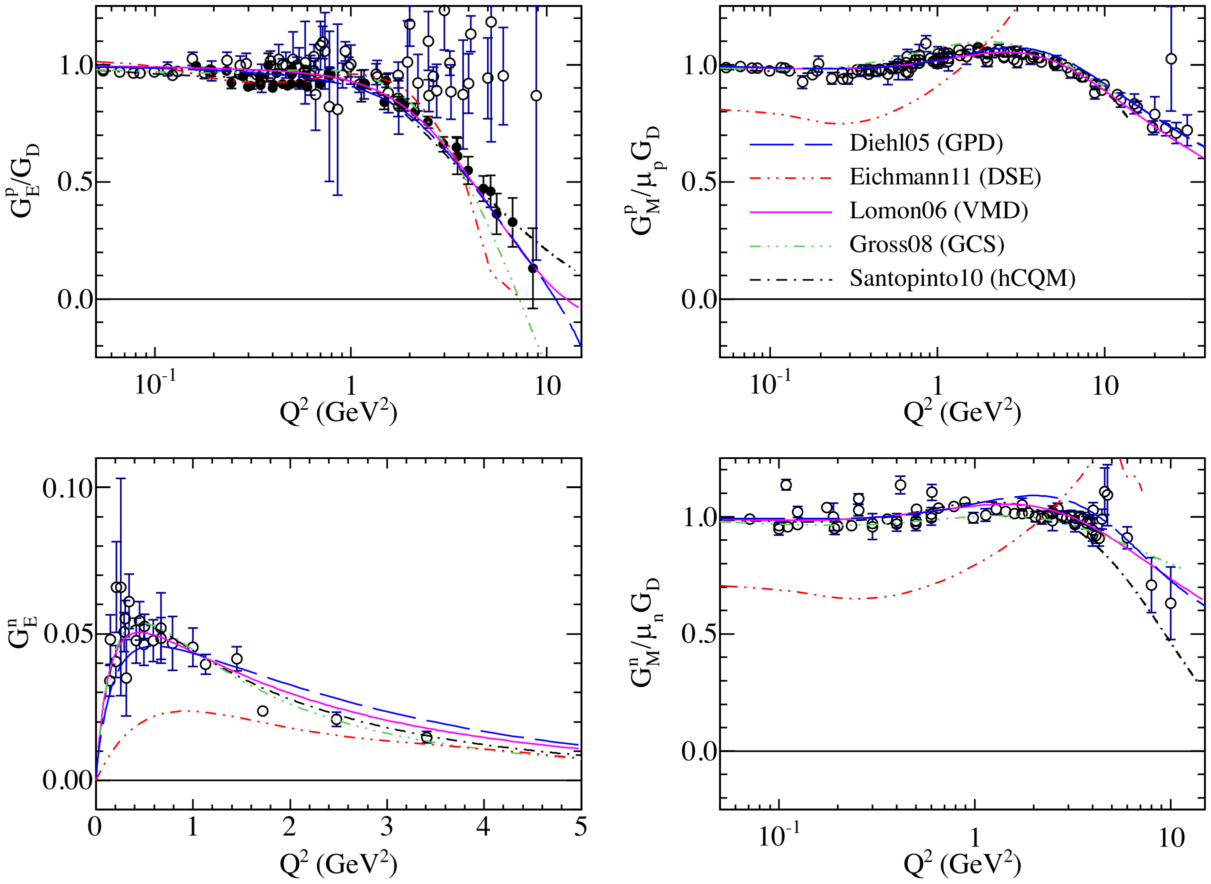
FIG. 24. Electron scattering from the proton at an incident energy of 188 Mev. The experimental points lie below the point-charge point-moment curve of Rosenbluth, indicating finite size effects.

R. Hofstadter, Rev. Mod. Phys., 28, 214 (1956)



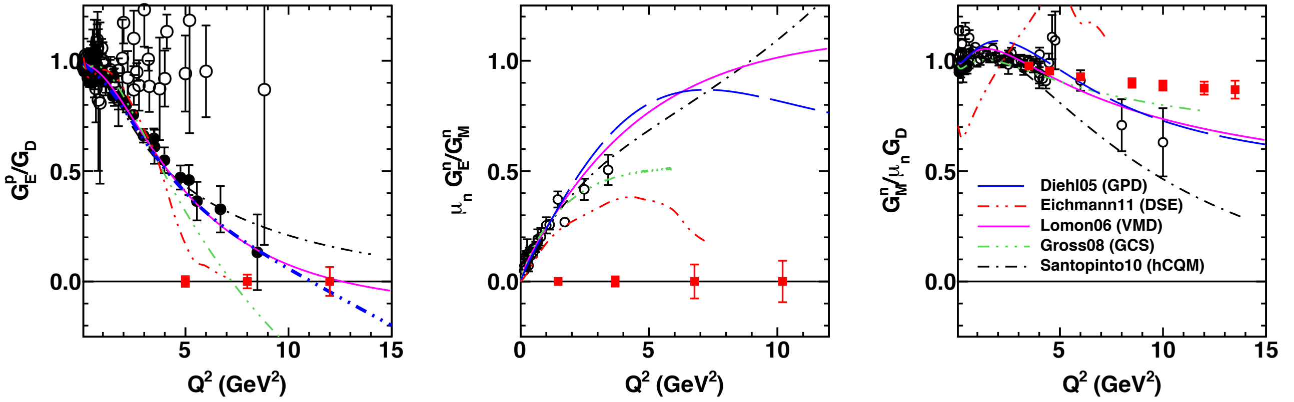
Above: (R. Hofstadter Nobel lecture): Nuclear charge densities as measured in electron scattering, within Fermi model of the shape

Elastic Scattering and Form Factors—Current and Future

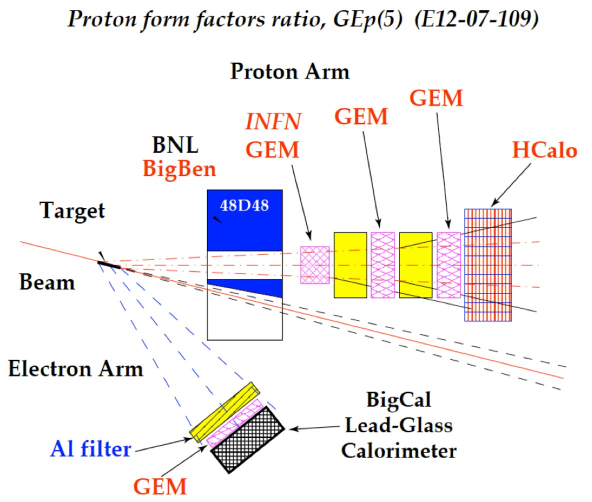


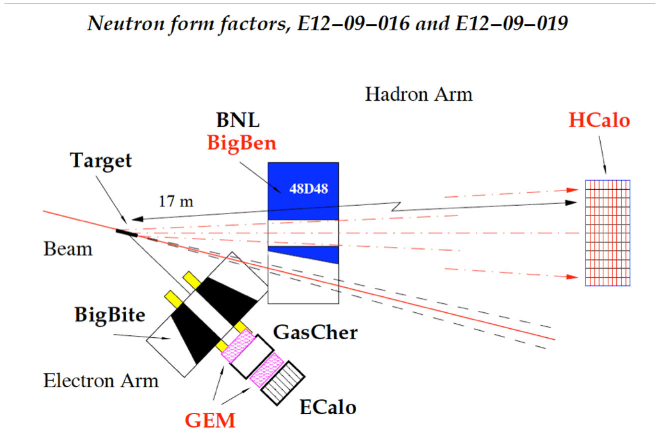
World data for G_{Ep}, G_{Mp}, G_{En}, G_{Mn} compared to selected theory/model calculations from **Puckett *et al.*, Phys. Rev. C, 85, 045203 (2012)**

$$G_D = \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-2}, \Lambda^2 = 0.71 \text{ GeV}^2$$

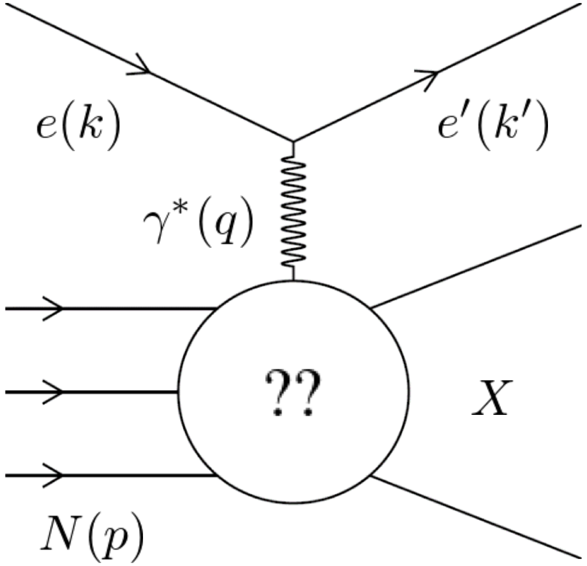


Above: Projected results from SBS Form Factor program (see P. Monaghan (CNU) talk in session R09 (Monday afternoon))





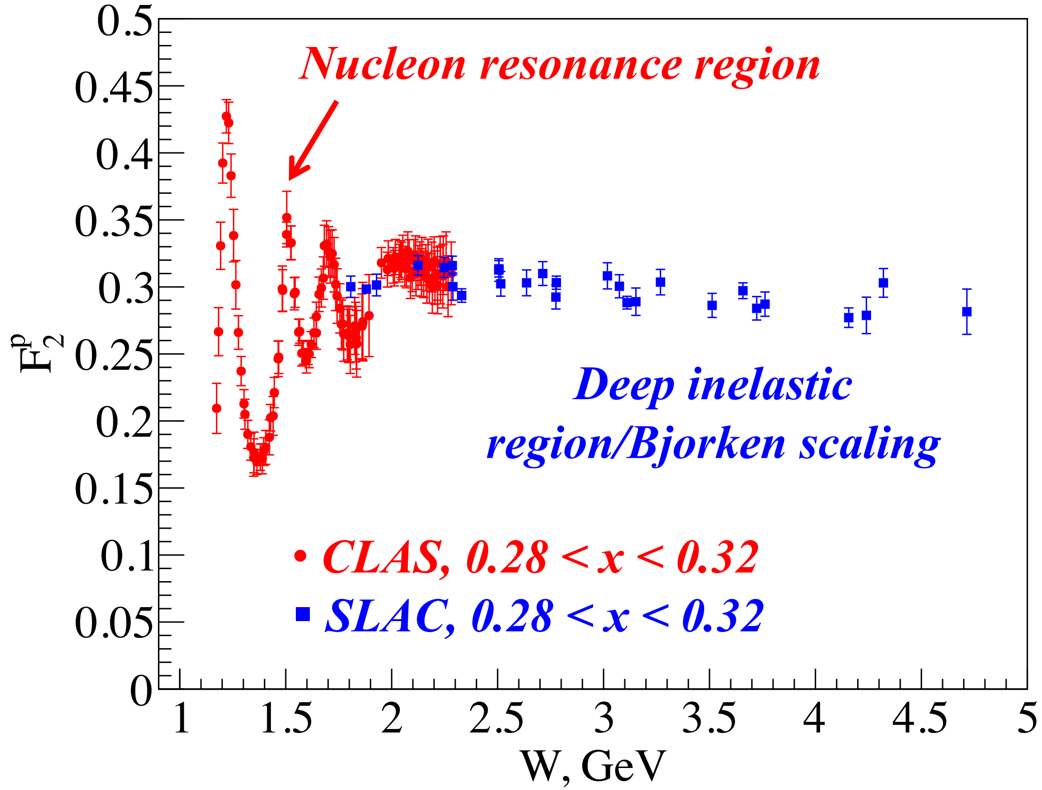
*In*elastic electron-nucleon scattering and Bjorken Scaling



$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y - \frac{M^2x^2y^2}{Q^2}\right)F_2(x,Q^2) + xy^2F_1(x,Q^2)\right]$$

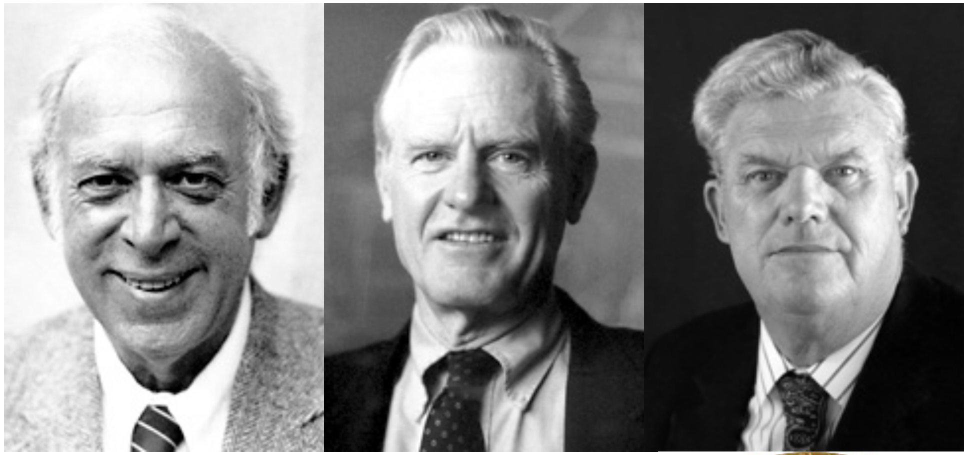
$$x = \frac{Q^2}{2p\cdot q}$$

$$W^2 = (p+q)^2 = M^2 + 2p\cdot q - Q^2$$
$$= M^2 + Q^2\frac{1-x}{x}$$



As Q^2/W^2 becomes "large" at fixed x, the proton structure functions exhibit the phenomenon of "scaling"—becoming independent of Q^2 for fixed "x"—this is called the ***"deep inelastic" (DIS)*** regime

Friedman, Kendall, Taylor, Nobel Prize 1990



"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

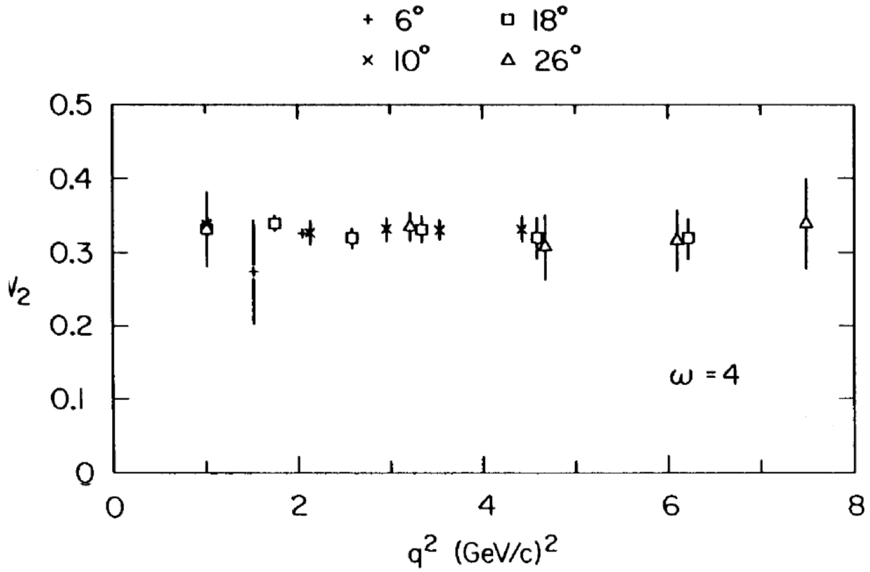


Fig. 13. An early observation of scaling: νW_2 for the proton as a function of q^2 for W > 2 GeV, at ω = 4.

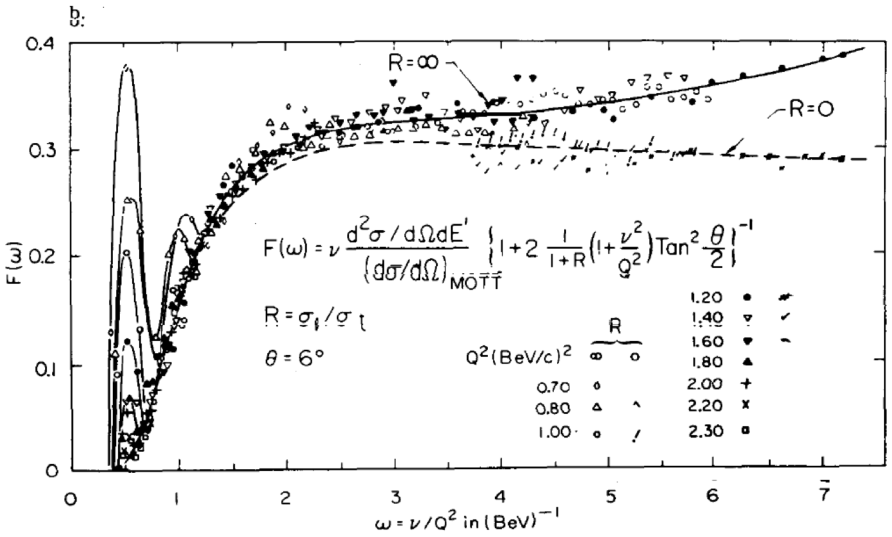
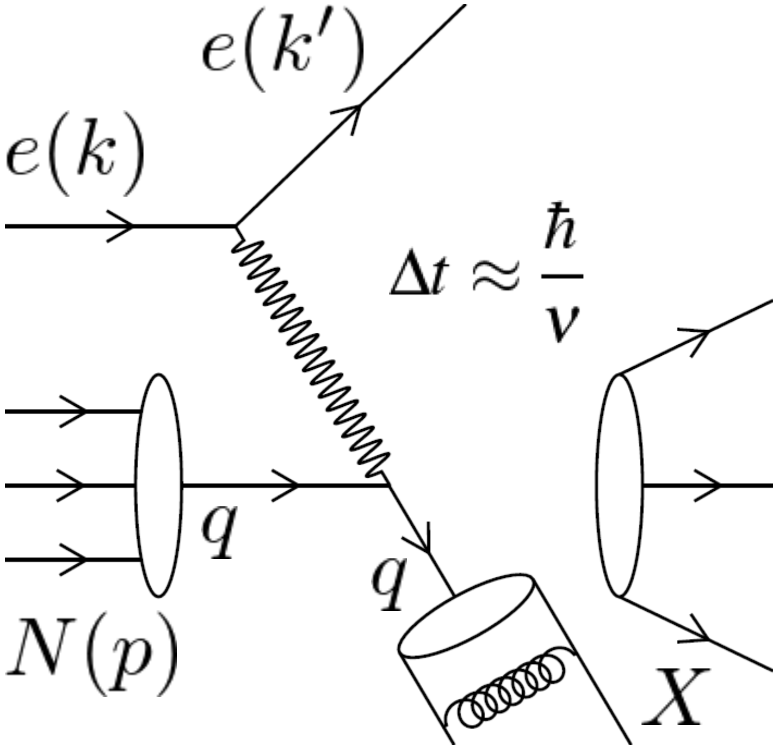


Fig. 12. **(a) The inelastic structure function $W_2(\nu,q^2)$ plotted against the electron energy loss ν.** (b) The quantity $F_1 = \nu W_2(\omega)$. The "nesting" of the data observed here was the first evidence of scaling. The figure is discussed further in the text.

Parton Model—The Physical Meaning of Bjorken Scaling



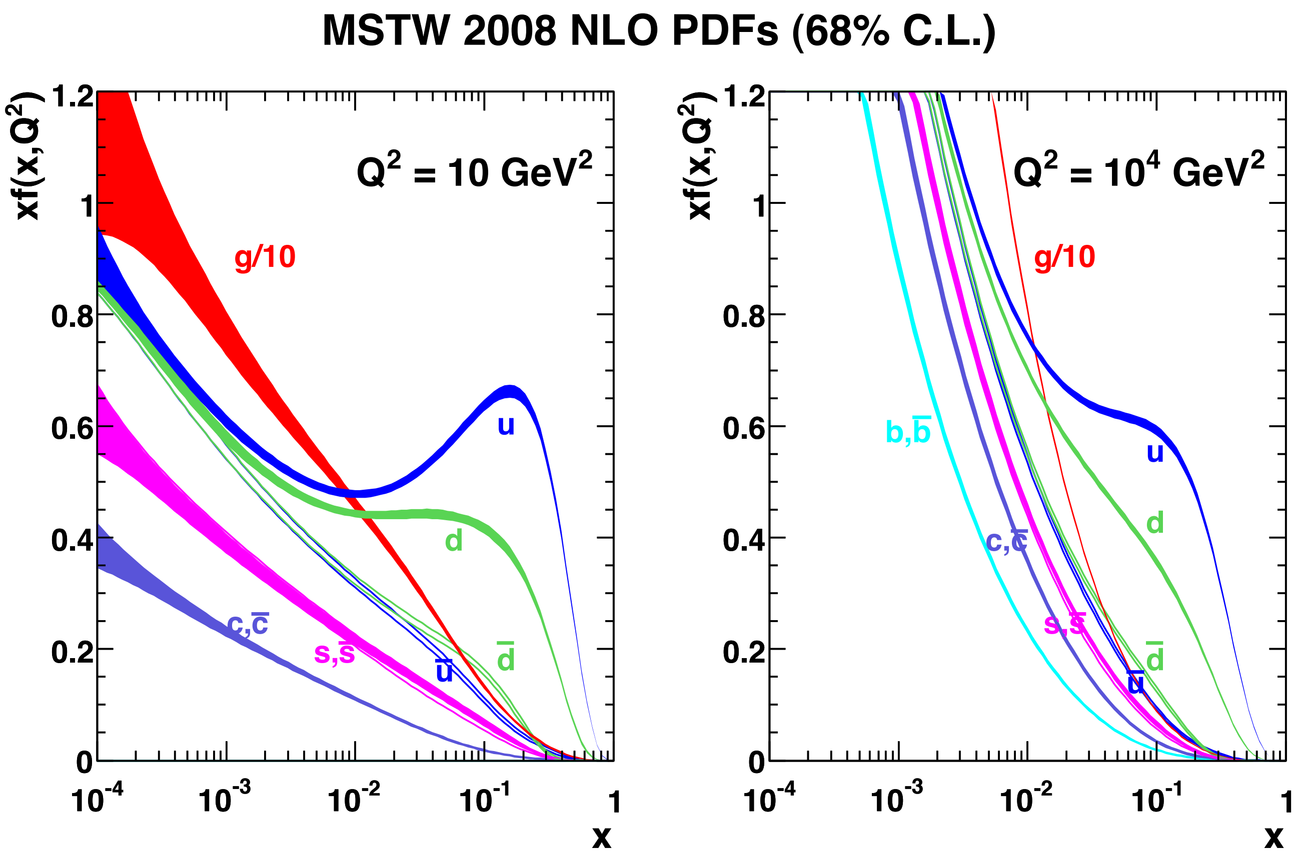
- In "hard" collisions ($\nu, Q^2 \to \infty$), the proton behaves approximately as a collection of quasi-free, non-interacting, fractionally charged, point-like spin-1/2 constituents moving collinearly with "infinite" momentum.
  - **In this limit, known as the "Bjorken limit"** ***inelastic*** **ep→eX behaves as** ***elastic*** **eq→eq**

- For elastic $eq \to eq$, we have $\frac{Q^2}{2p_q \cdot q} = 1$ due to four-momentum conservation and the relativistic energy-momentum relation.
- If $p_q = zp$, with p the initial nucleon momentum and $0 \le z \le 1$, then $x \equiv \frac{Q^2}{2p \cdot q} = \frac{zQ^2}{2p_q \cdot q} = z$, meaning that in the Bjorken limit, the observable kinematic quantity x in DIS is equivalent to the fraction of the nucleon momentum carried by the struck quark:

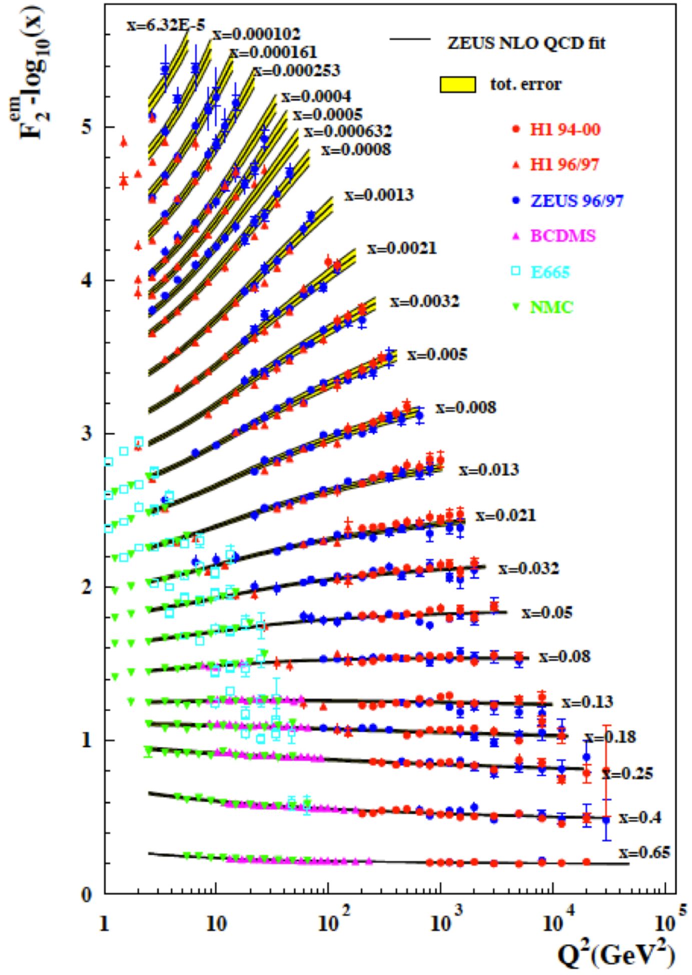
$$
\begin{aligned}
(F_2)_{eq\to eq} &= \delta\left(1-\frac{x}{z}\right) = x\delta(z-x) \\
(F_1)_{eq\to eq} &= \frac{1}{2x}\delta\left(1-\frac{x}{z}\right) = \frac{F_2}{2x} \\
F_{1,2}^{ep\to eX} &= \sum_i e_i^2 \int_0^1 dz q_i(z) F_{1,2}^{eq_i\to eq_i} \\
F_2^{ep}(x) &= 2xF_1^{ep}(x) = x\sum_i e_i^2 q_i(x)
\end{aligned}
$$

- The x dependence of the $ep \to eX$ structure function measures the *universal* longitudinal momentum distribution of the "partons" (quarks)
- ***Structure functions become Q^2-independent (for fixed x) due to energy-momentum conservation***
- ***Callan-Gross relation:*** **$F_2 = 2x\, F_1$ (consequence of partons having spin-1/2)**

Parton Distribution Functions



MSTW2008 NLO PDFs:
arXiv:0901.0002v3



HERA F_2^p
arXiv:hep-ex/0211051v1

- DIS structure functions for proton, deuteron mapped 5 orders of magnitude in x, Q^2
- Triumph of pQCD—description of scaling violations (Q^2 evolution)

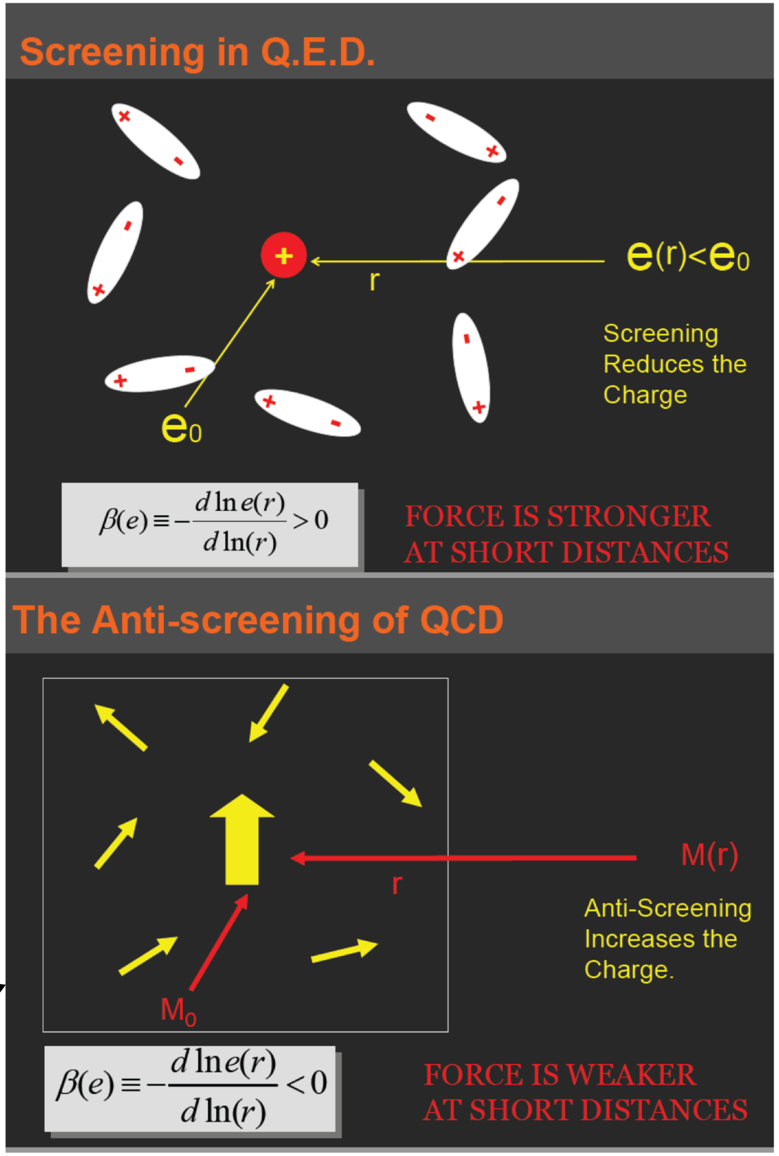
Gross, Politzer and Wilczek: Nobel Prize 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction".

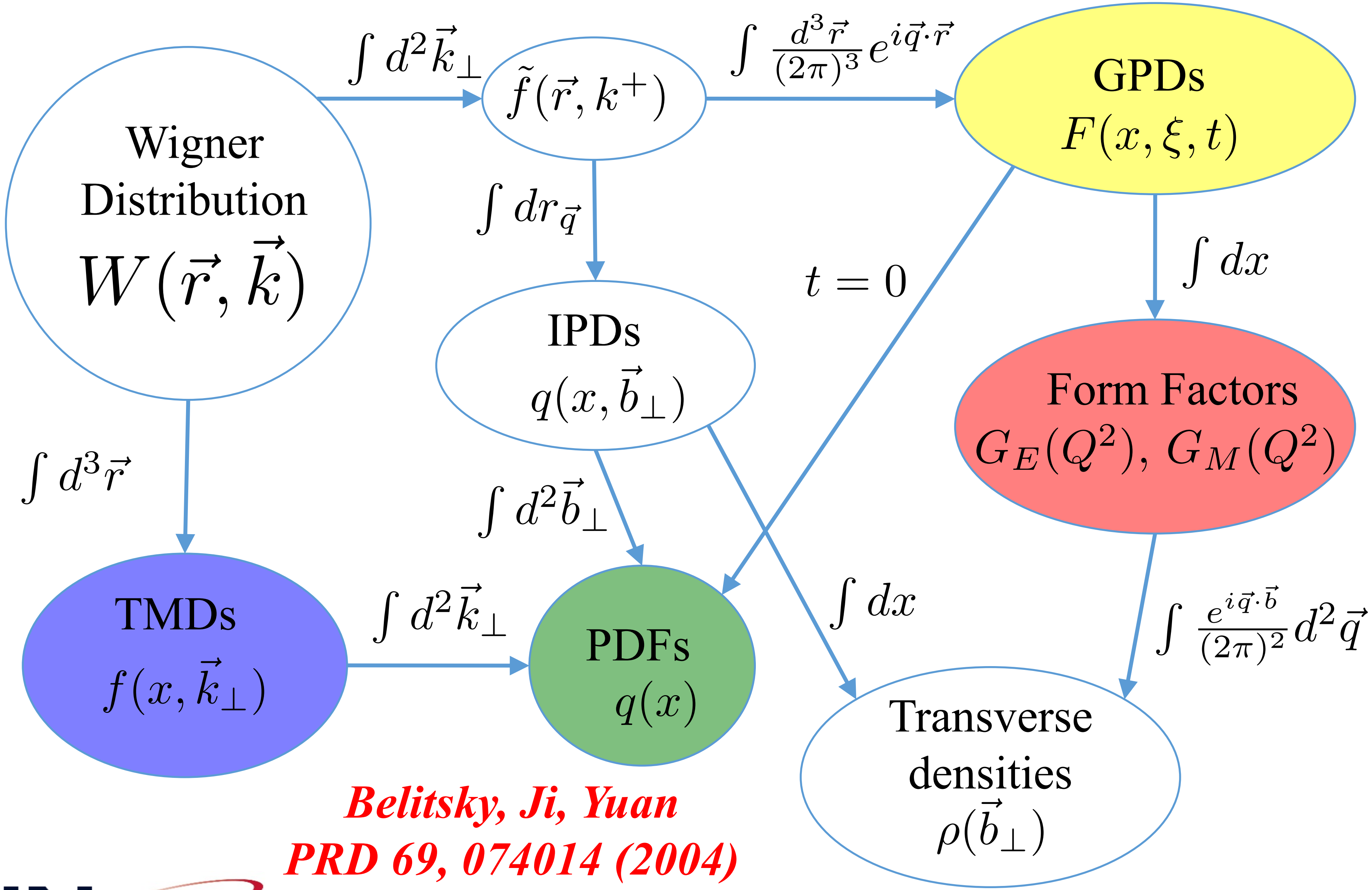
$$\beta(g) = -\frac{g^3}{16\pi^2}\left(\frac{11}{3}N_C - \frac{4}{3}\frac{N_F}{2}\right)$$

$$\beta < 0 \quad \Rightarrow \quad \alpha(\mu) \xrightarrow[\mu\to\infty]{} 0$$

Slides from D. Gross Nobel Lecture

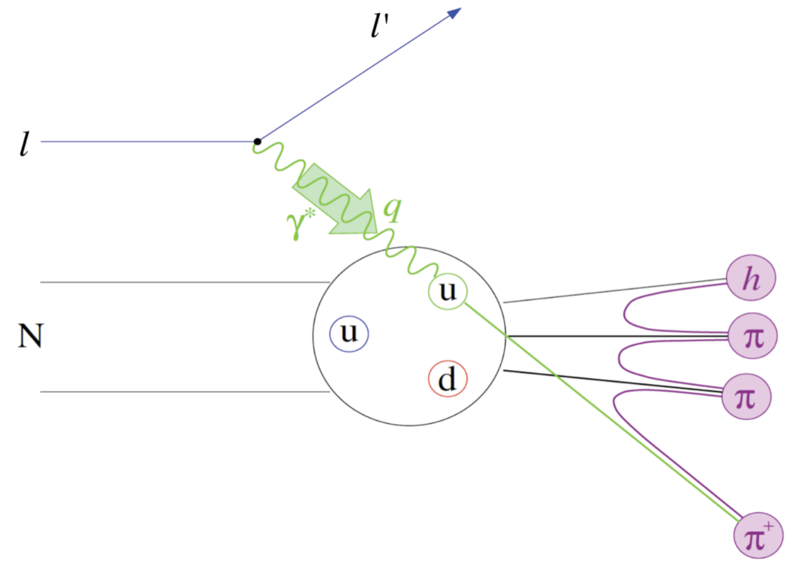


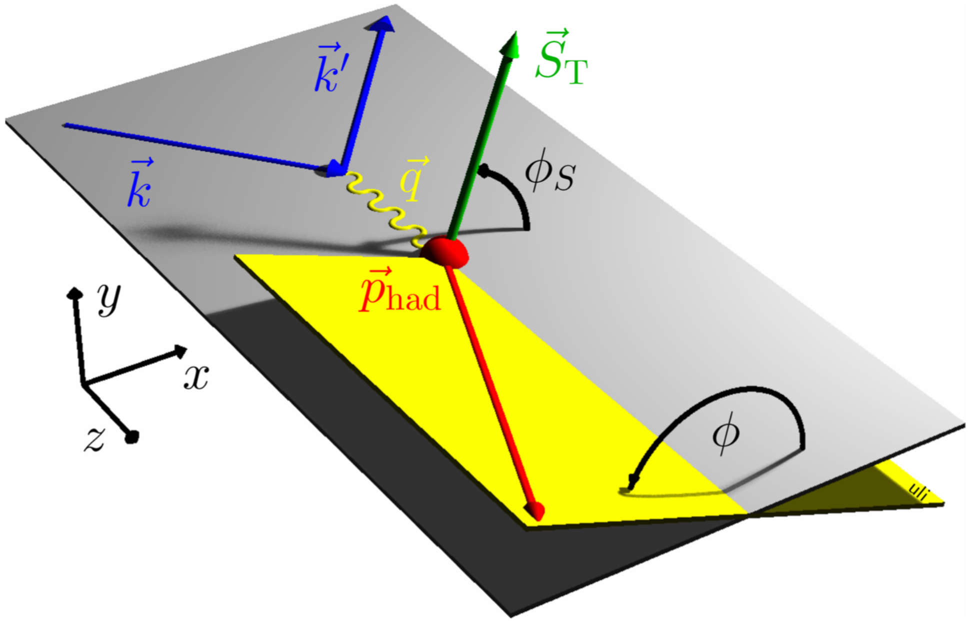
The Modern, Unified Description of Nucleon Structure (Schematically)



Belitsky, Ji, Yuan
PRD 69, 074014 (2004)

Semi-Inclusive Deep Inelastic Scattering





Additional Kinematic Variables for SIDIS	Description
$z \equiv \frac{p_h \cdot p}{q \cdot p} \overset{lab}{\Longrightarrow} \frac{E_h}{\nu}$	Fraction of virtual photon energy carried by observed hadron
$p_T \equiv \boldsymbol{p}_h - \frac{\boldsymbol{p}_h \cdot \boldsymbol{q}}{\lvert\boldsymbol{q}\rvert^2}\boldsymbol{q}$	Transverse momentum of observed hadron relative to momentum transfer direction
ϕ_h	Azimuthal angle between lepton scattering and hadron production planes
ϕ_S	Azimuthal angle between (transverse component of) target spin and lepton scattering plane
$M_X^2 \equiv (p + q - p_h)^2$	Missing mass of unobserved final state particles

• The single-hadron SIDIS process N(e,e'h)X, in which leading (high-energy) hadrons are detected at "small" finite transverse momentum in DIS collisions provides access to additional aspects of nucleon structure that are inaccessible in DIS:

- quark flavor
- quark transverse motion
- quark transverse spin

• ***Goal of SIDIS studies is (spin-correlated) 3D imaging of quarks in momentum space.***

• Transverse Momentum Dependent (TMD) PDF approach: ***Bacchetta et al. JHEP 02 (2007) 093, Boer and Mulders, PRD 57, 5780 (1998), etc.***

General Expression for SIDIS Cross Section at twist 3: *Bacchetta et al., JHEP 02, 093 (2007)*

$$
\begin{aligned}
\frac{d\sigma}{dxdydzd\phi_h d\phi_S dp_T^2} &= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{\boxed{F_{UU,T}} + \epsilon F_{UU,L} + \\
&\sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \boxed{\epsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}} + \\
&\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} + \\
&S_\parallel\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \boxed{\epsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}}\right] + \\
&S_\parallel\lambda_e\left[\boxed{\sqrt{1-\epsilon^2}F_{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right] + \\
&S_\perp\Bigg[\boxed{\sin(\phi_h-\phi_S)F_{UT}^{\sin(\phi_h-\phi_S)}} \\
&\boxed{\epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}} + \\
&\boxed{\epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}} \\
&\sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\right)\Bigg] + \\
&S_\perp\lambda_e\Bigg[\boxed{\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}} + \\
&\sqrt{2\epsilon(1-\epsilon)}\left(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\right)\Bigg]\Bigg\}
\end{aligned}
$$

- Sivers
- Collins
- “Pretzelosity”

- SIDIS structure functions depend on x, Q^2, z, p_T
- U, L, T subscripts indicate unpolarized, longitudinally and transversely polarized beam, target, respectively
- S = nucleon spin
- λ = lepton helicity
- **Eight terms survive at leading twist; the rest are twist-3 (M/Q suppressed)**
- Azimuthal angle dependence caused by spin-orbit effects.
- All leading-twist TMDs can be separately extracted from the azimuthal modulations of SIDIS cross section with polarized beam (longitudinal) and polarized target (longitudinal and transverse)

$$
\boxed{\begin{aligned}
\gamma &= \frac{2Mx}{Q} \\
\epsilon &= \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}
\end{aligned}}
$$

Parton Model Interpretation of SIDIS: Transverse Momentum Dependent PDFs (TMDs)

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^{\perp} =$ -
	L		$g_1 =$ -	$h_{1L}^{\perp} =$ -
	T	$f_{1T}^{\perp} =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^{\perp} =$ -

- Only f_1, g_1, h_1 survive integration over quark k_T
- Physical observables are convolutions over two (unobserved) transverse momenta:
    - Initial quark k_T
    - Hadron p_T relative to recoiling quark, generated during fragmentation
- Unambiguous extraction of TMD PDFs from SIDIS data also requires input from e^+/e^- annihilation experiments to constrain quark → hadron fragmentation functions!

$$
\begin{aligned}
F_{UU,T} &\sim f_1 \otimes D_1 \\
F_{UU}^{\cos 2\phi_h} &\sim h_1^{\perp} \otimes H_1^{\perp} \\
F_{UL}^{\sin 2\phi_h} &\sim h_{1L}^{\perp} \otimes H_1^{\perp} \\
F_{LL} &\sim g_1 \otimes D_1 \\
F_{UT}^{\sin(\phi_h - \phi_S)} &\sim f_{1T}^{\perp} \otimes D_1 \\
F_{UT}^{\sin(\phi_h + \phi_S)} &\sim h_1 \otimes H_1^{\perp} \\
F_{UT}^{\sin(3\phi_h - \phi_S)} &\sim h_{1T}^{\perp} \otimes H_1^{\perp} \\
F_{LT}^{\cos(\phi_h - \phi_S)} &\sim g_{1T} \otimes D_1
\end{aligned}
$$

$$
\begin{aligned}
D_1(z, Q^2, p_\perp^2) &= \text{Unpolarized TMD FF} \\
H_1^{\perp}(z, Q^2, p_\perp^2) &= \text{Collins TMD FF}
\end{aligned}
$$

Kinematic Conditions for applicability of TMD formalism

- Requires large Q^2 ($Q^2 > 1\ GeV^2$), large W ($W > 2\ GeV$), as in DIS
- Requires large (but not too large) z:
  - High enough for dominance of "current quark" fragmentation over "target remnant" fragmentation
  - Low enough to avoid dominance of exclusive/resonance region contributions
- Requires small (but not too small) p_T:
  - Large enough for meaningful sensitivity to effects of quark transverse motion/spin: $k_\perp \approx \Lambda_{QCD} \approx 200\ MeV$
  - Small enough for applicability of TMD formalism; i.e., dominance of TMD effects over pQCD effects (gluon radiation, etc.)

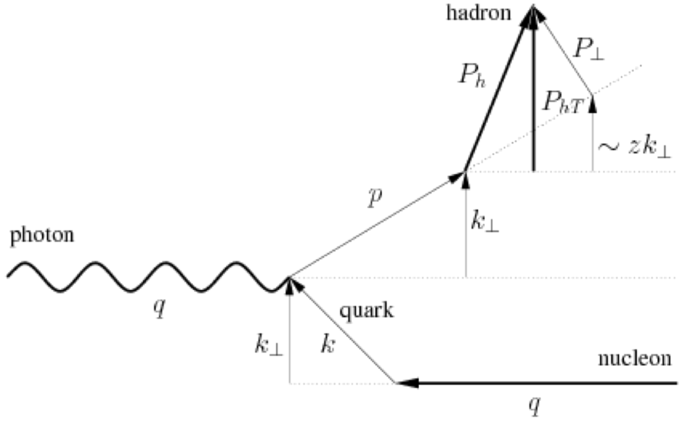


Figure credit: Bacchetta *et al.*, JHEP 1706 (2017) 081

At leading order in $k_\perp/Q$, we have:

$$\mathbf{P}_{hT} \approx z\mathbf{k}_\perp + \mathbf{P}_\perp$$

- Experimentalist's/phenomenologist's rule of thumb: $$\frac{|\mathbf{P}_{hT}|}{z} \ll Q$$
- For JLab-12 GeV: $0.3 \leq z \leq 0.7$ for pions; more restricted range for charged kaons, due to hadron mass/target fragmentation.

General Challenges of Measuring TMD-sensitive Observables

Statistics Requirements

Cross sections:

$$\sigma \propto N$$

$$\frac{\Delta\sigma}{\sigma} = \frac{1}{\sqrt{N}}$$

To measure a scattering cross section with a relative statistical precision of 1%, you need 10,000 events.

Asymmetries:

$$\Delta A = \sqrt{\frac{1 - A^2}{N}}$$

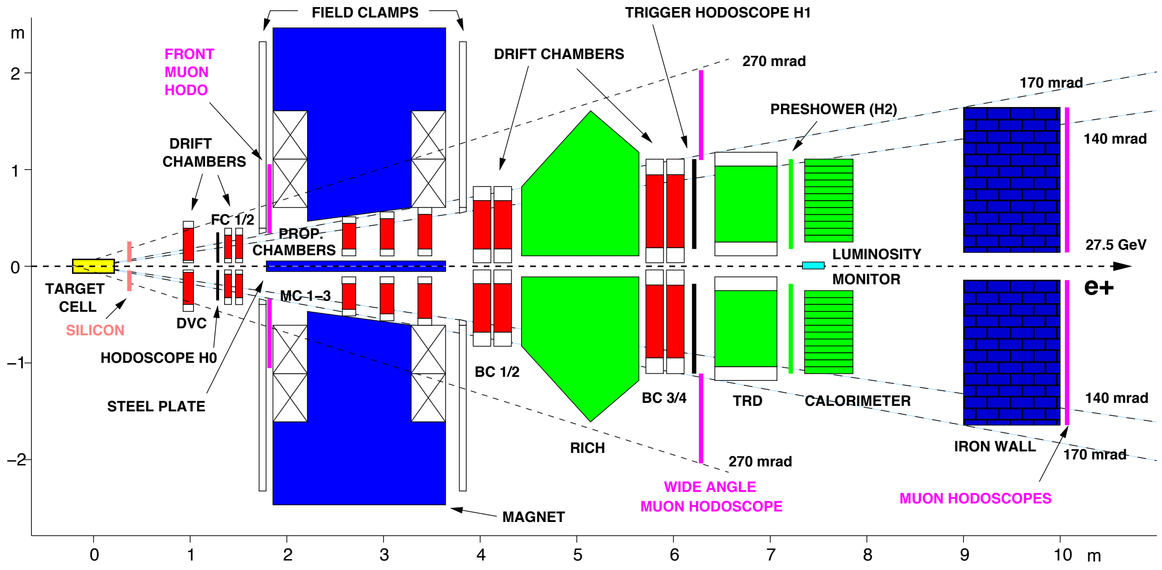
$$\frac{\Delta A}{A} = \sqrt{\frac{1 - A^2}{NA^2}}$$

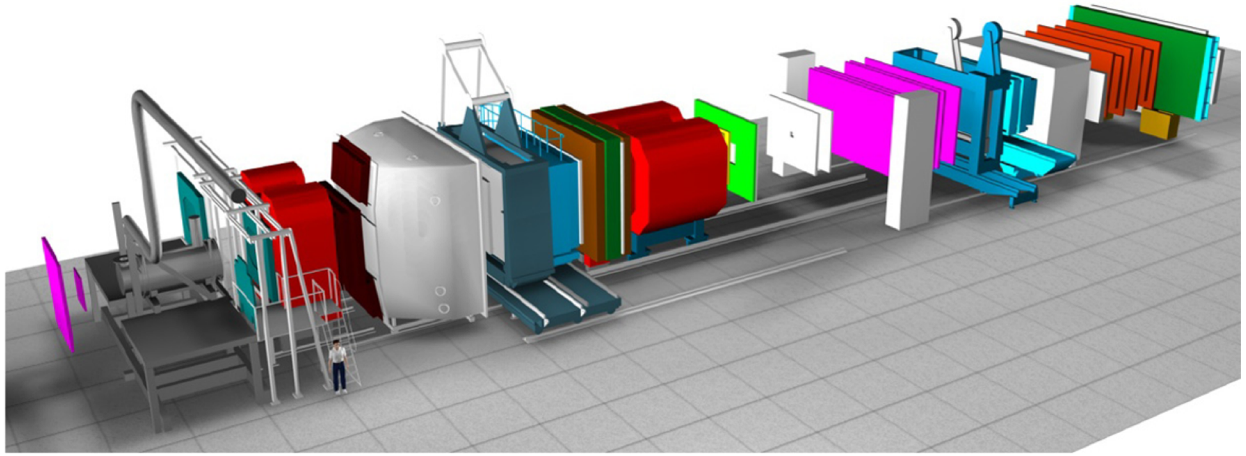
On the other hand, to measure an asymmetry A with a relative precision of 1%, you need $N = 10{,}000 \times \frac{1-A^2}{A^2}$.

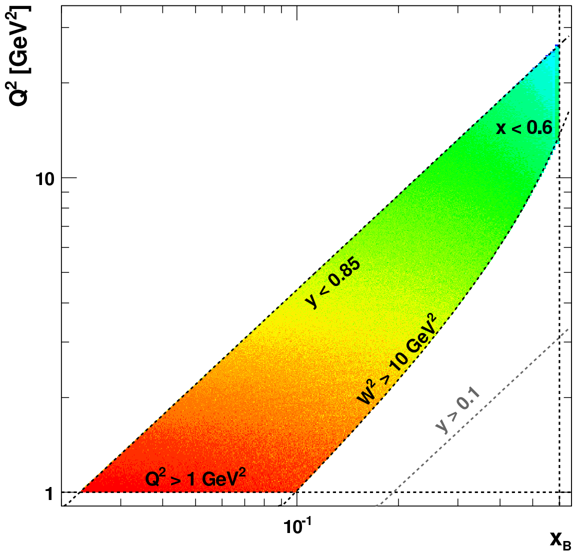
For example, if $A = 5\%, N = 4 \times 10^6$!

- SIDIS structure functions, *before* considering azimuthal angle dependence, are functions on a 4-D phase space (x, Q^2, z, p_T)
- Sufficiently high ***energy*** is needed to access this phase space
- Large ***acceptance*** is required to cover this phase space and unambiguously separate azimuthal modulations
- High ***luminosity*** is required to achieve reasonable statistical precision, especially for 4-D analysis
- High beam and/or target ***polarization*** is required for spin-dependent observables: FOM is ***luminosity*** × ***polarization***^{2}
- **Interpretability requires large Q^2**
  - Large Q^2 implies high *x* in fixed-target experiments (even in collider kinematics, Q^2 and *x* acceptances are correlated). DIS event rate typically falls ~exponentially with *x* in the valence region
- TMDs and nucleon spin structure are among the major goals of the future Electron-Ion-Collider (EIC).

HERMES@DESY and COMPASS@CERN Experiments

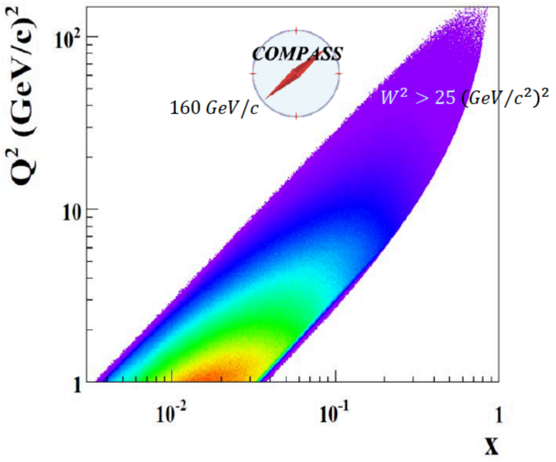






HERMES@DESY

- 27.5 GeV stored e^+ and e^- beams on polarized and unpolarized, isotopically pure internal gas H (and D) targets
- Luminosity (lepton-nucleon): $\sim 10^{31} - 10^{33}\ cm^{-2}\ s^{-1}$
- Data collection in various iterations from 1995-2007



COMPASS@CERN

- SIDIS program: 160 GeV polarized muon beam produced using CERN SPS on polarized ^{6}LiD and NH_3 targets (and also unpolarized LH_2, LD_2, etc.)
- Average luminosity (lepton-nucleon): $\approx 2{\times}10^{32}\ cm^{-2}s^{-1}$
- SIDIS running 2002-2007, 2010-2011, 2016-2017 (parasitic with dedicated DVCS run)
- Pion-induced Drell Yan 2015, 2018+
- More deuteron SIDIS 2021

Key Results of HERMES and COMPASS—Discovery of non-zero Collins and Sivers Effects

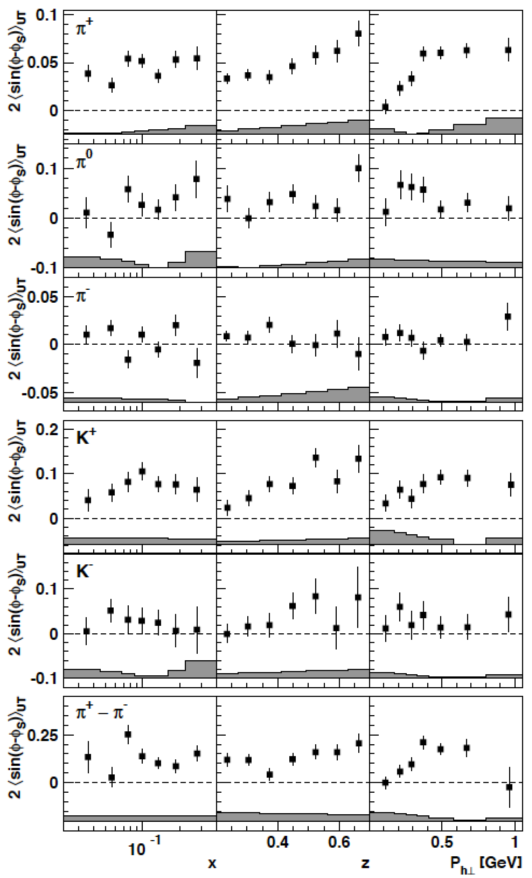


FIG. 1: Sivers amplitudes for pions, charged kaons, and the pion-difference asymmetry (as denoted in the panels) as functions of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the target-polarization measurement.

HERMES Sivers Results: Phys. Rev. Lett. 103 (2009) 152002

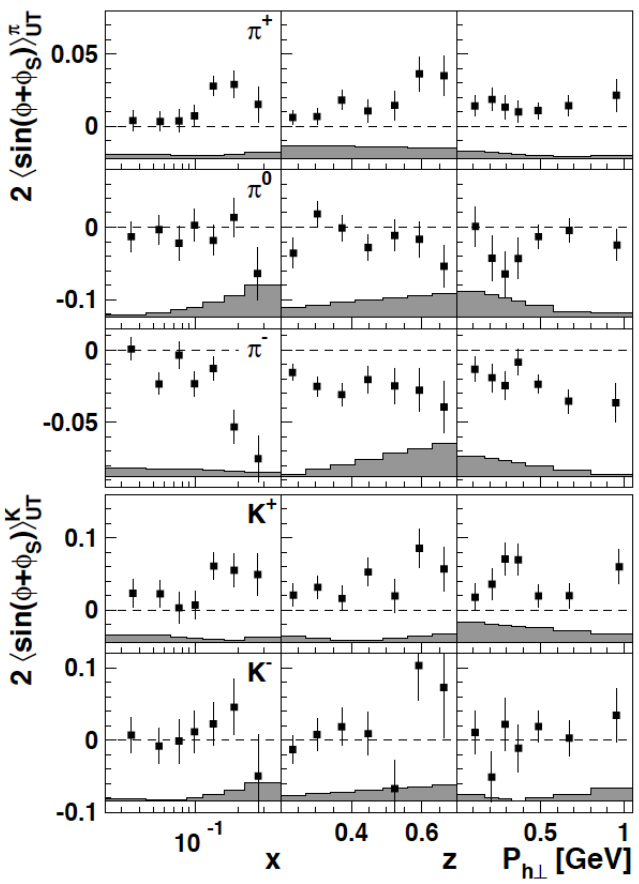


Fig. 2. Collins amplitudes for pions and charged kaons as a function of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the accuracy in the measurement of the target polarization.

HERMES Collins Results: Phys. Lett. B 693 (2010) 11-16

- Right: COMPASS proton Collins and Sivers asymmetries for identified hadrons: Phys.Lett. B744 (2015) 250-259
- See also: COMPASS deuteron target data for Collins and Sivers asymmetries

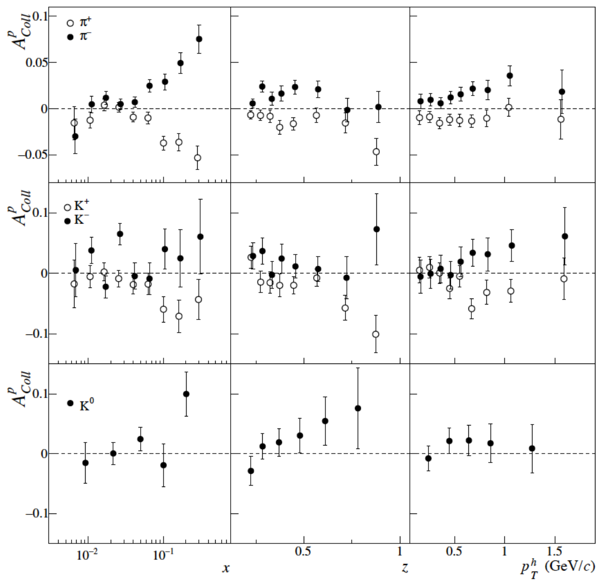


Fig. 6: The Collins asymmetries for charged pions (top), charged kaons (middle) and neutral kaons (bottom) on proton as a function of x, z and p^h_T.

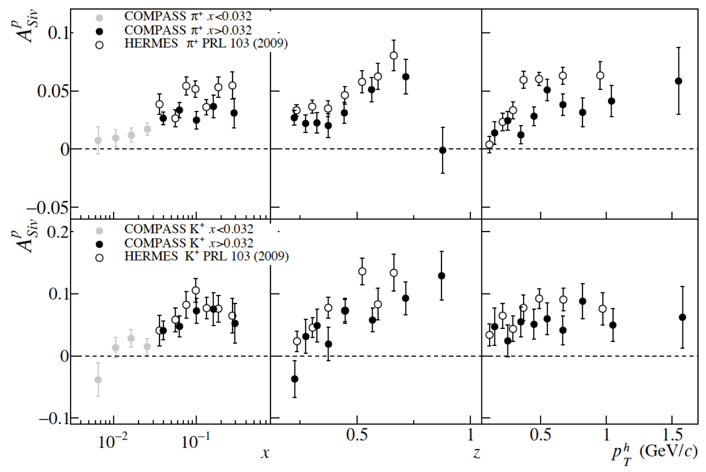


Fig. 11: The Sivers asymmetries for positive pions (top) and kaons (bottom) on proton as a function of x, z and p^h_T, requiring $x > 0.032$. The asymmetries are compared to HERMES results.

Unpolarized TMD global fitting—Pavia 2017

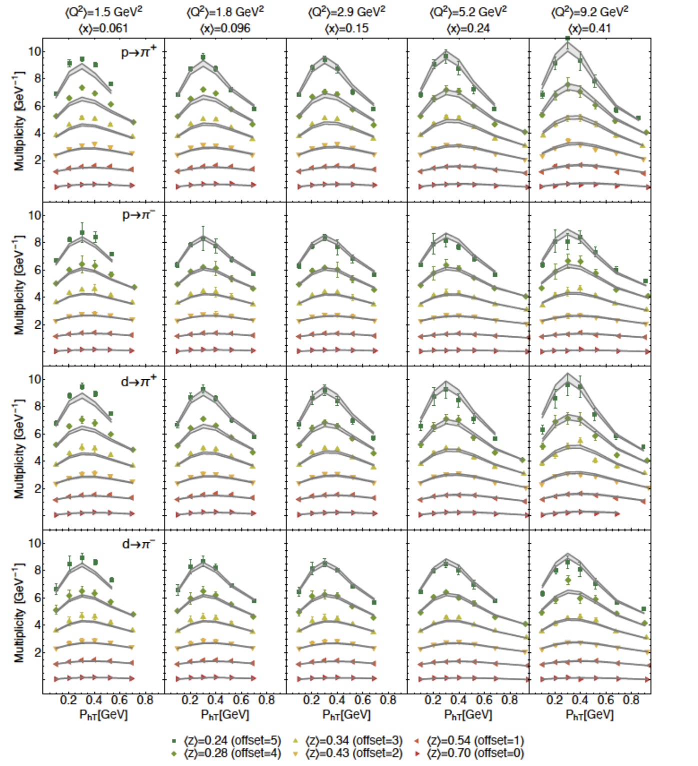


FIG. 3: HERMES multiplicities for production of pions off a proton and a deuteron for different $\langle x\rangle$, $\langle z\rangle$, and $\langle Q^2\rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. For clarity, each $\langle z\rangle$ bin has been shifted by an offset indicated in the legend.

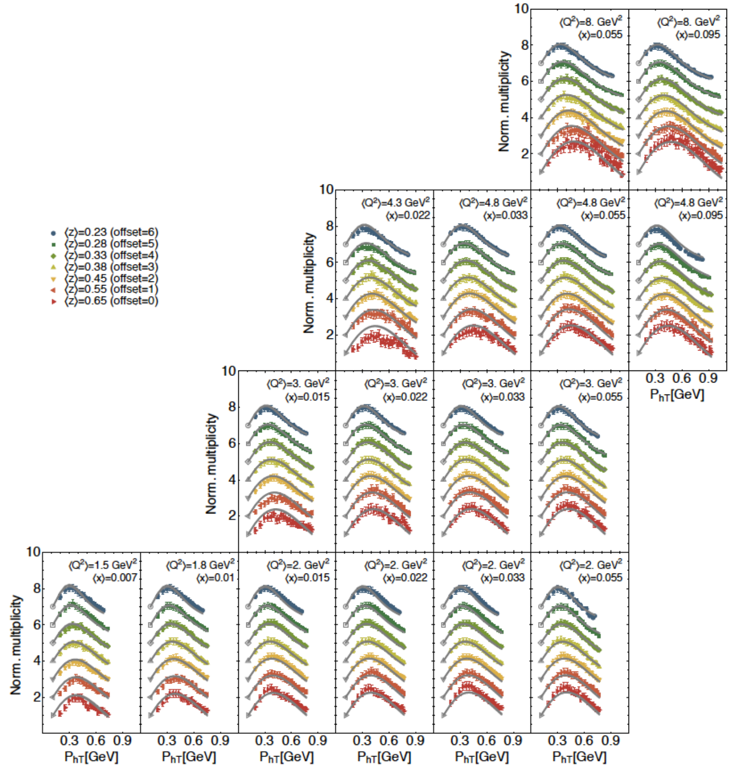


FIG. 6: COMPASS multiplicities for production of positive hadrons (π^+) off a deuteron for different $\langle x\rangle$, $\langle z\rangle$, and $\langle Q^2\rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. Multiplicities are normalized to the first bin in P_{hT} for each $\langle z\rangle$ value (see (41)). For clarity, each $\langle z\rangle$ bin has been shifted by an offset indicated in the legend.

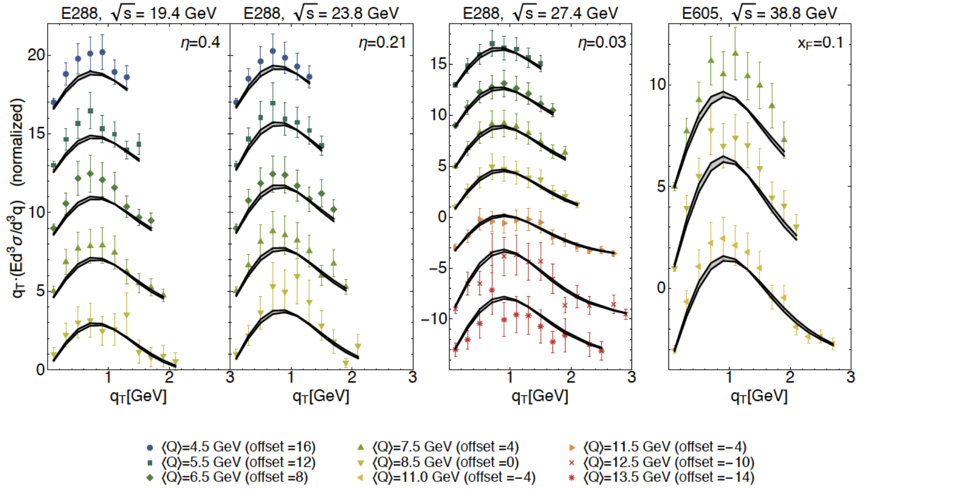


FIG. 7: Drell–Yan differential cross section for different experiments and different values of $\sqrt{s}$ and for different $\langle Q\rangle$ bins. For clarity, each $\langle Q\rangle$ bin has been normalized (the first data point has been set always equal to 1) and then shifted by an offset indicated in the legend.

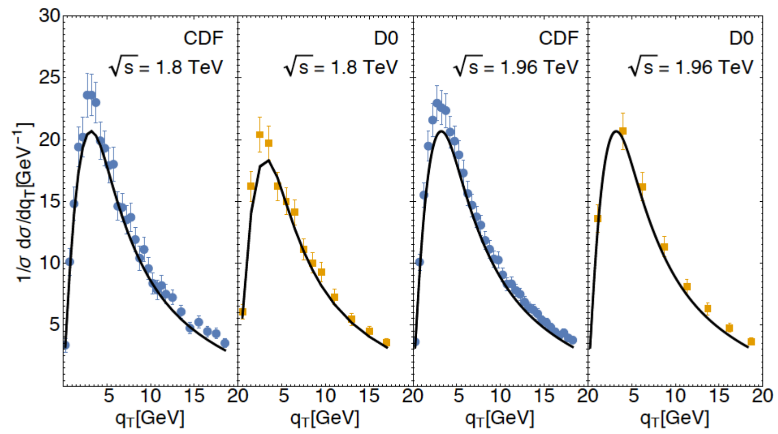
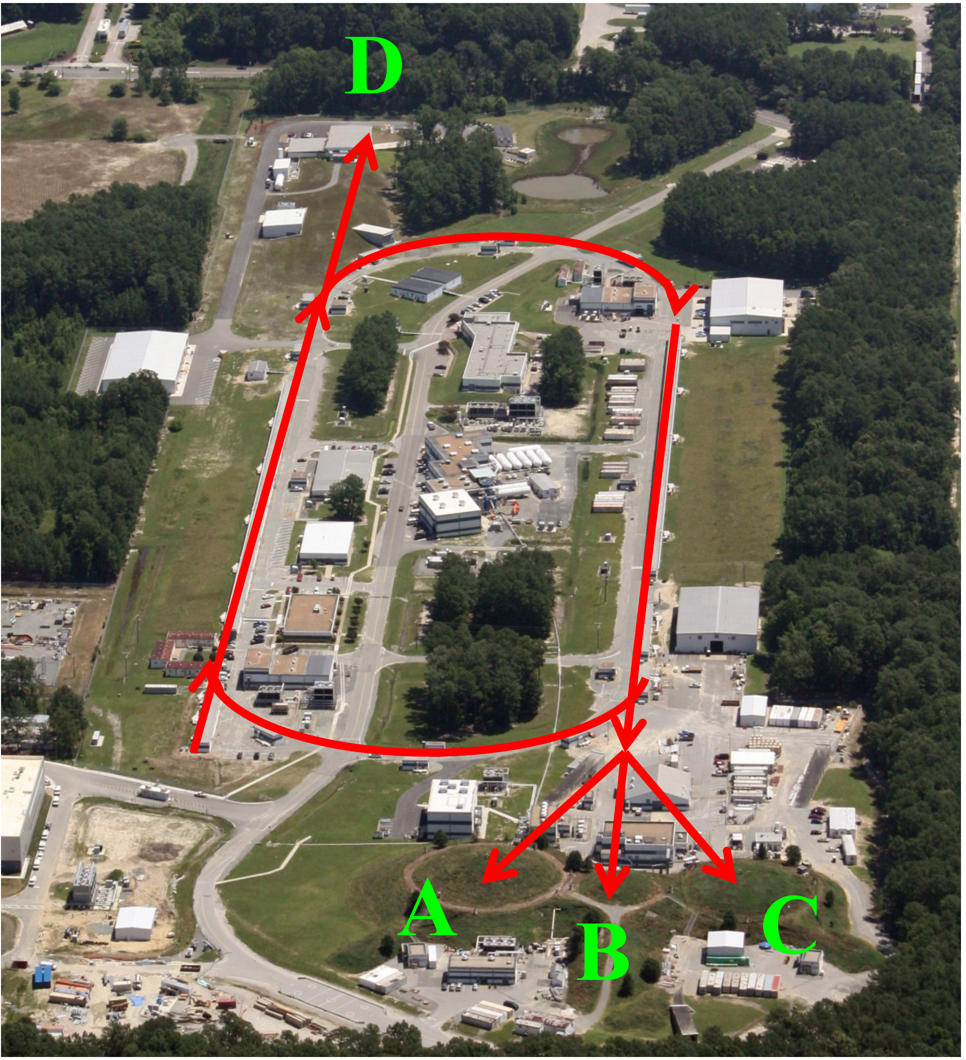


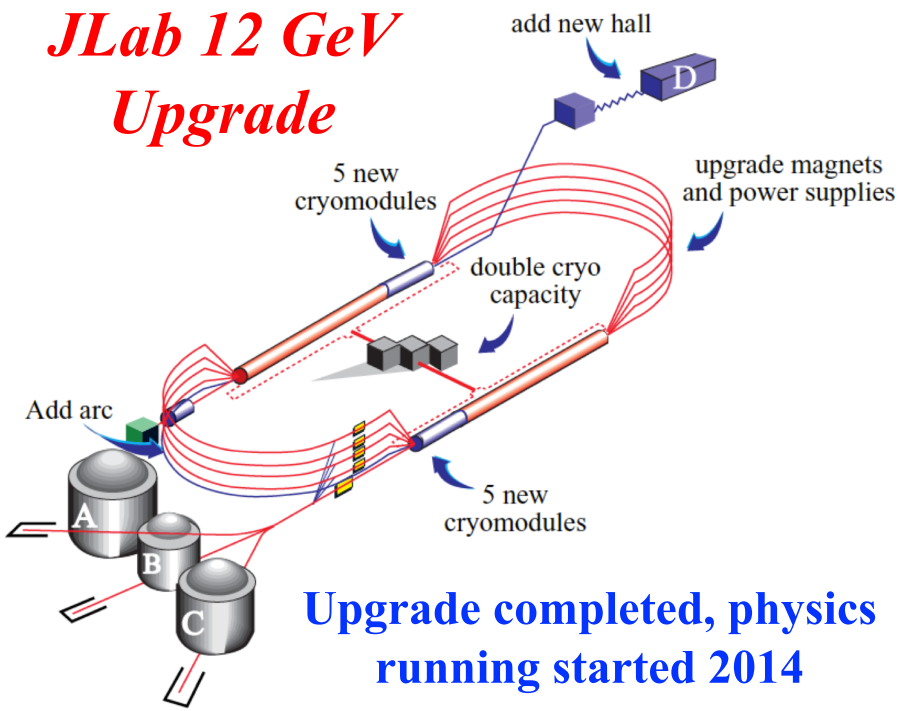
FIG. 8: Cross section differential with respect to the transverse momentum q_T of a Z boson produced from $p\bar{p}$ collisions at Tevatron. The four panels refer to different experiments (CDF and D0) with two different values for the center-of-mass energy ($\sqrt{s}$ = 1.8 TeV and $\sqrt{s}$ = 1.96 TeV). In this case the band is narrow due to the narrow range for the best-fit values of g_2.

- **Bacchetta *et al.*, JHEP 1706 (2017) 081**
- Simultaneous global fit of HERMES and COMPASS SIDIS data, Drell-Yan, and Z boson production data, achieving $\frac{\chi^2}{d.o.f.} = 1.55$ for ~8,000 data points with 11 adjustable parameters

Precision TMD studies in the valence region—JLab 12 GeV Era



Site Aerial, June 2012



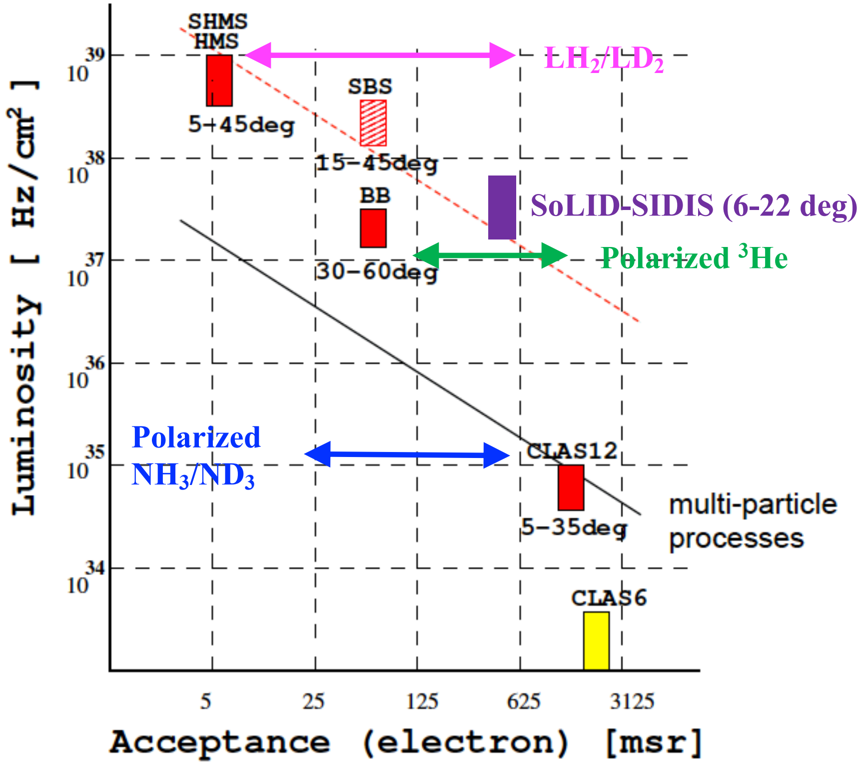
Seven-cell, High-Gradient Niobium SRF cavity for 12 GeV Upgrade

CEBAF Basic Parameters

- Superconducting RF electron linacs with up to 5X recirculation
- CW (100% duty factor) operation up to ~180 μA (A+B+C+D), 2 ns, 4 ns bunch structure possible
- Polarized source: up to 85-90% polarization
- Three experimental Halls
- Energy up to 11(12) GeV at 5 (5.5) passes to Halls A/B/C (D)

JLab detector landscape

Figure credit: B. Wojtsekhowski (JLab)



A range of 10^4 in luminosity.

A big range in solid angle:
from 5 msr (SHMS)
to about 1000 msr (CLAS12).
=========================
The SBS is in the middle:
for solid angle (up to 70 msr)
and high luminosity capability.

In several A-rated experiments
SBS was found to be the best
match to the physics.

GEM allows a spectrometer
with open geometry (->large
acceptance) at high L.

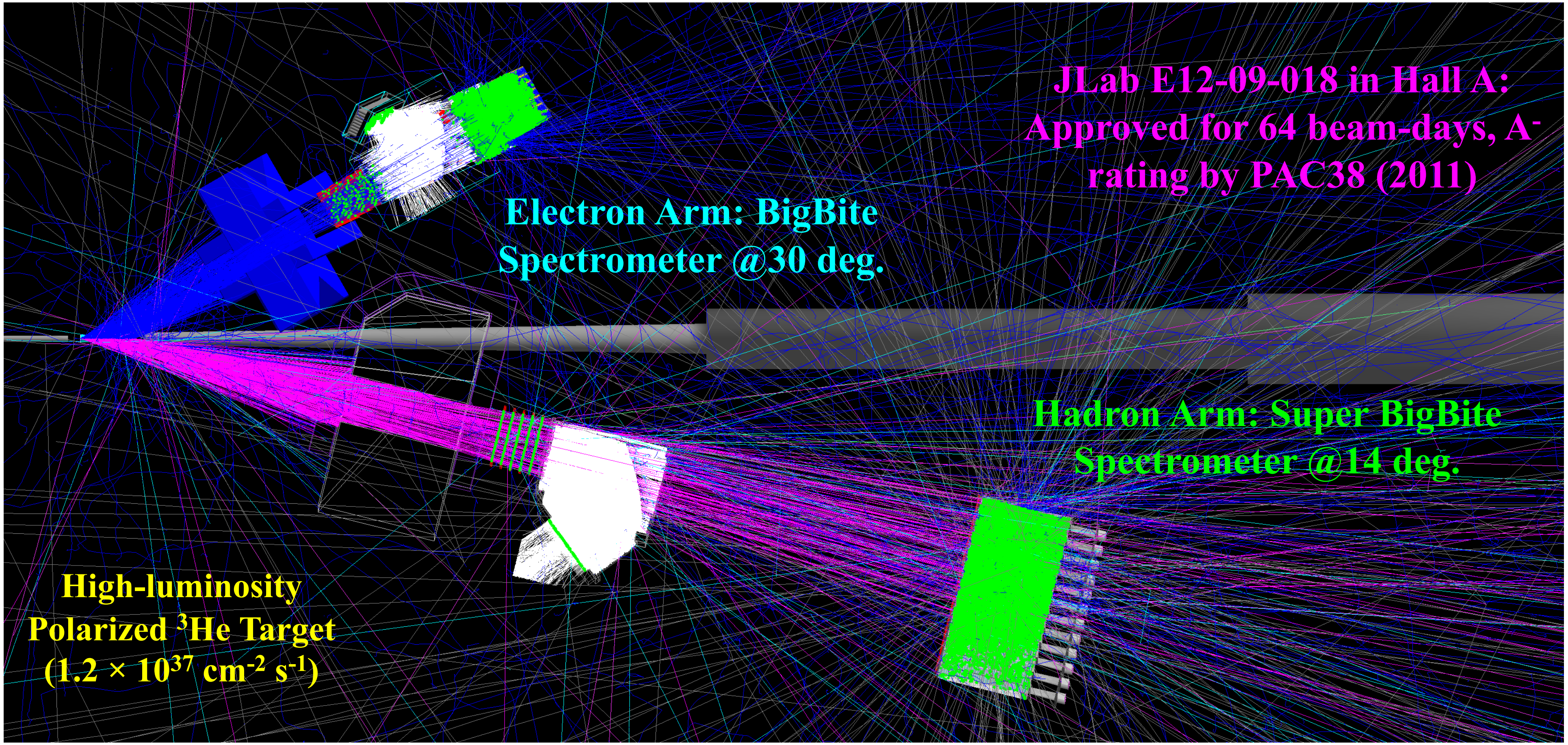
11/16/15 Super Bigbite Spectrometer Review slide 9

Unique roles of the CEBAF Halls in JLab-12 SIDIS program:

- **Hall A:** large, custom installation experiments. High luminosity and moderately large acceptance→BB+SBS (~2022) and SoLID (moving toward CD-0: late 2020s?)
- **Hall B:** large-acceptance, general-purpose spectrometer. Map unpolarized SIDIS cross sections in entire 11 GeV accessible phase space. Well matched to longitudinally polarized proton/deuteron targets
- **Hall C:** precision magnetic spectrometers for accurate cross section measurements, L/T separations, etc.

- Complementary equipment/capabilities of Halls A, B, C allow optimal matching of (Luminosity x Acceptance) of the detectors to the luminosity capabilities of the targets, including state-of-the-art polarized target technology.

E12-09-018—Transversely Polarized SIDIS on ^{3}He (“neutron”)

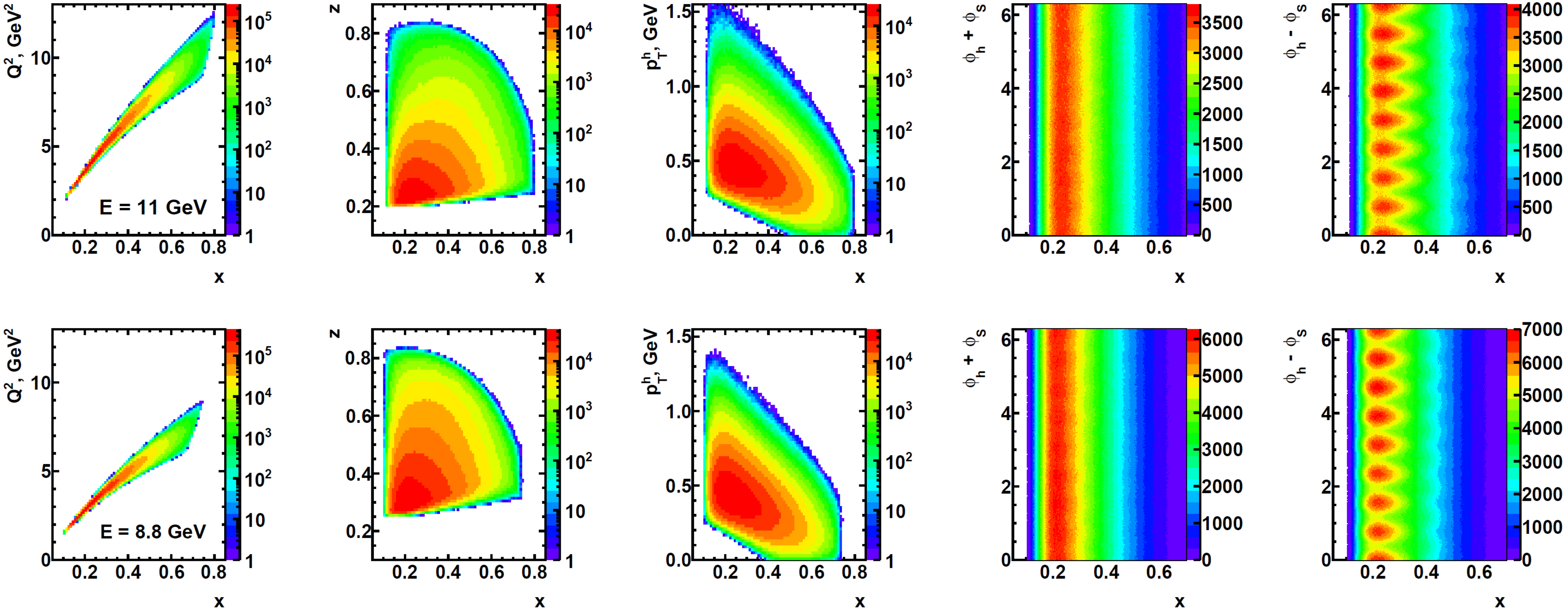


Key Features

- Cost-effective solution to enable high-impact transverse SSA measurements *soon*: re-use existing BigBite w/partially upgraded detector package
- Reuse other SBS components already being built for form factor program
- Reuse HERMES RICH
- Exploit high-luminosity ^{3}He target upgrade developed for G_E^n.
- Cover full SIDIS phase space in a single spectrometer configuration with moderate solid angle, large momentum bite
- http://hallaweb.jlab.org/collab/PAC/PAC38/SBS-SIDIS.pdf

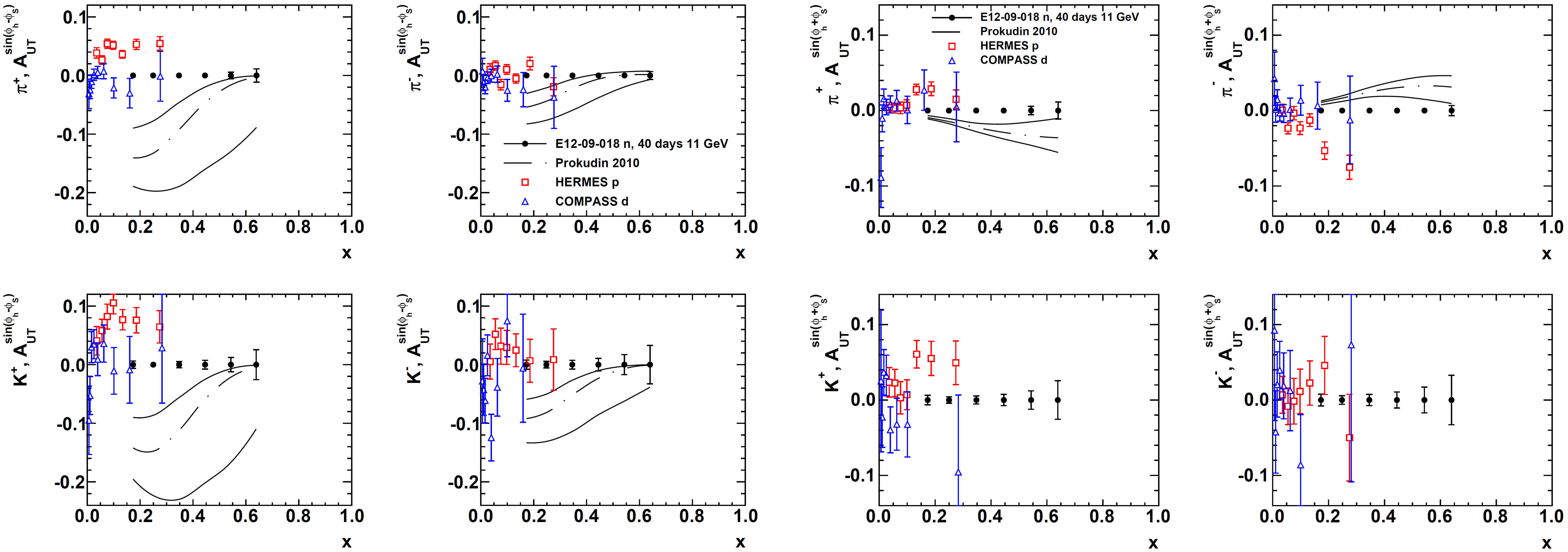
- **E12-09-018** in Hall A: transverse spin physics with high-luminosity polarized ^{3}He as effective polarized *n*.
- 40 (20) days production at E = 11 (8.8) GeV—significant Q^2 range at fixed x
- Collins, Sivers, Pretzelosity, A_{LT} for $\mathbf{n}(e, e'h)X, h = \pi^+, \pi^-, K^+, K^-, \pi^0$, etc.
- Re-use of HERMES RICH detector for charged hadron PID
- Reach high x (up to ~0.7) and high statistical FOM (~1,000X Hall A E06-010 @6 GeV)

SIDIS Kinematic Coverage in E12-09-018



- Cuts applied are: $Q^2 > 1\ GeV^2, W > 2\ GeV, P_h \geq 2\ GeV, M_X \geq 1.5\ GeV, y \leq 0.9$
- E12-09-018 emphasizes precision neutron measurements at high Q^2 and large x: complementary kinematic coverage to aid eventual interpretation of future, higher-precision data at (mostly) lower Q^2 from SOLID

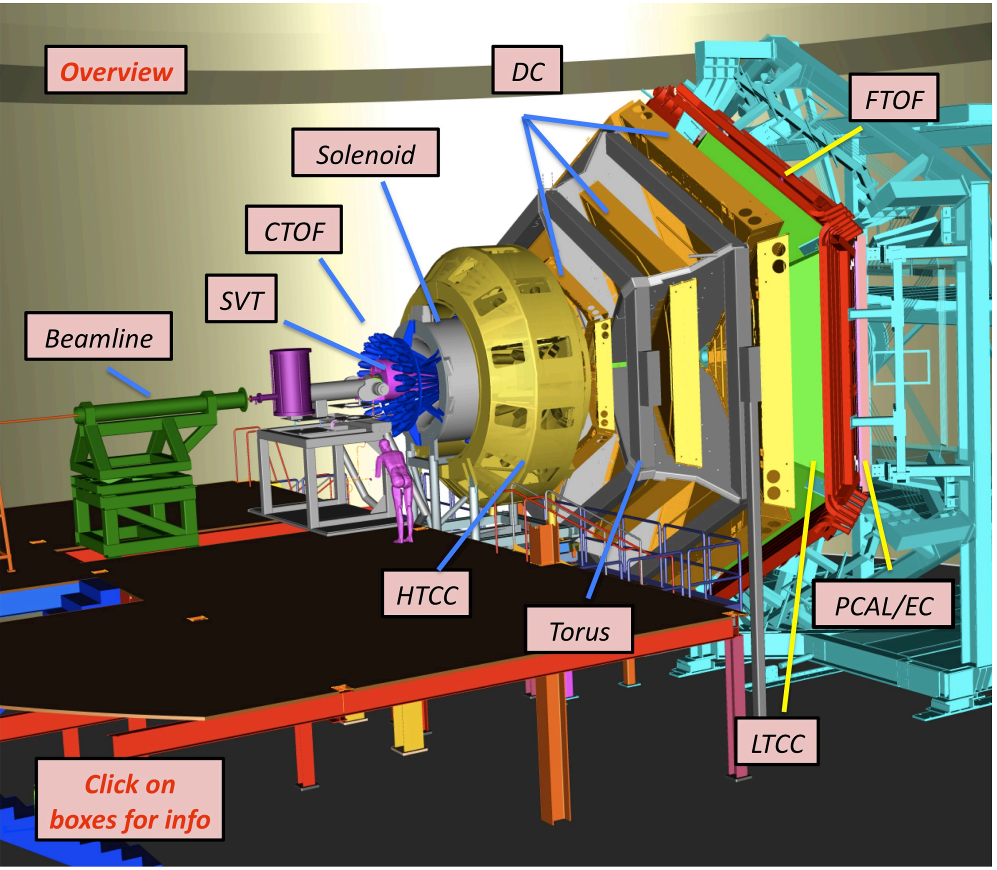
SBS+BB Projected Results: Collins and Sivers SSAs



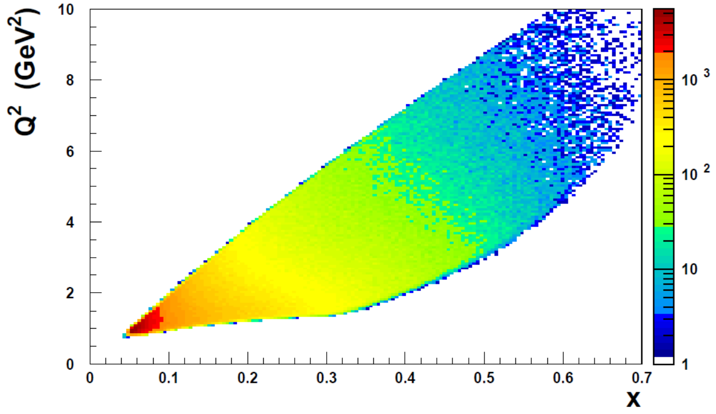
Projected A_{UT}^{Sivers} vs. x (11 GeV data only) **Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)**

- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than Hall A E06-010 neutron data. *Near-future more precise COMPASS deuteron data will sharpen expected impacts, urgency of E12-09-018*
- SBS installation starts 2020. E12-09-018 could run as early as 2022; 2023 more likely.

SIDIS Program with CLAS12 in Hall B

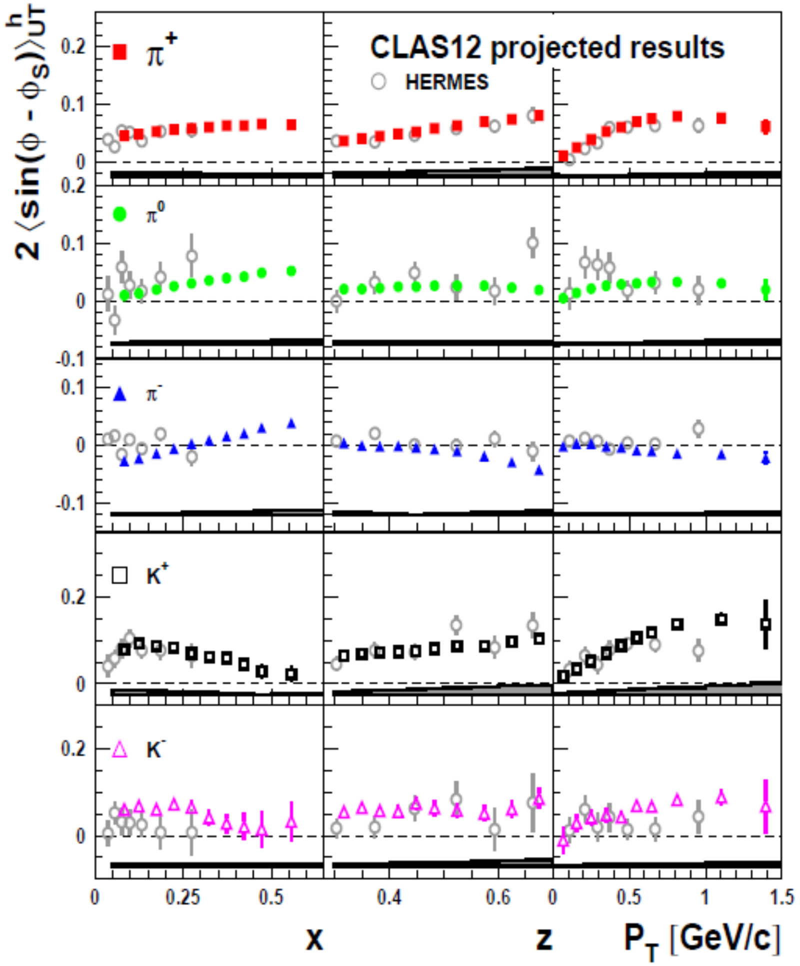


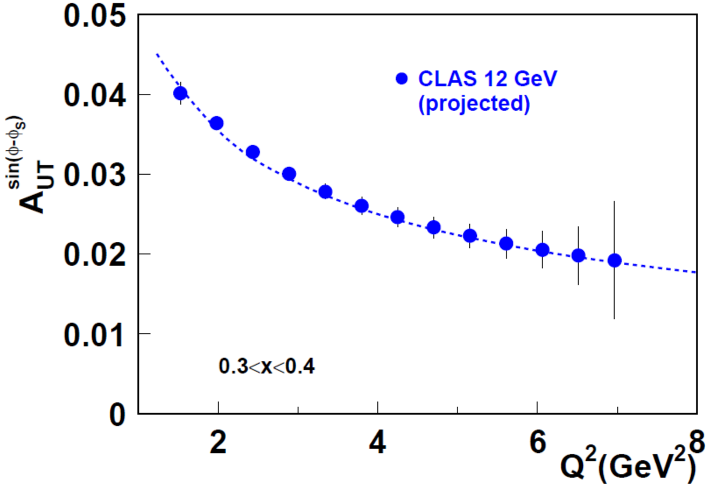
- SIDIS unpolarized cross section (F_{UU}, $A_{UU}^{\cos(2\phi)}$, $A_{UU}^{\cos(\phi)}$, etc.) and beam spin asymmetry $A_{LU}^{\sin(\phi)}$ measurements w/broad kinematic acceptance on unpolarized H, D targets:
  CLAS12 Run-group A (139 d, unpolarized H_2): E12-06-112 (A)
  CLAS12 Run-group B (90 d, unpolarized D_2): E12-11-109a, E12-09-007a (A-), E12-09-008 (A-)
- A_{LL}, A_{UL} for SIDIS on longitudinally polarized proton (NH_3) and deuteron (ND_3) targets:
  CLAS12 Run-group C (170 d): E12-07-107 (A-), E12-11-109b, E12-09-007b, E12-09-009 (B+)
- SIDIS on transversely polarized proton (HDice) target:
  - CLAS12 Run-group G (110 d): C12-11-111, C12-12-009.
  - **Proposed HDice luminosity ~10^{33}**
  - Run Group G timetable = ?

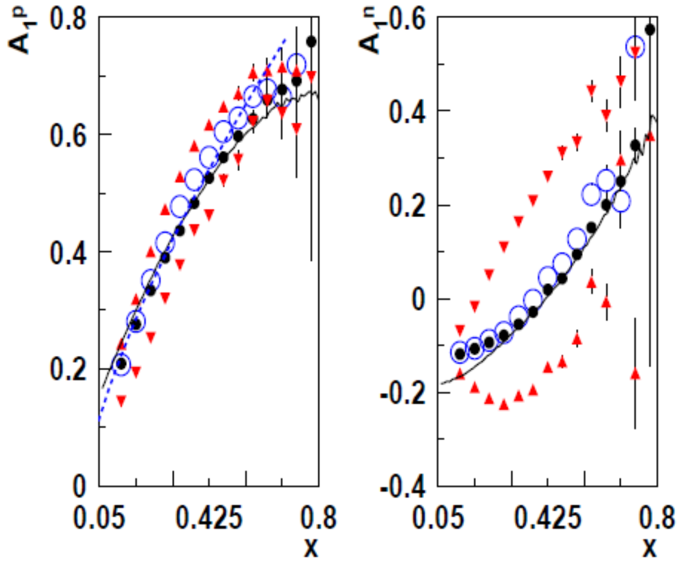


CLAS12 Q^2 vs x coverage

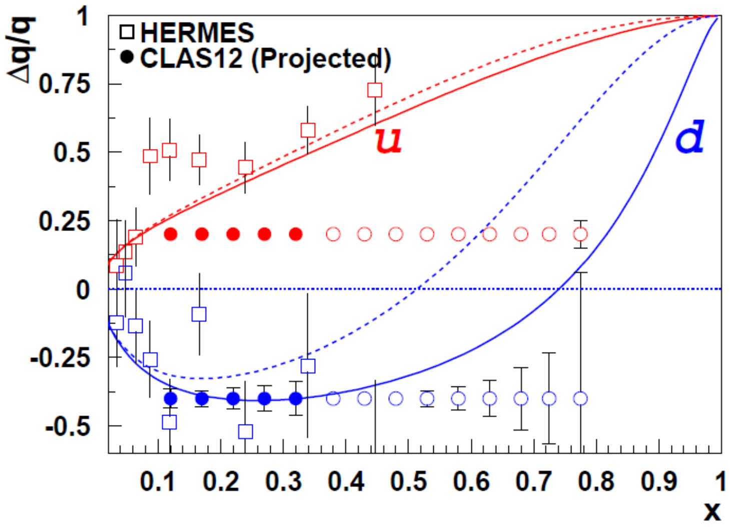
CLAS12 SIDIS program highlights







- Left: projected CLAS12 proton Sivers asymmetries (HDice program)
- Middle: example of projected Sivers Q^2 dependence for a single “x” bin
- Above, right: inclusive DIS and SIDIS asymmetries for longitudinally polarized NH_3 and ND_3 targets
- Below, right: projected precision of flavor decomposition of helicity pdfs, expressed as $\Delta q/q$



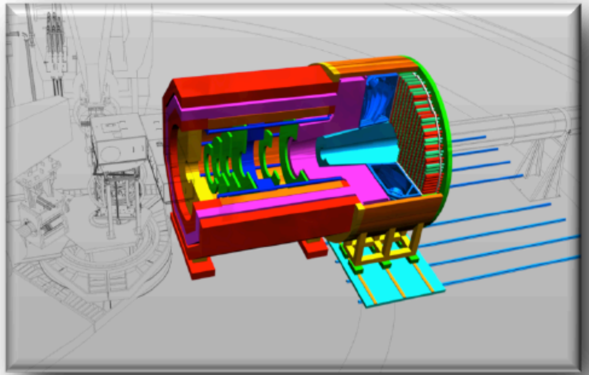
- Slide credit: Haiyan Gao, DIS 2018 workshop

Solenoidal Large Intensity Device (SoLID) Physics

SoLID provides unique capability:

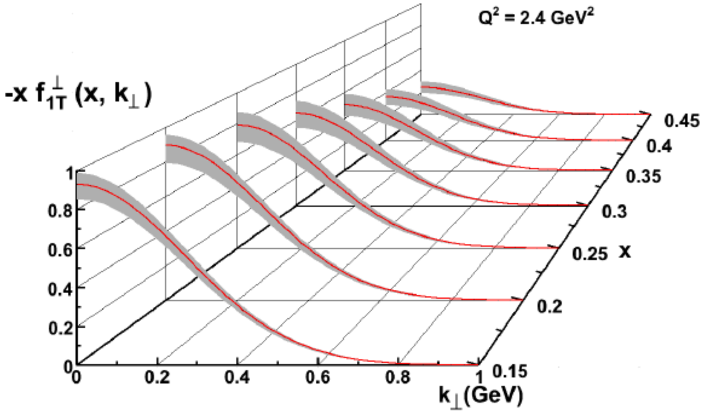
✓ high luminosity ($10^{37\text{-}39}$)

✓ large acceptance with full ϕ coverage

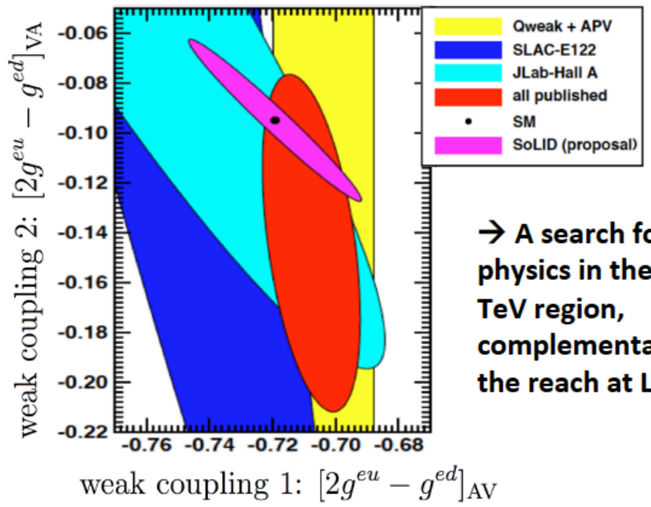


→ multi-purpose program to maximize the 12-GeV science potential

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

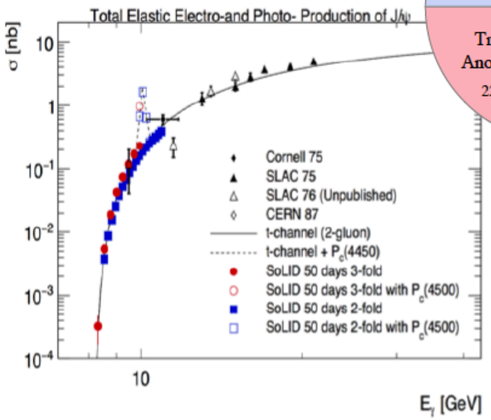


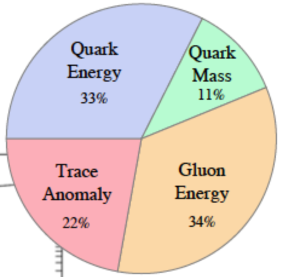
2) Precise determination of the electroweak couplings



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

3) J/ψ production cross section

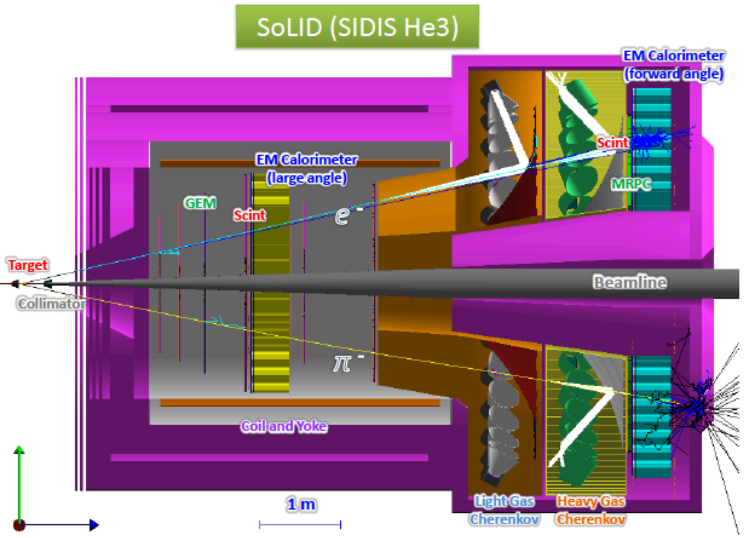




→ Constrain the QCD trace anomaly, Proton mass , LHCb charmed pentaquark

17

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



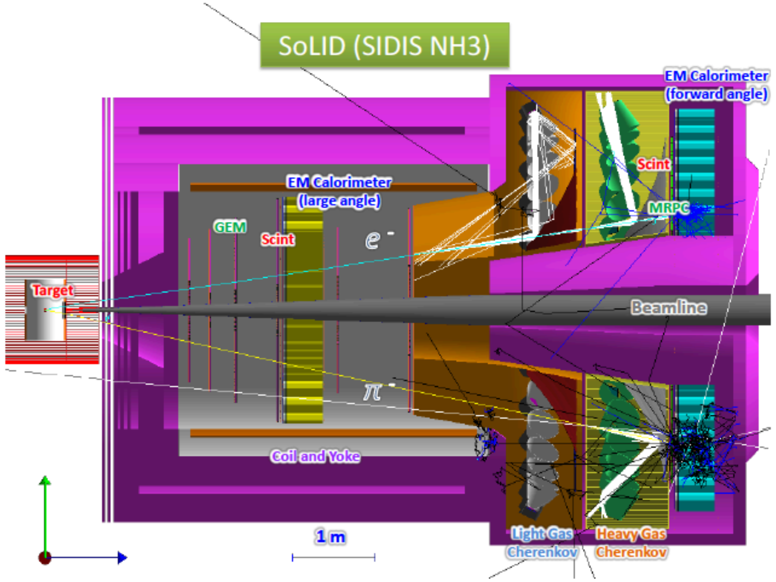


Table 2
Kinematic limits of SoLID. The bin-size for P_T is doubled when number of total events $< 5 \times 10^6$, and the bin size in x varies to keep number of events in one bin $\sim 10^6$. The actual bin size of the last bin with the center at $x = 0.6$ will extend up to $x \sim 0.7$.

Variable	Min	Max	Bin Size	Bins
Q^2	1.0 GeV^2	8.0 GeV^2	$\sim$1.0 GeV^2	6 bins
z	0.3	0.7	0.05	8 bins
P_T	0.0 GeV	1.6 GeV	0.2 GeV	$\leq$ 8 bins
x	0.05	0.6	NA	$\leq$ 8 bins

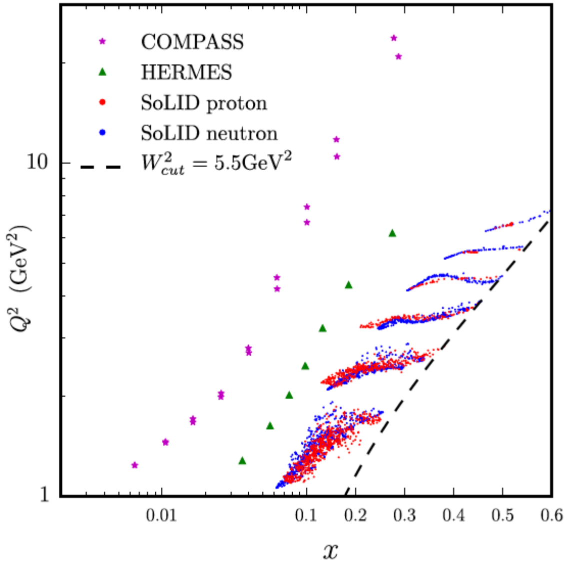


Fig. 1. $x - Q^2$ kinematical plane of bins for SoLID data with HERMES [28,29] and COMPASS [30–32] data sets.

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.

- Left: SOLID conceptual design and SIDIS program
- Above: SOLID Q^2-x coverage from Z. Ye *et al.*, Physics Letters B 767 (2017) 91–98

H. Gao

Example of Projected SOLID impacts: Nucleon isovector tensor charge

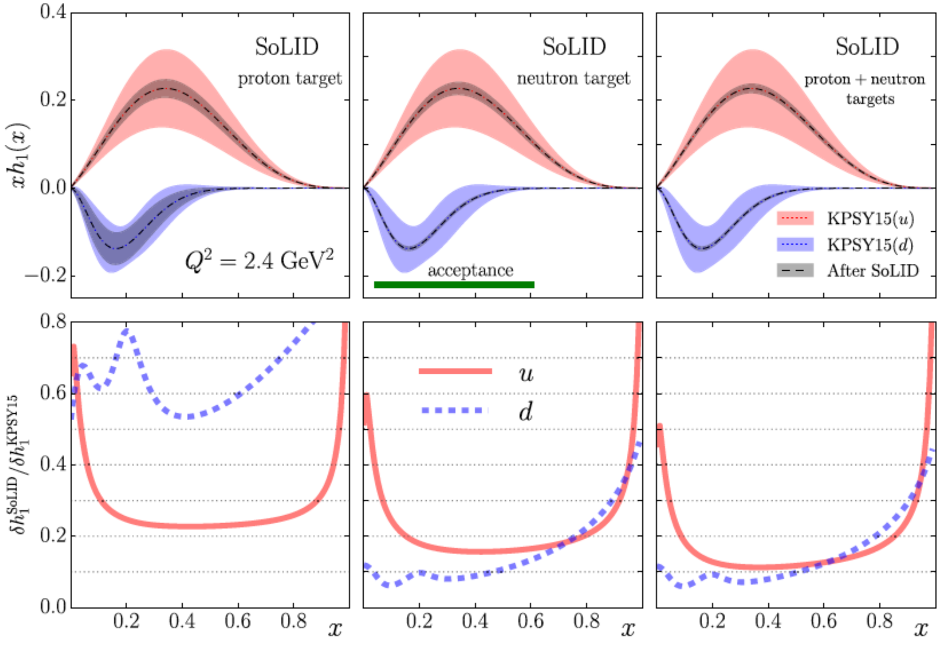


Fig. 2. Upper panels: u-quark and d-quark transversity distributions at $Q^2 = 2.4$ (GeV^2) as a function of x with existing errors from KPSY15 (light shade area) and the estimated errors after the SoLID data (both statistical and systematical errors are included in quadrature) are taken into account. The acceptance region in x of the SoLID experiment is indicated by the green horizontal line. Left plot: only the proton target data are taken into account, central plot: only the neutron target data are taken into account, right plot: combination of proton and neutron targets data are taken into account. **Bottom panels:** The ratio of the estimated errors and the current errors of transversity, $\delta h_1^{\mathrm{SoLID}}/\delta h_1^{\mathrm{KPSY15}}$, for u (solid line) and d (dashed line) quarks. Left plot: the proton target, central plot: the neutron target, right plot: combination of proton and neutron targets. The "bumps" around $x \simeq 0.2$ of the d-quark ratio plots are artifacts of usage of Soffer positivity bound [56] when parameterizing transversity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

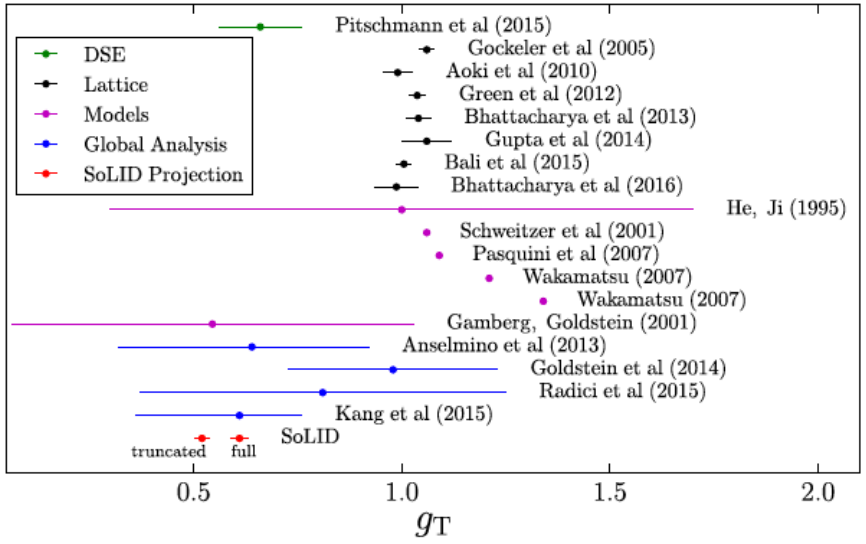


Fig. 3. The isovector nucleon tensor charge g_T after the pseudo-data of SoLID is taken into account is compared with result of Kang et al. 2015 [23] at $Q^2 = 10$ GeV^2, result from Ref. [42] (Radici et al. 2015) at 68% C.L. and $Q^2 = 4$ GeV^2, and result from Ref. [40] at 95% C.L. (Anselmino et al. 2013) at $Q^2 = 0.8$ GeV^2, and Ref. [57] (Gamberg, Goldstein 2001) at $Q^2 = 1$ GeV^2. Lattice computation are at $Q^2 = 4$ GeV^2 of Bali et al. Ref. [15], Gupta et al. Ref. [16], Green et al. Ref. [11], Aoki et al. Ref. [18], Bhattacharya et al. Ref. [12,13], Gockeler et al. Ref. [19]. Pitschmann et al. is DSE calculation Ref. [21] at $Q^2 = 4$ GeV^2. Model calculations include QCD sum rule estimate by He, Ji Ref. [58], Chiral Quark Soliton Model by Schweitzer et al. [59], Light Cone Wave Functions by Pasquini et al. [60], and bag models and CQSM results by Wakamatsu from Ref. [61]. Two SoLID points are the truncated and full tensor charges from Eq. (21).

Z. Ye *et al.*, Physics Letters B 767 (2017) 91–98: Comparison of projected precision of $g_T = \delta u - \delta_d$, for an assumed parametrization of the functional form of the valence quark transversities, to existing lattice QCD and phenomenological model calculations/global fits.

Future EIC—Figures from Eur. Phys. J. A (2016) 52: 268

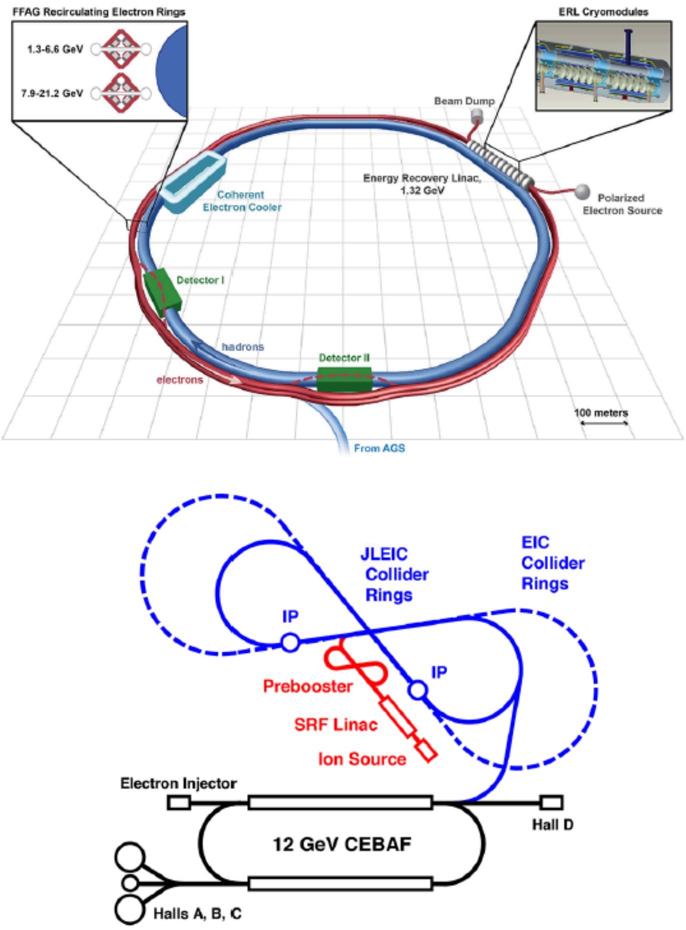


Fig. 4. Top: the schematic of eRHIC at BNL, which would require construction of an electron beam facility (red) to collide with the RHIC blue beam at up to three interaction points. Bottom: the schematic of JLEIC at JLab, which would require construction of an ion linac (red), and an electron-ion collider ring (blue) with at least two interaction points, around the 12 GeV CEBAF.

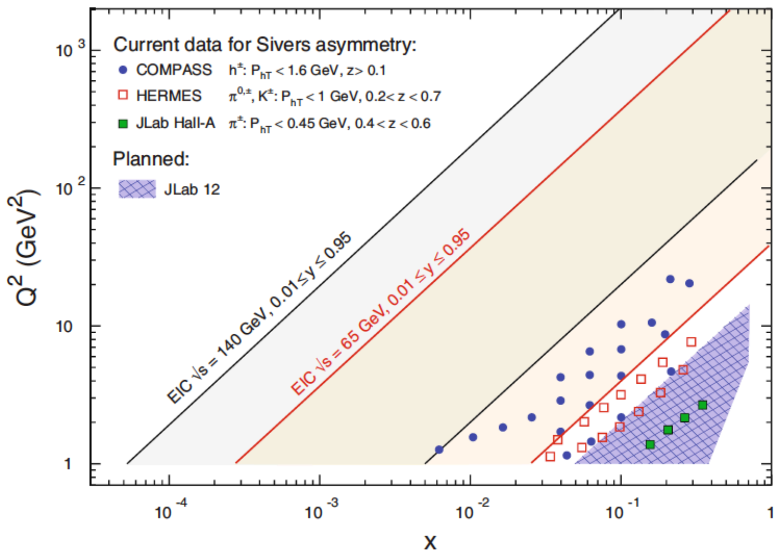


Fig. 18. Kinematic coverage in x and Q^2 for the EIC compared to the coverage of the planned JLab12 experiment. The kinematics of the existing experimental measurements are also shown for comparison.

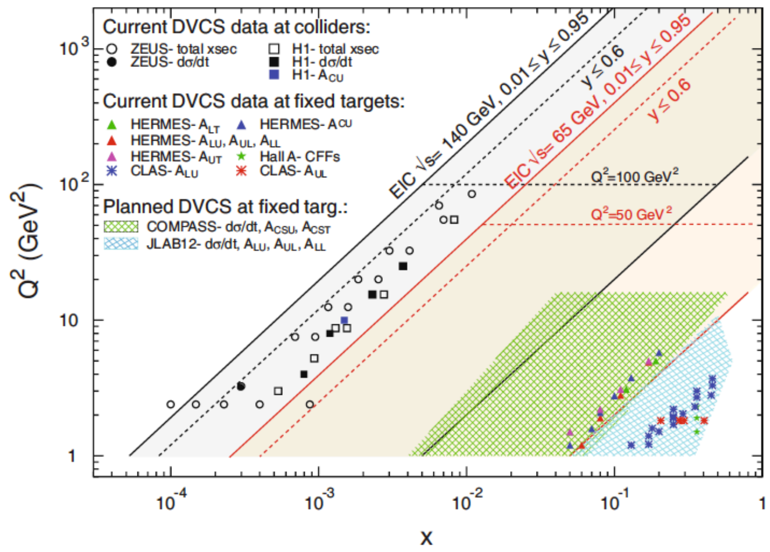


Fig. 24. An overview of existing and planned measurements of DVCS in the (x, Q^2)-plane.

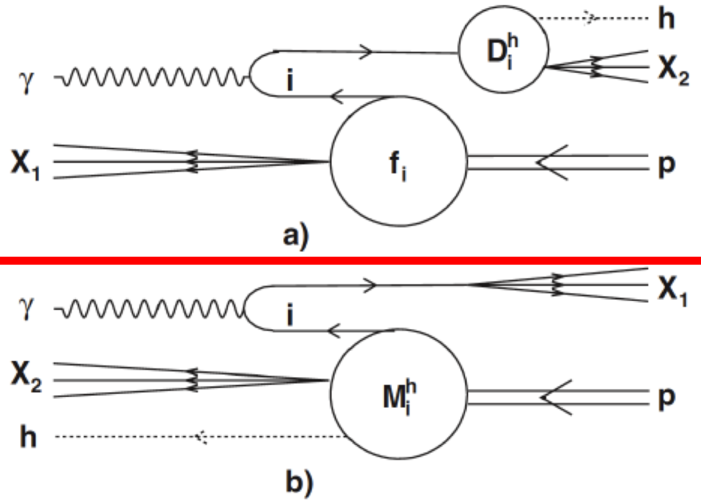
- Major EIC goals for nucleon structure (1D and 3D):
  - "Polarized HERA": bring kinematic coverage and precision of inclusive spin structure data roughly into parity with unpolarized structure function data
  - 3D structure: TMDs and GPDs: Luminosity × Polarization^2 of electron and ion beams is more essential for the 3D nucleon structure studies than maximizing $\sqrt{s}$
  - 100% acceptance detector design is essential for 3D PDF/GPD studies, regardless of $\sqrt{s}$

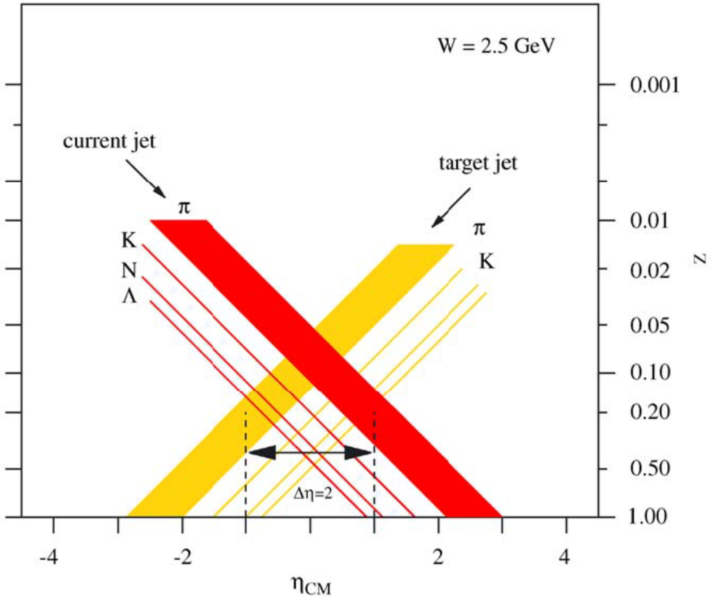
Summary and Conclusions

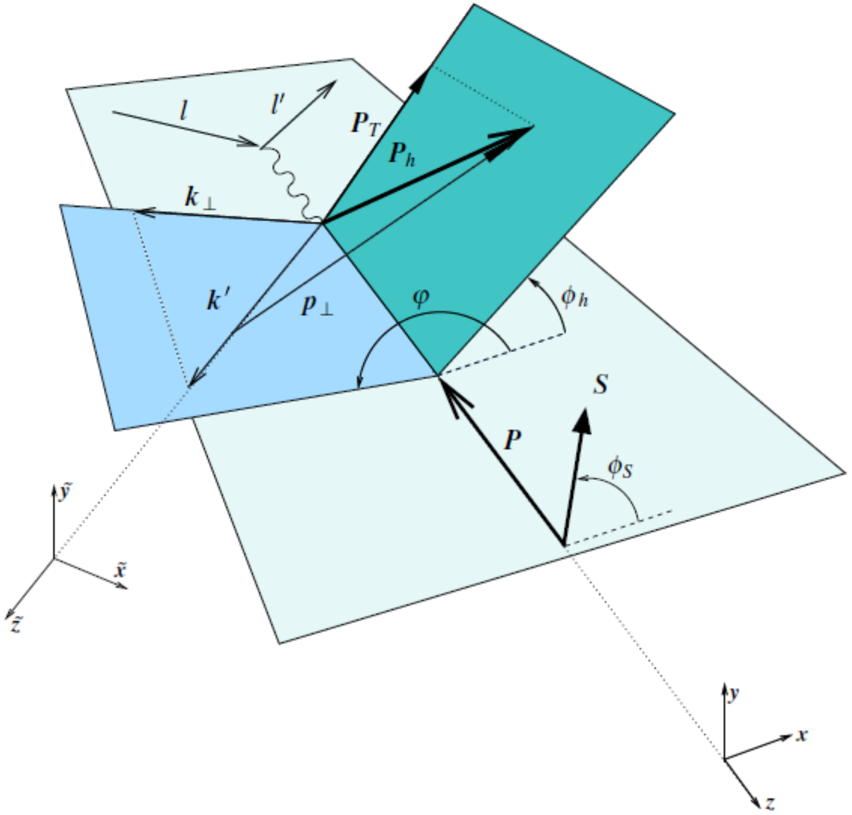
- HERMES, COMPASS, and other pioneering SIDIS experiments have shown that novel spin-orbit phenomena such as the Collins and Sivers effects exist and have highly non-trivial behavior
- Unpolarized SIDIS/DY, and other data can be described in the TMD framework over a wide kinematic range; supporting the notion of factorization and universality for TMDs
  - k_T, p_T dependence of TMD PDFs and fragmentation functions is a bit more interesting than the traditional (and convenient) Gaussian ansatz that trivially factorizes from the collinear (k_T-integrated) PDFs and FFs, but the complexity seems manageable.
- Only JLab at 12 GeV has the Luminosity × Polarization^2 capability to go from exploration/discovery to precision 4D mapping:
  - The kinematic region for applicability of the TMD framework at JLab kinematics is yet to be conclusively established—encouraging signs from published 6 GeV data, but even at 11 GeV, accessible phase space is limited to the valence region, relatively low Q^2, limited z range
  - Hall C and Hall B have already started collecting a subset of planned unpolarized SIDIS data
- Only a future high-luminosity, polarized EIC has the potential to map the 3D nucleon structure in the full 4D phase space in kinematics for which TMD factorization is unambiguously applicable
- Thank you for your attention and stay tuned!

Backup Slides

How does SIDIS access 3D quark information?

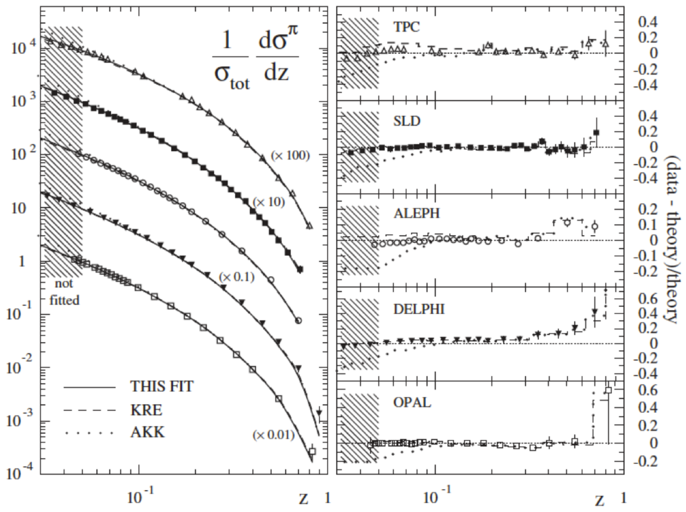


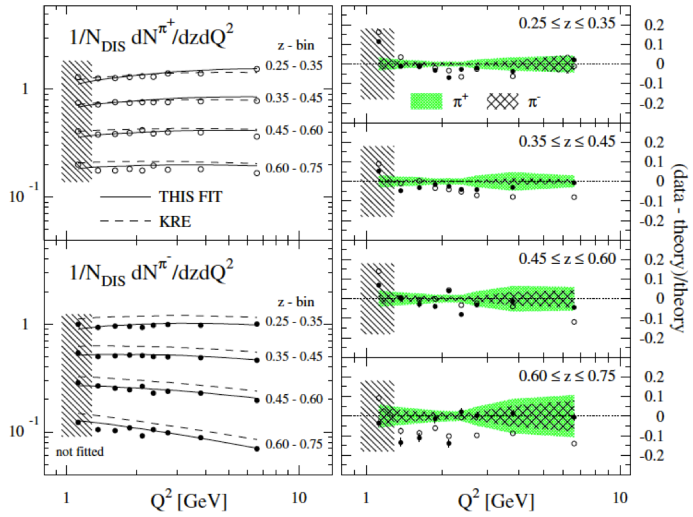


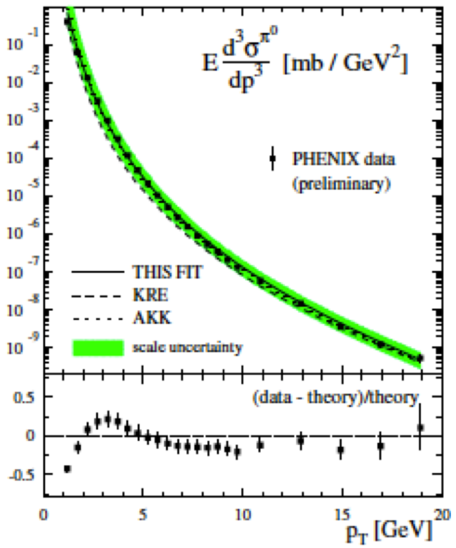


- Recoiling quark is not directly observed (confinement)—but “fragments” into observable hadrons (e.g., pions, kaons) with probability described by ***fragmentation functions*** $D_h^q(z,Q^2)$
- At “high” energies, fragmentation is independent of the hard scattering→ “factorization”!

Factorization and universality for FFs



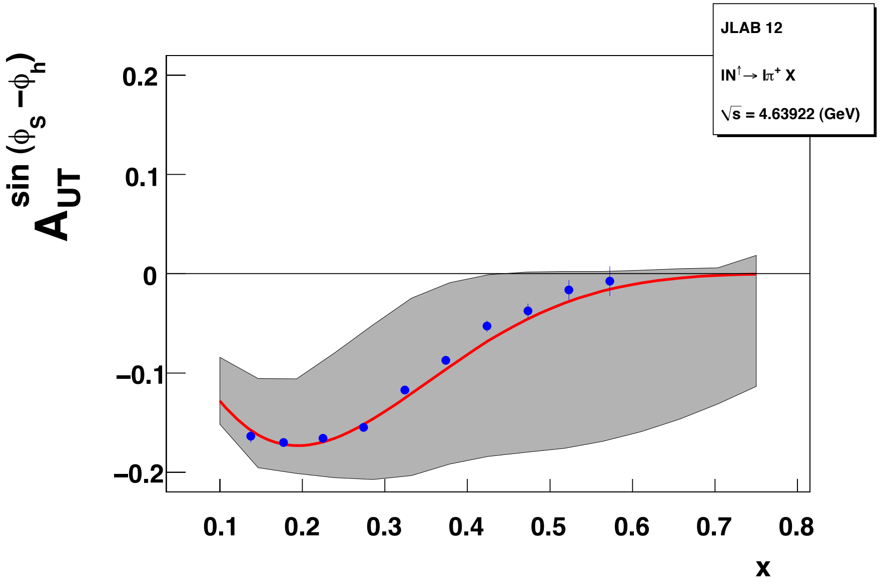


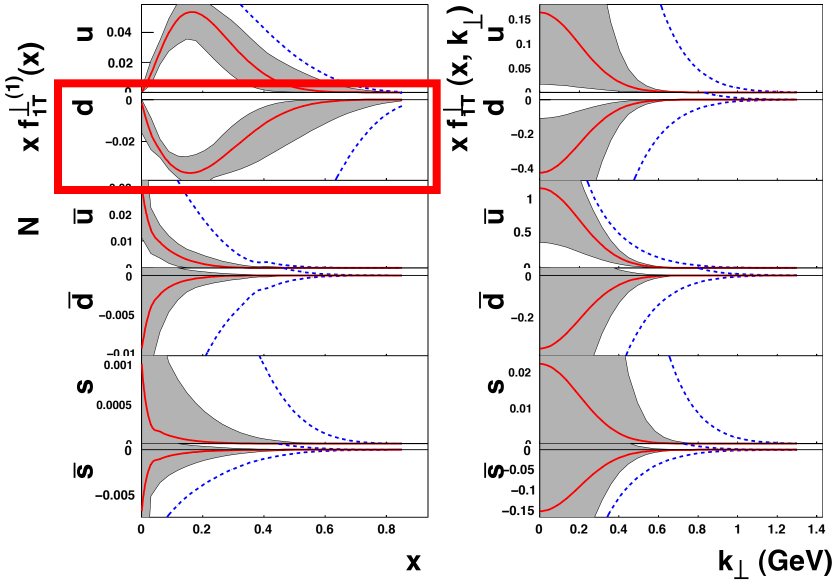


- Above: comparisons of unpolarized cross section data to NLO global QCD FF fits (DSS 2007)
  - Left: single inclusive e+/e- annihilation to charged pions
  - Middle: charged pion multiplicities in SIDIS
  - Right: inclusive π^0 production in pp collisions
- Below: factorization of SIDIS cross section at leading-order, including quark distribution q(x), hard scattering subprocess (eq→eq), and fragmentation function $D^h_q(z)$

$$d\sigma^{\ell p\to\ell' hX} = \sum_q \hat{f}_{q/p}(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{\ell q\to\ell q} \otimes \hat{D}_{h/q}(z, \boldsymbol{p}_\perp; Q^2).$$

Example Impacts of SBS SIDIS Experiment





- 2011 impact study by A. Prokudin, global fit with E12-09-018 projected results, π^+ Sivers moments at E = 11 GeV, ½ of projected statistics.
- Left: >5X shrinking of n(e,e' π^+)X Sivers A_{UT} band
- Right: reducing the uncertainty in d quark Sivers in six-flavor extraction
- **E12-09-018 will provide $\pi^{\pm}/\pi^0/K^{\pm}$ at similar precision (Kaon errors 2-3X pion errors) for both E = 8.8 GeV and E = 11 GeV Collins/Sivers (and Pretzelosity)**

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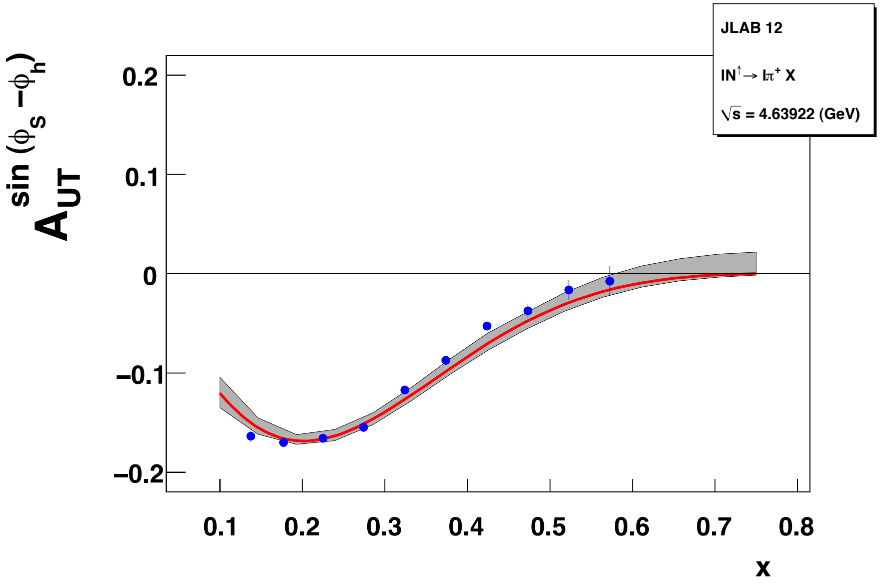

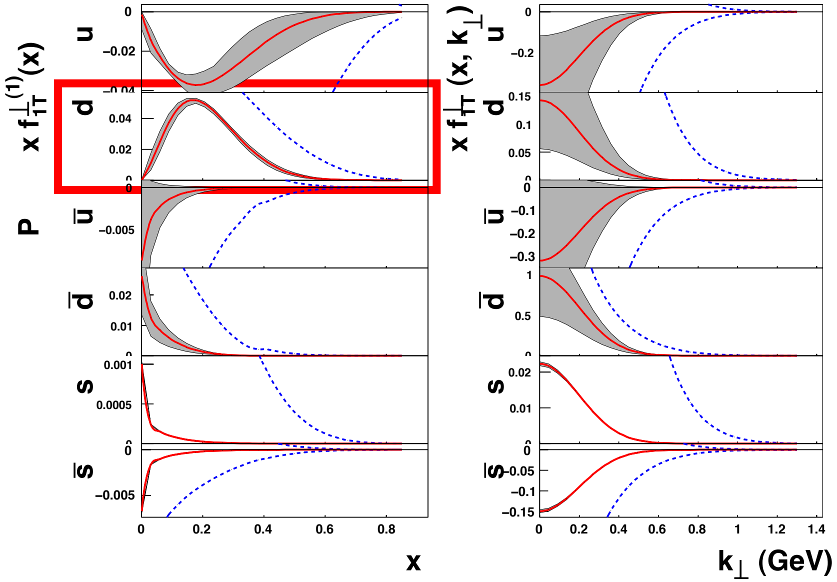

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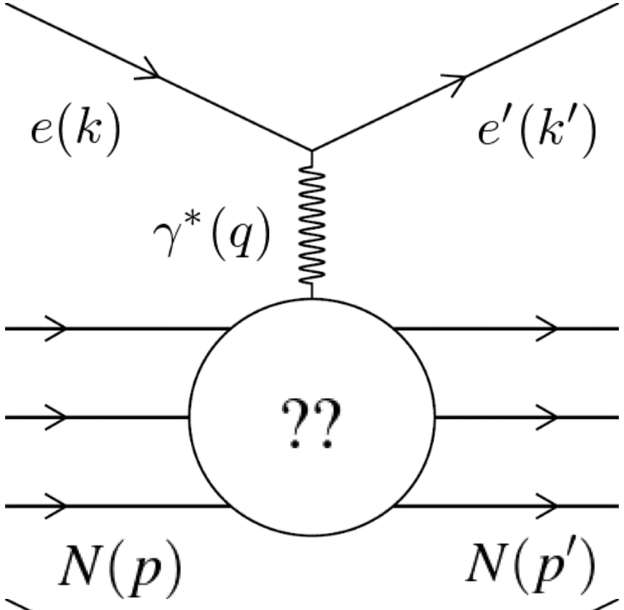
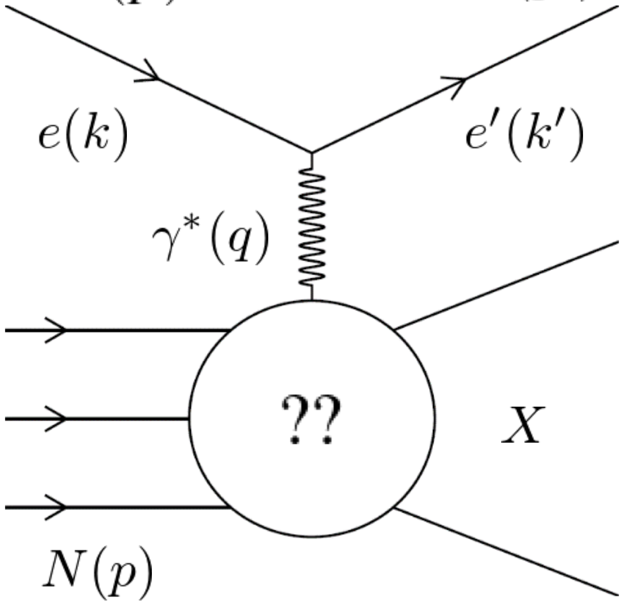
Electron-nucleon scattering: Glossary





- ***Elastic scattering:*** *e+N→e+N*
- Nucleon stays intact and in its ground state
- ***Inelastic scattering:*** *e+N→e+X*
  - **X = anything** allowed by overall energy/momentum conservation and nucleon internal structure/reaction dynamics
- ***Inclusive reactions:***
  - *Only* the scattered electron is detected in the final state
  - All possible hadronic final states satisfying energy/momentum conservation are integrated over.
- ***Exclusive reactions:***
  - *All* final-state reaction products are detected either directly or via "missing mass"
  - Examples include elastic scattering (e+N→e+N), virtual Compton Scattering (e+N→e+N+γ), exclusive meson production (e+N→e+N+h, h = π, K, ...), etc.
- ***Semi-inclusive reactions:***
  - *Some (but not all)* final-state particles are detected
  - Example: semi-inclusive hadron production e+N→e+h+X, where e and h are detected in the final state, and "X" represents all unobserved particles.

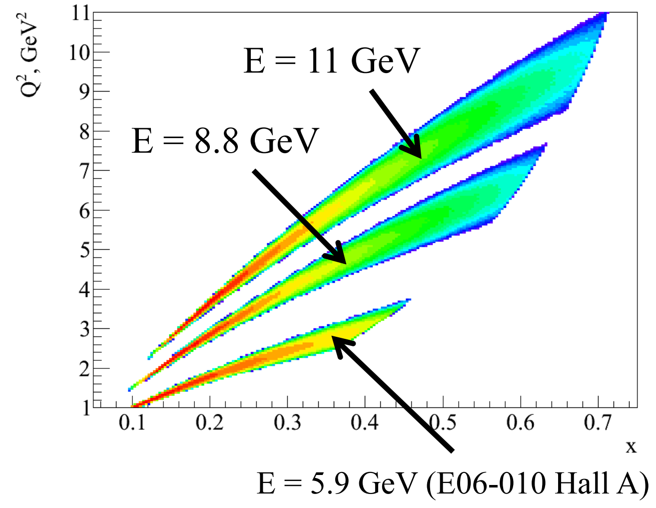
3D and "4D" extraction of SIDIS SSAs with SBS

Example result for 3D binning (x, z, p_T)

- E = 11 GeV, 40 days

$$A_{UT}^{\sin(\phi_h - \phi_S)} \text{ for } \mathbf{n}(e, e'\pi^+)X:$$
$$0.1 \le x \le 0.7, \Delta x = 0.1$$
$$0.2 \le z \le 0.7, \Delta z = 0.1$$
$$0 \le p_T(\text{GeV}) \le 1.2, \Delta p_T = 0.2 \text{ GeV}$$

- "4D" with Q^2 dependence from 20 days at 8.8 GeV:



Increasing z ➔

⬅ *Increasing p_T*