Precision study of Nucleon 3-D structure with Semi-Inclusive Deep Inelastic Scattering

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Physics Opportunities at an Electron-Ion Collider XI

Florida International University, Miami, FL

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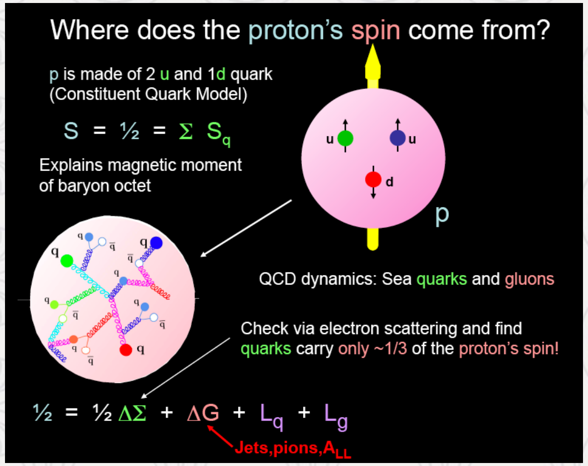
Nucleon Structure from 1D to 3D & orbital motion



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

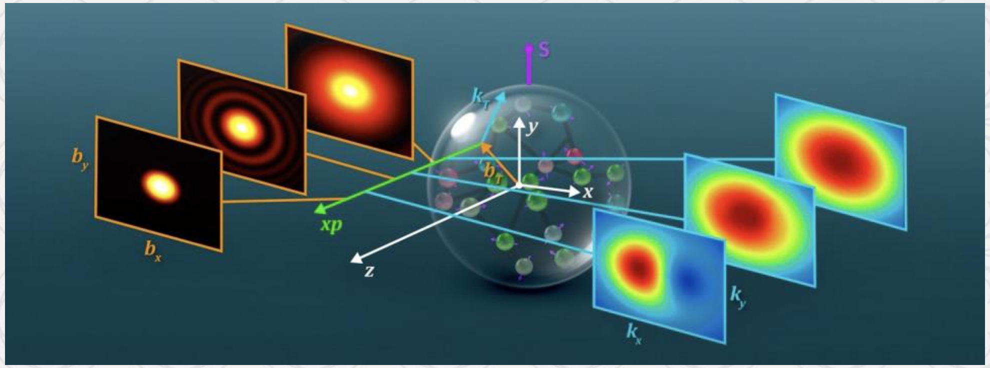
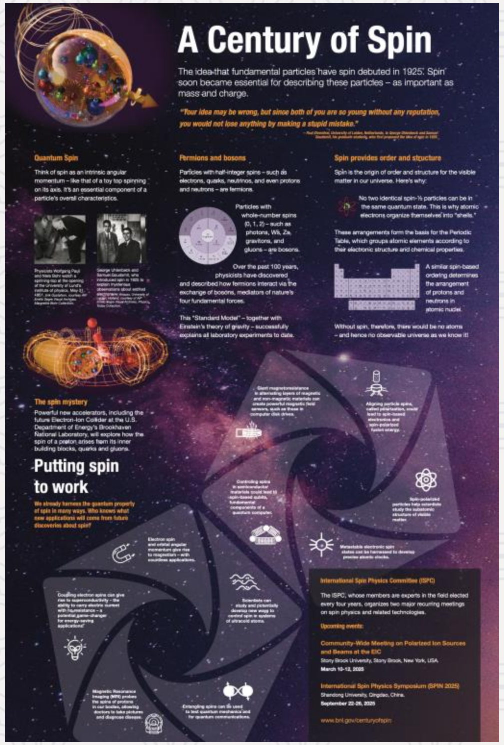
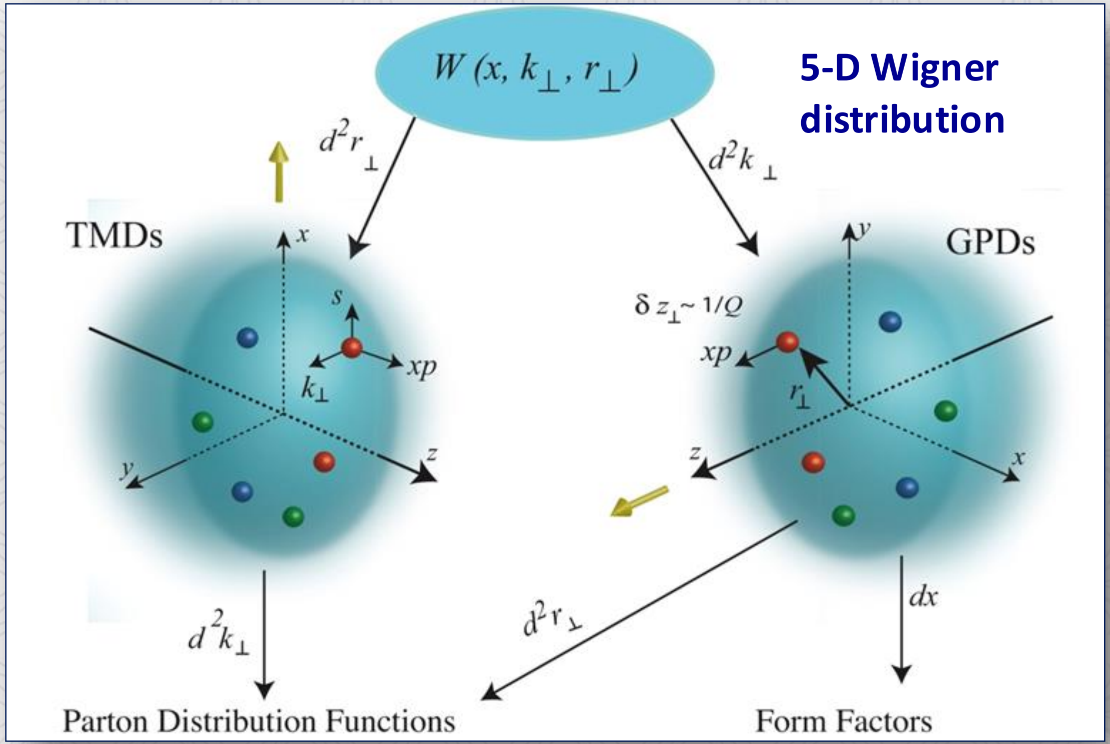


Image from 2023 NSAC LRP





Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)

X.D. Ji, PRL91, 062001 (2003);
Belitsky, Ji, Yuan, PRD69,074014 (2004)

Image from J. Dudek et al., EPJA 48,187 (2012)

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TMDs – confined motion inside the nucleon

→ Nucleon Spin
→ Quark Spin

Leading twist: 8 TMDs

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

A. Prokudin, Y. Zhao, L. Gamberg, A. Vossen, H. Avagyan at this workshop

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TMDs – confined motion inside the nucleon

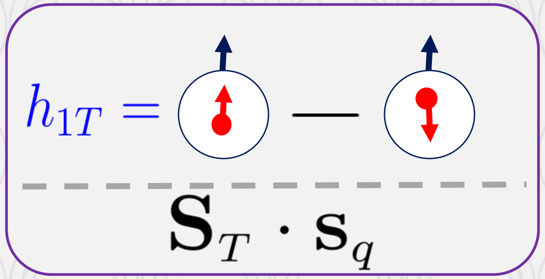
Transversely Polarized Nucleon TMDs

→ Nucleon Spin
→ Quark Spin

Relevant Vectors

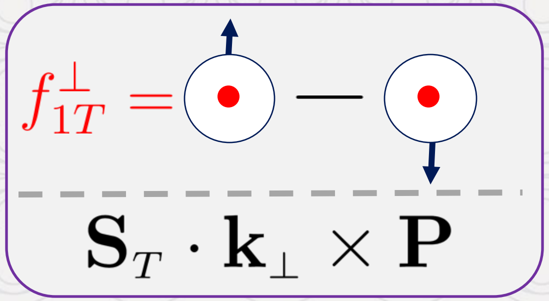
S_T: Nucleon Spin
s_q: Quark Spin
$k_\perp$: Quark Transverse Momentum
P: Virtual photon 3-momentum (defines z-direction)

Transversity



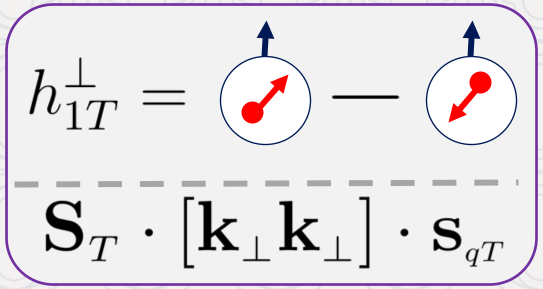
- h_{1T} (h_1) = g_1 (no relativity)
- h_{1T} → tensor charge (lattice QCD calculations)
- Connected to nucleon beta decay and EDM

Sivers



- Nucleon spin - quark orbital angular momentum (OAM) correlation – zero if no OAM (model dependence)

Pretzelosity



- Interference between components with OAM difference of 2 units (i.e., s-d, p-p) (model dependence)
- Signature for relativistic effect

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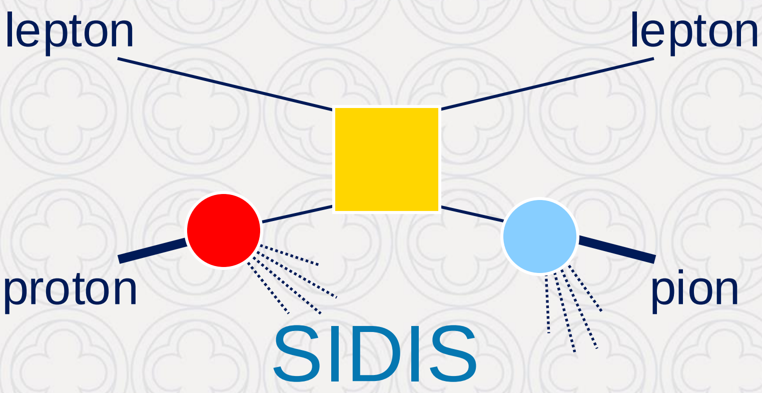
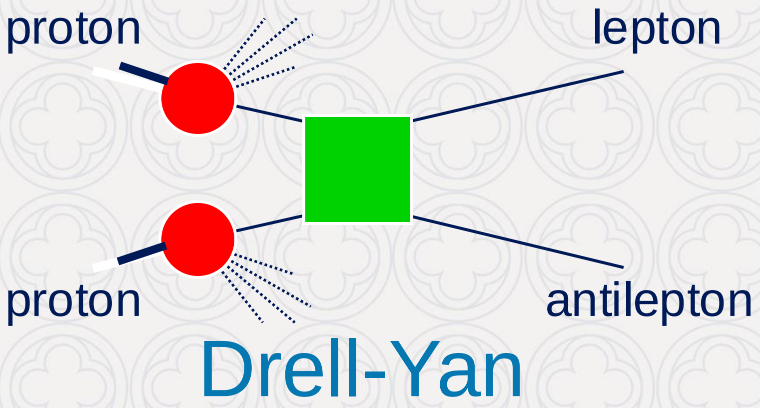
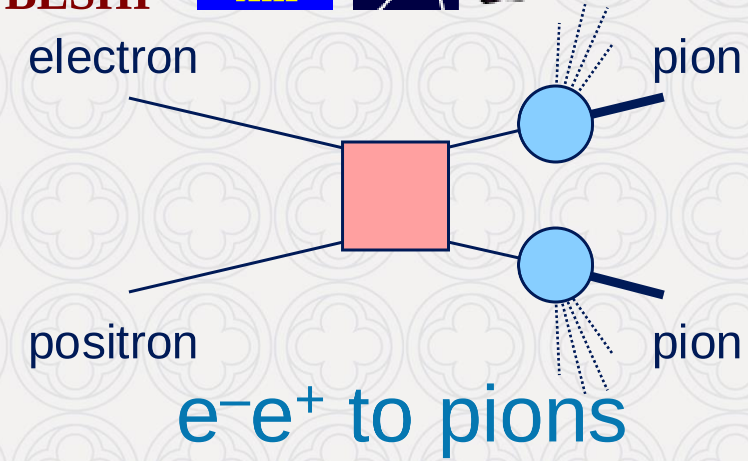
Access TMDs through Hard Processes







Close collaborations between experiment, theory, phenomenology, and computation

- Partonic scattering amplitude (yellow square)
- Fragmentation amplitude (blue circle)
- Distribution amplitude (red circle)

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

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

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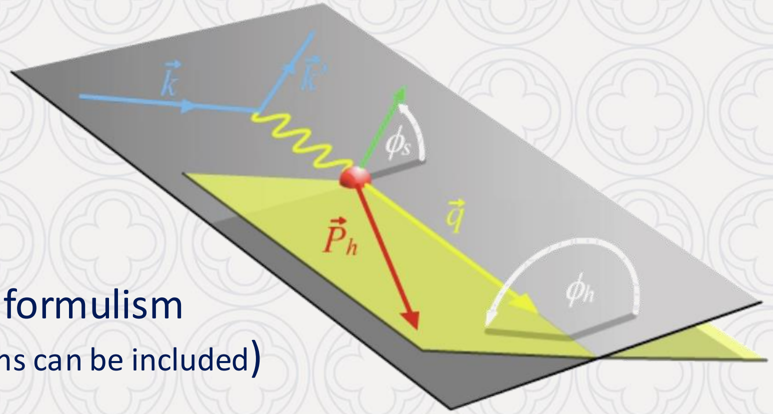
Separation of Collins, Sivers and Pretzelosity

SIDIS SSAs depend on 4-D variables (x, Q^2, z, P_T) and small asymmetries demand **large acceptance** + **high luminosity** allowing for measuring symmetries in 4-D binning with precision!

(2π azimuthal coverage)



$$A_{UT}(\phi_h,\phi_S) = \frac{1}{P_{t,pol}}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$$

Leading twist formulism
(higher-twist terms can be included)

$$= A_{UT}^{Collins}\sin(\phi_h+\phi_S) + A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S) + A_{UT}^{Sivers}\sin(\phi_h-\phi_S)$$

$$A_{UT}^{Collins} \propto \langle\sin(\phi_h+\phi_S)\rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Pretzelosity} \propto \langle\sin(3\phi_h-\phi_S)\rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins fragmentation function from e^+e^- collisions

$$A_{UT}^{Sivers} \propto \langle\sin(\phi_h-\phi_S)\rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

Unpolarized fragmentation function

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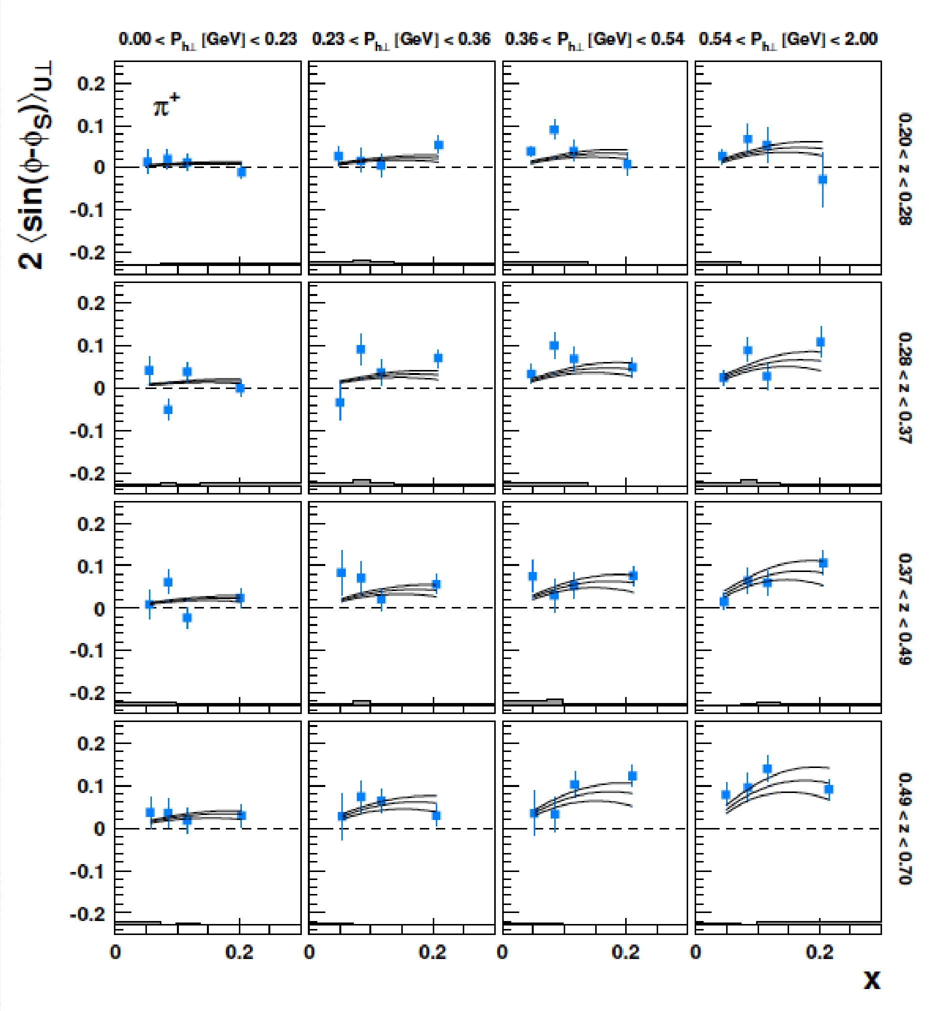
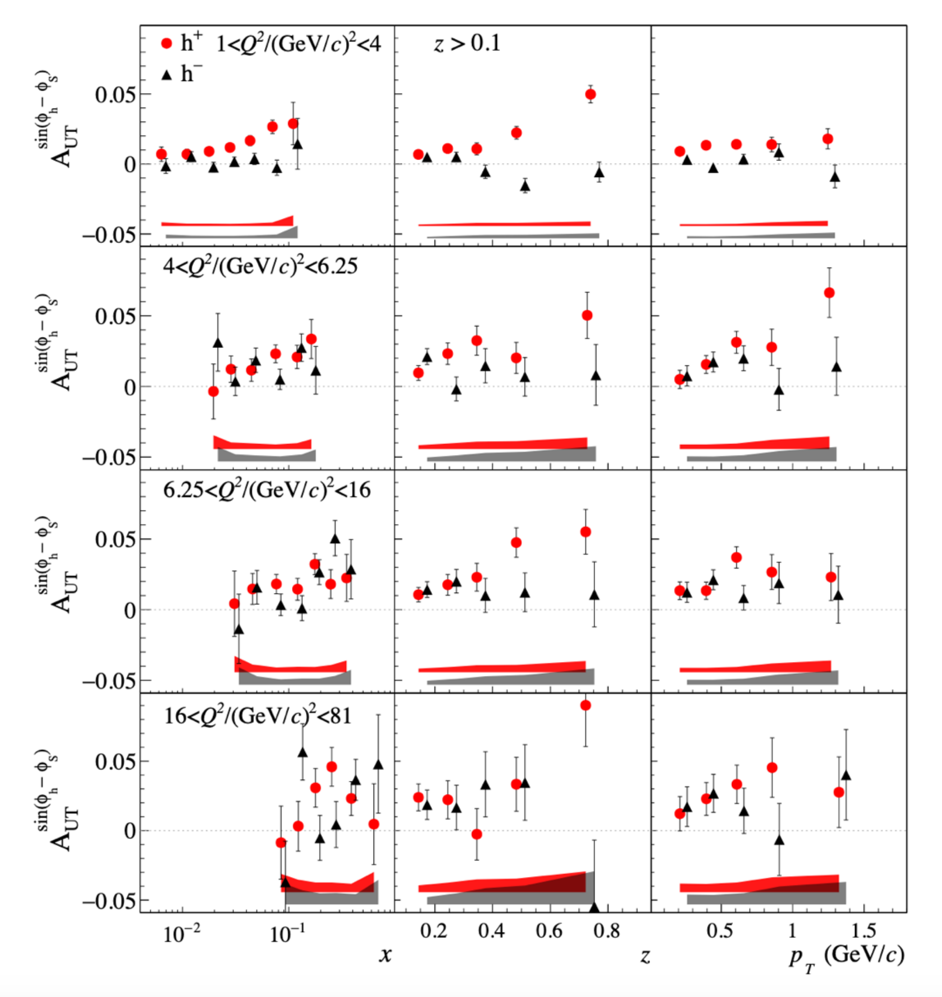
Pioneering Studies by HERMES and COMPASS

Multi-dimensional binning with precision – reduces systematics, constrain models, forms of TMDs, disentangle correlations, isolate phase-space region with large signal strength (HERMES, COMPASS)



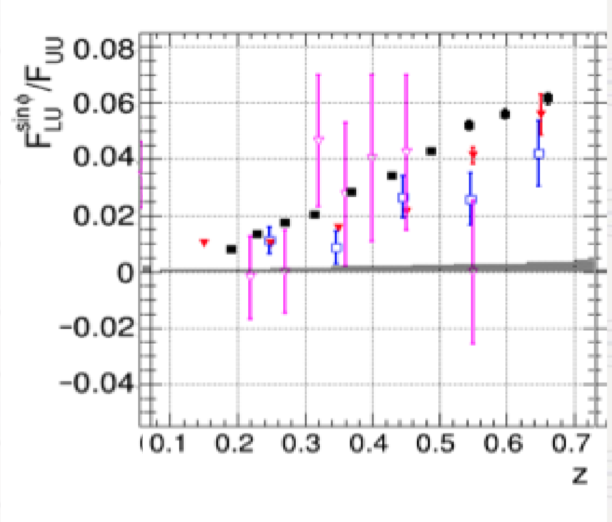
A. Airapetian et al., arXiv:2007.07755

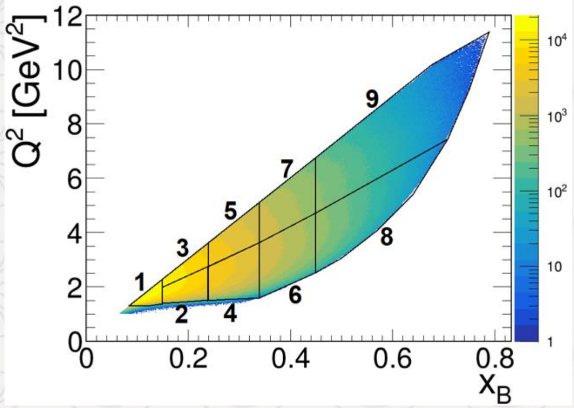


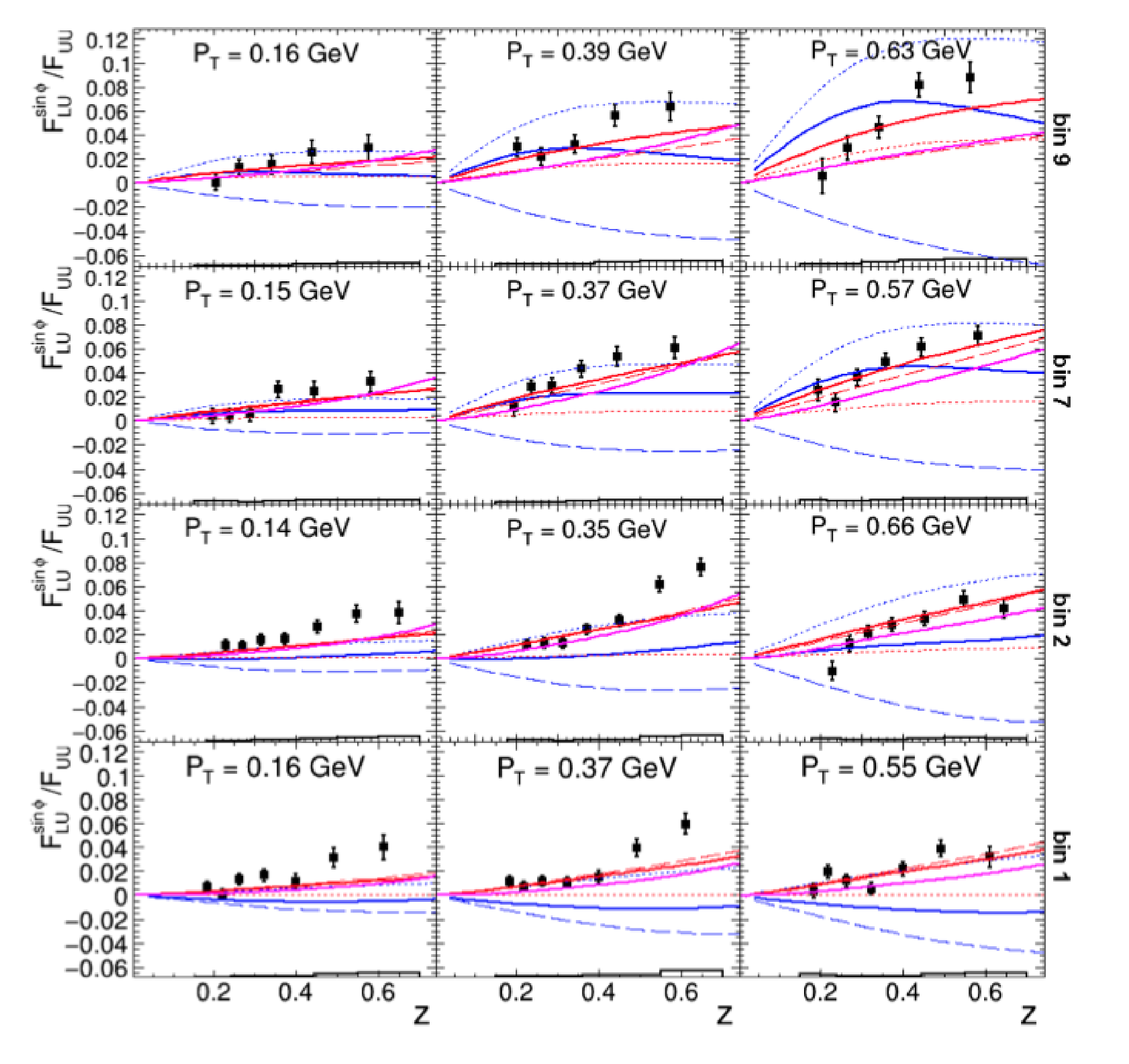
C. Adolph et al. PLB 770, 138 (2017)

State-of-the-art from CLAS 12

multi-dimensional binning with precision – reduces systematics, constrain models, forms of TMDs, disentangle correlations, isolate phase-space region with large signal strength (CLAS12)





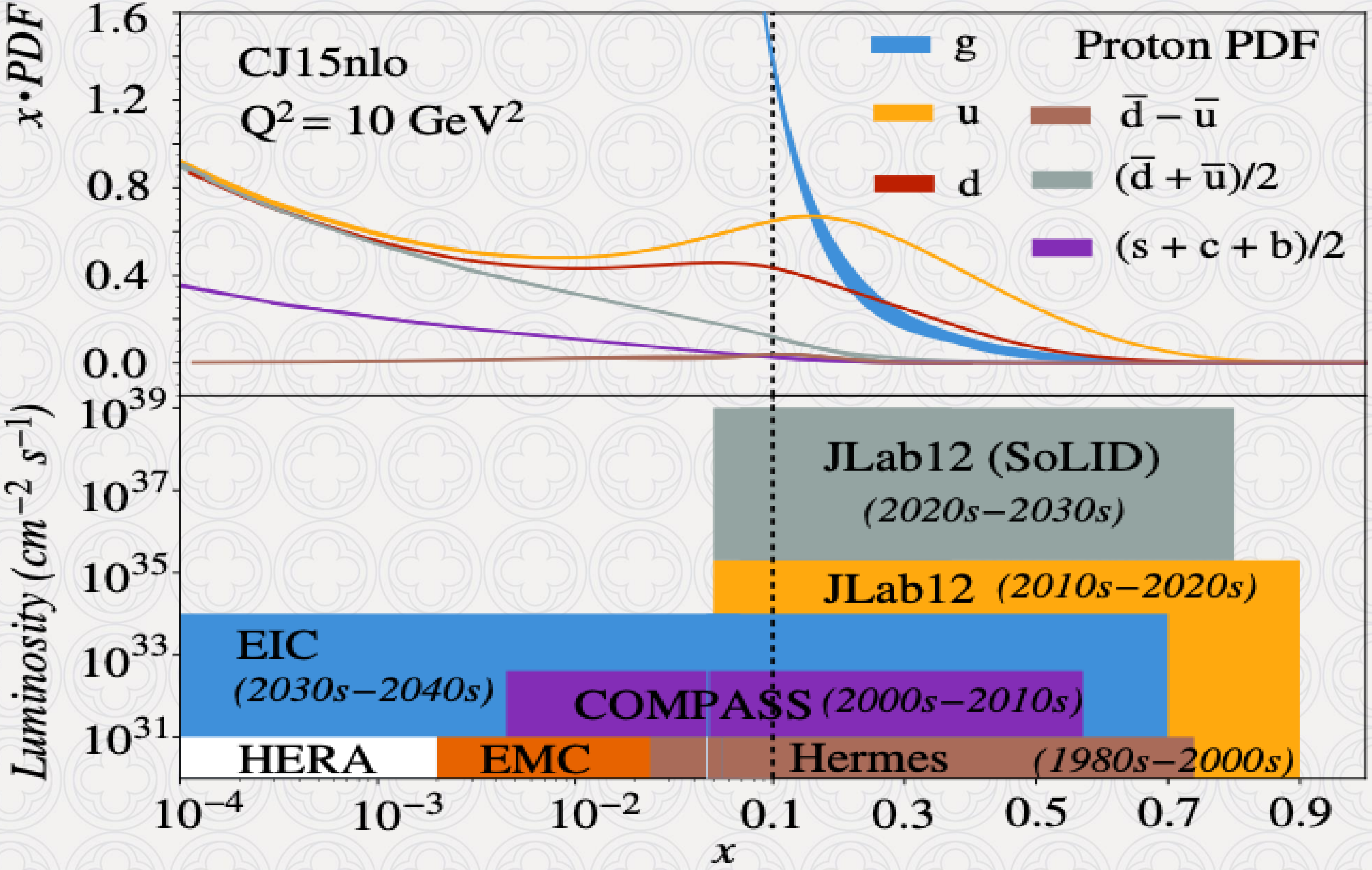


First multidimensional, high precision measurements of semi-inclusive π+ beam single spin asymmetries from the proton over a wide range of kinematics

S. Diehl *et al.* (CLAS Collaboration),
Phys. Rev. Lett. **128**, 062005

Interplay of Energy and Intensity

Structure of visible matter probed at JLab and the future EIC



Arrington, et al., Prog. In Part. and Nucl. Phys. 127,103985 (2022)

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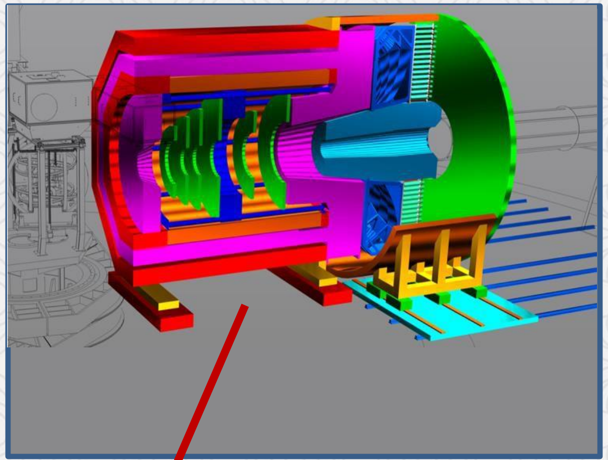
Solenoidal Large Intensity Device (SoLID)

SoLID will ***maximize*** the science return of the 12-GeV CEBAF upgrade by **combining**

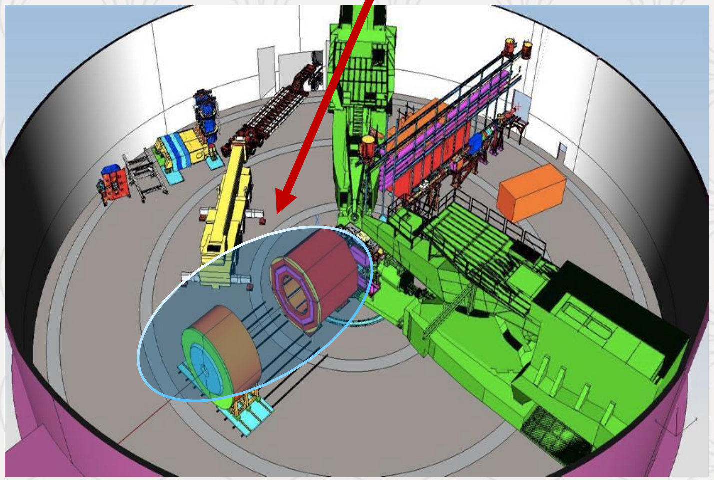
High Luminosity
$10^{37\text{-}39}$ /cm^2/s
[>100x CLAS12][>1000x EIC]

+

Large Acceptance
Full azimuthal ϕ coverage



Research at **SoLID** will have the ***unique*** capability to **explore** the QCD landscape while **complementing** the research of other key facilities



Two science pillars of the SoLID (**proton spin** and **mass**):
high-luminosity valence quark tomography and precision J/ψ production near threshold (EIC in the sea/gluon region, **both needed!)**
PVDIS: test of Standard Model & search for new physics

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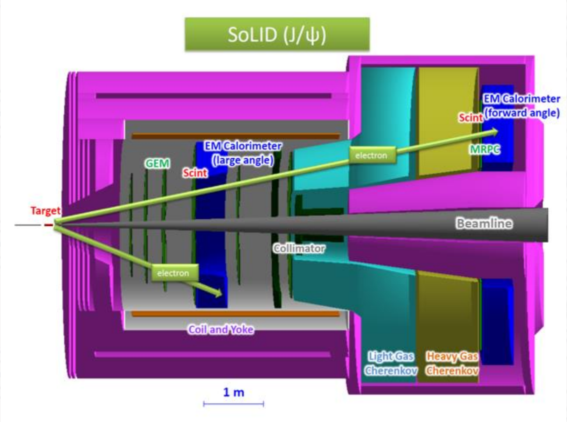
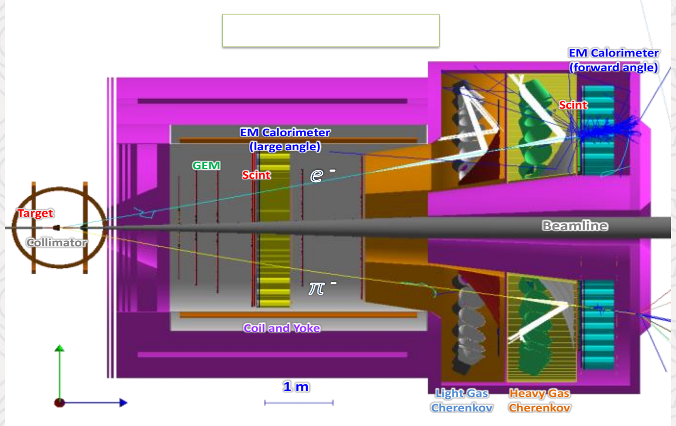
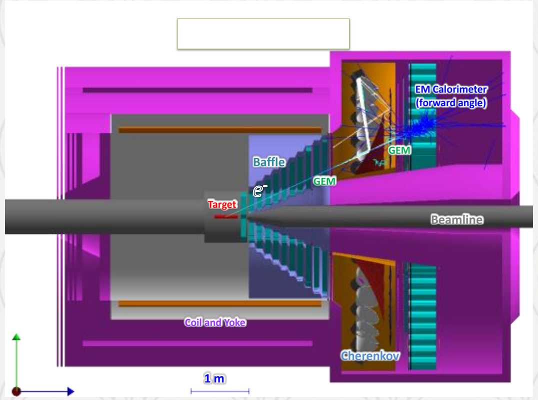
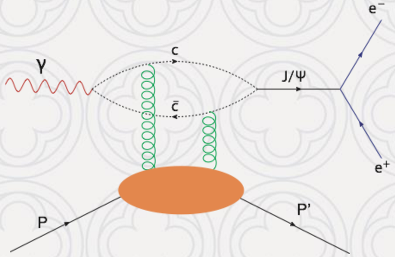
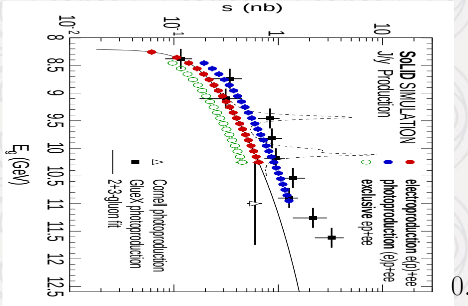
SoLID@JLab: QCD at the intensity frontier

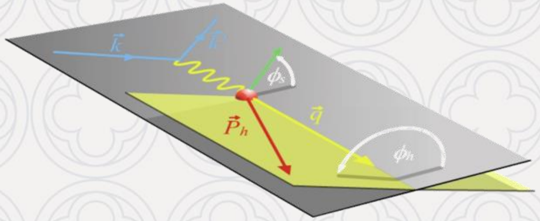


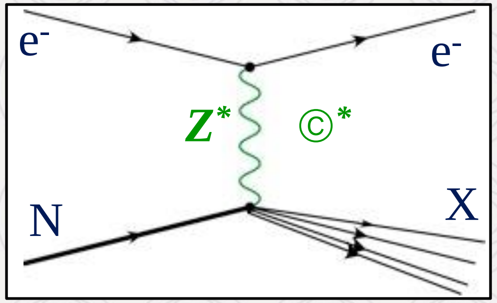


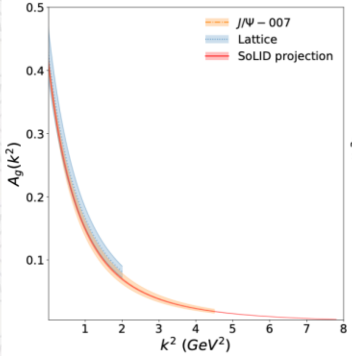


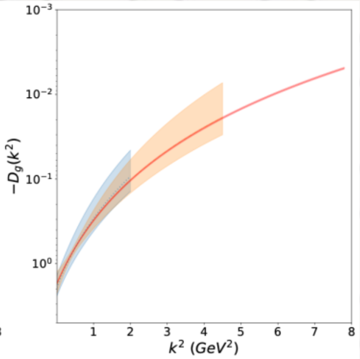


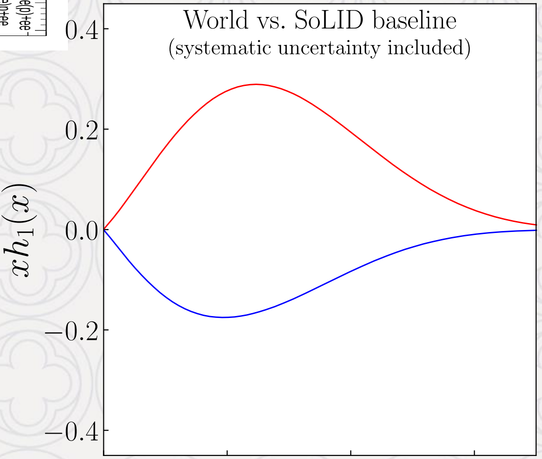


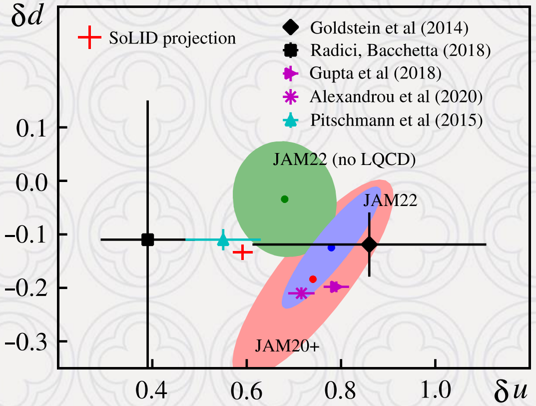


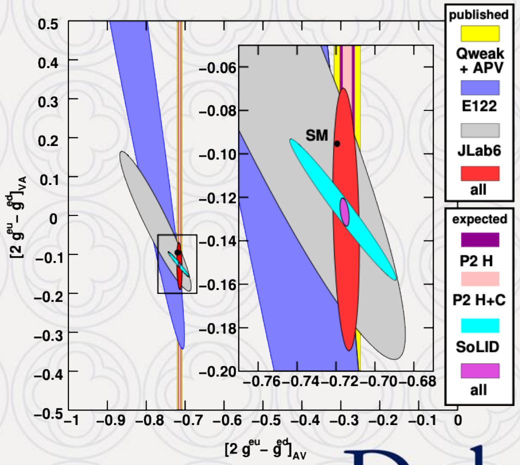










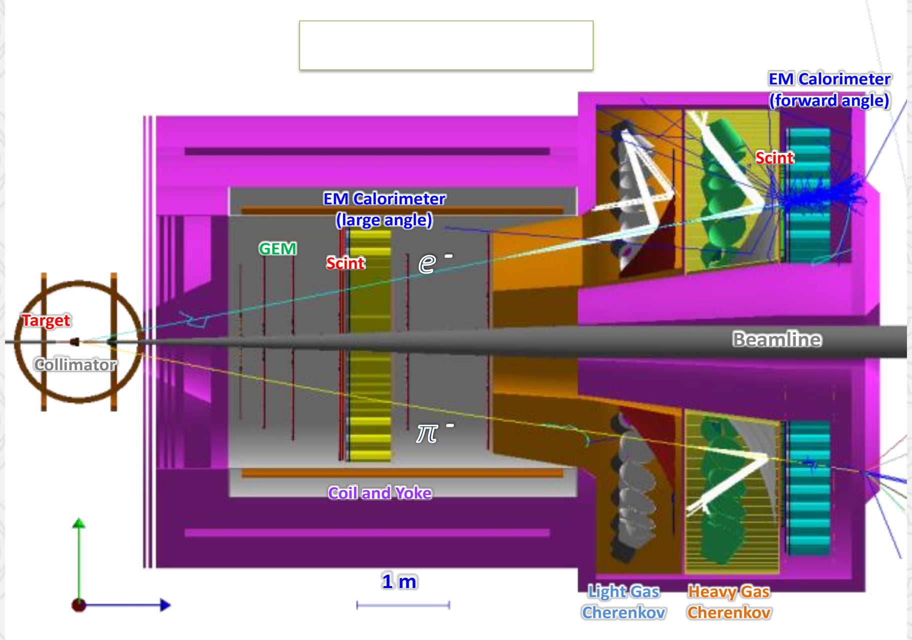


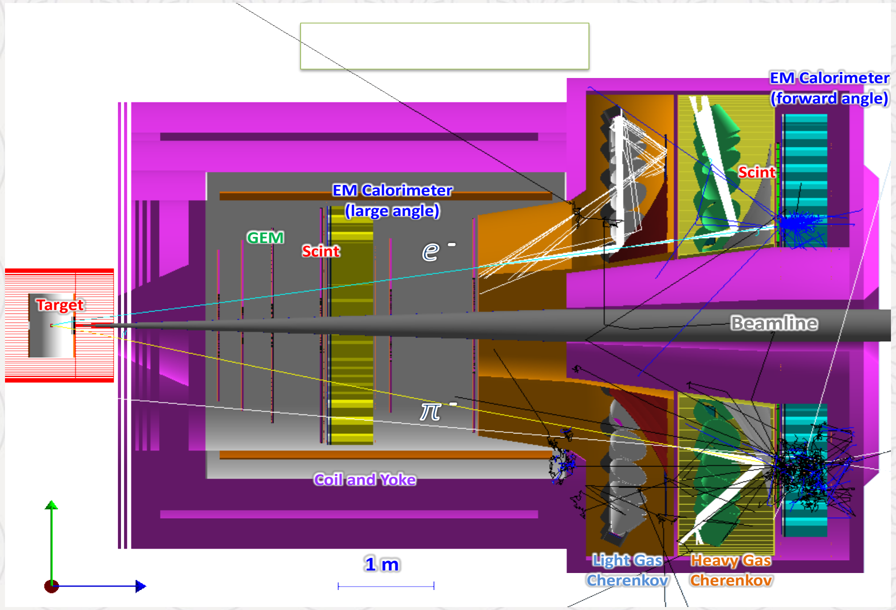
Z. Meziani at this workshop

Arrington *et al.*, J. Phys. G: Nucl. Part. Phys. 50, 110501 (2023)

https://www.innovationnewsnetwork.com/quantum-chromodynamics-at-the-intensity-frontier-with-a-precision-microscope/52920/

SIDIS with polarized "neutron" and proton @ SoLID





E12-10-006: **Rating A**	Single Spin Asymmetries on Transversely Polarized ^{3}He @ 90 days Spokespersons: J.P. Chen, H. Gao (contact), J.C. Peng, X. Qian
E12-11-007: **Rating A**	Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He @ 35 days Spokespersons: J.P. Chen (contact), J. Huang, W.B. Yan
E12-11-108: **Rating A**	Single Spin Asymmetries on Transversely Polarized Proton @ 120 days Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani

Run group experiments approved for TMDs, GPDs, and spin

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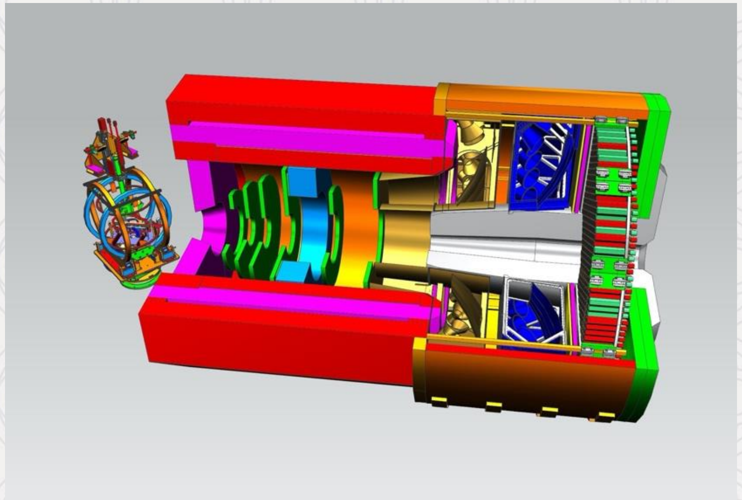
SoLID: large-acceptance & high luminosity

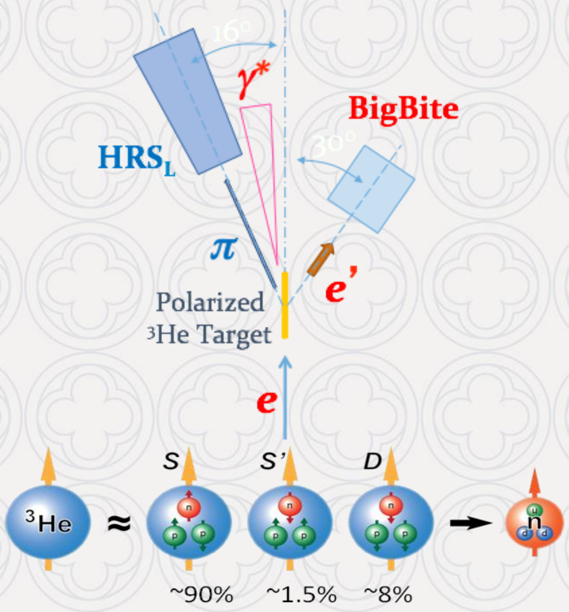


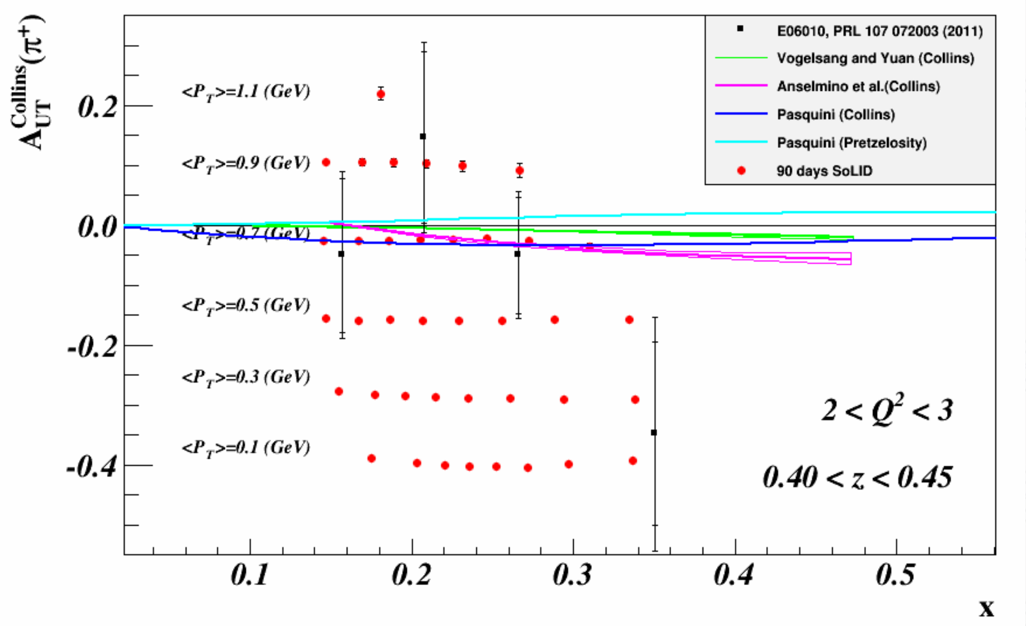
Big leap: 4-D binning for the first time!

SoLID-SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity

- 4-D mapping of asymmetries with precision

  $\Delta z = 0.05$, $\Delta P_T = 0.2$ GeV, $\Delta Q^2 = 1$ GeV^2, x bin sizes vary with median bin size 0.02 (statistical uncertainty for each bin: $\delta A \leq 0.02$)
- Constrain models and forms of TMDs, Tensor charge, …
- Lattice QCD, QCD dynamics, models





X. Qian et al., PRL107, 072003(2011)

- **More than 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.**

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SoLID SIDIS Projection

Compare SoLID with World Data

- Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation
- World data from HERMES, COMPASS
- e^+e^- data from BELLE, BABAR, and BESIII
- Monte Carlo method is applied
- Including both systematic and statistical uncertainties

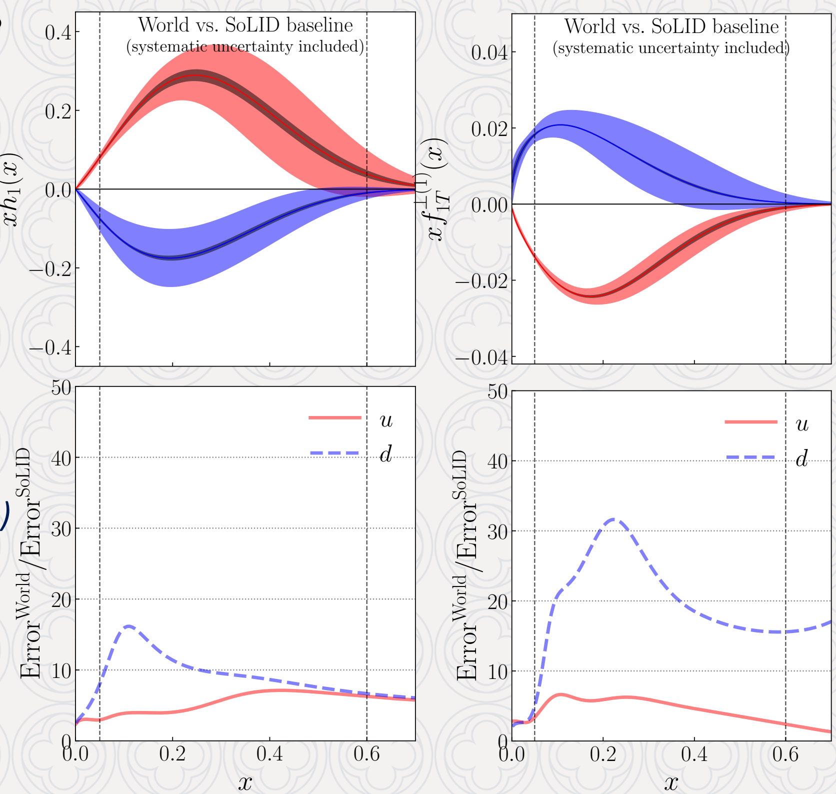
World data according to SoLID preCDR (2019)
https://solid.jlab.org/experiments.html

SoLID baseline used

D'Alesio et al., Phys. Lett. B 803 (2020)135347
Anselmino et al., JHEP 04 (2017) 046

Z. Ye et al., PLB 76, 91 (2017)
T. Liu (2018): https://pos.sissa.it/317/036

Transversity **Sivers**



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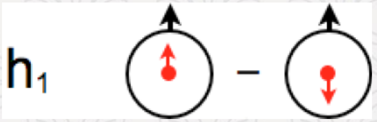
Transversity and Tensor Charge

Transversity distribution



(Collinear & TMD)

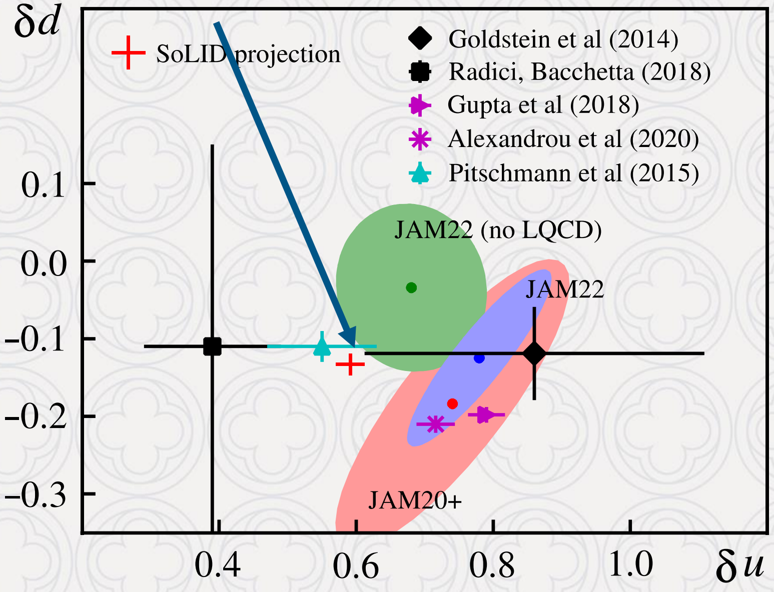
- Chiral-odd, unique for the quarks
- No mixing with gluons, simpler evolution effect
- Tensor charge:

$$\langle \mathrm{P,S}|\overline{\psi}_q i\sigma^{\mu\nu}\psi_q|\mathrm{P,S}\rangle = g_T^q \overline{u}(\mathrm{P,S}) i\sigma^{\mu\nu} u(\mathrm{P,S})$$

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

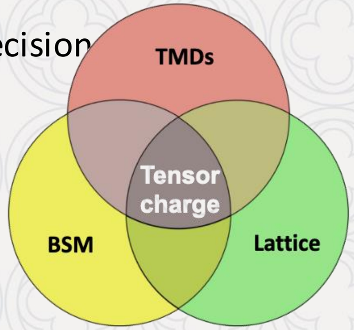
- A fundamental QCD quantity dominated by valence quarks
- Precisely calculated on the lattice
- Difference from nucleon axial charge is due to relativity
- SoLID measurements allows for high-precision test of LQCD predictions
- Global analysis including LQCD (PRL 120 (2018) 15, 152502

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



SoLID projection: statistical and systematic uncertainties included (shifted for visibility)

J. Cammarota et al, PRD 102, 054002 (2020) (JAM20+)
L. Gamberg et al., PRD 106, 034014 (2022) (JAM22)



Nucleon Electric Dipole Moment and Tensor Charge

$$d_n = g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s$$

$$d_p = g_T^u\, d_u + g_T^d\, d_d + g_T^s\, d_s$$

Image credit: D. Pitonyak

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Constraint on Quark EDMs

Constraint on quark EDMs with combined proton and neutron EDMs

	d_u upper limit	d_d upper limit
Current g_T + current EDMs	$1.27\times10^{-24}e$ cm	$1.17\times10^{-24}e$ cm
SoLID g_T + current EDMs	$6.72\times10^{-25}e$ cm	$1.07\times10^{-24}e$ cm
SoLID g_T + future EDMs	$1.20\times10^{-27}e$ cm	$7.18\times10^{-28}e$ cm

Include 10% isospin symmetry breaking uncertainty

Sensitivity to new physics

$$d_q \sim \; e m_q/(4\pi\Lambda^2)$$

Three orders of magnitude improvement on quark EDM limit → Probe to 30 ~ 40 times higher scale

Current quark EDM limit: $10^{-24}e$ cm → ~ 1 TeV

Future quark EDM limit: $10^{-27}e$ cm → 30 ~ 40 TeV

H. Gao, T. Liu, Z. Zhao, PRD 97, 074018 (2018)

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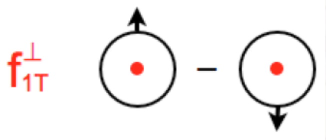
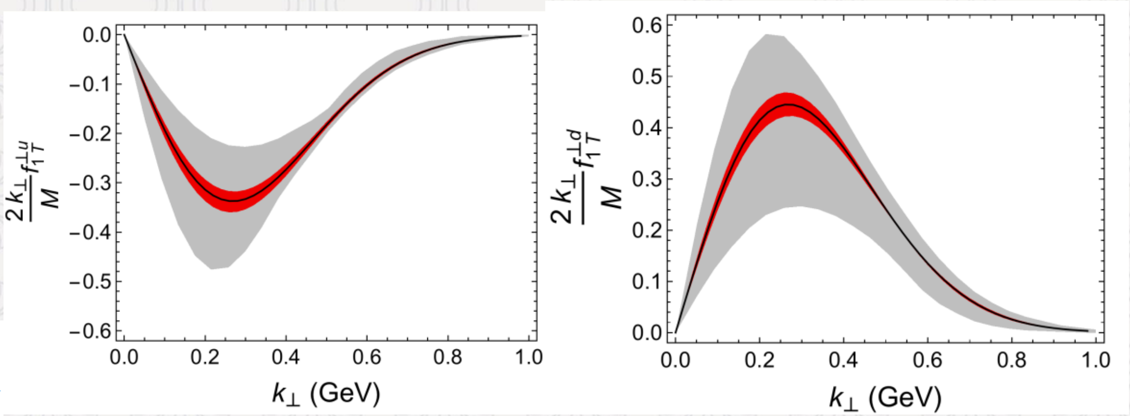
Confined motion inside the nucleon

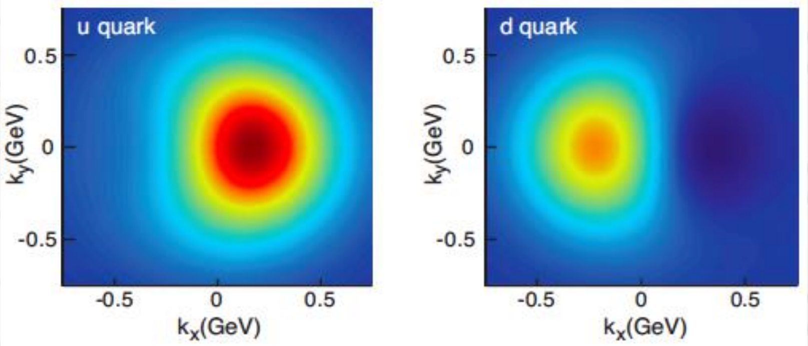
Sivers distribution



naively time-reversal odd

$$f_{1T}^{\perp q}(x, k_\perp)\Big|_{\rm SIDIS} = -f_{1T}^{\perp q}(x, k_\perp)\Big|_{\rm DY}$$





$$f_{q/p\uparrow}(x, \mathbf{k}_\perp) = f_1^q(x, k_\perp) - f_{1T}^{\perp q}(x, k_\perp)\frac{\widehat{\mathbf{P}} \times \mathbf{k}_\perp \cdot \mathbf{S}}{M}$$

$$\langle \mathbf{k}_\perp \rangle = -M \int dx\, f_{1T}^{\perp(1)}(x)(\mathbf{S} \times \widehat{\mathbf{P}})$$

Parametrization by M. Anselmino et al., EPJ A 39, 89 (2009)

SoLID projection with transversely polarized n/p

	$\langle k_\perp \rangle^u$	$\langle k_\perp \rangle^d$
(grey)	96^{+60}_{-28} MeV	-113^{+45}_{-51} MeV
(red)	$96^{+2.8}_{-2.4}$ MeV	$-113^{+1.3}_{-1.7}$ MeV

Nucleon spin - quark orbital angular momentum (OAM) correlation
– zero if no OAM (collinear, massless quarks)

Exact finding is model dependent but SoLID impact is model-independent!

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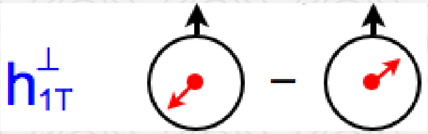
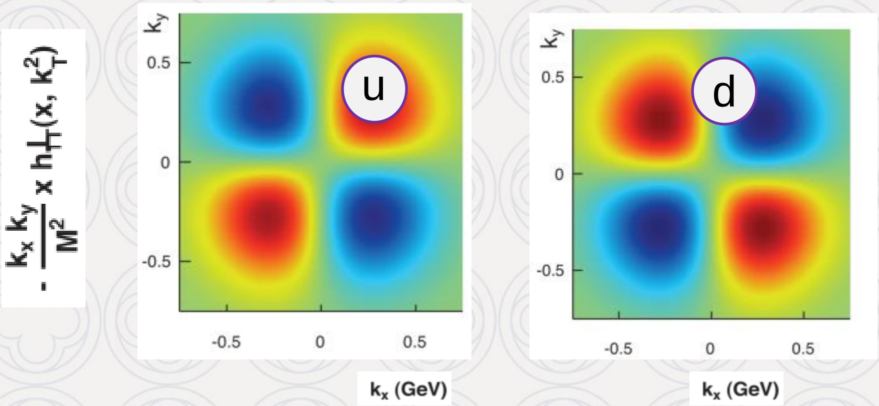
Confined motion inside the nucleon

Pretzelocity distribution



- Chiral-odd, no gluon analogy
- Quadrupole modulation of parton density in the distribution of transversely polarized quarks in a transversely polarized nucleon
- Measuring the difference between helicity and transversity (relativistic effects)



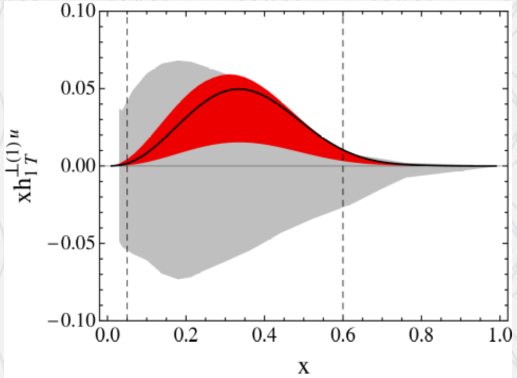
Images from PRD 91 034010 (2015)

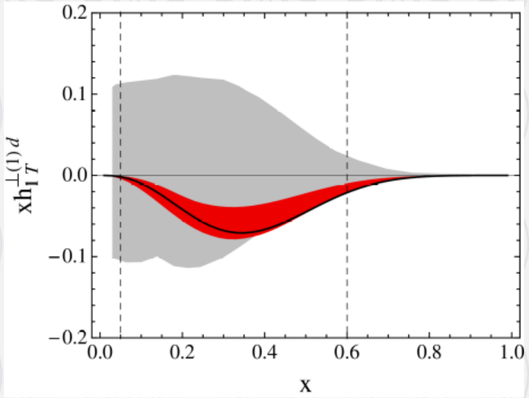
Parametrization by C. Lefky et al., PRD 91, 034010 (2015)

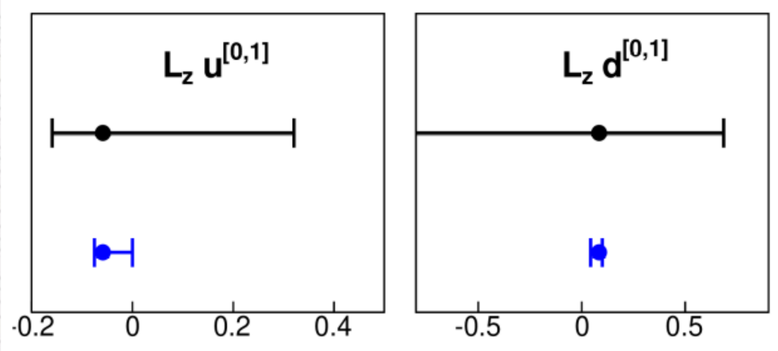
SoLID projection with transversely polarized n and p data

Relation to OAM (canonical)

$$L_z^q = -\int dx d^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int dx h_{1T}^{\perp(1)q}(x)$$





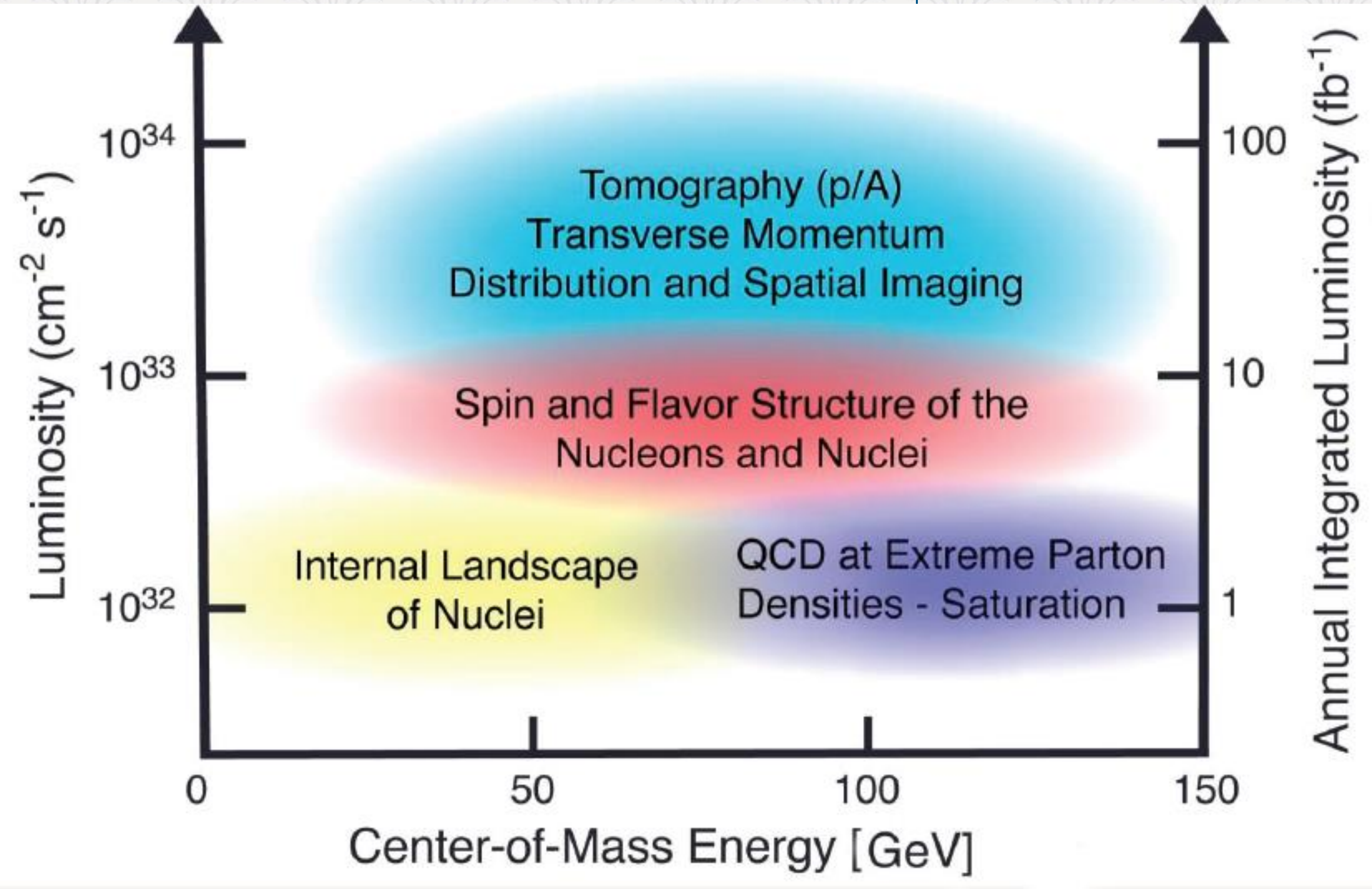


Lefky and Prokudin PRD 91, 034010 (2015)

SoLID projection

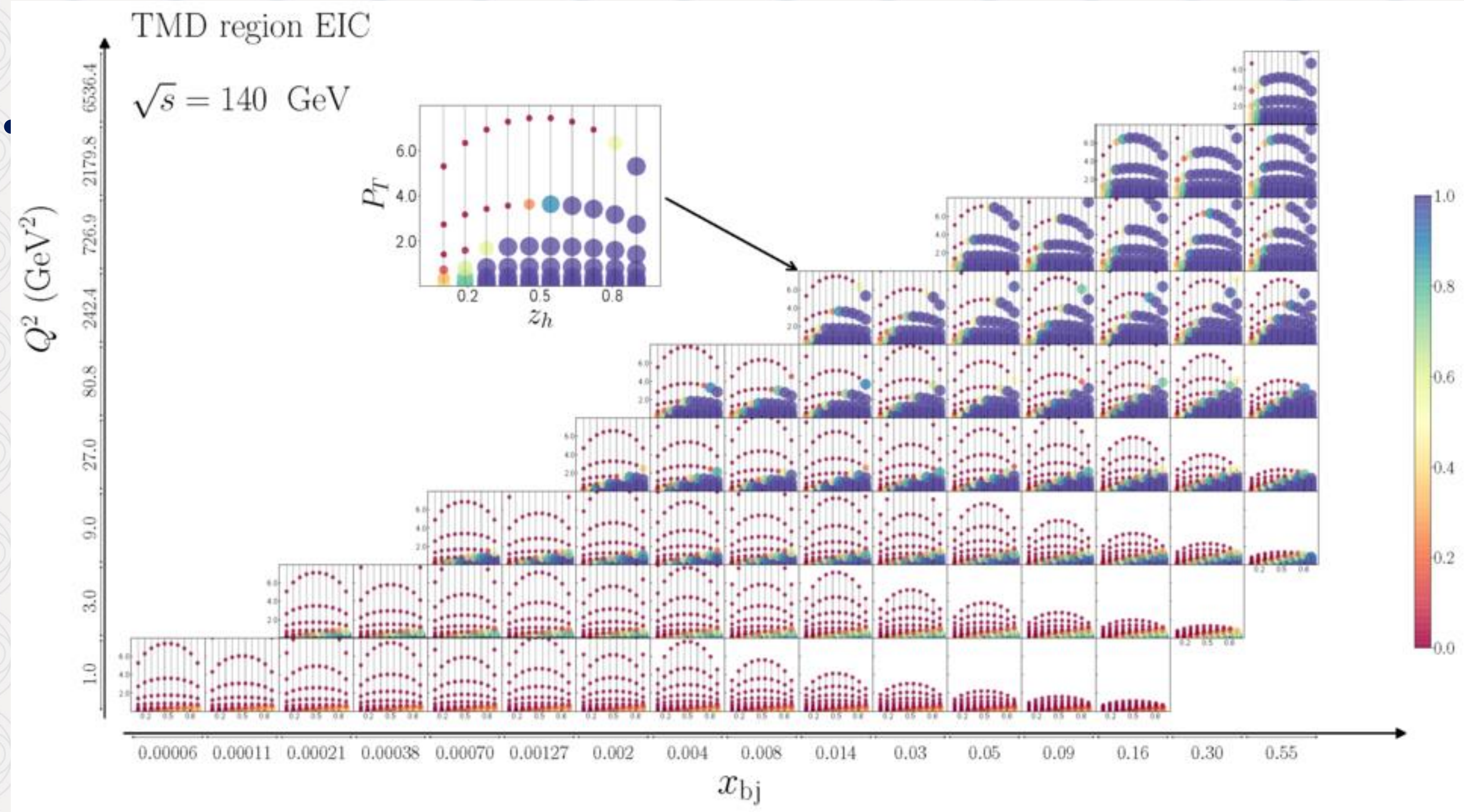
EIC Project Design Goals

- High Luminosity: L= 10^{33}–10^{34} $cm^{-2}sec^{-1}$, 10–100 fb^{-1}/year
- Highly Polarized Beams: ~70%
- Large Center of Mass Energy Range: E_{cm} = 29–140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)



Duke

Unpolarized TMDs and TMD evolution



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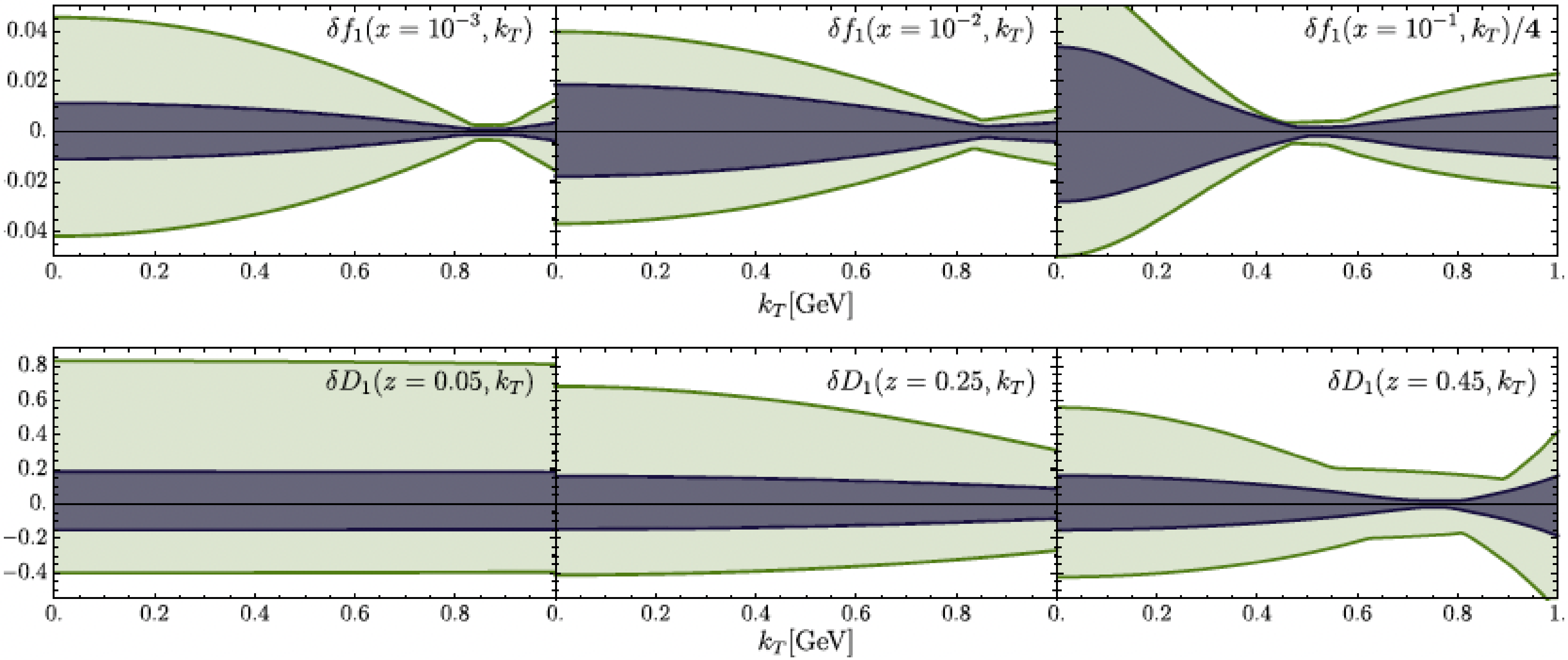

Figure 7.52: Comparison of relative uncertainty bands (i.e. uncertainties normalized by central value) for up-quark unpolarized TMD PDFs (upper panel) and $u \to \pi^+$ pion TMD FFs (lower panel), at different values of x and z as a function of k_T, for $\mu = 2$ GeV. Lighter band is the SV19 extraction, darker is SV19 with EIC pseudodata.

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Quark Sivers and Collins measurements

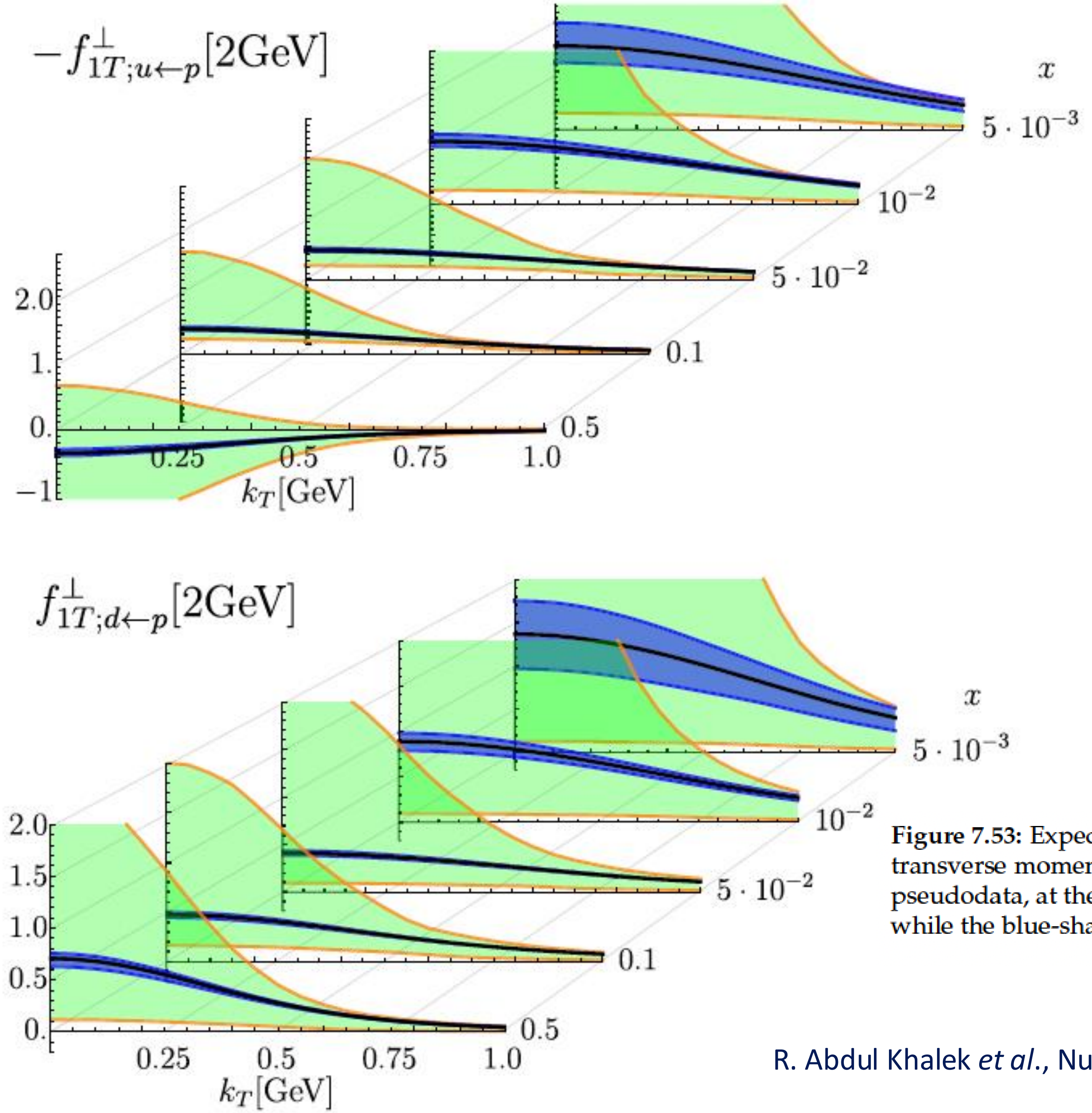

Figure 7.53: Expected impact on up and down quark Sivers distributions as a function of the transverse momentum k_T for different values of x, obtained from SIDIS pion and kaon EIC pseudodata, at the scale of 2 GeV. The green-shaded areas represent the current uncertainty, while the blue-shaded areas are the uncertainties when including the EIC pseudodata.

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Quark Sivers and Collins measurements

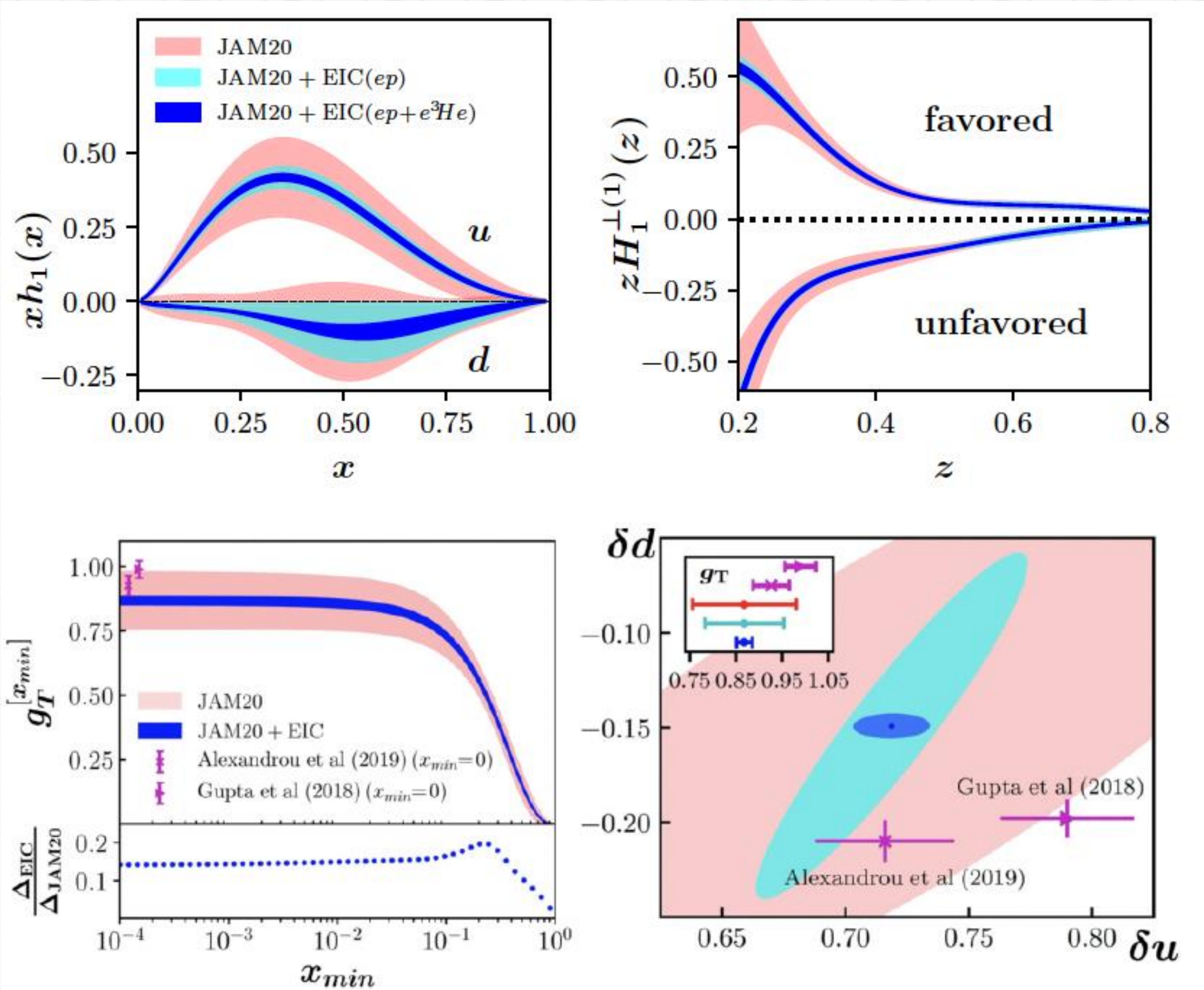

Figure 7.54: Top: Expected impact on the up and down quark transversity distributions and favored and unfavored Collins function first moment when including EIC Collins effect SIDIS pseudodata from e+p and e+He collisions [526]. Bottom left: Plot of the truncated integral $g_T^{[x_{min}]}$ vs. x_{min}. Also shown is the ratio $\Delta_{EIC}/\Delta_{JAM20}$ of the uncertainty in $g_T^{[x_{min}]}$ for the re-fit that includes pseudodata from the EIC to that of the original JAM20 fit [241]. Note that the results from two recent lattice QCD calculations [527,528] are for the full g_T integral (i.e., $x_{min} = 0$) and have been offset for clarity. Bottom right: The impact on the up quark (δu), down quark (δd), and isovector (g_T) tensor charges and their comparison to the lattice data.

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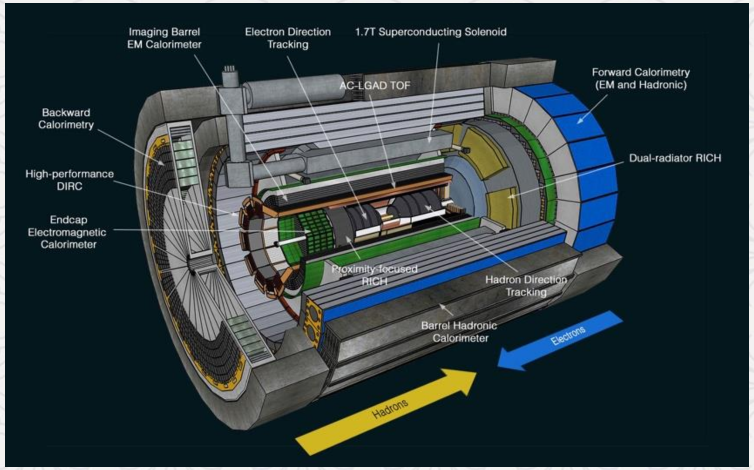
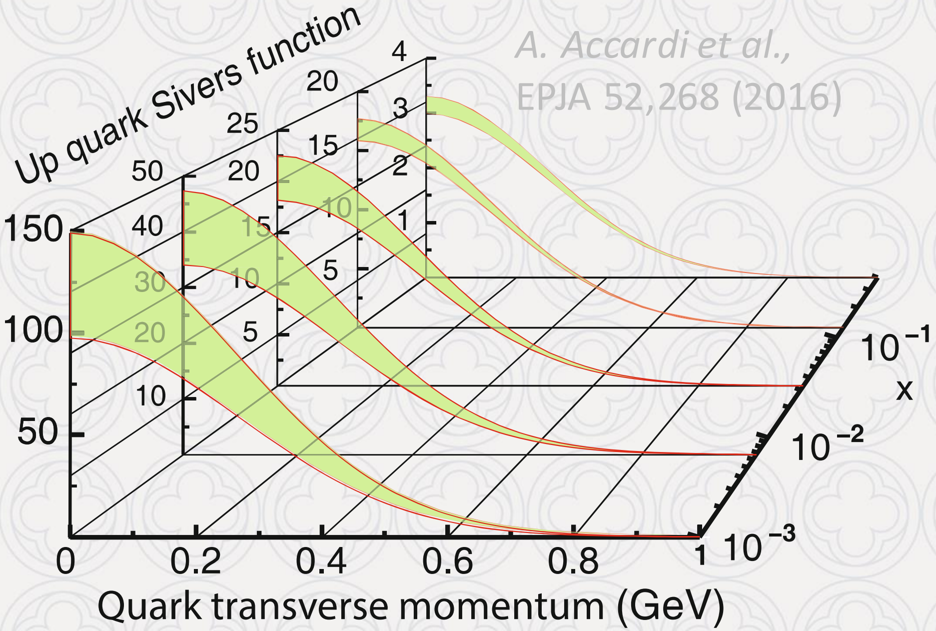
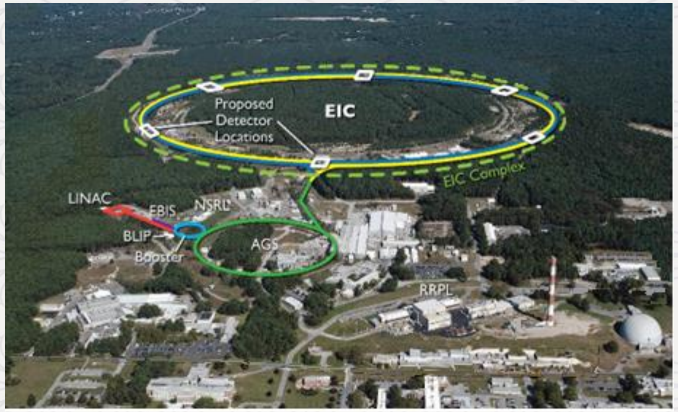
Di-hadron impact, A. Vossen at this workshop

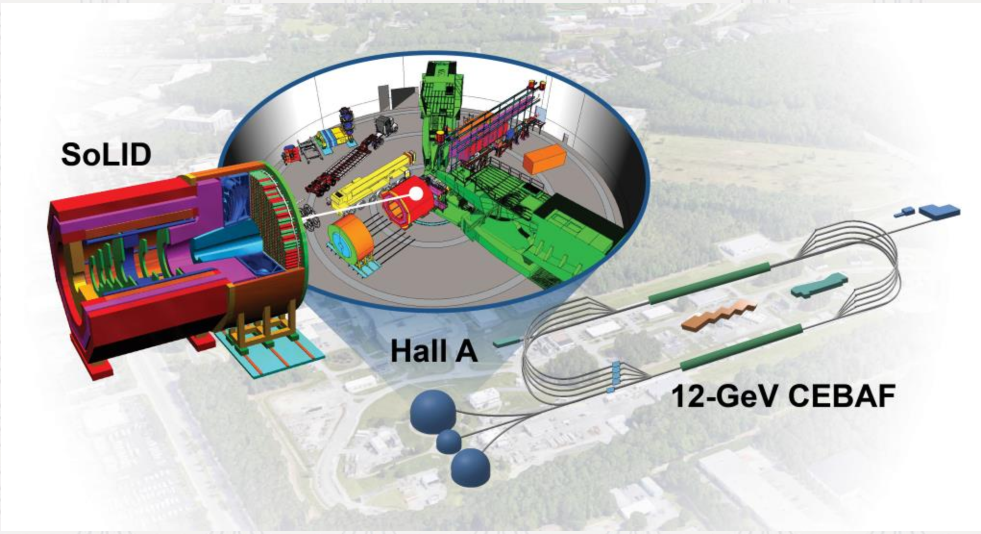
Precision tomography of the nucleon requires both valence quark and gluon region

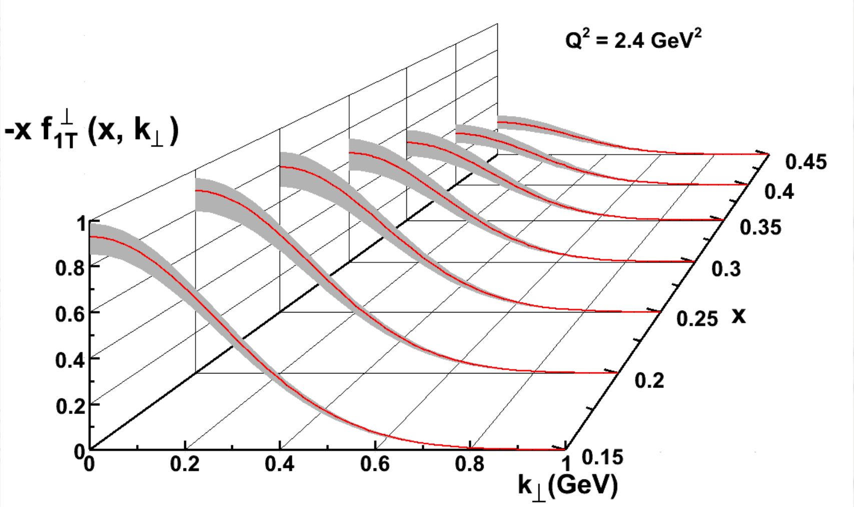




A. Accardi et al.,
EPJA 52,268 (2016)







J. Dudek et al.,
EPJA 48,187 (2012)

Precision and Challenges

- TMD factorization
- Higher twist effects
- Evolution
- Radiative corrections
- Vector meson production, e.g. ρ^0 meson
- Nuclear effects (^{3}He, d used for neutron)
- others

Data from JLab, EIC, and other facilities and from all relevant reactions will be essential, and close collaborations between experiment, theory, phenomenology, and computation are path to success.

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