SoLID Semi-Inclusive Deep Inelastic Scattering (SIDIS) Program

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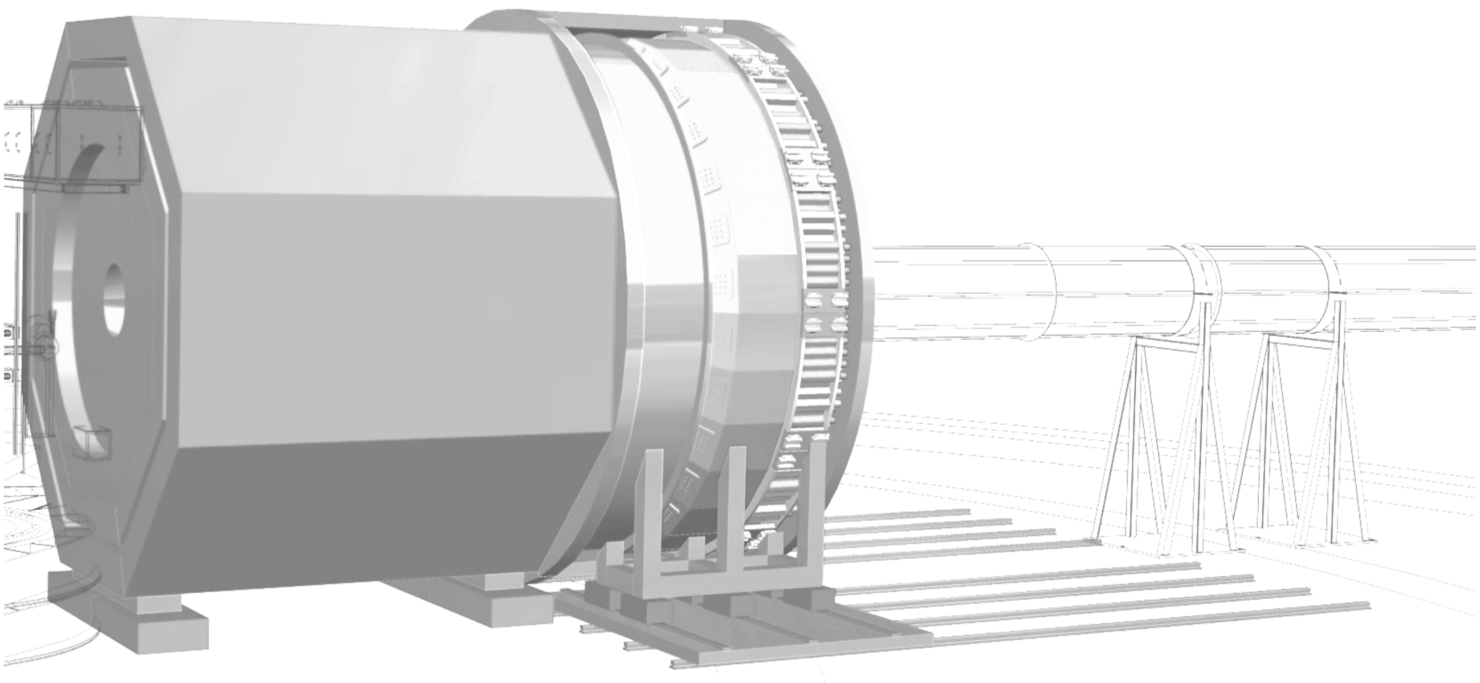
The SoLID Collaboration
Duke University

JLab Director's Review

February 9 -10, 2021

SOLENOIDAL LARGE INTENSITY DEVICE



The JLab Director's Review Charge:

- (**C1**) The significance of scientific questions identified by the SoLID Collaboration.
- (**C2**) The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities, including the US Electron Ion Collider.
- (**C3**) The new experimental and theoretical research efforts and technical capabilities needed to accomplish the proposed scientific program.
- (**C4**) The feasibility of the approach or method presented to carry out the proposed scientific program and the likelihood that significant results can be obtained in the first three years of detector operations.

This presentation will address C1, C2, C3 and C4 (also by J.P. Chen)
J.W. Qiu's presentation on C1-C4 (already mostly from the theory side)

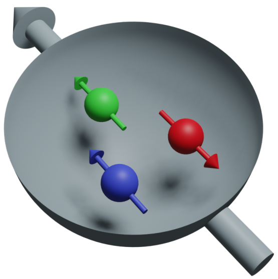
Outline

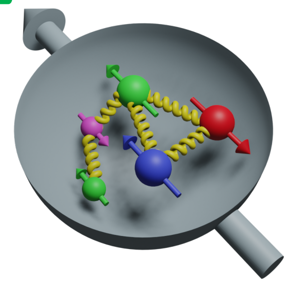
1. Introduction and motivation
2. Nucleon tomography in momentum space with **SoLID SIDIS**
3. Physics impact of SoLID SIDIS
4. SoLID SIDIS in the context of 12-GeV CEBAF and EIC
5. Summary

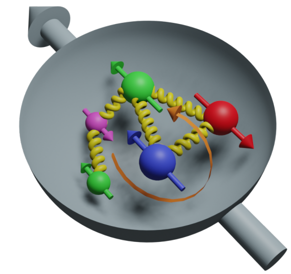
The incomplete nucleon: spin puzzle

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

Jaffe-Manohar, 90
Ji, 96







Quark helicity
Best known

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

$$\sim 30\%$$

Gluon helicity
Start to know

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

Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

With larger uncertainty → **~40% -- RHIC Spin data at $Q^2 = 10\ \mathrm{GeV}^2$**

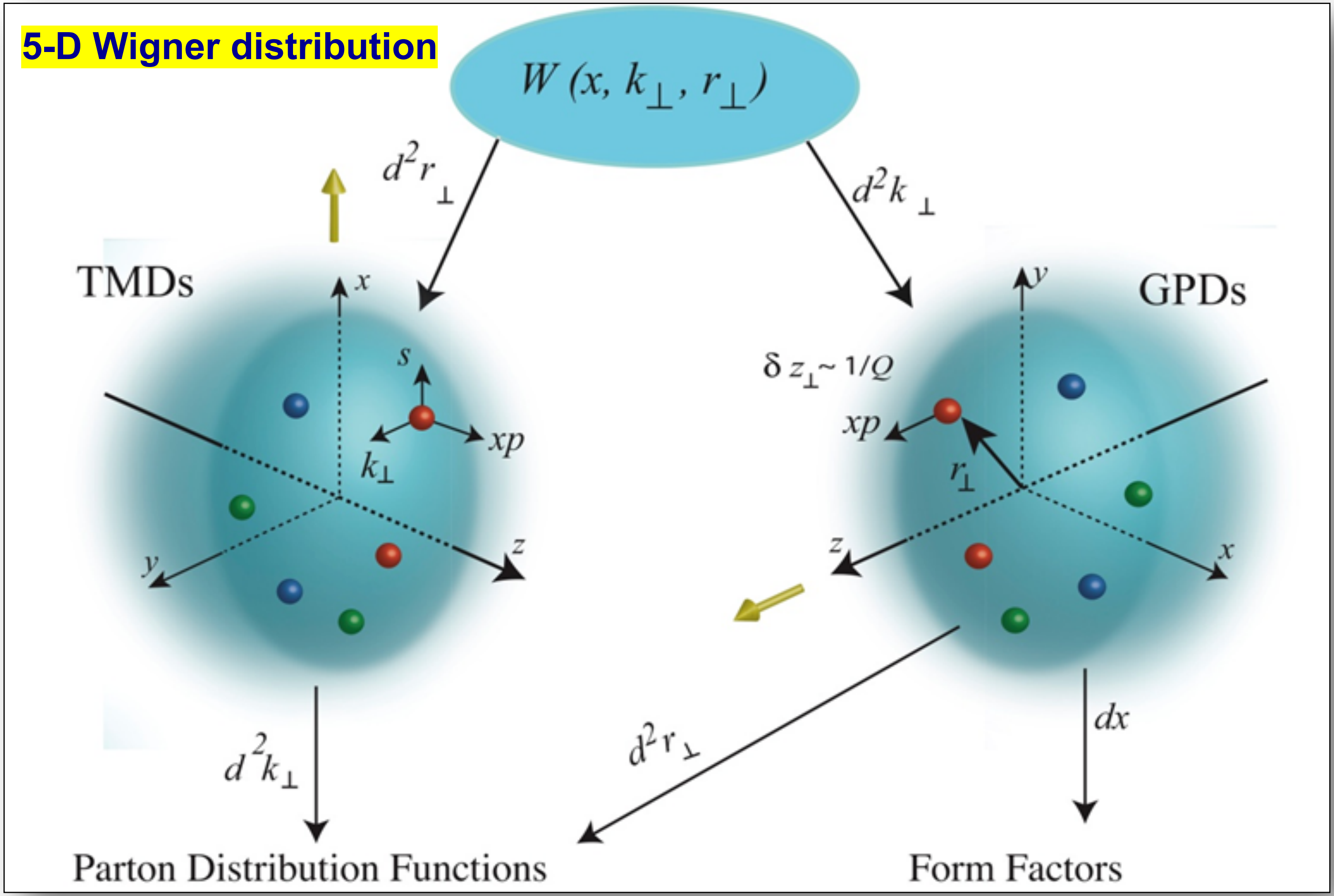
Lattice QCD →

$$L_{u+d+s} = 0.207(64)_{stat}(45)_{syst}$$
$$J_{u+d+s} = 0.408(61)_{stat}(48)_{syst}$$
$$J_g = 0.133(11)_{stat}(14)_{syst}$$

$$J_N = 0.54(6)_{stat}(5)_{syst}$$
$$(\overline{\mathrm{MS}} = 2\ \mathrm{GeV})$$

C. Alexandrou et al., PRL 119, 142002 (2017).

Nucleon Structure from 1D to 3D – orbital motion



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

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

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

SoLID@12-GeV JLab: QCD at the intensity frontier

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]

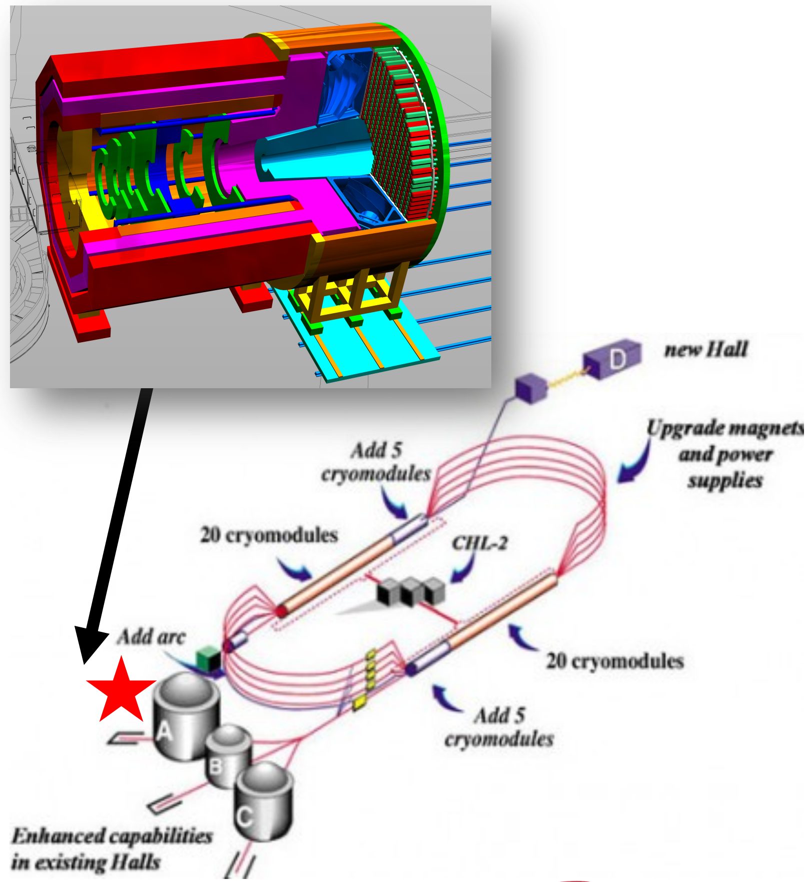
+

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

- Pushing the phase space in the search of new physics and of hadronic physics
- 3D momentum imaging of a relativistic strongly interacting confined system (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton mass**)

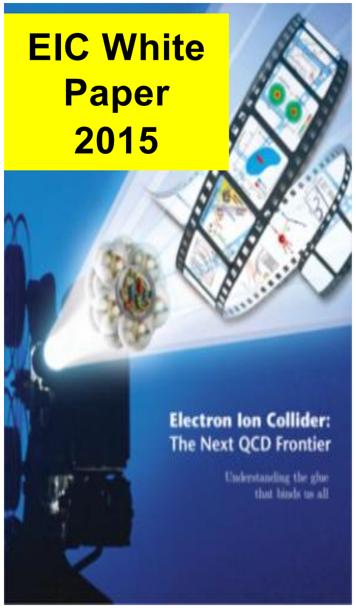
Synergizing with the pillars of EIC science (**proton spin** and **mass**) through high-luminosity valence quark tomography and precision J/ψ production near threshold

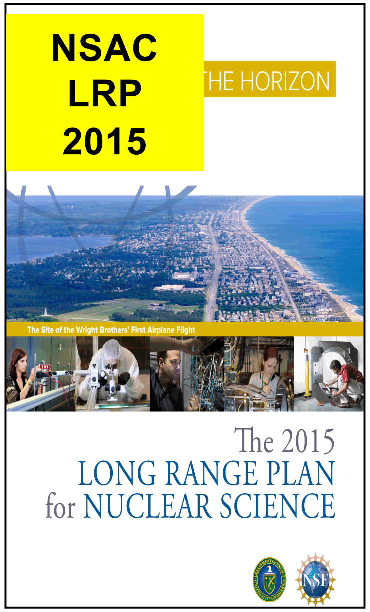


The Committee on U.S.-Based Electron Ion Collider Science Assessment

Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the **mass** of the nucleon arise?
- How does the **spin** of the nucleon arise?
- What are the emergent properties of dense systems of gluons?





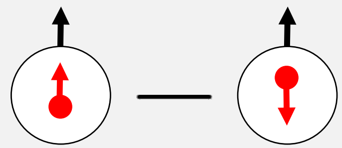
citation: National Academies of Sciences, Engineering, and Medicine. 2018. An Assessment of U.S.-Based Electron-Ion Collider Science. Washington, DC: The National Academies Press. https://doi.org/10.17226/25171

TMDs – confined motion inside the nucleon

Transversely Polarized Nucleon TMDs

→ Nucleon Spin
→ Quark Spin

Transversity

$h_{1T} =$ 

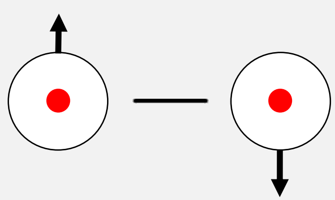
$$\mathbf{S}_T \cdot \mathbf{s}_q$$

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

Relevant Vectors

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

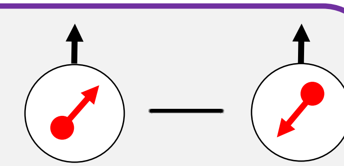
Sivers

$f_{1T}^{\perp} =$ 

$$\mathbf{S}_T \cdot \mathbf{k}_\perp \times \mathbf{P}$$

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

Pretzelosity

$h_{1T}^{\perp} =$ 

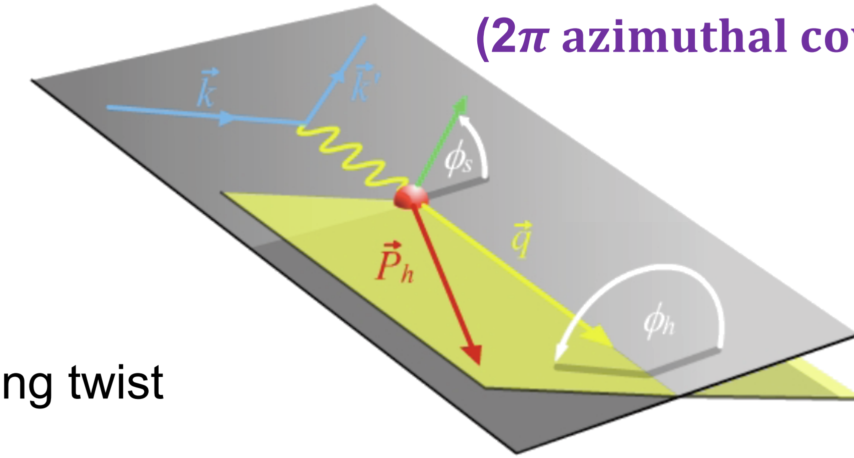
$$\mathbf{S}_T \cdot [\mathbf{k}_\perp \mathbf{k}_\perp] \cdot \mathbf{s}_{qT}$$

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

Separation of Collins, Sivers and Pretzelosity effects through angular dependence

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)



$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

Leading twist

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

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

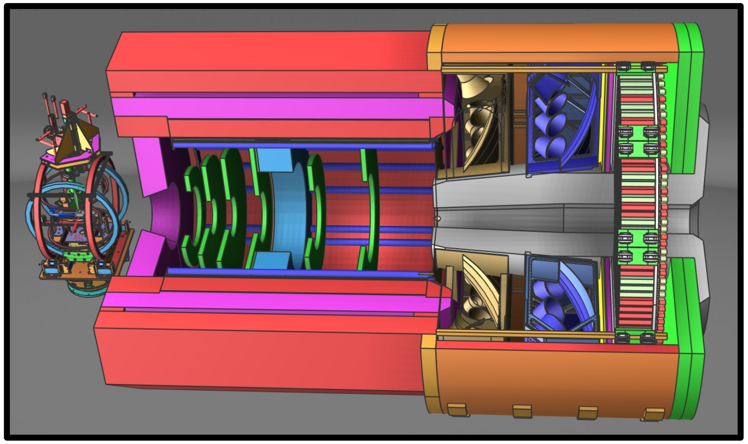
$$\boxed{A_{UT}^{Pretzelosity}} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins fragmentation function from e^+e^- collisions

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

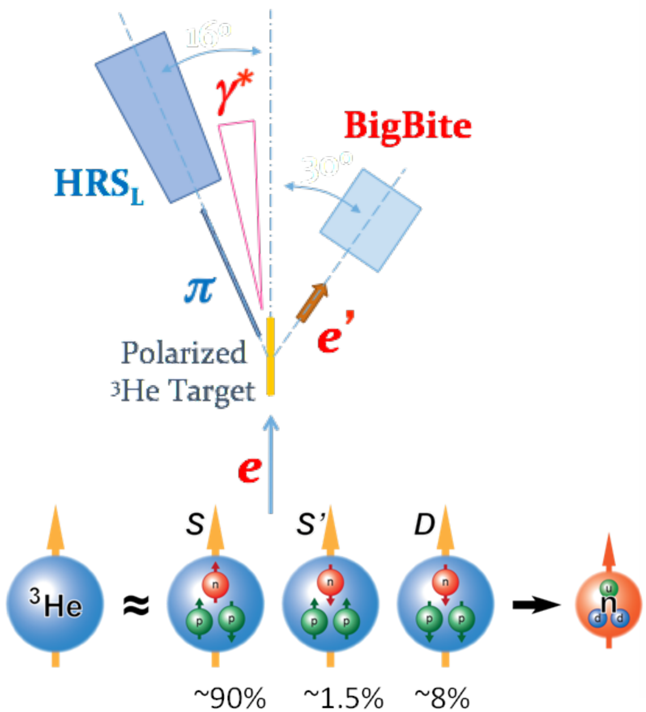
Unpolarized fragmentation function

QCD intensity frontier with SoLID: large-acceptance & high luminosity

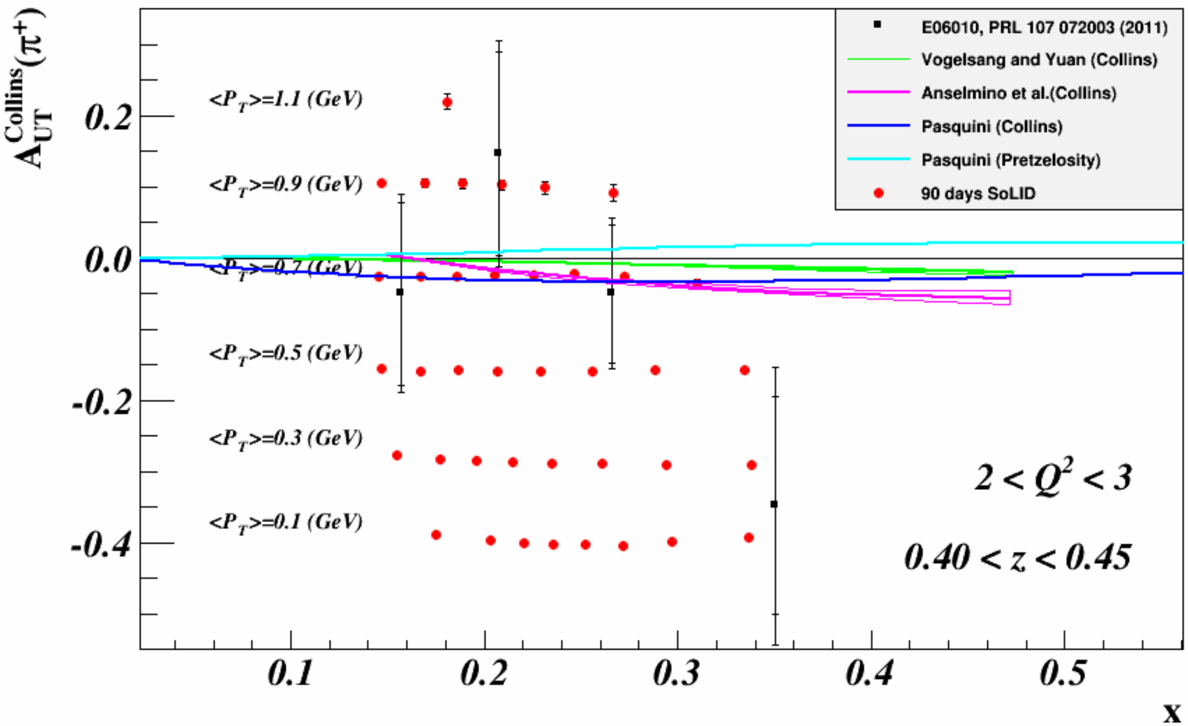


Key of SoLID-spin program:
Large acceptance, Full azimuthal coverage
+ High luminosity

- 4-D mapping of asymmetries
- Tensor charge, TMDs …
- Lattice QCD, QCD dynamics, models



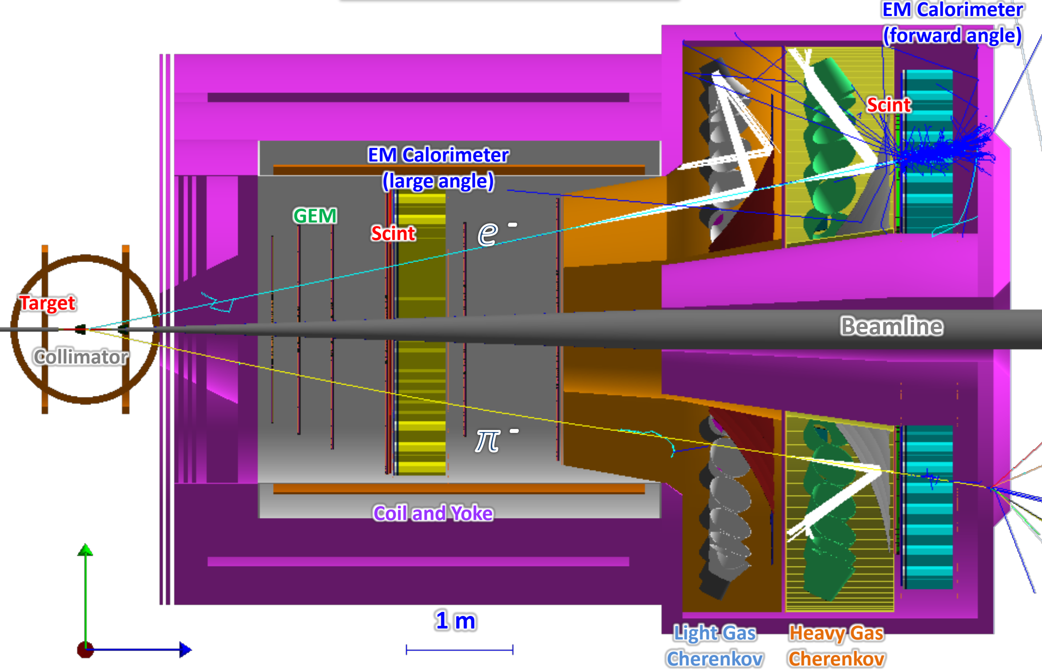
X. Qian et al., PRL107, 072003(2011)



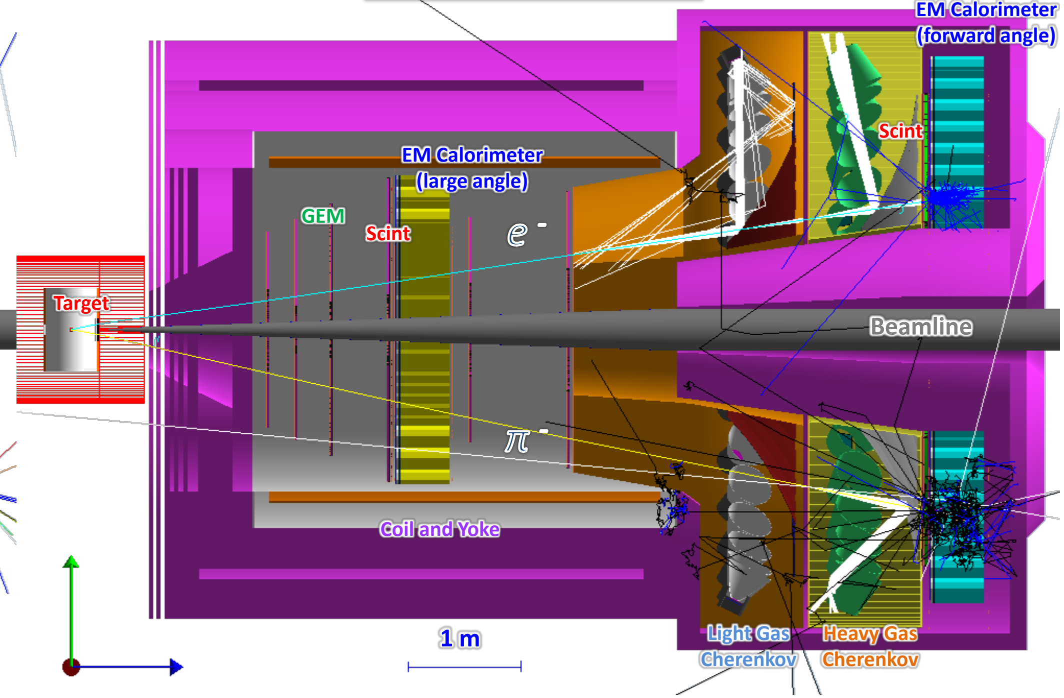
- Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.

SIDIS with polarized "neutron" and proton @ SoLID

SoLID (SIDIS He3)



SoLID (SIDIS NH3)



E12-10-006: Single Spin Asymmetries on Transversely Polarized ^{3}He @ 90 days
Rating A Spokespersons: J.P. Chen, H. Gao (contact), J.C. Peng, X. Qian

E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He @ 35 days
Rating A Spokespersons: J.P. Chen (contact), J. Huang, W.B. Yan

E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @ 120 days
Rating A Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani

Run group experiments approved for TMDs, GPDs, and spin

SoLID-SIDIS Measurements

- Deep inelastic kinematics at 8.8 GeV and 11 GeV incident electron beam energies
  - Coincidence detection of electrons and charged pions
  - Excellent particle identification of electrons and charged pions

- Single and double spin asymmetries and flavor separation
  - ^{3}He target with both transverse and longitudinal polarizations
  - NH_3 target with transverse polarization
  - Target in-beam polarization: ~60% (^{3}He), ~70% (NH_3)
  - Electron beam with polarization ~85% allows both single and double spin asymmetries

- Small asymmetries, 4-dimensional binning and high precision require high luminosity (polarized) ~ 10^{36} cm^{-2} s^{-1} (^{3}He), 10^{35} cm^{-2} s^{-1} (NH_3), and large acceptance

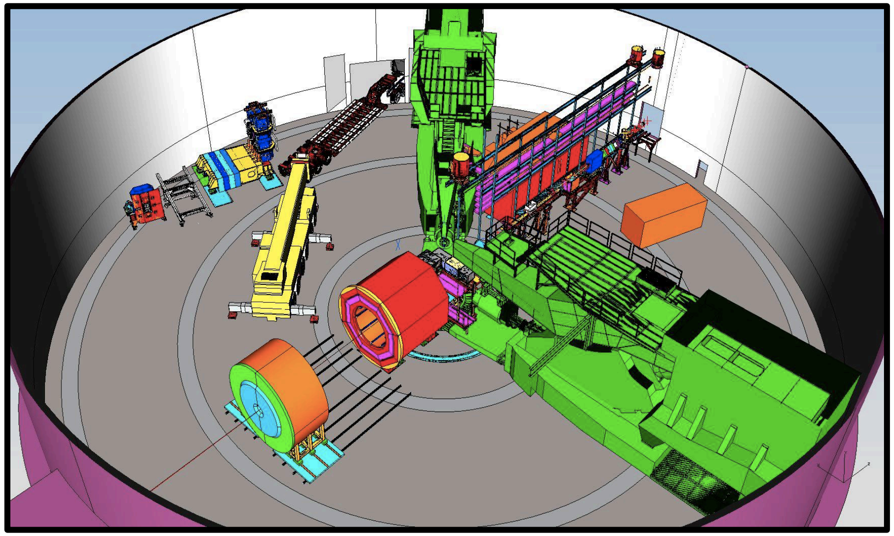
- Various azimuthal angular dependences and systematics require full azimuthal coverage

- Four-dimensional binning in (x, z, Q^2 and P_T): requires reasonably good momentum and angular resolutions
  - GEM detectors provide excellent tracking capability

- The capability to handle high rates and backgrounds associated with high luminosity and large acceptance
  - DAQ rate: less than 100 KHz

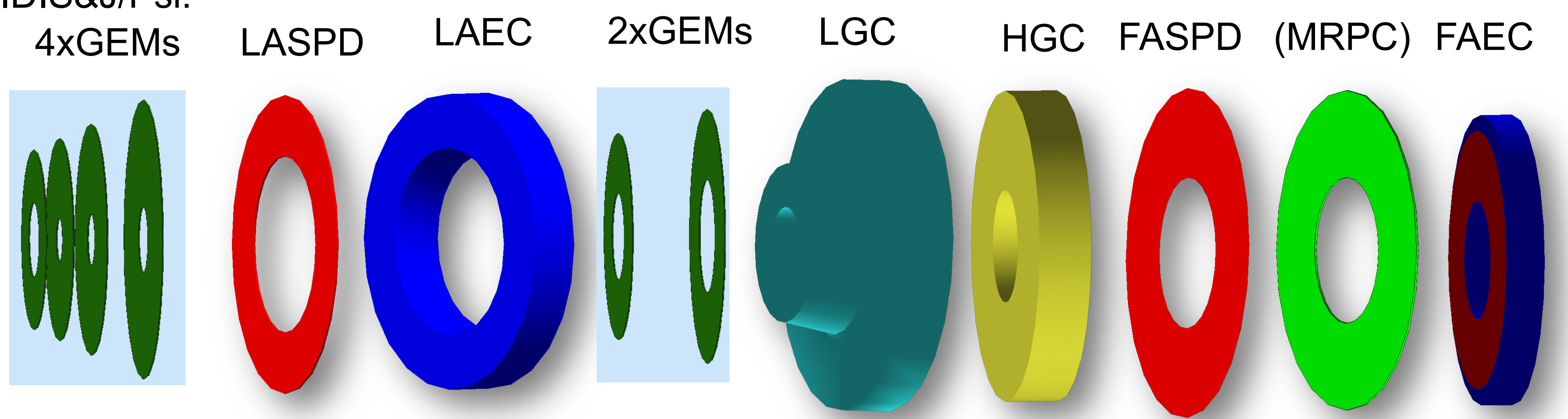
C3

SoLID in Hall A and SIDIS Subsystems



CLEO II coil at JLab

SIDIS&J/Psi:

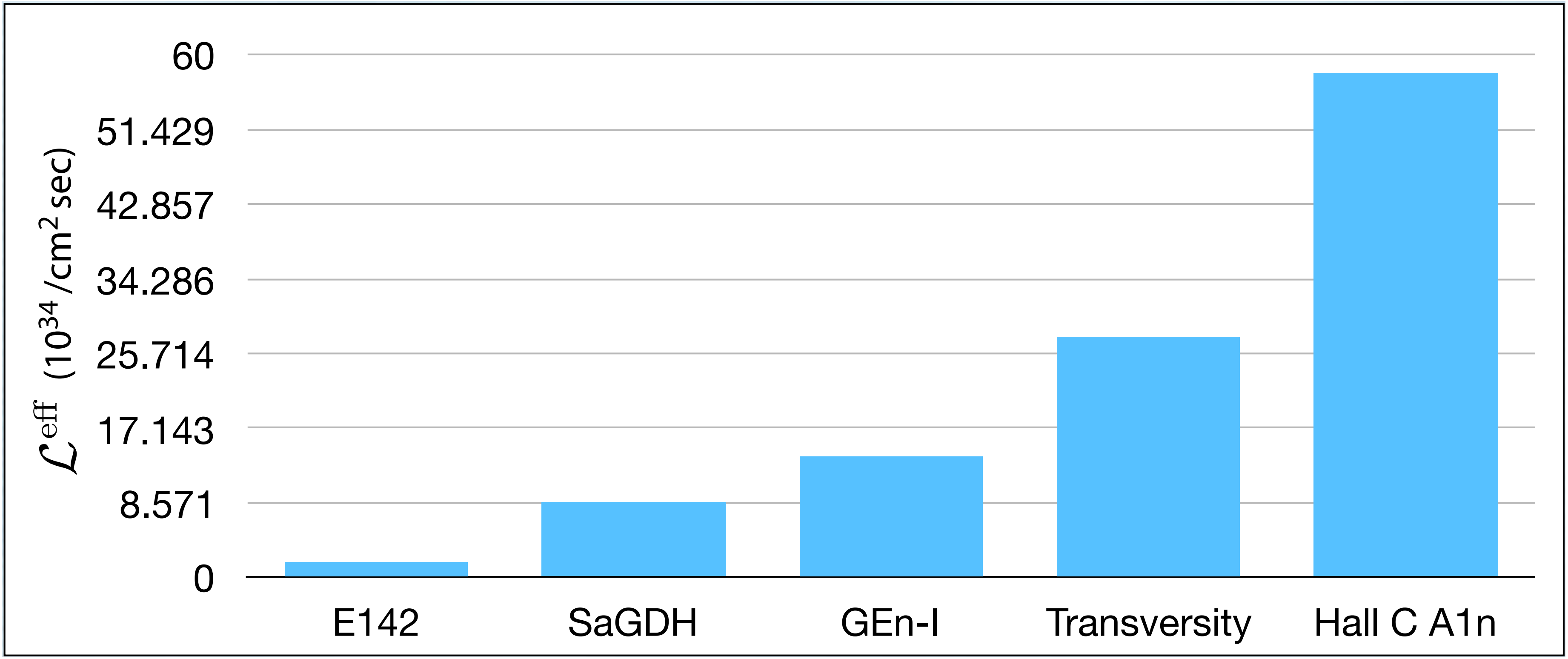


Pre-R&D items: LGC, HGC, GEM's, DAQ/Electronics, Magnet

MRPC: enhanced configuration

C3

Performance of Polarized ^{3}He target

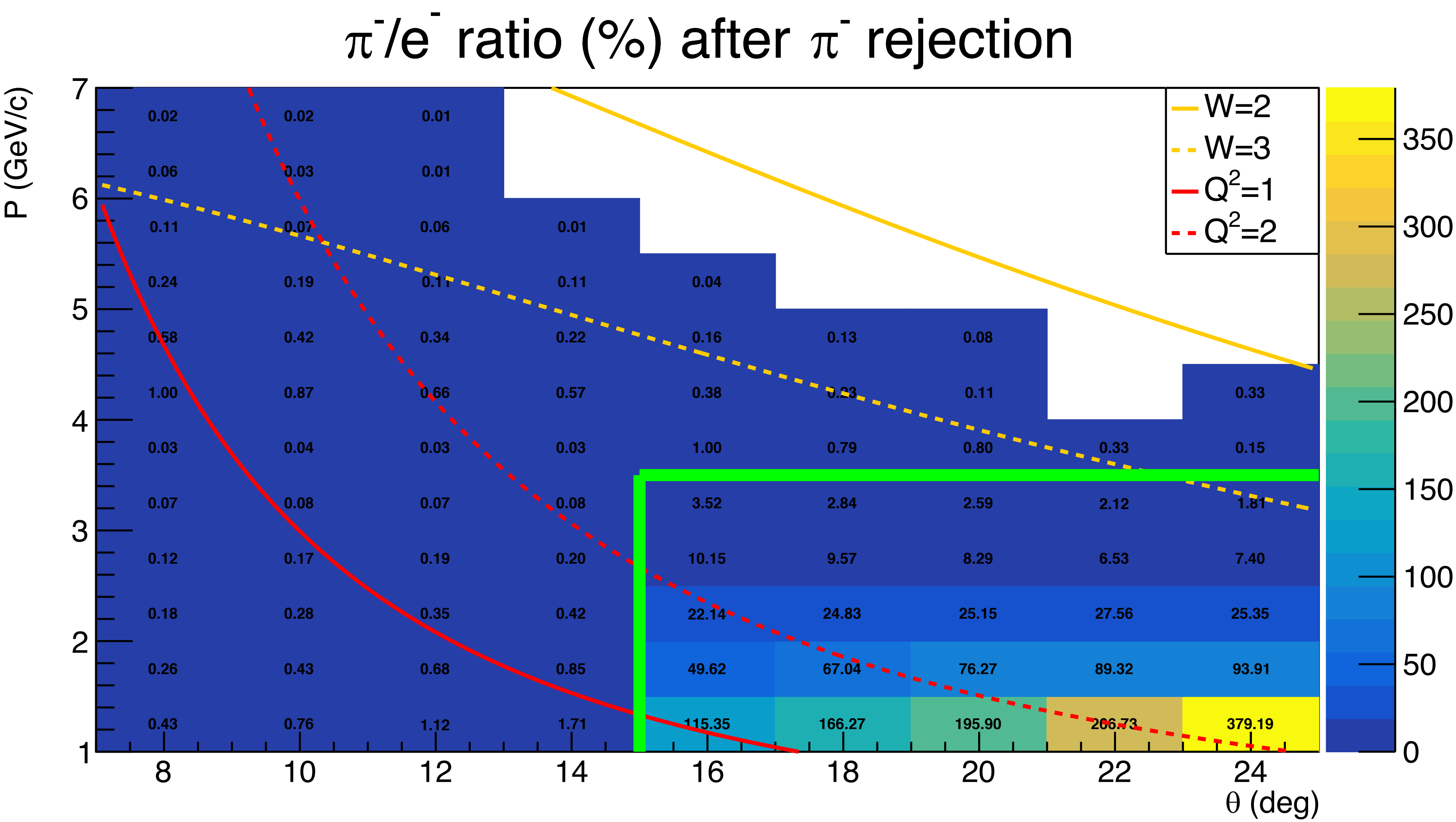


The effective luminosity is defined as $\mathbf{P}^2 \times \mathbf{L}$ where $\mathbf{P}$: target polarization, $\mathbf{L}$: luminosity

SoLID-SIDIS proposed effective luminosity: $36 \times 10^{34}/(\mathrm{cm}^2\ \mathrm{sec})$

C3

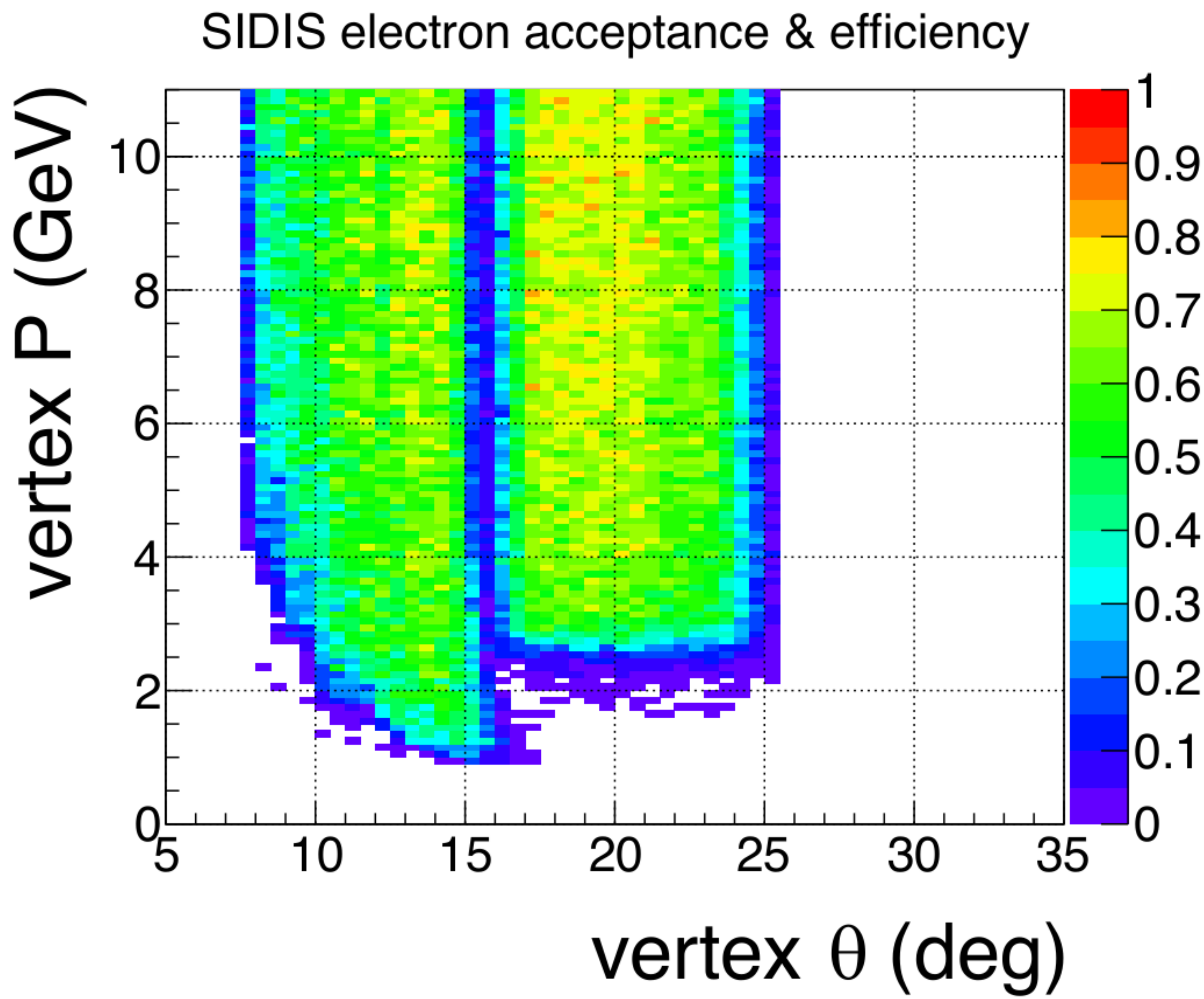
Image credit: G. Cates



C3

The ratio from combined Cherenkov and Calorimeter detector performance

SoLID-SIDIS acceptance & efficiency



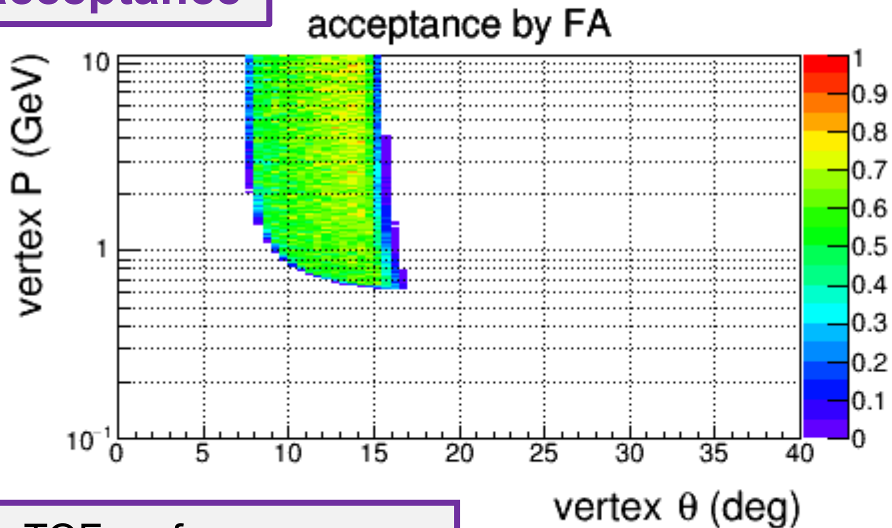
C3

Combined effect of acceptance and efficiency (except tracking)

Charged Pion detection at SIDIS He3

Introduction & Motivation	Nucleon Tomography with SoLID SIDIS	Physics Impact of SoLID SIDIS	SoLID SIDIS in the context of 12-GeV CEBAF & EIC	Summary

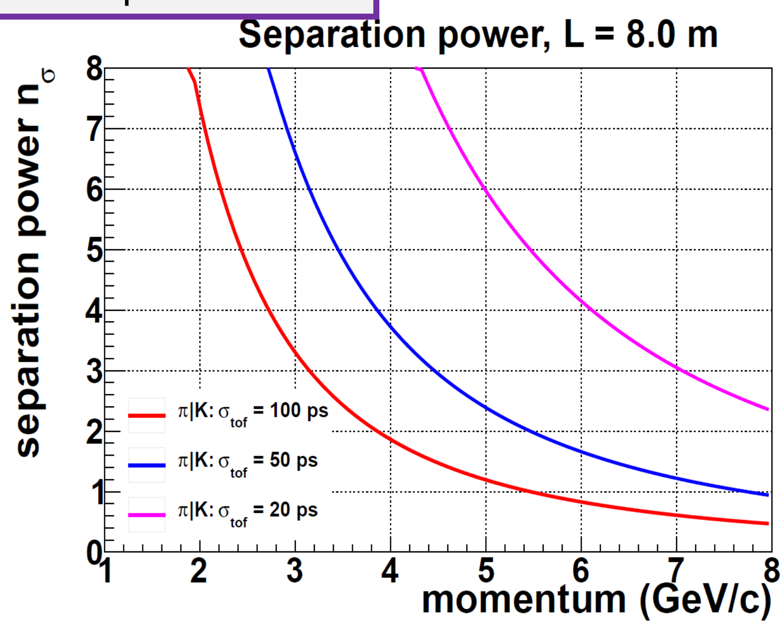
π acceptance



C3

- charged pion acceptance: $8^o < \theta < 15^o$, full 2π azimuthal angle
- MRPC cover P < 2.5 GeV (enhanced baseline)
- HGC covers 2.5 GeV < P < 7.5 GeV

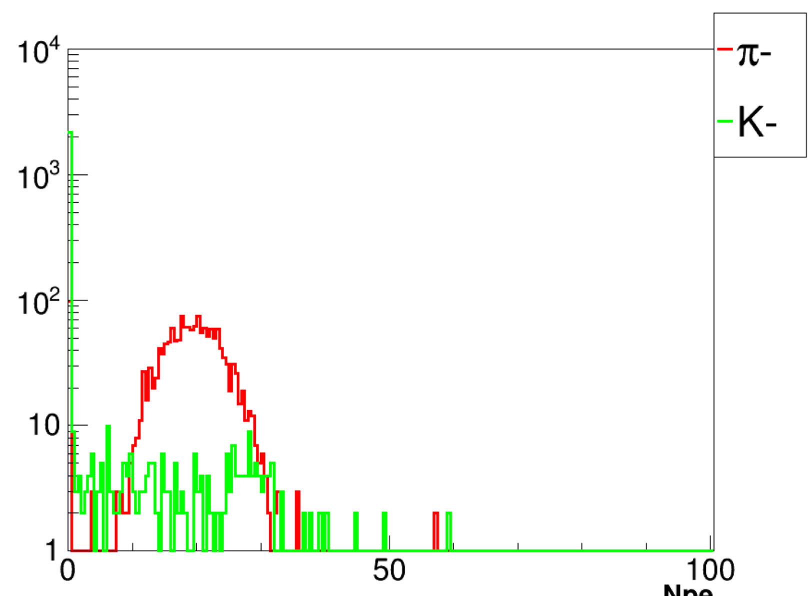
TOF performance
MRPC with ~30ps resolution



HGC performance at
2.5-3.0GeV, 8-9deg

K_{rej} ~10

π efficiency (~0.9)



- Studied the effect due to higher-twist terms

$A_{UT} = A_{Sivers}\sin(\phi_h - \phi_S) + A_{Collins}\sin(\phi_h + \phi_S) + A_{Pretzelosity}\sin(3\phi_h - \phi_S)$
$+ d\sin\phi_S + e\sin(2\phi_h - \phi_S)$
$= a\sin(\phi) + b\sin(2\phi_h - \phi) + c\sin(2\phi_h + \phi) + d\sin(\phi_h - \phi) + e\sin(\phi_h + \phi)$

- Advantage of full 2π azimuthal angular acceptance detector
  - For large acceptance solenoid detector, a full 2π azimuthal coverage has unique advantage in reducing systematic uncertainties associated with detection efficiencies and luminosity.
  - The experimental target single spin asymmetry is defined as:

$$A_{UT}^{h}(\phi_h,\phi_S) = \frac{2}{P_T^1 + P_T^2} \cdot \frac{\sqrt{N_1(\phi_h,\phi_S)N_2(\phi_h,\phi_S+\pi)} - \sqrt{N_1(\phi_h,\phi_S+\pi)N_2(\phi_h,\phi_S)}}{\sqrt{N_1(\phi_h,\phi_S)N_2(\phi_h,\phi_S+\pi)} + \sqrt{N_1(\phi_h,\phi_S+\pi)N_2(\phi_h,\phi_S)}} \quad (6)$$

Systematic uncertainties Pre-CDR

Table 37: The systematic uncertainties on the asymmetry measurements of SIDIS.

Systematic (abs.)		Systematic (rel.)	
Raw asymmetry	0.0014	Target polarization	3%
Detector resolution	< 0.0001	Nuclear effect	$(4-5)\%$
		Random coincidence	0.2%
		Radiative correction	$(2-3)\%$
		Diffractive meson	3%
Total	0.0014	Total	$(6-7)\%$

SoLID SIDIS Projection

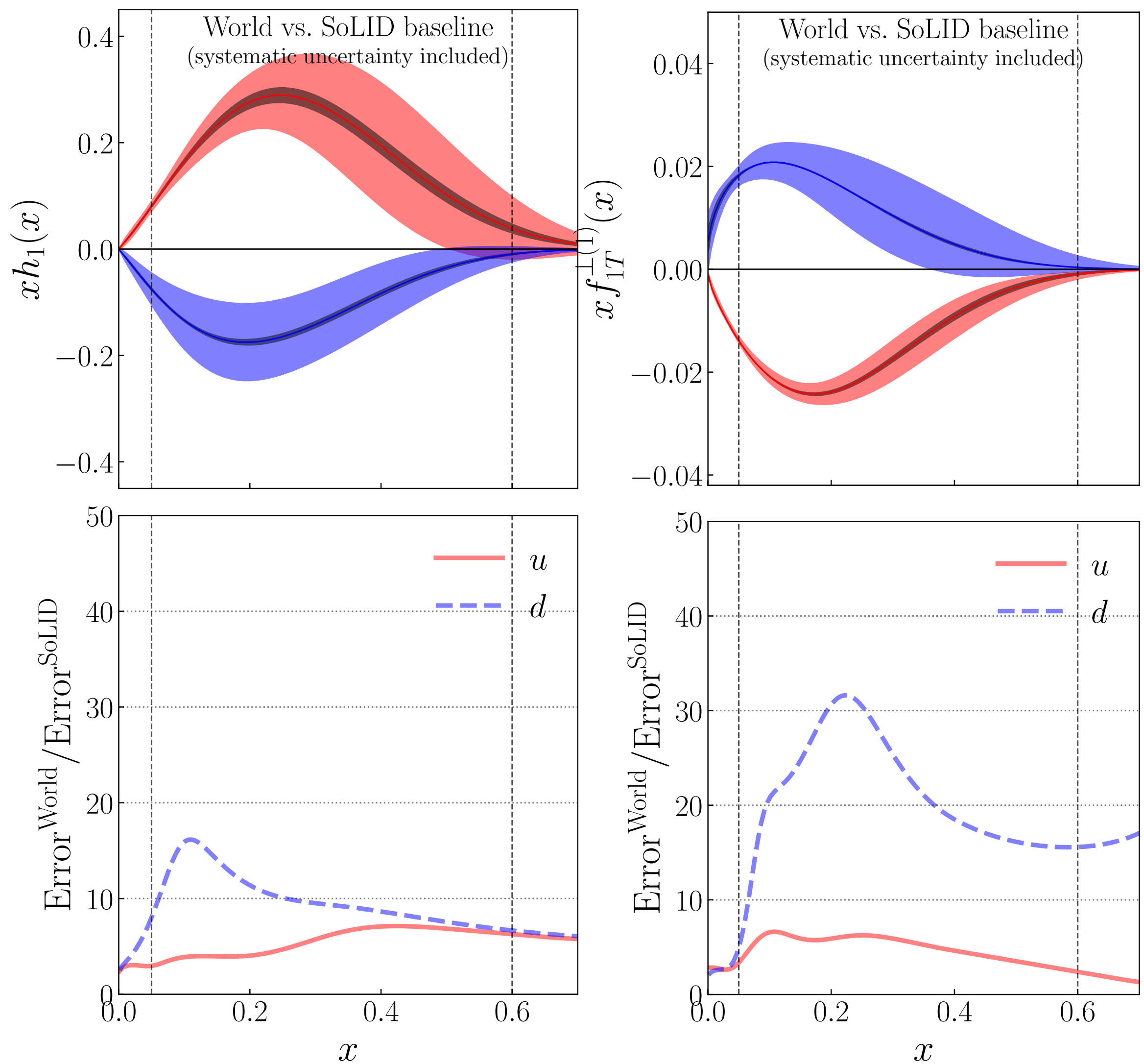
Compare SoLID with World Data

- 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

SoLID baseline used

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

Transversity **Sivers**



C2

Science questions addressed by SoLID 3-D nucleon tomography

- Can we provide a high precision test of lattice QCD predictions?
  - Tensor charge from Transversity TMD

- How to quantify the quark transverse motion inside the nucleon and observe spin-orbit correlations? Quark motions contribute to the proton mass
  - Sivers TMD
  - Is the confined motion in the transverse plane dependent on *x* Bjorken?

- Can we provide quantitative information about the quark orbital angular momentum (OAM) contribution to the proton spin (model-dependent)?
  - Pretzelocity TMD
  - Sivers TMD

- Are there clear signatures for relativity inside the nucleon and can we observe?
  - Transversity TMD
  - Pretzelocity TMD

C1

Science questions addressed by SoLID 3-D nucleon tomography

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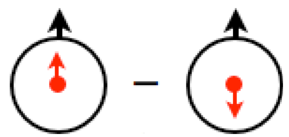
  - **Transversity TMD**
  - Pretzelocity TMD

C1

Transversity and Tensor Charge

Transversity distribution

h_1  (Collinear & TMD)

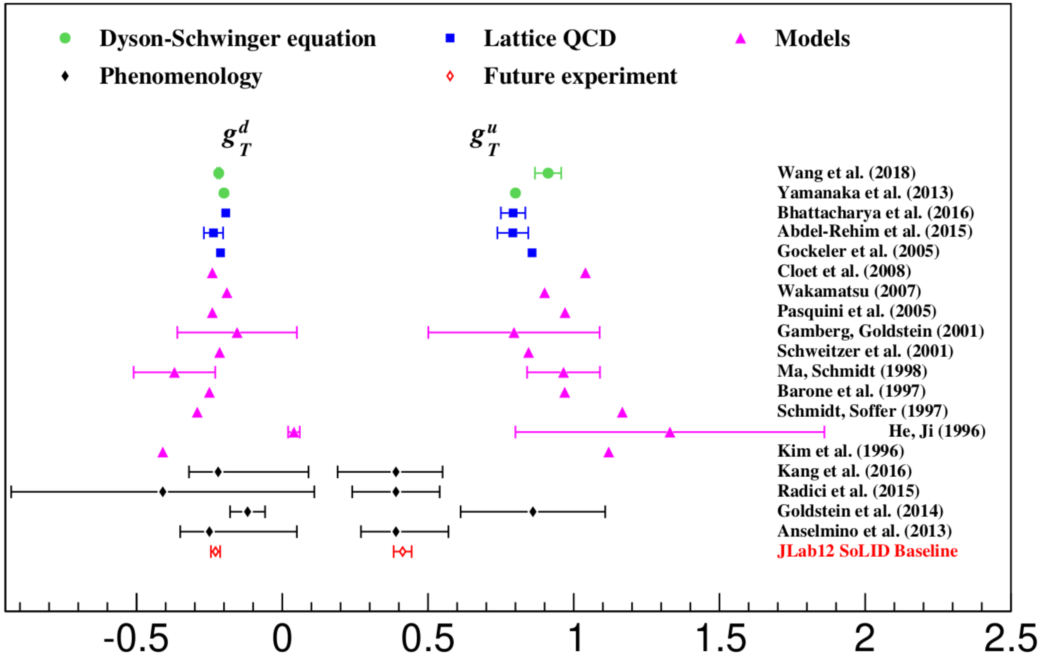
- Chiral-odd, unique for the quarks
- No mixing with gluons, simpler evolution effect
- A transverse counterpart to longitudinal spin g_1, difference shows the relativistic effect
- Zeroth moment gives tensor charge:

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

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

- A fundamental QCD quantity, valence quarks dominate
- Precisely calculated on the lattice
- Difference from nucleon axial charge is due to relativity
- High luminosity-large acceptance allows for high-precision test of LQCD predictions

C1 and C2



- Tensor charge also connected to neutron and proton EDMs, unique opportunity for SM tests and new physics

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

Z. Ye *et al*, Phys. Lett. B 767, 91 (2017)
H. Gao, T. Liu and Z. Zhao, PRD 97, 074018 (2018)

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- **Can we provide quantitative information about the quark orbital angular momentum (OAM) contribution to the proton spin (model-dependent)?**
  - Pretzelocity TMD
  - **Sivers TMD**

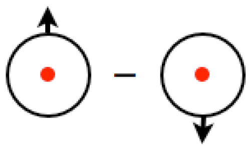
- Are there clear signatures for relativity inside the nucleon and can we observe?
  - Transversity TMD
  - Pretzelocity TMD

C1

TMDs – confined motion inside the nucleon

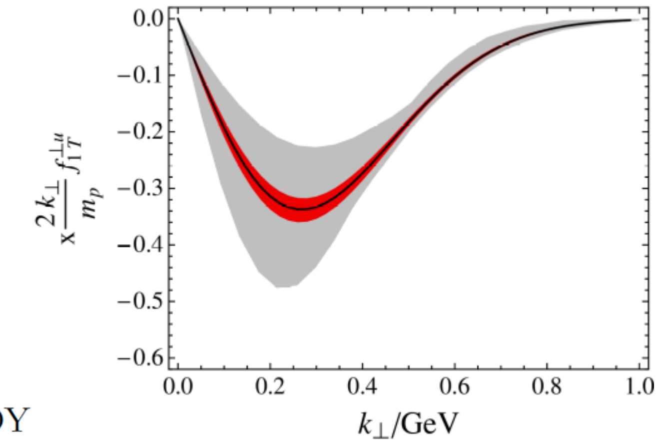
Sivers distribution

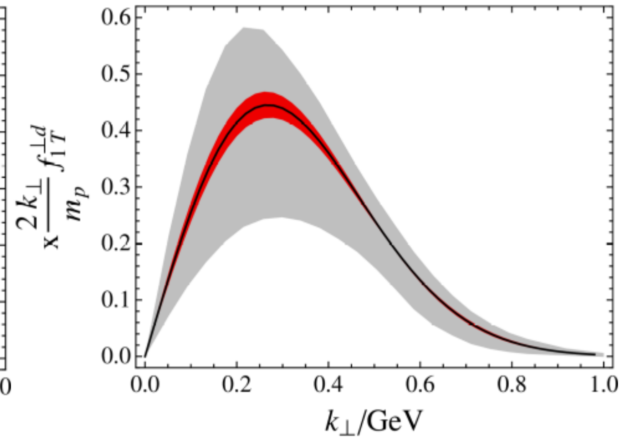
$f_{1T}^{\perp}$

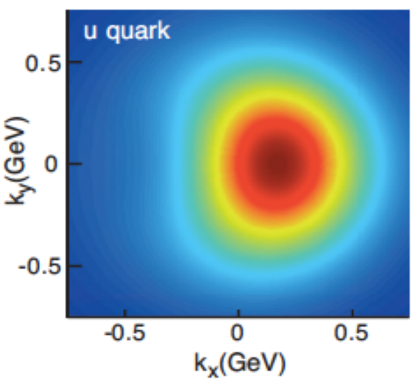


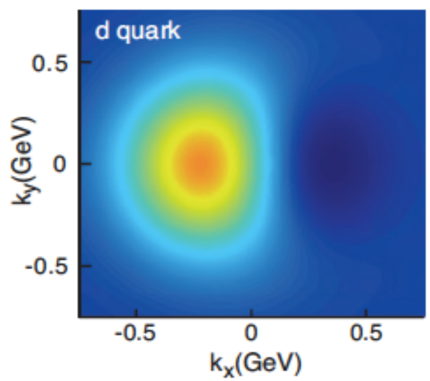
naively time-reversal odd

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









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

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

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

SoLID projection with transversely polarized n/p

C1 and C2

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

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

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

Science questions addressed by SoLID 3-D nucleon tomography

- Can we provide a high precision test of lattice QCD predictions?
  - Tensor charge from Transversity TMD

- How to quantify the quark transverse motion inside the nucleon and observe spin-orbit correlations? Quark motions contribute to the proton mass
  - Sivers TMD
  - Is the confined motion in the transverse plane dependent on *x* Bjorken?

- **Can we provide quantitative information about the quark orbital angular momentum (OAM) contribution to the proton spin (model-dependent)?**
  - **Pretzelocity TMD**
  - Sivers TMD

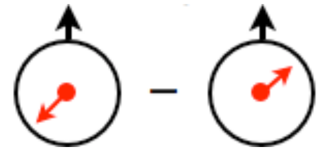
- **Are there clear signatures for relativity inside the nucleon and can we observe?**
  - Transversity TMD
  - **Pretzelocity TMD**

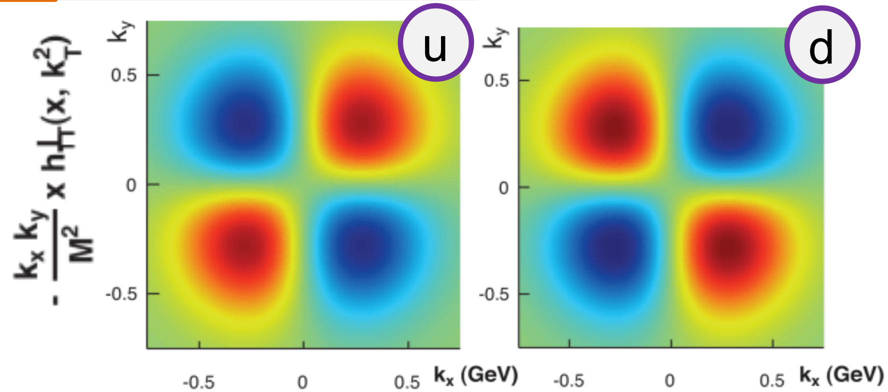
C1

TMDs – confined motion inside the nucleon

Pretzelocity distribution

$h_{1T}^{\perp}$



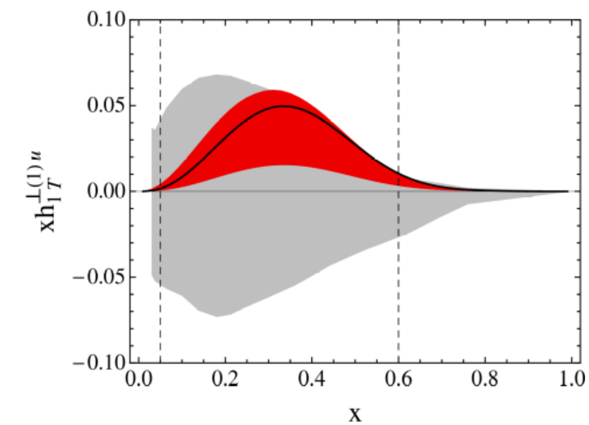


Images from PRD 91 034010 (2015)

- Chiral-odd, no gluon analogy
- Quadrupole modulation of parton density in the distribution of transversely polarized quarks in a transverse polarized nucleon
- Interference of light-front wave functions differing by ΔL = 2 (seen in many models)
- Measuring the difference between helicity and transversity, i.e. relativistic effects
- Expected to be small – high luminosity-large acceptance crucial

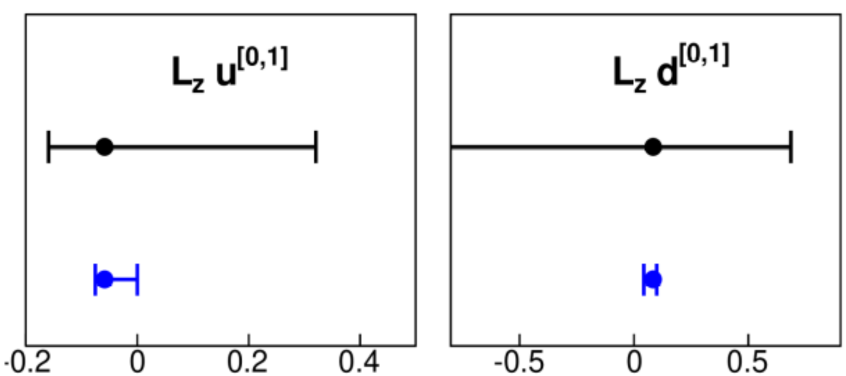
Parametrization by C. Lefky et al., PRD 91, 034010 (2015)

SoLID projection with transversely polarized n and p data



Relation to OAM (canonical)

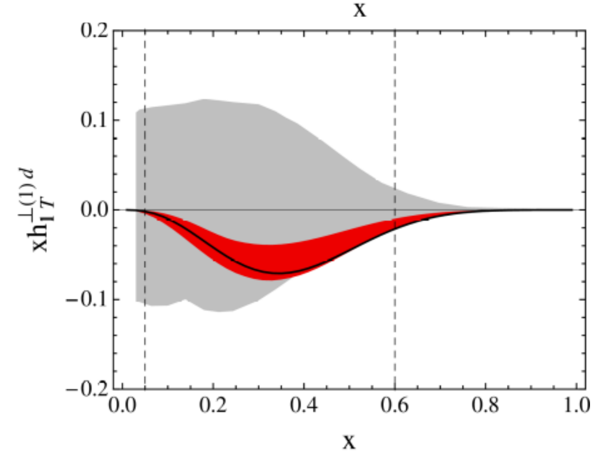
$$L_z^q = -\int \mathrm{d}x \mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int \mathrm{d}x h_{1T}^{\perp(1)q}(x)$$



Lefky and Prokudin PRD 91, 034010 (2015)

SoLID projection

C1 and C2

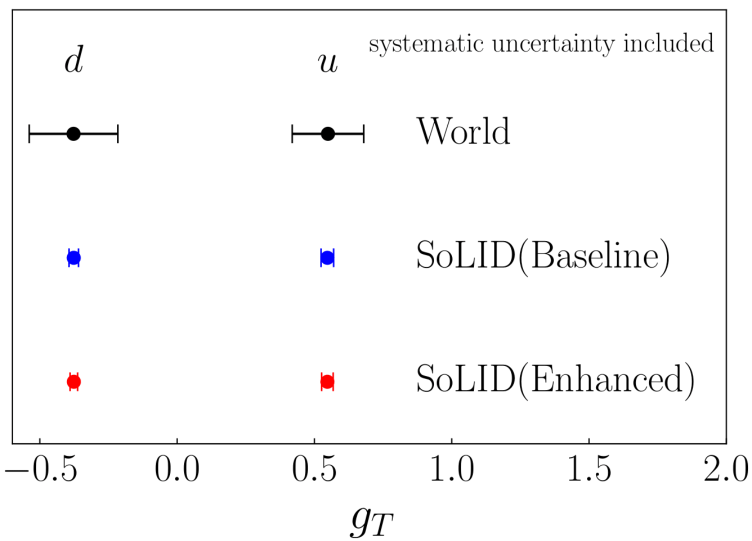


Exact finding is model dependent, but SoLID impact is model-independent!

SoLID projections: baseline and enhanced baseline

Enhanced baseline: baseline + MRPC
Enhance PID in pion detection and add kaon detection capability

Tensor charge



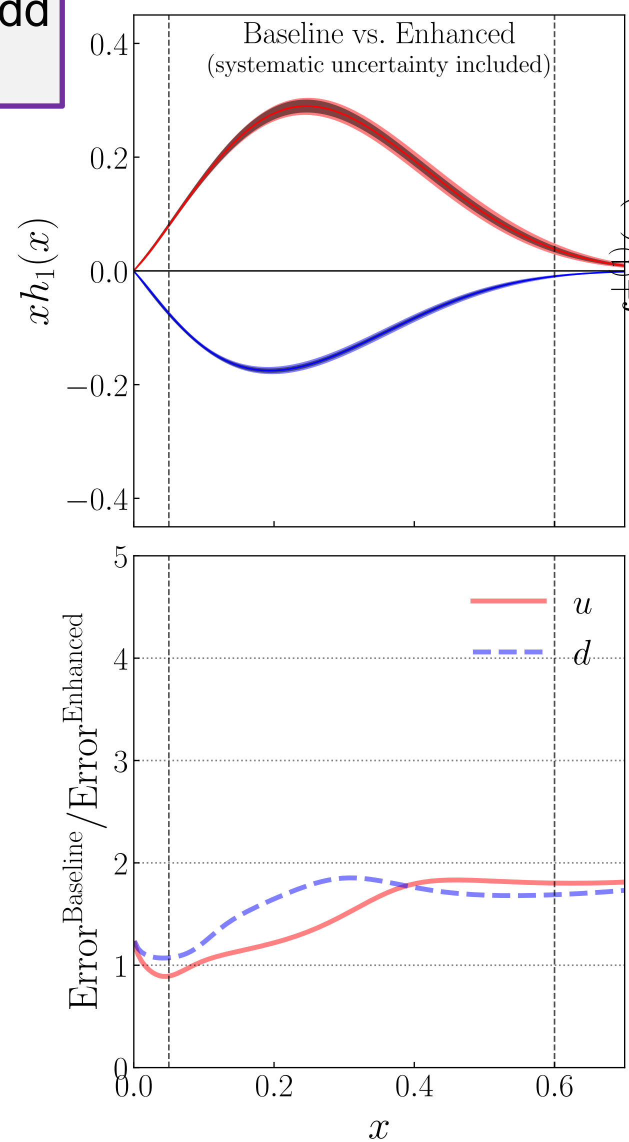
Enhanced baseline has ***~1.5*** higher precision than baseline

D'Alesio et al., Phys. Lett. B 803 (2020)135347

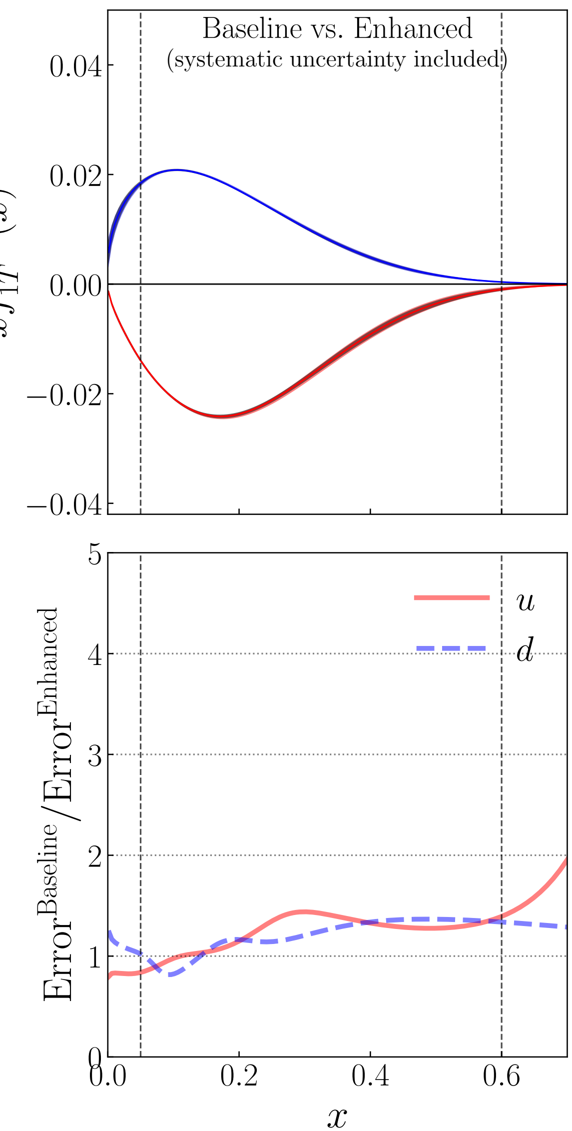
Anselmino et al., JHEP 04 (2017) 046

C2

Transversity



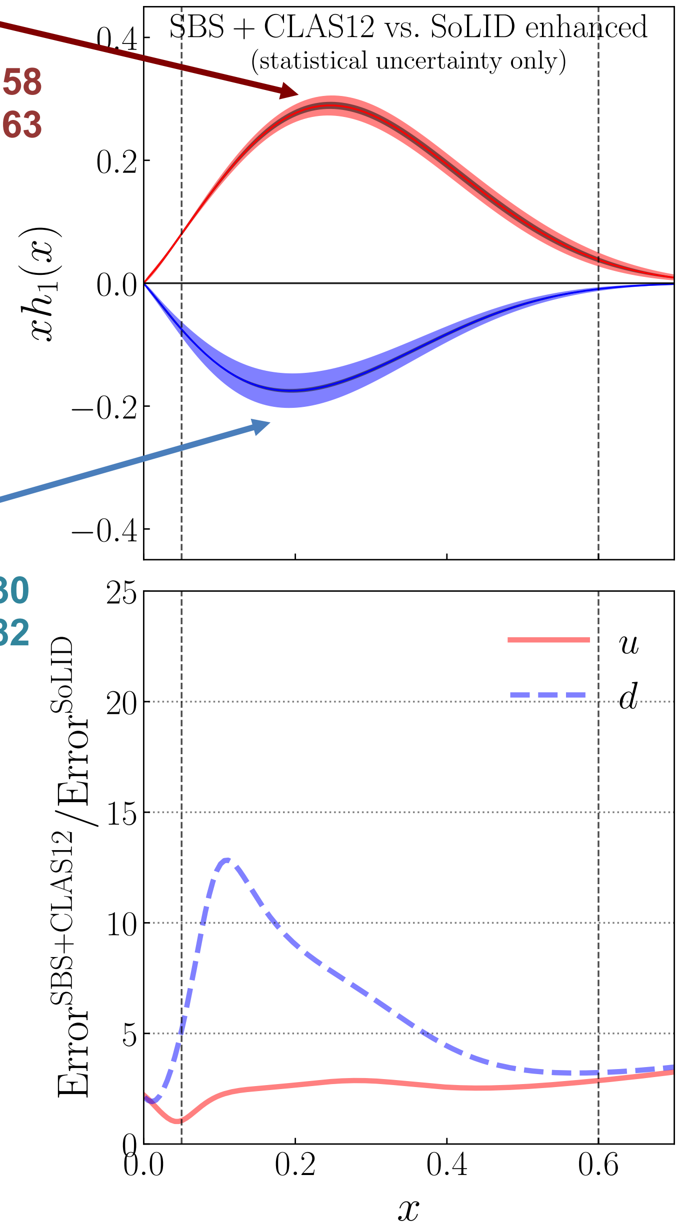
Sivers



SoLID versus SBS + CLAS12

Transversity

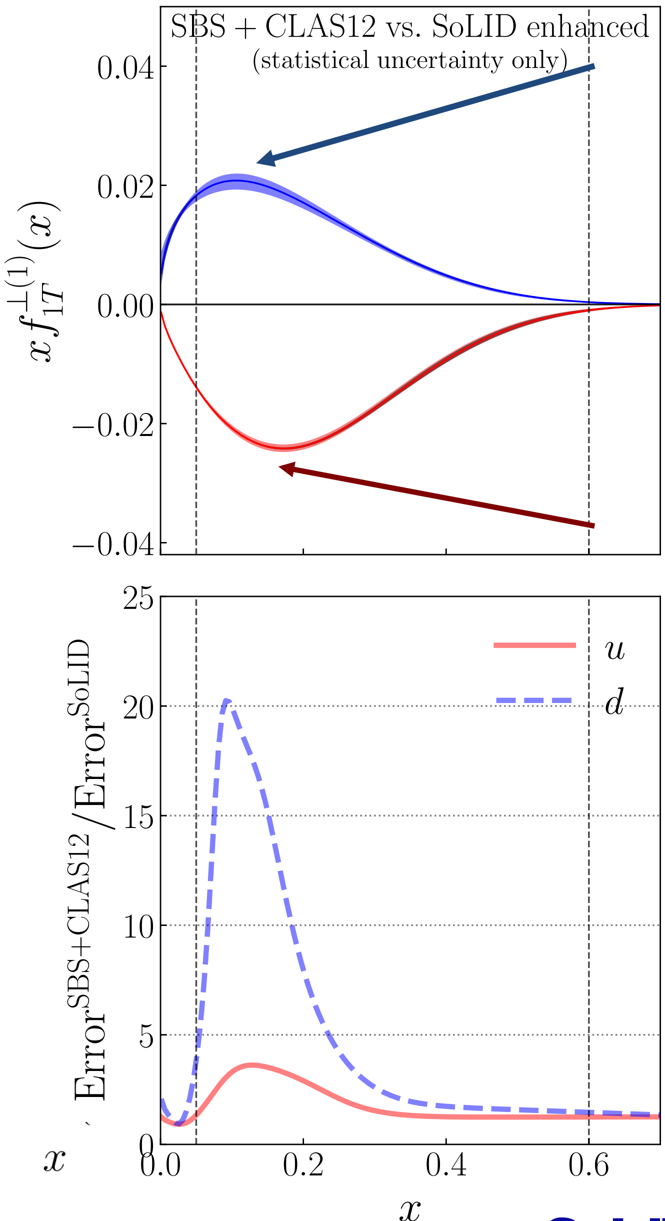
0.2892±0.0058
0.2892±0.0163



-0.1749±0.0030
-0.1749±0.0282

Sivers

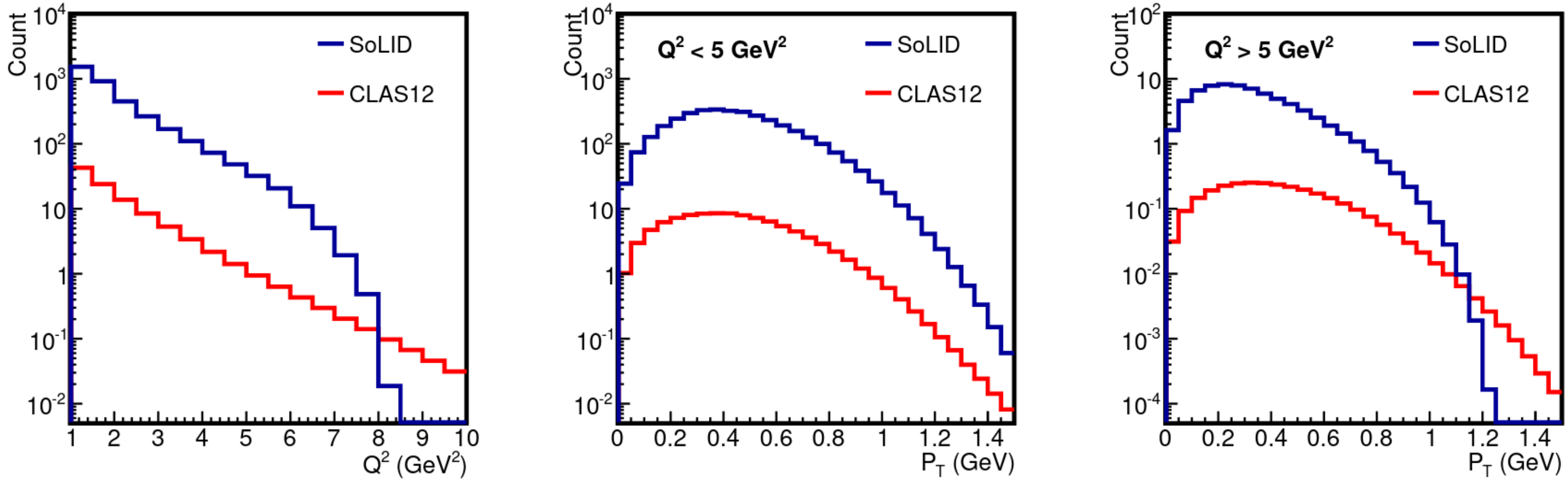
0.02063±0.00007
0.02063±0.00134



-0.02418±0.00019
-0.02418±0.00064

C2

SIDIS (charged pions) relative rate comparison between SoLID and CLAS12 (^{3}He)



C2

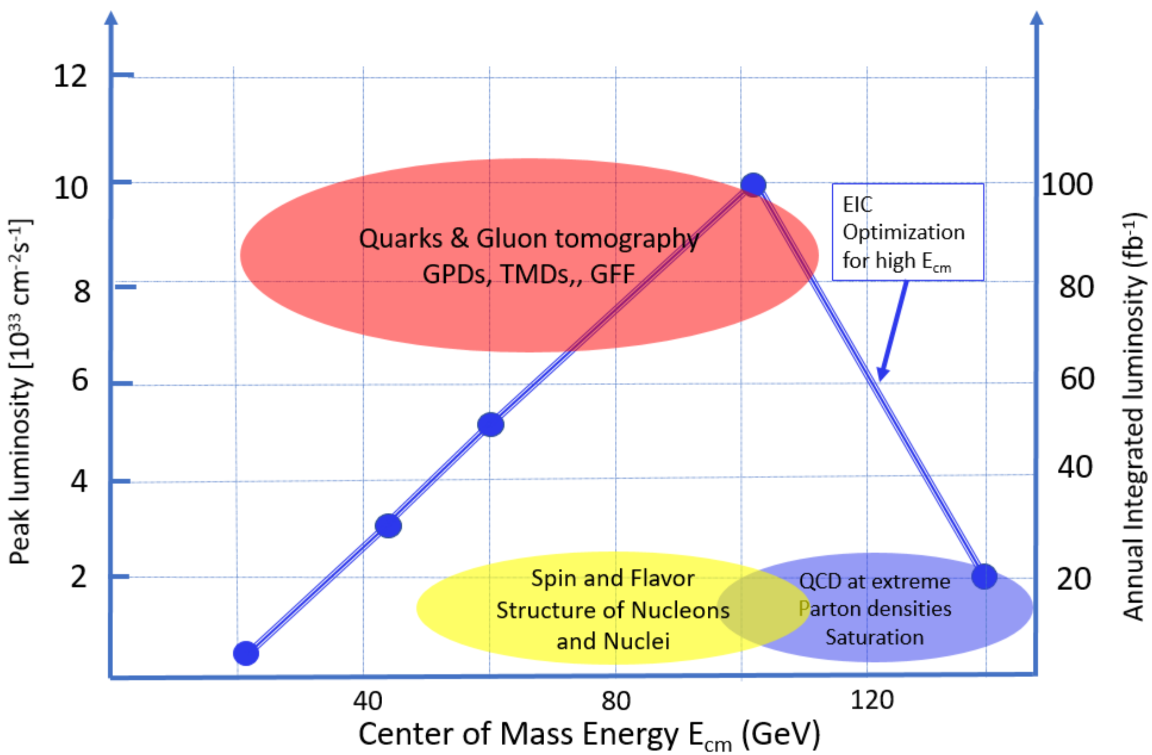
	SoLID ^{3}He (T)	CLAS12 ^{3}He (L)
Beam energy (GeV)	11	10.6[4]
Pol luminosity (cm^{-2} s^{-1})	1 x 10^{36} [1][2][3]	0.9 x 10^{34} [4][5]
Acceptance	1.0 GeV < P_e < 7.0 GeV 8 < θ_e < 24 2.5 GeV < P_π < 7.5 GeV 8 < θ_π < 15 $\phi = 2\pi$	0.5 GeV < P_e < 7.0 GeV 5 < θ_e < 125 0.5 GeV < P_π < 7.5 GeV 5 < θ_π < 125 $\phi = \pi$
Kinematic cuts	W > 2.3 GeV[3] W' > 1.6 GeV[3] 0.3 < z < 0.7[3] P_e > 3.0 GeV for θ_e > 15	W > 2 GeV[4] 0.2 < z < 0.9[4]

Reference
[1] *SoLID full simulation wiki webpage*
[2] *SoLID preCDR*
[3] *SoLID proposal PR12-11-007*
[4] CLAS12 proposal PR12-20-002
[5] PAC report on PR12-20-002

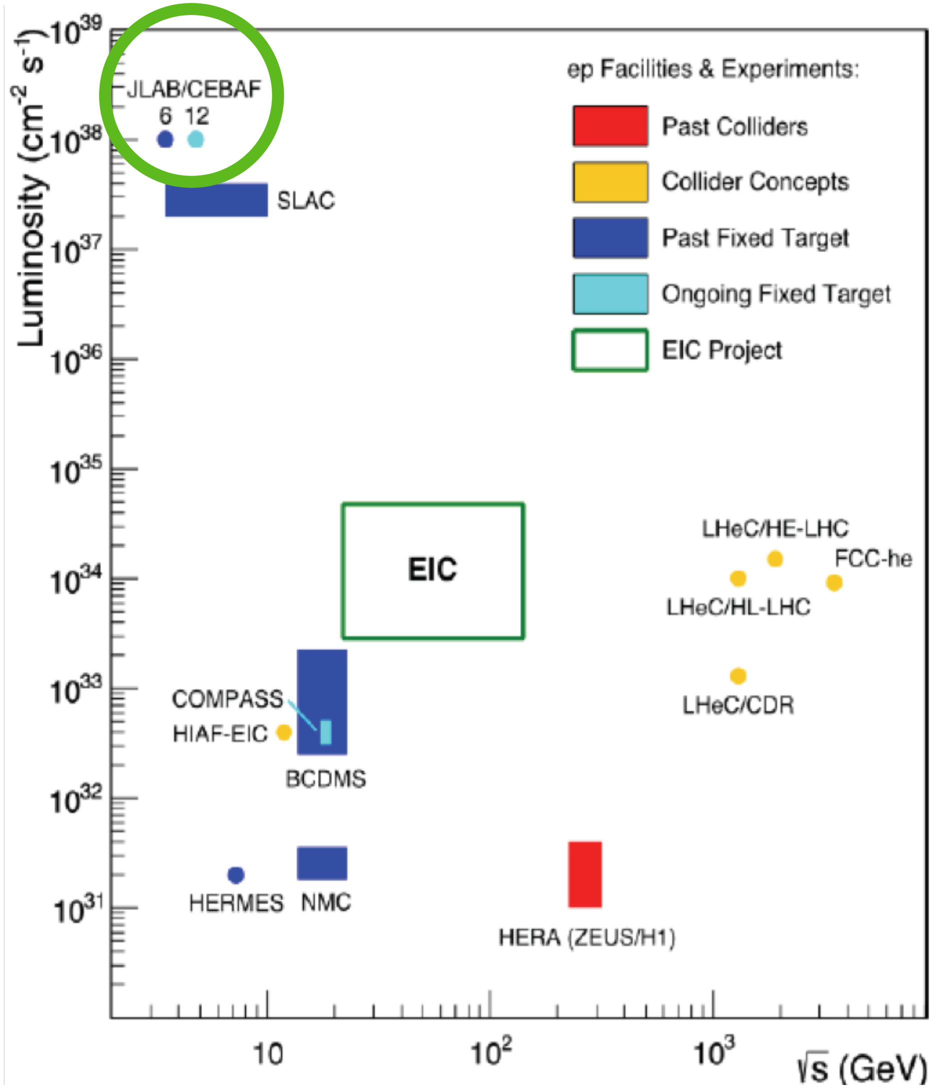
EIC: QCD at the energy frontier

EIC: QCD energy frontier

- Luminosity ($10^{33\text{-}34}$ /cm^2/s)
- Variable center-of-mass energy **(~30-140 GeV)**
- Sea quark and gluon region



(Figure credit: Volker Burkert)

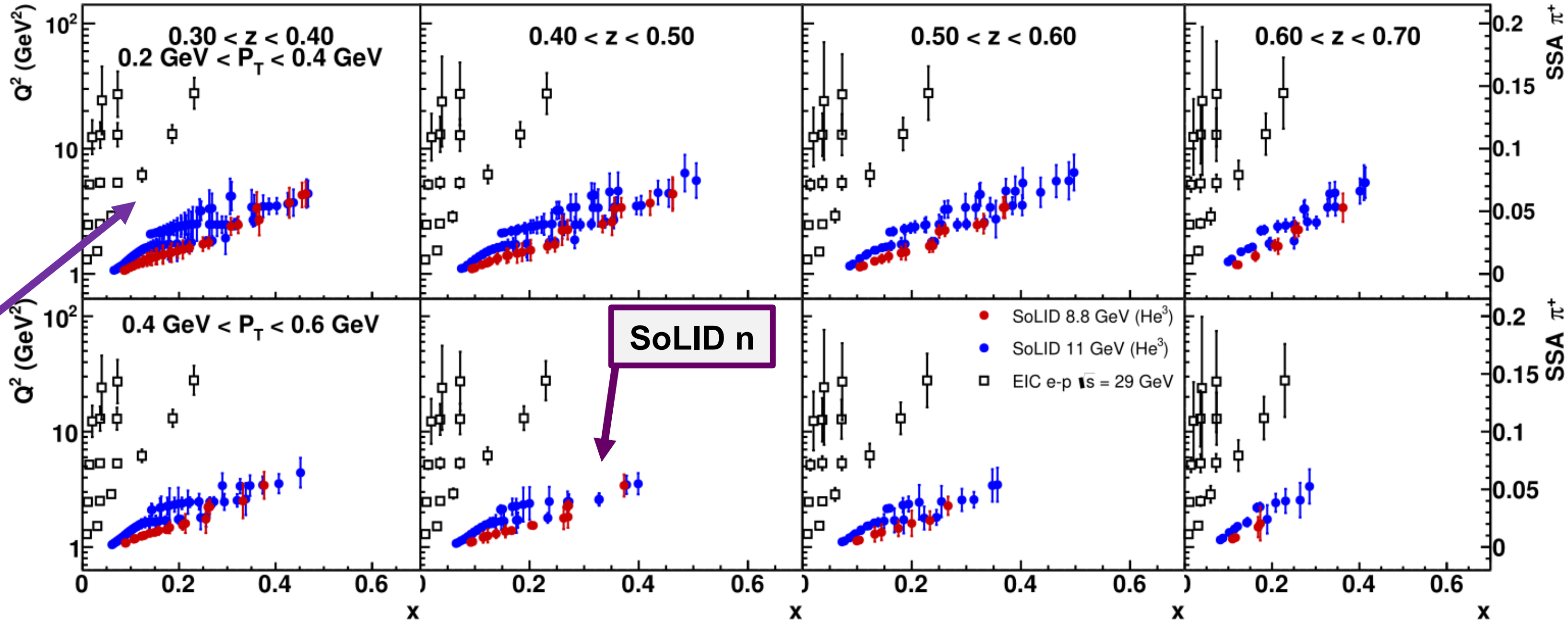


SoLID: precision and complementary kinematic reach

C2

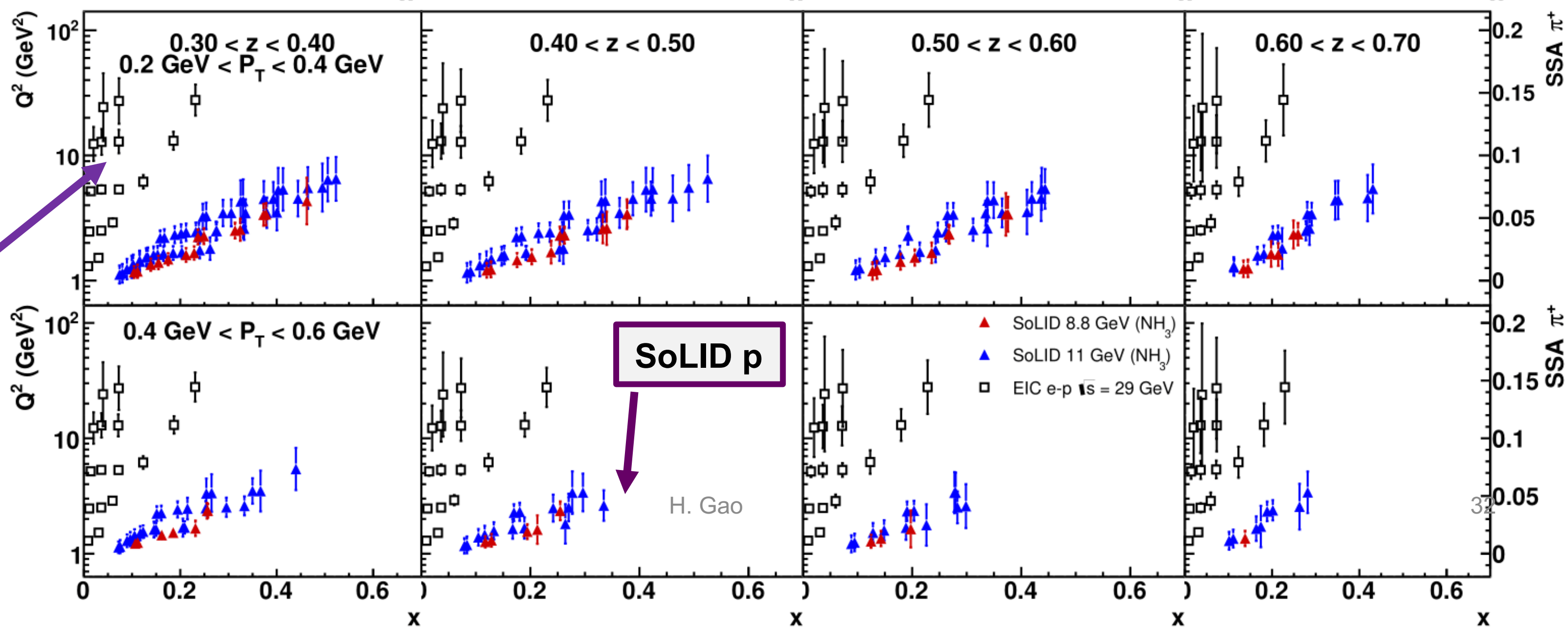
SoLID n

EIC-ep



SoLID p

EIC-ep



EIC (e-p): integrated luminosity 10 fb^{-1}

Timely Results from SoLID-SIDIS Expected

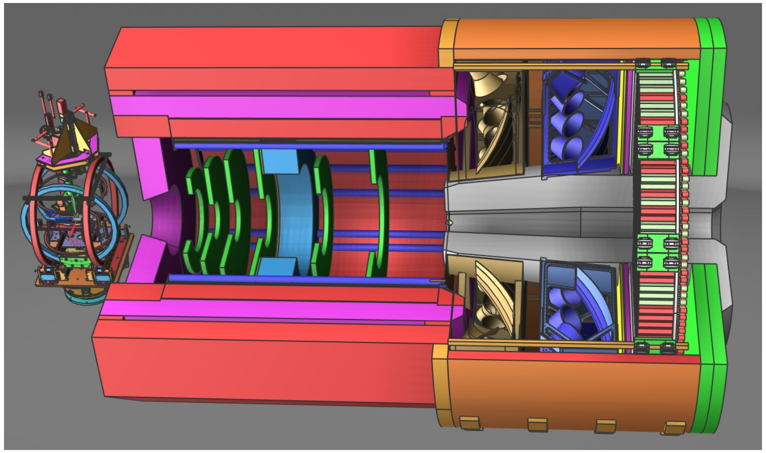
Significant results are expected within 3 years of detector operation!

- Synergy between experiments and theory (Jianwei Qiu's presentation)
- Prior 6-GeV SIDIS experiments in CLAS6 and polarized ^{3}He in Hall A
- Lessons learned from 11 GeV SIDIS experiments with SBS and CLAS12 prior to SoLID
- Experiences from large-acceptance new spectrometers/detectors: CLAS12 and GlueX
- Although SoLID is a new spectrometer, SSA analysis is relatively straightforward especially with **a full 2π azimuthal angular acceptance**
- We are working on simulations with flexible and versatile event generators including radiative corrections and other effects to address systematic issues and to speed up the data analysis process

C4

Nucleon momentum tomography and confined motion

Polarized ^{3}He ("neutron") @ SoLID



- Sivers: an example of TMDs
- Confined quark motion inside nucleon
- Quantum correlations between nucleon spin and quark motion
- QCD dynamics

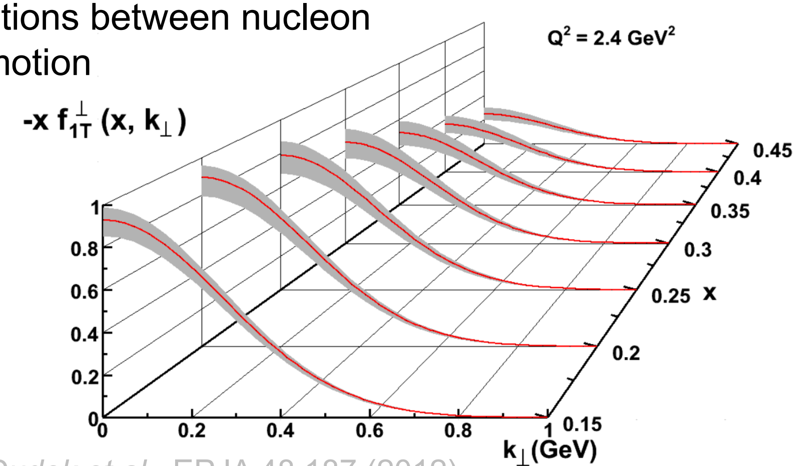
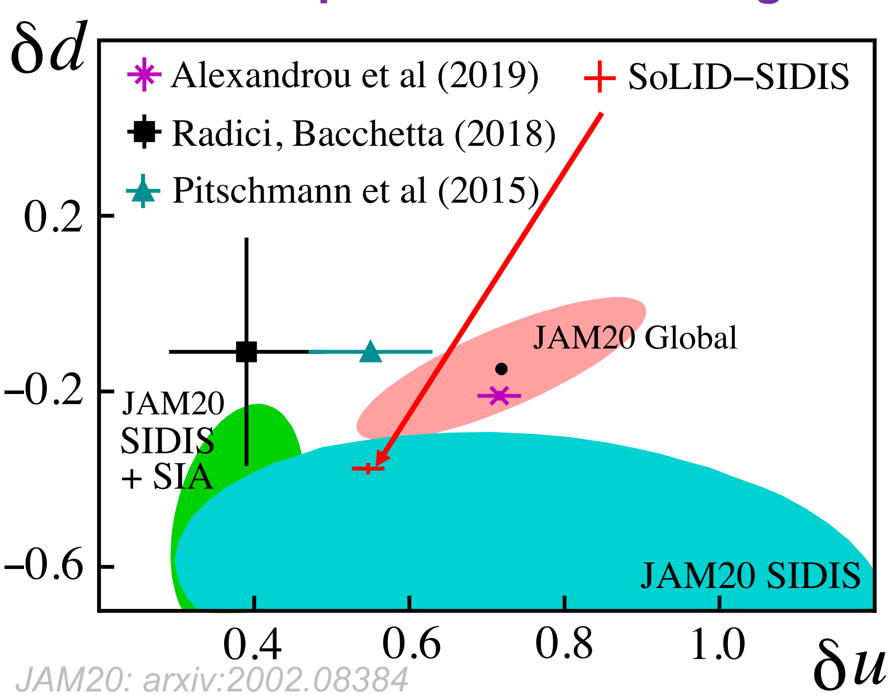


Image from J. Dudek et al., EPJA 48,187 (2012)

SoLID impact on tensor charge



JAM20: arxiv:2002.08384

- Tensor charge: a fundamental QCD quantity to test lattice QCD
- Probe new physics combined with EDMs

C2

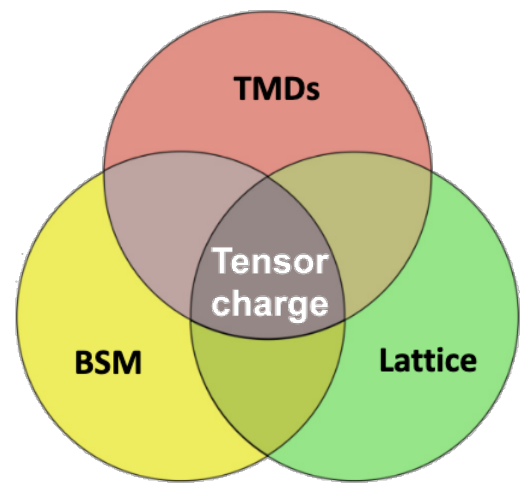
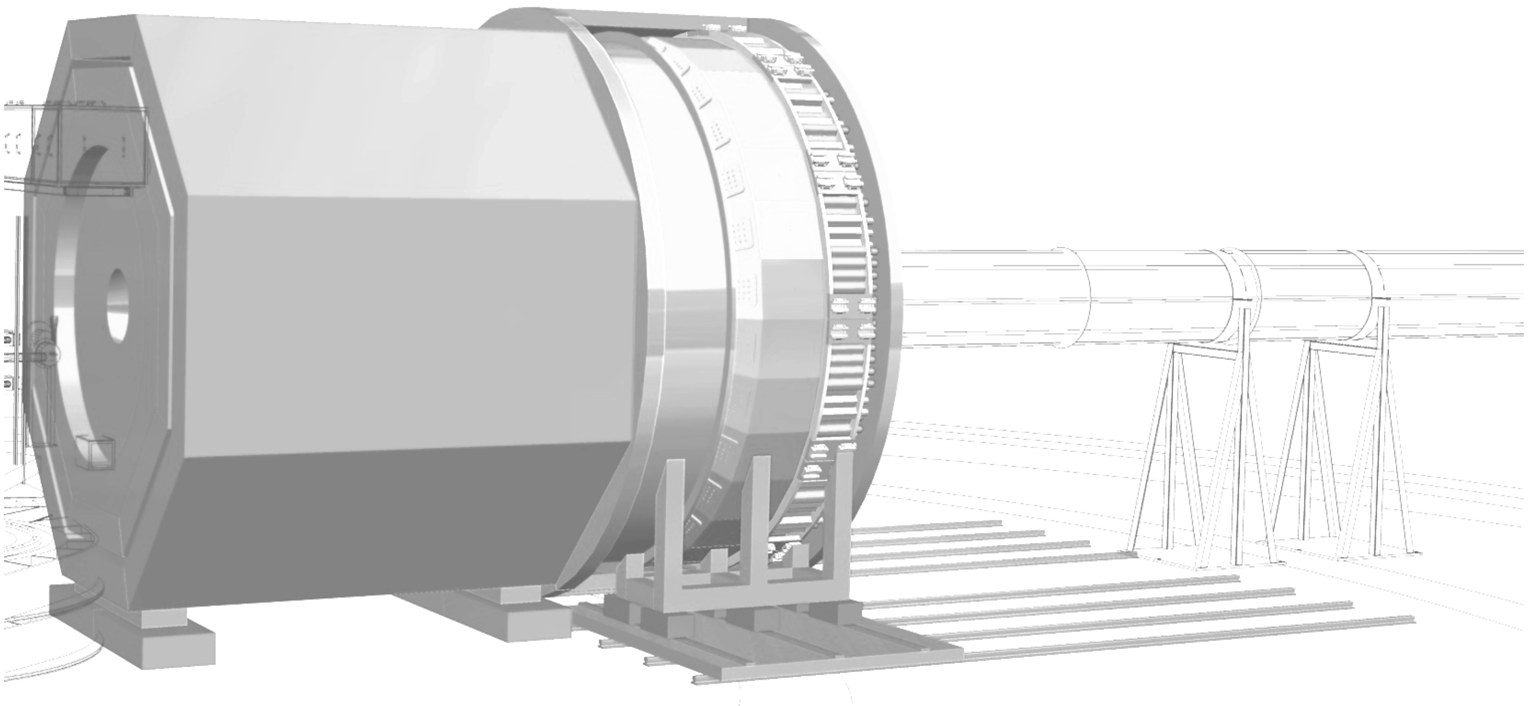


Image credit: D. Pitonyak

SoLID

SOLENOIDAL LARGE INTENSITY DEVICE



Thank you for your attention!

Questions?

Acknowledgement: E. Van Nieuwenhuizen, G. Matousek, T.B. Liu, Z. Zhao, V. Khachatryan, X. Li, J.P. Chen, J.W. Qiu, P. Souder, Z.-E. Meziani, X. Zheng, D. Pitonyak, A. Prokudin, N. Sato, many others.