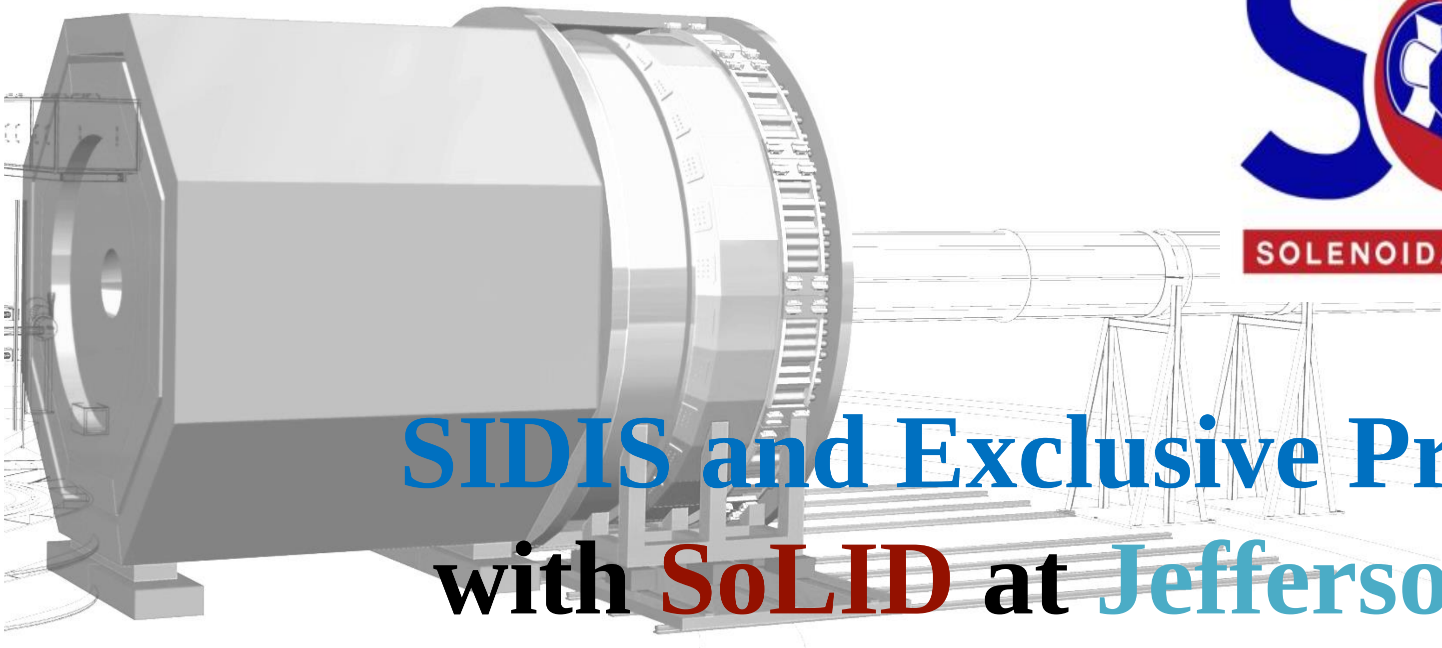


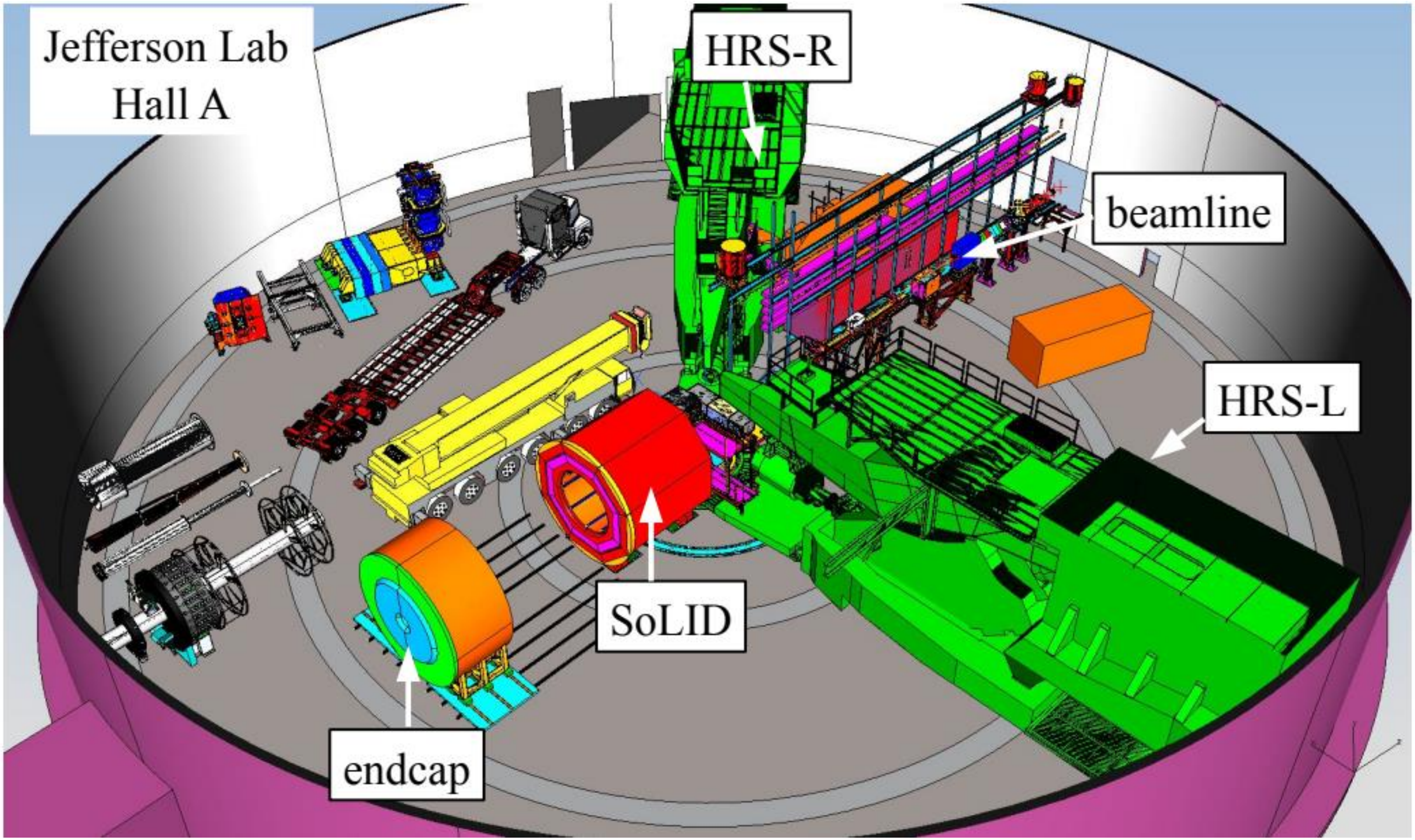
SIDIS and Exclusive Program with SoLID at Jefferson Lab

Zhiwen Zhao

SoLID Collaboration

Summer Hall A/C Meeting 2023/06/29

SoLID in the Future of Hall A



SoLID (Solenoidal Large Intensity Device)

Full exploitation of JLab 12 GeV upgrade with broad physics program

Lumi ~1e^{39}/cm^2/s (baffled geometry)

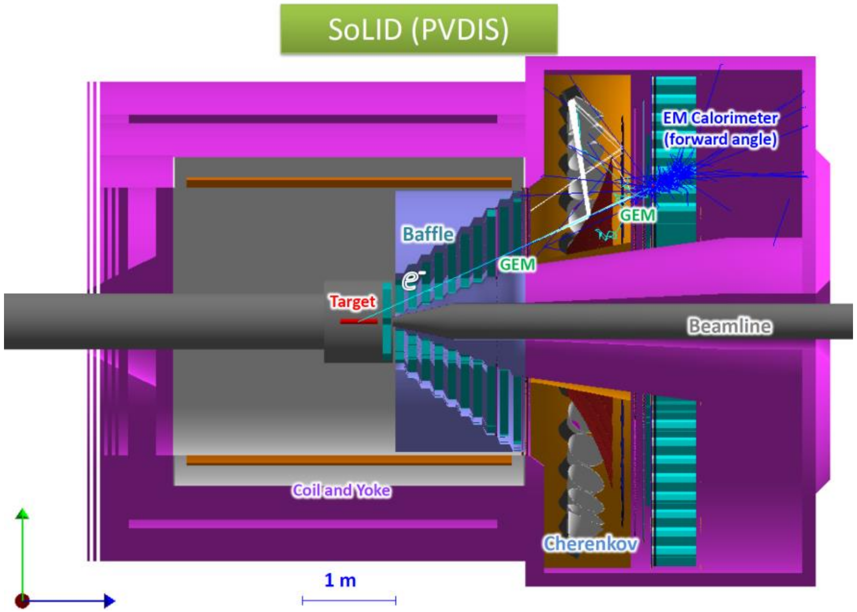
- Standard Model test and hadron structure
  - PVDIS on both deuterium and hydrogen

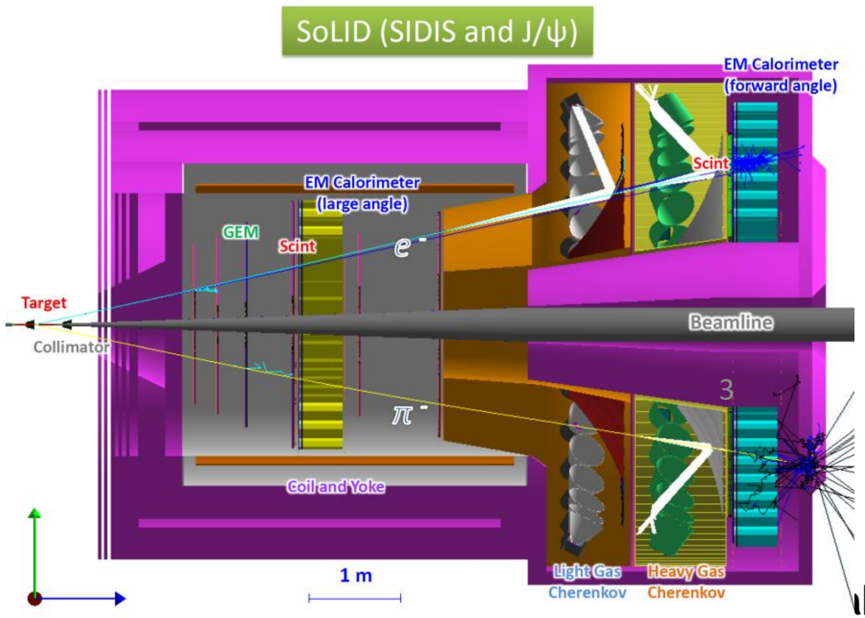
Lumi ~1e^{37}/cm^2/s (open geometry)

- 3D hadron imaging
  - TMD (SIDIS on both neutron and proton)
  - GPD (DVCS,DEMP,TCS,DDVCS)
- proton mass and gluonic interaction
  - J/ψ production at threshold

High Luminosity
Large Acceptance

https://solid.jlab.org/experiments.html



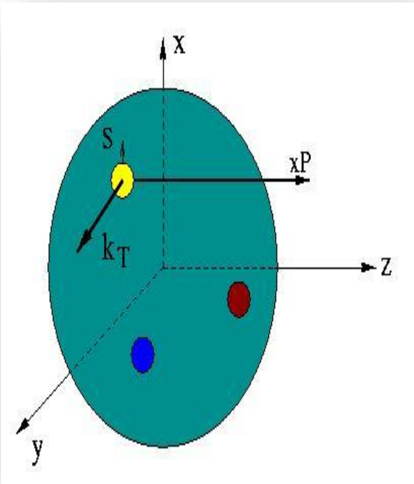


Nucleon's 3D Structure

$W_p^u(x, k_T, \boldsymbol{r_T})$ Wigner distributions **5D**

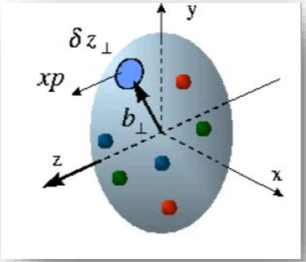
(X. Ji, D. Mueller, A. Radyushkin)

$d^2\boldsymbol{r_T}$ d^2k_T



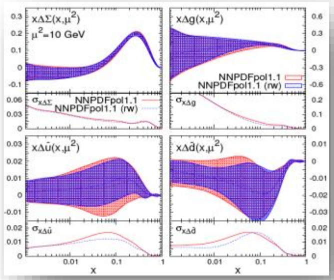
TMD
$f_1^u(x,k_T)$, $h_1^u(x,k_T)$,… **3D**

GPDs/IPDs
$H^u, E^u, \tilde{H}^u, \tilde{E}^u$

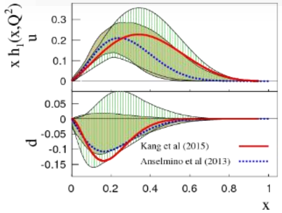


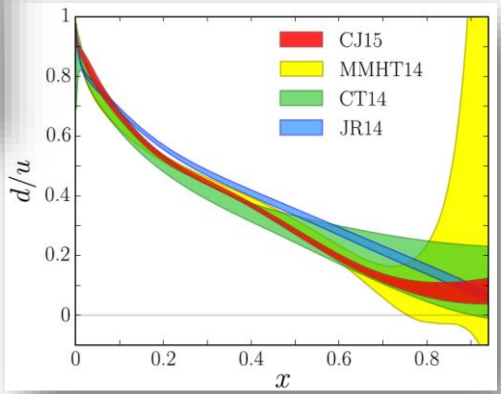
d^2k_T d^2r_T

dx & Fourier Transformation



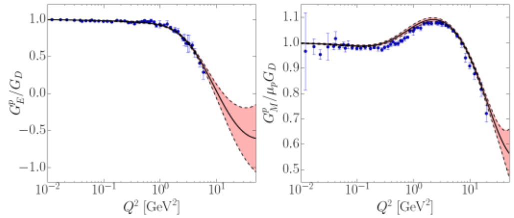
A. Accardi et. al.
B. Phys. Rev. D 93, 114017 (2016)





PDFs
$f_1^u(x)$, $g_1^u(x)$,
$h_1^u(x)$,… **1D**

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



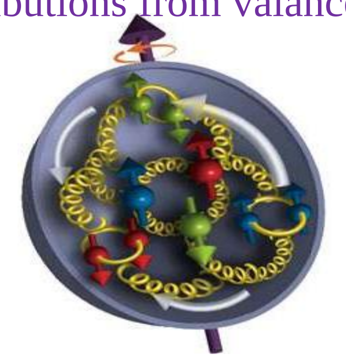
Z. Ye, et. al. Phys. Lett. B 777 8-15 (2018)

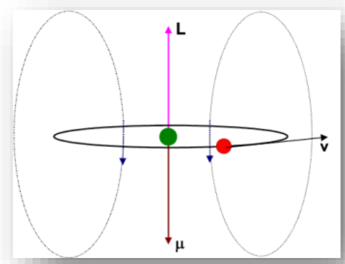
Transverse Momentum Distributions

- **Transverse Momentum Distribution Functions (TMDs)** → describe 3D motion in momentum space of all quarks & gluons in a nucleon

3D = 1D Longitudinally Momentum + 2D Transverse Momentum

✓ Spin contributions from valance quarks, sea quarks and gluons





✓ Also contributed by quarks & gluons' orbital angular momenta (OAM)

8 Quark-TMDs (leading twist)

Leading Twist TMDs		Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$ Unpolarized		$h_1^{\perp}(x,k_T^2)$ Boer-Mulders
Nucleon Polarization	L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^{\perp}(x,k_T^2)$ Long-Transversity
Nucleon Polarization	T	$f_{1T}^{\perp}(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity; $h_{1T}^{\perp}(x,k_T^2)$ Pretzelosity

Other TMDs are ZERO after integrating over k_T

Unpolarized Density Function:

$$f_1(x) = \int d^2\mathbf{k}_\perp\, f_1(x,k_\perp)$$

Helicity Function:

$$g_1(x) = \int d^2\mathbf{k}_\perp\, g_{1L}(x,k_\perp)$$

Transversity Function:

$$h_1(x) = \int d^2\mathbf{k}_\perp\, \left[h_{1T}(x,k_\perp) + \frac{k_\perp^2}{2M^2} h_{1T}^{\perp}(x,k_\perp)\right]$$

Key Features of TMDs:

✓ Represent the intrinsic confined motion of quark & gluons

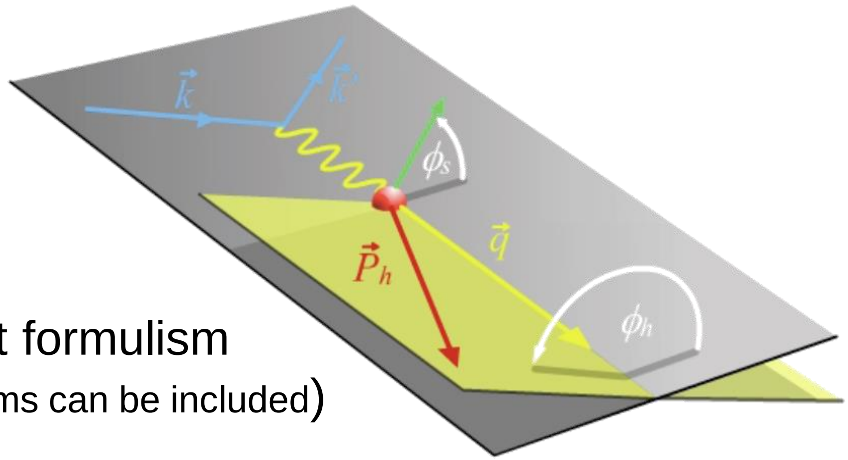
✓ Off-Diagonal TMDs vanish if no orbital angular momentum

✓ Most of TMDs are due to the spin-orbit correlations

Separation of Collins, Sivers and Pretzelosity 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)



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

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

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

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

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

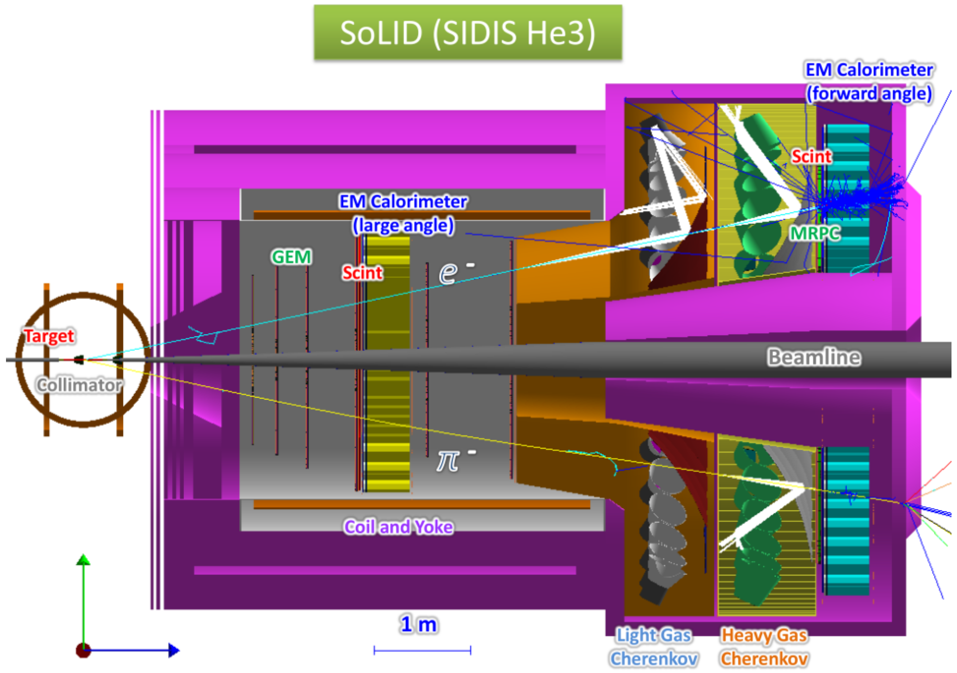
Collins fragmentation function from e^+e^- collisions

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

Unpolarized fragmentation function

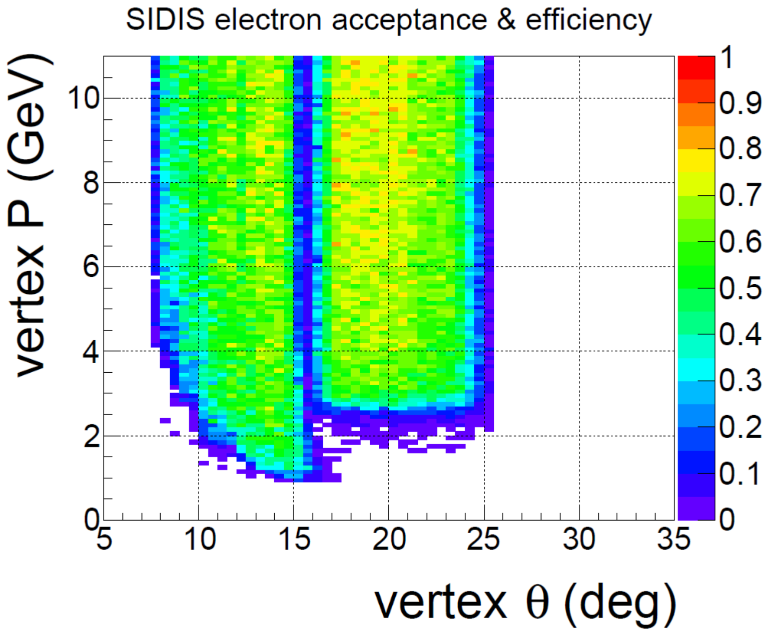
SoLID He3 Setup

- E12-10-006: SIDIS pion on transversely polarized ^{3}He, 90 days, **rated A**
- E12-11-007: SIDIS pion on longitudinally polarized ^{3}He, 35 days, **rated A**
- SIDIS kaon and dihadron as run groups



Detection

- e- at forward angle with EC and Cerenkov to reject pions
- e- above 3GeV detected at large angle with EC to reject pions
- pions detected at forward angle with TOF and Cerenkov to suppress kaons



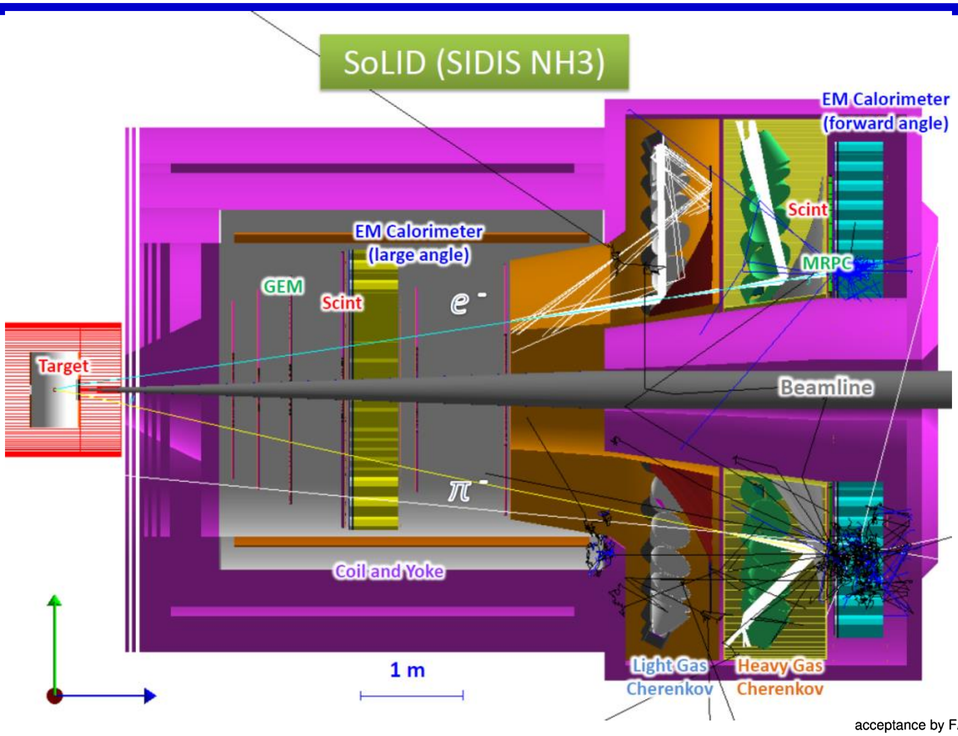
Polarized lumi ~1e^{36}/cm^2/s
Unpolarized lumi ~1e^{37}/cm^2/s

Coverage

- Polar angle: e^- 8-24 deg, π^-/π^+ 8-15deg
- Azimuthal angle: full

SoLID NH3 Setup

- E12-10-008: SIDIS pion on transversely polarized proton (NH_3), 120 days, **rated A**



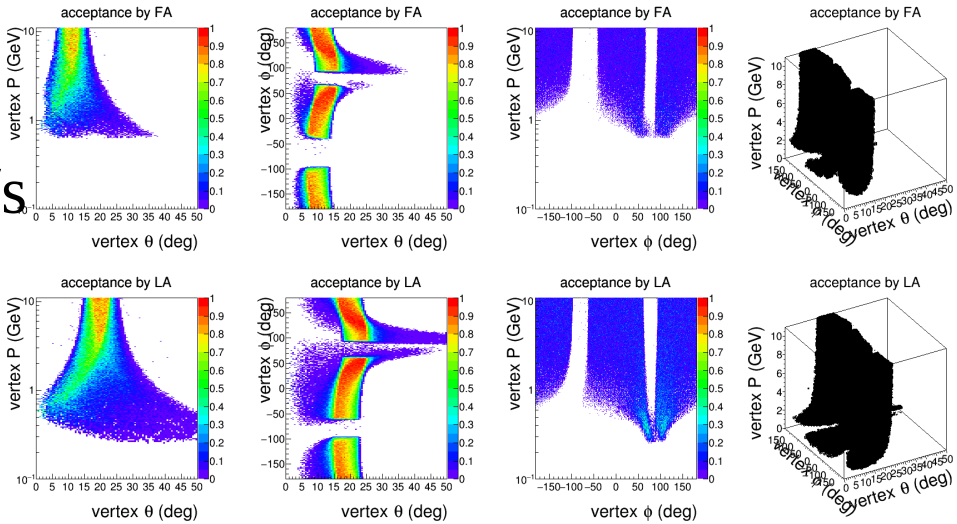
Detection is similar to He3 setup

Coverage is similar to He3 setup except some distortion from the target field

5T transverse target field
High radiation sheet of flame areas need to be cut away or shielded

Polarized lumi ~1e^{35}/cm^2/s
Unpolarized lumi ~6e^{35}/cm^2/s

e- acceptance shown
π^- acceptance is similar
π^+ acceptance is reversed along phi=0 plane



SoLID SIDIS Kinematic Coverage

$0.05 < x < 0.6$

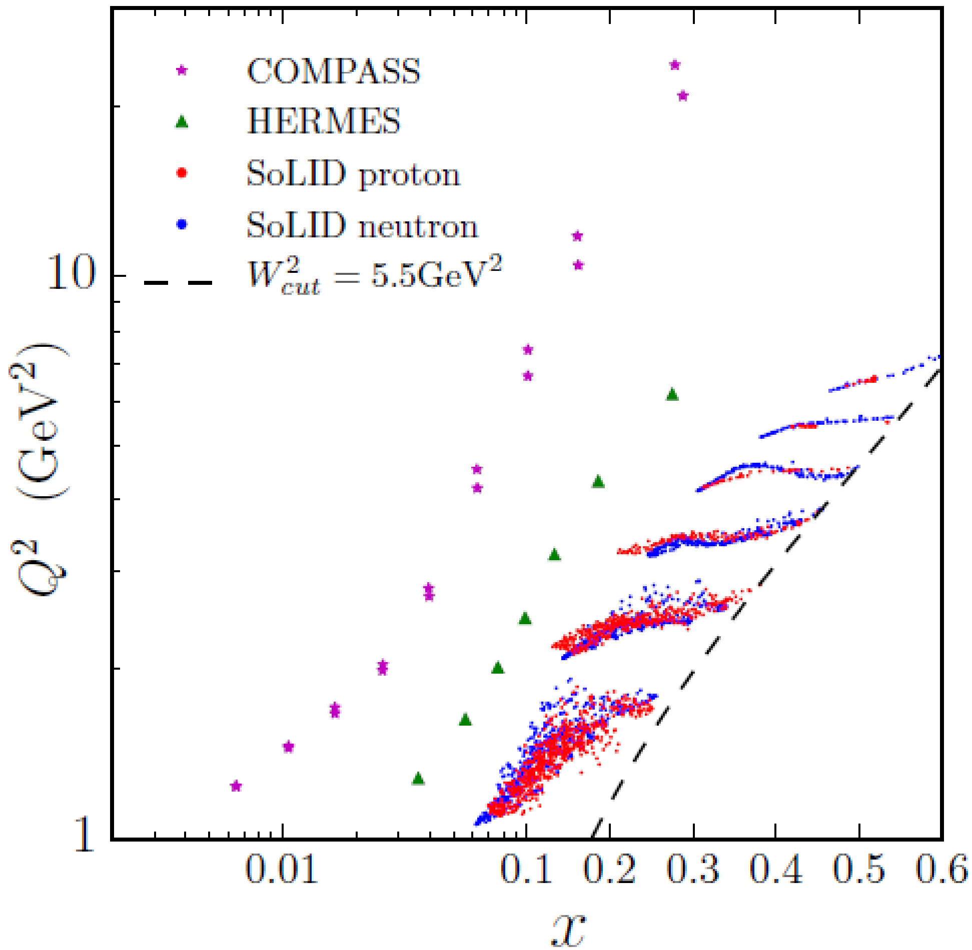
$1\text{GeV} < Q^2 < 8\text{GeV}$

$0.3 < z < 0.7$

$0 < P_T < 1.6\text{GeV}$

~ 2000 bins for n

~ 1000 bins for p



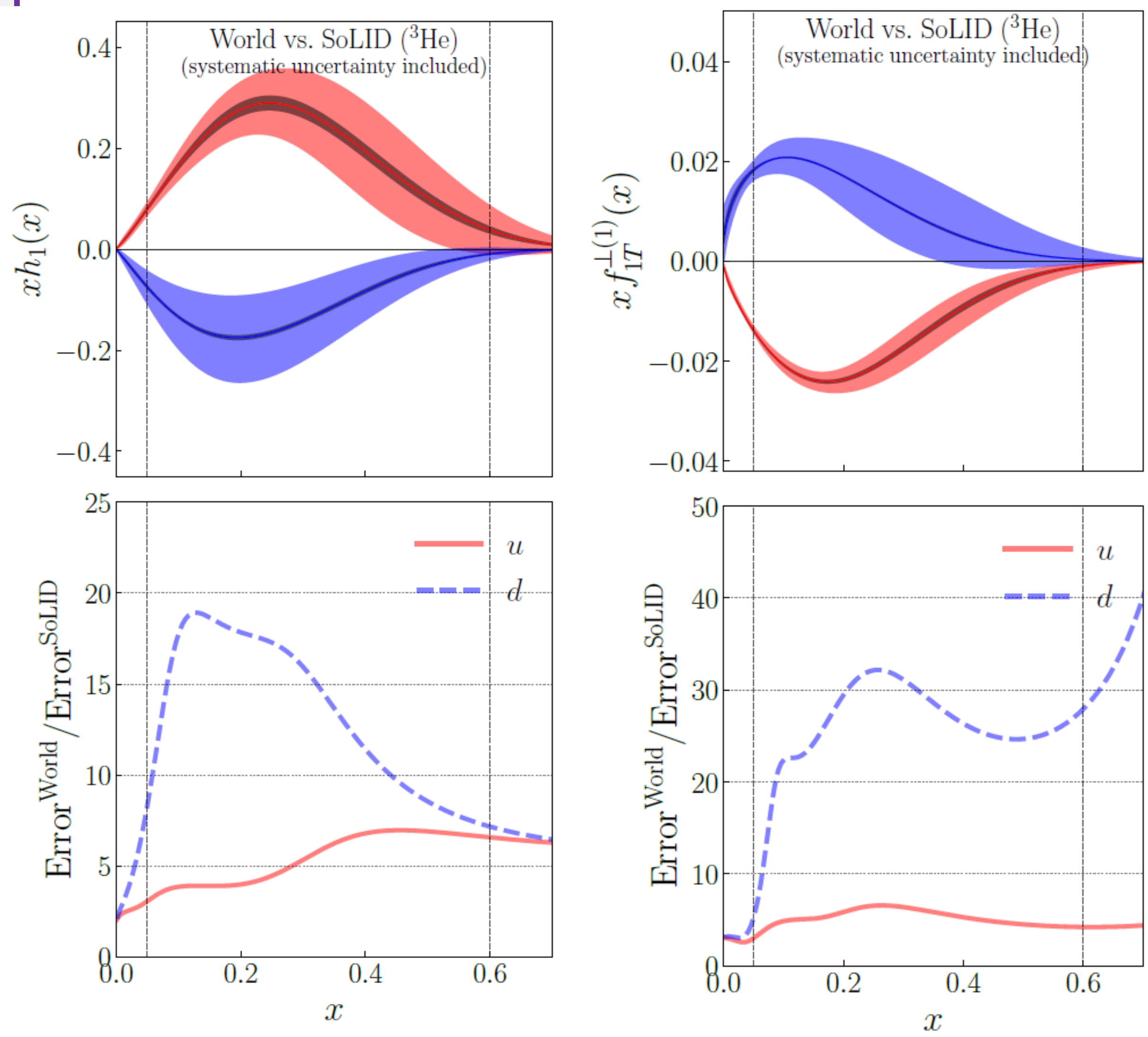
large acceptance and high luminosity enable wide coverage in all 4 kinematic bins with well controlled systematics

SoLID SIDIS Projection

Compare SoLID ^{3}He 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

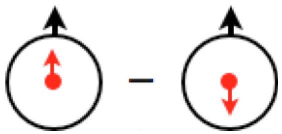
Transversity **Sivers**



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

Transversity and Tensor Charge

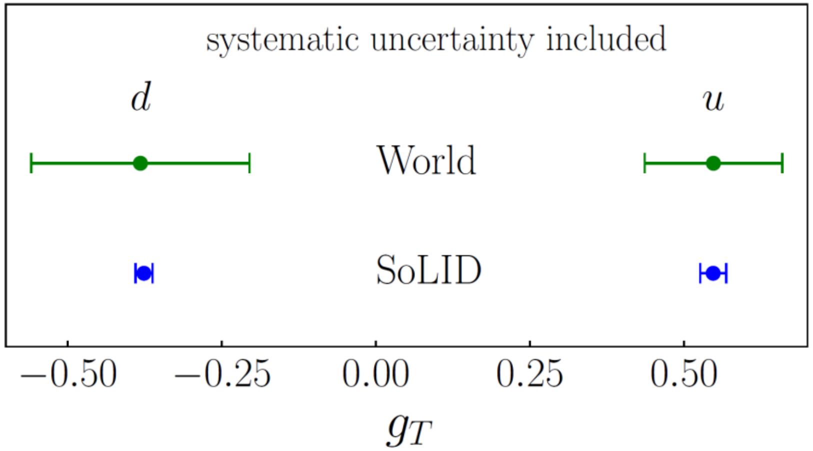
Transversity distribution

h_1  (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



g_T Flavor separation	World data	SoLID
u / *d* value	0.548 / -0.382	0.547 / -0.376
u / *d* error	0.112 / 0.177	0.021 / 0.014

SoLID projection: statistical and systematic uncertainties included

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

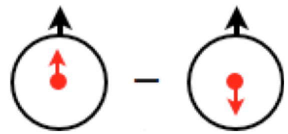
$$d_n = g_T^d d_u + g_T^u d_d + g_T^s d_s$$

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

Transversity and Tensor Charge

Transversity distribution

h_1



(Collinear & TMD)

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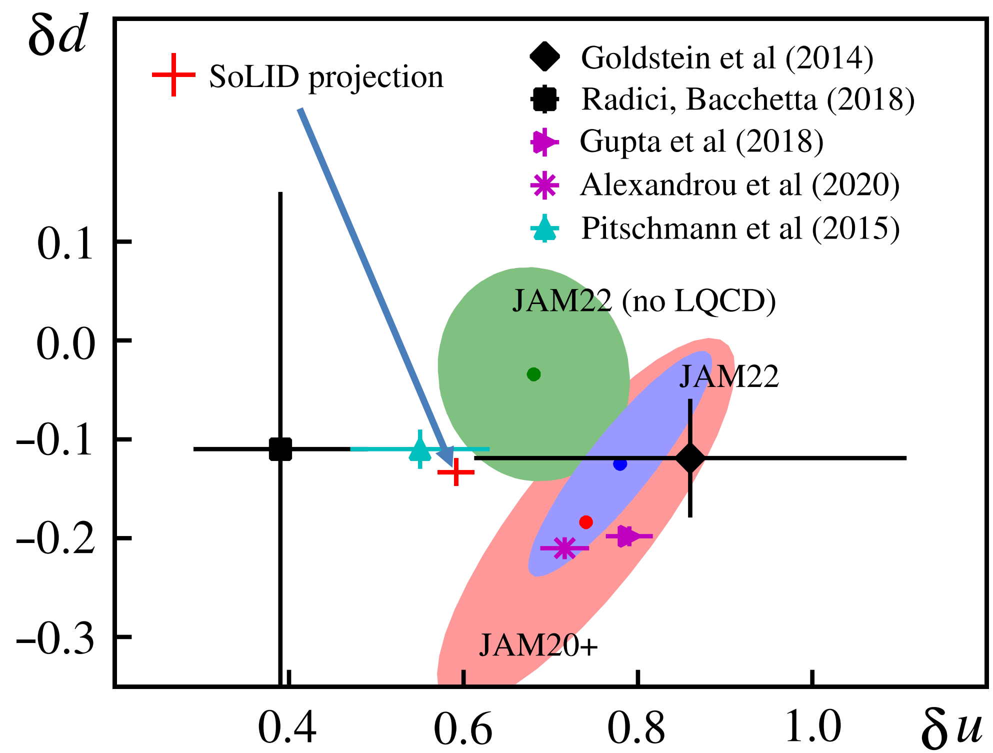
$$g_T^q = \int_0^1 \left[h_1^q(x) - h_1^{\overline{q}}(x)\right] dx$$

- 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



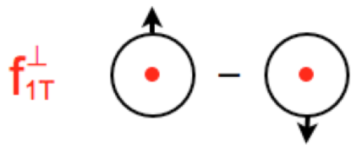
Combining E12-10-006 & E12-11-108

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

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

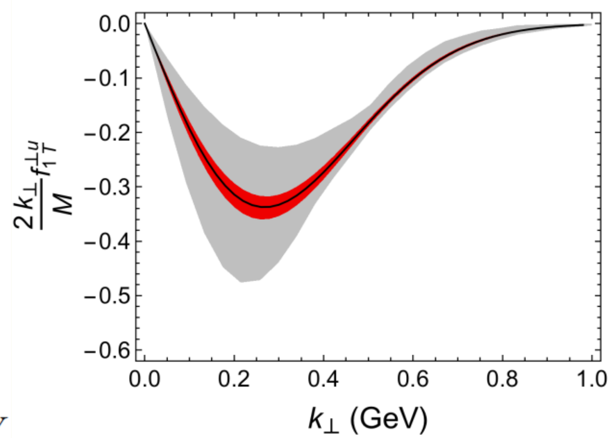
TMDs – confined motion inside the nucleon

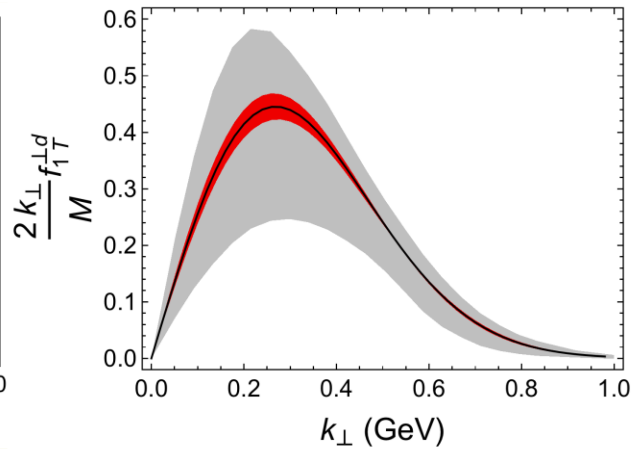
Sivers distribution



naively time-reversal odd

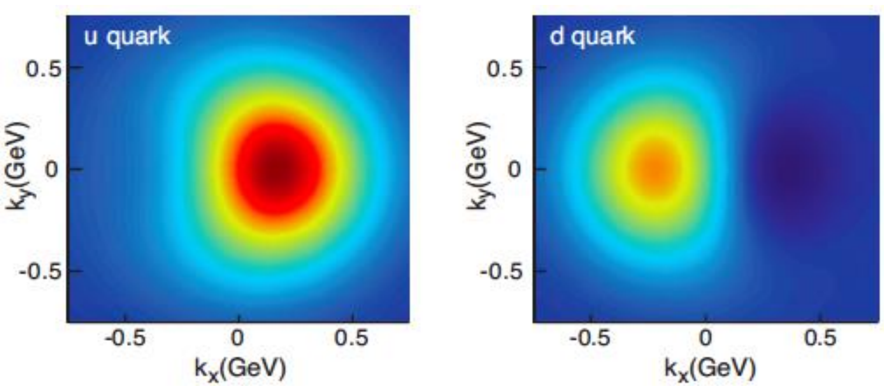
$$f_{1T}^{\perp q}(x, k_\perp)\Big|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x, k_\perp)\Big|_{\text{DY}}$$





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

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



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

SoLID projection with transversely polarized n/p

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

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

Combining E12-10-006 & E12-11-108

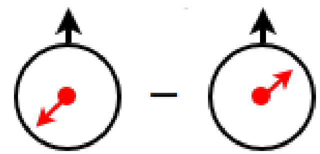
Exact finding is model dependent but SoLID impact is model-independent!

SoLID Jefferson Lab

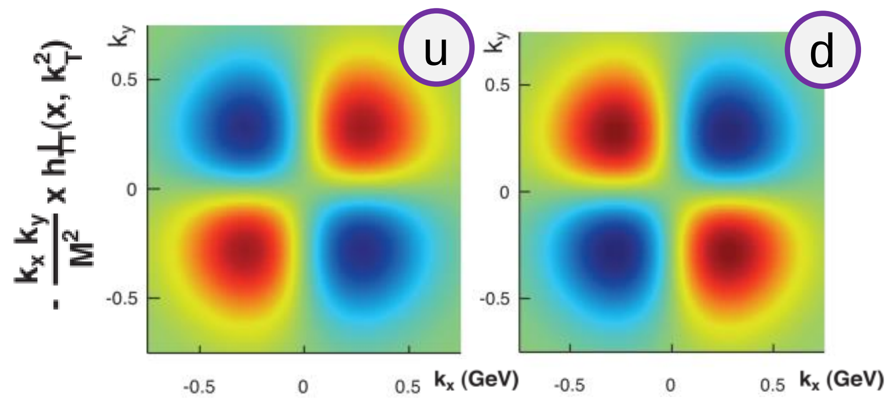
TMDs – confined motion inside the nucleon

Pretzelocity distribution

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



- 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)



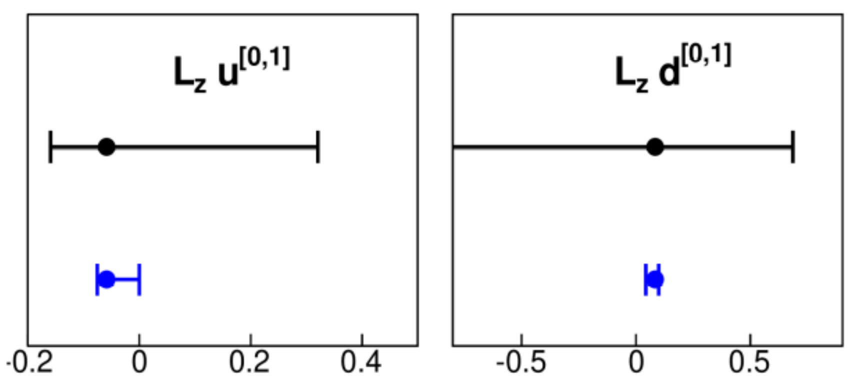
Images from PRD 91 034010 (2015)

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

SoLID projection with transversely polarized n and p data

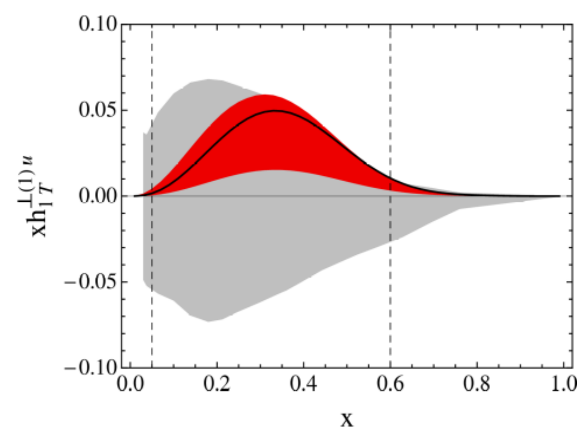
Relation to OAM (canonical)

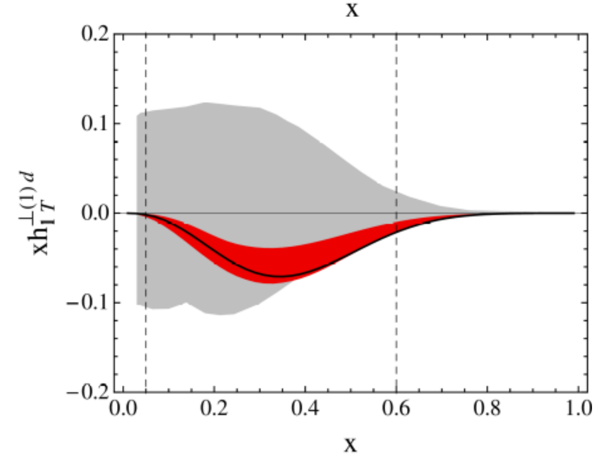
$$L_z^q = -\int \mathrm{d}x\mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int \mathrm{d}x h_{1T}^{\perp(1)q}(x)$$



Lefky and Prokudin PRD 91, 034010 (2015)

SoLID projection

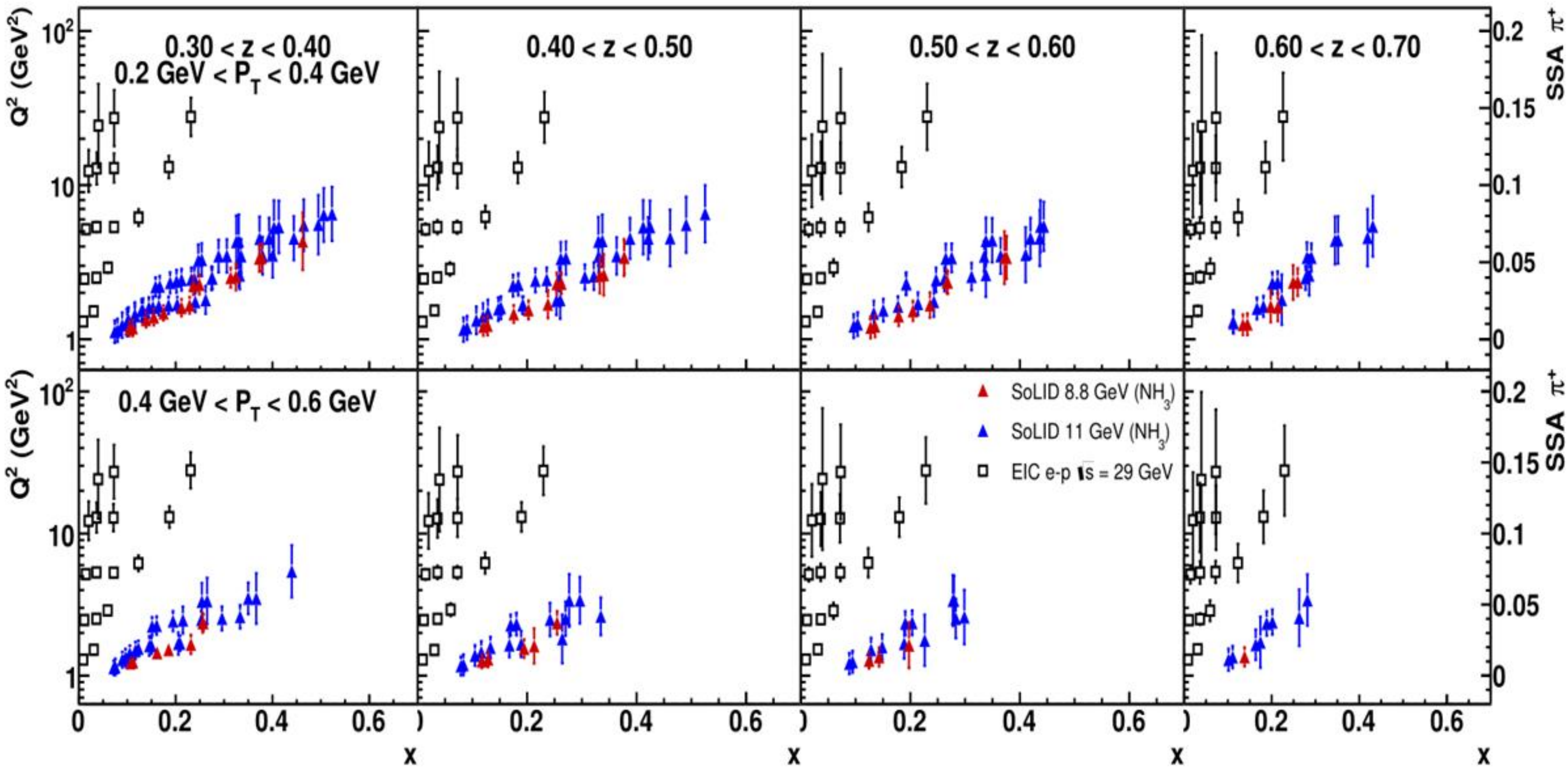




Combining E12-10-006 & E12-11-108

Transverse SSA projections: Complementarity to EIC

- SoLID SIDIS projections of A_{UT} in various 4-D bins at 11 / 8.8 GeV beam energies
- Projections at EIC kinematics for the same observable at 29 GeV center-of-mass energy
- SSA scale and uncertainties shown on the right-side axis of the right two figures
- SoLID and EIC projections synergistic towards each other, by covering different x and Q^2 ranges



E12-10-006B: Deep Exclusive π⁻ from Transversely Polarized n

Run group with SIDIS He3

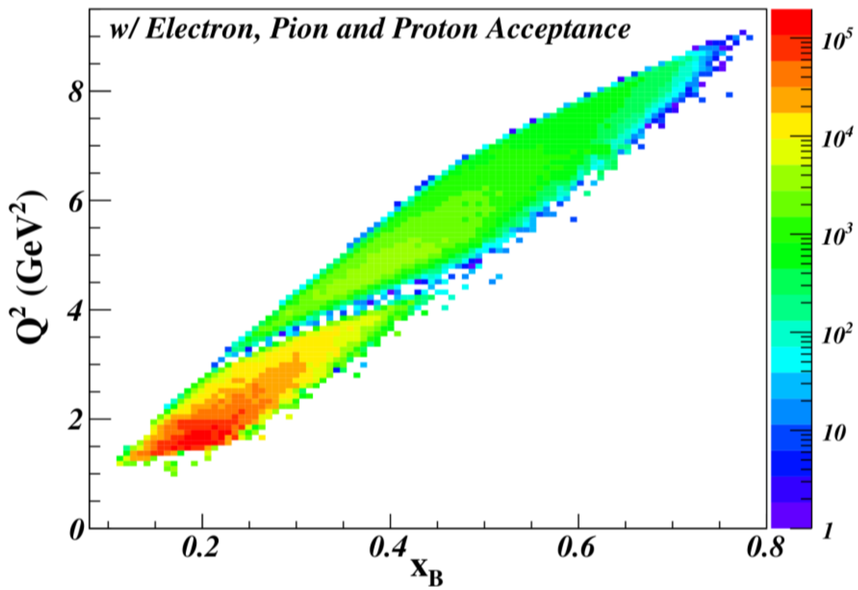
Need high luminosity

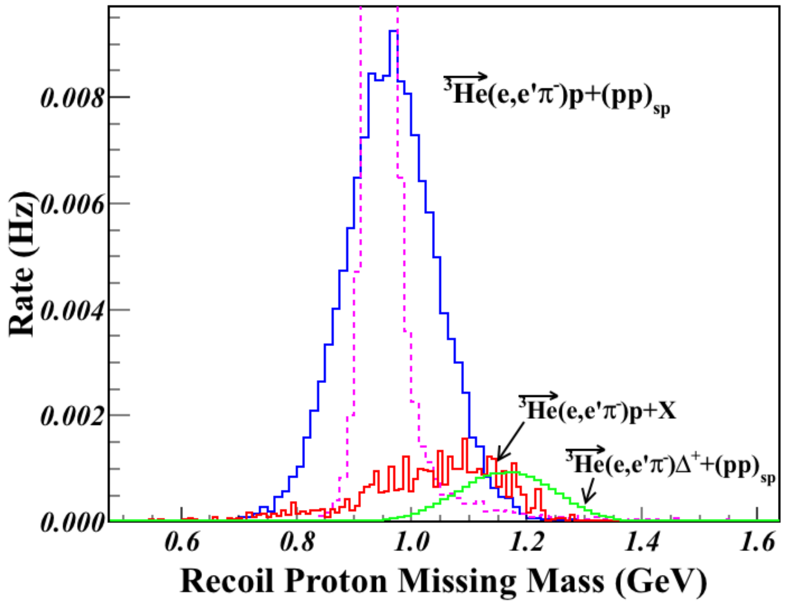
- **Azimuthal modulations of Transverse Single Spin Asymmetry allow access to different GPDs:**
  - sin(β=φ-φ_s) moment sensitive to helicity-flip GPD
  - sin(φ_s) moment sensitive to transversity GPDs

$\vec{n}(e,e'\pi^-)p$ with transversely polarized ^{3}He

$$\langle A_{UT}\rangle = \frac{1}{P\cdot\eta_n\cdot d}\left(\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}\right)$$

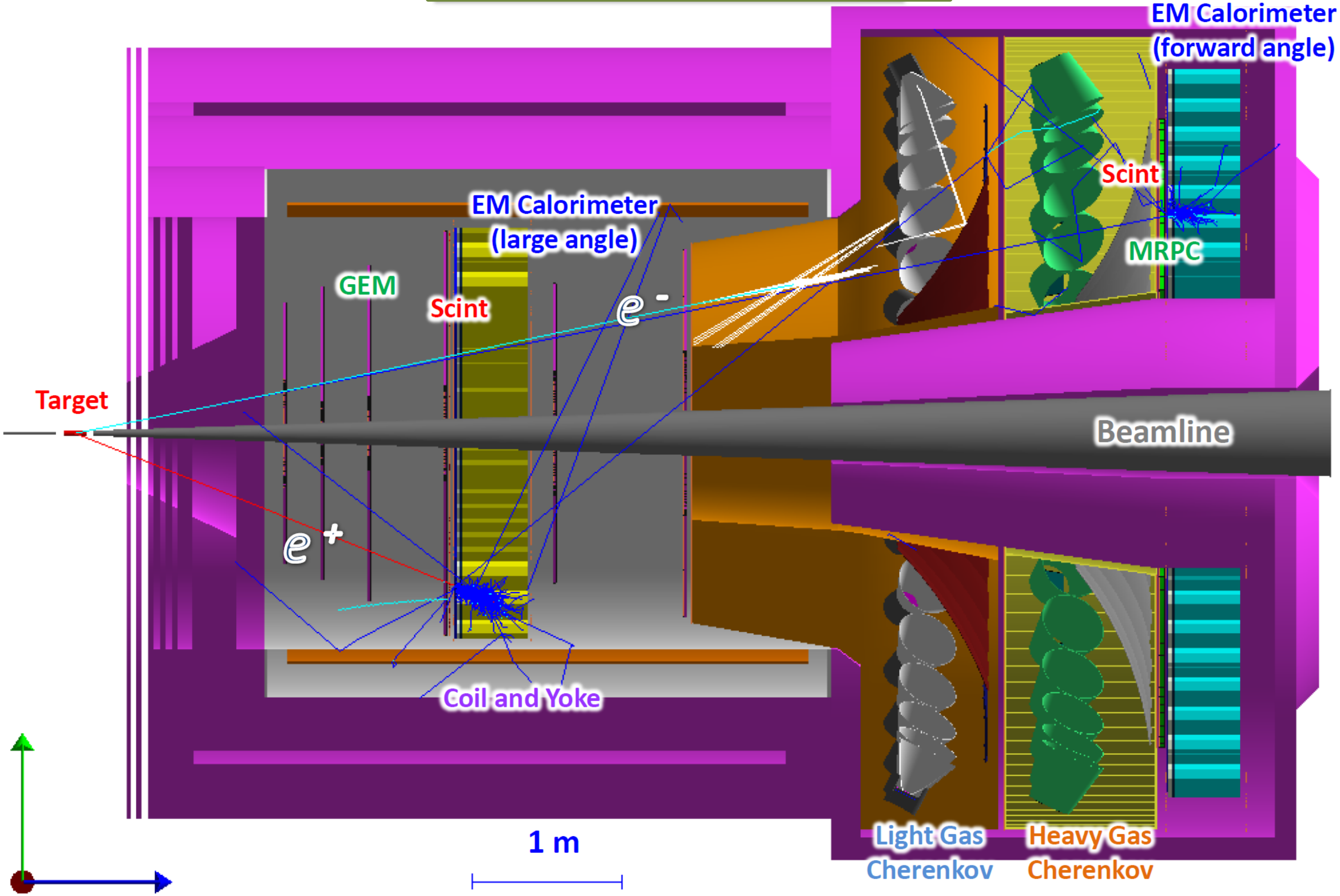
Q^2>1 GeV^2 W>2 GeV	Q^2>4 GeV^2 W>2 GeV
DEMP: $n(e,e'\pi^- p)$ Triple Coin (Hz)	
4.95	0.40
SIDIS: $n(e,e'\pi^-)X$ Double Coin (Hz)	
1425	35.8





Large kinematic coverage and well controlled background

SoLID J/ψ and TCS



E12-12-006: Near Threshold J/ψ production on LH2 target 60 days, **rating A**

run group E12-12-006A: TCS

Letter of Intent: DDVCS

Unpolarized lumi ~1e^{37}/cm^2/s

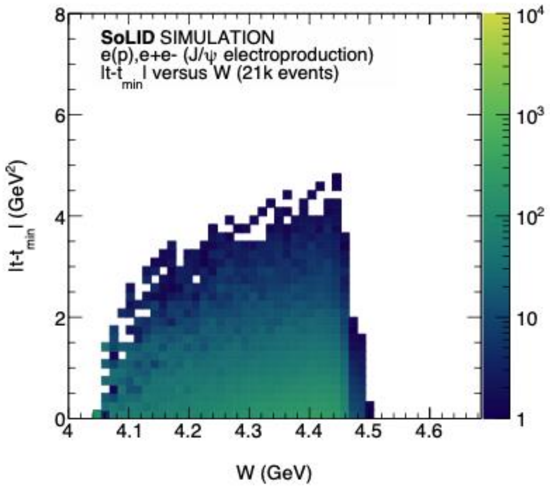
E12-12-006: Near Threshold J/ψ production on LH2 target

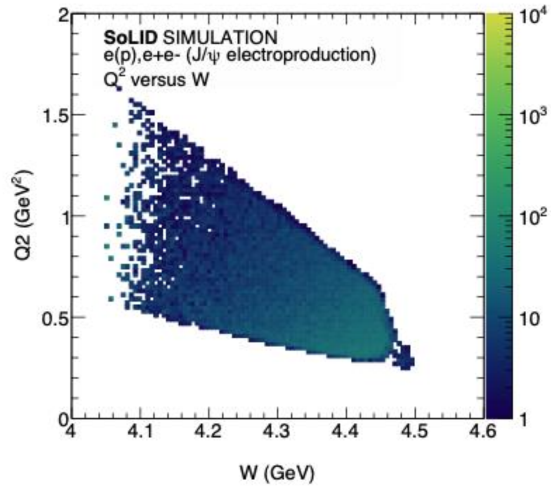
Ultimate factory for near-threshold J/ψ

50+10 days of 3μA beam on a 15cm long LH2 target ($10^{37}/cm^2/s$)

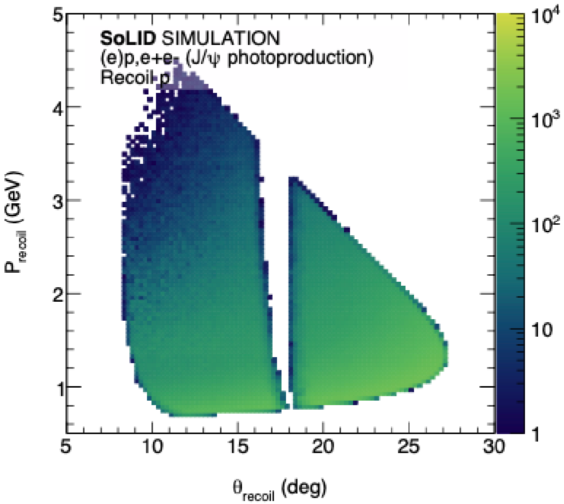
Ultra-high luminosity: $43.2 ab^{-1}$

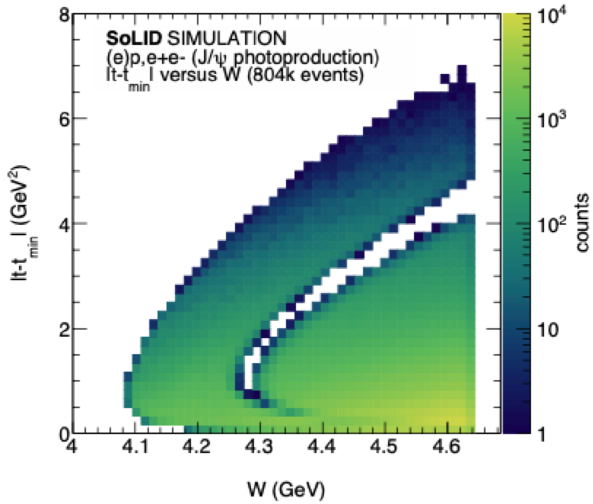
$$e\, p \rightarrow e'\, p'\, J/\psi(e^- e^+)$$

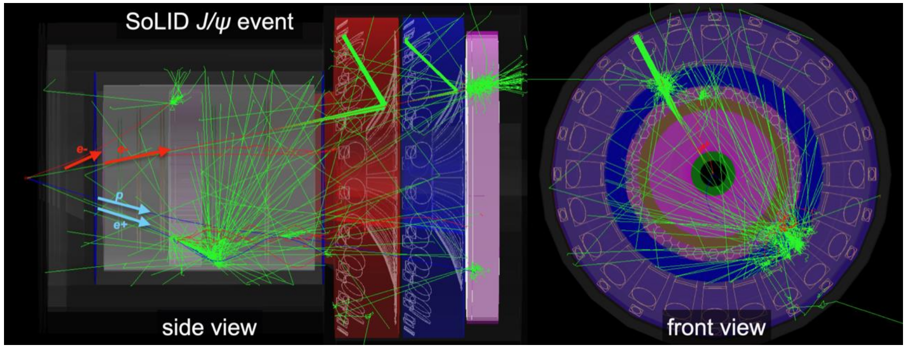




$$\gamma\, p \rightarrow p'\, J/\psi(e^- e^+)$$







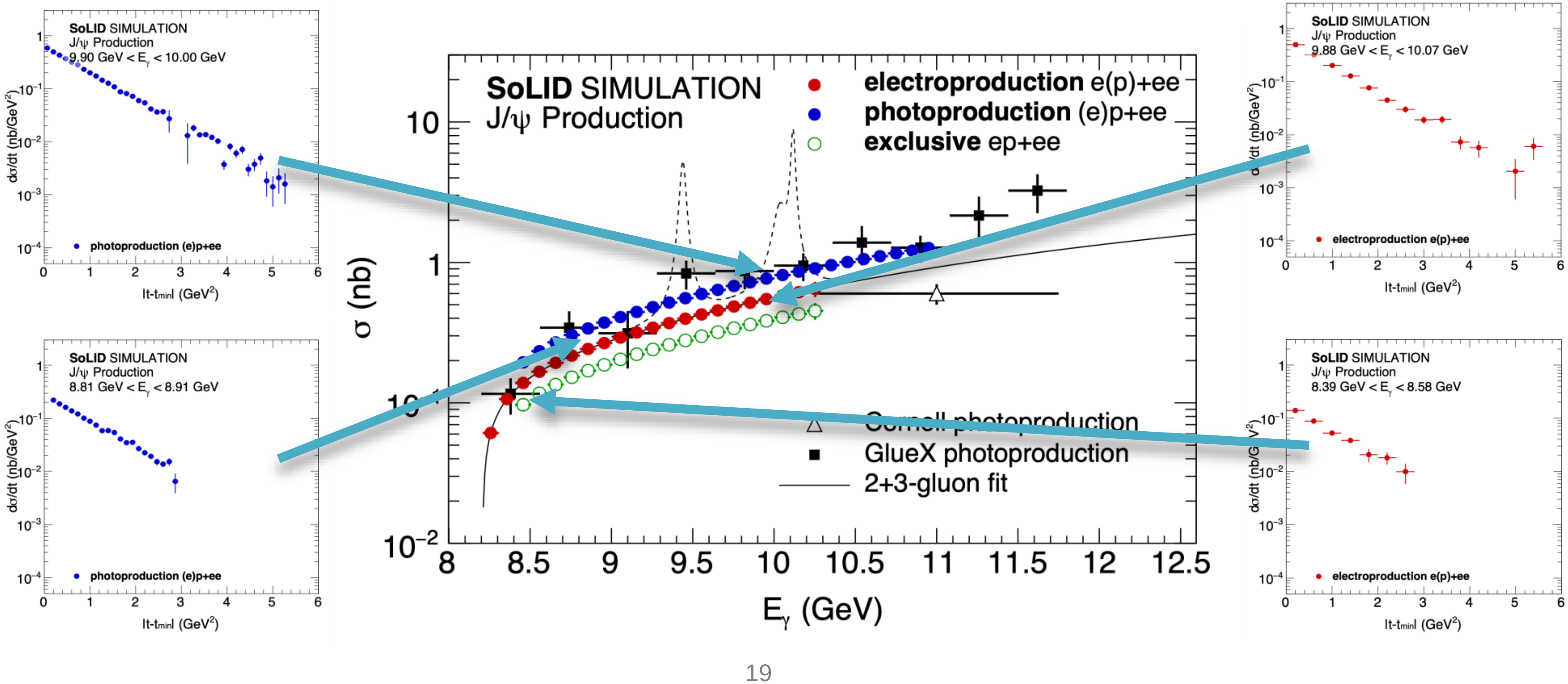
Measurements

- Electro-production:
    - 4-fold: detect decay $e^- e^+$ pair, scattered e^- and recoil proton
    - 3-fold: detect decay $e^- e^+$ pair, scattered e^- or recoil proton
- Photo-production:
    - 3-fold: detect decay $e^- e^+$ pair and recoil proton
- Trigger on decay $e^- e^+$ pair only
- Wide kinematic coverage

S. Joosten

SoLID J/ψ projection

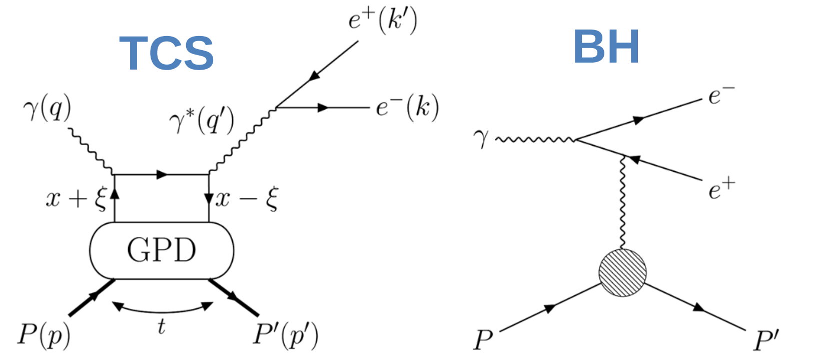
Precision at high t crucial for extrapolations to the forward limit (exponential, dipole, triple, …)



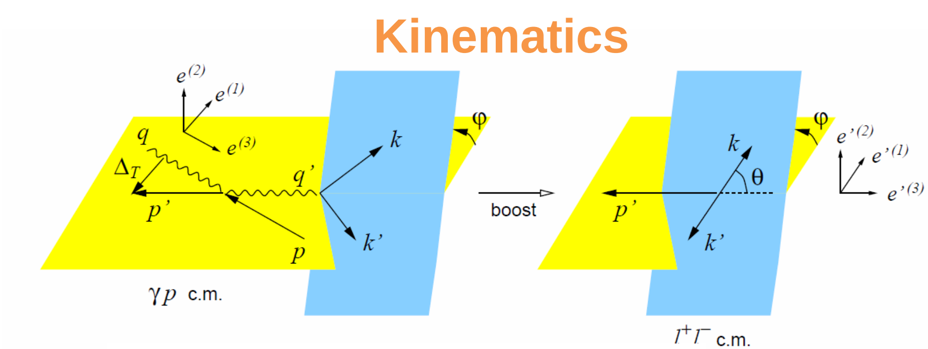
E12-12-006A: TCS with circular polarized beam and LH2 target

sharing beam time with J/psi run using same trigger on decay $e^- e^+$ pair only

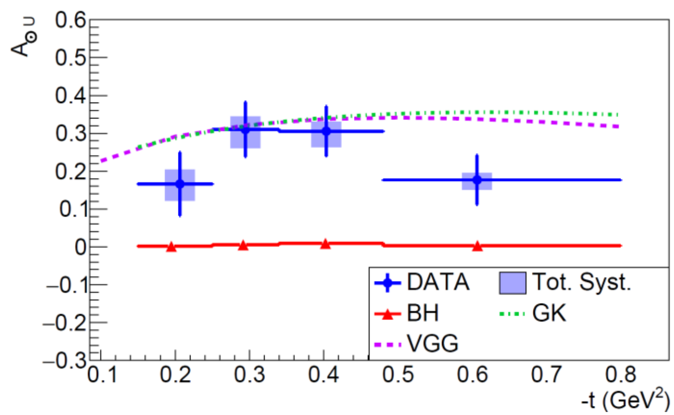
$$\gamma\, p \rightarrow \gamma^*(e^- e^+)\, p'$$

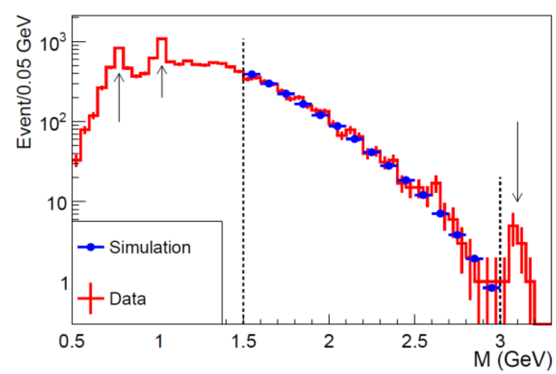


- Motivation
  - Timelike Compton Scattering (TCS) access the same GPDs like DVCS and test universality
  - Access real and imaginary part of GPD H through CFF
  - New observables for global GPD fits
- Status
  - exploration at CLAS 6GeV
  - First result at CLAS12 published at PRL, 127, 262501 (2021) obtain **nonzero** beam polarized asymmetry A_{LU} and forward backward asymmetry A_{FB}
  - Limited by low statistics



CLAS12 result

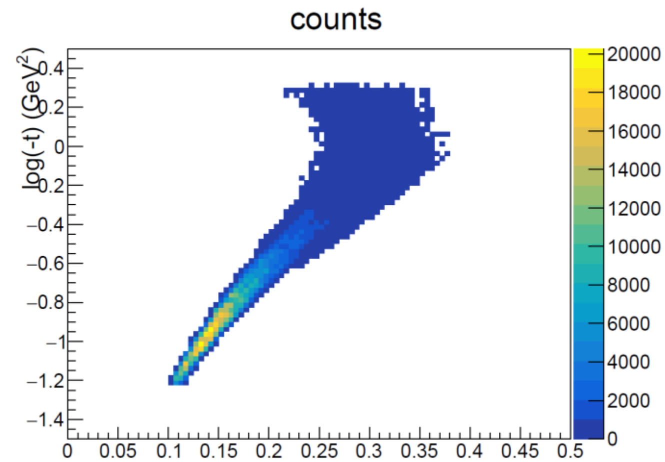


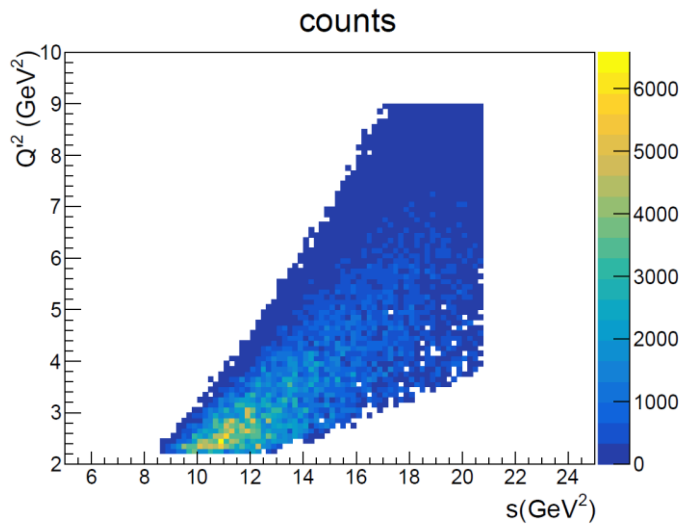


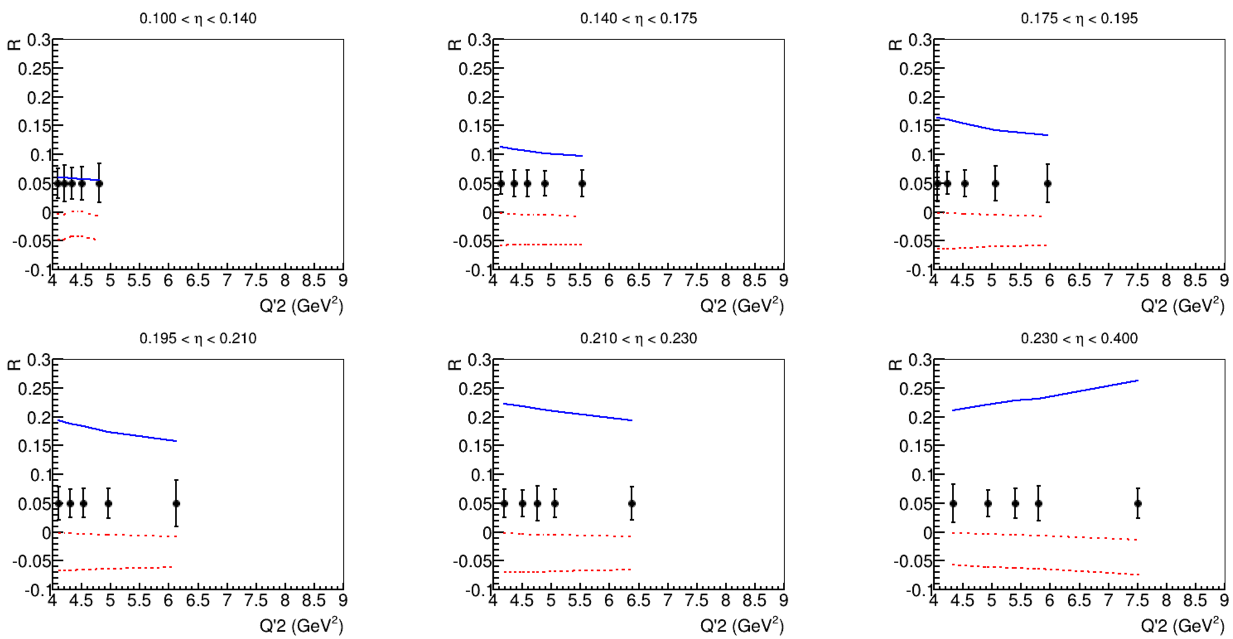
E12-12-006A: TCS with circular polarized beam and LH2 target

- SoLID TCS will have at least 1 order higher statistics than CLAS12 and usher TCS study into precision era with multi-dimensional binning
  - SoLID has 250 times more integrated luminosity than the CLAS12 TCS published result
  - SoLID acceptance to TCS events is about ¼ of CLAS12. But with full azimuthal coverage, (ideal for the forward backward asymmetry)
  - Crosssection measurement (moment)
- SoLID TCS could lead to study of NLO correction

SoLID TCS coverage







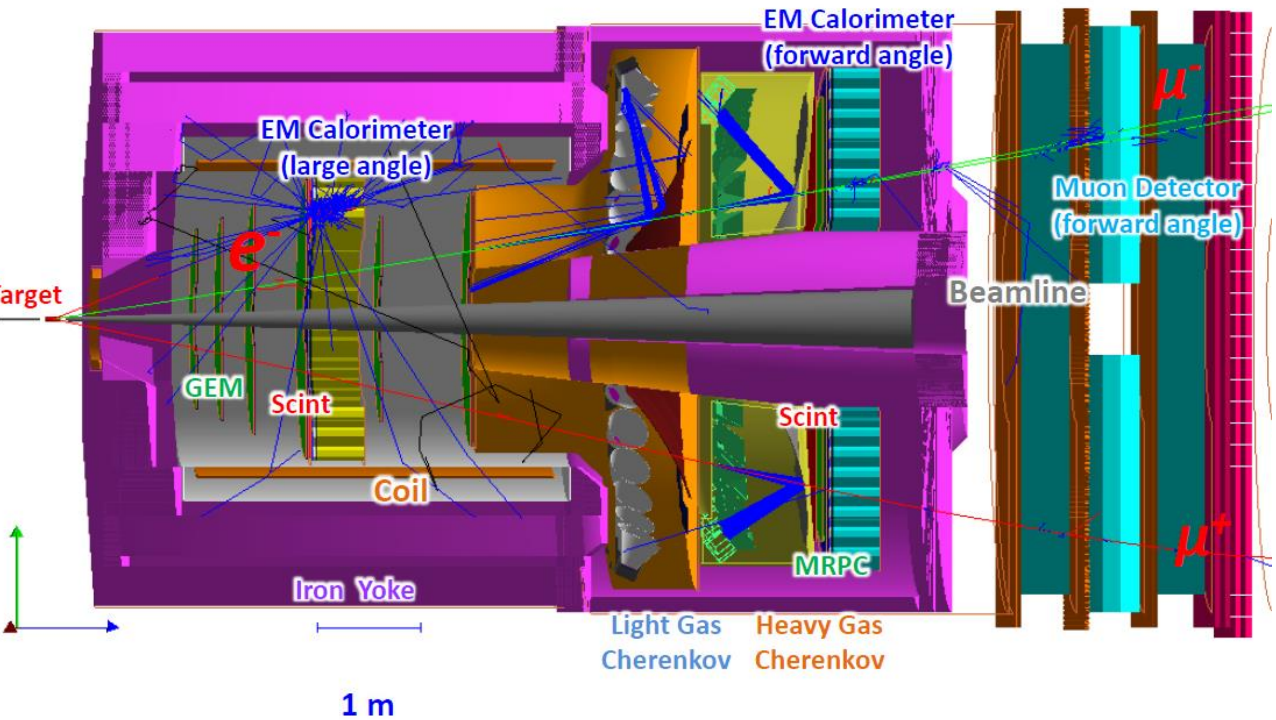
$$R=\frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ^2\,dt\,d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ^2\,dt\,d\varphi}}$$

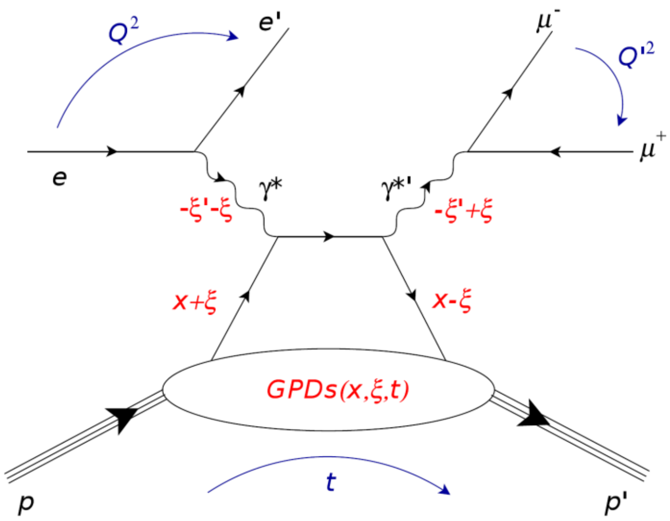
DDVCS with circular polarized beam and LH2 target

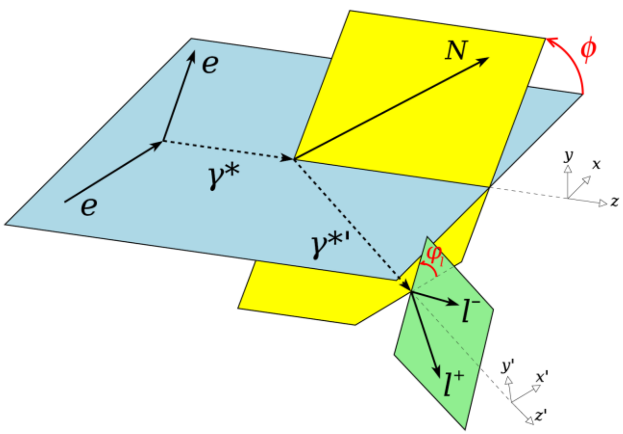
Letter of Intent 2015 and 2023

$$e^- p \rightarrow e^- \gamma^*(\mu^- \mu^+)\, p'$$

SoLID DDVCS







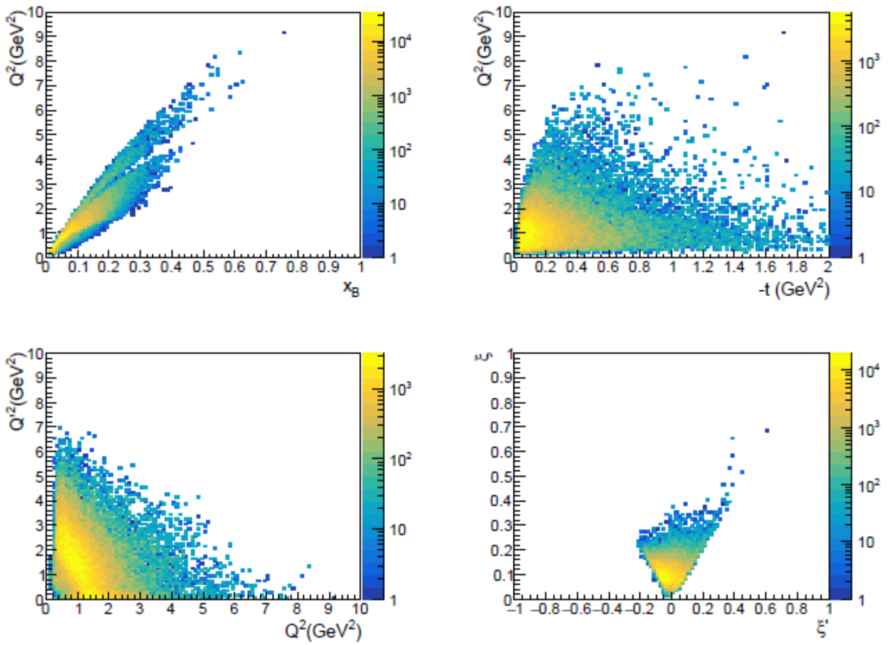
$$\xi = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

- Double Deeply Virtual Compton Scattering (DDVCS) explores wide off-axis kinematic region of GPDs, beyond DVCS and TCS
- SoLID with muon detectors at forward angle, enables DDVCS measurements with both polarized electron and positron beams at 11GeV
- Sharing running time and increase statistics for J/ψ and TCS

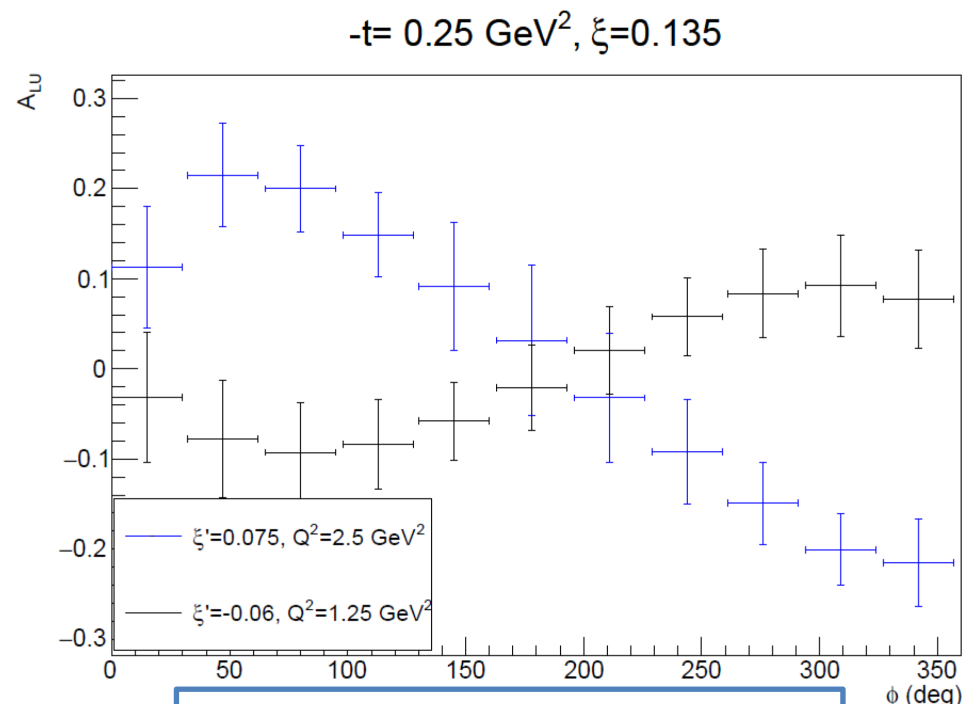
EPJA 57, 240 (2021)

DDVCS with circular polarized beam and LH2 target

coverage

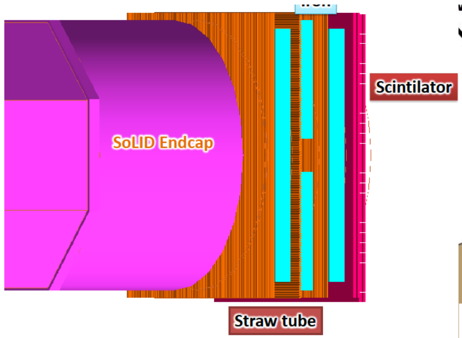


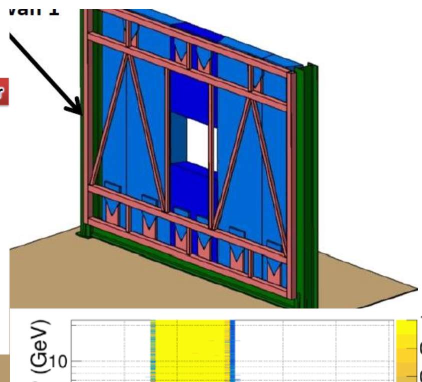
projection

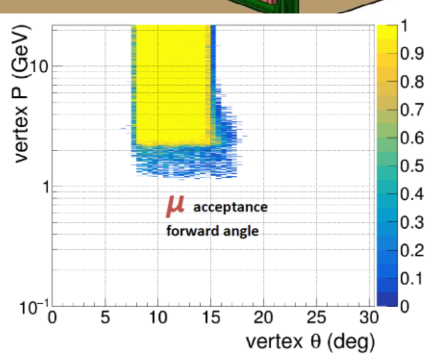


$$A^{\pm}_{LU}(\phi) = \frac{1}{\lambda^{\pm}} \frac{d^5\sigma^{\pm}_{+} - d^5\sigma^{\pm}_{-}}{d^5\sigma^{\pm}_{+} + d^5\sigma^{\pm}_{-}} \qquad (15)$$

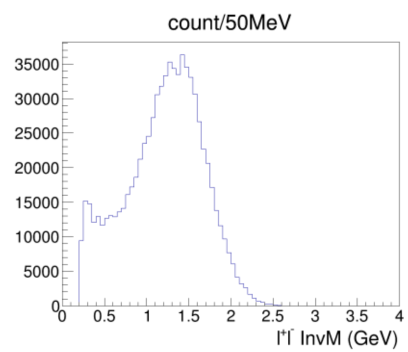
$$= \frac{d^5\widetilde{\sigma}_{DDVCS} \mp d^5\widetilde{\sigma}^{\mathrm{INT1}}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} \mp d^5\sigma_{INT_1}}$$





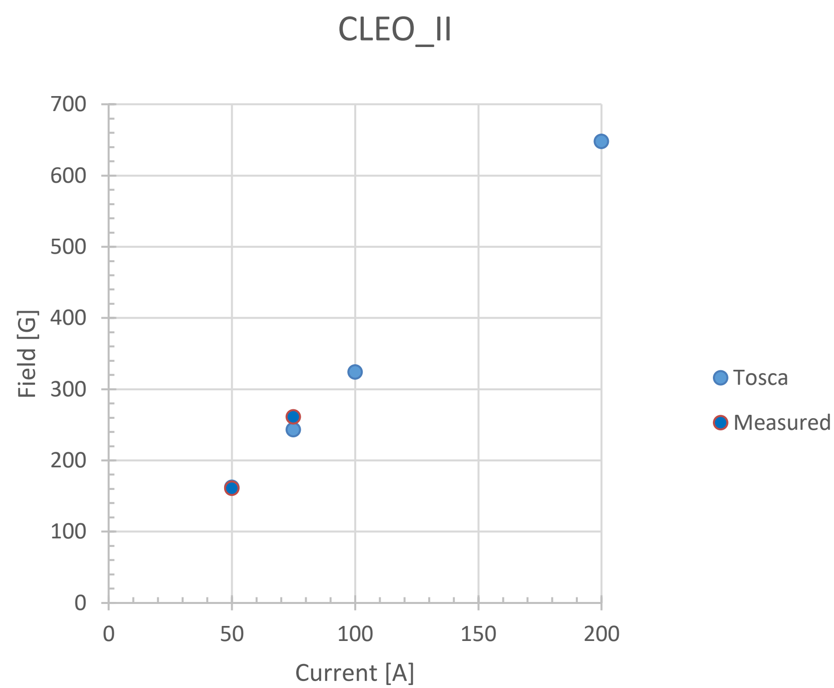


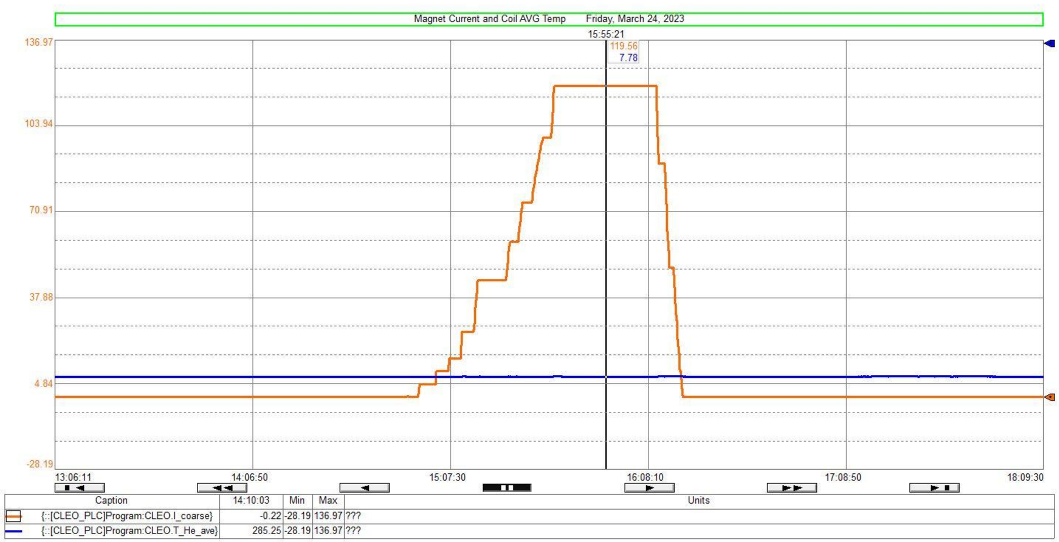
Iron plate to block pion, straw tube for tracking and scintillator for trigger



SoLID Update: CLEO-II Magnet Cold Test

- A low current test conducted on March 24th. The current for this test was ramped up to 120A and was held for 30 mins.
- PSU output voltage ~ 1.15V during ramp up at 0.5A/s.
- No increase in coil voltages observed during ramp up or while at 120A for 30 minutes.
- Coil believed to be superconducting with flat lined nature of temp curves during test.
- A 3 axis Hall probe was installed in the bore of the magnet for each of the tests. Data matched TOSCA model well.
- Coil average temperature remained constant during test.

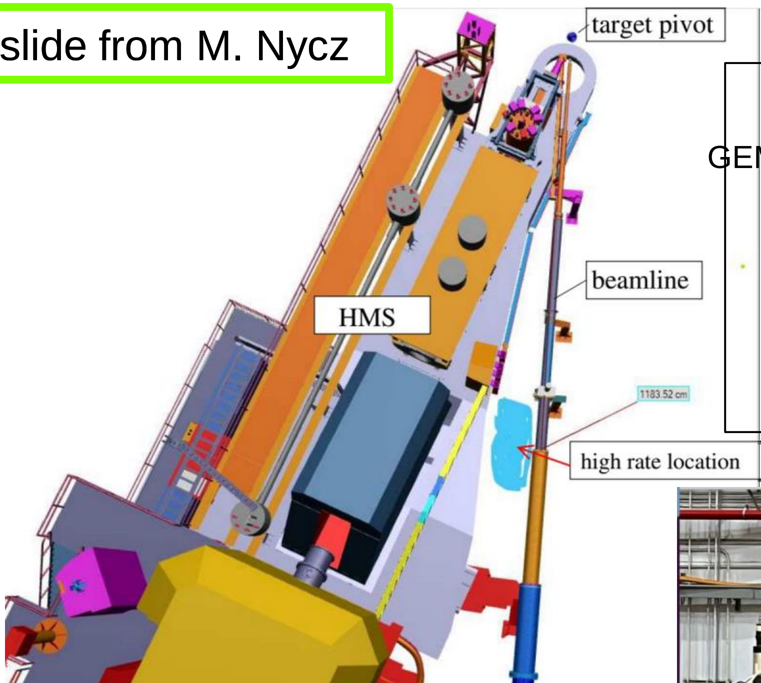


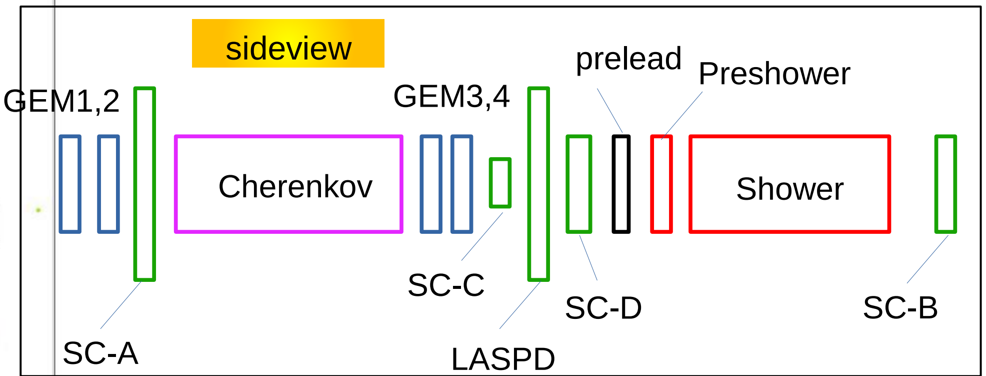


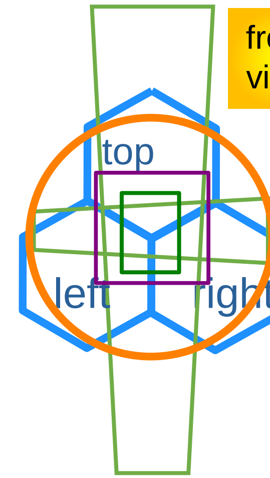
slide from W. Seay

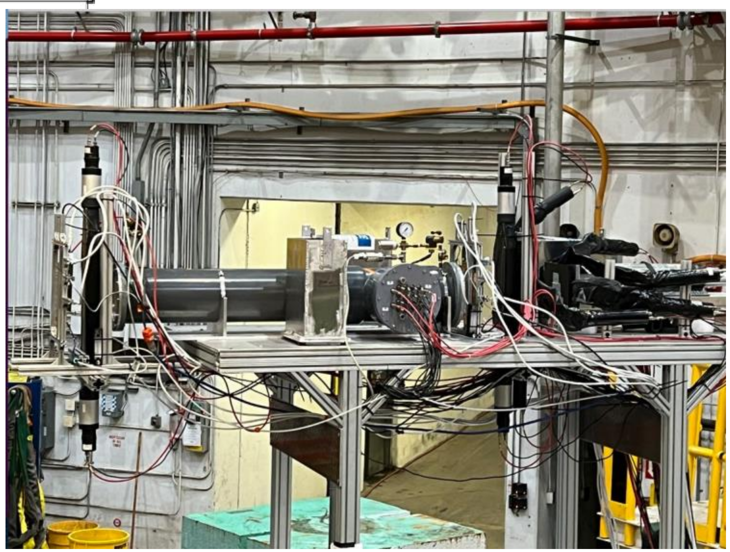
SoLID Update: Detector Beam Test (2022-23 Hall C)

slide from M. Nycz









Three stages:

- June 2022: install at (L) 82^o
  - X'mas 2022: cosmic
- Jan 2023: moved to (R) 7^o
- Feb 2023: moved to (R) 18^o

- Similar detector setup as SoLID (1/600), no magnet, ~10^2 krad
- Extensive simulation, PID study with both classical and AI/ML

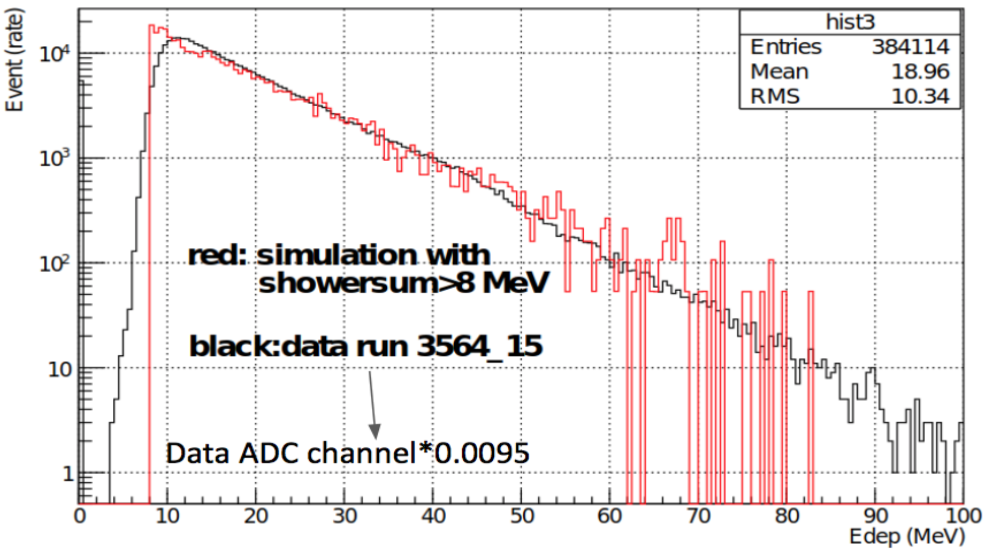
Collective effort of: X. Bai, A. Camsonne, J. Caylor, C. Hedinger, T. Holmstrom, M. Nycz, C. Peng, Y. Tian, D. Upton, Z. Ye, J. Zhang, Z. Zhao, JLab DAQ group, and Hall C(A) tech/staff

SoLID Update: Detector Beam Test (2022-23 Hall C)

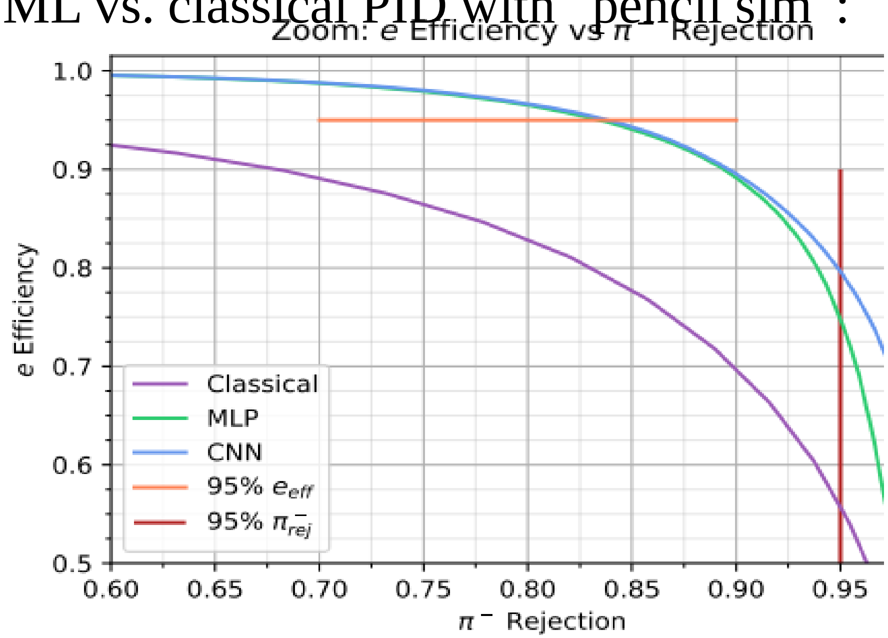
Preliminary

slide from Y. Tian & D. Upton

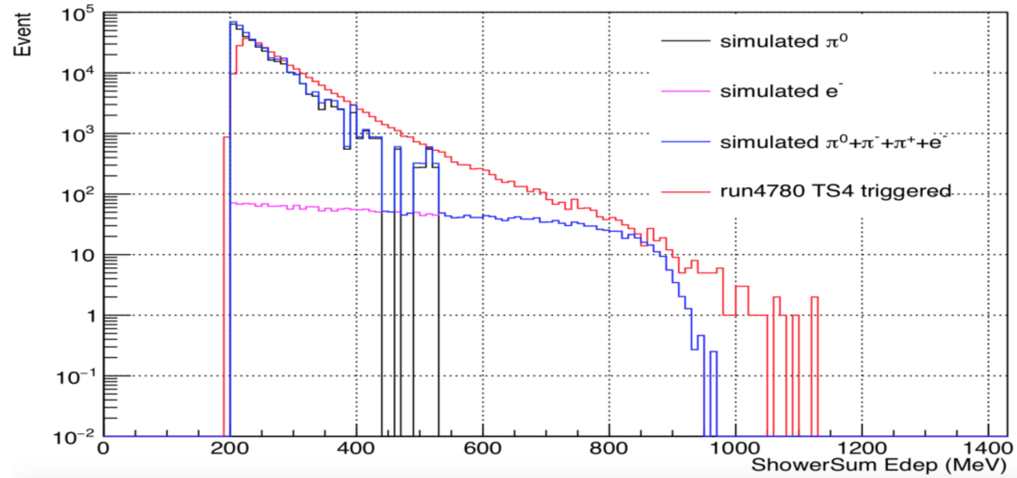
- 82 deg: Shower MIP not visible, calibrate sim/data using spectrum slope

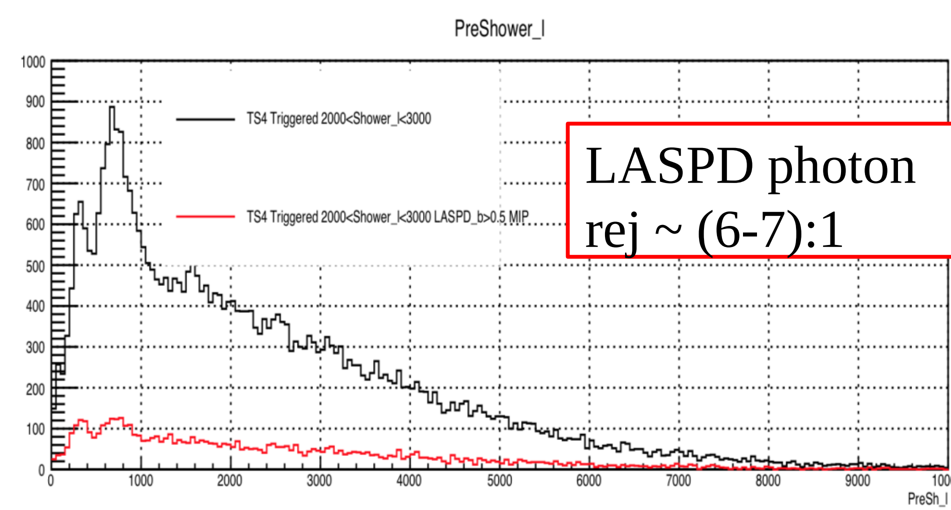


- ML vs. classical PID with "pencil sim":



- 7 and 18 deg:
  - ✓ detectors calibrated with sim using MIP location
  - ✓ rates agree with simulation to within (10-15)%





LASPD photon rej ~ (6-7):1

NSAC 2023 LRP Town Meetings – QCD

https://indico.mit.edu/event/538/
https://arxiv.org/abs/2303.02579

Recommendation 1: Capitalizing on past investments *(Yes: 335; No: 3; No Answer: 4)*

The highest priority for QCD research is to maintain U.S. world leadership in nuclear science for the next decade by capitalizing on past investments. Maintaining this leadership also requires recruitment and retention of a diverse and equitable workforce.

We recommend support for a healthy base theory program, full operation of the CEBAF 12-GeV and RHIC facilities, and maintaining U.S. leadership within the LHC heavy-ion program, along with other running facilities, including the valuable university-based laboratories, and the scientists involved in all these efforts.

This includes the following, unordered, programs:

- The 12-GeV CEBAF hosts a forefront program of using electrons to unfold the quark and gluon structure of visible matter and probe the Standard Model. We recommend executing the CEBAF 12-GeV program at full capability and capitalizing on the full intensity potential of CEBAF by the construction and deployment of the Solenoidal Large Intensity Device (SoLID).
- The RHIC facility revolutionized our understanding of QCD, as well as the spin structure of the nucleon. To successfully conclude the RHIC science mission, it is essential to complete the sPHENIX science program as highlighted in the 2015 LRP, the concurrent STAR data taking with forward upgrade, and the full data analysis from all RHIC experiments.
- The LHC facility maintains leadership in the (heavy ion) energy frontier and hosts a program of using heavy-ion collisions to probe QCD at the highest temperature and/or energy scales. We recommend the support of continued U.S. leadership across the heavy ion LHC program.
- Theoretical nuclear physics is essential for establishing new scientific directions, and meeting the challenges and realizing the full scientific potential of current and future experiments. We recommend increased investment in the base program and expansion of topical programs in nuclear theory.

Hot & Cold QCD 2022 Town Hall Meeting

SoLID info

- https://solid.jlab.org
- PreCDR 2019
  https://solid.jlab.org/DocDB/0002/000282/001/solid-precdr-2019Nov.pdf
- Whitepaper 2022
  https://arxiv.org/abs/2209.13357 (accepted by J. Phys. G)

Summary

- SoLID with open geometry has a broad physics program
  - TMD (SIDIS)
  - GPD (DEMP, TCS, DDVCS)
  - J/ψ near threshold

- High luminosity and large acceptance are keys to make those next generation experiments possible with multidimensional binning
- More ideas (e.g. deuterium and other nuclei target)

Thank you!

Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231

Strong Collaboration

SOLENOIDAL LARGE INTENSITY DEVICE

- 270+ collaborators, 70+ institutes from 13 countries
- Strong theory support
- Active development and validation of the pre-conceptual design and physics programs