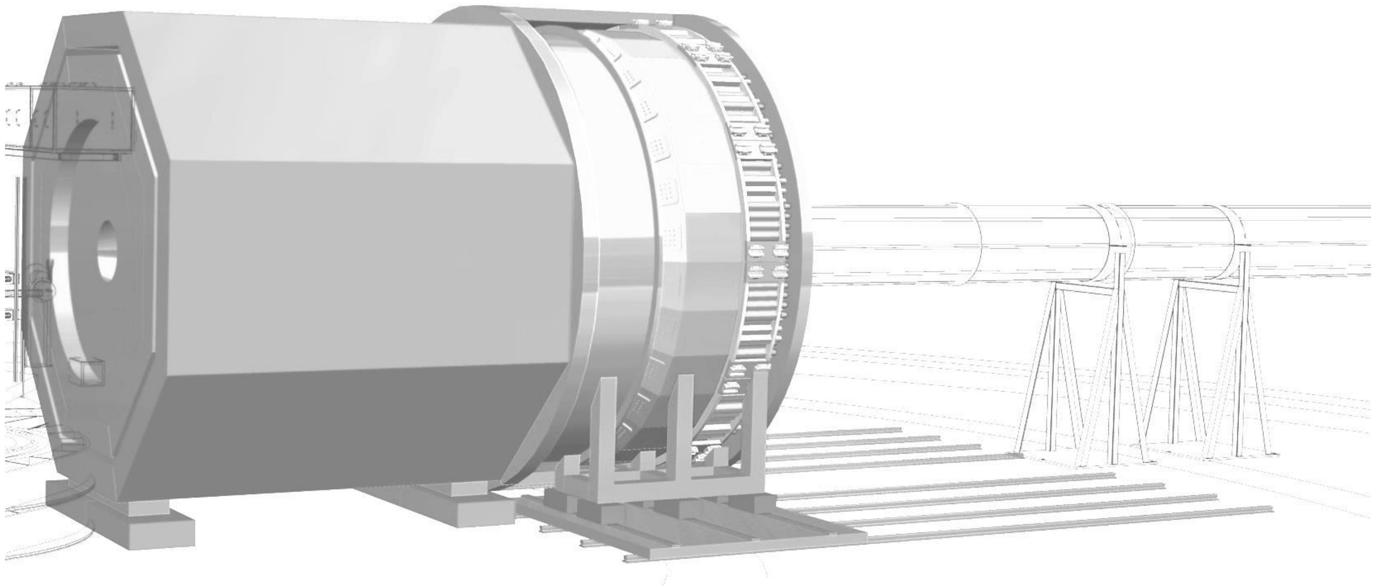
# SoLID Status Update



SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

https://solid.jlab.org/

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**On behalf of the SoLID Collaboration**

Hadron2023 Workshop, 06/05-06/10/2023

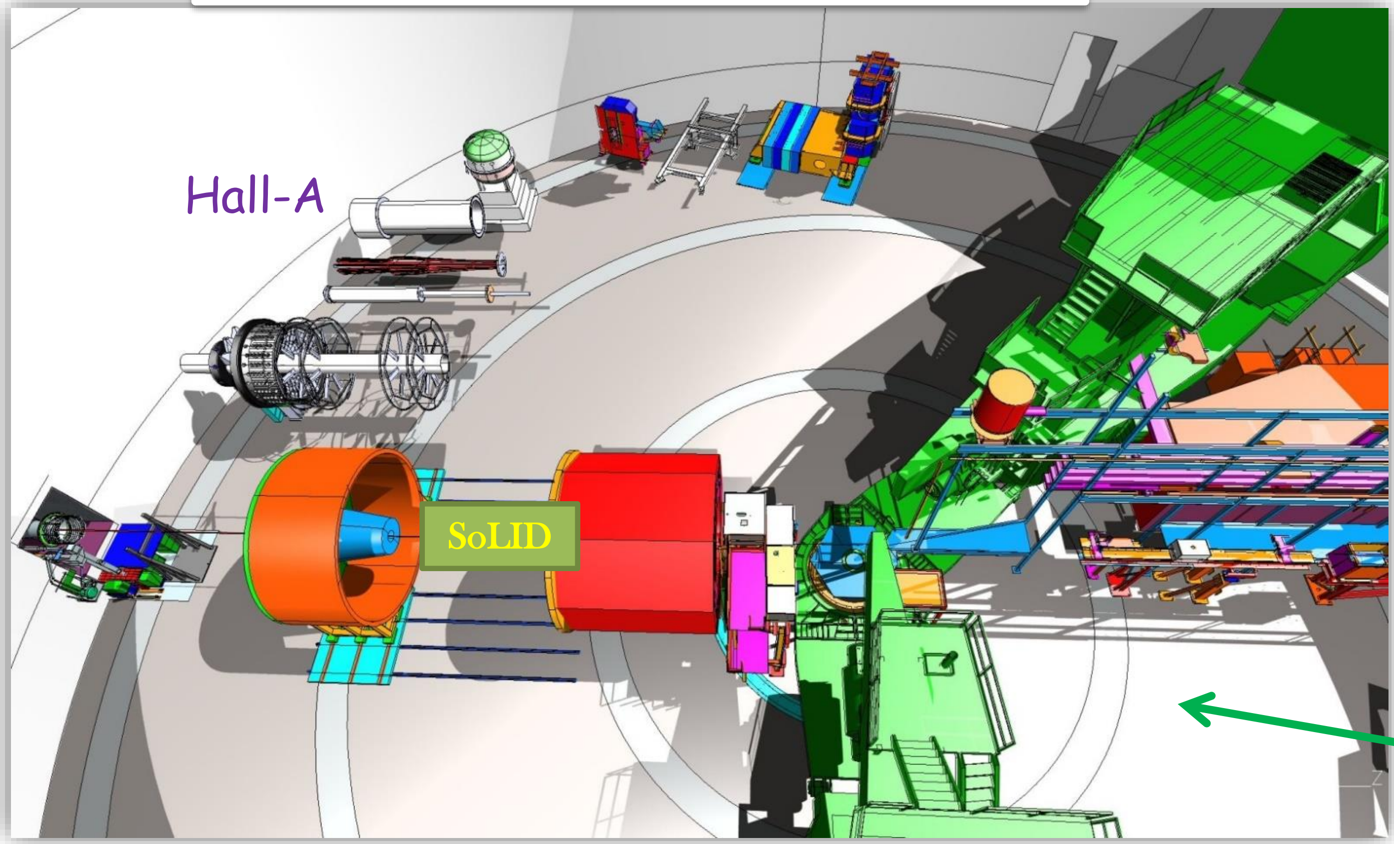
清華大學
Tsinghua University

# About SoLID



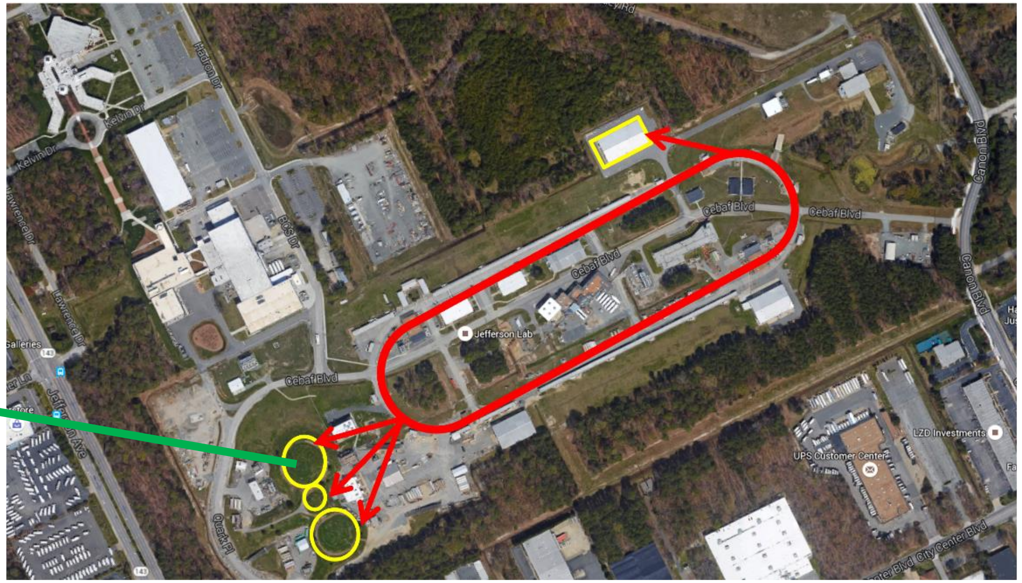
➢ **Solenoidal Large Intensity Device (Hall-A, Jefferson Lab):**

- ✓ High Intensity ($10^{37} \sim 10^{39}$ cm$^{-2}$s$^{-1}$),
- ✓ Large Acceptance, $4\pi$ Coverage




**Physics Programs:**

- ✓ Parity Violation DIS
- ✓ Near-Threshold J/ Ψ Production
- ✓ Semi-Inclusive DIS w/ polarized targets
- ✓ *NEW*: spin, GPD, eA physics, …

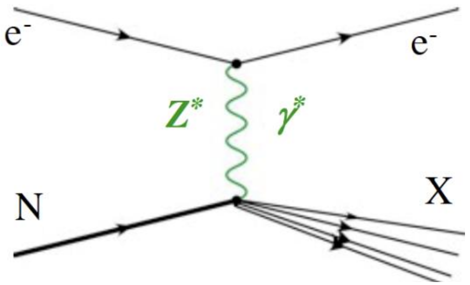


- SoLID White-Paper, arXiv:2303.03428, accepted by J. Phy. G

# SoLID Physics

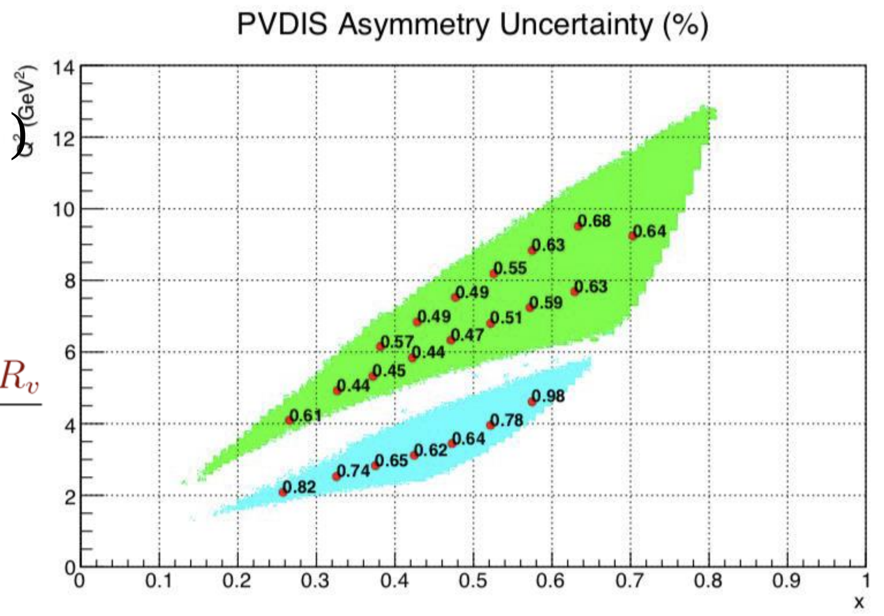
## ➢ PVDIS

- ❑ Parity Violation DIS w/ H2 and D2 (E12-10-007, 168 days, A rating )

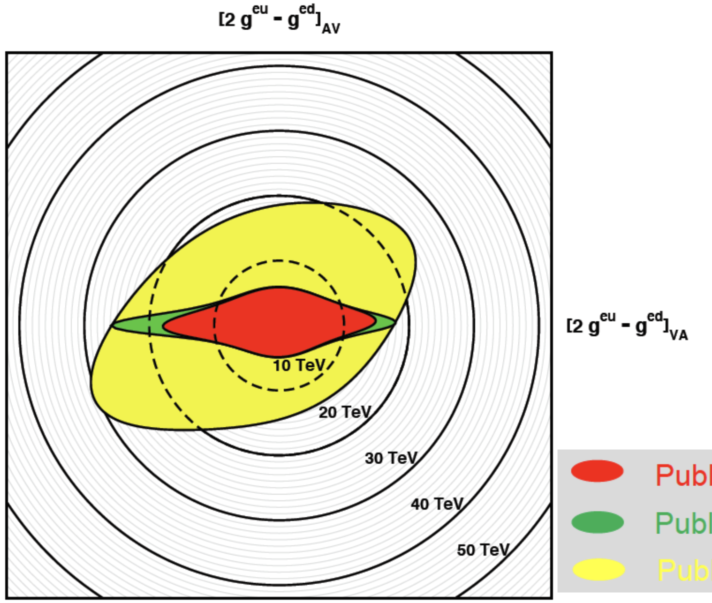



$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$eD = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s}$$



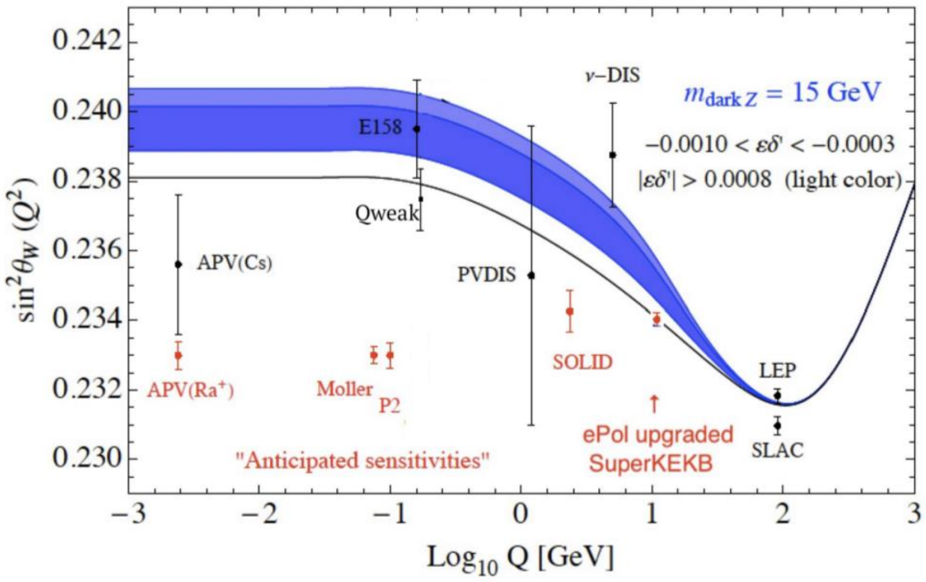

- ✓ sub-1% precision over broad kinematic range
- ✓ Sensitive to Standard Model test at high energy scale





- ✓ Search for CSV at quark level
- ✓ Explore quark-quark higher twist effects
- ✓ Dark boson $Z_d$ and other sub-TeV BSM models

*Davoudiasl, et al. PRD 92 •=(2015) 5, 055005*



# SoLID Physics



- **PVDIS**
  - Parity Violation DIS w/ H2 and D2 (E12-10-007, 168 days, A rating )
    - Detailed study of hadronic structure contributions
      - ✓ complementary other Jlab d/u program (PVDIS, BONUS (D), and MARATHON)
      - ✓ The MARATHON Data on d/u has different interpretations.
      - ✓ *Only PVDIS has no nuclear effects*

*PRL* 127 (2021) 24, 242001, *PRL* 128 (2022) 13, 132003

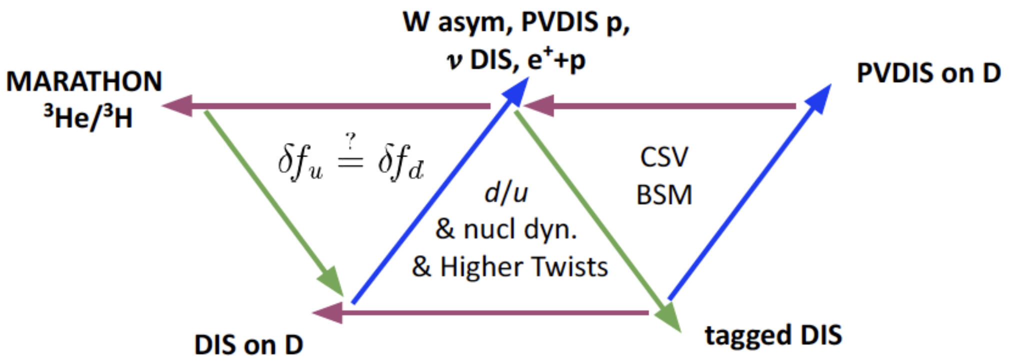
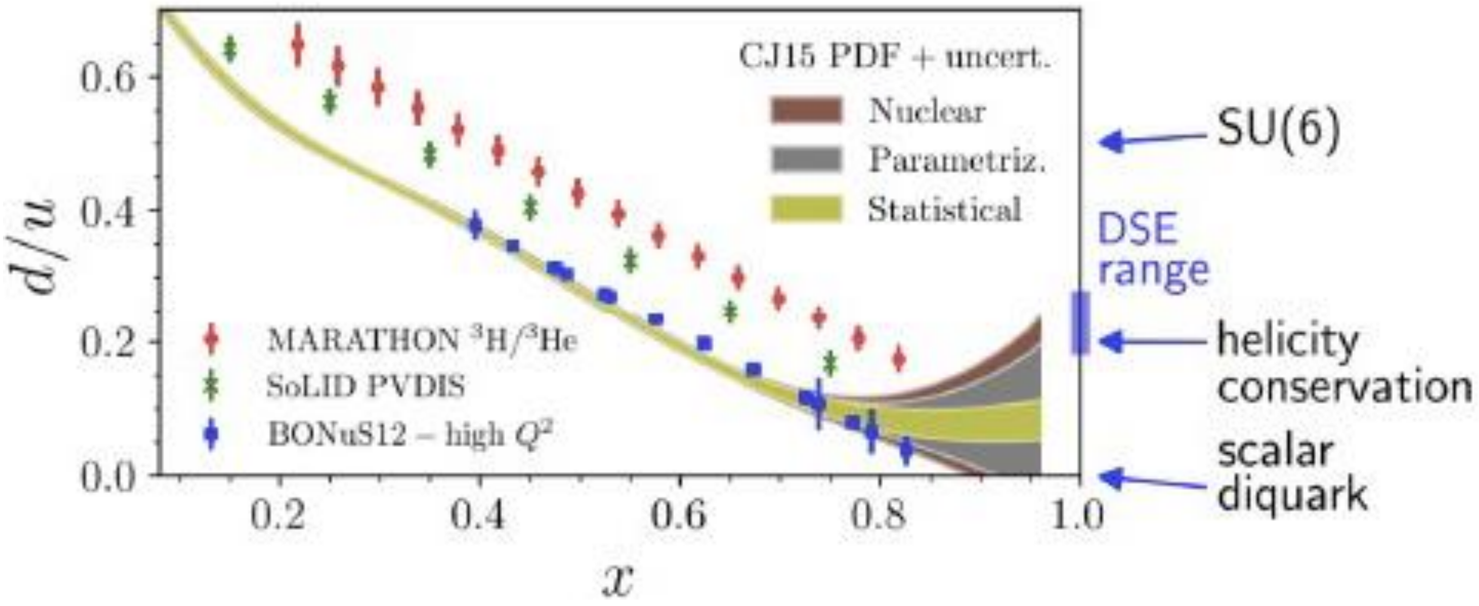



Figure courtesy of A. Accardi

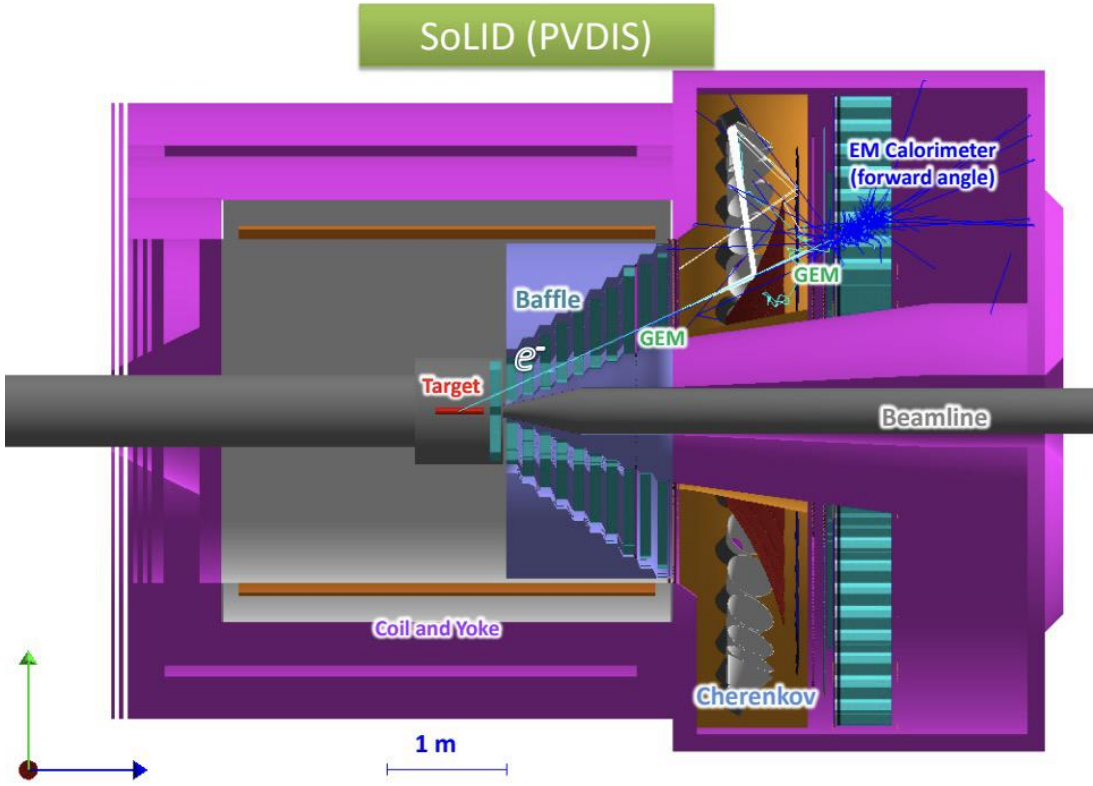


# SoLID Physics



## ➢ PVDIS

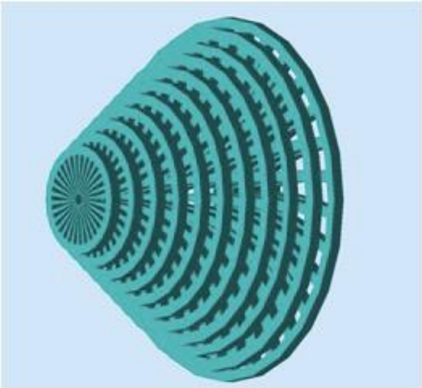
- ❑ SoLID-PVDIS Configuration:
  - ✓ 50 $\mu$A beam current.
  - ✓ 40 cm LH2 & LD2 target  Lumi=$10^{39}s^{-1}cm^{-2}$!!!
  - ✓ Azimuthally symmetric
  - ✓ Tracking: High-rate GEM tracking chambers
  - ✓ PID: Light-Gas Cherenkov (LGC) + Shashlyk EM




Experimental Uncertainty Budget

| Total | 0.6 |
|---|---|
| Polarimetry | 0.4 |
| $Q^2$ | 0.2 |
| Radiative Corrections | 0.2 |
| Event reconstruction | 0.2 |
| Statistics | 0.3 |

- ❑ Baffles:
  - ✓ ~40% azimuthal coverage
  - ✓ block positive and neutral background particles



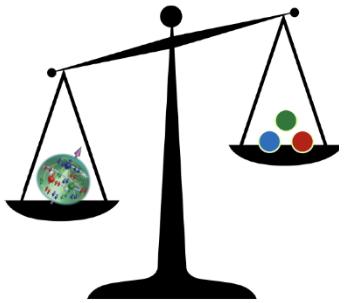
# SoLID Physics

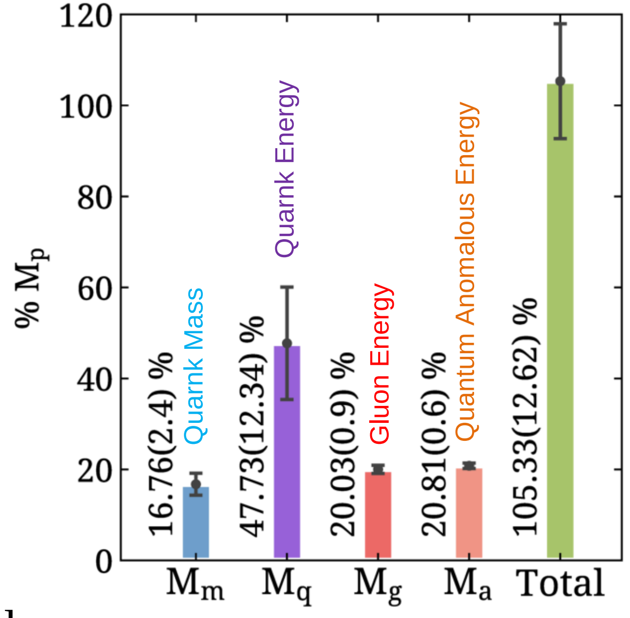


- **J/ Ψ**
  - Nucleon mass >> quark mas sum → QCD energy contribute!
  - Alslo quantum anomalous energy (Trace Anomaly)

$$H_{QCD} = H_q + H_m + Hg + H_a$$

X. Ji PRL 74 1071 (1995),
X. Ji & Y. Liu, arXiv: 2101.04483

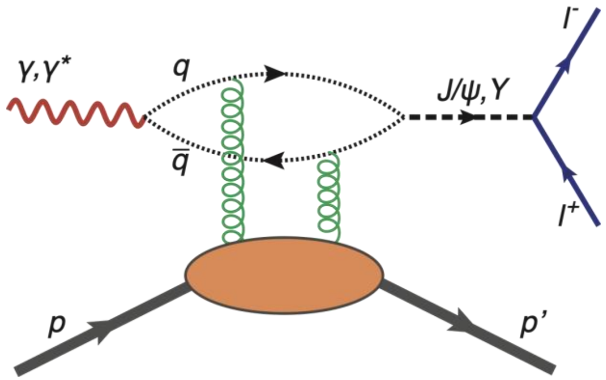





- ✓ $H_q$, $H_m$ & $H_g$ → from PDFs and pi-N sigma terms.
- ✓ Lattice QCD calculation

C. Alexandrouet al., (ETMC), PRL 119, 142002 (2017)
Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

- Diff. cross-section of J/Ψ production measurement at threshold → access Trace anomaly

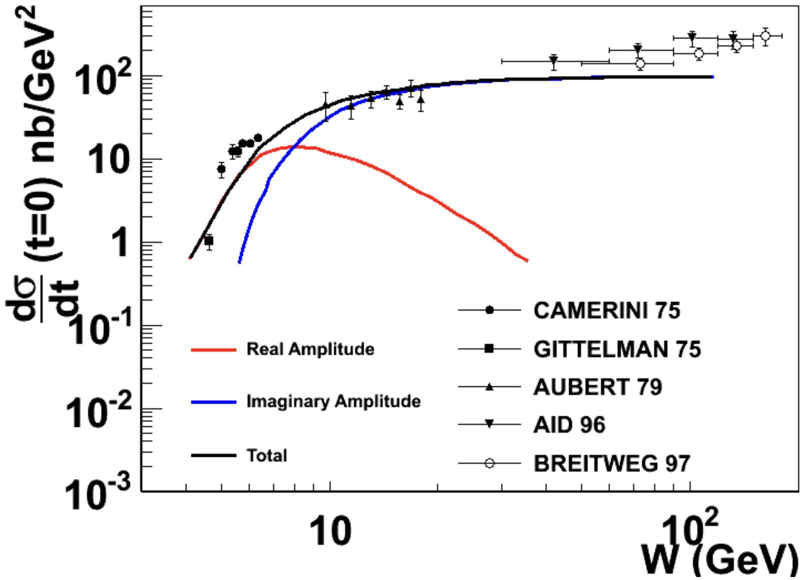



$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

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

- ✓ Imaginary part → related to total cross section
- ✓ Real part → contains the conformal (trace) anomaly; Dominates the near threshold

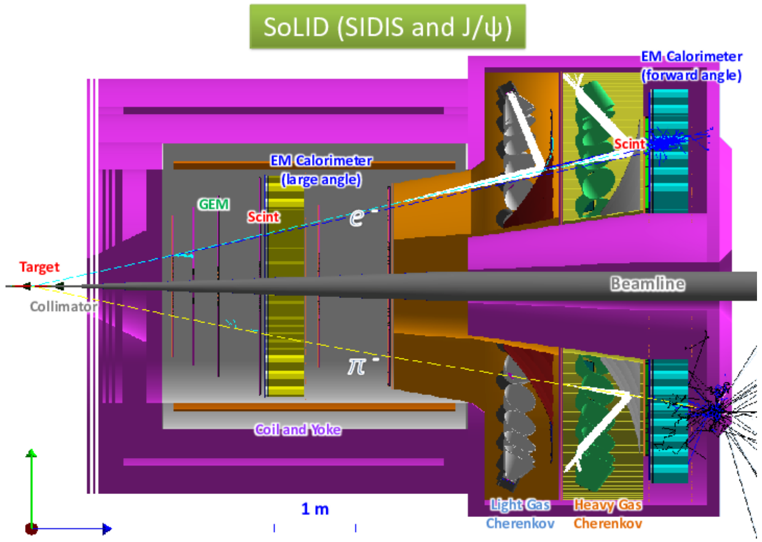
D. Kharzeev(1995);
Kharzeev, Satz, Syamtomov, and ZinovjevEPJC,9, 459, (1999);
Gryniukand Vanderhaeghen, PRD94, 074001 (2016)



# SoLID Physics



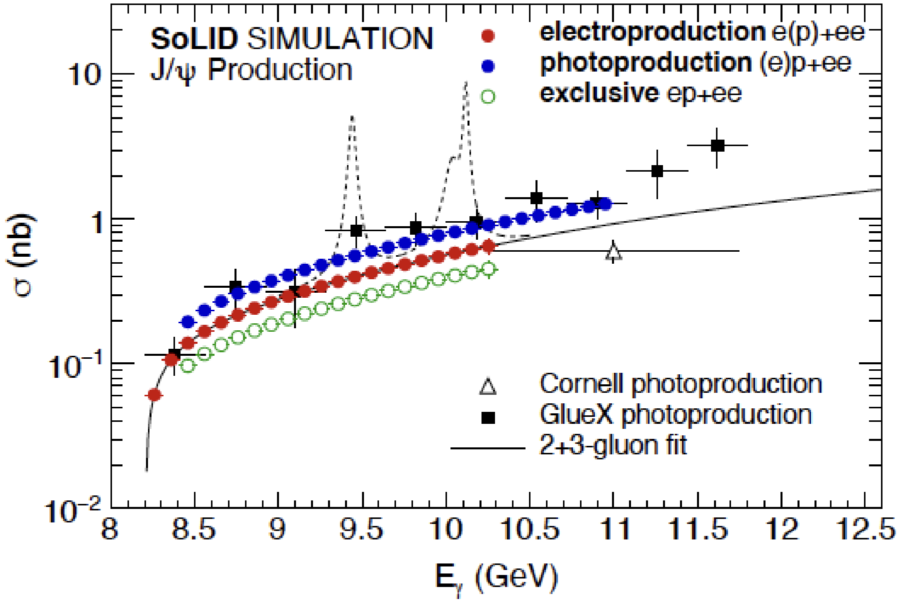
- **J/ Ψ**
  - Near Threshold J/ Ψ production (E12-12-006, 50 days, rating A)
    - ✓ 3uA unpol. beam on 15cm LH2 targets ($10^{37}$ cm$^{-2}$ s$^{-1}$)
    - ✓ Share the SIDIS detector configuration (see next)
    - ✓ Various triggers:
      - Photoproduction ((e)p → e+e-) : 3-fold coincidence
      - Electroproduction (e(p) → e+e-) : 3-fold coincidence
      - Exclusive (ep → e+e-) : 4-fold coincidence
      - Inclusive (e+e-) : 2-fold coincidence




- Precise measurement of t-dependence near threshold w/ high Lumi
- Access to Gluon Form Factor (radii, pressures, shear …)

$$\langle N'|T^{\mu,\nu}_{q,g}|N\rangle = \bar{u}(N')\left(A_{g,q}(t)\gamma^{(\mu}p^{\nu)} + B_{q,g}\frac{iP^{(\mu}\sigma^{\nu)\rho}\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu}\right)u(N)$$

| | GlueX Hall D | J/Ψ 007 Hall C | SoLID Hall A |
|---|---|---|---|
| J/Ψ counts (photoproduction) | 469 published ~10k phase I+II | 2k electron channel 2k muon channel | 804k |
| J/Ψ counts (electroproduction) | N/A | N/A | 21k |
| Features | Good reach near threshold No high-t reach | Reach high-t Low statistics | Reach high-t High statistics |
| Timeline | Finished/ongoing | Finished | Future |



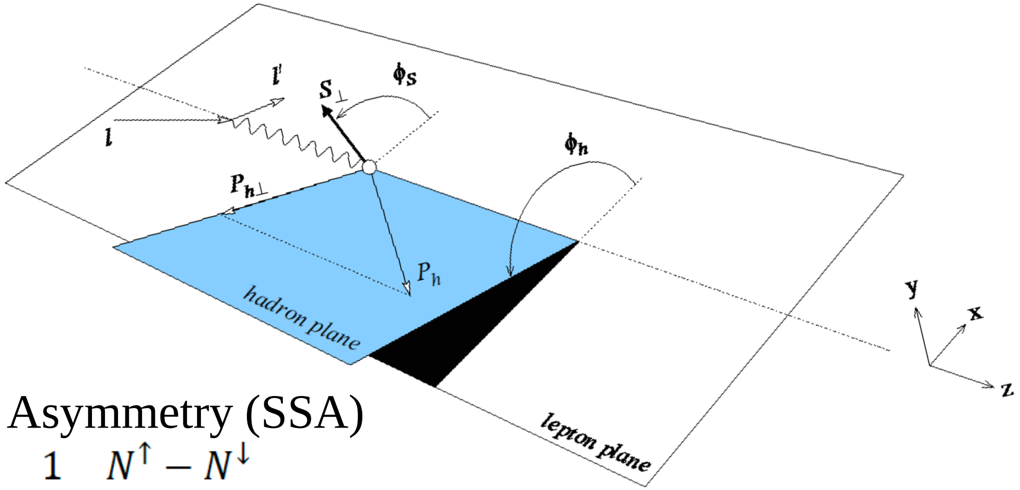

S. Joosten, Z.E. Meziani, PoS308 (2017);
Gryniuk, Joosten, Meziani, and Vanderhaeghen, PRD 102, 014016 (2020)

# SoLID Physics



## ➢ TMD w/ SIDIS

- ❑ Access quarks' transverse momentum dependence distribution (TMD) in nucleon → Semi-Inclusive Deep Inelastic Scattering (SIDIS)




- ❑ Single-Spin Asymmetry (SSA)

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

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

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

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

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

### 8 Quark-TMDs (leading twist)

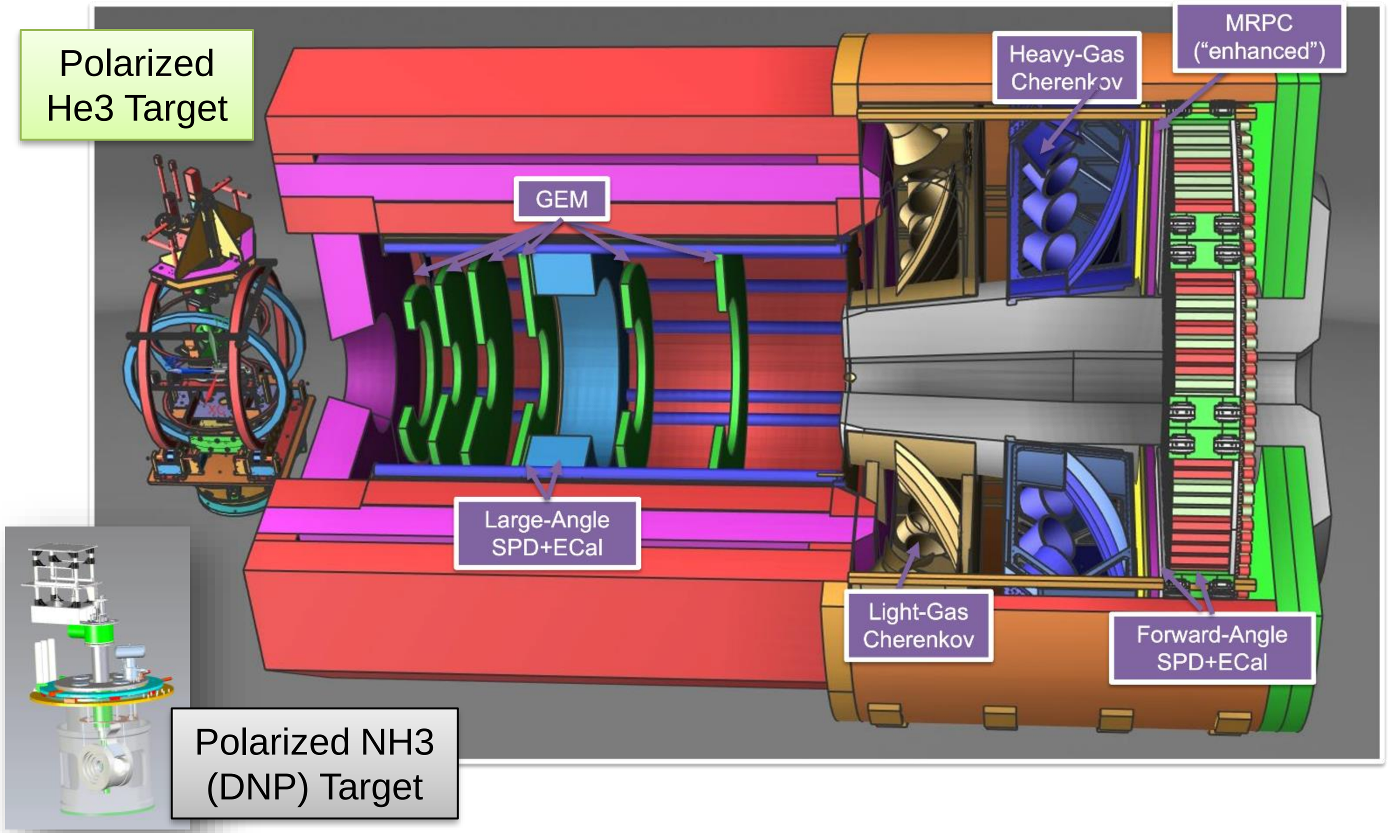
| Leading Twist TMDs | | Quark Polarization: Unpolarized (U) | Longitudinally Polarized (L) | Transversely Polarized (T) |
|---|---|---|---|---|
| Nucleon Polarization | U | $f_1(x,k_T^2)$ Unpolarized | | $h_1^{\perp}(x,k_T^2)$ Boer-Mulders |
| | L | | $g_1(x,k_T^2)$ Helicity | $h_{1L}^{\perp}(x,k_T^2)$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

- ❑ Double-Spin Asymmetry (DSA)

$$A_{LT}^{Worm-Gear} \propto \langle\cos(\phi_h-\phi_s)\rangle_{LT} \propto g_{1T} \otimes D_1$$

# SoLID Physics

- **TMD w/ SIDIS**
  - Three initial SIDIS proposals (just went through Jlab PAC Jeopardy Review in 2022):
    - ❑ **E12-10-006:** Single Spin Asymmetries on Transversely Polarized 3He @ 90 days, Rating A
    - ❑ **E12-11-007:** Single and Double Spin Asymmetries on Longitudinally Polarized 3He @ 35 days, Rating A
    - ❑ **E12-11-108:** Single Spin Asymmetries on Transversely Polarized Proton @ 120 days, Rating A

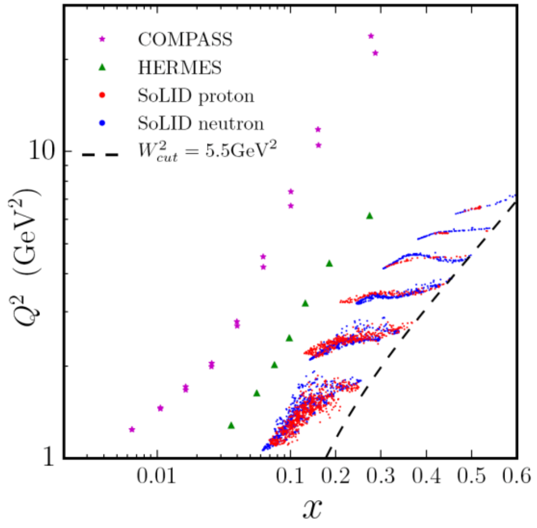


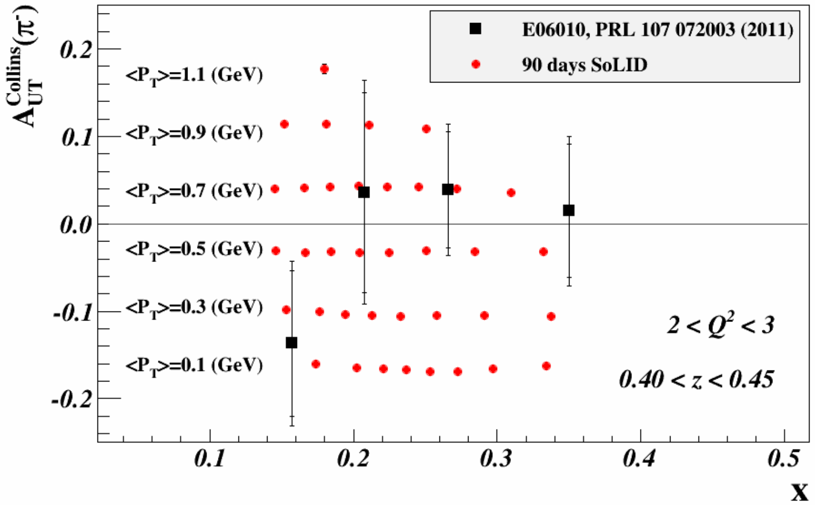

- Run-Group (same beam time / configuration):
  - ❑ SIDIS Dihadron with Transversely Polarized 3He (E12-10-006A)
  - ❑ SIDIS in Kaon Production with Transversely Polarized 3He (E12-10- 006D)
  - ❑ Ay with Transversely Polarized 3He (E12-10-006A)
  - ❑ g2n and d2n with Transversely and Longitudinally Polarized 3He (E12-10-006E)
  - ❑ Deep exclusive $\pi -$ Production with Transversely Polarized 3He (E12-10-006B)

# SoLID Physics

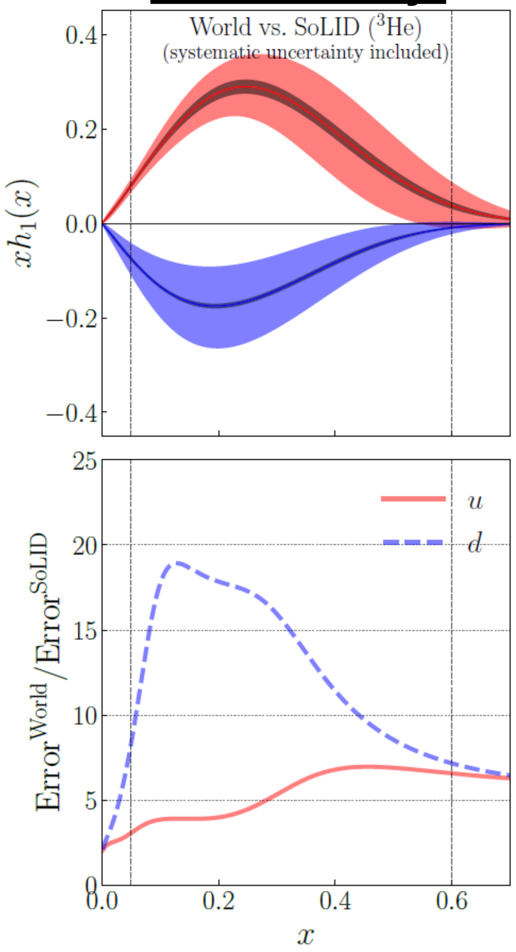
## ➤ TMD w/ SIDIS

- ✓ Wide phase-space & high-statistics for 4D binning in (x, $p_T$, $Q^2$, z)
- ✓ Precisely extract Transversity & Tensor-Charge, Sivers etc.

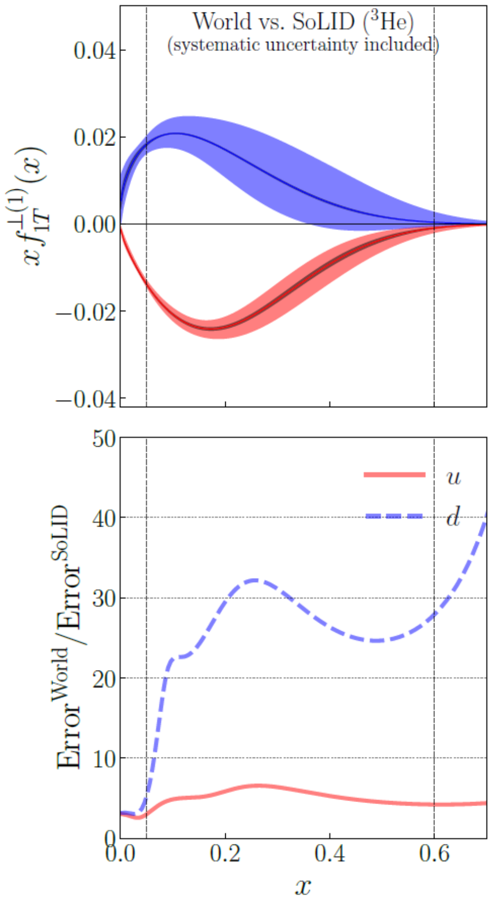



### Transversity



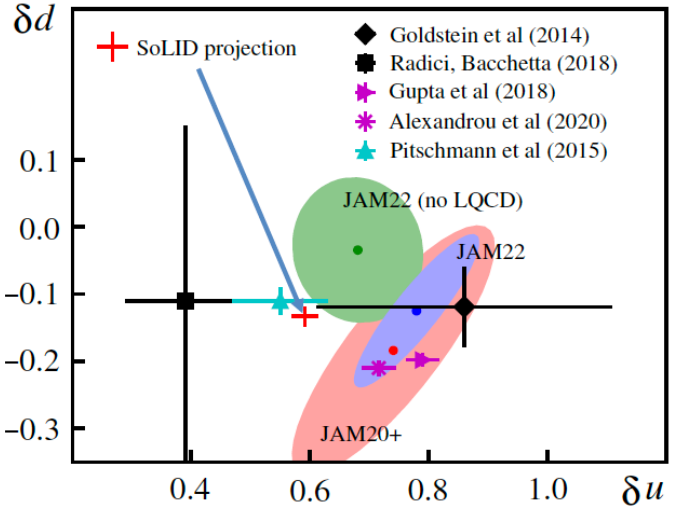

### Sivers




## Tensor charge:

$$\delta u = \int_0^1 dx \, \left(h_1^u(x) - h_1^{\bar{u}}(x)\right)$$

$$\delta d = \int_0^1 dx \, \left(h_1^d(x) - h_1^{\bar{d}}(x)\right)$$




SoLID projection: stat+syst included

D'Alesio et al., Phys. Lett. B 803 (2020)135347
H. Gao, T. Liu and Z. Zhao, PRD 97, 074018 (2018)
Z. Ye, et al, Phys. Lett. B 767, 91 (2017)

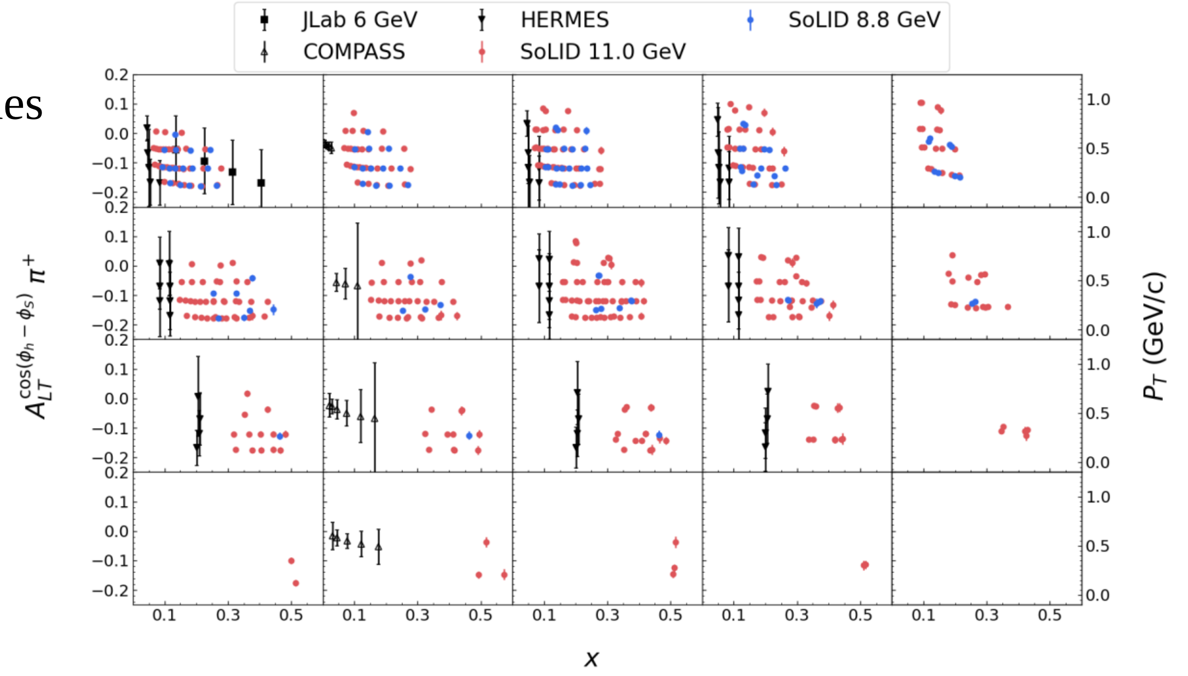
J. Cammarota et al, PRD 102, 054002 (2020) (JAM20+)
L. Gamberg et al., PRD106 (2022) 3, 034014 (JAM22)

# SoLID Physics

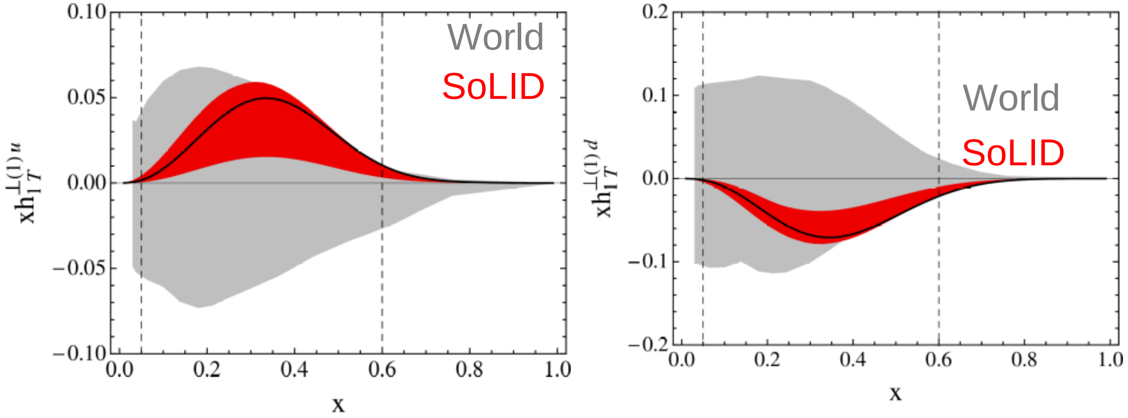
- **TMD w/ SIDIS**
  - Precisely extract small Pretzelocity & Worm-Gear asymmetries
    - Link to quark OAM

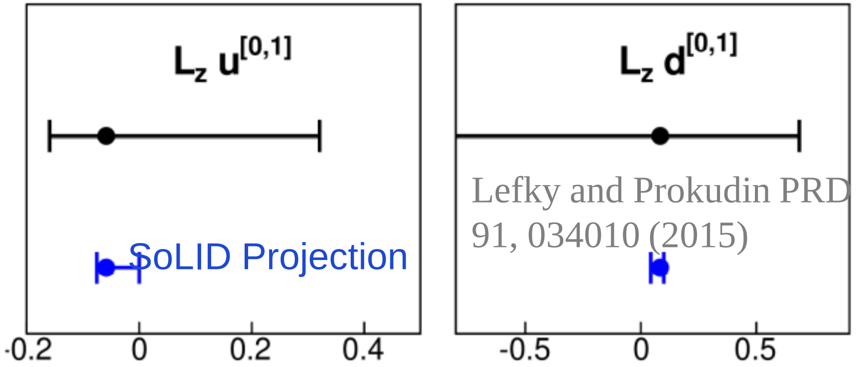
$$L_z^q = -\int \mathrm{d}x\mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int \mathrm{d}x h_{1T}^{\perp(1)q}(x)$$

    - A genuine sign of intrinsic transverse motion




## Pretzelocity

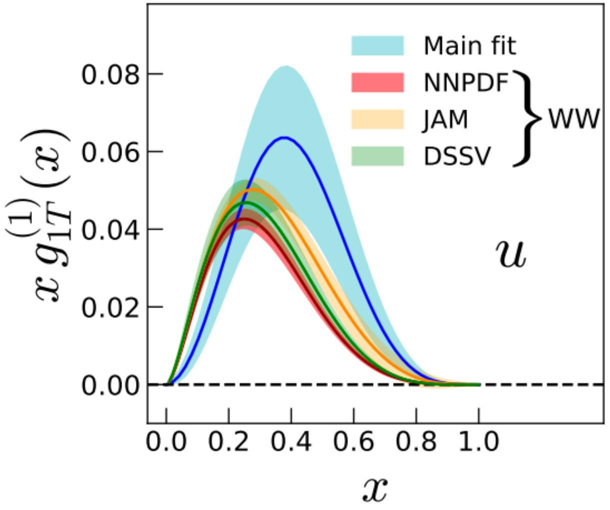



Lefky and Prokudin PRD 91, 034010 (2015)

## Worm-Gear

S. Bhattacharya et al., Phys. Rev. D105, 034007 (2022)



# SoLID Physics



## ➢ GPD w/ SIDIS

- 8 Leading-Twist Generalized Parton Distributions (GPD):

Chiral Even $H^{q/g}, E^{q/g}, \widetilde{H}^{q/g}, \widetilde{E}^{q/g}$

Chiral Odd $H_T^{q/g}, E_T^{q/g}, \widetilde{H}_T^{q/g}, \widetilde{E}_T^{q/g}$

| Nucleon Polarization | | Quark Polarization: Unpolarized (U) | Quark Polarization: Longitudinally Polarized (L) | Quark Polarization: Transversely Polarized (T) |
|---|---|---|---|---|
| | U | $H$ | | $2\widetilde{H}_T + E_T$ |
| | L | | $\widetilde{H}$ | $\widetilde{E}_T$ |
| | T | $E$ | $\widetilde{E}$ | $H_T, \widetilde{H}_T$ |

- Access parton distributions in 3D

X. Ji, PRL 78, 610 (1997)
M. Diehl, Physics Reports 388 (2003) 41–277,
Belitsky, Radyushkin, Physics Reports 418 (2005) 1–387

- Connect to FF & PDFs: e.g.

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$
$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

Dirac&Pauli Form Factors

$$\int_{-1}^{1} dx \widetilde{H}^q(x,\xi,t) = G_A^q(t)$$
$$\int_{-1}^{1} dx \widetilde{E}^q(x,\xi,t) = G_P^q(t)$$

Axial&Pseudoscaler Form Factors

$$H^q(x,0,0) = q(x), x > 0$$
$$\widetilde{H}^q(x,0,0) = \Delta q(x), x > 0$$

PDFs

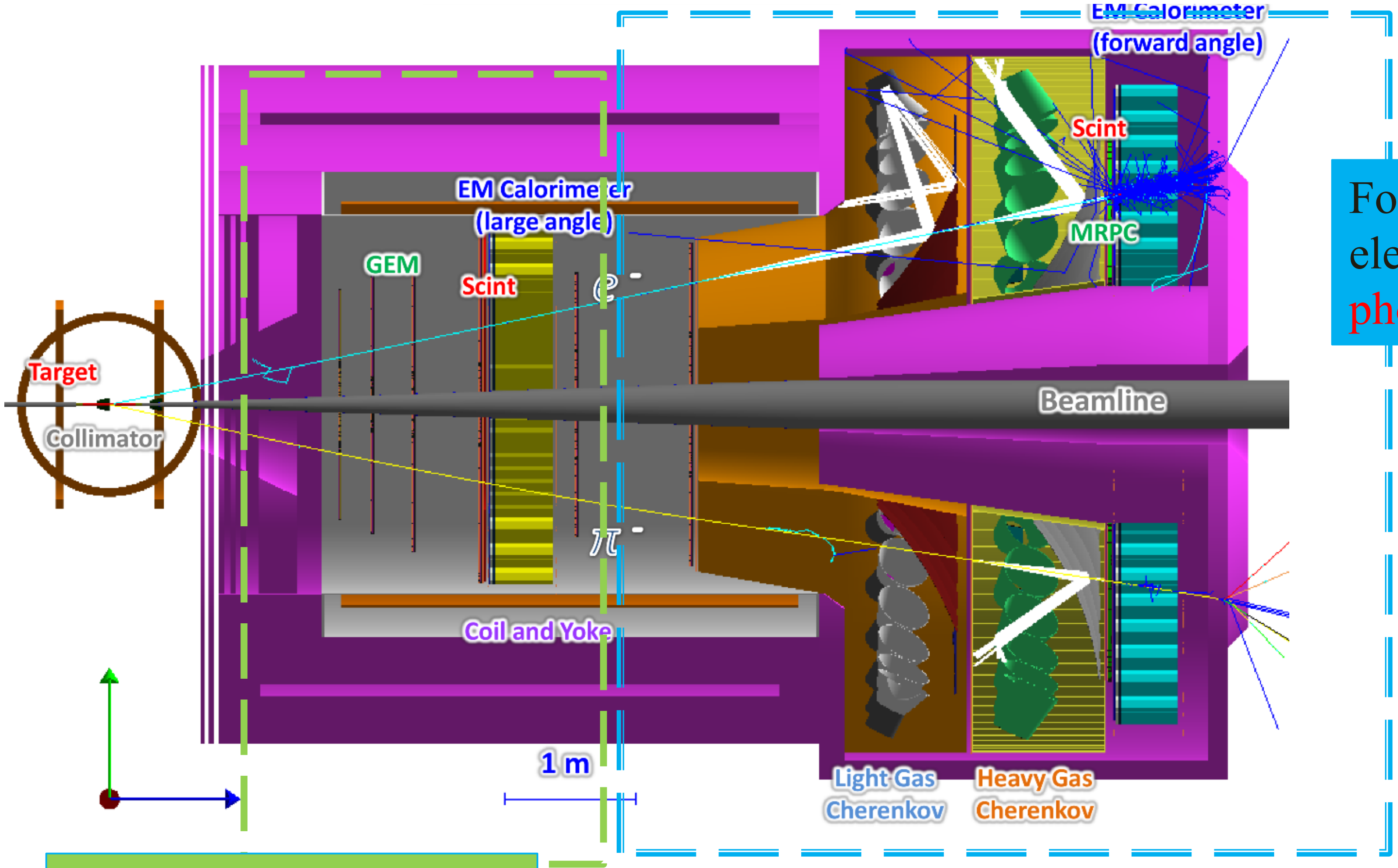
- Access Angular Momenta?
  - ✓ Ji's Sum Rule (X. Ji, PRL 78, 610 (1997)

$$J_{q/g} = \lim_{t,\xi \to 0} \frac{1}{2} \int x dx \left[ \boldsymbol{H^{q/g}}(x,\xi,t) + \boldsymbol{E^{q/g}}(x,\xi,t) \right]$$

*Generalized Parton Distributions (GPD)*

# SoLID Physics

➢ SIDIS/Jpsi Setup for GPDs:




Forward-Angle : electrons, pion, photons and proton

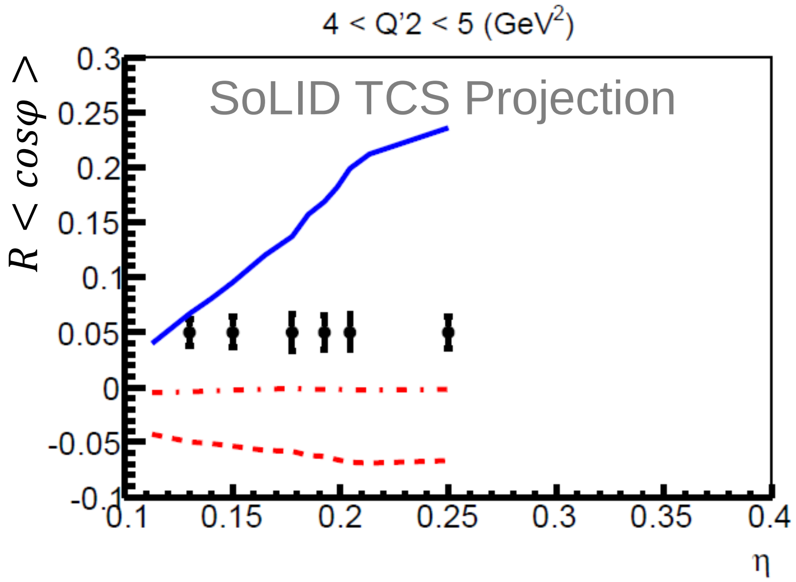
Large-Angle→electrons, photons and proton

# SoLID Physics

- **SIDIS/Jpsi Setup for GPDs:**
  - Time-Like Compton Scattering (SoLID-TCS, E12-12-006A):
    - ✓ Parallel data taking with J/Psi
    - ✓ Different angular moments for TCS & BH Interference-terms

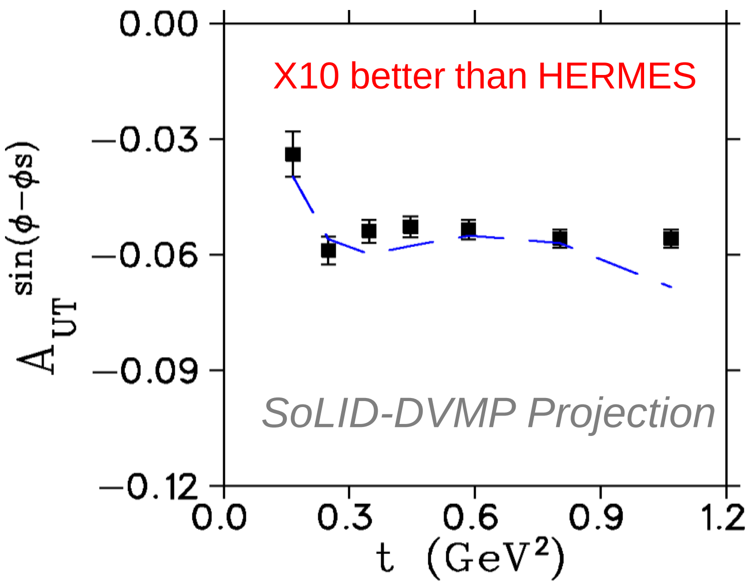
$$\sigma_{INT}^{TCS,unpol} \propto \boldsymbol{cos\varphi} Re\tilde{M}^{--},\ \sigma_{INT}^{TCS,cir-pol} \propto \boldsymbol{sin\varphi} Im\tilde{M}^{--}$$

$$\tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{M}\frac{1-\eta}{1+\eta}\left[F_1\mathcal{H}_1 - \eta(F_1+F_2)\tilde{\mathcal{H}}_1 - \frac{t}{4M^2}F_2\mathcal{E}_1\right]$$




  - Deep-Virtual Meson Production (SoLID-DVMP, E12-10-006A):
    - ✓ First neutron DVMP experiment
    - ✓ In parallel with E12-10-006 (SIDIS with polarized He3)
    - ✓ Exclusive events from missing mass reconstruction
    - ✓ Analyze angular modules to decouple GPDs

$$A_{UT}^{\sin(\phi-\phi_s)} \sim \frac{d\sigma_{00}^{+-}}{d\sigma_L\binom{++}{00}} \sim \frac{\mathrm{Im}(\tilde{E}^*\tilde{H})}{\left|\tilde{E}\right|^2} \text{ where } \tilde{E} \gg \tilde{H}$$

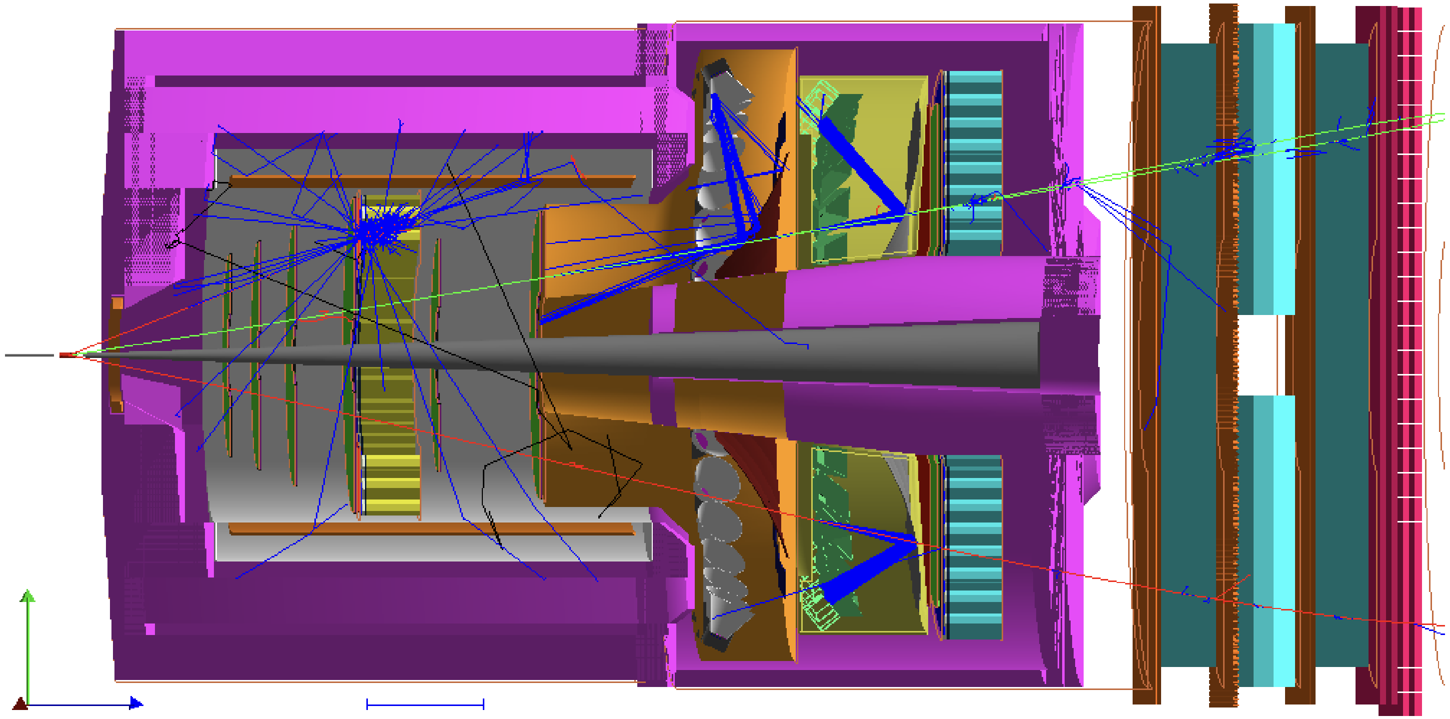


# SoLID Physics

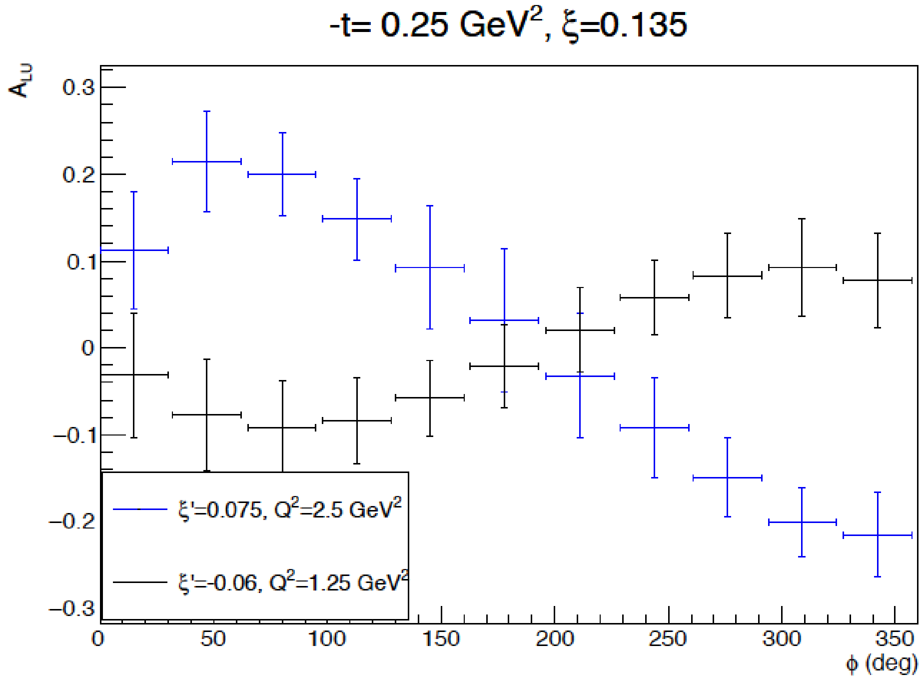
- **Under development: DVCS with both polarized neutron and protons**

- **DDVCS with new setup**
  - SoLID is likely the best place to do Doubly-DVCS measurement
  - Detector upgrade needed to detect muons

New SoLID-DDVCS Configuration



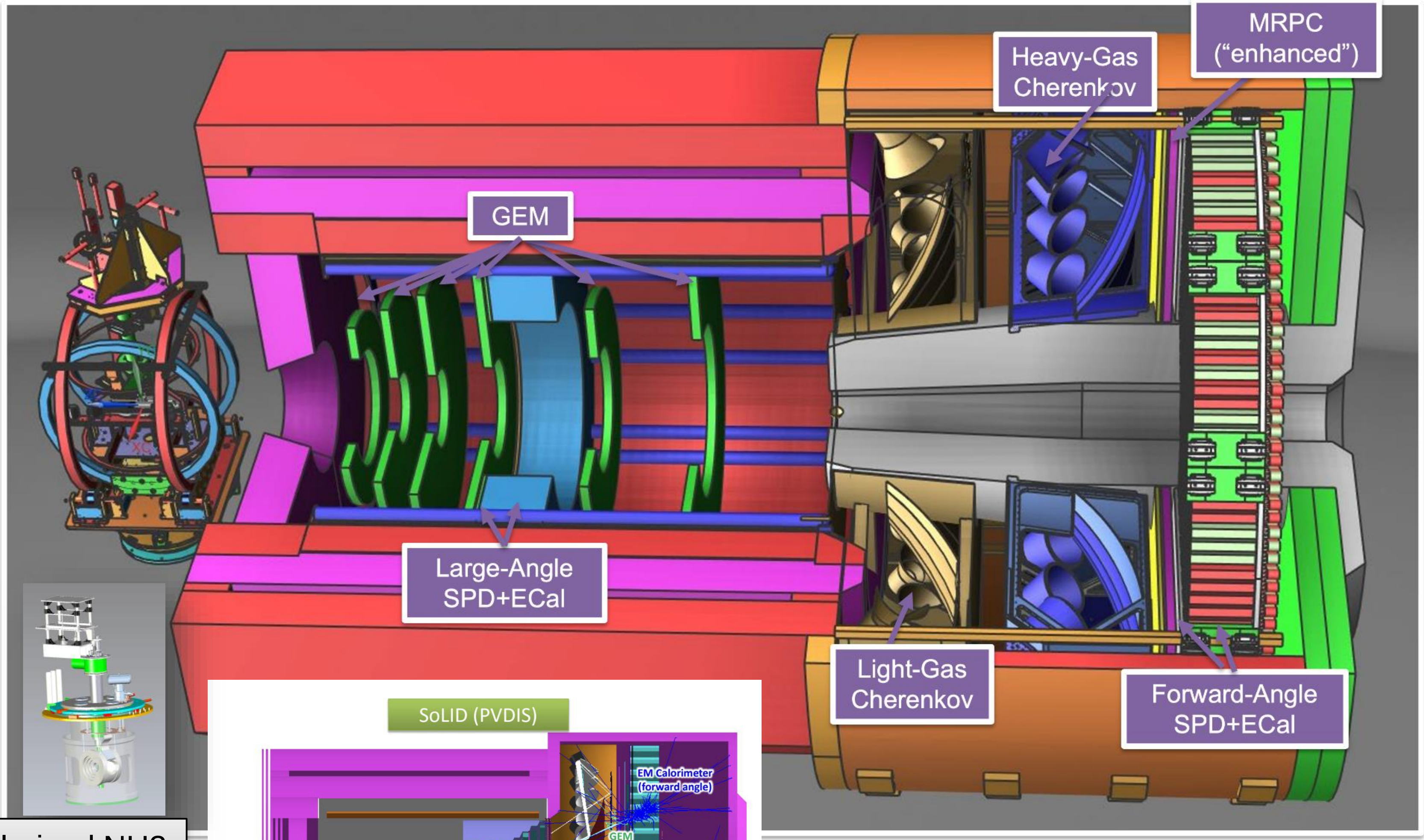
✓ DDVCS with J/Psi +muon detectors → New LOI submitted to PAC51 in 2023



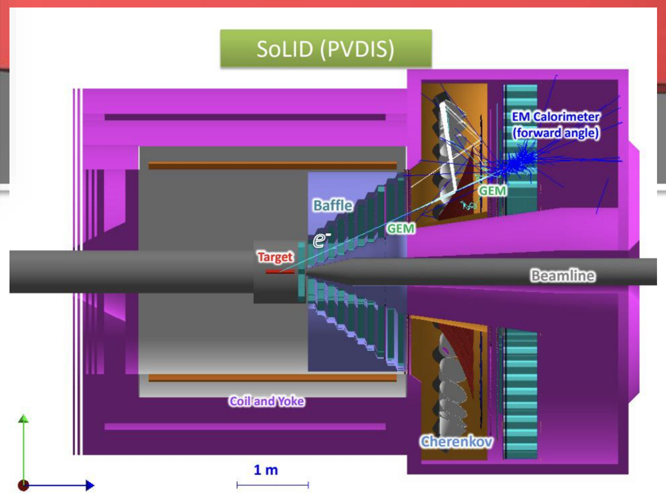
# SoLID Detectors

## ➢ Two Detector Setups:

- ✓ Easy recofiguration between PVDIS and SIDIS&J/Psi)
- ✓ CLEO magnet, DAQ, Electronics
- ✓ Share GEM, LGC, SPD & ECal
- ✓ Baffle for PVDIS only
- ✓ Polarized Targets for SIDIS only




Polarized NH3 (DNP) Target




## Detector Requirements:

- High rate capabilities
- High background
- High radiation
- Large Area
- Low systematics
- Huge data size

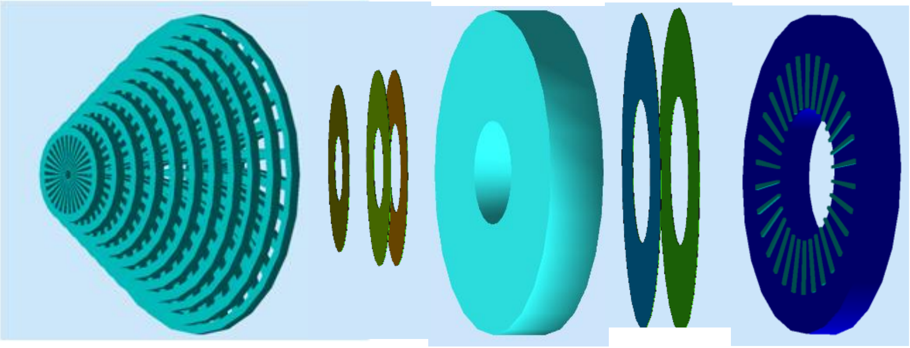
Details please see:
https://solid.jlab.org/experiments.html.

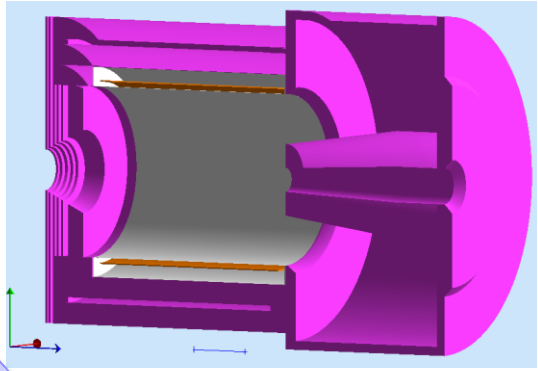
# SoLID Detectors



➢ **Two Detector Setups:**

PVDIS: Baffle 3xGEMS LGC 2xGEMs EC

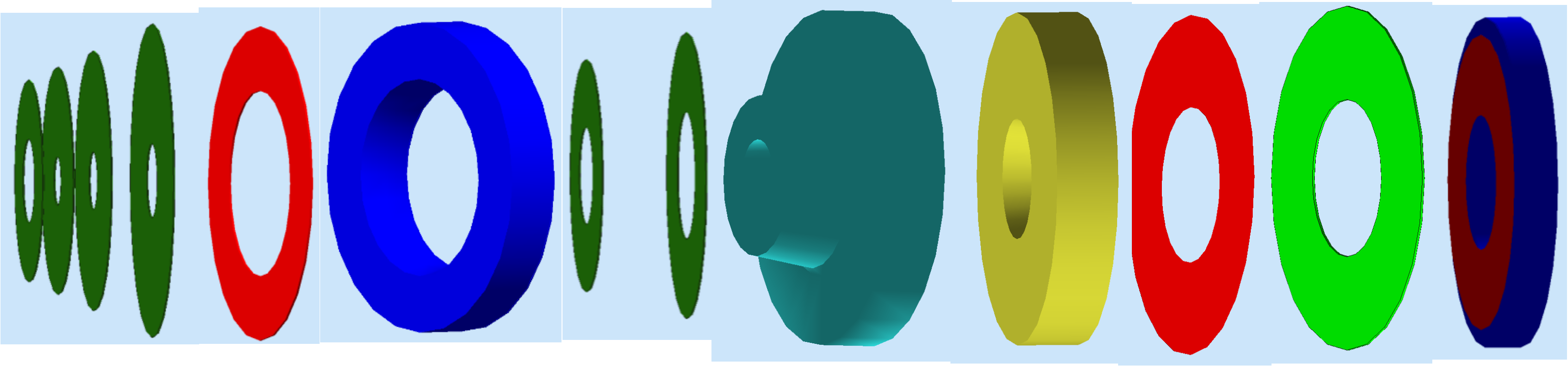




Uses full capability of JLab electronics

SIDIS&J/Psi:

4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC



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

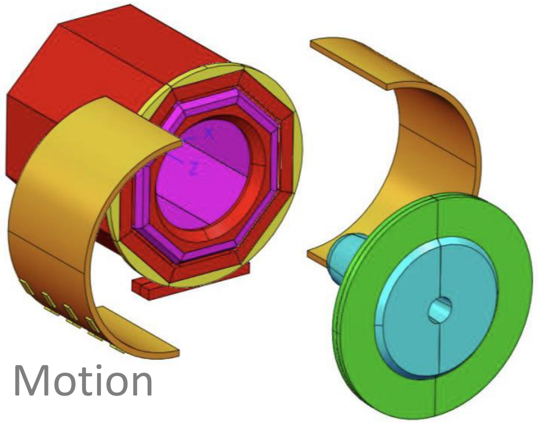
# SoLID Detectors



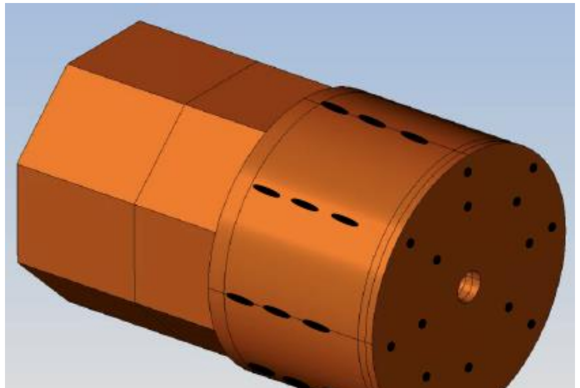
➢ **The CLEO Magnet:**

- 1.5 T, 1.0 meter in radius, super-conducting
- Transferred from Cornell to Jlab (2016)
- Assembly completed
  - ✓ Cryogenic system assembled and commissioned
  - ✓ Instrumentation and control system commissioned
  - ✓ Energized the coil with 120 A.
  - ✓ 4K cold test in March 2023 (Data analysis in progress)

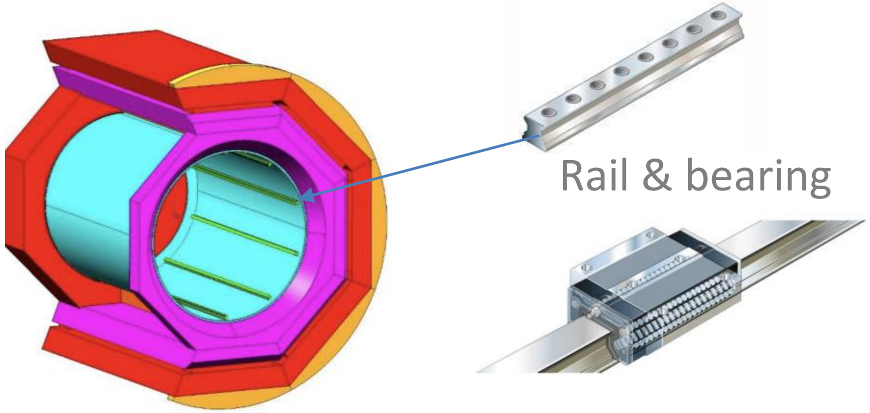
- Engineering & Designs of Detector Support Structure
  - ✓ Universal mounting system for each detector group.
  - ✓ Same concept for internal magnet and endcap locations.
  - ✓ Uses off the shelf rails and bearings.



Endcap Motion



Holes for cabling

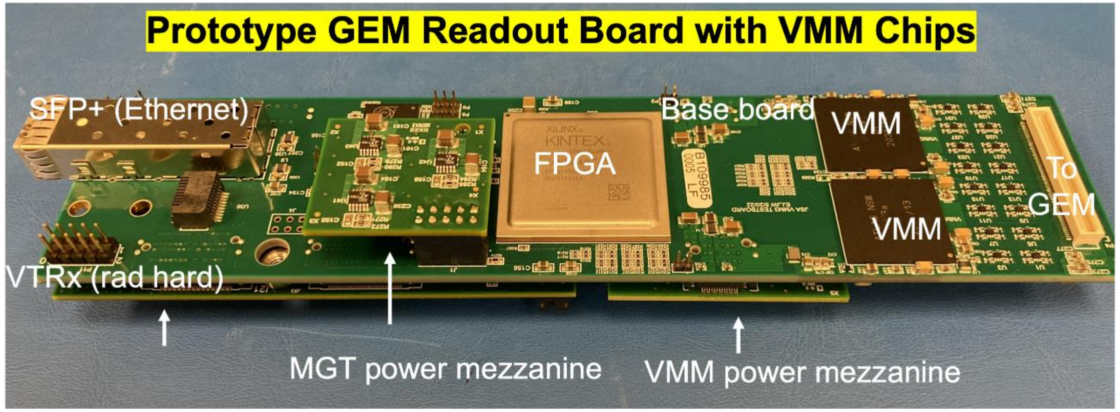


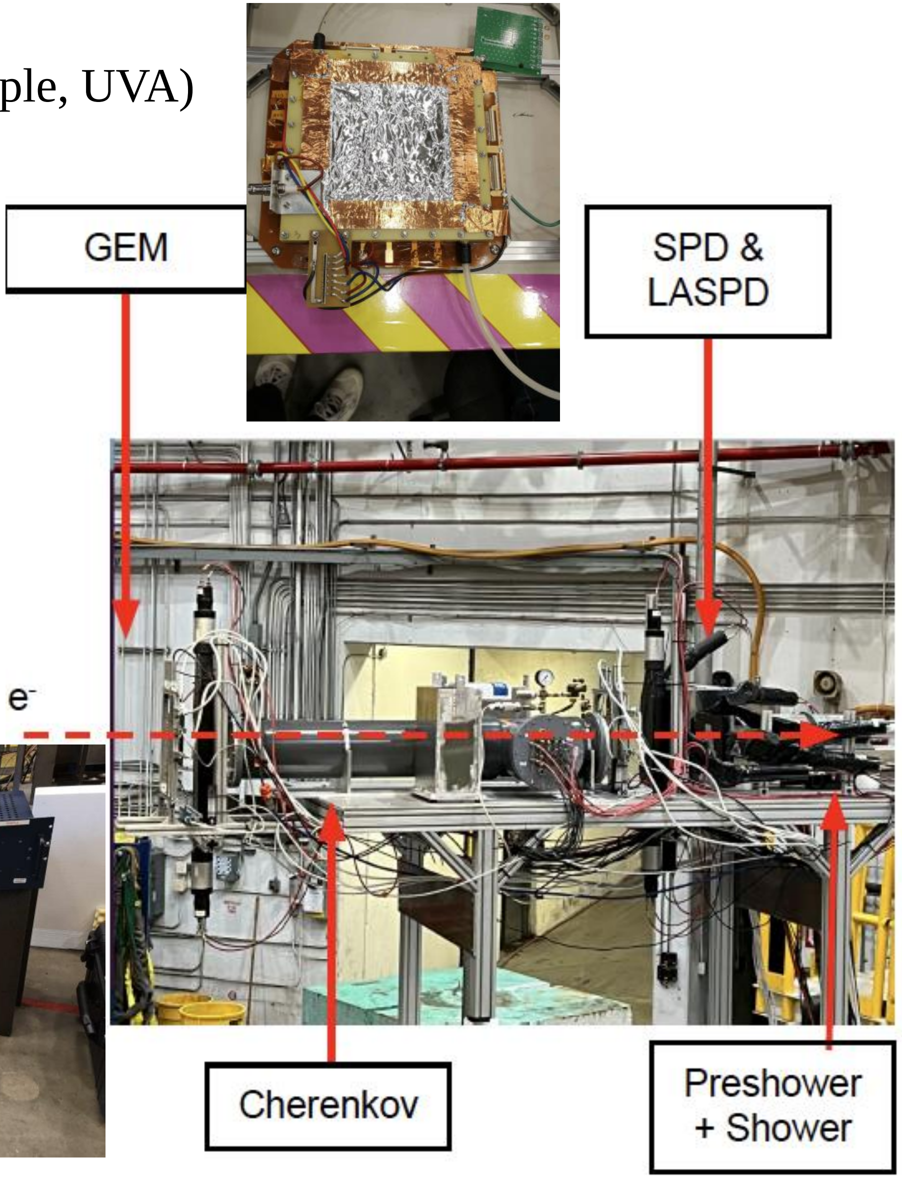
# SoLID Detectors



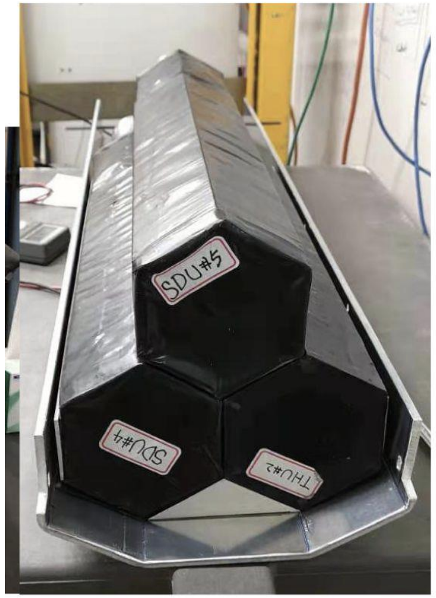
- **Detector R&D Activities:**

  - 1st DOE founded preR&D (2020-2022)
    - ✓ $600K for detector beam test (ANL, Duke, Temple, UVA)
    - ✓ $400K for DAQ at JLab

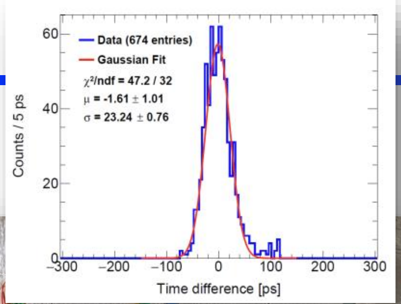


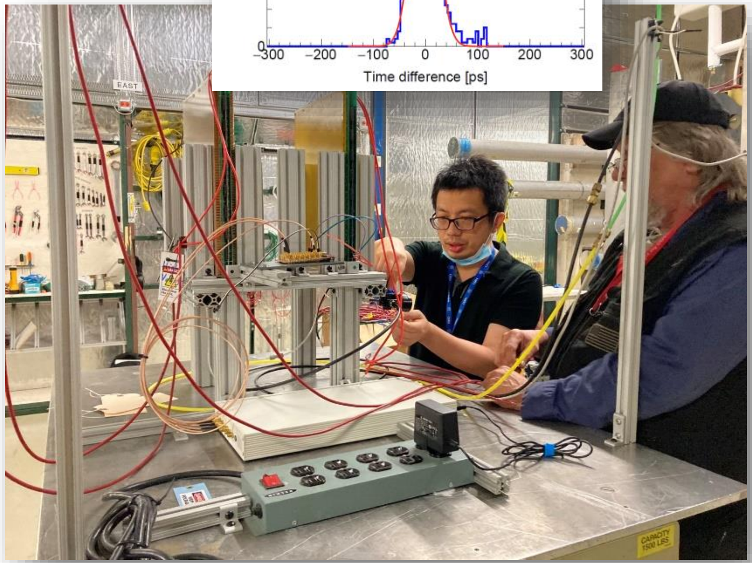




- 2nd DOE founded preR&D (2022-2023)
  - ✓ Continue supporting detector beam test
  - ✓ Continue supporting DAQ development at JLab



# SoLID Detectors

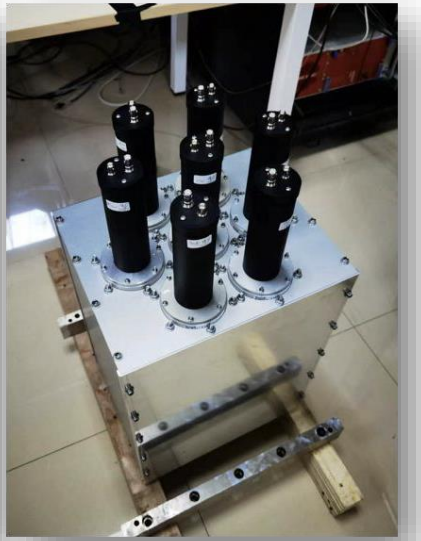


## ➢ Detector R&D Activities:

- ❑ mRPC with <30ps resolution (enriched for Kaon-SIDIS etc)
  - ✓ Sealed mRPC with intrinsic time resol. <17ps (Tsinghua)
  - ✓ Initial test at Fermi-Lab MRPC in 2022 (Tsinghua + UIC)
  - ✓ Plan on 2023/2024 beam test at Jlab (Tsinghua + UIC)

- ❑ Shashlyk-Ecal super-modules (Tsinghua & Shandong Univ)
  - ✓ Performance of a full shower in a super-module
  - ✓ Optimize supporting structure (designed by ANL)
  - ✓ Excersice assembly, quality-check, and calibration, etc.
  - ✓ Plan on 2023/2024 beam test at Jlab with new MCP-PMT



- ❑ GEM and uRWELL tracking detector R&D by USTC


# About SoLID



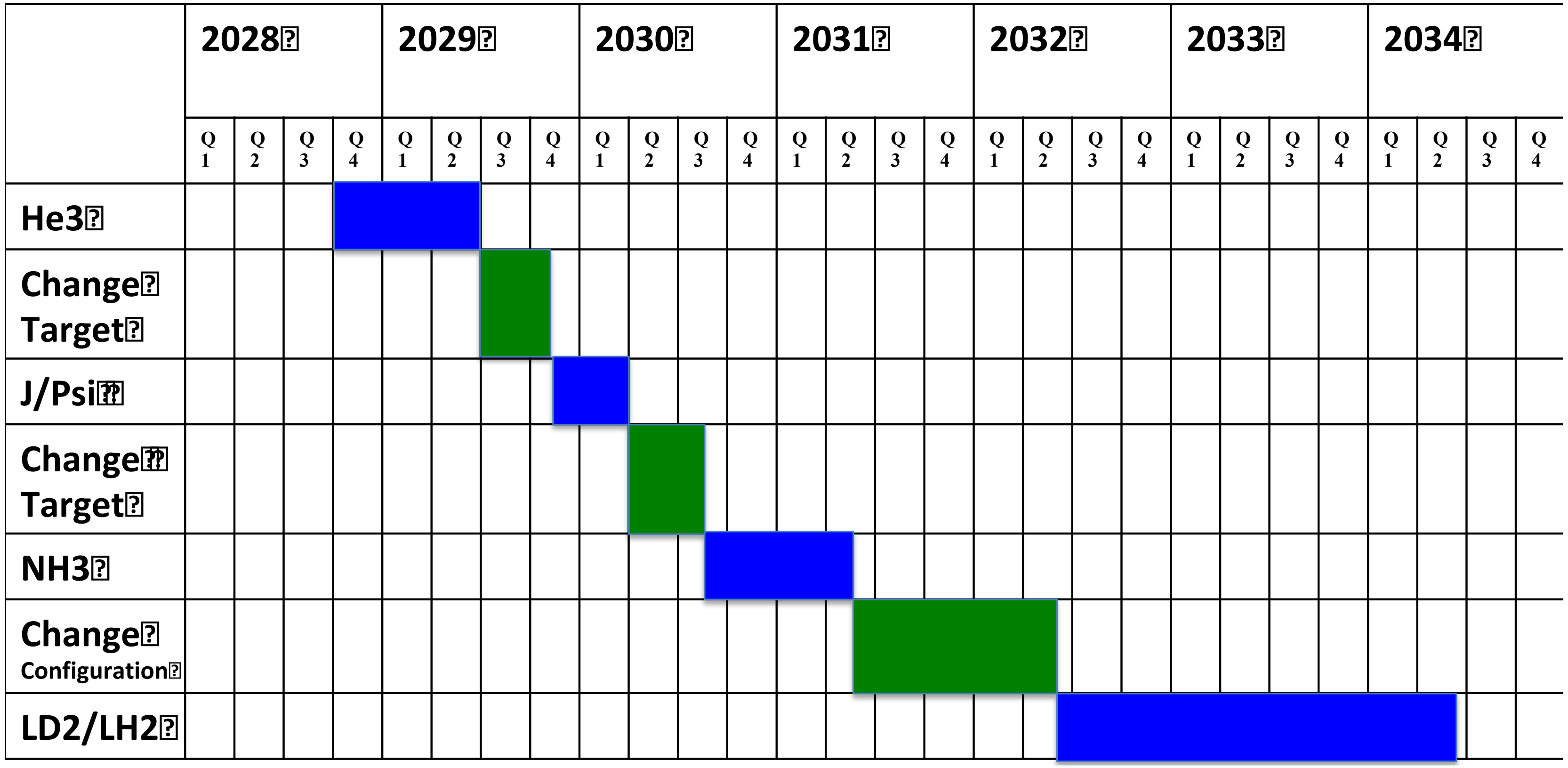
## ➢ Recent Progresses:

- ❑ Submitted pre-conceptual design report (pCDR) in 2014, and updated in 2017 & 2019 with new cost-estimation
- ❑ Jlab director reviews in 2014, 2017 & 2019
- ❑ 2020: MIE submitted to DOE; 2021, DOE Science Review, Report is positive and recommends to move forward
- ❑ Actively contribute to the Long-Range-Plan (LRP)
  - SoLID White-Paper (arXiv:2303.03428, accepted by J. Phy. G)
  - QCD town meeting identify SoLID as part of Recommendation#1
- ❑ Last PAC (2022), all SoLID proposals went through jeopardy process/review
  - All 5 SoLID proposals were re-approved.
  - 4 retaining A rating, 1 upgrade from A- to A.
  - Newly approved experiment:
    - ✓ Single beam normal spin asymmetry approved (E12-22-004, 38 days, A- rating)
    - ✓ PVEMC (PR12-22-002, conditional approved)
  - New Proposals under development: DDVCS, DVCS, more run-group proposals
- ❑ SoLID@JLab22

# About SoLID

## ➢ Tentative Run-Plan (2021 Science Review):

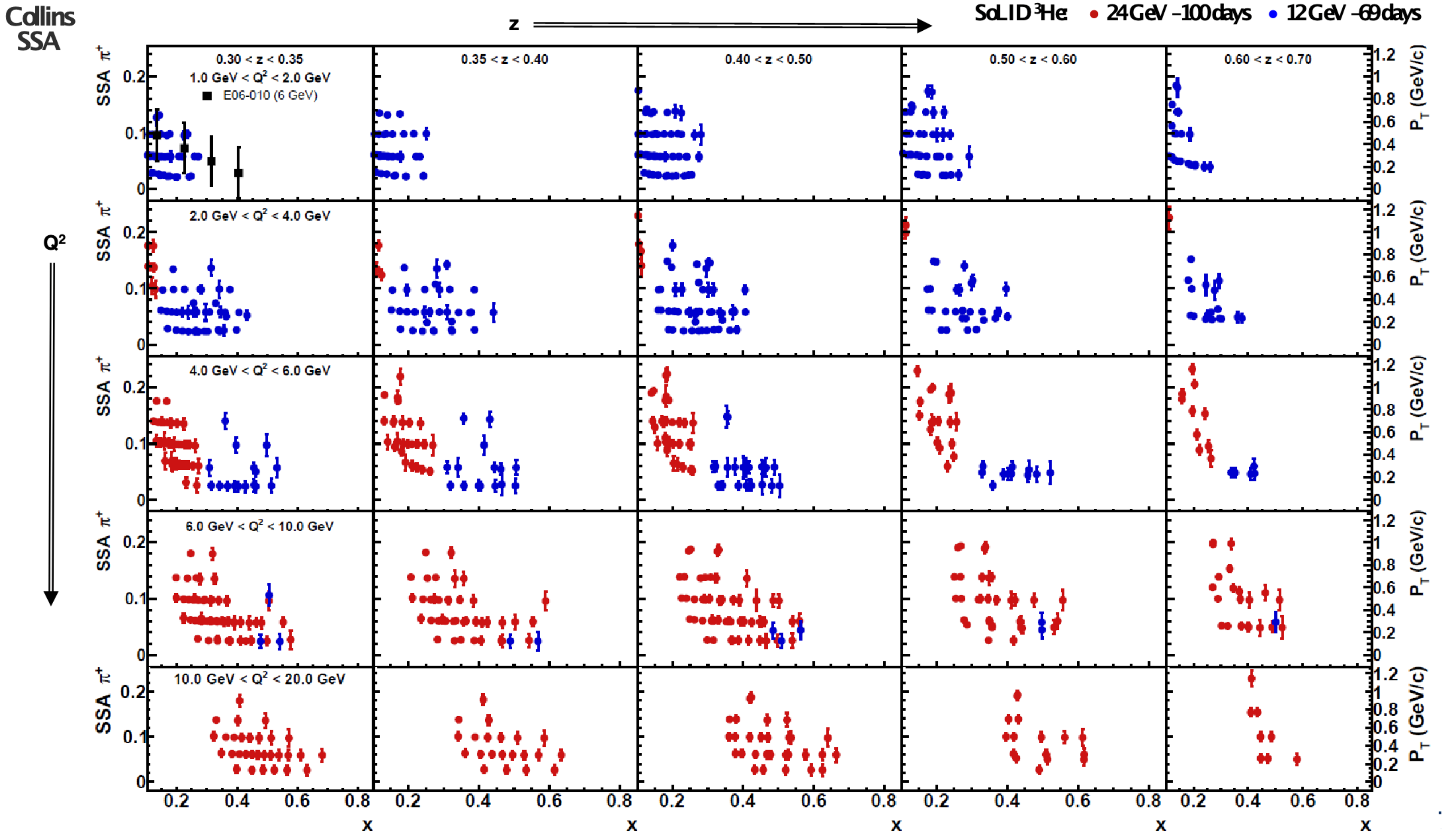
- Start with standard dependencies (polarized $^3He$, $LH_2$)
- Minimize switchover time (radiation level)
- Assuming starting data taking from FY2029 and ~ 50% efficiency)



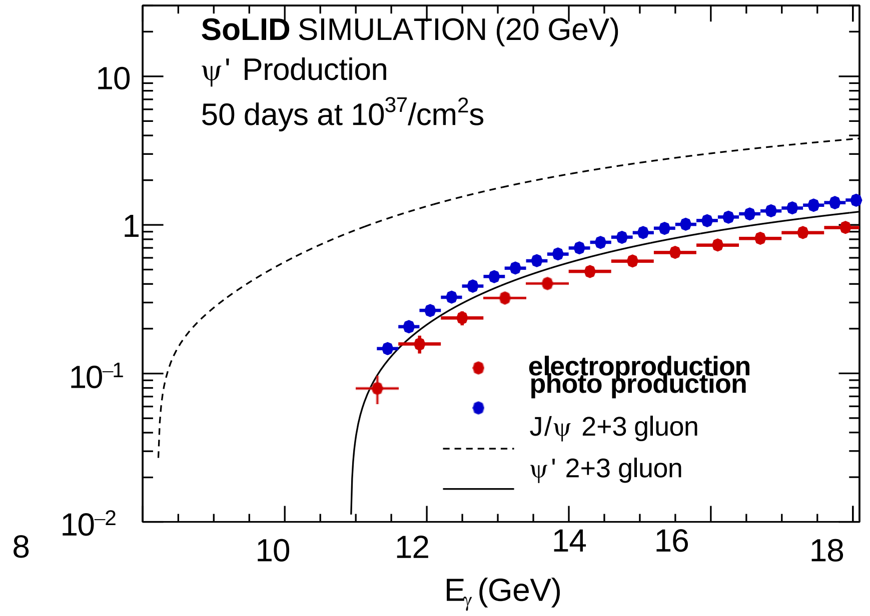
# SoLID @ 22GeV



## 1) SIDIS: Collins Asymmetry: 20 GeV and 12GeV




## 2) ψ' : Complementary probe of the gluonic field (color dipole size)




## 3) PVDIS@JLab20+:

a) Standard Model test with deuterium, Alex Emmert/Xiaochao Zheng
b) Precision study of strange sea, Mark/Dalton

## 4) Electron weak coupling C3 with e+ and e-

LOI by Xiaochao Zheng

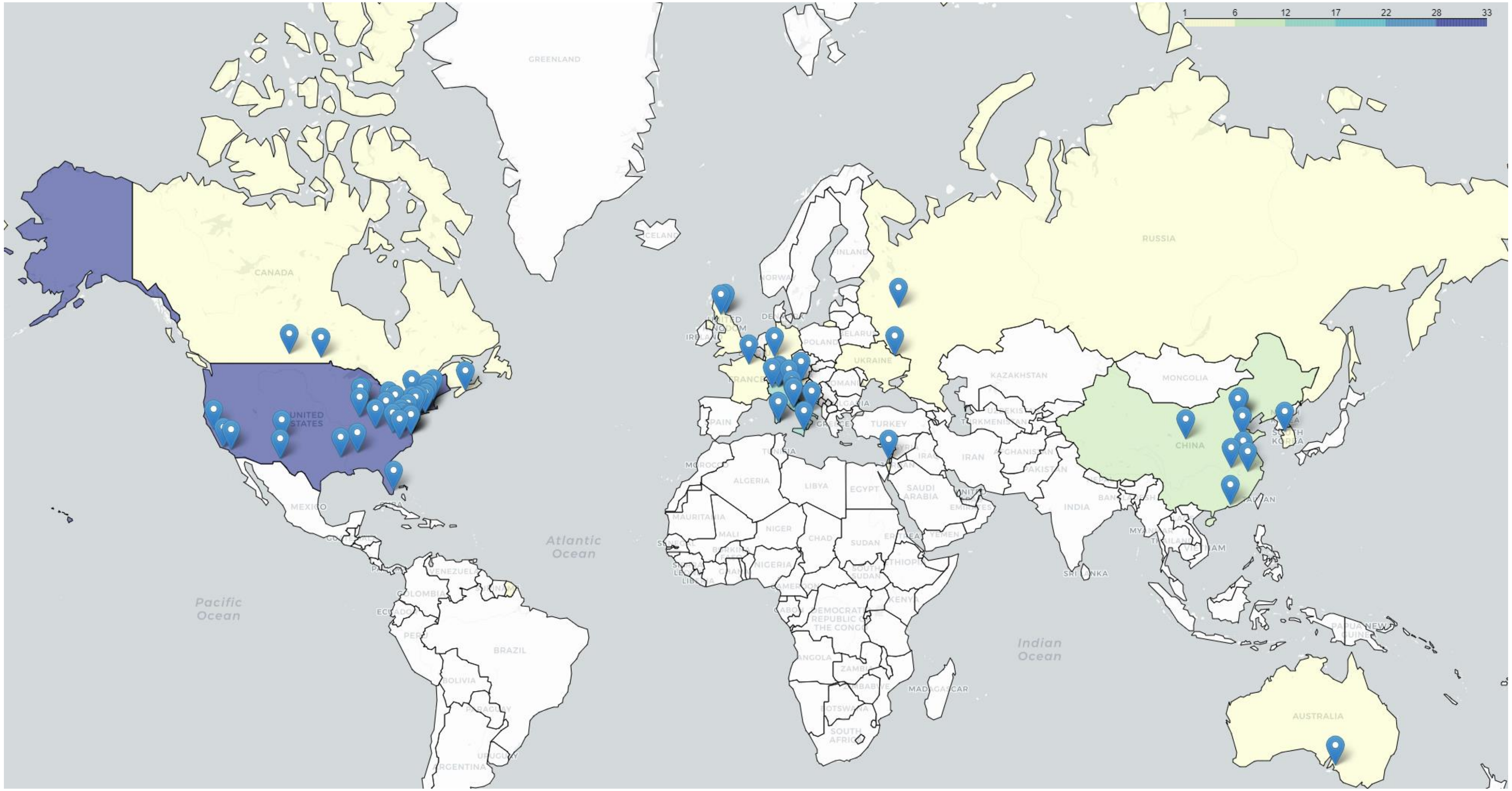
## 5) DDVCS, Alexandre Camsonne

………..

# SoLID Collaboration



- 270+ collaborators, 70+ institutions from 13 countries
- Large international participations and anticipate contributions
- Strong theory support



# Summary



- SoLID detector provides both high luminosity & large acceptance, with both polarized neutron and proton targets
- Will Maximize the science return of the 12-GeV CEBAF upgrade
- Physics on SoLID are rich and unique:
  - ✓ Pushing the phase space in the search of new physics
  - ✓ Sensitive to gluon energy, proton mass
  - ✓ 3D nucleon structure with SIDIS experiment (TMD & GPD)
- Jlab Direction Review in 2014, 2017 & 2019; MIE submitted to DOE and Science Review in 2021
- Very Active detector R&D
- Strong support from Jlab management and staff scientists
- Working closely with JLab, DOE/ONP to move SoLID forward

# Backup

# SoLID Publication

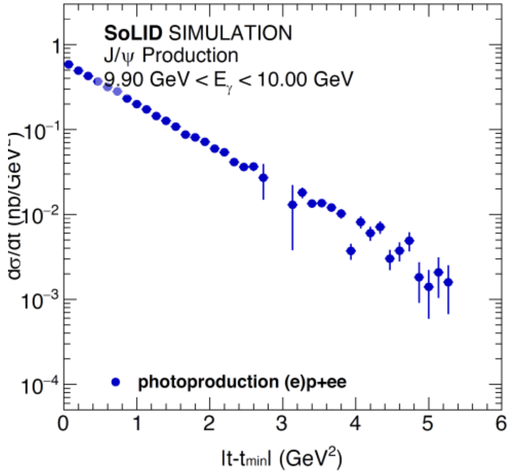


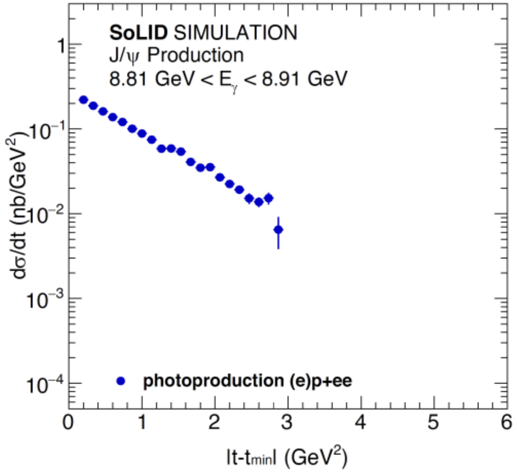

1. Y. Wang, et al., “A MRPC prototype for SOLID-TOF in JLab”, JINST 8 (2013) P03003.
2. J. P. Chen, et al. "A White Paper on SoLID (Solenoidal Large Intensity Device)". (2014) https://arxiv.org/abs/1409.7741
3. Z. Ye et al., “Unveiling the nucleon tensor charge at Jefferson Lab: A study of the SoLID case”, Phys. Lett. B767 (2017) 91.
4. Y. Tian et al., “Electromagnetic Calorimeter Prototype for the SoLID Project at Jefferson Lab”, Springer Proc. Phys. 213 (2018) 80
5. C. Peng, et al., “Performance of photosensors in a high-rate environment for gas Cherenkov detectors”, JINST 17 (2022) 08, P08022
6. John Arrington, et al. "The Solenoidal Large Intensity Device (SoLID) for JLab 12 GeV", (2022) https://arxiv.org/abs/2209.13357

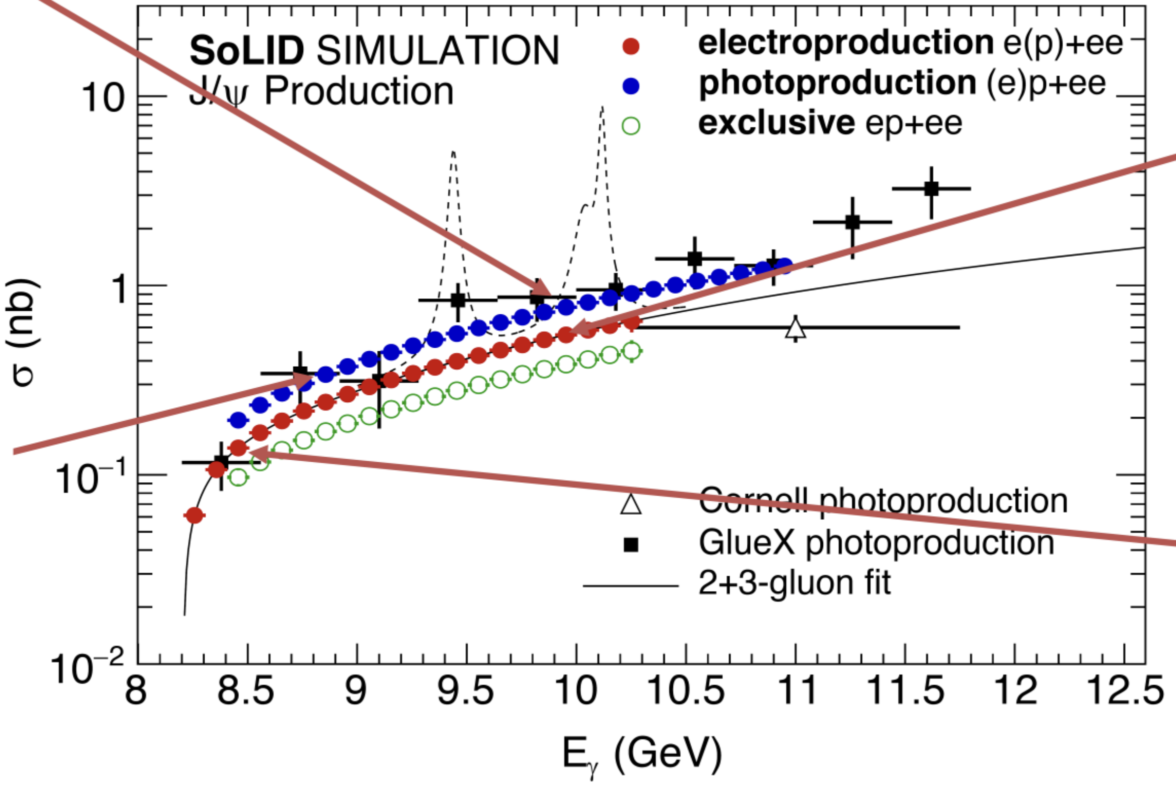
# SoLID Physics

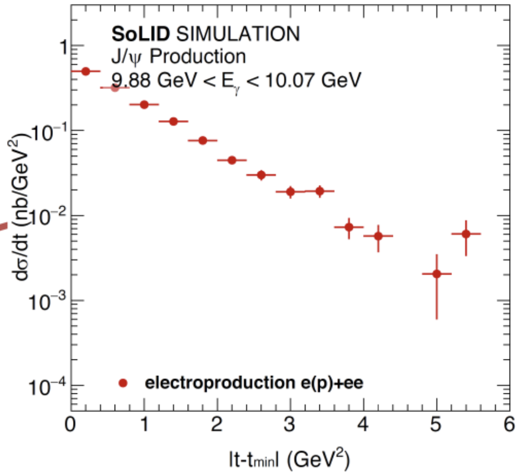


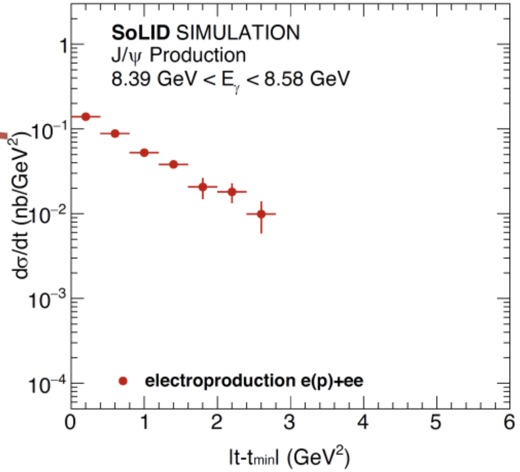
- J/ Ψ



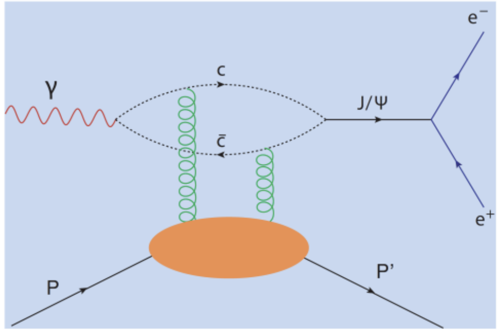




Sensitivity at threshold at about $10^{-3}$ nb!

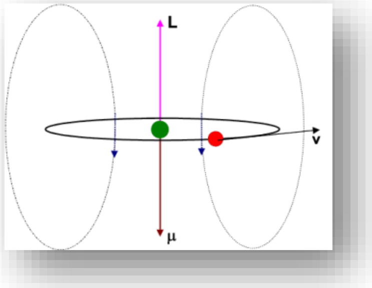


# Transverse Momentum Distributions

- **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)

**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

## 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 |
| | L | | $g_1(x,k_T^2)$ Helicity | $h_{1L}^\perp(x,k_T^2)$ Long-Transversity |
| | T | $f_{1T}^\perp(x,k_T^2)$ Sivers | $g_{1T}(x,k_T^2)$ Trans-Helicity | $h_1(x,k_T^2)$ Transversity<br>$h_{1T}^\perp(x,k_T^2)$ Pretzelosity |

Other TMDs are ZERO after integrating over $k_T$

Unpolarized Density Function:

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

Helicity Function:

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

Transversity Function:

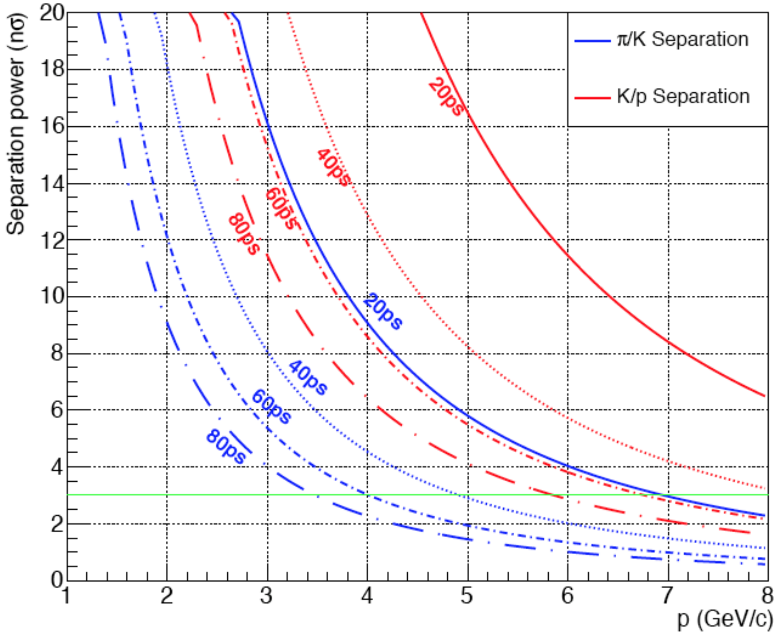
$$h_1(x) = \int d^2\boldsymbol{k}_\perp \left[h_{1T}(x,k_\perp) + \frac{k_\perp^2}{2M^2} h_{1T}^\perp(x,k_\perp)\right]$$

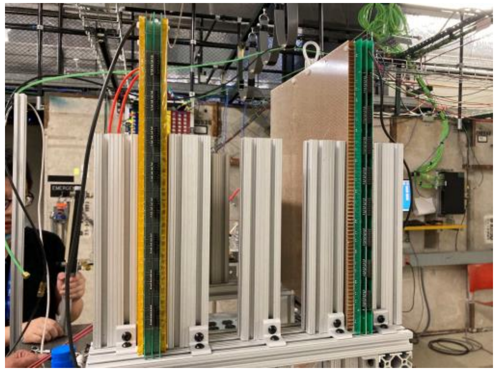
# SoLID Physics

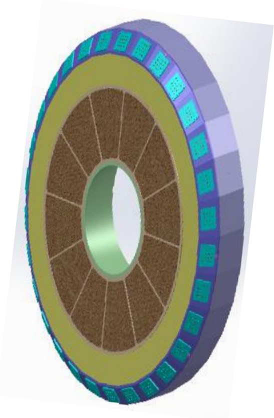


## ➢ TMD w/ SIDIS

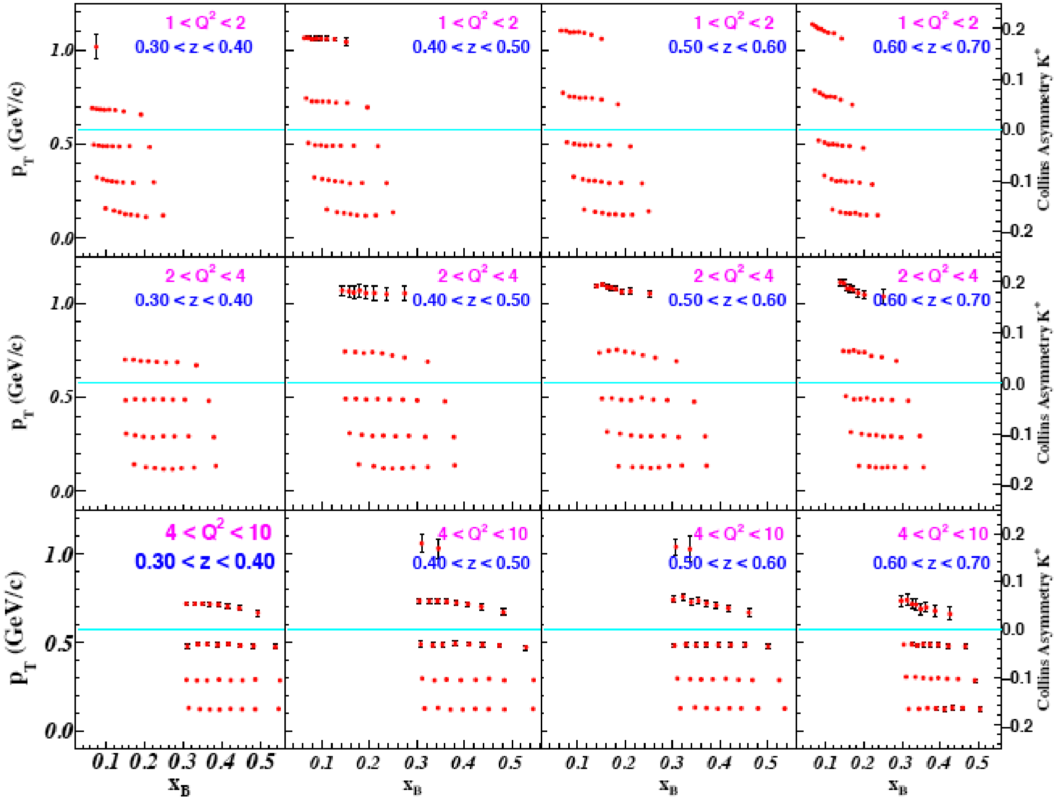
- ❑ Look for $K^{\pm}$ production in SIDIS using both the transversely polarized 3He and NH3 Targets
- ❑ Extract $K^{\pm}$ Collins, Sivers and other TMD asymmetries
- ❑ Flavor decomposition of u, d and sea quarks' TMDs
- ❑ Kaon-Identification: HGC + 30ps MRPC-TOF





Projection on Collins K+



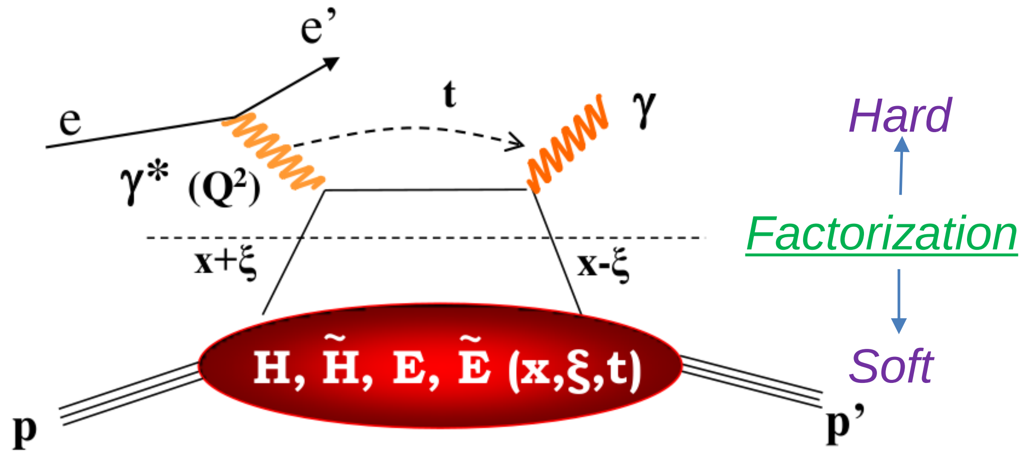

(a) $\vec{n}(e, e'K^+)X$

### ❑ Enhanced configuration

- ✓ MRPC modules contributed by Chinese resources (Tsinghua, USTC, etc.)
- ✓ High-time resolution Readout electronics possibly contributed by other US funding resources (UIC, etc.)

# Generalized Parton Distributions

## ➢ Deep Virtual Compton Scattering (DVCS):




- ❑ Golden channel to study GPD

- ❑ DVCS only measures Compton Form Factors (CFFs):

$$\tau_{DVCS} \propto \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi \mp i\varepsilon} dx = \overbrace{P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx}^{\mathrm{Re}(\mathcal{H})} - \overbrace{i\pi H(\pm\xi,\xi,t)}^{\mathrm{Im}(\mathcal{H})},$$

(8 CFFs for $H, E, \tilde{H}, \tilde{E}$ )

- ❑ Asymmetry: $A = \dfrac{I}{|\tau_{DVCS}|^2 + I + |\tau_{BH}|^2} = \dfrac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

  ✓ Decouple GPDs by angular modulations:

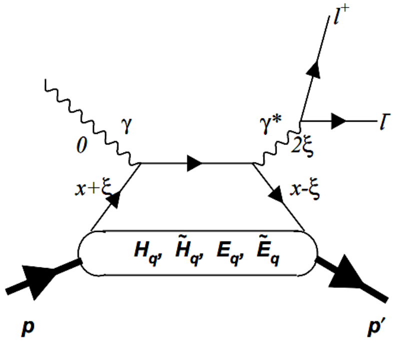
$$d\sigma_{UU}^{\mathrm{I}} = \frac{-K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \sum_{n=0}^{3} c_{n,\mathrm{unp}}^{\mathrm{I}} \cos(n\phi), \qquad d\sigma_{LU}^{\mathrm{I}} = \frac{-K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \sum_{n=1}^{2} s_{n,\mathrm{unp}}^{\mathrm{I}} \sin(n\phi),$$

$$d\sigma_{UU}^{\mathrm{DVCS}} = \frac{1}{Q^2} \sum_{n=0}^{2} c_{n,\mathrm{unp}}^{\mathrm{DVCS}} \cos(n\phi), \qquad d\sigma_{LU}^{\mathrm{DVCS}} = \frac{1}{Q^2} s_{1,\mathrm{unp}}^{\mathrm{DVCS}} \sin\phi,$$

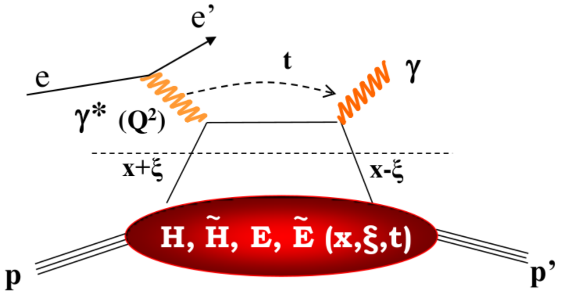
| Polarization | Asymmetries | CFFs |
|---|---|---|
| *Longitudinal Beam* | $A_{LU}$ | $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$ <br> $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_p, \mathcal{E}_n\}$ |
| *Longitudinal Target* | $A_{UL}$ | $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ <br> $Im\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$ |
| *Long. Beam + Long. Target* | $A_{LL}$ | $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ <br> $Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$ |
| *Transverse Target* | $A_{UT}$ | $Im\{\mathcal{H}_p, \mathcal{E}_p\}$ <br> $Im\{\mathcal{H}_n, \mathcal{E}_n\}$ |
| *Long. Beam +Trans. Targt* | $A_{LT}$ | $Re\{\mathcal{H}_p, \mathcal{E}_p\}$ <br> $Re\{\mathcal{H}_n, \mathcal{E}_n\}$ |

# SoLID Physics

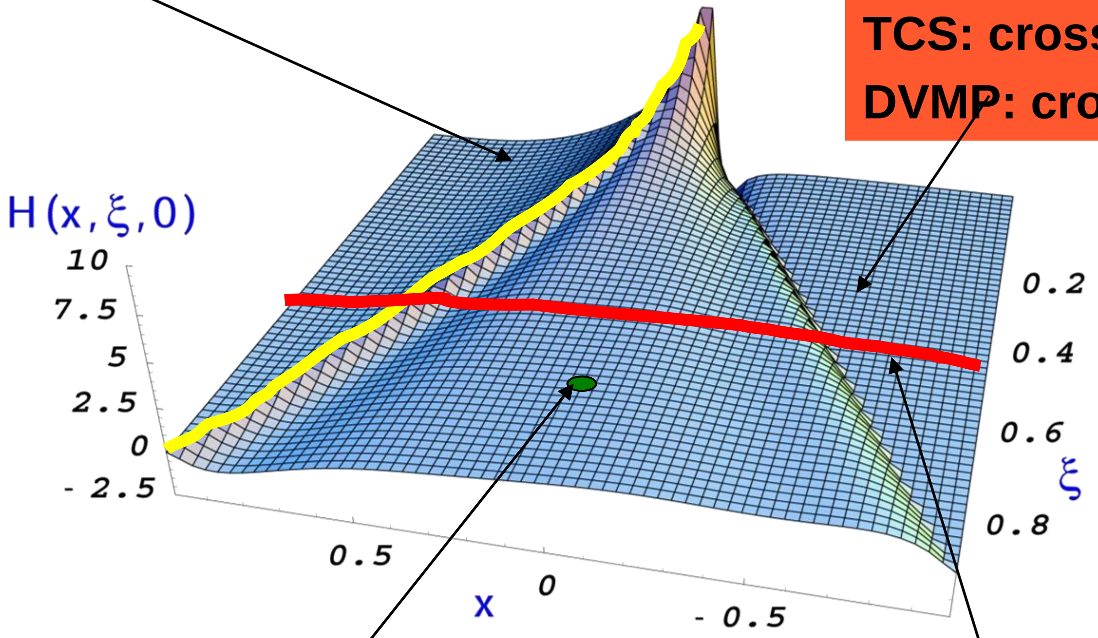
- Exclusive processes to fully extract GPDs

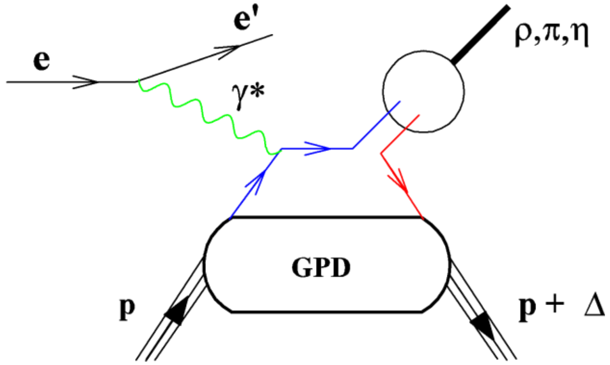


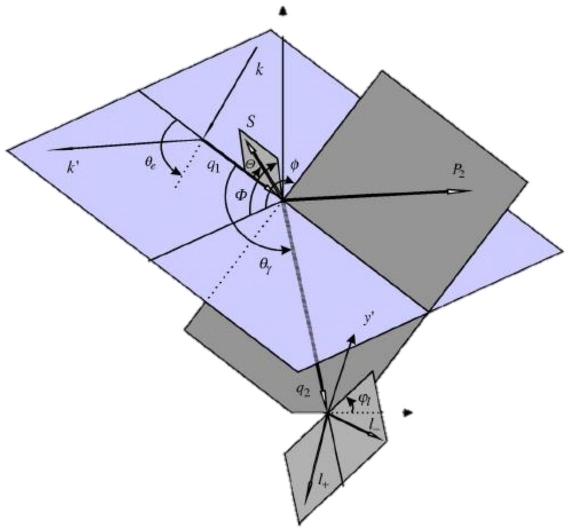

**(Im, $x=\xi$)**
**DVCS: spin asymmetries**
**TCS with polarized beam**




**(Re)**
**DVCS: charge asymmetry**
**TCS: cross-section, lin beam asymmetry**
**DVMP: cross-section, asymmetries**



**(Im, $x \neq \xi$, $x < |\xi|$ )**
**Double DVCS**

**($|Im|^2+|Re|^2$)**
**DVCS: cross section**
**DVMP: cross-section, asymmetries**

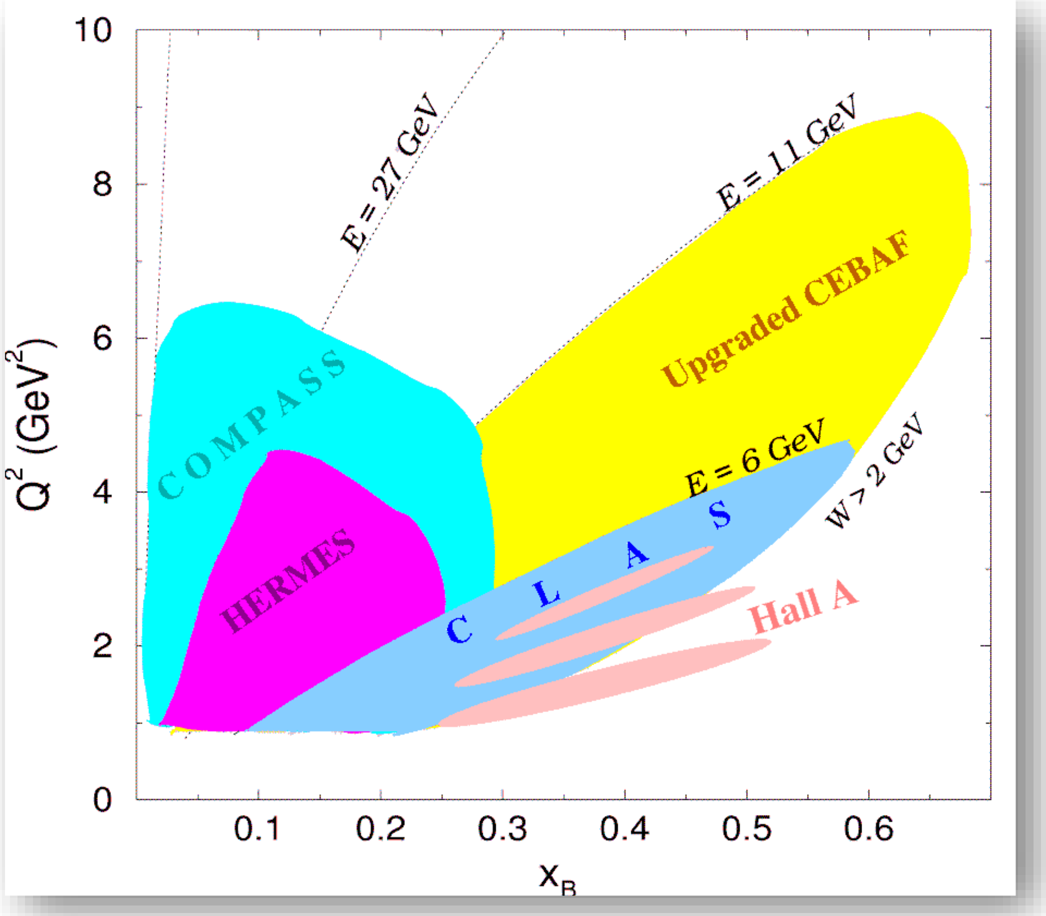
# Generalized Parton Distributions

## ➢ Jlab12GeV DVCS Experiments:

- ❑ DVCS not directly sensitive to flavor → proton & neutron needed for u & d
- ❑ Need multiple observables to decouple 8 CFFs, → XS, BSA, TSA, DSA
- ❑ 3D → wide kinematic-coverage + high rate

**Approved 12GeV DVCS experiments:**

- E12-16-010B (Hall-B): unpol. proton, XS
- E12-11-003 (Hall-B): unpol. Deuteron, BSA
- E12-06-119 (Hall-B): long-pol proton, BSA, TSA,
- C12-12-010 (Hall-B): *conditional approved*, trans. pol. Proton, TSA,BSA
- C12-15-004 (Hall-B): *conditional approved*, long. pol. Deuteron, TSA, BSA
- E12-06-114 (Hall-A&C): unpol. proton, XS & BSA, limited coverage
- E12-13-010 (Hall-C): unpol. proton, XS,
- E12-15-001 (Hall-C): proton, XS
- ***LOI:*** nDVCS w/ TDIS setup (Hall-A), tagged neutron, XS

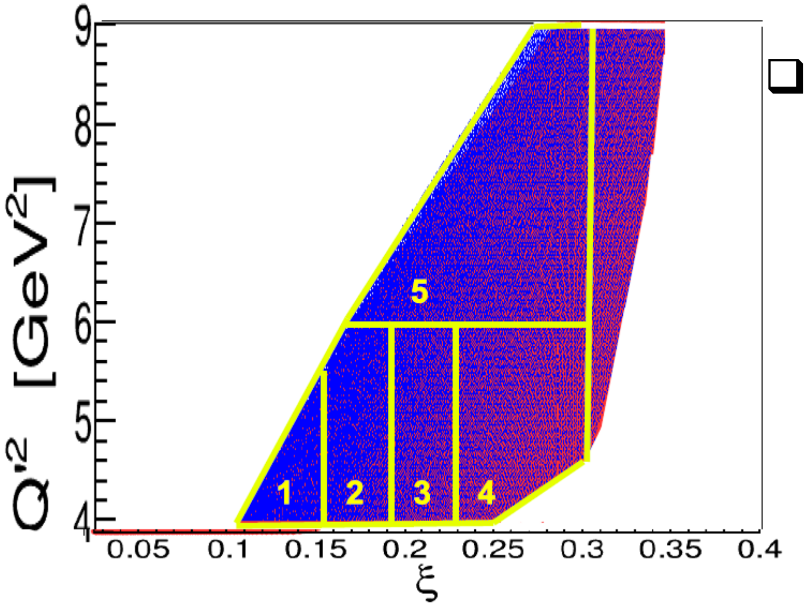



❖ SoLID (SIDIS configuration) will provide:

- ✓ DVCS asymmetries w/ polarized beam & target data
- ✓ DVCS neutron data (Deuteron or He3)

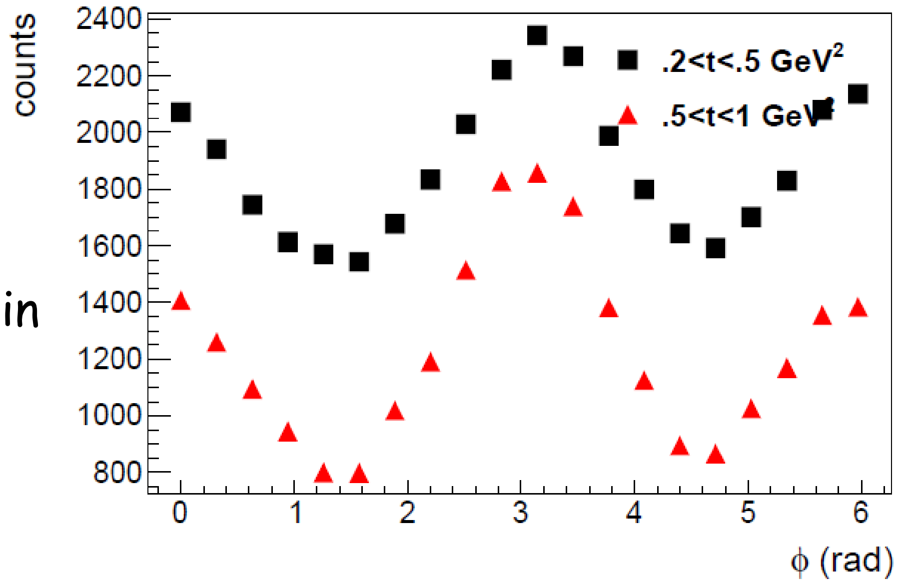
# GPDs on SoLID

- **SoLID-TCS:** (E12-12-006A, M. Boer, P. Nadel-Turonski, J. Zhang, Z. Zhao)

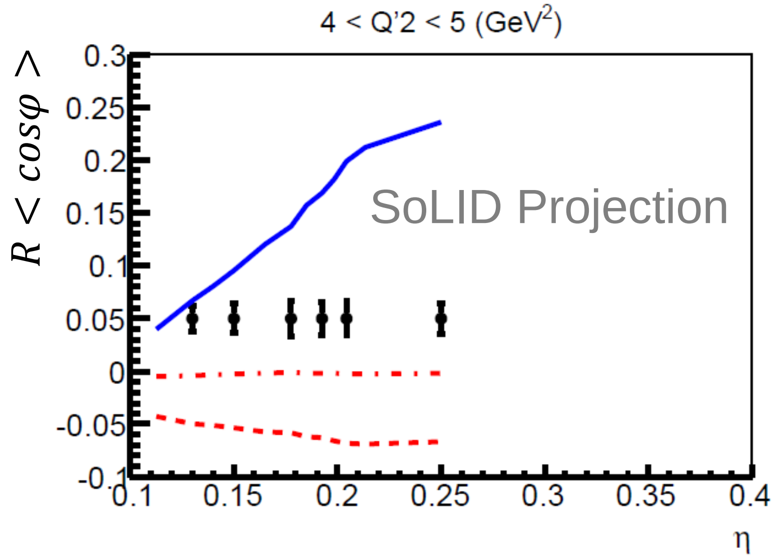


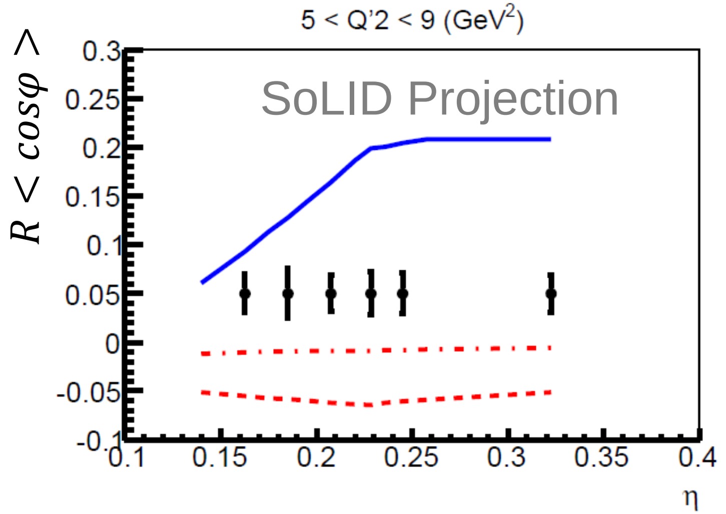

- ❑ Proper Q2 and ξ binning

- ❑ Fit to the angular distribution in each bin




- ❑ Projections of two highest bins



# GPDs on SoLID

## ➢ SoLID-DVMP:

- ❑ In parallel with E12-10-006 (SIDIS with polarized He3)
- ❑ Exclusive events from pion-DVMP reactions (first neutron DVMP experiment)

$$A_{UT}^{\sin(\phi_S)} \sim \mathrm{Im}[M^*_{0+++}M_{0-0+} - M^*_{0-++}M_{0+0+}],$$

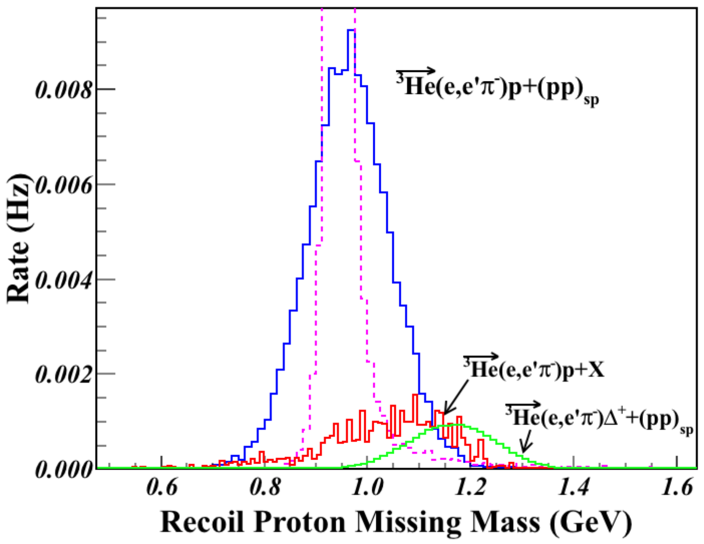
helicities: [pion, neutron, photon, proton]

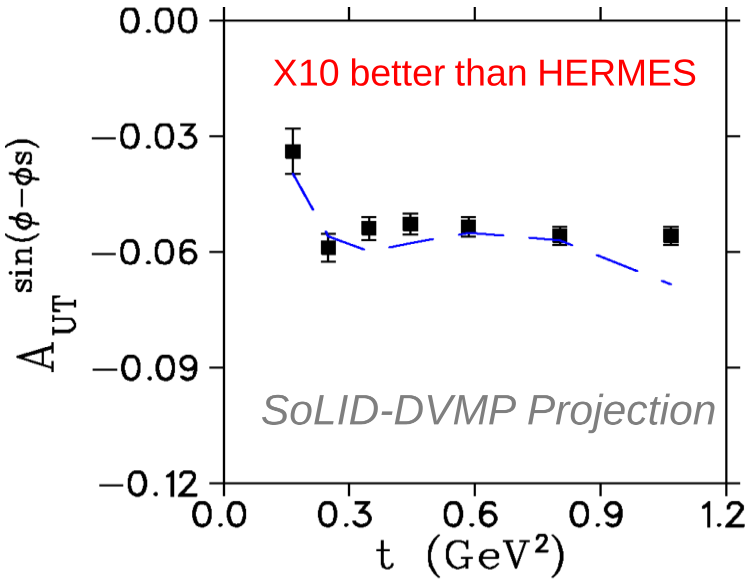
$$\mathcal{M}_{0-,++} = e_0\sqrt{1-\xi^2}\int \mathrm{d}x\mathcal{H}_{0-,++}H_T,$$

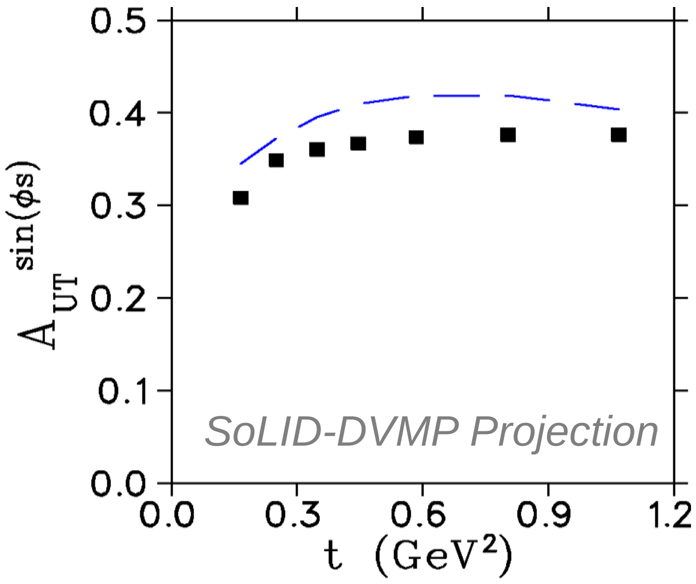
$$\mathcal{M}_{0+,\pm+} = -e_0\frac{\sqrt{t_{\min}-t}}{4m}\int \mathrm{d}x\mathcal{H}_{0-,++}\bar{E}_T.$$

- ❑ Analyze angular modules to decouple GPDs

$$A_{UT}^{\sin(\phi-\phi_s)} \sim \frac{d\sigma_{00}^{+-}}{d\sigma_L\binom{++}{00}} \sim \frac{\mathrm{Im}(\tilde{E}^*\tilde{H})}{\left|\tilde{E}\right|^2} \text{ where } \tilde{E} \gg \tilde{H}$$

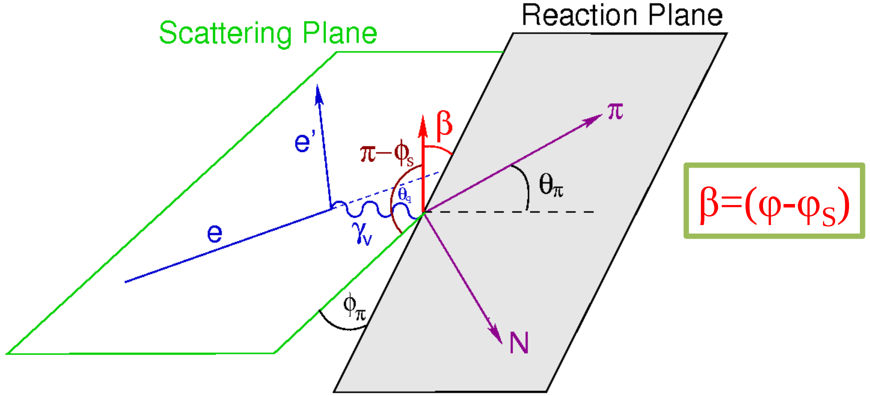


# GPDs on SoLID

- **SoLID-DVMP:** (E12-10-006B, Z. Ahmed, G. Huber, Z. Ye)




## DVMP advantages:

- ✓ Direct probe of quark flavor
- ✓ Vector mesons sensitive to ***H*** and ***E***
- ✓ Pseudoscaler mesons sensitive to $\tilde{H}$ and $\tilde{E}$ (uniquely w/ neutron)
- ✓ Sensitive to transverse GPDs ($H_T, E_T, \tilde{H}_T, \tilde{E}_T$)

## DVMP disadvantages:

- ✓ Usually requires $Q^2$ >10 $GeV^2$ for factorization
- ✓ Higher twist contaminations
- ✓ Long. photons to link to GPD (LT separation)

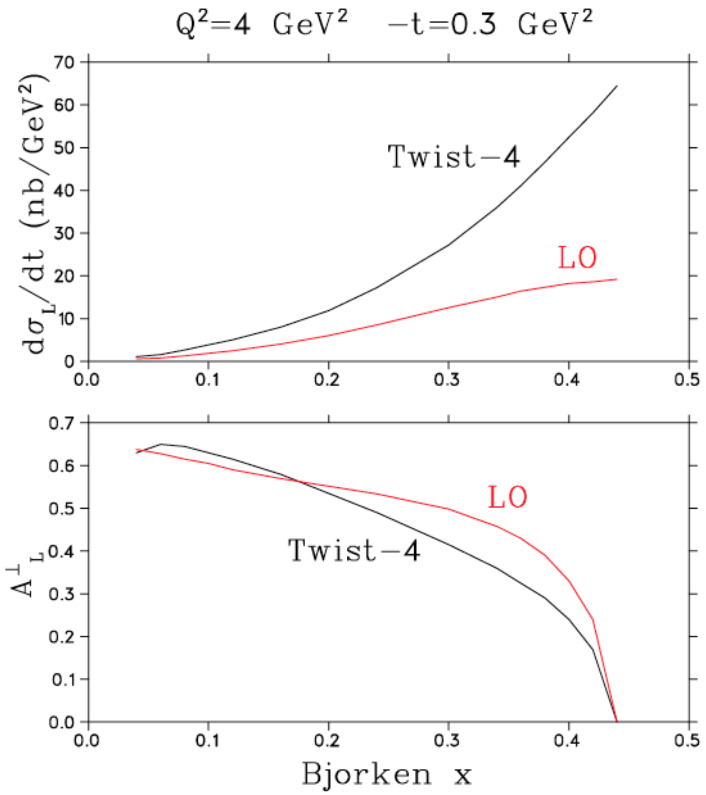
$$2\pi\frac{d^2\sigma}{dtd\phi} = \epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

## DVMP w/ asymmetries:

*Belitsky & Műller PLB 513(2001)349, CIPANP 2003).*

- ✓ $A_L^{\perp}$ displays factorization even at only $Q^2$~2-4 $GeV^2$:

$$A_L^{\perp} = \frac{\sqrt{-t'}}{m_p}\frac{\xi\sqrt{1-\xi^2}\,\mathrm{Im}(\tilde{E}^*\tilde{H})}{(1-\xi^2)\tilde{H}^2 - \frac{t\xi^2}{4m_p}\tilde{E}^2 - 2\xi^2\mathrm{Re}(\tilde{E}^*\tilde{H})}.$$



# Generalized Parton Distributions

## ➢ Deep Virtual Compton Scattering (DVCS):

❑ With polarization: $\sigma^{BH+I+DVCS} = \underbrace{\sigma_{UU}}_{unpol} + \underbrace{P_L\sigma_{LU}}_{beam\ pol} + \underbrace{S_{L,T}\sigma_{UL,UT}}_{target\ pol} + \underbrace{P_L S_{L,T}\sigma_{LL,LT}}_{double\ pol}$

❑ Asymmetry: $A = \dfrac{I}{|\tau_{DVCS}|^2 + I + |\tau_{BH}|^2} = \dfrac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

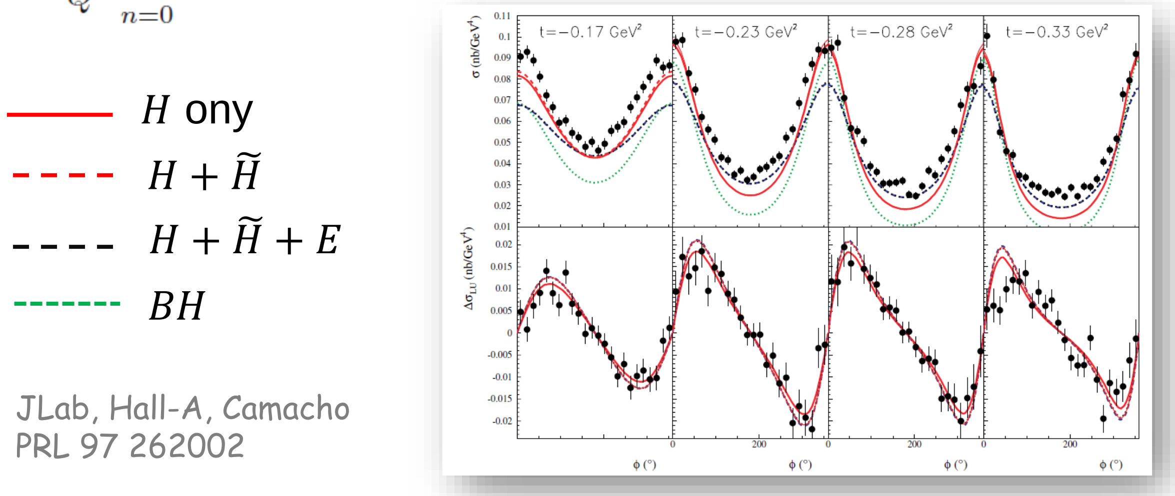
| Polarization | Asymmetries | CFFs |
|---|---|---|
| *Longitudinal Beam* | $A_{LU}$ | $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$<br>$Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_p, \mathcal{E}_n\}$ |
| *Longitudinal Target* | $A_{UL}$ | $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$<br>$Im\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$ |
| *Long. Beam + Long. Target* | $A_{LL}$ | $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$<br>$Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$ |
| *Transverse Target* | $A_{UT}$ | $Im\{\mathcal{H}_p, \mathcal{E}_p\}$<br>$Im\{\mathcal{H}_n, \mathcal{E}_n\}$ |
| *Long. Beam +Trans.Targt* | $A_{LT}$ | $Re\{\mathcal{H}_p, \mathcal{E}_p\}$<br>$Re\{\mathcal{H}_n, \mathcal{E}_n\}$ |

Belitsky, Mueller, PRD (2009,2010), NPB (2014)

❑ Decouple by angular modulations:

$$d\sigma_{UU}^{I} = \frac{-K_I}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \sum_{n=0}^{3} c_{n,\mathrm{unp}}^{I} \cos(n\phi), \qquad d\sigma_{LU}^{I} = \frac{-K_I}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \sum_{n=1}^{2} s_{n,\mathrm{unp}}^{I} \sin(n\phi),$$

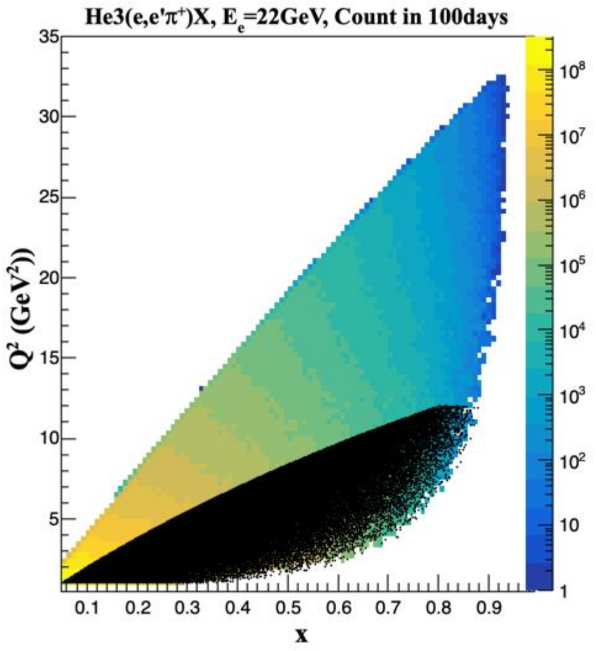
$$d\sigma_{UU}^{\mathrm{DVCS}} = \frac{1}{Q^2} \sum_{n=0}^{2} c_{n,\mathrm{unp}}^{\mathrm{DVCS}} \cos(n\phi), \qquad d\sigma_{LU}^{\mathrm{DVCS}} = \frac{1}{Q^2} s_{1,\mathrm{unp}}^{\mathrm{DVCS}} \sin\phi,$$

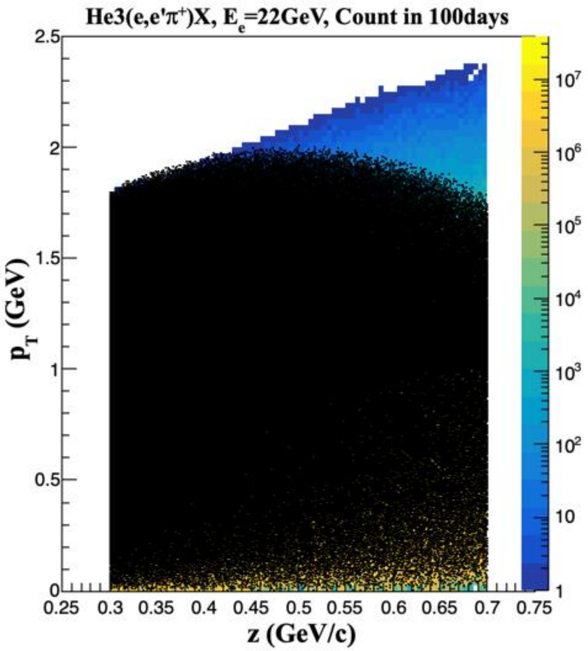



JLab, Hall-A, Camacho
PRL 97 262002

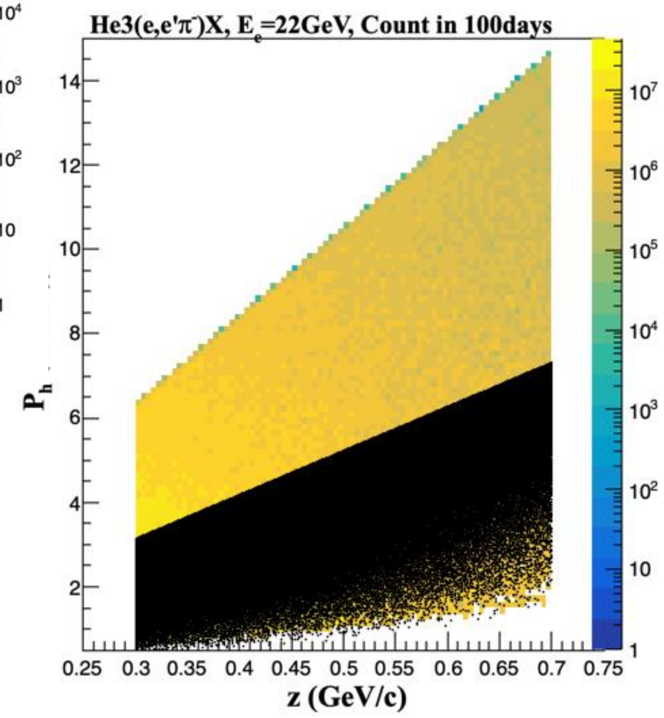
# SoLID at 22GeV

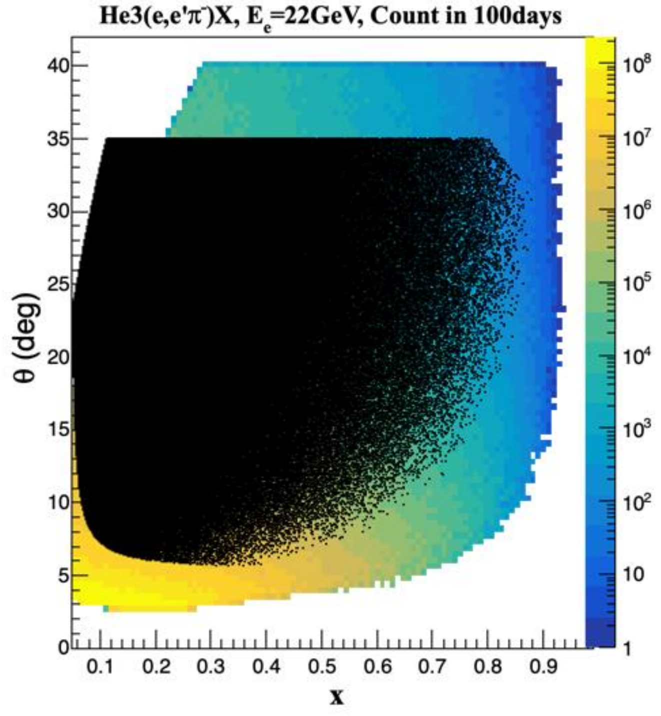
- Larger Phase-Space




Back dots→11GeV
Color dots→22GeV



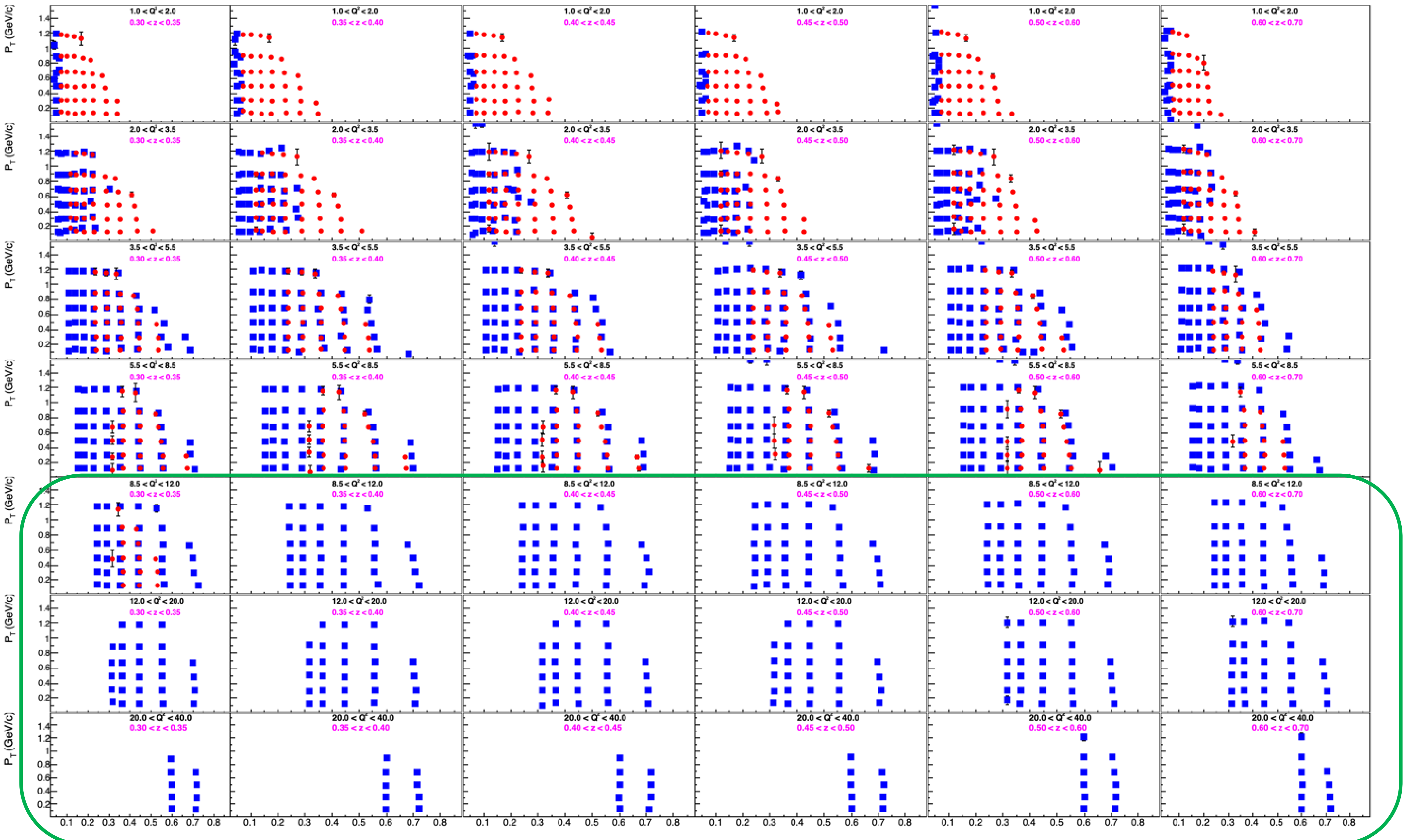



# SoLID-SIDIS at 22GeV

Pio-SIDIS Projection

- 11GeV
- 22GeV

→Lumi~$10^{37}cm^{-2}s^{-1}$,
→1-day w/ SoLID



# SoLID-SIDIS at 22GeV

Kaon-SIDIS Projection

- 11GeV
- 22GeV

→Lumi~$10^{37}cm^{-2}s^{-1}$,
→1-day w/ SoLID