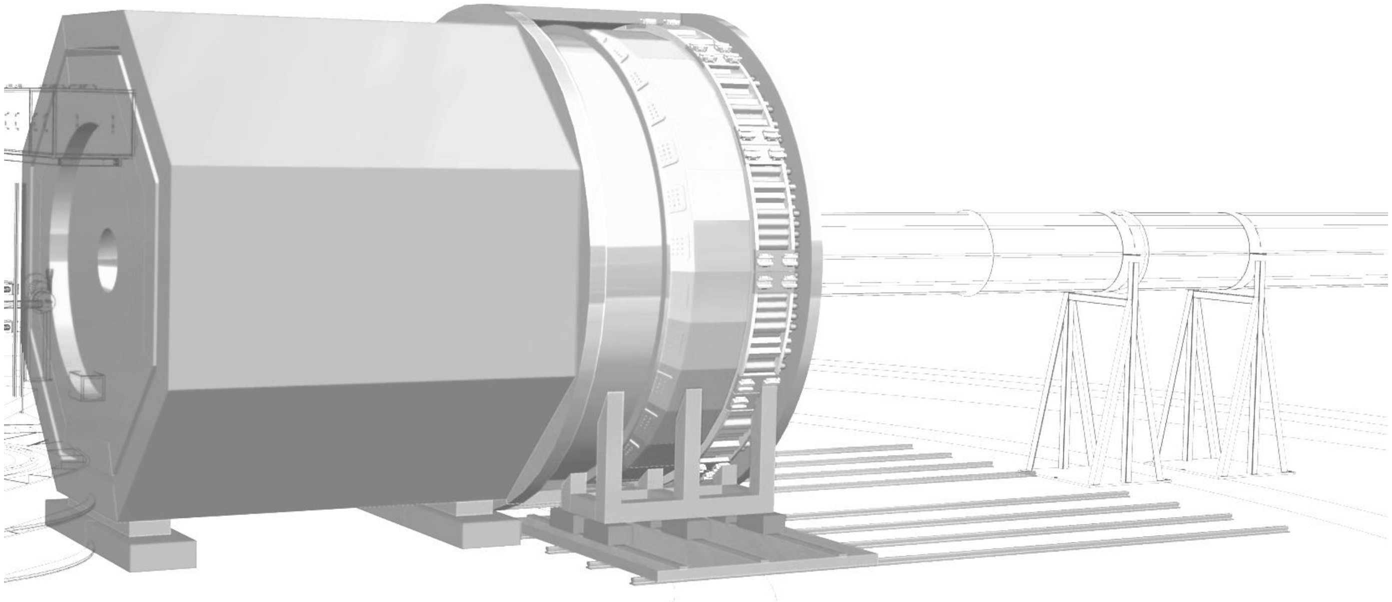
Overview of the proposed Solenoidal Large Intensity Device (SoLID) and its physics programs at Jefferson Lab



Vladimir Khachatryan
Duke University

JLab Hall A/C Collaboration Meeting
July 8-9, 2021

On behalf of the SoLID Collaboration

SOLENOIDAL LARGE INTENSITY DEVICE

Outline

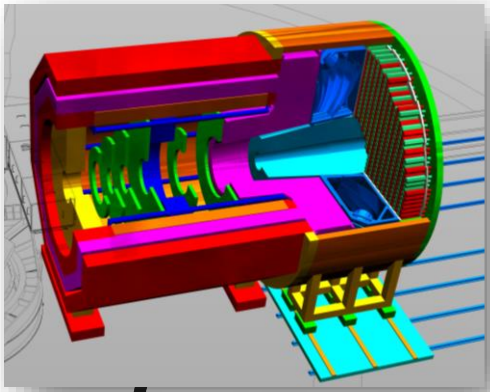
- Introduction
- The three pillars of the SoLID program
  - Nucleon 3-D momentum tomography with **SIDIS**
  - QCD with **PVDIS**
  - Quantum anomalous energy with **J/Ψ**
- SoLID run-group proposals
- The SoLID device
- Summary

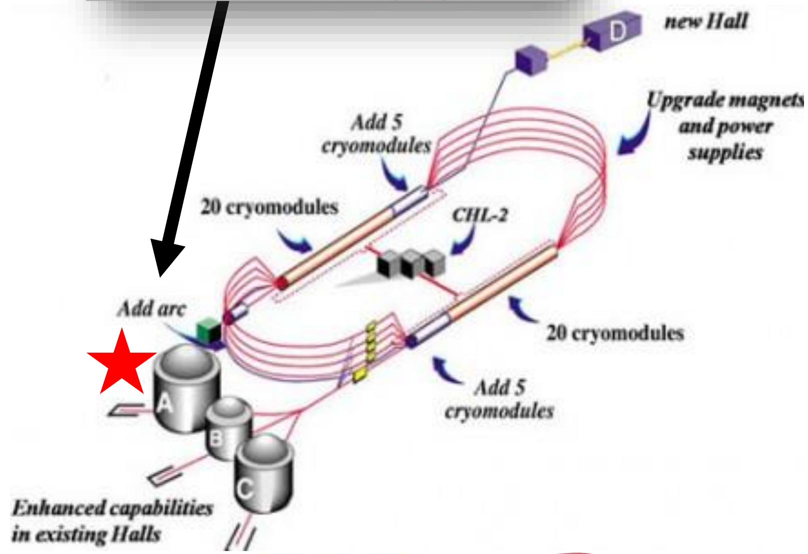
SoLID@12-GeV JLab: QCD at the intensity frontier

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 a ***unique*** capability to **explore** the QCD landscape while **complementing** the research of other key facilities





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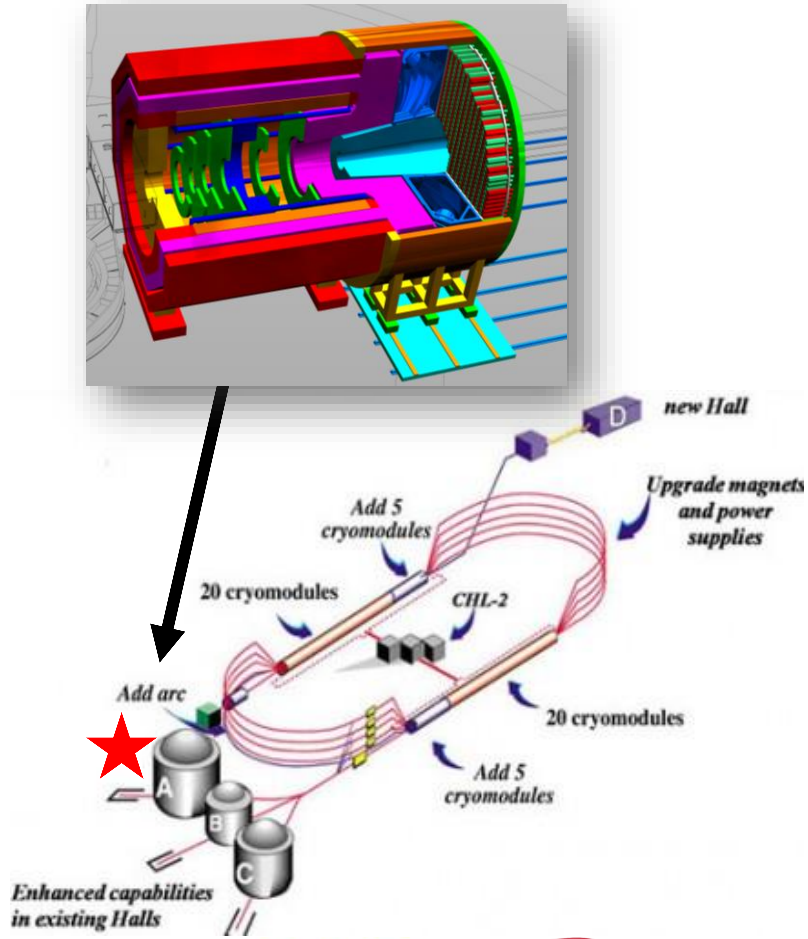
- Pushing the phase space in the search of new physics and of hadronic physics
- 3D momentum imaging of a relativistic strongly interacting confined system (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton mass**)



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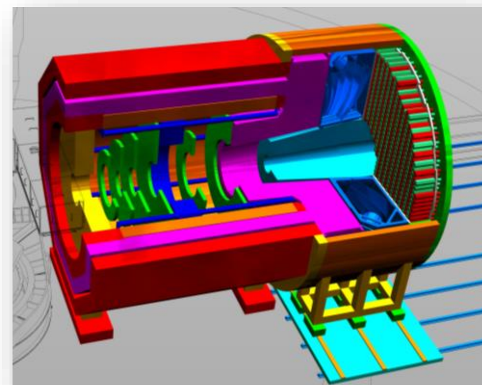
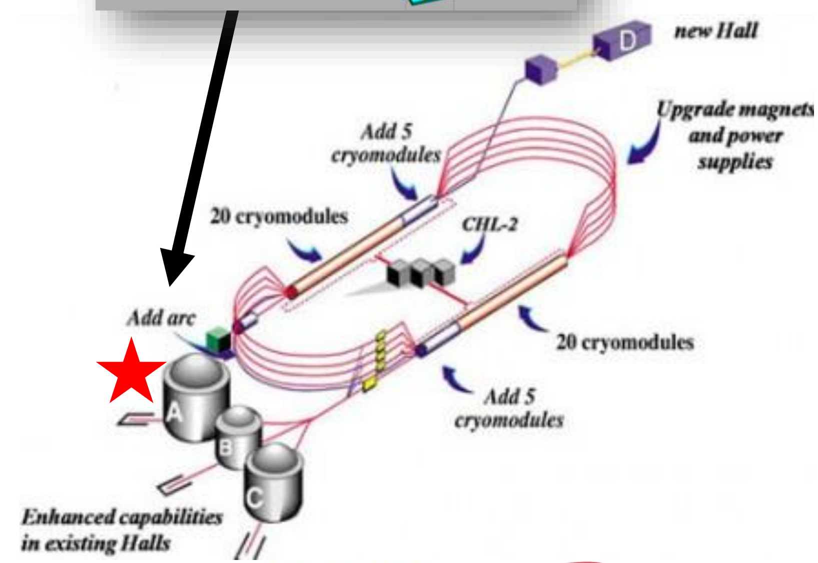




Synergizing with the pillars of EIC science (**proton spin** and **mass**) through high-luminosity valence quark tomography and precision J/ψ production near threshold

Nucleon Structure from 1D to 3D – orbital motion

5-D Wigner distribution

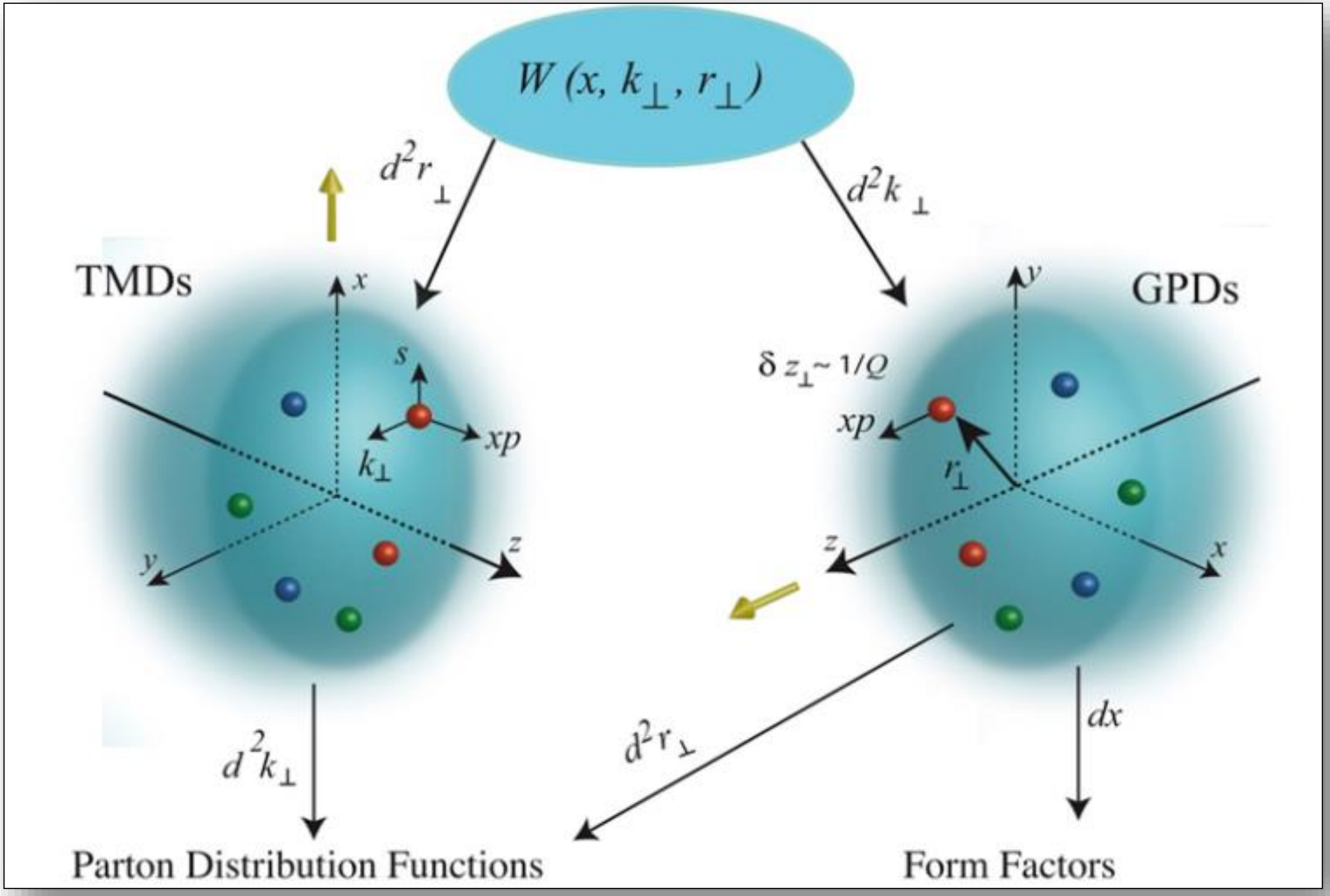


Image from J. Dudek et al., EPJA 48,187 (2012)

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

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

TMDs – confined motion inside the nucleon

Leading twist: 8 TMDs

→ Nucleon Spin
→ Quark Spin

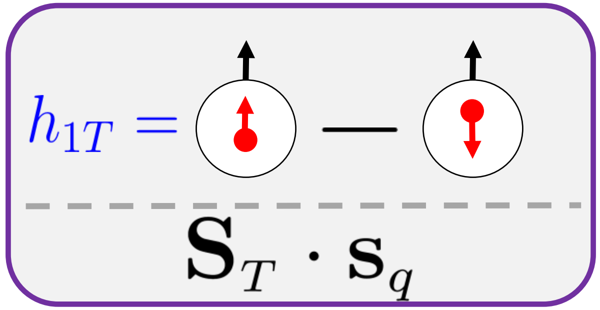
		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 =$		$h_1^{\wedge} = \quad - \quad$ Boer-Mulder
	L		$g_1 = \quad - \quad$ Helicity	$h_{1L}^{\wedge} = \quad - \quad$
	T	$f_{1T}^{\wedge} = \quad - \quad$ Sivers	$g_{1T}^{\wedge} = \quad - \quad$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

TMDs – confined motion inside the nucleon

Transversely Polarized Nucleon TMDs

Nucleon Spin
Quark Spin

Transversity

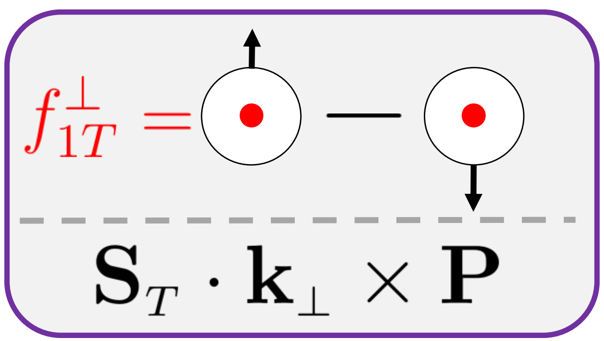


- h_{1T} (h_1) = g_1 (no relativity)
- $h_{1T} \longrightarrow$ tensor charge (lattice QCD calculations)
- Connected to nucleon beta decay and EDM

Relevant Vectors

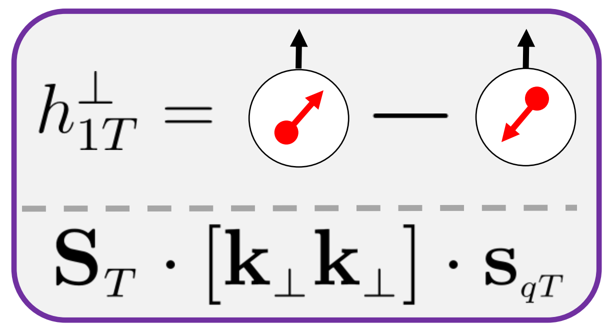
S_T: Nucleon Spin
s_q: Quark Spin
$k_\perp$: Quark Transverse Momentum
P: Virtual photon 3-momentum (defines z-direction)

Sivers



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

Pretzelosity

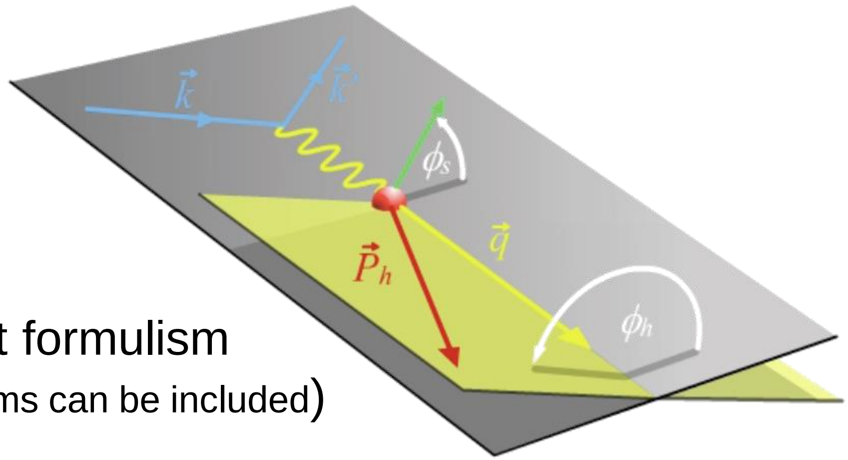


- Interference between components with OAM difference of 2 units (i.e., s-d, p-p) (model dependence)
- Signature for relativistic effect

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 asymmetries in 4-D binning with precision!

(2π azimuthal coverage)



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

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

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

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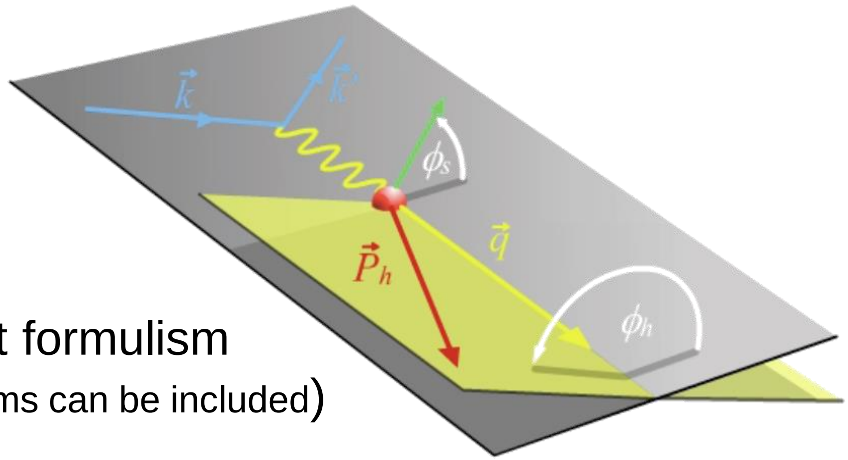

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$$= A_{UT}^{Collins}\sin(\phi_h+\phi_S) + A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S) + A_{UT}^{Sivers}\sin(\phi_h-\phi_S)$$

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

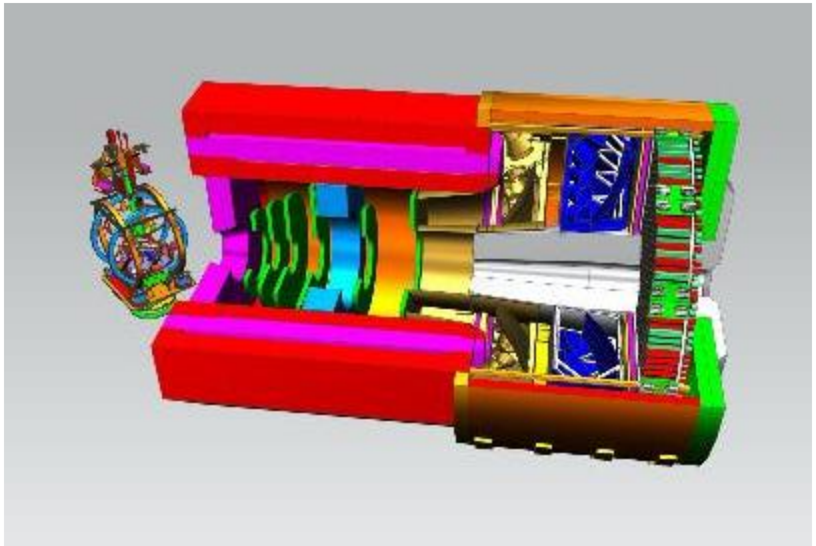
$$\boxed{A_{UT}^{Pretzelosity}} \propto \langle\sin(3\phi_h-\phi_S)\rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

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

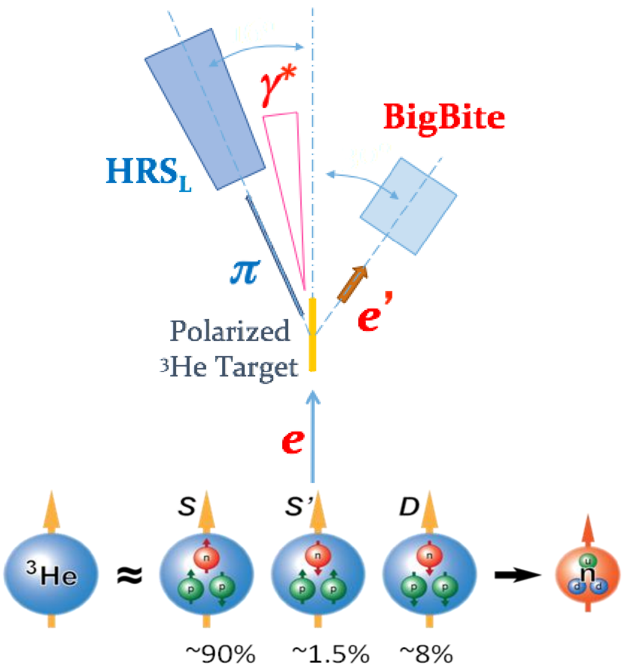
QCD intensity frontier with SoLID: large-acceptance & high luminosity



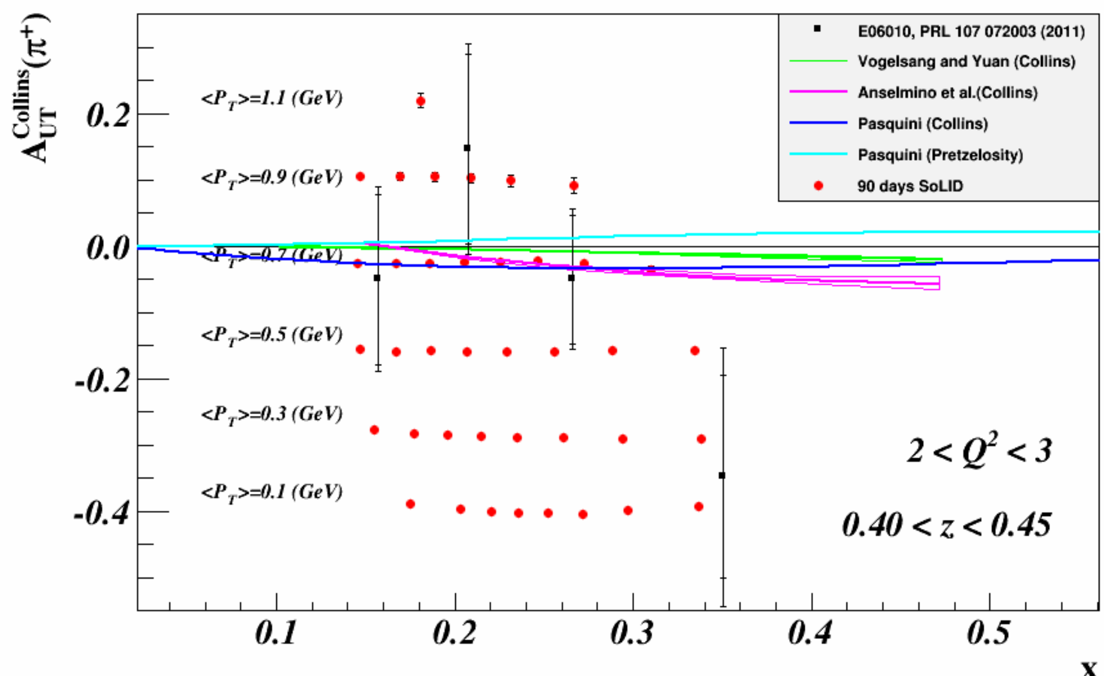
Quantum leap: 4-D binning for the first time!

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

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

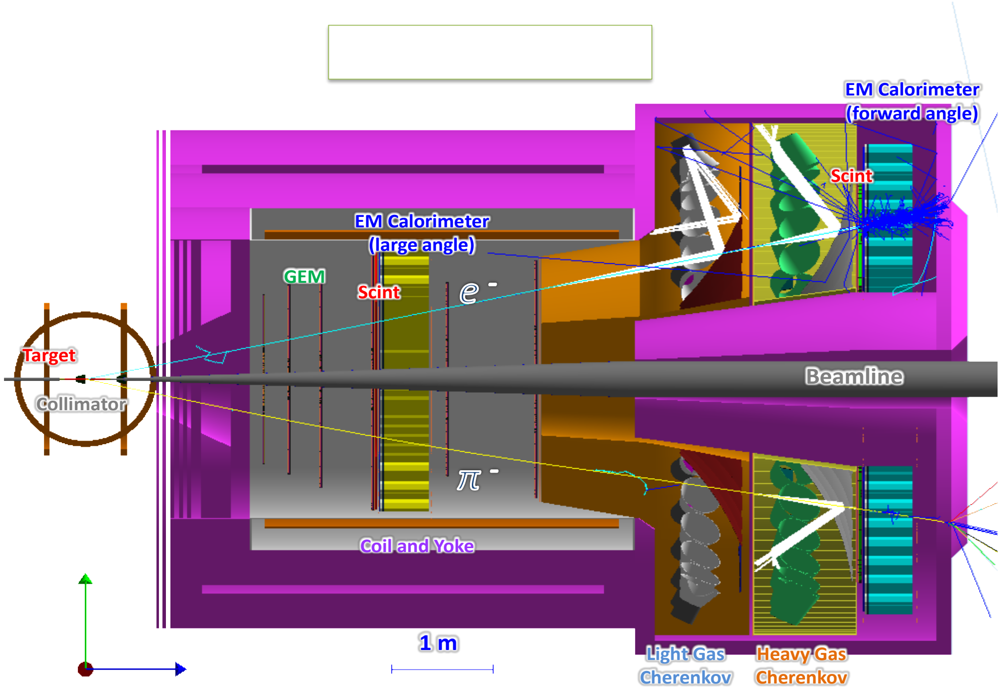


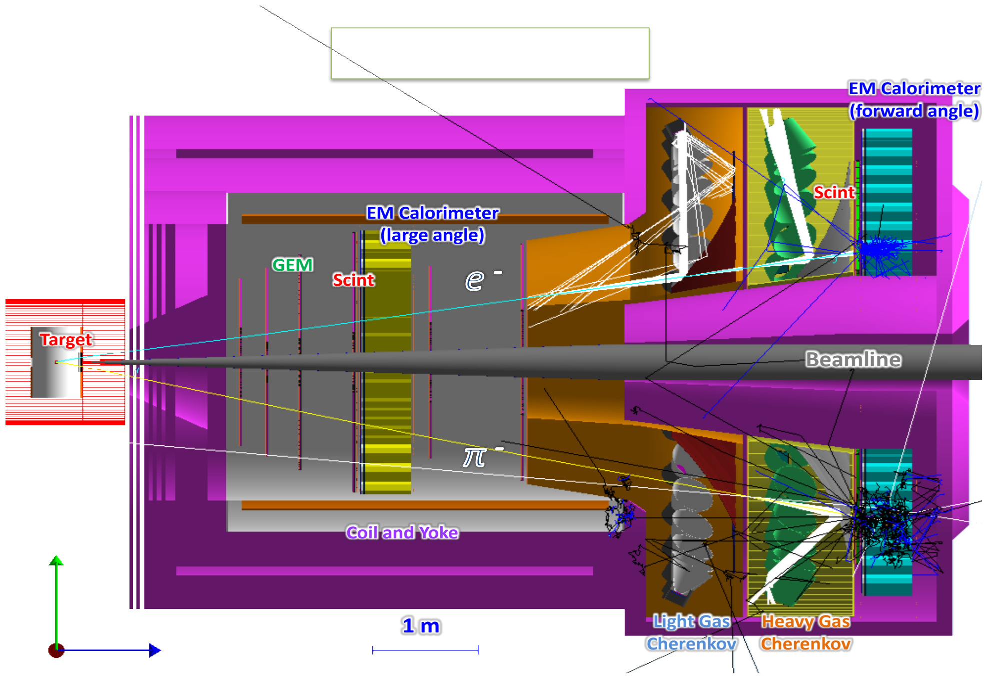
X. Qian et al., PRL107, 072003(2011)



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

SIDIS with polarized "neutron" and "proton" @ SoLID





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

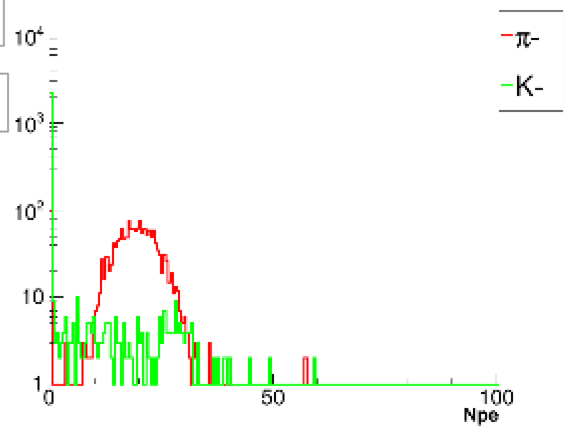
SoLID-SIDIS and Subsystems

- Coincidence detection of electrons and charged pions: good pid for electrons (LGC+EC); moderate PID for pions (HGC)
- ^{3}He target: transverse and longitudinal in-beam polarizations of ~60%; NH_3 target: in-beam transverse polarization ~70%
- Large acceptance with full azimuthal coverage @ pol. Lumi. 10^{36} cm^{-2} s^{-1} (^{3}He), 10^{35} cm^{-2} s^{-1} (NH_3); 4-d kinematic binning requires good momentum and angular resolutions – GEMs offer excellent tracking capability
- DAQ rate: up to 100 KHz (unpol. Lumi 10^{37} cm^{-2} s^{-1} (^{3}He))

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

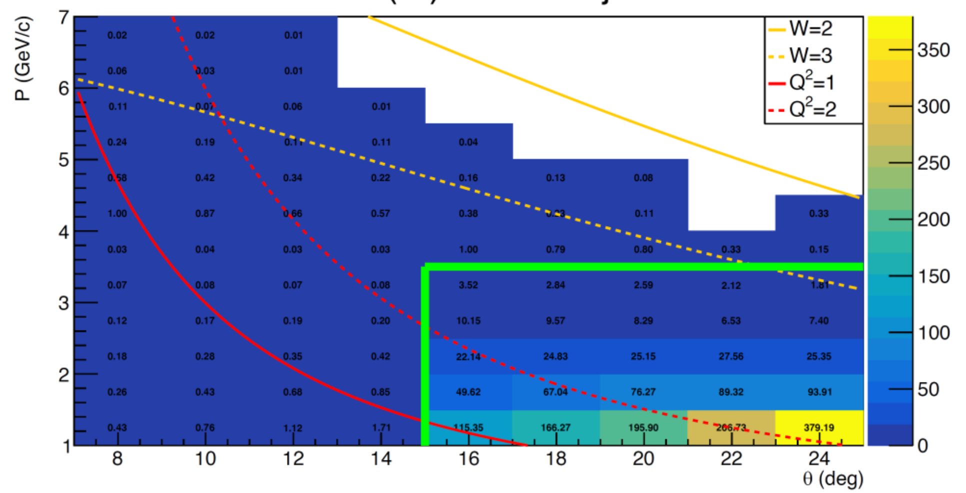
π efficiency (~0.9)

K_{rej} ~10



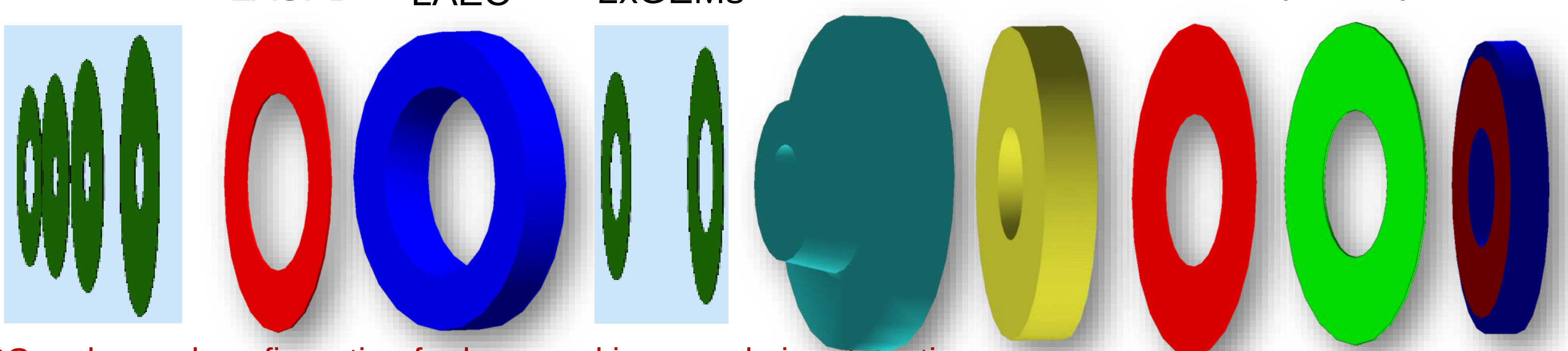
Combined light gas Cherenkov and Calorimeter detector performance

π^-/e^- ratio (%) after π^- rejection



SIDIS&J/Ψ :

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



MRPC: enhanced configuration for kaon and improved pion detection

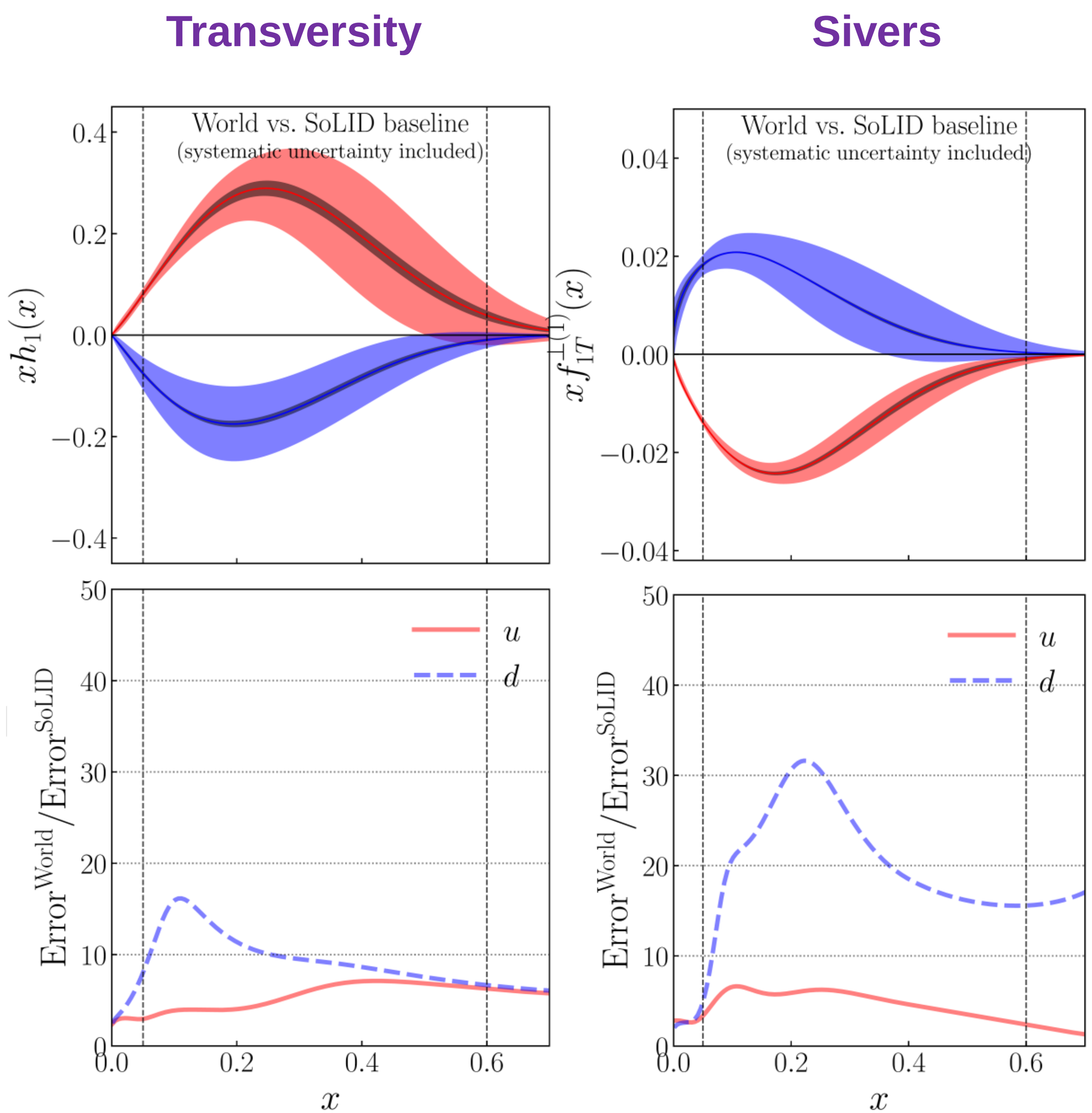
SoLID SIDIS Projection

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

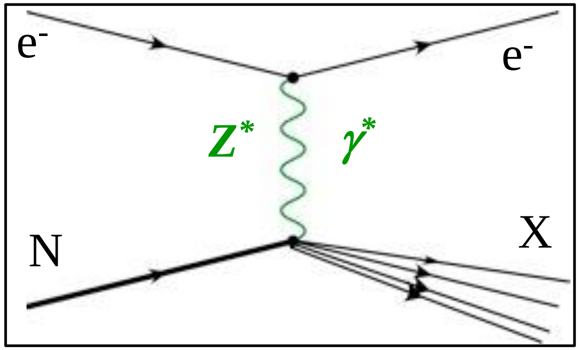
SoLID baseline used

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



PV Deep Inelastic Scattering

Off the simplest isoscalar nucleus and at high Bjorken *x*



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

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

$Q^2 >> 1\ GeV^2,\ W^2 >> 4\ GeV^2$

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x, Q^2) = \sigma^l/\sigma^r \approx 0.2$$

$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r}$$

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

At high x, A_{iso} becomes independent of pdfs, x & W, with well-defined SM prediction for Q^2 and y

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

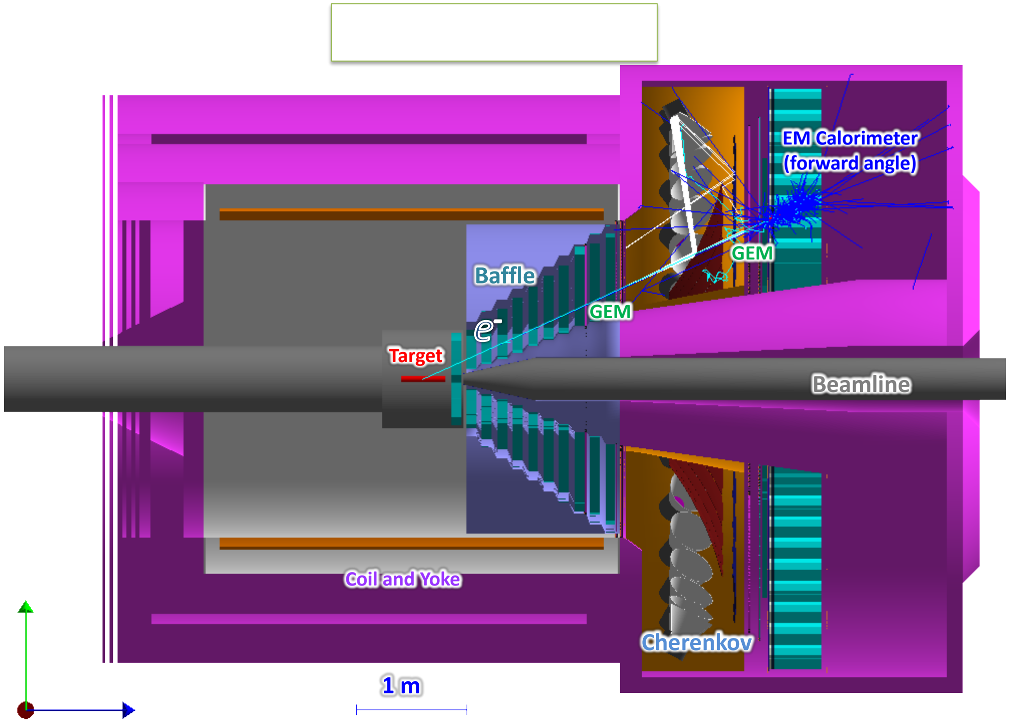
Interplay with QCD

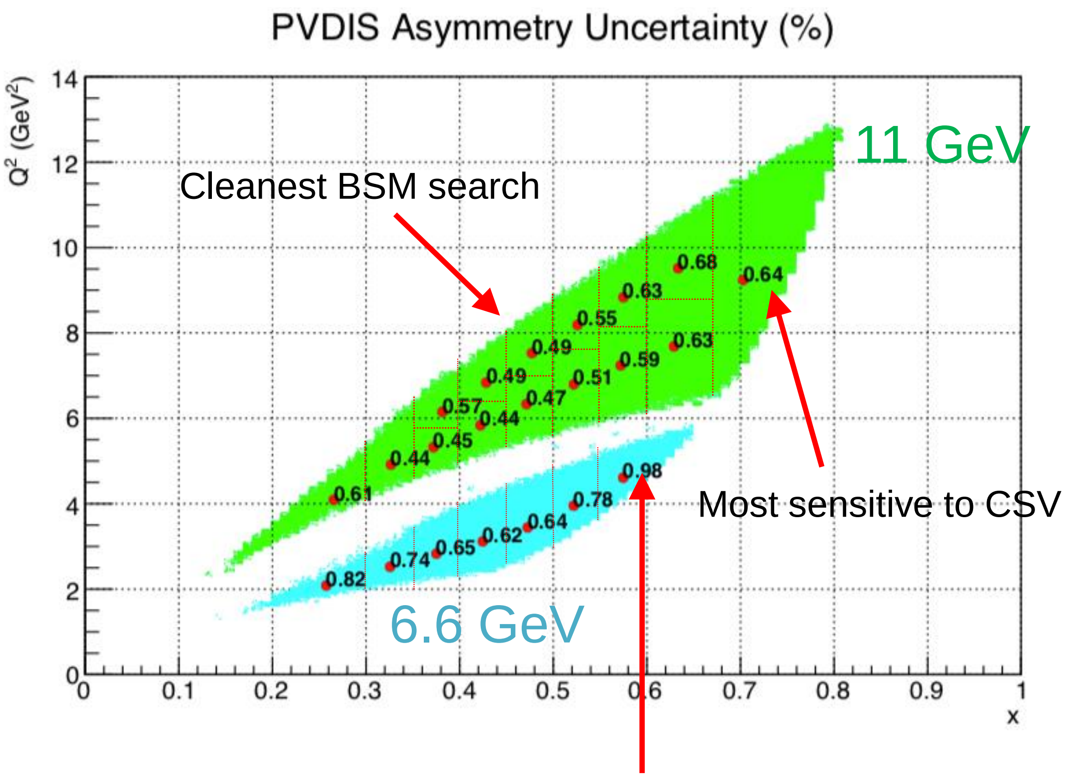
- **Parton distributions (u, d, s, c)**
- **Charge Symmetry Violation (CSV)**
- **Higher Twist (HT) – quark-quark correlation**

PVDIS @ SoLID: Experiment E12-10-007

12 GeV CEBAF: Extraordinary opportunity to do the ultimate PVDIS measurement

Strategy: sub-1% precision over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

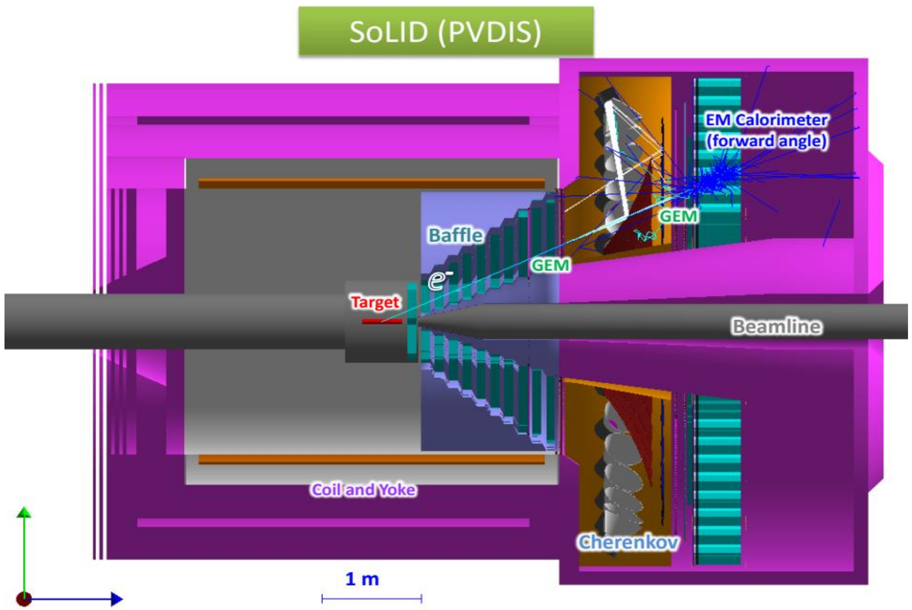




Spokesperson: Paul Souder

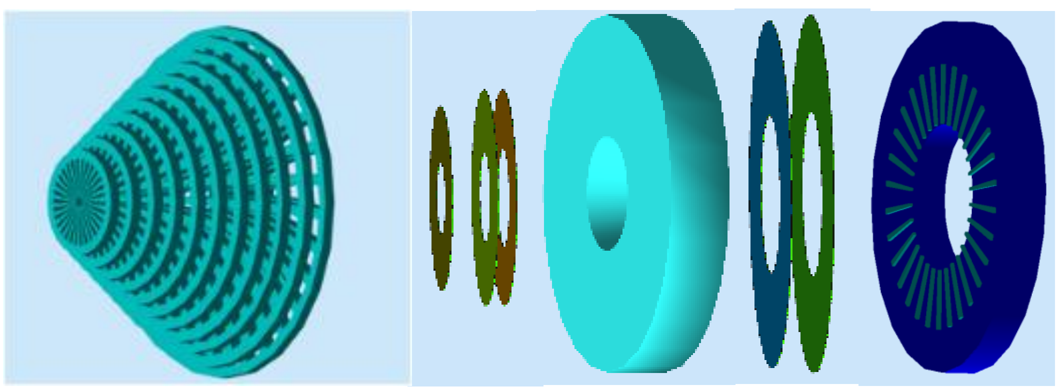
SoLID Apparatus

- ***Kinematic Requirements***
  (x: 0.25-0.7: untangle physics
  $W^2 > 4\ GeV^2$, isolate DIS
  Q^2 range a factor of 2 for each x bin:
  Measure Higher Twist
- ***Achieving High Luminosity***
  (target, beam current, GEMs, Baffles)
- ***Requirements for Particle Identification and Trigger***
  (light gas Cherenkov,
  identify electrons for trigger;
  EMcal (coincident trigger, further pid,..)

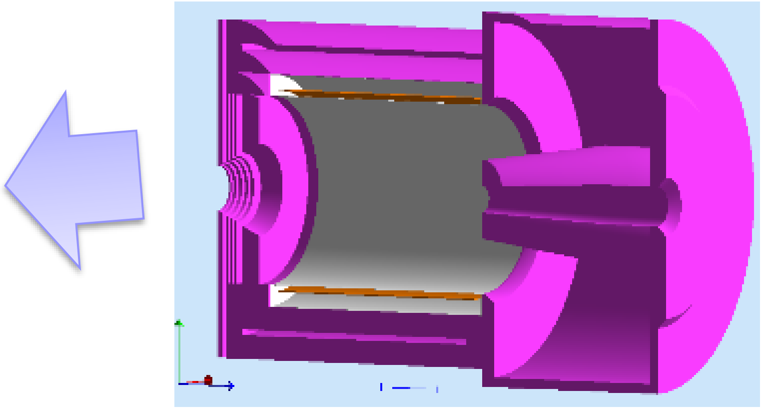


CLEO magnet with the LD_2 or LH_2 target in the center provides the desired acceptance.

Baffle 5xGEMs EC



LGC

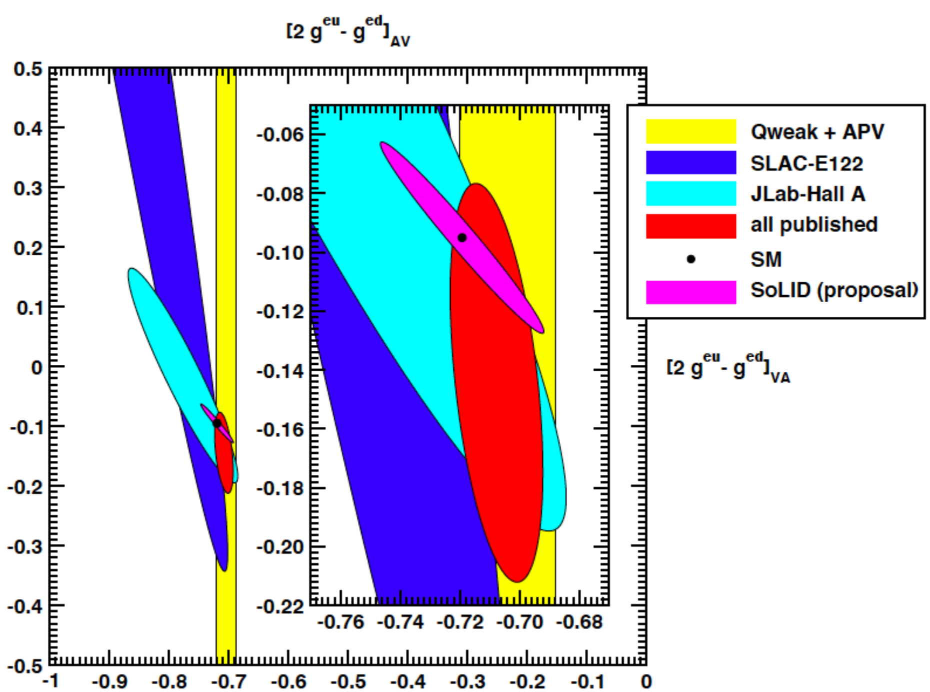


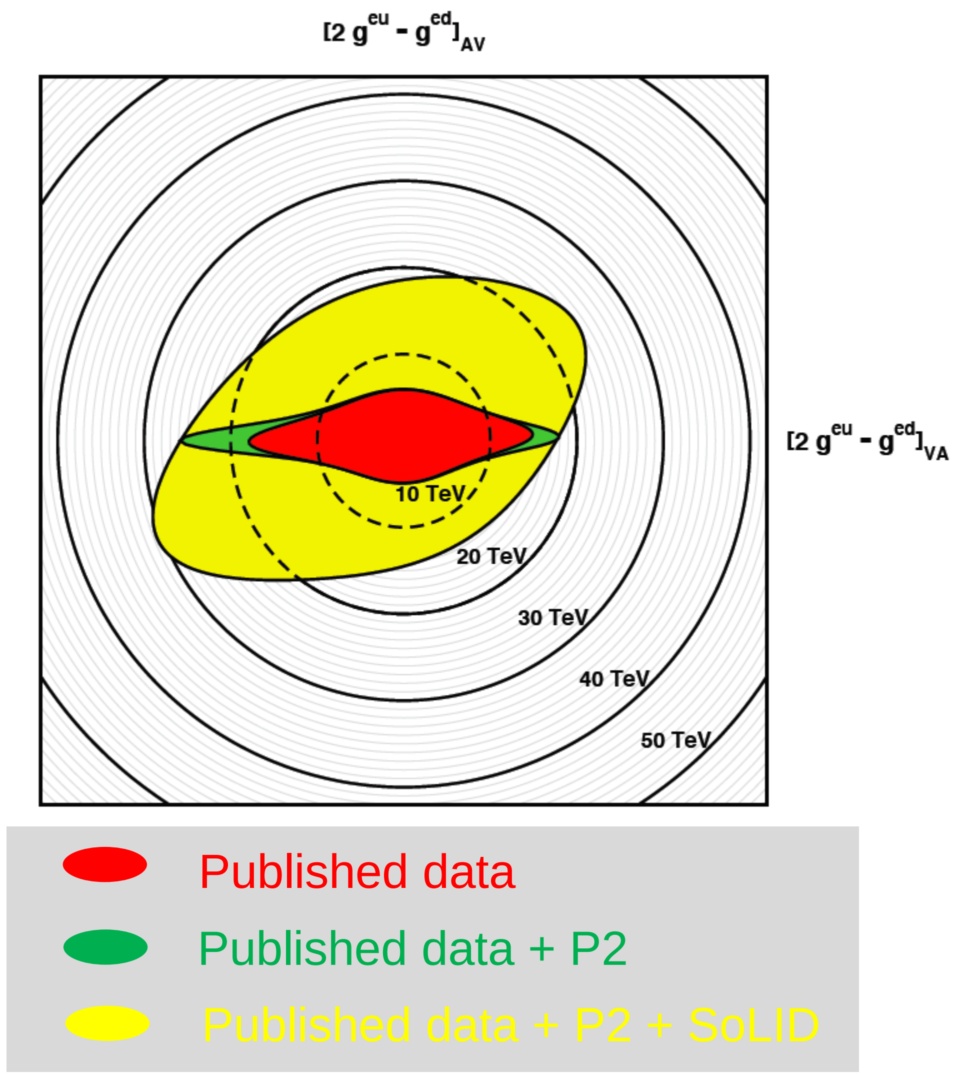
Projected Results

With this precision,
SoLID makes a unique contribution
to the SMEFT program.

Improvement in
energy reach for
electron-nucleon couplings

Improvement in
couplings





Structure Function Ratio d/u for the Proton

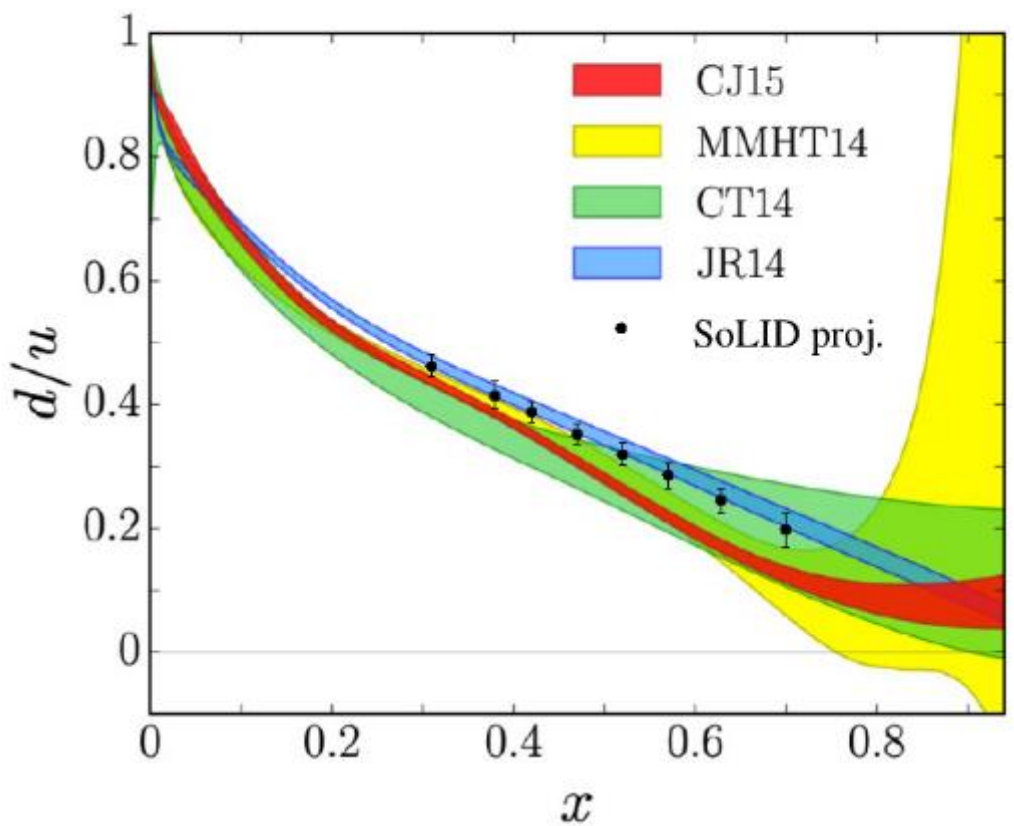
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi a}\left[a(x) + f(y)b(x)\right]$$

$$A^{p}_{PVDIS}(x) \approx \frac{u(x) + 0.91\, d(x)}{u(x) + 0.25\, d(x)}$$

Phys. Rev. D 87 (2013) 094012

PVDIS is complementary to the rest of the JLab d/u program.

PVDIS has no nuclear effects



Proton Mass and Quantum Anomalous Energy

- **Nucleon mass is the total QCD energy in the rest frame (QED contribution small)**

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

$$H_q = \quad \text{Quark energy} \quad \int d^3x \; \psi^\dagger \left(-i\mathbf{D}\cdot\alpha\right)\psi$$

$$H_m = \quad \text{Quark mass} \quad \int d^3x \; \bar{\psi} m \psi$$

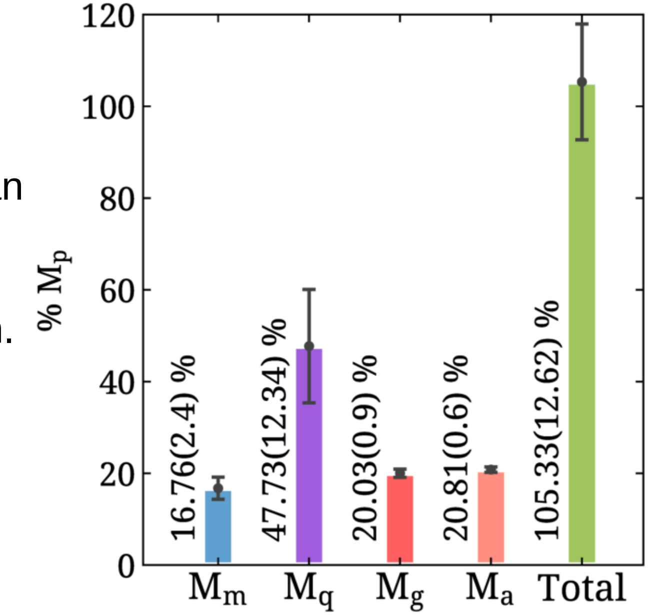
$$H_g = \quad \text{Gluon energy} \quad \int d^3x \; \frac{1}{2}\left(\mathbf{E}^2 + \mathbf{B}^2\right)$$

$$H_a = \quad \text{Quantum Anomalous energy} \quad \int d^3x \; \frac{9\alpha_s}{16\pi}\left(\mathbf{E}^2 - \mathbf{B}^2\right)$$

Sets the scale for the hadron mass!

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

First three contributions can be determined from PDFs and pi-N sigma term. And also from lattice QCD→

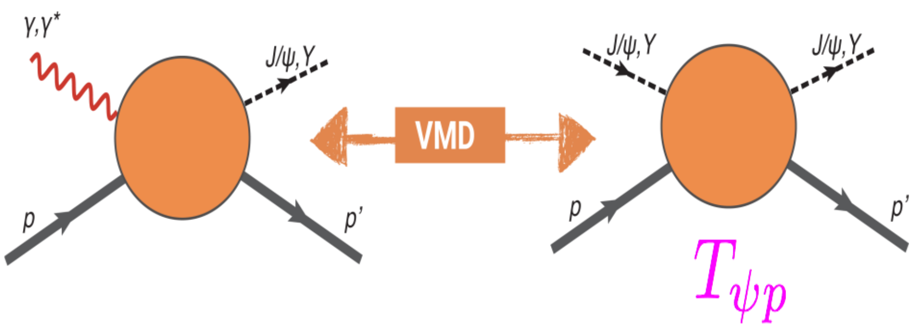


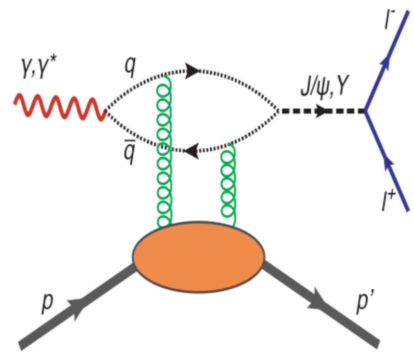
C. Alexandrou et al., (ETMC), PRL 119, 142002 (2017)
Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

- **Measuring quantum anomalous energy contribution in experiments is an important goal in the future**

  Can be accessed through heavy quarkonium threshold (J/psi & Upsilon) production,
  D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130, 105 (1996)
  R. Wang et al, Eur.Phys.J.C 80 (2020) 6, 507

From Cross section to the Trace Anomaly





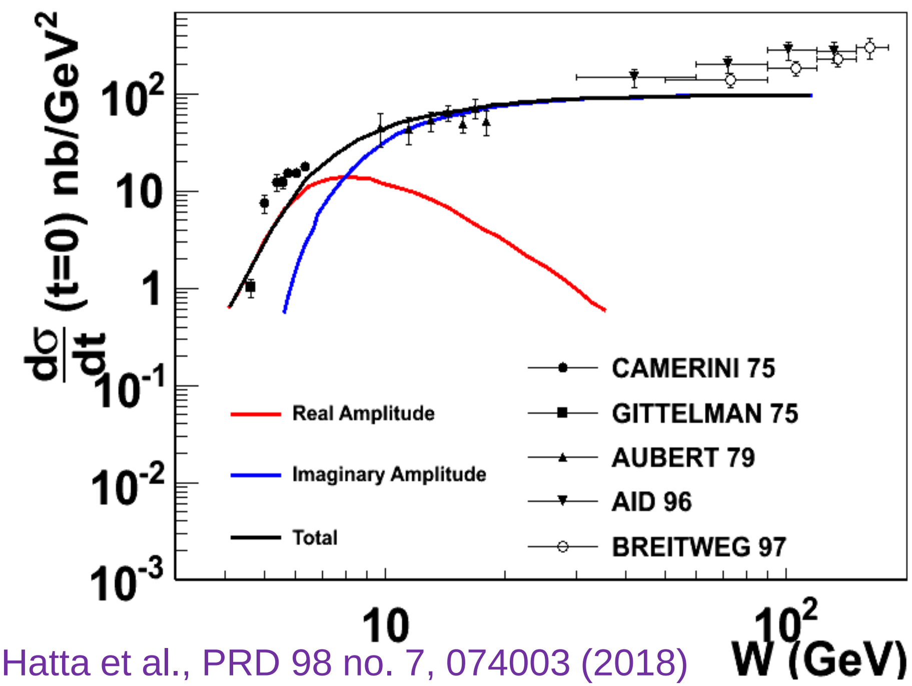
$$\boxed{\gamma^* + N \to N + J/\psi}$$

Heavy quark – dominated by two gluons

$$\langle P|T^\alpha_\alpha|P\rangle = 2P^\alpha P_\alpha = 2M_p^2$$

$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0)=\frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)=\frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$



VMD relates photoproduction cross section to quarknium-nucleon scattering amplitude

- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly;** Dominates the near threshold region and is constrained through dispersion relation

D. Kharzeev (1995); Kharzeev, Satz, Syamtomov, and Zinovjev EPJC,9, 459, (1999); Gryniuk and Vanderhaeghen, PRD94, 074001 (2016)

Y. Hatta et al., PRD 98 no. 7, 074003 (2018)
Y. Hatta et al., 1906.00894 (2019)

K. Mamo & I. Zahed Phys. Rev. D 101, 086003 (2020)
R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C **80**, no.6, 507 (2020)

A measurement near threshold could allow access to the trace anomaly

J/ψ @ SoLID: Experiment E12-12-006

$1 \times 10^{37} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

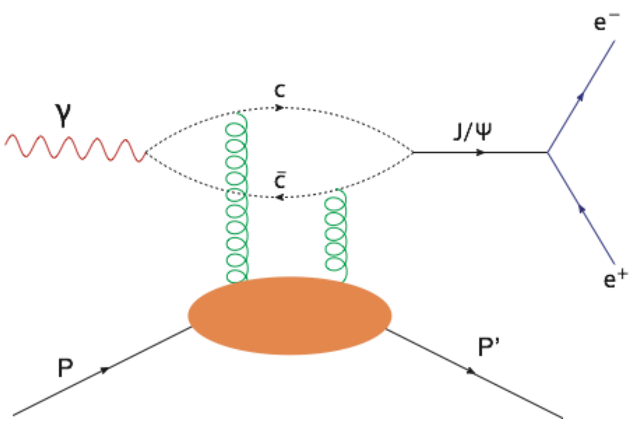
50 days of 3 μA beam on a 15 cm long LH_2 target at
10 more days including calibration/background run
SoLID configuration overall compatible with SIDIS

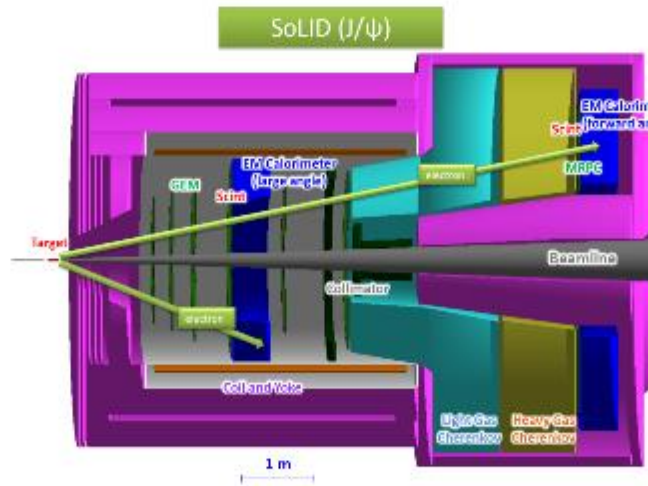
Electroproduction trigger: 3-fold coincidence of e, e^-e^+

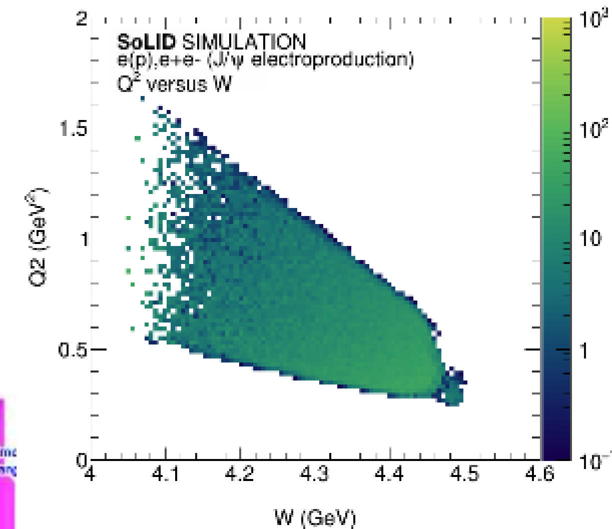
Photoproduction trigger: 3-fold coincidence of p, e^-e^+

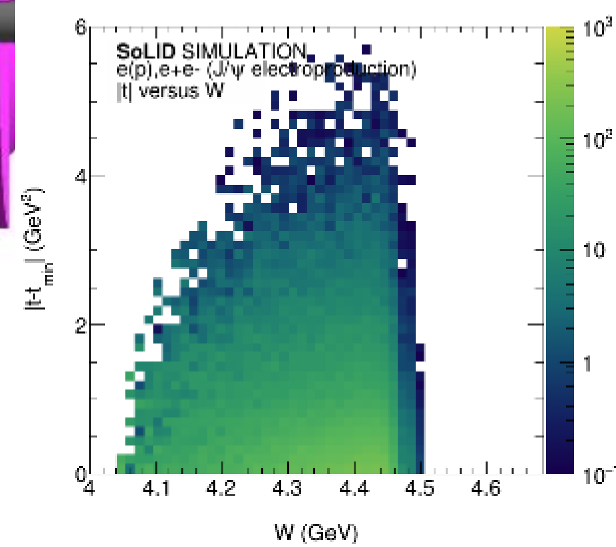
Additional trigger: 4-fold coincidence of ep, e^-e^+

And (inclusive) 2-fold coincidence e^+e^-







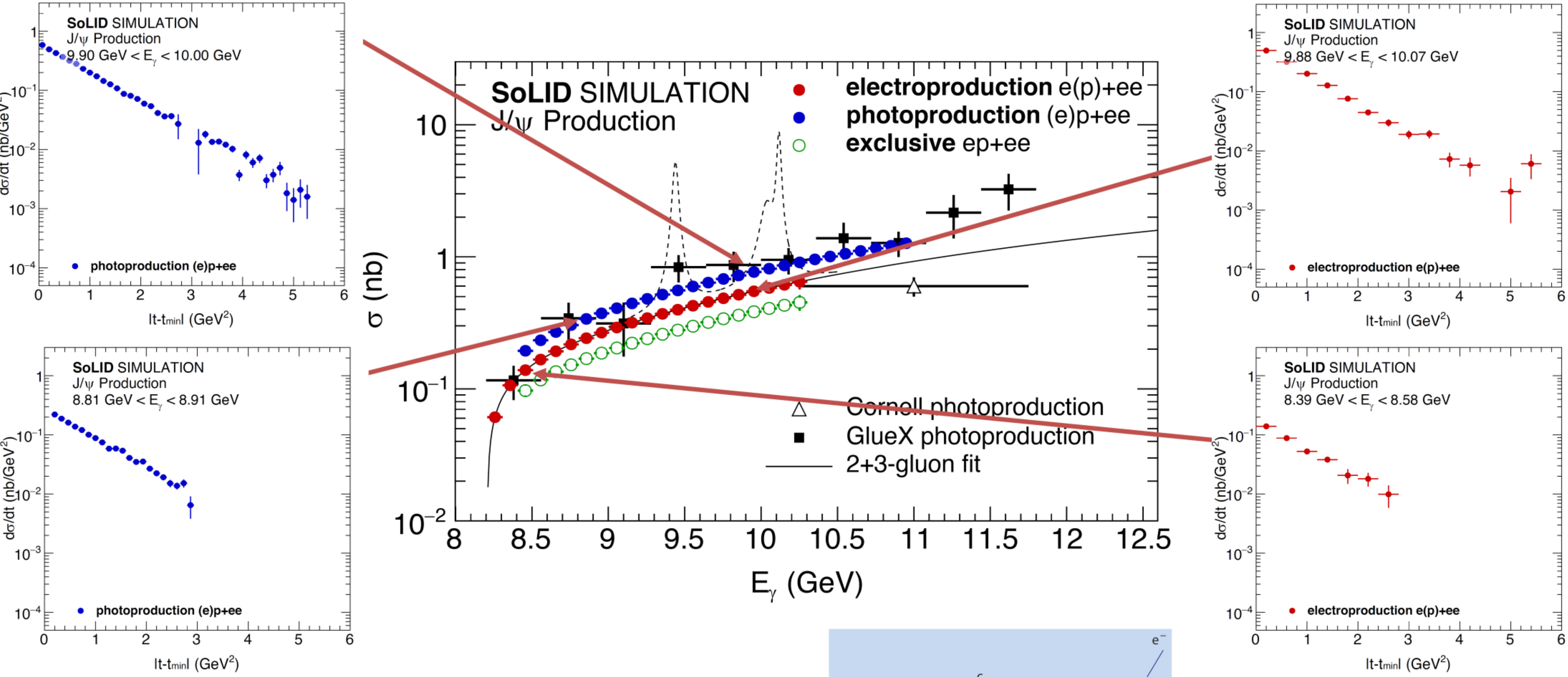


$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

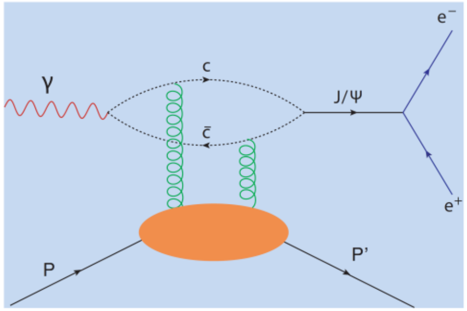
$$\gamma\ p \rightarrow p'\ J/\psi(e^-\ e^+)$$

Spokespersons: K. Hafidi, X. Qian, N. Sparveris, Z.-E. Meziani (contact), Z. Zhao

J/Ψ Experiment E12-12-006 @ SoLID

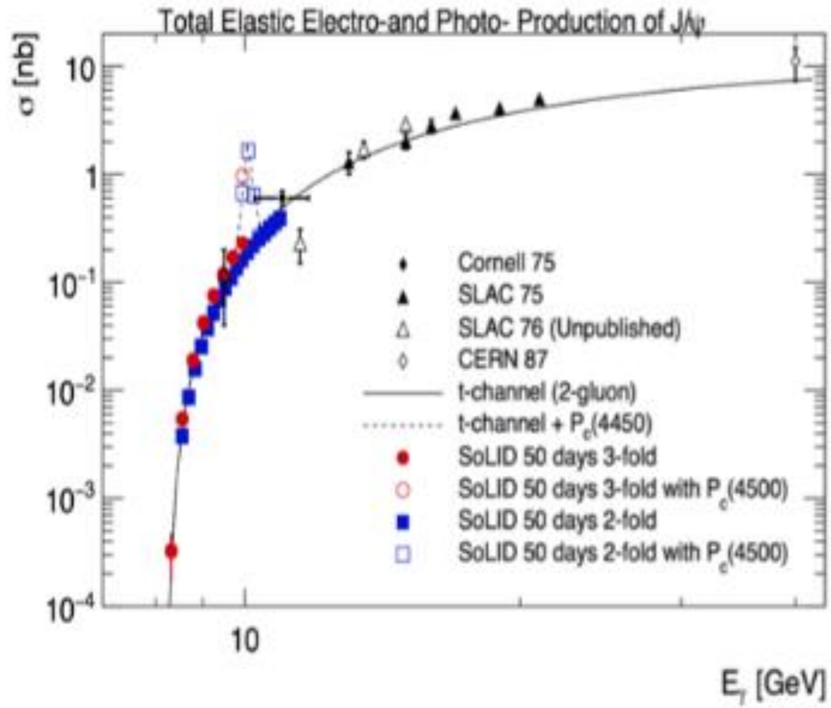


Sensitivity at threshold at about 10^{-3} nb!



Impact on the Quantum Anomalous Energy Extraction and the EIC

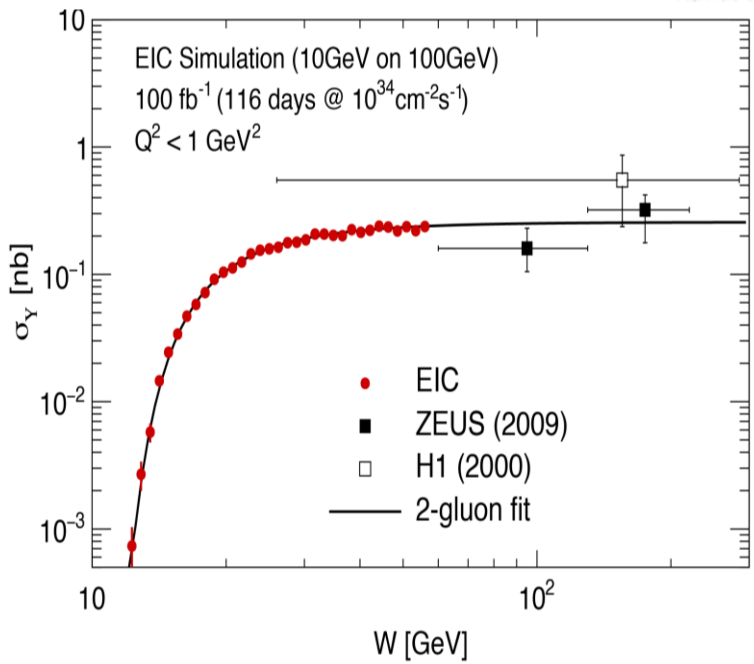
Charm @ SoLID



S. Joosten, Z.E. Meziani, PoS 308 (2017) doi.org/10.22323/1.308.0017

Gryniuk, Joosten, Meziani, and Vanderhaeghen, PRD 102, 014016 (2020) (for update)

Beauty @ EIC



GlueX on J/ψ Ali et al., PRL 123, 072001(2019)

SoLID Program on GPDs

- **Following the 2015 Director's Review recommendation *"The SoLID Collaboration should investigate the feasibility of carrying out a competitive GPD program. Such a program would seem particularly well suited to their open geometry and high luminosity"*, there are several GPD experiments in different stages of study/approval:**
  - **Deep Exclusive π^- Production using Transversely Polarized ^{3}He Target**
    - *G.M. Huber, Z. Ahmed, Z. Ye*
    - *Approved as run group with Transverse Pol. ^{3}He SIDIS (E12-10-006B)*
  - **Timelike Compton Scattering (TCS)** with circularly polarized beam and unpolarized LH_2 target
    - *Z.W. Zhao, P. Nadel-Turonski, J. Zhang, M. Boer*
    - *Approved as run group with J/ψ (E12-12-006A)*
  - **Double Deeply Virtual Compton Scattering (DDVCS)** in di–lepton channel on unpolarized LH_2 target
    - *E. Voutier, M. Boer, A. Camsonne, K. Gnanvo, N. Sparveri, Z. Zhao*
    - *LOI12-12-005 reviewed by PAC43*
  - **DVCS on polarized proton and 3He targets**
    - *Z.Y. Ye, N. Liyanage, W. Xiong, A. Cansomme and Z.H. Ye (under study)*

Other approved SoLID run group experiments

- SIDIS Dihadron with Transversely Polarized ^{3}He

  J.-P. Chen, A. Courtoy, H. Gao, A. W. Thomas, Z. Xiao, J. Zhang
  Approved as run group (E12-10-006A)

- SIDIS in Kaon Production with Transversely Polarized Proton and ^{3}He

  T. Liu, S. Park, Z. Ye, Y. Wang, Z.W. Zhao
  Approved as run group (E12-11-108B/E12-10-006D)

- Ay with Transversely Polarized Proton and ^{3}He

  T. Averett, A. Camsonne, N. Liyanage
  Approved as run group (E12-11-108A/E12-10-006A)

- g2n and d2n with Transversely and Longitudinally Polarized ^{3}He

  C. Peng, Y. Tian
  Approved as run group (E12-11-007A/E12-10-006E)

Summary

- SoLID: A **large acceptance** device which can handle **very high luminosity** to allow full exploitation of JLab12 potential
  → pushing the limit of the luminosity frontier
- SoLID has rich and vibrant science programs complementary and synergistic to the proposed EIC science program
  - Three pillars on SIDIS, PVDIS and J/ψ production
  - A diverse set of approved run-group experiments including GPD program
- After a decade of hard work, we have a mature pre-conceptual design with expected performance to meet the challenging requirements for the three major science programs
- Recently completed the DOE science review (March 8-10, 2021)
- SoLID collaboration is active and international with many theory collaborators
- We welcome new collaborators!

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