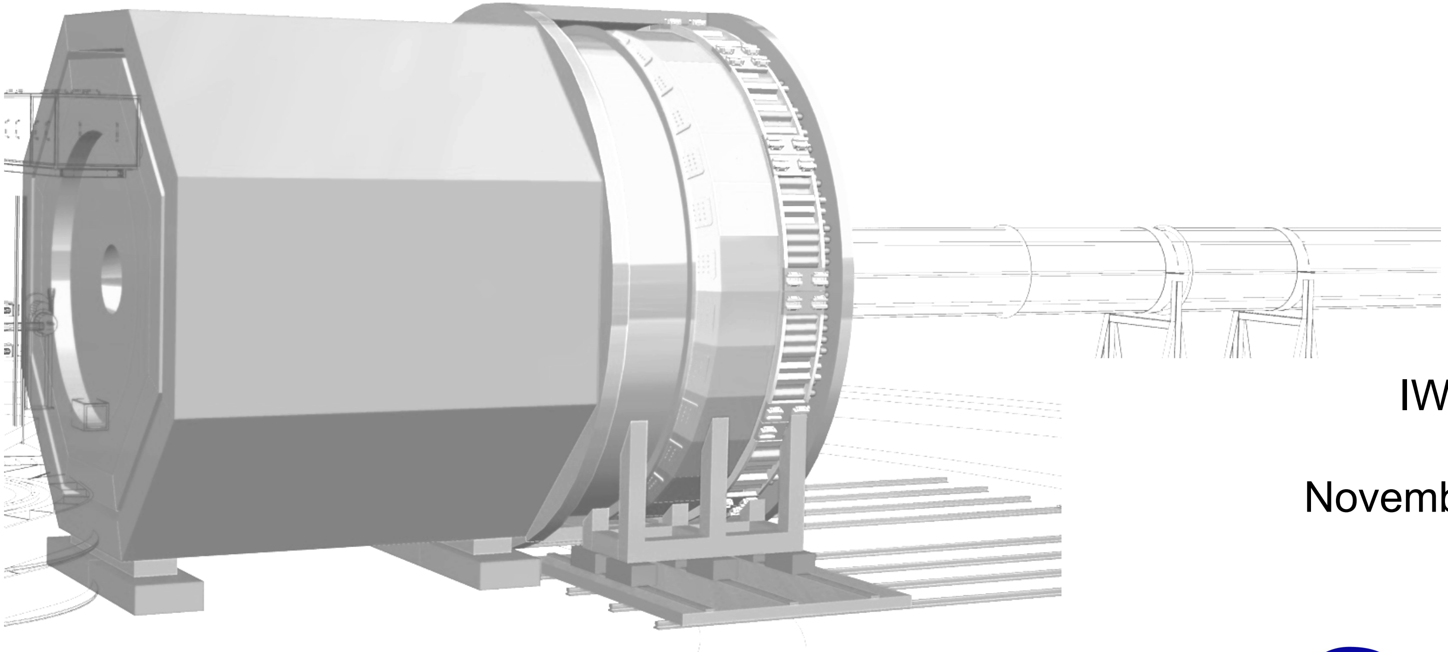
The physics programs with the SoLID device proposed for JLab 12-GeV



IWHSS 2020

November 16-18, 2020

Haiyan Gao

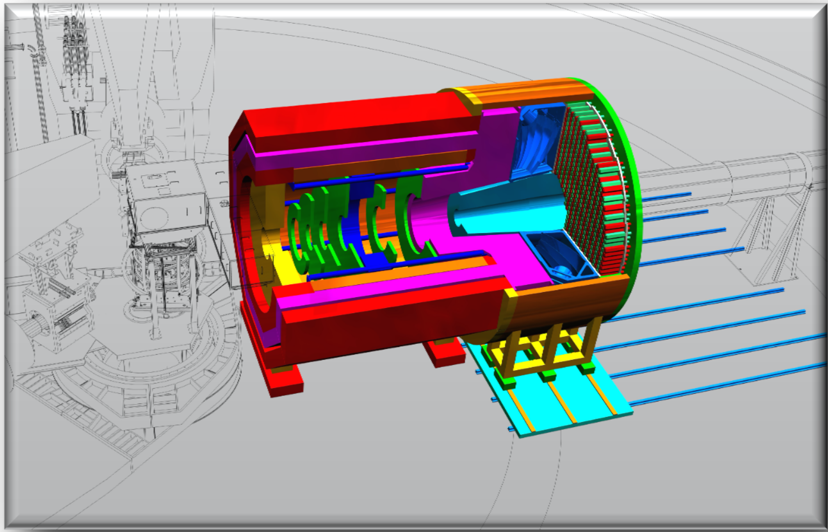
The SoLID Collaboration
Duke University

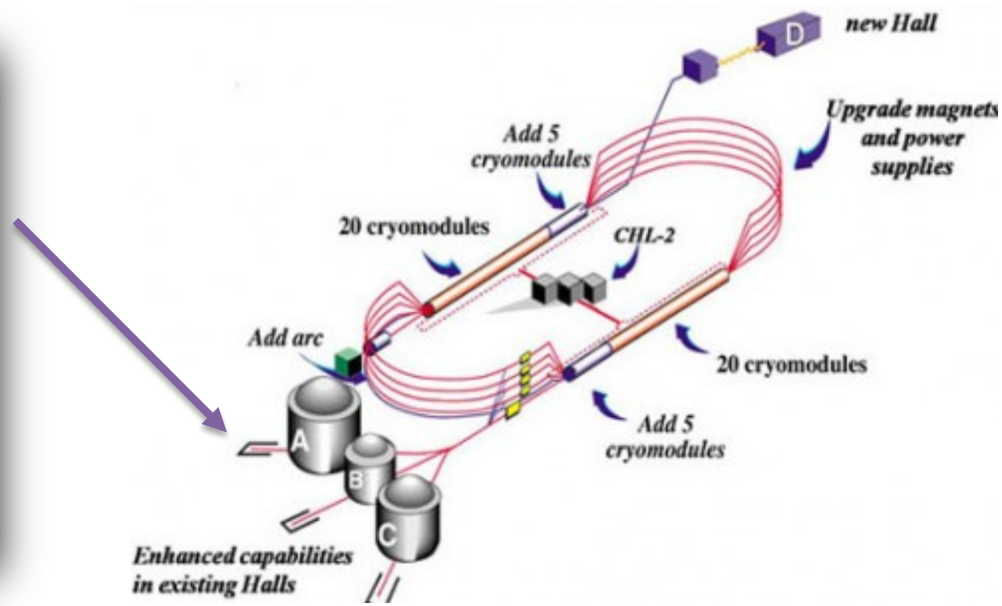
Outline

1. Overview
2. Three pillars of the SoLID science
   A. Nucleon 3-D momentum tomography with **SIDIS**
   B. New Physics and QCD with **PVDIS**
   C. QCD trace anomaly and proton mass with **J/ψ**
3. SoLID run-group proposals
4. The SoLID device
5. Summary

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

SoLID provides *unique* capability combining high luminosity (10^{37-39} /cm^2/s) (>100 of CLAS12; >1000 times of EIC) and **large acceptance** with full ϕ coverage to maximize the science return of the 12-GeV CEBAF upgrade





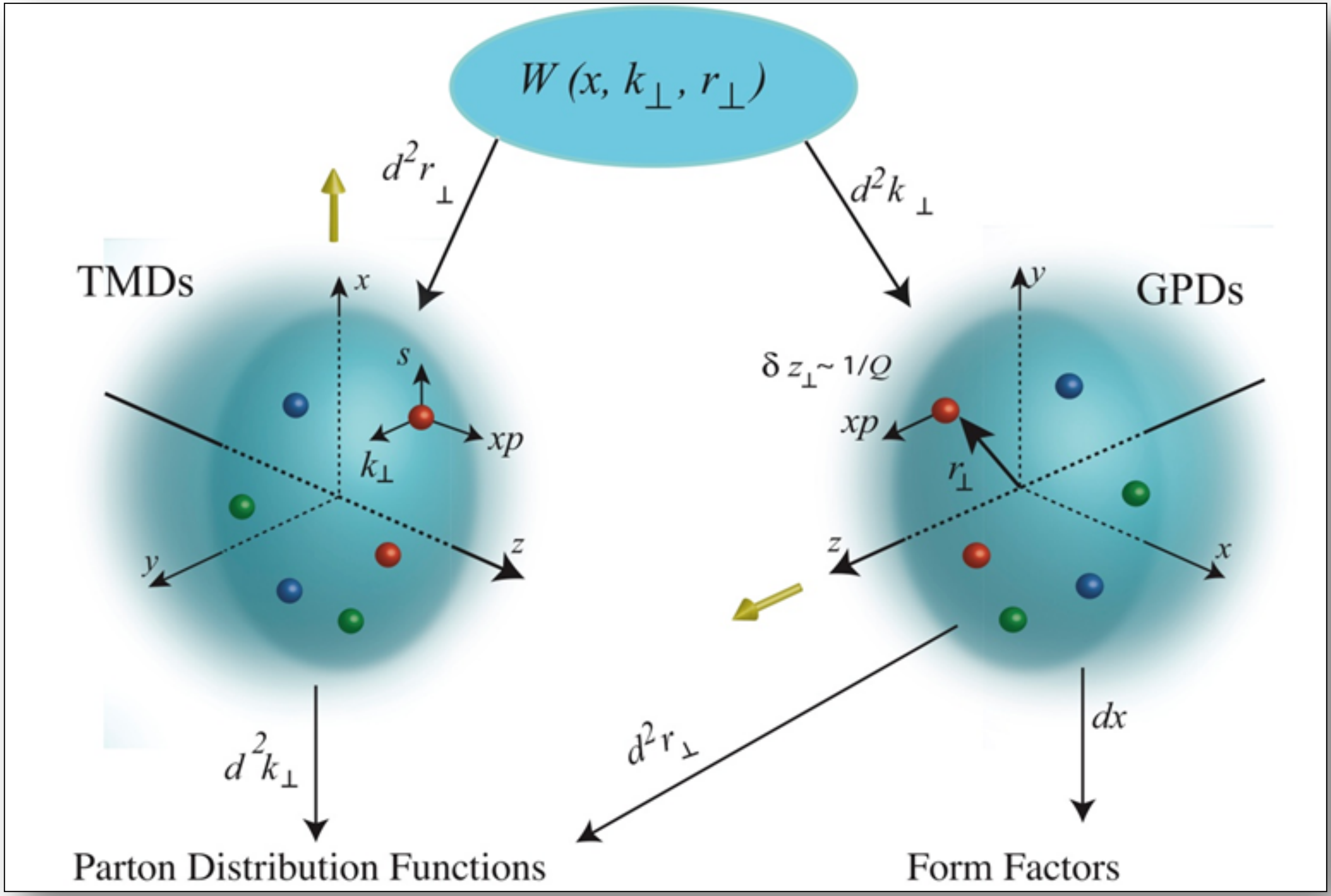
SoLID with unique capability for rich physics programs

- ✓ 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)

SoLID physics is complementary and synergistic with the EIC science (proton spin and mass, two important EIC science questions) – high-luminosity SoLID unique for valence quark tomography (separation of structure from collision) and precision J/ψ production near the threshold

Nucleon Structure from 1D to 3D – orbital motion

5-D Wigner distribution



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

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

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

TMDs – confined motion inside the nucleon

Leading twist: 8 TMDs

→ Nucleon Spin
→ Quark Spin

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

Nucleon spin - quark transverse motion correlation – zero if no orbital angular momentum (OAM)

h_{1T} (h_1) = g_1 (no relativity)
h_{1T} → tensor charge (lattice QCD calculations, connected to nucleon EDM)

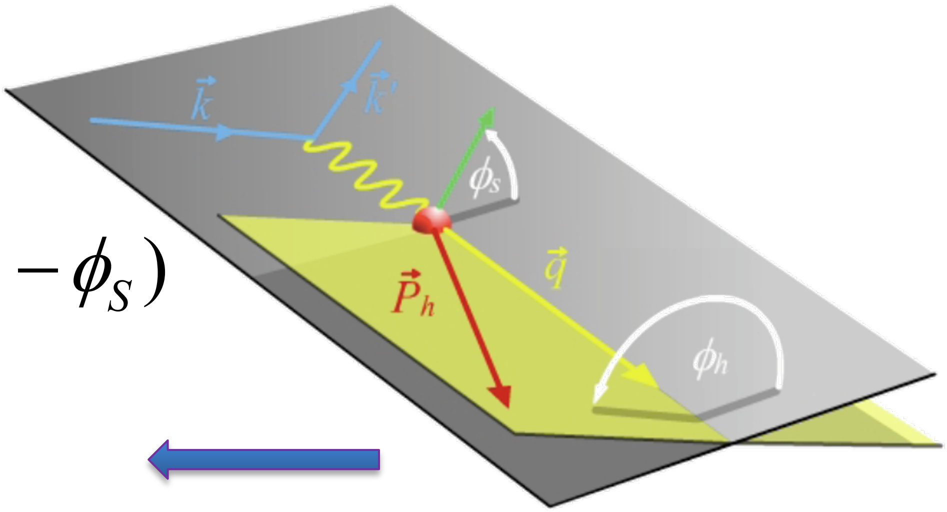
Interference between components with OAM difference of 2 units (i.e., s-d, p-p)
Signature for relativistic effect

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

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

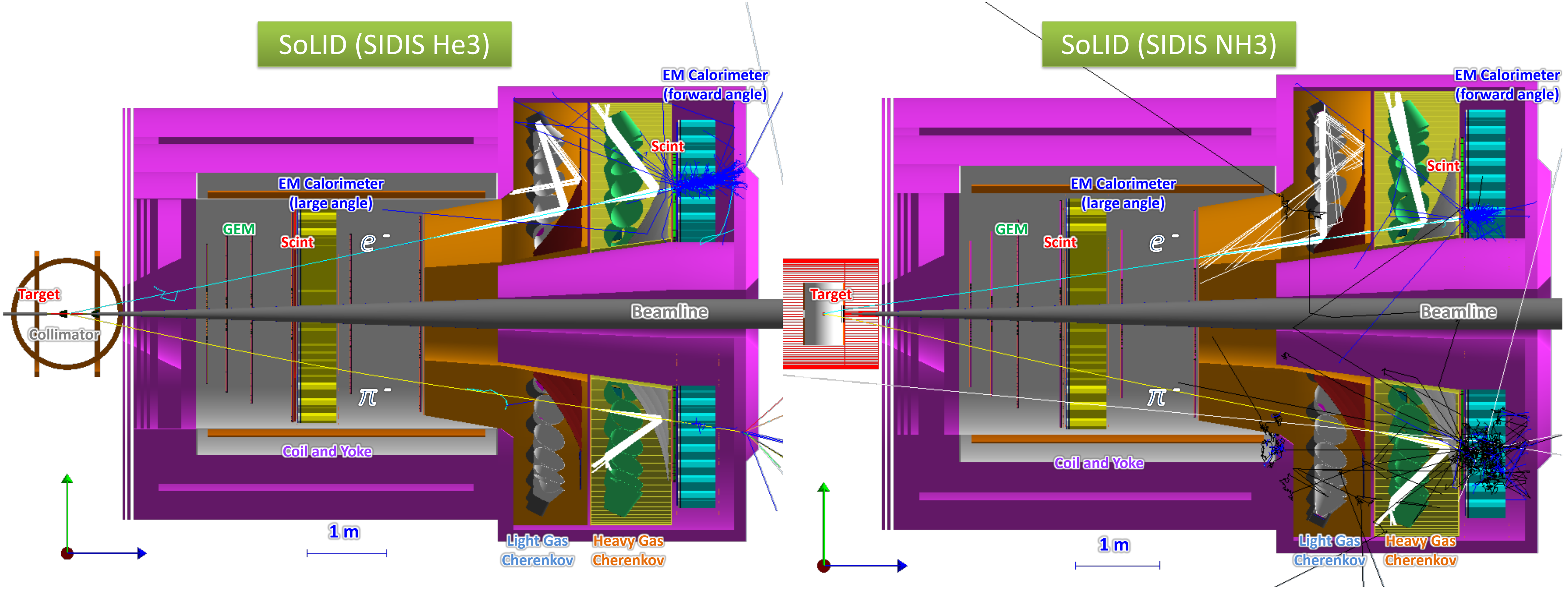
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins frag. Func. from e^+e^- collisions

Unpol. frag. Func.

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

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

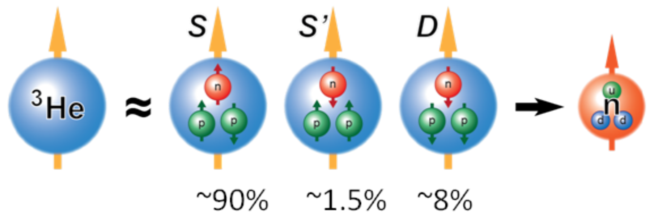
E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He @ 35 days, **rating A**
Spokespersons: J.P. Chen (contact), J. Huang, W.B. Yan

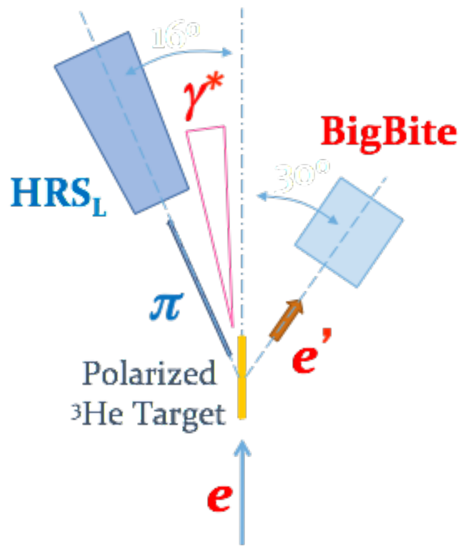
E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @120 days, **rating A**
Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani

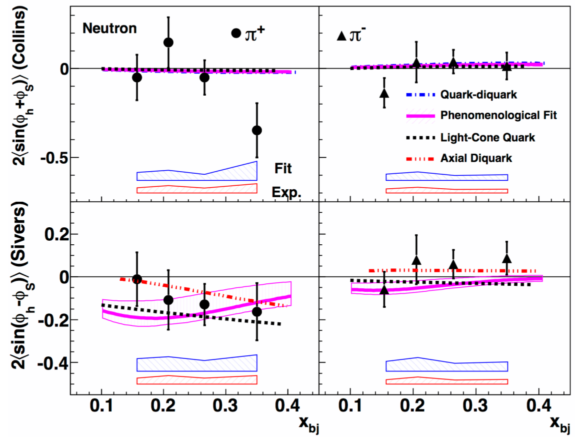
Run group experiments approved for TMDs and GPDs

Key of SoLID-spin program:
Large acceptance, full azimuthal coverage
+ High luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD dynamics, models.

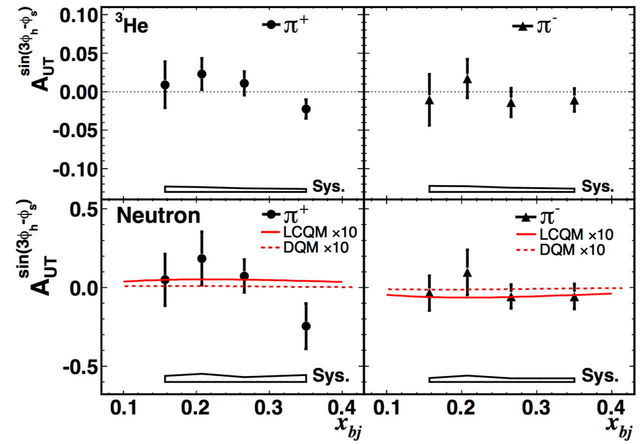
QCD intensity frontier with SoLID: large-acceptance & high luminosity



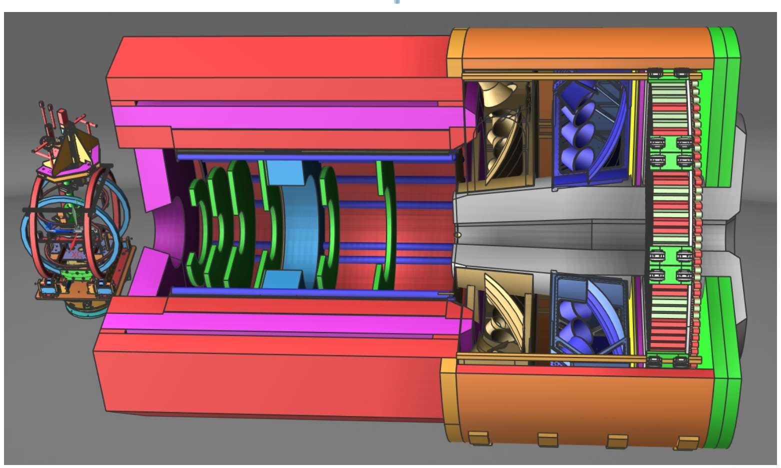


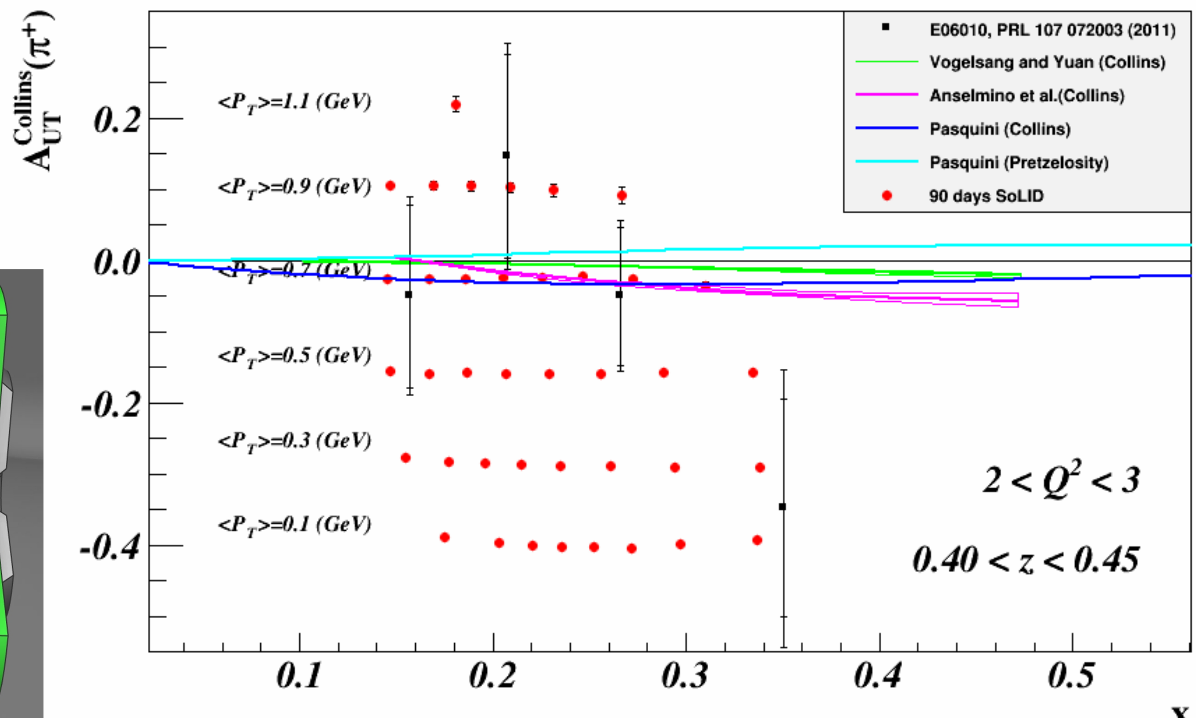


X. Qian *et al.*, PRL 107, 072003 (2011)



Y. Zhang *et al.*, PR C90, 055209 (2014)





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

HERMES, COMPASS pioneered on SIDIS measurements

SoLID SIDIS Projection

Compare SoLID with World Data

Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation

World data from HERMES, COMPASS and JLab-6 GeV

e^+e^- data from BELLE and BABAR

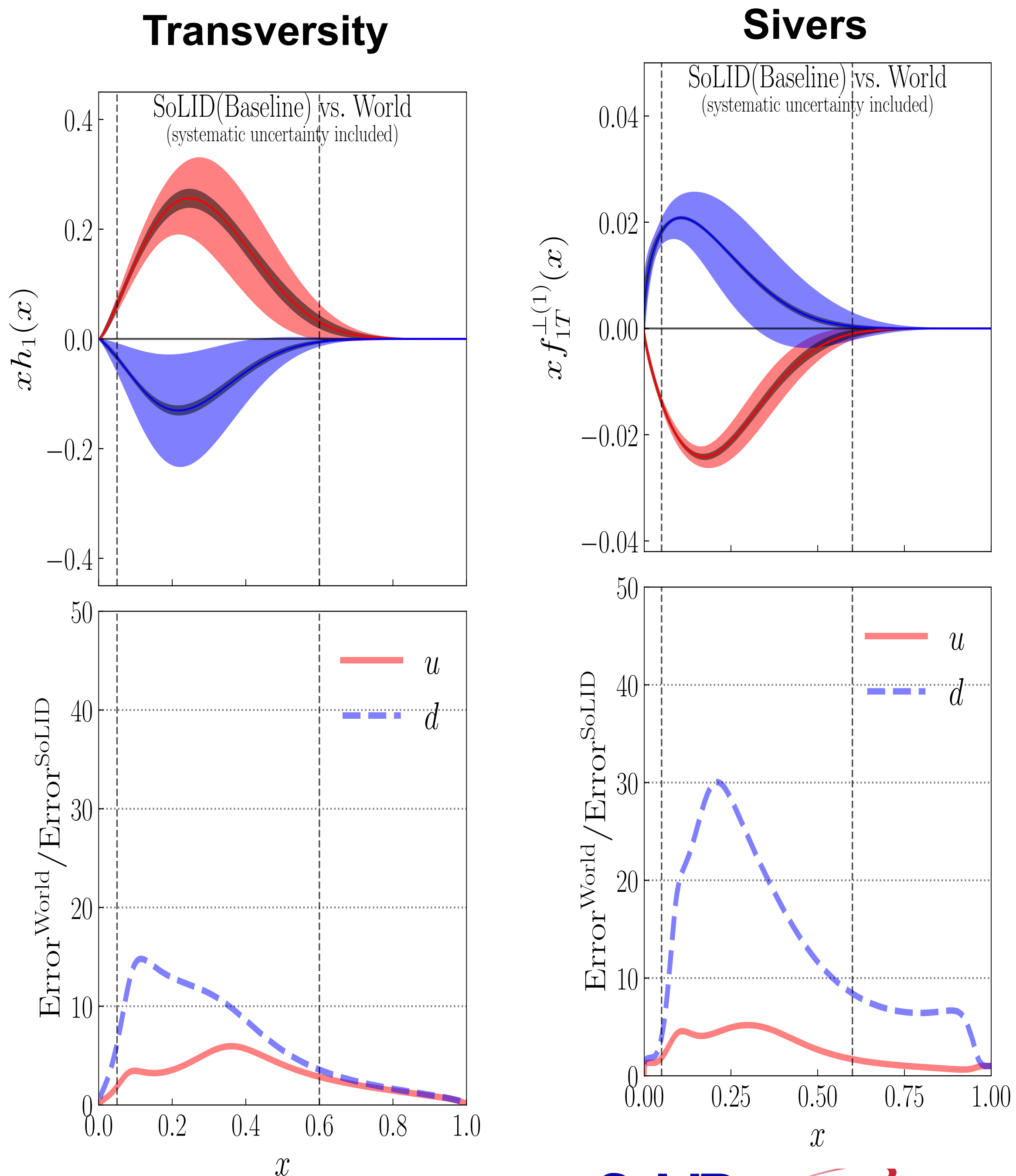
Monte Carlo method with nested sampling algorithm is applied

Including both systematic and statistical uncertainties

SoLID baseline used

Enhanced baseline has ~1.5 higher precision than baseline

Z. Ye *et al*, Phys. Lett. B 767, 91 (2017)



SoLID impact on tensor charge and confined motion

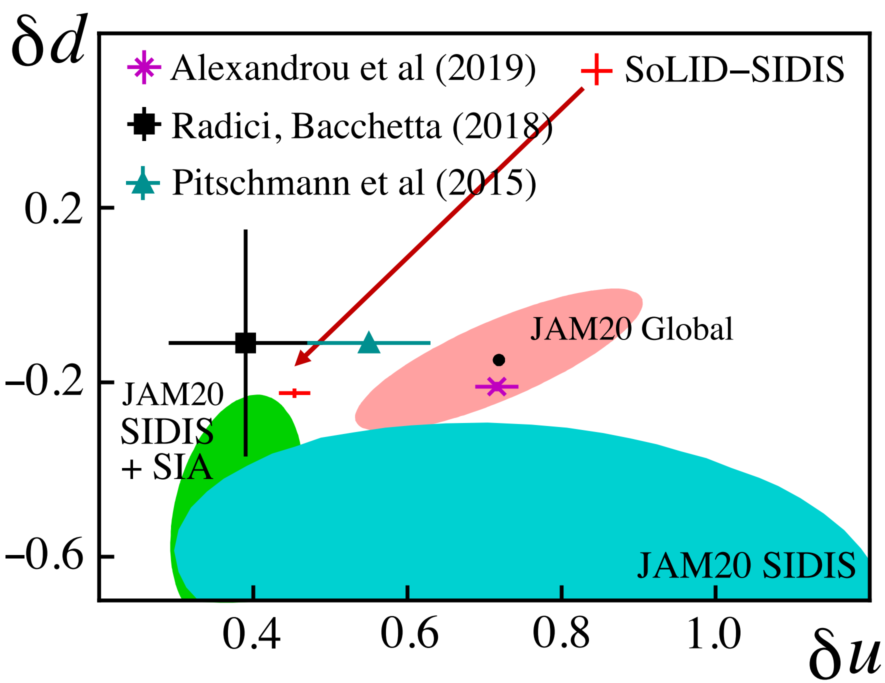
- Tensor charge: a fundamental QCD quantity to test lattice QCD
- Probe new physics combined with EDMs

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

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

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

SoLID impact on tensor charge



JAM20: arxiv:2002.08384

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

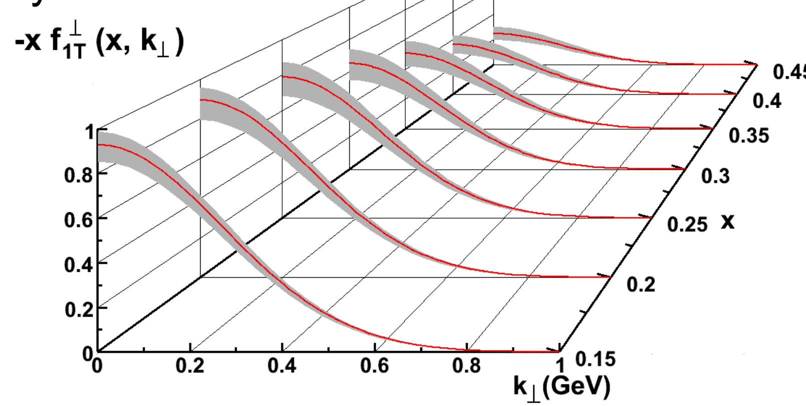


Image from J. Dudek et al., EPJA 48,187 (2012)

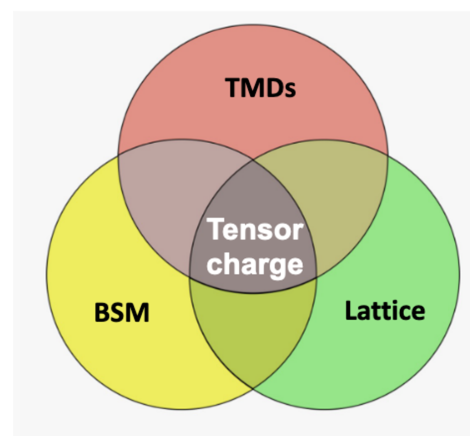
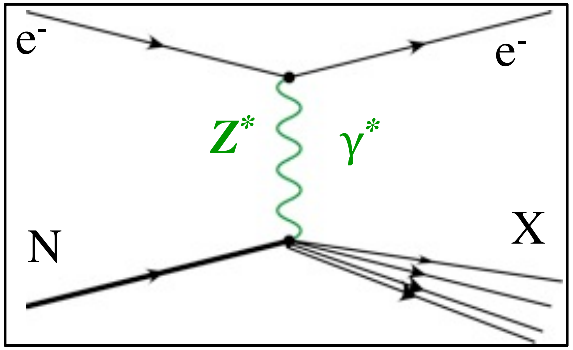


Image credit: D. Pitonyak

PV Deep Inelastic Scattering

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



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

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

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

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

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

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

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

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

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

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

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

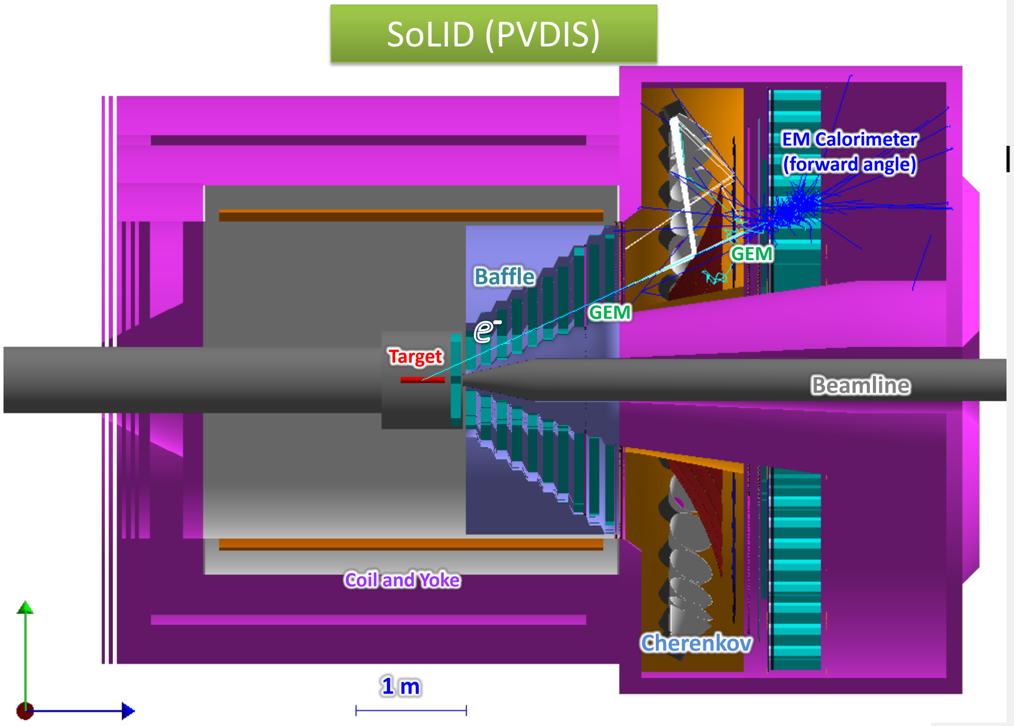
Interplay with QCD

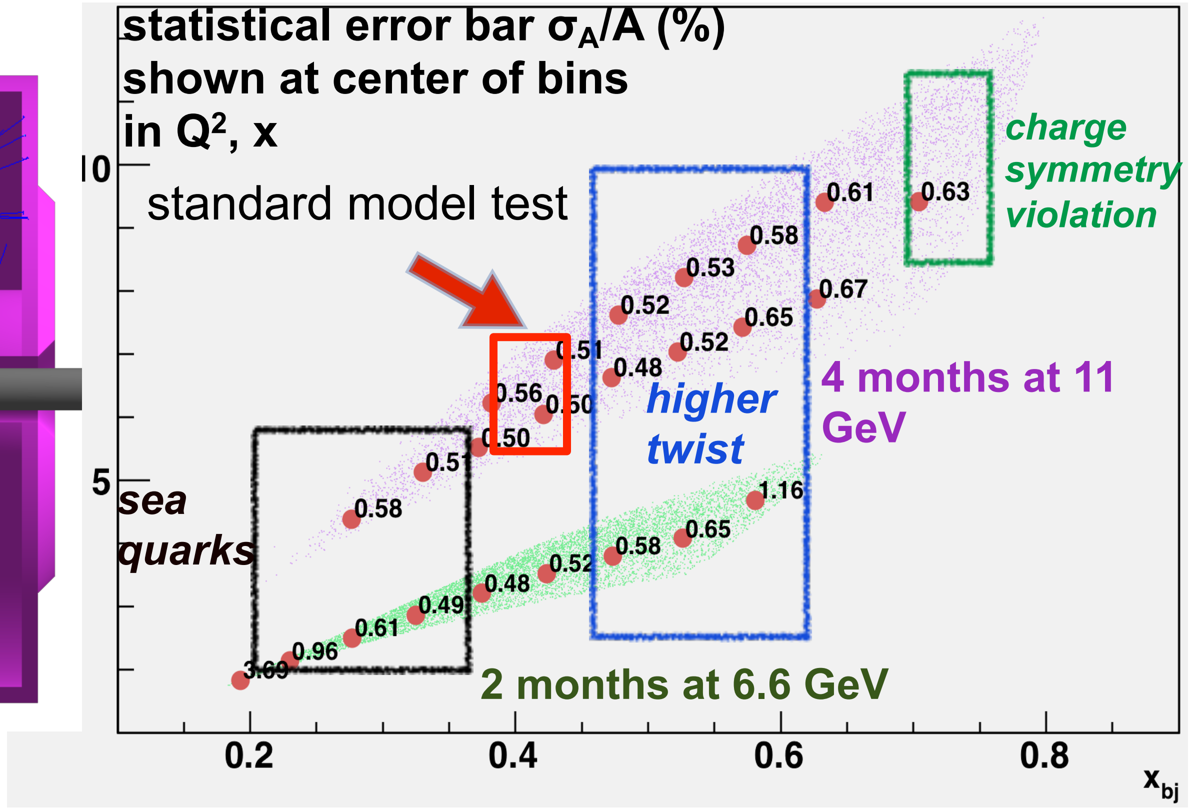
- Parton distributions (u, d, s, c)
- Charge Symmetry Violation (CSV)
- Higher Twist (HT) – quark-quark correlation

PVDIS @ SoLID: Experiment E12-10-007

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

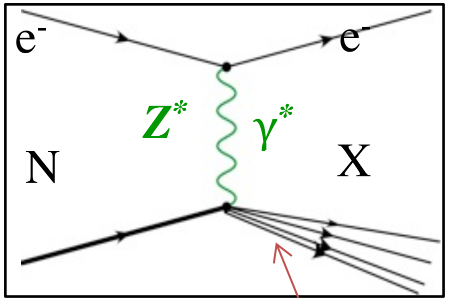
Strategy: **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**





Spokesperson: Paul Souder

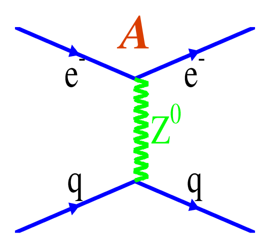
Projection of SoLID PVDIS and Impact



Pure electron-quark scattering.

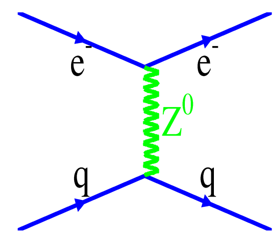
PVDIS
- Measure A_{DIS} (g^{eq}_{AV}, g^{eq}_{VA})
- Negligible hadronic corrections

$g^{eq}_{AV}(\sin^2\theta_W)$



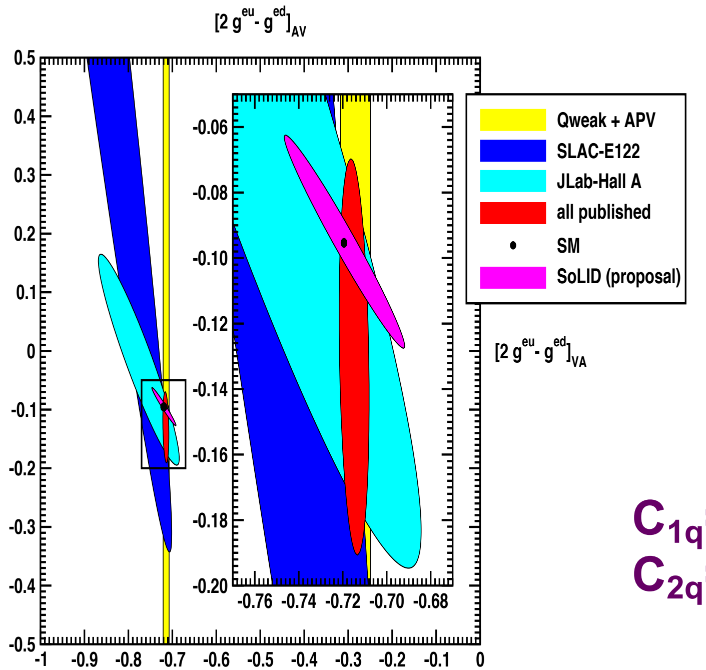
Atomic Parity Violation (APV), Qweak, SoLID

$g^{eq}_{AV}(\sin^2\theta_W)$



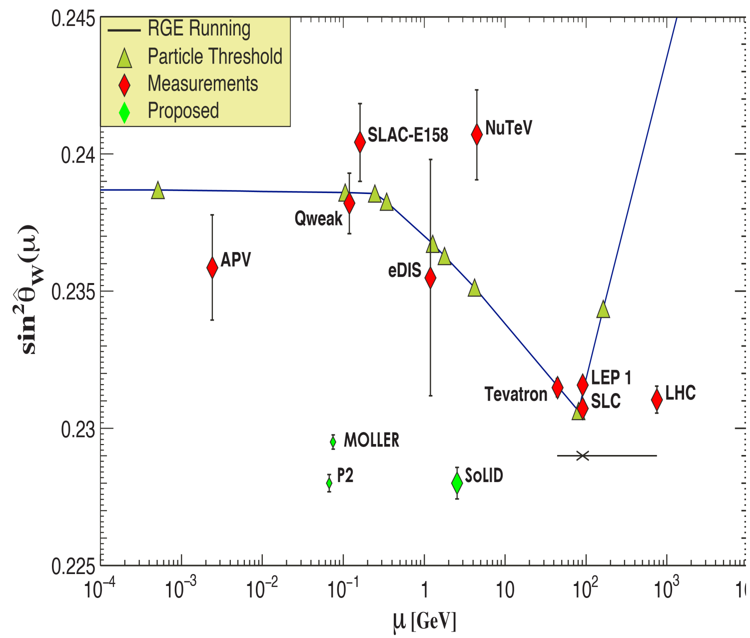
Only SoLID can measure g^{eq}_{VA}

Goals for SoLID
- Measure $2g^{eu}_{VA} - g^{ed}_{VA}$ precisely
- Measure $\sin^2\theta_W$ precisely at $Q^2 \approx 5(\mathrm{GeV/c})^2$



$C_{1q}=g^{eq}_{AV}$
$C_{2q}=g^{eq}_{VA}$

Assume Standard Model is exact.

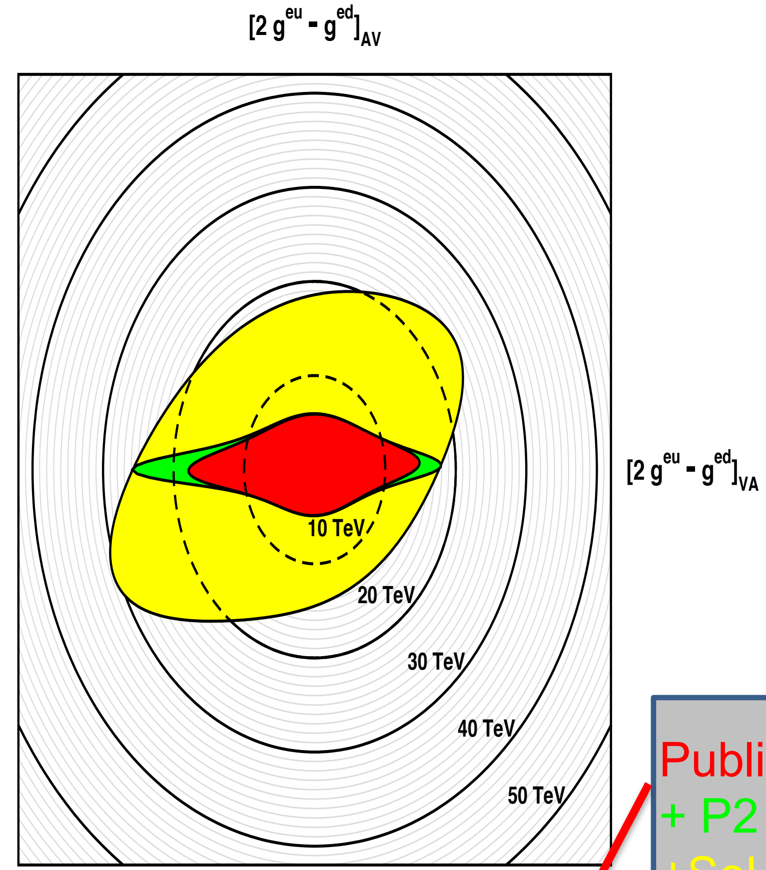


Extensions to the Standard Model

Possible scenarios:

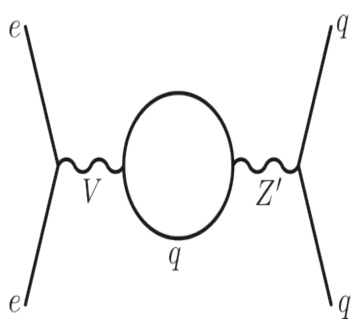
- All data fall on Standard Model $\sin^2\theta_W(Q^2)$ curve.
- Dark Z' modifies $\sin^2\theta_W(Q^2)$ curve for all experiments.
- Other BSM Physics can make additional contributions to the g^{eq} in any pattern.

PVDIS in high-x SoLID has high-energy reach complimentary with the LHC.



Published data
+ P2 at Mainz
+SoLID

Example: lepto-phobic Z' contributes only to g^{eq}_{VA}



PVDIS also probes hadronic physics:

- Charge symmetry at the quark level.
- Isovector EMC effect.
- Isolate quark-quark correlations.

Nature **557**, no. 7704, 207 (2018)

Nature **506**, no. 7486, 67 (2014)

Proton Mass and Conformal (Trace) Anomaly

- **Nucleon mass related to trace of energy-momentum tensor at zero momentum transfer**
- **At low momentum transfer, heavy quark decouples, only light quarks enter**

M. Shifman et al., Phys. Lett. 78B (1978), D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130 (1996),…

$$\left\langle P \right| \frac{\beta(g)}{2g} G^{\alpha\beta\gamma} G^{\gamma}_{\alpha\beta} + \sum_{q=u,d,s} m_q (1+\gamma_m)\ \bar{\psi}_q \psi_q \left| P \right\rangle = 2M^2_p$$

Trace Anomaly

Light Quark Mass

Decomposition with pressure effects

C. Lorce', EPJC 78 (2018) 2;
C. Lorce', H. Moutarde and A. Trawińsk, EPJC79 (2019)

(Proton rest frame decomposition)

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

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

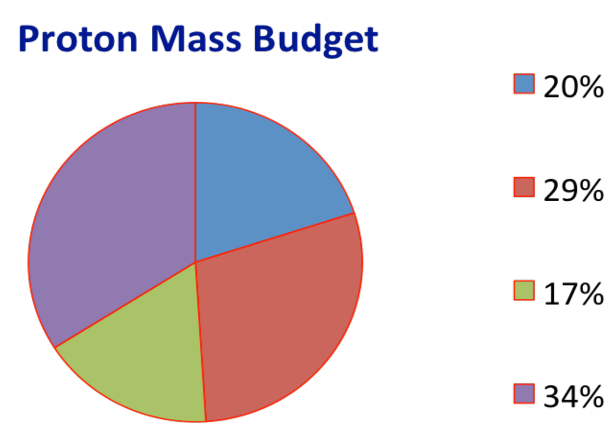
$H_m =$ Quark mass $\int d^3x\ \bar{\psi} m \psi$

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

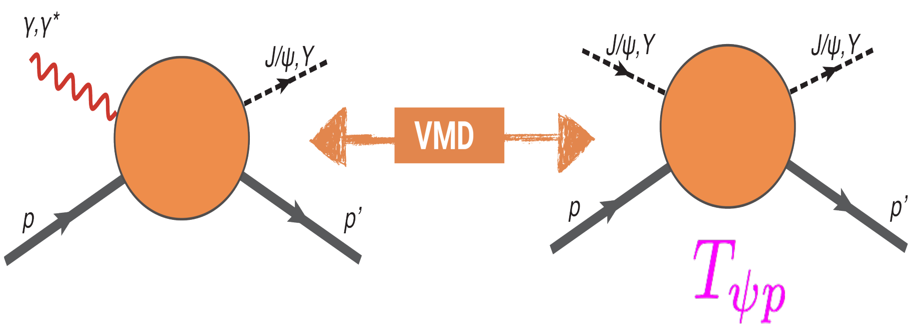
$H_a =$ Trace anomaly $\int d^3x\ \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2)$

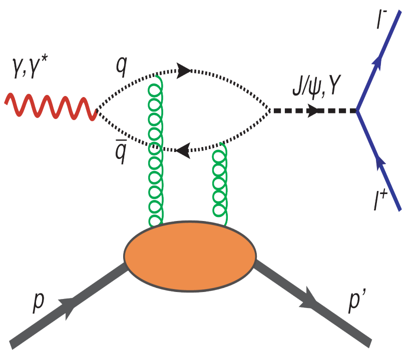
Sets the scale for the hadron mass!

X. Ji PRL 74 1071 (1995)



From Cross section to the Trace Anomaly





$$\gamma^* + N \rightarrow N + J/\psi$$

Heavy quark – dominated by two gluons

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

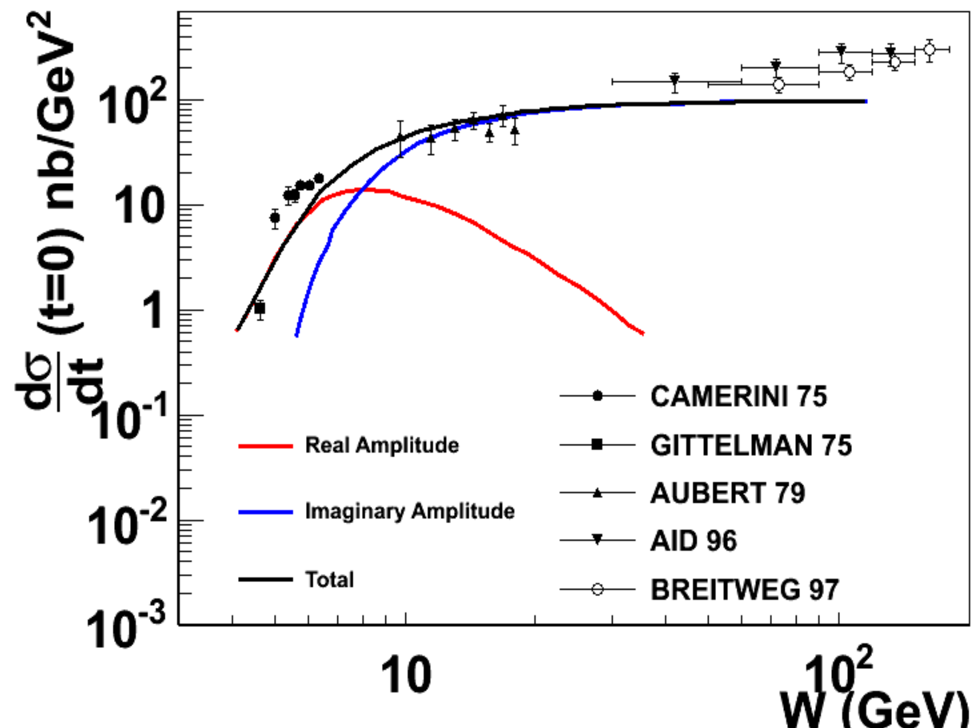
$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0) = \frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

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

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 constrained through dispersion relation

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



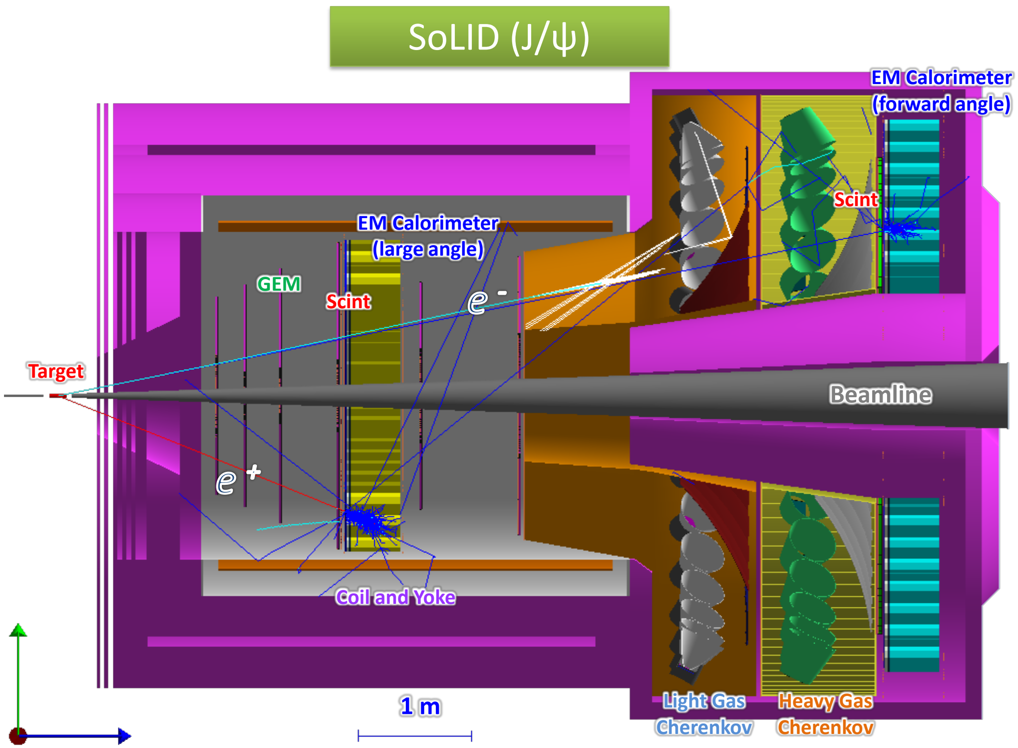
Y. Hatta et al., PRD 98 no. 7, 074003 (2018)
Y. Hatta et al., 1906.00894 (2019)

A measurement near threshold could allow access to the trace anomaly

J/ψ @ SoLID: Experiment E12-12-006

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

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



Measurements

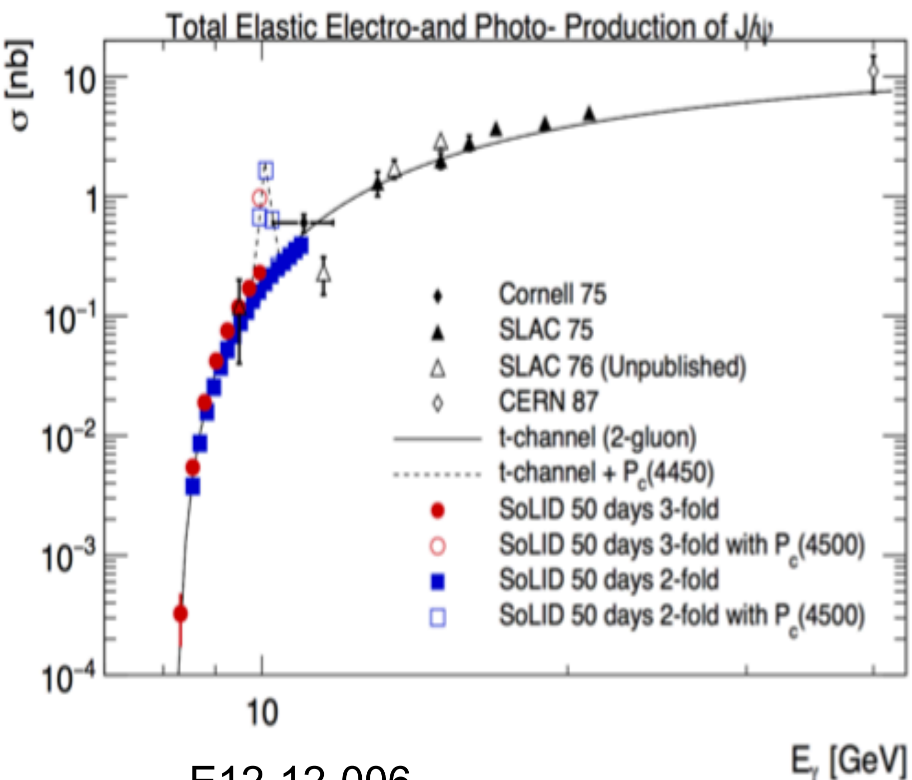
- Electro-production:
  - 4-fold: detect decay $e^-\,e^+$ pair, scattered e^- and recoil proton
  - 3-fold: detect decay $e^-\,e^+$ pair, scattered e^- or recoil proton
- Photo-production:
  - 3-fold: detect decay $e^-\,e^+$ pair and recoil proton
- Kinematics:
  - $4.05 < W < 4.45$ GeV
  - $|t - t_{min}| < 2.5$ GeV^2

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

Charm @ SoLID and Beauty @ EIC

SoLID with J/ψ

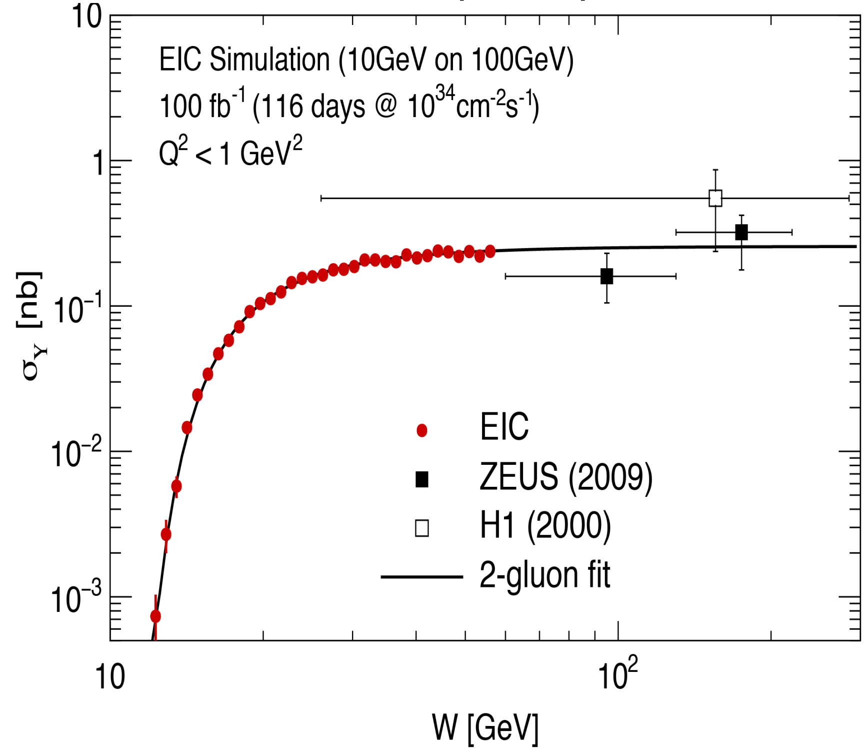
Total elastic electro and photo-production of J/psi



E12-12-006

EIC with Upsilon

Total elastic electro and photo-production of Upsilon



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)

GlueX on J/ψ Ali et al., Phys. Rev. Lett. 123, 072001(2019)

Trace of EMT proportional to Quarkonium-proton scattering amplitude
to be measured at JLab with J/psi at SoLID or Upsilon at EIC

Both SoLID and EIC are needed to confirm the trace anomaly extraction and could lead to a solution of the nucleon mass puzzle

The SoLID GPD Program

- **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*
    - *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 ^{3}He**
    - *Z. Ye (under study)*

Garth Huber, huberg@uregina.ca

Slide from Garth Huber

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)

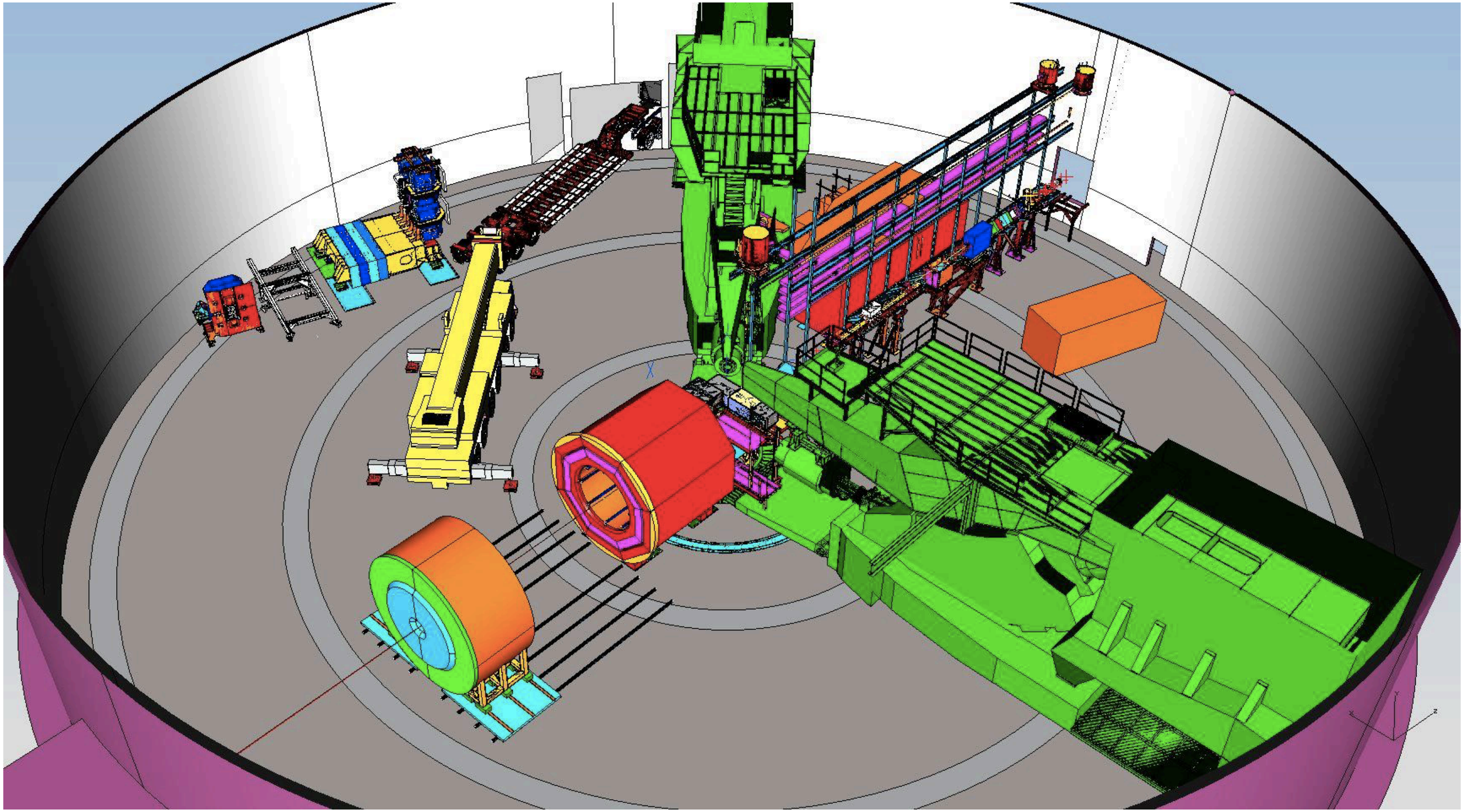
- Ay with Transversely Polarized Proton and ^{3}He

  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)

SoLID in Hall A



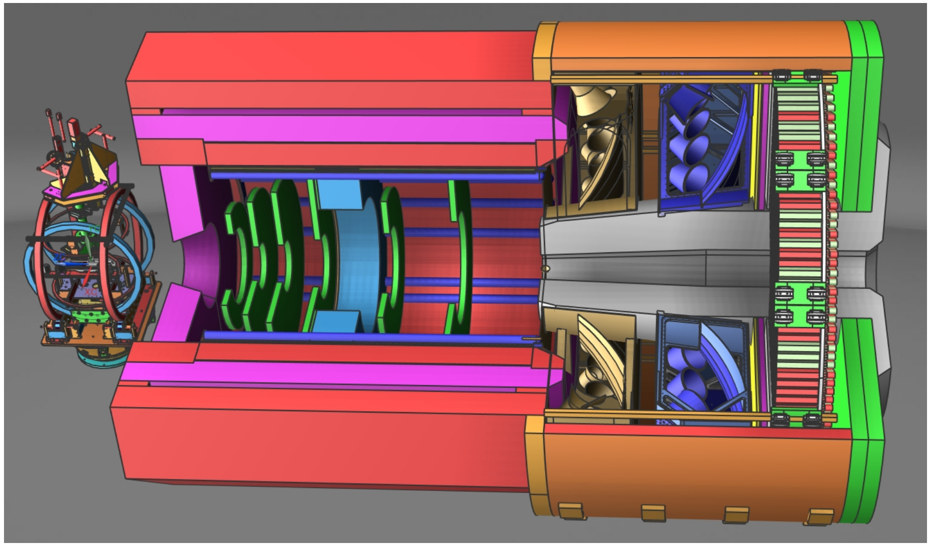
Plan for installing SoLID in Hall A with other equipment moved out of the way.

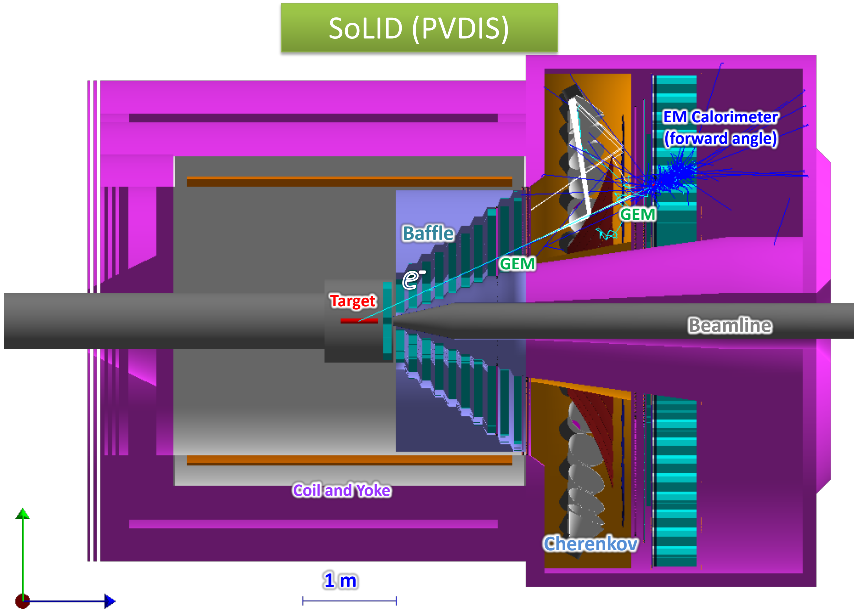
SoLID Apparatus

Requirements are Challenging

- High Luminosity (10^{37}-10^{39})
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale
- New Technologies
  - GEM’s
  - Shashlyk Ecal
  - Pipeline DAQ

Polarized ^{3}He (``neutron”) @ SoLID

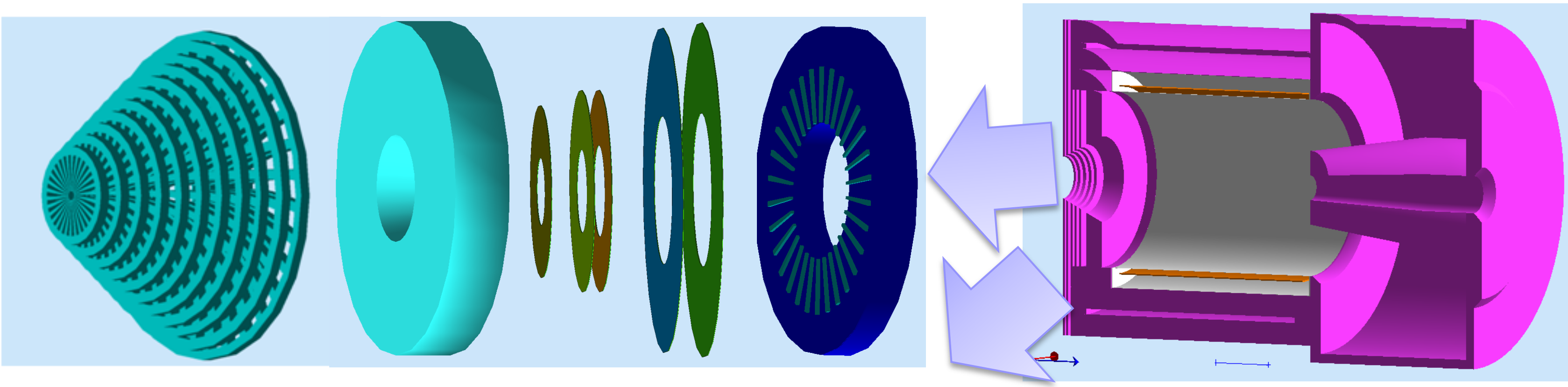




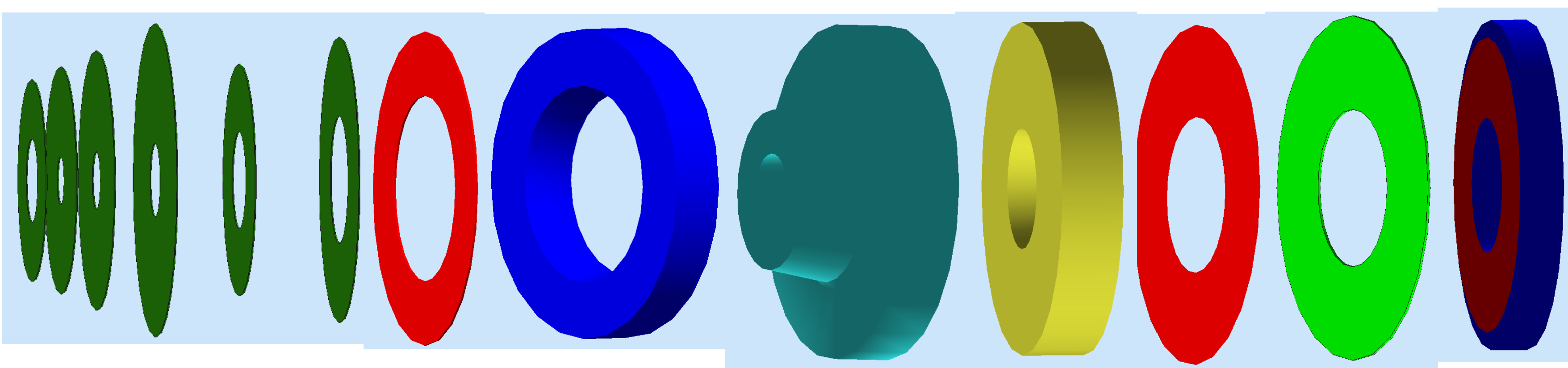
SoLID Detector Subsystems

Uses full capability of JLab electronics

PVDIS: Baffle LGC 5xGEMs EC



SIDIS&J/Psi:
6xGEMs LASPD LAEC LGC HGC FASPD MRPC FAEC



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

Magnet: Requirement and Design

CLEO II coil at JLab

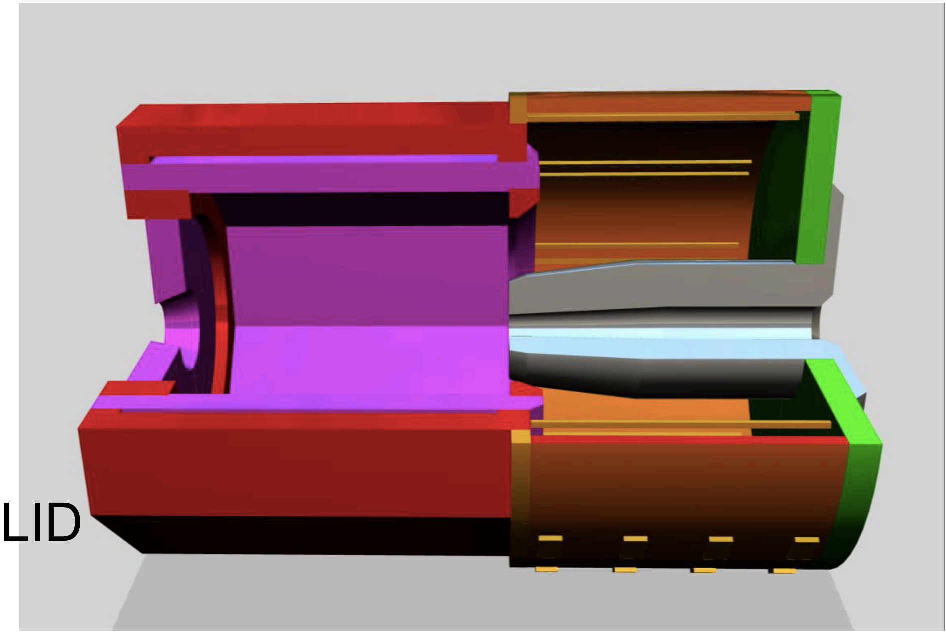
Requirements:

→Acceptance: Φ: 2π, θ: 8^o-24^o (SIDIS), 22^o-35^o (PVDIS), P: 1.0 – 7.0 GeV/c,

→ Resolution: $\delta P/P \sim 2\%$ (requires 0.1 mm tracking resolution)

→ Fringe field at the 3He target < ~5 Gauss

- Use CLEO II magnet with the following modifications
  - Two of three layers of return yoke needed
  - Add thickness to front endcap
  - Add extended endcap



Yoke for SoLID

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/Psi 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
- US DOE science review of SoLID scheduled for March 8-10, 2021
- SoLID collaboration is active and international with many theory collaborators
- We welcome new collaborators!

Acknowledgement: J.P. Chen, Z.-E. Meziani, P. Souder, and many others in the SoLID collaboration, supported in part by the U.S. Department of Energy under contract number DE-FG02-03ER41231

https://solid.jlab.org/