12 GeV Upgrade
Future Science at Jefferson Lab

SoLID Program at Jefferson Lab

Hadron 2019
Aug 16-21 2019, Guiling, China

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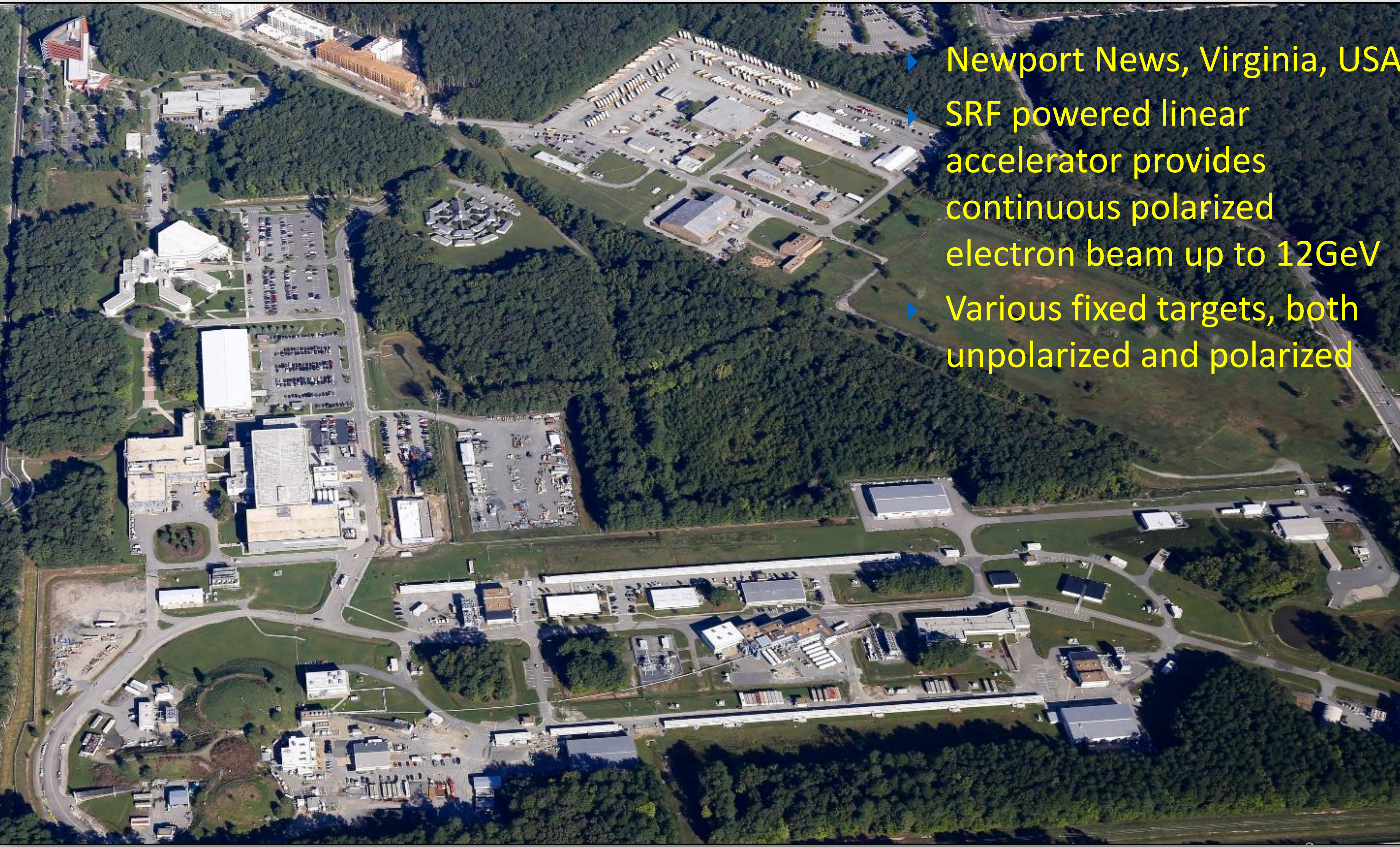
Duke University
SoLID Collaboration

Duke University

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Jefferson Lab



- Newport News, Virginia, USA
- SRF powered linear accelerator provides continuous polarized electron beam up to 12GeV
- Various fixed targets, both unpolarized and polarized

SoLID (Solenoidal Large Intensity Device)

Full exploitation of JLab 12 GeV upgrade with broad physics program

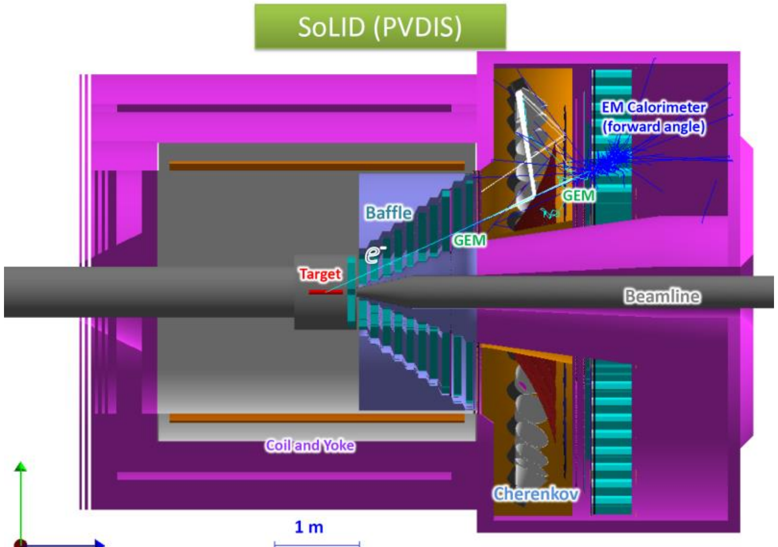
Lumi ~1e^{39}/cm^2/s (baffled geometry)

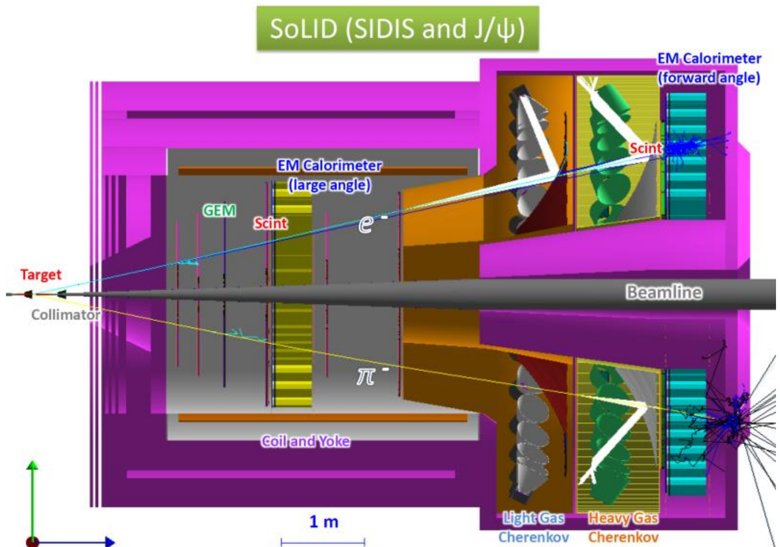
- Standard Model test and hadron structure
  - PVDIS on both deuterium and hydrogen

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

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

High Luminosity
Large Acceptance





Parity Violation DIS (PVDIS)

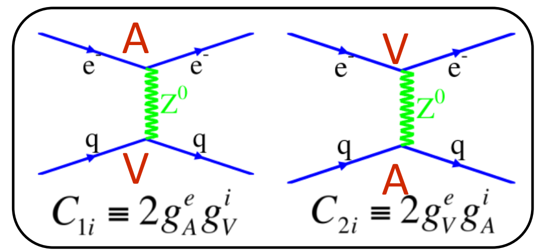
Weak PV

Electromagnetic

$$A_{\rm PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{Z^0} - \mathcal{M}^r_{Z^0}}{\mathcal{M}_\gamma}$$

Kinematic factor

$$\propto -\left(\frac{G_{\rm F} Q^2}{4\pi\alpha}\right)\left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$



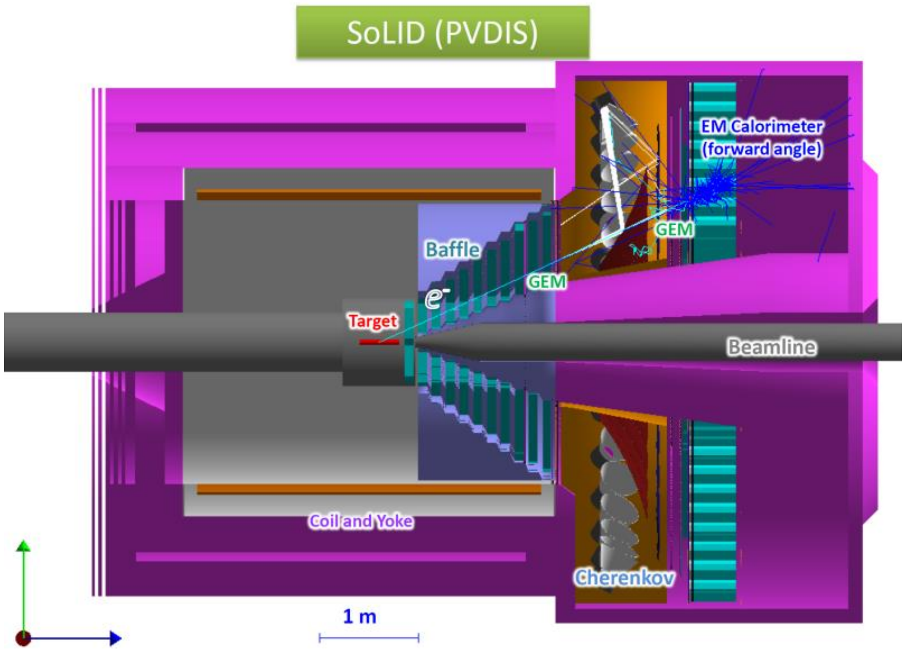
$$\begin{aligned}
C_{1u} &= -\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W &&\approx -0.19\\
C_{1d} &= \tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W &&\approx 0.35\\
C_{2u} &= -\tfrac{1}{2} + 2\sin^2\theta_W &&\approx -0.04\\
C_{2d} &= \tfrac{1}{2} - 2\sin^2\theta_W &&\approx 0.04
\end{aligned}$$

- The couplings g depend on electroweak physics as well as on the weak vector and axial-vector hadronic current.
- Both **new physics at high energy scales** as well as interesting **features of hadronic structure** come into play.
- A program with many targets and a broad kinematic range can reveal the physics.

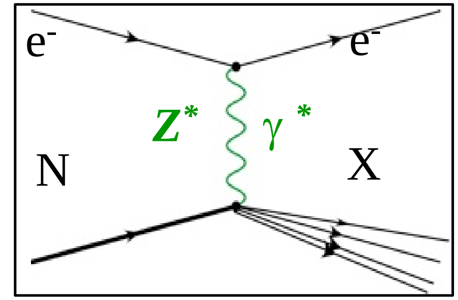
Is the glass half full or half empty?

SoLID PVDIS

12 GeV Upgrade: Extraordinary opportunity to do the ultimate PVDIS Measurement



Pure electron-quark scattering.

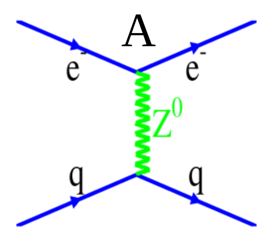


$$A_{PV} = \frac{G_F Q^2}{\sqrt{2} pa}[a(x) + f(y)b(x)]$$

PVDIS

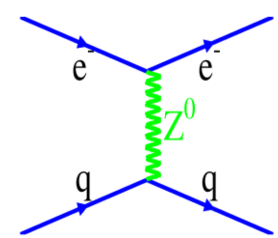
- Measure A_{DIS} (g^{eq}_{AV}, g^{eq}_{VA})
- Negligible hadronic corrections

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



Atomic Parity Violation (APV), Qweak, SoLID

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



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

<u>SoLID PVDIS Strategy:</u>

sub-1% precision over broad kinematic range

sensitive Standard Model test *and* **detailed study of hadronic structure contributions**

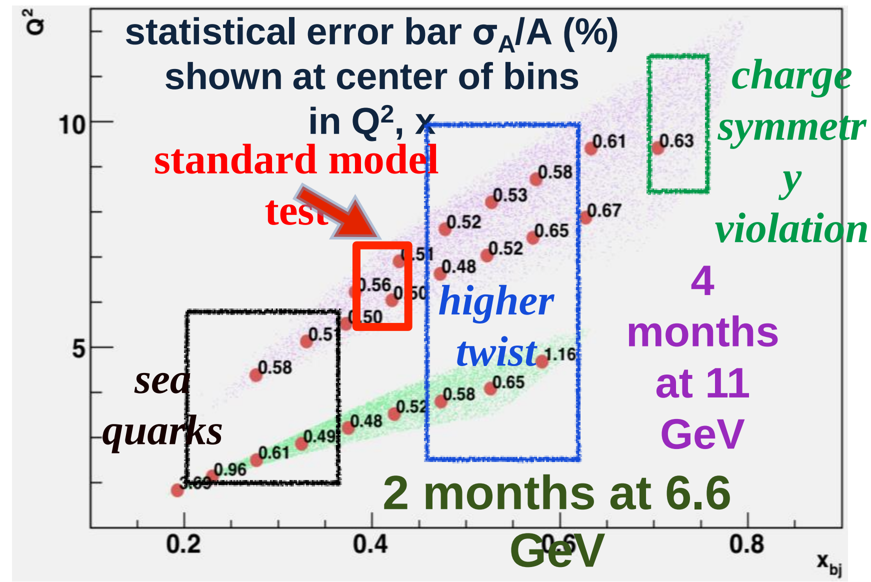
LH2 and LD2 target (charge symmetry)

b(x): function of c_2, axial-vector quark coupling

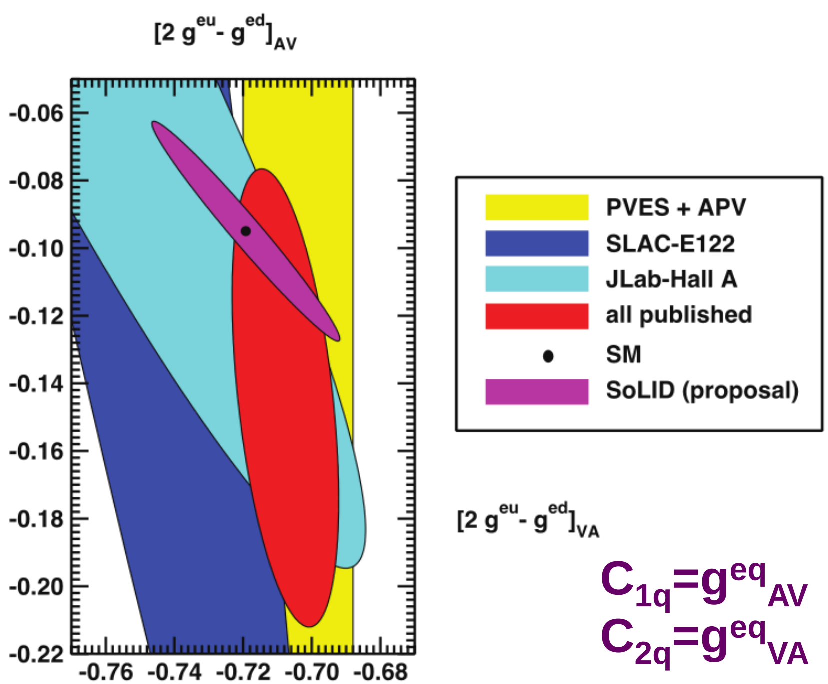
SoLID PVDIS Projection and Impact

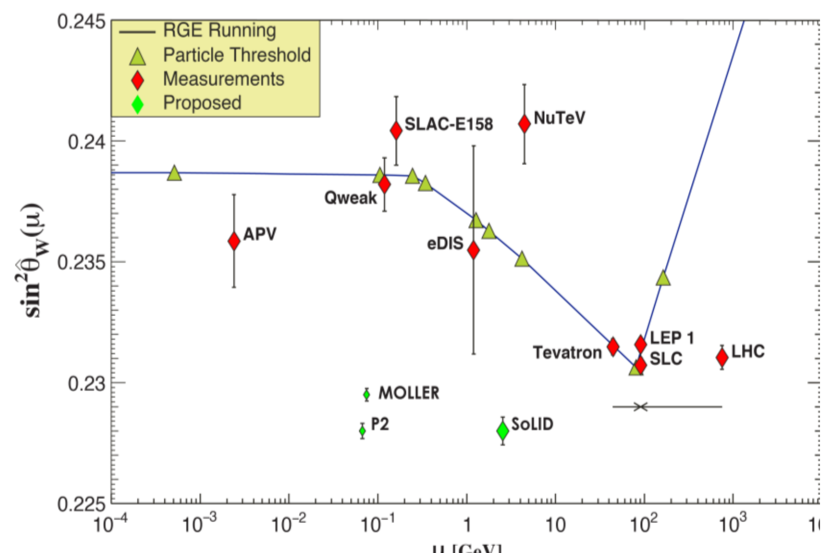
- Measure $2g^{eu}_{VA} - g^{ed}_{VA}$ precisely
- Measure $\sin^2\theta_W$ precisely

- **High Luminosity with E > 10 GeV**
- **Large scattering angles (for high x & y)**
- **Better than 1% errors for small bins**
- **x-range 0.25-0.75**
- **$W^2 > 4$ GeV^2**
- **Q^2 range a factor of 2 for each x (except at very high x)**
- **Moderate running times**



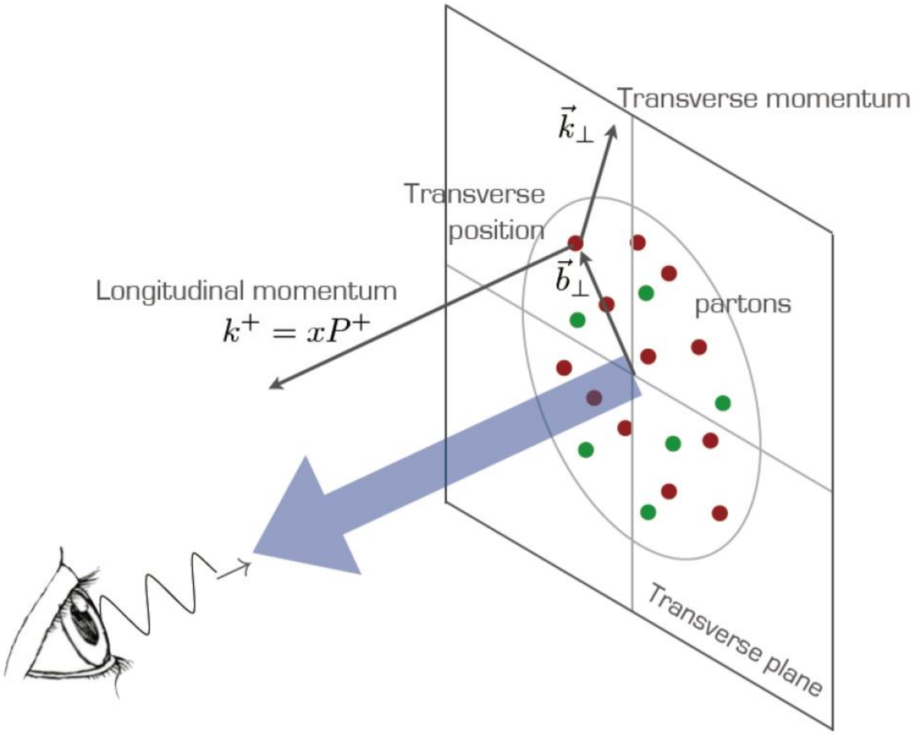
Assume Standard Model is exact.

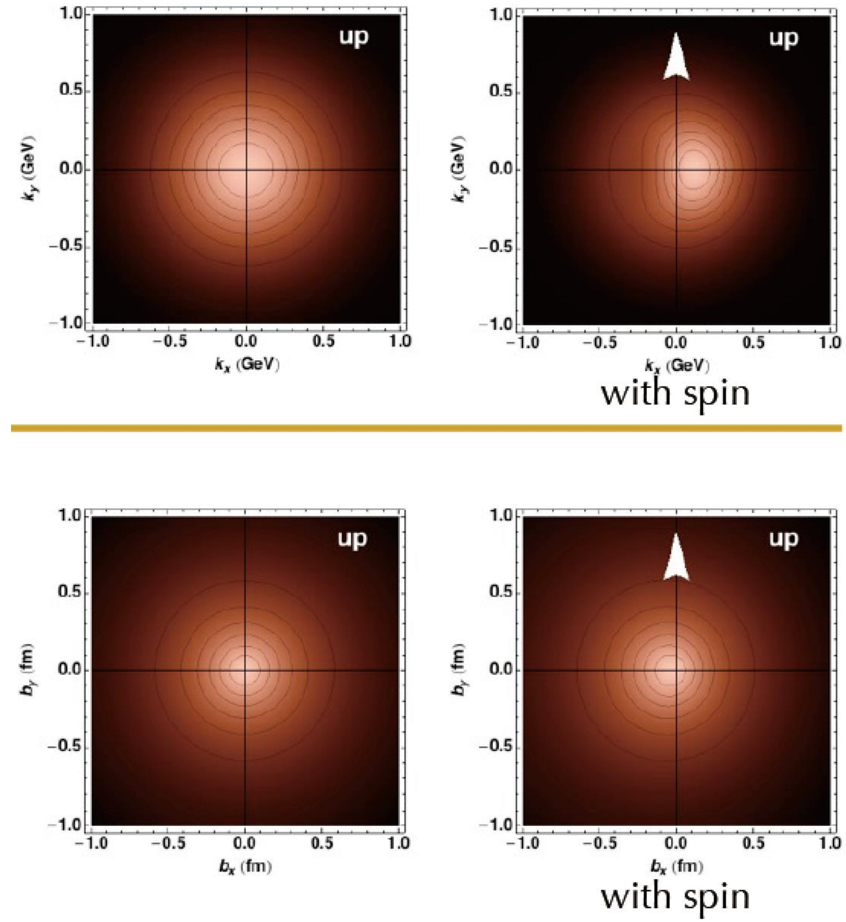




$C_{1q} = g^{eq}_{AV}$
$C_{2q} = g^{eq}_{VA}$

Orbital motion - Nucleon Structure from 1D to 3D

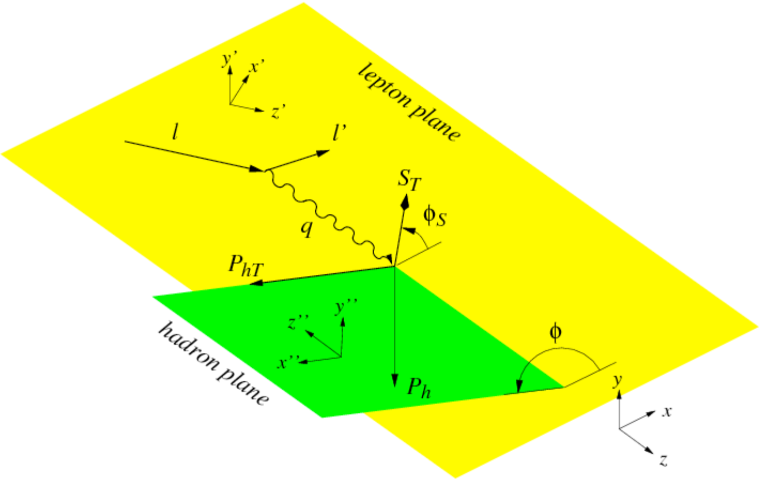




Transverse momentum dependent parton distribution (TMD)

Generalized parton distribution (GPD)

TMD Structure Functions



[Diehl&Sapeta EPJC2005]

SIDIS differential cross section

18 structure functions $F(x, z, Q^2, P_T)$,
model independent. (one photon exchange approximation)

$$\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\times\Big\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+S_L\Big[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h+\epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\Big]+\lambda_e S_L\Big[\sqrt{1-\epsilon^2}F_{LL}+\sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\Big]$$

$$+S_T\Big[\big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\big)\sin(\phi_h-\phi_S)+\epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)+\epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)$$

$$+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$

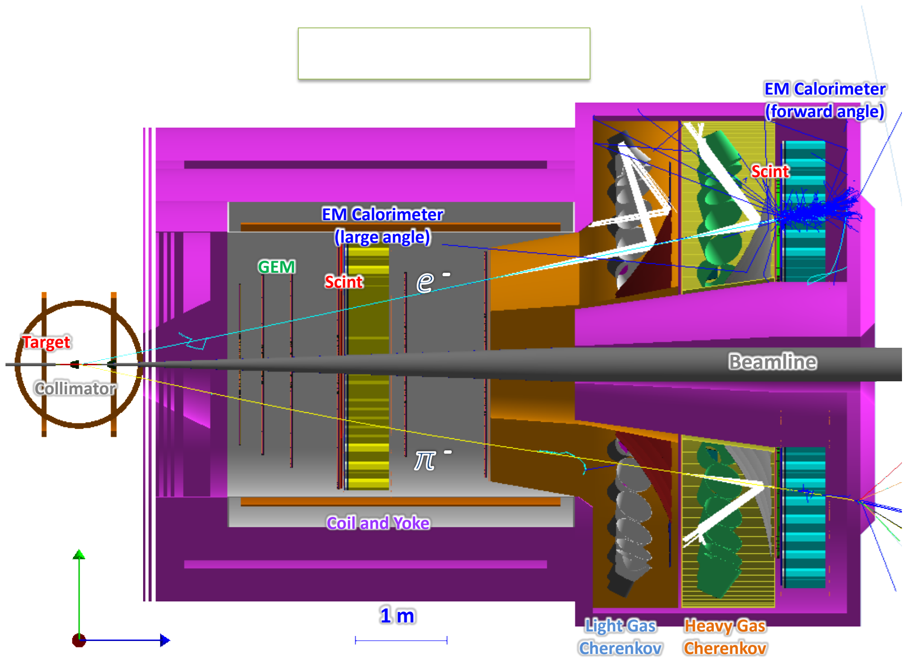
$$+\lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)$$

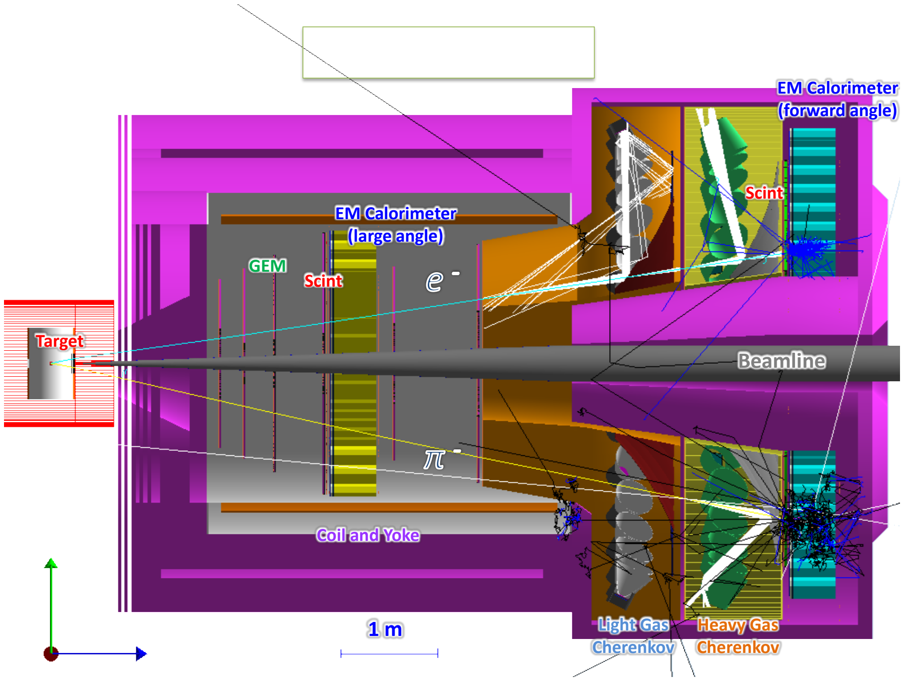
$$+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}$$

SoLID:
4D binning and high precision

In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMD and fragmentation function.

SoLID SIDIS Program





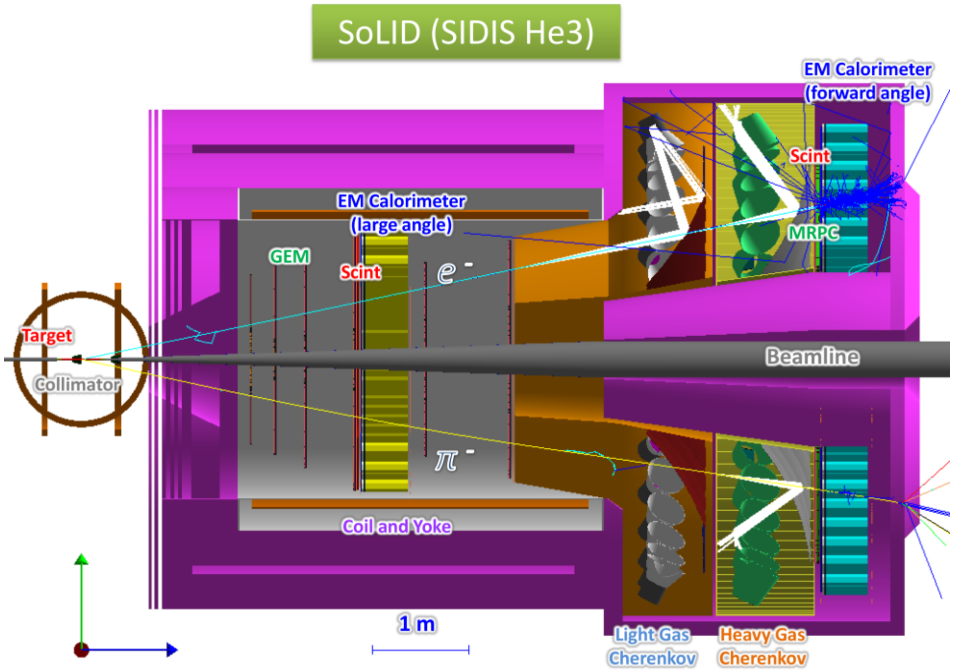
E12-10-006: Single Spin Asymmetries on Transversely polarized ^{3}He @ 90 days, **rating A**

E12-11-007: Single and Double Spin Asymmetries on longitudinally polarized ^{3}He @ 35 days, **rating A**

E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @120 days, **rating A**

Key of SoLID-SIDIS program:
Large Acceptance, full azimuthal coverage
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→ Lattice QCD, QCD Dynamics, Models.

SoLID He3 Setup

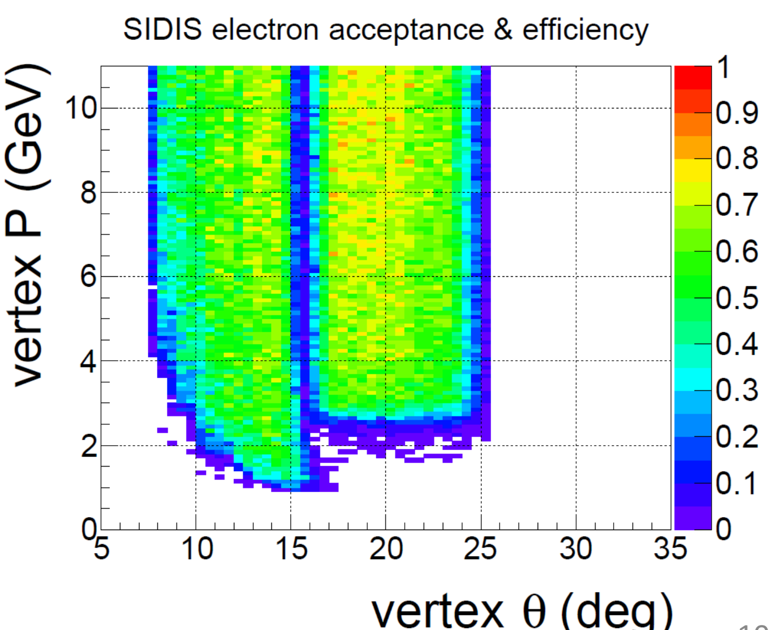


Polarized lumi ~1e^{36}/cm^2/s

Coverage
- Polar angle: e$^-$ 8-24 deg, π^-/π^+ 8-15deg
- Azimuthal angle: full
- Mom: 1-7GeV

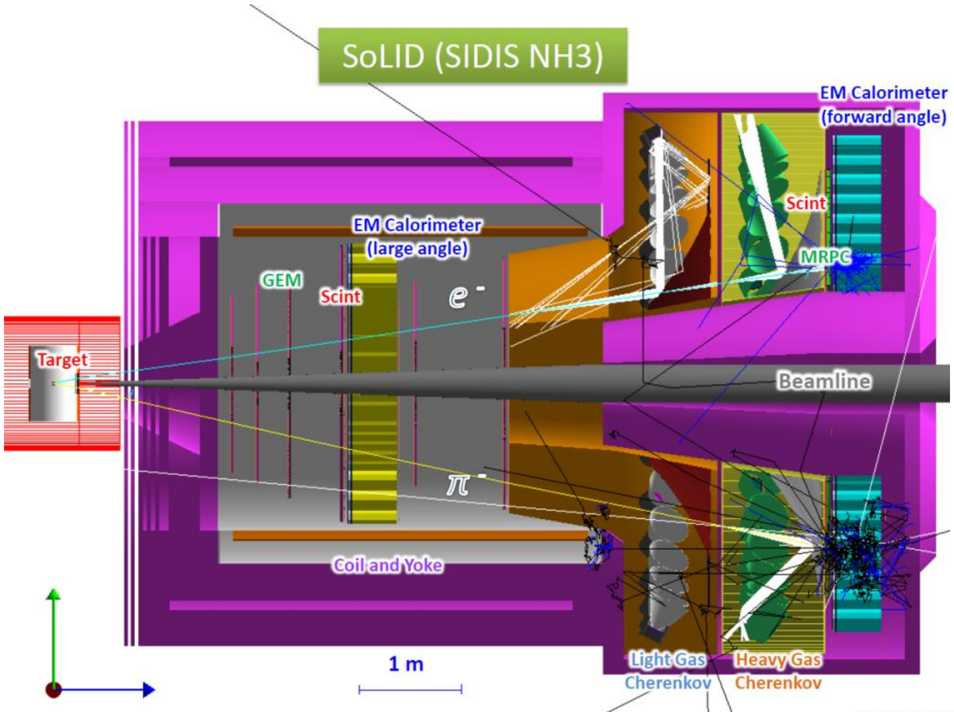
- E12-10-006: Single Spin Asymmetry on transversely polarized ^{3}He, 90 days, **rated A**
- E12-11-007: Single and Double Spin Asymmetries on longitudinally polarized ^{3}He, 35 days, **rated A**
- Dihadron process as run group

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



SoLID NH3 Setup

• E12-10-008: Single Spin Asymmetry on transversely polarized proton (NH_3), 120 days, **rated A**



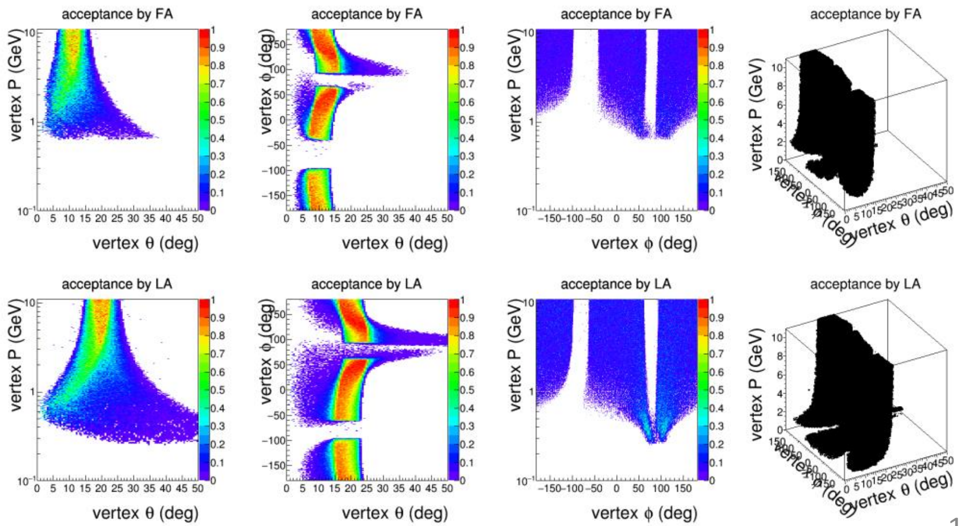
Detection is similar to He3 setup

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

5T transverse target field
High radiation sheet of flame areas are cut away

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

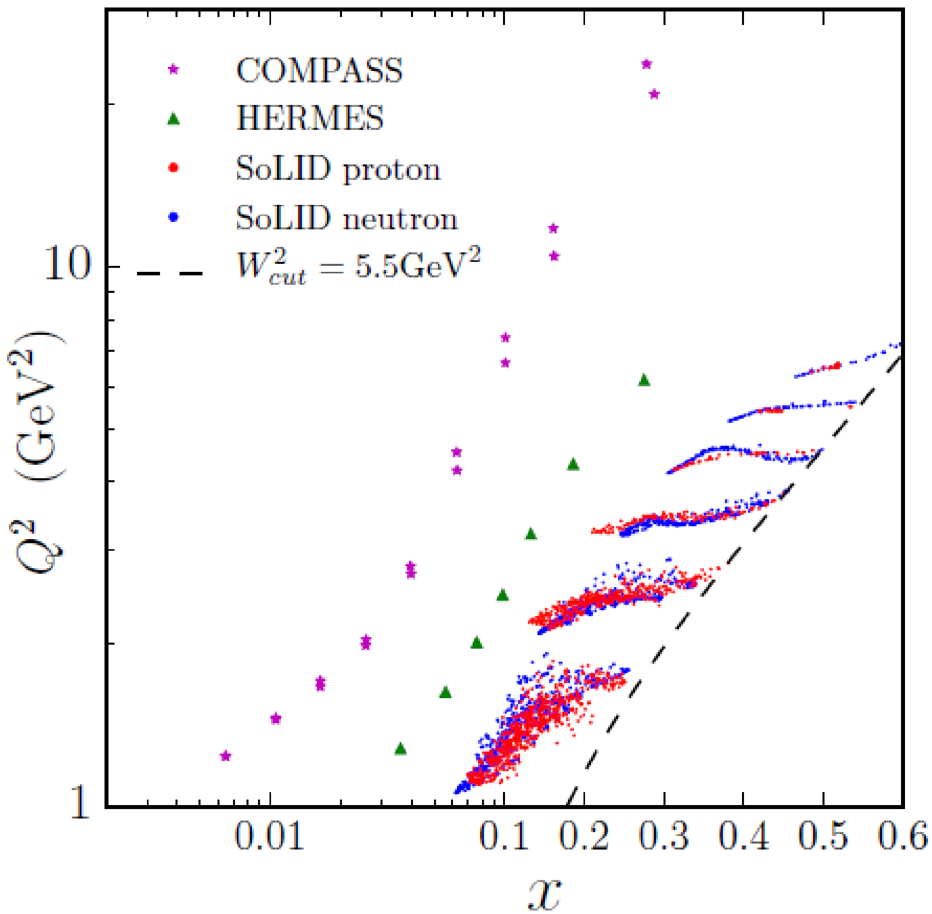
e- acceptance shown
π^- acceptance is similar
π^+ acceptance is reversed along phi=0 plane



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 Impact on Sivers

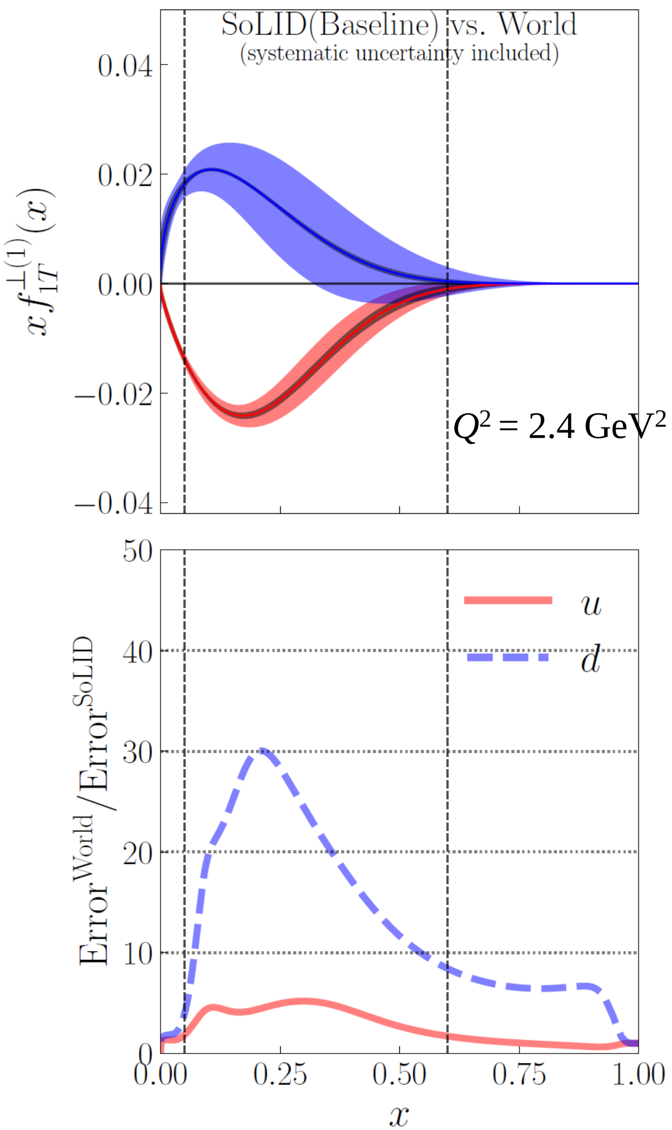
Fit SIDIS Sivers asymmetries data from HERMES, COMPASS and Jlab-6 GeV

Monte Carlo method with nested sampling algorithm is applied

TMD evolution is not included

Both statistical and systematic uncertainties are included

one order improvement



SoLID Impact on Transversity

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

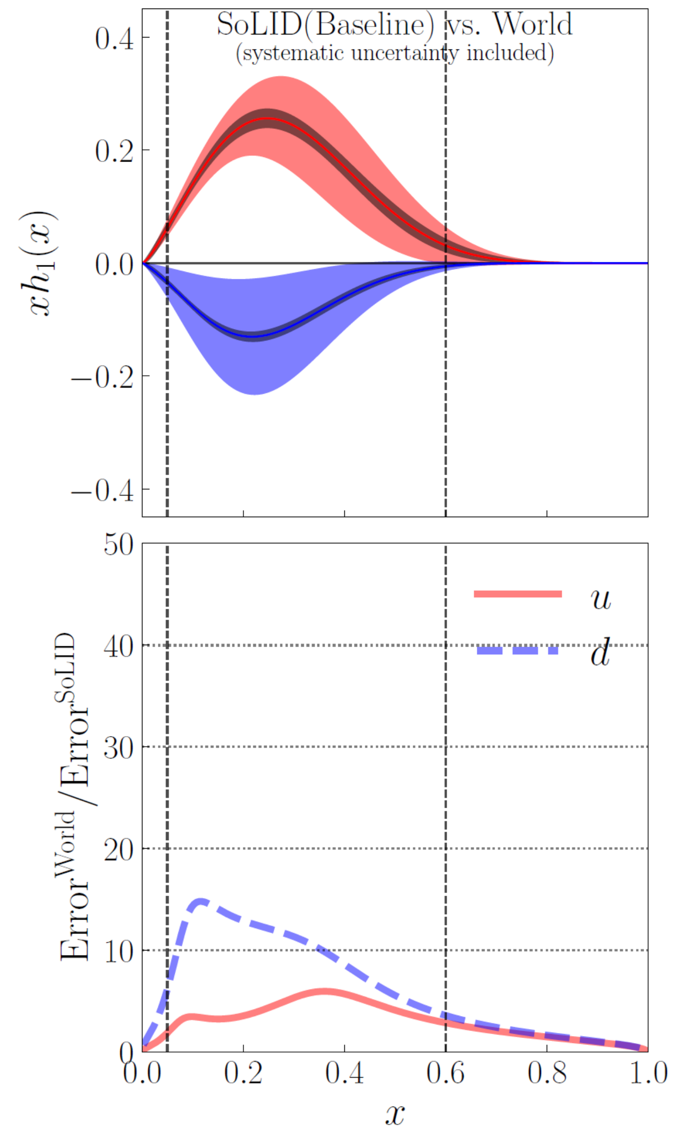
SIDIS data from HERMES, COMPASS and JLab-6 GeV

e^+e^- data from BELLE and BABAR

TMD evolution is included

Both statistical and systematic uncertainties are included

one order improvement



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

KPSY 15: Z.-B. Kang *et al.*, PR D 93, 014009 (2016).

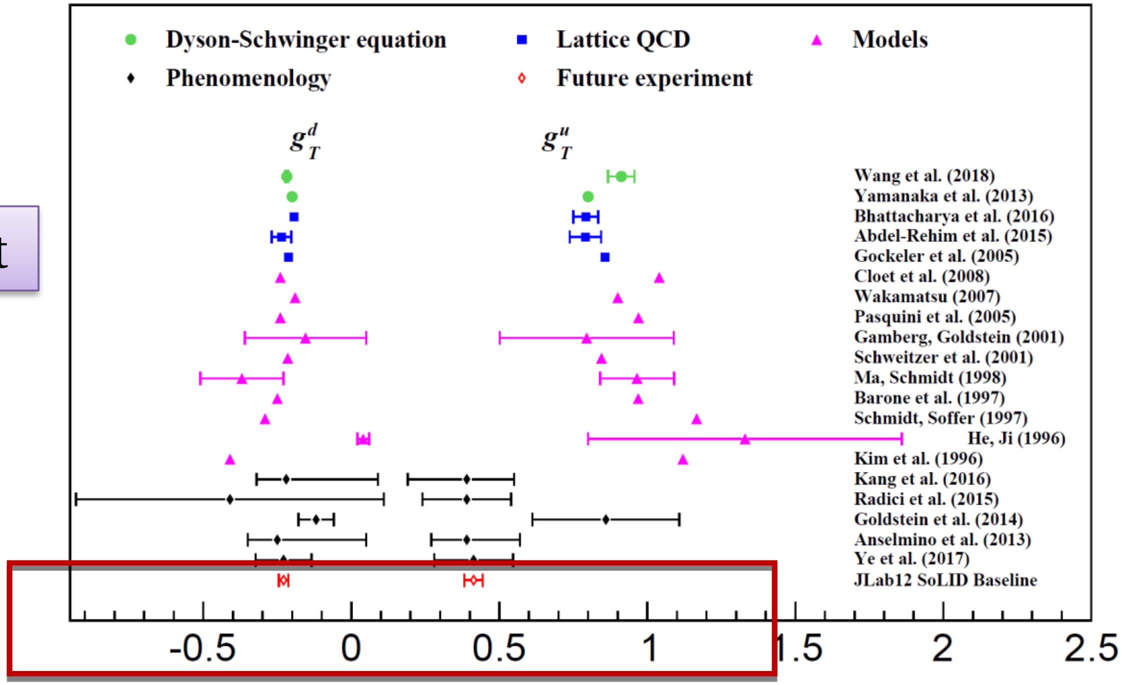
SoLID Impact on Tensor Charge

Definition

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = \delta_T q\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S) \qquad \delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] \mathrm{d}x$$

A fundamental QCD quantity. Matrix element of local operators.
Moment of transversity distribution. Valence quark dominant.
Calculable in lattice QCD.

one order improvement



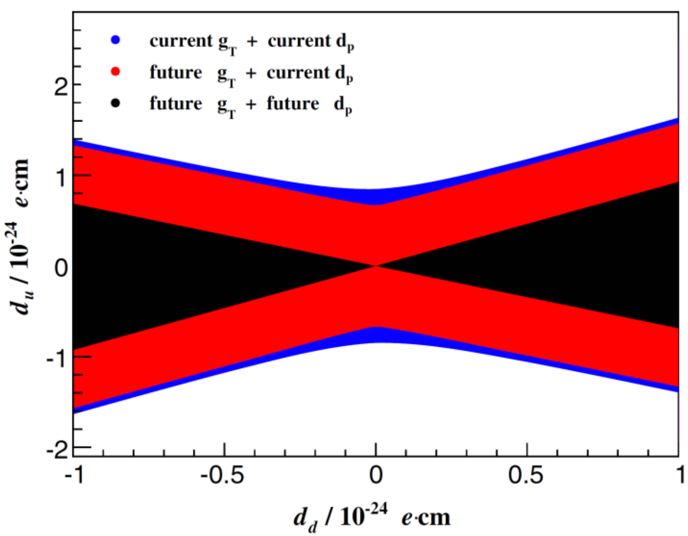
Including both systematic and statistical errors

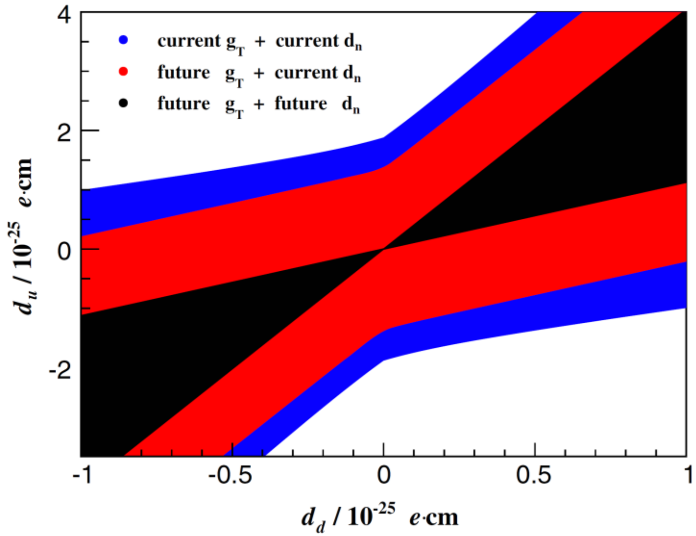
SoLID Constraint on Quark EDMs with Tensor Charge

Tensor charge and EDM $d_n = g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s$ g_T^s lattice calculation

	d_u upper limit	d_d upper limit
Current g_T + current EDMs	$1.27\times10^{-24} e$ cm	$1.17\times10^{-24} e$ cm
SoLID g_T + current EDMs	$6.72\times10^{-25} e$ cm	$1.07\times10^{-24} e$ cm
SoLID g_T + future EDMs	$1.20\times10^{-27} e$ cm	$7.18\times10^{-28} e$ cm

Include 10% isospin symmetry breaking uncertainty



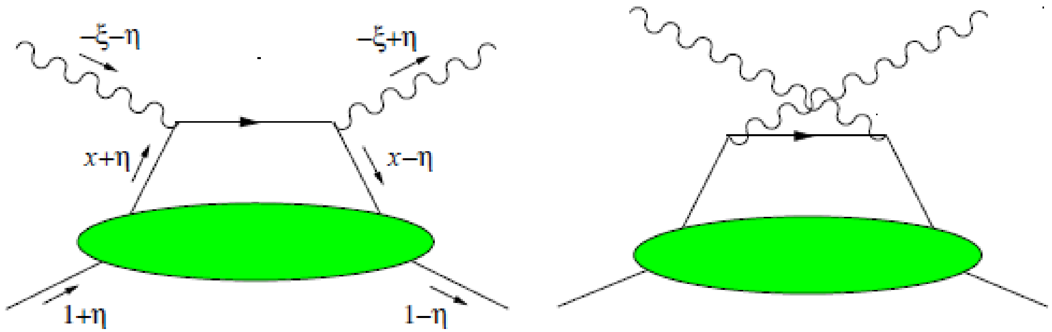


T. Liu, Z.W. Zhao and H. Gao, PRD 97, 074018 (2018)

General Compton Process accessing GPD

$$\gamma(q) + p(p) \to \gamma(q') + p(p')$$

$$Q^2 = -q^2, \quad Q'^2 = q'^2, \quad s = (p+q)^2, \quad t = \Delta^2,$$



DVCS	$(\gamma' \to \gamma)$
TCS	$(\gamma \to \gamma')$
DDVCS	$(\gamma' \to \gamma')$

Compton Form Factor (CFF)

$$\mathcal{H}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{H^q(x,\eta,t)}{\xi - x - \mathrm{i}\epsilon} - \frac{H^q(x,\eta,t)}{\xi + x - \mathrm{i}\epsilon} \right),$$

$$\mathcal{E}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{E^q(x,\eta,t)}{\xi - x - \mathrm{i}\epsilon} - \frac{E^q(x,\eta,t)}{\xi + x - \mathrm{i}\epsilon} \right),$$

$$\tilde{\mathcal{H}}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{\tilde{H}^q(x,\eta,t)}{\xi - x - \mathrm{i}\epsilon} + \frac{\tilde{H}^q(x,\eta,t)}{\xi + x - \mathrm{i}\epsilon} \right),$$

$$\tilde{\mathcal{E}}_1(\xi,\eta,t) = \sum_q e_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{\tilde{E}^q(x,\eta,t)}{\xi - x - \mathrm{i}\epsilon} + \frac{\tilde{E}^q(x,\eta,t)}{\xi + x - \mathrm{i}\epsilon} \right)$$

$$\xi = -\frac{(q+q')^2}{2(p+p')\cdot(q+q')} \approx \frac{Q^2 - Q'^2}{2s + Q^2 - Q'^2},$$

$$\eta = -\frac{(q-q')\cdot(q+q')}{(p+p')\cdot(q+q')} \approx \frac{Q^2 + Q'^2}{2s + Q^2 - Q'^2},$$

$$x = \frac{(k+k')^+}{(p+p')^+}, \quad \xi \approx -\frac{(q+q')^+}{(p+p')^+}, \quad \eta \approx \frac{(p-p')^+}{(p+p')^+}.$$

E.R. Berger et al. Eur. Phys. J. C 23, 675–689 (2002)

General Compton Process accessing GPD

(Im, $x = \xi$)

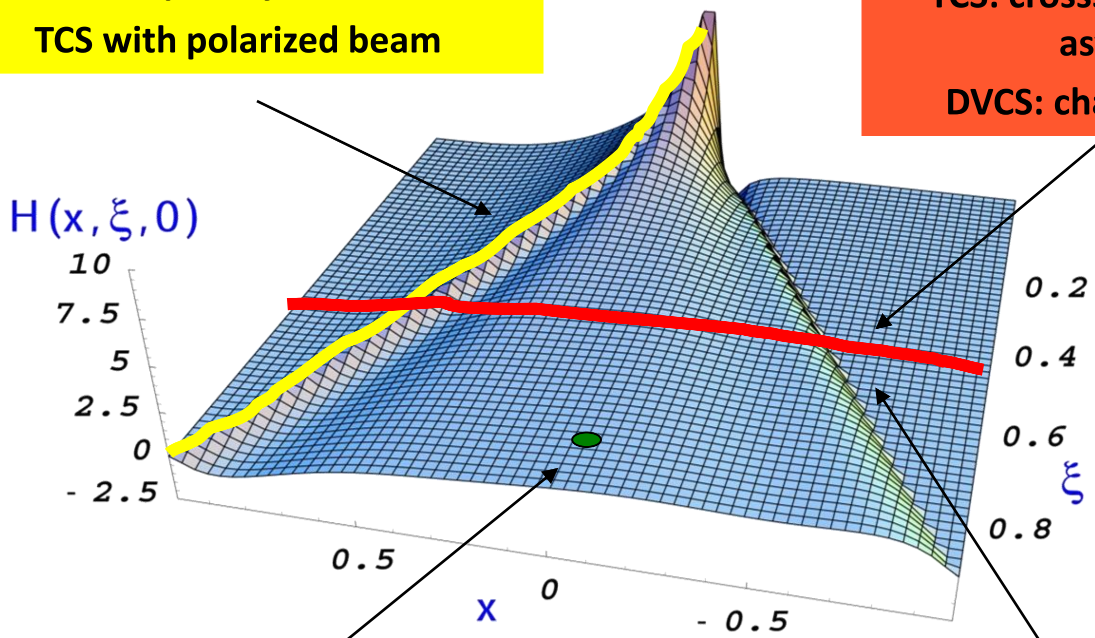
DVCS: spin asymmetries

TCS with polarized beam

(Re)

TCS: crosssection, lin beam asymmetry

DVCS: charge asymmetry



(Im, $x \neq \xi$, $x < |\xi|$)

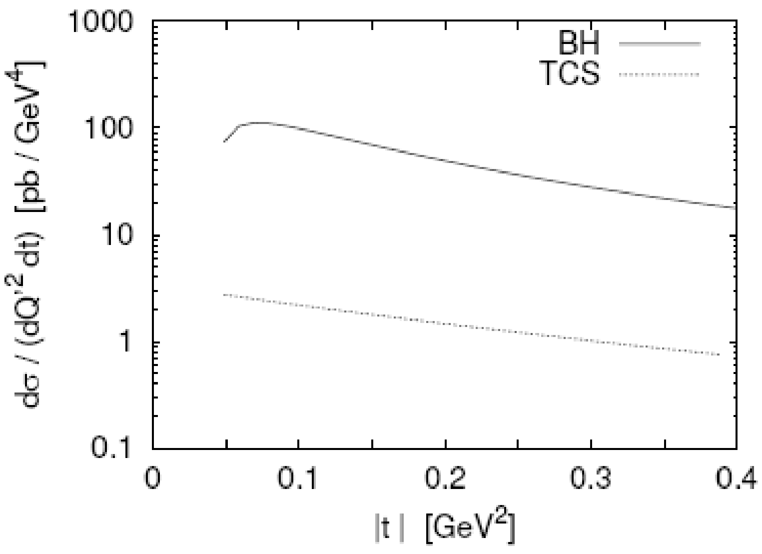
Double DVCS

($|Im|^2 + |Re|^2$)

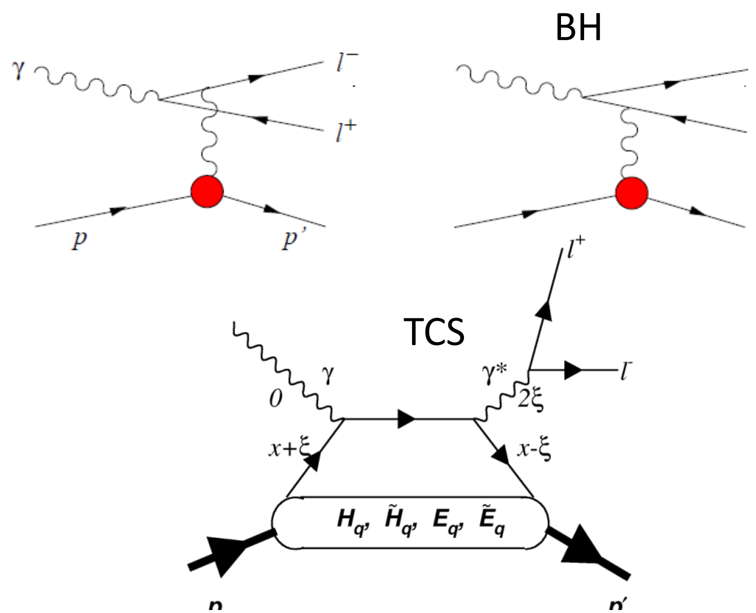
DVCS: cross section

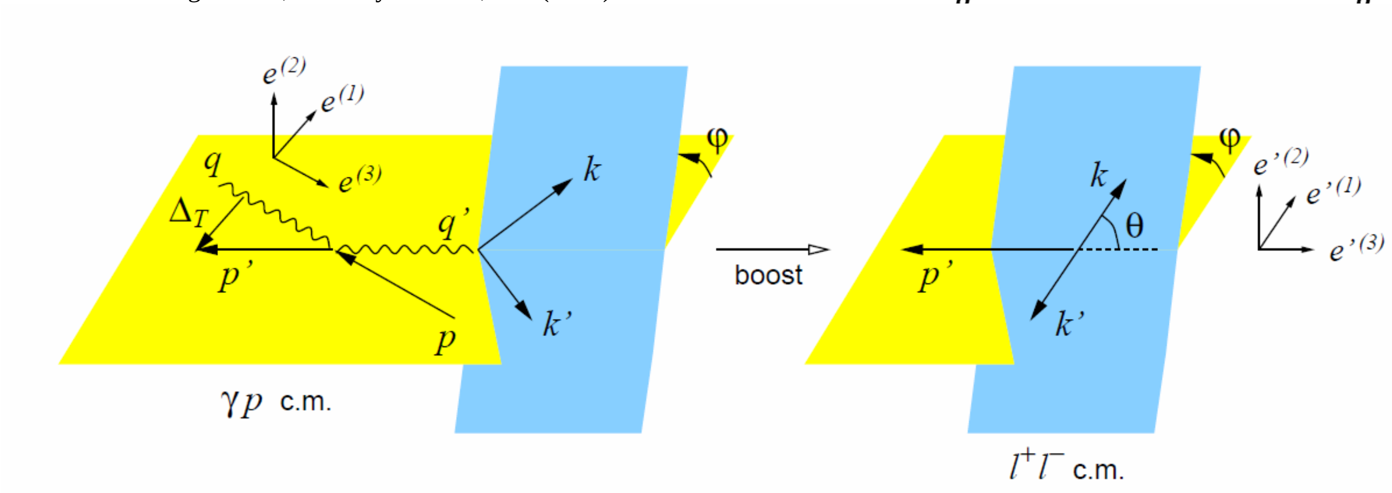
Timelike Compton Scattering

Real (imaginary) part of the Compton amplitude of GPD can be obtained from photoproduction of lepton pairs using unpolarized (circularly polarized) photons

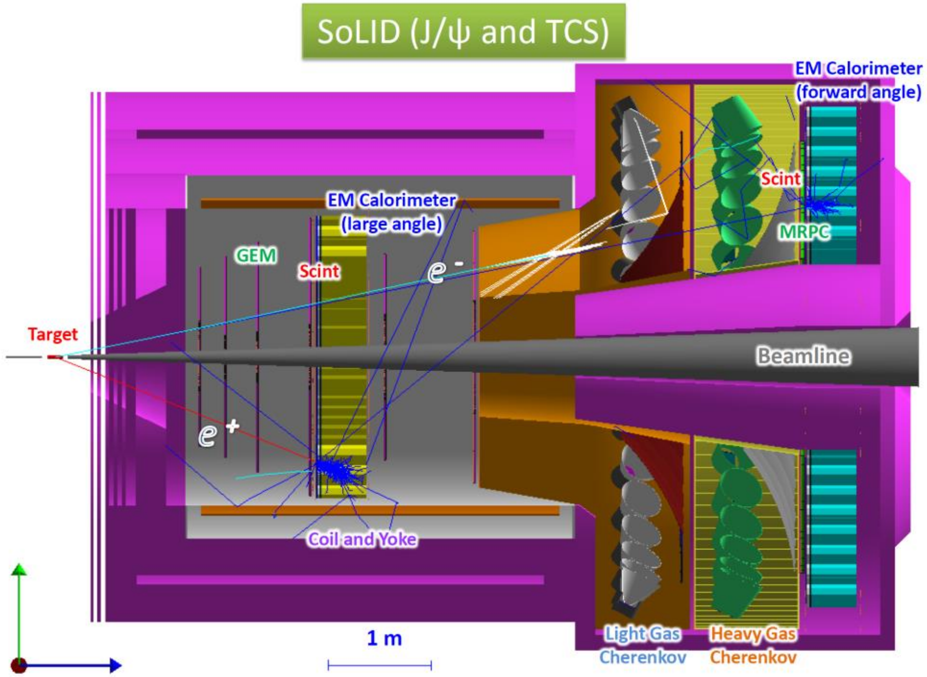


E. Berger *et al.*, Eur. Phys. J. C23, 675 (2002)





SoLID TCS Setup

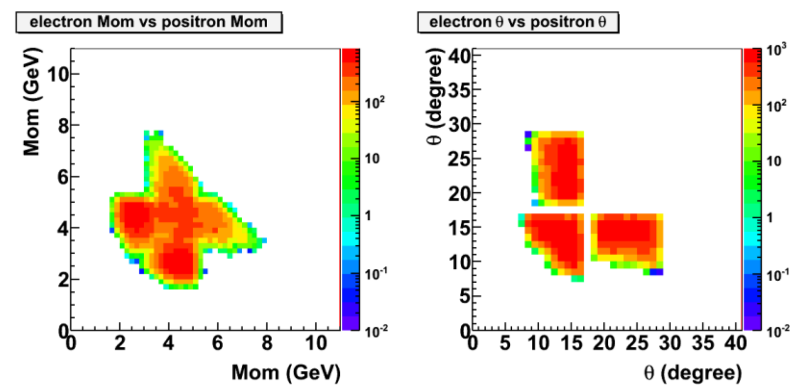


lumi ~1e^{37}/cm^2/s

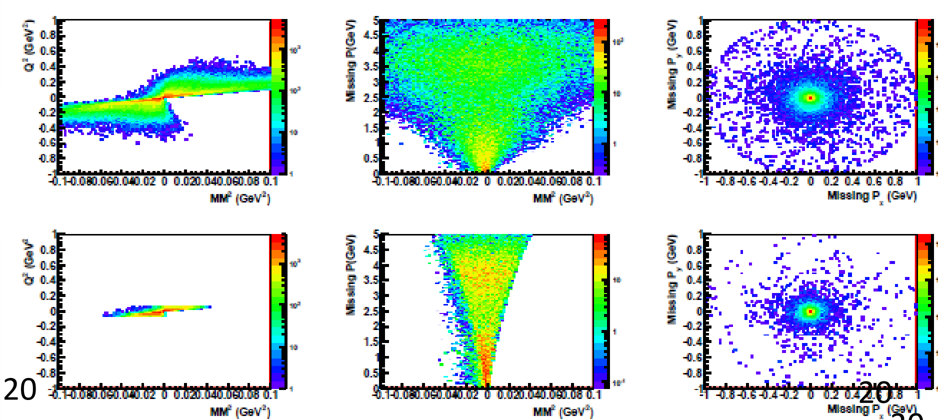
Target 15cm LH

Detection

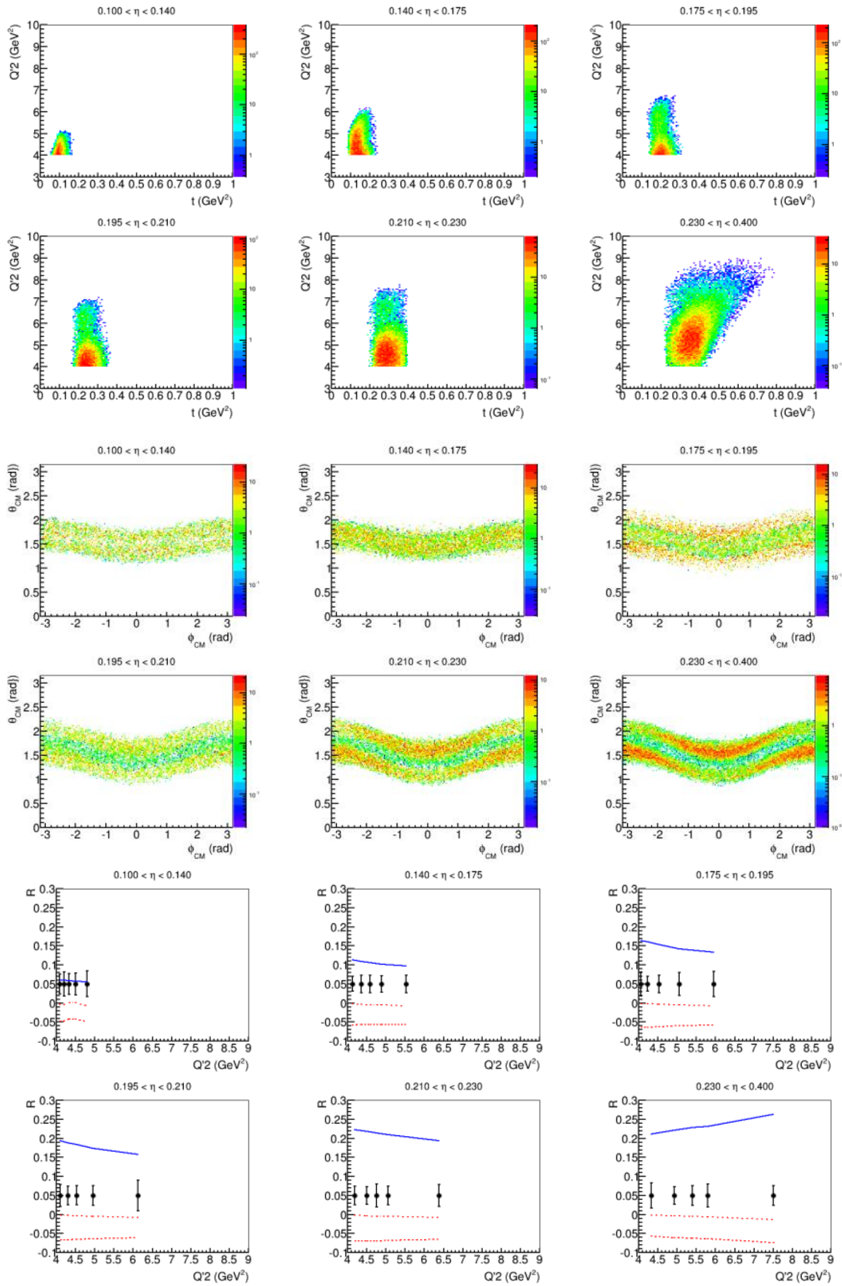
- at least one of e- and e+ at forward angle with Cerenkov to reject pions
- proton detected at both forward and large



Cut on missing variables to ensure exclusivity



SoLID TCS Projection



Enough data for kinematic binning

Construct Moment from crosssection

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

$$\frac{dS}{dQ^2\,dt\,d\varphi}=\int \frac{L(\theta,\varphi)}{L_0(\theta)} \frac{d\sigma}{dQ^2\,dt\,d\varphi\,d\theta}\,d\theta$$

Compare to different GPD model

SoLID TCS Projection

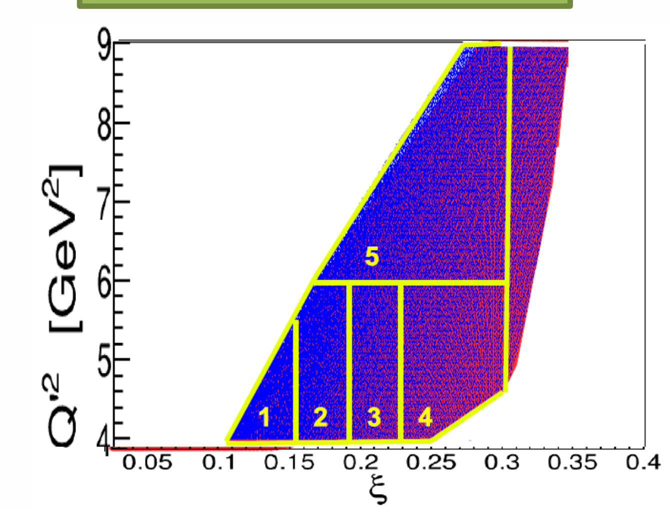
TCS circular beam asymmetry helps constrain Im{H} in fitting

Fit exercise (general)

	$(\sigma, \Delta\sigma_{LU})$ DVCS 5%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_ℓ 15%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_c 15%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_ℓ 5%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_c 5%
$\sigma^+(Re\{\mathcal{H}\})$	+1.21	+0.92	+0.80	+0.54	+0.55
$\sigma^-(Re\{\mathcal{H}\})$	-0.84	-0.79	-0.83	-0.44	-0.45
$\sigma^+(Im\{\mathcal{H}\})$	+0.23	+0.20	+0.15	+0.11	+0.12
$\sigma^-(Im\{\mathcal{H}\})$	-0.50	-0.40	-0.21	-0.27	-0.19

Go through SoLID simulation to get acceptance and counts for 50 days of running, then fit it

Fit exercise (SoLID TCS)



	$(\sigma, \Delta\sigma_{LU})$ DVCS + TCS_c
$\sigma^+(Re\{\mathcal{H}\})$	+0.82
$\sigma^-(Re\{\mathcal{H}\})$	-0.77
$\sigma^+(Im\{\mathcal{H}\})$	+0.16
$\sigma^-(Im\{\mathcal{H}\})$	-0.40

Michel Guidal and Marie Boer

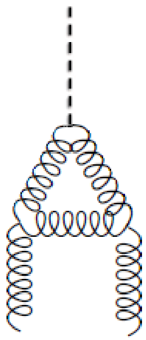
Conformal (Trace) Anomaly

- **Connecting**

<u>**Trace of energy momentum tensor**</u>

<u>**“Beta” function**</u> energy evolution of strong interaction coupling constant

$$\boxed{G^{\alpha\beta\gamma} G^{\gamma}_{\alpha\beta}}$$



$$\boxed{< N \,|\, \frac{\beta(g)}{2g} G^{\alpha\beta\gamma} G^{\gamma}_{\alpha\beta} + \sum_{u,d,s,} m_q \bar{q} q \,|\, N >= M_N}$$

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

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

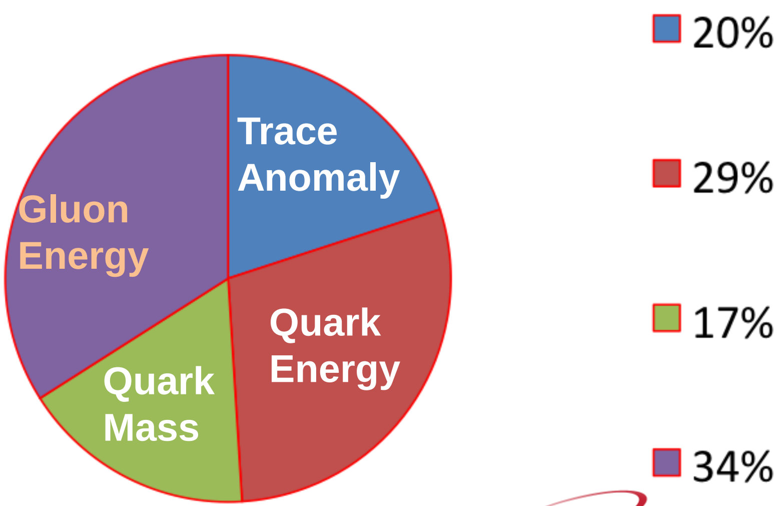
$H_m =$ Quark mass $\int d^3x\, \bar{\psi} m \psi$

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

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

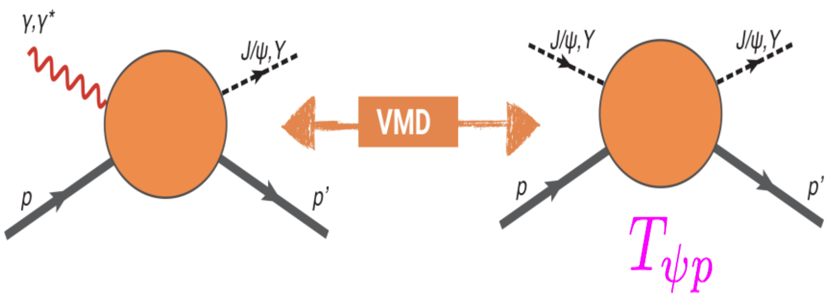
Sets the scale for the Hadron mass!

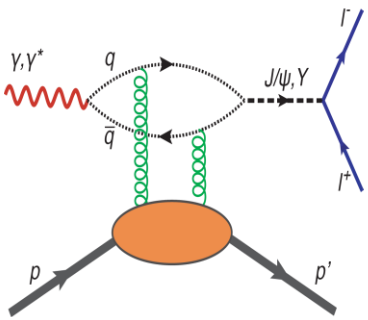
Proton Mass Budget



X. Ji PRL 74 1071 (1995)

From Cross section to the Trace Anomaly





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

Heavy quark – dominated by two gluons

$$\langle P|T^{\alpha}_{\alpha}|P\rangle = 2P^{\alpha}P_{\alpha} = 2M_p^2$$

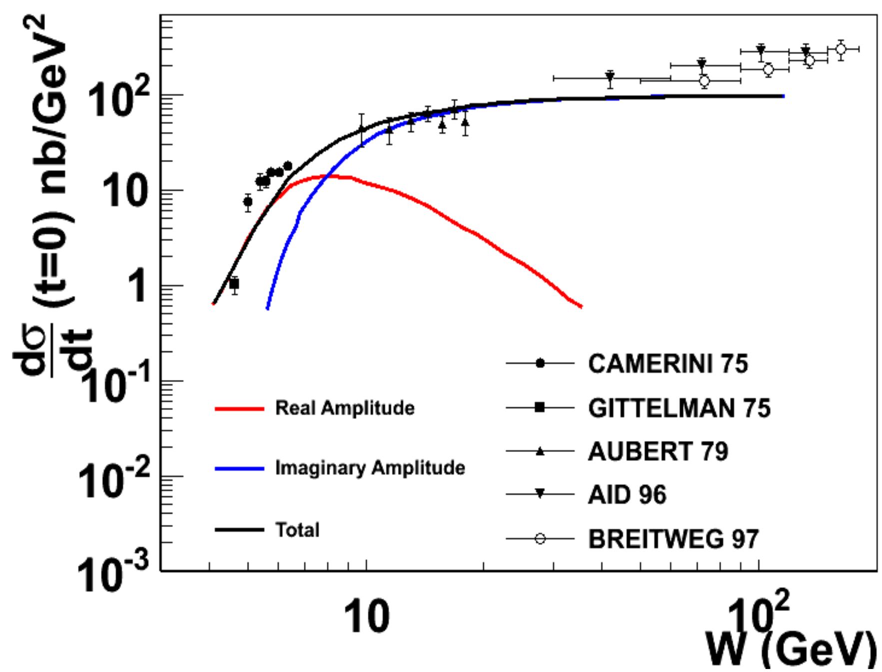
$$\frac{d\sigma_{\gamma N \to \psi N}}{dt}(s, t=0) = \frac{3\Gamma(\psi \to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N \to \psi N}}{dt}(s, t=0)$$

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

- **VMD relates photoproduction cross section to quarknium-nucleon scattering amplitude**

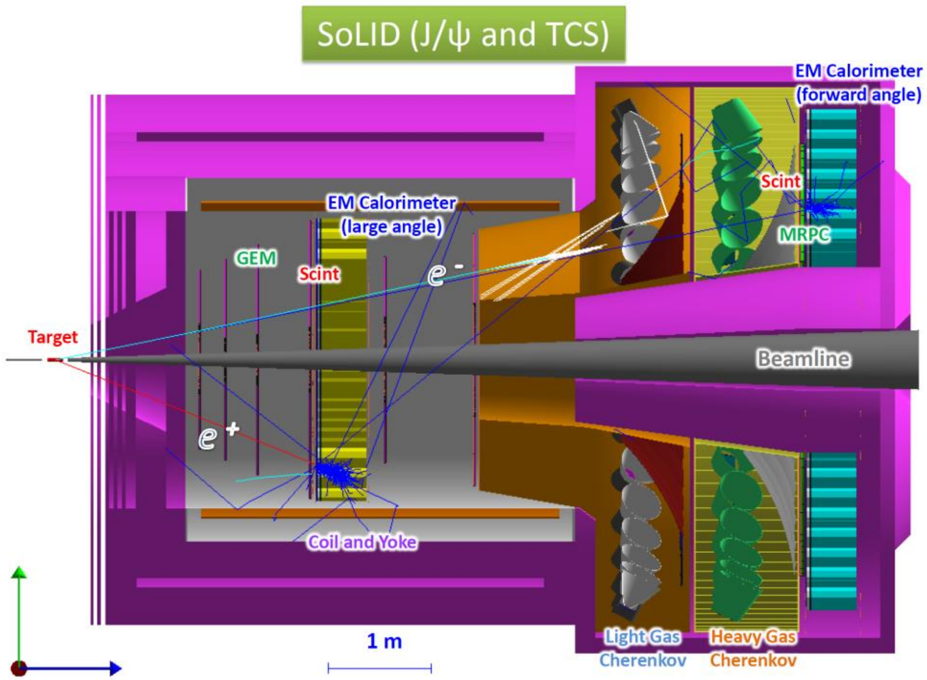
- **Imaginary part** is related to the total cross section through optical theorem

- **Real part contains the conformal (trace) anomaly;** Dominate the near threshold region and constrained through dispersion relation



A measurement near threshold could allow access to the trace anomaly

SoLID J/ψ Program

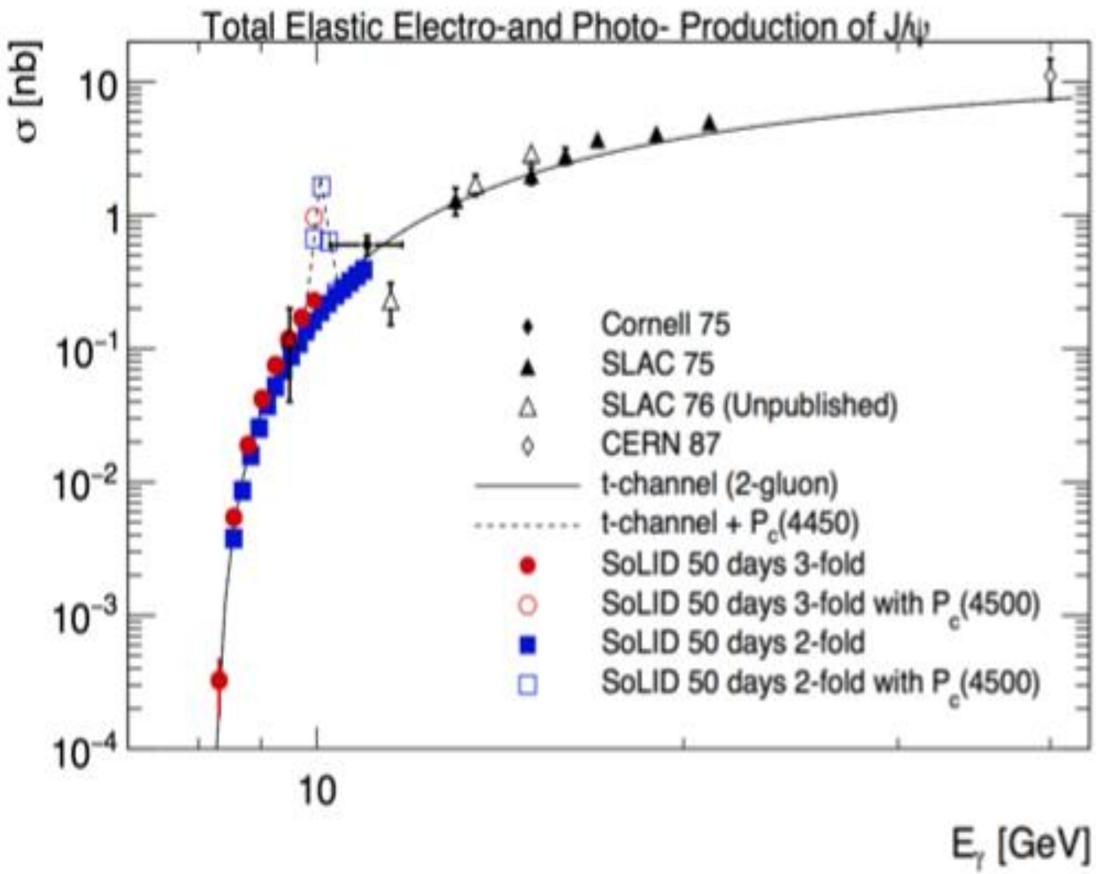


$$e\ p \rightarrow e'\ p'\ J/\psi(e^-\ e^+)$$
$$\gamma\ p \rightarrow p'\ J/\psi(e^-\ e^+)$$

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
- Goals: 10% stats and 15% syst. Uncertainties
- Kinematics:
  - $4.05 < W < 4.45$ GeV
  - $|t - t_{min}| < 2.5$ GeV^2

SoLID J/ψ Projection



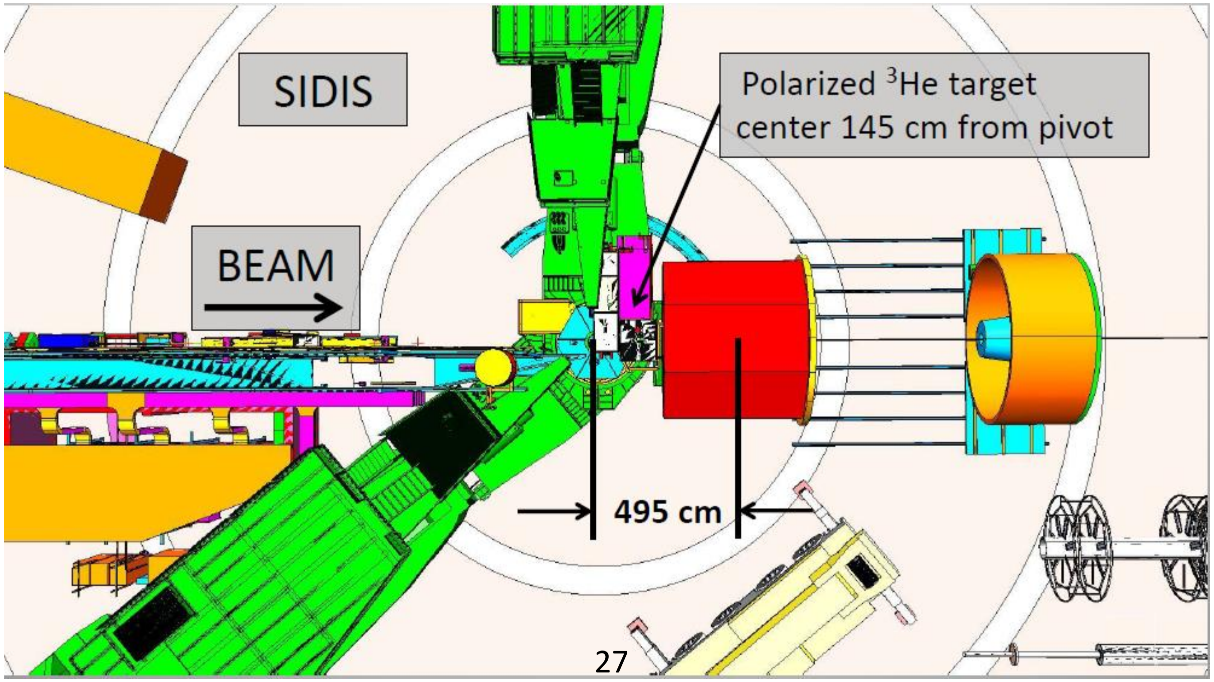
Total and differential crosssection precision measurement near threshold

Explore trace anomaly extraction and access to proton mass

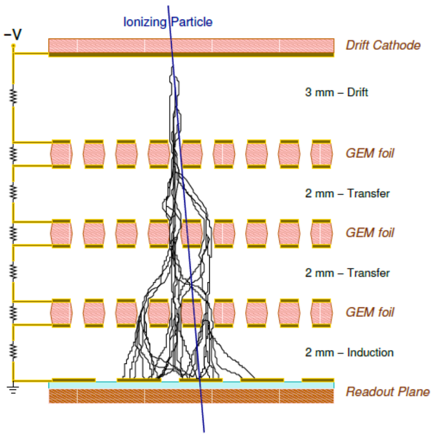
SoLID Subsystems - Magnet

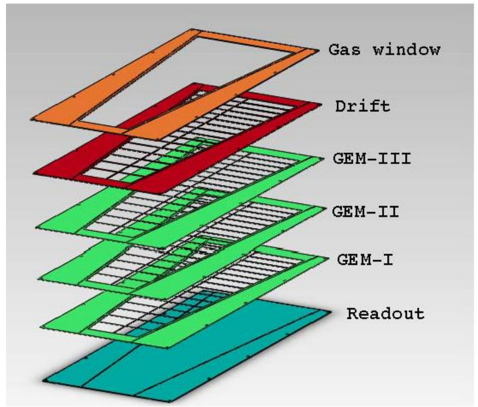
CLEO-II magnet,
3m diameter, 3.5m long,
field ~1.5T

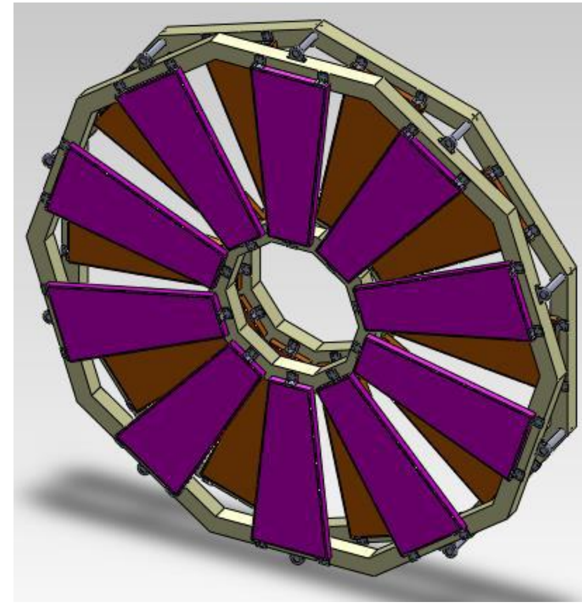
moved to JLab in 2016

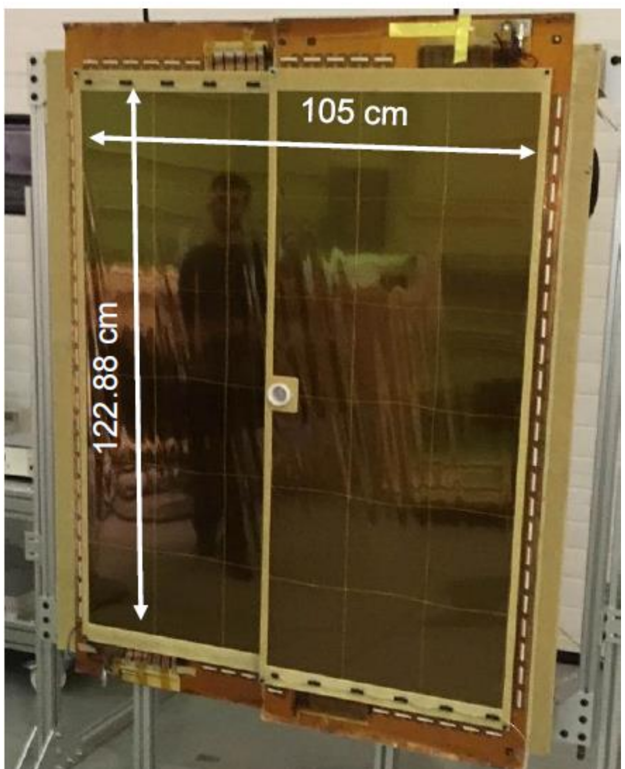


SoLID Subsystems - GEM



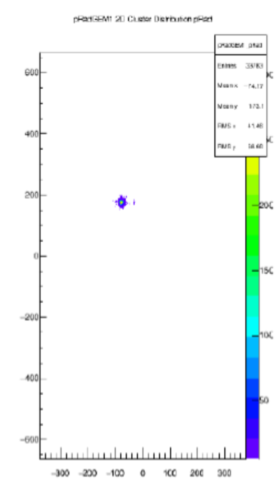






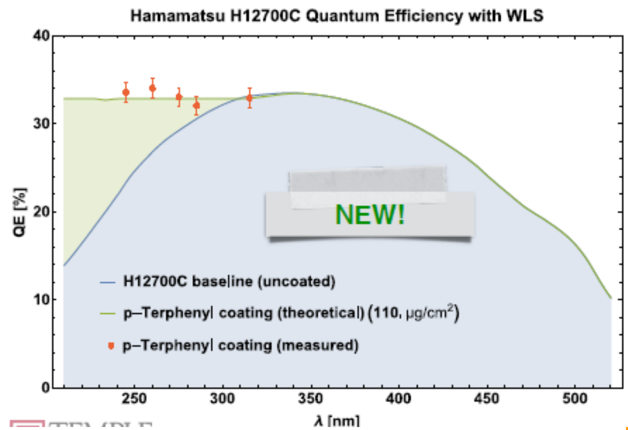
Gas Electron Multiplier

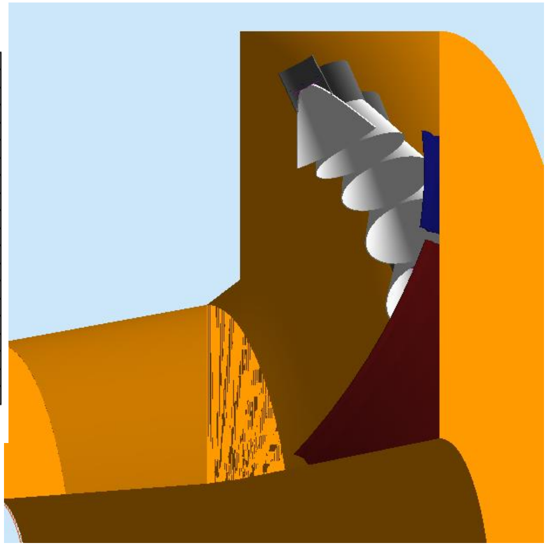
High rate capable trackers with multi-layers and large area



Largest GEM built and ran in experiment, PRad June 2016

SoLID Subsystems - Cherenkov

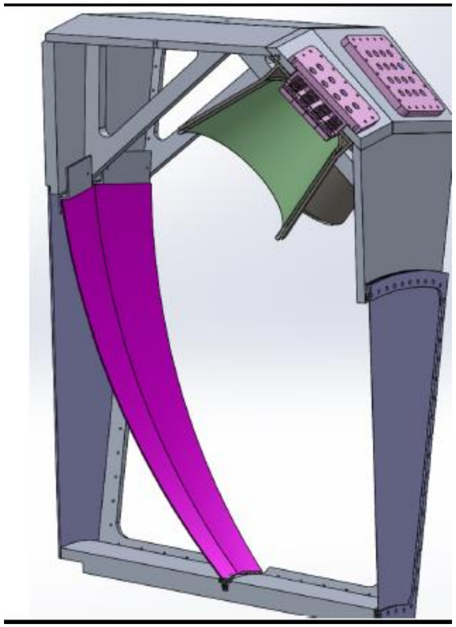


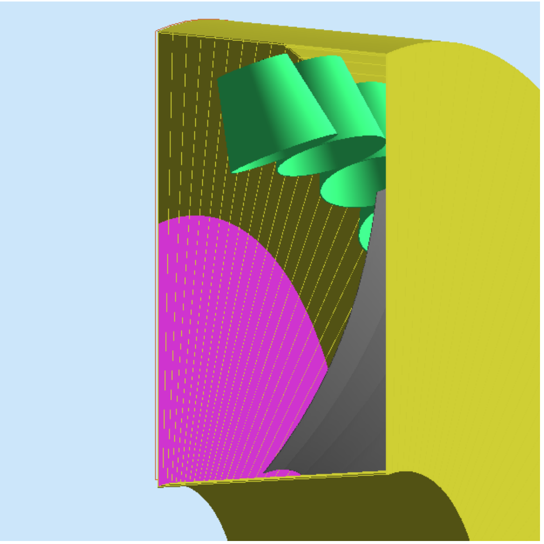


Light gas (CO_2)

identify electrons

suppress pions



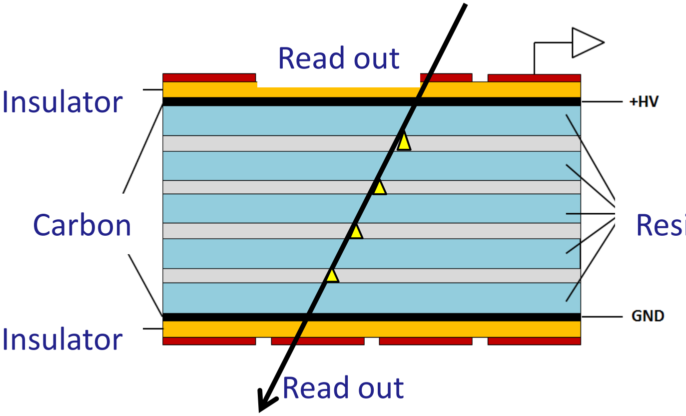


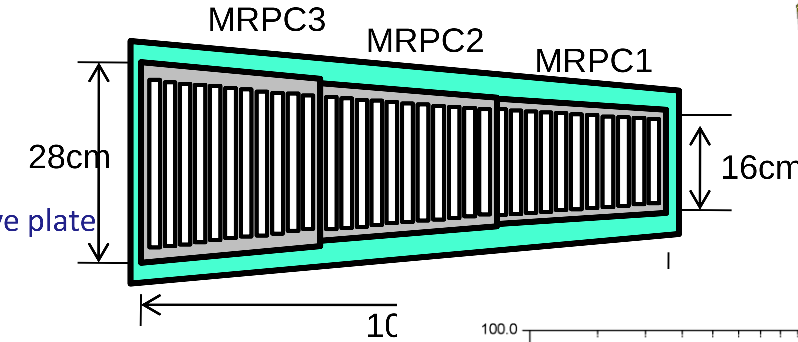
Heavy gas

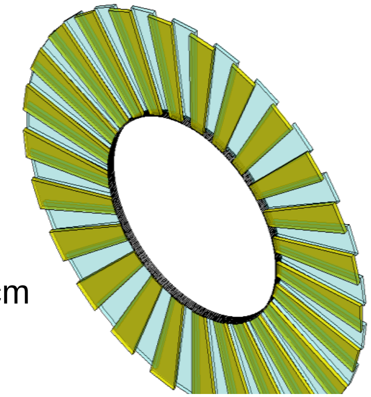
identify pions

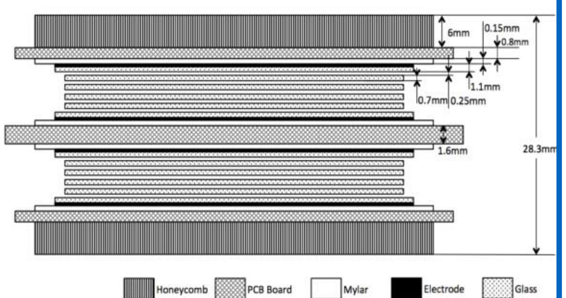
suppress kaons

SoLID Subsystems - MRPC



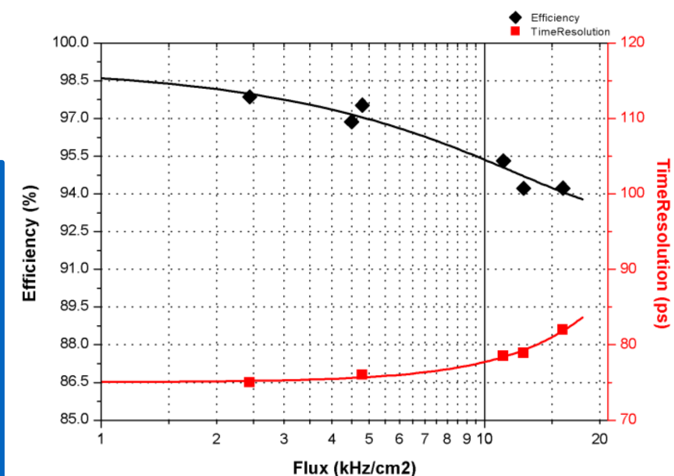


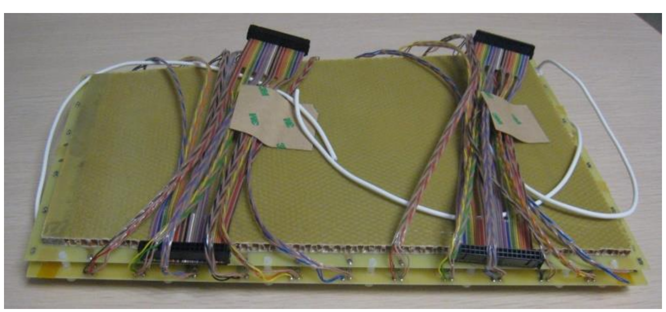


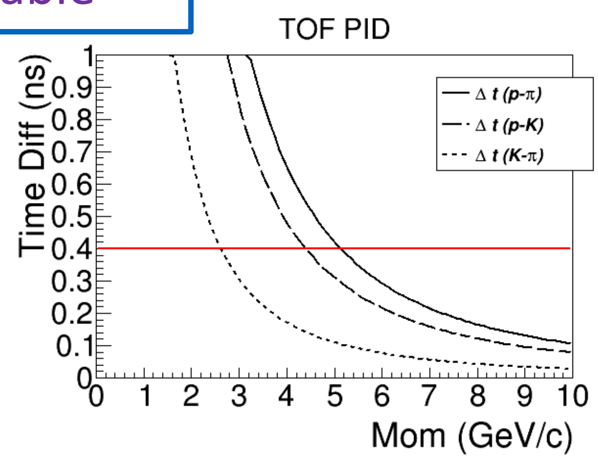


Multi-gap Resistive Plate Chamber

~100ps time resolution, fast and high rate capable

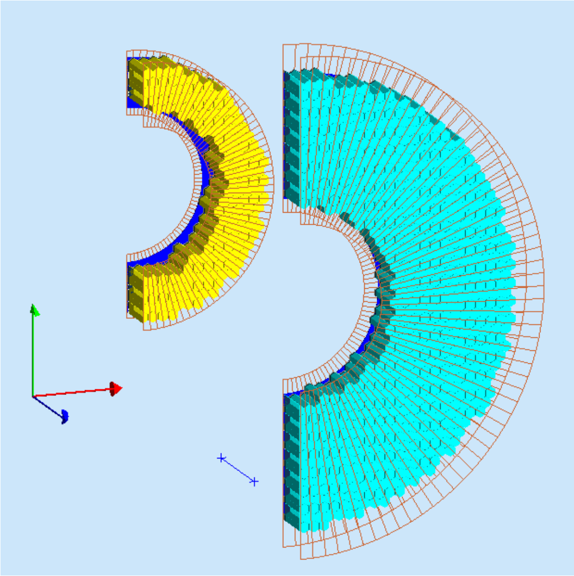


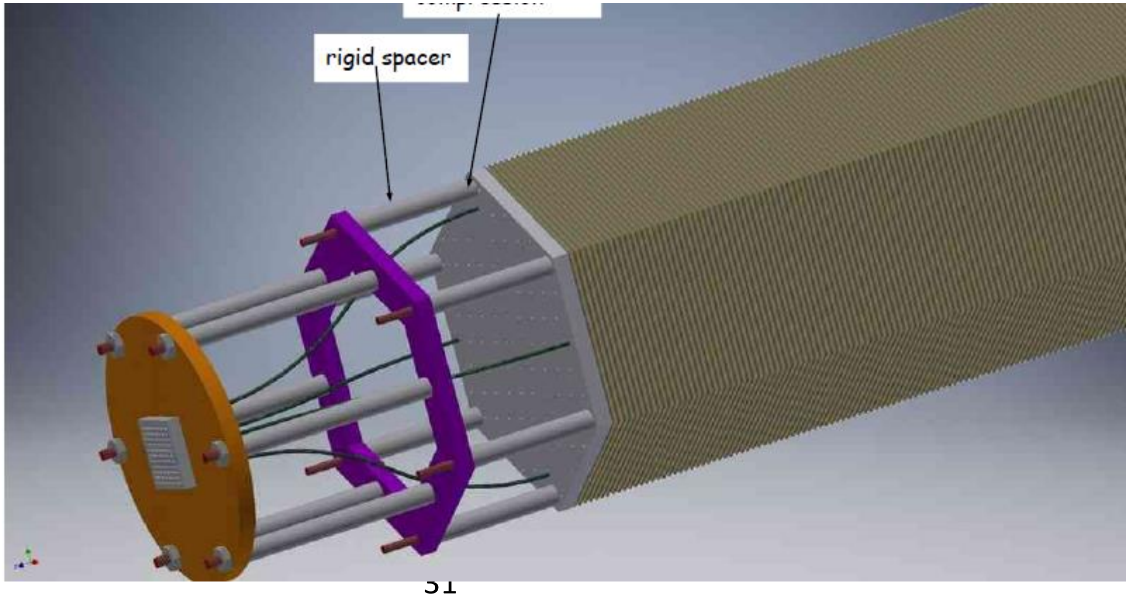




SoLID Subsystems - ECAL

shashlik calorimeter, good resolution and radiation hardness

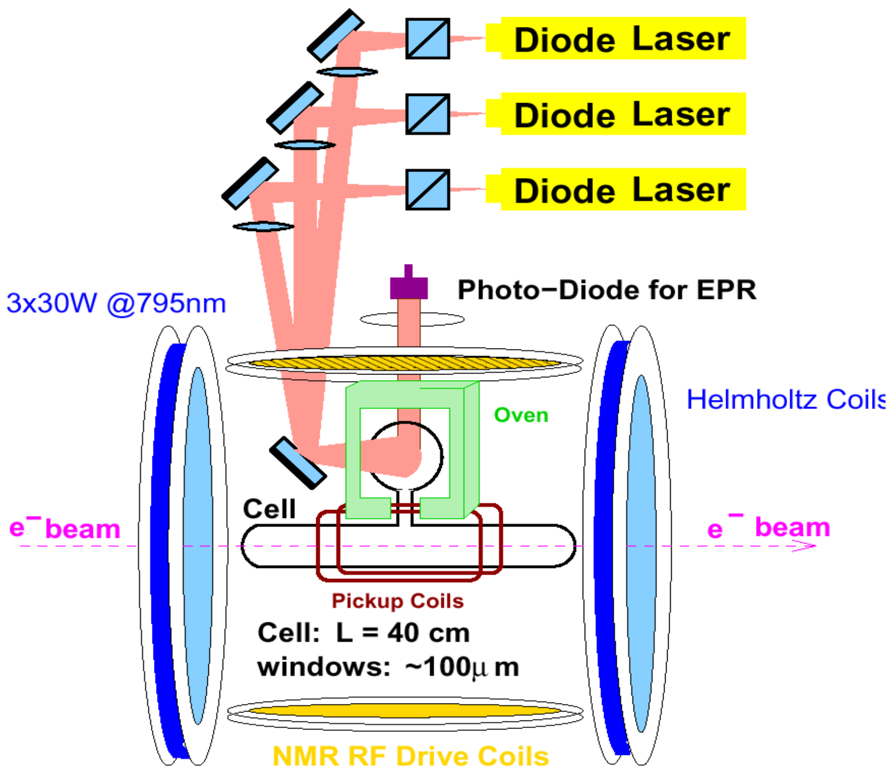




SoLID Subsystems – Target

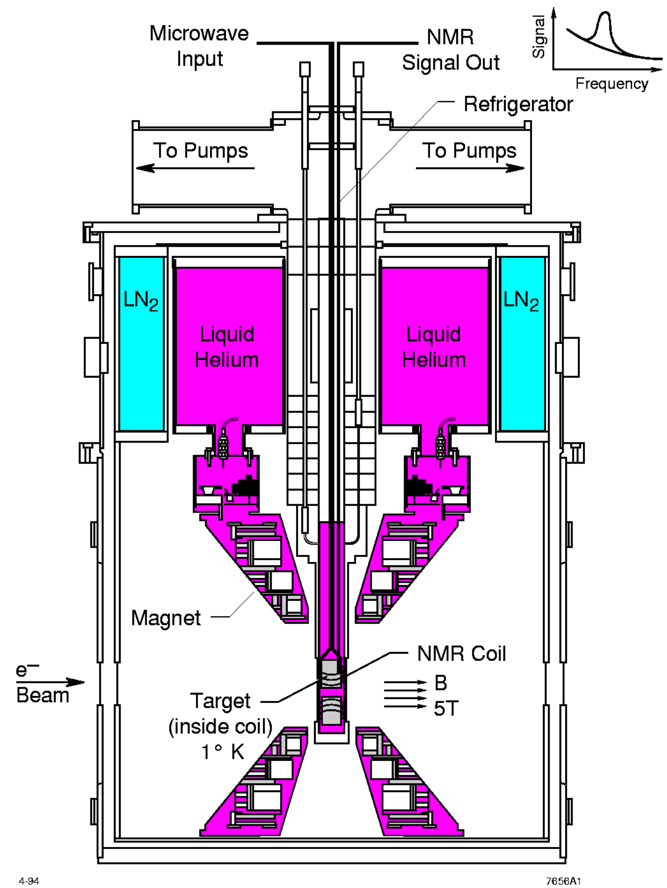
polarized ^{3}He target

luminosity >= $10^{36}/cm^2/s$ (world record)
High in-beam polarization ~ 60%



polarized NH_3 target

luminosity >= $10^{35}/cm^2/s$
High in-beam polarization ~ 70%



Summary of SoLID Program

- PVDIS: Standard Model test and hadron structure
- Nucleon 3D imaging:
  - Precision TMD measurement via SIDIS
  - Additional GPD measurement via TCS
- J/ψ near threshold: trace anomaly and proton mass
- More experiments will be proposed
- With high luminosity and large acceptance, SoLID will fully exploit the capabilities of JLab 12GeV upgrade

Thank you!

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

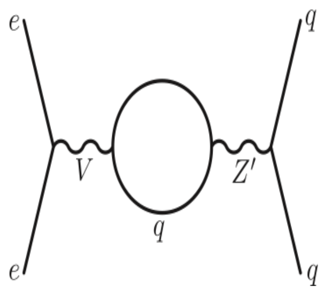
backup

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.

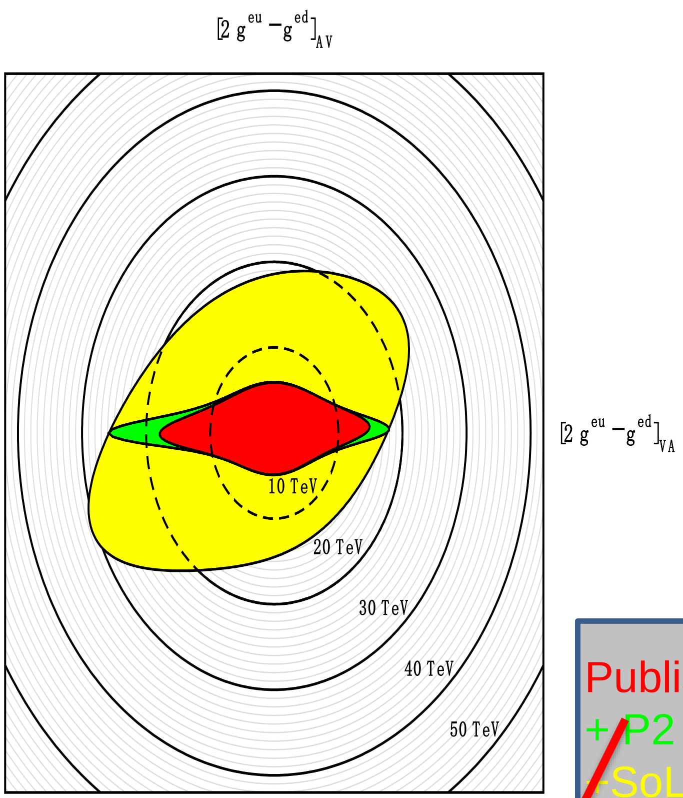
Example: lepto-phobic Z' contributes only to g^{eq}_{VA}



PVDIS also probes hadronic physics:

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

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

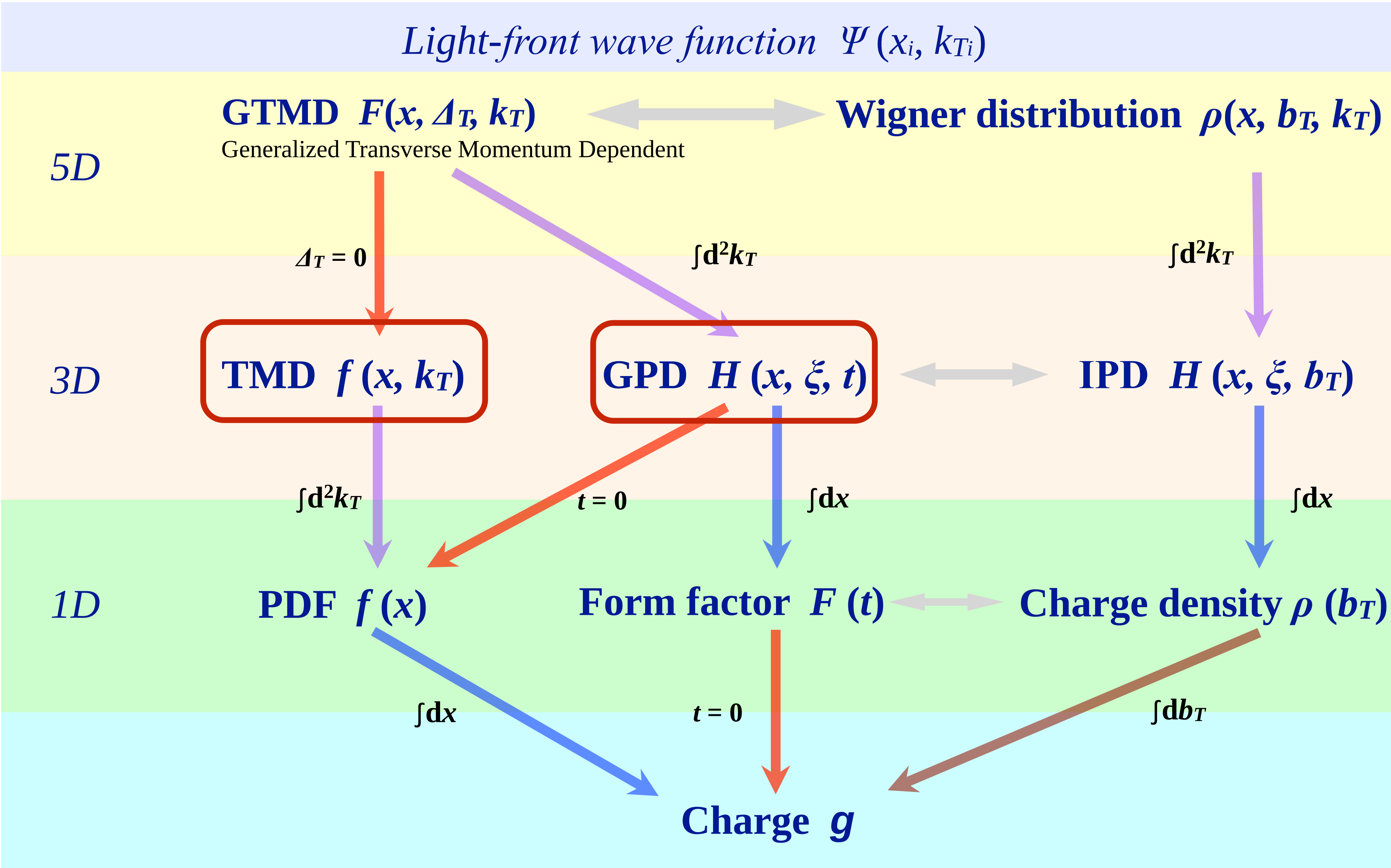


Published data
+ P2 at Mainz
+SoLID

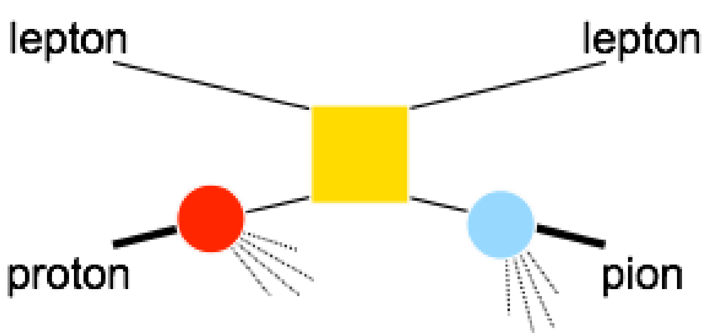
Nature **557**, no. 7704, 207 (2018)

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

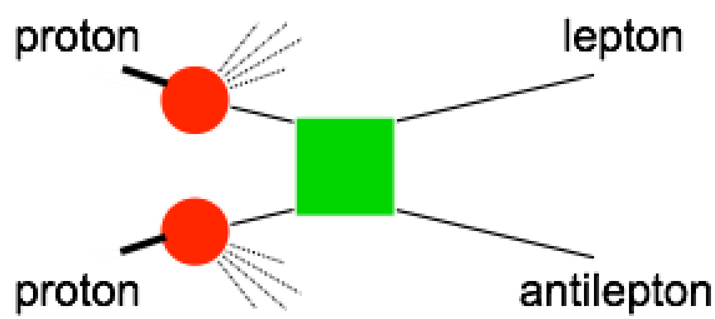
Unified View of Nucleon Structure



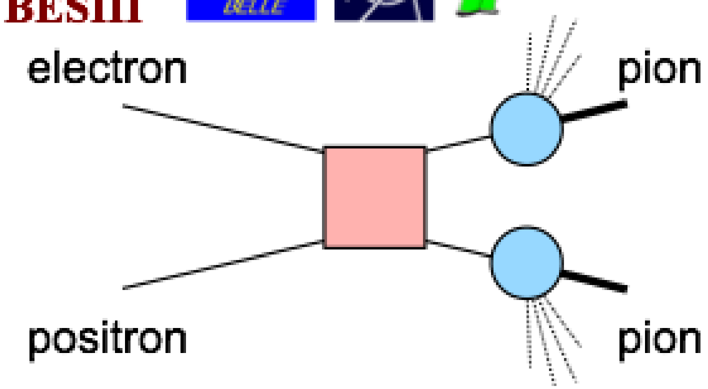
Access TMDs through Hard Processes



SIDIS



Drell-Yan



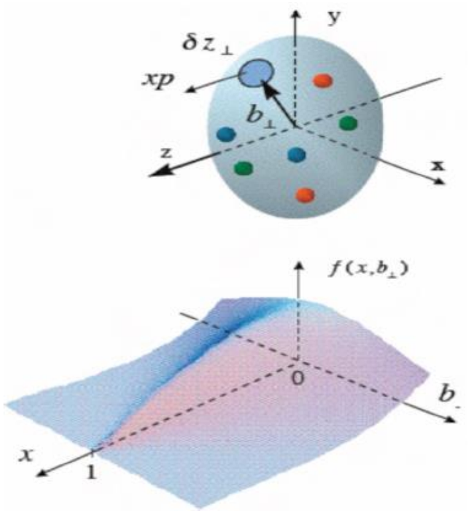
$e^{-}e^{+}$ to pions

Partonic scattering amplitude

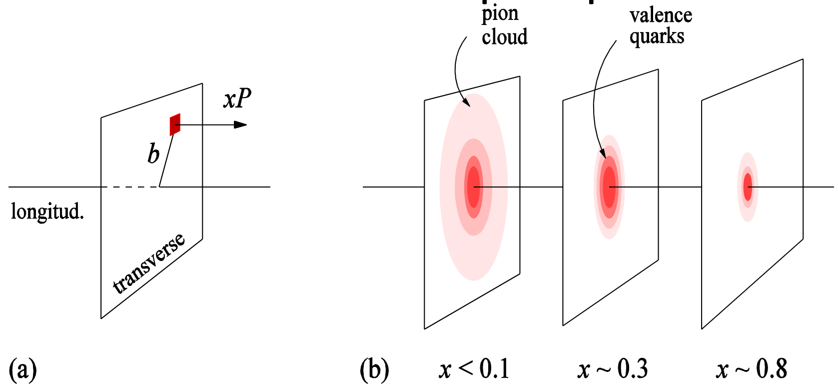
Fragmentation amplitude

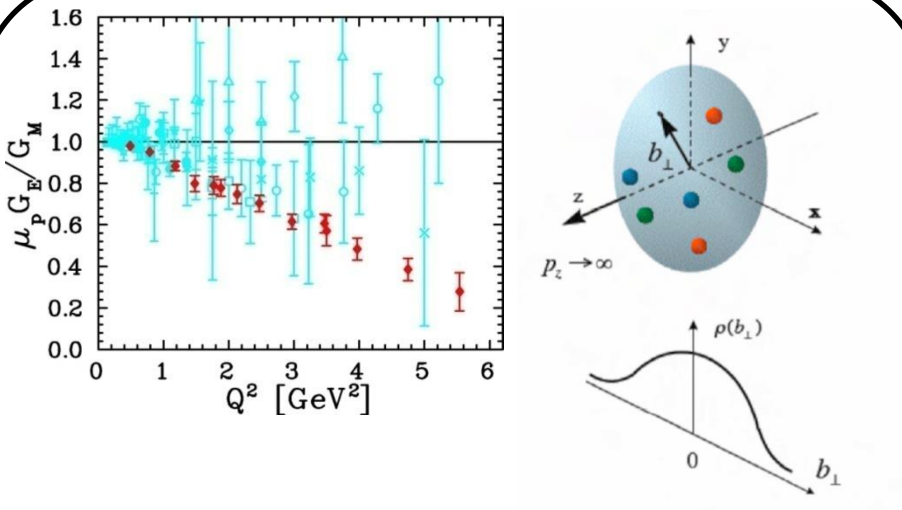
Distribution amplitude

Generalized Parton Distribution (GPD)



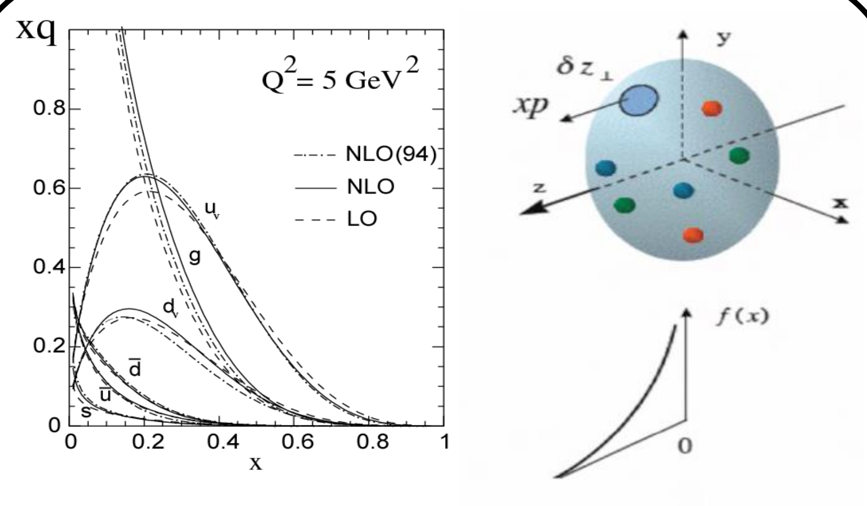
A unified descriptions of partons (quarks and gluons) in the momentum and impact parameter space





Elastic form factors

Transverse spatial distributions



Parton Distribution Functions

Longitudinal momentum distributions

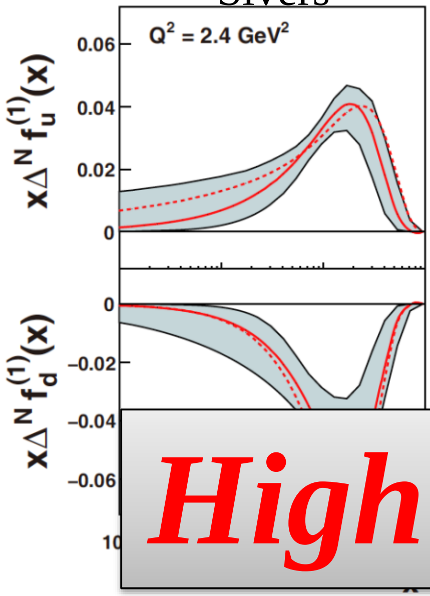
Leading Twist TMDs

→ Nucleon Spin
→ Quark Spin

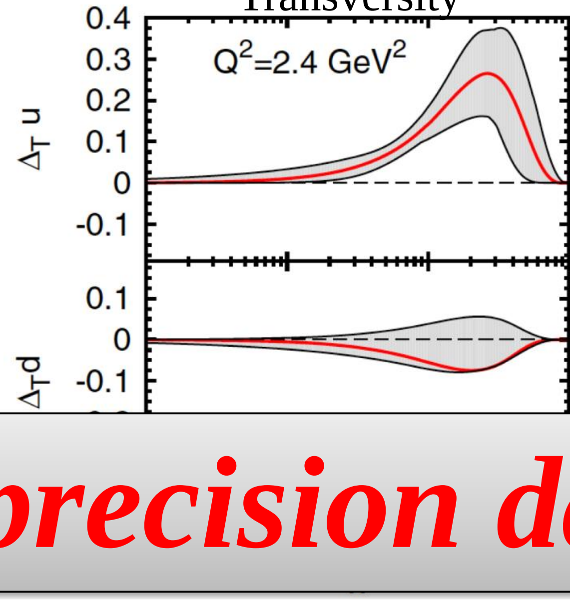
Nucleon Polarization	Quark Polarization: U	Quark Polarization: L	Quark Polarization: T
U	f_1 unpolarized		$h_1^\perp$ Boer-Mulders
L		g_{1L} helicity	$h_{1L}^\perp$ longi-transversity (worm-gear)
T	$f_{1T}^\perp$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity $h_{1T}^\perp$ pretzelosity

Present Status On TMD Extractions

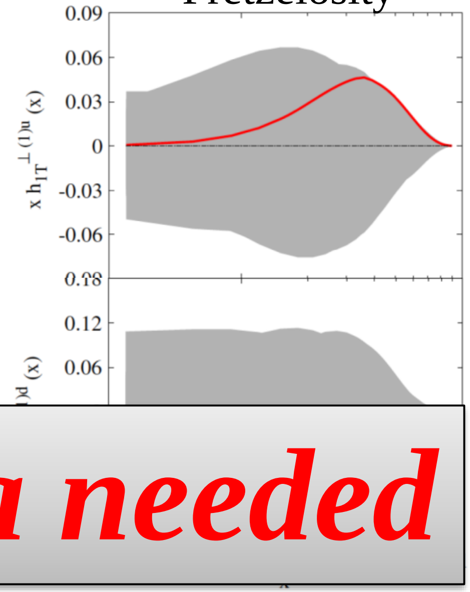
Sivers



Transversity



Pretzelosity



High precision data needed

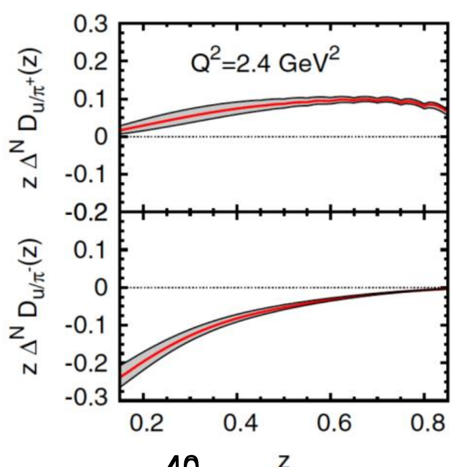
Anselmino et al, EPJA39, 89 (2009)

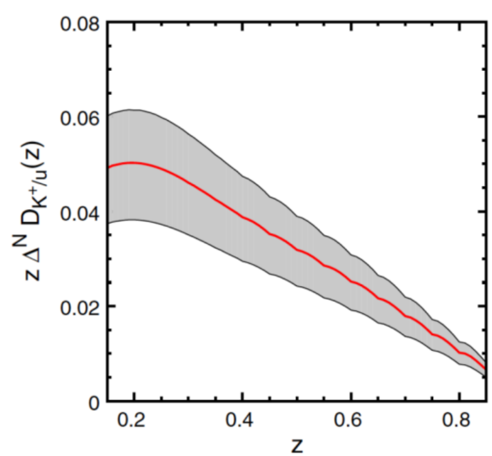
Anselmino et al, PRD92, 114023 (2015)

Lefky et al, PRD91, 034010 (2015)

Collins fragmentation

Anselmino et al, PRD92, 114023 (2015)
PRD93, 034025 (2016)





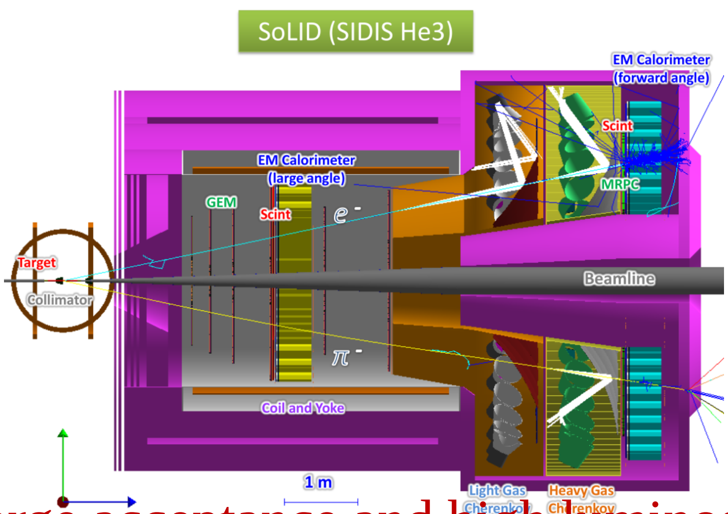
SIDIS @ SoLID

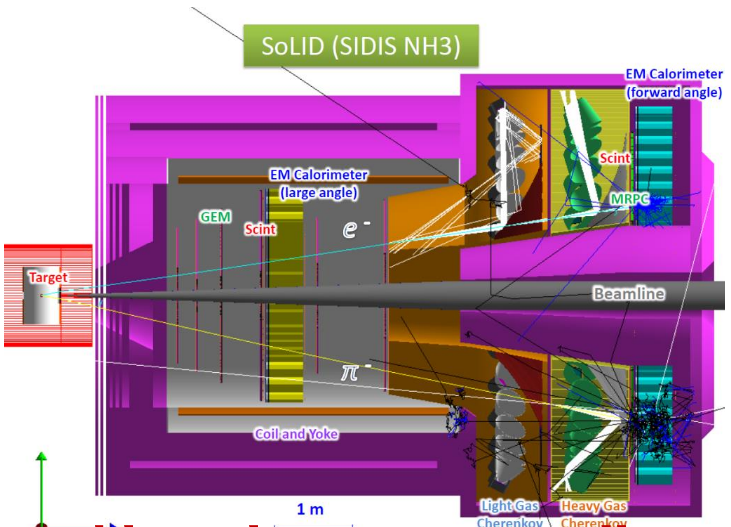
Approved SIDIS experiments rated with A
11/8.8 GeV beam, polar angle 8˚~24˚, full 2π azimuthal angle

- E12-10-006: Single Spin Asymmetry on transversely polarized ^{3}He, 90 days, **rated A**
- E12-11-007: Single and Double Spin Asymmetries on longitudinally polarized ^{3}He, 35 days, **rated A**

- run group
  - Dihadron process
  - Ay inclusive

- E12-10-008: Single Spin Asymmetry on transversely polarized proton (NH_3), 120 days, **rated A**





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

SoLID SIDIS Resolution and Error

	θ angle (mrad)	ϕ angle (mrad)	Vertex z (cm)	p (%)
SIDIS ^{3}He fwd angle (e)	1.3	5.7	0.9	1.7
SIDIS ^{3}He fwd angle (π)	1.2	5.2	0.9	1.1
SIDIS ^{3}He large angle (e)	1.0	1.7	0.5	1.2
PVDIS (e)	0.8	1.7	0.3	1.2

Table 21: Averaged resolutions by track fitting with most of material energy loss and without background

$E_{\rm beam}$ (GeV)	x	z	Q^2(GeV^2)	$P_{h\perp}$(GeV)	ϕ_h(rad)	ϕ_S(rad)
11	0.002	0.003	0.02	0.006	0.015	0.006
8.8	0.002	0.004	0.02	0.006	0.018	0.006

Table 23: Resolution of kinematical variables (in the Trento convention) with the ^{3}He target setup.

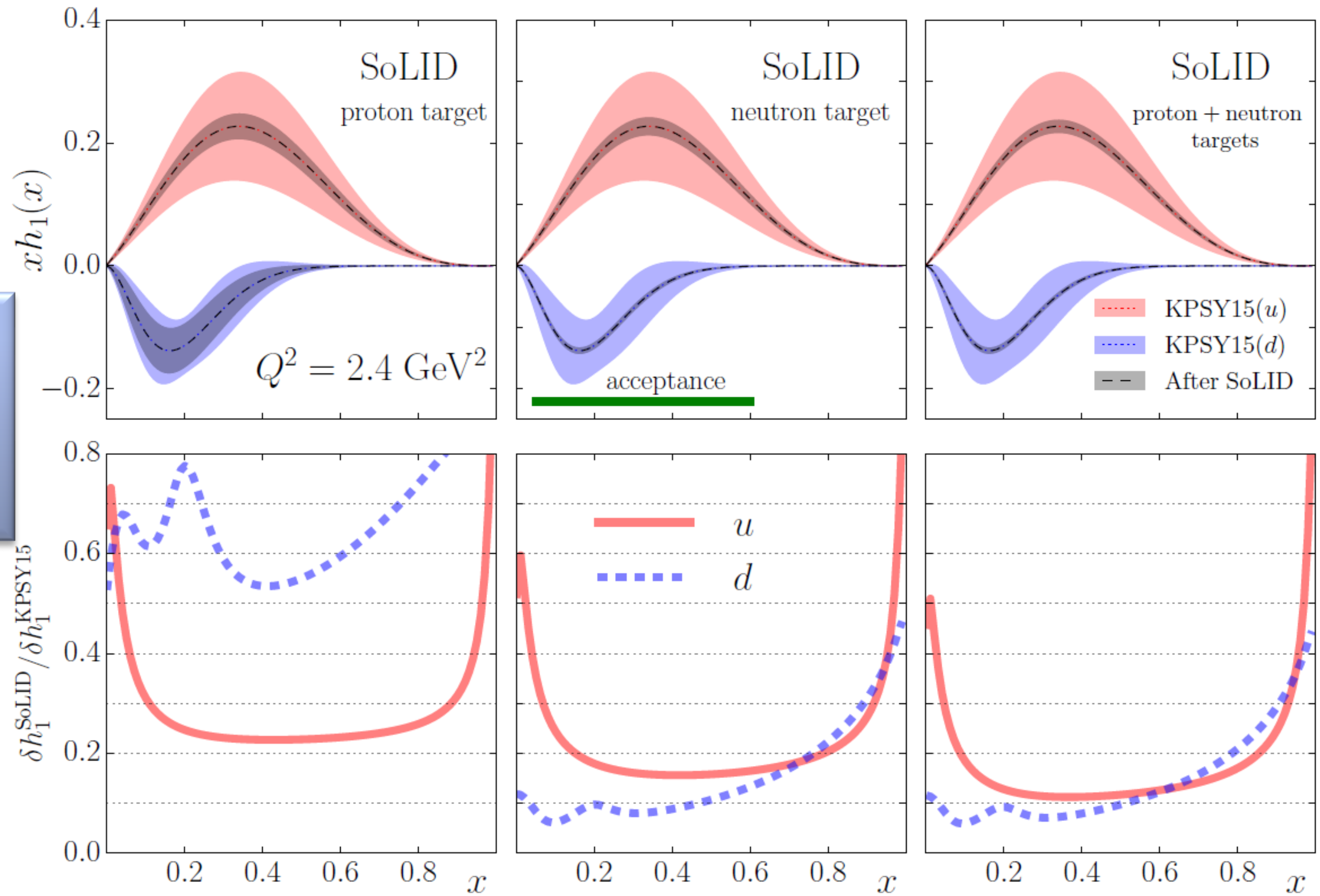
$P_{h\perp}$(GeV/c)	[0.0, 0.2]	[0.2, 0.4]	[0.4, 0.6]	[0.6, 0.8]	[0.8, 1.0]	[1.0, 1.2]
11 GeV beam (π^+)	110	160	150	105	75	40
11 GeV beam (π^-)	120	160	140	90	70	50
8.8 GeV beam (π^+)	75	95	80	50	45	
8.8 GeV beam (π^-)	65	95	75	50	45	

Table 24: The ratio of SIDIS signal and random coincidence background within 6 ns. These values are estimated with the ^{3}He target. Similar results are obtained for the proton target.

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

Table 25: The systematic uncertainties on the asymmetry measurements of SIDIS.

SoLID Impact on Transversity



1 order improve-ment

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

Including both systematic and statistical errors

KPSY 15: Z.-B. Kang *et al.*, PR D 93, 014009 (2016).

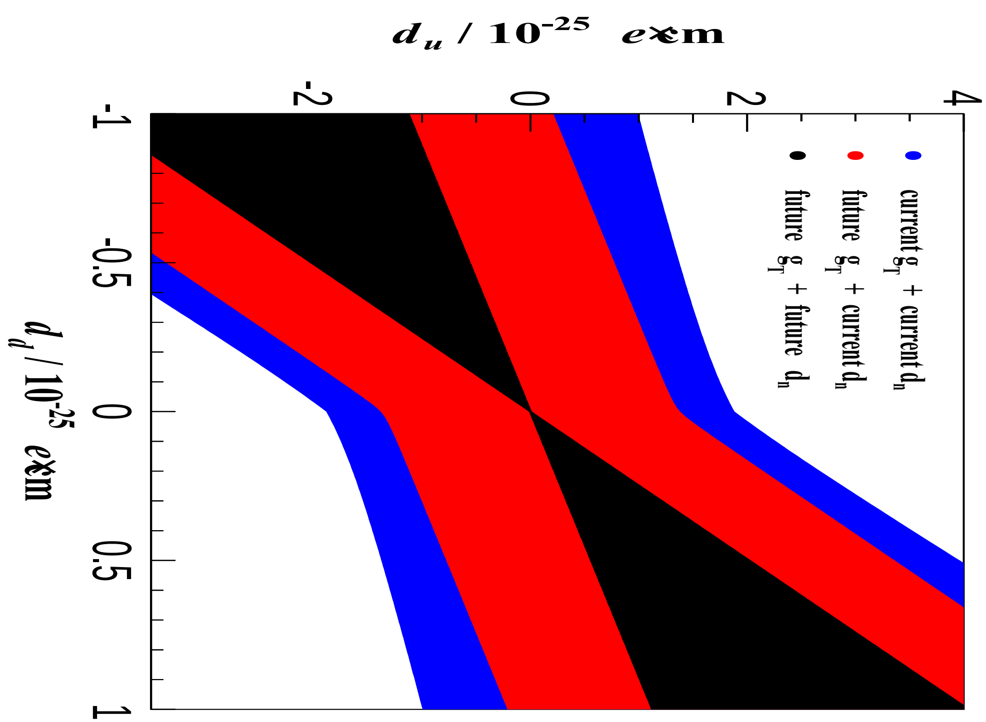
Constraint on Quark EDMs

Current upper limit on the neutron EDM

$$3.0 \times 10^{-26}\, e\,\mathrm{cm} \quad (90\%\ \mathrm{CL})$$

J.M. Pendlebury et al., Phys. Rev. D 92, 092003 (2015). [Re-analysis]
C.A. Baker et al., Phys. Rev. Lett. 97, 131801 (2006).

Constraint on quark EDMs with tensor charge



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

Using g_T^s from lattice calculation

- Future g_T: SoLID projected tensor charge
- Future d_n: $3.0\times10^{-28} e$ cm

H. Gao, T. Liu, Z. Zhao, arXiv:1704.00113, to appear in PRD

Constraint on Quark EDMs

Current upper limit on the proton EDM

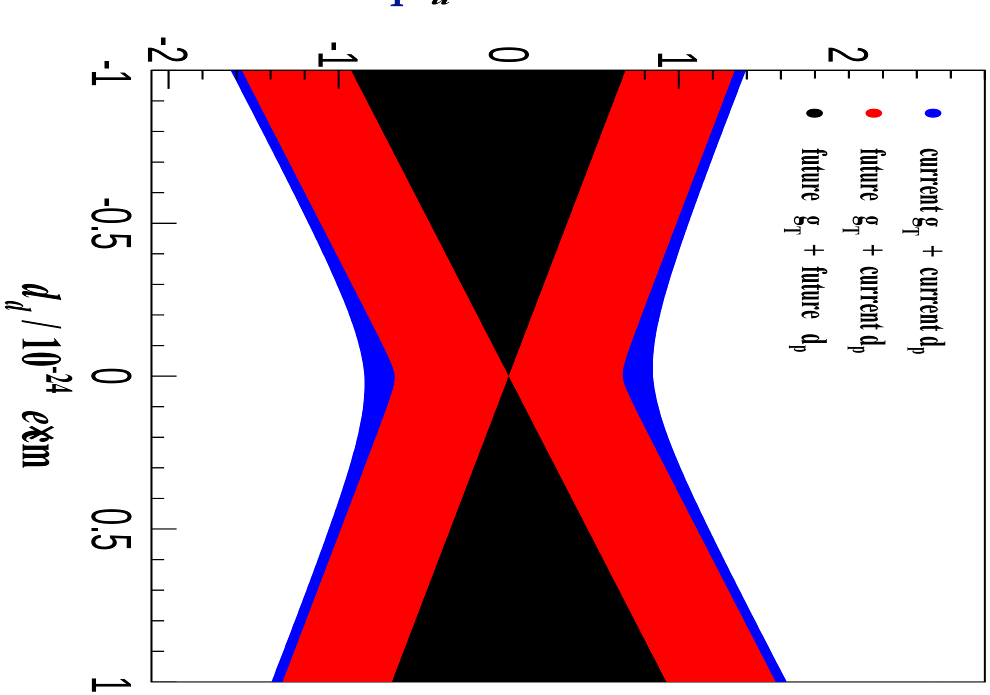
- Mercury atom EDM
  limit: $7.4 \times 10^{-30}\, e\,\mathrm{cm} \quad (95\%\ \mathrm{CL})$

- Derived proton EDM
  limit: $2.6 \times 10^{-25}\, e\,\mathrm{cm}$

B. Graner et al., Phys. Rev. Lett. 116, 161601 (2016).

Schiff moment method including the uncertainty among different theoretical models

Constraint on quark EDMs with tensor charge



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

Using g_T^s from lattice calculation

- Future g_T: SoLID projected tensor charge

- Future d_p: $2.6\times10^{-29} e$ cm

H. Gao, T. Liu, Z. Zhao, arXiv:1704.00113, to appear in PRD

Constraint on Quark EDMs (III)

Constraint on quark EDMs with combined proton and neutron EDMs

	d_u upper limit	d_d upper limit
Current g_T + current EDMs	$1.27\times10^{-24} e$ cm	$1.17\times10^{-24} e$ cm
SoLID g_T + current EDMs	$6.72\times10^{-25} e$ cm	$1.07\times10^{-24} e$ cm
SoLID g_T + future EDMs	$1.20\times10^{-27} e$ cm	$7.18\times10^{-28} e$ cm

Include 10% isospin symmetry breaking uncertainty

Sensitivity to new physics

$$d_q \sim e m_q/(4\pi\Lambda^2)$$

Three orders of magnitude improvement on quark EDM limit → Probe to 30 ~ 40 times higher scale

Current quark EDM limit: $10^{-24} e$ cm → ~ 1 TeV

Future quark EDM limit: $10^{-27} e$ cm → 30 ~ 40 TeV

H. Gao, T. Liu, Z. Zhao,
arXiv:1704.00113, to appear in PRD

Unpolarized Quark in $p\uparrow$

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

Sivers distribution

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

naively time-reversal odd.

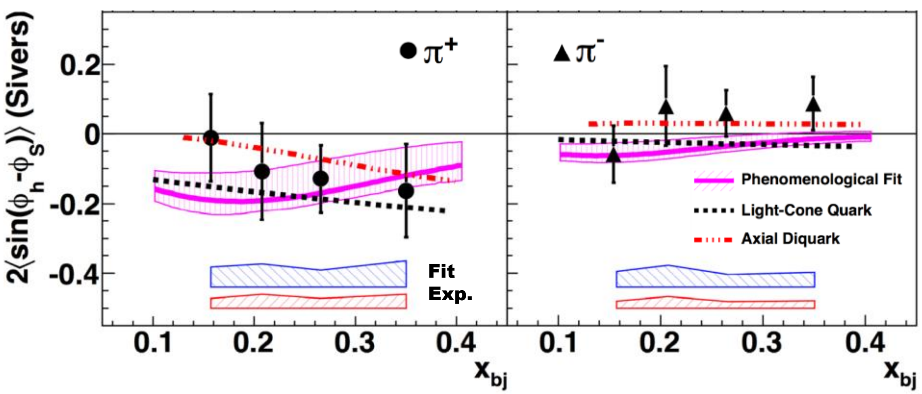
$$f_{1T}^{\perp q}(x,k_\perp)\Big|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x,k_\perp)\Big|_{\text{DY}}$$

Measurement in SIDIS

Single spin asymmetry

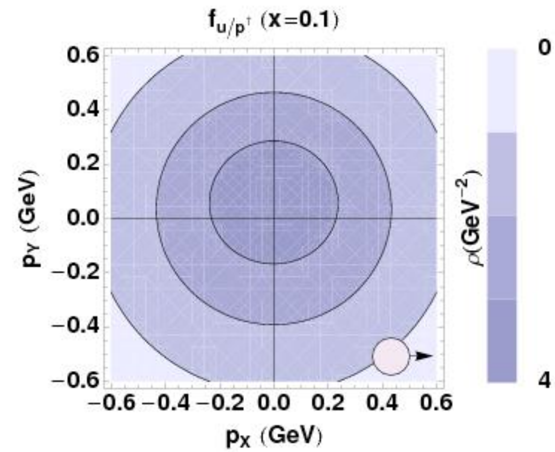
(Sivers asymmetry)

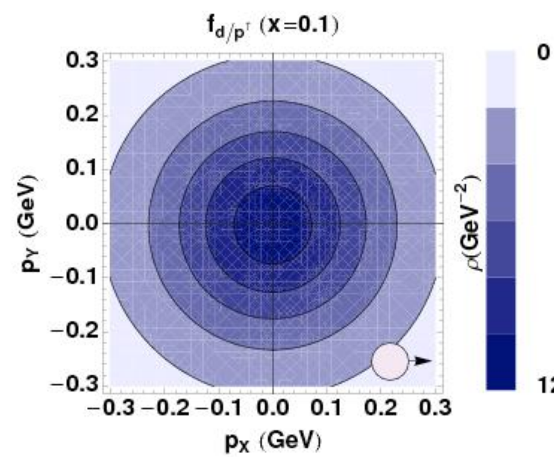
$$A_{UT}^{\sin(\phi_h-\phi_S)} \sim f_{1T}^{\perp}(x,k_\perp)\bigotimes D_1(z,p_\perp)$$



6 GeV JLab E06-010, X. Qian *et al.*, PRL 107, 072003 (2011).

Model Calculation

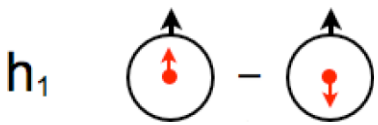




Bacchetta, Conti, Radici
PR D 78, 074010 (2008).

Transverse Spin Structure

Transversity



(Collinear & TMD)

A transverse counter part to the longitudinal spin structure: helicity g_{1L}

They are NOT the same due to relativity.

Chiral-odd

Unique for the quarks.
No mixing with gluons.
Simpler evolution effect.

NOT accessible via inclusive DIS process.
Must couple to another chiral-odd function.
(*e.g.* Collins function $H_1^{\perp}$)

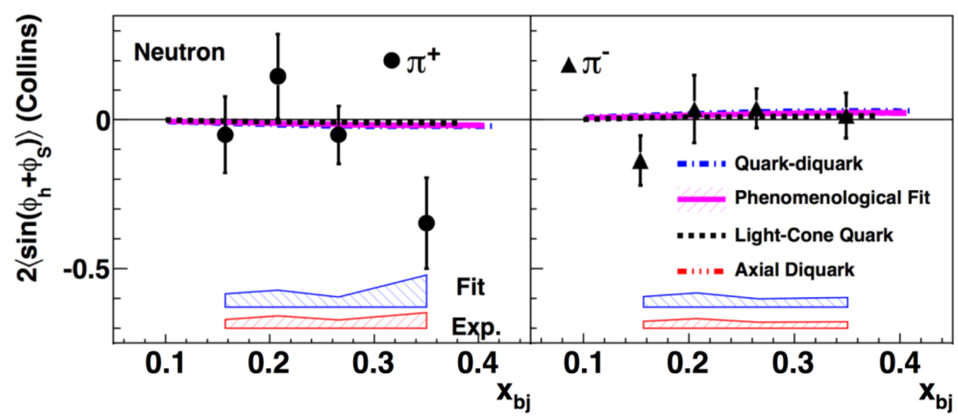
Measured via
SIDIS (E12-10-006, E12-11-008), Drell-Yan
Di-hadron (E12-10-006A)

Measurement in SIDIS

Single spin asymmetry
(Collins asymmetry)

$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1(x, k_\perp) \bigotimes H_1^{\perp}(z, p_\perp)$$

$H_1^{\perp}(z, p_\perp)$ Collins fragmentation function



6 GeV JLab E06-010, X. Qian *et al.*, PRL 107, 072003 (2011).

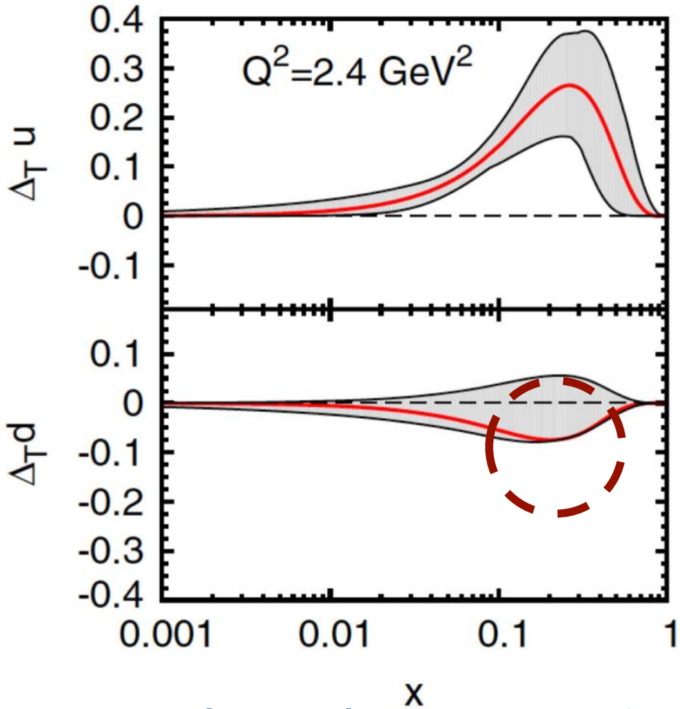
Soffer's Inequality

Soffer's bound

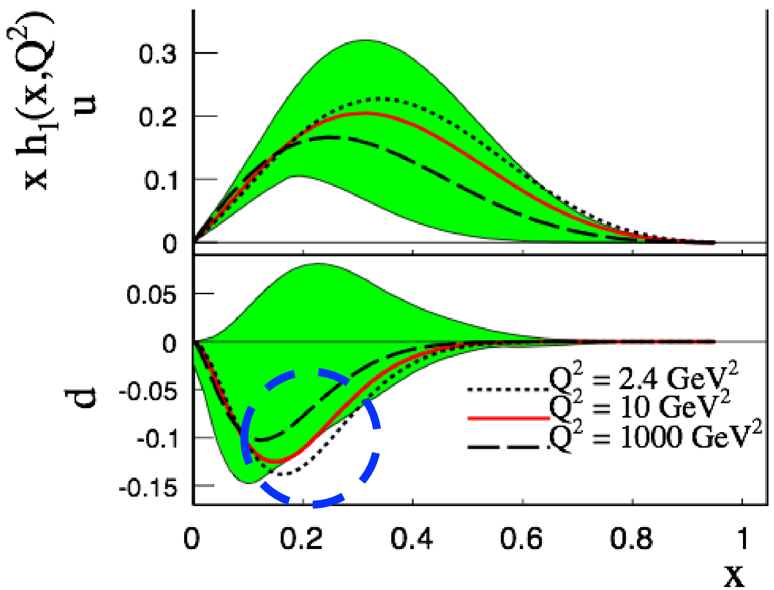
$$|h_1(x)| \leq \frac{1}{2}\left[f_1(x) + g_{1L}(x)\right]$$

Derived by using the positivity constraint on the forward scattering helicity amplitude.

Global fits of transversity



M. Anselmino *et al.*, PR D 92, 114023 (2015).



Z.-B. Kang *et al.*, PR D 93, 014009 (2016).

Test Soffer's inequality @ SoLID

Deep Exclusive Meson Production

A special kinematic regime is probed in DEMP, where the initial hadron emits $q\bar{q}$ or *gg* pair.

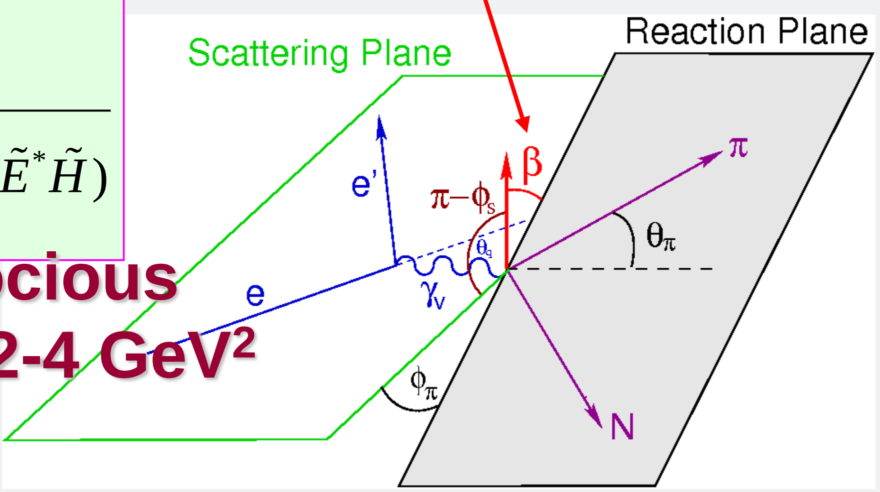
- GPD $\tilde{E}$ not related to an already known parton distribution.
- Experimental information on $\tilde{E}$ can provide new nucleon structure info unlikely to be available from any other source.
- The most sensitive observable to probe $\tilde{E}$ is the transverse single-spin asymmetry in exclusive π production

$$A_L^\perp = \frac{\left(\int_0^\pi d\beta \frac{d\sigma_L^\pi}{d\beta} - \int_\pi^{2\pi} d\beta \frac{d\sigma_L^\pi}{d\beta}\right)}{\left(\int_0^{2\pi} d\beta \frac{d\sigma_L^\pi}{d\beta}\right)}$$

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

$d\sigma_\pi^L$ = exclusive π cross section for longitudinal γ*

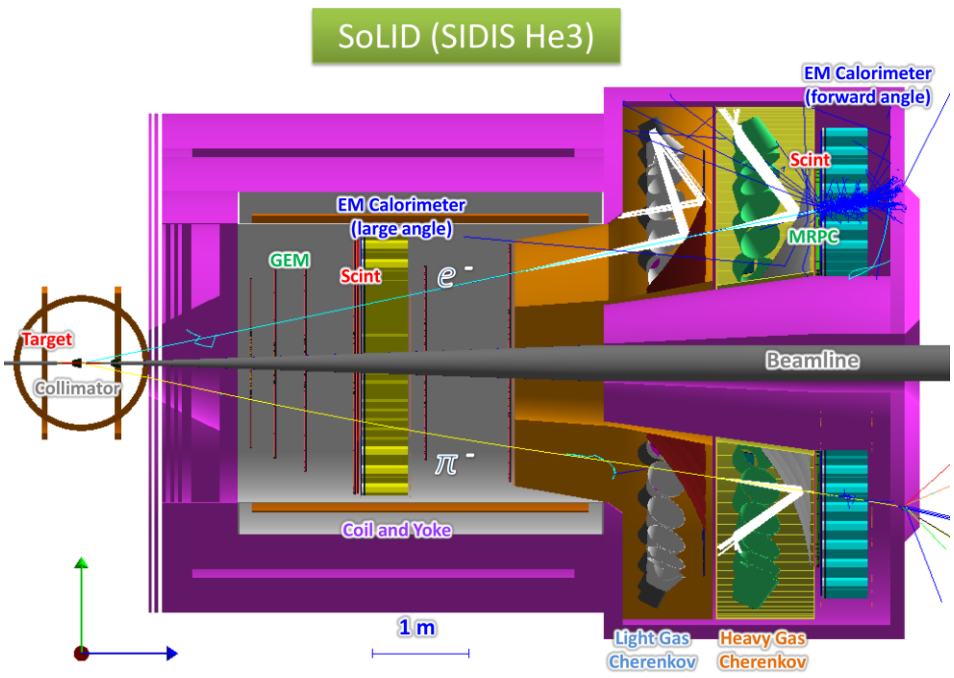
β =angle between transversely polarized target vector and the reaction plane.



$A_L^\perp$ expected to display precocious factorization at moderate Q^2~2-4 GeV^2

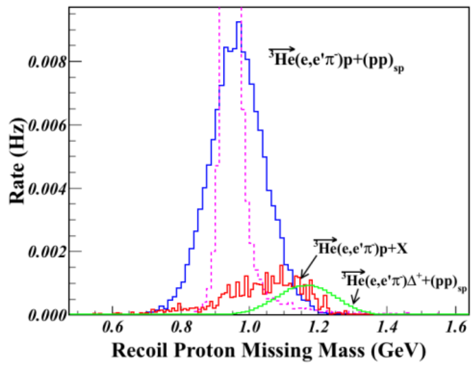
Refs: A.V. Belitsky, D. Mueller, PL**B513** (2001) 349
L.L. Frankfurt, et al., PRD **60**(1999) 014101

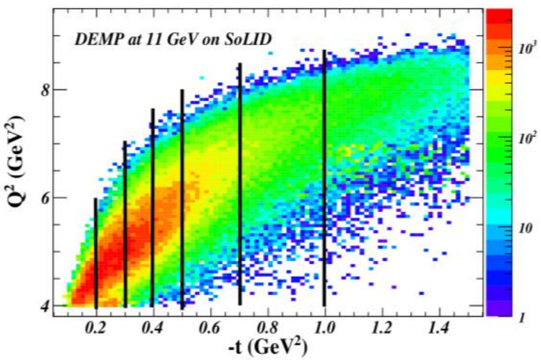
SoLID DEMP Setup

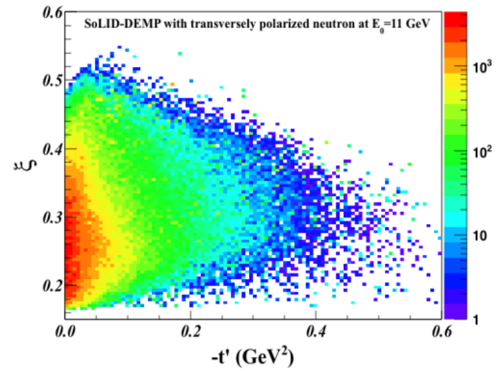


Polarized lumi ~1e^{36}/cm^2/s

- Run group with SIDIS He3 11GeV
- Proton PID offline, not in trigger
- Complete azimuthal and large polar angle coverage
- **The measurement is valuable as it is the only practical way to obtain $A_{UT}^{\sin(\phi-\phi_s)}$ over a wide kinematic range.**
- We will also measure $A_{UT}^{\sin(\phi_s)}$ and its companion moments, as was done by HERMES.
- **Provides vital GPD information not easily available in any other experiment prior to EIC.**





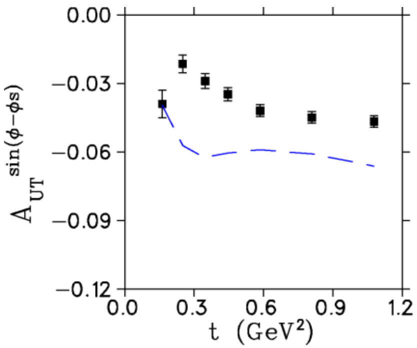


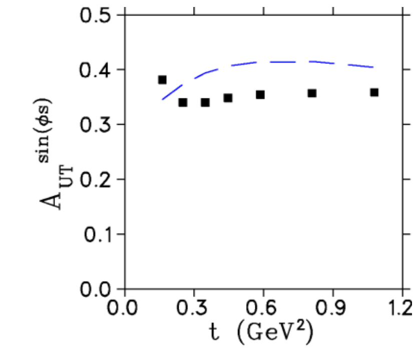
SoLID DEMP Projection

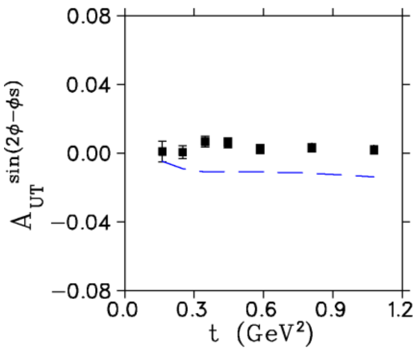
Unbinned Maximum Likelihood (UML) Method, same as **HERMES** PLB **682**(2010)345

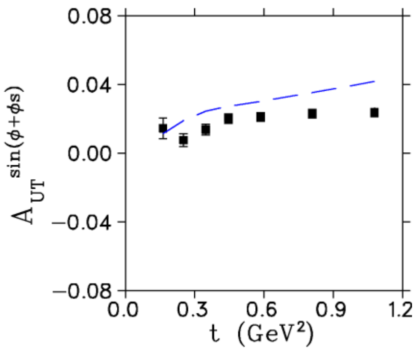
All effects on.

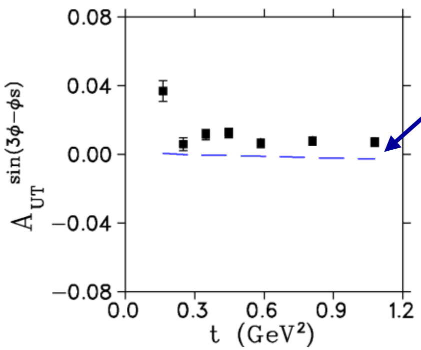
Includes all scattering, energy loss, resolution and Fermi momentum effects.







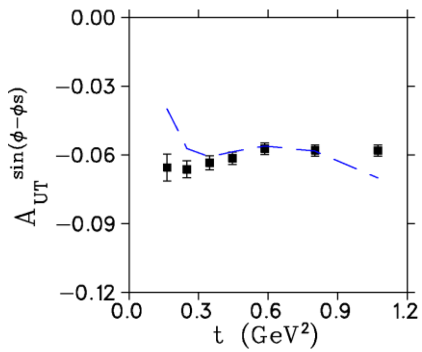


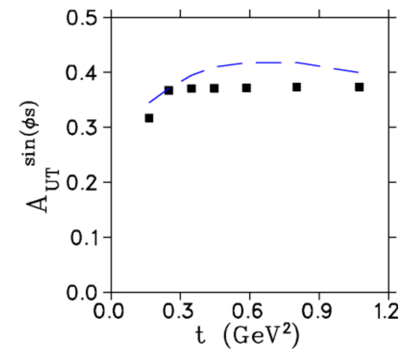


Average input asymmetry per bin.

Only Fermi momentum off.

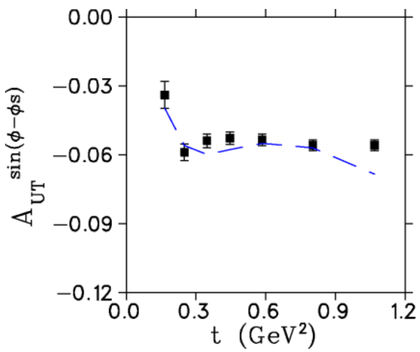
Includes all scattering, energy loss, resolution effects. Similar to where proton resolution is good enough to correct for Fermi momentum effects.

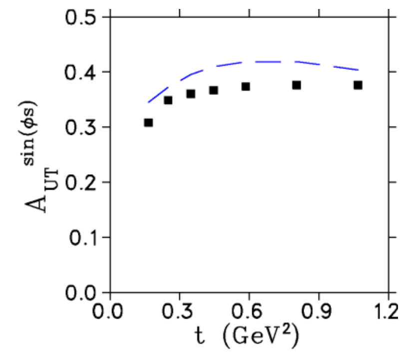




All effects off.

- Agreement between input and output fit values is very good. Validates the UML procedure.





Single Spin Asymmetry in Exclusive π Production

- **Frankfurt et al. have shown $A_L^{\perp}$ vanishes if $\tilde{E}$ is zero** [PRD **60**(1999)014010]**.**
  - **If $\tilde{E}\neq 0$, the asymmetry will produce a sinβ dependence.**
- They also argue that precocious factorization of the π production amplitude into three blocks is likely:
  1. overlap integral between γ, π wave functions.
  2. the hard interaction.
  3. the GPD.
  - **Higher order corrections, which may be significant at low Q^2 for σ_L, likely cancel in $A_L^{\perp}$.**
- **$A_L^{\perp}$ expected to display precocious factorization at moderate Q^2~2-4 GeV^2.**

GPD information in $A_L^{\perp}$ may be particularly clean

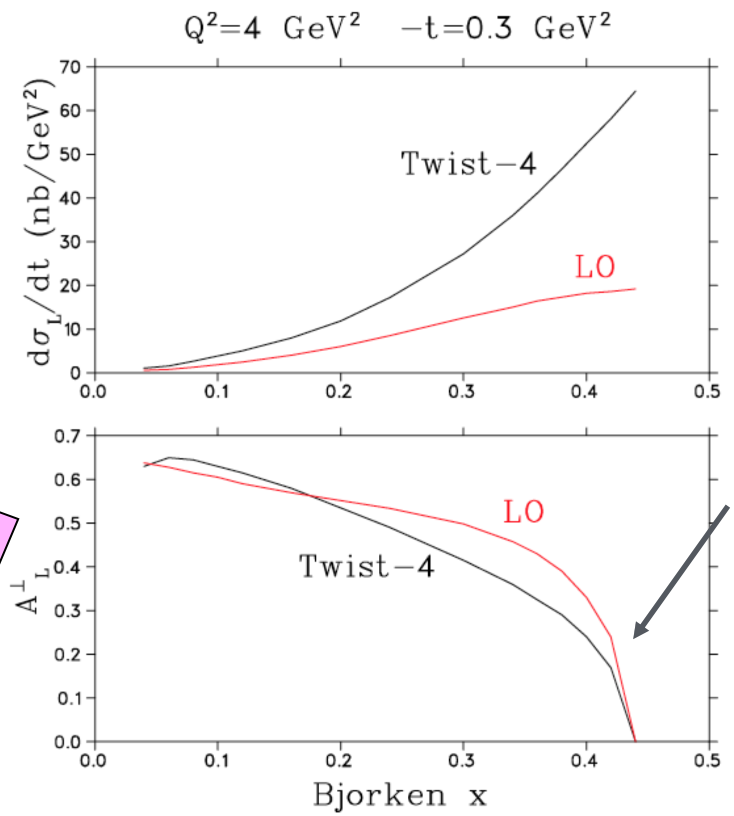
- **$A_L^{\perp}$ is expected to display precocious factorization at only Q^2~2-4 GeV^2:**

  - At Q^2=10 GeV^2, Twist–4 effects can be large, but cancel in $A_L^{\perp}$

    (Belitsky & Műller PLB **513**(2001)349).

  - At Q^2=4 GeV^2, higher twist effects even larger in σ_L, but still cancel in the asymmetry

    (CIPANP 2003).



$A_L^{\perp}$=0 at parallel kinematic limit, where $\varphi-\varphi_s$ is not well defined.

This relatively low value of Q^2 for the expected onset of precocious scaling is important, because it is experimentally accessible at Jefferson Lab.

Transverse Target Single Spin Asymmetry in DEMP

Unpolarized Cross section

$$2\pi\frac{d^2\sigma_{UU}}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Transversely polarized cross section has additional components

$$\frac{d^3\sigma_{UT}}{dt\,d\phi\,d\phi_s}=-\frac{P_\perp\cos\theta_q}{\sqrt{1-\sin^2\theta_q\sin^2\phi_s}}\begin{pmatrix}\sin\beta\,\mathrm{Im}(d\sigma_{++}^{+-}+\varepsilon d\sigma_{00}^{+-})\\+\sin\phi\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}(d\sigma_{+0}^{+-})\\+\sin(\phi+\phi_s)\frac{\varepsilon}{2}\mathrm{Im}(d\sigma_{+-}^{+-})\\+\sin(2\phi-\phi_s)\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}(d\sigma_{+0}^{-+})\\+\sin(3\phi-\phi_s)\frac{\varepsilon}{2}\mathrm{Im}(d\sigma_{+-}^{-+})\end{pmatrix}$$

$\sigma_{mn}^{ij}\rightarrow$ nucleon polarizations $ij=(+1/2,-1/2)$

photon polarizations $mn=(-1,0,+1)$

Gives rise to Asymmetry Moments

$$A(\phi,\phi_s)=\frac{d^3\sigma_{UT}(\phi,\phi_s)}{d^2\sigma_{UU}(\phi)}=-\sum_k A_{UT}^{\sin(\mu\phi+\lambda\phi_s)_k}\sin(\mu\phi+\lambda\phi_s)_k$$

Unseparated sinβ=sin(φ-φ$_s$) Asymmetry Moment

$$A_{UT}^{\sin(\phi-\phi_s)}\propto\frac{d\sigma_{00}^{+-}}{d\sigma_L\begin{pmatrix}++\\00\end{pmatrix}}\propto\frac{\mathrm{Im}(\tilde{E}^*\tilde{H})}{|\tilde{E}|^2}\text{ where }\tilde{E}\gg\tilde{H}$$

Ref: M. Diehl, S. Sapeta, Eur.Phys.J. C**41**(2005)515.

Note: Trento convention used for rest of talk

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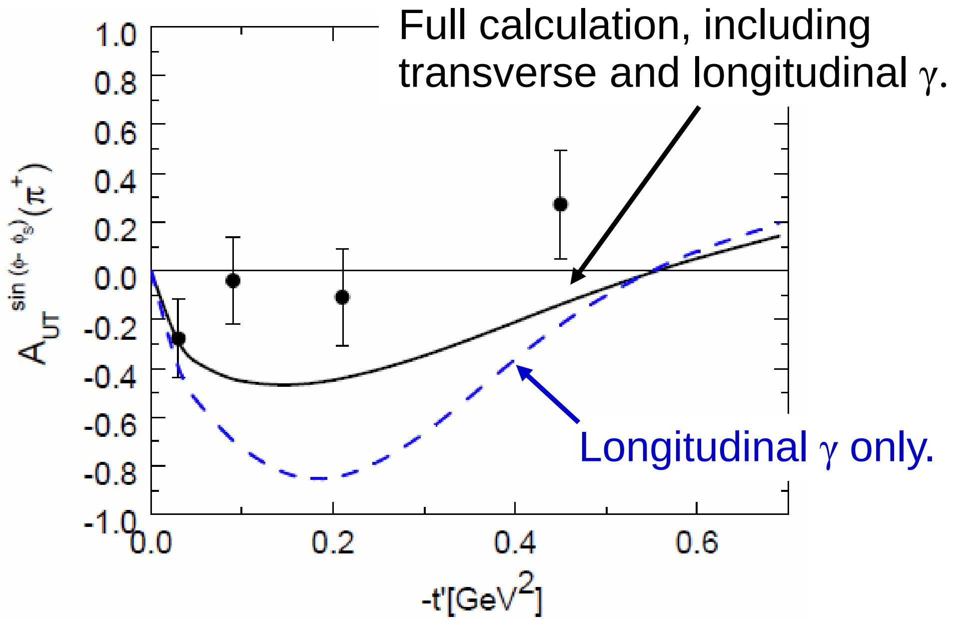
HERMES $\sin(\beta=\varphi-\varphi_s)$ Asymmetry Moment

- Exclusive π^+ production by scattering 27.6 GeV positrons or electrons from transverse polarized ^{1}H **without L/T separation.** [PLB **682**(2010)345].
- Analyzed in terms of 6 Fourier amplitudes for φ_π, φ_s.
- Asymmetry is diluted by ~50%.
- $\langle x_B \rangle=0.13$, $\langle Q^2 \rangle=2.38$ GeV^2, $\langle -t \rangle=0.46$ GeV^2.



- Goloskokov and Kroll indicate the HERMES results have significant contributions from transverse photons, as well as from L and T interferences [Eur Phys.J. **C65**(2010)137].
- **Nonetheless, the HERMES data are consistent with GPD models based on the dominance of $\tilde{E}$ over $\tilde{H}$ at low $-t$.**
  - **In fact, the sign crossing in the model curve at $-t\approx0.5$ GeV^2 is due to the large contribution from $\tilde{E}$ demanded by the data.**

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Example Cuts to Reduce Background

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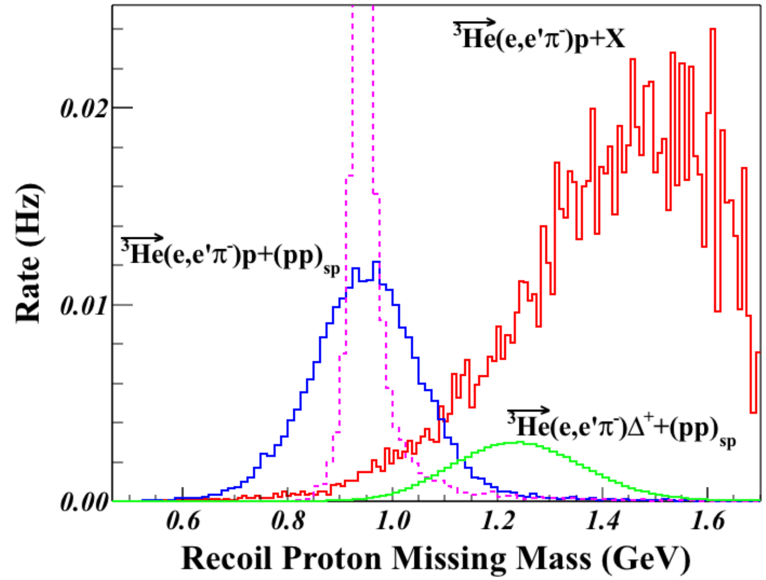
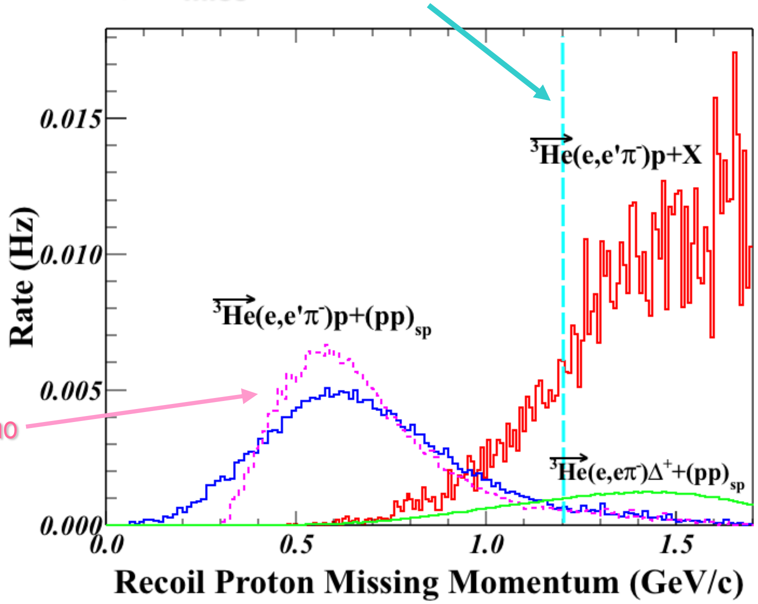
Two different background channels were simulated:

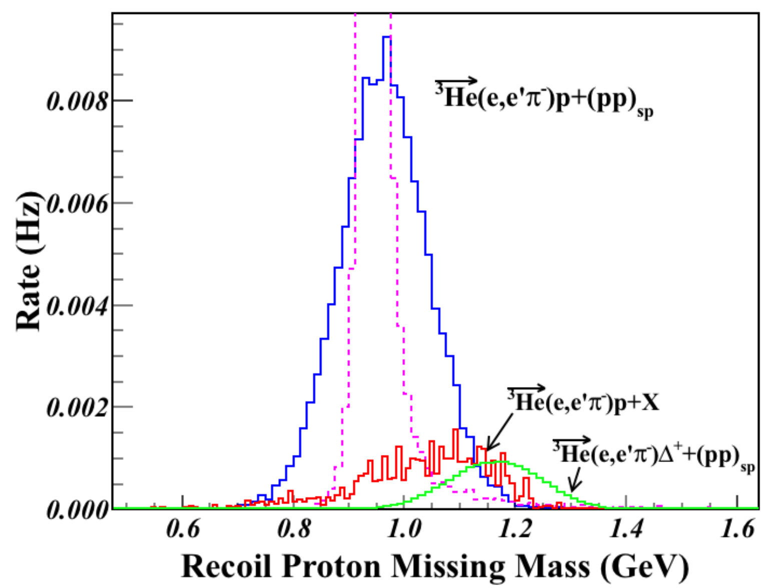
- SoLID-SIDIS generator $p(e,e'\pi^-)X$ and $n(e,e'\pi^-)X$, where we assume all X fragments contain a proton (over-estimate).
- $en \rightarrow \pi^- \Delta^+ \rightarrow \pi^- \pi^0 p$ where the Δ^+ (polarized) decays with l=1, m=0 angular distribution (more realistic).



Apply P_{miss}>1.2 GeV/c cut



Background remaining after P_{miss} cut



Summary

- $A_{UT}^{\sin(\varphi-\varphi_s)}$ transverse single-spin asymmetry in exclusive π production is particularly sensitive to the spin-flip GPD $\tilde{E}$. Factorization studies indicate precocious scaling to set in at moderate Q^2~2-4 GeV^2, while scaling is not expected until Q^2>10 GeV^2 for absolute cross section.
- $A_{UT}^{\sin(\varphi_s)}$ asymmetry can also be extracted from same data, providing powerful additional GPD-model constraints and insight into the role of transverse photon contributions at small $-t$, and over wide range of ξ.
- **High luminosity and good acceptance capabilities of SoLID make it well-suited for this measurement. It is the only feasible manner to access the wide –*t* range needed to fully understand the asymmetries.**
- We propose to analyze the E12-10-006 event files off-line to look for e-π^--p triple coincidence events. To be conservative, we assume the recoil proton is only identified, and its momentum is not used to further reduce SIDIS (and other) background.
- **We used a sophisticated UML analysis to extract the asymmetries from simulated data in a realistic manner, just as was used in the pioneering HERMES data. The projected data are expected to be a considerable advance over HERMES in kinematic coverage and statistical precision.**
- SoLID measurement is also important preparatory work for future EIC.

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