Deep Exclusive π^- Production using a Transversely Polarized ^{3}He Target and SoLID

SOLENOIDAL LARGE INTENSITY DEVICE

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Towards 3D Imaging of the Nucleon

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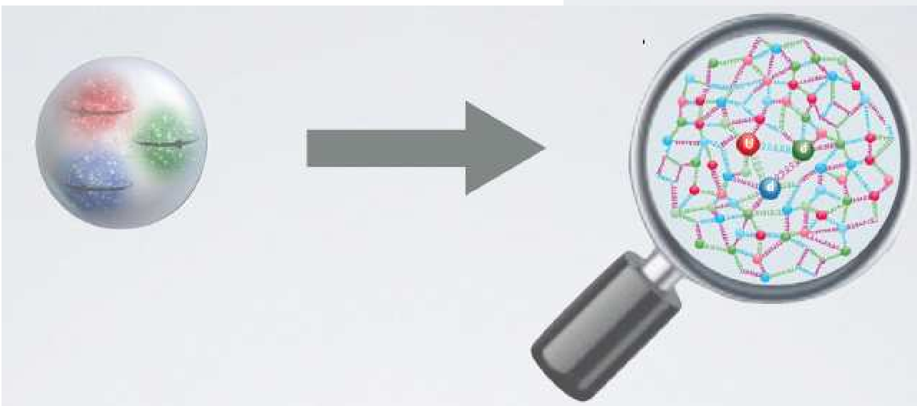
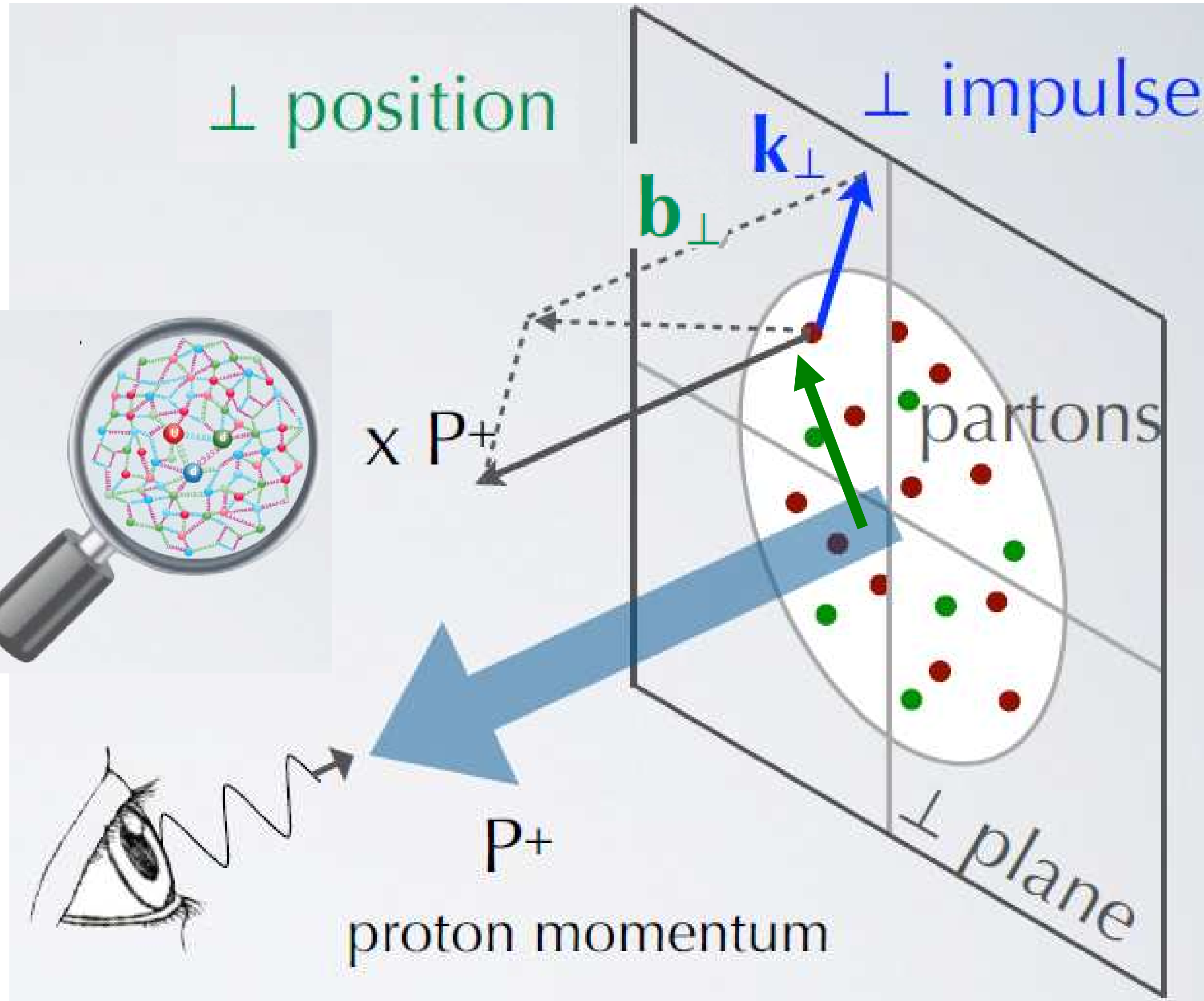
Motivation: in other sciences, imaging the physical systems under study has been key to gaining new understanding.





Structure mapped
in terms of
$\mathbf{b}_T$ = transverse position
$\mathbf{k}_T$ = transverse momentum

Taken from a talk by Rolf Ent, Jefferson Lab

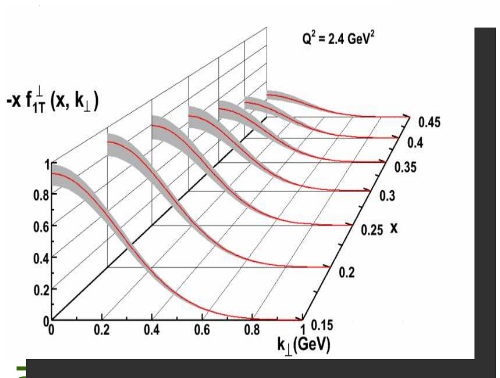
3D Imaging of the Nucleon

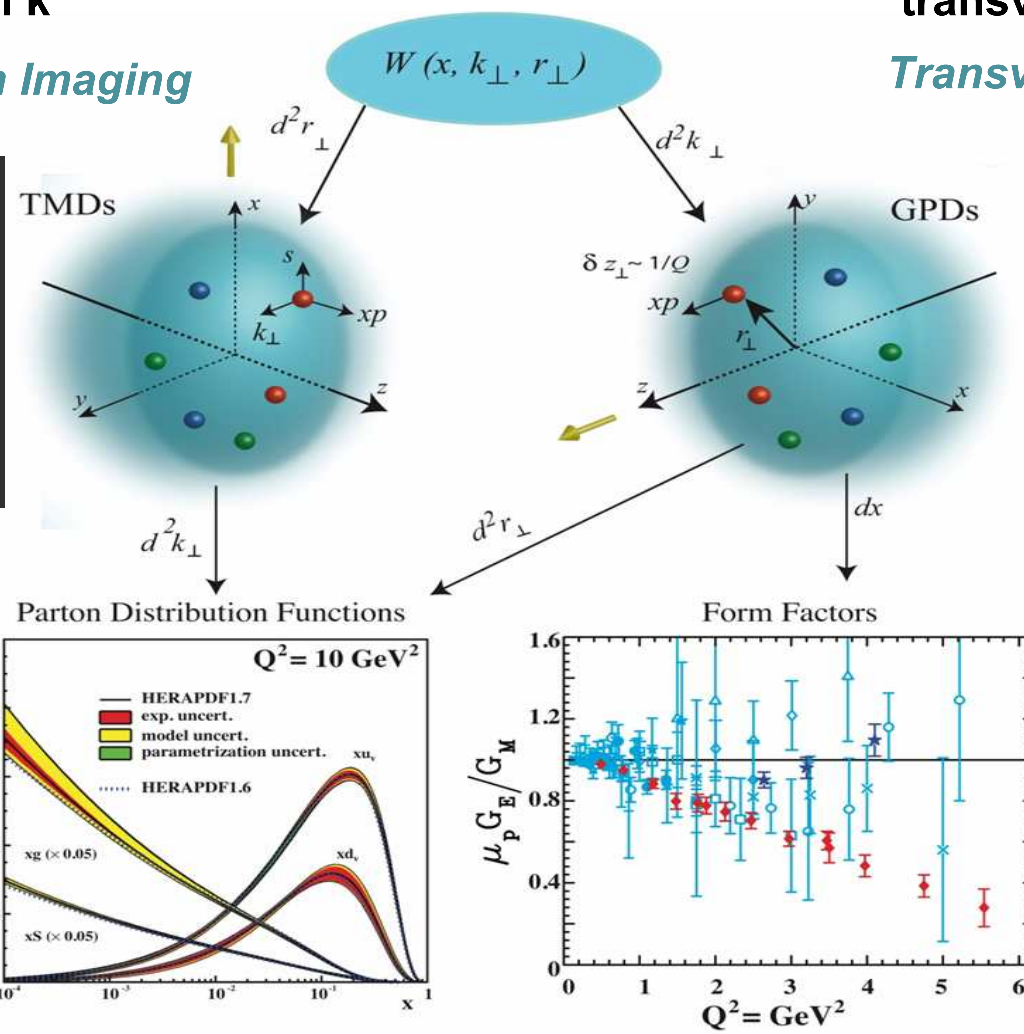
TMDs: Longitudinal momentum fraction x and transverse momentum k

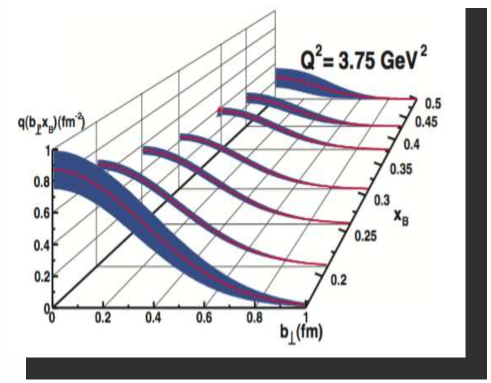
Transverse Momentum Imaging

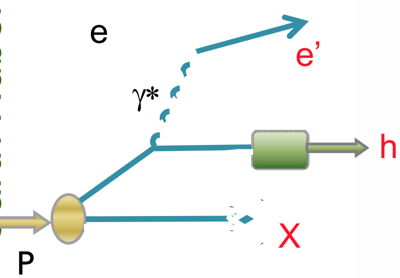
GPDs: Longitudinal momentum fraction x at transverse location b

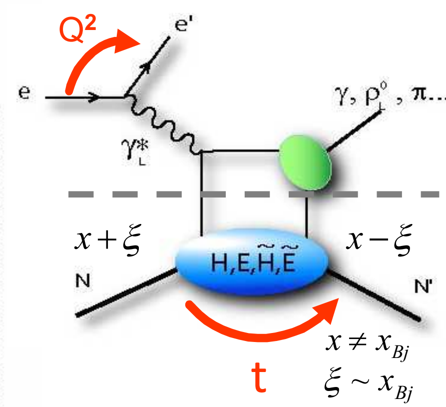
Transverse Spatial Imaging











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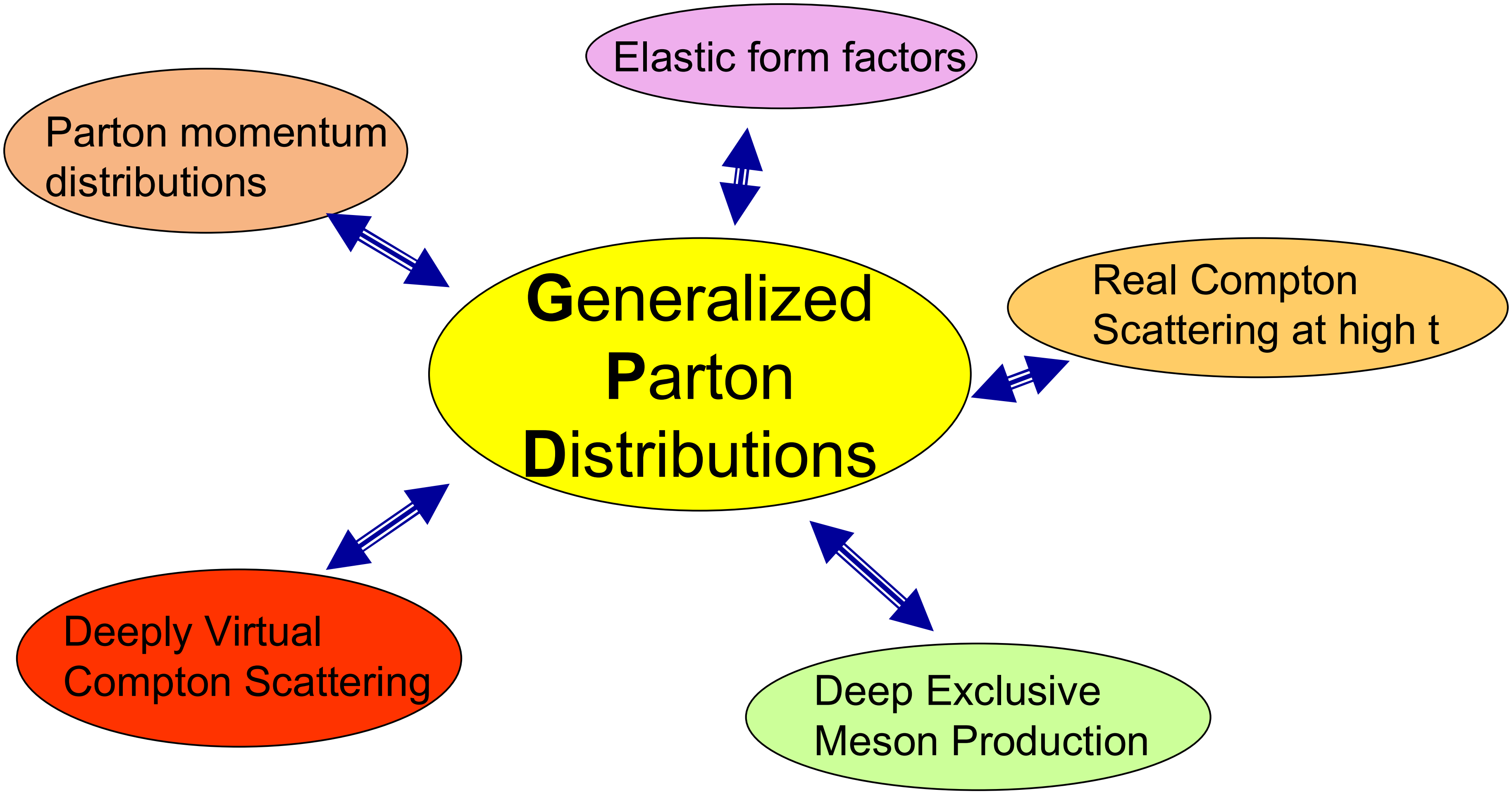
GPDs – A Unified Description of Hadron Structure



- **GPDs interrelate the longitudinal momentum and transverse spatial structure of partons within a fast moving hadron.**
- **GPDs are universal quantities and reflect nucleon structure independently of the probing reaction.**

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Leading Twist GPD Parameterization

Leading order QCD predicts:

- Vector meson production sensitive to unpolarized GPDs, H and E.
- Pseudoscalar mesons sensitive to polarized GPDs, $\tilde{H}$ and $\tilde{E}$.

$H^{q,g}(x,\xi,t)$ spin avg no hel. flip	$E^{q,g}(x,\xi,t)$ spin avg helicity flip
$\tilde{H}^{q,g}(x,\xi,t)$ spin diff no hel. flip	$\tilde{E}^{q,g}(x,\xi,t)$ spin diff helicity flip

Dirac and Pauli elastic form factors.
t -dependence fairly well known.

$$\begin{cases} \sum_q e_q \int_{-1}^{+1} dx\, H^q(x,\xi,t) = F_1(t) \\ \sum_q e_q \int_{-1}^{+1} dx\, E^q(x,\xi,t) = F_2(t) \end{cases}$$

Isovector axial form factor.
t –dep. poorly known. $\longrightarrow$ $\sum_q e_q \int_{-1}^{+1} dx\, \tilde{H}^q(x,\xi,t) = G_A(t)$

Pseudoscalar form factor.
Very poorly known. $\longrightarrow$ $\sum_q e_q \int_{-1}^{+1} dx\, \tilde{E}^q(x,\xi,t) = G_P(t)$

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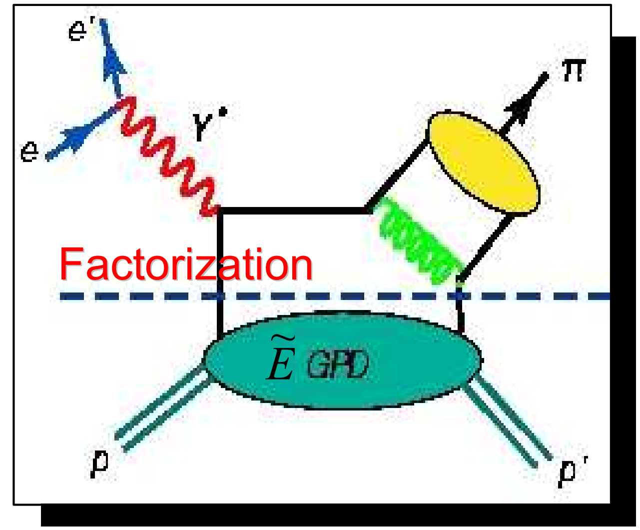
Next Generation Study: Polarized GPD $\tilde{E}$

- $\tilde{E}$ **involves a helicity flip:**
  - Depends on the spin difference between initial and final quarks.

$$\sum_q e_q \int_{-1}^{+1} dx\ \tilde{E}^q(x,\xi,t) = G_P(t)$$

$G_P(t)$ is highly uncertain because it is negligible at the momentum transfer of β-decay.



- $\tilde{E}$ **not related to an already known parton distribution → essentially unknown.**
- Experimental information can provide new nucleon structure information unlikely to be available from any other source.

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Exclusive π^- from Transversely Polarized Neutron

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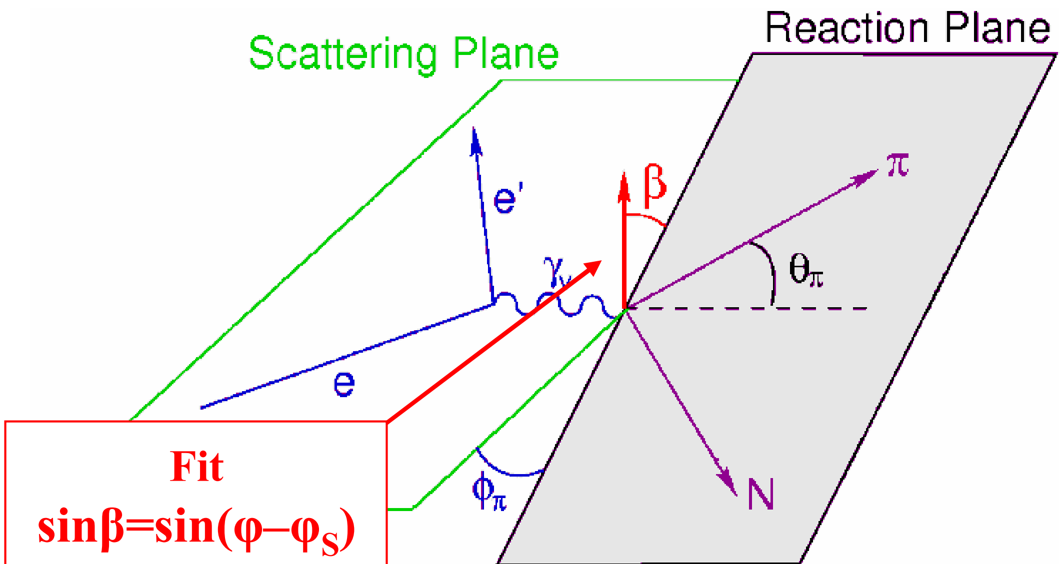
The most sensitive observable to probe $\tilde{E}$ is the transverse target single-spin asymmetry in exclusive π production:

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



Fit
$\sin\beta = \sin(\varphi - \varphi_S)$
dependence.

$$A_{\perp} = \frac{\int_0^{\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta} - \int_{\pi}^{2\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta}}{\int_0^{2\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta}}$$

$d\sigma^{\pi}_L$ → exclusive cross section for longitudinal γ^*

$\beta = \varphi - \varphi_S$ → angle between polarized target and reaction plane

The asymmetry vanishes if $\tilde{E}$ is zero. If $\tilde{E}$ is non–zero, the asymmetry will display a $\sin(\varphi - \varphi_s)$ dependence.

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

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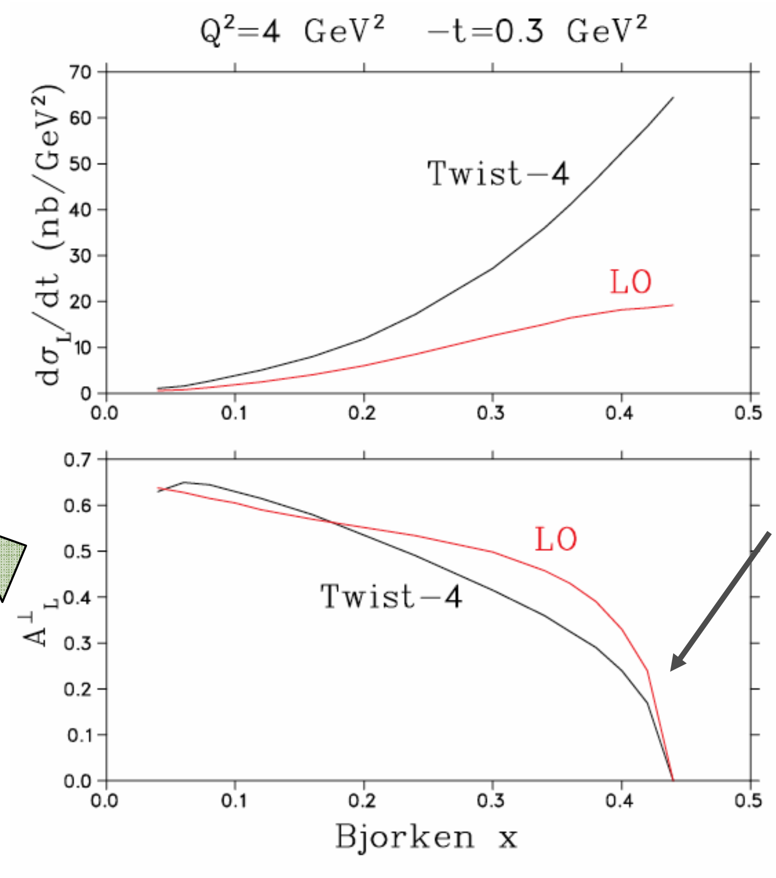
- **$A_L^{\perp}$ is expected to display precocious factorization at only Q^2~2–4 GeV^2:**
  - At Q^2=10 GeV^2, Twist–4 effects can be large, but cancel in $A_L^{\perp}$
    (Belitsky & Műller PLB 513(2001)349).
  - At Q^2=4 GeV^2, higher twist effects even larger in σ_L, but still cancel in the asymmetry
    (CIPANP 2003).



$A_L^{\perp}$=0 at parallel kinematic limit, where φ–φ_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 JLab 12 GeV.

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Transverse Target Single Spin Asymmetry in DEMP

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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

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

$\sigma_{mn}^{ij} \rightarrow$ 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

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

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

Note: Trento convention used for rest of talk

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L–T Separated versus Unseparated Expts

- **Our reaction of interest is $\vec{n}(e,e'\pi^-)p$ from the neutron in transversely polarized ^3He.**
- **It has not yet been possible to perform an experiment to measure $A_L^{\perp}$.**
  - Conflicting experimental requirements of transversely polarized target, high luminosity, L–T separation and closely controlled systematic uncertainties make this an exceptionally challenging observable to measure.
- **The most closely related measurement, of the transverse single-spin asymmetry in $\vec{p}(e,e'\pi^+)n$, without an L–T separation, was published by HERMES in 2010.**
  - Significant GPD information was obtained.
  - Our proposed SoLID measurements will be a significant advance over the HERMES data in terms of kinematic coverage and statistical precision.

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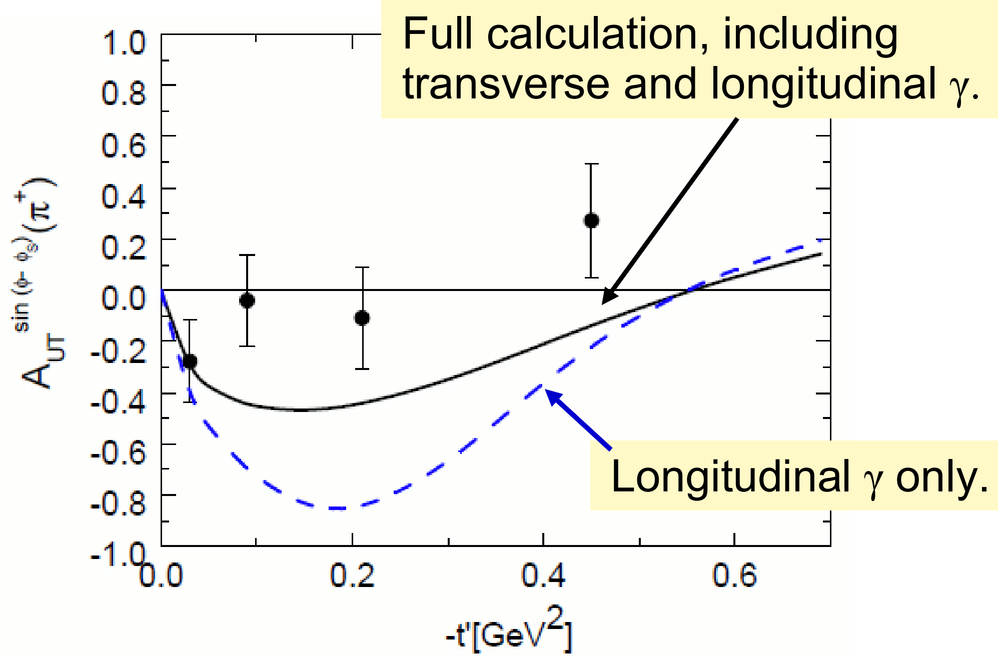
HERMES $\sin(\varphi - \varphi_S)$ Asymmetry Moment

- Exclusive π^+ production by scattering 27.6 GeV positrons or electrons from transverse polarized ^{1}H [PL **B682**(2010)345].
- Analyzed in terms of 6 Fourier amplitudes for φ_π, φ_s.
- $\langle x_B \rangle = 0.13$, $\langle Q^2 \rangle = 2.38$ GeV^2, $\langle -t \rangle = 0.46$ GeV^2.

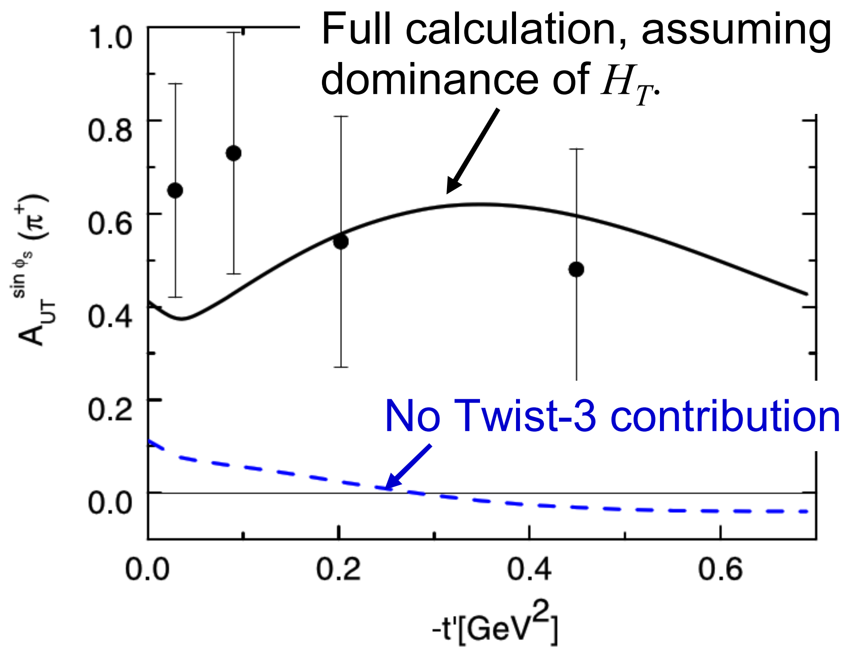


- **Since there is no L/T separation, $A_{UT}^{\sin(\varphi-\varphi s)}$ is diluted by the ratio of the longitudinal cross section to the unseparated cross section.**
- Goloskokov and Kroll indicate the HERMES results have significant contributions from transverse photons, as well as from L and T interferences [Eur Phys.J. **C65**(2010)137].
- Because no factorization theorems exist for exclusive π production by transverse photons, these data cannot be trivially interpreted in terms of GPDs.

HERMES sin(φ_s) Asymmetry Moment

- **Additional chiral–odd GPDs (H_T E_T $\tilde{H}_T$ $\tilde{E}_T$) offer a new way to access transversity–dependent quark–content of nucleon**

- While most theoretical interest and the primary motivation of our experiment is sin(φ–φ_s) asymmetry moment, there is growing interest in sin(φ_s) moment, which may be interpretable in terms of transversity GPDs



- **HERMES sin(φ_S) modulation large and nonzero at $-t'$=0, giving first clear signal for strong contributions from transversely polarized photons at rather large values of W and Q^2**
- Goloskokov and Kroll calculation [Eur.Phys.J. **C65**(2010)137] assumes H_T dominates and the other three can be neglected

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SoLID @ 12 GeV JLab: **the QCD 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]

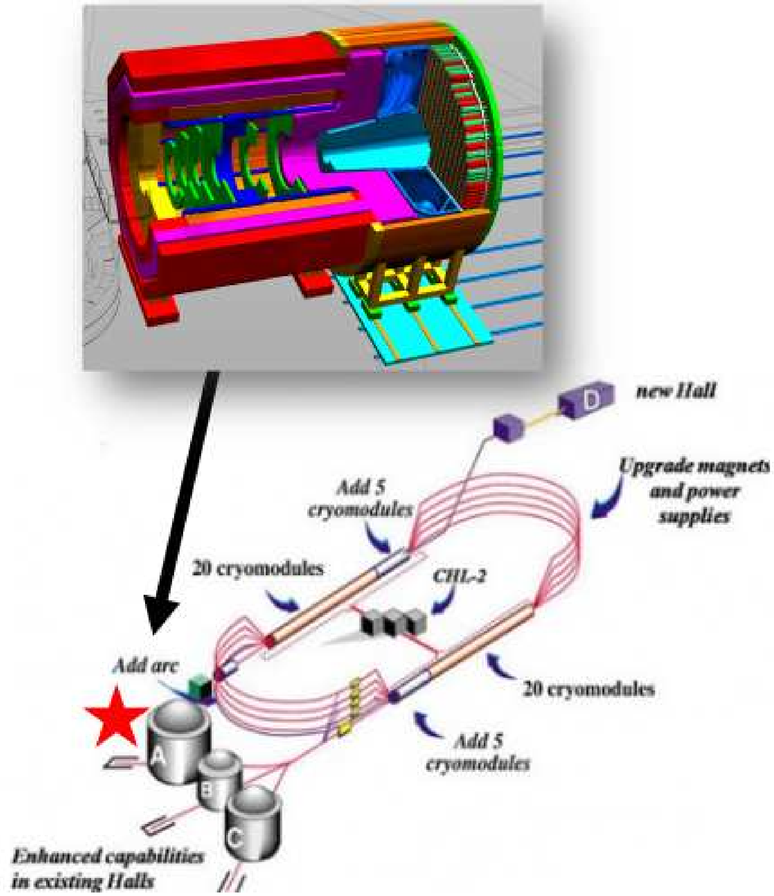
+

Large Acceptance
Full azimuthal ϕ coverage

Research at **SoLID** will have the ***unique*** capability to **explore** the QCD landscape while **complementing** the research of other key facilities

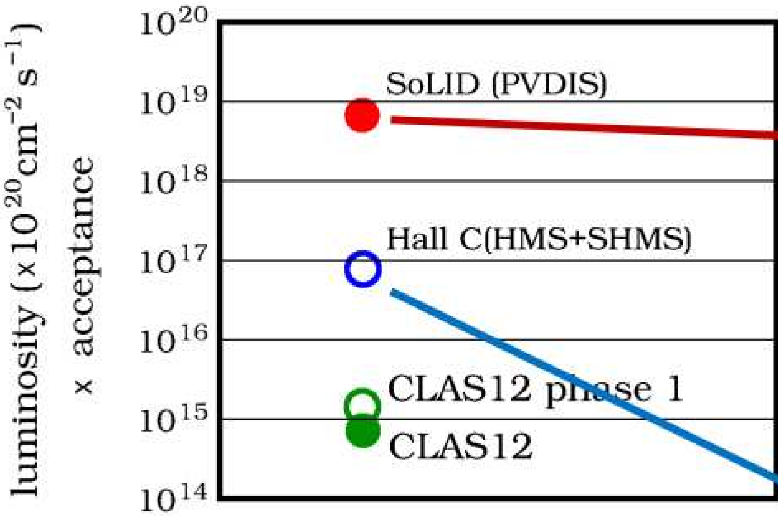
- **Precision lepto-quark couplings** at unique mass and sensitivity scales
- 3D momentum imaging of a relativistic strongly interacting confined system (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton mass**)

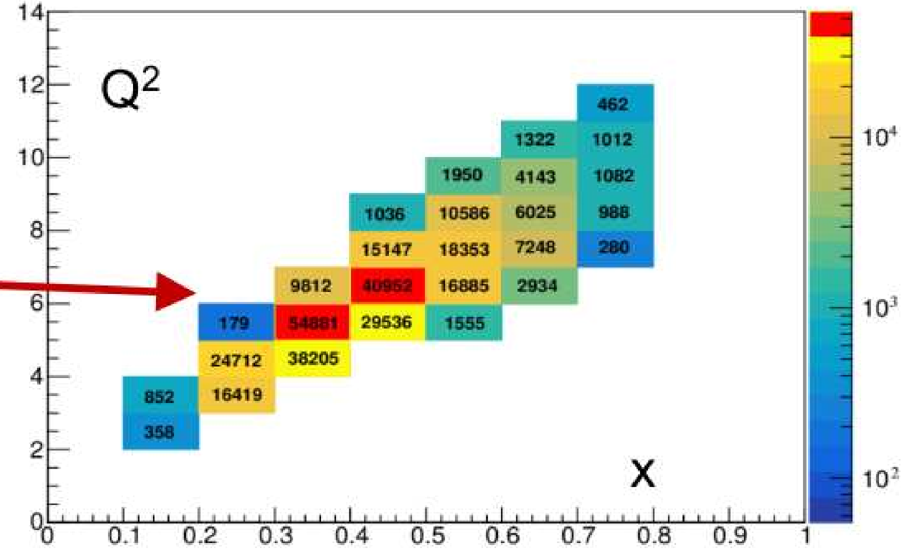
Synergizing with the pillars of EIC science (**proton spin** and **mass**) through high-luminosity valence quark tomography and precision J/ψ production near threshold

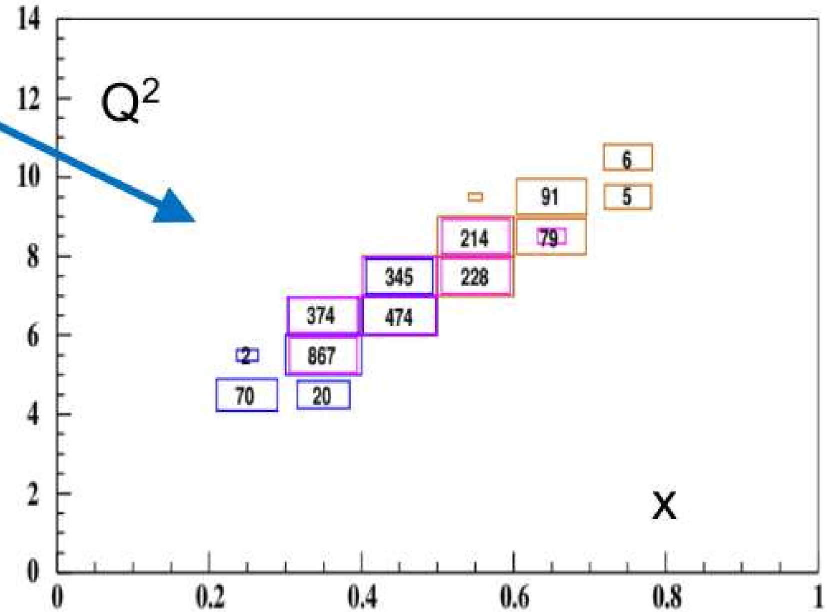


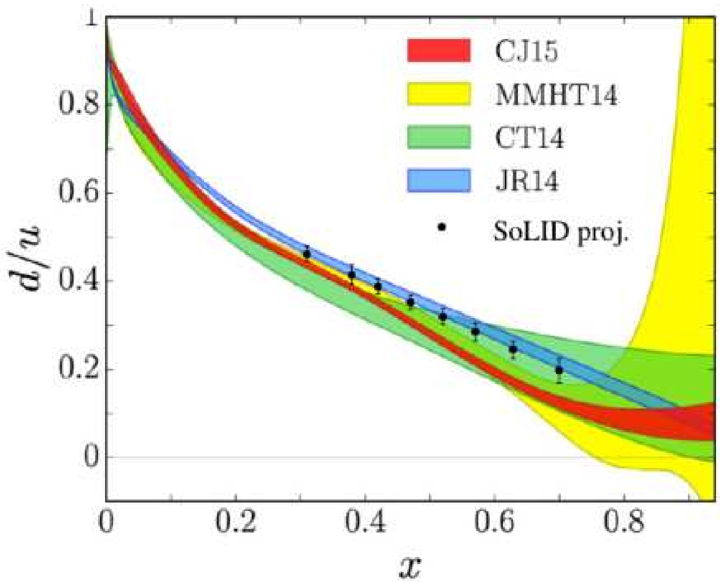
SoLID Optimized for High Luminosity Science

SoLID has >1000 times the rate of CLAS12
and ~100 times the rate of Halls A or C





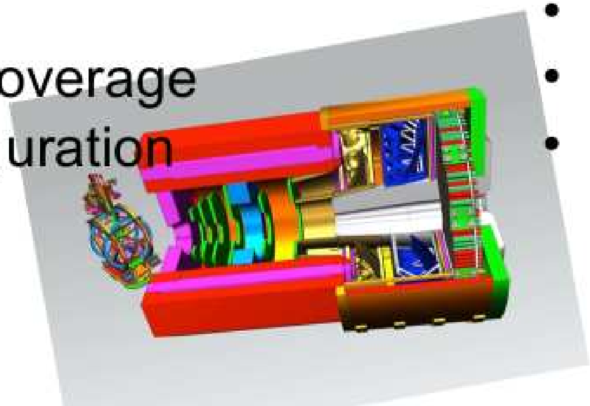




SoLID State–of–the–Art Technology

Quantum Leap Science
Requirements are Challenging

- High Luminosity (10^{37}-10^{39})
  - beam currents ~100 microA) on ~10 cm liquid targets
  - beam currents of ~50 microA on ~30cm polarized ^{3}He target
- Solenoidal field provides access to azimuthal asymmetry
- High data rate (~100 KHz)
- High background (~ GHz)
- Low systematic uncertainties
- High Radiation
- Broad kinematic coverage
- Flexibility in configuration

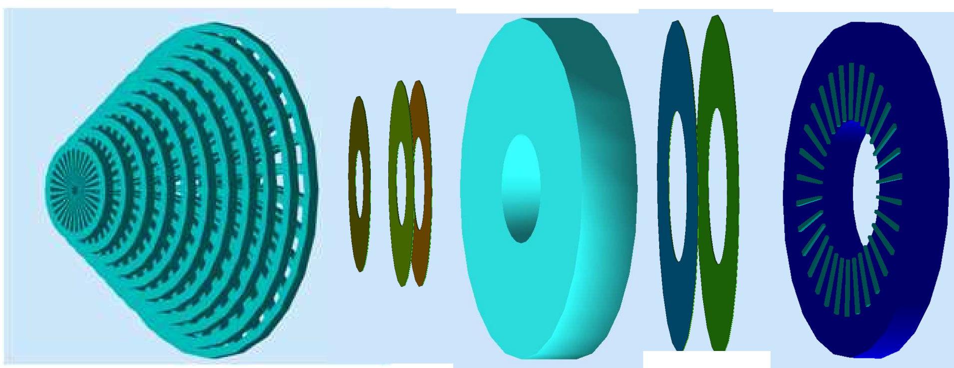


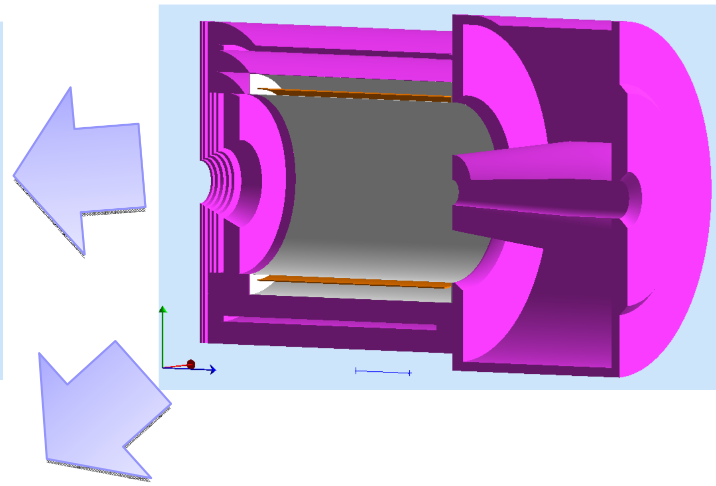
SoLID pre-conceptual design began "ground up" with the latest available advanced technologies to ensure every piece of sub-systems can meet the challenging requirements

- GEM tracking
- Shashlik Electron Calorimetry
- High Performance Cerenkovs
- Pipeline DAQ
- Rapidly Advancing Computational Capabilities
- Parity beamline
- Advanced polarimetry
- High power and polarized targets

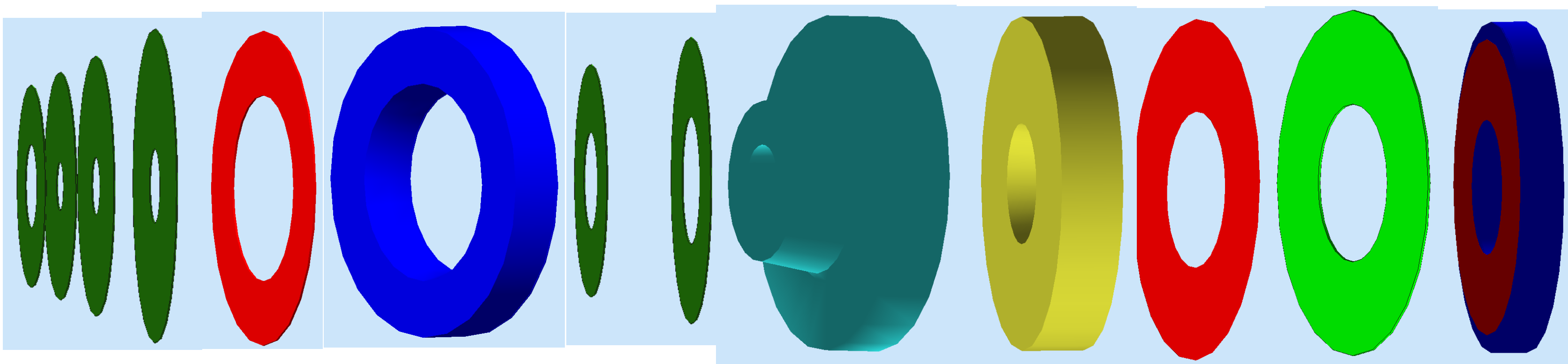
SoLID Detector Technologies

PVDIS: Baffle 3xGEMS LGC 2xGEMs EC





SIDIS&J/y:
4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC



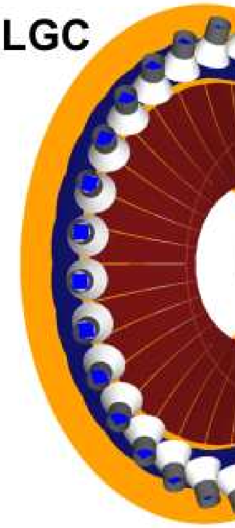
Pre-R&D items: LGC, HGC, GEM's, DAQ/Electronics, Magnet

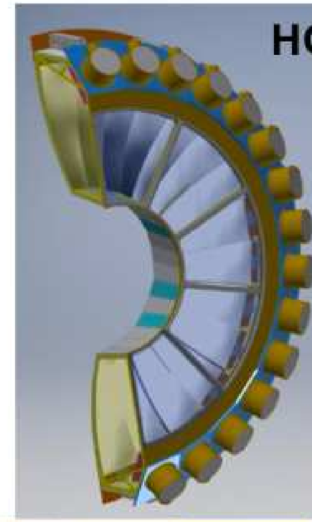
High Performance Cherenkovs

State of the art design:

- Electron/pion (LGC) and pion/kaon (HGC) separation with good rejection factors while maintaining good detection efficiencies
- Provide input at trigger level in a 2π, high-luminosity, non-negligible magnetic field environment while minimizing complexity and cost
- Exceeds the PID requirements for SoLID science

LGC





Pixelized photodetector arrays:

- Allows for flexibility in the trigger design
- Provides data for use in signal pattern recognition
- Efficient photon detection in magnetic fields of ~100 Gauss

High-Rate Test:

- Photodetector arrays and front-end electronics successfully tested in Hall C in 2020
- Analysis confirms the efficacy of SoLID electronics
- Data collected will help with calibration/verification of simulation

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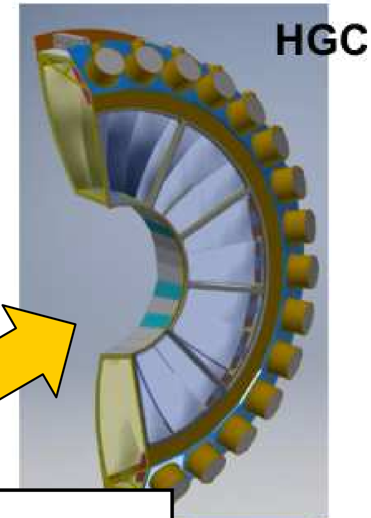


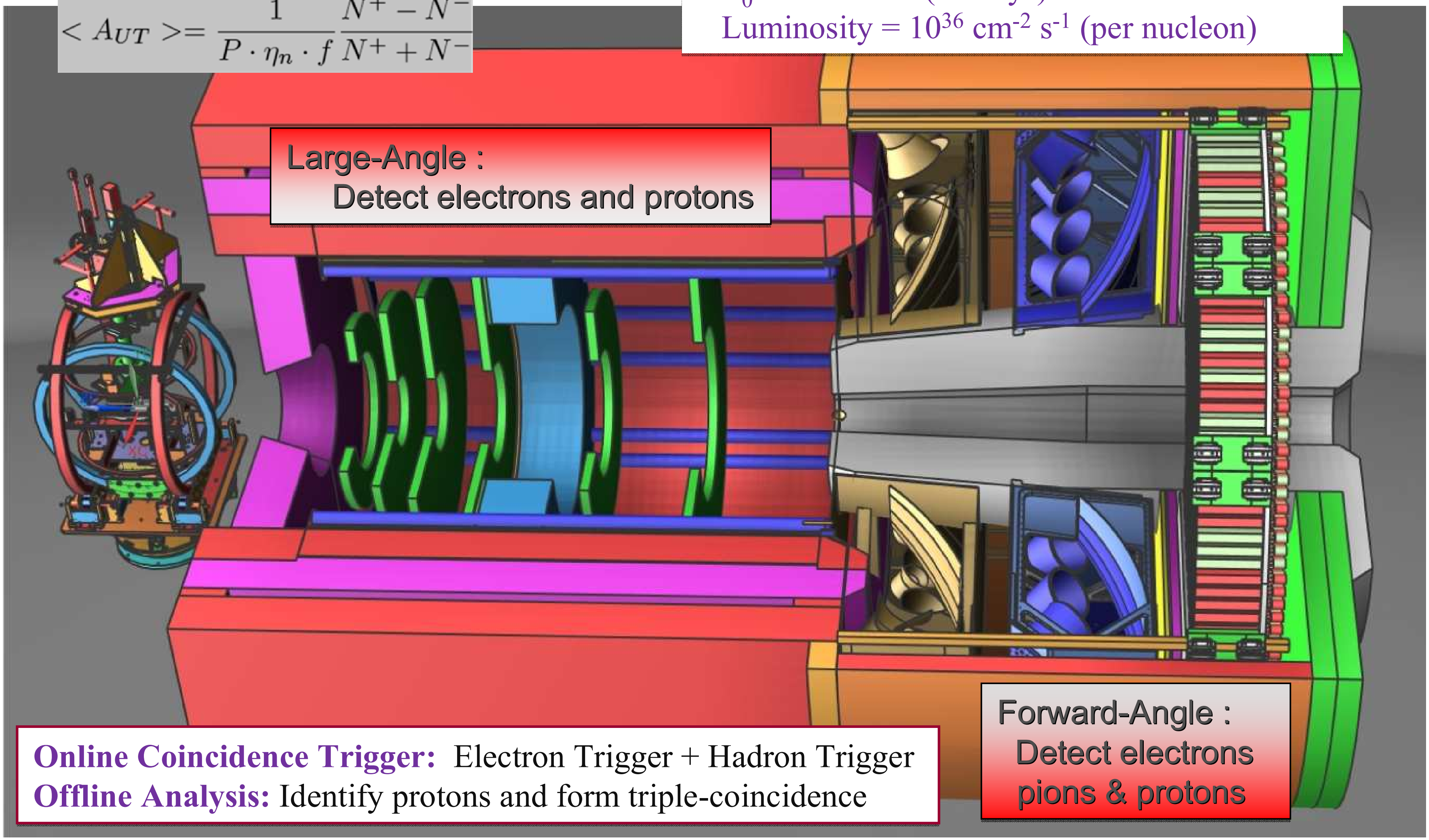
CFI–IF application for HGC vessel & entrance windows

Measure DEMP with SoLID – Polarized ^{3}He

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

$$< A_{UT} >= \frac{1}{P \cdot \eta_n \cdot f} \frac{N^+ - N^-}{N^+ + N^-}$$

Run in parallel with E12-10-006:
E_0 = 11.0 GeV (48 days)
Luminosity = 10^{36} cm^{-2} s^{-1} (per nucleon)



Online Coincidence Trigger: Electron Trigger + Hadron Trigger
Offline Analysis: Identify protons and form triple-coincidence

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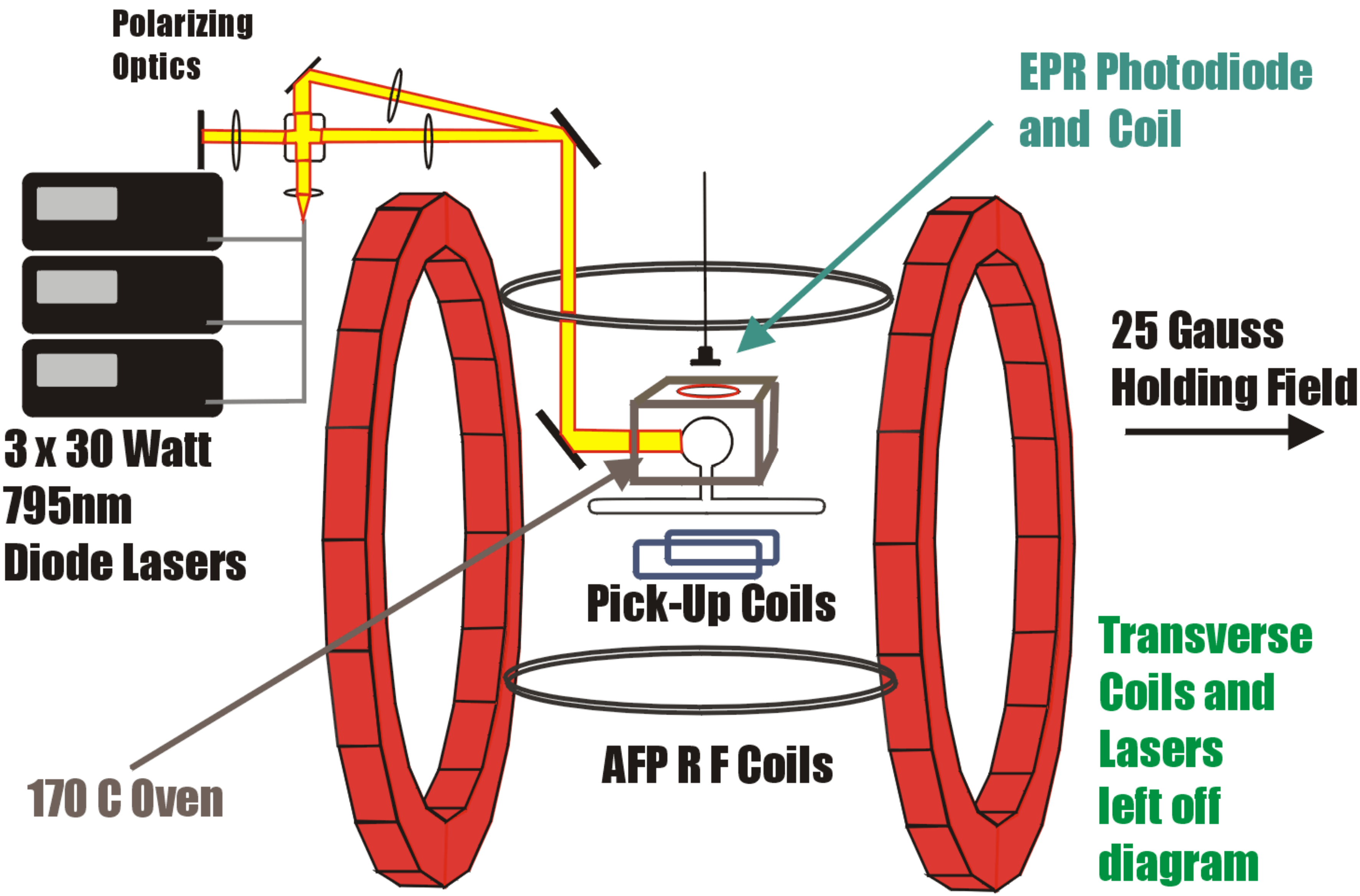
Hall A Polarized ^{3}He Target: FOM(P^2L)=0.22E+36



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Asymmetry Moment Modeling

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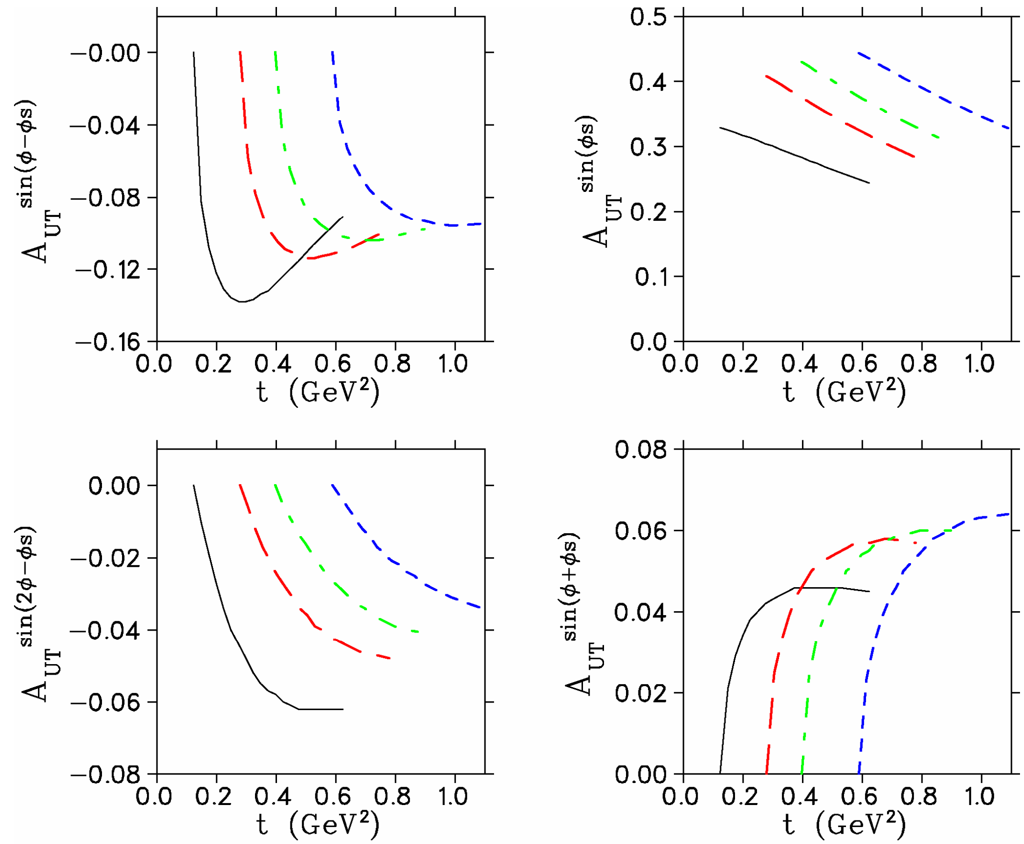
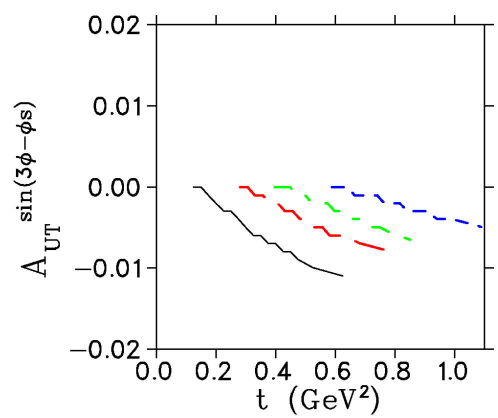
- **Event generator incorporates A_{UT} moments calculated by Goloskokov and Kroll for kinematics of this experiment.**
- GK handbag approach for π^- from neutron:
  - Eur.Phys.J. C**65**(2010)137.
  - Eur.Phys.J. A**47**(2011)112.
- **Simulated data for target polarization up and down are subjected to same *Q*²>4 GeV², *W*>2 GeV, 0.55<ε<0.75 cuts.**

Q^2	W
4.11	3.17
5.14	2.80
6.05	2.72
6.89	2.56





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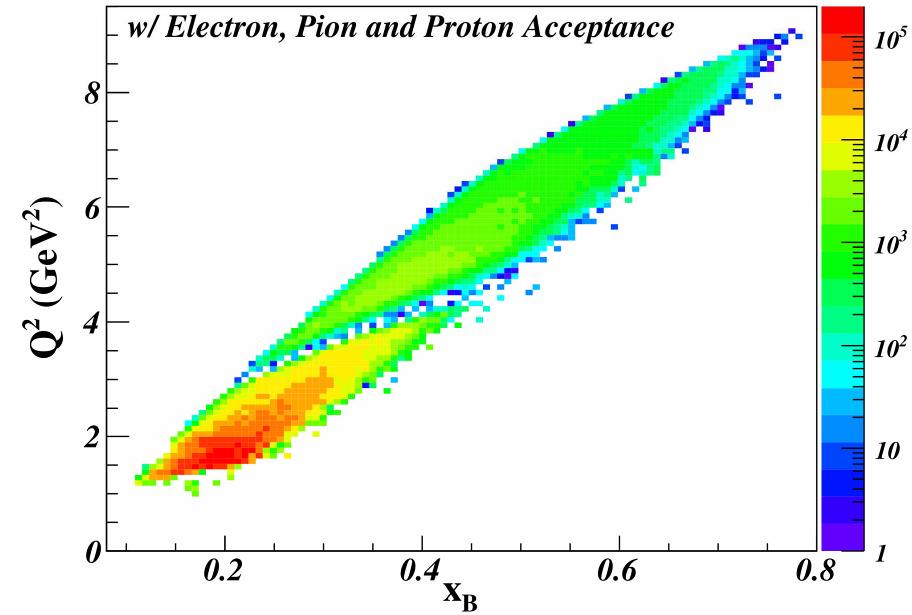
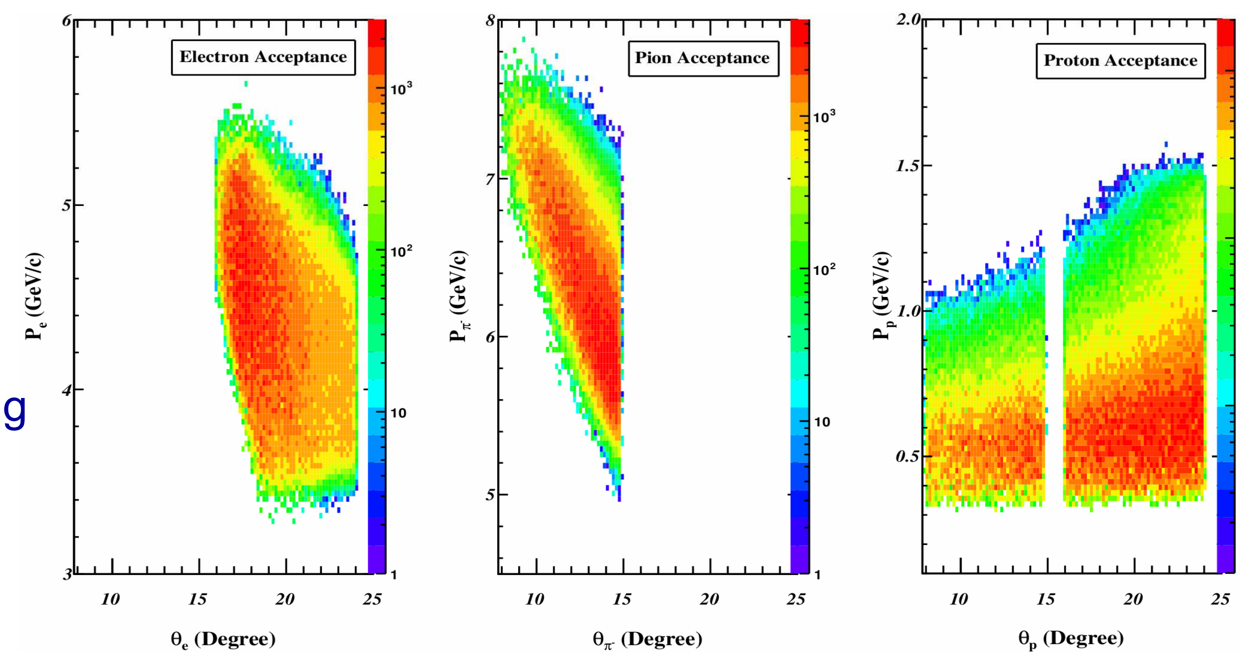
SoLID Acceptance and Projected Rates

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

- Event generator is based on data from HERMES, Halls B,C with VR Regge+DIS model used as a constraint in unmeasured regions.
- Generator includes electron radiation, multiple scattering and ionization energy loss.
- Every detected particle is smeared in (P,θ,φ) with resolution from SoLID tracking studies, and acceptance profiles from SoLID-SIDIS GEMC study applied.



Q^2>4 GeV^2, W>2 GeV, 0.55<ε<0.75 cuts applied.



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Example Cuts to Reduce Background

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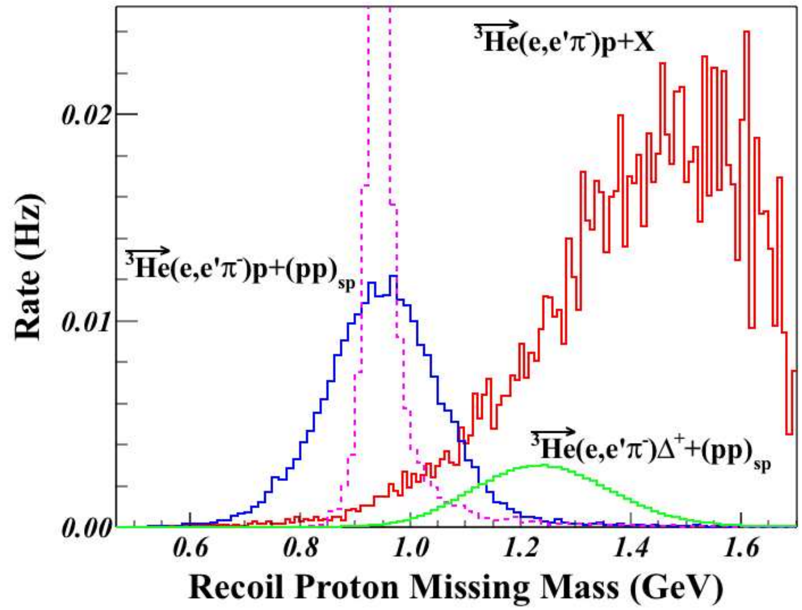
Two different background channels were simulated:

- 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).

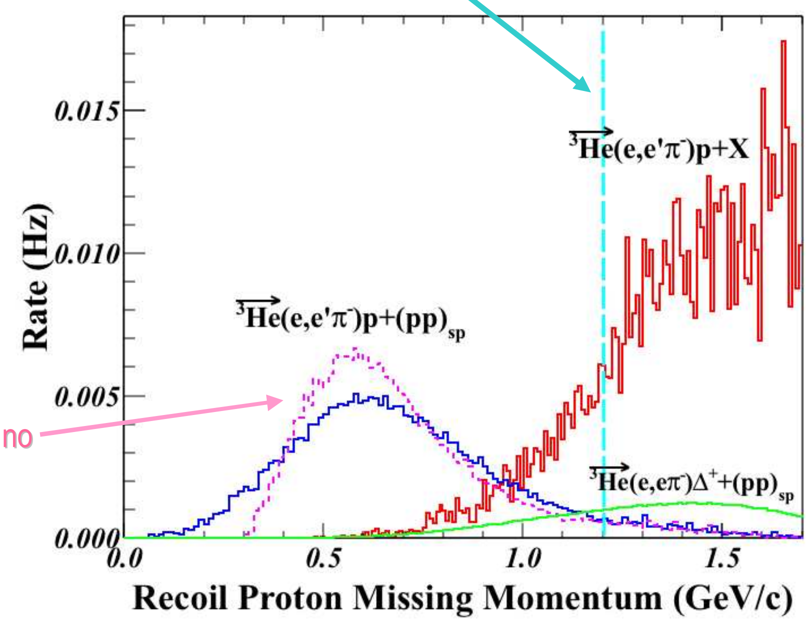


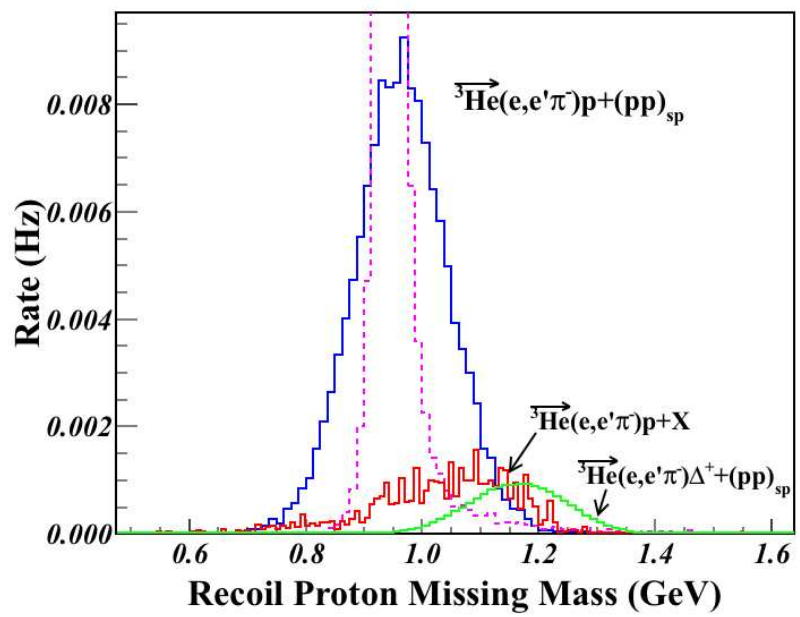
Apply P_{miss}>1.2 GeV/c cut

$$p_{miss} = \left|\vec{p}_e - \vec{p}_{e'} - \vec{p}_{\pi^-}\right|$$

Background remaining after P_{miss} cut

Scattering & radiation but no resolution smearing





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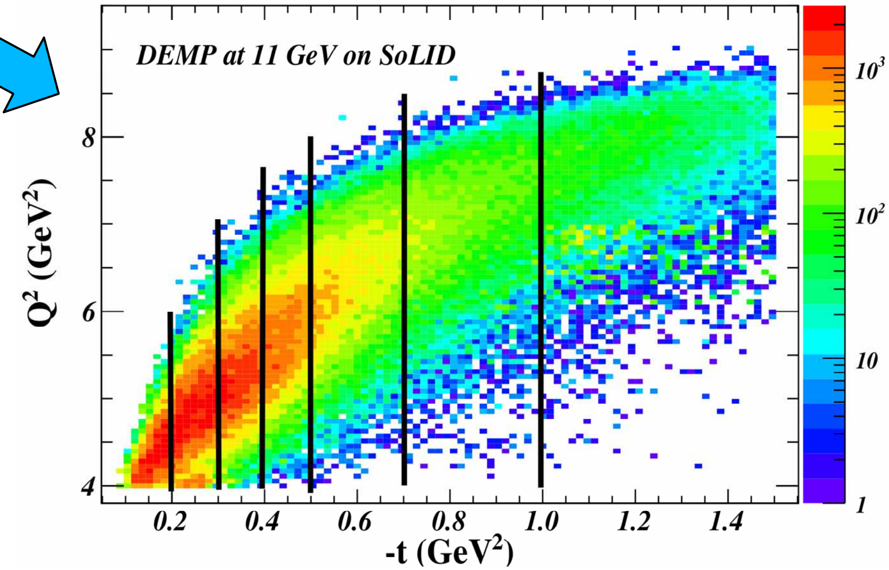
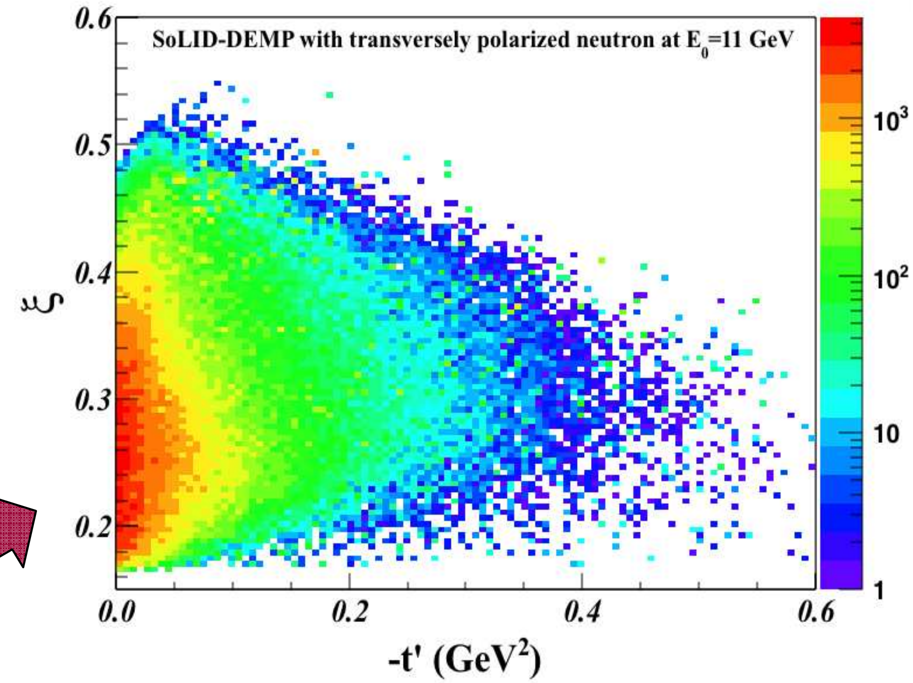
Kinematic Coverage and Binning

- We binned the simulated data in 7 t–bins.
- **In actual data analysis, we will consider alternate binning.**
- All JLab data cover a range of Q^2, x_{Bj} values.
  - x_{Bj} fixes the skewness (ξ).
  - Q^2 and x_{Bj} are correlated. In fact, we have an almost linear dependence of Q^2 on x_{Bj}.
- HERMES and COMPASS experiments are restricted kinematically to very small skewness (ξ<0.1).
- **With SoLID, we can measure the skewness dependence of the relevant GPDs over a fairly large range of ξ.**





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Unbinned Maximum Likelihood (UML)

- **Same method used by HERMES in their DEMP analysis** [PLB **682**(2010)345].
- Instead of dividing the data into (φ,φ_s) bins to extract the asymmetry moments, UML takes advantage of full statistics of the data, obtains much better results when statistics are limited.

1. Construct probability density function

$$f_{\uparrow\downarrow}(\phi,\phi_s;A_k)=\frac{1}{C_{\uparrow\downarrow}}\left(1\pm\frac{|P_T|}{\sqrt{1-\sin^2(\theta_q)\sin^2(\phi_s)}}\times\sum_{k=1}^{5}A_k\sin(\mu\phi+\lambda\phi_s)\right)$$

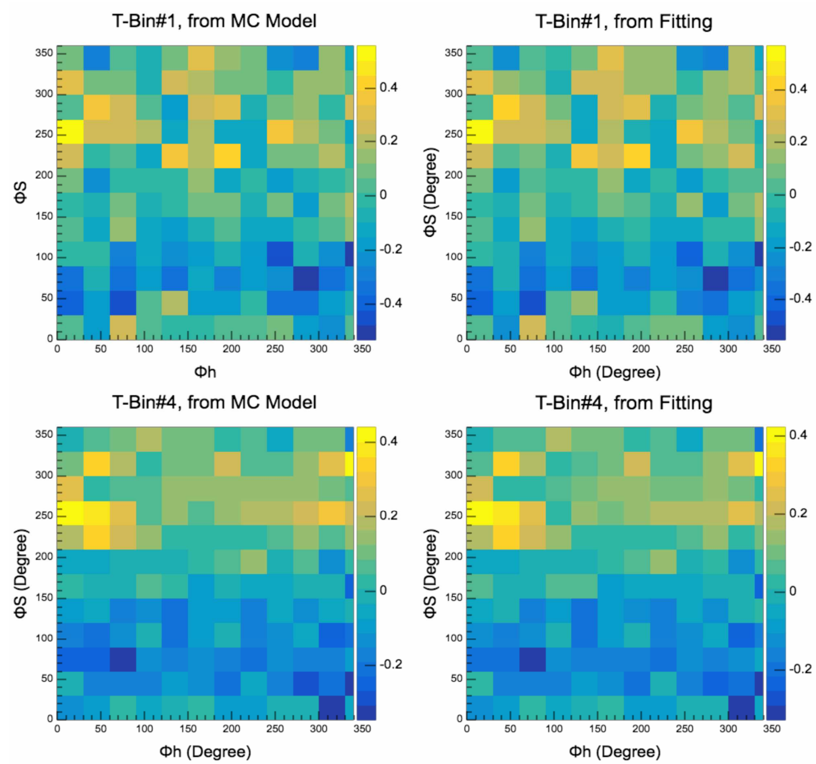
where A_k are the asymmetries that can minimize the likelihood function.

2. Minimize negative log-likelihood function:

$$-\ln L(A_k)=-\ln L_{\uparrow}(A_k)-\ln L_{\downarrow}(A_k)$$
$$=\sum_{l=1}^{N_{MC}^{\uparrow}}\left[w_l^{\uparrow}\cdot\ln f_{\uparrow}(\phi_l,\phi_{s,l};A_k)\right]-\sum_{m=1}^{N_{MC}^{\downarrow}}\left[w_m^{\downarrow}\cdot f_{\downarrow}(\phi_m,\phi_{s,m};A_k)\right]$$

where w_l, w_m are MC event weights based on cross section & acceptance.

3. As an illustration, reconstruct azimuthal modulations & compare:



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E12–10–006B Projected Uncertainties

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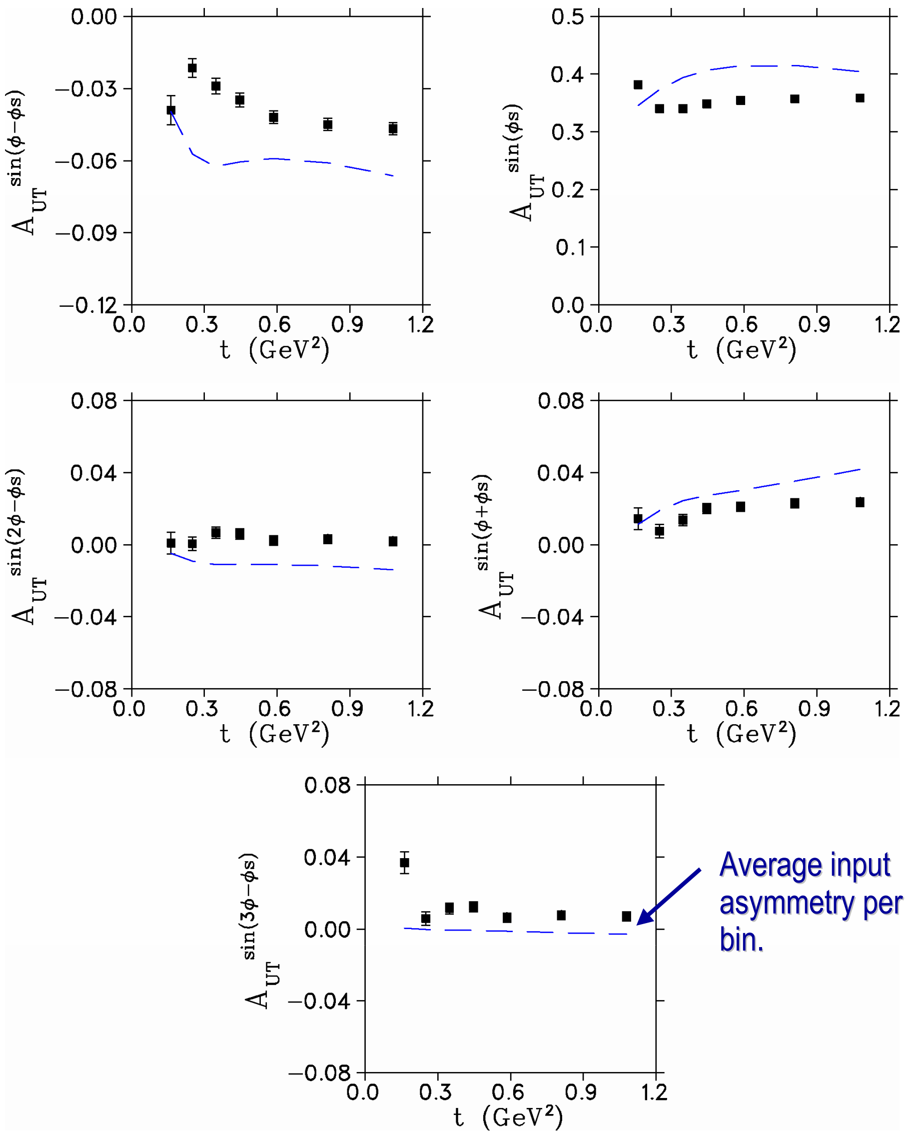
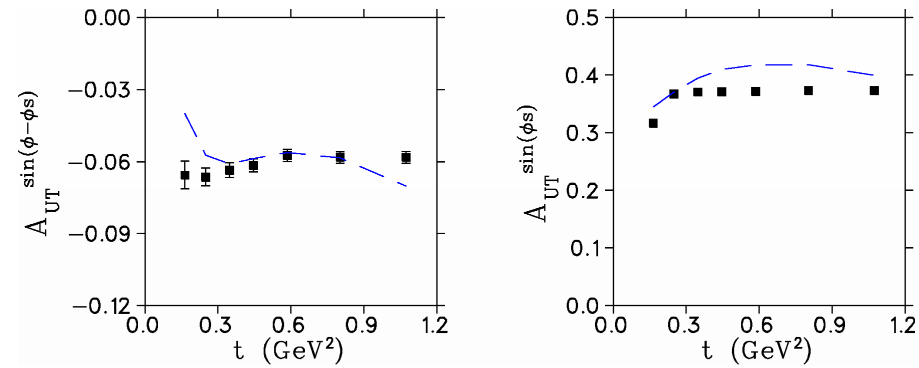
All effects on.

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



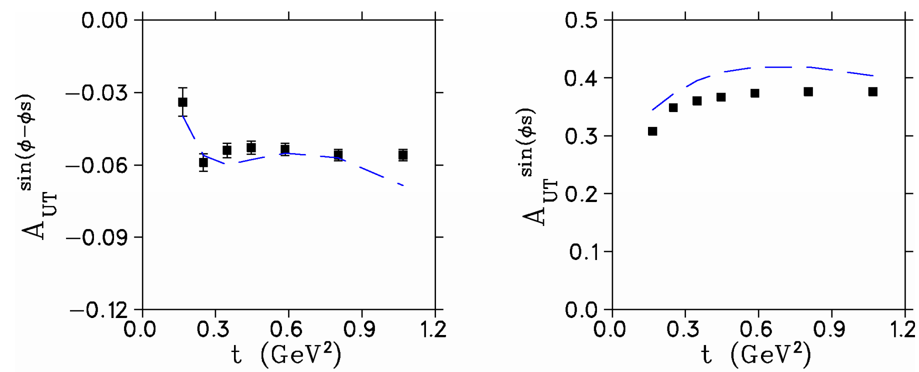
Only Fermi momentum off.

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 Unbinned Maximum Likelihood analysis procedure.



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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.**
- **SoLID measurement is also important preparatory work for EIC.**

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