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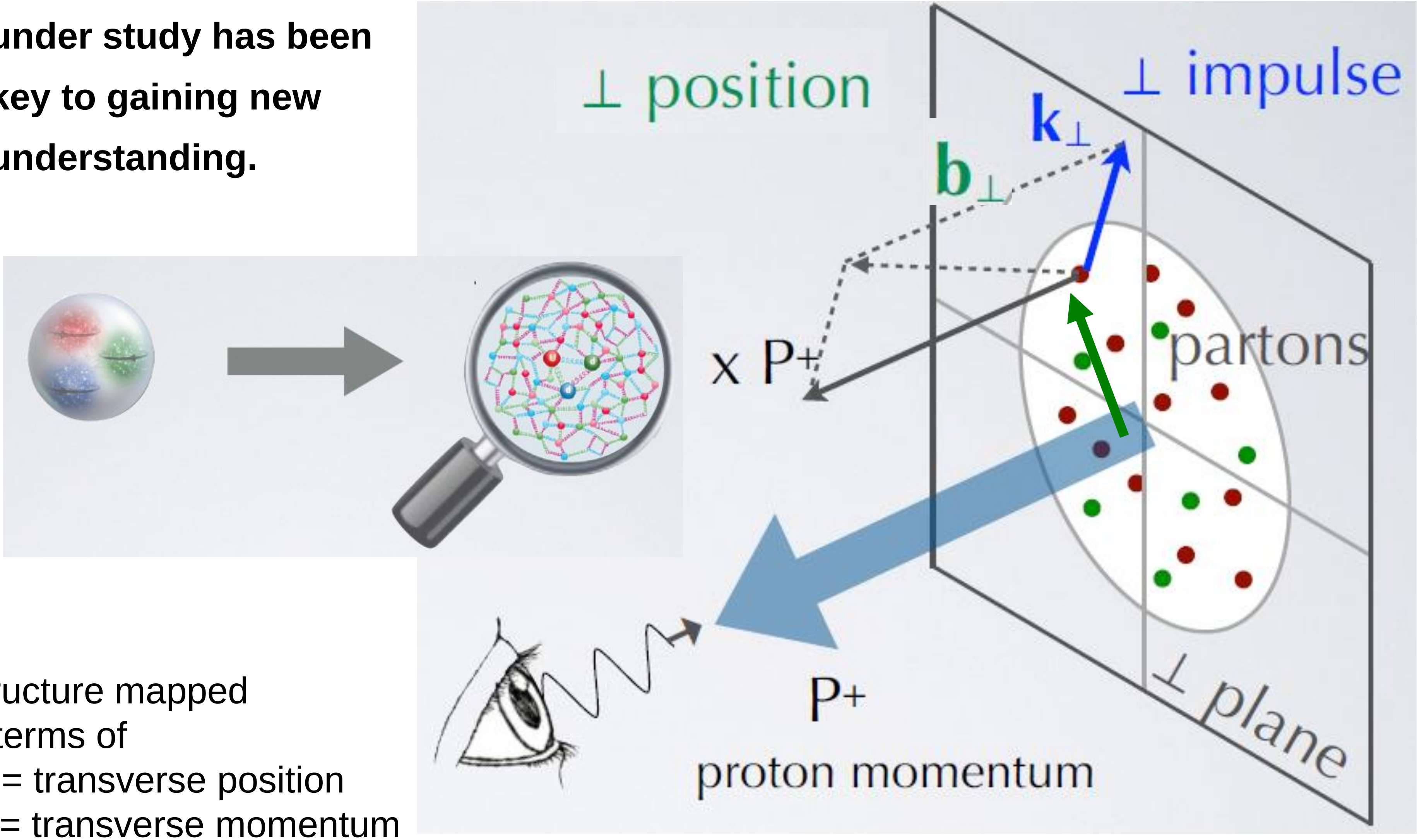
Motivation: in other sciences, imaging the physical systems under study has been key to gaining new understanding.



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

Taken from a talk by Rolf Ent, Jefferson Lab

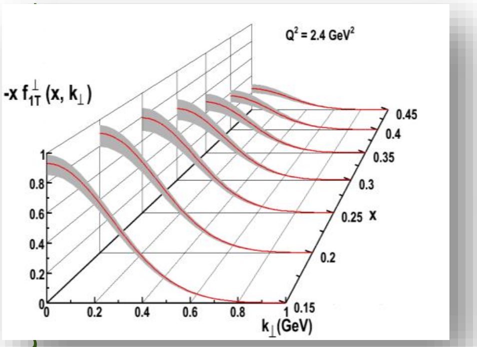
3D Imaging of the Nucleon

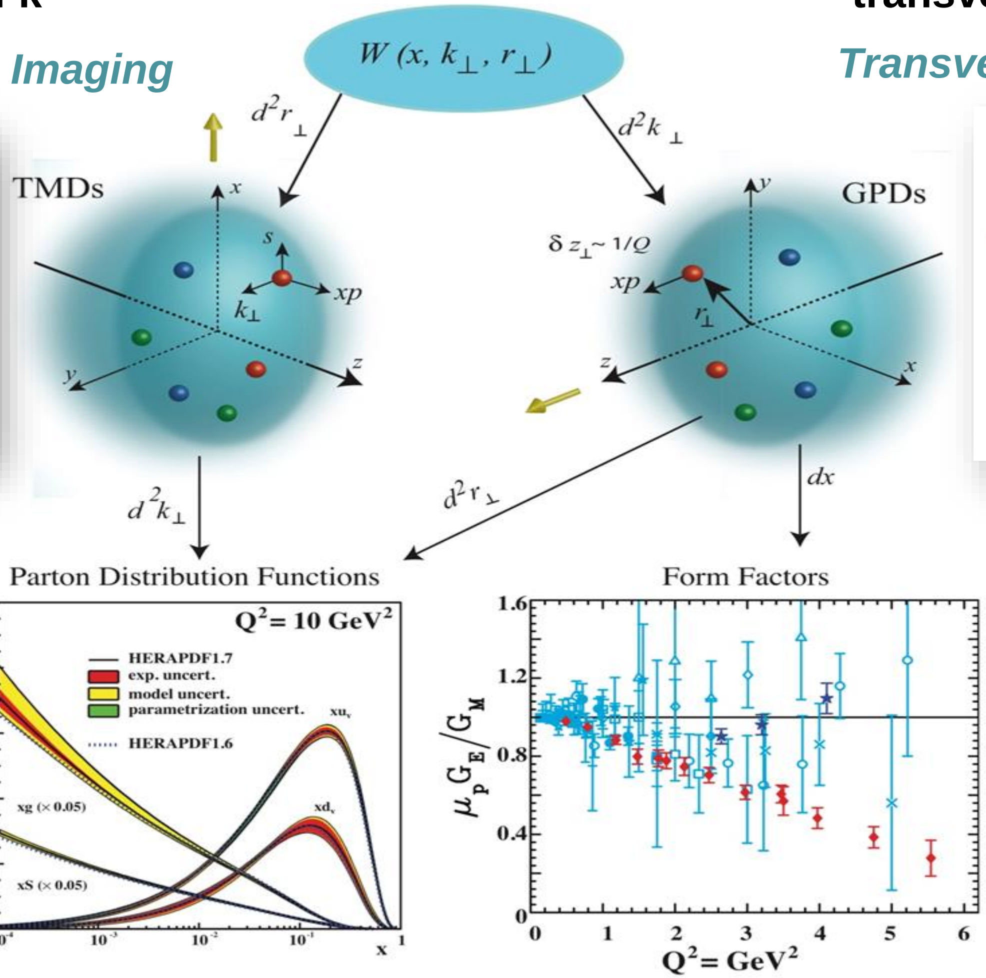
TMDs: Longitudinal momentum fraction x and transverse momentum k

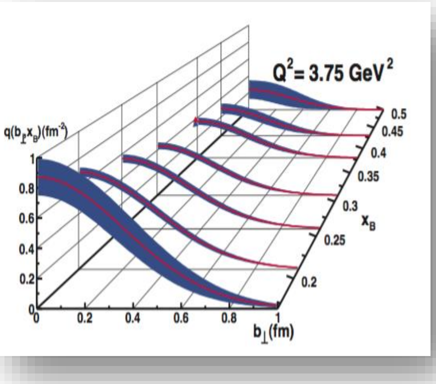
Transverse Momentum Imaging

GPDs: Longitudinal momentum fraction x at transverse location b

Transverse Spatial Imaging







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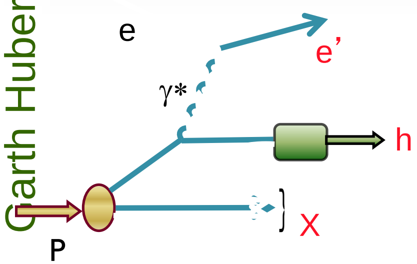
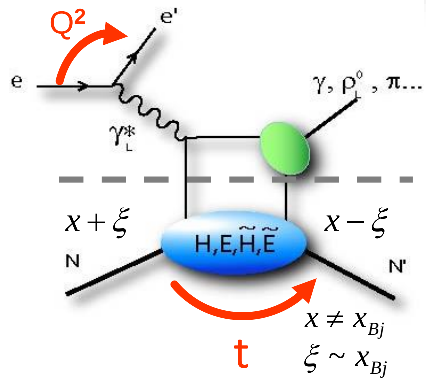
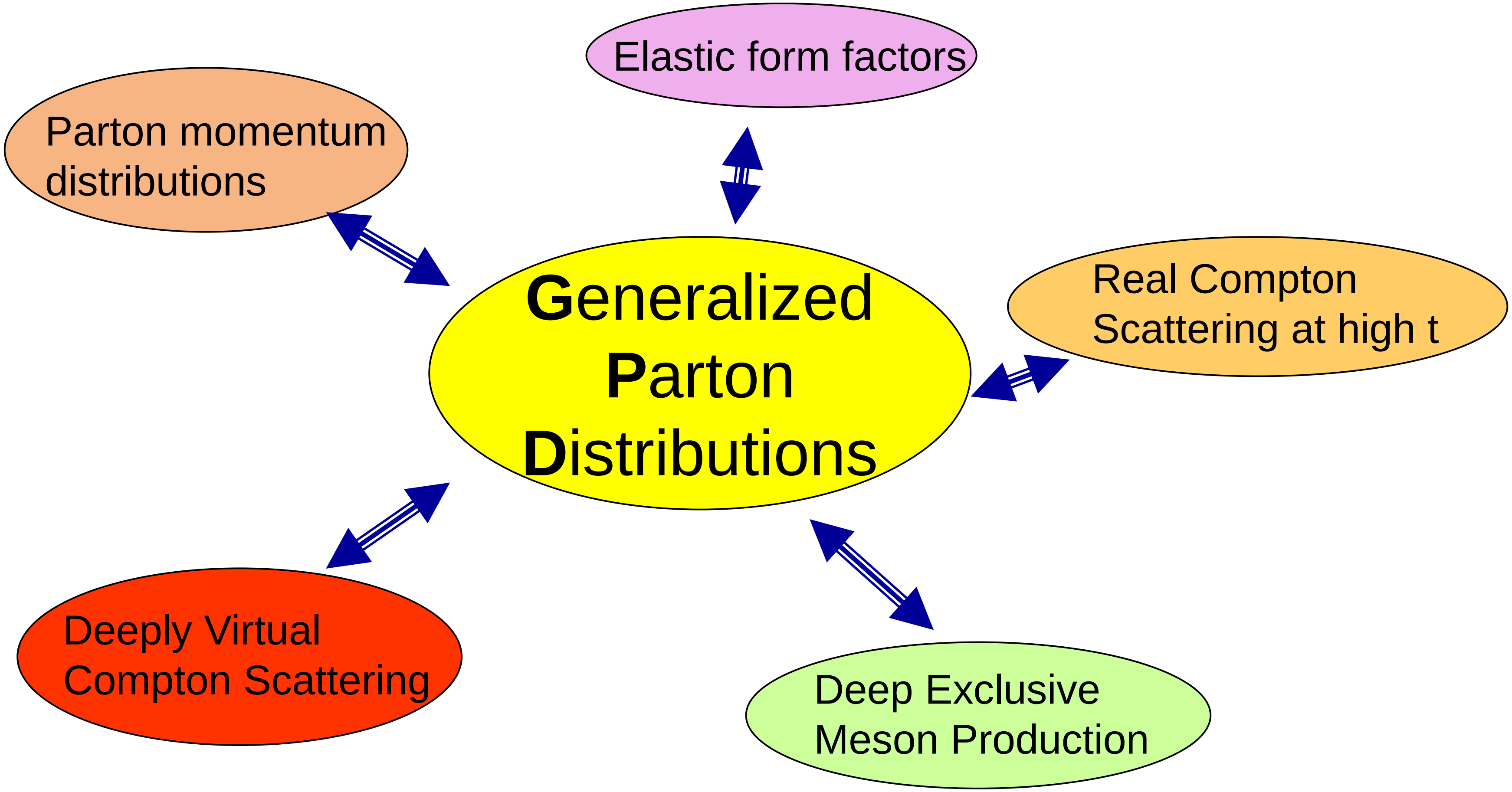




Taken from a talk by Rolf Ent, Jefferson Lab

GPDs – A Unified Description of Hadron Structure



Elastic form factors

Parton momentum distributions

Generalized **P**arton **D**istributions

Real Compton Scattering at high t

Deeply Virtual Compton Scattering

Deep Exclusive Meson Production

- **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.

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

Isovector axial form factor.
t –dep. poorly known.

$$\longrightarrow \quad \sum_q e_q \int_{-1}^{+1} dx\, \tilde{H}^q(x,\xi,t) = G_A(t)$$

Pseudoscalar form factor.
Very poorly known.

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

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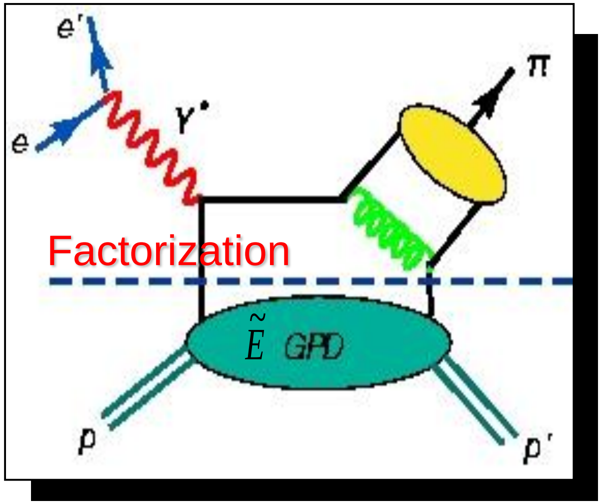
Next Generation Study: Polarized GPD $\tilde{E}$

- **$\tilde{E}$ 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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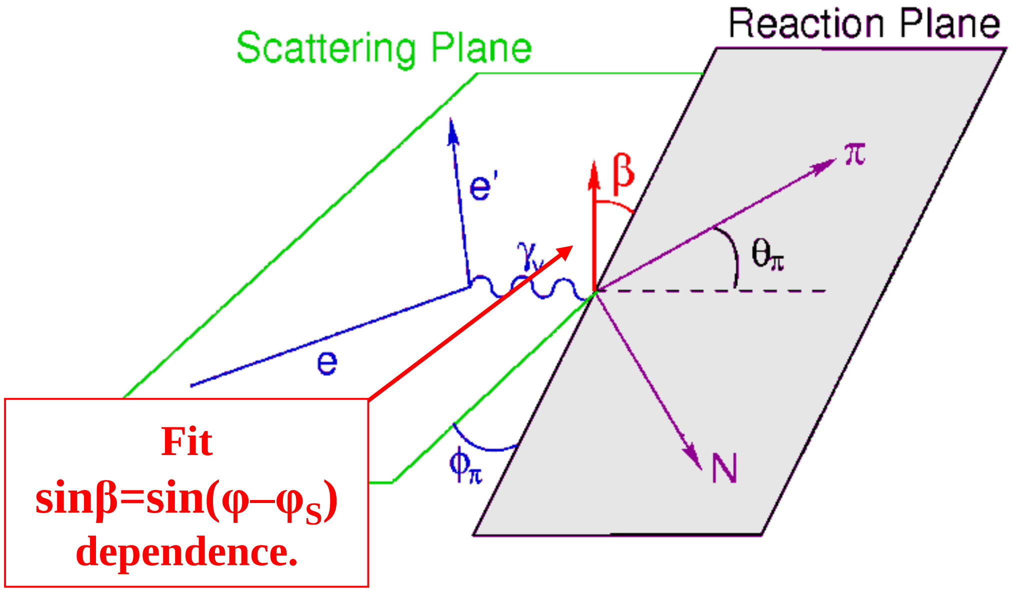
Exclusive π^- from Transversely Polarized Neutron

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.

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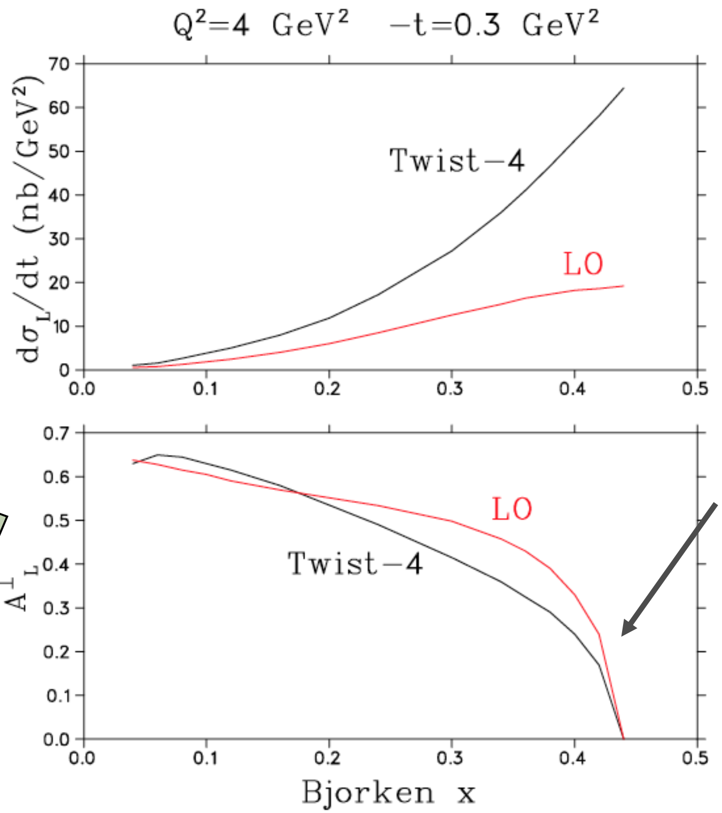
GPD information in $A_L^{\perp}$ may be particularly clean

- **$A_L^{\perp}$ 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 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

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

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

$\sigma^{ij}_{mn} \rightarrow$ 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 $\sin\beta=\sin(\varphi-\varphi_s)$ Asymmetry Moment

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

Note: Trento convention used for rest of talk

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

L–T Separated versus Unseparated Expts

- **Our reaction of interest is $\vec{n}(e,e'\pi^-)p$ from the neutron in transversely polarized ^{3}He.**
- **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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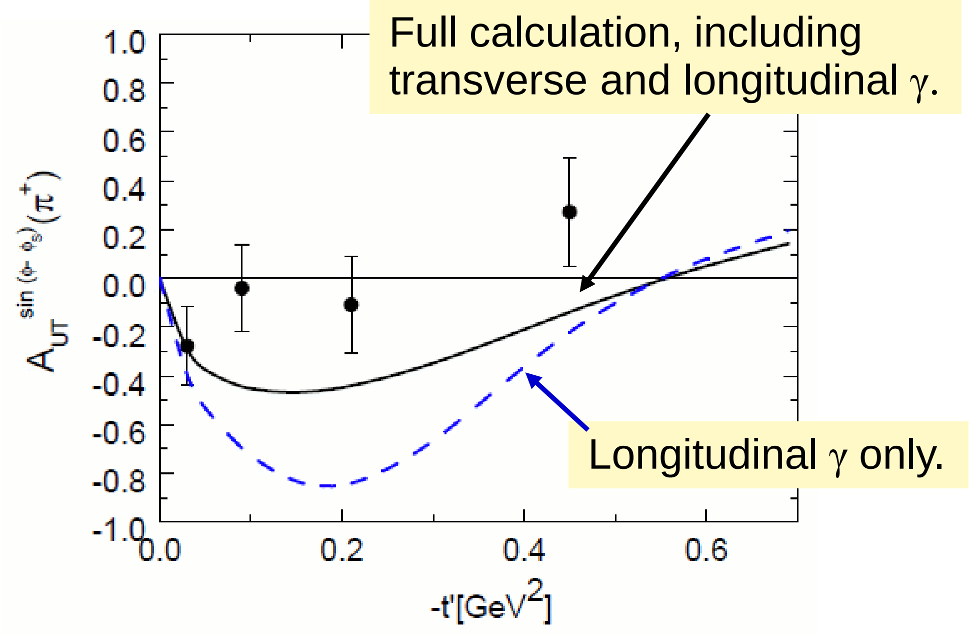
HERMES sin($\varphi - \varphi_S$) Asymmetry Moment

- 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.



Full calculation, including transverse and longitudinal γ.

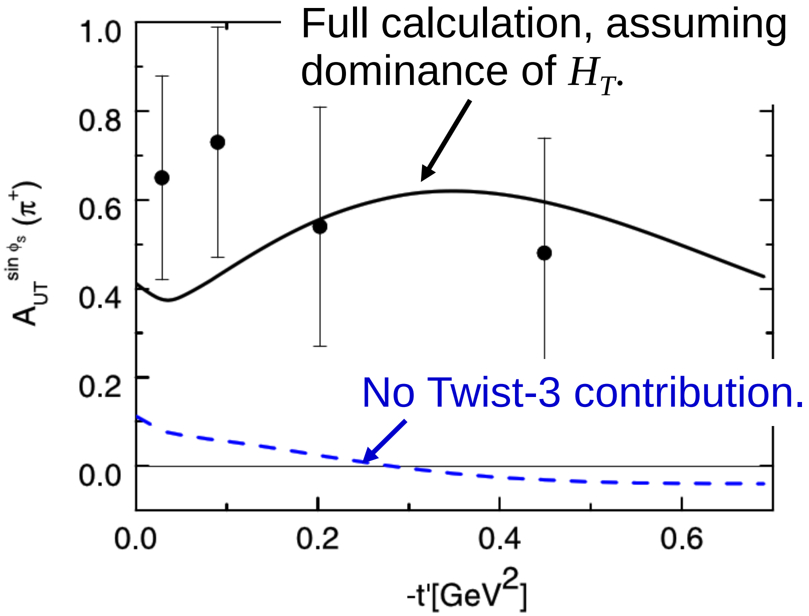
Longitudinal γ only.

- **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



Full calculation, assuming dominance of H_T.

No Twist-3 contribution.

- **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]

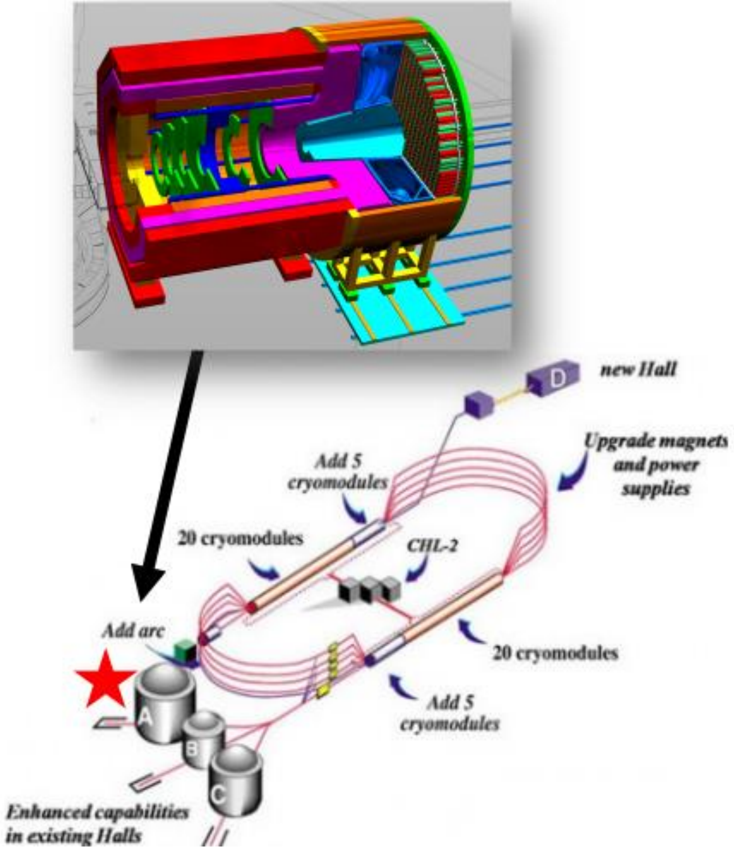
+

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

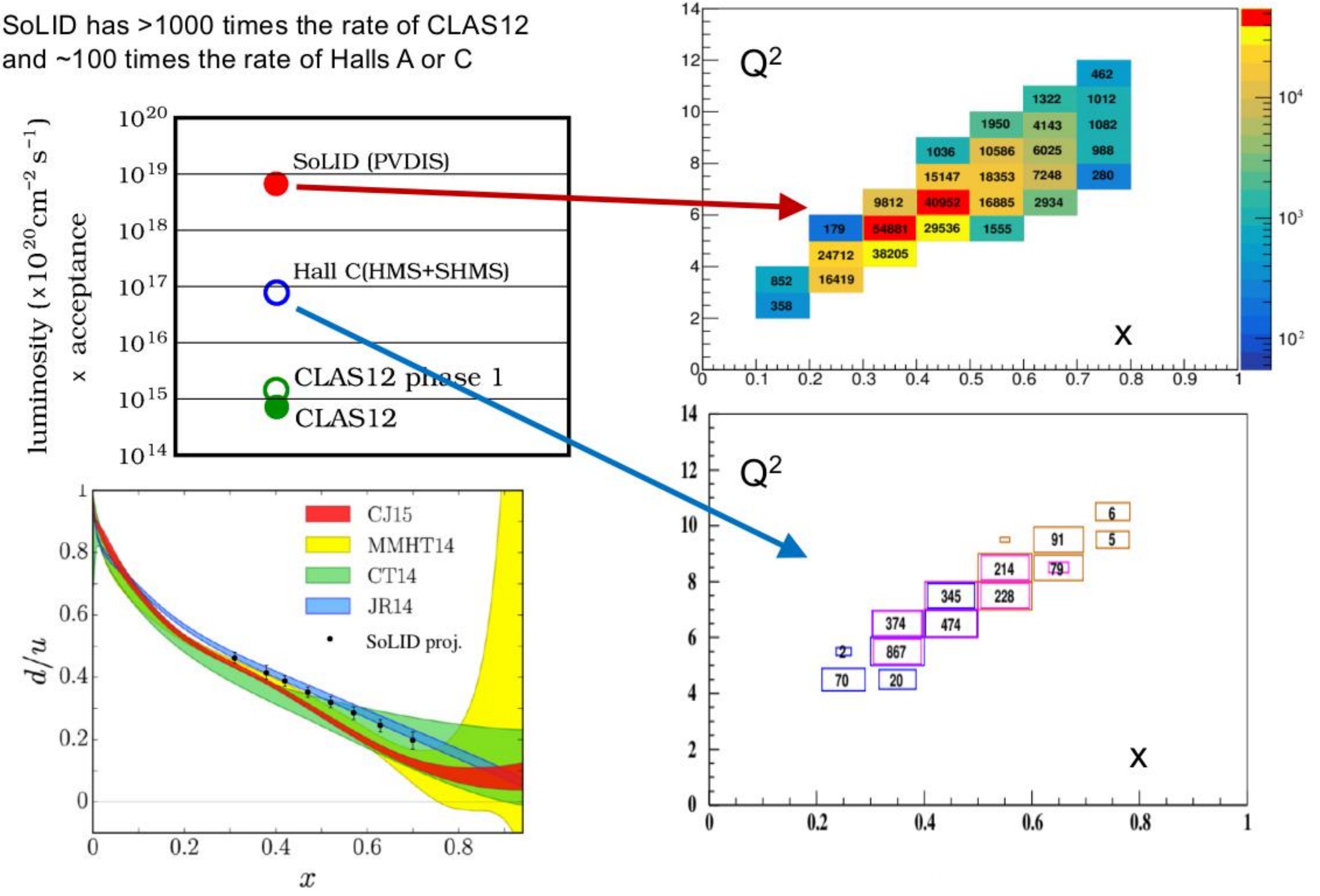
- **Precision lepto-quark couplings** at unique mass and sensitivity scales
- 3D momentum imaging of a relativistic strongly interacting confined system (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton mass**)

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



Optimized for High Luminosity Science

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



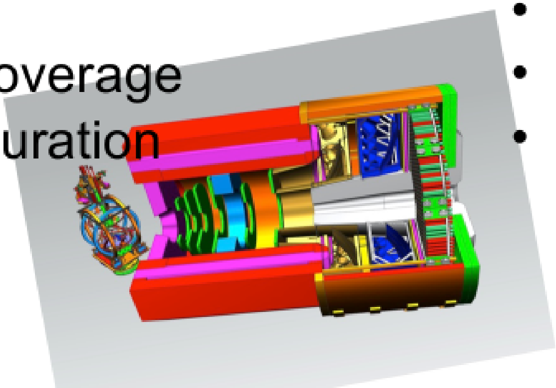
State–of–the–Art Technology

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

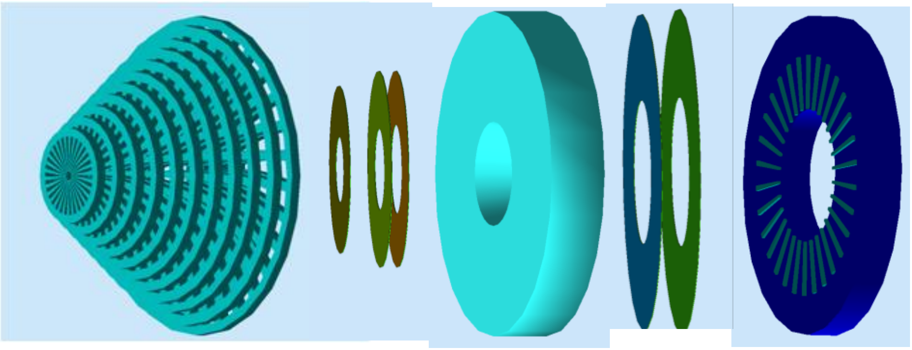
SoLID pre-conceptual design began "ground up" with the latest available advanced technologies to ensure every piece of sub-systems can meet the challenging requirements

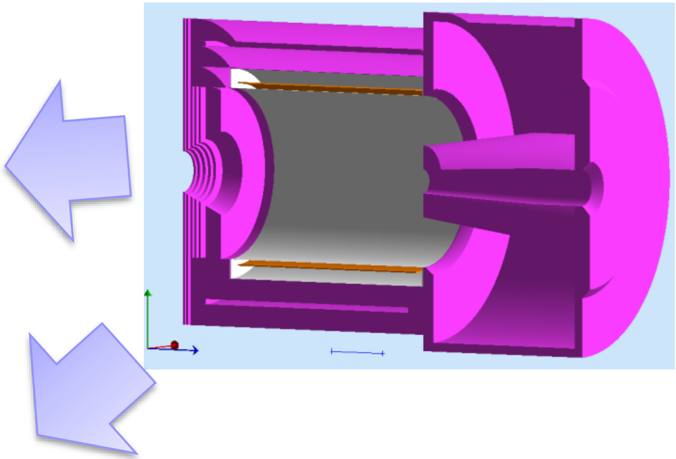
- GEM tracking
- Shashlik Electron Calorimetry
- High Performance Cerenkovs
- Pipeline DAQ
- Rapidly Advancing Computational Capabilities
- Parity beamline
- Advanced polarimetry
- High power and polarized targets



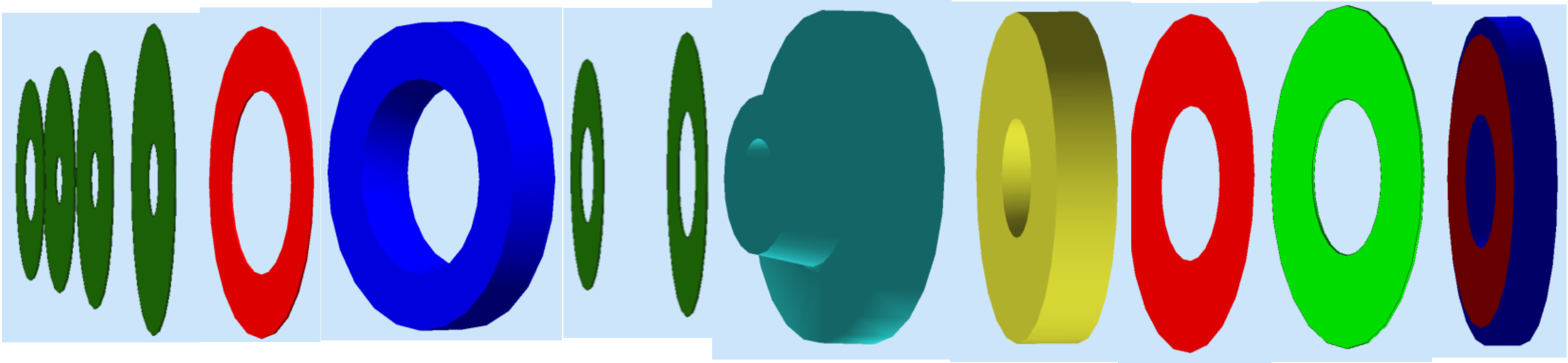
Detector Technologies

PVDIS: Baffle 3xGEMS LGC 2xGEMs EC





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

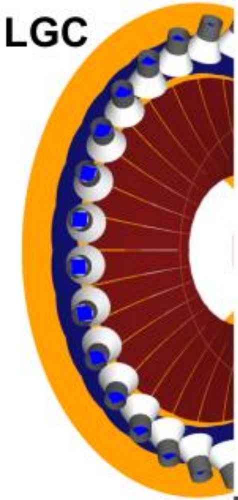


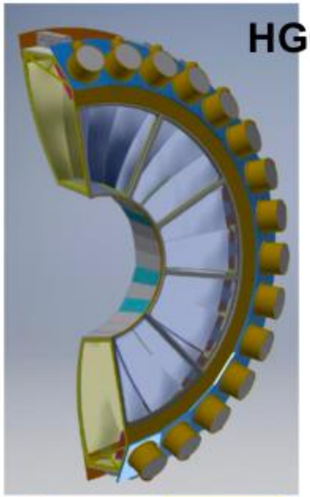
Pre-R&D items: LGC, HGC, GEM’s, DAQ/Electronics, Magnet

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





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

High Performance Cherenkovs

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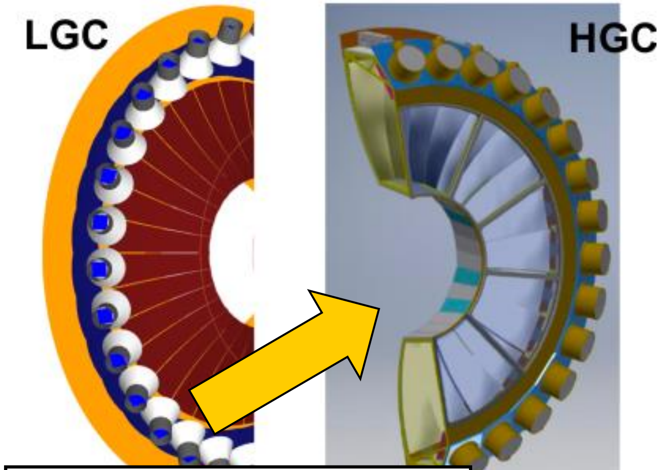


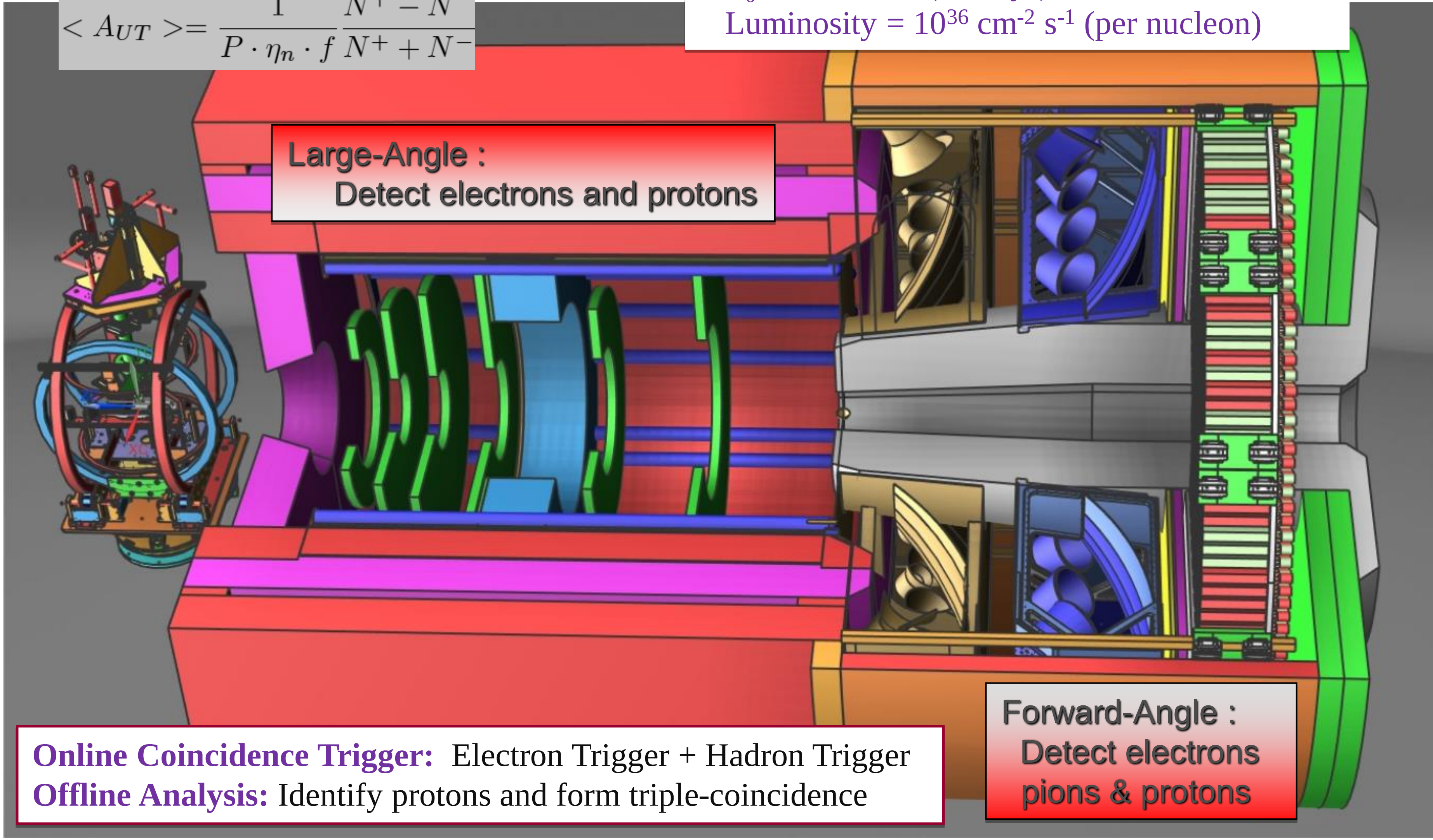
CFI–IF application for HGC vessel & entrance windows

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)



Large-Angle :
Detect electrons and protons

Forward-Angle :
Detect electrons
pions & protons

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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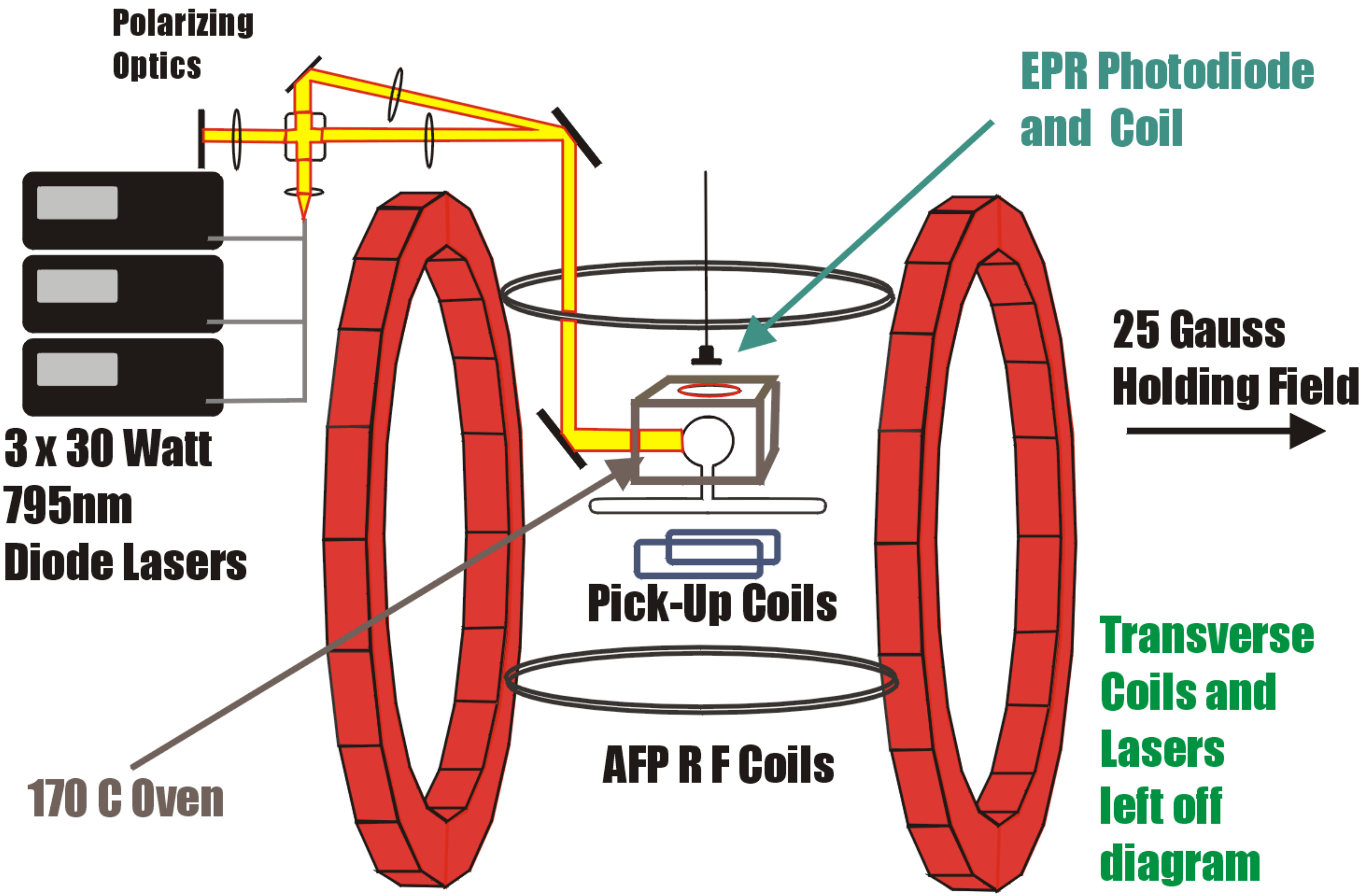

Transverse Coils and Lasers left off diagram

Asymmetry Moment Modeling

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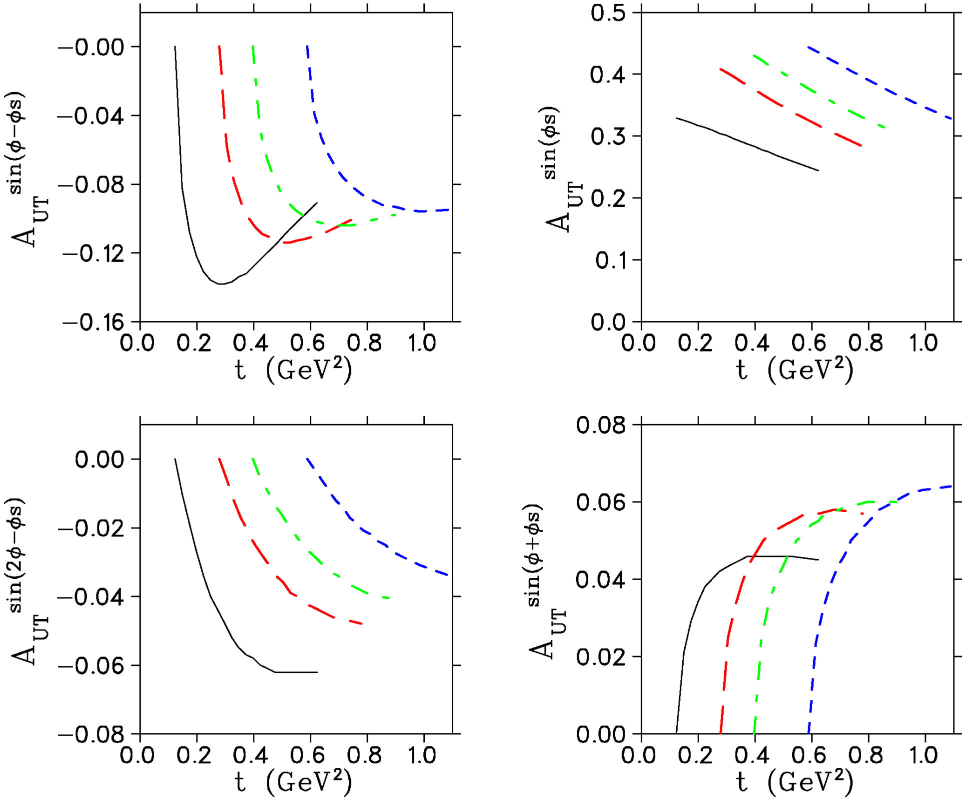
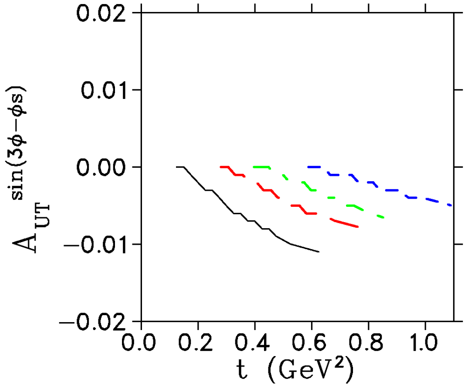
- **Event generator incorporates A_{UT} moments calculated by Goloskokov and Kroll for kinematics of this experiment.**
- GK handbag approach for $\pi^{\square}$ from neutron:
  - Eur.Phys.J. C**65**(2010)137.
  - Eur.Phys.J. A**47**(2011)112.
- **Simulated data for target polarization up and down are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



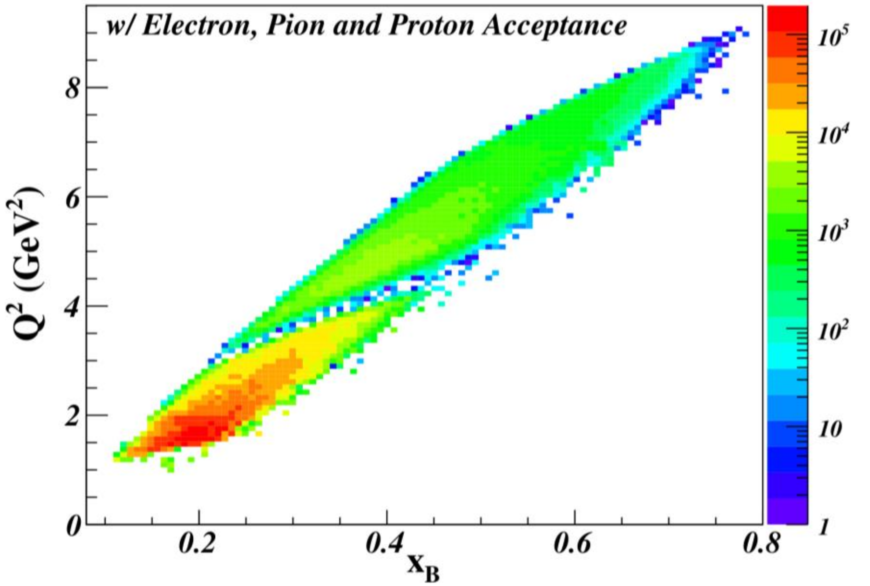
Q^2	W
4.11	3.17
5.14	2.80
6.05	2.72
6.89	2.56



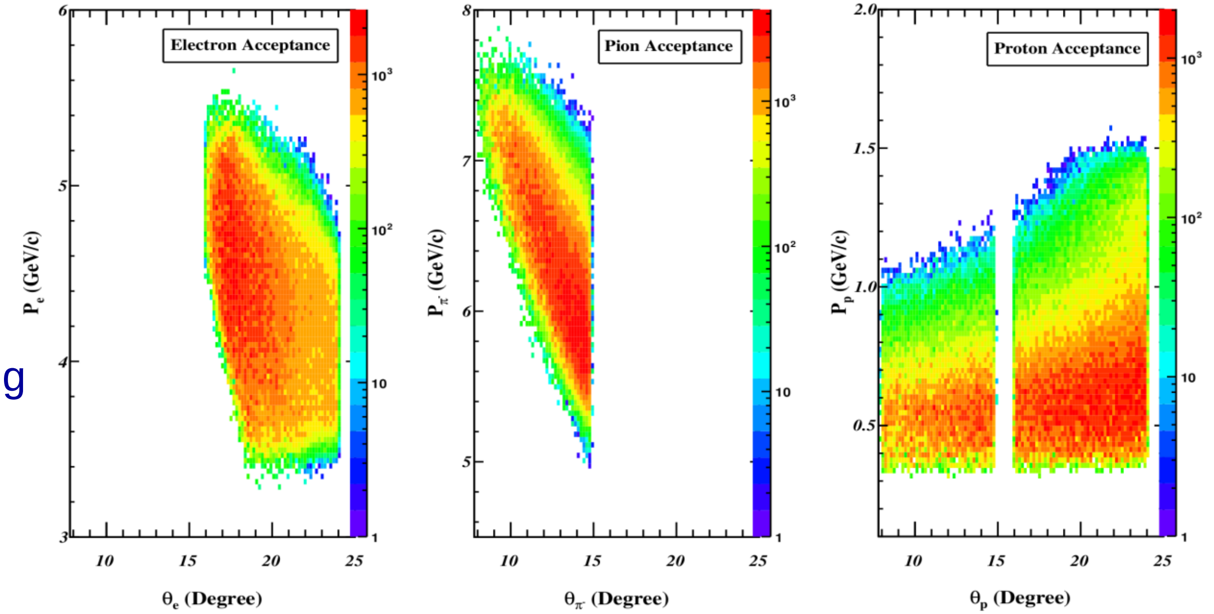
SoLID Acceptance and Projected Rates

$Q^2>1$ 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, $0.55<\varepsilon<0.75$ cuts applied.



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Example Cuts to Reduce Background

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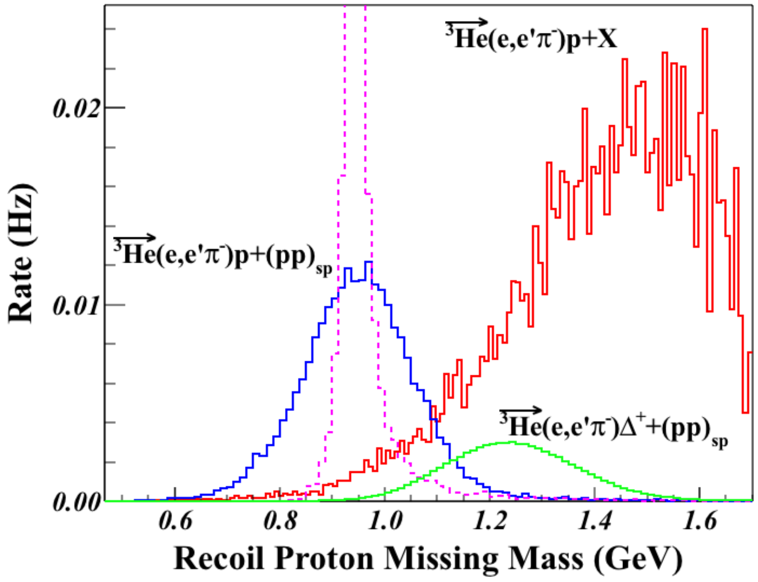
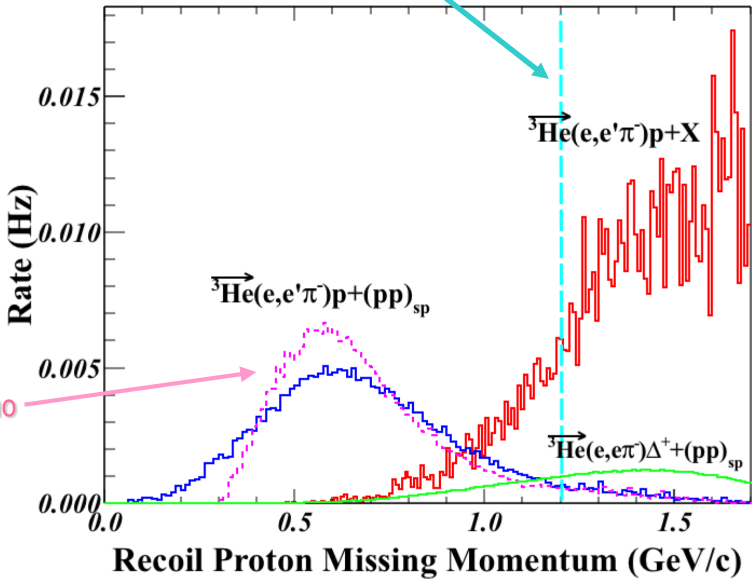
Two different background channels were simulated:

- 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).
- $en\rightarrow\pi^-\Delta^+\rightarrow\pi^-\pi^0p$ where the Δ^+ (polarized) decays with l=1, m=0 angular distribution (more realistic).



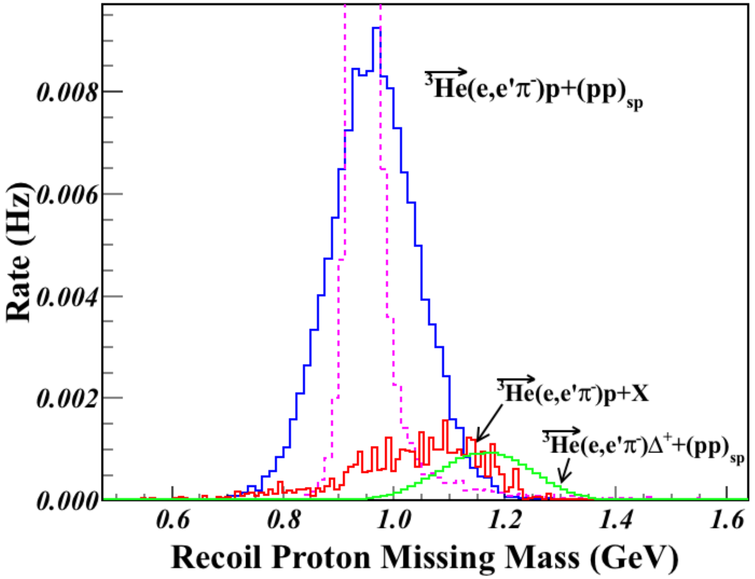
Apply P_{miss}>1.2 GeV/c cut

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



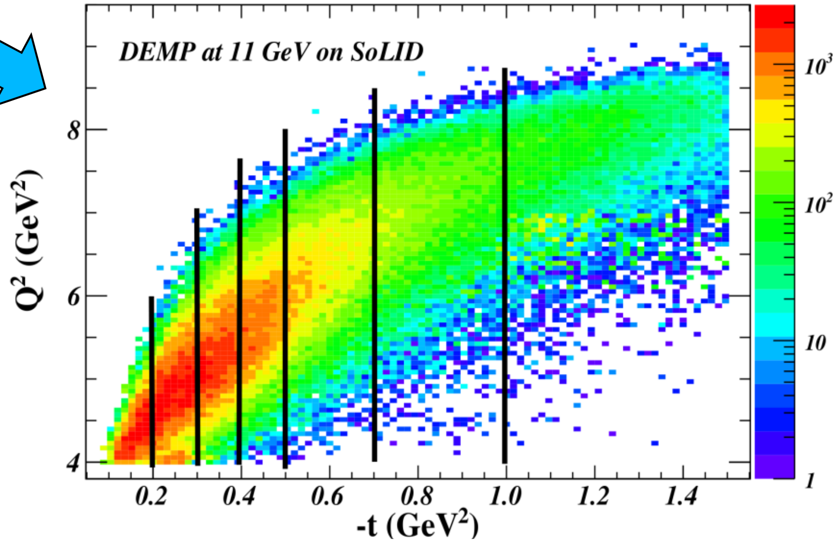
Scattering & radiation but no resolution smearing

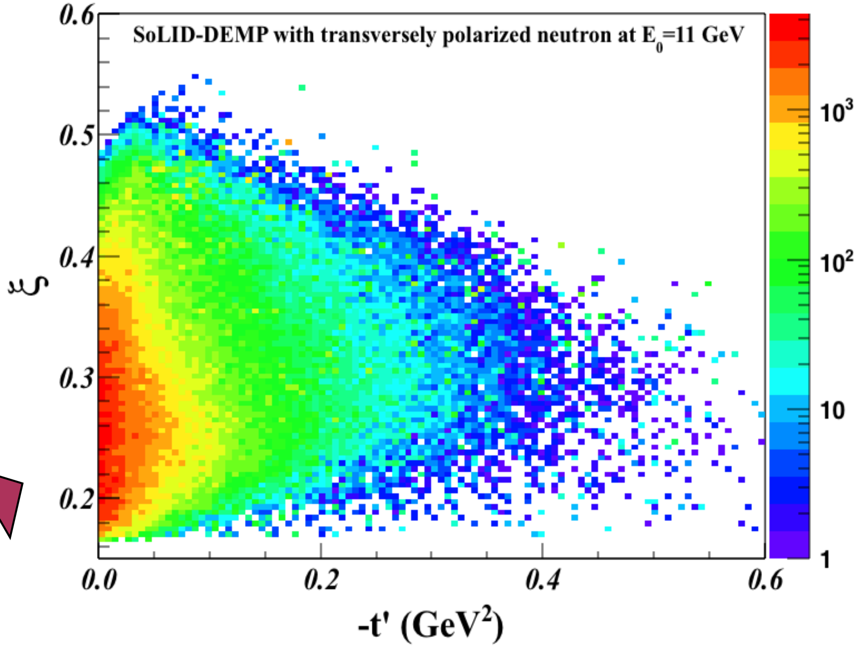
Background remaining after P_{miss} cut



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.**





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

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

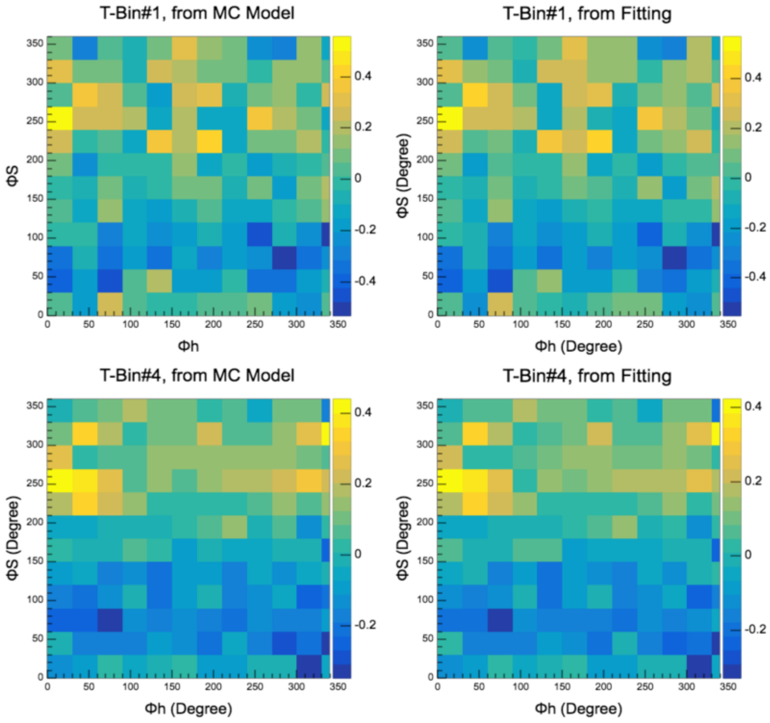
where A_k are the asymmetries that can minimize the likelihood function.

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:



E12–10–006B Projected Uncertainties

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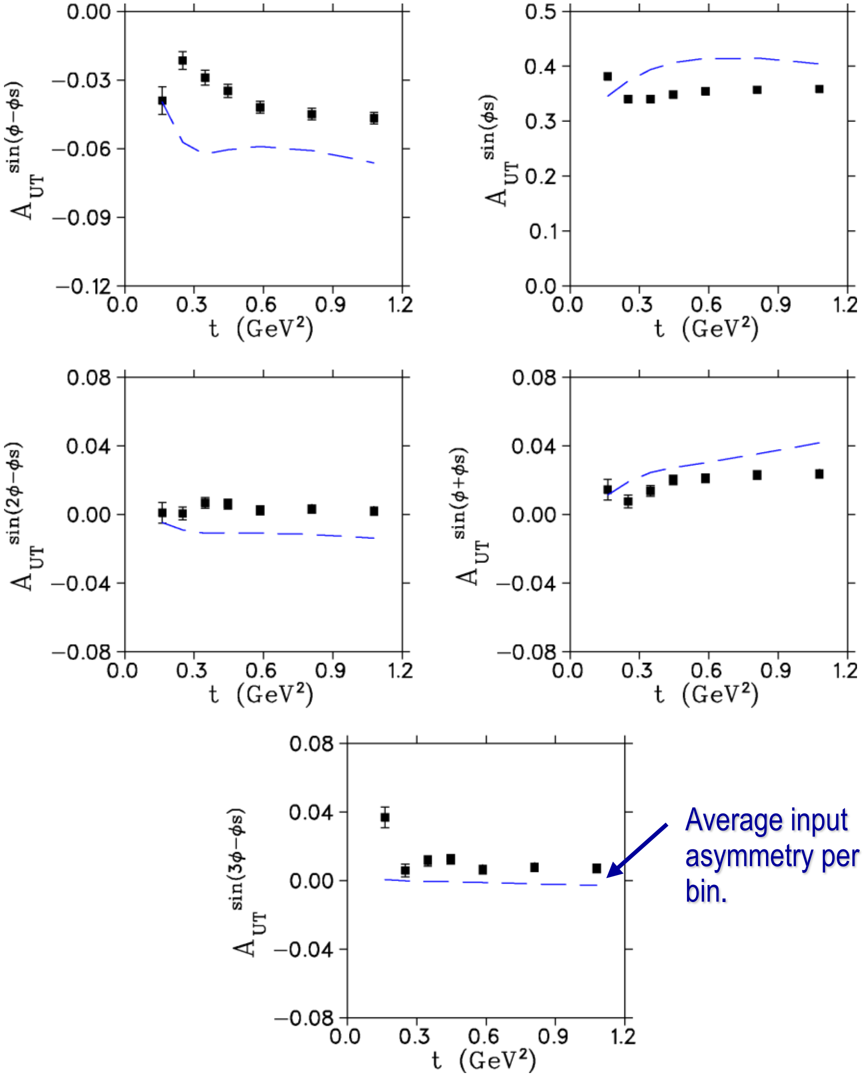
All effects on.

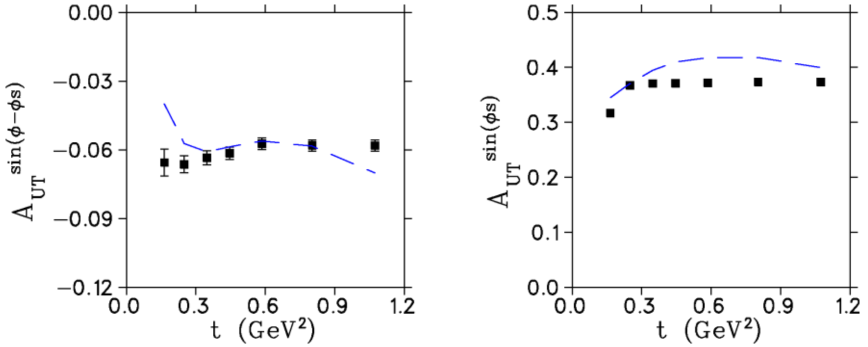
Includes all scattering, energy loss, resolution and Fermi momentum effects.



Average input asymmetry per bin.

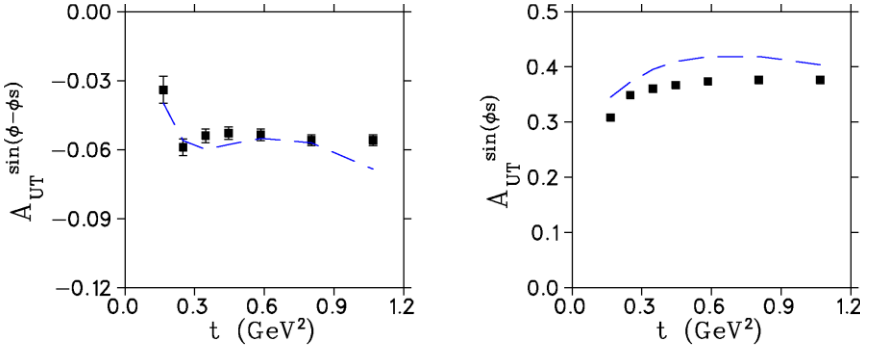
Only Fermi momentum off.

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 Unbinned Maximum Likelihood analysis procedure.



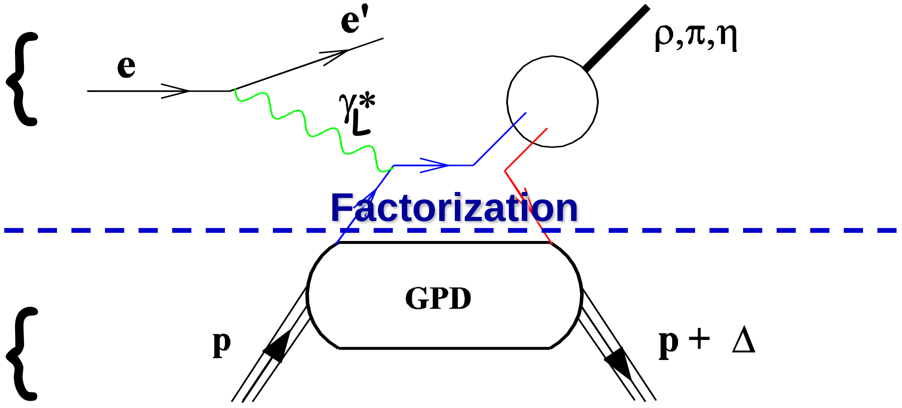
Summary

- $A_{UT}^{\sin(\varphi-\varphi s)}$ 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.**

GPDs require Hard Exclusive Reactions

- **In order to access the physics contained in GPDs, one is restricted to the hard scattering regime.**

- **Factorization property of hard reactions:**
  - **Hard probe creates a small size $q\bar{q}$ and gluon configuration,**
    - **interactions can be described by pQCD.**
  - **Non-perturbative part describes how hadron reacts to this configuration, or how the probe is transformed into hadrons (parameterized by GPDs).**



- Hard Exclusive Meson Electroproduction first shown to be factorizable by Collins, Frankfurt & Strikman [PRD **56**(1997)2982].
- Factorization applies when the γ^* is longitudinally polarized.
  - corresponds to small size configuration compared to transversely polarized γ^*.

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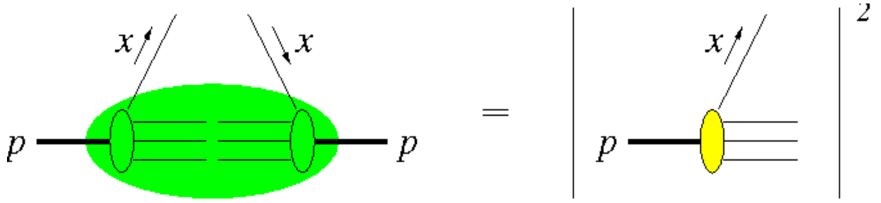
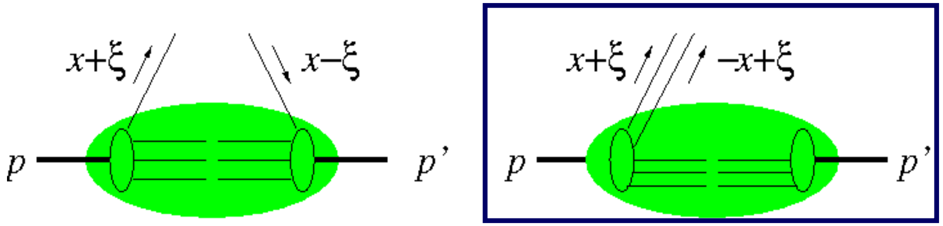
GPDs in Deep Exclusive Meson Production

PDFs : **probability of finding a parton with longitudinal momentum fraction x and specified polarization in fast moving hadron.**



GPDs : **interference between partons with $x+\xi$ and $x-\xi$, interrelating longitudinal momentum & transverse spatial structure of partons within fast moving hadron.**

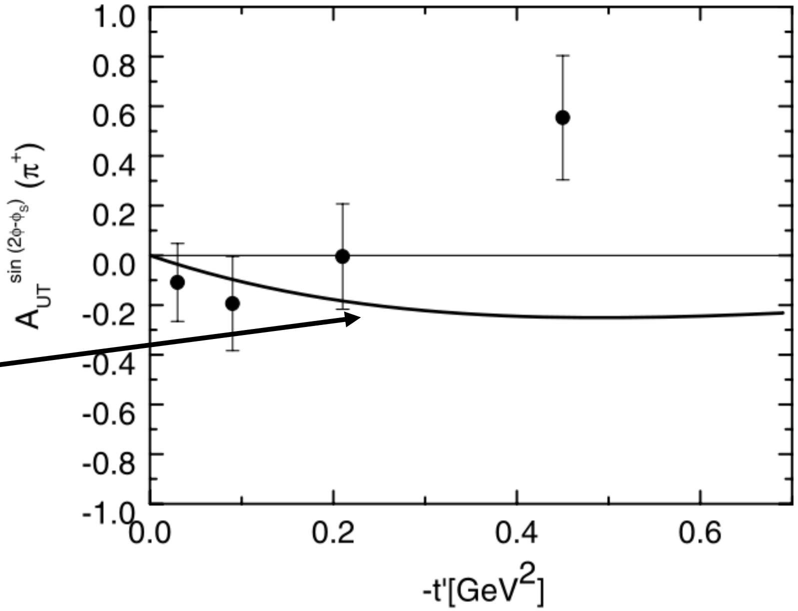


A special kinematic regime is probed in Deep Exclusive Meson Production, where the initial hadron emits $q\bar{q}$ or gg pair.

- No counterpart in usual PDFs.
- Since GPDs correlate different parton configurations in the hadron at quantum mechanical level,
  - GPDs determined in this regime carry information about $q\bar{q}$ and gg-components in the hadron wavefunction.

HERMES sin(2φ–φ$_s$) Asymmetry Moment

- ‹Q^2›=2.38 GeV^2, ‹W›=3.99 GeV.
- Experimental values and model calculation are both small.



Handbag approach calculation by Goloskokov & Kroll [Eur.Phys.J. **C65**(2010)137] .

- **sin(2φ-φ$_S$) modulation has additional LT interference amplitudes contributing that are not present in sin(φ$_S$).**
    - Improvement to calculation to reproduce sign change would require a more detailed modeling of these smaller amplitudes.
    - This would also improve description of other amplitude moments. **In this sense, different moments provide complementary amplitude term information.**
- **The remaining sin(φ+φ$_s$), sin(2φ+φ$_s$), sin(3φ–φ$_s$) moments are only fed by TT interference and are even smaller.**

Missing Mass and Missing Momentum

Separating Exclusive Events from Inclusive Background:

- Although we will detect the recoil proton to separate the exclusive channel events, here, we do not assume that the proton momentum resolution is sufficiently good to provide an additional constraint.
- Thus, we compute the missing mass and momentum as if the proton were not detected:

$$M_{miss} = \sqrt{(E_e + m_n - E_{e'} - E_{\pi^-})^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_{\pi^-})^2}$$

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

- **Of course, in the actual analysis, we will try to reconstruct the proton momentum as accurately as possible.**
- If the resolution is sufficiently good, this would allow additional background discrimination, as well as the effect of Fermi momentum to be removed from the asymmetry moments on an event-by-event basis.

Complementarity of Hall C and SoLID Expts

SHMS+HMS:

- HMS detects scattered e'.

  SHMS detects forward, high momentum π.
- **Expected small systematic uncertainties to give reliable L/T separations.**
- Good missing mass resolution to isolate exclusive final state.
- Multiple SHMS angle settings to obtain complete azimuthal coverage up to 4^o from q-vector.
- **It is not possible to have complete azimuthal coverage at larger –*t*, where $A_L^{\perp}$ is largest.**
- **PR12-12-005 by GH, D. Dutta, D. Gaskell, W. Hersman** based on next generation polarized ^{3}He target (e.g. UNH).

SoLID:

- Complete azimuthal coverage (for π) up to θ=24^o.
- **High luminosity, particle ID and vertex resolution capabilities well matched to the experiment.**
- L/T separation is not possible, the $\sin(\varphi\text{-}\varphi_s)$ asymmetry moment is "diluted" by LL, TT contributions.
- **The measurement is valuable as it is the only practical way to obtain $A_{UT}^{\sin(\varphi-\varphi_s)}$ over a wide kinematic range.**
- We will also measure $A_{UT}^{\sin(\varphi_s)}$ and its companion moments, as was done by HERMES.
- **Provides vital GPD information not easily available in any other experiment prior to EIC.**

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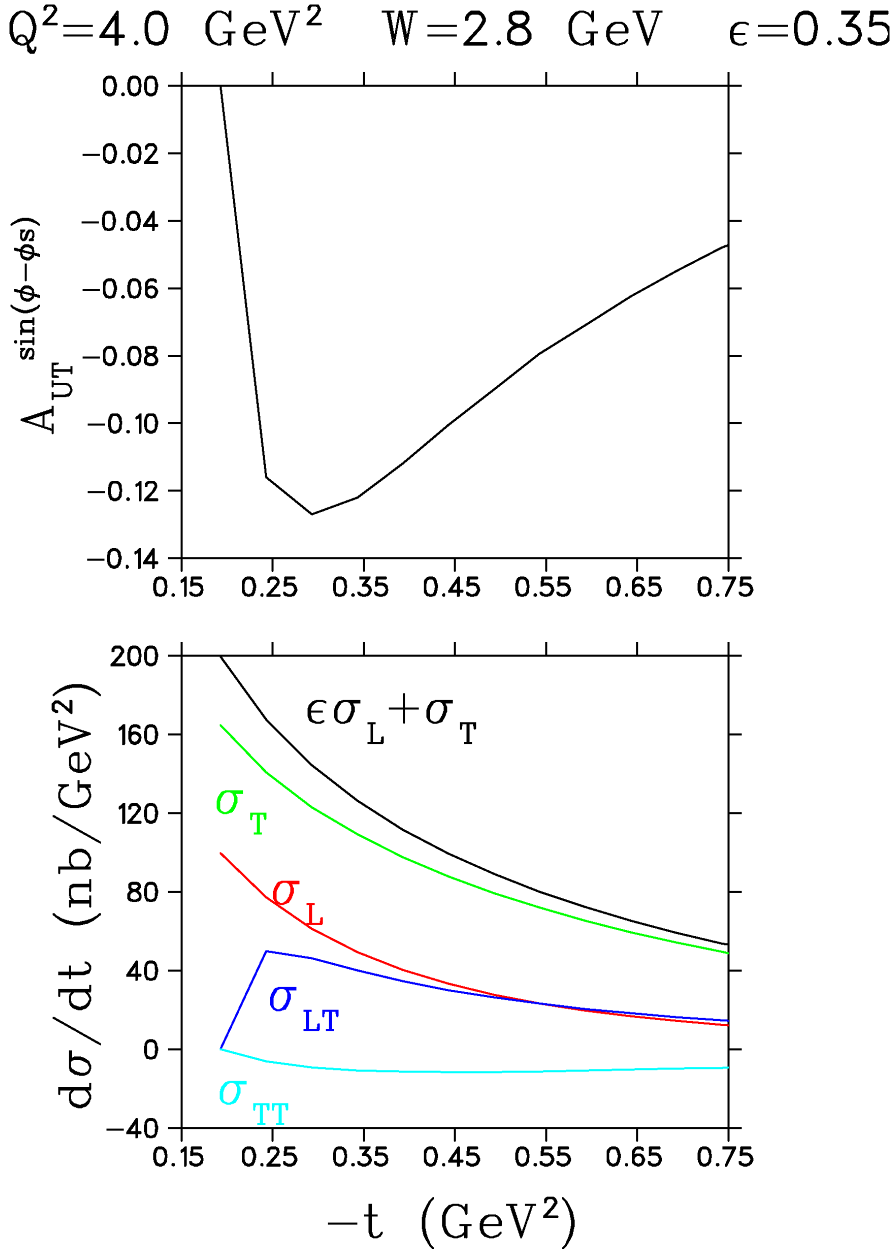
Asymmetry Dilution with SoLID

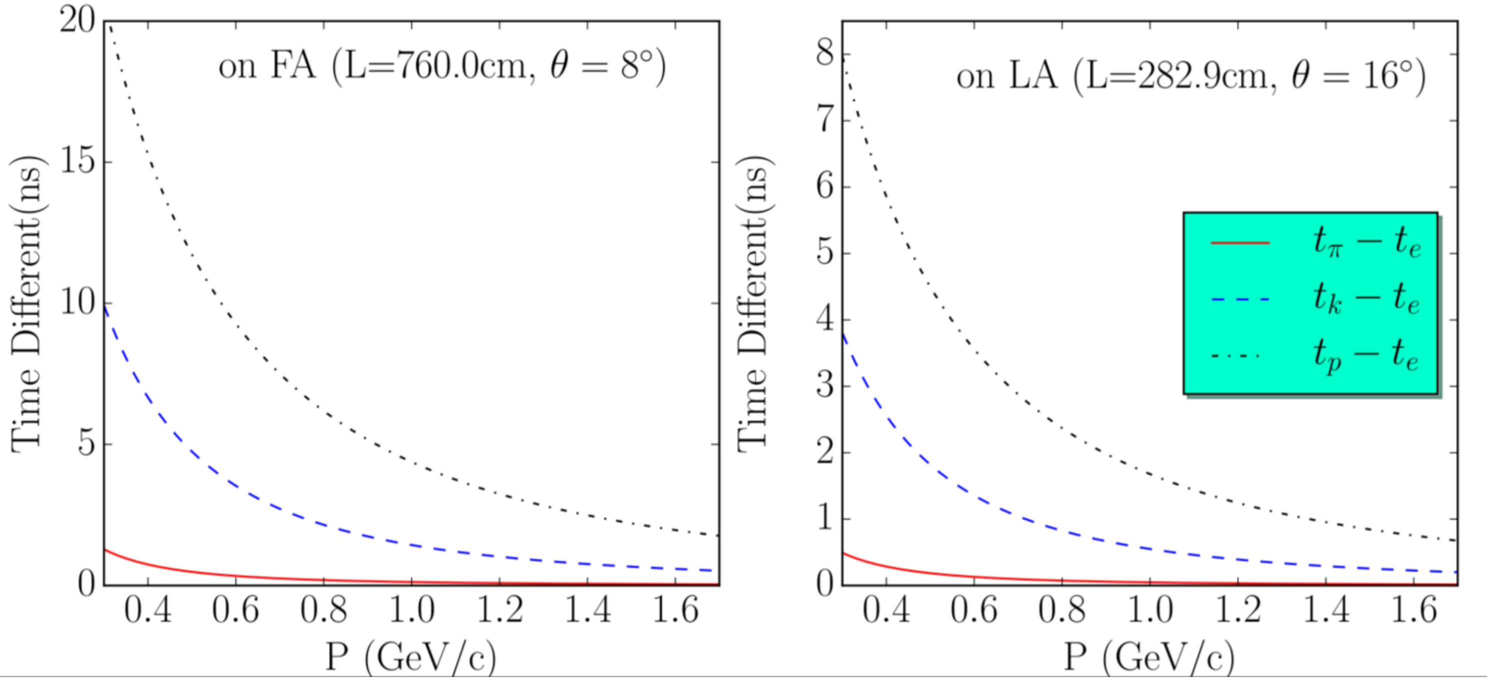
- **Calculation of cross section components and sin($\beta=\varphi-\varphi_s$) asymmetry moment in handbag approach by Goloskokov & Kroll for our kinematics.**
  - Although their calculation tends to underestimate σ_L values measured by JLab Fπ–2, their model is in reasonable agreement with unseparated dσ/dt.
- Similar level of $A_{UT}^{\sin(\varphi-\varphi s)}$ asymmetry dilution as observed by HERMES is expected in SoLID measurement.
- **SoLID measurement at higher *Q^2* than HERMES, will cover a wide range of *–t* (and ξ) with good statistical precision.**



Recoil Particle Detection: Time of Flight

$^{3}He(e,e'\pi^{-}p)pp_{sp}$

- Need >5σ timing resolution to identify protons from other charged particles



- **Exisiting SoLID Timing Detectors:**
  - MRPC & FASPC at Forward-Angle: cover 8º~14.8º, >3 ns separation.
  - LASPD at Large-Angle: cover 14º~24º, >1 ns separation.
- The currently designed timing resolution is sufficient for proton identification using TOF.

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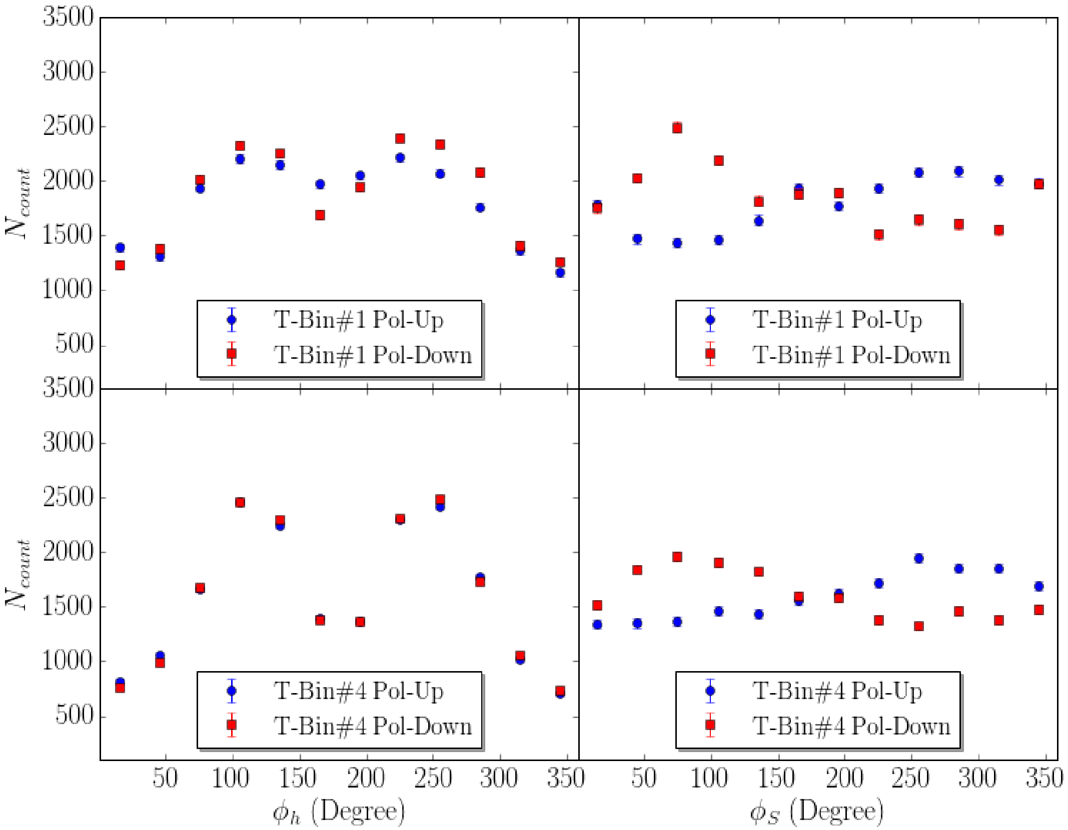
Acceptance Effects vs. (φ, φ_s)

- Expected yield as function of φ, φ_s for *t*–bins:
  - #1 (0.05–0.20)
  - #4 (0.40–0.50)
- Acceptance fairly uniform in φ_s.
- Some drop off on edges of φ distribution, since *q* is not aligned with the solenoid axis.
  - Critical feature is that φ drop off is same for target pol. up, down.



- **UML analysis shows that sufficient statistics are obtained over full (φ,φ_s) plane to extract asymmetry moments with small errors.**

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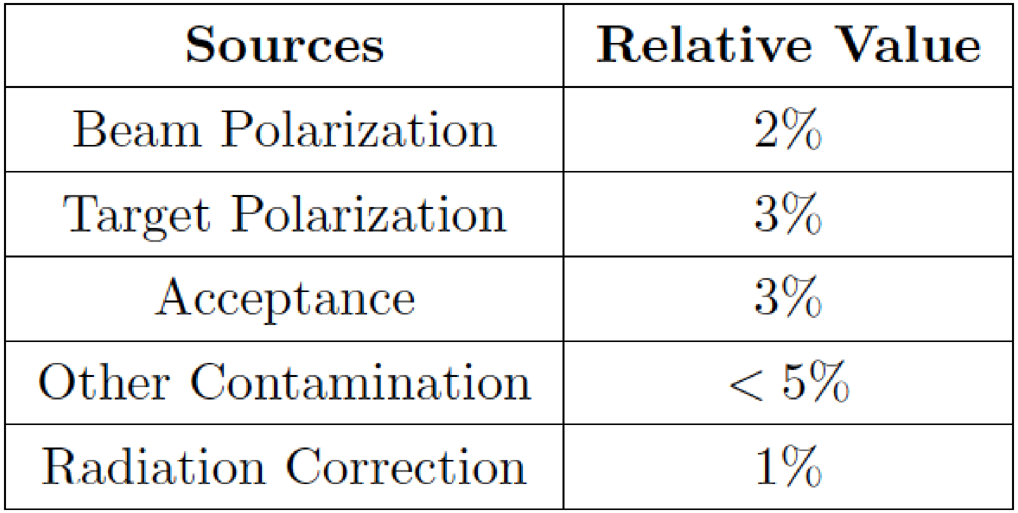
Systematic Uncertainties

- Detector–wide, DEMP measurement shares the same systematic uncertainties with SIDIS experiments



Sources	**Relative Value**
Beam Polarization	2%
Target Polarization	3%
Acceptance	3%
Other Contamination	$< 5\%$
Radiation Correction	1%

- Other sources of uncertainties are still under estimation.

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Fermi Momentum Effects

- **If the recoil proton momentum resolution is sufficiently good, it will be possible to correct for Fermi momentum on an event–by–event basis.**
- For the purposes of the proposal, we take the more conservative view that the resolution is not good enough, even though the removal of the Fermi momentum effect would simplify the physics interpretation of our data.
- To estimate the impact of Fermi momentum, we ran the generator in a variety of configurations and repeated our analysis:
  - Multiple scattering, energy loss, radiation effects ON/OFF.
  - Fermi momentum ON/OFF.
- The effect of Fermi momentum is about –0.02 on the $\sin(\varphi-\varphi_s)$ moment, and about –0.04 on the $\sin(\varphi_s)$ moment.
- We hope this estimate of Fermi momentum effects at an early stage will encourage theorists to calculate them for a timely and correct utilization of our proposed data, as suggested in last year's Theory review.
- 2017 Theory review appeared to be satisfied with this response.

Final State Interaction (FSI) Effects

- To estimate FSI effects, we used an empirical (phase–shift) parameterization of $\pi^- N$ differential cross sections.
- Based on this model, and the fact that there are only two proton spectators in the final state to interact with, we anticipate about 1% of events will suffer FSI interactions. The FSI fraction is weakly dependent on Q^2, rising to about 1.2% for Q^2>5 GeV^2 events. Of these, a large fraction of FSI events are scattered outside the triple-coincidence acceptance, reducing the FSI fraction to ~0.4%. This will be further reduced by analysis cuts such as P_{miss}<1.2 GeV/c.
- Over the longer term, we will consult with theoretical groups for a more definitive FSI effect study.
  - e.g. Del Dotto, Kaptari, Pace, Salme and Scopetta recent study of FSI effects in SIDIS from a transversely polarized ^{3}He target [arXiv:1704.06182] showed that extracted Sivers and Collins asymmetries are basically independent of FSI. A similar calculation for DEMP, after this proposal is accepted, would be a natural extension of their work.

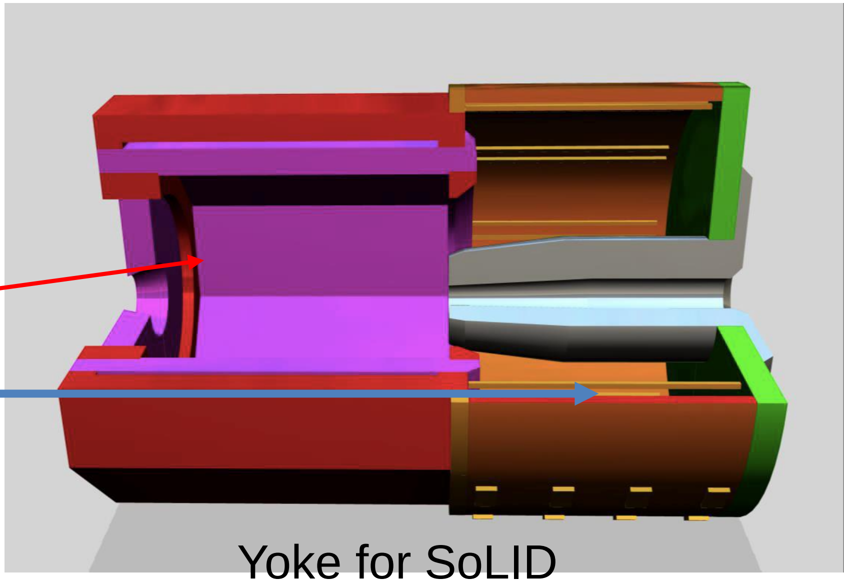
Magnet: Requirement and Design

Requirements:

→Acceptance: P: 1.0 – 7.0 GeV/c;
Φ: 2π; θ: 8°-24° (SIDIS), 22°-35° (PVDIS)
→ Resolution: δP/P ~ 2%
(requires 0.1 mm tracking resolution)
→ Fringe field at the ^{3}He target < 5 Gauss

CLEO–II coil at JLab

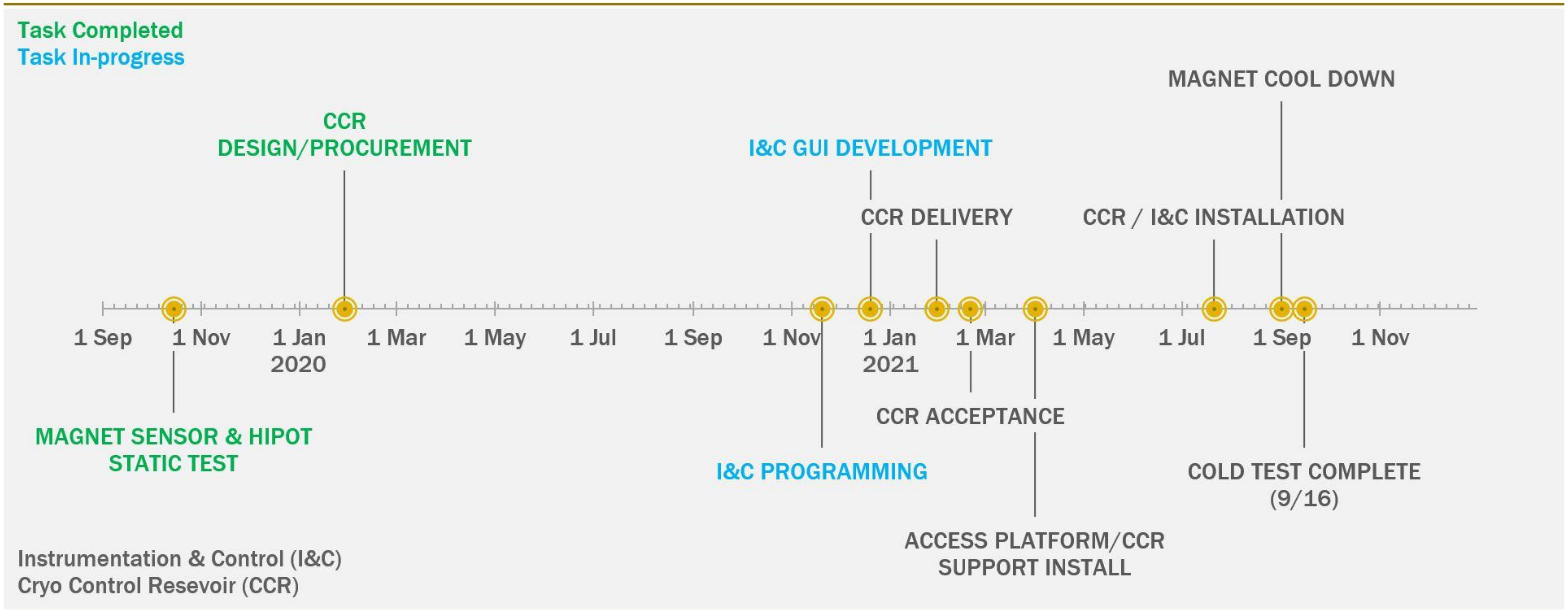
- Use CLEO II magnet with the following modifications
  - Two of three layers of return yoke needed
  - Add thickness to front endcap
  - Add extended endcap

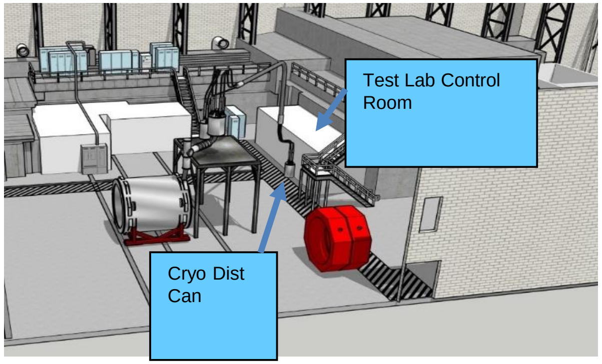


Yoke for SoLID

Cold Test Update – Cold Test Milestones

Phase 1 Solenoid Rehab Milestones

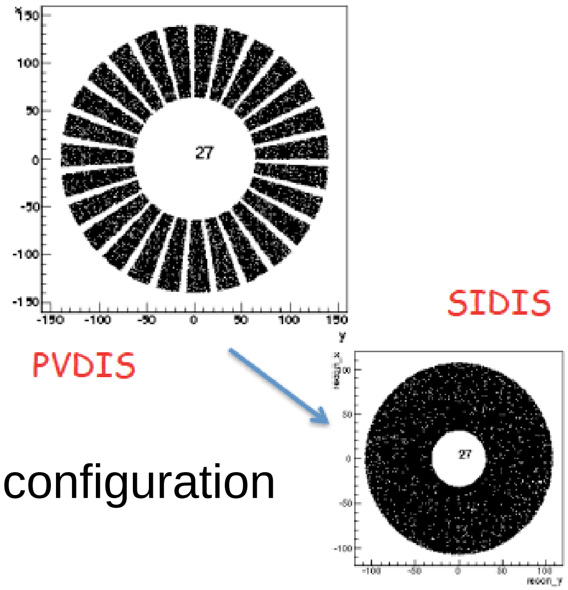




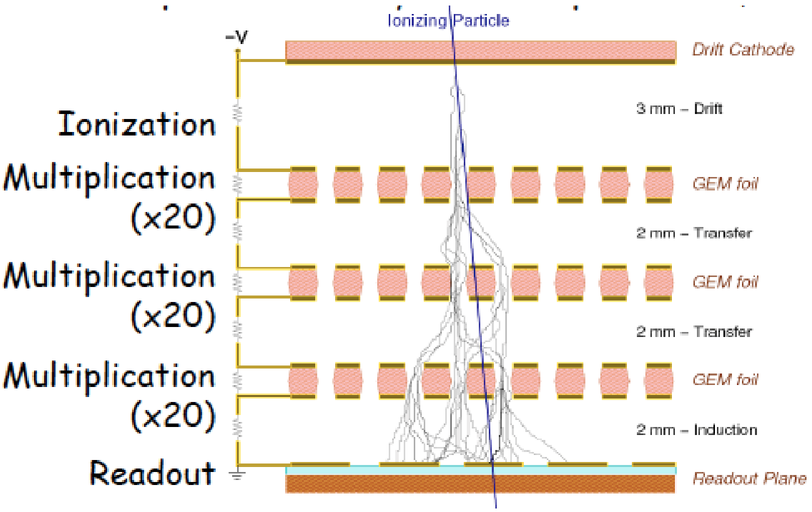
- Solenoid rehab will confirm condition of the magnet
- Provide risk reduction to the project
- Improve magnet cost estimate
- Estimated completion Sept 2021

GEM tracking

- Rate capabilities > many MHz/cm^2
- High position resolution
- Cover large areas at reasonable cost
- Low thickness (~0.5 radiation length)
- Used in many experiments (COMPASS, STAR, ALICE, PRad@**JLab**…) and planned for many future experiments SBS@JLab, CMS upgrade, EIC…)



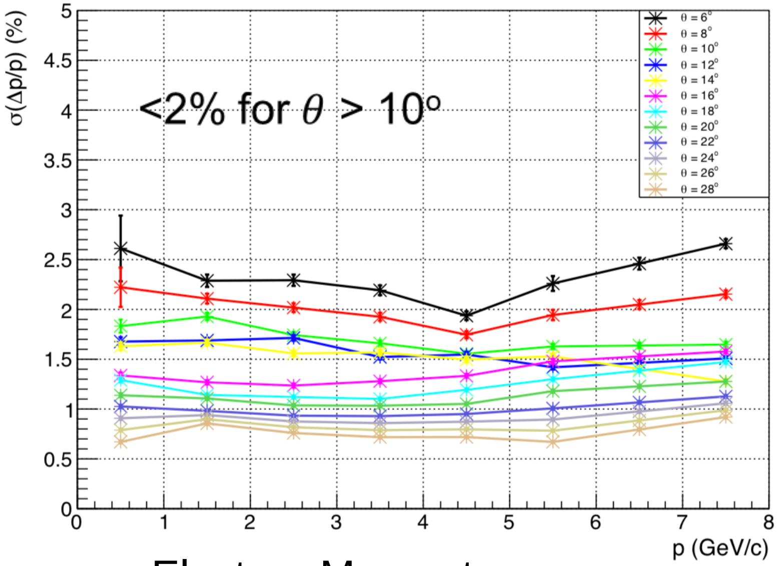
GEM configuration



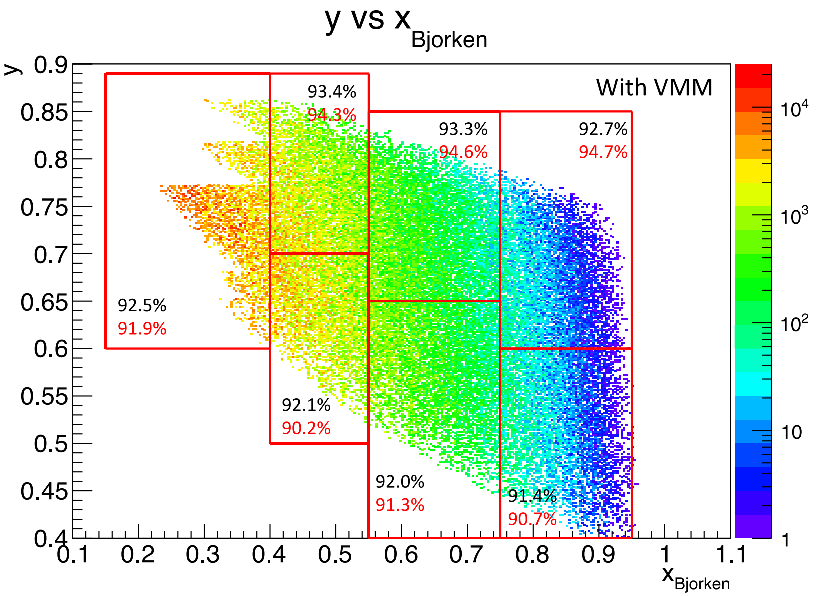
GEM Technology

EIC Prototype: similar to SoLID design

Simulated GEM Performance

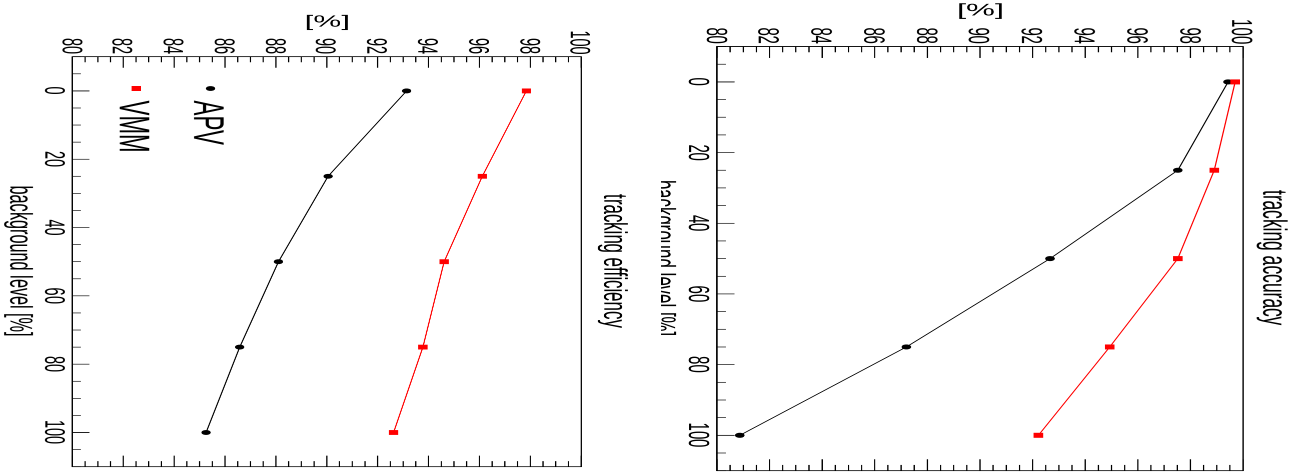


Electron Momentum Resolution versus angle



Efficiency and accuracy for PVDIS versus kinematics

Risk:
VMM chips need testing:
addressed in Pre R&D plan

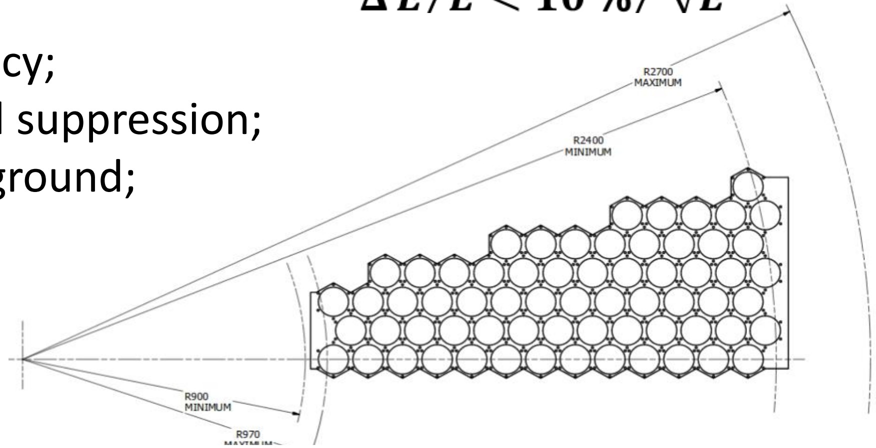


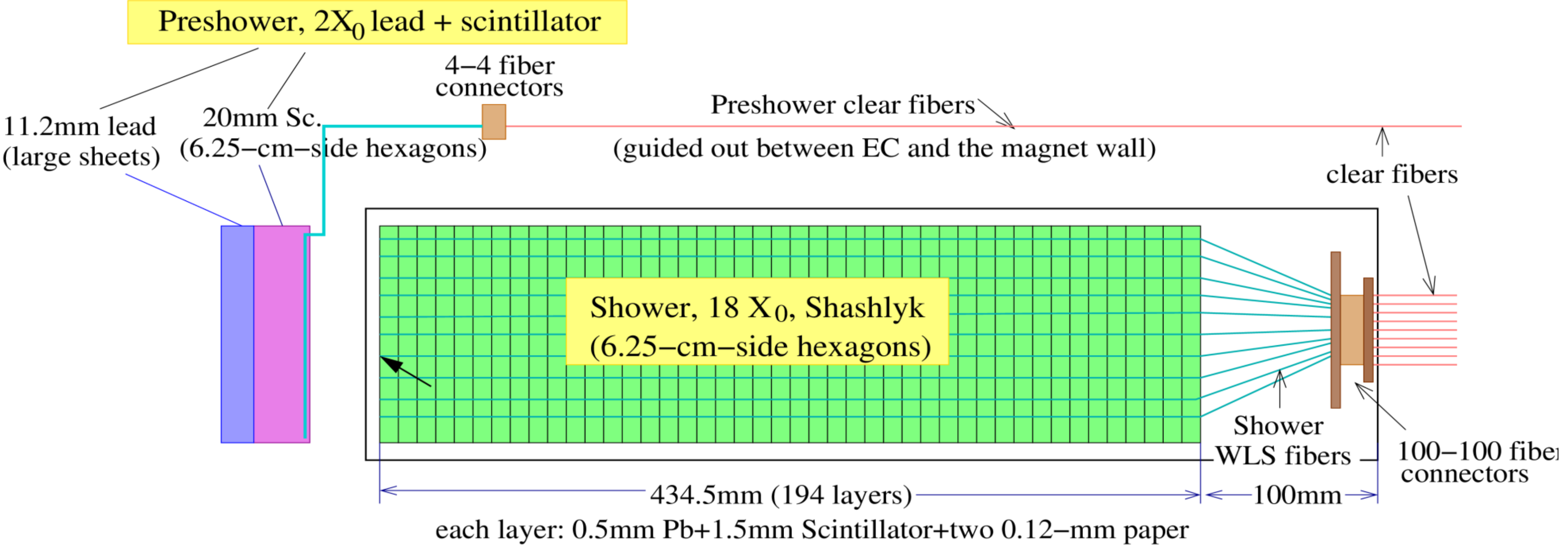
APV versus VMM

ECal Requirement and Design

- – Combined with LGC to **provide triggering**;
- – **50:1 pion rejection** with 90% electron efficiency;
- – provide ~1cm shower position for background suppression;
- – **radiation hard**: >500 krad, high neutron background;
- – inside 1.5 T field
- – modules swappable between PVDIS and SIDIS

$\Delta E/E < 10\%/\sqrt{E}$





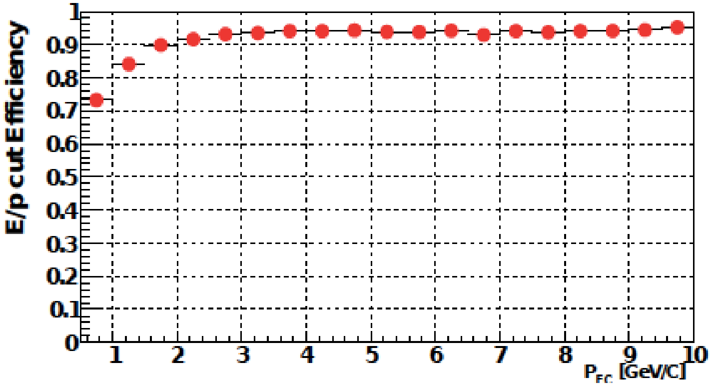
ECAL Performance

Realistic simulation with background and supporting material

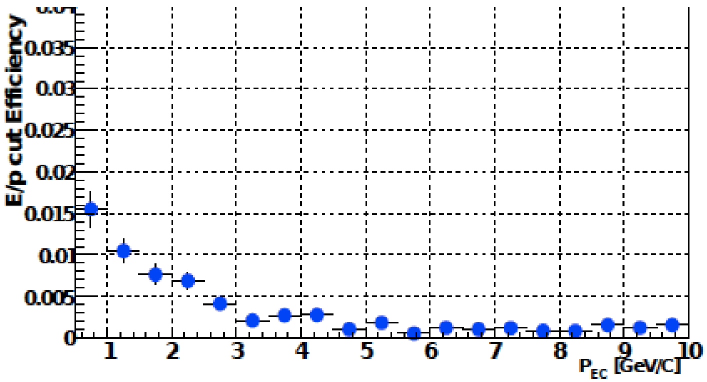
Resolution: for all angles, **reached p0~(5-6)% and p2~(5-6)%**

$$\sqrt{\left(\frac{p0}{\sqrt{E}}\right)^2 + (p1)^2 + \left(\frac{p2}{E}\right)^2}$$

FAEC electron



FAEC pion



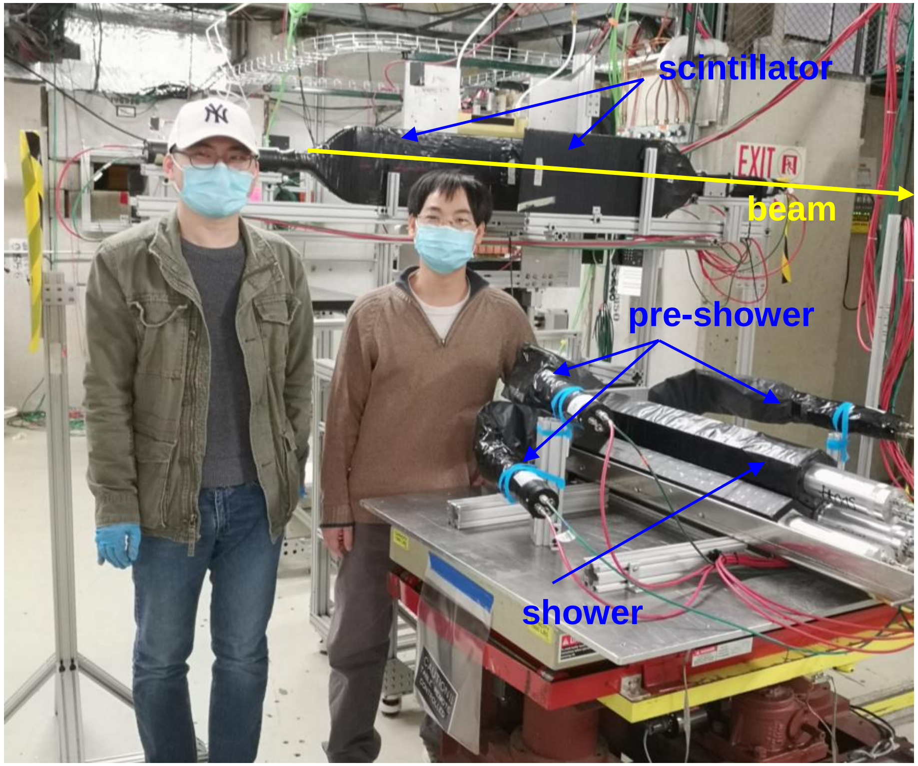
Pion rejection > 50:1

Fermilab Beam Test with Shashlyk Modules

- Goal: Understand the detection resolution and efficiency of the Shashlyk modules
- Beam time: Jan 13-26, 2021
- Setup: $2X_0$ lead, 3 preshower, 2-cm Al support, 3 Shashlyk modules; FTBF's MWPC+Cherenkov

People power: (UVA) Jixie Zhang, Xinzhan Bai; (JLab) Alexandre Camsonne, David Flay; (ANL) Paul Reimer, Junqi Xie, Manoj Jadhav

Beam energy (GeV)	total trigger	total electron trigger (online)
1	3.1M	3.0M
2	2.9M	2.7M
4	4.5M	3.9M
6	2.8M	2.1M
8	5.5M	3.4M
10	6.8M	3.6M
12	3.0M	1.3M
16	7.6M	2.3M



Scintillator Pad Detector: Requirements and Design

LASPD: photon rejection 5:1;

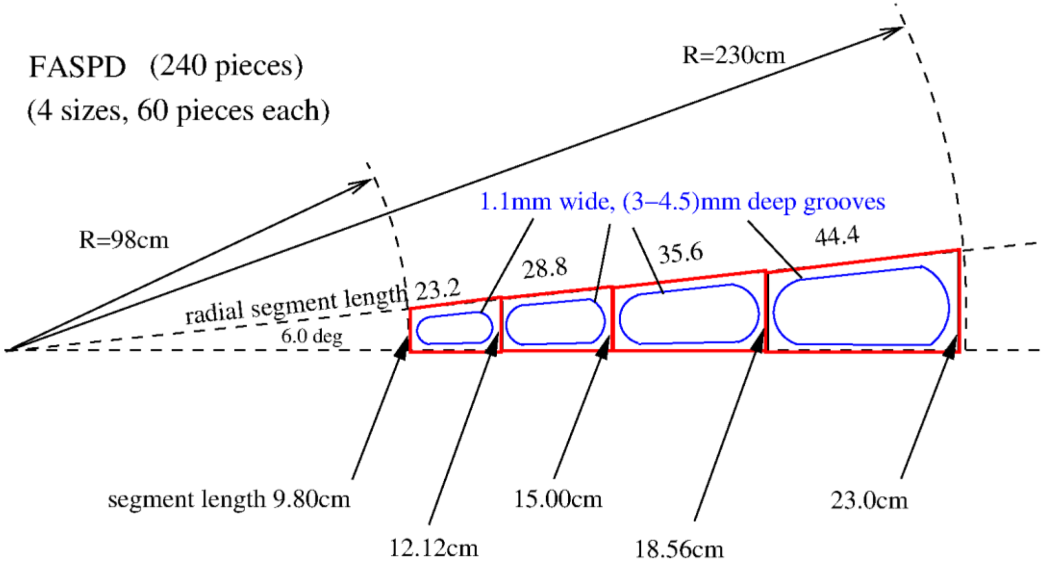
coincidence TOF (150ps)

→ design: 20mm-thick,

60 azimuthal segments,

direct coupling to fine-mesh PMT (for FMPMT study see NIMA 827 (2016) 137-144)

a LASPD prototype equipped with (regular) PMTs



FASPD: **photon rejection 5:1**

→ design: 5-10mm-thick

240 segments (60 X 4)

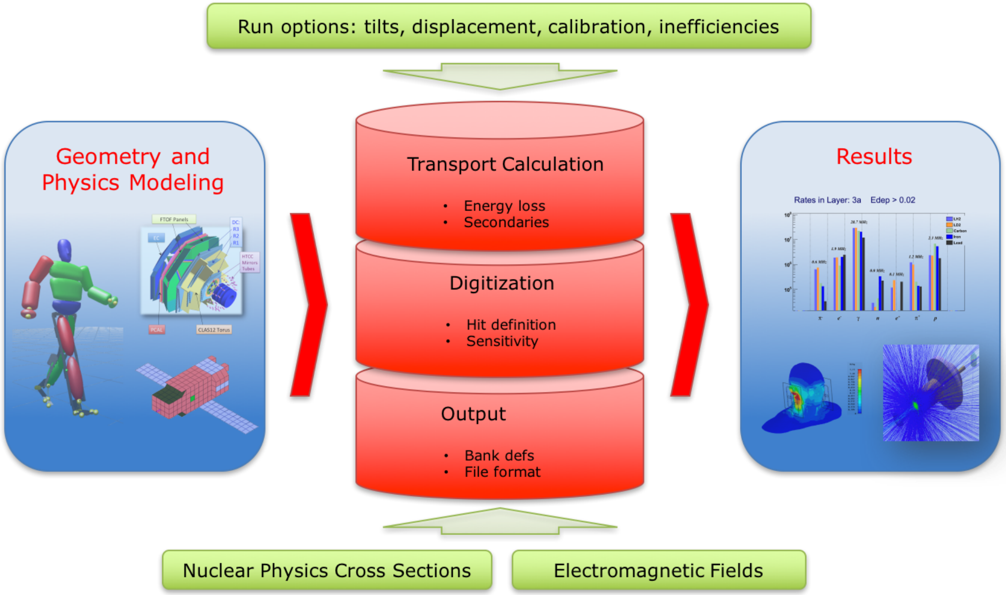
WLS fiber embedding,

MAPMT (outside magnet)

Software and Simulations

Existing simulations: SoLID_GEMC

- GEMC is a Geant4-based simulation package, used by CLAS12.
- Added SoLID detector description and signal digitization, esp. for GEMs.
- Used extensively for SoLID pre-CDR and in current pre-R&D studies.
- Variety of physics generators available.



Run options: tilts, displacement, calibration, inefficiencies

Geometry and Physics Modeling

Transport Calculation
- Energy loss
- Secondaries

Digitization
- Hit definition
- Sensitivity

Output
- Bank defs
- File format

Results

Nuclear Physics Cross Sections

Electromagnetic Fields

The architecture of gemc

Long-term goals

- Develop end-to-end simulation and reconstruction chain.
    - Integrated software environment for (almost) all parts of data processing
    - Modern, multi-threaded, grid-enabled framework written in C++
    - Common conditions data and geometry database API
    - Consistent ROOT-based event data file format w/ metadata storage
    - Python or JSON/YAML-based job configuration
- Provide online and offline analysis software, event display, calibration tools etc. as well as complete set of simulation and digitization modules.
- Feasibility studies underway in collaboration with other JLab groups.

DAQ Requirements and Design

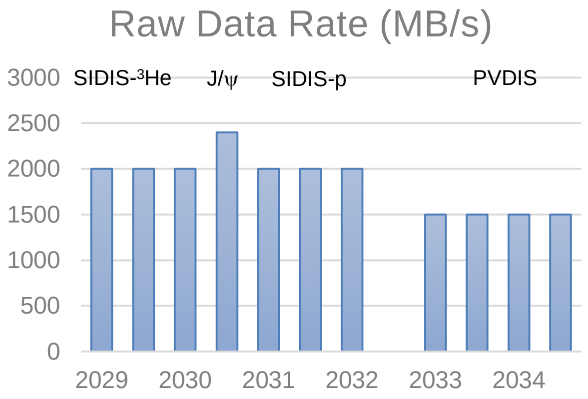
- DAQ based on 12 GeV FADC base pipelined electronics designed for 200 KHz trigger rates,100 kHz rates demonstrated in Hall B and D
- VMM chip based readout for GEMs

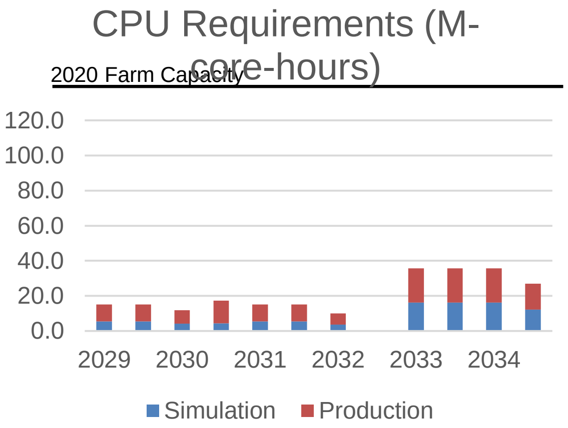
  ATLAS Small Wheel Micromegas readout chip : up to 4 MHz trigger rate per channel, limited by occupancy in detector – designed for 200 KHz

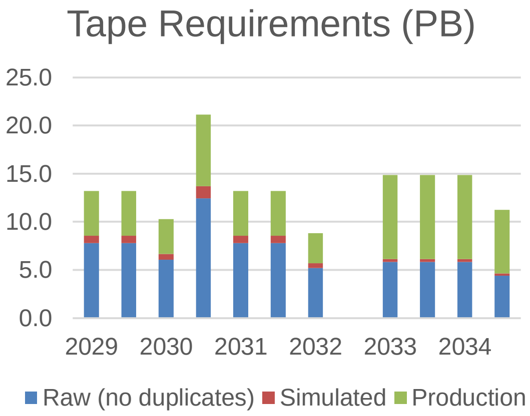
  Older chip APV25 used by SBS as backup option
- Design goal well within hardware capabilities with some safety margin
  - 60 KHz/sector for PVDIS, expect 20 KHz/sector, ~ 2 GB/s, 30 sectors
  - 120 KHz total for SIDIS, expect 100 KHz, ~ 2 GB/s
  - 100 KHz total for J/Psi, expect 60 KHz, ~ 3 GB/s
- Pre-R&D to validate required rates and determine maximum rates achievable
- Existing infrastructure
  - Network : 10 GB/s
  - Silo
    - Current setup: data rate 6 GB/s
    - IBM TS3500 highly scalable: Data rate upgradable up to 69 GB/s
    - Maximum data 250 PB
- Rate limitation mostly from storage cost

Computing Requirements

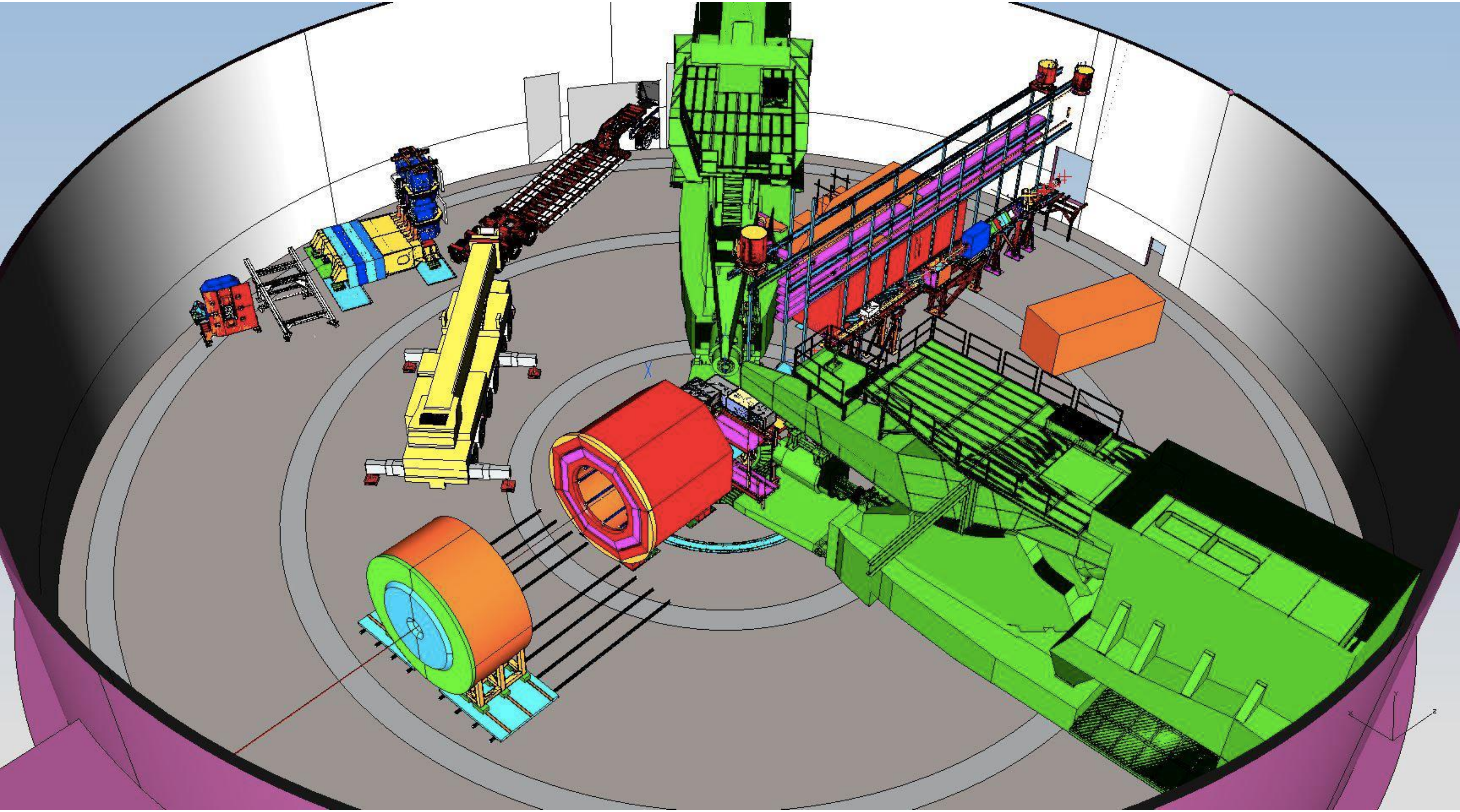
- Raw data rate comparable to GlueX & CLAS12 (~2 GB/s).
- Estimated CPU requirements already manageable with today's farm resources
- Tape requirements (25–30 PB/yr) significantly higher than current experiments.
- J/ψ has ~50% higher storage requirements due to larger event size.







SoLID in Jefferson Lab Hall A



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

Apparatus

Requirements are Challenging

- High Luminosity (10^{37}-10^{39}/cm^2/s)
- High data rate
- High background
- Low systematics
- High Radiation Tolerance
- Large scale detectors
- Modern Technologies
  - GEM’s
  - Shashlik ECal
  - Pipeline DAQ
  - Rapidly Advancing Computational Capabilities
- High Performance Cherenkovs
- Baffles (for PVDIS)

Polarized ^{3}He (“neutron”) @ SoLID