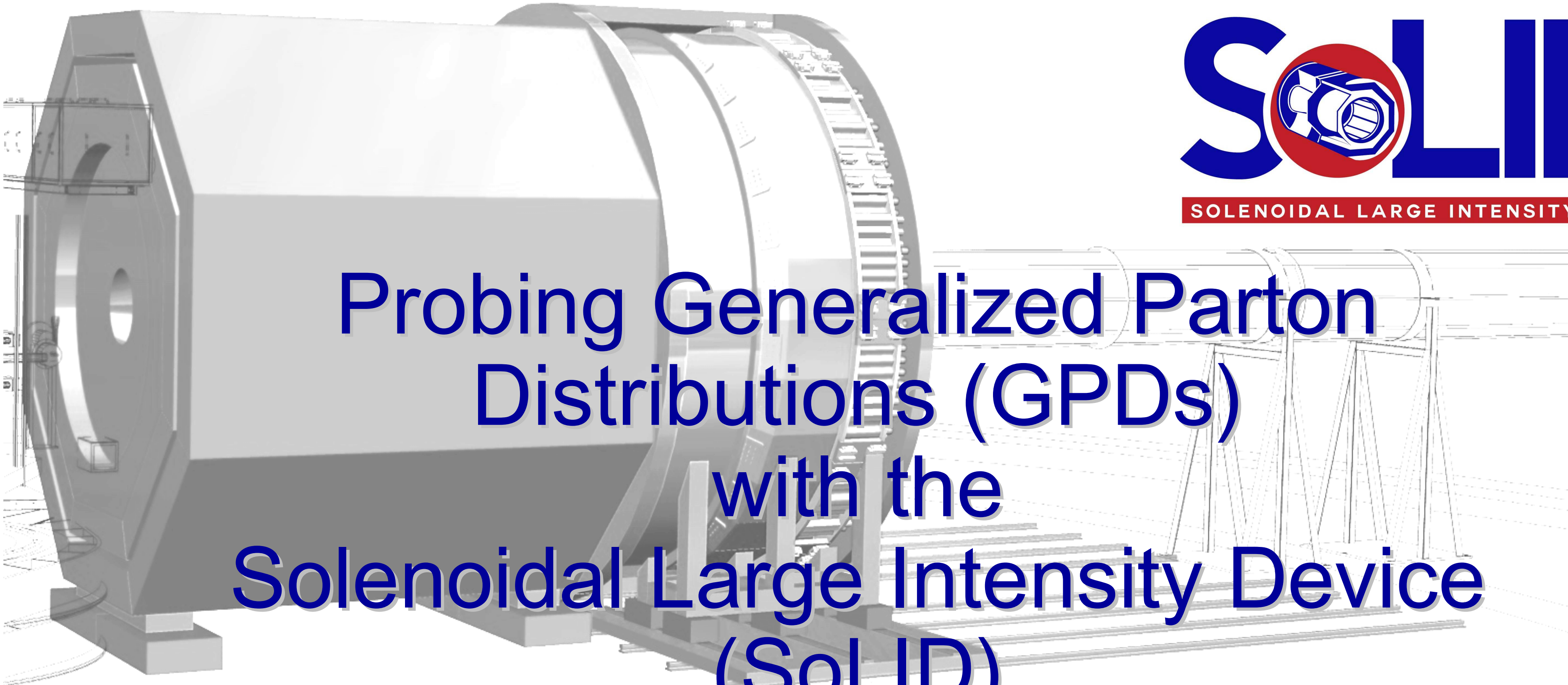


Probing Generalized Parton Distributions (GPDs) with the Solenoidal Large Intensity Device (SoLID)

Garth Huber

University of Regina

On behalf of the SoLID Collaboration

Supported by: NSERC CRSNG

SAPIN-2026-00043

CAP Congress, University of Ottawa

June 22, 2026

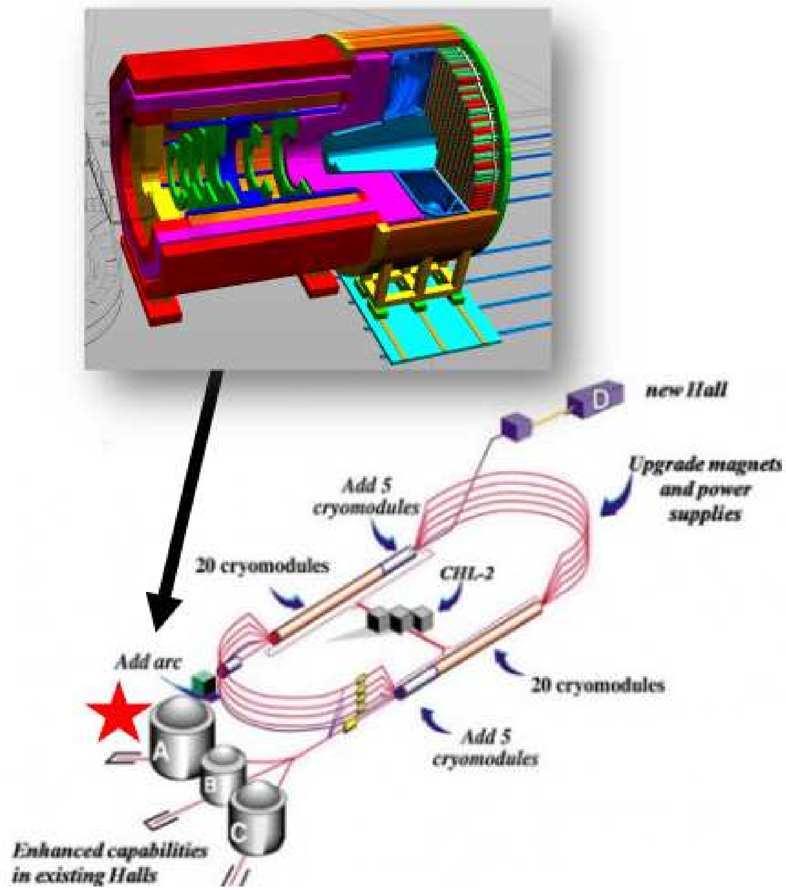
SoLID @ 12 GeV JLab: **the QCD Intensity Frontier**

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

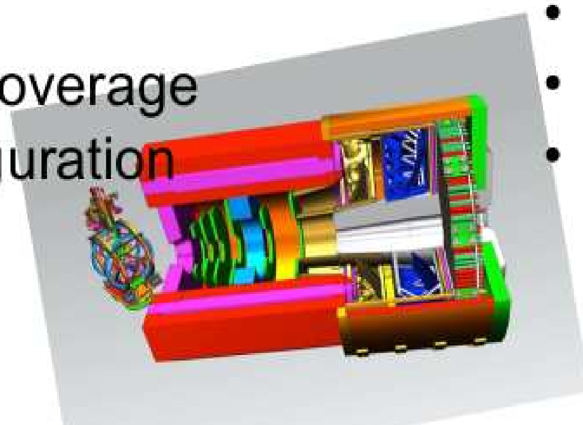
SoLID State–of–the–Art Technology

Quantum Leap Science Requirements are Challenging

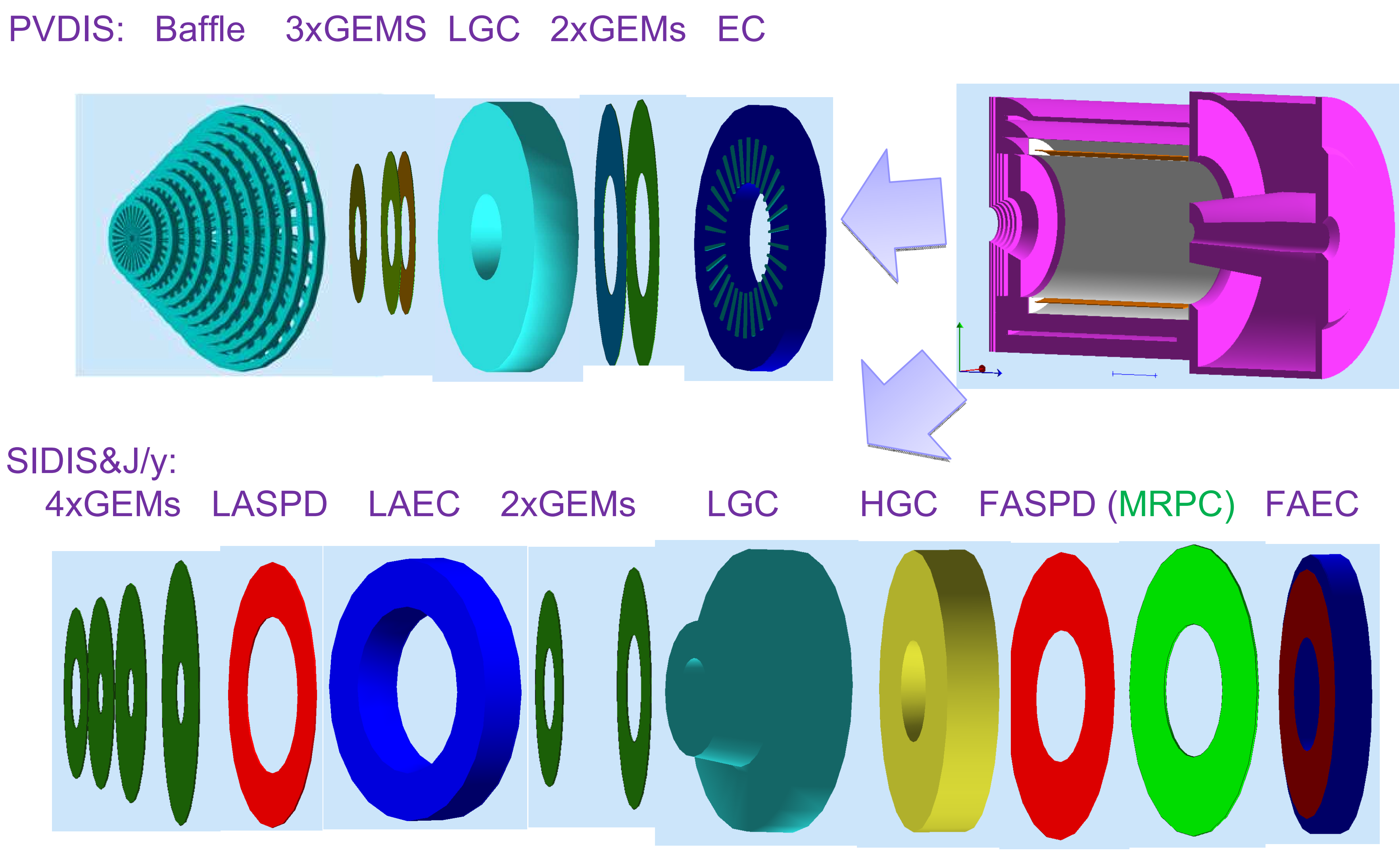
- High Luminosity (10^{37}-10^{39})
  - beam currents ~100 microA) on ~10 cm liquid targets
  - beam currents of ~50 microA on ~30cm polarized ^{3}He target
- Solenoidal field provides access to azimuthal asymmetry
- High data rate (~100 KHz)
- High background (~ GHz)
- Low systematic uncertainties
-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



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

SoLID High Performance Cherenkovs

State of the art design:

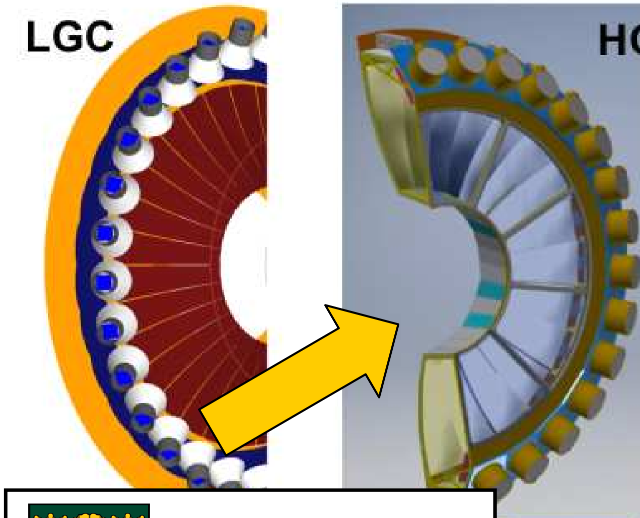
- Electron/pion (LGC) and pion/kaon (HGC) separation with good rejection factors while maintaining good detection efficiencies
- Provide input at trigger level in a 2π, high-luminosity, non-negligible magnetic field environment while minimizing complexity and cost
- Exceeds the PID requirements for SoLID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

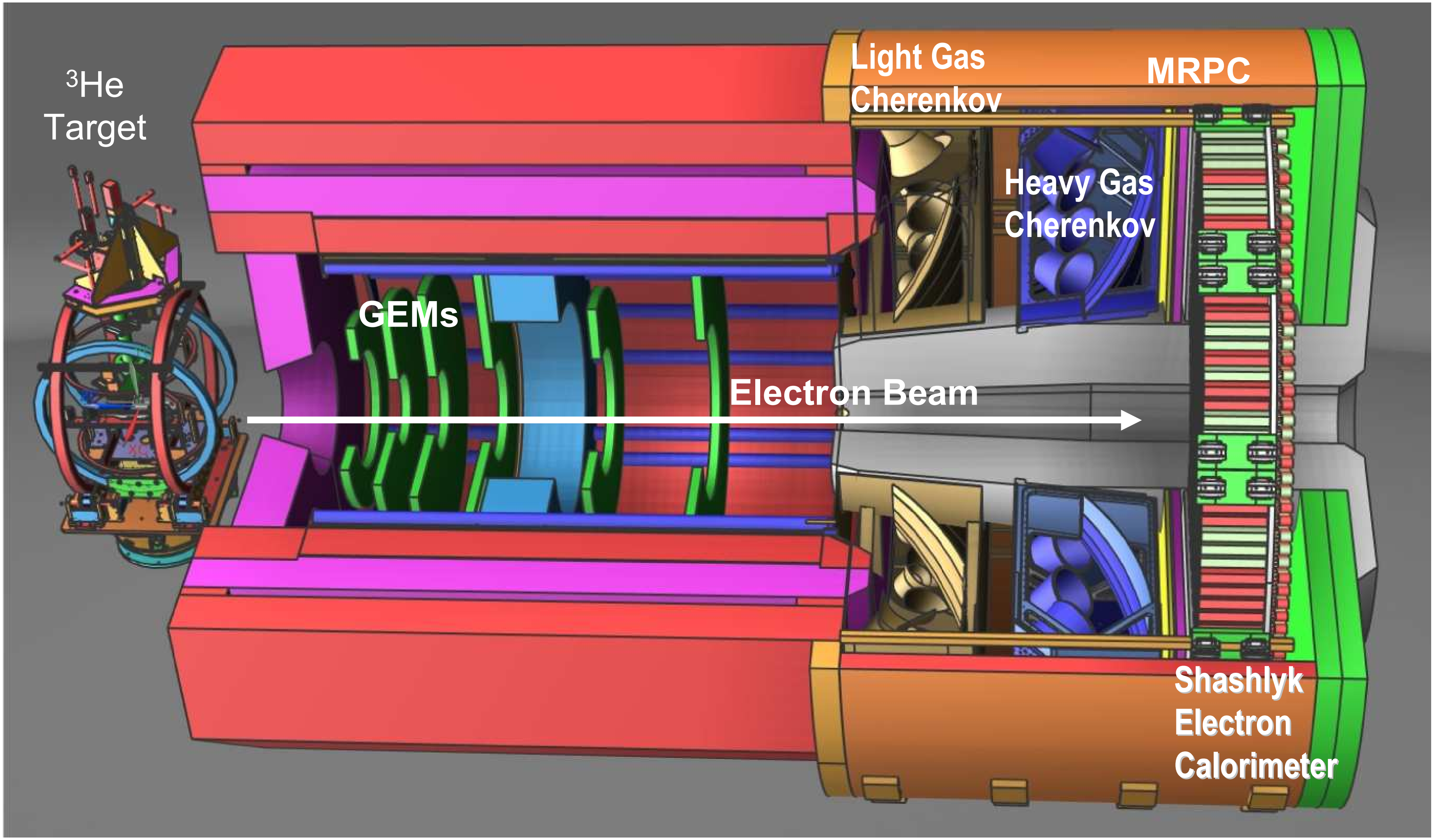
High-Rate Test:

- 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



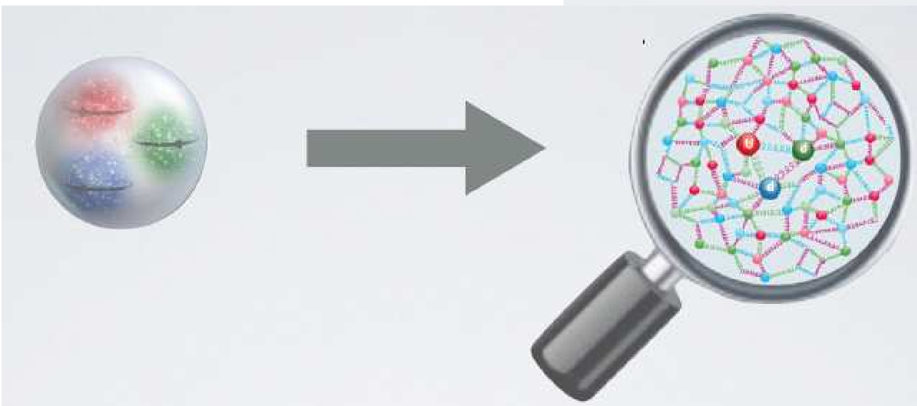
CFI–IF awarded for HGC vessel & entrance windows

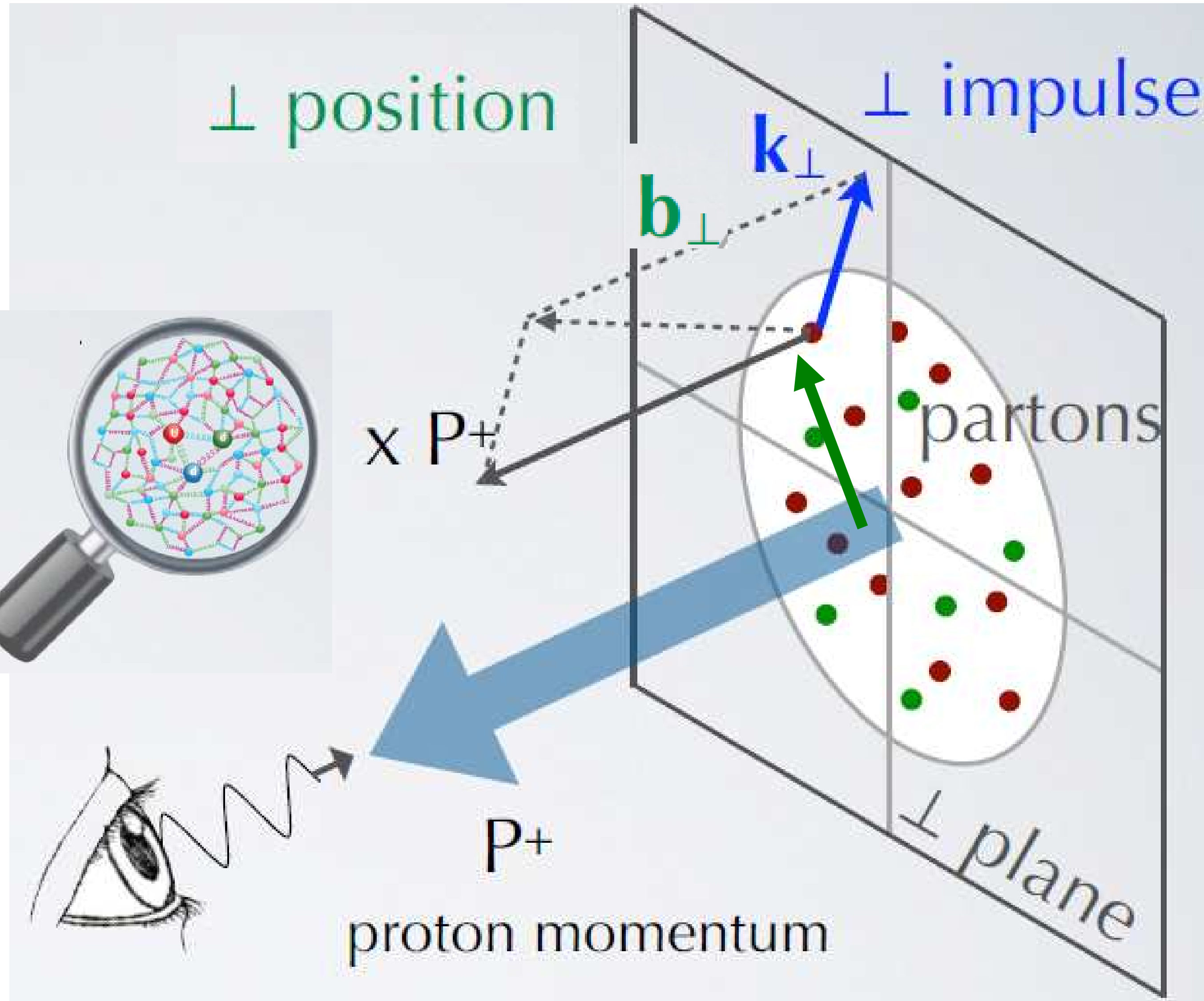
SoLID Configured with Polarized ^{3}He Target



Towards 3D Imaging of the Nucleon

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

Garth Huber, huberg@uregina.ca

Taken from a talk by Rolf Ent, Jefferson Lab

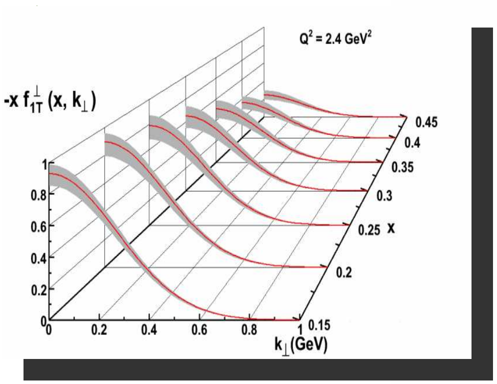
3D Imaging of the Nucleon

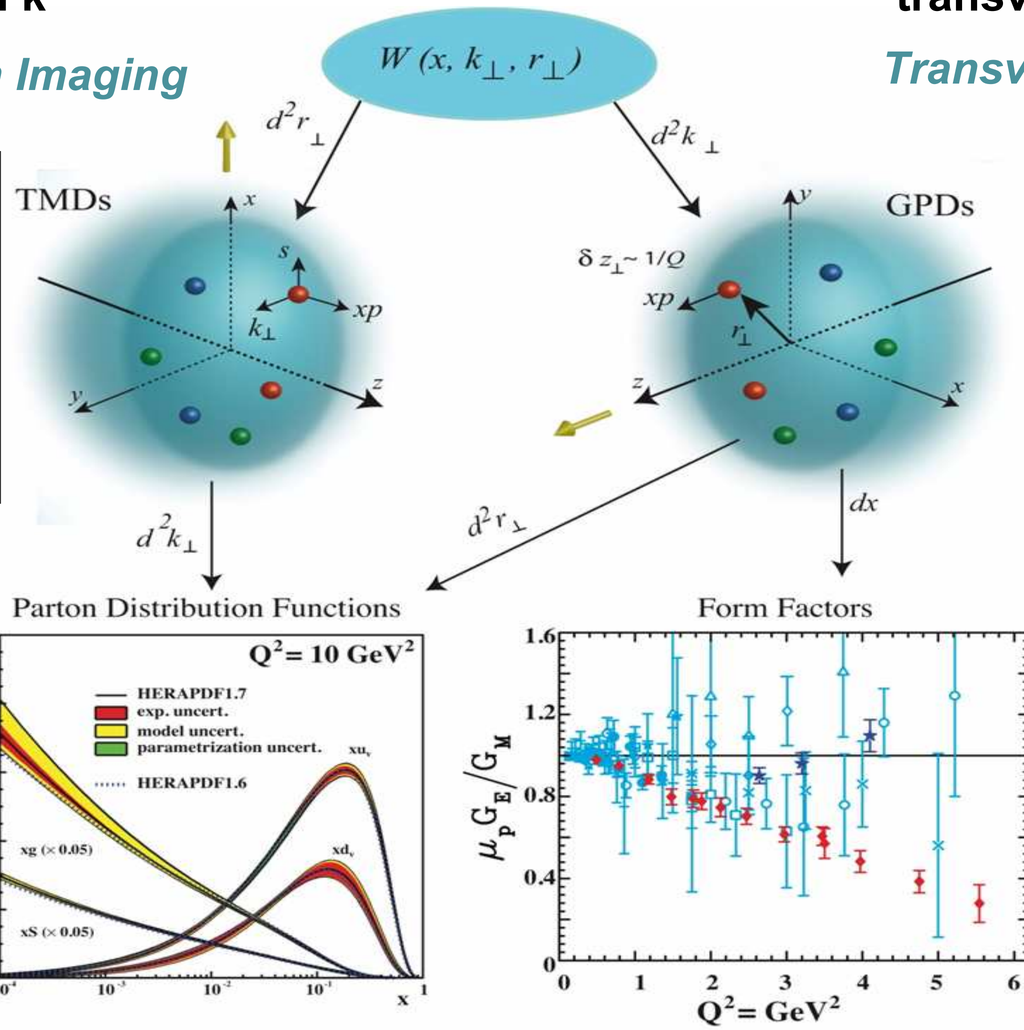
TMDs: Longitudinal momentum fraction x and transverse momentum k

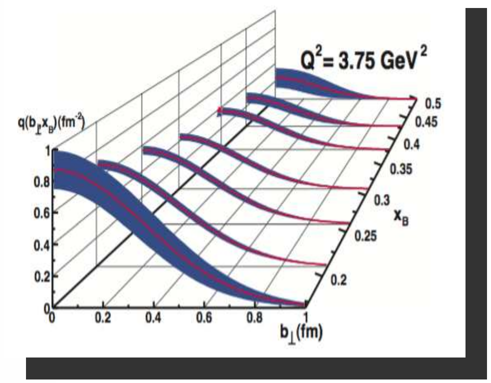
Transverse Momentum Imaging

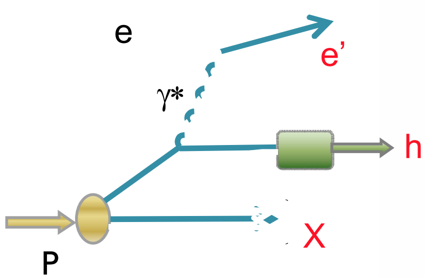
GPDs: Longitudinal momentum fraction x at transverse location b

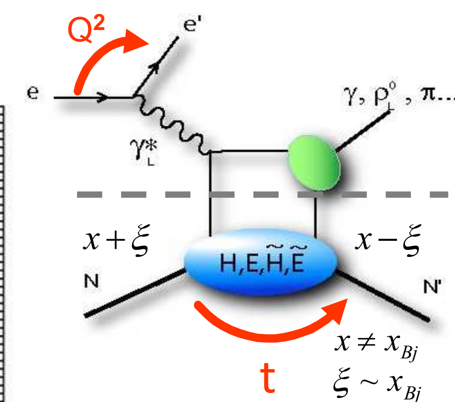
Transverse Spatial Imaging





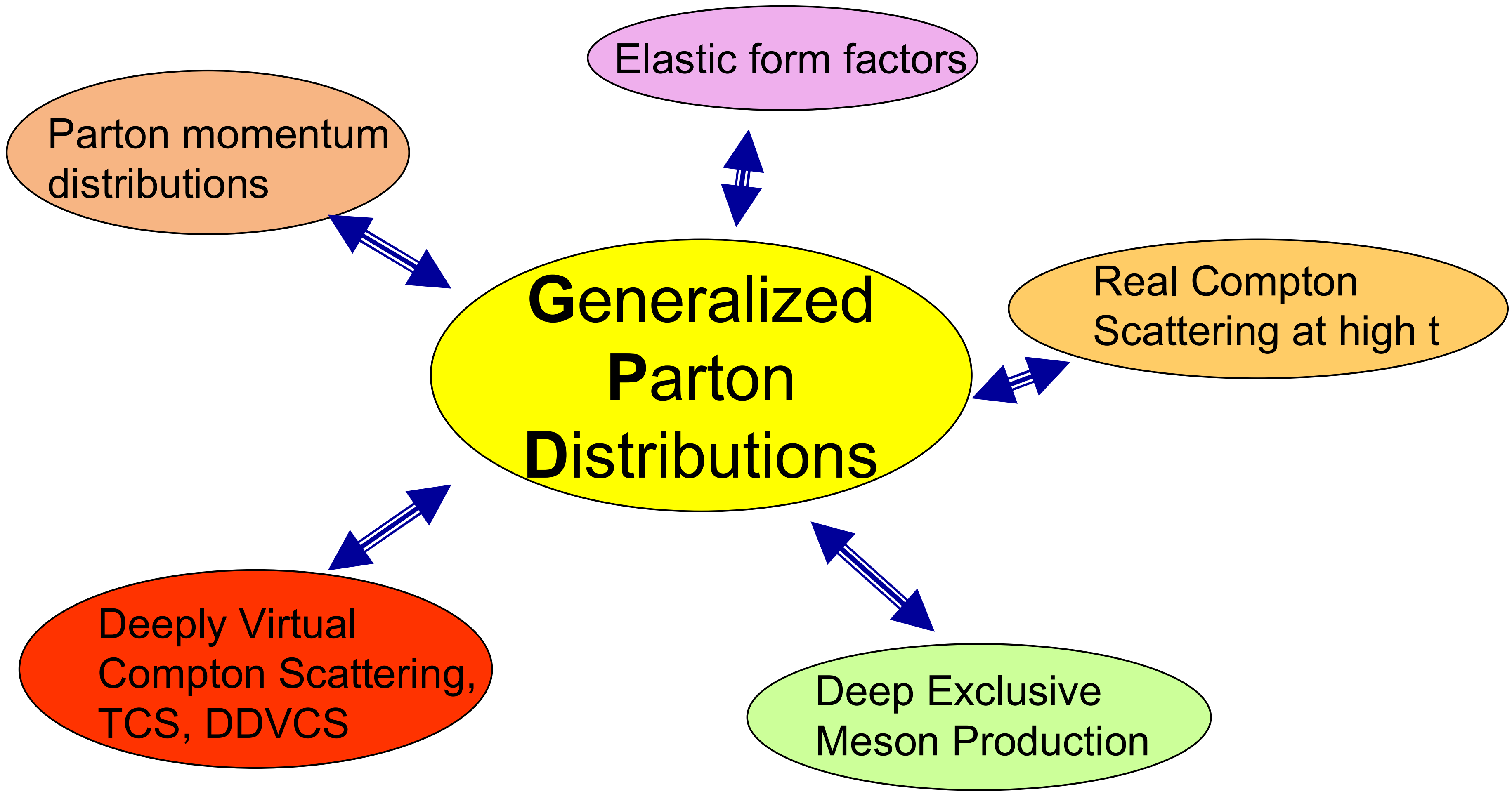






Taken from a talk by Rolf Ent, Jefferson Lab

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.**

Garth Huber, huberg@uregina.ca

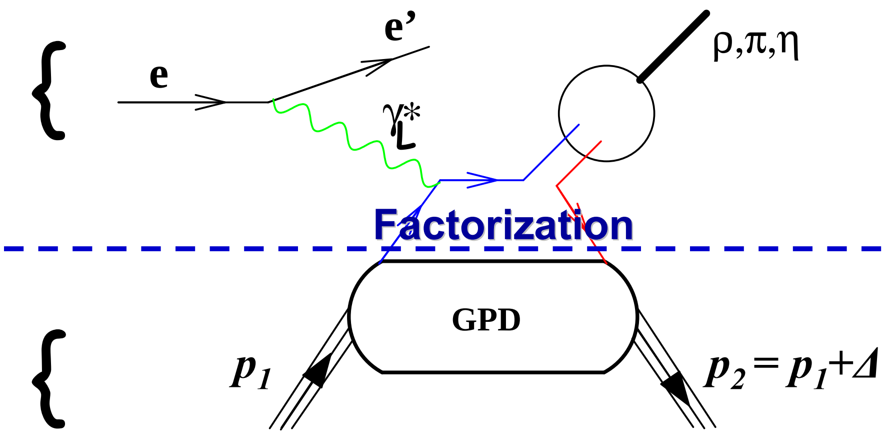
GPDs require Hard Exclusive Reactions

University of Regina

- **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).**



- GPDs depend on x, ξ_t and $t=(\Delta^t)^2=(p_2-p_1)^2$
- An important variable is the "Skewness", defined as:

$$\xi_t = \frac{p_1^{\ +} - p_2^{\ +}}{p_1^{\ +} + p_2^{\ +}}$$ where $p_{1,2}$ refer to light cone + components

Garth Huber, huberg@uregina.ca

Leading Twist GPD Parameterization

University of Regina

- **GPDs are universal quantities and reflect nucleon structure independently of the probing reaction.**
  - At leading twist–2, four chirality conserving GPDs for each quark, gluon type
  - Because quark helicity is conserved in the hard scattering regime, the produced meson acts as a helicity filter

$H^{q,g}(x,\xi,t)$ 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

- **Need a variety of Hard Exclusive Measurements to disentangle the different GPDs.**

Deeply Virtual Compton Scattering (DVCS):
- Sensitive to all four GPDs

Deep Exclusive Meson Production (DEMP):
- Vector mesons sensitive to spin–average H, E
- Pseudoscalar sensitive to spin–difference $\tilde{H}$ $\tilde{E}$

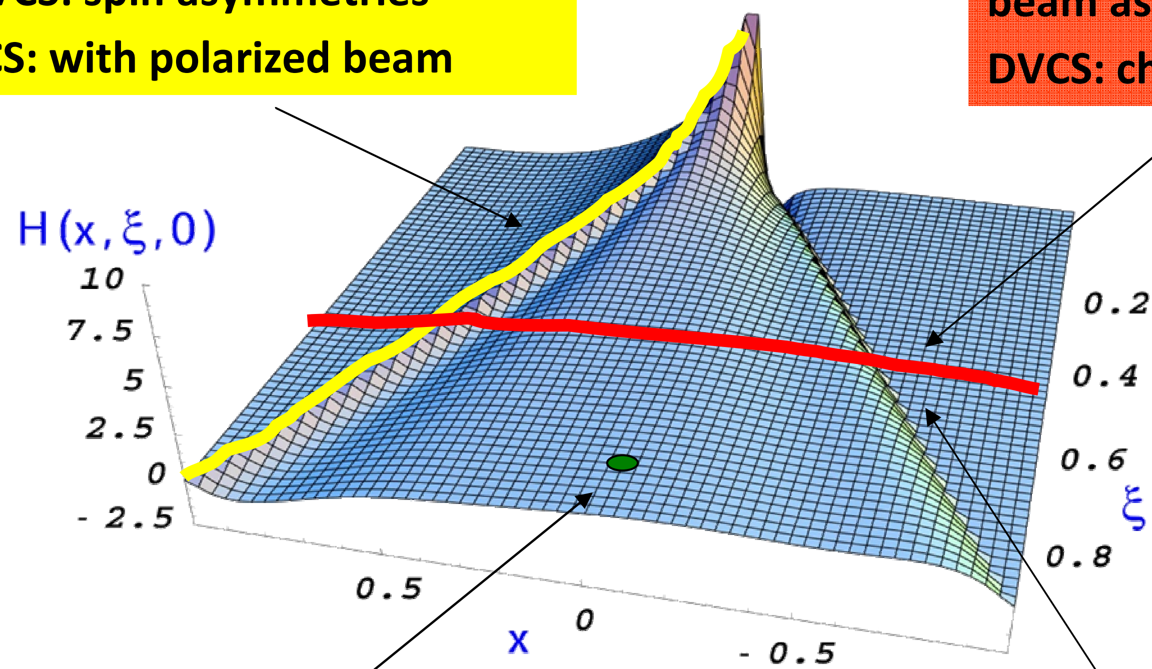
Garth Huber, huberg@uregina.ca

Compton Processes Accessing GPDs

$$\gamma^* + p \rightarrow \gamma + p$$

(Im, x=ξ)
DVCS: spin asymmetries
TCS: with polarized beam

(Re)
TCS: cross section, linear beam asymmetry
DVCS: charge asymmetry



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

(|Im|^2+|Re|^2)
DVCS: cross section

TCS = Timelike Compton Scattering **DVCS** = Deeply Virtual Compton Scattering

Garth Huber, huberg@uregina.ca

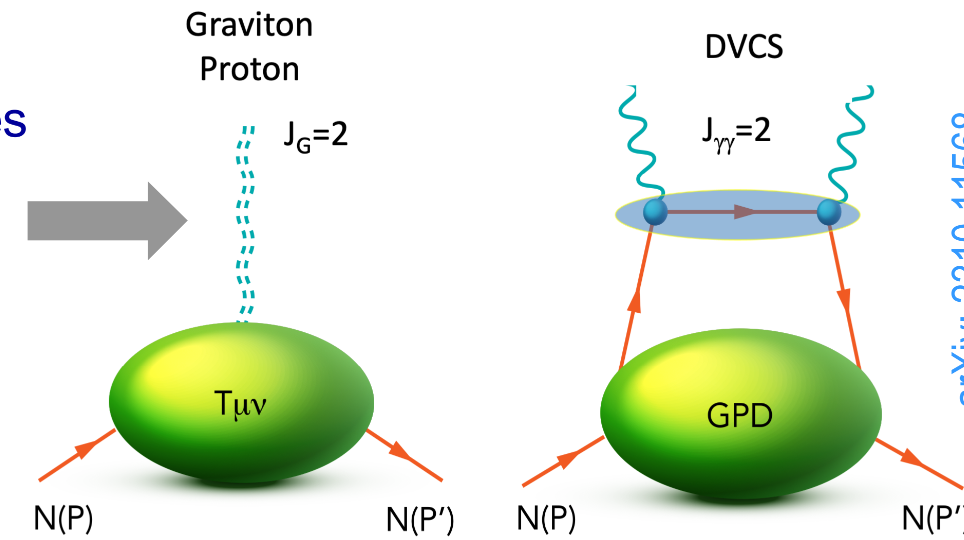
Gravitational Structure via DVCS

University of Regina

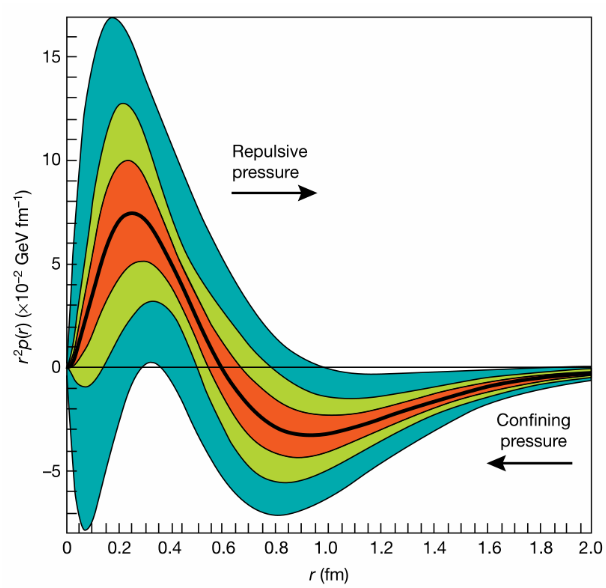
- **The proton's structure has been studied via EM and Weak interactions for 70 years, in contrast the internal mechanical properties of the proton are essentially unknown**
- GPDs enable our first access to the *gravitational structure* of proton

Left: Hypothetical graviton-proton $J_G=2$ interaction probes mechanical properties

Right: DVCS provides $J_{\gamma\gamma}=2$ interaction which mimics graviton-proton interaction providing access to similar information via GPDs



arXiv: 2310.11568



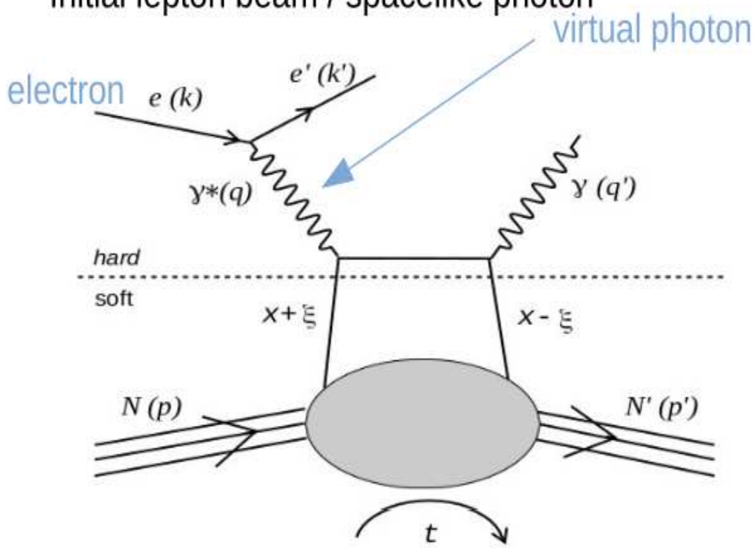
Burkert, Elouadhriri, Girod, Nature **557** (2018) 396

Radial pressure distribution $r^2p(r)$ in proton, extracted from JLab Hall B DVCS data for GPD $H(\xi)$, resulting from the interactions of quarks in the proton

Garth Huber, huberg@uregina.ca

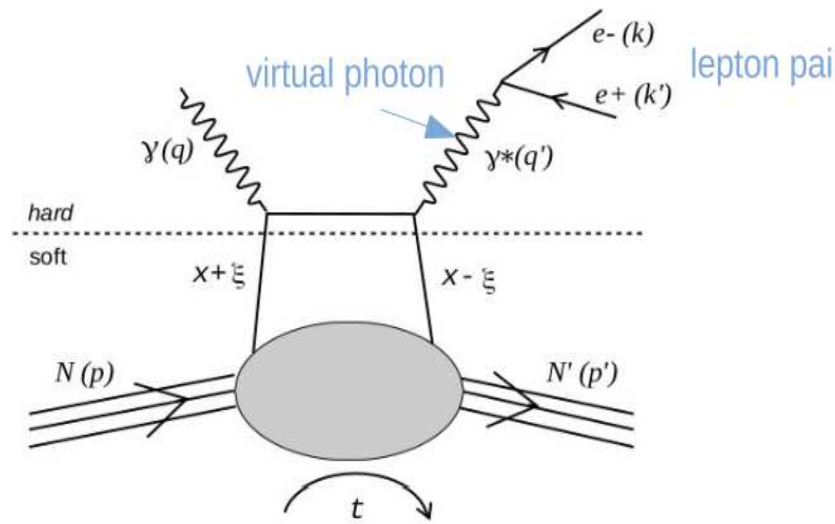
Complementarity of DVCS and TCS

Initial lepton beam / spacelike photon



Deeply Virtual Compton Scattering (DVCS)

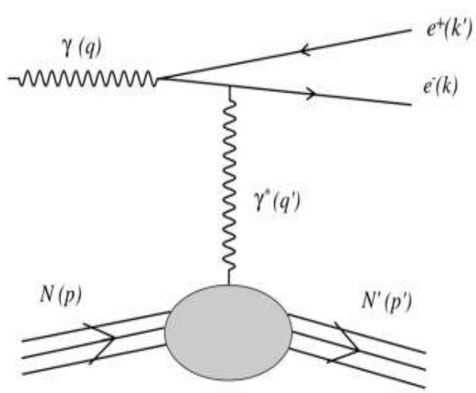
Final lepton pair / timelike photon



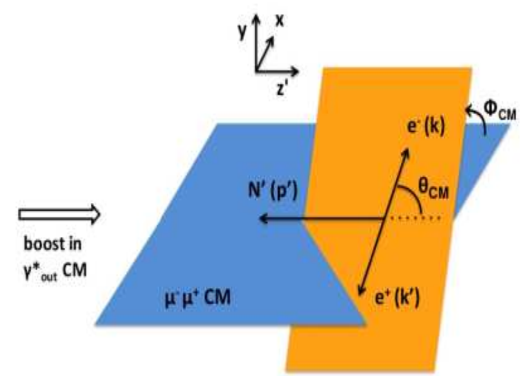
Timelike Compton Scattering (TCS)

Interference with "BH"
Harmonics in φ (φ_S)

Measuring cross section,
beam/target spin asymmetries...



BH interferes with TCS

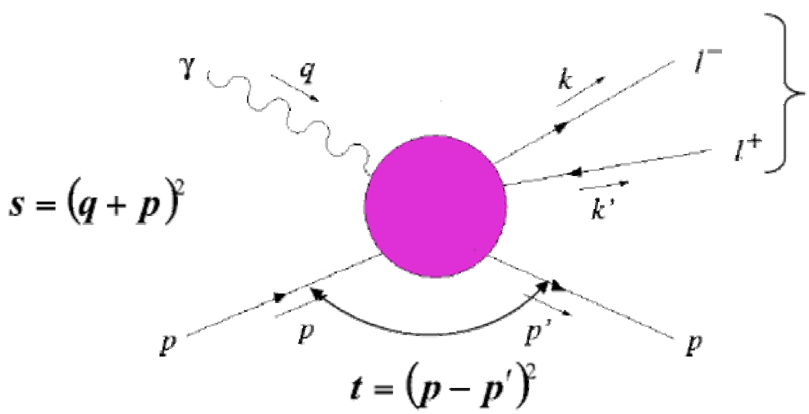


Garth Huber, huberg@uregina.ca

Marie Boer

SoLID Timelike Compton Scattering

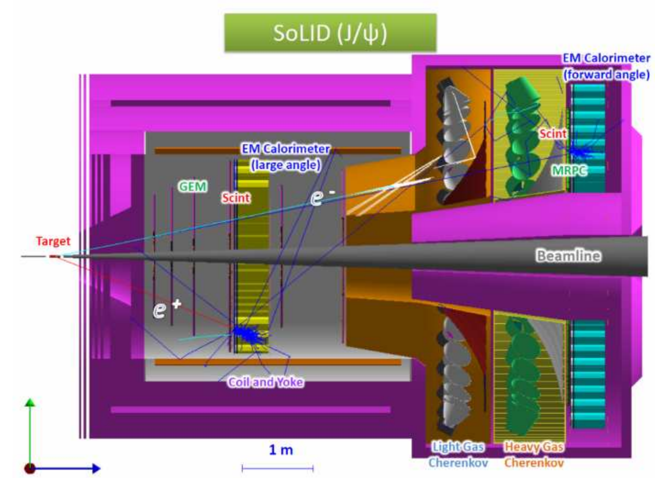
- **Unpolarized data** access to real part of CFFs, sensitive to D-term in GPD parametrization with observables cross section ratio (R) and forward backward asymmetry (A_{FB})
- **Circularly polarized data** access to imaginary part of CFFs with BSA (similar to DVCS) to study GPD universality

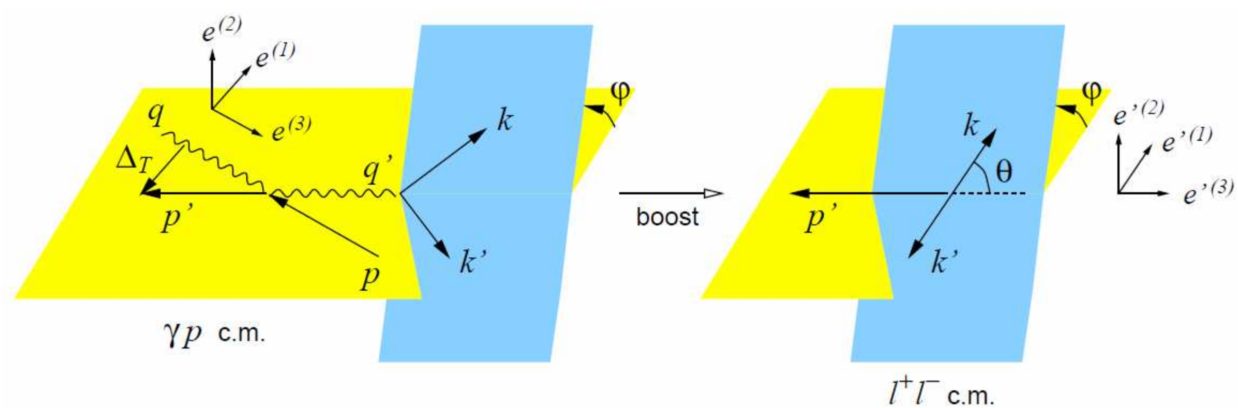


Hard scale

$$Q'^2 = M^2_{l^+l^-} = (k + k')^2$$

$$\eta = \frac{Q'^2}{2s - Q'^2}$$





$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ - \theta, 180^\circ + \phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ - \theta, 180^\circ + \phi)}$$

Zhiwen Zhao, Duke

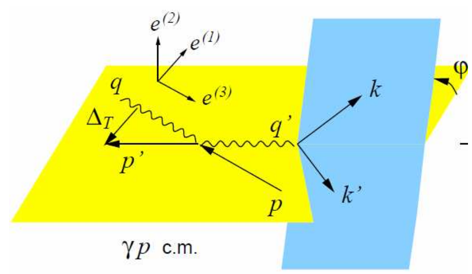
Garth Huber, huberg@uregina.ca

SoLID TCS Impact

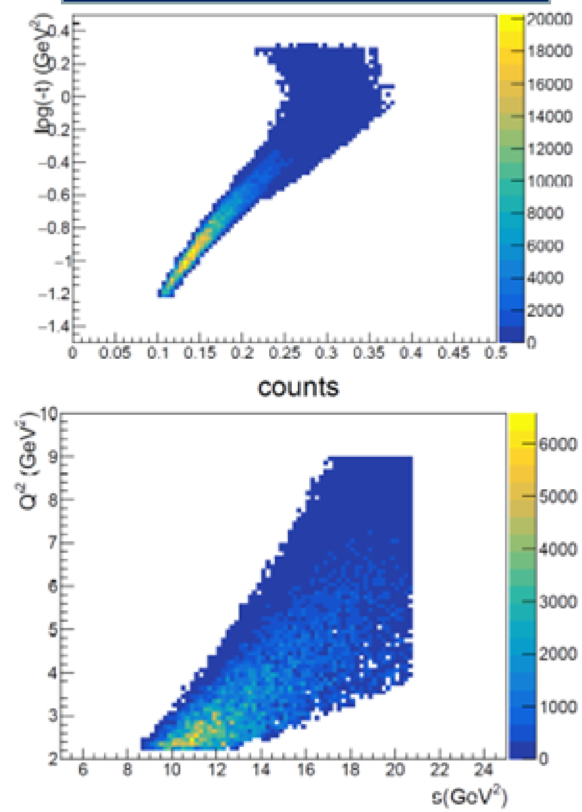
E12–12–006A: 15cm LH2 target, 3μA current, $1.2\times10^{37}/cm^2/s$ luminosity for 50+10 days

- **SoLID TCS will have at least 1 order of magnitude larger statistics than CLAS12 and usher TCS study into precision era with multi–dimensional binning**
  - 250x more integrated luminosity, but ¼ CLAS12 acceptance
  - Full azimuthal coverage ideal for forward–backward asymmetry
  - SoLID TCS could lead to study of NLO correction

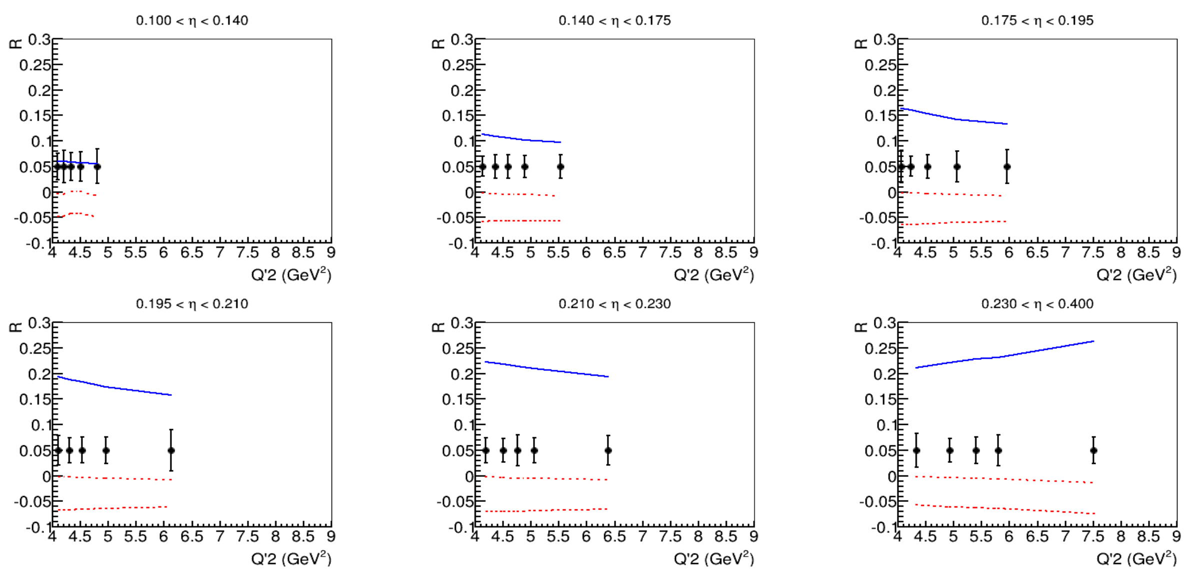
$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ^2\, dt\, d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ^2\, dt\, d\varphi}}$$



Kinematic coverage



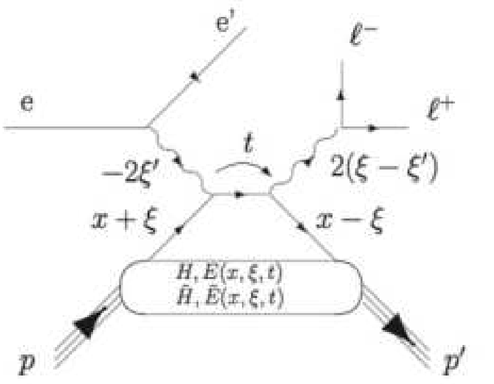
R projection



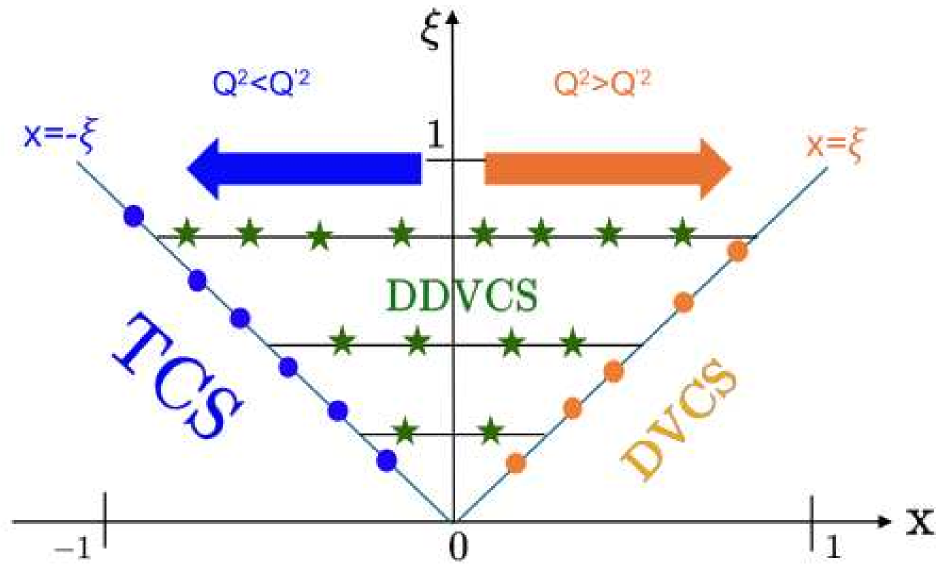
Zhiwen Zhao, Duke

Garth Huber, huberg@uregina.ca

GPDs via Double DVCS



Kinematics of two photons are described by ξ and ξ'.



$$\xi' = \frac{x_B}{2 - x_B}$$

$$\xi = \xi' \frac{Q^2}{Q^2 + Q'^2}$$

$$x = 2\xi' - \xi$$

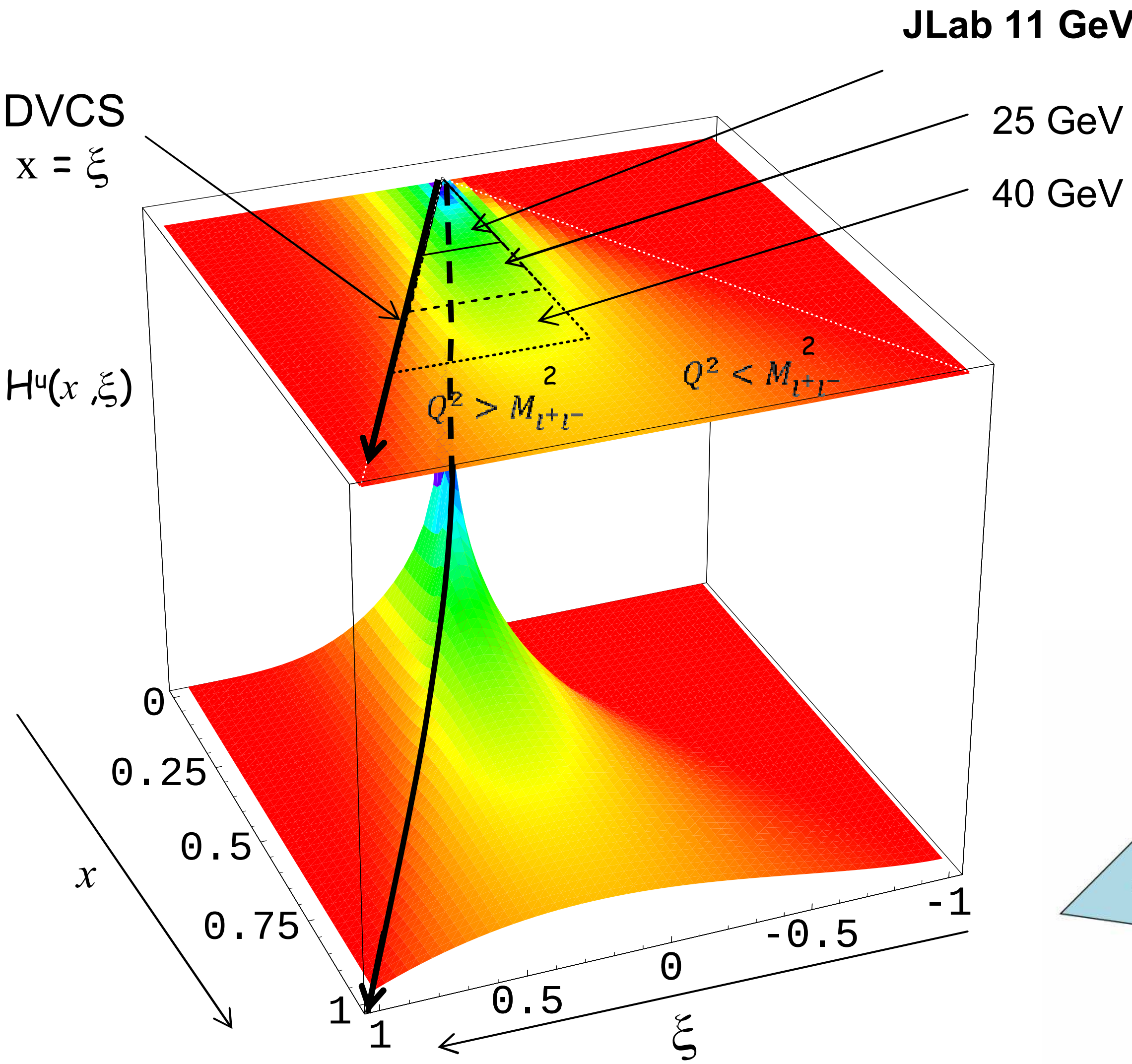
Quark propagators between two photons now reads as:

$$\frac{1}{x-(2\xi'-\xi)+i\epsilon} + \frac{1}{x+(2\xi'-\xi)-i\epsilon}$$

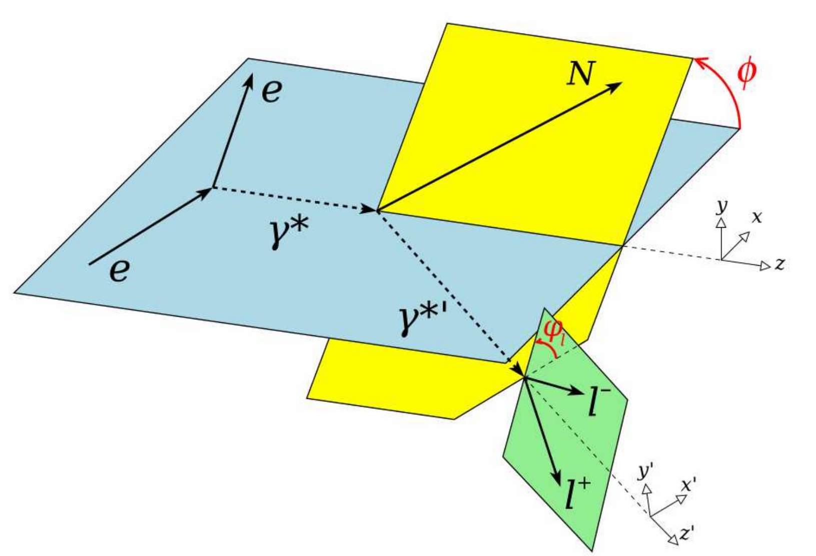
Observables (e.g. BSA) proportional to the Im part of the amplitude, allow direct measurement of GPDs at ($x=2\xi'-\xi$, ξ, t) points.

Here one can get away from the $x=\xi$ line by varying virtualities of incoming and outgoing photons

Double DVCS with SoLID



- DVCS only probes $\xi = x$ line
- TCS only probes $\xi = -x$ line
- Example with model of GPD H for up quark
- JLab: $Q^2>0$
- Kinematical range increases with beam energy (larger dilepton mass)

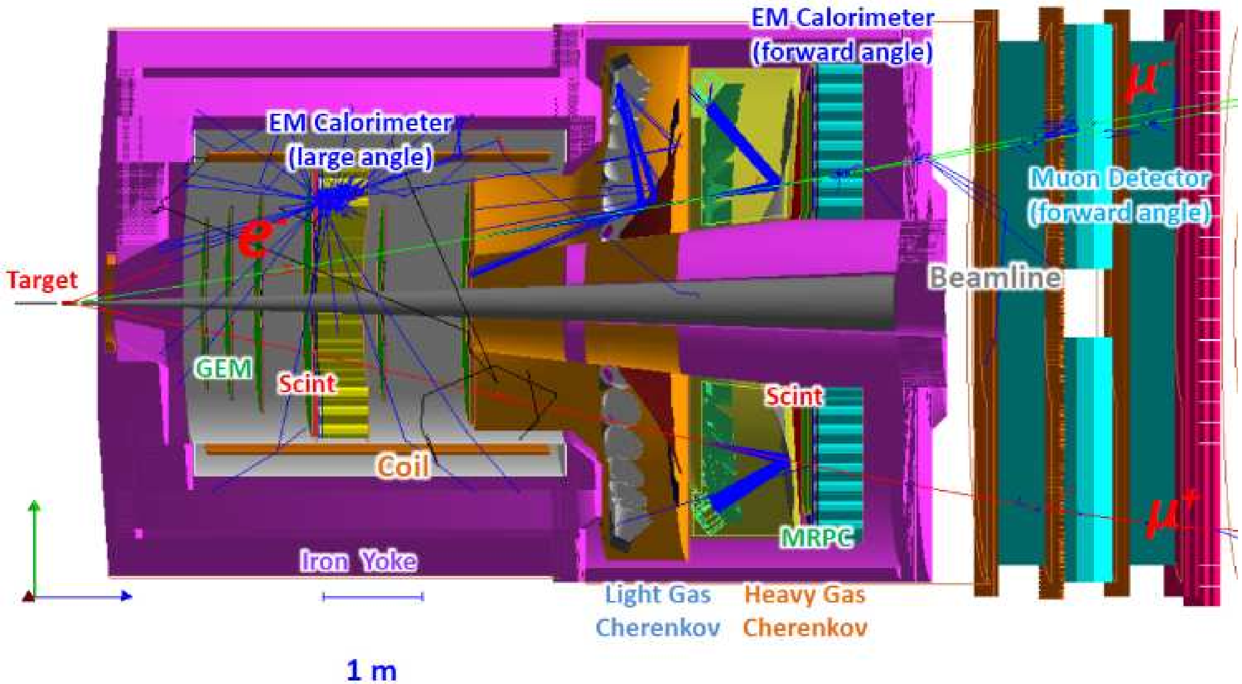


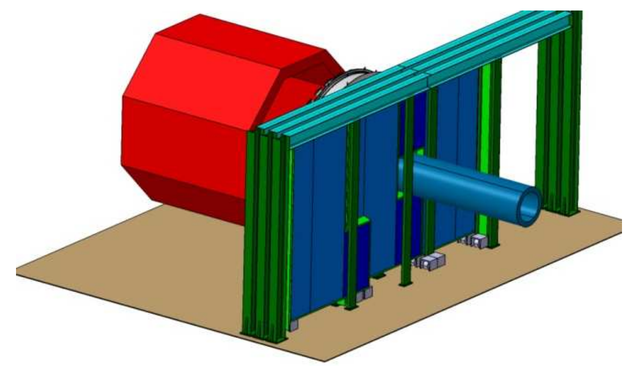
Garth Huber, huberg@uregina.ca

SoLID Double DVCS Setup

University of Regina

SoLID DDVCS





- Solenoidal configuration ideal for high luminosity
- Based on J/ψ and TCS setup with forward muon detector added
- Double Deeply Virtual Compton Scattering with SoLIDμ spectrometer, JLab Experiment *E12–25–010*

J.-S. Alvarado, M. Boer, A. Camsonne, E. Voutier, Z. Zhao

Garth Huber, huberg@uregina.ca

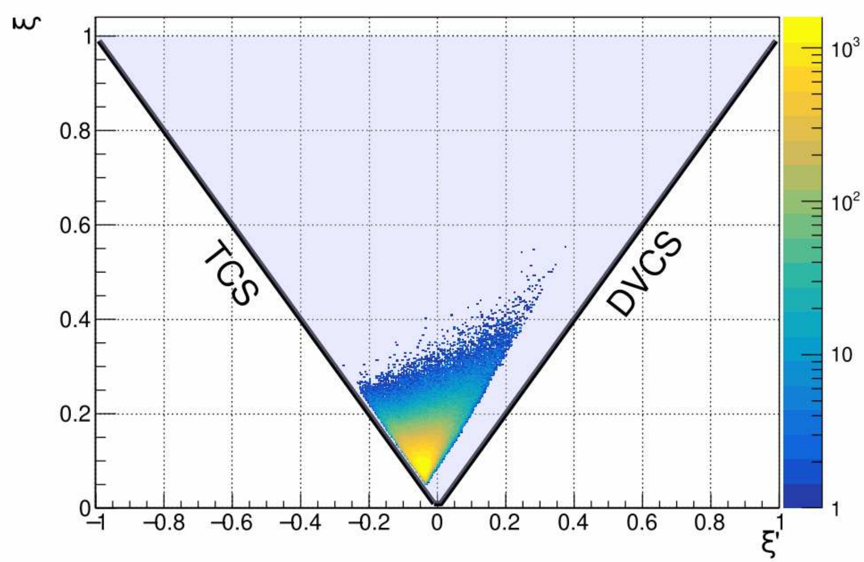
SoLID DDVCS Impact

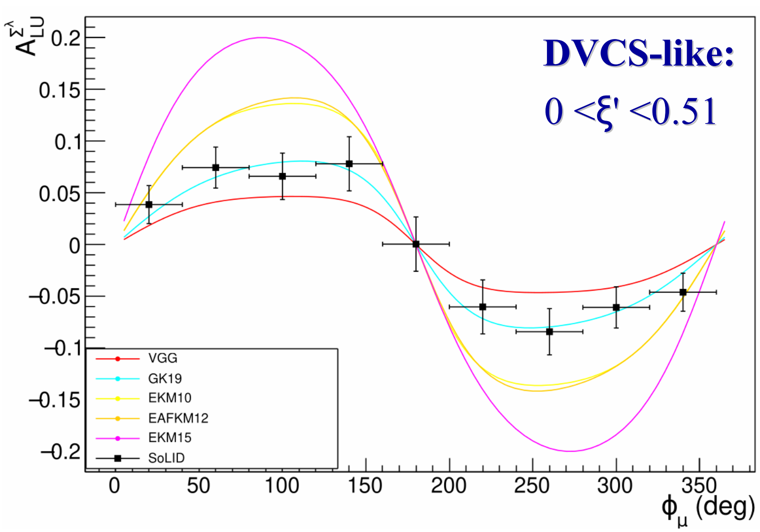
University of Regina

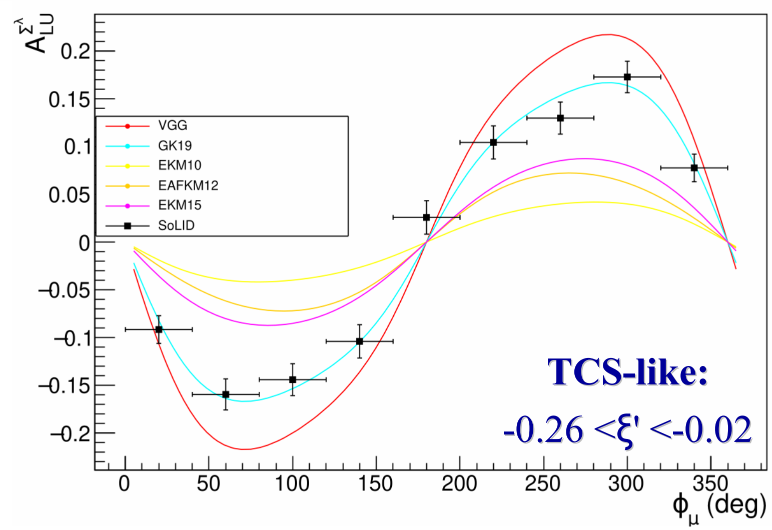
$$A_{LU}^{\pm}(\phi) = \frac{1}{\lambda^{\pm}} \frac{d^5\sigma_{+}^{\pm} - d^5\sigma_{-}^{\pm}}{d^5\sigma_{+}^{\pm} + d^5\sigma_{-}^{\pm}}$$

$$= \frac{d^5\widetilde{\sigma}_{DDVCS} \mp d^5\widetilde{\sigma}^{\mathrm{INT1}}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} \mp d^5\sigma_{INT_1}}$$

Beam Spin Asymmetry (BSA)
SoLID will allow first observation of sign change between DVCS-like and TCS-like regions







- **BSA at large skewness 0.3<ξ<0.4:** access "shadow GPDs"
- **$\mu^+\mu^-$ Charge Asymmetry** at same point of phase-space: accesses real part of DDVCS Compton Form Factors in leading twist analysis

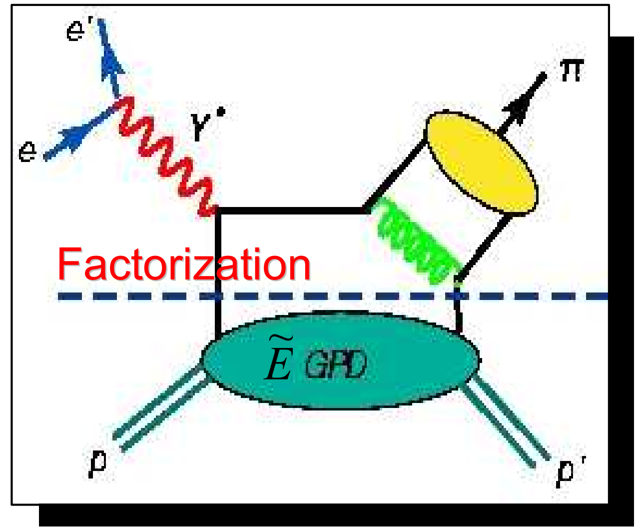
Garth Huber, huberg@uregina.ca

Acessing the 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.



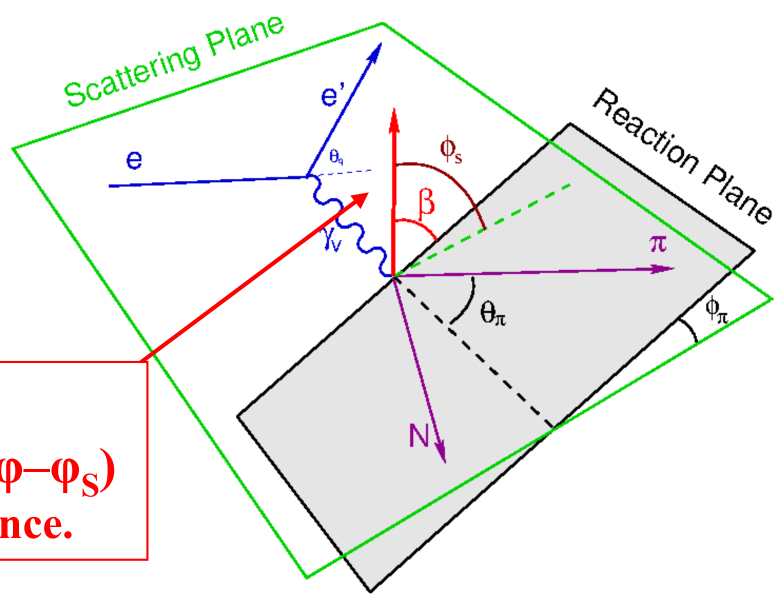
- **$\tilde{E}$ not related to an already known parton distribution → essentially unknown!**
- Experimental information can provide new nucleon structure information unlikely to be available from any other source.

Z. Ahmed, GMH, Z. Ye

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^*

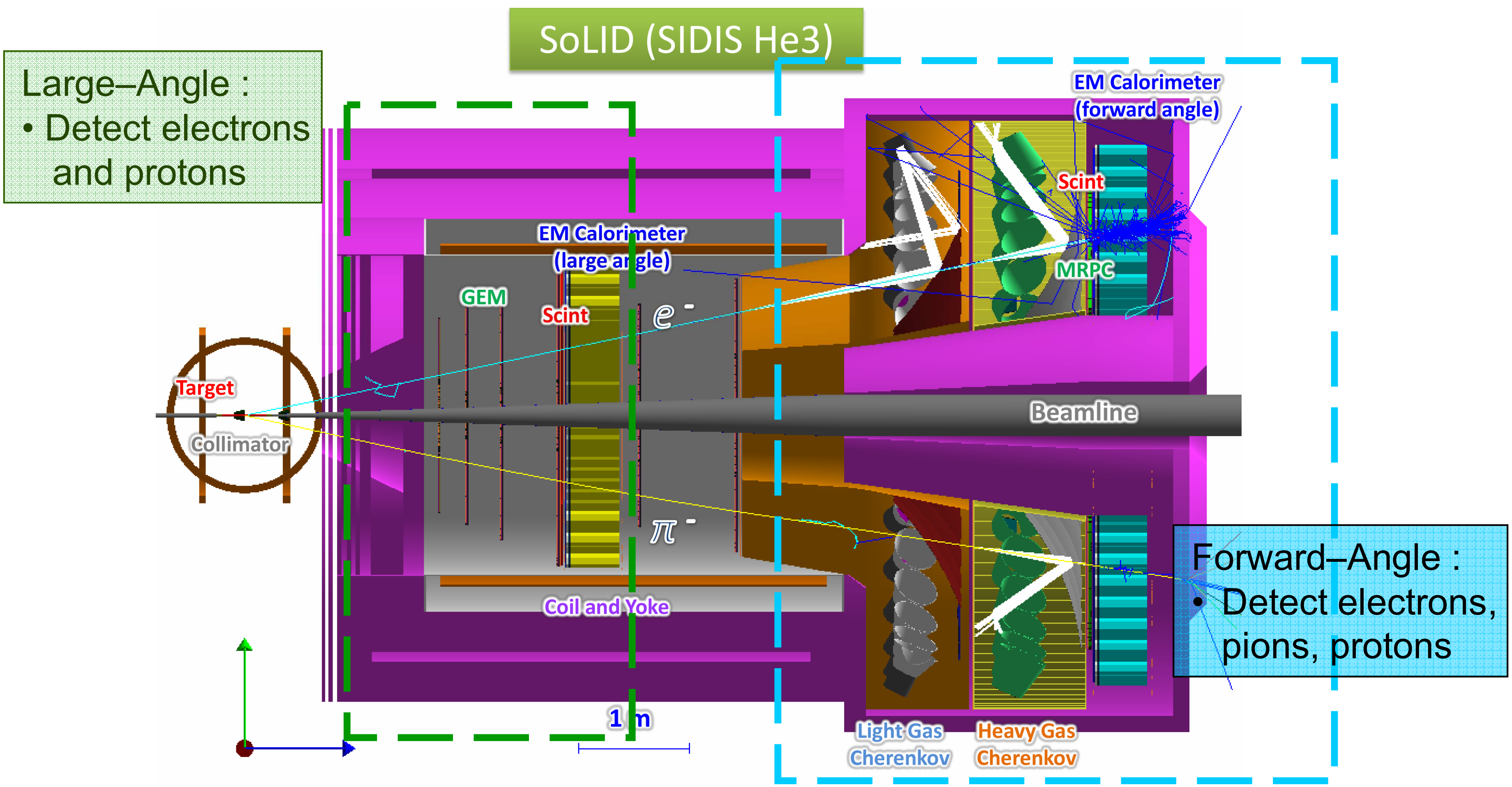
$\beta=\varphi-\varphi_S$ → angle between polarized target and reaction plane

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

Garth Huber, huberg@uregina.ca

SoLID – Polarized ^{3}He SIDIS Configuration

Run in parallel with E12–10–006: E_0 = 11.0 GeV (48 days)
Online Coincidence Trigger: Electron Trigger + Hadron Trigger (pions)
Offline Analysis: Identify (tag) protons and form triple–coincidence
SoLID's Large Acceptance, Full Azimuthal Coverage,
High Luminosity Capability are Essential for this Measurement!



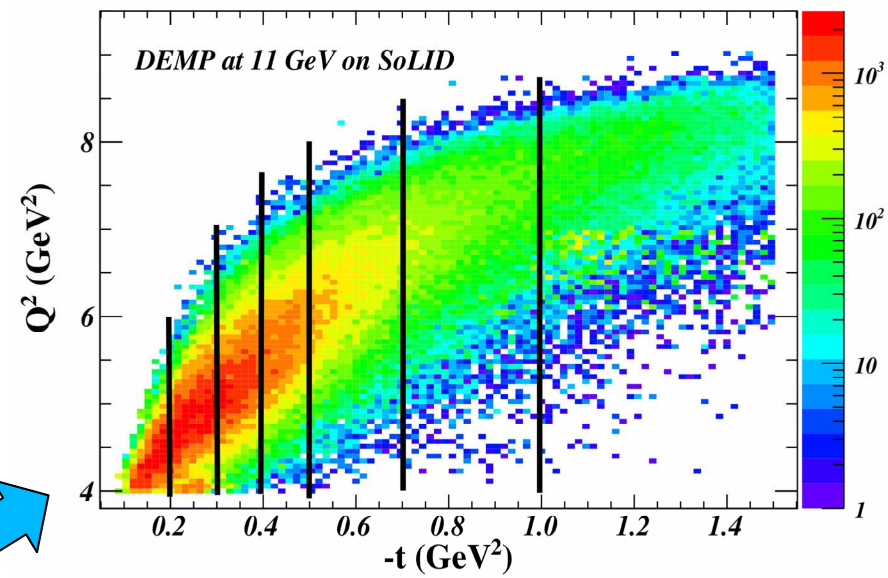
Garth Huber, huberg@uregina.ca

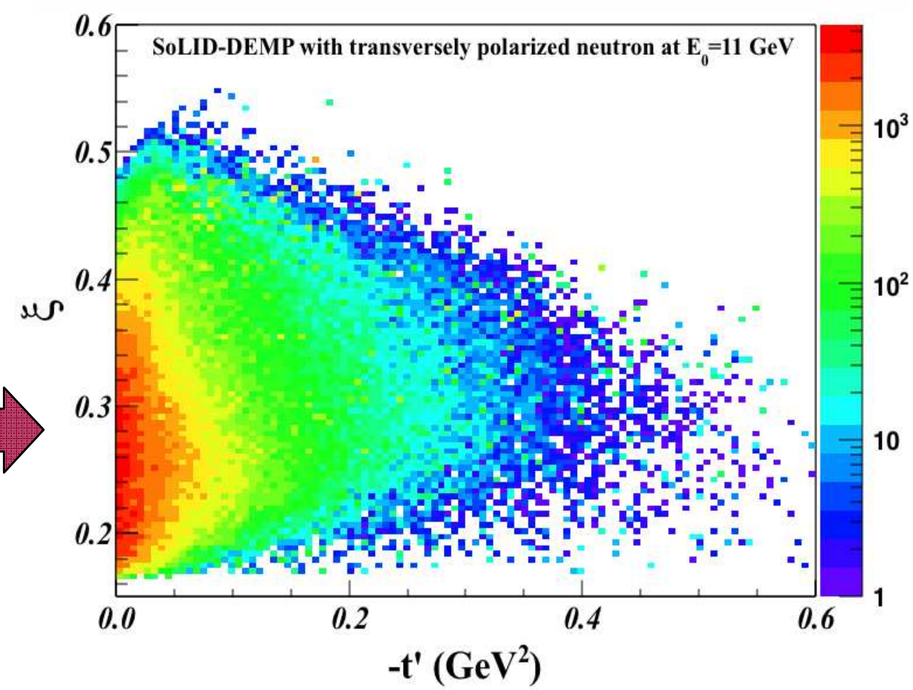
E12–10–006B Kinematic Coverage

University of Regina

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

- 7 t-bins concentrating on Q^2>4 GeV^2 region of greatest physics interest
- HERMES and COMPASS experiments are restricted kinematically to very small skewness (ξ<0.1)
- **With SoLID, we can measure skewness dependence of relevant GPDs over a fairly large range of ξ**





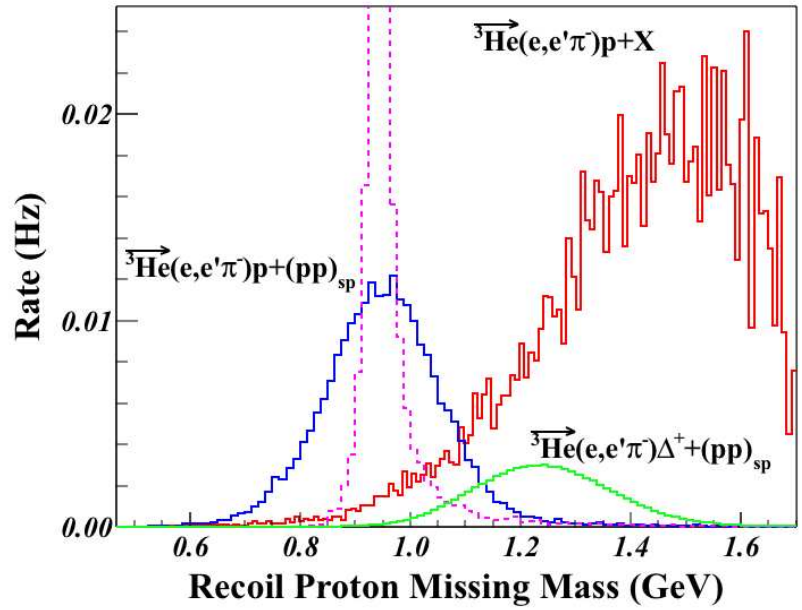
Garth Huber, huberg@uregina.ca

Example Cuts to Reduce Inclusive Background

University of Regina

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).

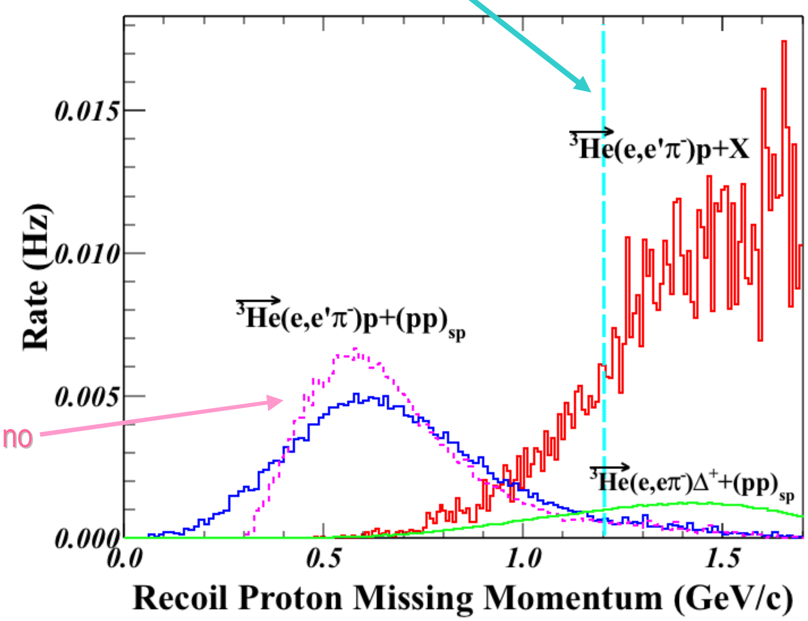


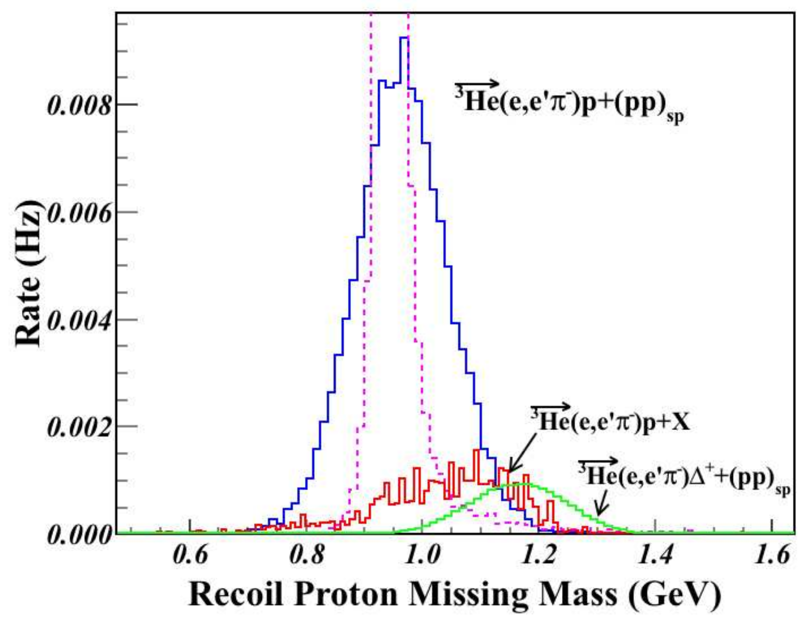
Apply P_{miss}>1.2 GeV/c cut

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

Background remaining after P_{miss} cut

Scattering & radiation but no resolution smearing

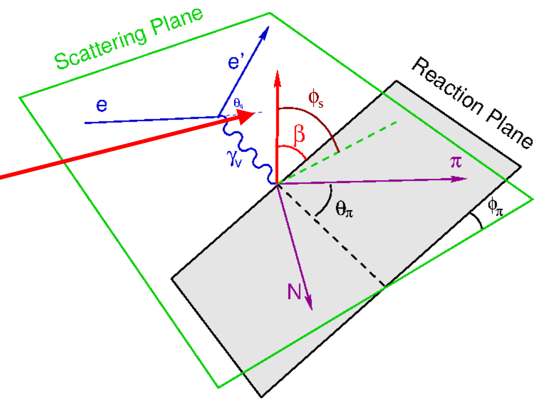




Garth Huber, huberg@uregina.ca

E12–10–006B Projected Data

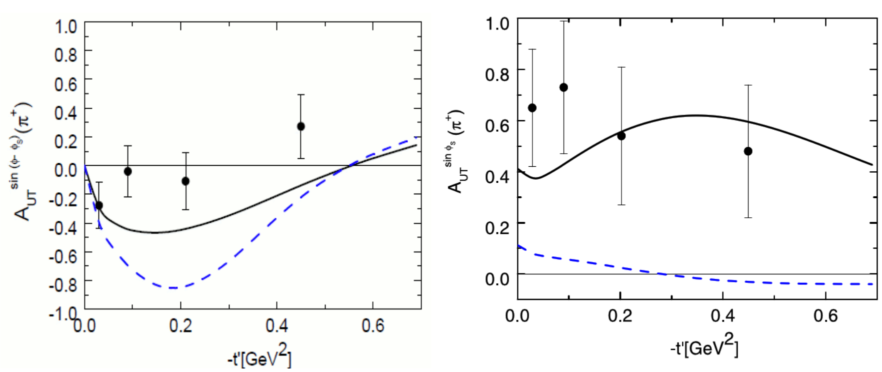
- **Azimuthal modulations of Transverse Single Spin Asymmetry allow access to different GPDs:**
  - $\sin(\beta=\varphi-\varphi_s)$ moment sensitive to helicity-flip GPD $\tilde{E}$
  - $\sin(\varphi_s)$ moment sensitive to transversity GPDs



World Data: HERMES

Pioneering measurement [PLB **682**(2010)345]

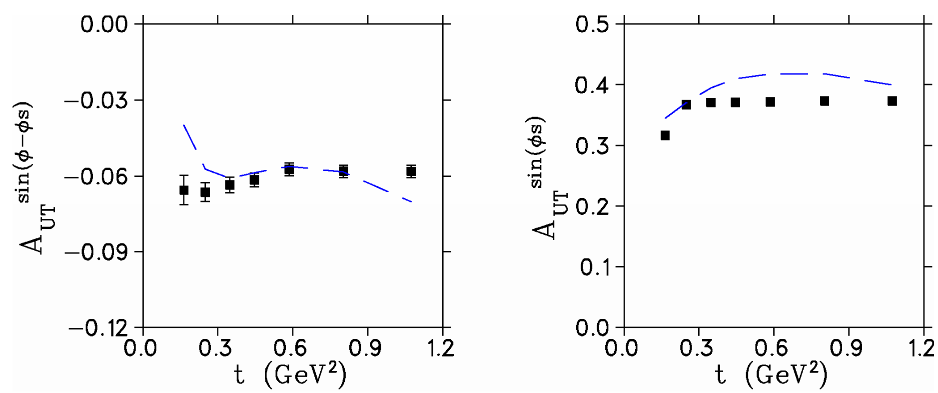
Q^2=2.45 GeV^2 W=3.99 GeV



SoLID Projected Uncertainties

Proton is tagged to isolate exclusive π^- events

Q^2>4 GeV^2 W>2 GeV



SoLID's large acceptance and high luminosity essential to this measurement

- **Dramatically better statistics, at higher *Q^2* and x_B, with broader –*t* coverage than pioneering HERMES measurement**
- **World unique, cannot be done anywhere else!**

Garth Huber, huberg@uregina.ca

Summary

- **SoLID's Large Acceptance and High Luminosity capabilities are key to measuring GPDs using deep exclusive processes**
- Allows multi–dimension binning with high statistics
- **SoLID has a broad exclusive physics program for GPD measurements:**
  - DVCS on polarized ^{3}He — under study
  - TCS — approved, *J/ψ* run group *(E12-12-006A)*
  - DDVCS with muons — *E12-25-010* (conditionally) approved with "A" rating
  - DEMP — approved, SIDIS run group *(E12-10-006B)*
  - More ideas under study (e.g. deuterium and other nuclear targets)
- ***Collaborators welcome!***

Garth Huber, huberg@uregina.ca

Garth Huber, huberg@uregina.ca

NSAC Long Range Plan & Community Strong Support

1 | EXECUTIVE SUMMARY

RECOMMENDATION 4
We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

Today's investments enable tomorrow's discoveries, with corresponding benefits to society. We underscore the importance of innovative projects and emerging technologies to extend discovery science, which plays a unique role in supporting national needs.

1.3.1. Opportunities to Advance Discovery

Strategic opportunities exist to realize a range of projects that lay the foundation for the discovery science of tomorrow. These projects include the 400 MeV/u energy upgrade to FRIB (FRIB400), the Solenoidal Large Intensity Device (SoLID) at Jefferson Lab, targeted upgrades for the LHC heavy ion program, emerging technologies for measurements of neutrino mass and electric dipole moments, and other initiatives that are presented in the body of this report.

NSAC 2023 LRP Town Meetings – QCD

Recommendation 1: Capitalizing on past investments *(Yes: 335; No: 3; No Answer: 4)*

The highest priority for QCD research is to maintain U.S. world leadership in nuclear science for the next decade by capitalizing on past investments. Maintaining this leadership also requires recruitment and retention of a diverse and equitable workforce.

We recommend support for a healthy base theory program, full operation of the CEBAF 12-GeV and RHIC facilities, and maintaining U.S. leadership within the LHC heavy-ion program, along with other running facilities, including the valuable university-based laboratories, and the scientists involved in all these efforts.

This includes the following, unordered, programs:

- The 12-GeV CEBAF hosts a forefront program of using electrons to unfold the quark and gluon structure of visible matter and probe the Standard Model. We recommend executing the CEBAF 12-GeV program at full capability and capitalizing on the full intensity potential of CEBAF by the construction and deployment of the Solenoidal Large Intensity Device (SoLID).

SoLID Project Status

- **The SoLID physics program:**
  - Five A rated experiments, one A- rated experiment, conditional approved experiment and 7 run group expts
- **Difficult budget times for a new project now:**
  - SoLID Collaboration is working on a plan for an initial high luminosity spectrometer using CLEO magnet and subset of detectors
  - Strategy is to start with one approved "A" rating experiment (e.g. J/Ψ) with reduced detector configuration and minimum cost that JLab can support from its internal budget
  - This is under discussion with new JLab management (Jens Dilling et al.). The SoLID Collaboration is encouraged to work out a detail plan of options to continue discussions/iterations with JLab management
- **Collaboration is planning to have workshop in Sept 2026 at JLab**

Garth Huber, huberg@uregina.ca