Probing Hadron Structure with Deep Exclusive Reactions at Halls A/C

Garth Huber

University of Regina

Halls A/C Summer Workshop
June 29, 2023

Supported by:

NSERC CRSNG

SAPPJ-2021-00026

Thanks to those who provided slides!

- Andrew Puckett
- Simon Sirca
- David Hamilton
- Dipangkar Dutta
- Arun Tadepalli
- Julie Roche
- Alexandre Camsonne
- Zhiwen Zhao
- Marie Boer
- Pawel Nadel–Turonski
- Wenliang Li

I've tried to be complete. Please accept my apologies if I've missed yours!

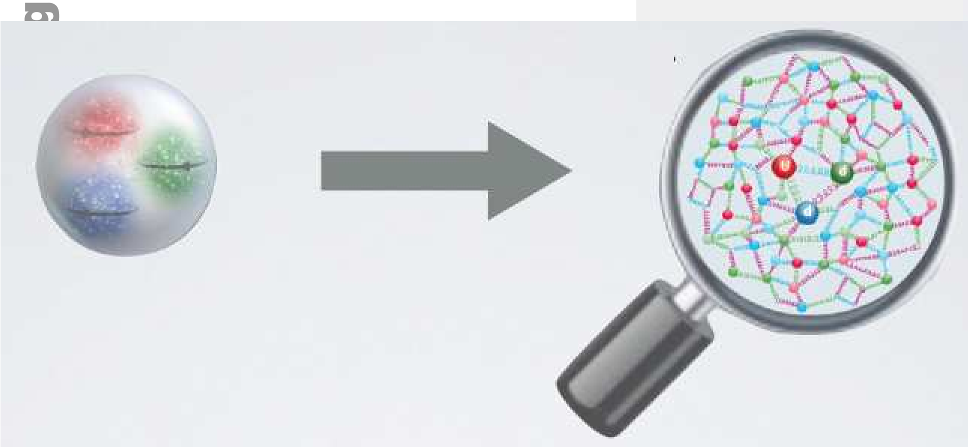
I've also made extensive use of presentations by Rolf Ent on similar topics. They were very useful!

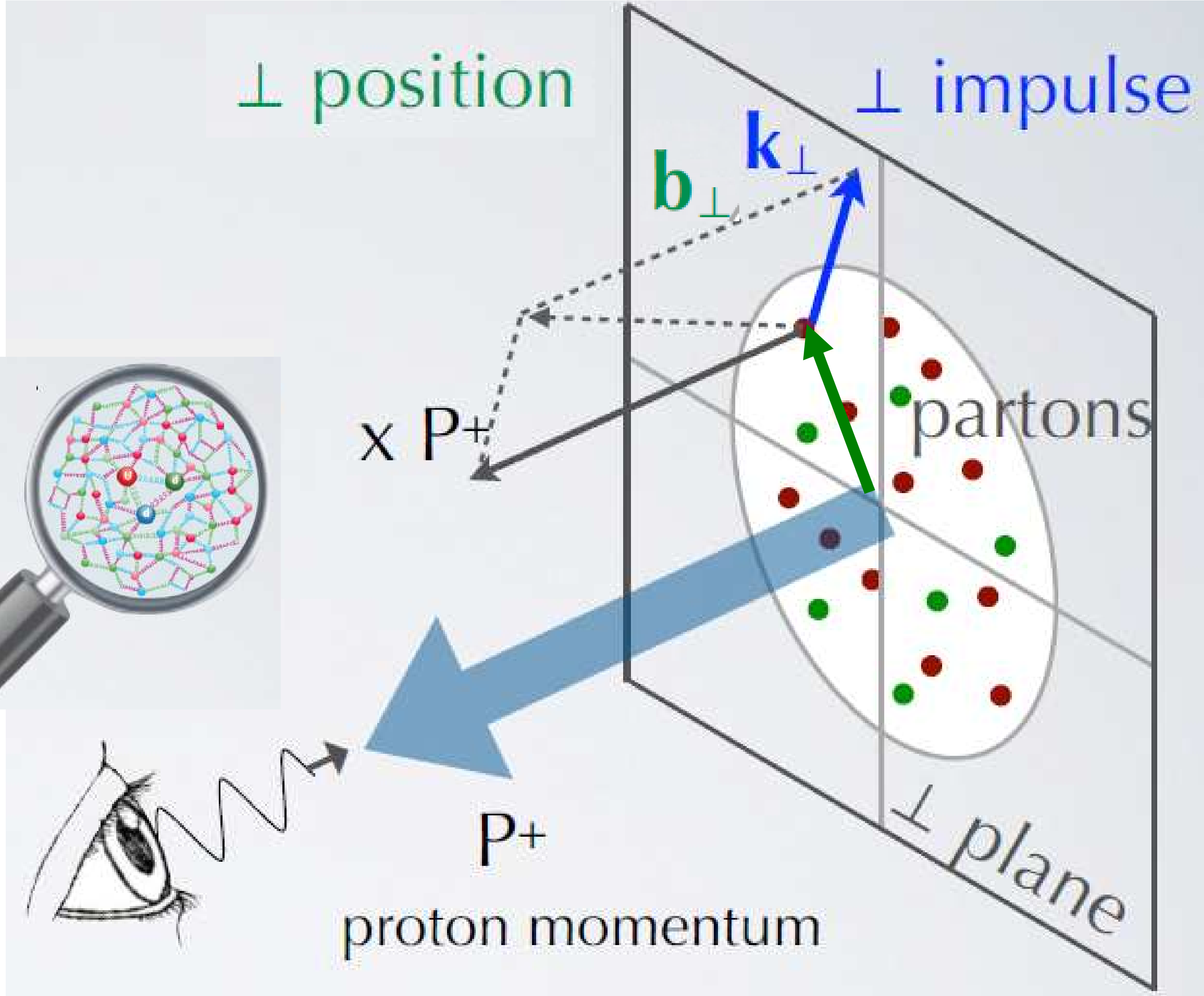
Garth Huber huberg@uregina.ca

Towards 3D Imaging of Hadrons

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

Exclusive reactions have a key role!





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

Gar
g@uregina.ca

Role of Halls A/C in JLab 3D Imaging Program

- **1D: Form Factors!** – Nucleon, Pion (and Kaon?)
- **1D: Real Compton Scattering** – one of the processes leading to the birth of the 3D formalism, and perhaps still the least understood elementary process → Wide Angle (Real) Compton Scattering
- **3D: DVCS, TCS, DDVCS**
- **3D: DEMP (t–channel and u–channel)**
- **Precision Cross Sections required for 3D imaging!**
  - Separation of longitudinal and transverse cross sections towards understanding of reaction mechanism of DVCS, and charged and neutral light meson (pion, kaon) electro–production
  - Precision helicity–dependent cross section ratios (aka spin asymmetries) making use of the Halls A/C versatility, such as high–intensity photon beams, longitudinal and transverse polarized target compatibility

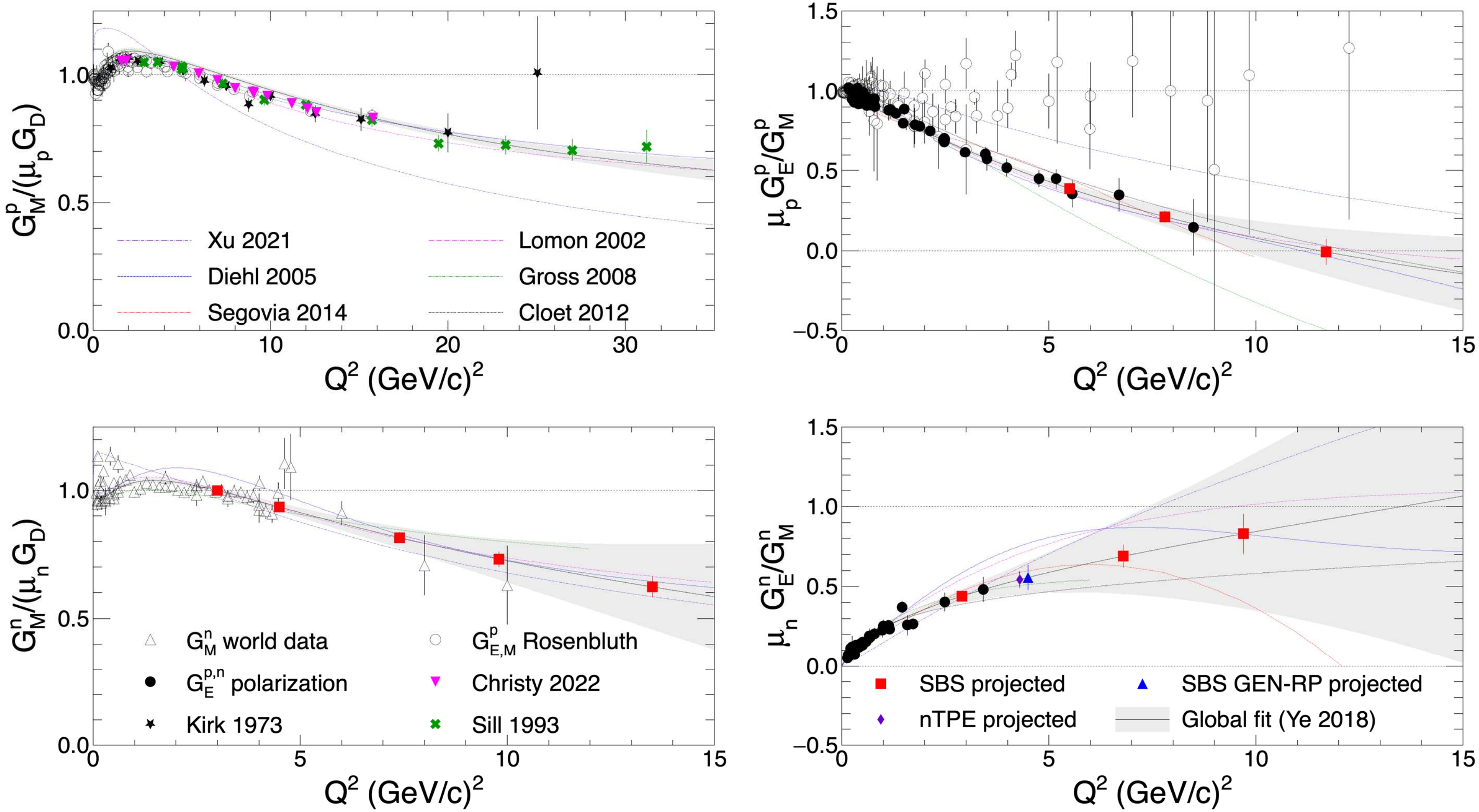
Rolf's analogy is that Halls A/C should provide the structure of the house, and Hall B the floors/roof. You need both to make your house habitable.

Garth Huber huberg@uregina.ca

Extending Q^2 Range of Nucleon Form Factors

Physics Reach extended by Super BigBite Spectrometer (SBS) in Hall A:

– Use high luminosity + open geometry + GEM detectors



– Pushes G_E^p/G_M^p, G_E^n, G_M^n to high Q^2 (>10 GeV^2)

– Allows for flavor decomposition to distance scales deep inside the nucleon

Data and theory curves are as described in section 10.1 of "50 years of QCD": https://inspirehep.net/literature/2617065

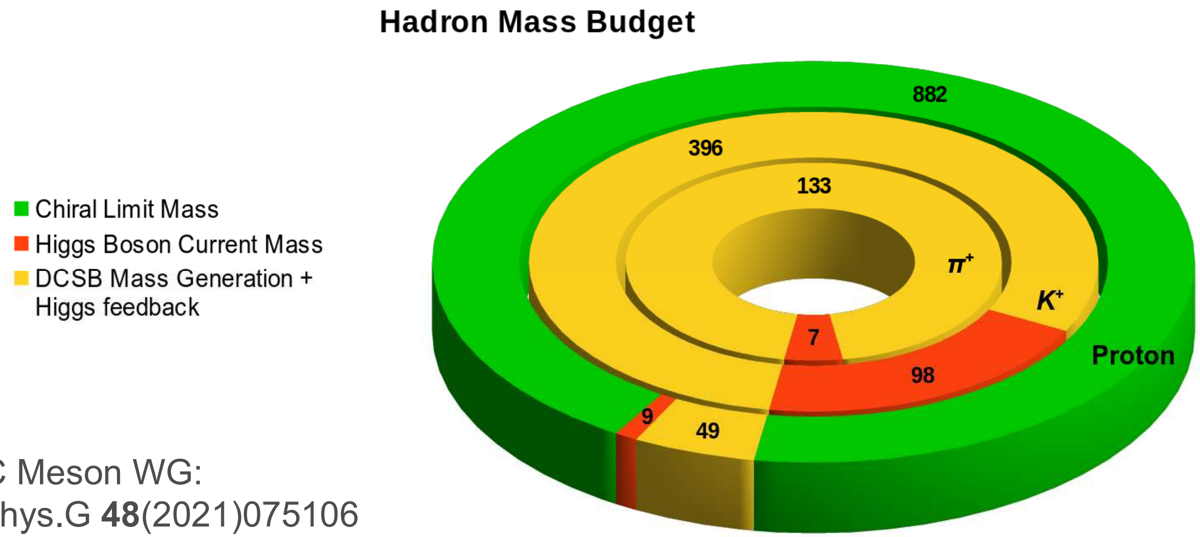
Garth Huber huberg@uregina.ca

Status of SBS High–Q^2 Form Factor Program

- **E12–09–019 (G_M^n to Q^2 = 13.5 GeV^2) and E12–20–010 (neutron TPE experiment): Completed Oct. 2021–Feb. 2022** [D. Hamilton, B. Quinn, B. Wojtsekhowski]
- **E12–09–016 (G_E^n/G_M^n to 10 GeV^2 with polarized ^{3}He): Started Oct. 2022, ~70% complete as of March 2023, extended running fall 2023** [T. Averett, G. Cates, S. Riordan, B. Wojtsekhowski]
- **E12–17–004 (G_E^n/G_M^n at Q^2 = 4.5 GeV^2 with polarization transfer in d(e,e'n)p): Scheduled for winter 2024** [J. Annand, B. Wojtsekhowski, B. Sawatzky, N. Piskunov, V. Bellini, M. Kohl]
- **E12–07–109 (G_E^p/G_M^p to 12 GeV^2 via polarization transfer): Scheduled for fall 2024** [E. Cisbani, M.K. Jones, N. Liyanage, L. Pentchev, A. Puckett, B. Wojtsekhowski]

Garth Huber huberg@uregina.ca

Emergent Hadronic Mass



EIC Meson WG:
J.Phys.G **48**(2021)075106

Stark Differences between proton, K$^+$, π^+ mass budgets

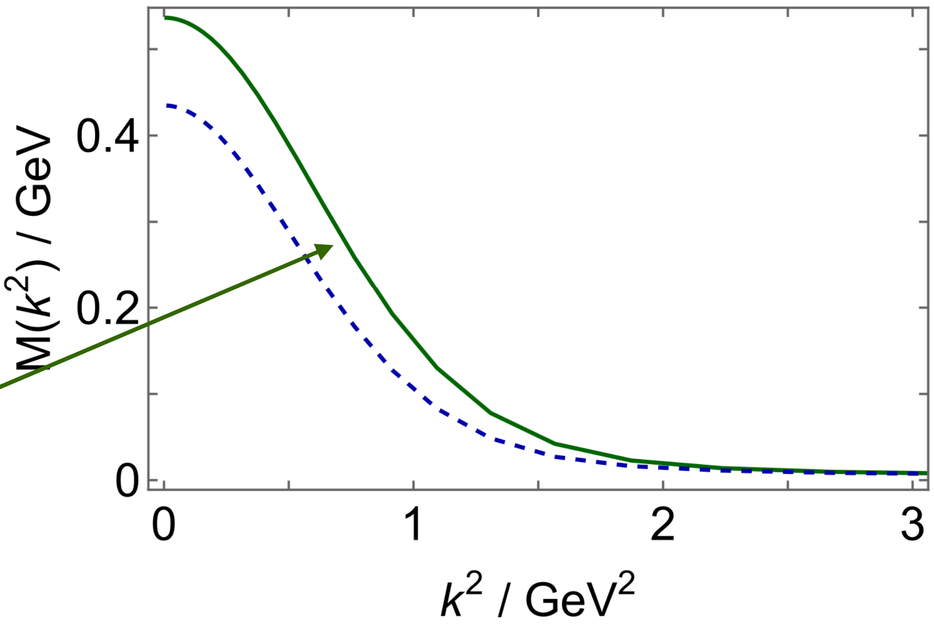
- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons of QCD).
- The mass budgets of these crucially important particles demand interpretation.
- Equations of QCD stress that any explanation of the proton's mass is incomplete, unless it simultaneously explains the light masses of QCD's Goldstone bosons, the π and *K*.

Garth Huber huberg@uregina.ca

Synergy: Emergent Mass and π^+ Form Factor

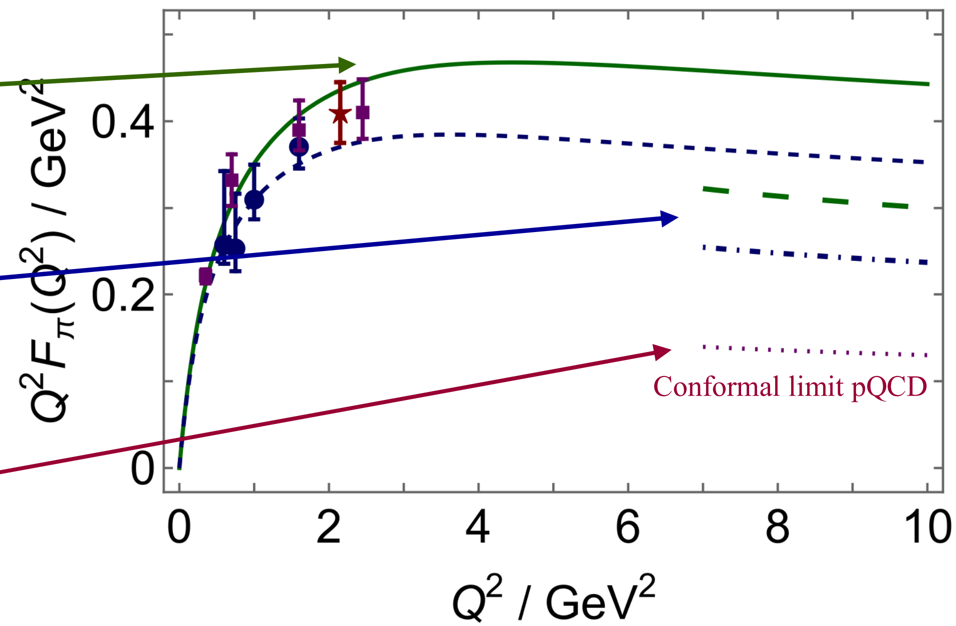
At empirically accessible energy scales, π^+ form factor is sensitive to emergent mass scale in QCD

- **Two dressed–quark mass functions distinguished by amount of DCSB**
  - DCSB emergent mass generation is 20% stronger in system characterized by solid green curve, which is more realistic case



- ***$F_\pi(Q^2)$* obtained with these mass functions**
  - r_π=0.66 fm with solid green curve
  - r_π=0.73 fm with solid dashed blue curve
- ***$F_\pi(Q^2)$* predictions from QCD hard scattering formula, obtained with related, computed pion PDAs**
- **QCD hard scattering formula, using conformal limit of pion's twist–2 PDA**

$$\phi_\pi^{cl}(x) = 6x(1-x)$$



Chen, et al., PRD **98**(2018)091505(R); Aguilar et al, EPJA **55**(2019)190

Garth Huber huberg@uregina.ca

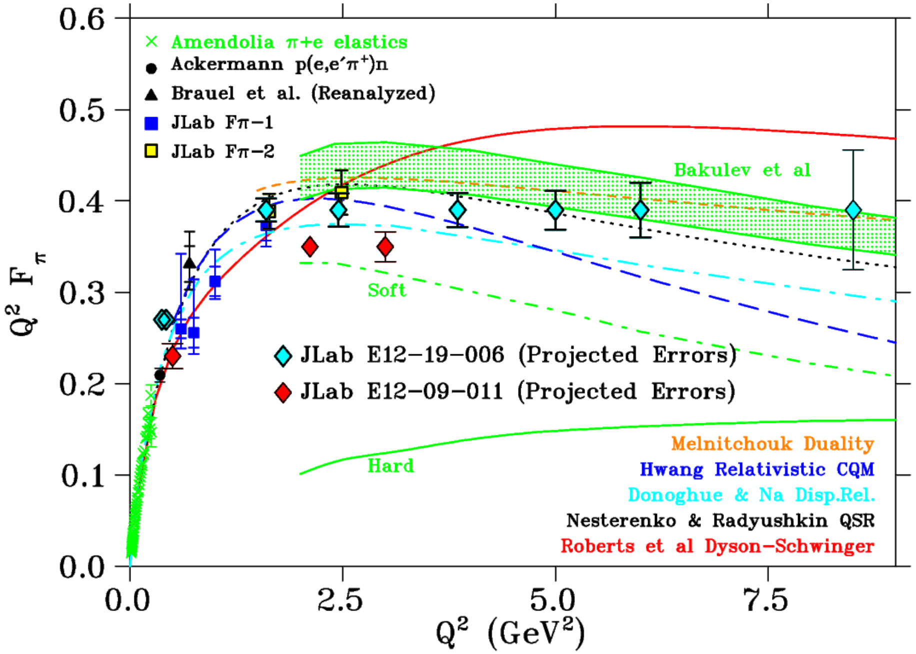
Projected π^+ and K^+ Form Factors

Garth Huber huberg@uregina.ca

Measurement of $F\pi$ to Q^2=6.0 to high precision, and to 8.5 GeV^2 with lower precision. Will we see the first quantitative access to hard scattering regime?

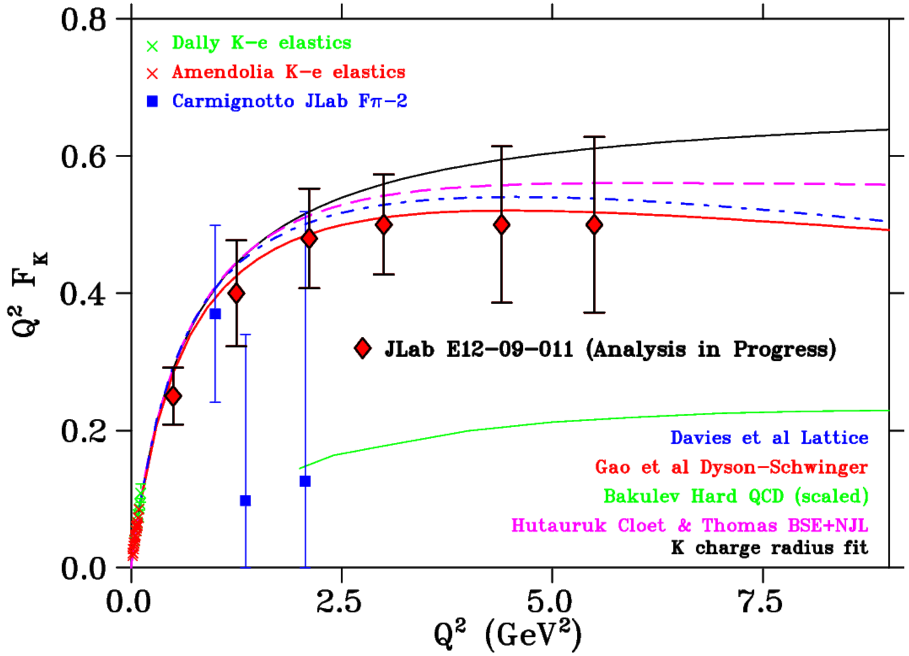
First measurement (and L/T–separation!) of *p(e,e'K+)Λ* well above the resonance region (*W*>2.5 GeV). If *K*+ pole dominates $d\sigma_L/dt$, it allows for extraction of F_K.

p(e,e'π+)n



Data taking completed September 2022 (E12–19–006: G. Huber, D. Gaskell and T. Horn, spokespersons)

p(e,e'K+)Λ



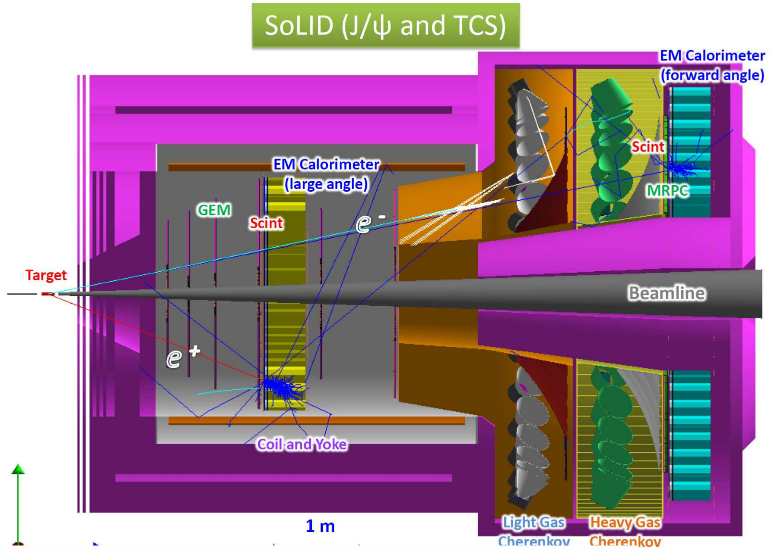
Partially completed in 2019 as an early SHMS commissioning experiment: LT–separation (E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)

These measurements are only possible because of forward angle and high momentum capabilities of SHMS+HMS.
No other facility worldwide can perform these measurements.

y–positions of projected points are arbitrary. Error bars calculated from obtained statistics and projected systematics.

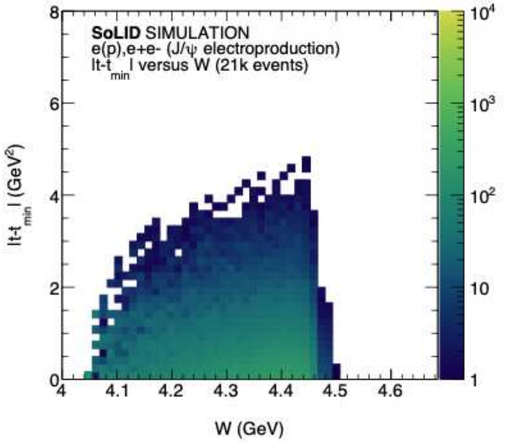
Near Threshold J/ψ production with SoLID

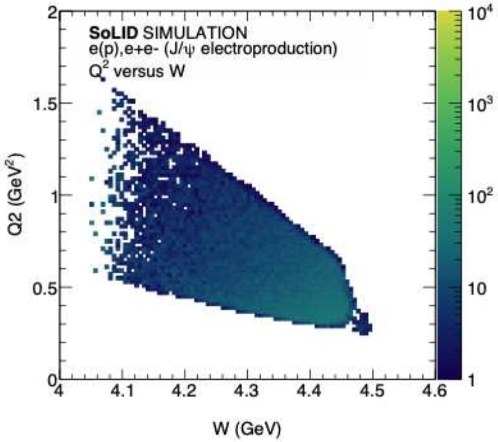
Uniquely sensitive to non–perturbative gluonic structure of proton, and role of QCD trace anomaly in Emergent Hadronic Mass



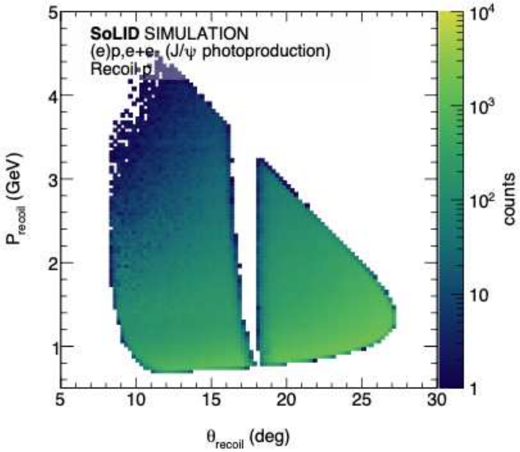
Ultimate factory for near–threshold J/ψ
Ultra–high luminosity: 43.2ab^{-1}

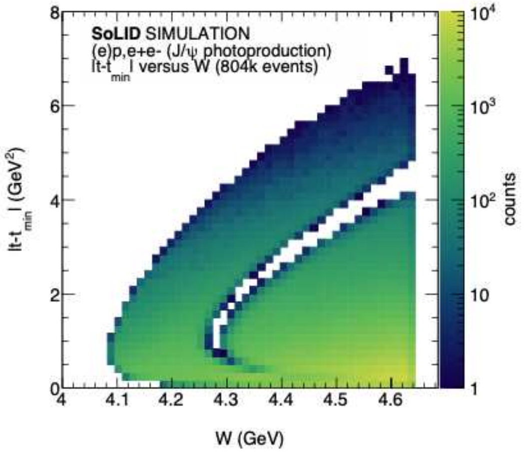
$e\,p \rightarrow e'\,p'\,J/\psi(e^- e^+)$

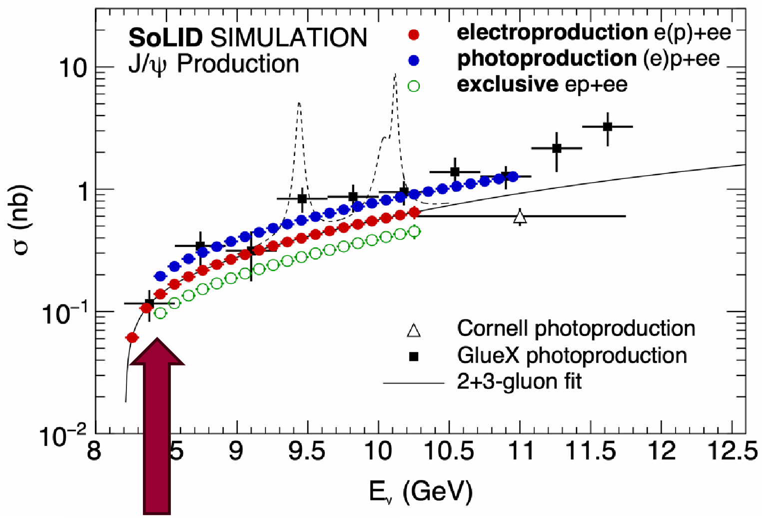


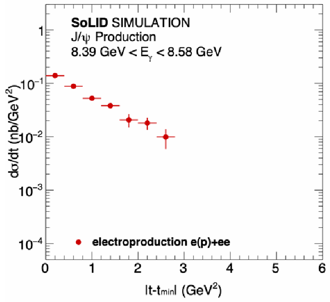


$\gamma\,p \rightarrow p'\,J/\psi(e^- e^+)$









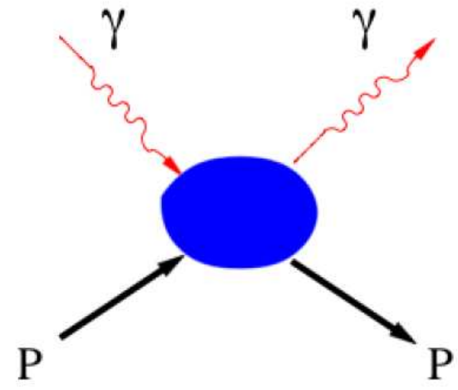
E12–12–006: S. Joosten, Z-E Meziani, X. Qian, N. Sparveris, Z. Zhao (spokespersons)

Garth Huber huberg@uregina.ca

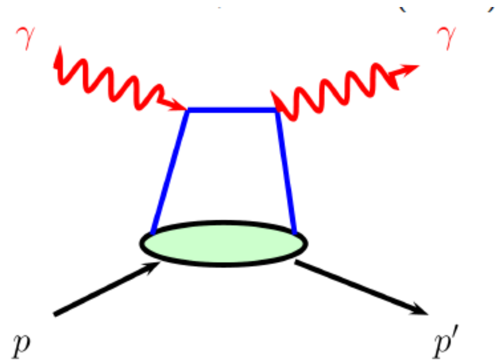
Wide–Angle (Real) Compton Scattering (WACS)

NPS Collaboration, Experiment E12–14–003
D. J. Hamilton (U of Glasgow), S. Širca, B. Wojtsekhowski (JLab)

- **Physics motivation**
  - Applicability of pQCD scaling (?)
  - Handbag mechanism and GPDs
  - Advances in soft collinear effective theory (SCET)
  - Connection to elastic e–p scattering and DVCS



- Compton scattering on proton in wide–angle regime (s, −t, −u » M^2) is a powerful and under–utilized probe of nucleon structure
- Arguably the least understood of the fundamental reactions in several–GeV regime
- Wide–Angle Compton Scattering cross section behavior nonetheless was a foundation leading to the GPD formalism
- Reaction mechanism intrinsically intertwined with basic of hard e–q scattering process (handbag diagram), yet also sensitive to transverse structure like high–Q^2 form factors

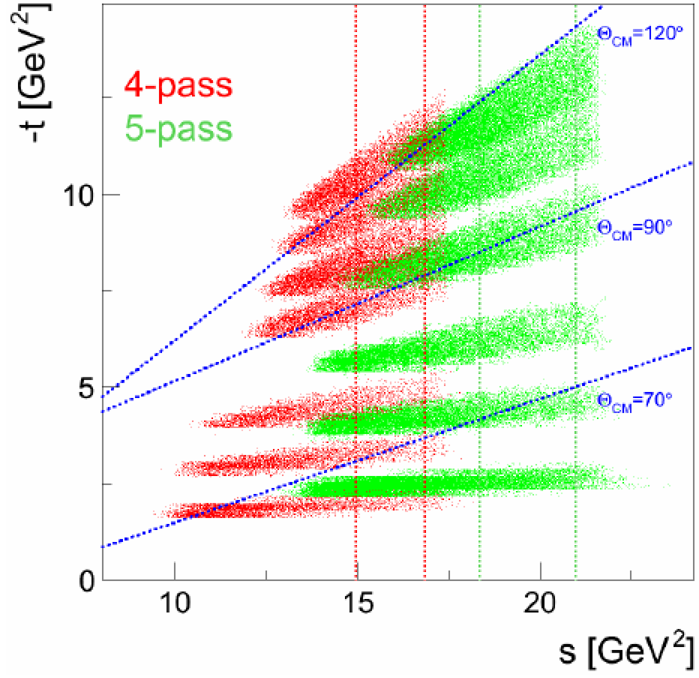


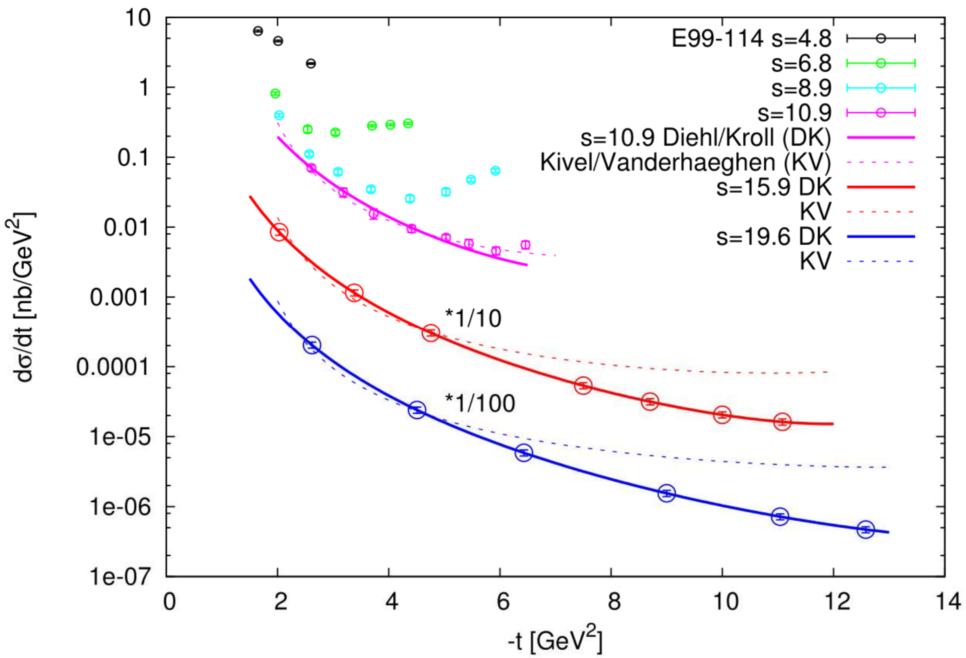
Garth Huber huberg@uregina.ca

WACS @ 12 GeV Projected Results

- **Experiment E12–14–003**
  - Measure 13 kinematic points
  - Determine scaling power Q^{-n} at fixed θ_{cm} and therefore dominant reaction mechanism
- **Most important features**
  - Wide-angle condition (s, −t, −u »M^2) satisfied in all settings
    - broad range in −t
    - extract RCS form-factor R(t)
    - evidence for factorization
    - constraints on GPDs at high x
    - constraints on 2γ effects in e-p elastic scatt. at high Q^2
- $15.0 < s < 21.0$ GeV^2
  $2.0 < -t < 12.0$ GeV^2
  $3.0 < -u < 15.3$ GeV^2

Also polarized now with NPS and CPS

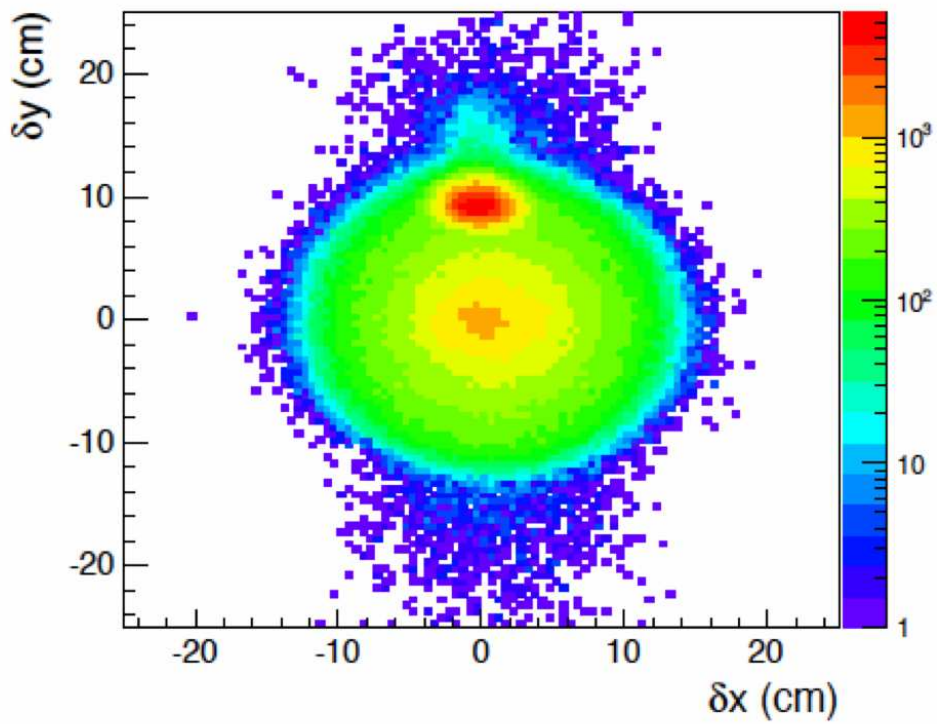




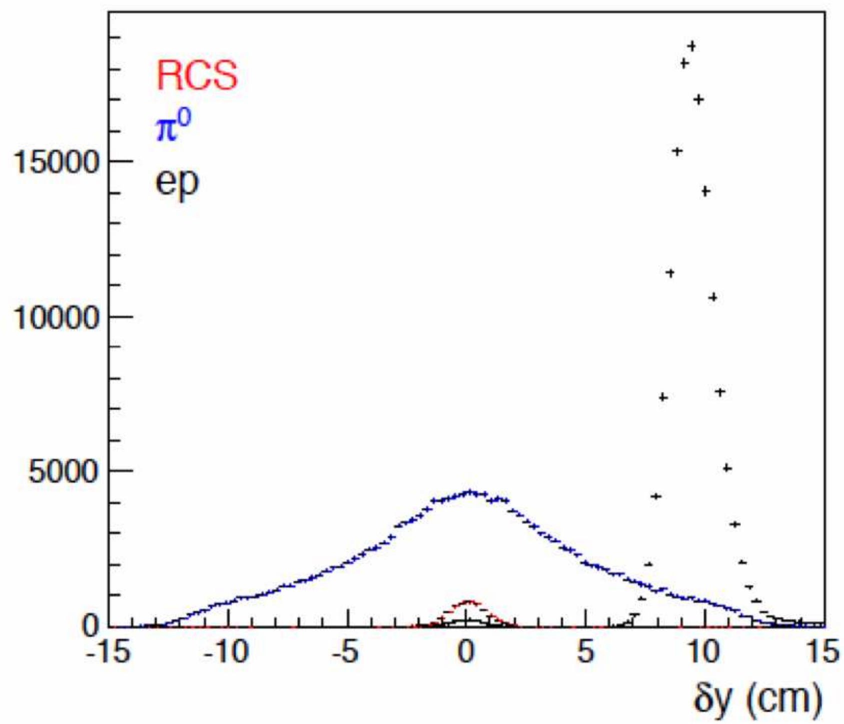
Garth Huber huberg@uregina.ca

Wide Angle π^0 Photoproduction

π^0 production is the largest background in the wide angle Compton scattering (WACS) experiment. This experiment will run parasitic to WACS



Typical distributions of position difference (δy vs δx) between NPS hits and prediction of 2-body kinematics.

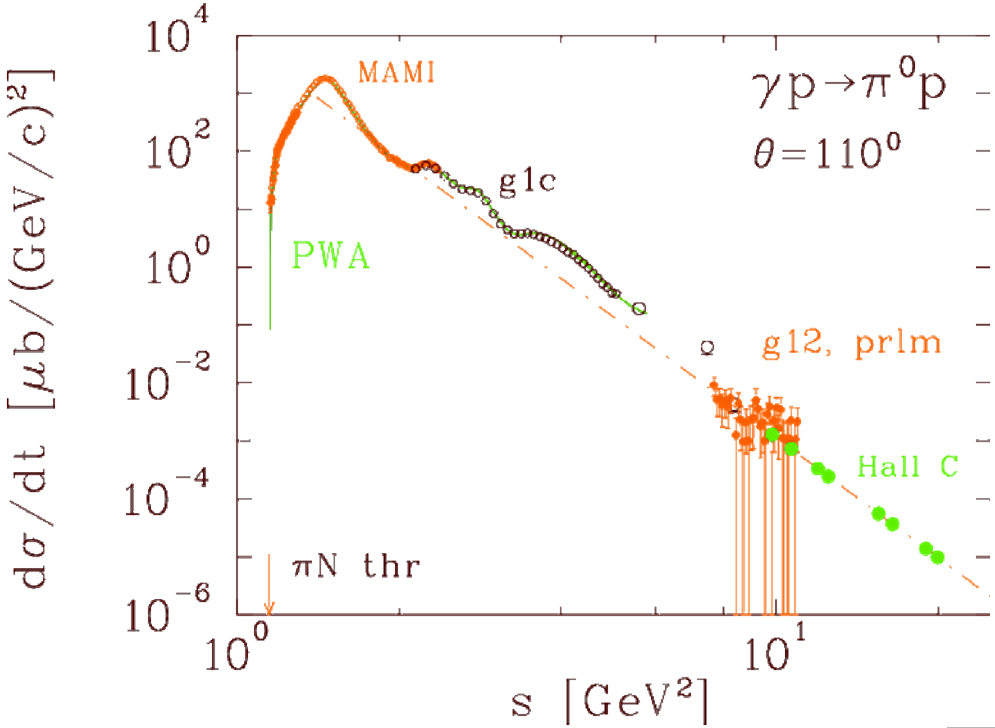


Projection of the δx = 0 events

Wide Angle π^0 cross section will help test dominance of handbag mechanism (next simplest process after Compton scattering)

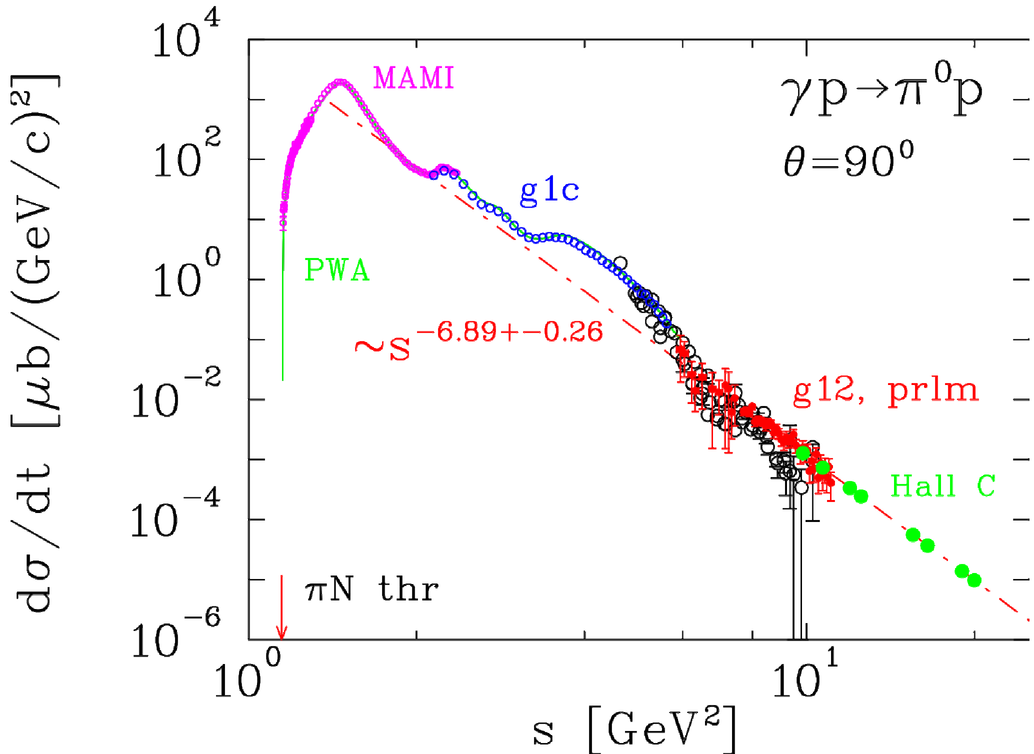
Garth Huber huberg@uregina.ca

E12–14–005 Wide Angle π^0 Projected Results



The experiment will study energy and angular dependence of constituent scaling laws and oscillations about the scaling laws

It will help identify energy scale for transition from soft to hard factorization regimes and help understand non–pertubative structure of proton



M. Amaryan, D. Dutta, H. Gao, M. Kunkel, S. Sirca, I. Strakovsky (spokespersons)

Wide Angle π^+ Photoproduction

- **Wide angle pion photo–production is a powerful tool to study the interaction mechanism**
- A handbag approach in the framework of GPDs has been proposed, which can be independently tested via polarization observables A_{LL} and K_{LL}
- LD_2 target with 6% Cu radiator upstream for K_{LL}, polarized ^3He target for A_{LL}
- BigBite+SBS will be used as pion and nucleon detection arms
- **A_{LL} E12–21–005:** G. Cates, R. Montgomery, A. Tadepalli, B. Wojtsekhowski
- **K_{LL} E12–20–008:** J. Arrington, A. Puckett, A. Tadepalli, B. Wojtsekhowski

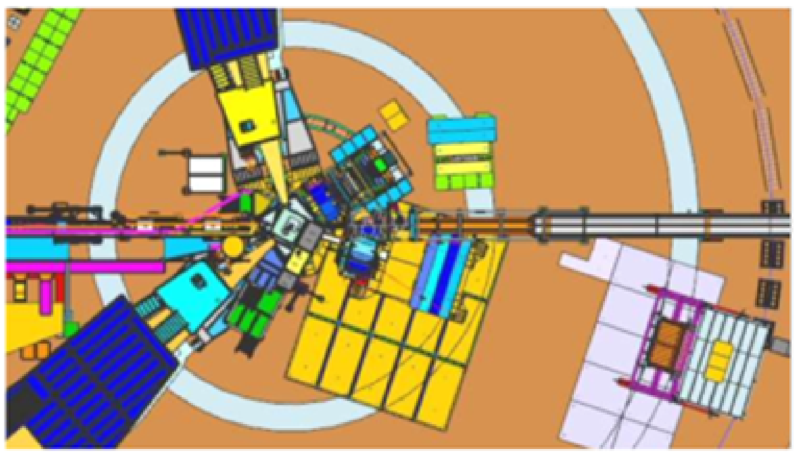
$$A_{LL}^{twist-2} = K_{LL}^{twist-2}$$

$$A_{LL}^{twist-3} = -K_{LL}^{twist-3}$$

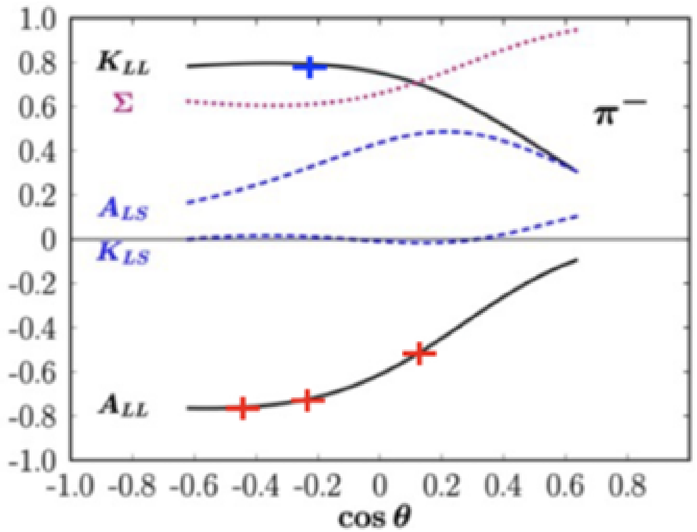
$$K_{LL} = \frac{d\sigma(+,\rightarrow) - d\sigma(-,\rightarrow)}{d\sigma(+,\rightarrow) + d\sigma(-,\rightarrow)}$$

$$A_{LL} = \frac{d\sigma(+\rightarrow) - d\sigma(-\rightarrow)}{d\sigma(+\rightarrow) + d\sigma(-\rightarrow)}$$

A_{LL} = beam and polarized target
K_{LL} = beam and outgoing nucleon



Experimental setup for A_{LL}



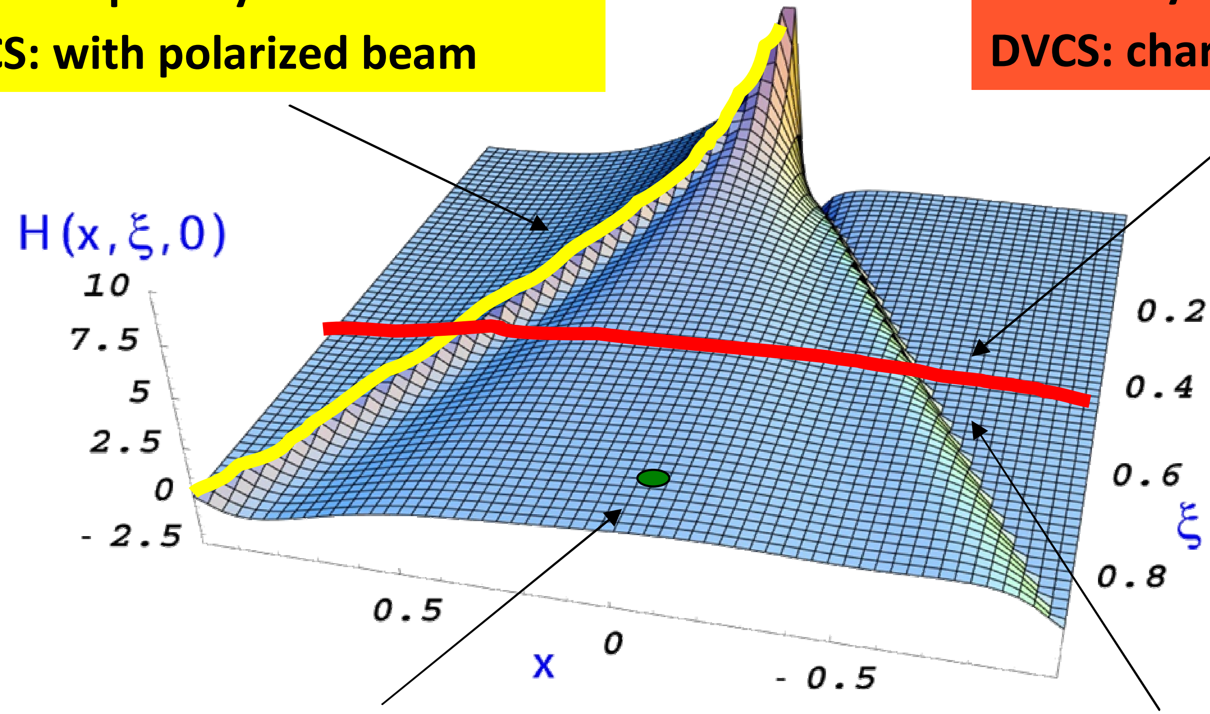
Projections for A_{LL} and K_{LL}

Garth Huber huberg@uregina.ca

Virtual Compton Processes Accessing GPDs

(Im, $x=\xi$)
DVCS: spin asymmetries
TCS: with polarized beam

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



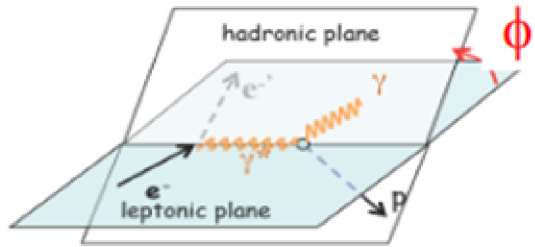
(Im, $x \neq \xi$, $x < |\xi|$)
Double DVCS

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

Garth Huber huberg@uregina.ca

DVCS – Spatial Imaging

Simplest process: **e + p → e' + p + γ (DVCS)**



$$\frac{d^4\sigma(lp \to lp\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_l \; d\sigma^{DVCS}_{pol} + e_l\left(Re(I) + P_l Im(I)\right)$$

$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

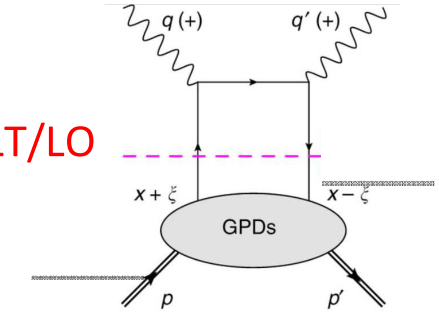
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

$$Re\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

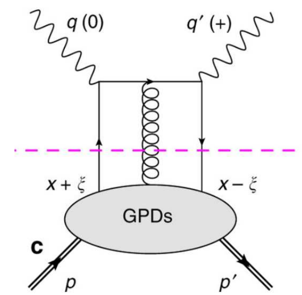
$$Im\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$

$$s_1^I = F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}$$

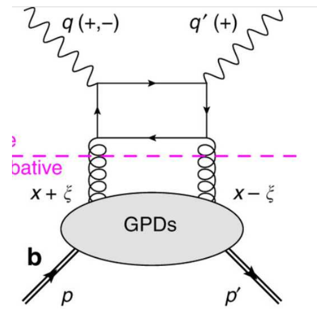
LT/LO



HT



NLO

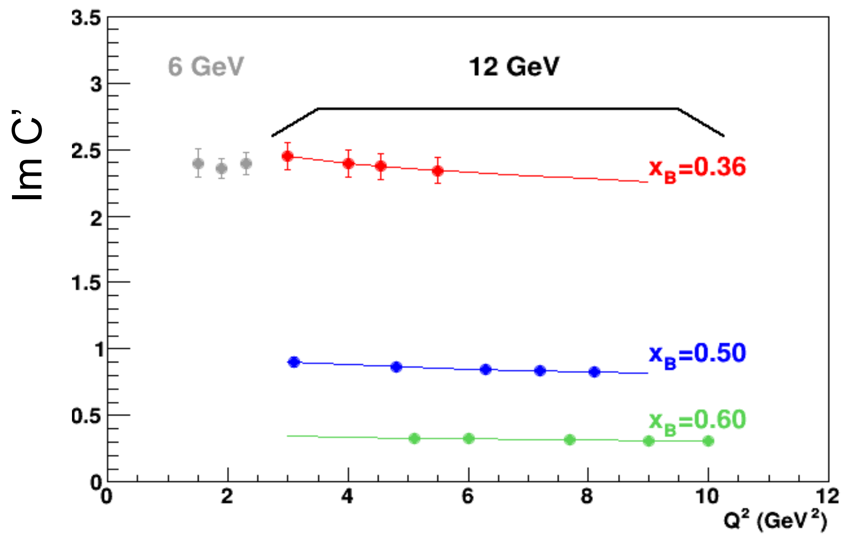


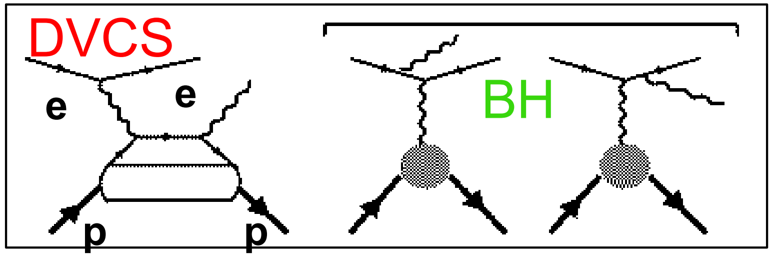
Cross-sections analysis include more or less terms:
both in terms of harmonics (c's and s's) and
In term of GPD/CFFs.

Garth Huber huberg@uregina.ca

E12–13–010 DVCS Projected Results

Garth Huber huberg@uregina.ca





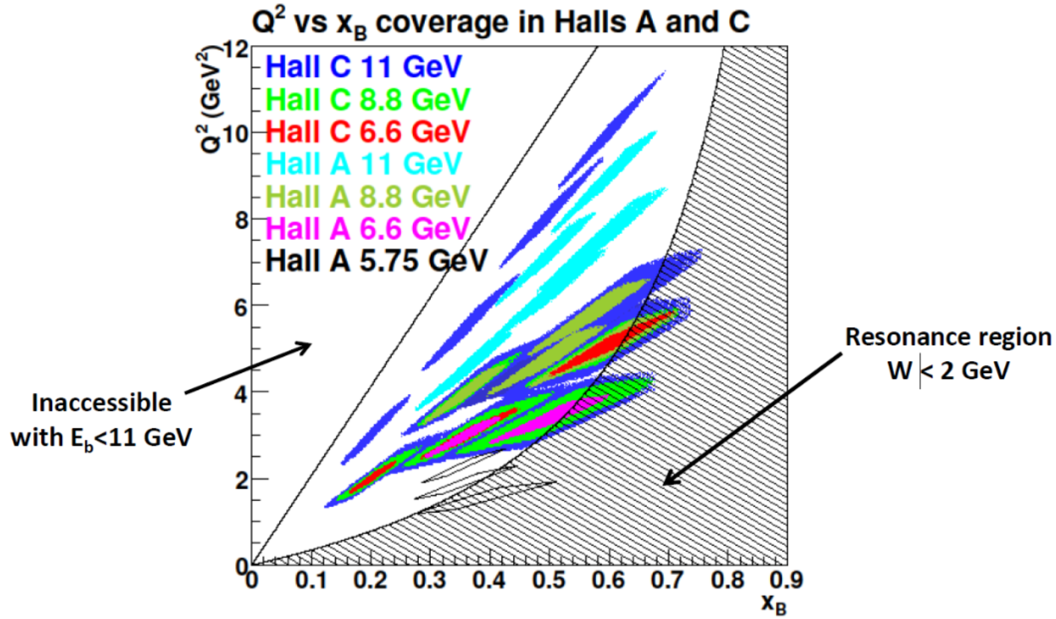
- Hall A 6 GeV data for Compton Form Factor (CFF) (over *limited* Q^2 range) agrees with hard scattering
- 12 GeV measurements in Halls A and C with NPS combined cover a large kinematic range
- Exclusive π^0 L/T–separations will probe transversity

E12–13–010 Goals:

- Confirm scaling of Compton Form Factor (CFF)
- Extraction of real part of CFFs through Rosenbluth–like separation of DVCS through cross section measurements at multiple beam energies

$$\sigma = |BH|^2 + \mathrm{Re}\left[\underbrace{DVCS^{\perp}\, BH}_{\sim E_{beam}^2}\right] + \underbrace{|DVCS|^2}_{\sim E_{beam}^3}$$

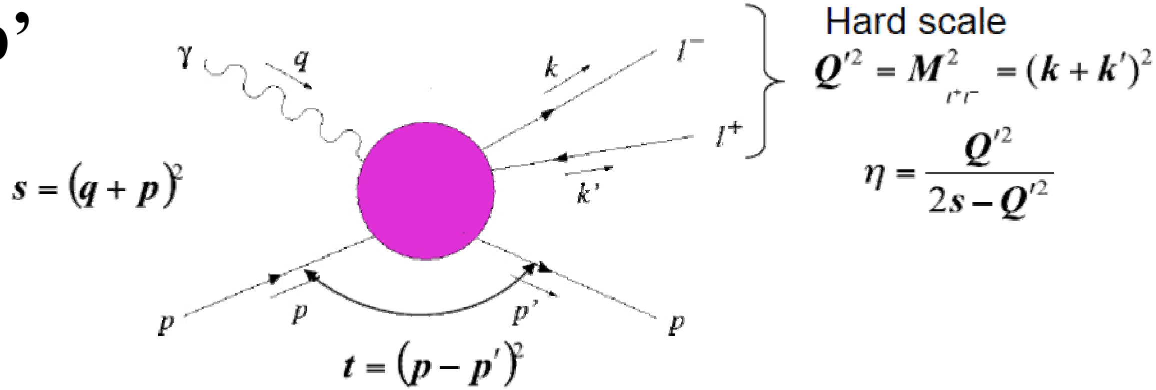
- Higher Q^2: measurement of higher twist contributions
- Low x_B extension (thanks to a sweeping magnet)



C. Munoz-Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche

Timelike Compton Scattering (TCS) with SoLID

$\gamma\, p \rightarrow e^+ e^- p'$



At LO, TCS and (spacelike) DVCS CFFs are equivalent, but at NLO there is a non–trivial difference

$$ {}^T\mathcal{H} \overset{\text{LO}}{=} {}^S\mathcal{H}^*, $$

$$ {}^T\widetilde{\mathcal{H}} \overset{\text{LO}}{=} -{}^S\widetilde{\mathcal{H}}^*, $$

$$ {}^T\mathcal{H} \overset{\text{NLO}}{=} {}^S\mathcal{H}^* - i\pi\,\mathcal{Q}^2 \frac{\partial}{\partial \mathcal{Q}^2}\,{}^S\mathcal{H}^*, $$

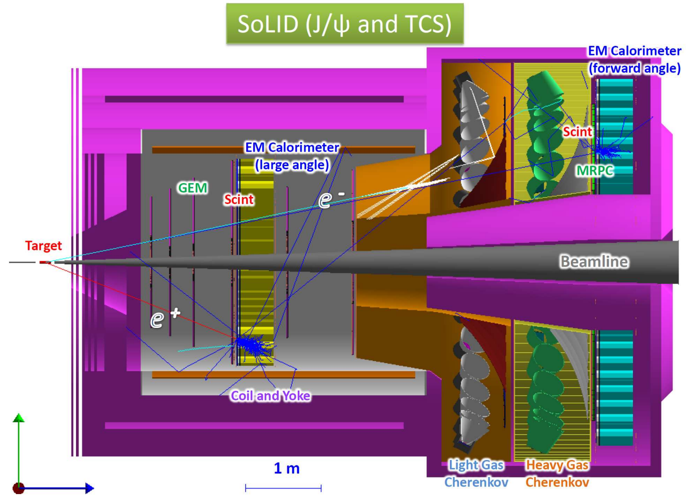
$$ {}^T\widetilde{\mathcal{H}} \overset{\text{NLO}}{=} -{}^S\widetilde{\mathcal{H}}^* + i\pi\,\mathcal{Q}^2 \frac{\partial}{\partial \mathcal{Q}^2}\,{}^S\widetilde{\mathcal{H}}^*. $$

- **A comparison of TCS and (spacelike) DVCS offers the best way of demonstrating the universality (process-independence) of GPDs**
  - Analogous to the way a comparison of (timeline) Drell–Yan and (spacelike) DIS was used to establish the universality of PDFs
- **NLO corrections are different for TCS and DVCS**
  - NLO is important at low x (EIC)
  - Higher-twist is important at low Q^2 (JLab)
  - Measurements in both kinematics will help
- **TCS is sensitive to the real part and the D–term**
  - Pressure balance in the nucleon

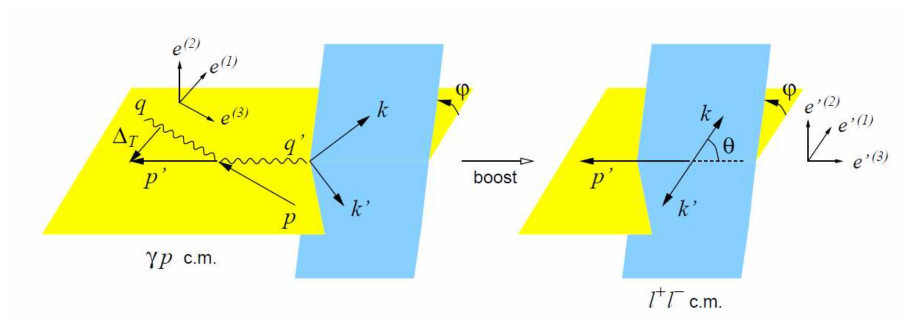
Garth Huber huberg@uregina.ca

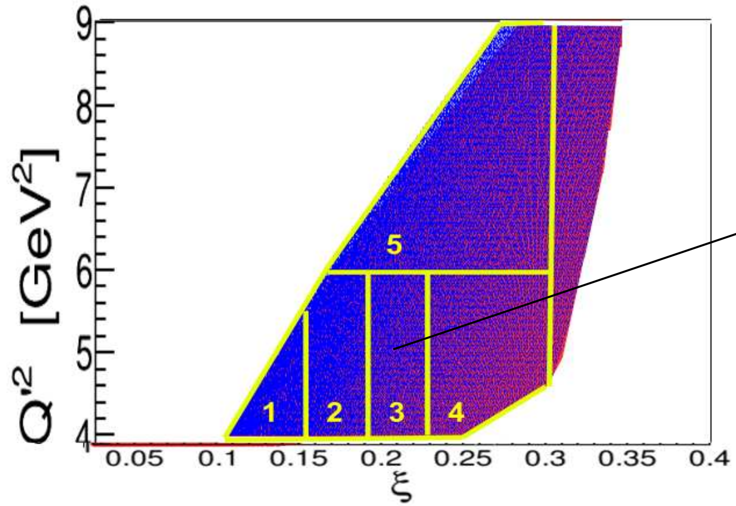
TCS E12–12–006A Projected Results

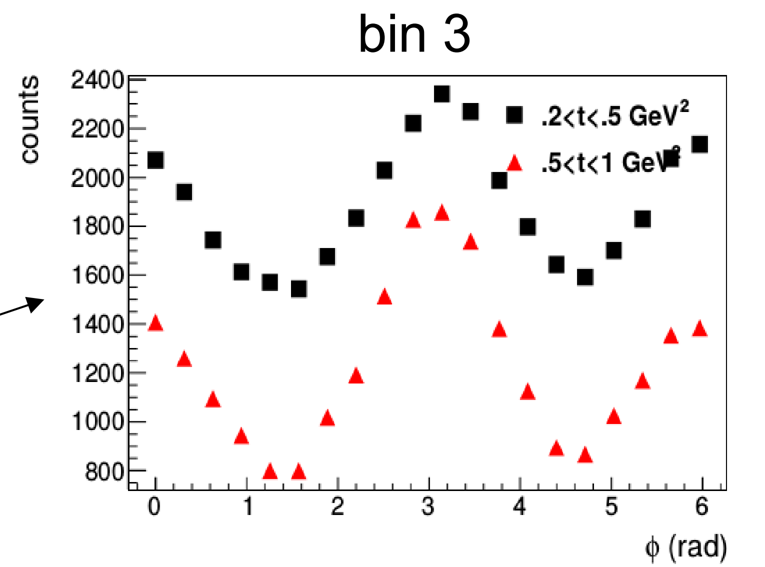
SoLID setup for J/ψ approved expt.
50 days at flux 10^{37} $cm^{-2}s^{-1}$ LH2 unpolarized target



x-sec and BSA with high statistics
→ binning in Q'²: evolution...
→ study GPD universality by comparing TCS vs DVCS







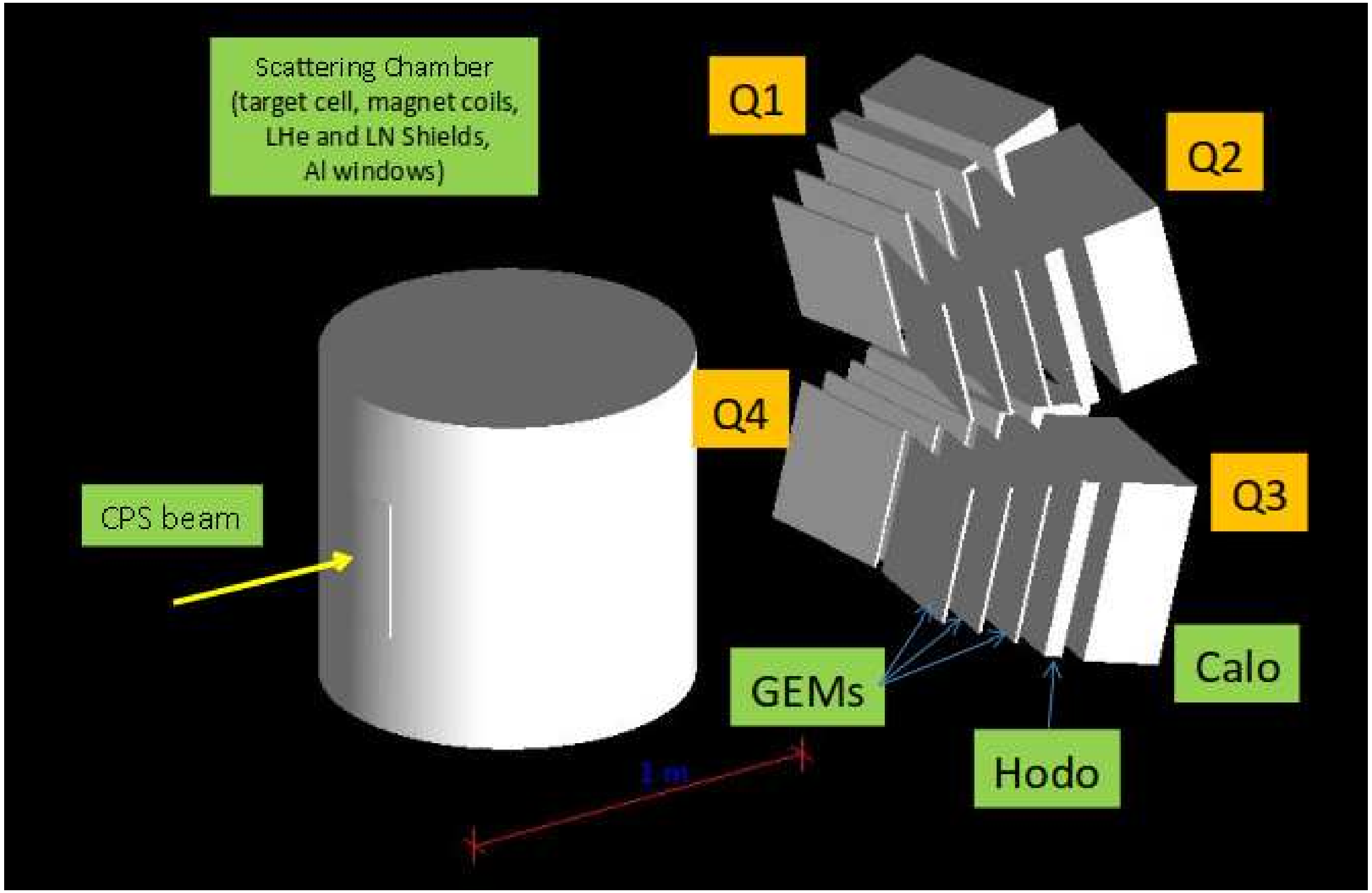
statistics in 2 bins in t, bin #3 (Q'², ξ)

Boër, Nadel-Turonski, Zhang, Zhao: run group E12-12-006A

Garth Huber huberg@uregina.ca

Transversely polarized TCS in Hall C

$$\gamma\, p \rightarrow e^{+}\, e^{-}\, p'$$



1. High intensity photon source 1.5×10^{12} γ/sec (CPS)

2. Target chamber: NH_3, 3cm Polarized via DNP

3. Tracking: GEM+hodoscopes, 4 symmetric quadrants

4. Calorimeters: 4 symmetric quadrants, equivalent of 2 NPS

~ 6° to 27° aperture
Lumi request: 5.85×10^{5} pb^{-1}

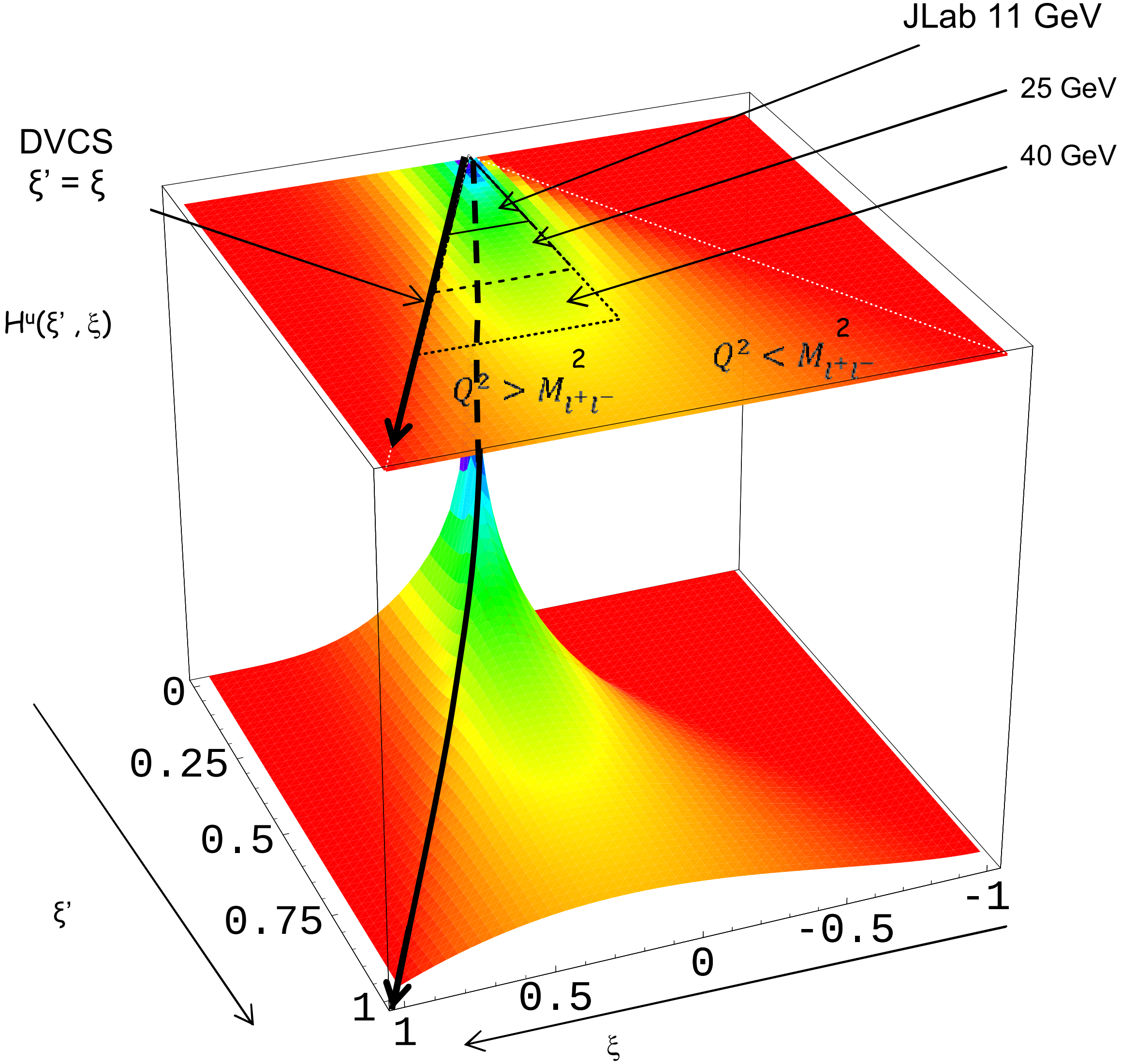
C12-15-005 (deferred in 2022, asked for more simulations): Boër, Camsonne, Keller, Tadevosyan

Garth Huber huberg@uregina.ca

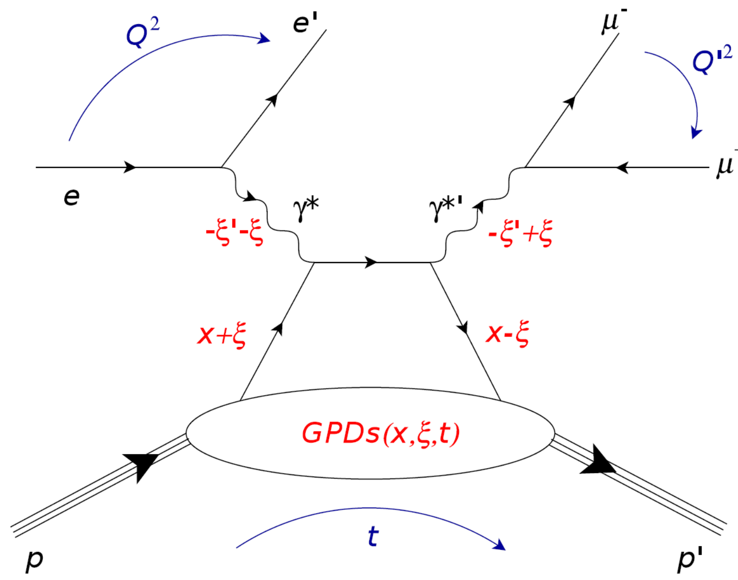
Double Deeply Virtual Compton Scattering (DDVCS)

Garth Huber huberg@uregina.ca

$$\gamma^* + p \rightarrow \gamma^{*\prime} + p' \rightarrow l^+ + l^- + p'$$



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

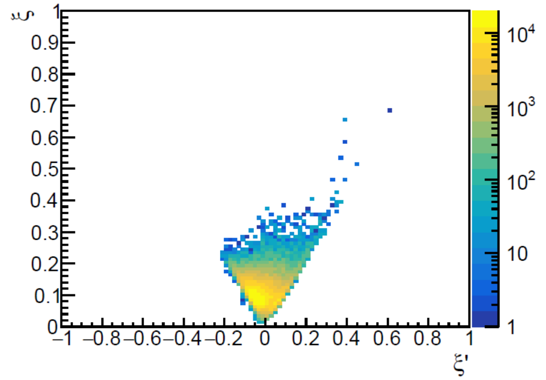


$$\xi' = \frac{Q^2 - Q'^2 + t/2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

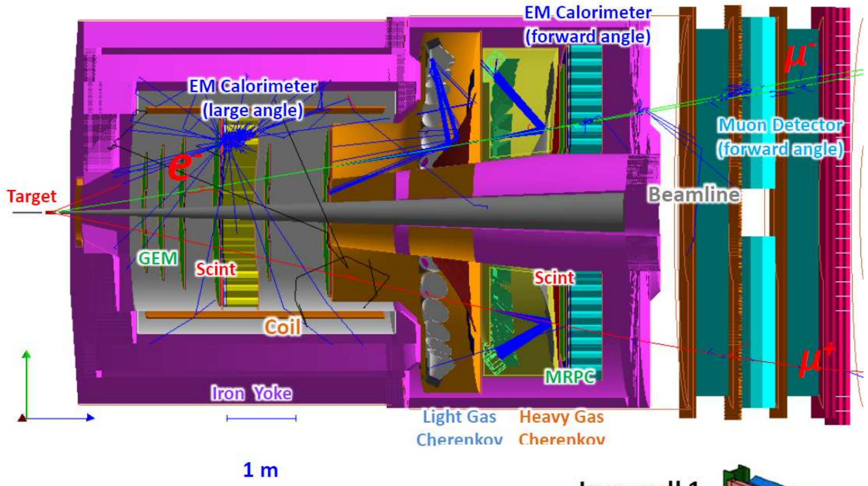
$$\xi = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

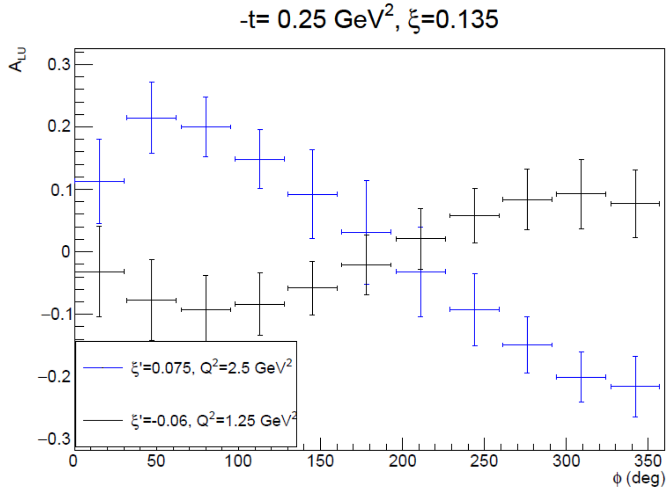
Projections for DDVCS with SoLID

- **Goal:** Beam spin asymmetry to go "off diagonal", extrapolation of GPD to zero skewness purely coming from interference between BH(1+2)*DDVCS
- Change of sign to be observed in different kinematic regions
- SoLID completed with muon detectors at forward angle, enables DDVCS measurements with both polarized electron and positron beams at 11 GeV

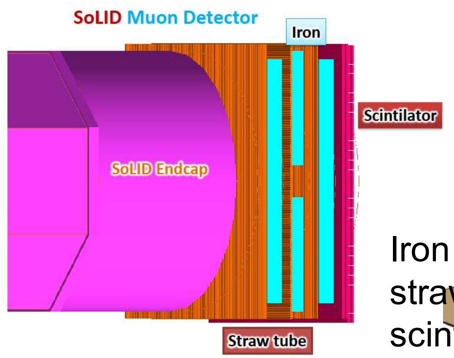


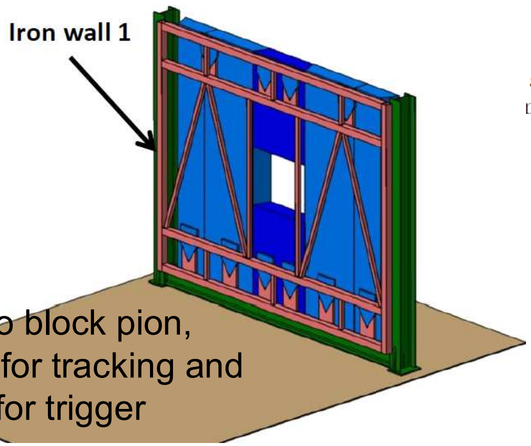
SoLID DDVCS





50 days of electron BSA (stat error only)





Iron plate to block pion, straw tube for tracking and scintillator for trigger

asymmetry as a function of ϕ angle for a bin centered at ξ=0.135 and t = -0.25 GeV^2
nd ξ', one can notice the sign change of asymmetry when ξ' changes from negative to

$$A^{\pm}_{LU}(\phi) = \frac{1}{\lambda^{\pm}}\frac{d^5\sigma^{\pm}_{+} - d^5\sigma^{\pm}_{-}}{d^5\sigma^{\pm}_{+} + d^5\sigma^{\pm}_{-}} \quad (15)$$

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

S. Zhao, EPJ A 57 (2021) 240

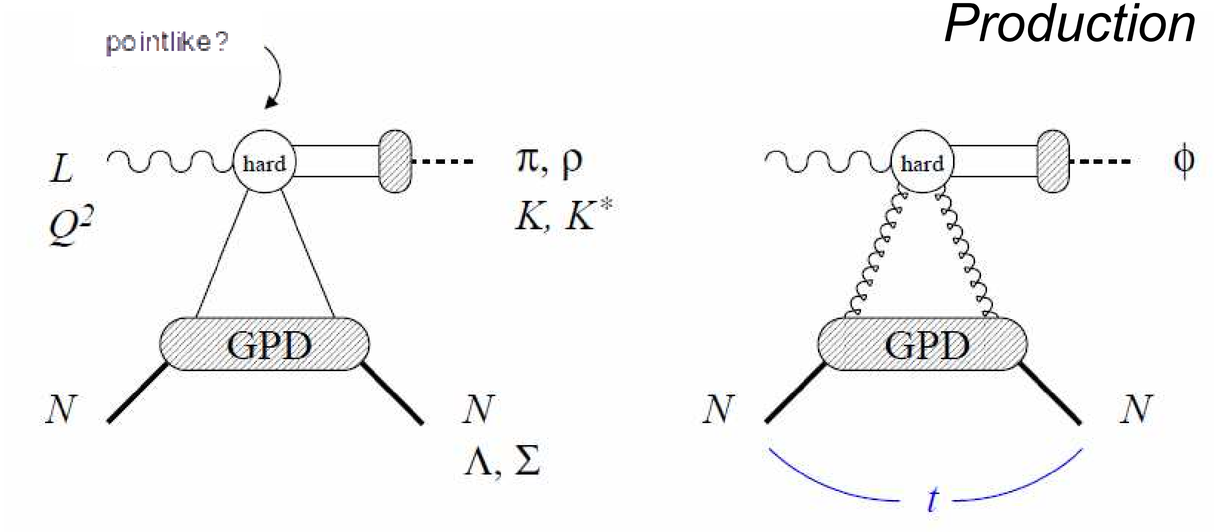
LOI12–15–005 (M. Boer, A. Camsonne, K. Gnanvo, E. Voutier, Z.W. Zhao et al.)

Garth Huber huberg@uregina.ca

Towards Spin/Flavor Separation

Exclusive Reactions: $\gamma^* N \rightarrow M + B$

Deep Exclusive Meson Production (DEMP)



- Nucleon structure described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarized), $\tilde{H}, \tilde{E}$ (polarized)

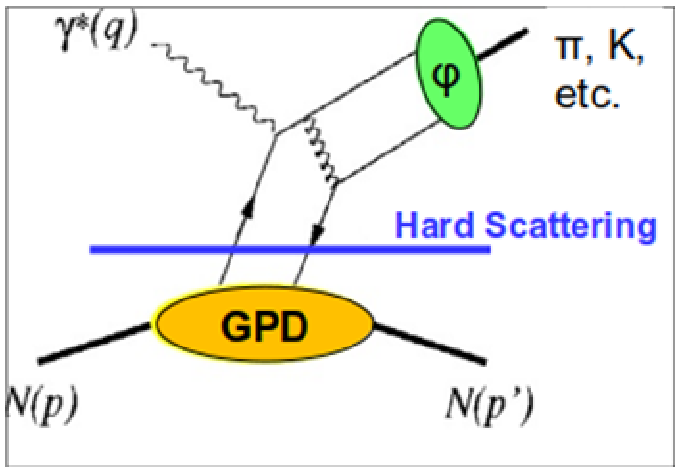
- Quantum numbers in DEMP probe individual GPD components selectively
  - Vector: ρ^o / ρ^+ / K* select *H*, *E*
  - Pseudoscalar: π, η, K select the polarized GPDs, $\tilde{H}$ and $\tilde{E}$

- Need good understanding of reaction mechanism
  - QCD factorization for mesons
  - Can be verified experimentally through L/T separated cross sections

Garth Huber huberg@uregina.ca

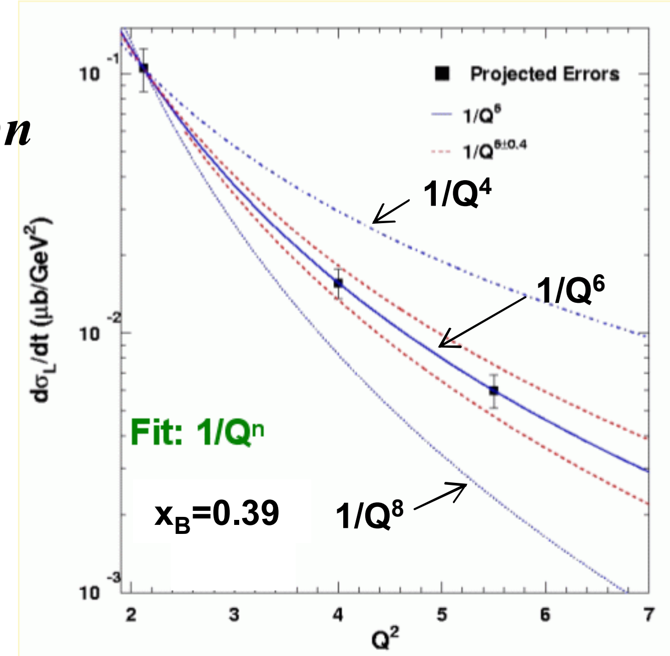
Factorization Tests in π^+ and K⁺ Electroproduction

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



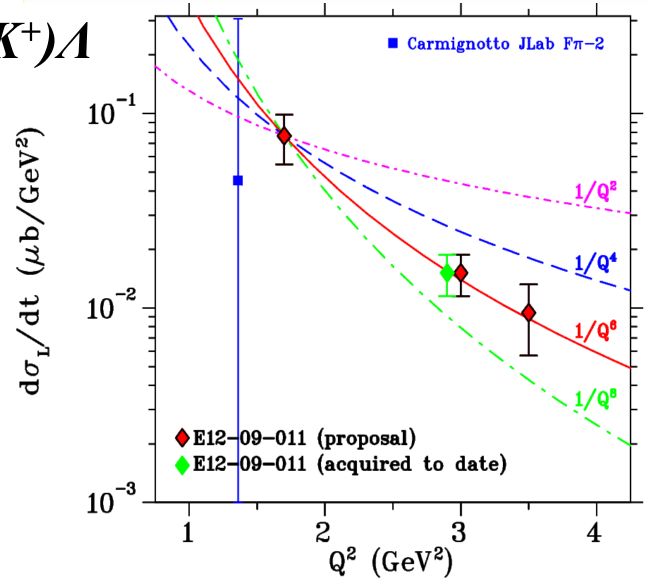
- **One of the most stringent tests of factorization is the Q^2 dependence of π and K cross sections**
  - σ_L scales to leading order as Q^{-6}
- **Experimental validation of factorization essential for reliable interpretation of results from the JLab GPD program at 12 GeV for meson electro–production**
  - K and π together provide quasi model–independent study

p(e,e'π⁺)n



E12–19–006 Projections

p(e,e'K⁺)Λ



E12–09–011 Projections

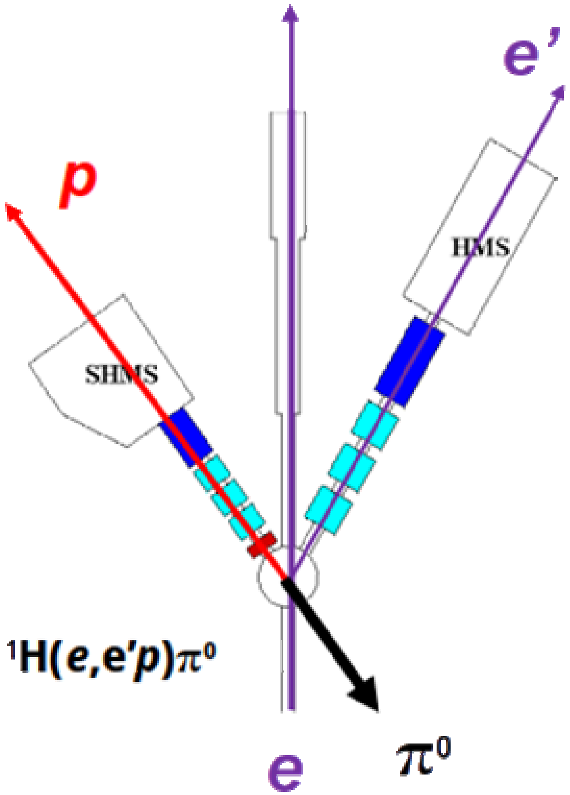
Garth Huber huberg@uregina.ca

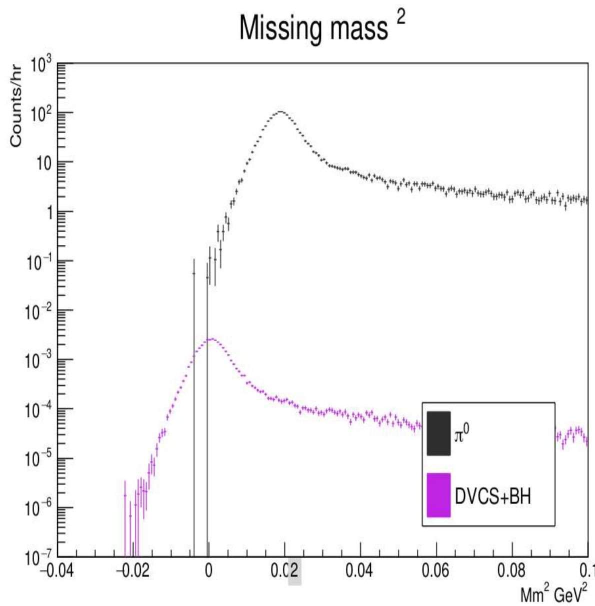
Hard–Soft Factorization in Backward Exclusive π^0

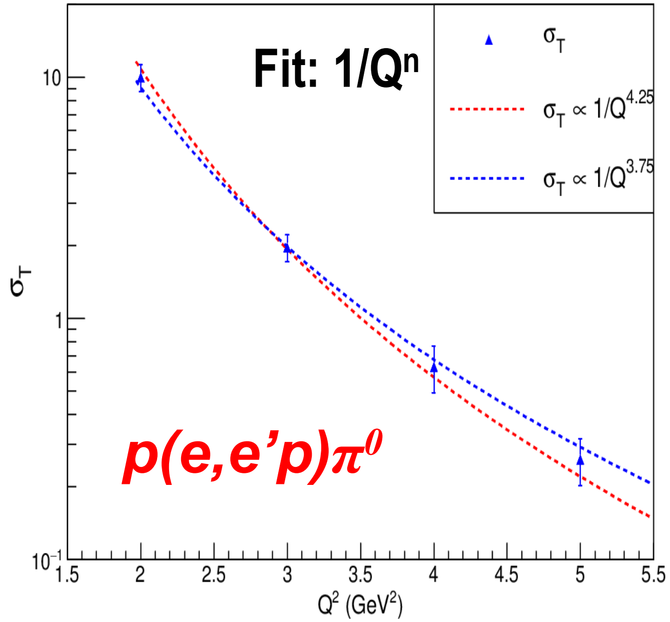
Extension of collinear factorization to u–channel

- Proposed by Frankfurt, Polykaov, Strikman, Zhalov, Zhalov [arXiv:hep-ph/0211263]
- Transition Distribution Amplitude (TDA) formalism by: B. Pire, K. Semenov–Tian–Shansky, L. Szymanowski, Phys. Rep. **920**(2021)1

Garth Huber huberg@uregina.ca







E12–20–007: W.B. Li, G.M. Huber, J. Stevens (spokespersons)

- **First *dedicated u*–channel electroproduction study above resonance region:**
  - Demonstrate existence of far backward u–channel cross section peak
  - Q^{-n} scaling behavior of $d\sigma_T/dt$
  - u–dependence of L/T separated cross sections

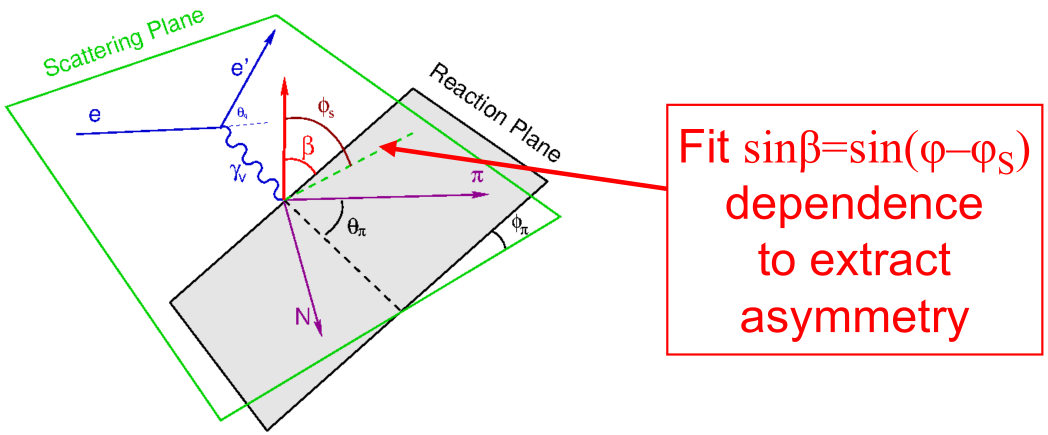
Exclusive π^- from Transversely Polarized Neutron

- Probe GPD $\tilde{E}$ with DEMP

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

  - *GPD $\tilde{E}$ is not related to any already known parton distribution*
  - *$G_P(t)$ is highly uncertain because it is negligible at the momentum transfer of β–decay*
  - *Experimental measurements can provide new nucleon structure information unlikely to be available from any other source*

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



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

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

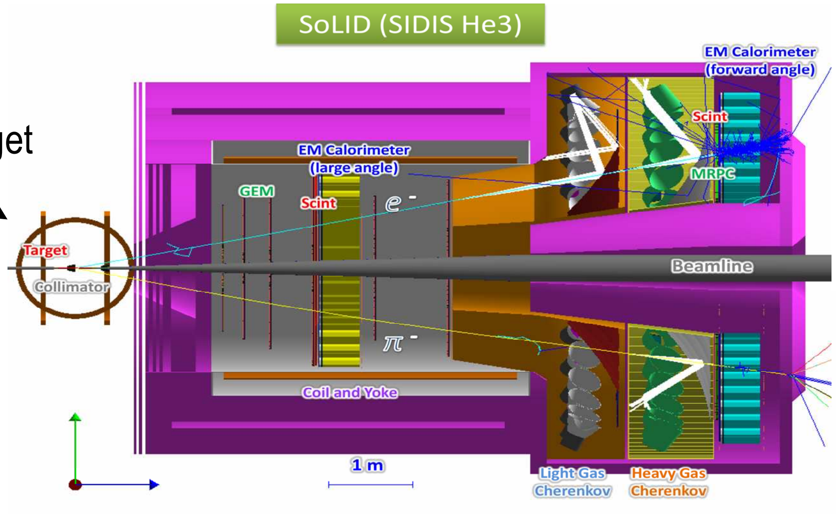
Theoretical calculations suggest higher twist corrections, which may be significant at low Q^2 for σ_L, likely cancel in $A_\perp$

- **May allow access to GPDs at Q^2~4 GeV^2 while Q^2>10 GeV^2 needed for σ_L**

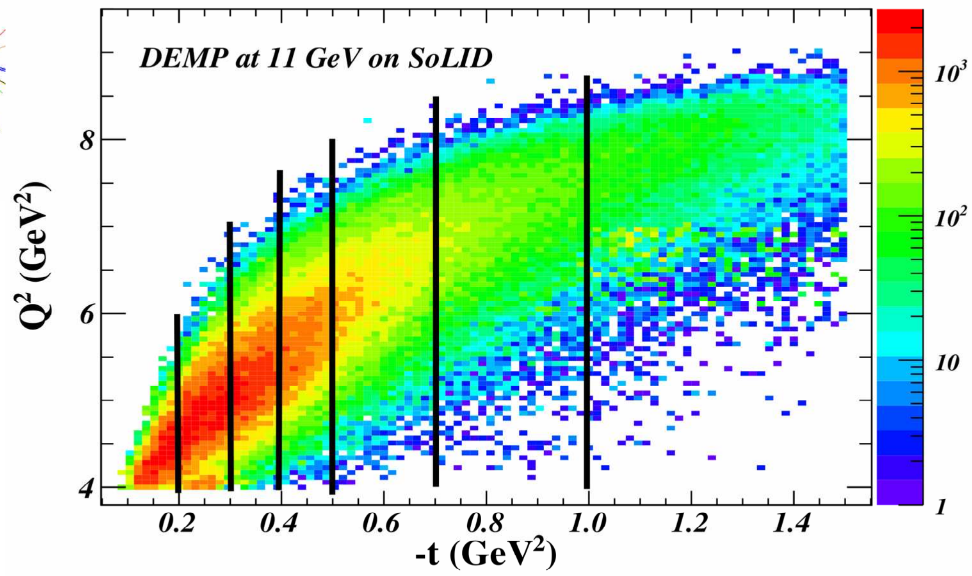
Garth Huber huberg@uregina.ca

Projections for Polarized $n(e,e'\pi^-)p$ with SoLID

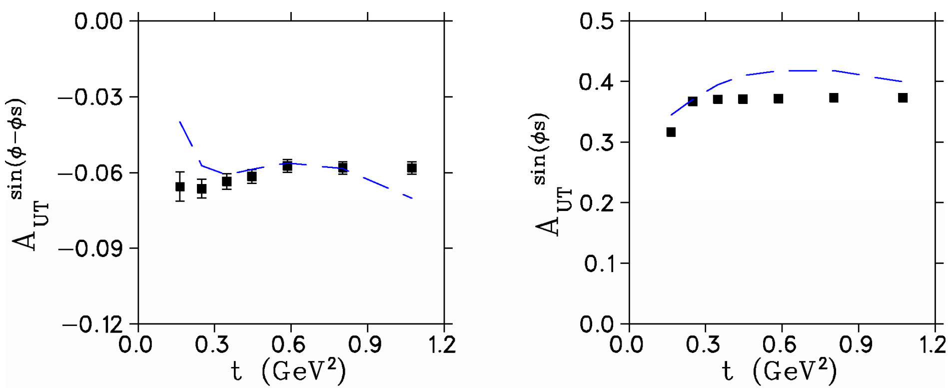
Transversely polarized ^{3}He (neutron) target



Projected E12–10–006B data
→ analyze 2–track (e' π^-) data offline for recoil proton track



- Data divided in 7 *t*–bins concentrating on Q^2>4 GeV^2 region of greatest physics interest
- $A_{UT}^{sin(\varphi-\varphi S)}$ and $A_{UT}^{sin(\varphi S)}$ asymmetries can be extracted from same data, providing powerful additional GPD model constraints
- Dramatic improvement in kinematic coverage and statistics compared to pioneering HERMES data at lower Q^2

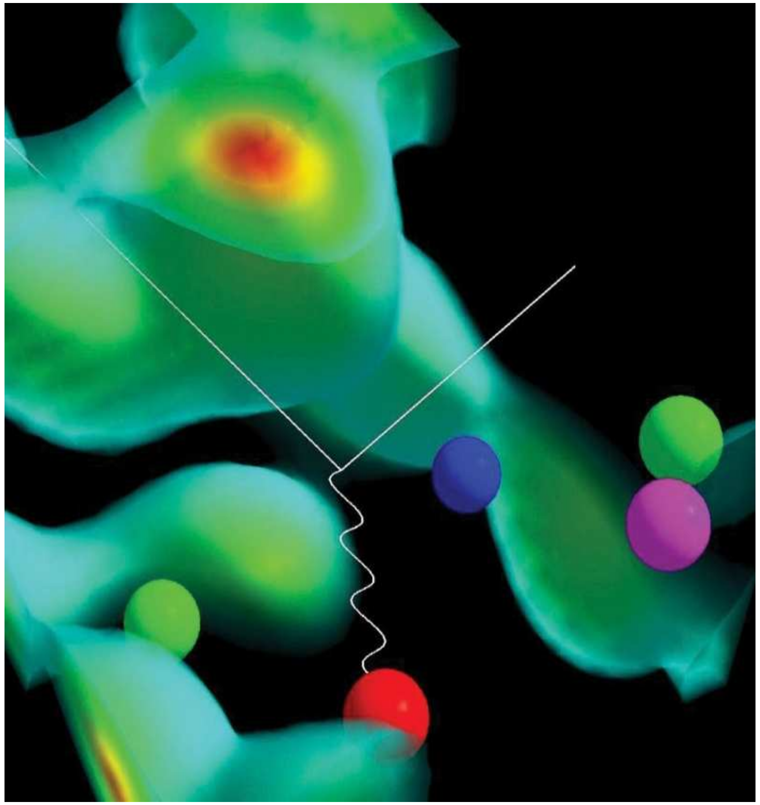


E12–10–006B: G.M. Huber, Z. Ye, Z. Ahmed (spokespersons)

Garth Huber huberg@uregina.ca

Summary – The Big Problem

- **One of the top 10 unsolved problems in physics is our poor understanding of how quark and gluon interactions give rise to the observed properties of mesons and nucleons**



Lattice QCD simulation of the quark and gluon "color field" inside the nucleon, being probed by a deep electron scattering, D. Leinweber & W. Detmold, CSSM Adelaide.

- Deep Exclusive electron scattering reactions provide a clearer picture of the inner workings of QCD (the theory of strong interactions in the Standard Model)
- Rich science program of 1D–3D hadron structure enabled with 12 GeV and Halls A/C equipment

Garth Huber huberg@uregina.ca

Garth Huber huberg@uregina.ca

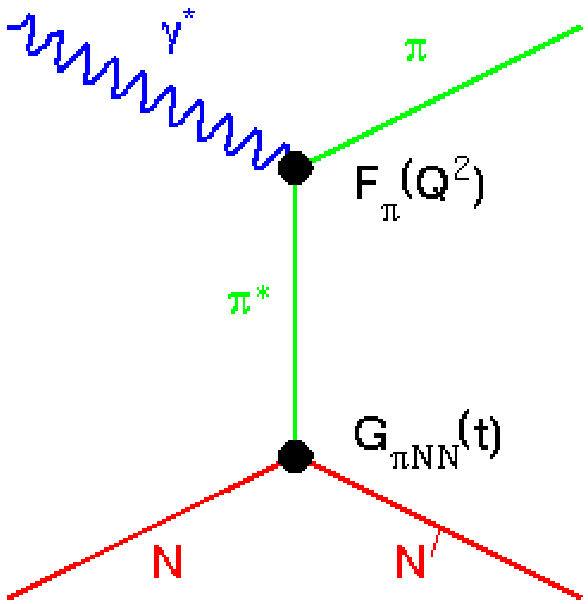
Measurement of F_π via Electroproduction

Above Q^2>0.3 GeV^2, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2,t)$$



Drawbacks of this technique:

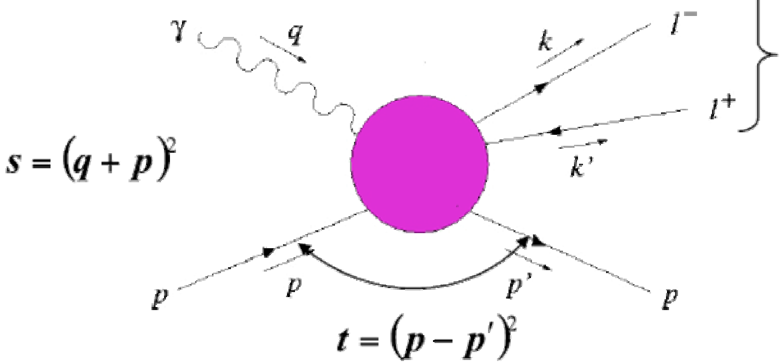
1. Isolating σ_L experimentally challenging.
2. The F_π values are in principle dependent upon the model used, but this dependence is expected to be reduced at sufficiently small $-t$.

Garth Huber huberg@uregina.ca

Timelike Compton Scattering (TCS) at SoLID

As a key reaction for studying GPDs, SoLID TCS will have

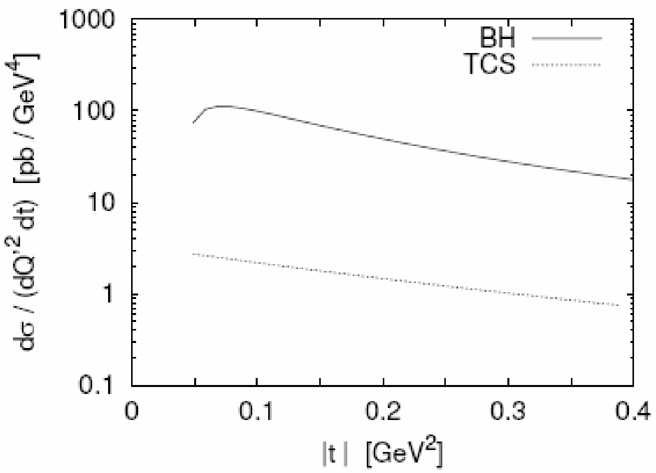
- Unpolarized data access to the real part of CFFs, sensitive to the D–term in GPD parametrization with observables cross section ratio (R) and forward backward asymmetry (A_{FB})
- Circularly polarized data access to imaginary part of CFFs with BSA (similar to DVCS) to study universality



Hard scale

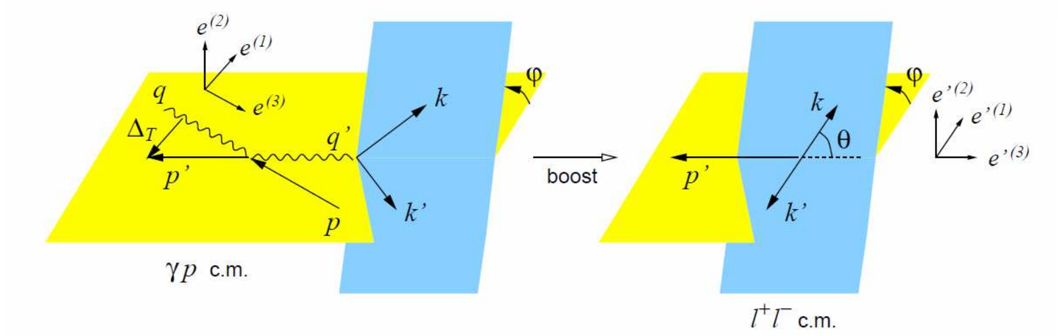
$$Q'^2 = M^2_{l^+l^-} = (k + k')^2$$

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



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

$\gamma\, p \rightarrow e^+ e^- p'$



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

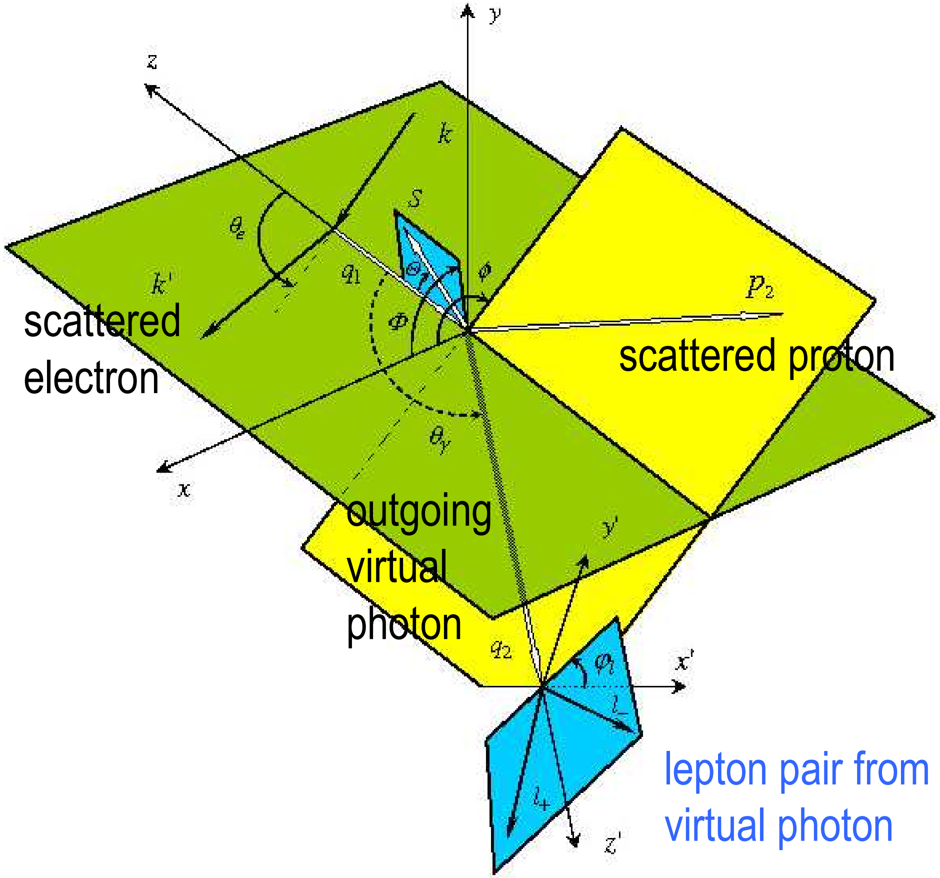
$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ - \theta, 180^\circ + \phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ - \theta, 180^\circ + \phi)}$$

Garth Huber huberg@uregina.ca

Double Deeply Virtual Compton Scattering (DDVCS)

Garth Huber huberg@uregina.ca

$$\gamma^* + p \rightarrow \gamma^{*\prime} + p' \rightarrow l^+ + l^- + p'$$



$p = p1+p2$

$q = \frac{1}{2}(q1+q2)$

$\Delta = p1 - p2 = q2 - q1$

$$\eta = \frac{\Delta . q}{p.q}$$

$$Q^2 = -(k-k')^2$$

$$\xi = \frac{Q^2}{2p.q}$$

$$x_{bj} = \frac{Q^2}{2p_1 q_1}$$

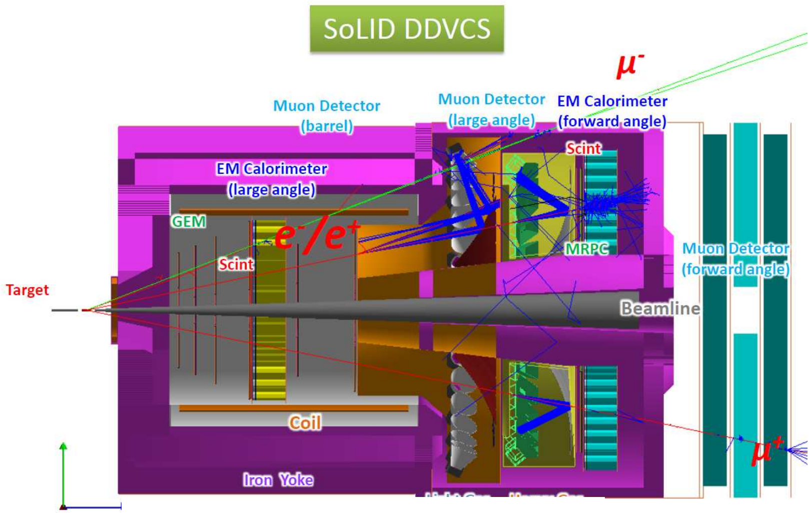
$$\left\{ \begin{matrix} A_{\mathrm{LU}}^{\sin\phi} \\ A_{\mathrm{LU}}^{\sin\varphi_\mu} \end{matrix} \right\} = \frac{1}{\mathcal{N}} \int_{\pi/4}^{3\pi/4} d\theta_\mu \int_0^{2\pi} d\varphi_\mu \int_0^{2\pi} d\phi \left\{ \begin{matrix} 2\sin\phi \\ 2\sin\varphi_\mu \end{matrix} \right\} \frac{d^7\overrightarrow{\sigma} - d^7\overleftarrow{\sigma}}{dx_B\, dy\, dt\, d\phi\, dQ'^2\, d\Omega_\mu}$$

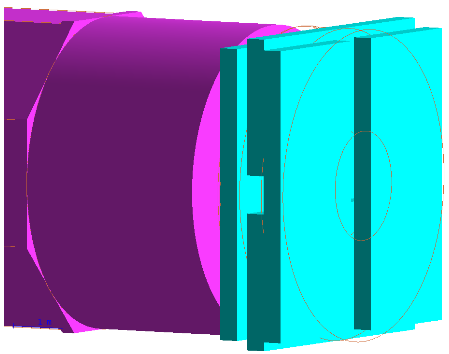
$$\propto \Im\mathrm{m} \left\{ F_1 \mathcal{H} - \frac{t}{4M_N^2} F_2 \mathcal{E} + \xi (F_1 + F_2) \widetilde{\mathcal{H}} \right\},$$

Belitsky Radyushkin : Unraveling hadron structure with generalized parton distributions (arXiv:hep-ph/0504030v3 27 Jun 2005)

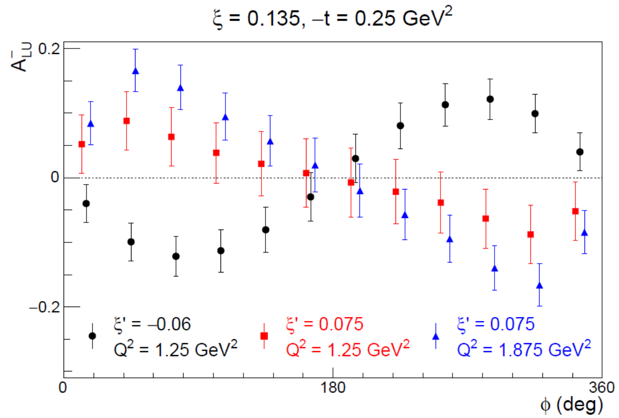
Projections for DDVCS with SoLID

- **Goal:** Beam spin asymmetry to go “off diagonal”, extrapolation of GPD to zero skewness purely coming from interference between BH(1+2)*DDVCS
- Change of sign to be observed in different kinematic regions
- SoLID apparatus, completed with muon detectors at forward and large angles and barrel, enables DDVCS measurements with both polarized electron and positron beams at 11GeV

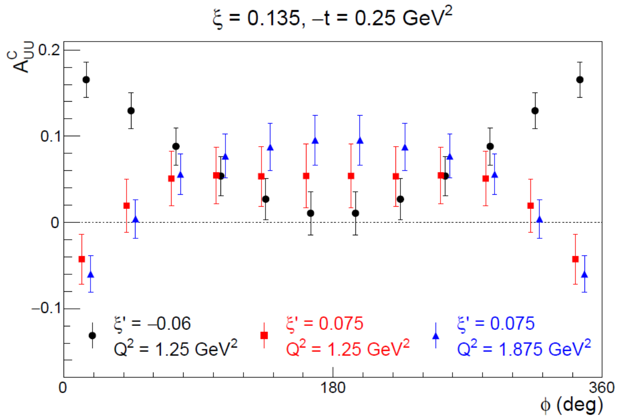




Iron plate for forward angle muon detector



50 days of electron BSA



plus 50 days of positron BCA

S. Zhao, EPJ A 57 (2021) 240

LOI12–15–005 (M. Boer, A. Camsonne, K. Gnanvo, E. Voutier, Z.W. Zhao et al.)

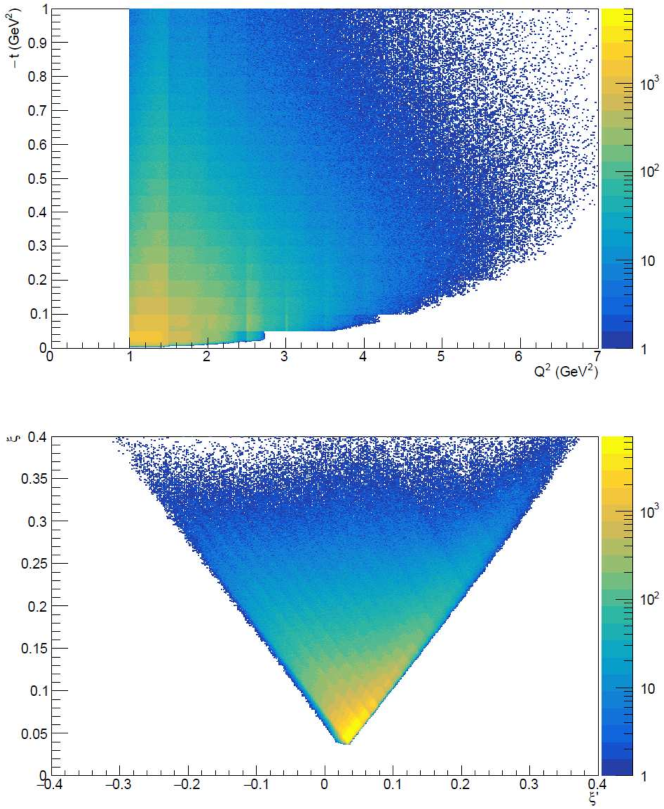
$$A^{\pm}_{LU}(\phi) = \frac{1}{\lambda^{\pm}} \frac{d^5\sigma^{\pm}_{+} - d^5\sigma^{\pm}_{-}}{d^5\sigma^{\pm}_{+} + d^5\sigma^{\pm}_{-}} = \frac{d^5\widetilde{\sigma}_{DDVCS} \mp d^5\widetilde{\sigma}^{\mathrm{INT1}}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} \mp d^5\sigma_{INT_1}} \quad (15)$$

$$A^{C}_{UU}(\phi) = \frac{(d^5\sigma^{+}_{+} + d^5\sigma^{+}_{-}) - (d^5\sigma^{-}_{+} + d^5\sigma^{-}_{-})}{d^5\sigma^{+}_{+} + d^5\sigma^{+}_{-} + d^5\sigma^{-}_{+} + d^5\sigma^{-}_{-}} = \frac{d^5\sigma_{INT_1}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS}}$$

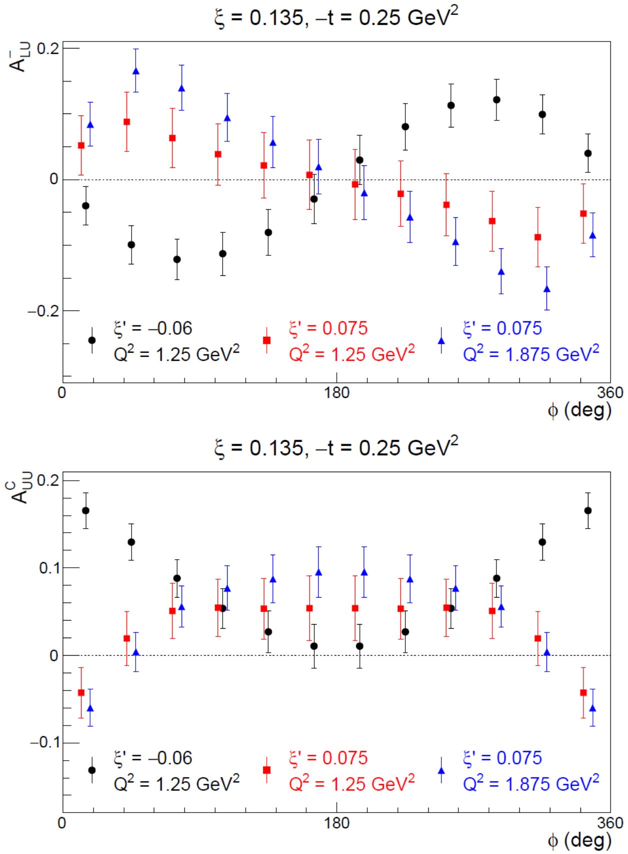
Garth Huber huberg@uregina.ca

DDVCS with 11GeV circular polarized beam and LH2 target

coverage



projection



50 days of electron BSA

plus 50 days of positron BCA

$$A^{\pm}_{LU}(\phi) = \frac{1}{\lambda^{\pm}} \frac{d^5\sigma^{\pm}_{+} - d^5\sigma^{\pm}_{-}}{d^5\sigma^{\pm}_{+} + d^5\sigma^{\pm}_{-}} \quad (15)$$
$$= \frac{d^5\tilde{\sigma}_{DDVCS} \mp d^5\tilde{\sigma}^{\mathrm{INT1}}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} \mp d^5\sigma_{INT_1}}$$

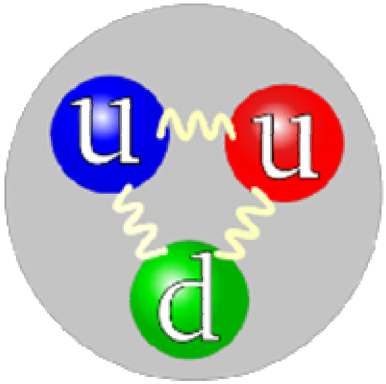
$$A^{C}_{UU}(\phi) = \frac{(d^5\sigma^{+}_{+} + d^5\sigma^{+}_{-}) - (d^5\sigma^{-}_{+} + d^5\sigma^{-}_{-})}{d^5\sigma^{+}_{+} + d^5\sigma^{+}_{-} + d^5\sigma^{-}_{+} + d^5\sigma^{-}_{-}}$$
$$= \frac{d^5\sigma_{INT_1}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS}}$$

EPJA 57, 240 (2021)

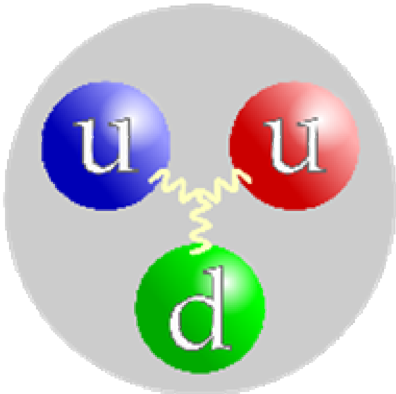
Garth Huber huberg@uregina.ca

Exclusive u–Channel Meson Production

Which proton picture is more correct?



A



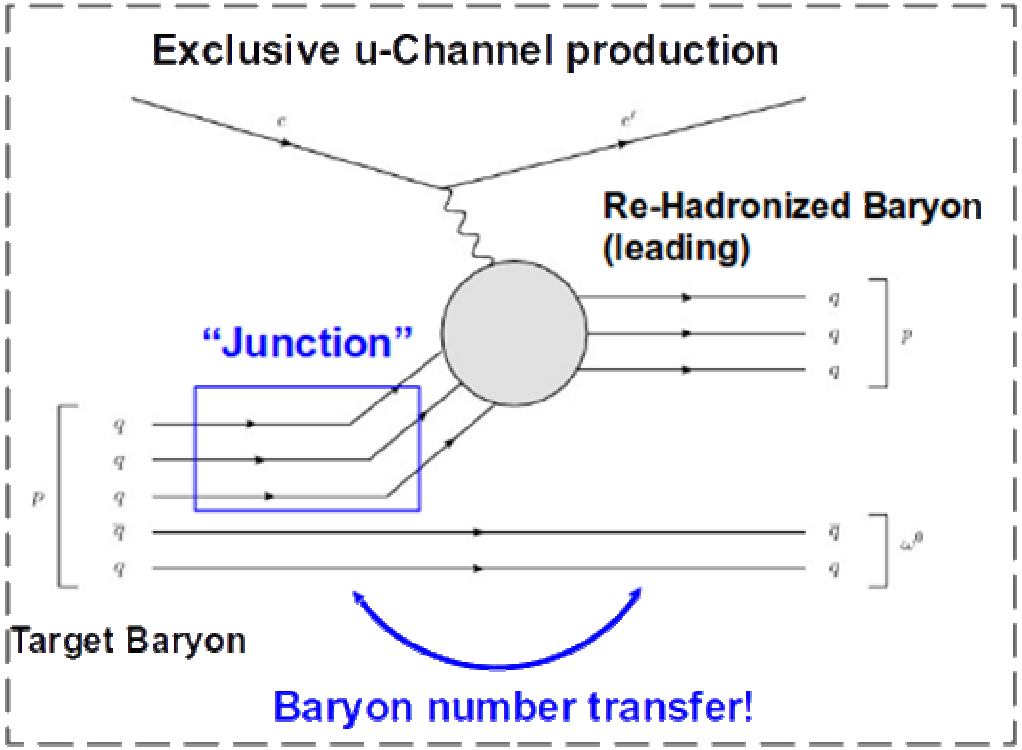
B

A: implies quark carries fractional baryon number

B: existence of a **"Junction" like structure** that carries the whole baryon number (D. Kharzeev, https://arxiv.org/abs/nucl-th/9602027, 1996)

How do we probe this at JLab 12 GeV?

- Can we directly probe the "junction" structure?
- May be. If manage to force the transfer of baryon number in the target and recoil particles, then Yes.



Garth Huber huberg@uregina.ca