Accessing GPDs in High Energy Exclusive Processes

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Outline

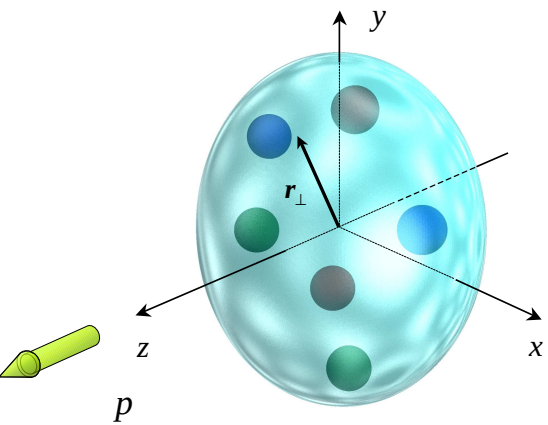
1. Very brief experimental introduction to GPDs
   (and how they can be accessed through DVCS)

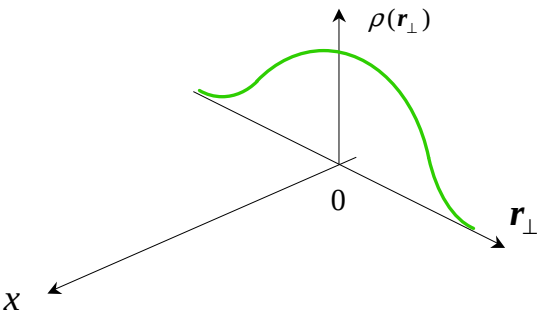
2. Selection of recent results (2015–2016):
   - Recent DVCS results (2015) published from both Hall A & B
   - New results on L/T separated π^0 cross section from Hall A
   - Preliminary results from Compass 2012 pilot run (DVCS & π^0)

3. Outlook:
   - Jefferson Lab at 12 GeV

Studying nucleon structure experimentally

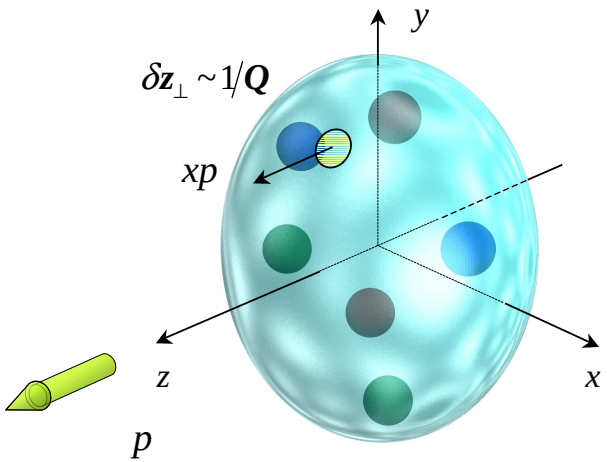
Elastic scattering

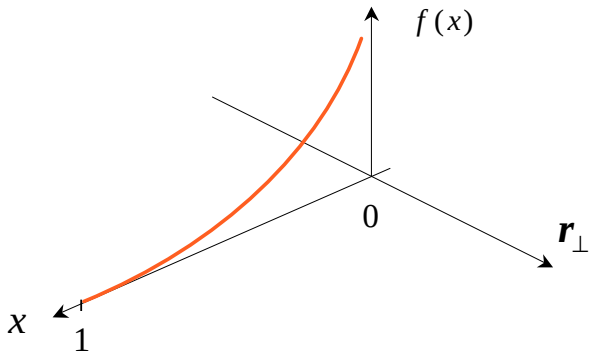




Form factors

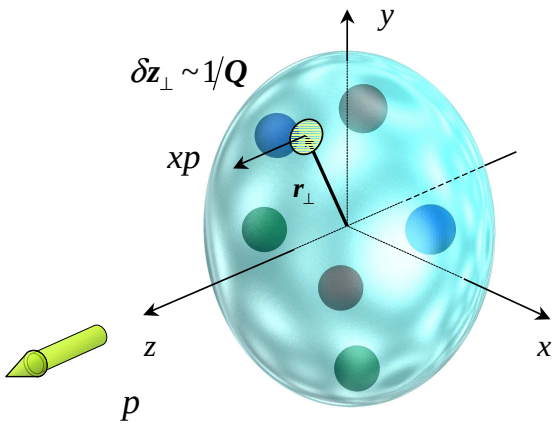
Deep inelastic scattering

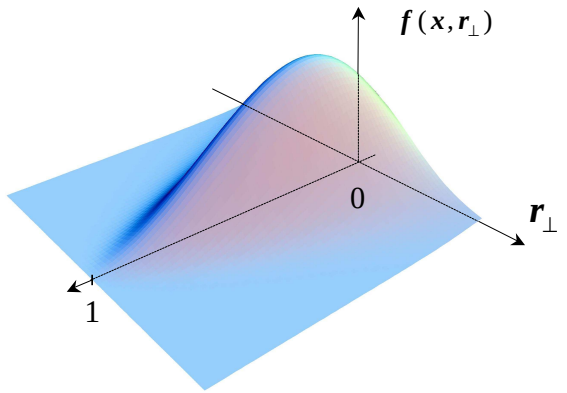




Parton distributions

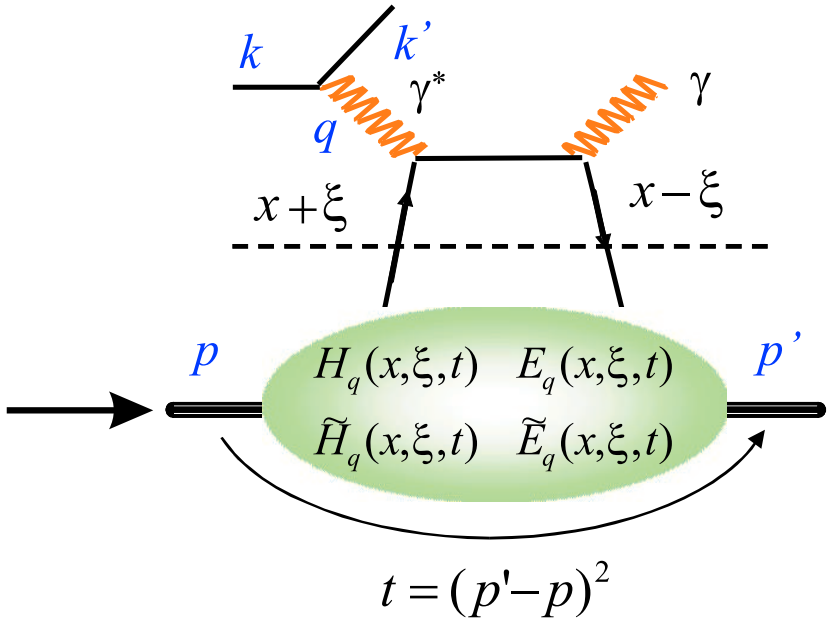
Hard exclusive processes





Generalized Parton Distributions (GPDs)

Deeply Virtual Compton Scattering (DVCS): $\gamma^* p \to \gamma p$



Handbag diagram

High Q^2
Perturbative QCD

Non-perturbative
GPDs

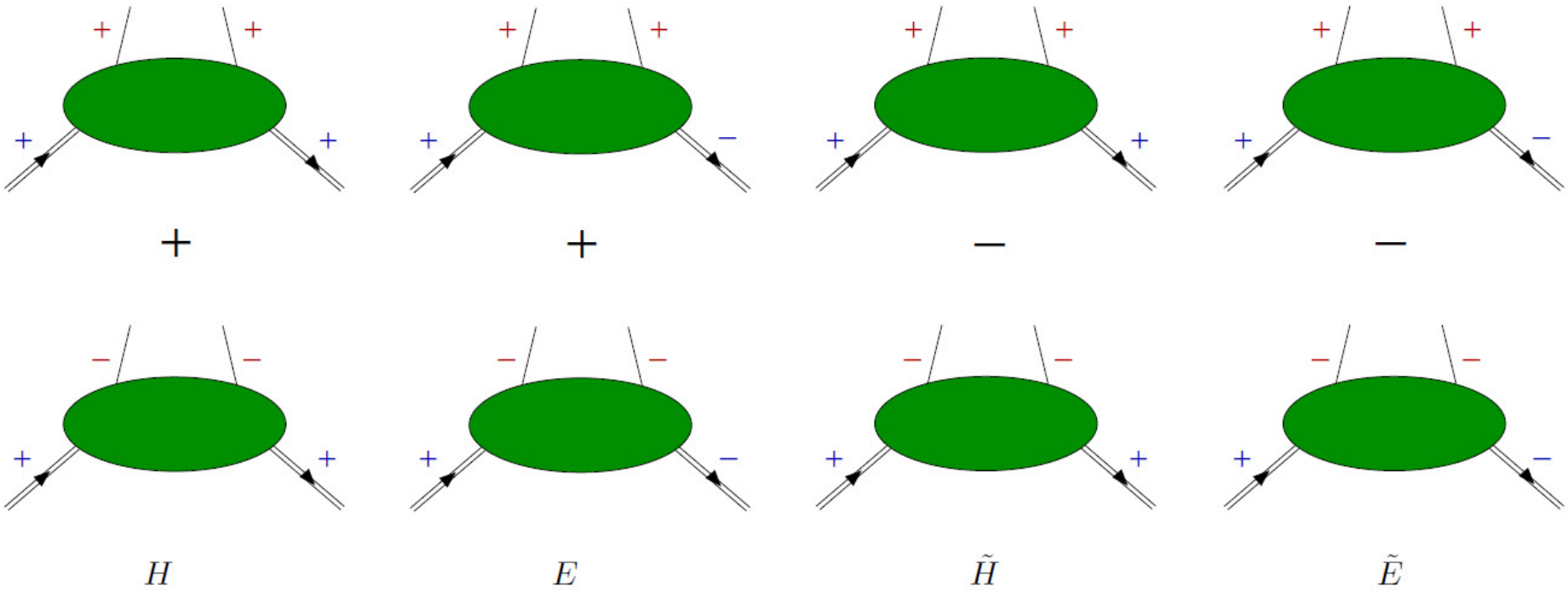
Bjorken limit:

$$\left.\begin{array}{rcl} Q^2 = & -q^2 \to & \infty \\ & \nu \to & \infty \end{array}\right\} \quad x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$

- GPDs accesible through DVCS *only* at $Q^2 \to \infty$
- Actual value of Q^2 *must* be tested and established **by experiment**

Leading twist GPDs

8 GPDs related to the different combination of quark/nucleon helicities

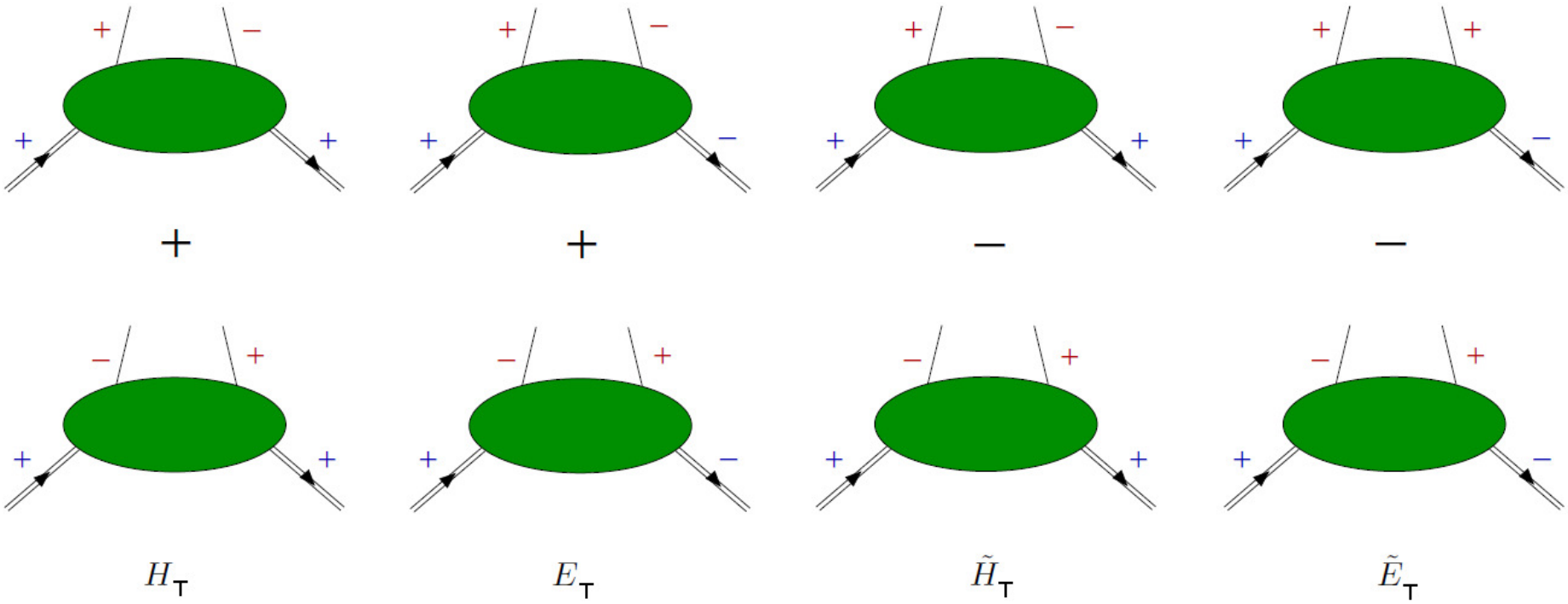


4 chiral-even GPDs: conserve the helicity of the quark

Access through DVCS (and DVMP)

Leading twist GPDs

8 GPDs related to the different combination of quark/nucleon helicities

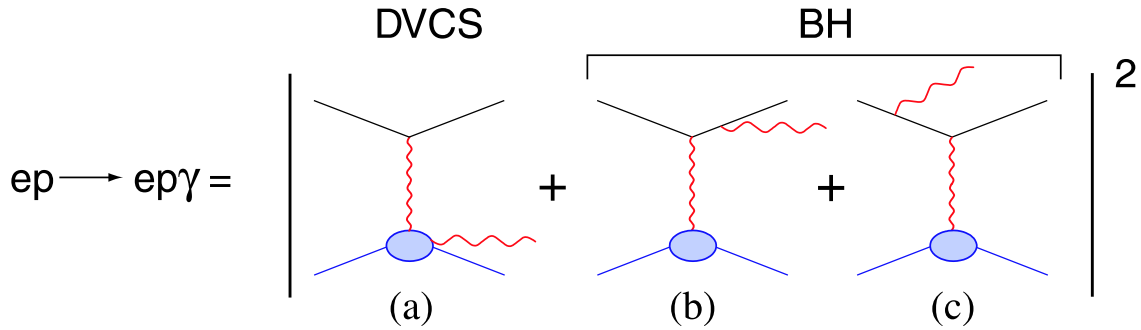


4 chiral-odd GPDs: flip helicity of the quark

"transversity GPDs"

Experimental access more complicated (π^0 electroproduction?)

DVCS experimentally: interference with Bethe-Heitler



At leading twist:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = 2\,\Im m\left(T^{BH}\cdot T^{DVCS}\right)$$

$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + 2\,\Re e\left(T^{BH}\cdot T^{DVCS}\right) + |DVCS|^2$$

$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots =$$

$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi\; H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$

Accessing different GDPs

Polarized beam, unpolarized target (BSA)

$$d\sigma_{LU} = \sin\phi \cdot \mathcal{I}m\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

Unpolarized beam, longitudinal target (ITSA)

$$d\sigma_{UL} = \sin\phi \cdot \mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_B kF_2\tilde{\mathcal{E}}\ldots\}d\phi$$

Polarized beam, longitudinal target (BITSA)

$$d\sigma_{LL} = (A + B\cos\phi) \cdot \mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\ldots\}d\phi$$

Unpolarized beam, transverse target (tTSA)

$$d\sigma_{UT} = \cos\phi \cdot \mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$$

The GPD experimental program

- Early results from HERA and DESY
- Jefferson Lab (recent exciting results):
  - Hall A: high accuracy, limited kinematic coverage
  - Hall B: wide kinematic range, limited precision
  - Hall C: high precision program at 11 GeV

Partially overlapping, partially complementary programs with different experimental setups

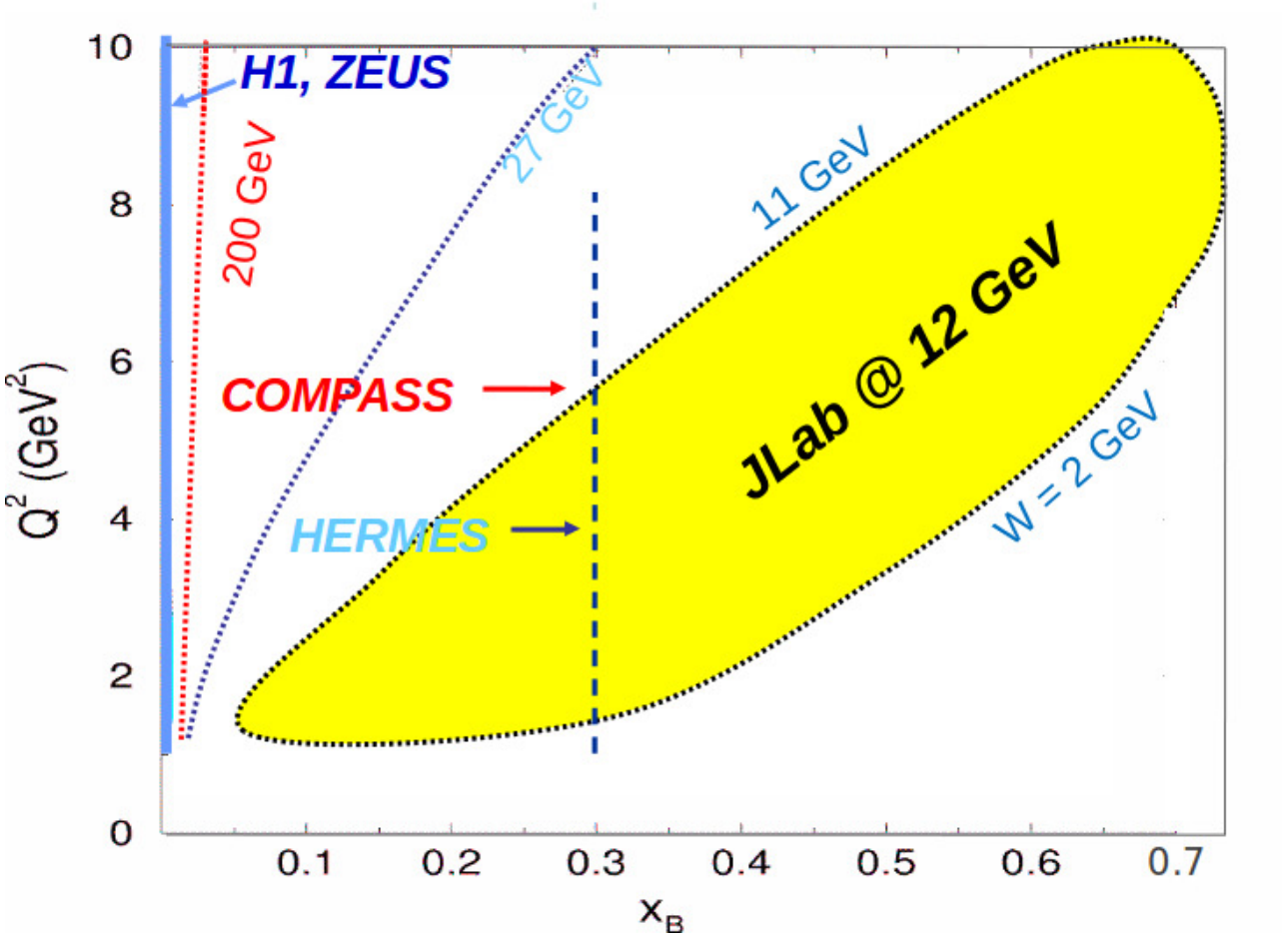
- COMPASS at CERN (preliminary results from 2012 pilot run)

The roadmap:

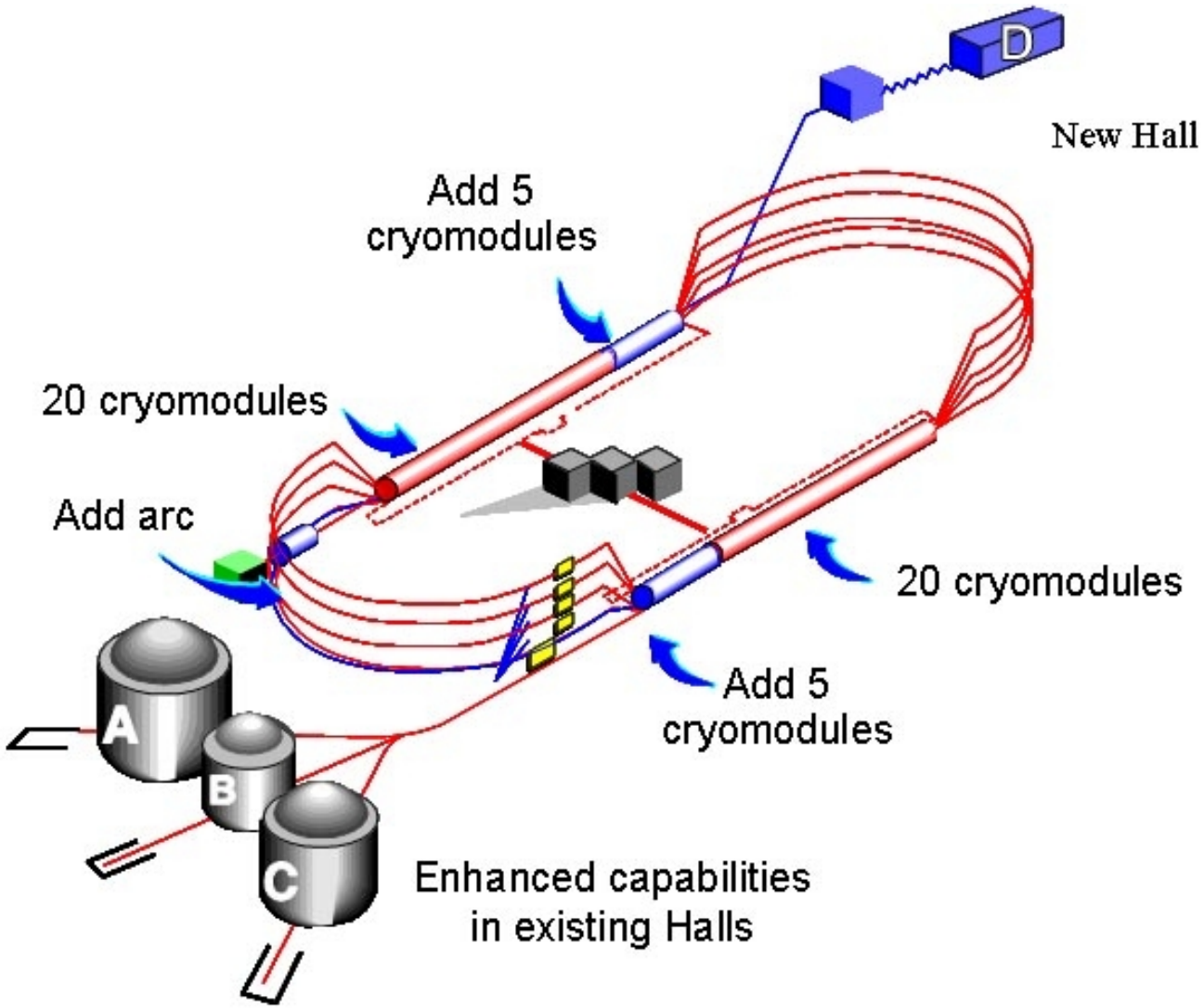
- Early results (2001) from non-dedicated experiment (CLAS)
- 1st round of dedicated experiments in Halls A/B in 2004/5
- 2nd round on 2008–2010: precision tests + more spin observables
- Compeling DVCS experiments in Halls A+B+C at 11 GeV ($\gtrsim$2017)
- Exciting program at COMPASS (started in 2016!)

Kinematic coverage

Kinematic complementarity between different facilities:

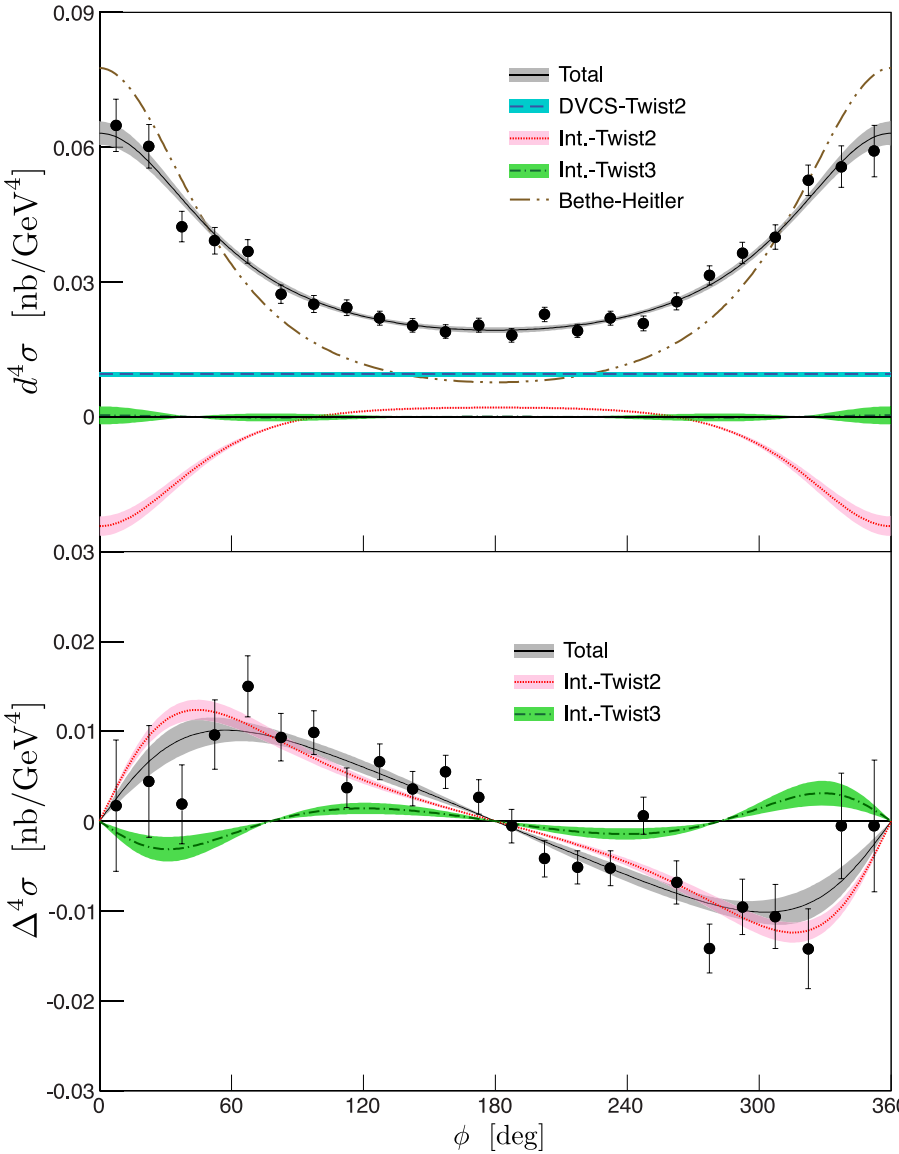


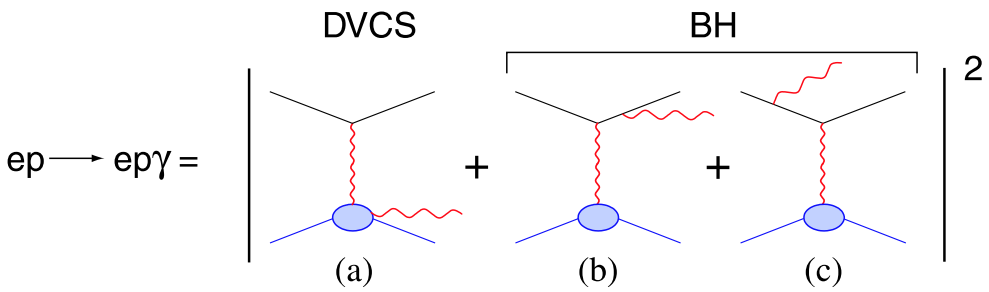
Jefferson Lab and its Upgrade to 12 GeV



DVCS cross sections: azimuthal analysis

$Q^2 = 2.36\ \text{GeV}^2$, $x_B = 0.37$, $-t = 0.32\ \text{GeV}^2$





$$d^4\sigma = \mathcal{T}^2_{\text{BH}} + \mathcal{T}_{\text{BH}}\mathcal{R}e(\mathcal{T}_{\text{DVCS}}) + \mathcal{T}^2_{\text{DVCS}}$$

$$\mathcal{R}e(\mathcal{T}_{\text{DVCS}}) \sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}}\cos\phi + c_2^{\mathcal{I}}\cos 2\phi$$

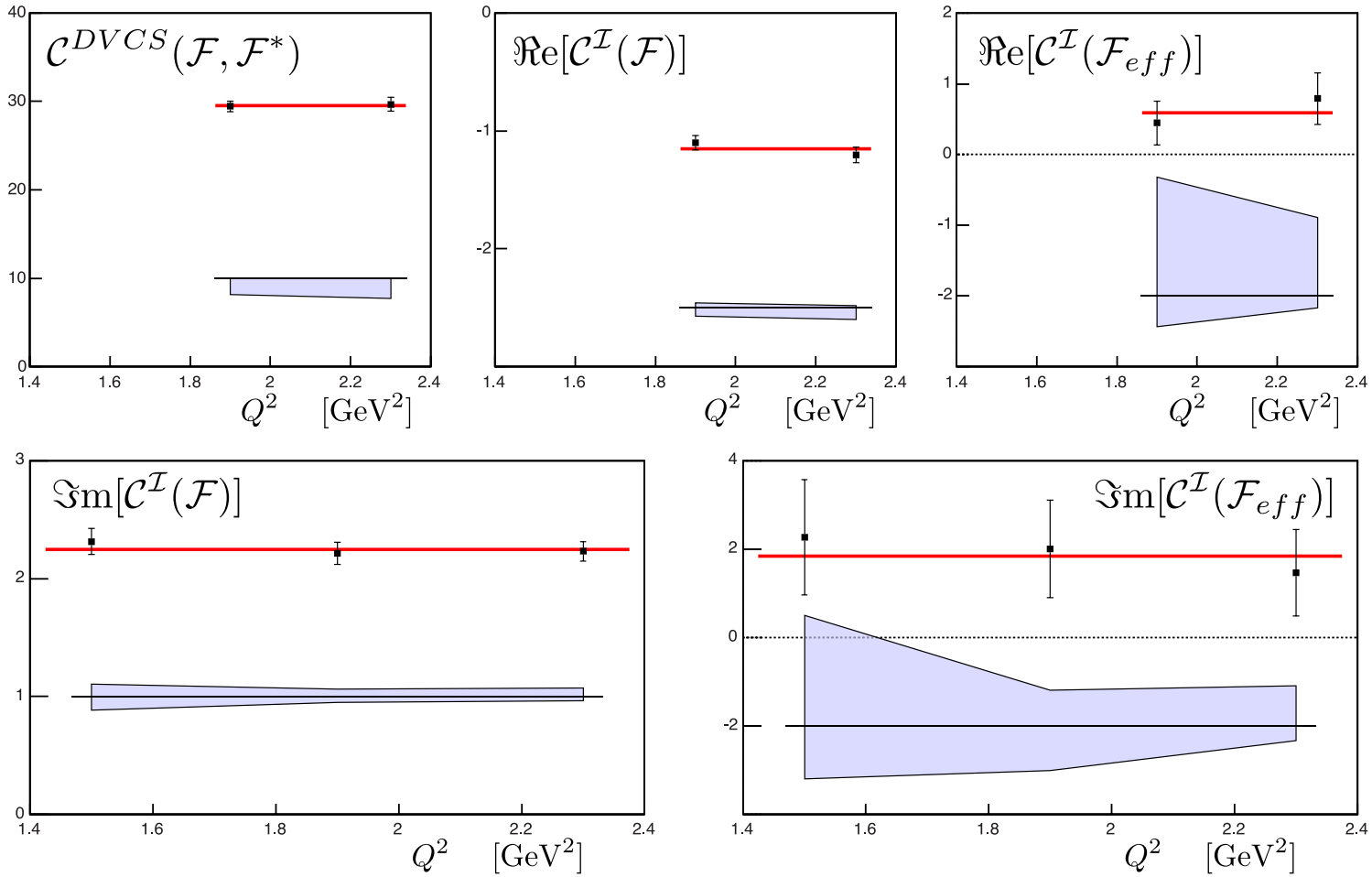
$$\mathcal{T}^2_{\text{DVCS}} \sim c_0^{\text{DVCS}} + c_1^{\text{DVCS}}\cos\phi$$

$$\Delta^4\sigma = \frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{2} = \mathcal{I}m(\mathcal{T}_{\text{DVCS}})$$

$$\mathcal{I}m(\mathcal{T}_{\text{DVCS}}) \sim s_1^{\mathcal{I}}\sin\phi + s_2^{\mathcal{I}}\sin 2\phi$$

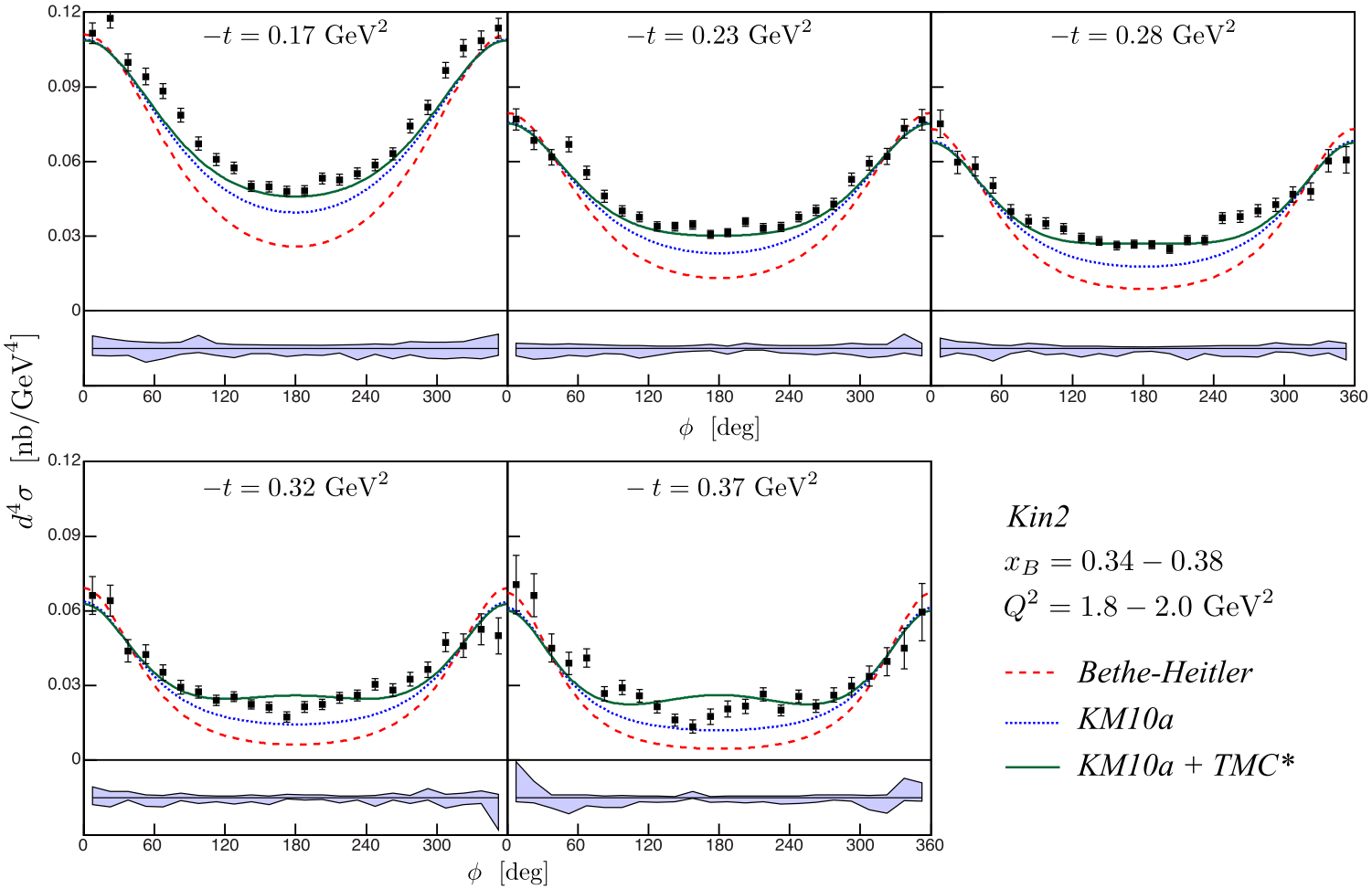
M. Defurne *et al.* Phys. Rev. C 92, 055202 (2015)

DVCS cross sections: Q^2–dependance



No Q^2-dependance within limited range $\Rightarrow$ leading twist dominance

DVCS cross sections: higher twist corrections



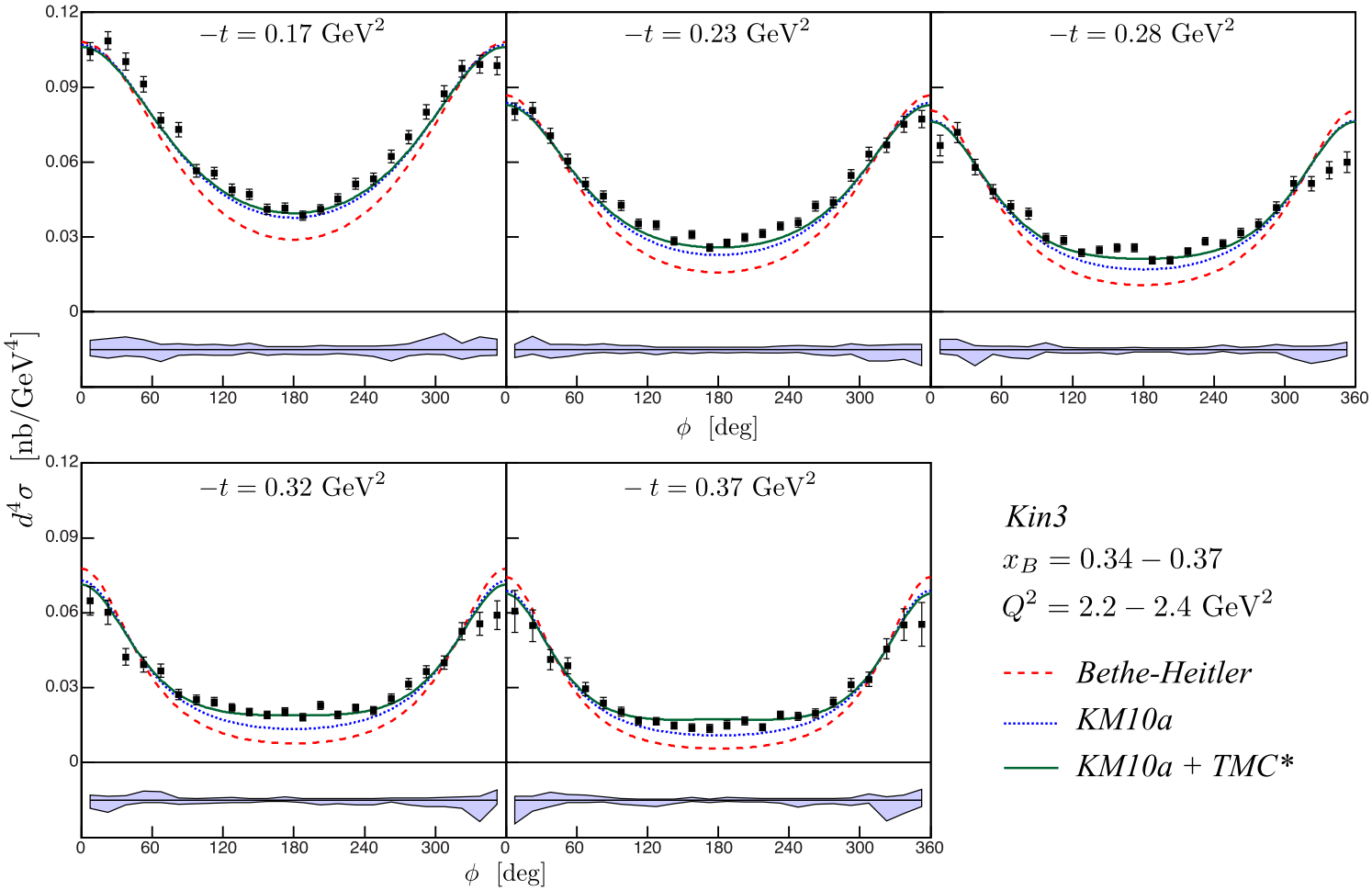
- KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries

  Kumericki and Mueller (2010)

- Target-mass corrections (TMC): $\sim \mathcal{O}(M^2/Q^2)$ and $\sim \mathcal{O}(t/Q^2)$

  Braun, Manashov, Mueller and Pirnay (2014)

DVCS cross sections: higher twist corrections

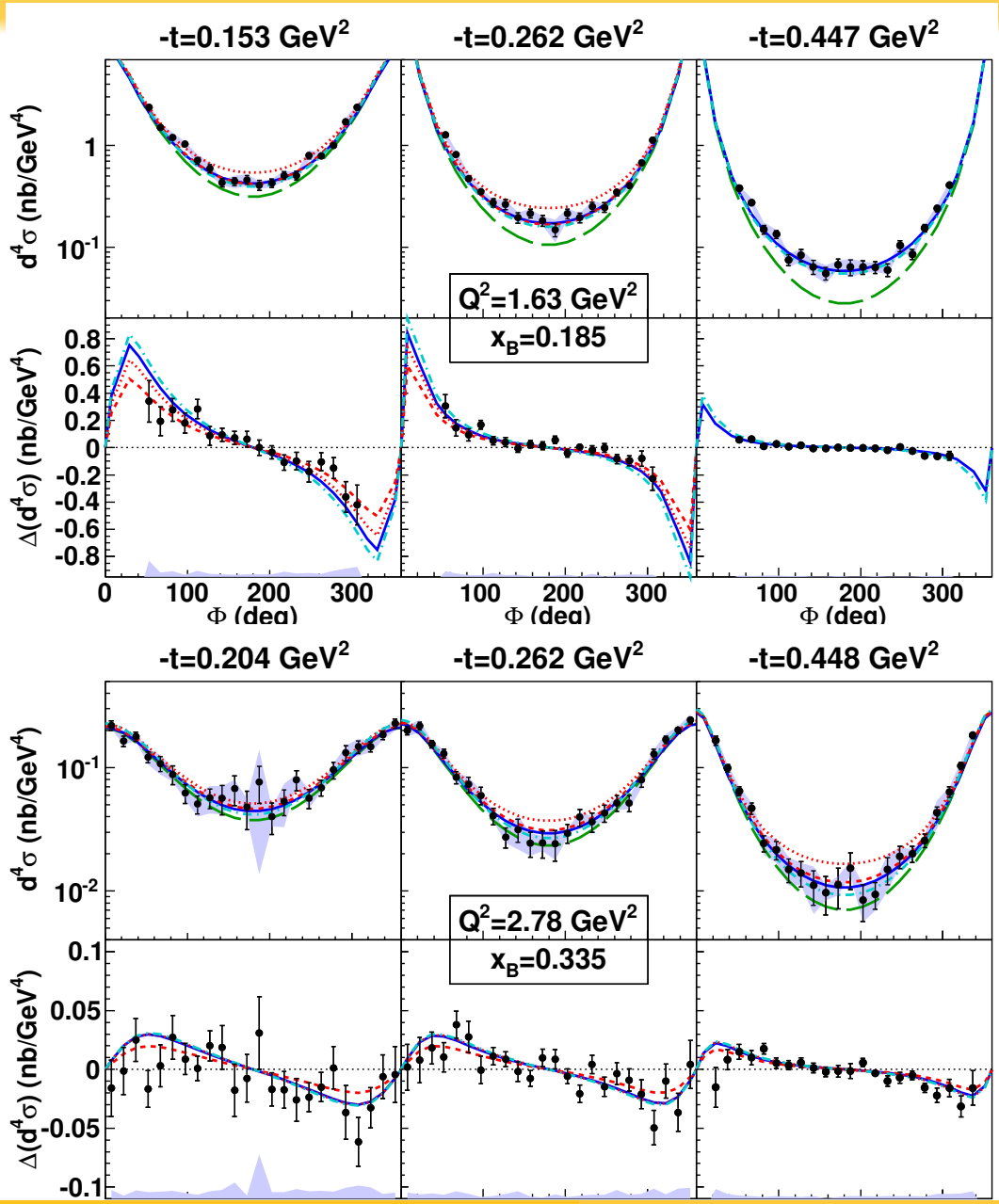


- Significant deviation from BH cross section
- Twist-4 corrections may be necessary to fully explain experimental data

Hall A DVCS precision measurements

1. Initial indications of validity of GPD formalism at moderate Q^2
2. Significant deviation from BH
3. Higher twist corrections likely necessary to fully describe the data
4. Extremely accurate data to constrain model and global fits

Hall B DVCS cross-section measurements

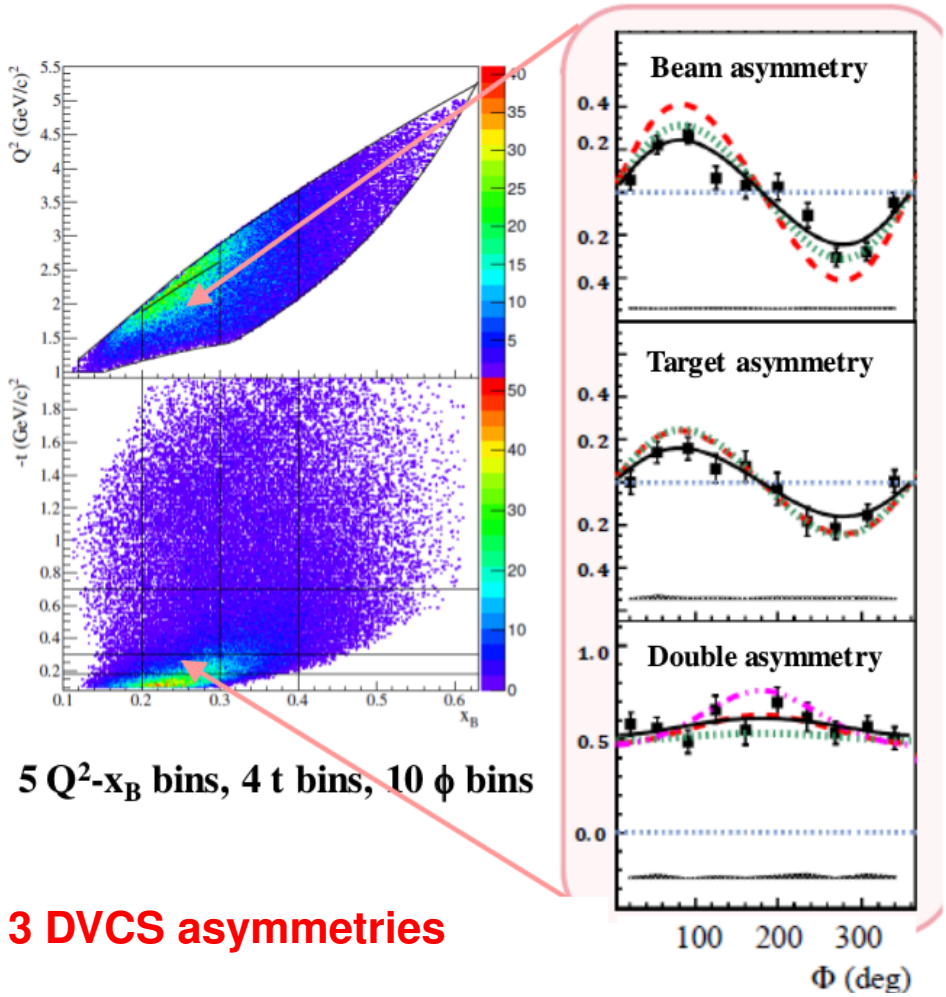


- Larger kinematic range covered:
  110 (Q^2, x_B, t) bins
- Compatible with Hall A results in overlap region
- Leading twist models describe the data within uncertainties

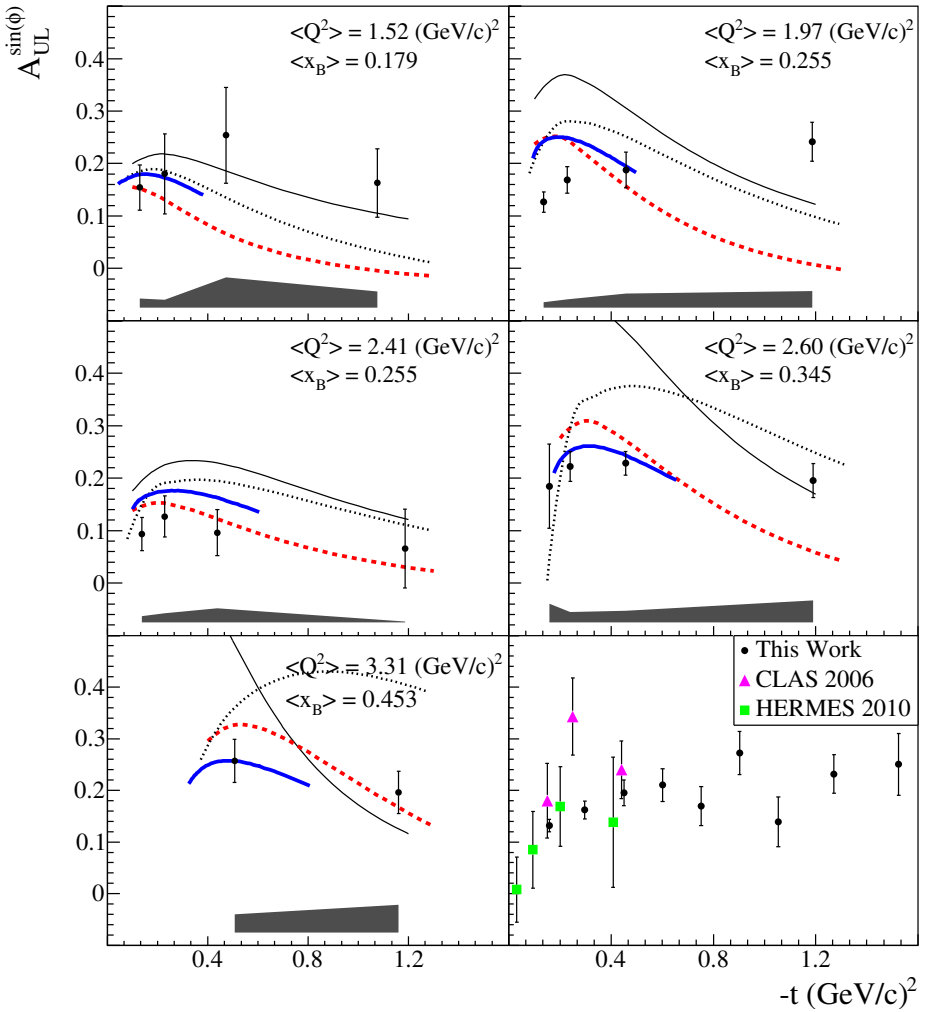
H.S. Jo *et al.* PRL 115, 212003 (2015)

DVCS target spin asymmetry from CLAS

- Data taken in 2009, $E_b = 5.9$ GeV.
- CLAS+IC to detect forward photons
- Long. polarized NH_3 target ($\mathcal{P}$ ~80%)



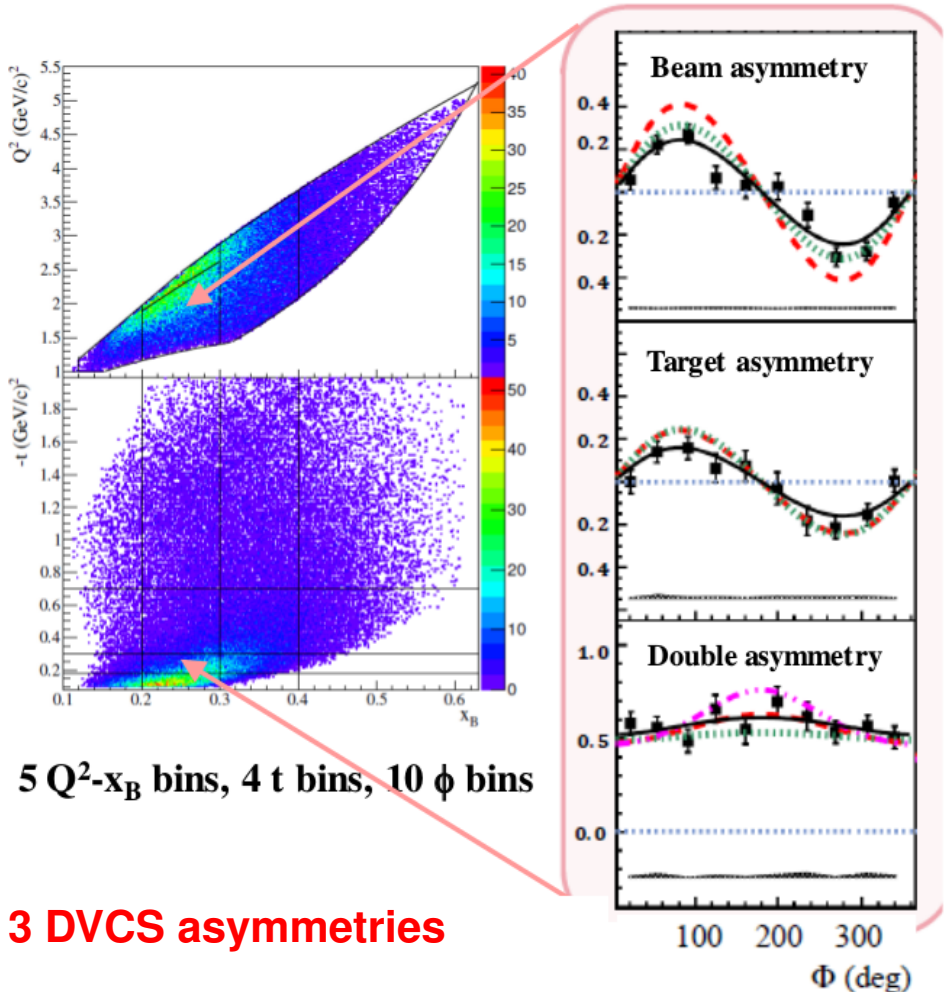
3 DVCS asymmetries



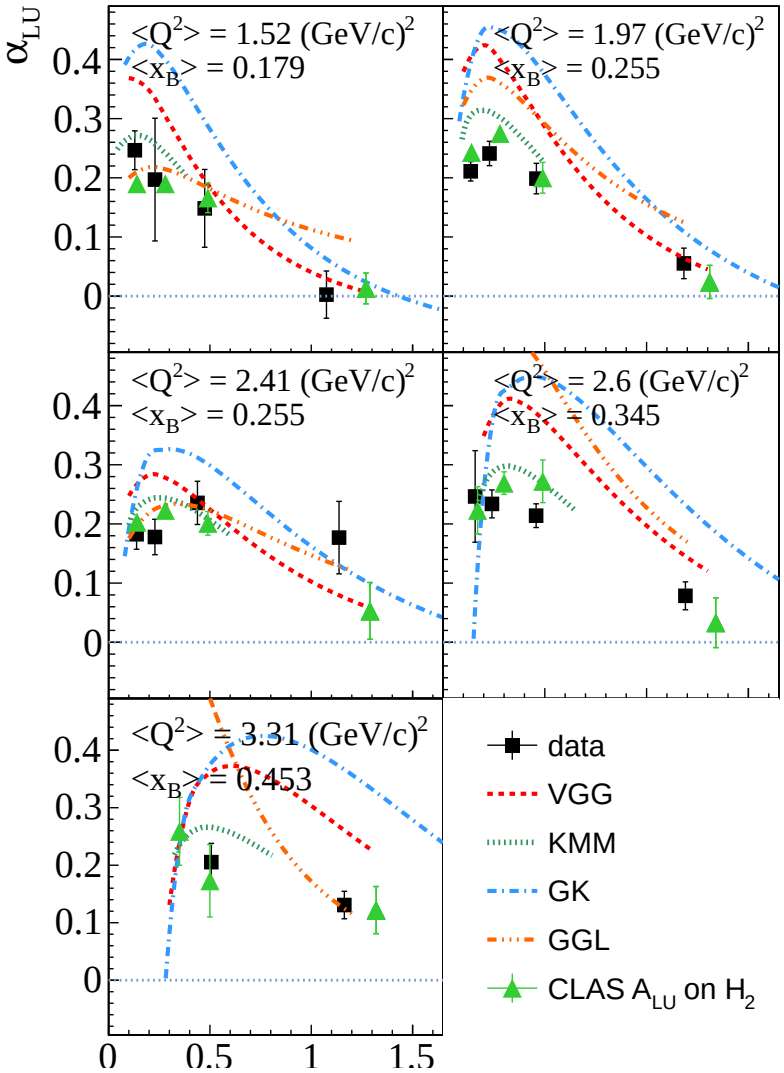
E. Seder et al., PRL 114 (2015) 032001

Beam Spin Asymmetry from CLAS

- Data taken in 2009, $E_b = 5.9$ GeV.
- CLAS+IC to detect forward photons
- Long. polarized NH_3 target ($\mathcal{P}$ ~80%)



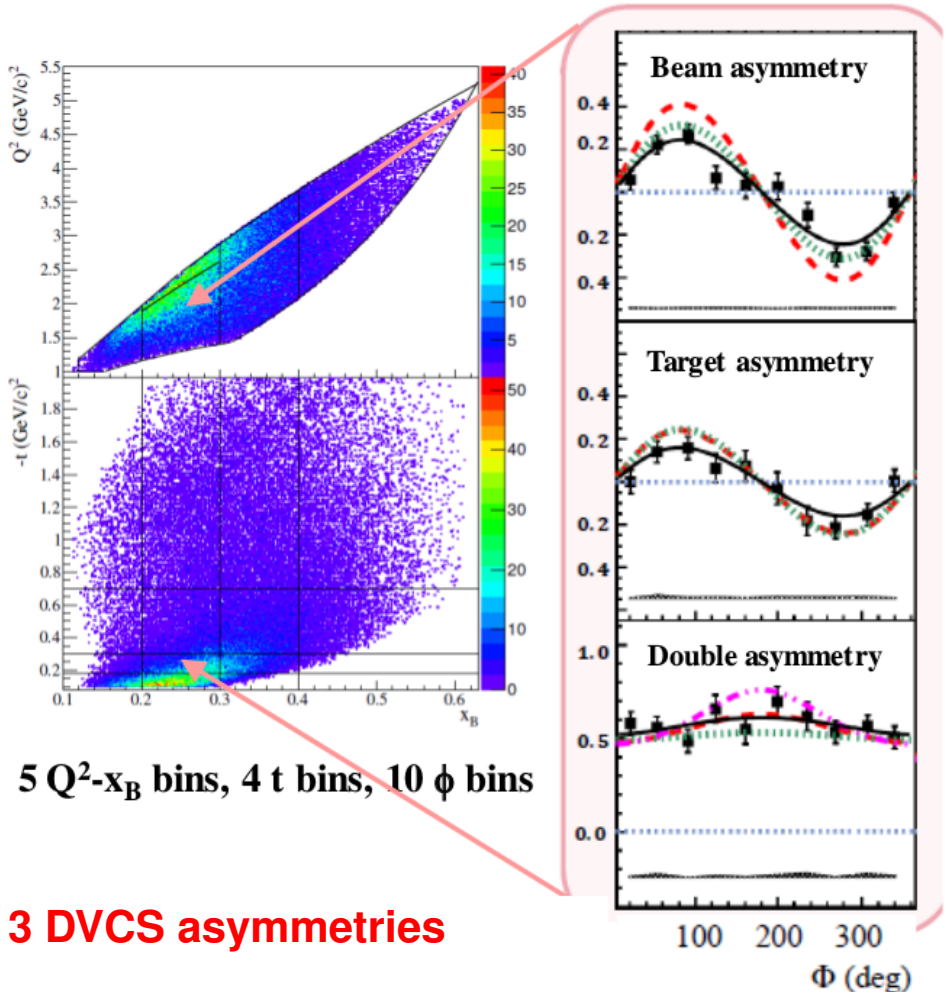
3 DVCS asymmetries



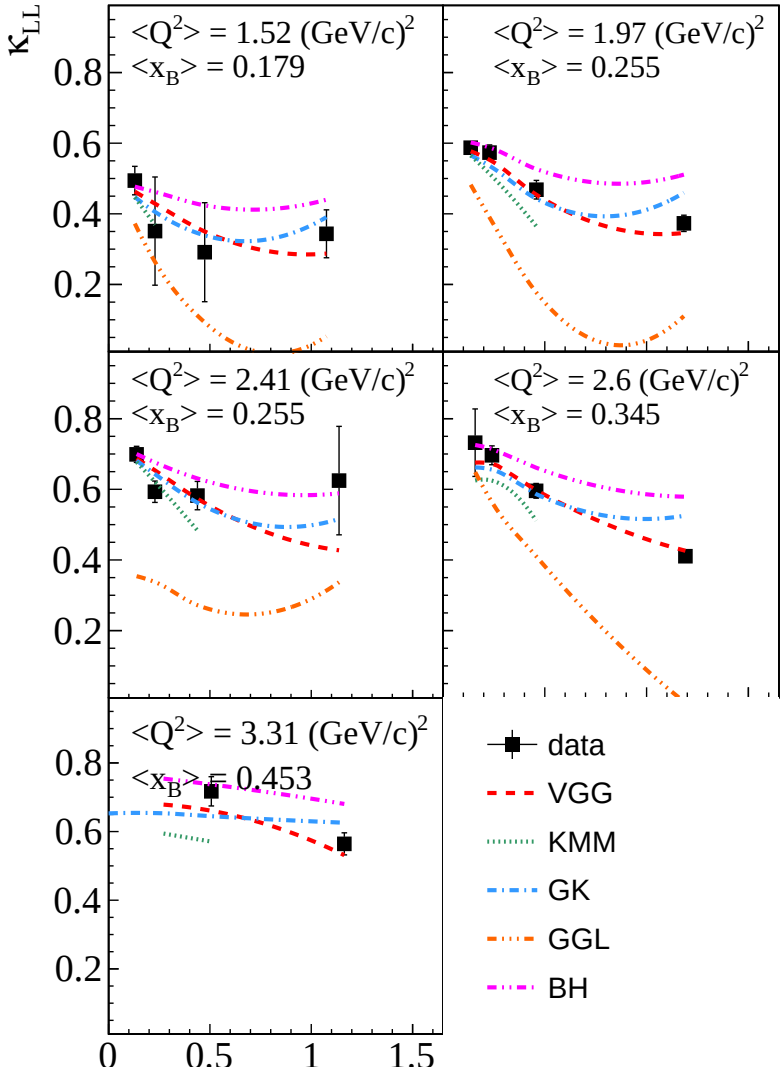
S. Pisano et al., PRD 91, 052014 (2015)

Double Spin Asymmetry

- Data taken in 2009, $E_b = 5.9$ GeV.
- CLAS+IC to detect forward photons
- Long. polarized NH_3 target ($\mathcal{P}$ ~80%)



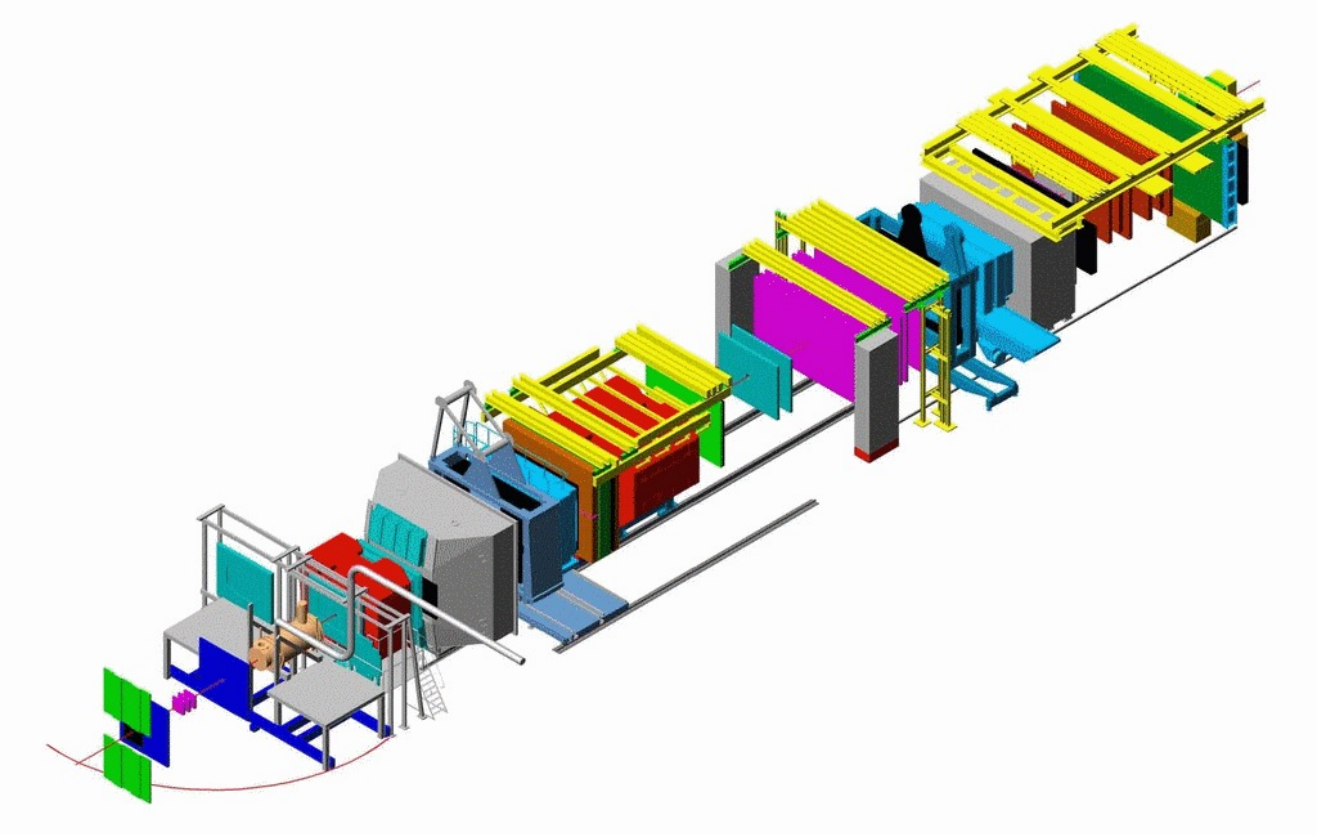
3 DVCS asymmetries



S. Pisano et al., PRD 91, 052014 (2015)

COMPASS spectrometer

- 60 m long two-stage spectrometer
- High energy beam from CERN Super Proton Synchrotron (SPS)



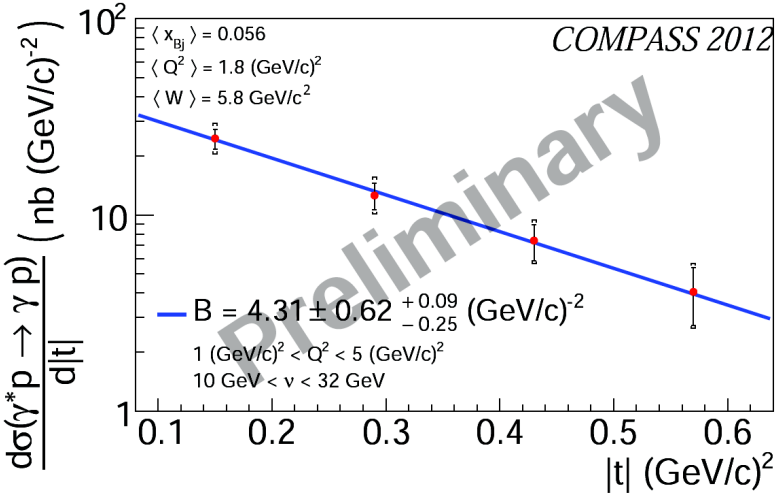
- 160 GeV polarized μ^+ or μ^- beam onto a fixed target (LH2)

Compass-II: 2012 pilot run

Beam Charge and Spin SUM:

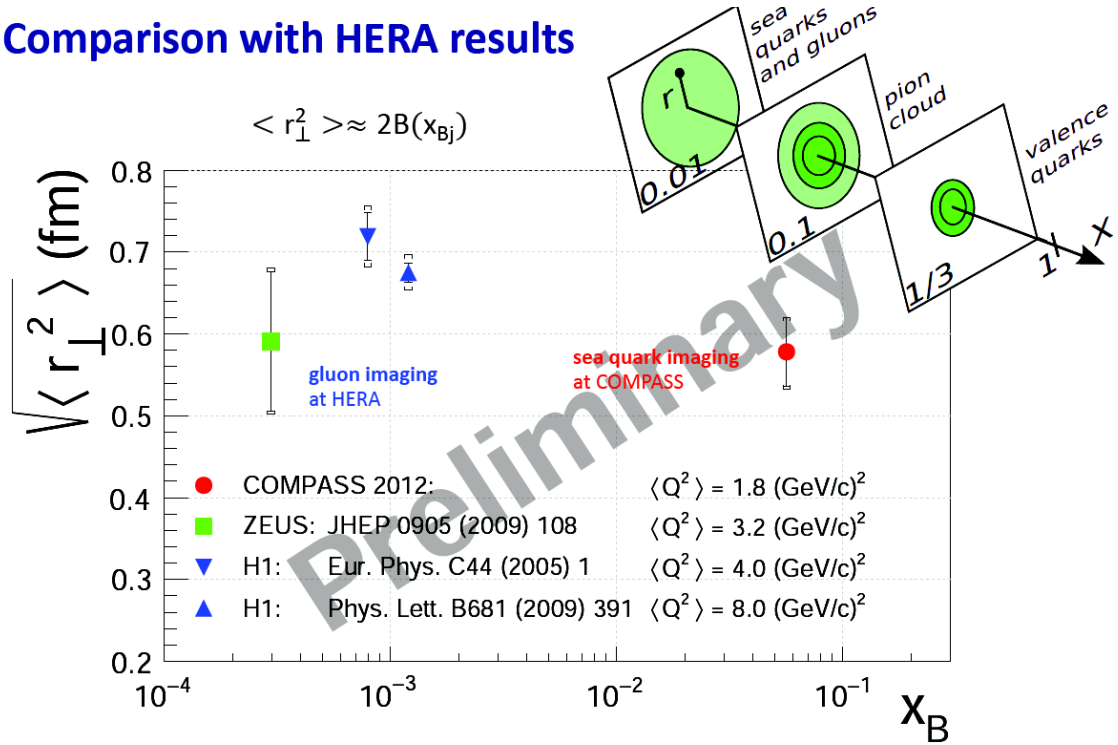
$$d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \propto$$

$$d\sigma^{\mathrm{BH}} + d\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + Ks_1^{\mathrm{I}} \sin\phi$$



$$d\sigma^{\mathrm{DVCS}}/dt \sim e^{-B|t|}$$

Comparison with HERA results

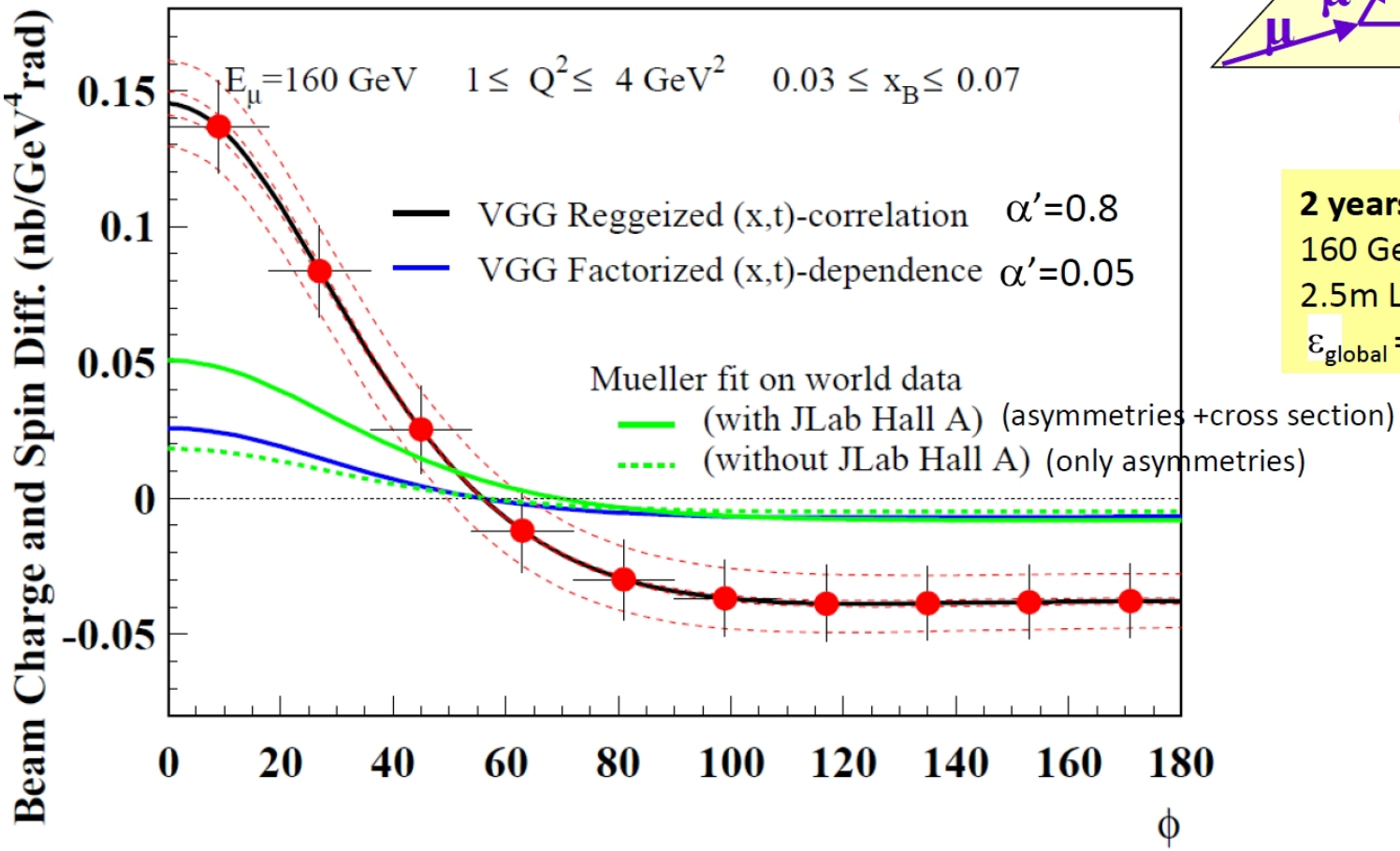


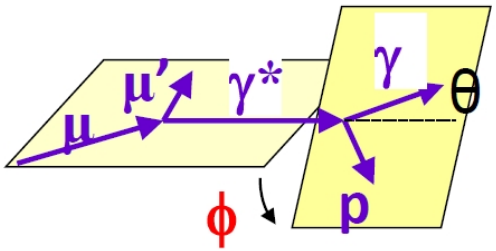
$r_\perp \rightarrow$ distance between struck and spectator partons

A. Ferrero – Tuesday's parallel session

DVCS with Compass-II

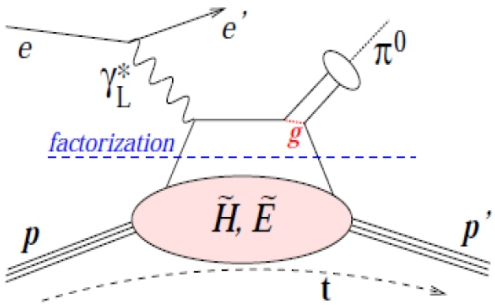
Comparison to different models





2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

π^0 electroproduction ($ep \to ep\pi^0$)



At leading twist:

$$\frac{d\sigma_L}{dt} = \frac{1}{2}\Gamma \sum_{h_N, h_{N'}} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6} \qquad \sigma_T \propto \frac{1}{Q^8}$$

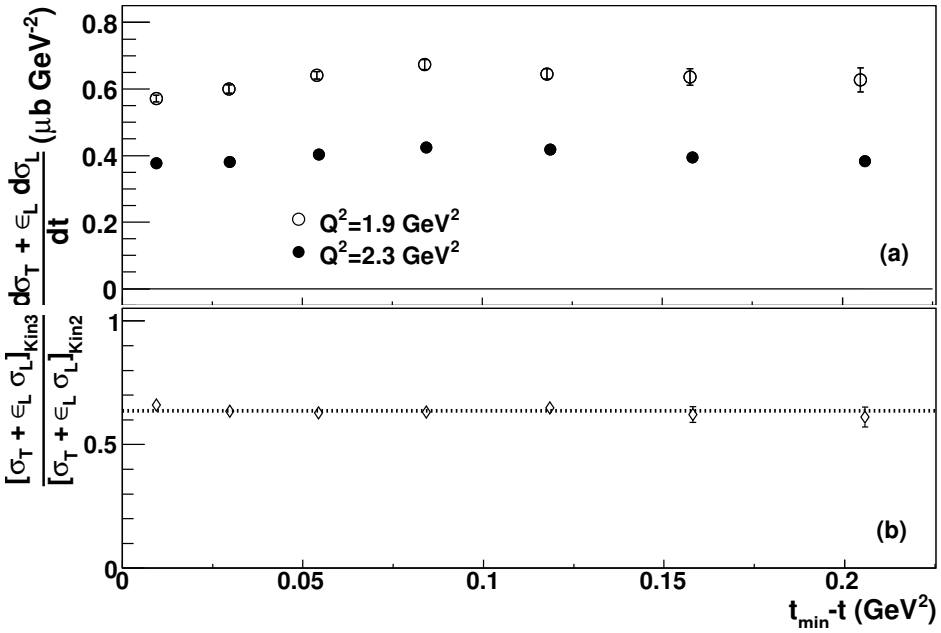
$$\mathcal{M}^L \propto \left[\int_0^1 dz \frac{\phi_\pi(z)}{z}\right] \int_{-1}^1 dx \left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right] \times \left\{\Gamma_1 \widetilde{H}_{\pi^0} + \Gamma_2 \widetilde{E}_{\pi^0}\right\}$$

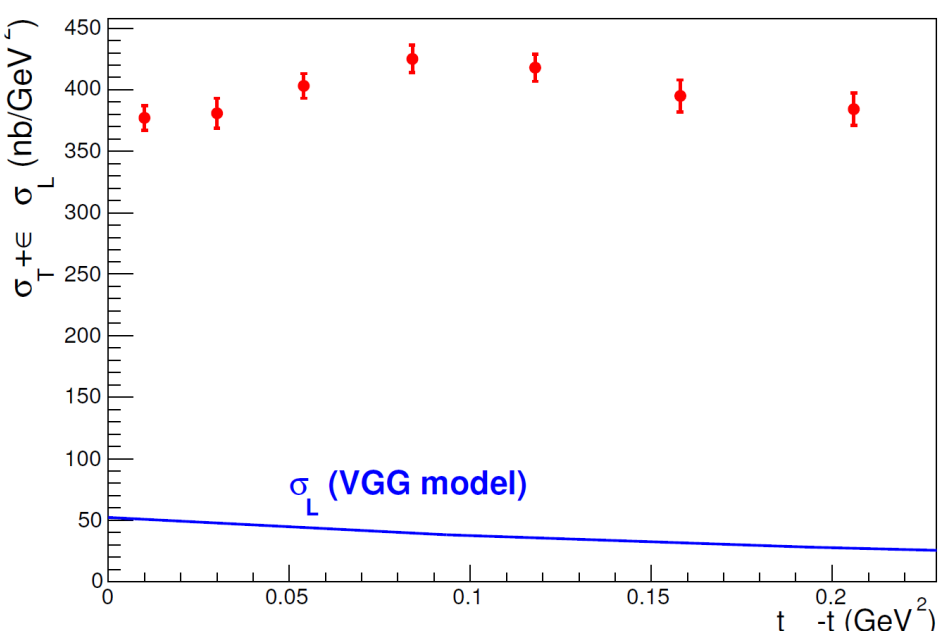
Different quark weights: flavor separation of GPDs

$$|\pi^0\rangle = \tfrac{1}{\sqrt{2}}\{|u\bar{u}\rangle - |d\bar{d}\rangle\} \qquad \widetilde{H}_{\pi^0} = \frac{1}{\sqrt{2}}\left\{\frac{2}{3}\widetilde{H}^u + \frac{1}{3}\widetilde{H}^d\right\}$$

$$|p\rangle = |uud\rangle \qquad H_{DVCS} = \frac{4}{9}H^u + \frac{1}{9}H^d$$

Exclusive π^0 electroproduction cross-sections – Hall A

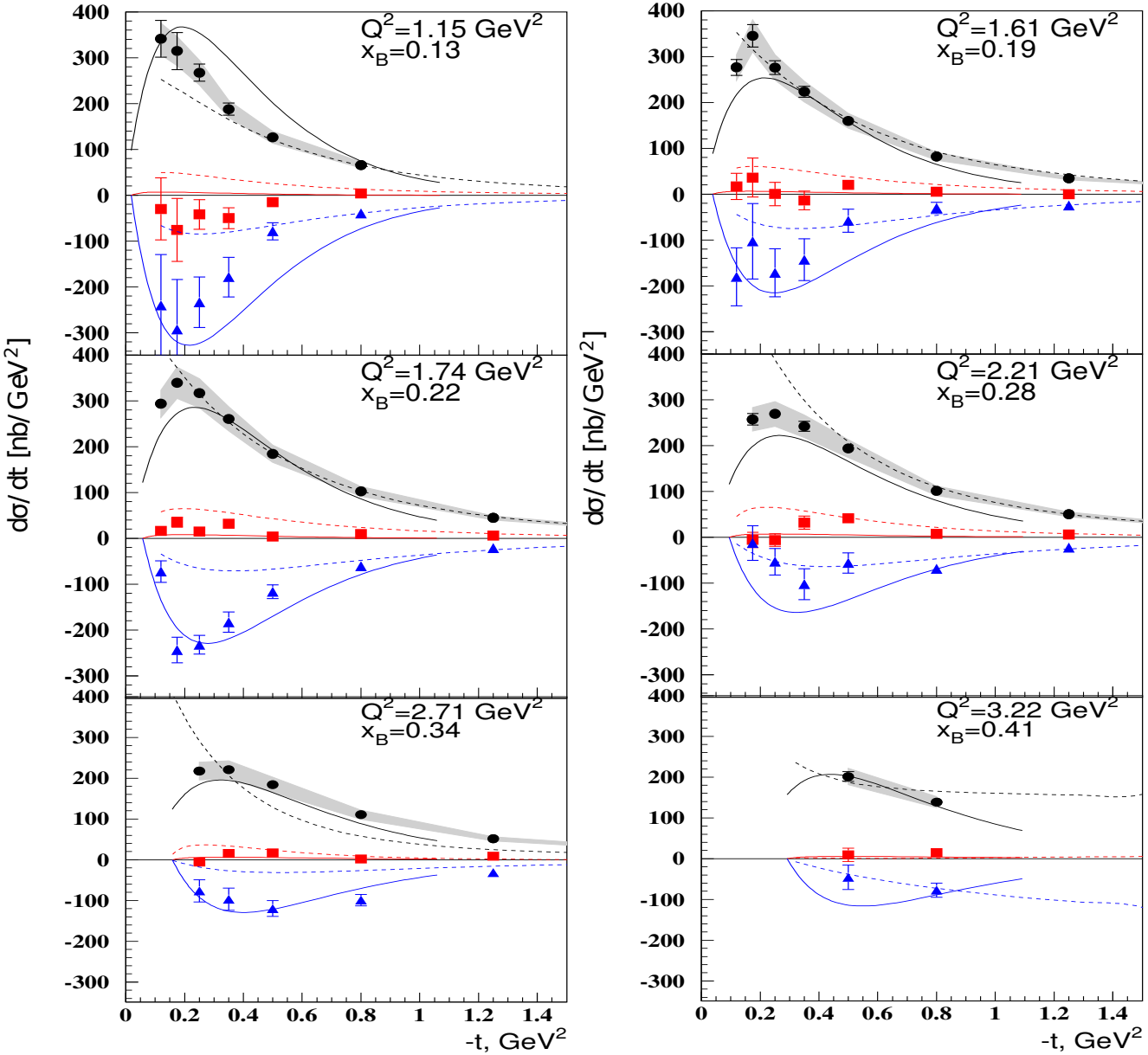




- $\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$
  (similar to $\sigma_T(ep \to ep\pi^+)$ measured in Hall C)
- GPDs predict $\sigma_L \sim Q^{-6}$
- σ_T likely to dominate at these Q^2,
  but L/T separation necessary ($\to$ new experiment...)

E. Fuchey et al., Phys. Rev. C83 (2011), 025125

Exclusive π^0 electroproduction cross-sections – Hall B



- $\sigma_T + \epsilon\sigma_L$
- σ_{TL}
- σ_{TT}

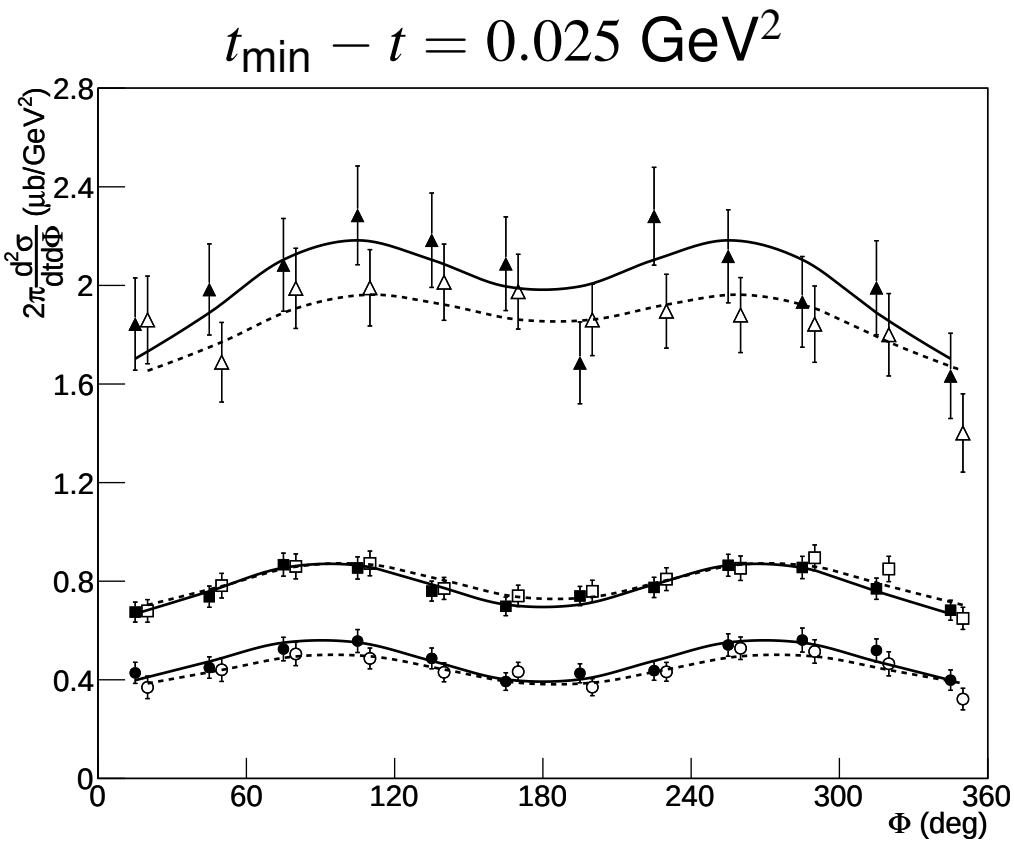
- Very large cross section compared to leading chiral even GPD models
- Fair agreement w/ models of trans. photon (modified) factorization (& transversity GPDs)

Rosenbluth separation

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi\right]$$

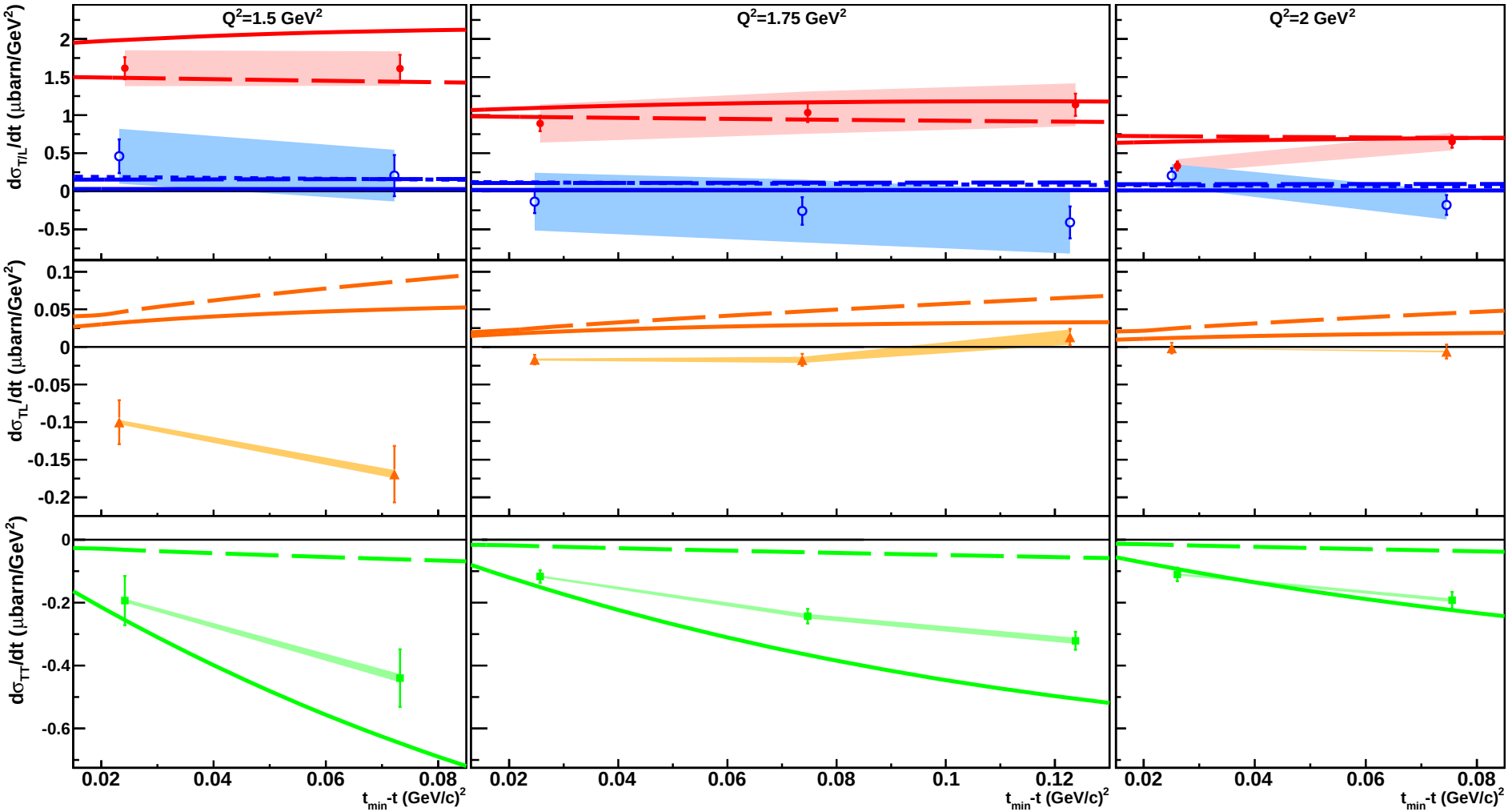
Kinematics

Setting	Q^2 (GeV^2)	x_B	E^{beam} (GeV)	ϵ
Kin1	1.50	0.36	3.355	0.52
			5.55	0.84
Kin2	1.75	0.36	4.455	0.65
			5.55	0.79
Kin3	2.00	0.36	4.455	0.53
			5.55	0.72



Talk M. Defurne – Tues parallel session

π^0 separated response functions



Goloskokov, Kroll (2011)

Goldstein, Hernandez, Liuti (2011)

Vanderhaeghen, Guichon, Guidal (1999)

arXiv:1608.01003

π^0 L/T separated cross section

- Cross section largely dominated by transverse component

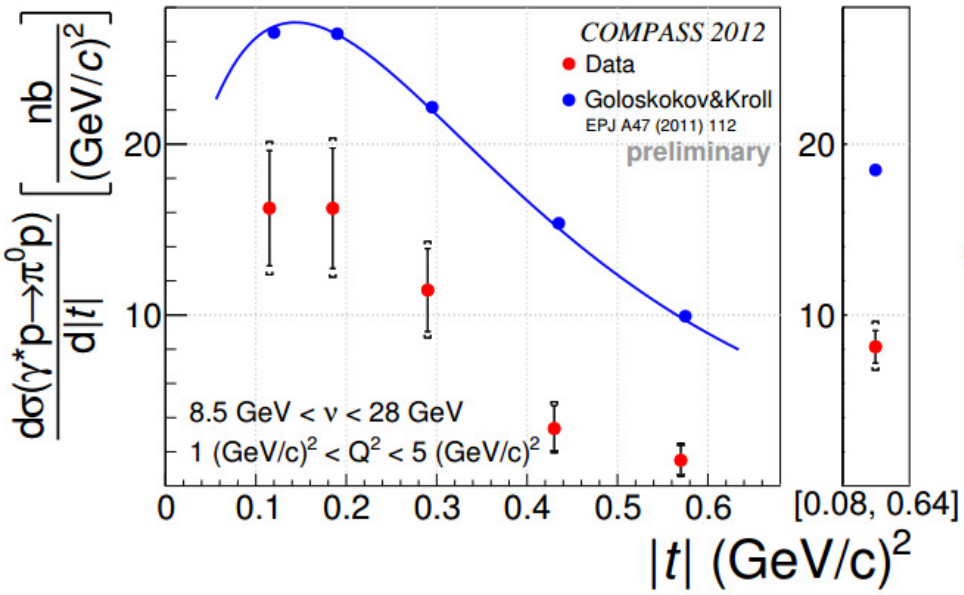
  $\rightarrow$ far from asymptotic prediction of QCD

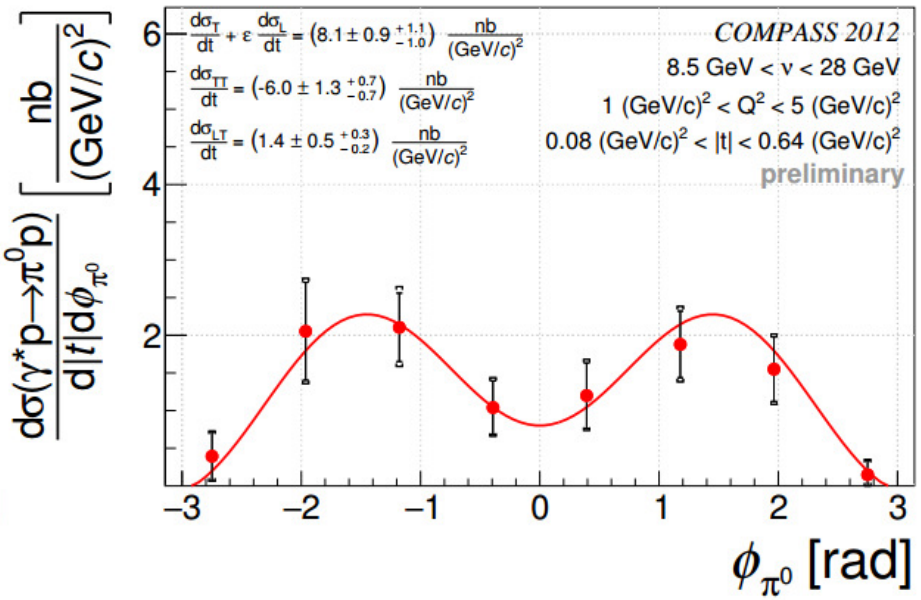
- Fair agreement with models using modified factorization approach

  $\rightarrow$ potential access to transversity GPDs

- Indications of small longitudinal response through non-zero σ_{LT}

Exclusive π^0 cross section from COMPASS 2012 run





M. Gorzellik – Tuesday's parallel session

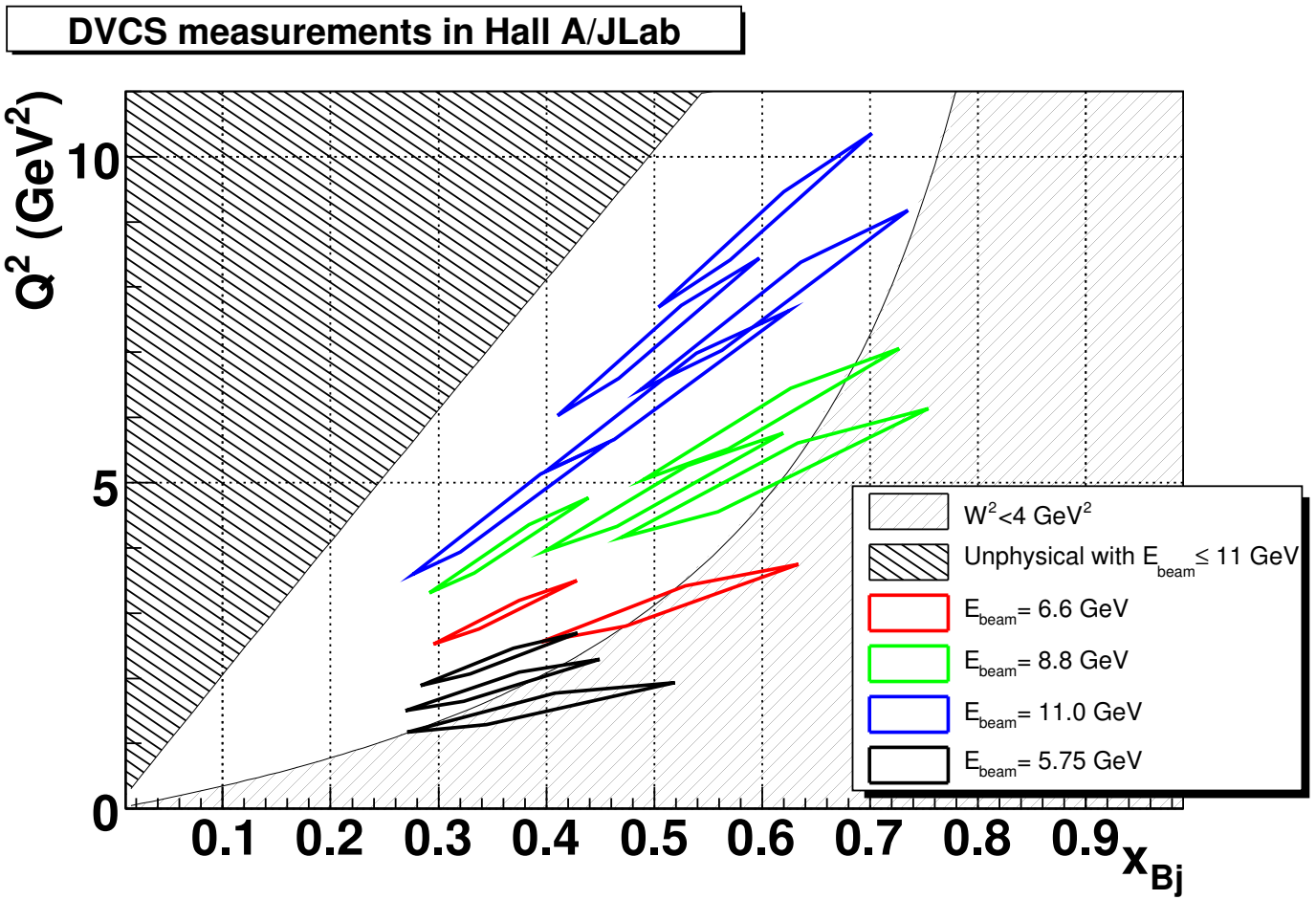
Results also in fair agreement with transversity GPD models

JLab 12 GeV DVCS experiments

- E12-06-114: Hall A unpolarized protons
- E12-06-119: Hall B unpolarized protons
- E12-11-003: Hall B unpolarized neutrons
- E12-06-119: Hall B long polarized protons
- E12-12-010: Hall B tran polarized protons
- E12-13-010: Hall C unpolarized protons

E12-06-114: JLab Hall A at 11 GeV

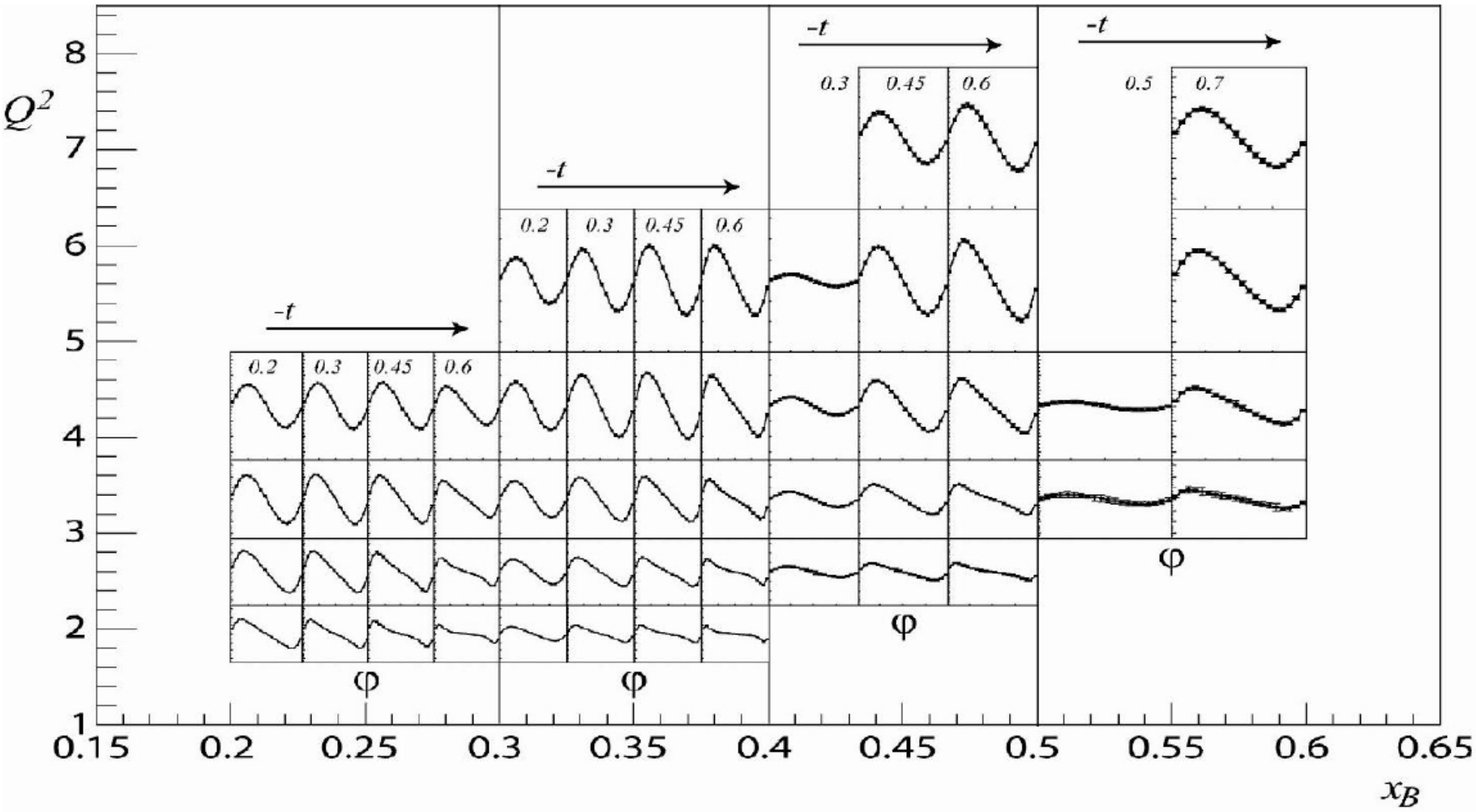
JLab12 with 3, 4, 5 pass beam
(6.6, 8.8, 11.0 GeV beam energy)



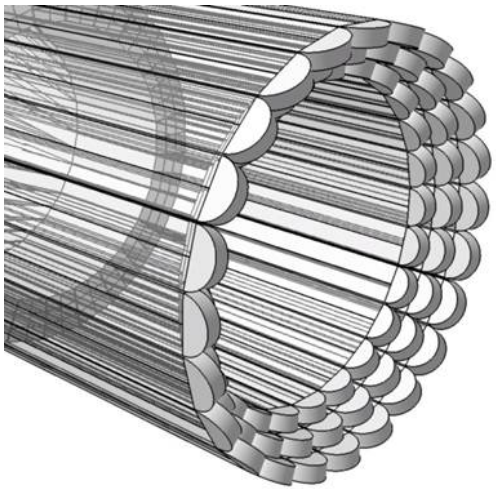
88 days
250k events/setting

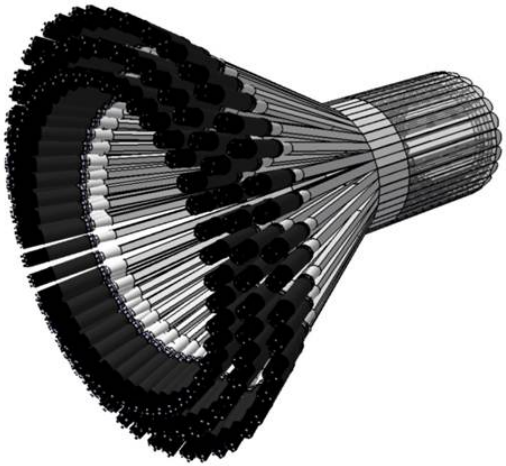
1 year of operations in JLab/Hall A

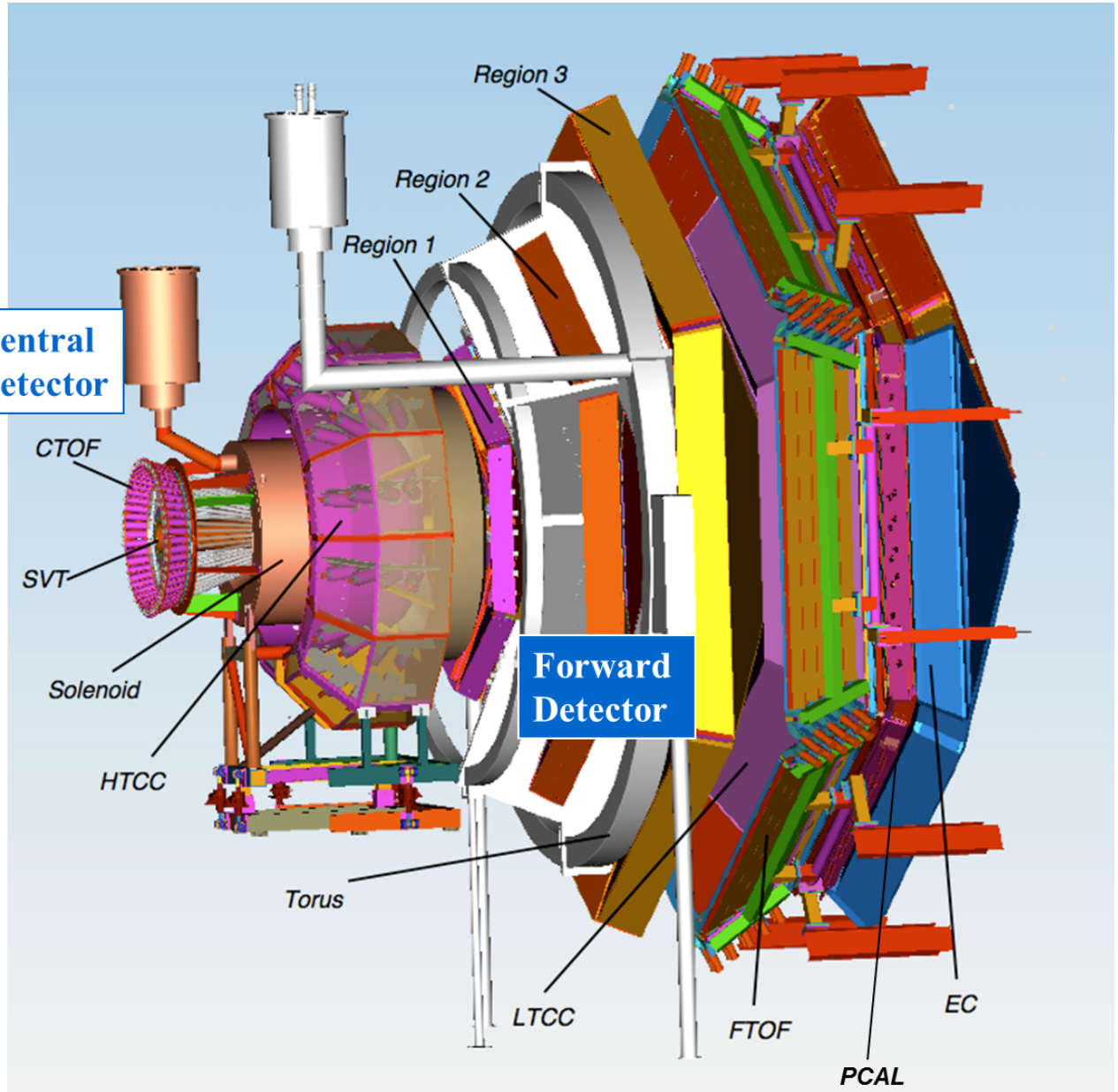
E12-06-119: DVCS on the proton with CLAS12



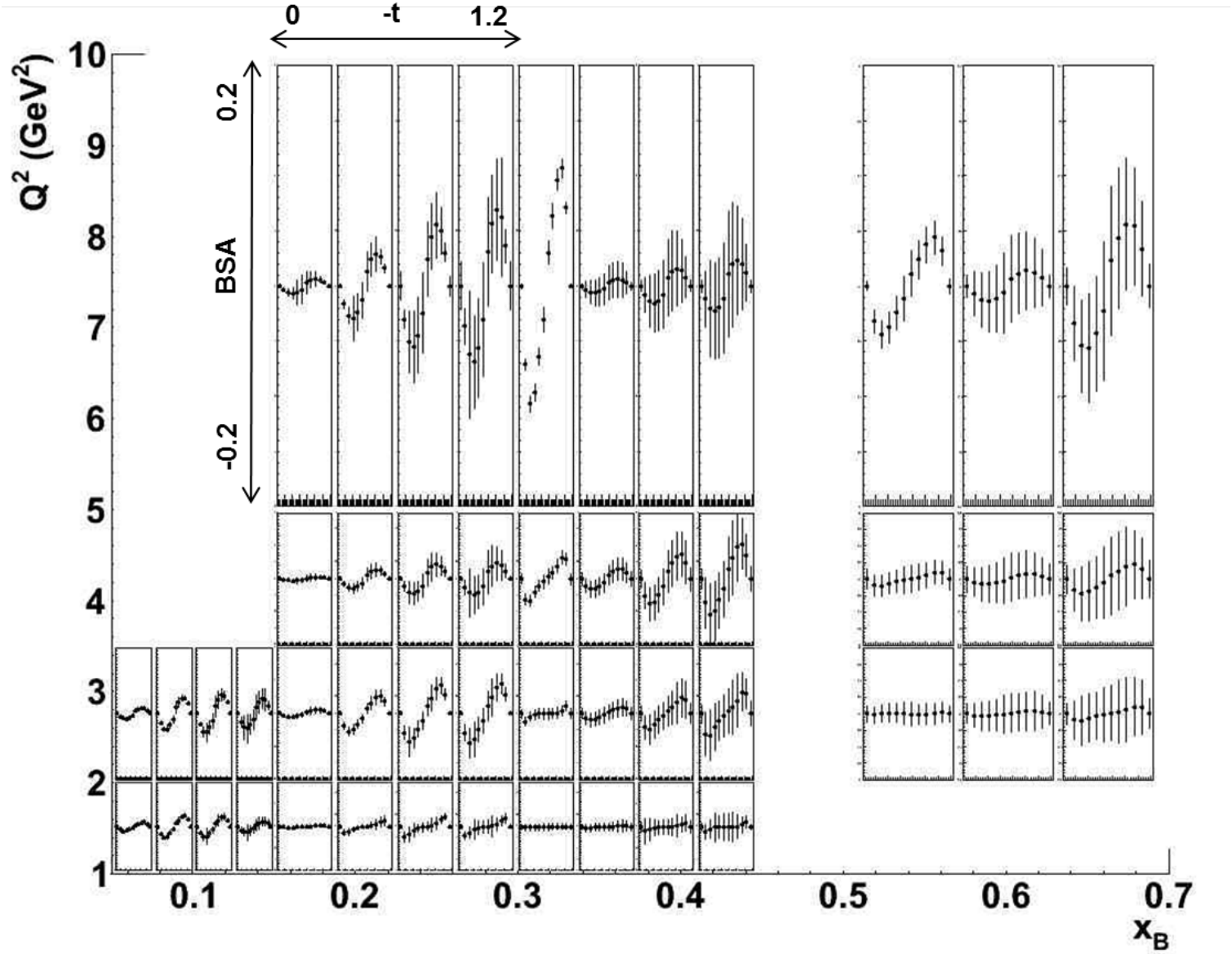
E12-11-003: DVCS on the neutron with CLAS12





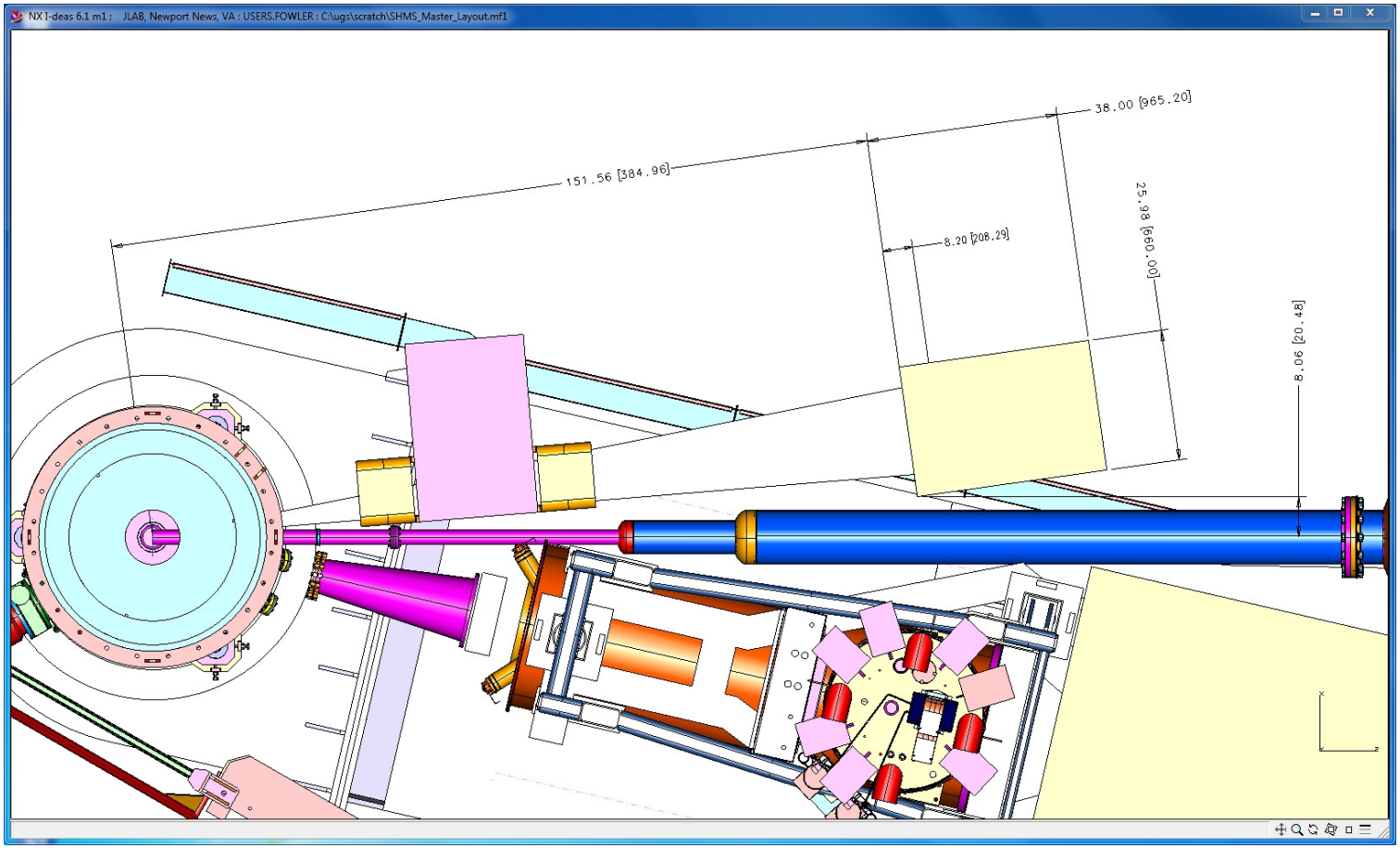


E12-11-003: projections



E12-13-010: DVCS in Hall C

- HMS ($p < 7.3GeV$): scattered electron
- $PbWO_4$ calorimeter: γ/π^0 detection
- Sweeping magnet



Rosenbluth-like separation of the DVCS cross section

$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

$$\mathcal{I} \propto 1/y^3 = (k/\nu)^3,$$

$$\left|\mathcal{T}^{DVCS}\right|^2 \propto 1/y^2 = (k/\nu)^2$$

BKM-2010 – at leading twist $\to$ 7 independent GPD terms:

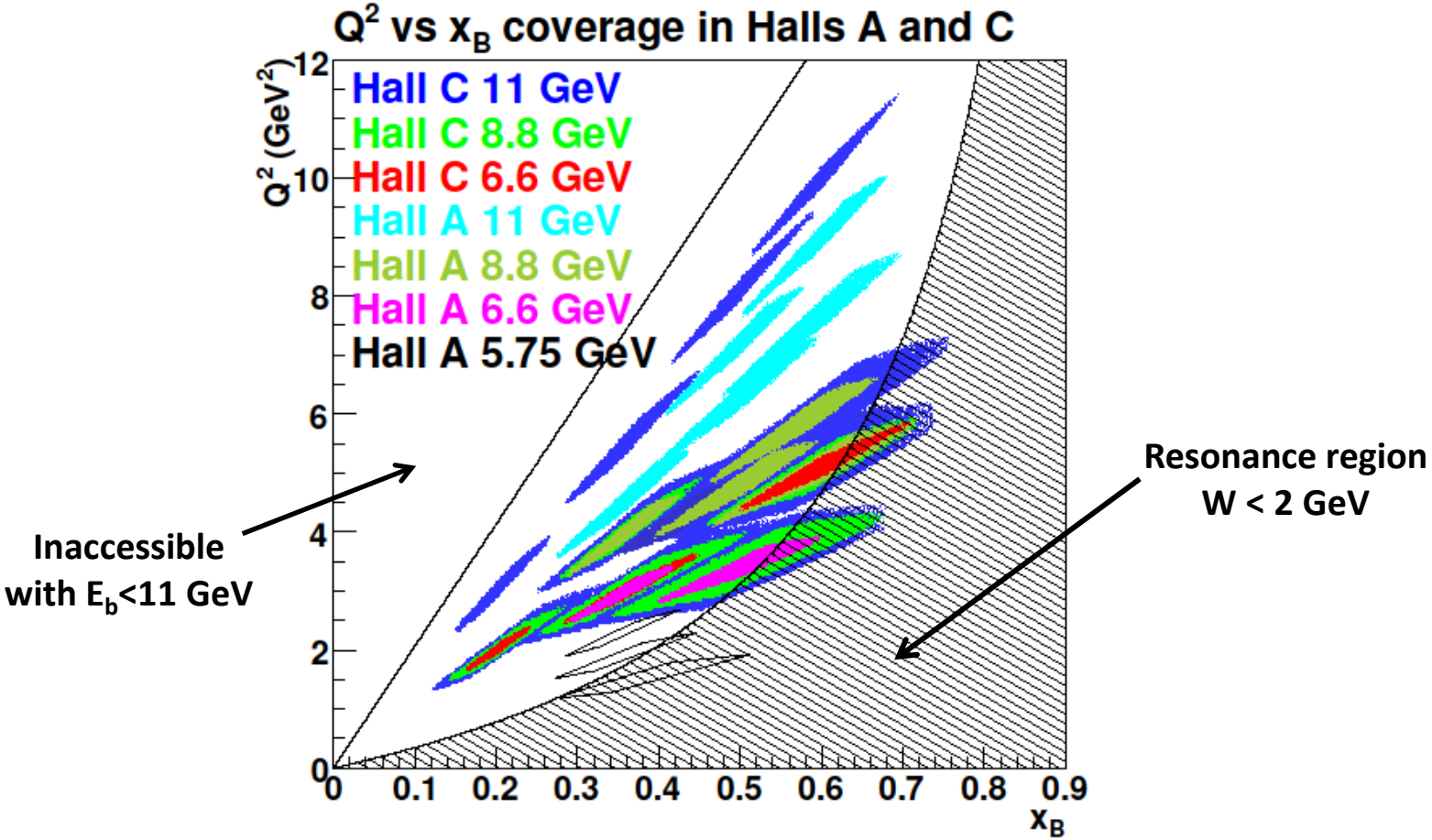
$$\left\{\Re\mathrm{e}, \Im\mathrm{m}\left[\mathcal{C}^{\mathcal{I}}, \mathcal{C}^{\mathcal{I},V}, \mathcal{C}^{\mathcal{I},A}\right](\mathcal{F})\right\}, \quad \text{and} \quad \mathcal{C}^{DVCS}(\mathcal{F}, \mathcal{F}*).$$

φ-dependence provides 5 independent observables:

$$\sim 1, \sim \cos\varphi, \sim \sin\varphi, \sim \cos(2\varphi), \sim \sin(2\varphi)$$

The measurement of the cross section at two or more beam energies for exactly the same Q^2, x_B, t kinematics, provides the additional information in order to extract all leading twist observables independently.

E12-13-010: beam energy separation in Hall C



Approved by the PAC, possible running in $\gtrsim 2020$

Summary

- DVCS golden channel to access GPDs experimentally, but also accessible in:
  - Deep meson production
  - Time-like Compton Scattering, Double DVCS...
- Large and accurate set of data (cross-sections and asymmetries) is now available in the valence region
  - Dominance of leading twist, but...
  - Necessity of higher twist corrections to explain high precision data
- Compeling GPD program in the future at Jefferson Lab 12 GeV in all 3 electron Hall A, B & C and COMPASS at CERN