New Deeply Virtual Compton Scattering results from Jefferson Lab

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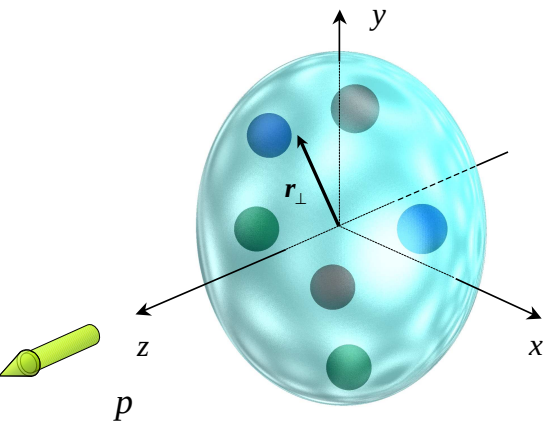
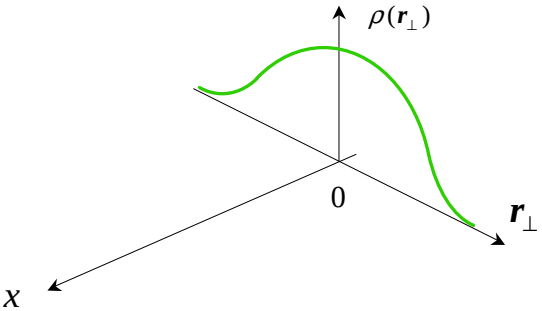
Outline

1. Very brief experimental introduction to GPDs
   (and how they can be accessed through DVCS)
2. Jefferson Lab overview:
   - Complementary DVCS programs in Hall A and Hall B
   - Very recent results (April 2015) released from both Hall A & B
3. Outlook
   - Jefferson Lab at 12 GeV
   - Hall A & B + new DVCS program in Hall C
4. Conclusion

Studying nucleon structure experimentally

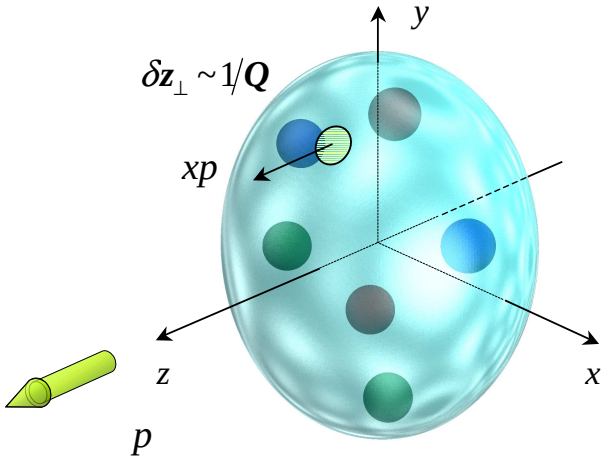
Elastic scattering

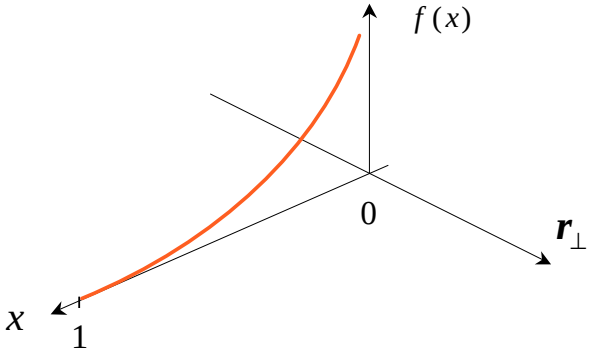




Form factors

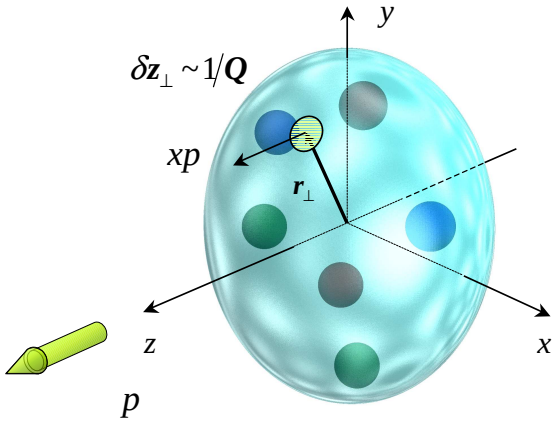
Deep inelastic scattering

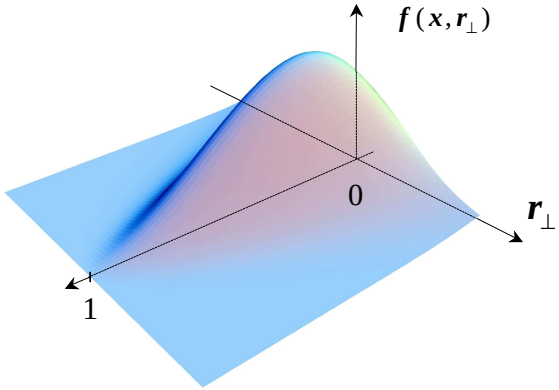




Parton distributions

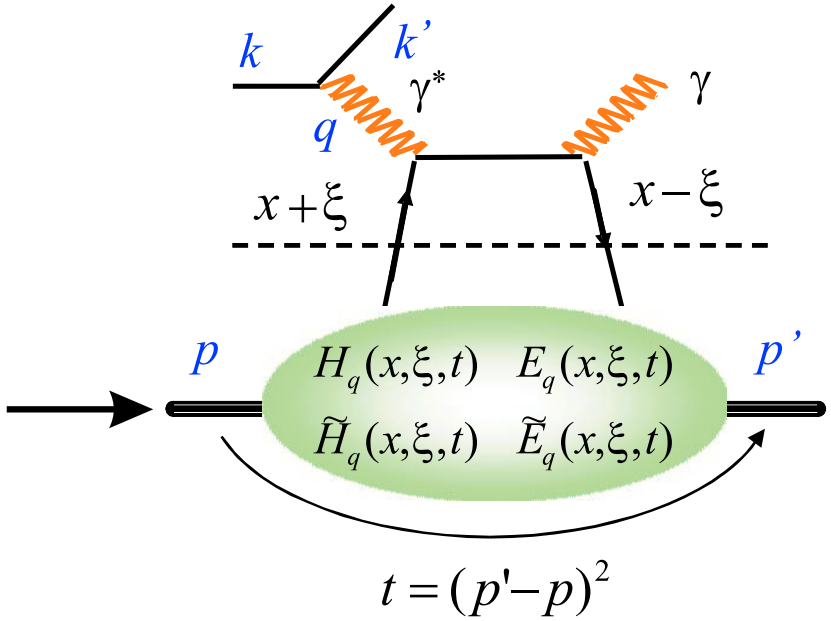
Hard exclusive processes





Generalized Parton Distributions (GPDs)

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



Handbag diagram

High Q^2
Perturbative QCD

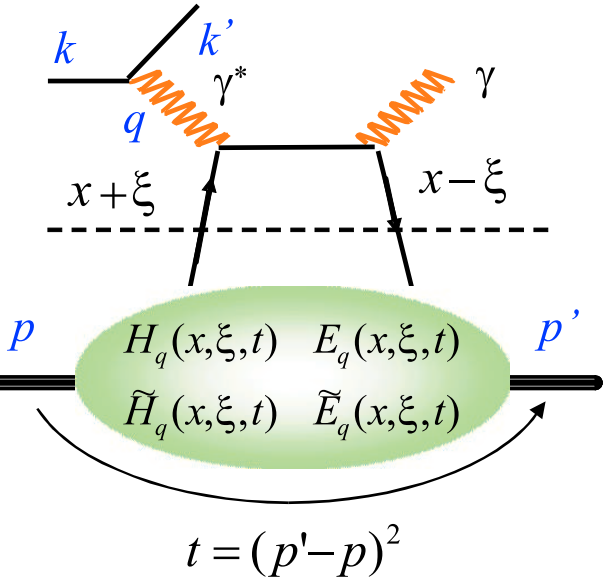
Non-perturbative
GPDs

Bjorken limit:

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

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

Generalized Parton Distributions



- Correlate between different partonic states
- Correlate momentum and position of partons
- Access to new fundamental properties of the nucleon

Contribution of the **angular momentum of quarks** to proton spin:

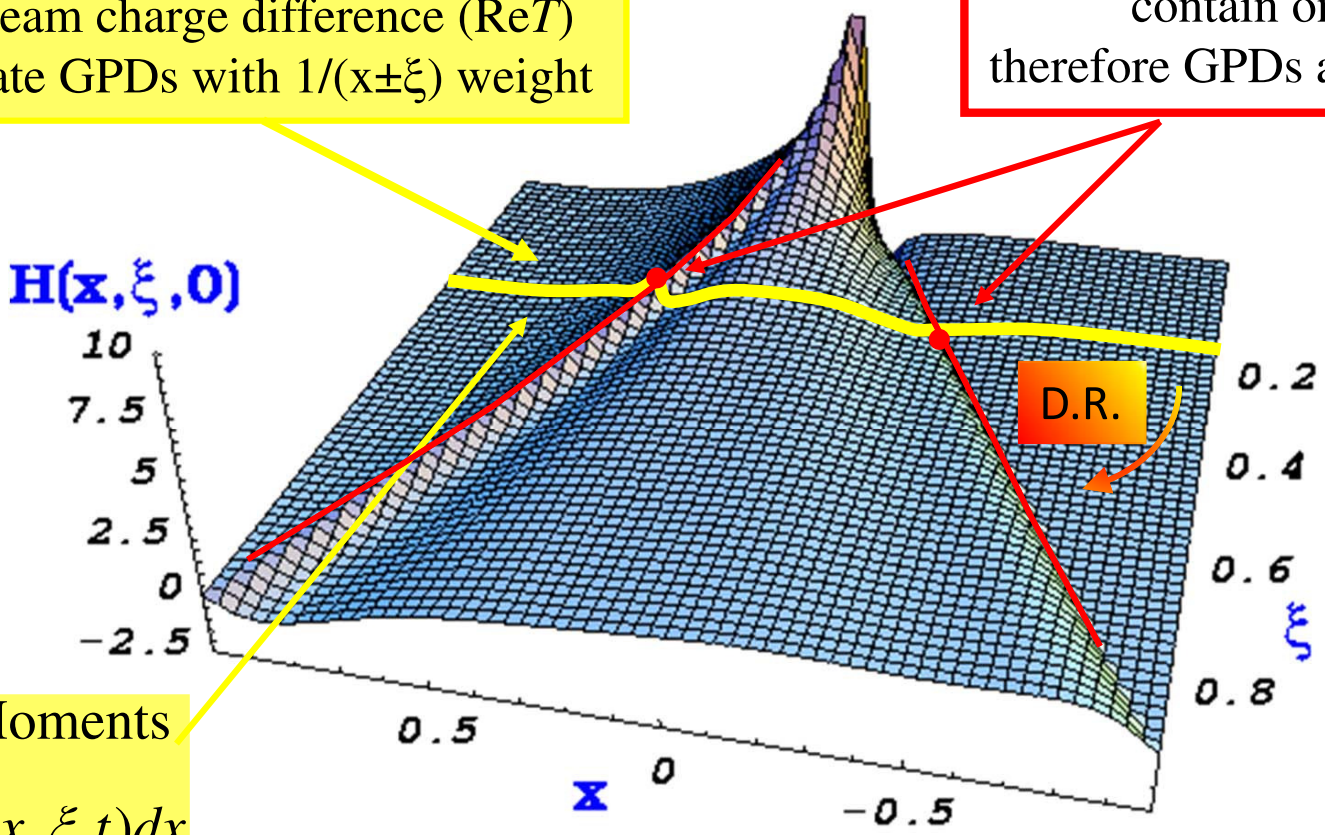
$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g \quad \Rightarrow \quad J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

DVCS cleanest process to access GPDs

GPD experimentally: Compton Form Factors (CFFs)

Cross-section (σ) measurement and beam charge difference (Re*T*) integrate GPDs with 1/(x±ξ) weight

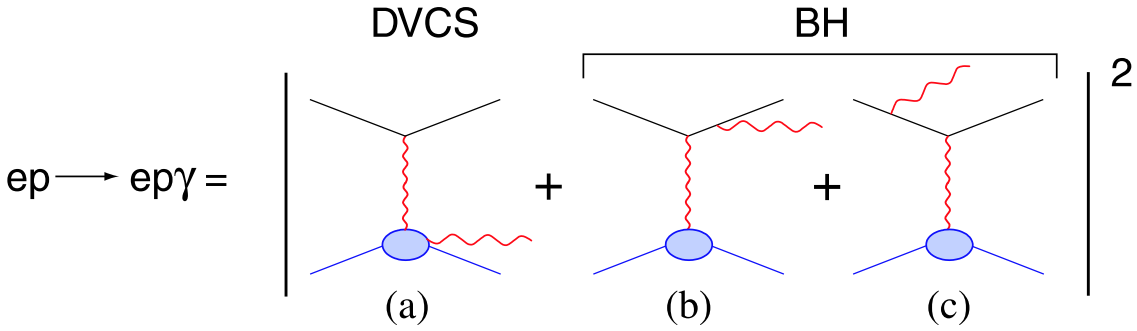
Beam or target spin Δσ contain only Im*T*, therefore GPDs at $x = \xi$ and $-\xi$



Lattice Moments

$$= \int x^n H(x,\xi,t)dx$$

DVCS experimentally: interference with Bethe-Heitler



At leading twist:

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

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

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

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

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)

$$d\sigma_{UL} = \sin\phi \cdot \mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_BkF_2\tilde{\mathcal{E}}\ldots\}d\phi$$

Polarized beam, longitudinal target (BITSA)

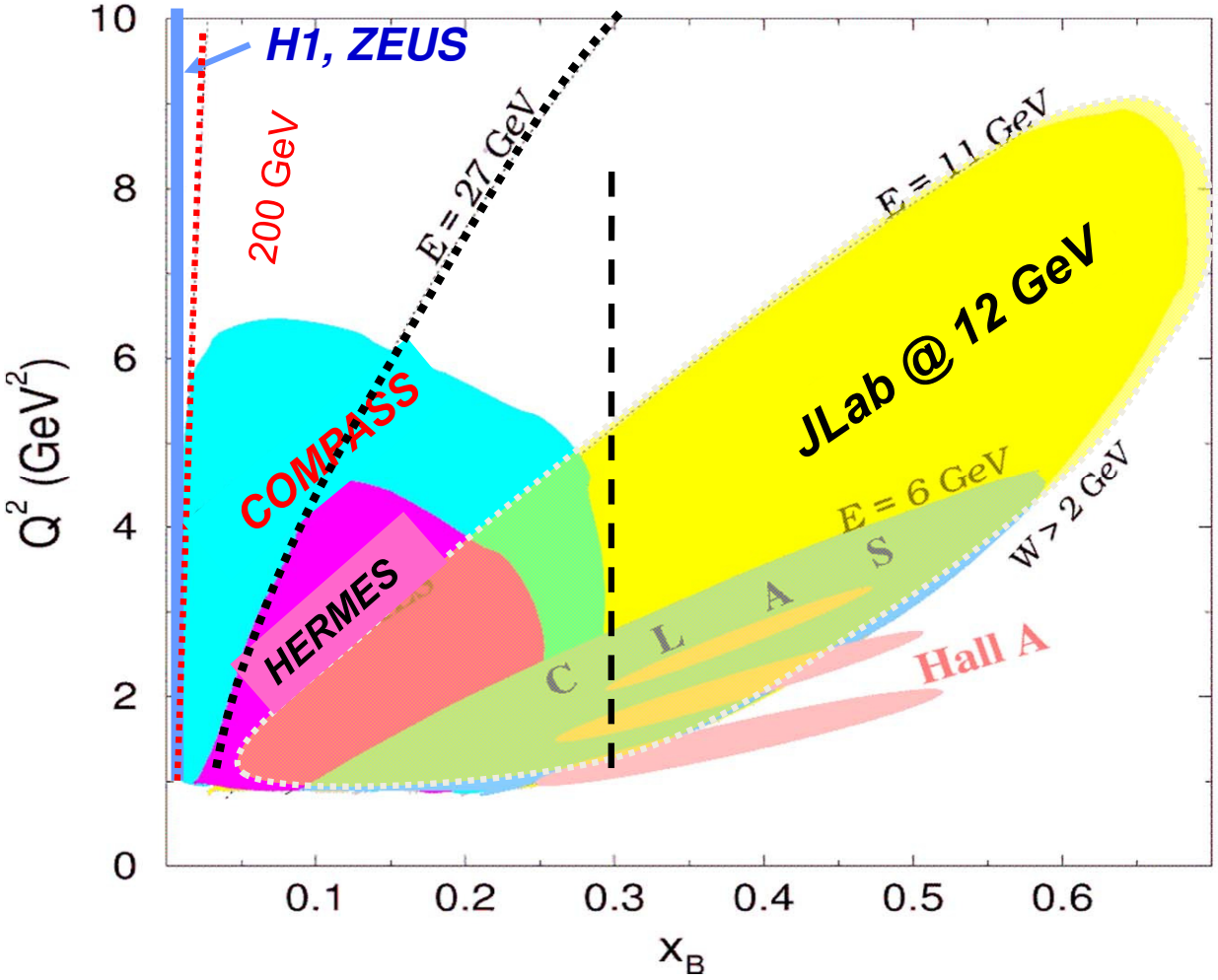
$$d\sigma_{LL} = (A + B\cos\phi) \cdot \mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\ldots\}d\phi$$

Unpolarized beam, transverse target (tTSA)

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

Kinematic coverage

Kinematic complementarity between different facilities:



The DVCS program at Jefferson Lab

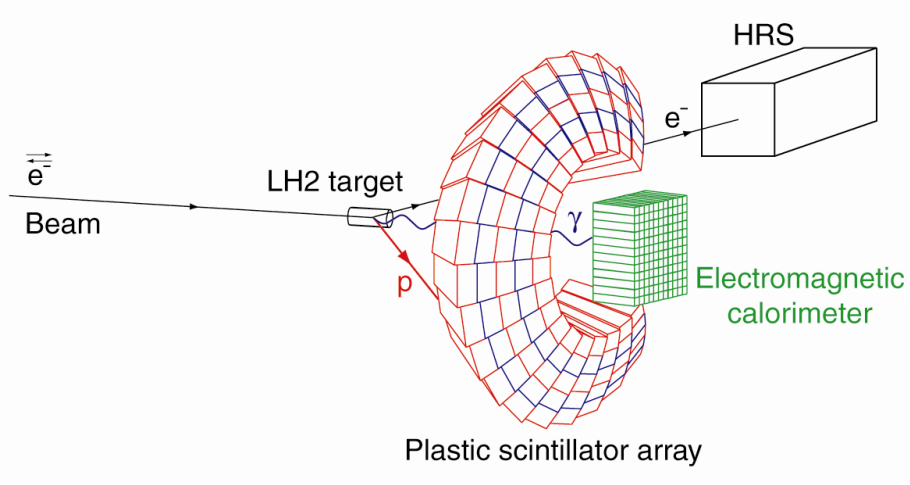
- Hall A: high accuracy, limited kinematic coverage
- Hall B: wide kinematic range, limited precision
- Hall C: high precision program at 11 GeV

Partially overlapping, partially complementary programs with different experimental setups

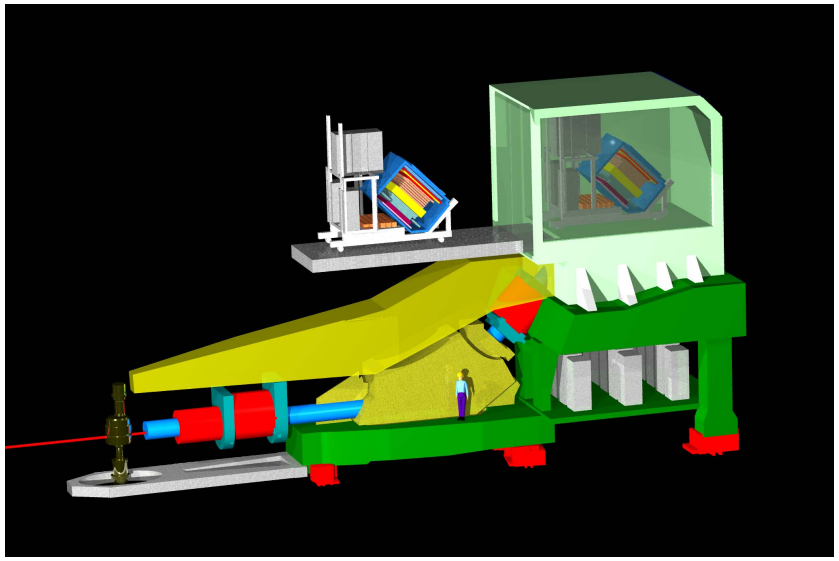
The roadmap:

- 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 + additional spin observables
- Compeling DVCS experiments in Halls A+B+C at 11 GeV ($\gtrsim$2017)

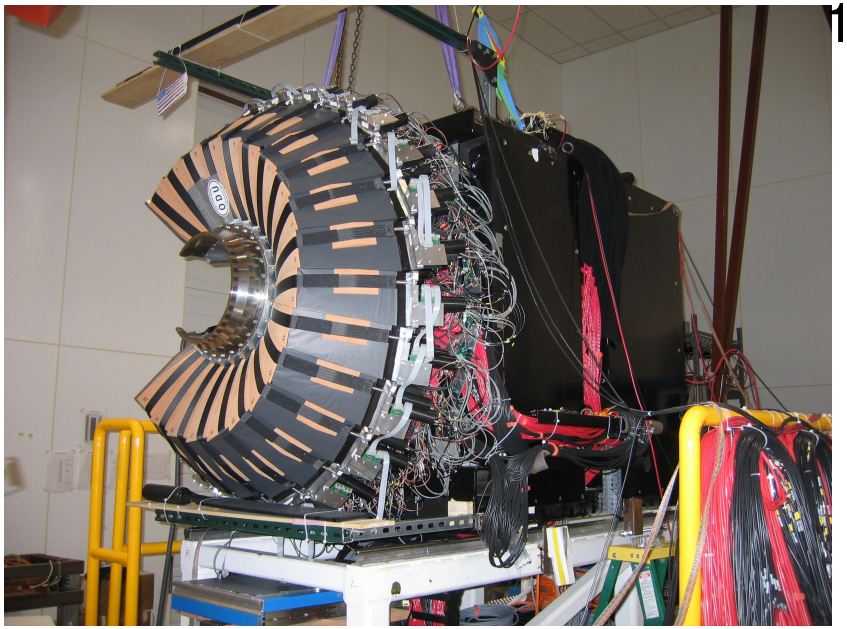
E00-110 experimental setup



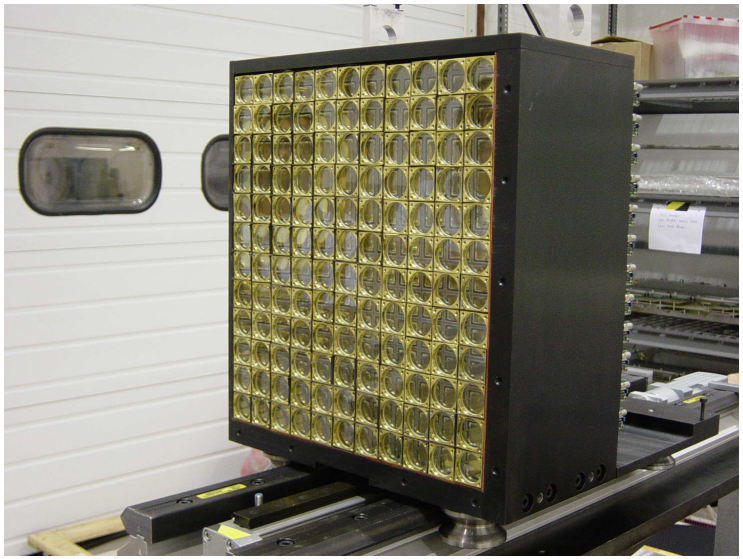
High Resolution Spectrometer



100-channel scintillator array

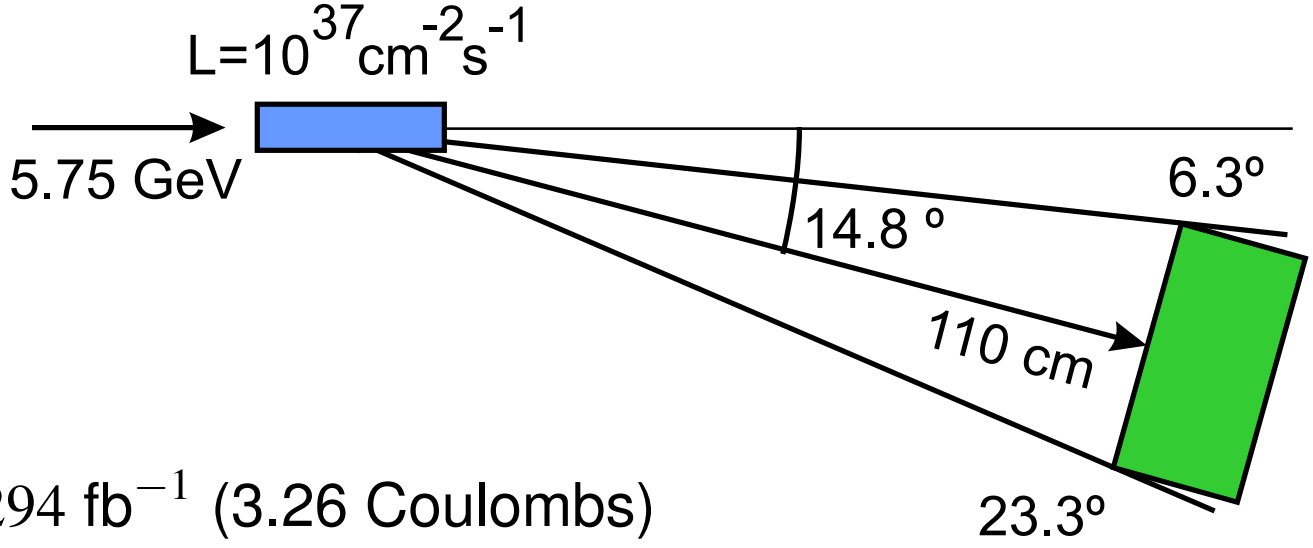


132-block PbF_2 electromagnetic calorimeter



Kinematic settings: testing Q^2–dependance

Kin	Q^2 (GeV^2)	x_B	θ_e (deg.)	θ_{γ^*} (deg.)	P_e (GeV)
1	**1.5**	0.36	15.6	**22.3**	3.6
2	**1.9**	0.36	19.3	**18.3**	2.9
3	**2.3**	0.36	23.9	**14.8**	2.3

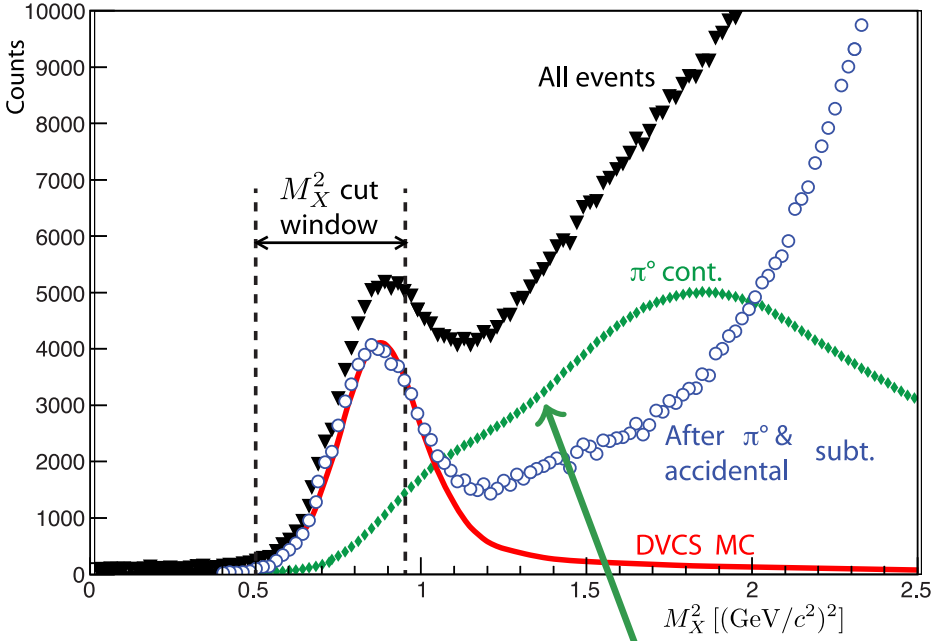


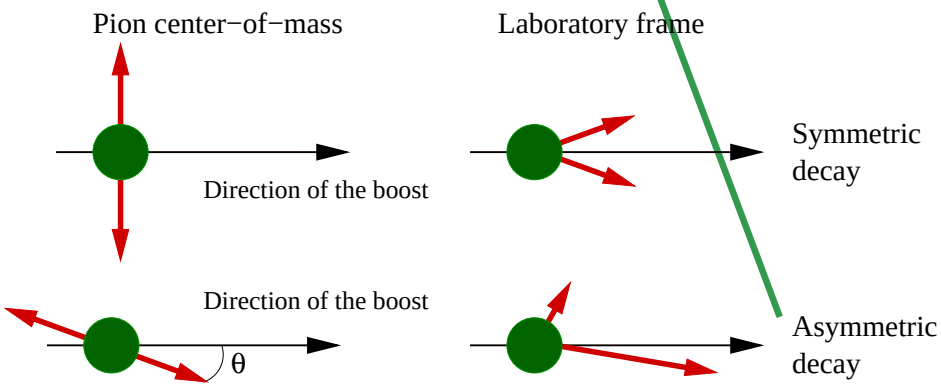
$\mathcal{P} = 75.3\%$

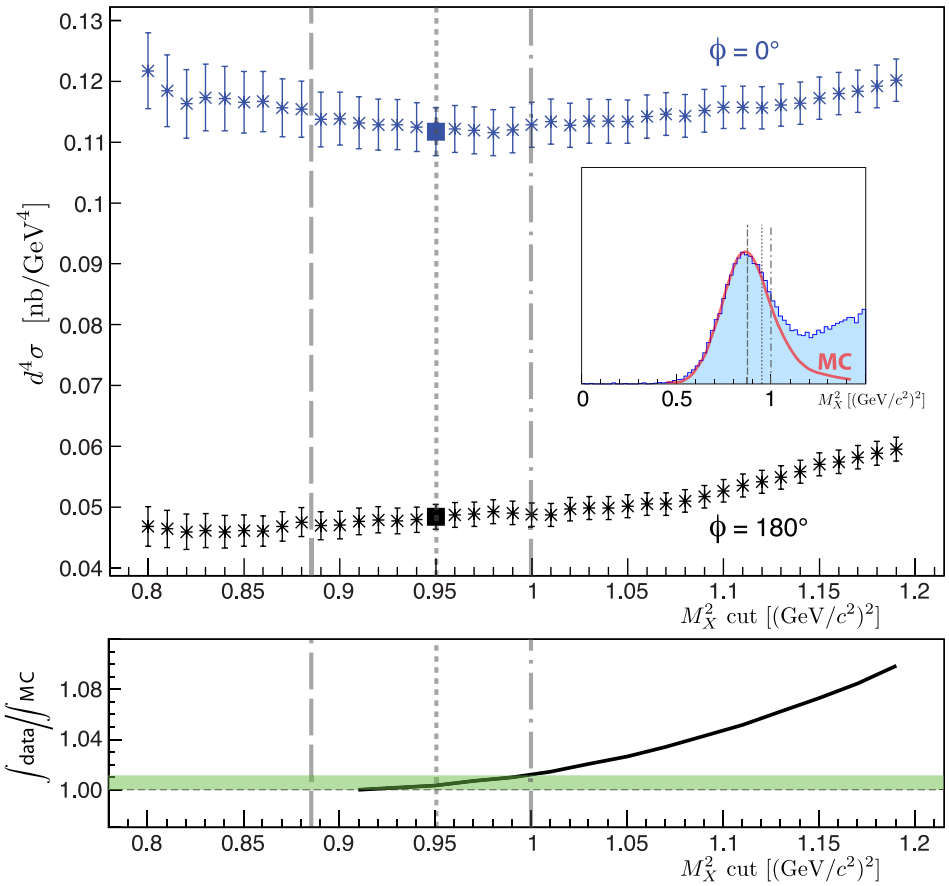
$\int \mathcal{L}\, dt = 13294$ fb^{-1} (3.26 Coulombs)

Data analysis: exclusivity and background subtraction

$ep \to e\gamma X$ missing mass squared



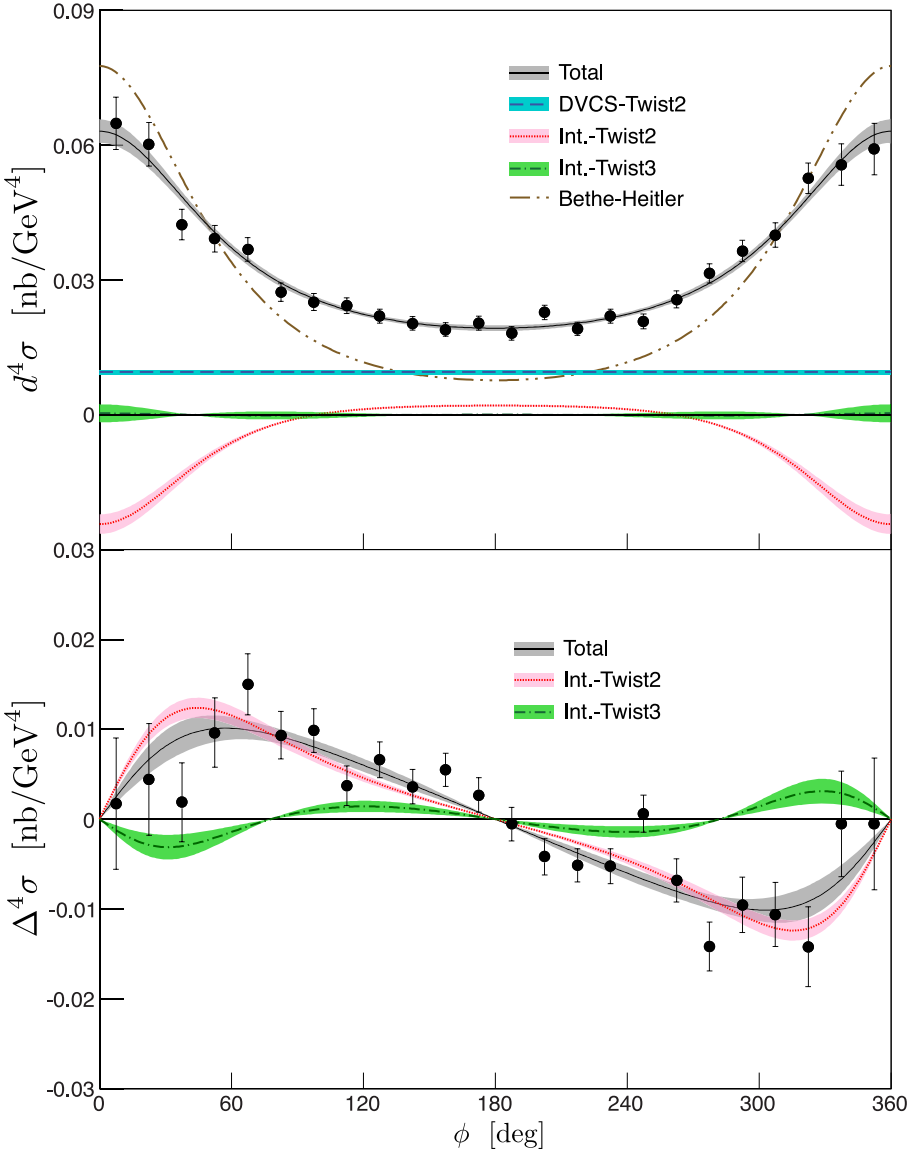


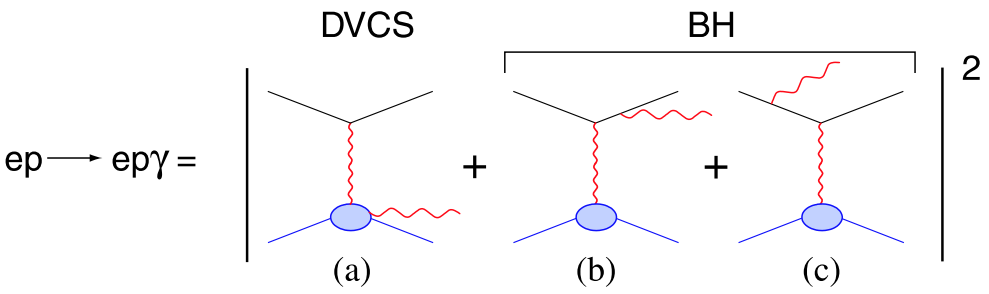


- Only e' & γ detected + M_X^2-cut
- 2-3% uncertainty on exclusivity

DVCS cross sections: azimuthal analysis

$Q^2 = 2.36$ GeV^2, $x_B = 0.37$, $-t = 0.32$ GeV^2





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

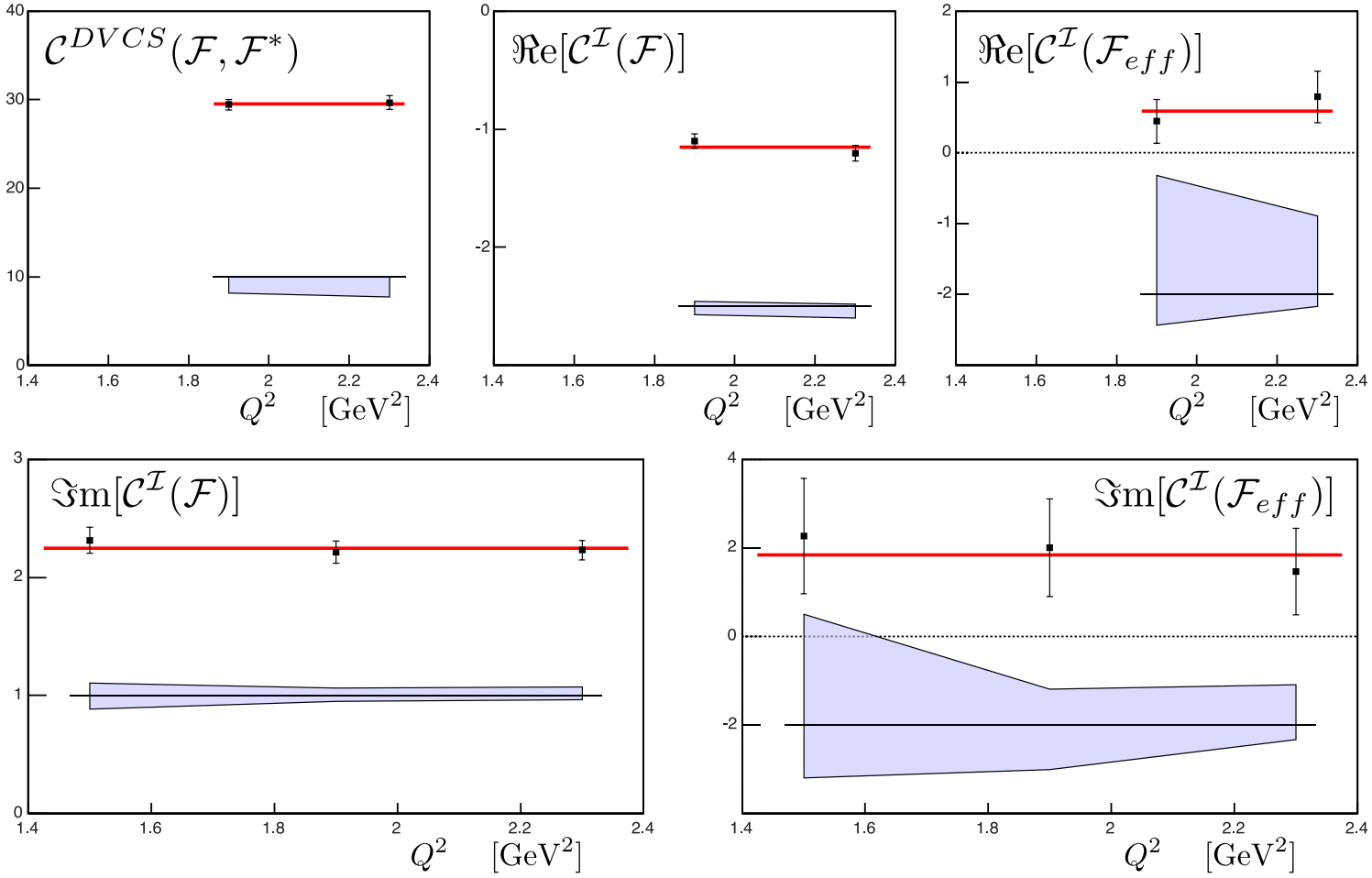
$$\mathcal{R}e(\mathcal{T}_{\mathrm{DVCS}}) \sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}}\cos\phi + c_2^{\mathcal{I}}\cos 2\phi$$

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

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

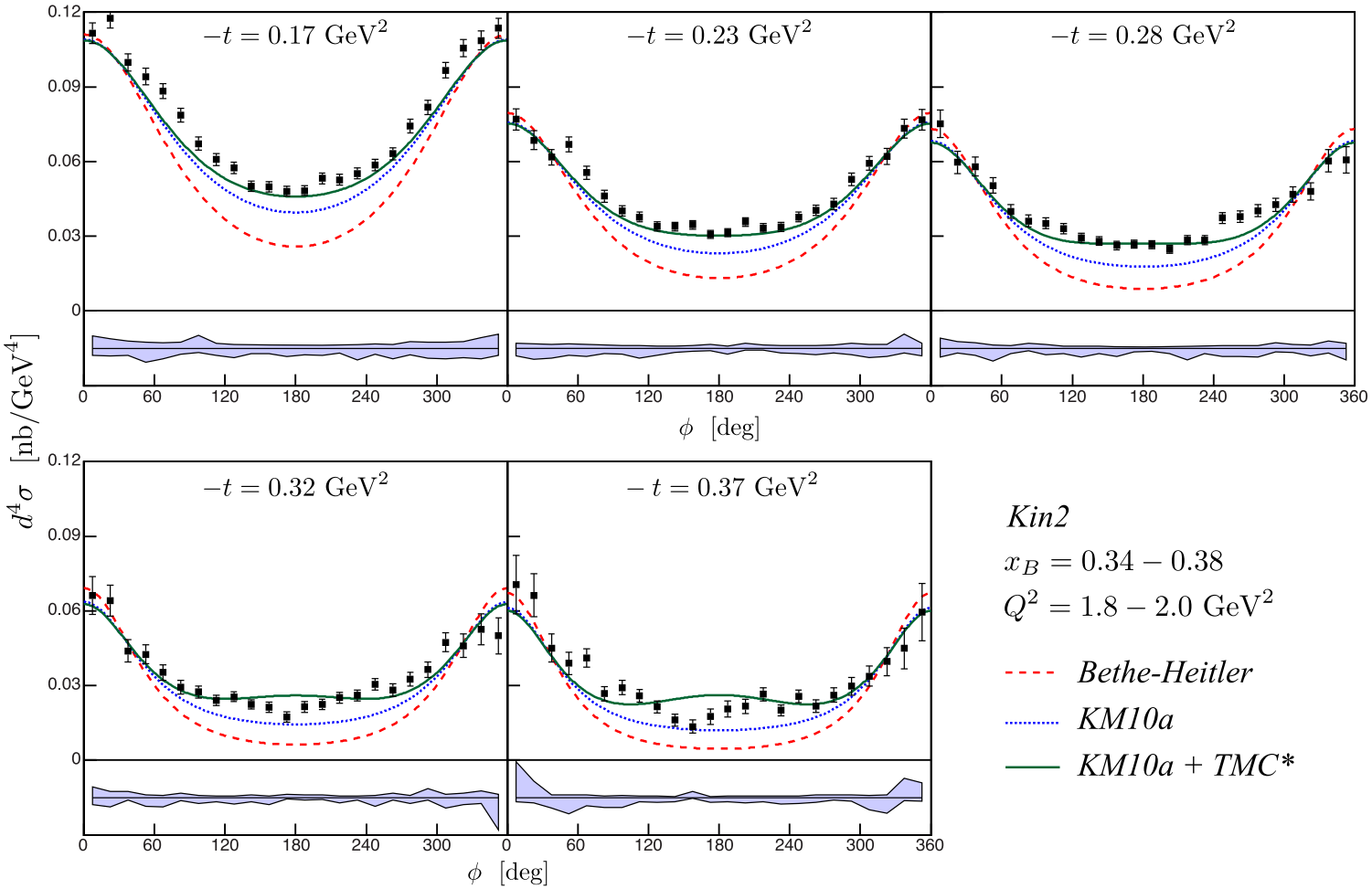
$$\mathcal{I}m(\mathcal{T}_{\mathrm{DVCS}}) \sim s_1^{\mathcal{I}}\sin\phi + s_2^{\mathcal{I}}\sin 2\phi$$

DVCS cross sections: Q^2–dependance



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

DVCS cross sections: higher twist corrections



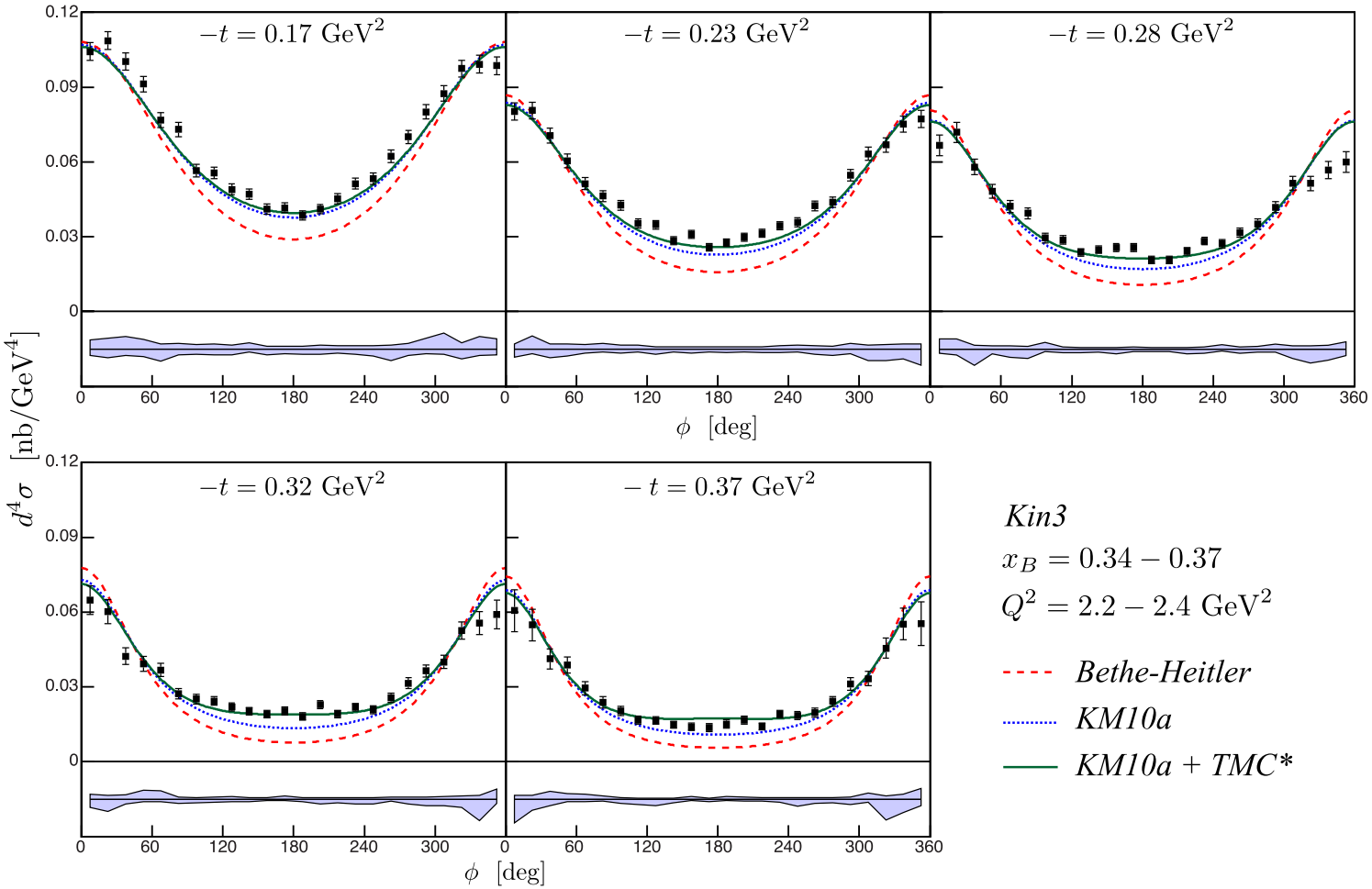
- KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries

  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



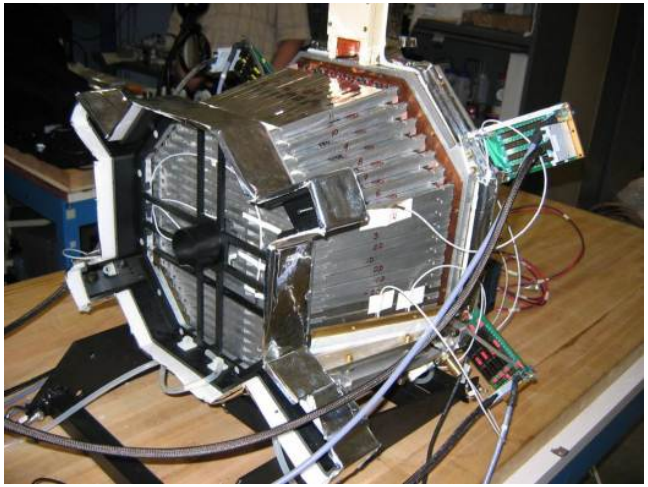
- Significant deviation from BH cross section
- Twist-4 corrections may be necessary to fully explain experimental data

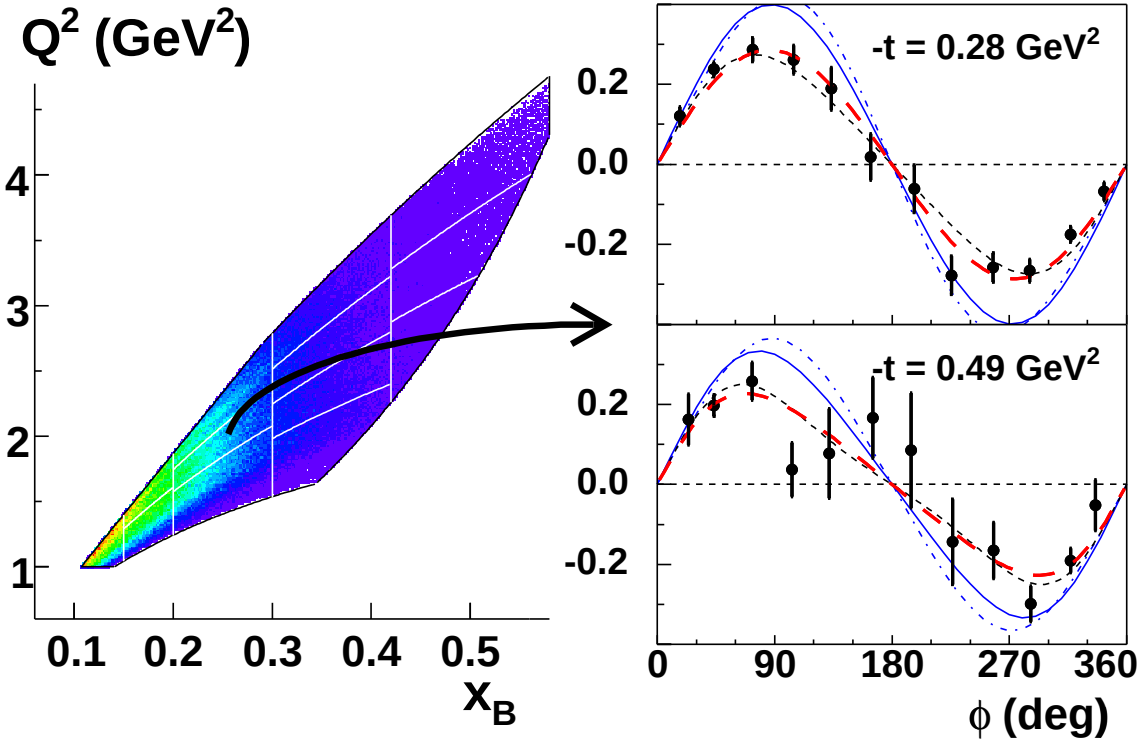
Hall A DVCS precision measurements

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

E01-113: BSA in a large kinematic domain (Hall B)

CLAS+
dedicated calorimeter

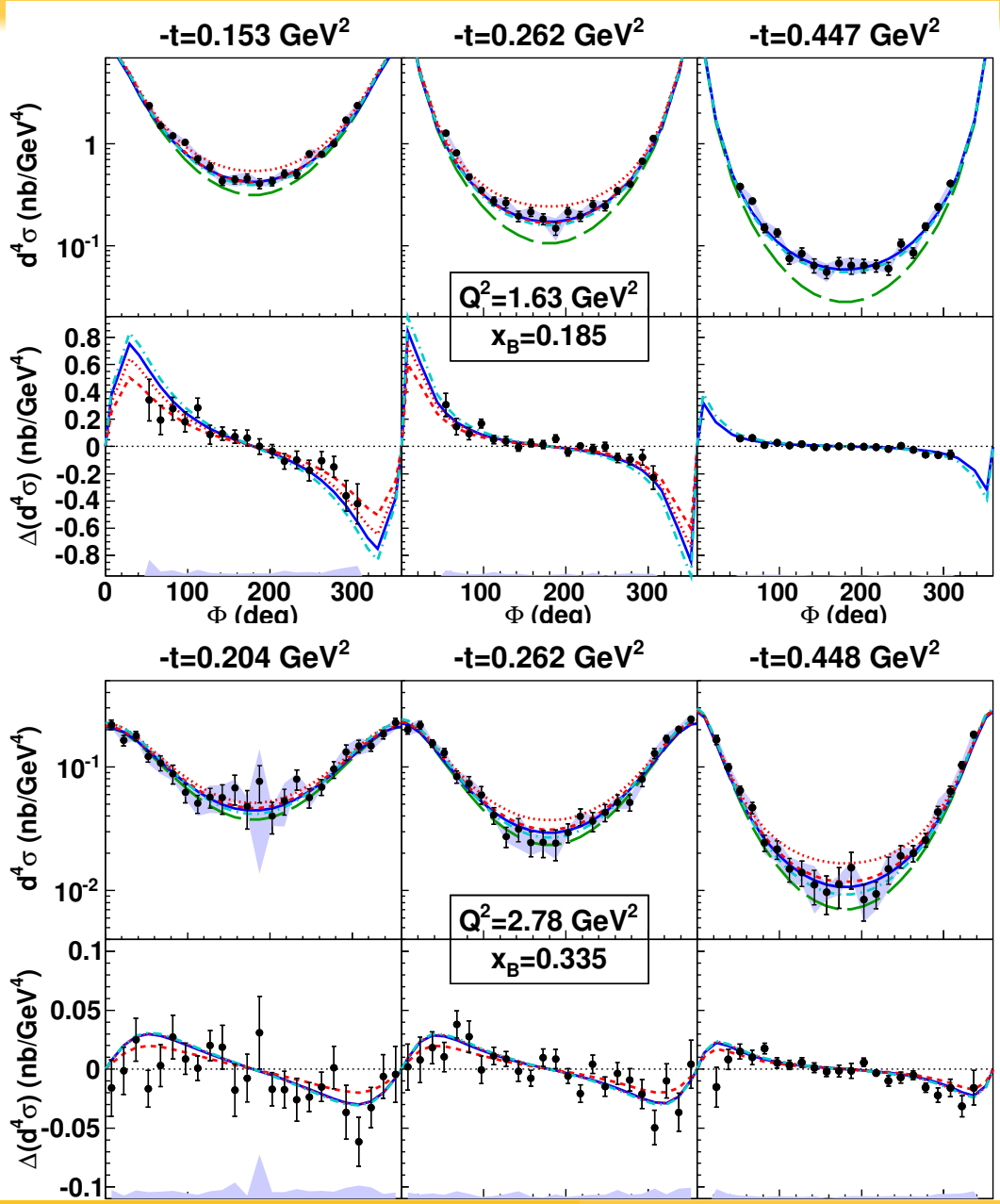




$$A = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \approx \frac{\alpha \sin\phi}{1 + \beta \cos\phi}$$

F.X. Girod *et al.* PRL **97**, 072002 (2006)

Hall B DVCS cross-section measurements



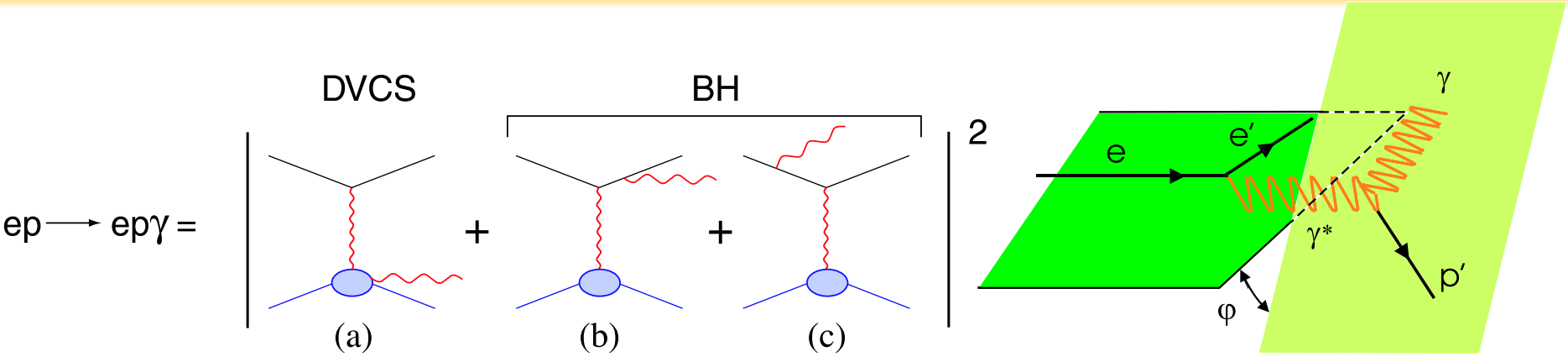
- Larger kinematic range covered:
  110 (Q^2, x_B, t) bins
- Compatible with Hall A results in overlap region
- Leading twist models describe the data within uncertainties

H.S. Jo *et al.*
arXiv:1504.02009, Apr 8 (2015)

JLab 6 GeV program and beyond

1. Complementarity of Hall A and Hall B programs:
   - Precision measurements:
     Q^2-dependences, higher-twist corrections...
   - Large kinematic coverage:
     x_B and t dependences of observables
2. Upcoming at 6 & 12 GeV:
   - Beam energy depedence of the cross sections
   - Higher values and lever-arm in Q^2

E07-007 (Hall A)



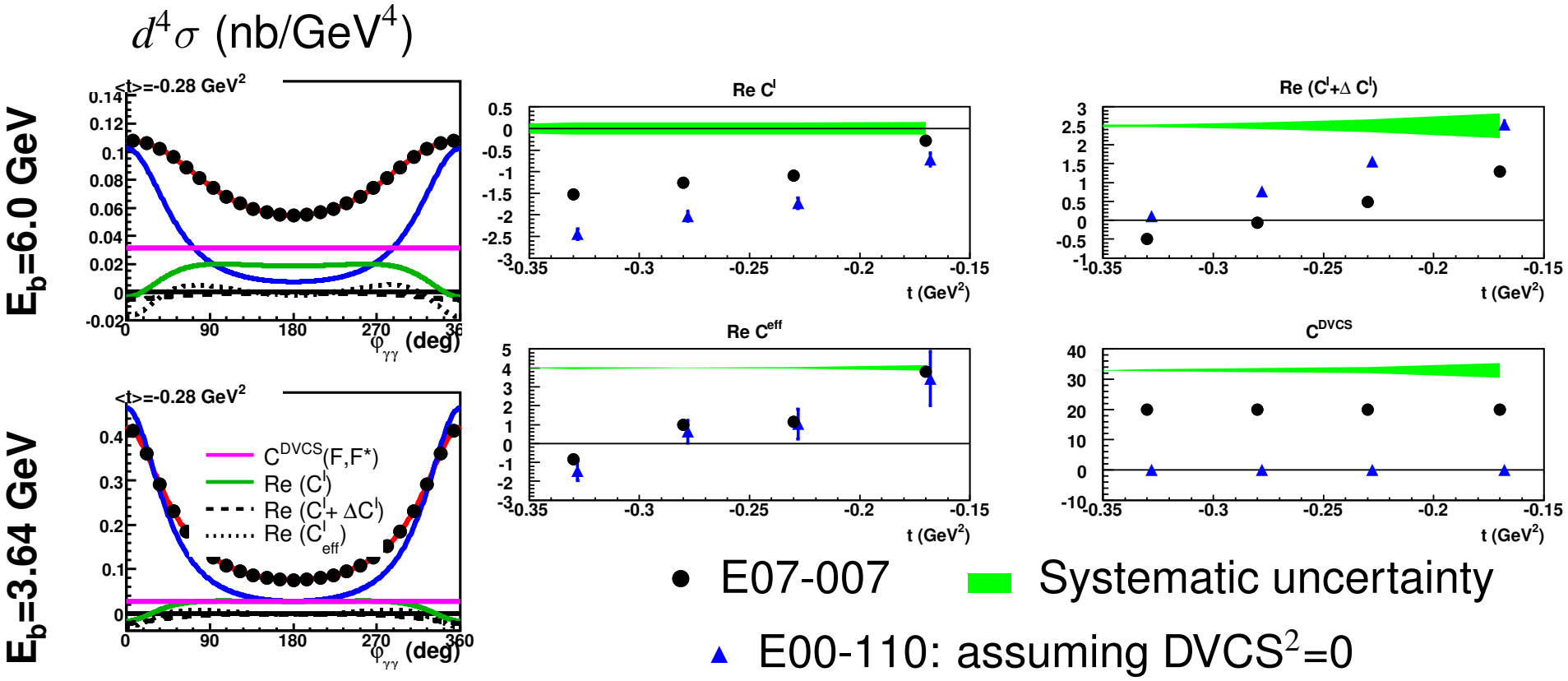
$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

DVCS cross section has a very rich azimuthal structure:

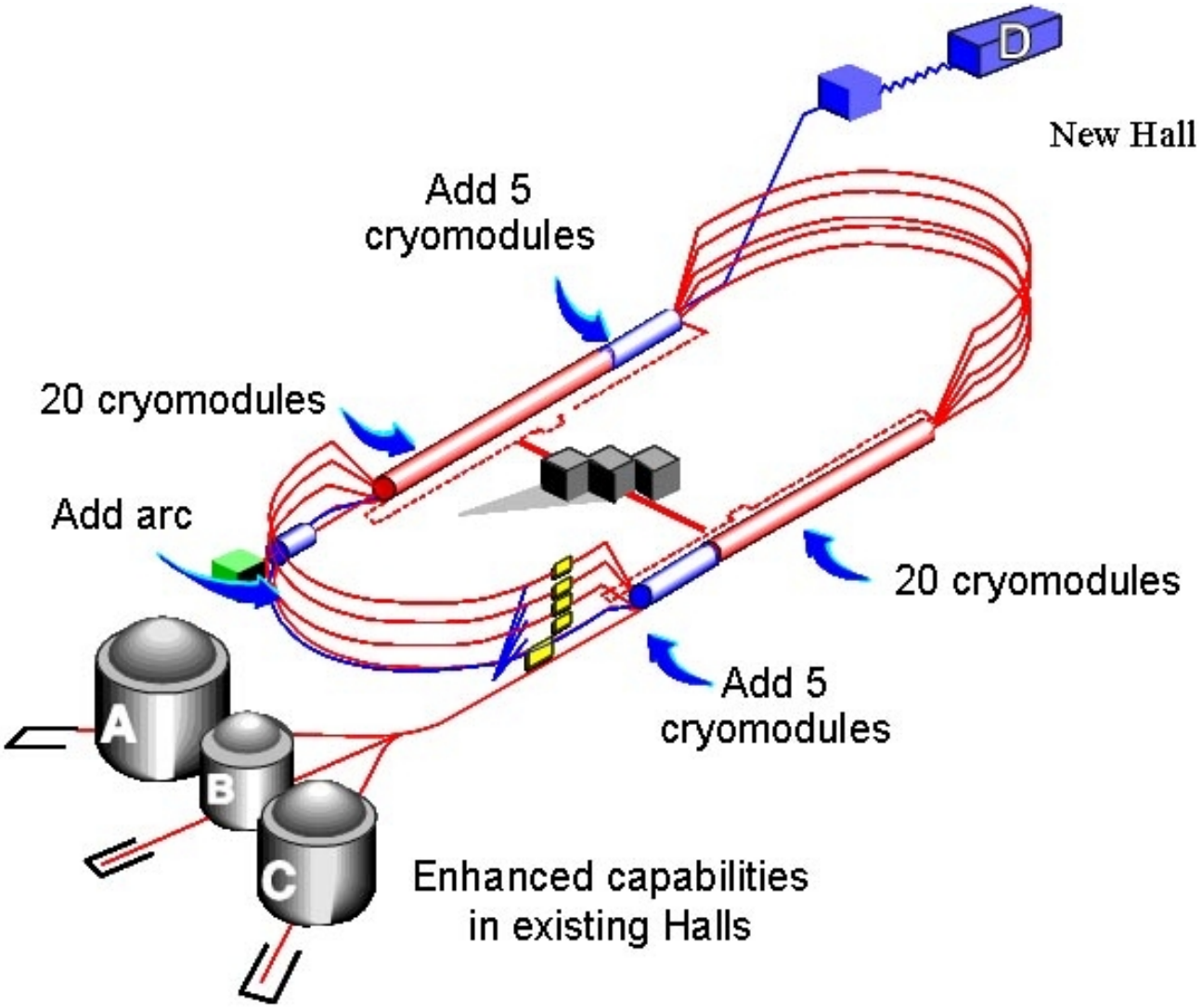
- Azimuthal analysis allows the separation of the different contributions to $\mathcal{I}$ if DVCS^2 is negligeble.
- If DVCS^2 is important, $\mathcal{I}$ and DVCS^2 terms **MIX** in an azimuthal analysis.
- The **different energy dependence** of $\mathcal{I}$ and DVCS^2 allow a full separation

E07-007: Rosenbluth-like DVCS^2–$\mathcal{I}$ separation

- Clean separation of BH-DVCS intereference term from pure DVCS^2
- Scaling test on the real part of the DVCS amplitude
- Rosenbluth separation of σ_L/σ_T for $ep \to ep\pi^0$



Upgrade of Jefferson Lab to 12 GeV



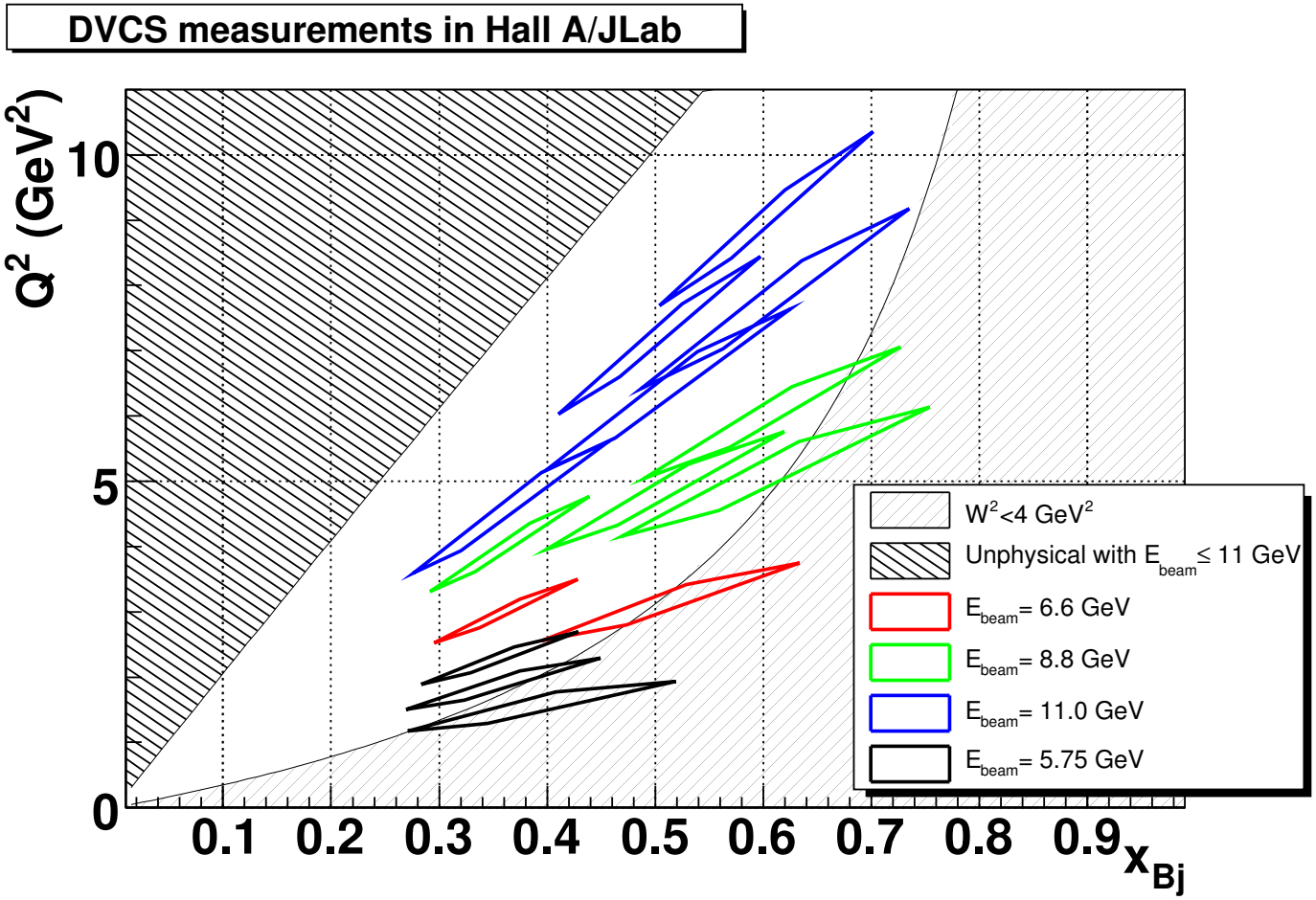
JLab 12 GeV DVCS experiments

- 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)

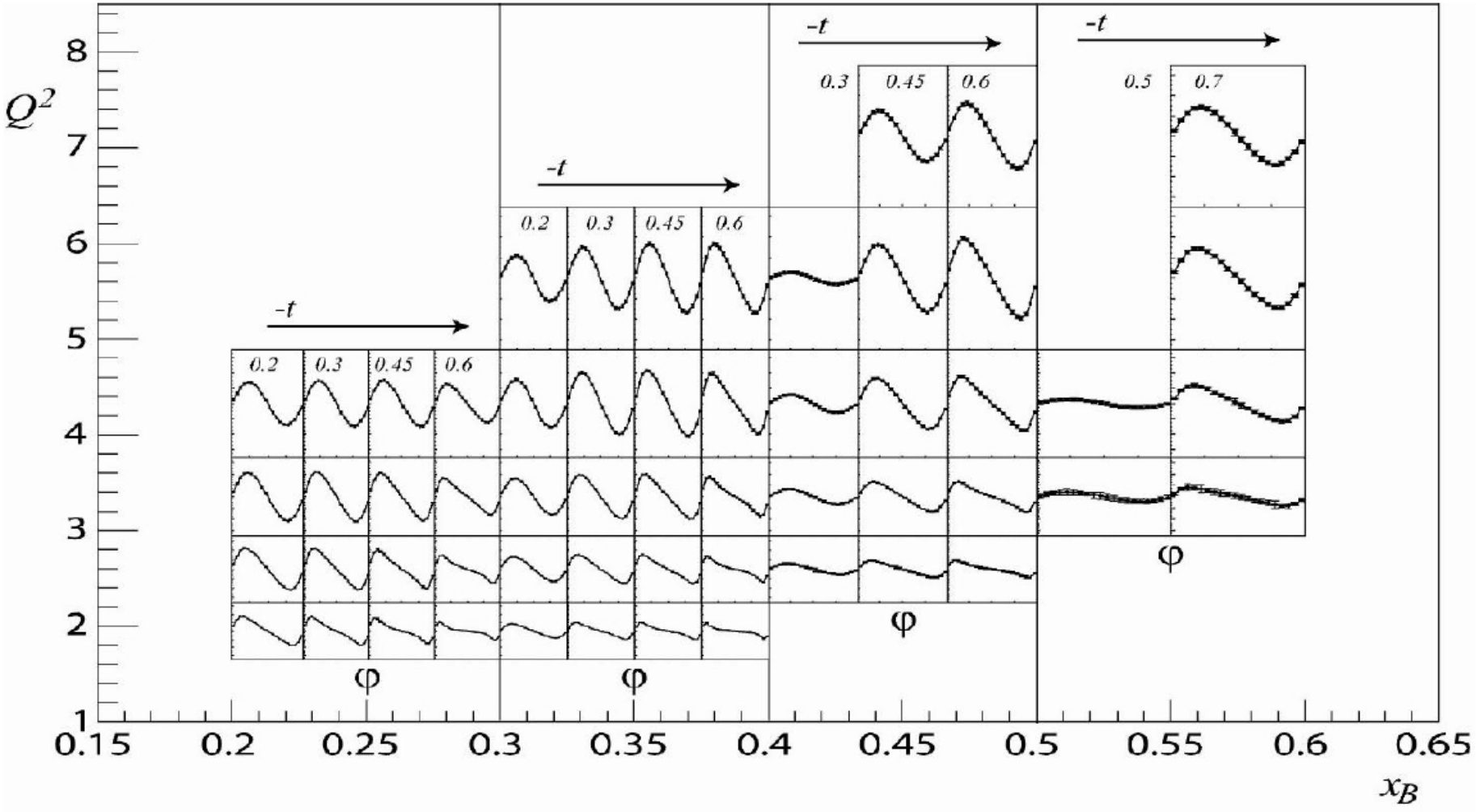


88 days

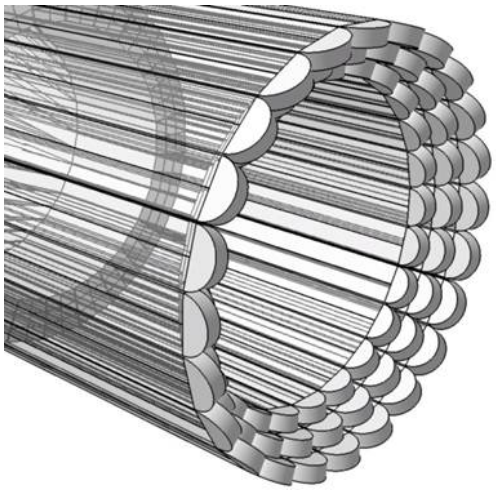
250k events/setting

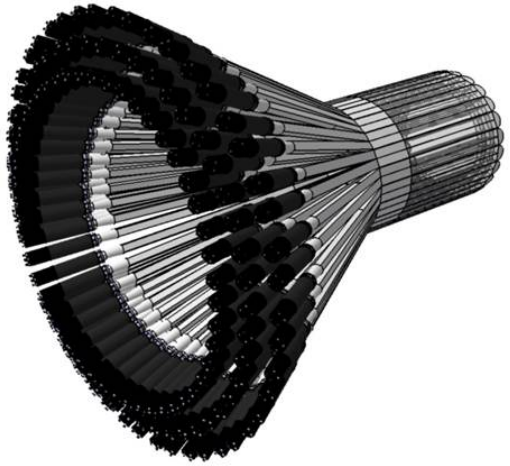
1 year of operations in JLab/Hall A

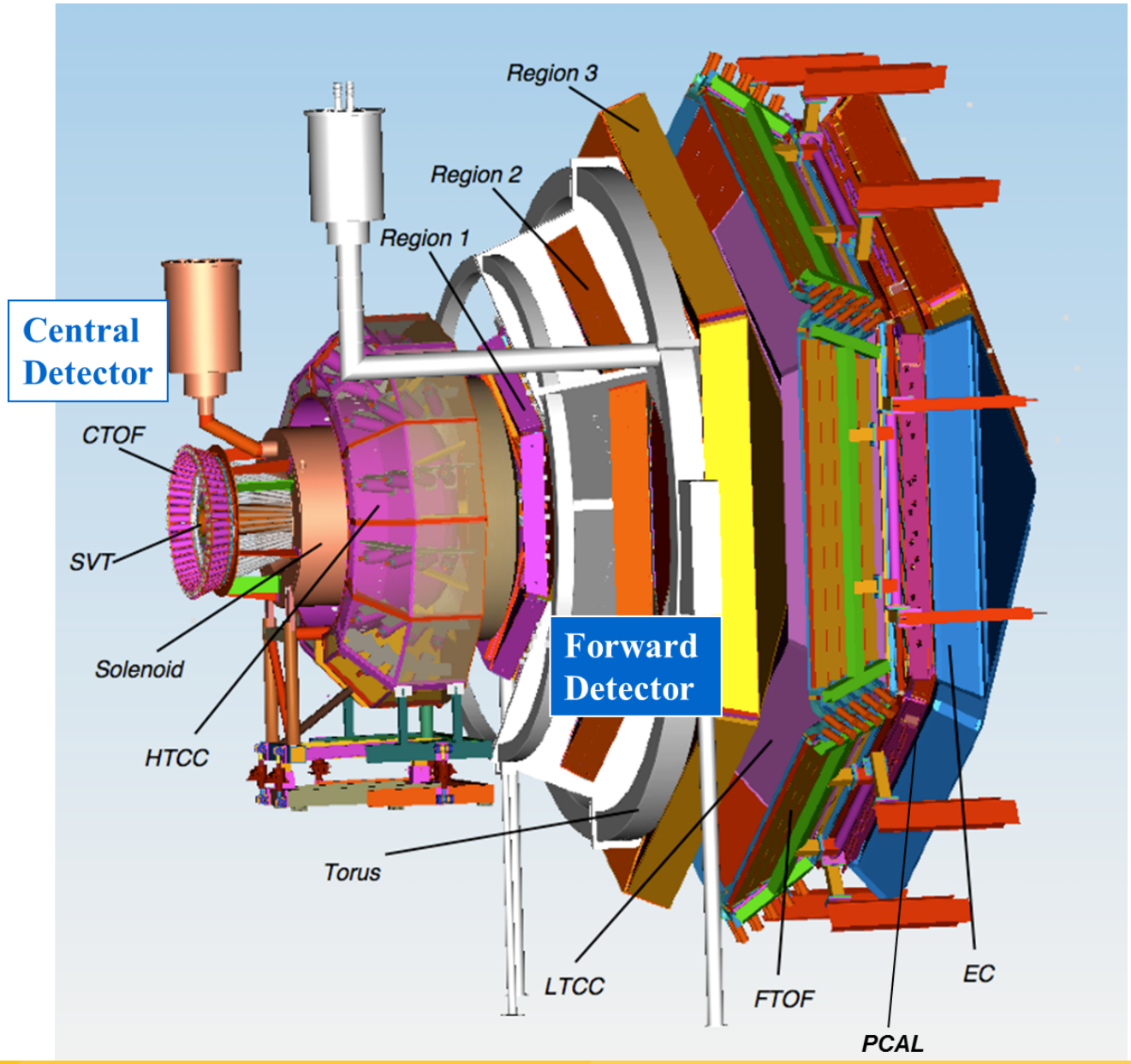
E12-06-119: DVCS on the proton with CLAS12



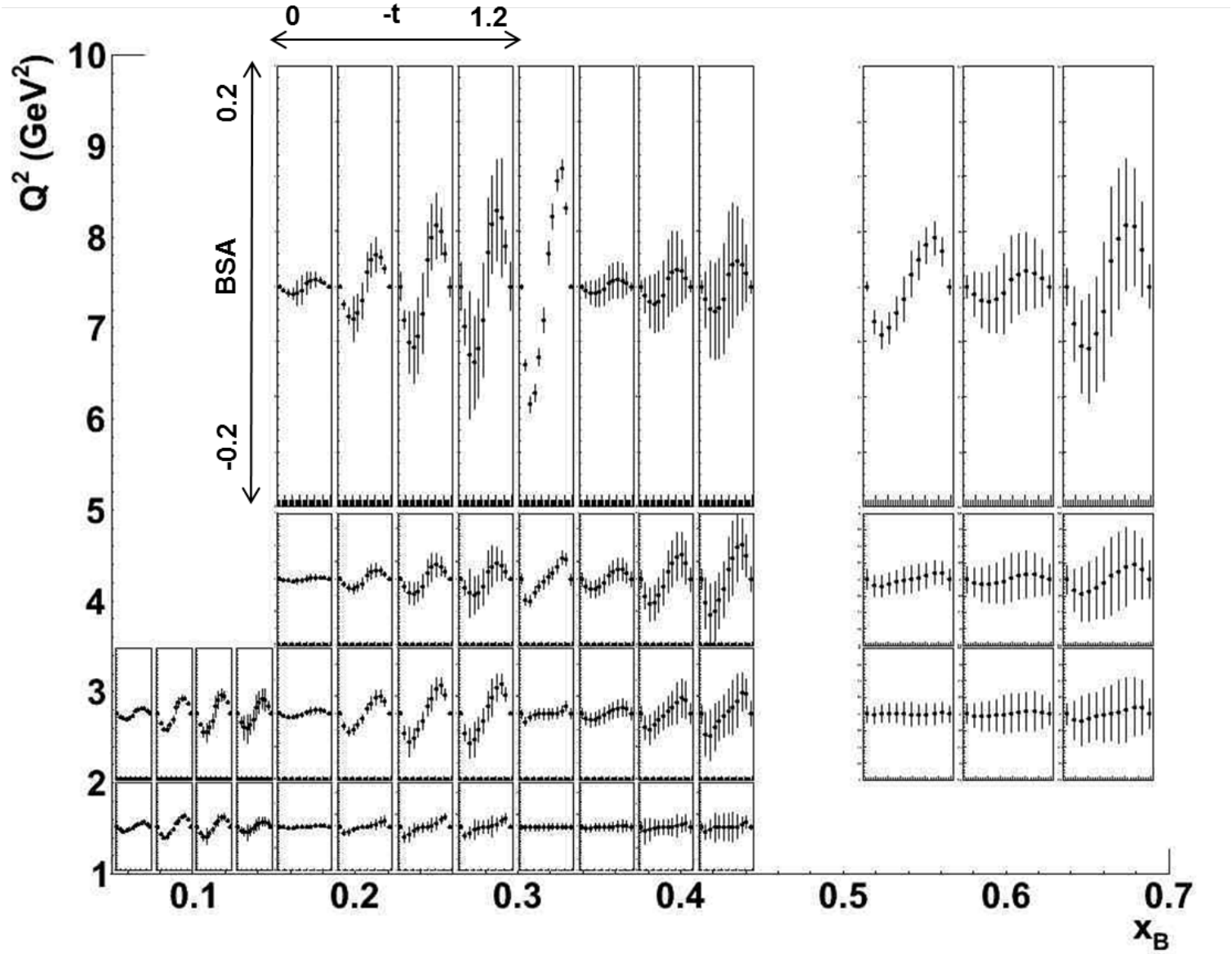
E12-11-003: DVCS on the neutron with CLAS12





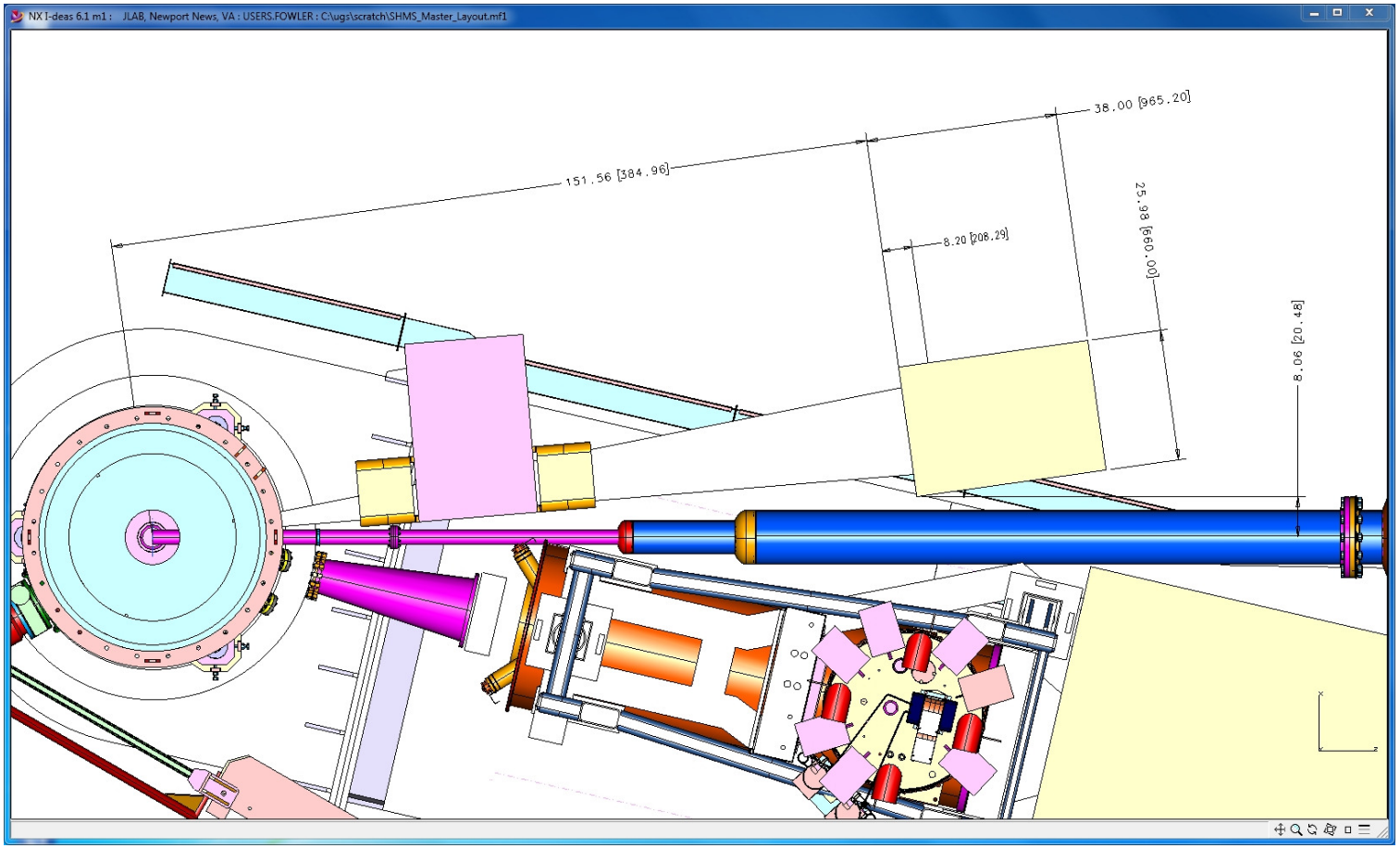


E12-11-003: projections

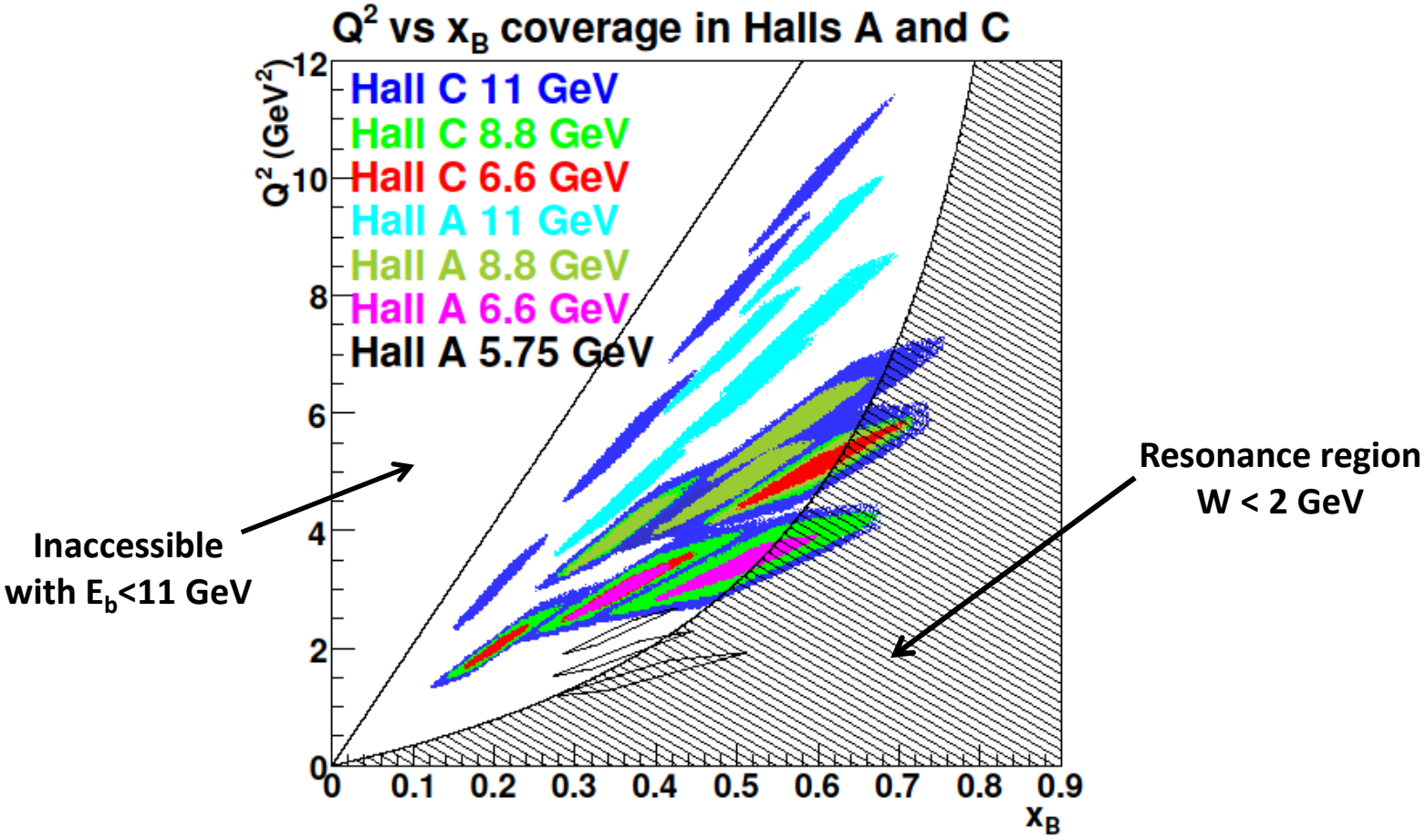


E12-13-010: DVCS in Hall C

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



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:
  - Time-like Compton Scattering (WG1 M. Boër's talk)
  - Deep meson production (WG6 M. Defurne's next talk)
- 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