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Award #2209199

# Precision studies of the DVCS process at JLab

Julie Roche

- Generalized Parton Distributions (GPD) are accessible through many exclusive processes. So far, the most studied channels are Deeply Virtual Compton Scattering (DVCS) and Deep Virtual Meson production (DVMP).
- Our JLab Hall A/C collaboration measures DVCS and DVMP-$\pi$0 absolute cross-section using a "simple" dedicated apparatus since 2006.
- Our precise (5%) measurements are essential to interpret the data.
- We just completed a new set of measurements in Hall C/JLab using a new $PbWO_4$ calorimeter and expanding our kinematic reach.



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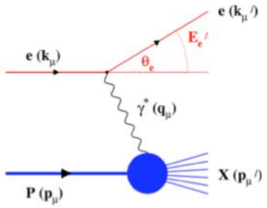
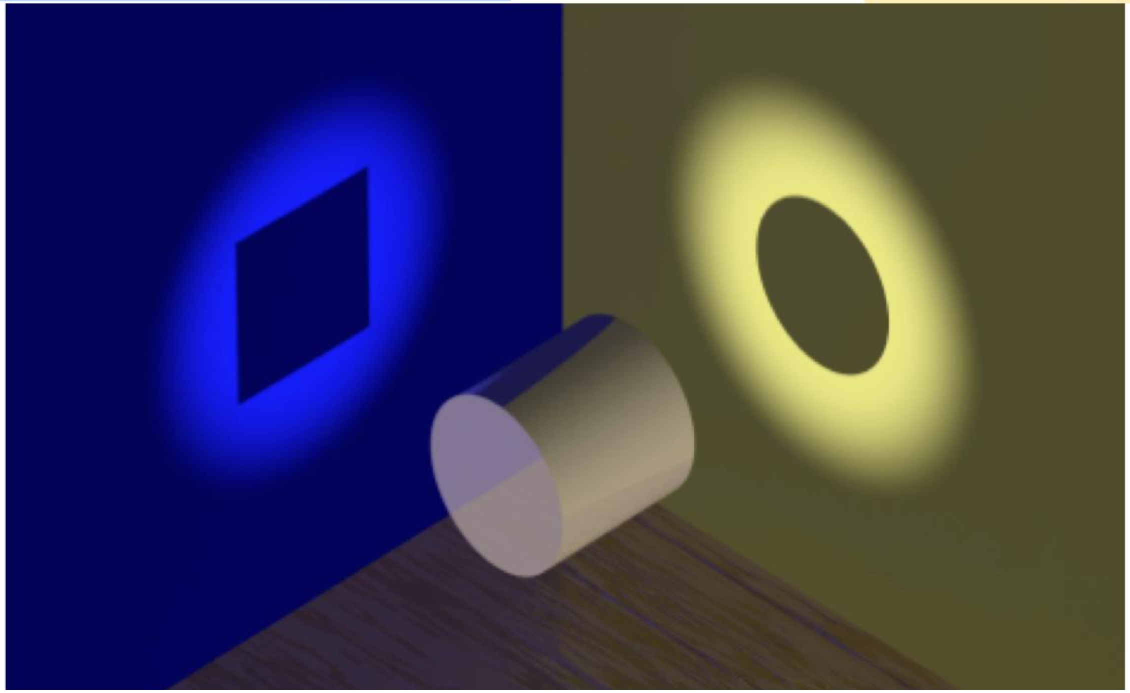
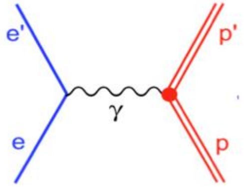
## DIS Parton Distribution Functions

## Elastic Form Factors




No information on the spatial location of the constituents

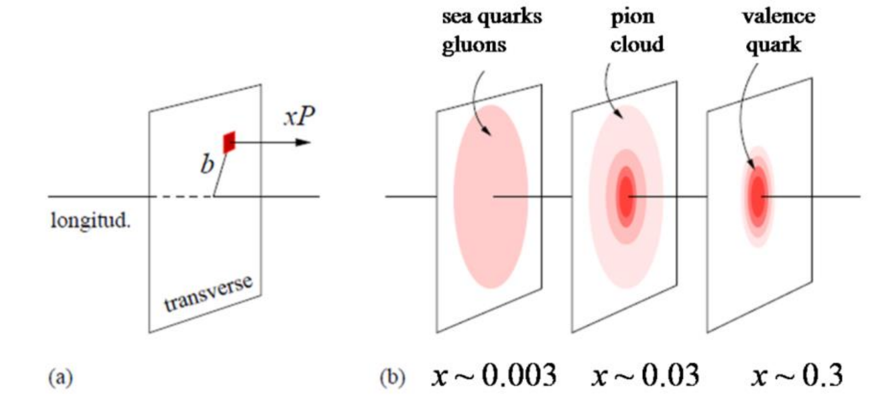




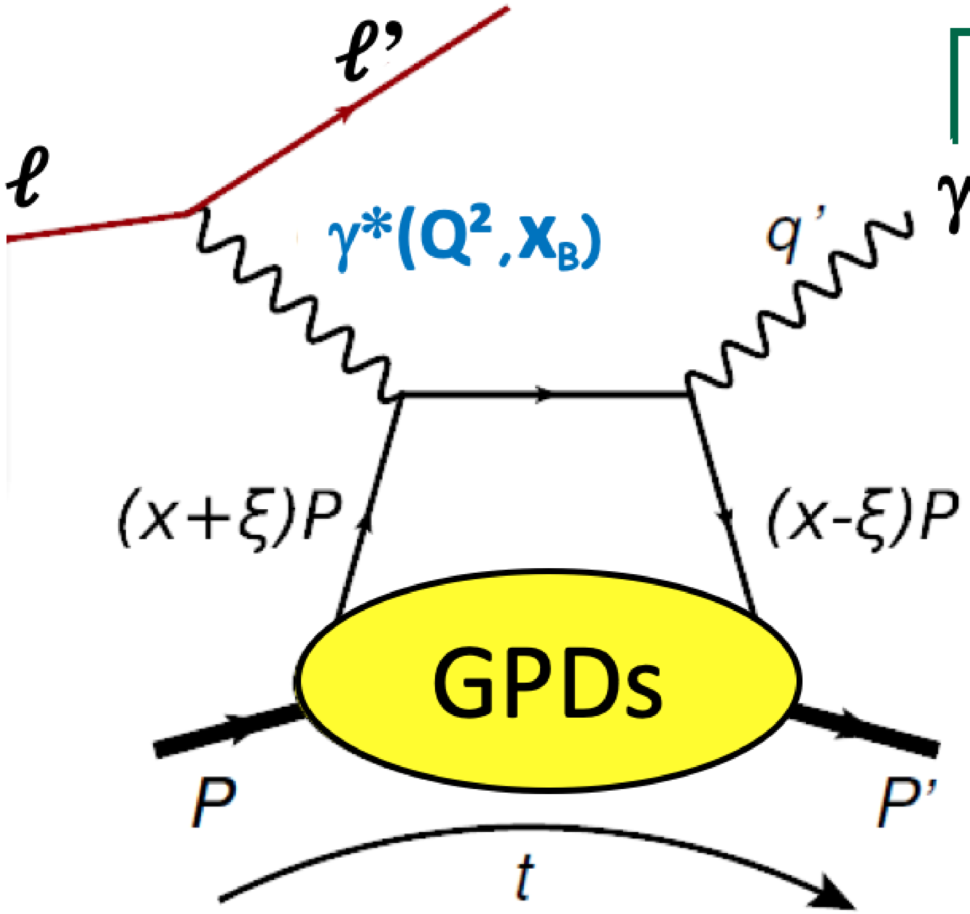

No information about the underlying dynamics of the system

**Generalized Parton Distribution Function** :

3-D imaging of the nucleon with access to **correlations** between **transverse spatial distribution and longitudinal momentum distributions.**



# Exclusive reactions: handbag diagram




$\gamma$ or $\pi, \rho, \phi, J/\psi, \ldots$

DVCS : golden channel

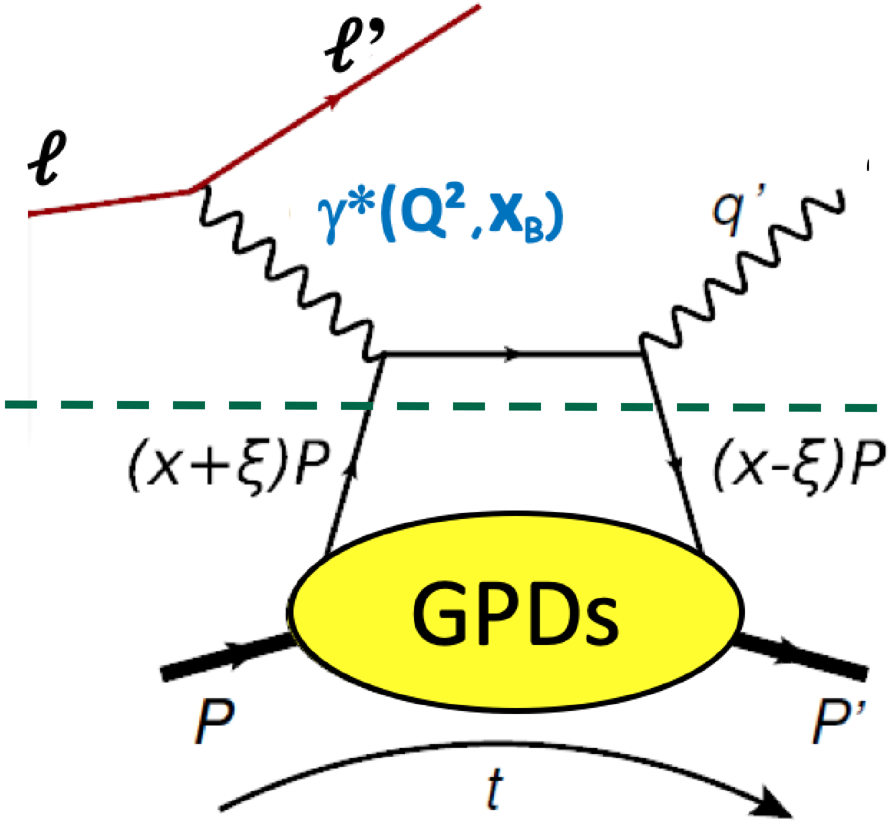
DVMP

Definition of variables:

- x: average long. momentum
- $\xi$: long. mom. difference $\simeq x_B/(2 - x_B)$
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

# GPDs and factorization

In the Bjorken limit: $\left.\begin{matrix} Q^2 = -q^2 \to \infty \\ \nu \to \infty \end{matrix}\right\} \quad x_B = \frac{Q^2}{2M\nu} \quad \text{fixed}$




Hard process
LO: QED
NLO: QCD perturbative

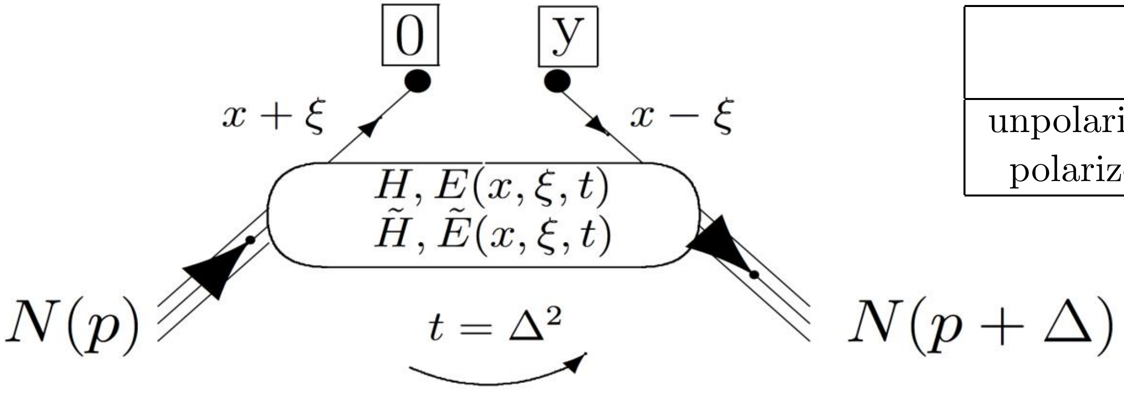
D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

Soft process
Non perturbative QCD
described by GPD(x,ξ,t)

x is not accessible, one measures CFF(ξ,t)=CFF($x_B$,t)

$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\pi H(x=\xi,\xi,t)$$

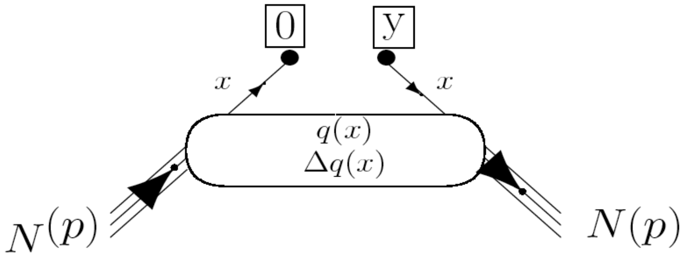
# Generalized Parton Distributions




| | Nucleon Helicity | |
|---|---|---|
| | conserving | non-conserving |
| unpolarized GPD | H | E |
| polarized GPD | $\tilde{\text{H}}$ | $\tilde{\text{E}}$ |

$$\lim_{t\to 0}(GPD) \to PDF$$

DIS

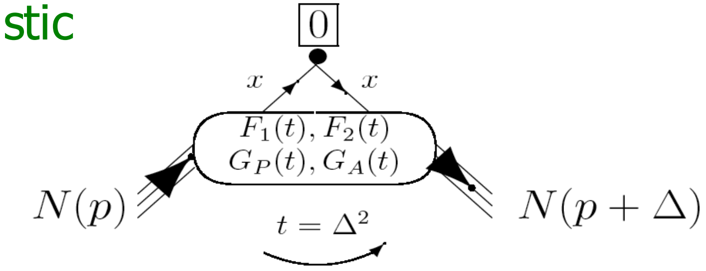



$$H^q(x,0,0) = q(x), -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \Delta\bar{q}(-x)$$

$GPD$ first moments $\to$ Form Factors

Elastic



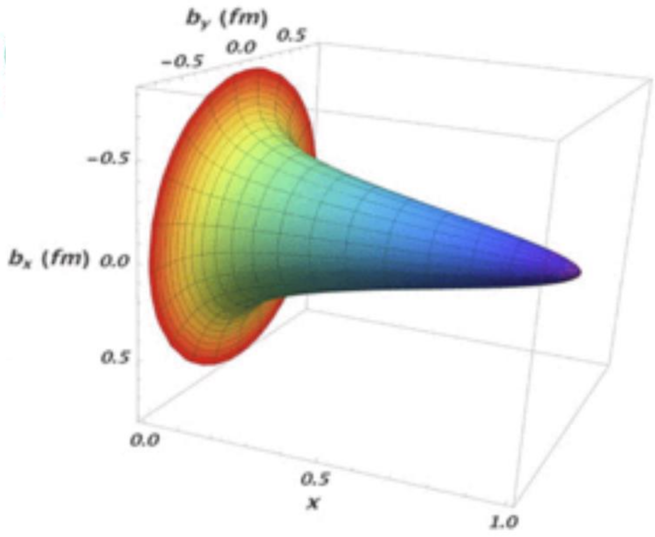

$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \quad \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t)$$

$$\int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t) \quad \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

No relation for the GPD E and $\tilde{\text{E}}$

RPP 76(2013) 066202

# GPDs and hadronic physics issues




**Nucleon tomography**

R. Dupré et al. PRD95 (2017)

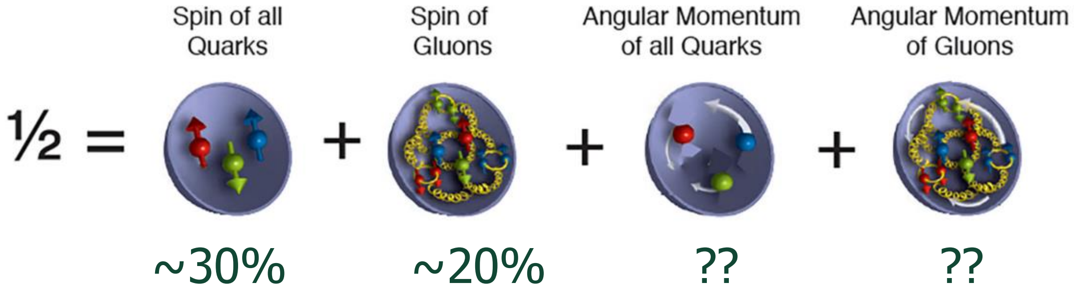
Local fits from Hermes, CLAS & Hall A data

Assume H contribution only

Model dependent assumptions for $x_B$ dependence

Contribution of the **angular momentum of quark** to the proton spin (Ji's sum rule: PRL 78(4):610-613, 1997)

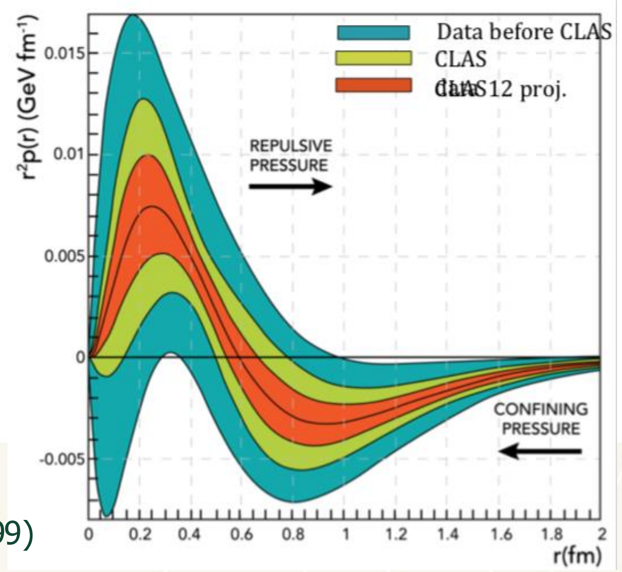
$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g \quad \Rightarrow \quad J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$




Access to the **mechanical properties/gravitational form factors** of the proton

$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\pi H(x=\xi,\xi,t)$$

$$\mathbf{D(t)} = -\mathbf{Re}(\mathcal{H}) + \int \mathbf{dx} \frac{\mathbf{Im}\mathcal{H}}{\mathbf{x}+\xi}$$




V. Burkert, L. Elouadrhiri, F.X. Girod

Nature 557 (2018, 7705, 396-399)

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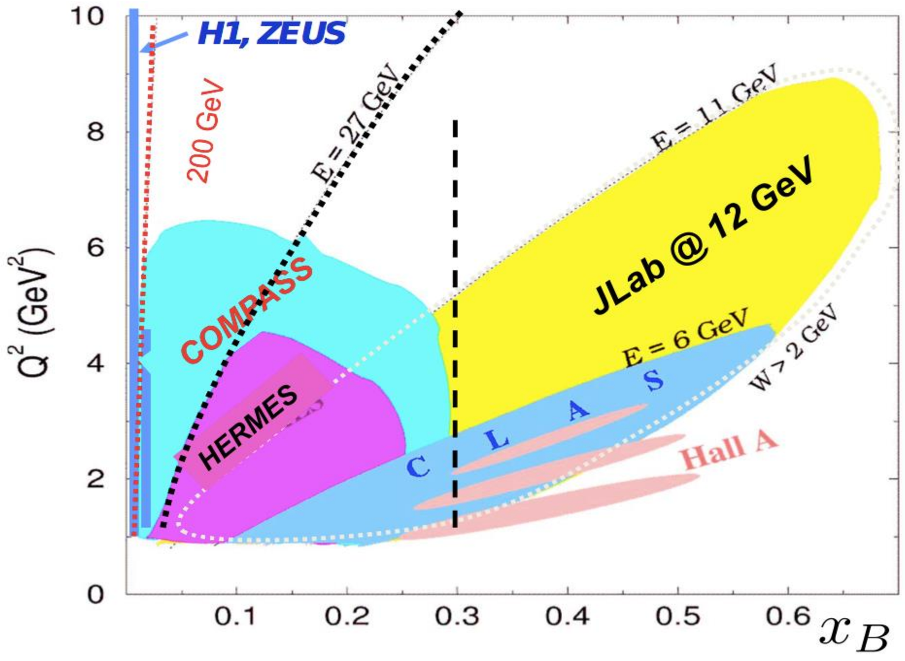
# JLab Exclusive reactions for GPDs program

Tables by C. Munoz-Camacho

| Measurement | Hall |
|---|---|
| DVCS Polarized beam and/or target | A,B,C |
| nDVCS Deuterium/He3 | B,C, A(Solid) |
| DVCS w/ e+ | B, C |
| TCS | A (Solid), B, C |
| Excl. $\pi^0$ | A,B,C |
| Excl. $\pi^-$ | A (Solid), (B) |
| Excl. $\phi$, $\eta$ | B |
| L/T separation (K, $\pi$+) | C |
| WACS ($\gamma$, $\pi^0$) | A, C |
| Backwards $\pi^0$ | C |




**In the valence region (JLab 6 and JLab 12)**

Partially complimentary, overlapping

- Hall A/C: Test the validity of the formalism
  - high accuracy (~5%)
  - limited kinematic
- Hall B: Map the GPDS
  - limited accuracy (15+%)
  - wide kinematic range

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# JLab Exclusive reactions for GPDs program

This talk focuses on
recent
**DVCS and DVMP- $\pi^0$ using the Hall A/C scheme**
and the future of this niche technique.

| | Experiment | PAC | Goal | Results |
|---|---|---|---|---|
| 6 GeV | E00-110 | PAC18 | 1st dedicated DVCS experiment at JLab | PRL97 (2006), PRC83 (2011), PRC92 (2015) |
| 6 GeV | E03-106 | PAC24 | 1st neutron DVCS experiment | PRL99 (2007) |
| 6 GeV | E07-007 | PAC31 | DVCS Rosenbluth-like separation (proton) | PRL117 (2016), Nature Commun. 8 (2017) |
| 6 GeV | E08-025 | PAC33 | DVCS Rosenbluth-like separation (neutron) | PRL118 (2017), Nature Physics 16 (2020) |
| 12 GeV | E12-06-114 | PAC30+38+41+47 | 1st 12 GeV experiment | PRL127 (2021), PRL128 (2022) |
| 12 GeV | E12-13-010 | PAC40 | DVCS Rosenbluth-like separation (proton) | *Scheduled 2023-2024* |



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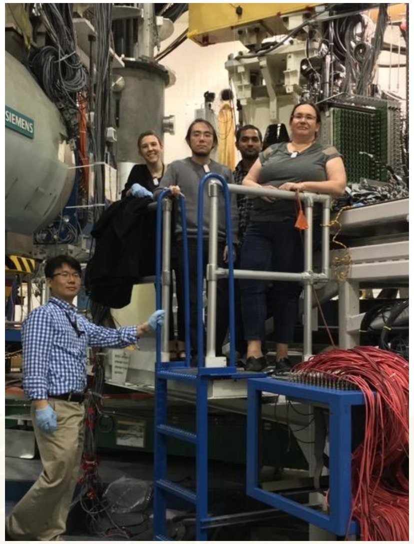
F. Georges,[1] M. N. H. Rashad,[2] A. Stefanko,[3] M. Dlamini,[4] B. Karki,[4] S. F. Ali,[5] P-J. Lin,[1] H-S Ko,[1,6] N. Israel,[4] D. Adikaram,[7] Z. Ahmed,[8] H. Albataineh,[9] B. Aljawrneh,[10] K. Allada,[11] S. Allison,[2] S. Alsalmi,[12] D. Androic,[13] K. Aniol,[14] J. Annand,[15] H. Atac,[16] T. Averett,[17] C. Ayerbe Gayoso,[17] X. Bai,[18] J. Bane,[19] S. Barcus,[17] K. Bartlett,[17] V. Bellini,[20] R. Beminiwattha,[21] J. Bericic,[7] D. Biswas,[22] E. Brash,[23] D. Bulumulla,[2] J. Campbell,[24] A. Camsonne,[7] M. Carmignotto,[5] J. Castellano,[25] C. Chen,[22] J-P. Chen,[7] T. Chetry,[4] M. E. Christy,[22] E. Cisbani,[26] B. Clary,[27] E. Cohen,[28] N. Compton,[4] J. C. Cornejo,[17,3] S. Covrig Dusa,[7] B. Crowe,[29] S. Danagoulian,[10] T. Danley,[4] F. De Persio,[26] W. Deconinck,[17] M. Defurne,[30] C. Desnault,[1] D. Di,[18] M. Duer,[28] B. Duran,[16] R. Ent,[7] C. Fanelli,[11] G. Franklin,[3] E. Fuchey,[27] C. Gal,[18] D. Gaskell,[7] T. Gautam,[22] O. Glamazdin,[31] K. Gnanvo,[18] V. M. Gray,[17] C. Gu,[18] T. Hague,[12] G. Hamad,[4] D. Hamilton,[15] K. Hamilton,[15] O. Hansen,[7] F. Hauenstein,[2] W. Henry,[16] D. W. Higinbotham,[7] T. Holmstrom,[32] T. Horn,[5,7] Y. Huang,[18] G. M. Huber,[8] C. E. Hyde,[2] H. Ibrahim,[33] C-M. Jen,[34] K. Jin,[18] M. Jones,[7] A. Kabir,[12] C. Keppel,[7] V. Khachatryan,[7,35,36] P. M. King,[4] S. Li,[37] W. B. Li,[8] J. Liu,[18] H. Liu,[38] A. Liyanage,[22] J. Magee,[17] S. Malace,[7] J. Mammei,[39] P. Markowitz,[25] E. McClellan,[7] M. Mazouz,[40] F. Meddi,[26] D. Meekins,[7] K. Mesik,[41] R. Michaels,[7] A. Mkrtchyan,[5] R. Montgomery,[15] C. Muñoz Camacho,[1,*] L. S. Myers,[7] P. Nadel-Turonski,[7] S. J. Nazeer,[22] V. Nelyubin,[18] D. Nguyen,[18] N. Nuruzzaman,[22] M. Nycz,[12] O. F. Obretch,[27] L. Ou,[11] C. Palatchi,[18] B. Pandey,[22] S. Park,[35] K. Park,[2] C. Peng,[42] R. Pomatsalyuk,[31] E. Pooser,[7] A. J. R. Puckett,[27] V. Punjabi,[43] B. Quinn,[3] S. Rahman,[39] P. E. Reimer,[44] J. Roche,[4] I. Sapkota,[5] A. Sarty,[45] B. Sawatzky,[7] N. H. Saylor,[46] B. Schmookler,[11] M. H. Shabestari,[47] A. Shahinyan,[48] S. Sirca,[49] G. R. Smith,[7] S. Sooriyaarachchilage,[22] N. Sparveris,[16] R. Spies,[39] T. Su,[12] A. Subedi,[47] V. Sulkosky,[50] A. Sun,[3] L. Thorne,[3] Y. Tian,[51] N. Ton,[18] F. Tortorici,[20] R. Trotta,[52] G. M. Urciuoli,[26] E. Voutier,[1] B. Waidyawansa,[7] Y. Wang,[17] B. Wojtsekhowski,[7] S. Wood,[7] X. Yan,[53] L. Ye,[47] Z. Ye,[18] C. Yero,[25] J. Zhang,[18] Y. Zhao,[35] and P. Zhu[54]

Author's list from our most recent DVCS paper (June 2022)

Students/Postdocs Spoke-persons

The Jefferson Lab Hall A/C technical staff
The Jefferson Lab Accelerator staff



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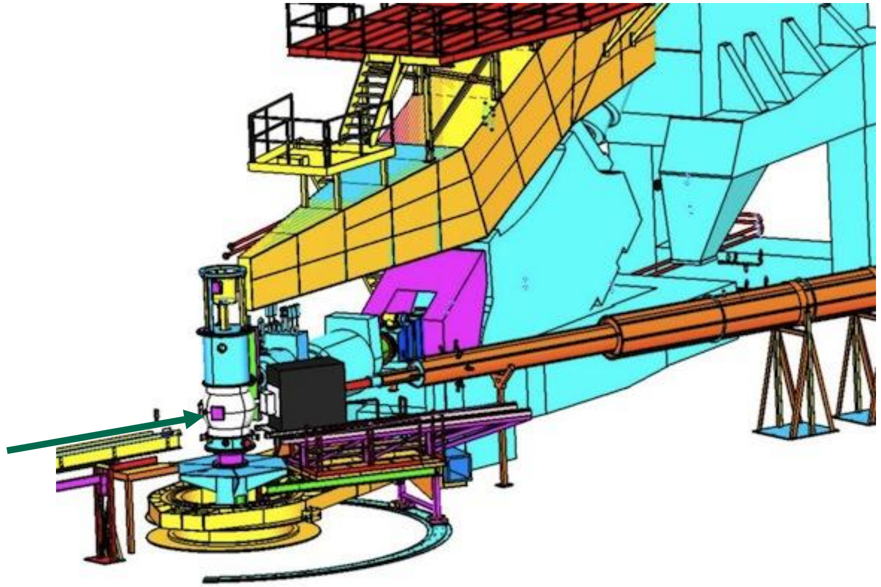
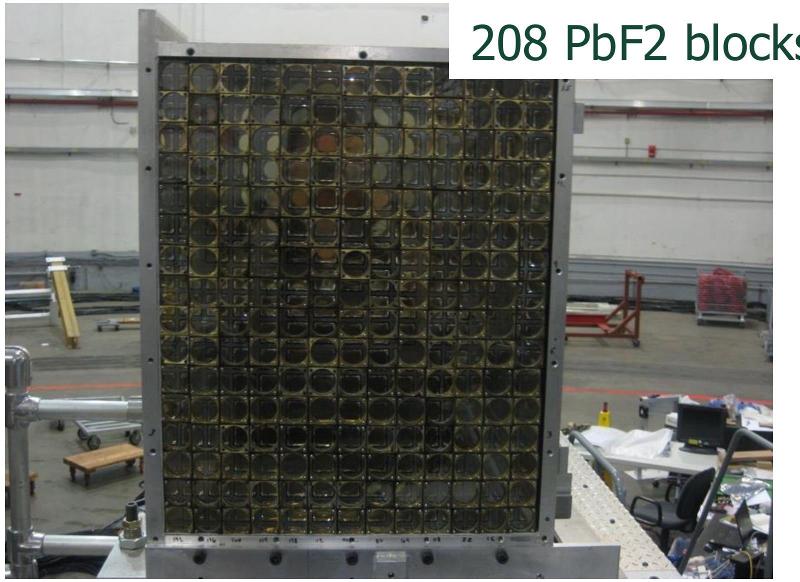
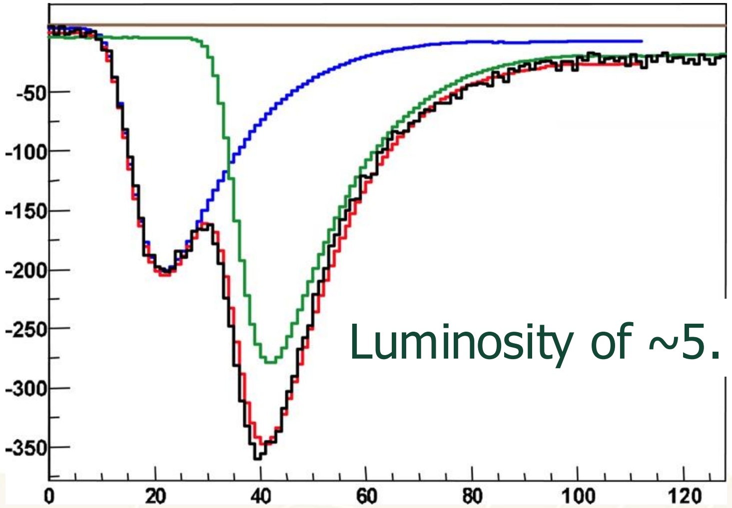
# Dedicated apparatus e.g. the Hall A scheme

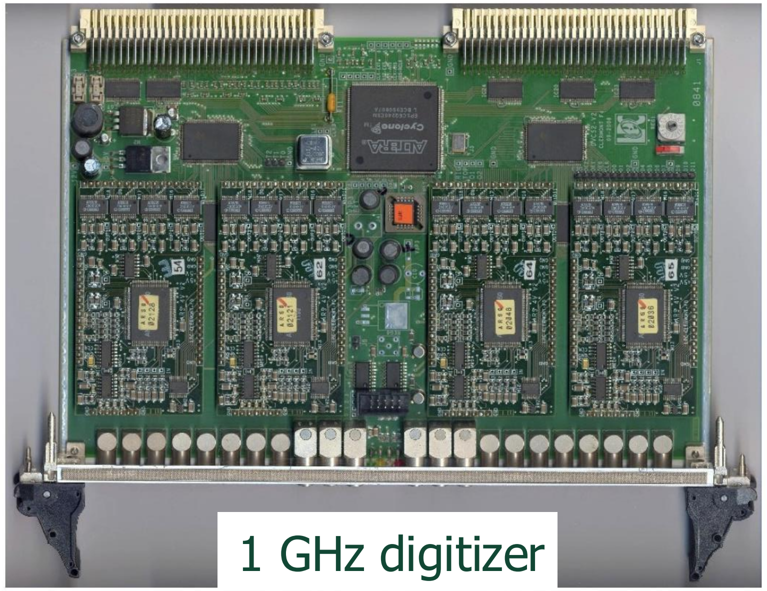




208 PbF2 blocks




Luminosity of ~5. $10^{37}$ Hz/cm$^2$



1 GHz digitizer

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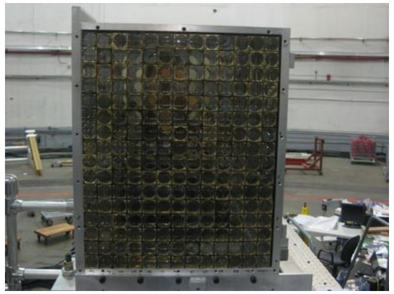
# Exclusivity : the DVCS@Hall A scheme

85% polarized beam → LH2/LD2

scattered electron →

$dp/p \sim 10^{-4}$

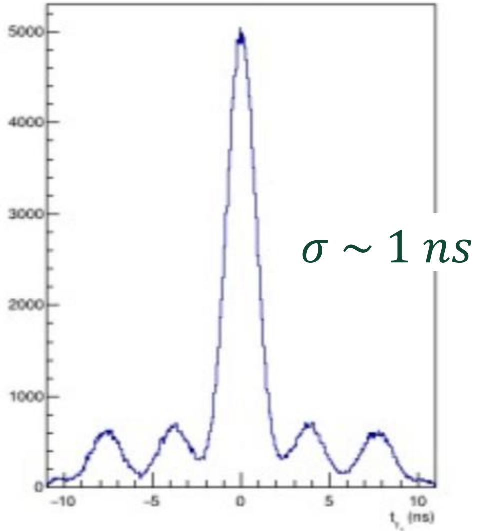
$\gamma$ →

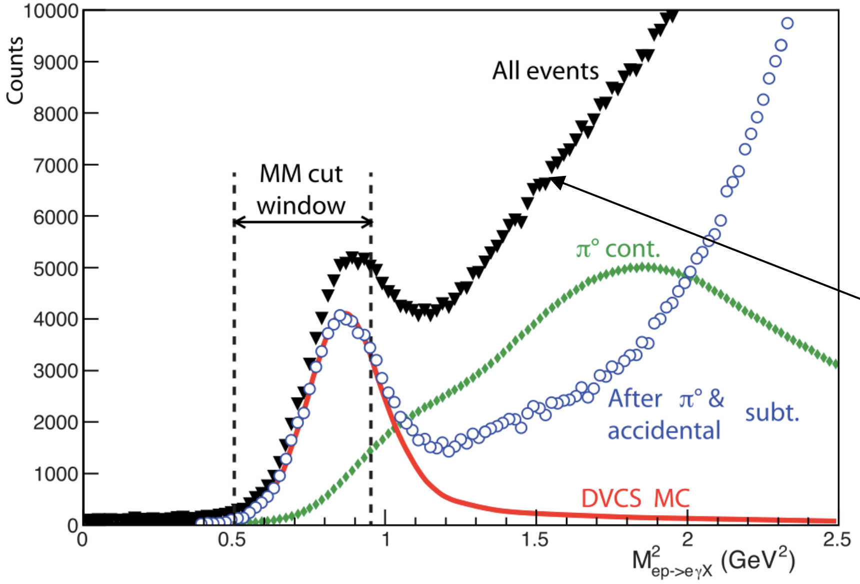


$\Delta E/E \sim 3.6\%$ at 4.5 GeV

PbF2

**Coincidence time (e-γ)**




## H(e,e'γ)X

X can be

- p : $ep \to ep\gamma$
- γp : $ep \to ep\,\pi^0, \pi^0 \to \gamma(\gamma)$
- γγp : $ep \to ep\,\pi^0, \pi^0 \to \gamma\gamma$
- Nπ: $ep \to eN\gamma\pi$

…



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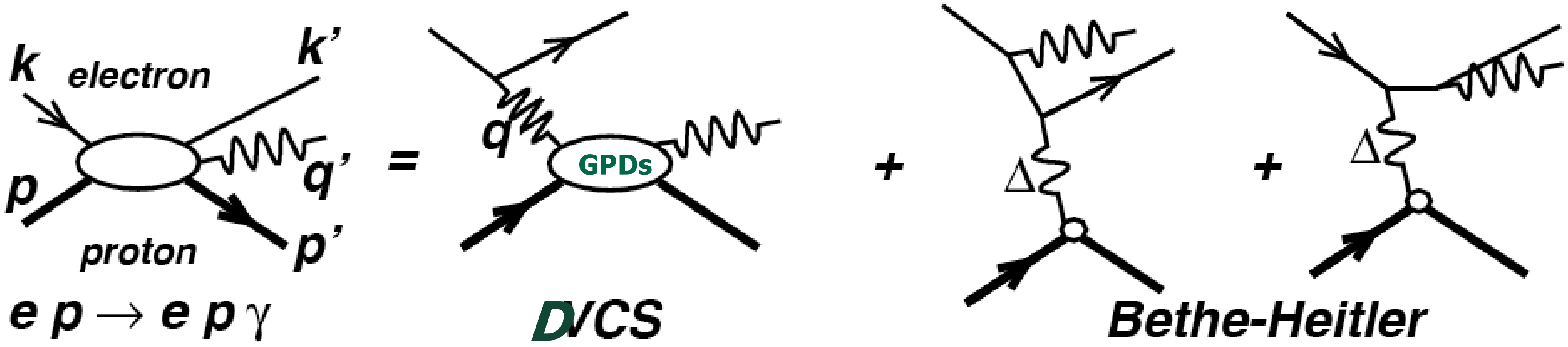
# Measuring DVCS to access GPDs information




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

Known if Nucleon FFs are known

Bilinear combinations of GPD/CFFs

Linear combinations of GPD/CFFs and FFs

$P_l$ : polarization target or beam

$e_l$ : charge of the lepton beam



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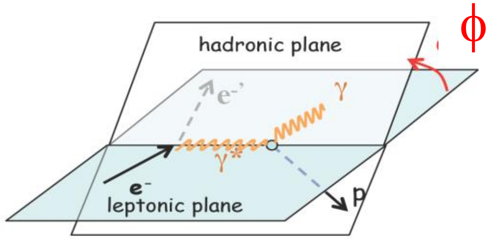
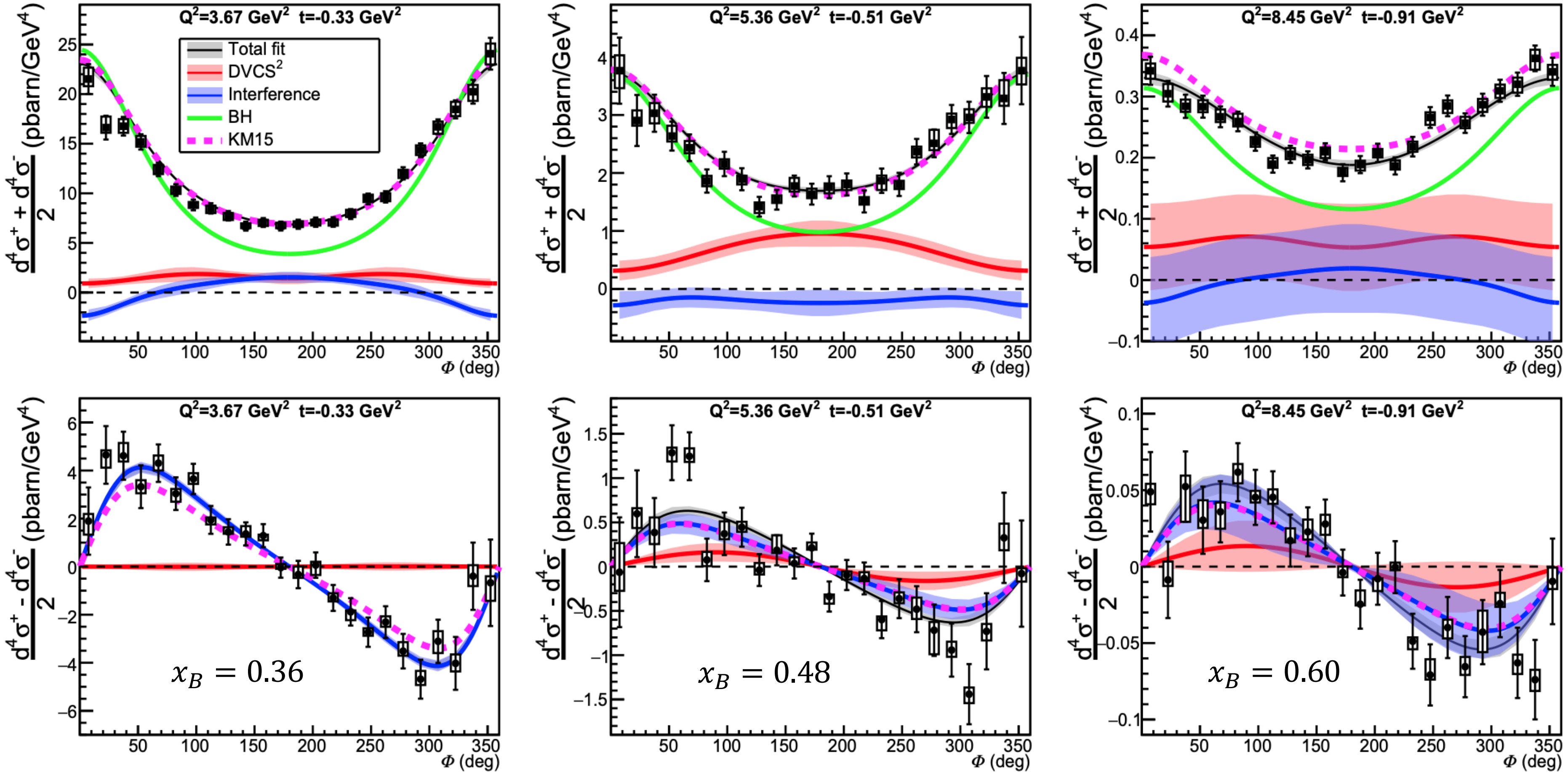
# DVCS in Hall A: 12 GeV result

F. Georges et al., *Phys.Rev.Lett.* 128 (2022) 25, 252002

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




[KM15] K. Kumericki and D. Mueller, *EPJ Web Conf.* 112 (2016) 01012

Braun-Manashov-Müller-Pirnay formalism, Phys. Rev. D 89, 074022 (2014).

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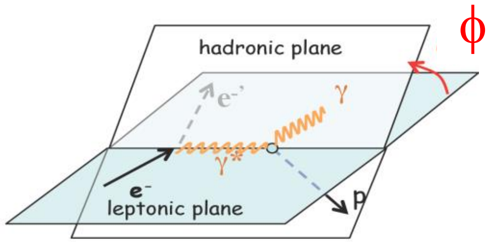
# How to parametrize the DVCS cross-sections?

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




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

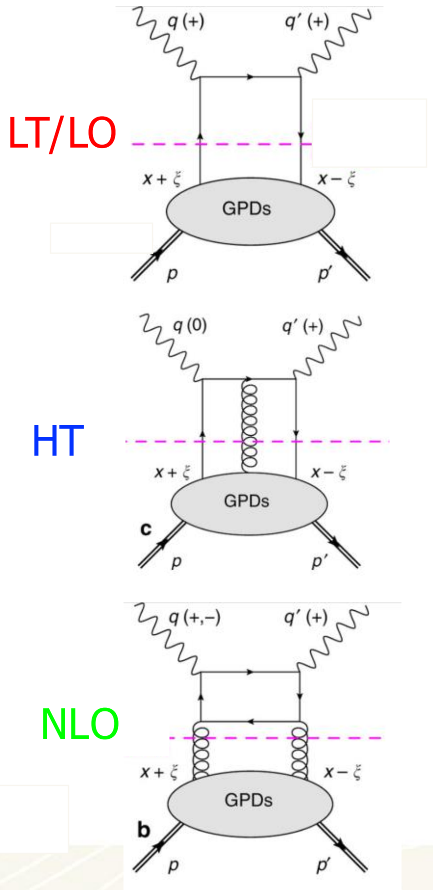
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

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

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

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

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




**World-wide GPDs analysis include more or less terms: both in terms of harmonics ($c_i$'s and $s_i$'s) and in term of GPD/CFFs.**

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# DVCS in Hall A@Jlab program

## 1st Generation (2004)

$Q^2$ dependence study (of red terms)

## 2nd Generation (2010)

Beam energy dependence study at fixed $x_B$ and $Q^2$

- Separate $C_0^{DVCS}$ from $C_0^I$
- Separate HT and NLO from LT/LO coefficients

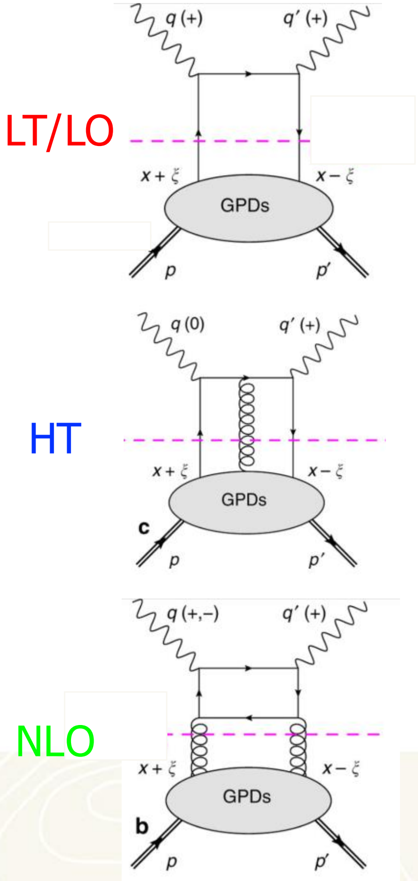
## 3rd Generation (2014-2016)

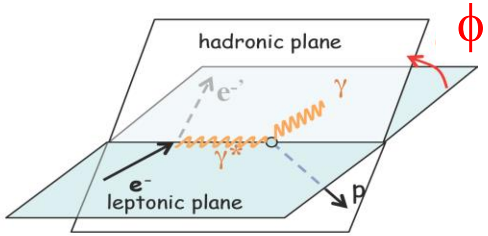
Multiple $x_B$ and $Q^2$ measurements

- Experimental extraction of the CFFs as a function of $x_B$
- Importance of considering all CFFs when extracting CFFs

$$
\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma^{DVCS}_{pol} &\propto s_1^{DVCS}\sin\phi \\
\mathrm{Re}\, I &\propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \\
\mathrm{Im}\, I &\propto s_1^I\sin\phi + s_2^I\sin 2\phi
\end{aligned}
$$

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




Results:

**off LH2 and LD2 (neutron) on DVCS and DVMP- $\pi^0$**

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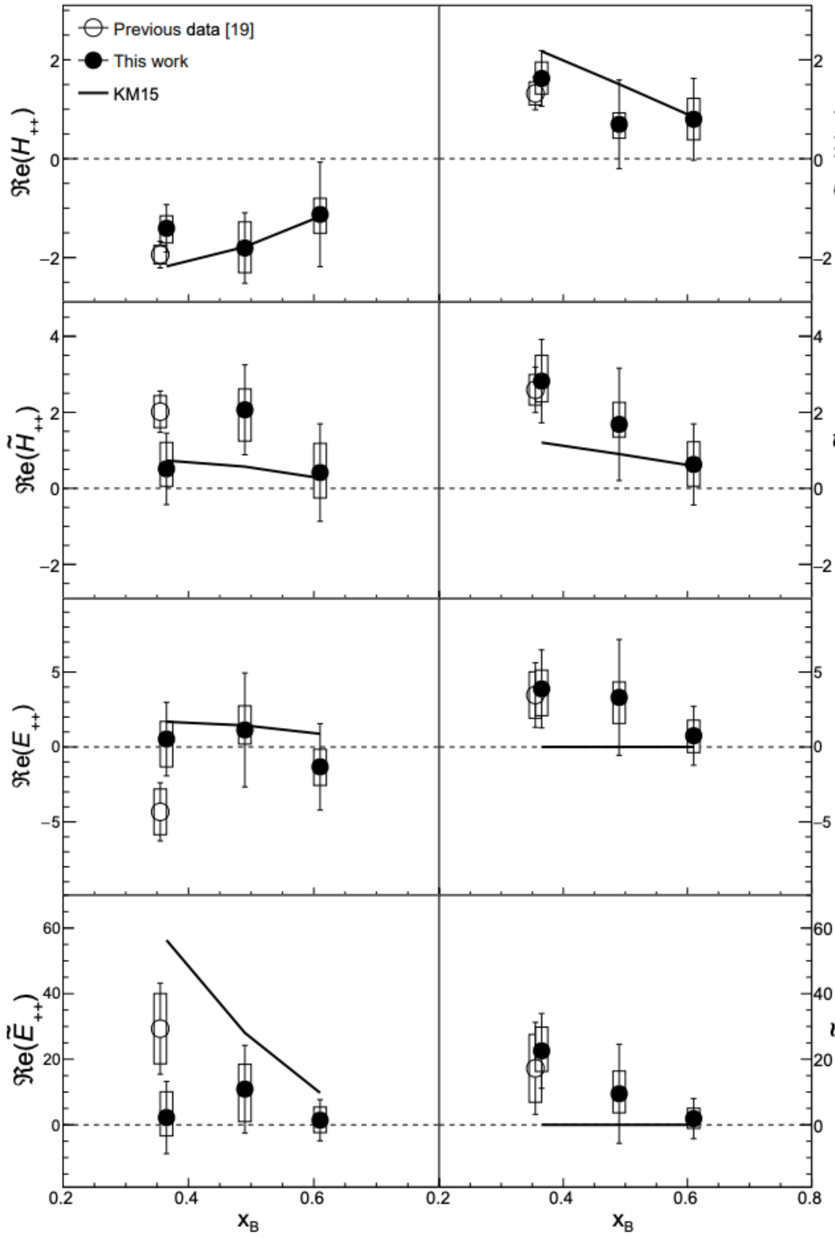
# DVCS in Hall A: 12 GeV results




[This work] **F. Georges, *Phys.Rev.Lett.* 128 (2022) 25, 252002**
Error bars: statistical
Error boxes: systematic
[19] M. Defurne et al., Phys. Rev. C92, 055202 (2015)
[KM15] K. Kumericki and D. Mueller, *EPJ Web Conf.* 112 (2016) 01012

**The precise measurement of cross-sections at the same $x_B$-$Q^2$ bin but multiple beam energies is essential for this extraction.**

Also demonstrated in
M. Defurne et al., Nat. Commun. 8, 1408 (2017).
B. Kriesten et al., Phys. Rev. D 101, 054021 (2020).
M. Čuić et al., Phys. Rev. Lett. 125, 232005 (2020).

$CFF_{\lambda\lambda'}$ $\lambda$ : polarization state of virtual photon (0,+,-)
$\lambda'$: polarization state of outgoing real photon (+,-)

Fit has 24 CFF
$$(\tilde{H}, H\ \tilde{E}, E)\otimes(\Re e, \Im m)\otimes(++, 0+, +-)$$
but **only the results from the LO ones (++) are shown.**
Fits performed at constant $x_B$ and t over $Q^2$ and $\phi$ bins.
No $Q^2$ evolution of the CFFs.

The average $t$ values are $-0.281$ GeV$^2$ for [19] and $-0.345$, $-0.702$, $-1.050$ GeV$^2$ at $xB$=0.36, 0.48, 0.60, respectively for this work..

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# DVCS@Hall A neutron data

**A combined neutron and proton targets data allows for flavor separation of the GPDs.**

**Neutron data are uniquely sensitive to the elusive GPD E (no connection to PDFs).**

Below the two pions threshold: $D(e,e'\pi^0)X = d(e,e'\pi^0)d + n(e,e'\pi^0)n + p(e,e'\pi^0)p.$

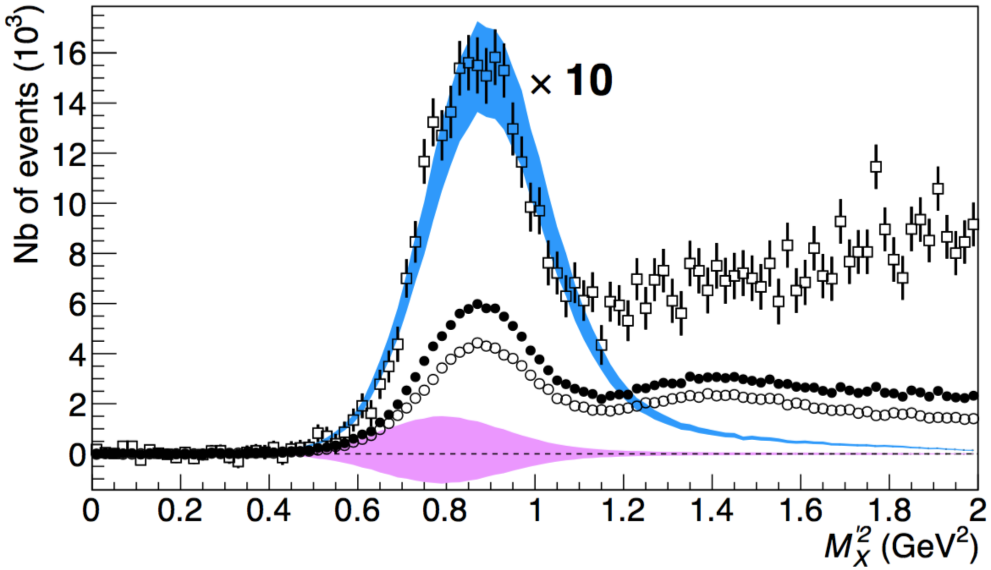
- ● LD2
- ○ LH2
- □ LD2-LH2

$d(e,e'\pi^0)d$

$n(e,e'\pi^0)n$

separated by

$\Delta M_X^2 = t(1 - M/M_d) \approx t/2$

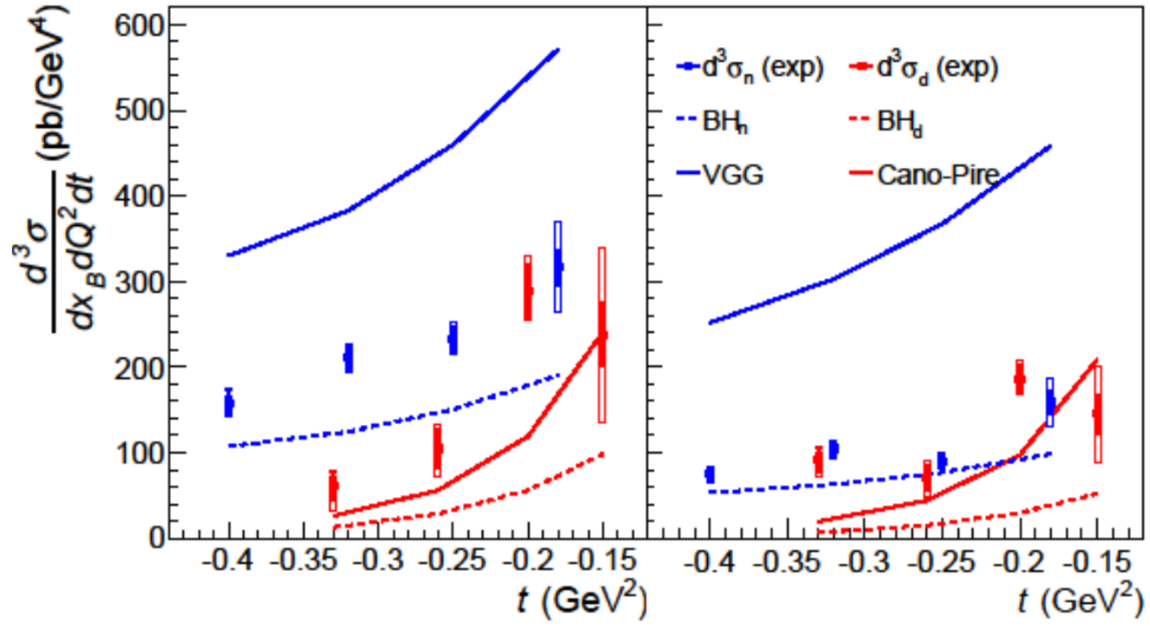



Computed for $n(e,e'\pi^0)X$

Figure from M. Mazouz PRL 118 (2017) 22, 222002

# DVCS2@Hall A neutron data

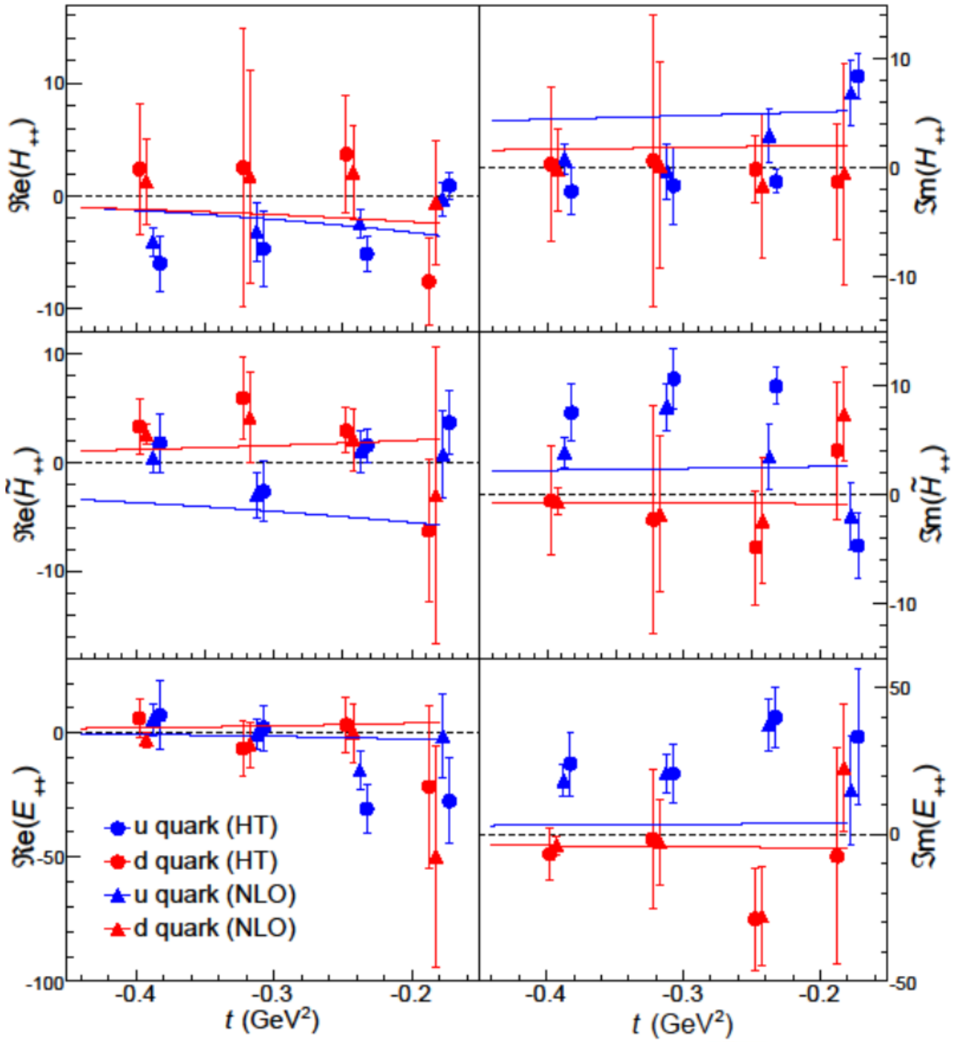
Cross section measurements from E08-205




$Q^2$=1.9 GeV$^2$, $x_B$=0.36

Benali et al, Nature Phys. 16, 191 (2020)

Flavor separation of Compton Form Factors



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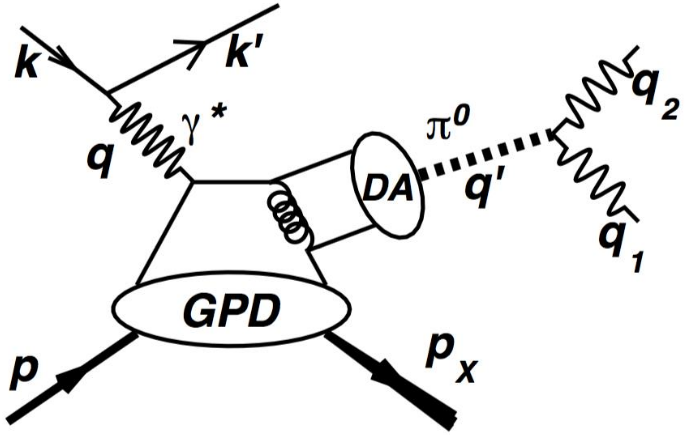
# L/T pion production separation: E07-007

*M. Defurne et al. PRL 117, 26 (2015)*

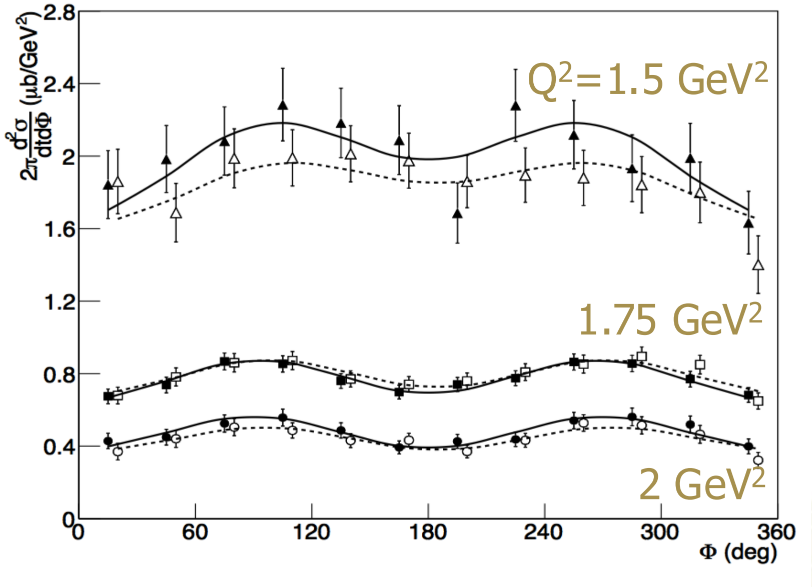



4 chiral-even GPDs
4 chiral-odd GPDS (not seen in DVCS)

Leading twist , leading order factorization is only proven for $d\sigma_L/dt$ (Collins et al. 1997)

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

| Setting | $E$ (GeV) | $Q^2$ (GeV$^2$) | $x_B$ | $\epsilon$ |
|---|---|---|---|---|
| 2010-Kin1 | (3.355 ; 5.55) | 1.5 | 0.36 | (0.52 ; 0.84) |
| 2010-Kin2 | (4.455 ; 5.55) | 1.75 | 0.36 | (0.65 ; 0.79) |
| 2010-Kin3 | (4.455 ; 5.55) | 2 | 0.36 | (0.53 ; 0.72) |




Dominance of $d\sigma_T/dt$ observed (directly or not) also at
- Hermes & Hall C $\pi^+$
- Hall B, Hall A $\pi^0$

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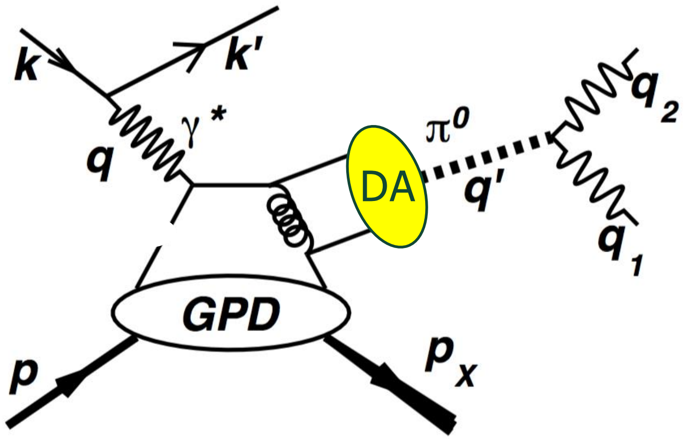
# GPDs through DVMP-$\pi^0$

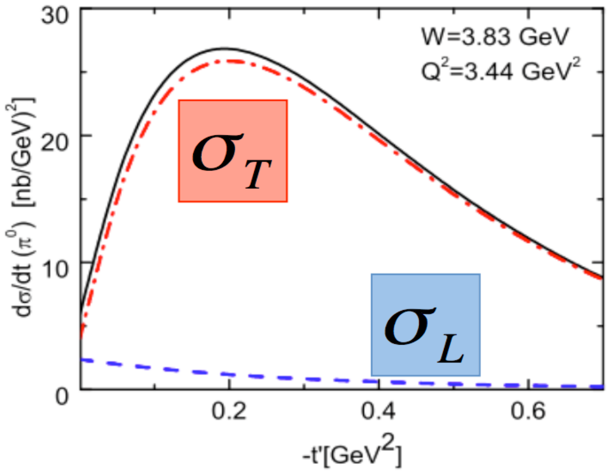



Factorization is only exact for longitudinal photons (Collins et al., 1997).

At large $Q^2$, QCD predicts that $\sigma_L \to Q^2\,\sigma_T$

Effective transverse factorization schemes exploit and explain the observed $\sigma_T > \sigma_L$ for existing high x data.

S. Goloskokov and P. Kroll (Eur.Phys.J A47, 112(2011))
S. Liuti and G. Golstein (Phys.Rev.D79, 054014 (2009))

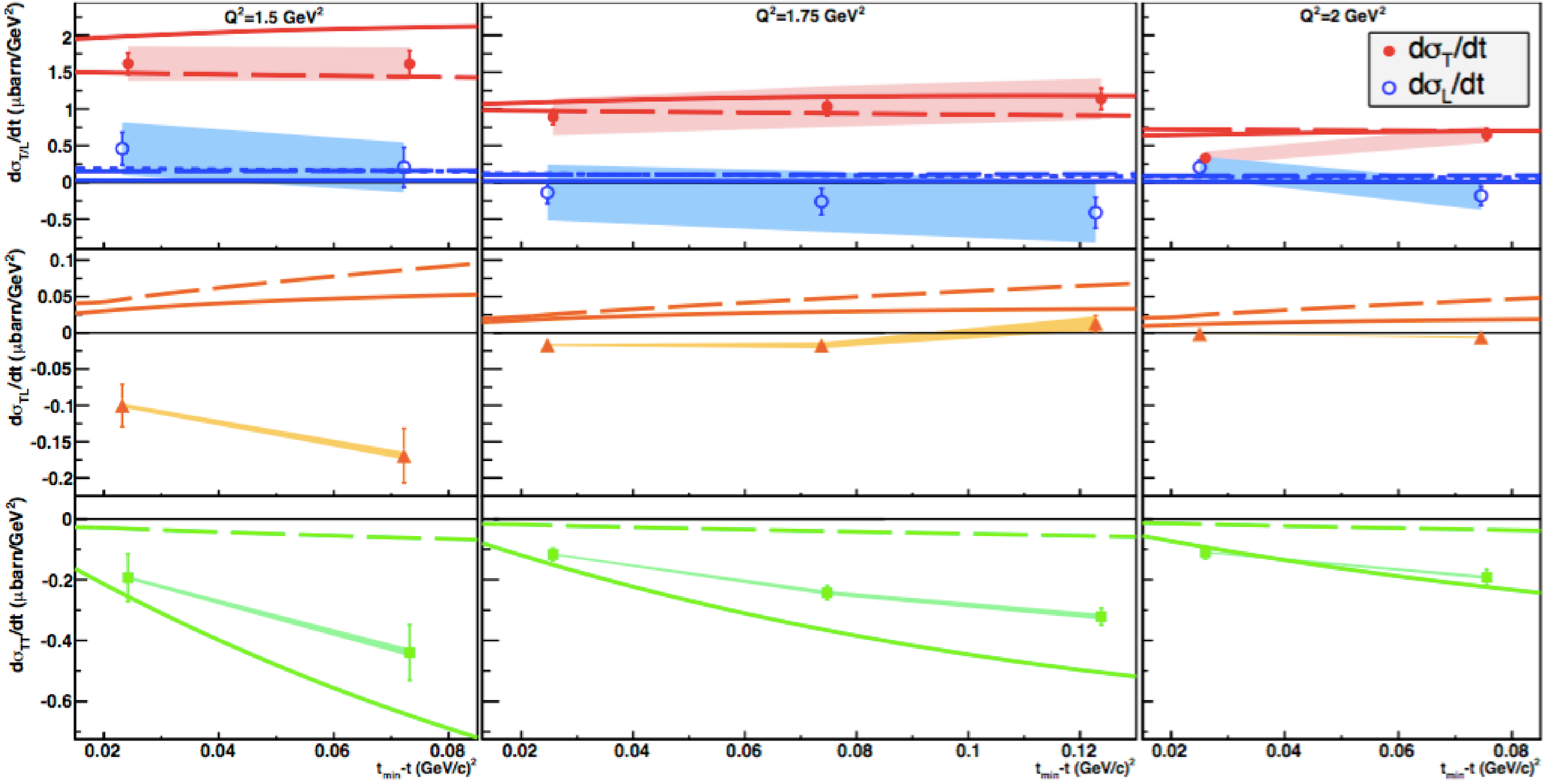



Twist 3 Distribution Amplitudes (DA) couple with transversity GPDs.

The dominant contribution is not the leading twist contribution

# E07-007: $\pi^0$ fully separated contributions

*M. Defurne et al. PRL 117, 26 (2015)*




Models with $d\sigma_T$ factorization scheme

— — — G-H-L ( JPG:NPP39 '12)

——— G-K (EPJA47 '11)

We observed:

- Small $d\sigma_L$, large $d\sigma_T$: models ok with these
- Wrong sign and t dependence for $d\sigma_{TL}$ and $d\sigma_{TT}$
- sizeable $d\sigma_{TL}$ => $d\sigma_L$ is small but not null

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# Precision studies of the DVCS process at JLab

Julie Roche

- GPDs are accessible through many exclusive processes. So far, the most studied channels are Deeply Virtual Compton Scattering (DVCS) and Deep Virtual Meson production (DVMP).
- Our JLab Hall A/C collaboration measures DVCS and DVMP-$\pi 0$ absolute cross-section using a “simple” dedicated apparatus since 2006.
- Our precise (5%) measurements are essential to interpret the data.
- We just completed a new set of measurements in Hall C/JLab using a new $PbW0_4$ calorimeter and expanding our kinematic reach.



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# Neutral Particle Spectrometer (Hall C/JLab)

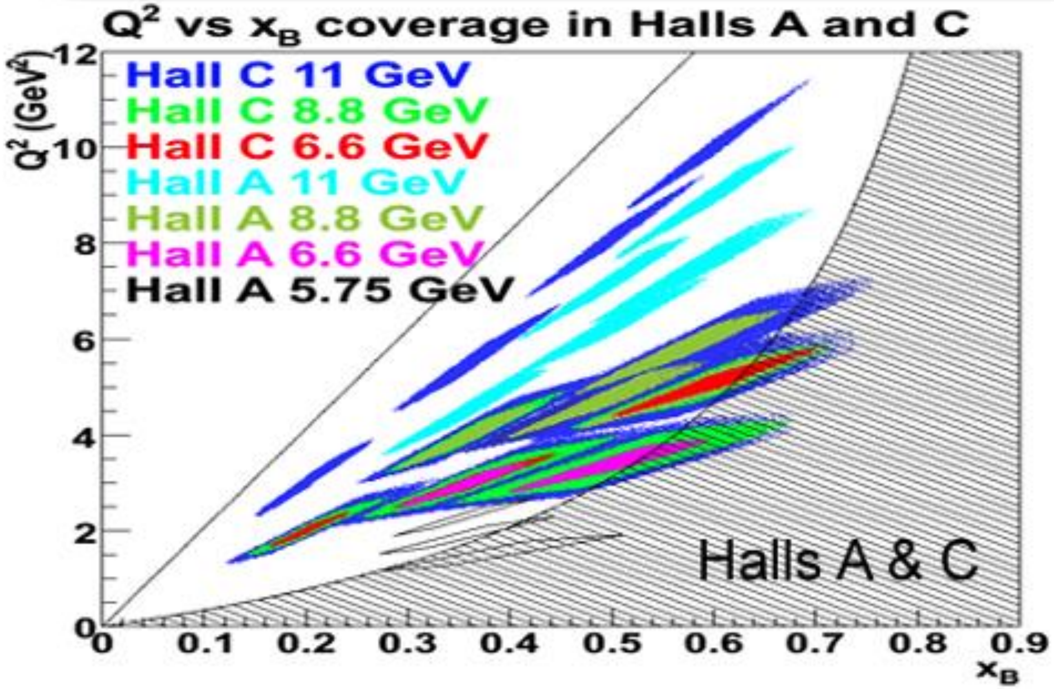
**E12-13-010 DVCS measurements follow up on measurements in Hall A:**

- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \mathrm{Re}\left[DVCS^{\perp}\ BH\right] + |DVCS|^2$$

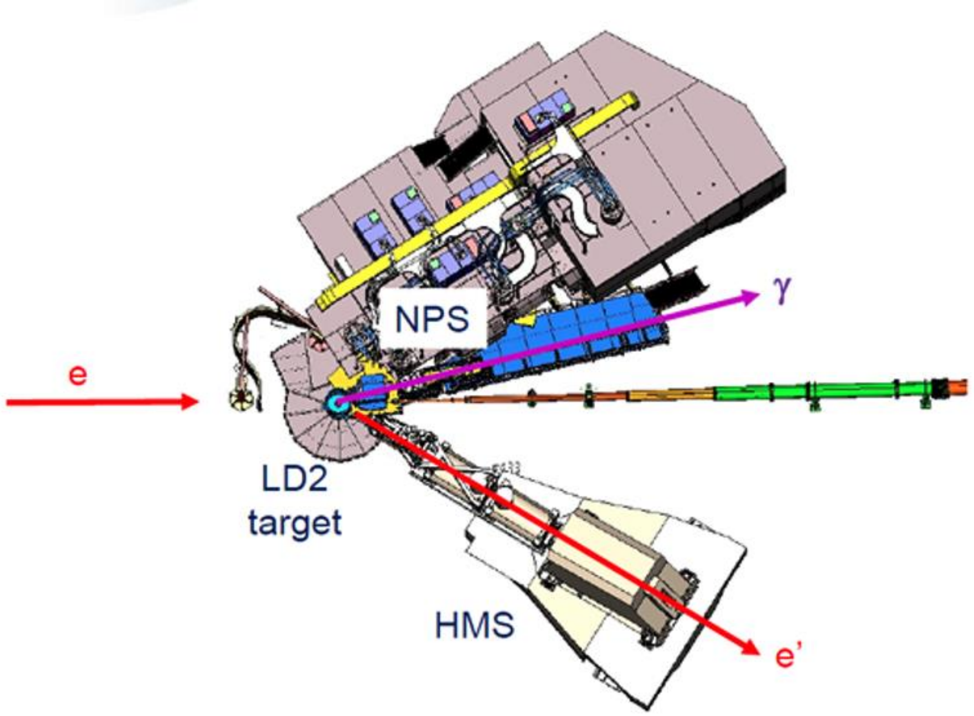
$$\sim E_{beam}^2 \qquad \sim E_{beam}^3$$

- L/T separation of $\pi^0$ production




- The NPS calorimeter consists of 1080 $PbWO_4$ crystals, the preferred material for high-resolution calorimetry, also at EIC – NPS has the largest set of PbWO4 crystals in an operating calorimeter in the US

- The NPS Science Program consists of ten approved experiments. **4** experiments have been running in parallel from Sept '23 to May '24.

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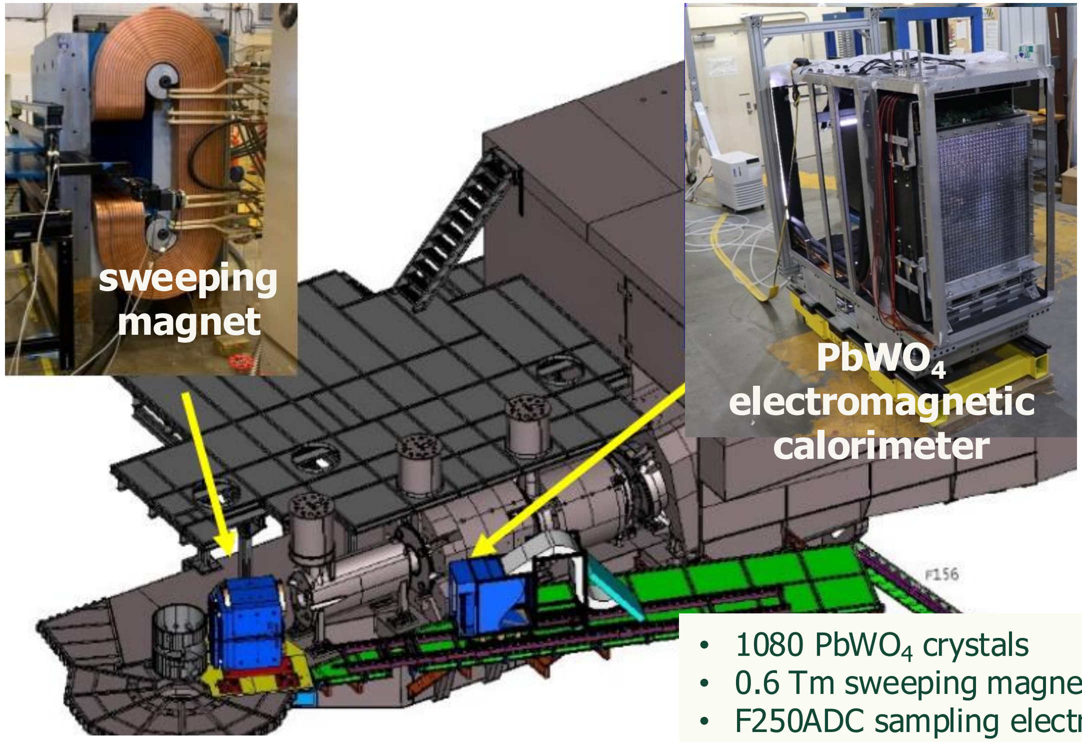
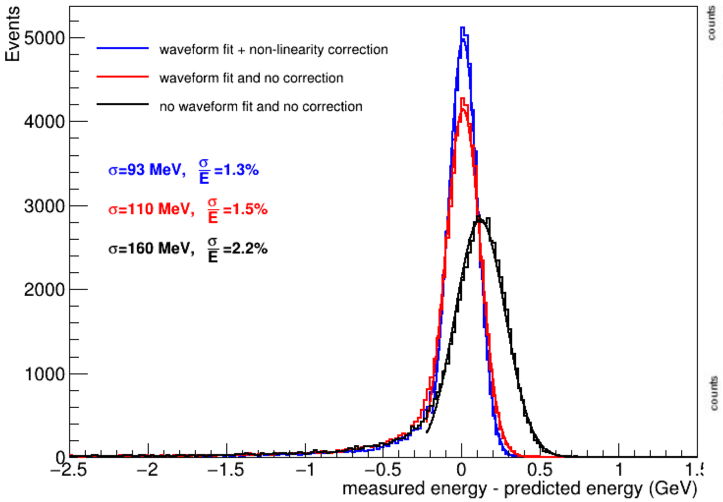
# Neutral Particle Spectrometer (Hall C/JLab)

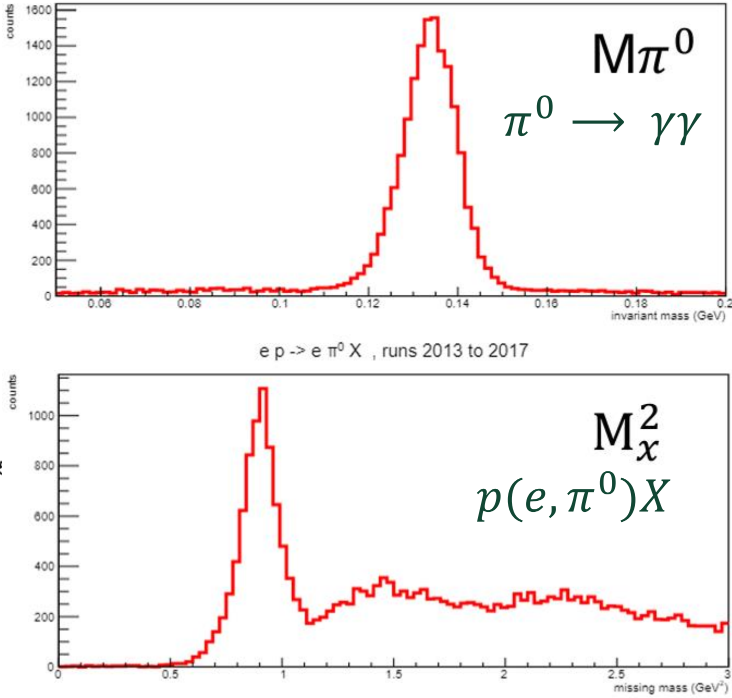


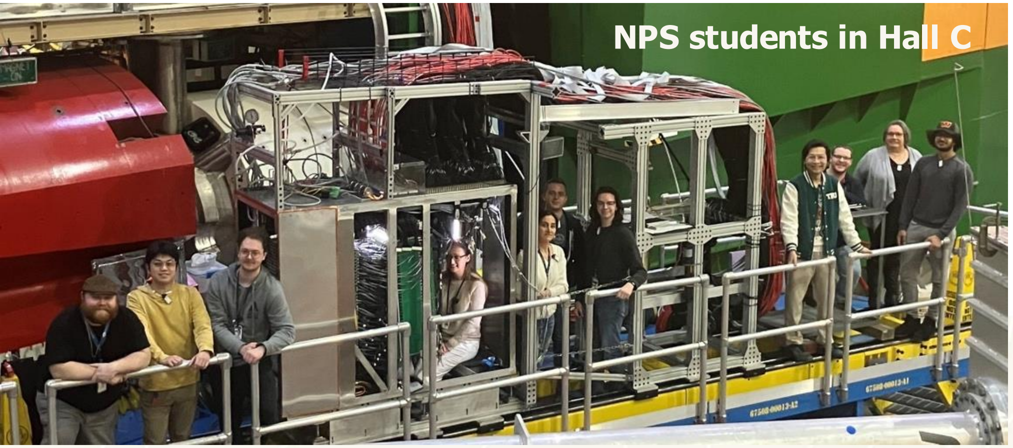

- 1080 $PbWO_4$ crystals
- 0.6 Tm sweeping magnet
- F250ADC sampling electronics

## Elastic NPS Energy Resolution




## $\pi^0$ Resolution




All channels perform well at very high luminosity on LH2 and LD2(≈ 8x10$^{37}$ cm$^2$/s).

The expected resolution energy resolution was achieved (1.3% at 7.3 GeV).

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# Precision studies of the DVCS process at JLab

- Our JLab Hall A/C collaboration measures DVCS and DVMP-$\pi^0$ absolute cross-section using a "simple" dedicated apparatus since 2006.
- Our precise (5%) measurements are essential to interpret the data.
  - proton, neutron and exclusive pi-zero absolute cross section measurement
  - total and beam helicity correlated cross section measurement
  - cover the valence region ($x_B$=0.2 to 0.6) with $Q^2$ in the 1-10 $GeV^2$ range
  - repeated ($x_B$-$Q^2$) measurement at different beam energies
- We just completed a new set of measurements in Hall C/JLab using a new $PbWO_4$ calorimeter and expanding our kinematic reach.

**Thank you for your attention!**



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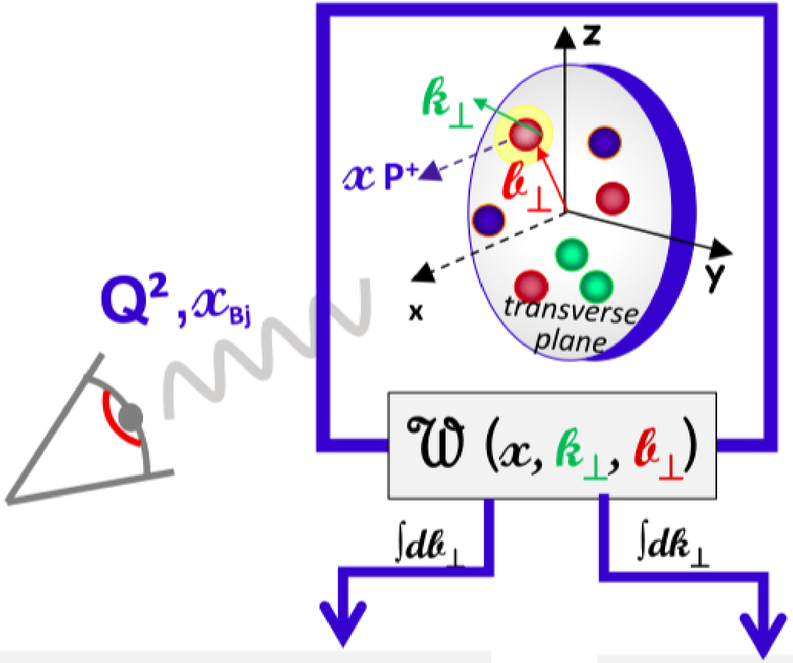
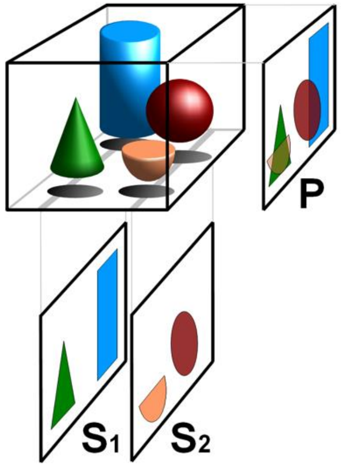
# Thank you for your attention!

# Toward a more complete description of the nucleon




**Quantum tomography of the nucleon**

Ji, PRL91 (2003)
Belitsky, Ji, Yuan, PRD69 (2004)
Lorcé et al, JHEP1105 (2011)




**Transverse momentum**

$f(x, k_\perp)$
**8 TMDs**

*accessible in* SIDIS *and* Drell-Yan

$\int dk_\perp$ → **PDFs ($x$)** ← $\int db_\perp$

**Transverse position**

$q(x, b_\perp)$
**8 GPDs**

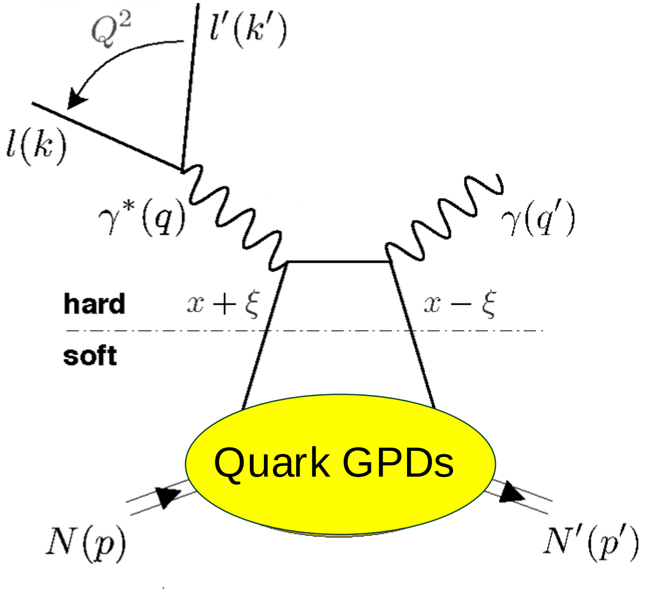
$\int dx$ → **Form Factors**

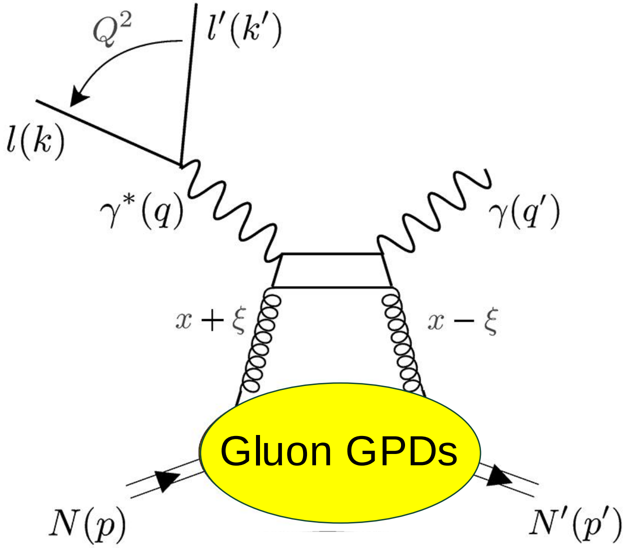
*accessible in* **exclusive reactions**

**DVCS**: Deeply Virtual Compton Scattering
**HEMP**: Hard Exclusive Meson Production

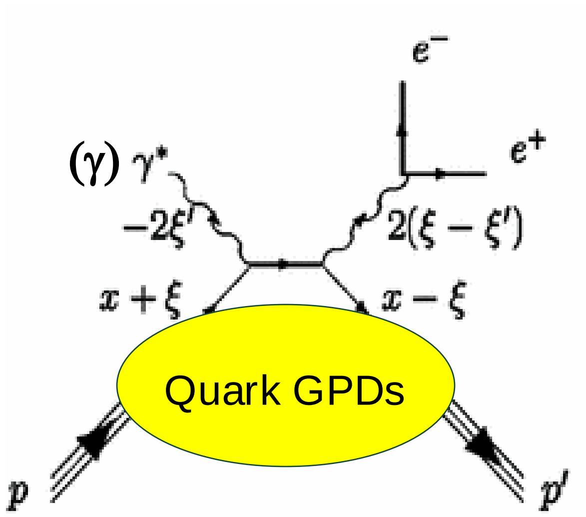
Slide from N. d'Hose, APS-April meeting 2019.

# Universality of GPDs

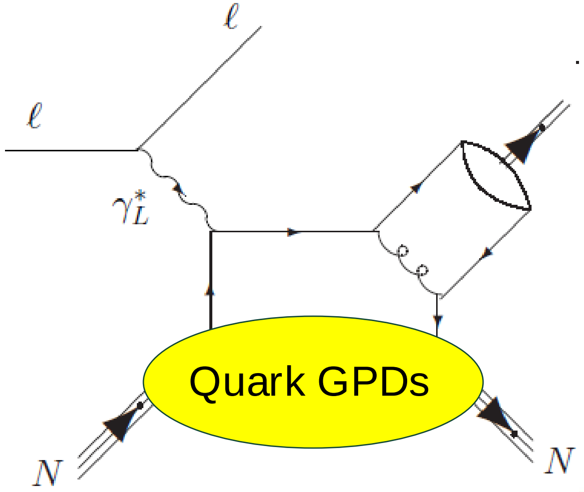


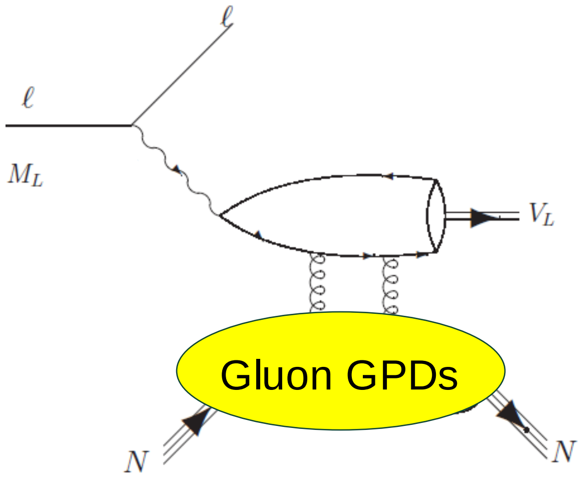

DVCS



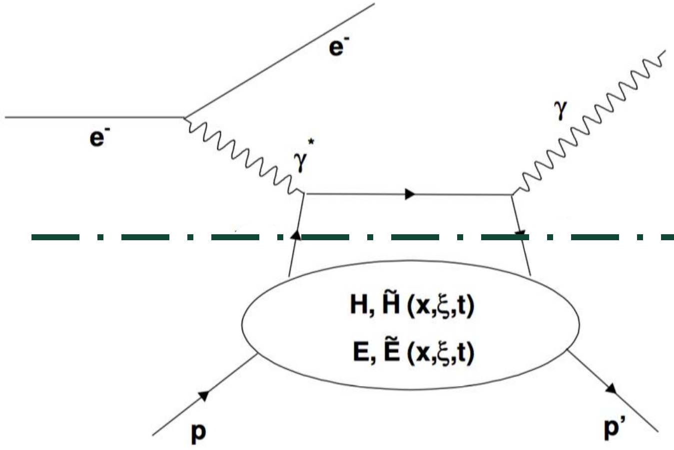

(TCS), DDVCS

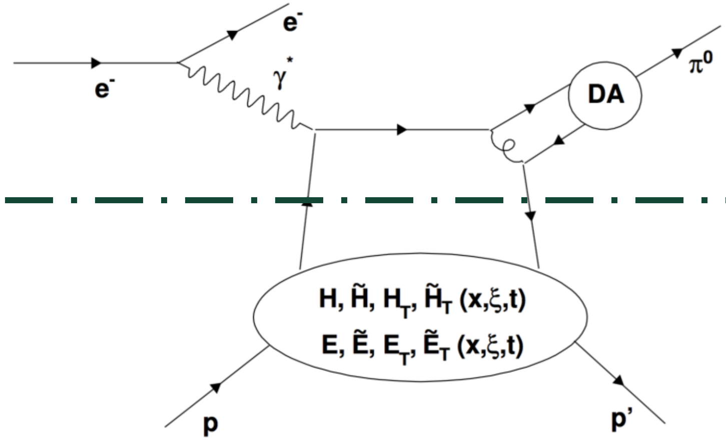



DVMP



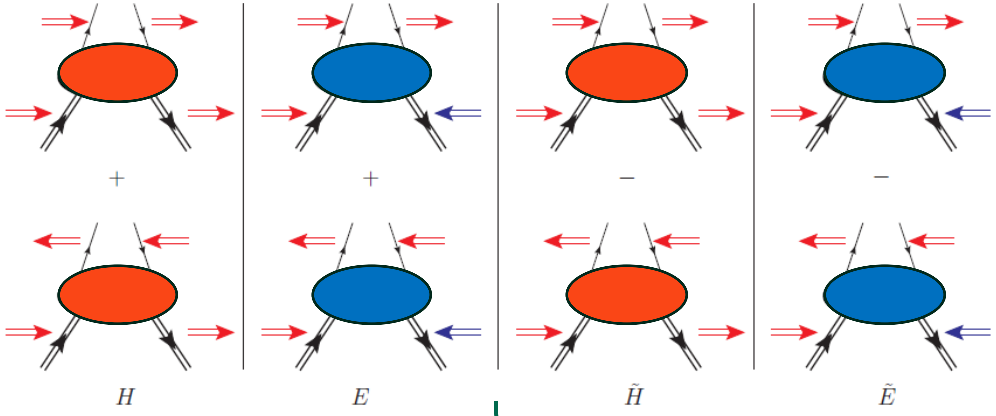
# DVCS/DVMP : same GPDs??




**Chiral even GPDs:**
(helicity of the parton is conserved)

Chiral even GPDs
+
**Chiral-odd GPDs:**
(helicity of the parton can flip)




conserve nucleon spin
flip nucleon spin

)24)

parton helicity sensitive

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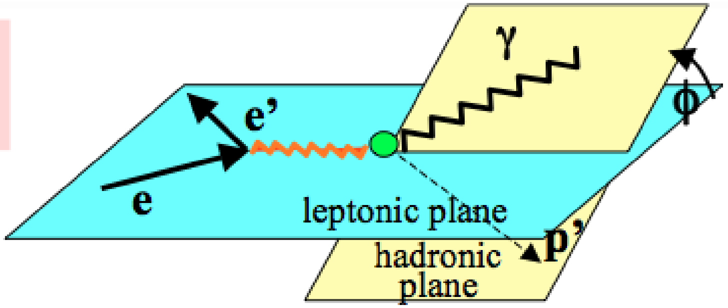
# Sensitivity to different GPDs (at leading order and twist)

Slide from M. Vanderhaeghen

$$\Delta\sigma = d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma}$$

$\xi = x_B/(2-x_B)$
$k = -t/4M^2$




Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1H + \xi(F_1+F_2)\tilde{H} + kF_2E\}d\phi$$

Kinematically suppressed

→ $H_p, \tilde{H}_p, E_p$

Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + \ldots\}d\phi$$

→ $H_p, \tilde{H}_p$

Unpolarized beam, transverse proton target:

$$\Delta\sigma_{UT} \sim \sin\phi\,\mathrm{Im}\{k(F_2H - F_1E) + \ldots\}d\phi$$

→ $H_p, E_p$

Polarized beam, unpolarized neutron target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1H + \xi(F_1+F_2)\tilde{H} - kF_2E\}d\phi$$

→ $H_n, \tilde{H}_n, E_n$

Suppressed because $F_1(t)$ is small

Suppressed because of cancellation between PPD's of u and d quarks

$$H_p(x,\xi,t) = 4/9\,H_u(x,\xi,t) + 1/9\,H_d(x,\xi,t)$$
$$H_n(x,\xi,t) = 1/9\,H_u(x,\xi,t) + 4/9\,H_d(x,\xi,t)$$



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# The DVCS program worldwide

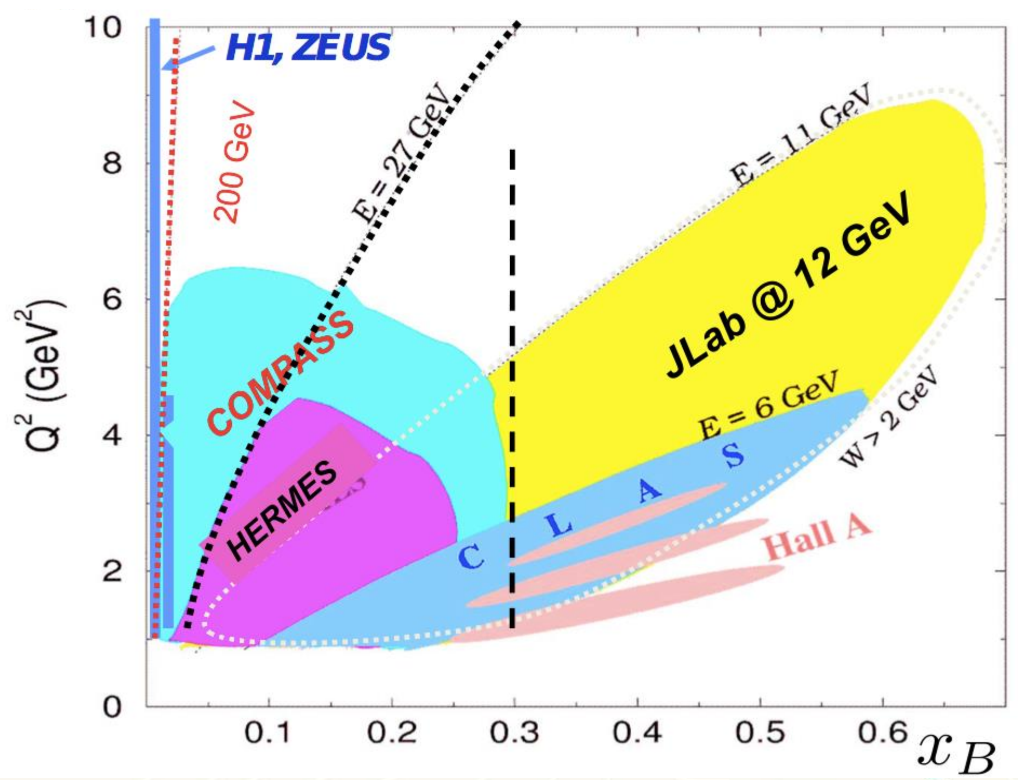
## Experimental timeline

- Pioneering results from non-dedicated experiments (Hall B and Hermes): ~2001
- First round of dedicated experiments (Hall A/B, Hermes, H1&ZEUS): ~ 2005
- Second round of dedicated experiments (Halls A/B): ~2010
- Compelling DVCS program at JLab-12 GeV and Compass: 2015 and later
- EIC program…

## In the valence region (JLab 6 and JLab 12)

Partially complimentary, overlapping

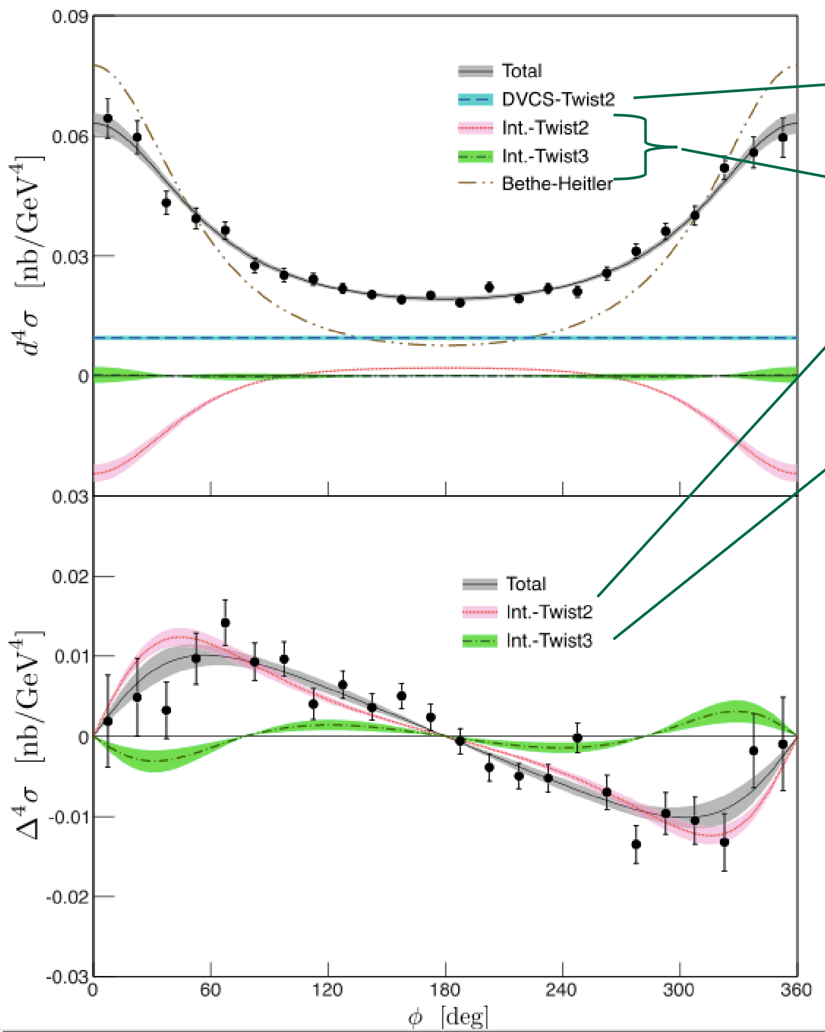
- Hall A/C: Test the validity of the formalism
  - high accuracy (~5%)
  - limited kinematic
- Hall B: Map the GPDS
  - limited accuracy (15+%)
  - wide kinematic range



# DVCS Hall A@Jlab 1rst generation

PRC C92, Nov '15

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




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

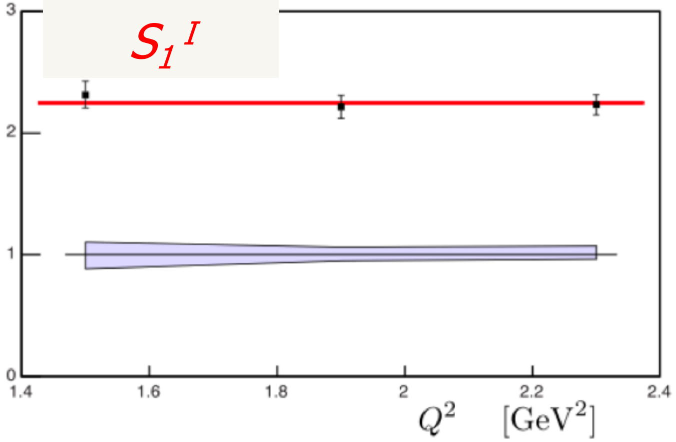
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS} \cos\phi + c_2^{DVCS} \cos 2\phi$$

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

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

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

LT/LO HT NLO




No $Q^2$ dependence within this limited range => leading twist dominance
Needs to be checked over a larger $Q^2$ bite

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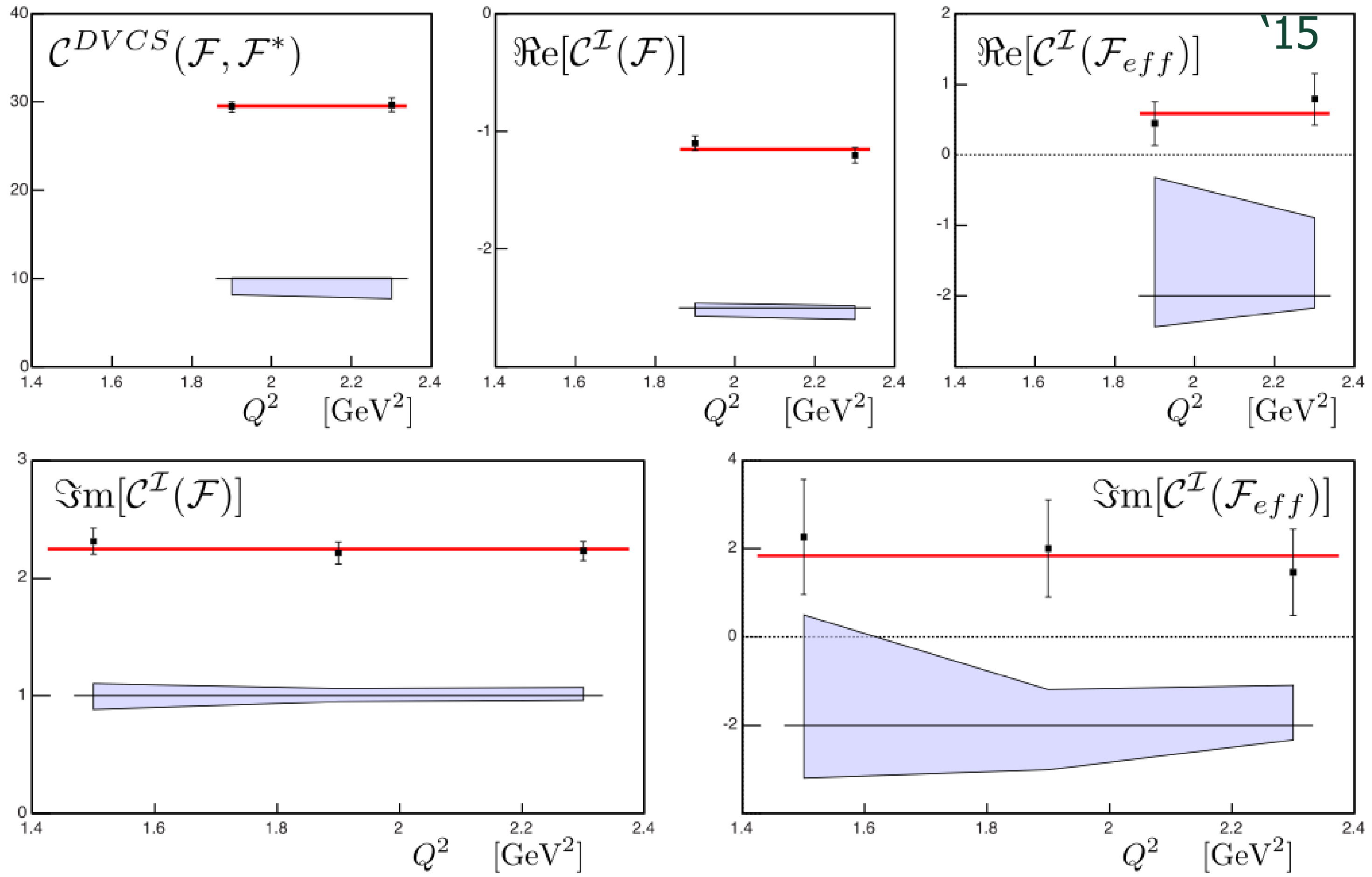
# Hall A E00-110: cross section **$Q^2$ dependence**

PRC C92, Nov '15




No $Q^2$ dependence within this limited range => leading twist dominance
Need to be checked over a larger $Q^2$ bite



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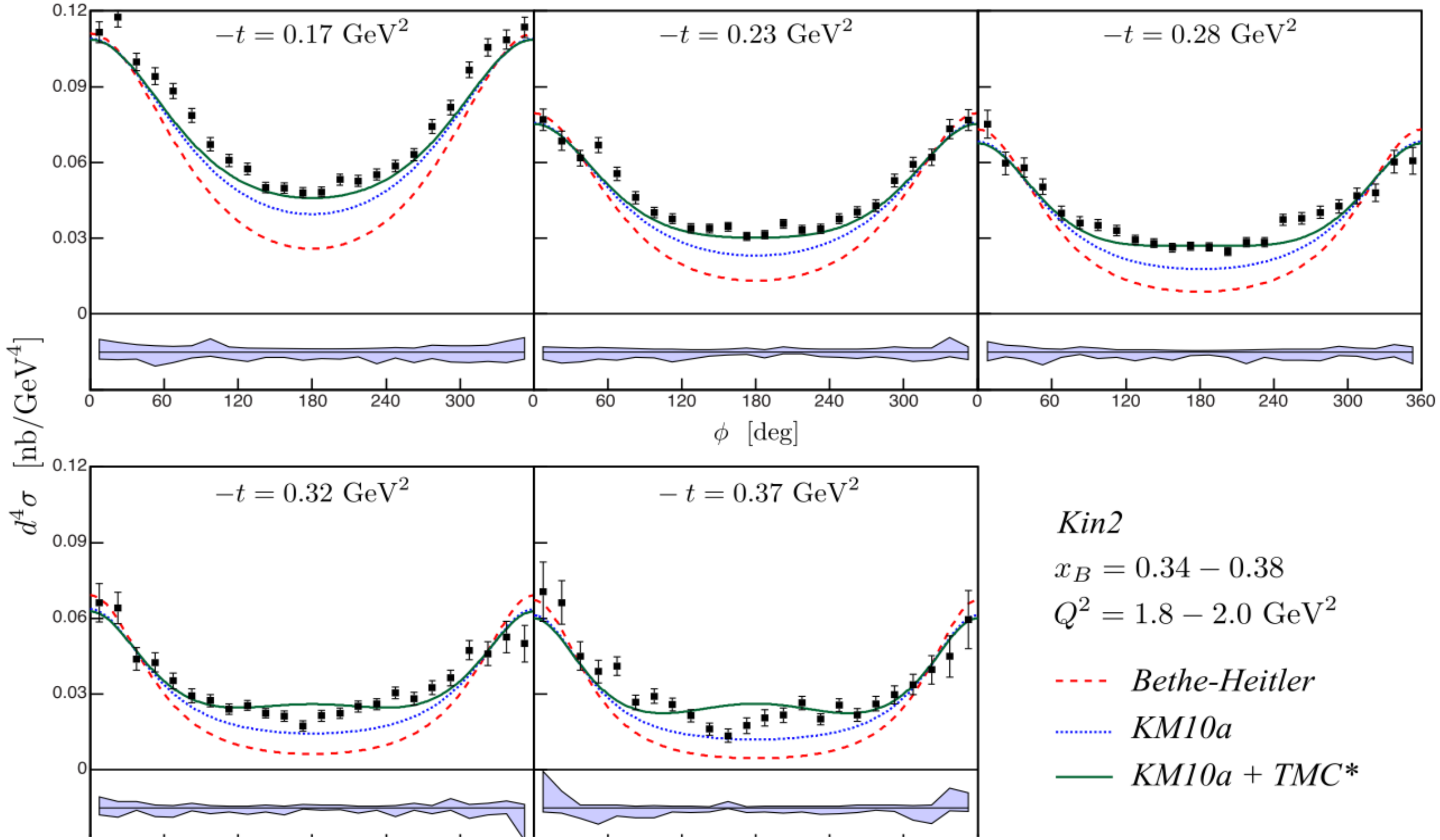
# Hall A E00-110 cross sections: **higher twist corrections**

PRC C92, Nov '15




Higher twist corrections might be necessary to fully explain experimental data

Confirmation of the significant deviation from BH => Need to measure $T^2_{DVCS}$



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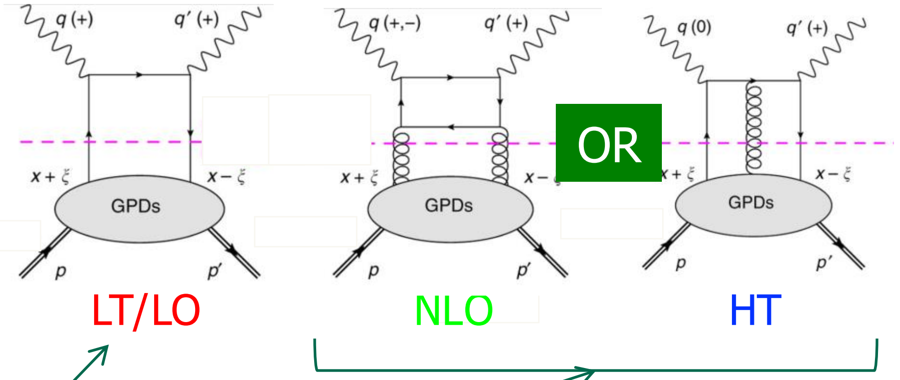
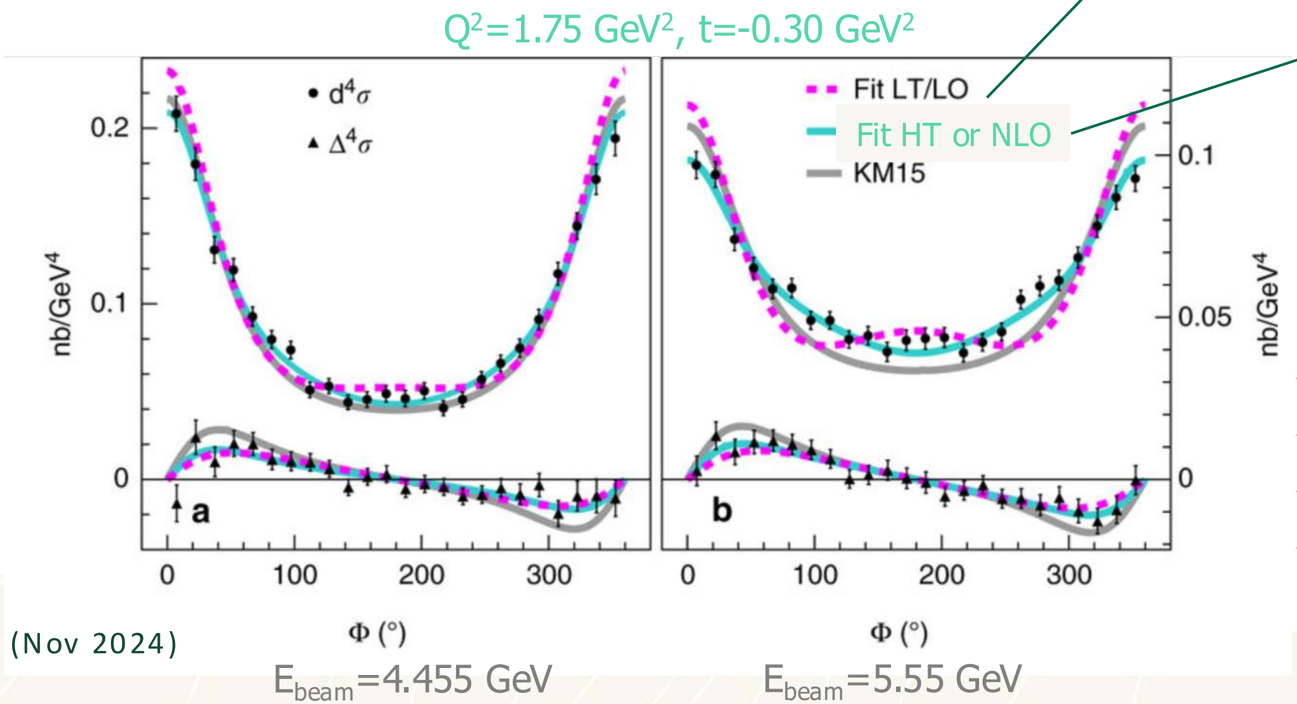
# Hall A E07-007 (JLab 6 GeV)

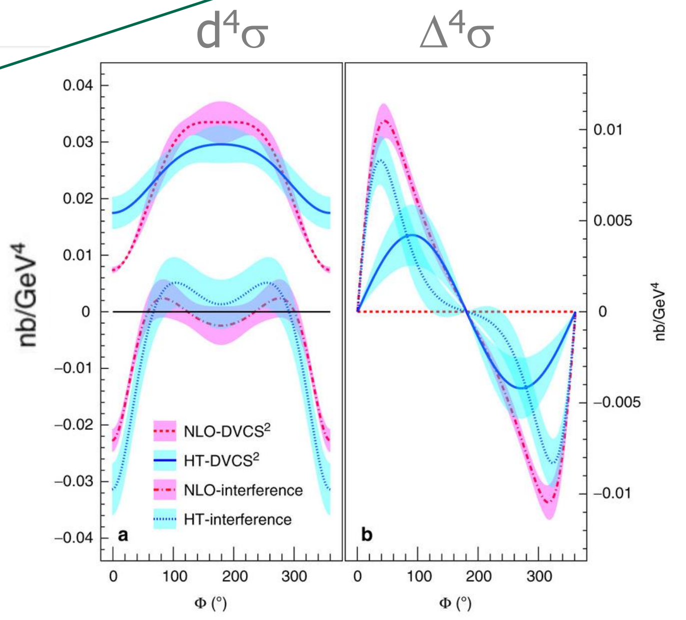
Goal: **To separate the BH.DVCS interference contribution from the DVCS² contribution.**

Nature Commun. 8 (2017) no.1, 1408

$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



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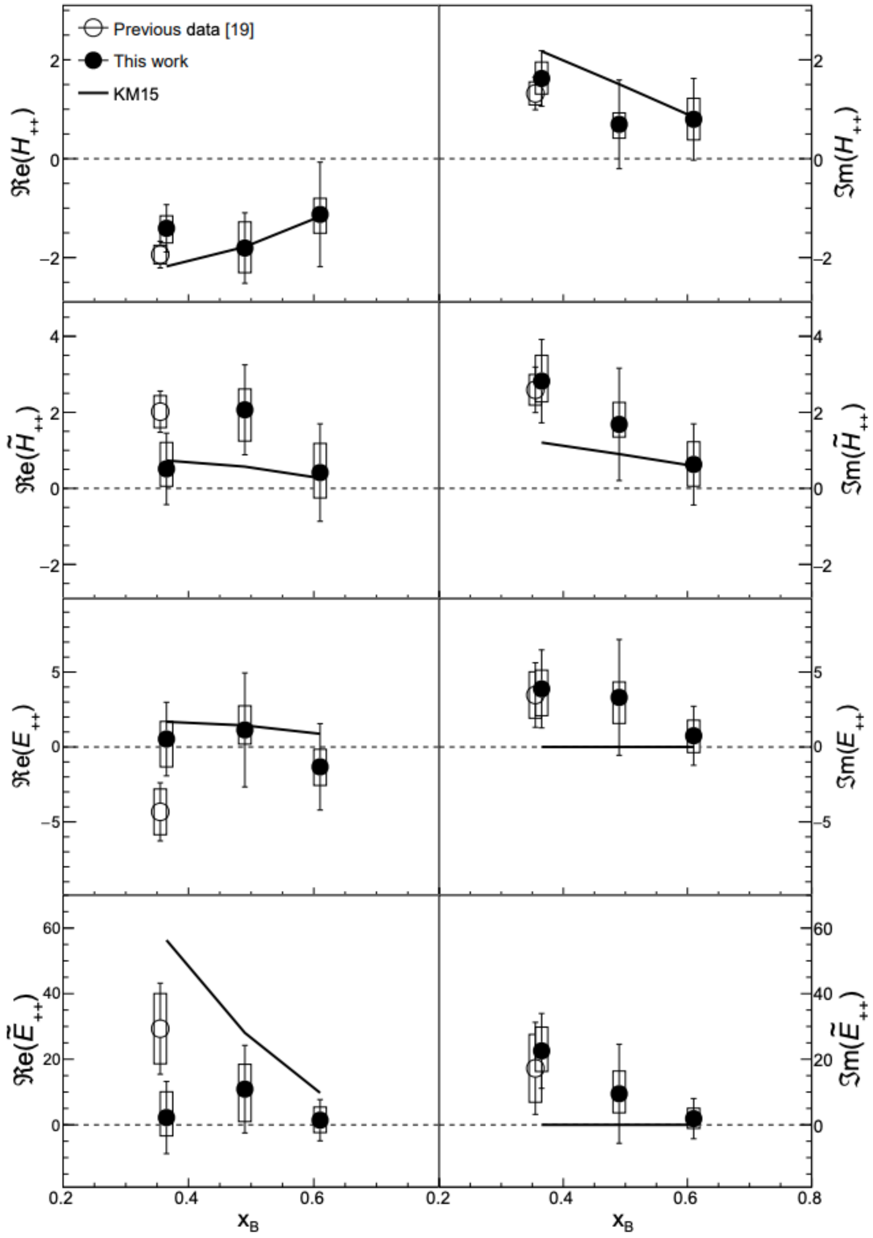
# DVCS in Hall A: 12 GeV results




[This work] **F. Georges,**
***Phys.Rev.Lett.* 128 (2022) 25, 252002**

Error bars: statistical

Error boxes: systematic

$CFF_{\lambda\lambda'}$ λ: polarization state of virtual photon (0,+,-)

λ□: polarization state of outgoing real photon (+,-)

Fit has 24 CFF

$$(\tilde{H}, H\ \tilde{E}, E)\otimes(\Re e, \Im m)\otimes(+\,+, 0+, +\,-)$$

but **only the results from the LO ones (++) are shown.**
Fits performed at constant $x_B$ and t over $Q^2$ and $\phi$ bins.
No $Q^2$ evolution of the CFFs.


[19] M. Defurne et al., Phys. Rev. C92, 055202 (2015)
[KM15] K. Kumericki and D. Mueller, *EPJ Web Conf.* 112 (2016) 01012


**The precise measurement of cross-sections at multiple values of center-of-mass energy ($\sqrt{s}$) but same $Q^2$ and it is essential for this extraction.**

Also demonstrated in

M. Defurne et al., Nat. Commun. 8, 1408 (2017).
B. Kriesten et al., Phys. Rev. D 101, 054021 (2020).
M. Čuić et al., Phys. Rev. Lett. 125, 232005 (2020).

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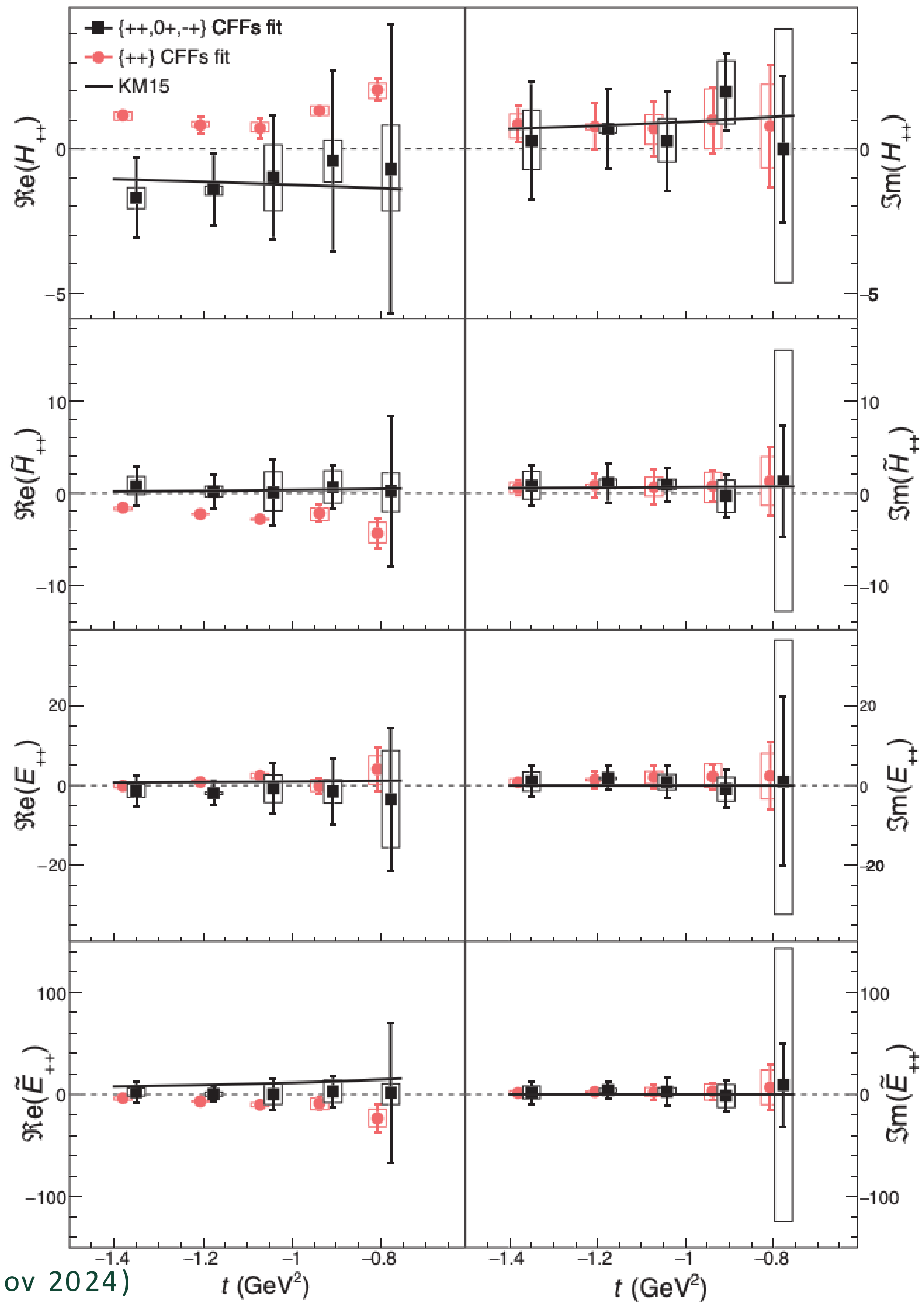
# DVCS in Hall A: 12 GeV results

**F. Georges, *Phys.Rev.Lett.* 128 (2022) 25, 252002**




Results shown at $x_B$=0.60
Fits performed at constant $x_B$ and t over $Q^2$ and $\phi$ bins.
No $Q^2$ evolution of the CFFs.

■ Fit has 24 CFF

$$(\tilde{H}, H\ \tilde{E}, E) \otimes (\Re e, \Im m) \otimes (+\,+, 0+, +\,-)$$

but **only the results from the LO ones (++) are shown.**

● Fit has only 8 CFF

$$(\tilde{H}, H\ \tilde{E}, E) \otimes (\Re e, \Im m) \otimes (+\,+)$$

**Fitting all CFFs is essential to get realistic estimates of their uncertainties.**



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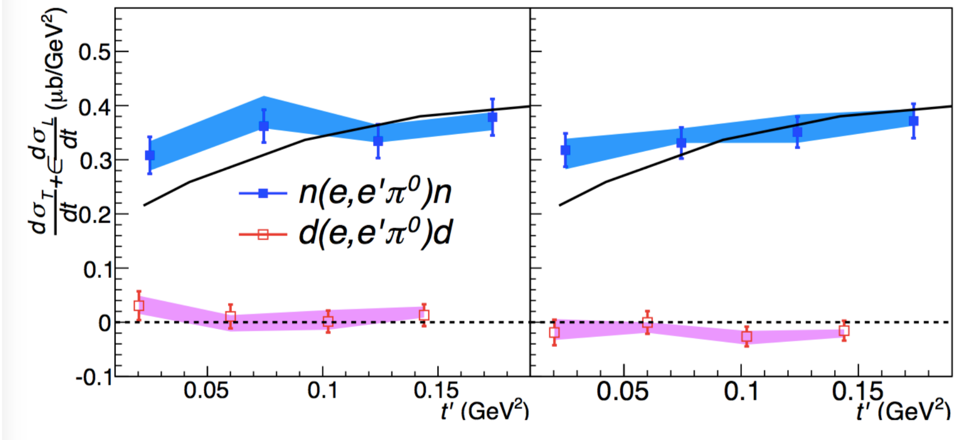
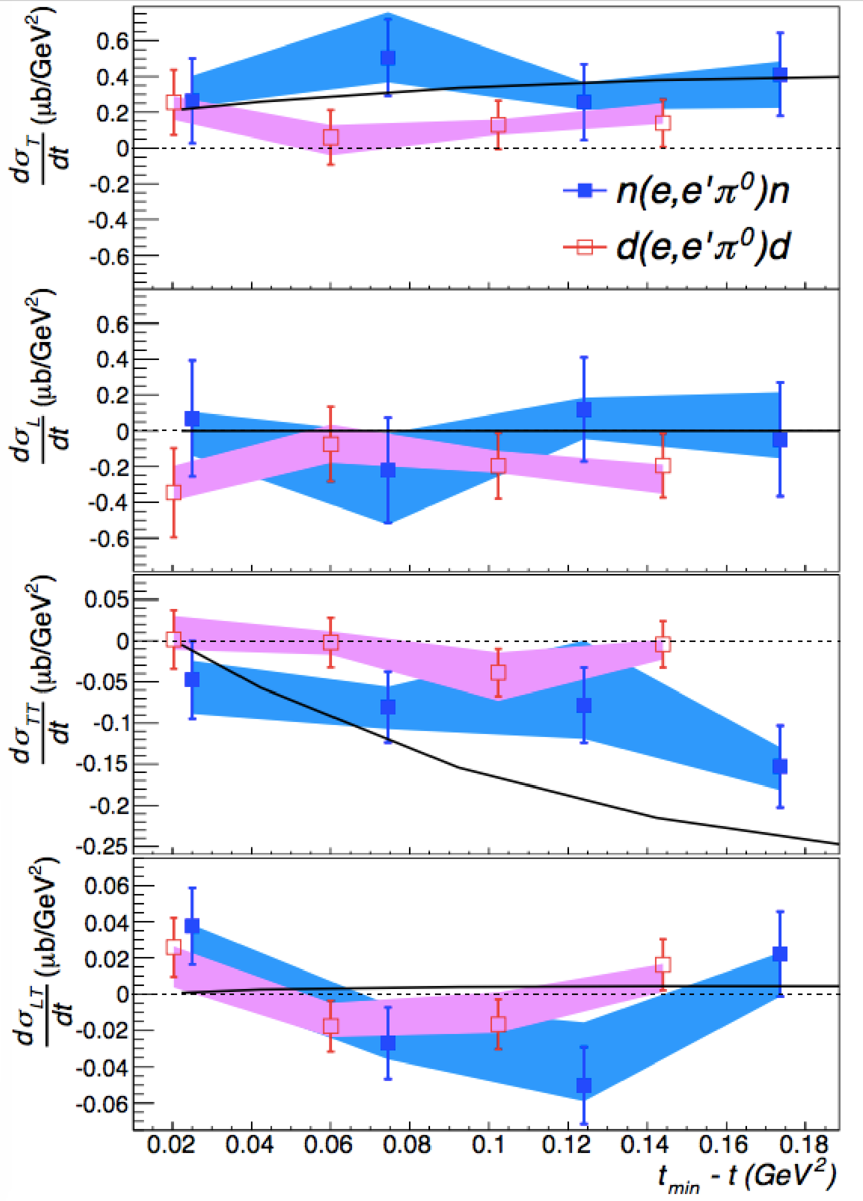
# $\pi^0$ DVCS2n results: fully separated contributions

M. Mazouz PRL 118 (2017) 22, 222002

$Q^2$=1.75 GeV$^2$ and $x_B$=0.36




Goloskokov and Kroll
Eur Phys J A47 (2012)

$$\frac{d\sigma_T}{dt} = \Lambda \left[ \left(1-\xi^2\right) \left|\langle H_T \rangle\right|^2 - \frac{t'}{8M^2} \left|\langle \bar{E}_T \rangle\right|^2 \right]$$

$$\frac{d\sigma_{TT}}{dt} = \Lambda \, \frac{t'}{8M^2} \left|\langle \bar{E}_T \rangle\right|^2 .$$

$$\bar{E}_T = 2\tilde{H}_T + E_T$$

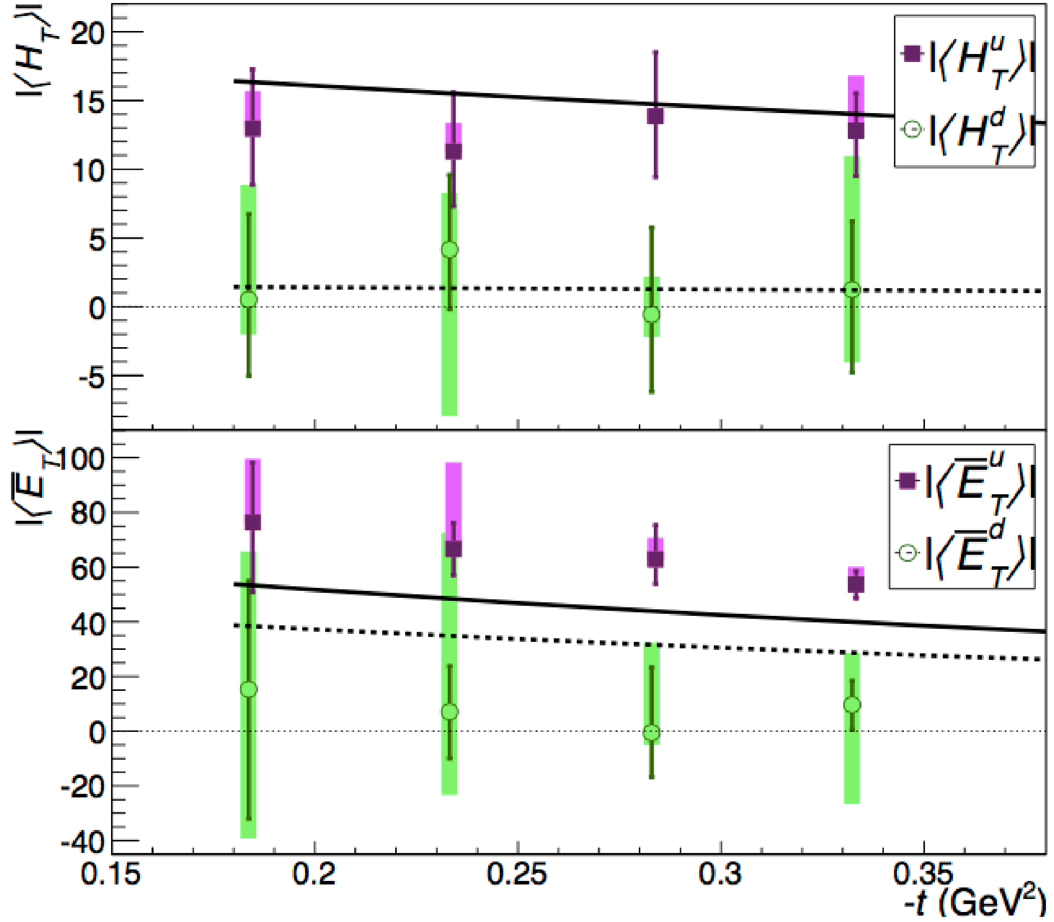
# $\pi^0$ DVCS2n results: flavor separation

M. Mazouz PRL 118 (2017) 22, 222002

$$|\langle H_T^{p,n}\rangle|^2 = \frac{1}{2}\left|\frac{2}{3}\left\langle H_T^{u,d}\right\rangle + \frac{1}{3}\left\langle H_T^{d,u}\right\rangle\right|^2$$

$Q^2$=1.75 $GeV^2$ , $x_B$=0.36

account for the unknown phase variation between u and the d amplitude $\gamma^*q \to q'\pi^0$ convoluted with $(H,E)_T$




Goloskokov and Kroll
Eur Phys J A47 (2012)

——— u quark
------------ d quark

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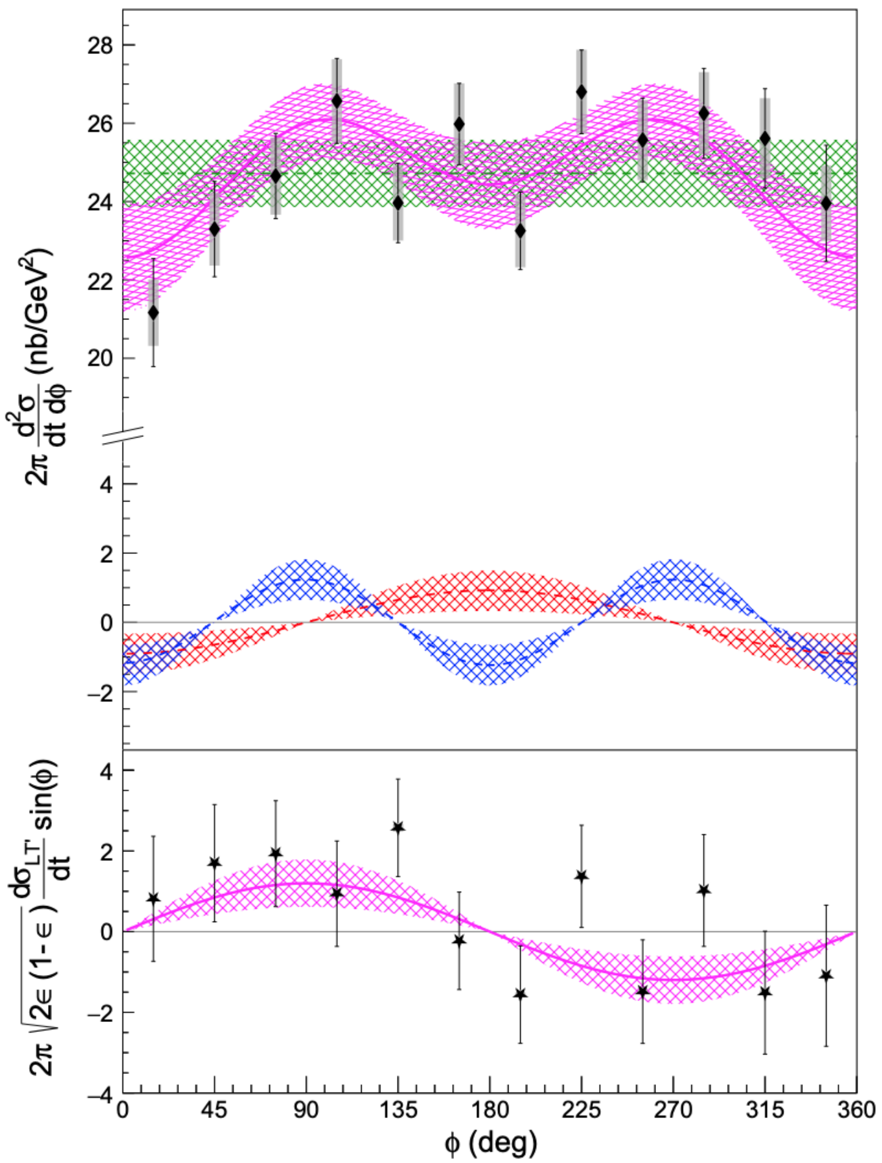
# $ep \to ep\pi^0$ in Hall A : 12 GeV result

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301




At sufficient high $Q^2$, meson production should be understandable in terms of the "handbag" diagram.

But the factorization is only exact for longitudinal virtual photons (Collins, Frankfurt, Strikman, 1997). Effective factorization of the transverse part exists.

Asymptotic QCD predicts that

$$\sigma_L \to Q^{-6}\ , \qquad \sigma_T \to Q^{-8} \ \text{and} \quad \frac{\sigma_T}{\sigma_L} \to \frac{1}{Q^2}$$

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\frac{d^2\Gamma_\gamma}{dQ^2 dx_B}(Q^2, x_B, E)$$

$$\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin(\phi)\right]$$

$d\sigma_U = d\sigma_T + \varepsilon\, d\sigma_L$



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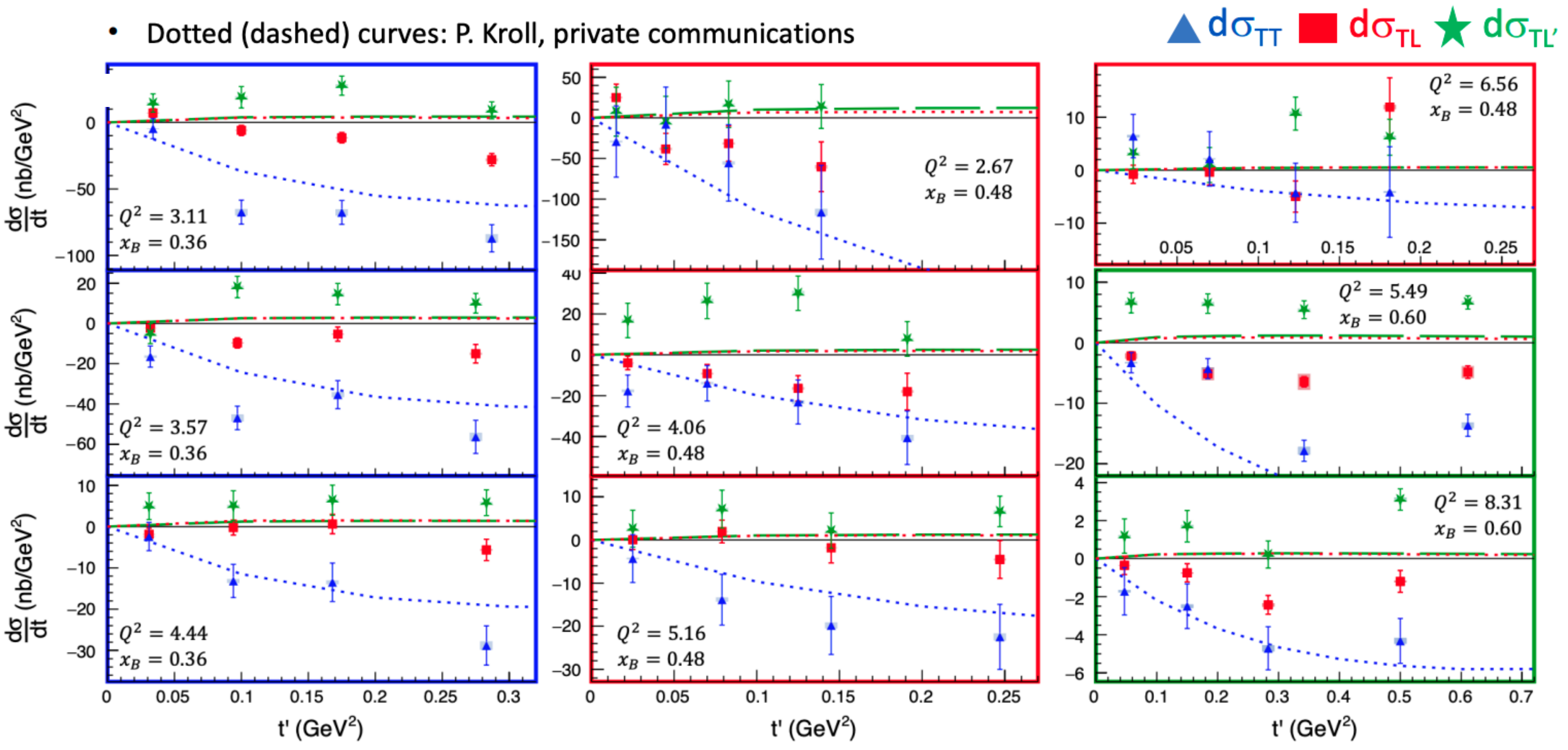
# $ep \rightarrow ep\pi^0$ in Hall A : 12 GeV result

- Dotted (dashed) curves: P. Kroll, private communications




$t' = t_{min} - t$

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301

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- $\sigma_{TT}$ larger than $\sigma_{TL}$ and $\sigma_{TL'}$ : hint of dominance of the transverse amplitude as suggested by the GK model
- $\sigma_{TL}$ and $\sigma_{TL'}$ underestimated by the GK model: larger contribution of the longitudinal amplitude than the one expected by GK
- sign difference between GK and $\sigma_{TL}$ (Hall B & COMPASS results agree with GK)



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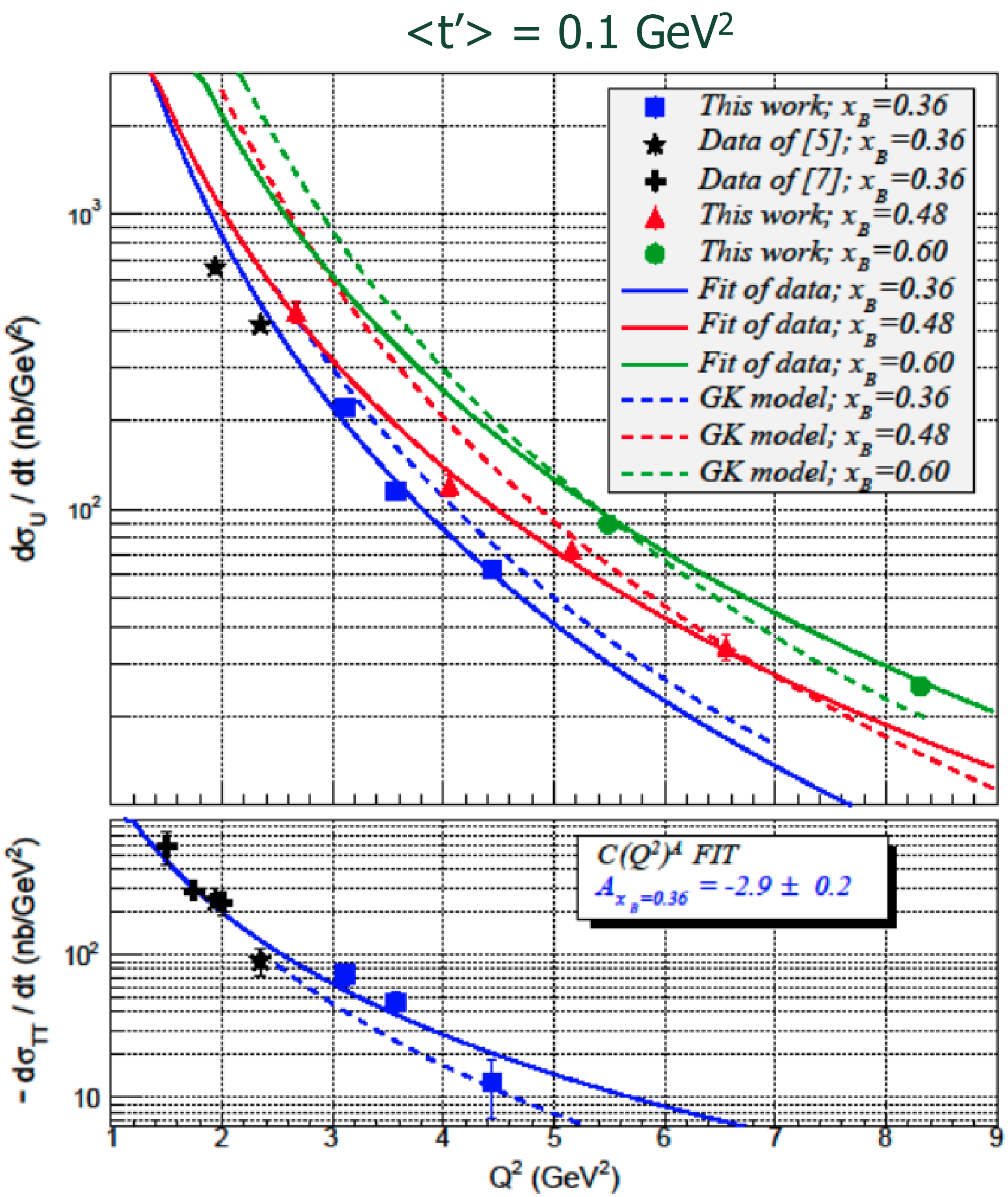
# $ep \rightarrow ep\pi^0$ in Hall A : 12 GeV result

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301

$$\frac{d\sigma_u}{dt} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}$$




dashed lines: P. Kroll private communication

- This work, $x_B = 0.36$
- This work, $x_B = 0.48$
- This work, $x_B = 0.60$
- E. Fuchey *et al*, Phys. Rev. C 83, 025201 (2011)
- M. Defurne *et al*, Phys. Rev. Lett. 117, 262001 (2016)

- $C(Q^2)^A \exp(-Bt')$ fit to experimental results of $d\sigma_U$ in different $x_B$ → solid curves
  - $x_B = 0.36 \rightarrow A = -3.3 \pm 0.1$
  - $x_B = 0.48 \rightarrow A = -2.9 \pm 0.1$
  - $x_B = 0.60 \rightarrow A = -3.1 \pm 0.1$
- $Q^2$ dependence closer to $Q^{-6}$, rather than $Q^{-8}$ as expected for $\sigma_T$ at high $Q^2$



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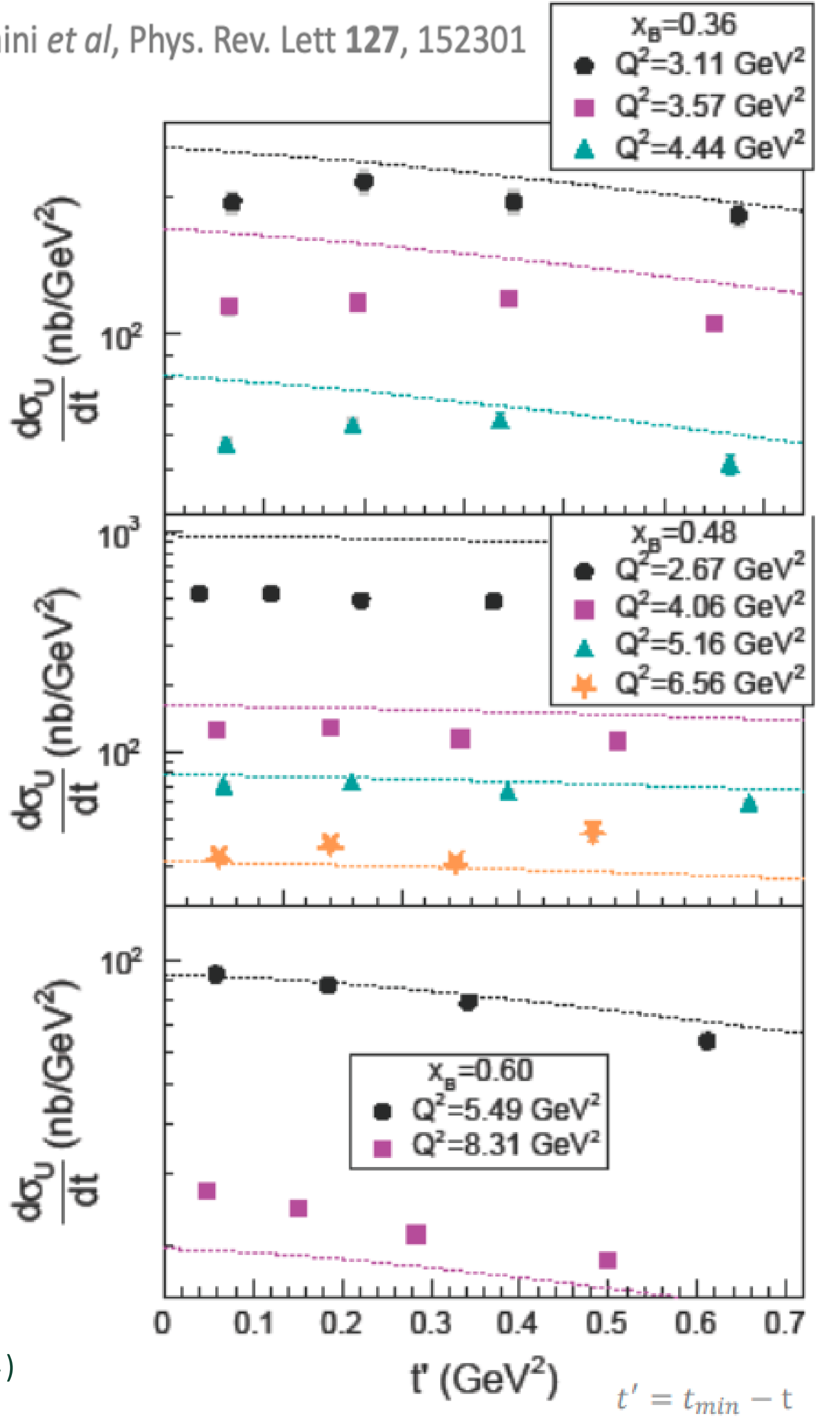
M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301




$t' = t_{min} - t$

$$\frac{d\sigma_u}{dt} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}$$

dashed lines: P. Kroll private communication



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# E12-13-010: precision DVCS/$\pi^0$ cross sections

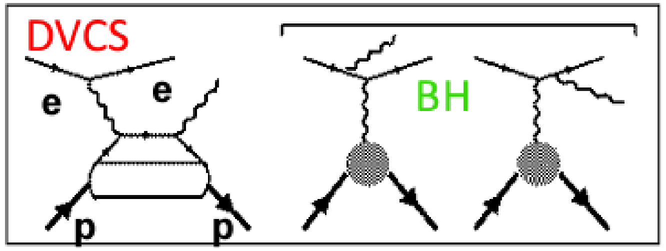
Simplest process: **e + p → e' + p + γ (DVCS)**

**E12-13-010 DVCS measurements follow up on measurements in Hall A:**

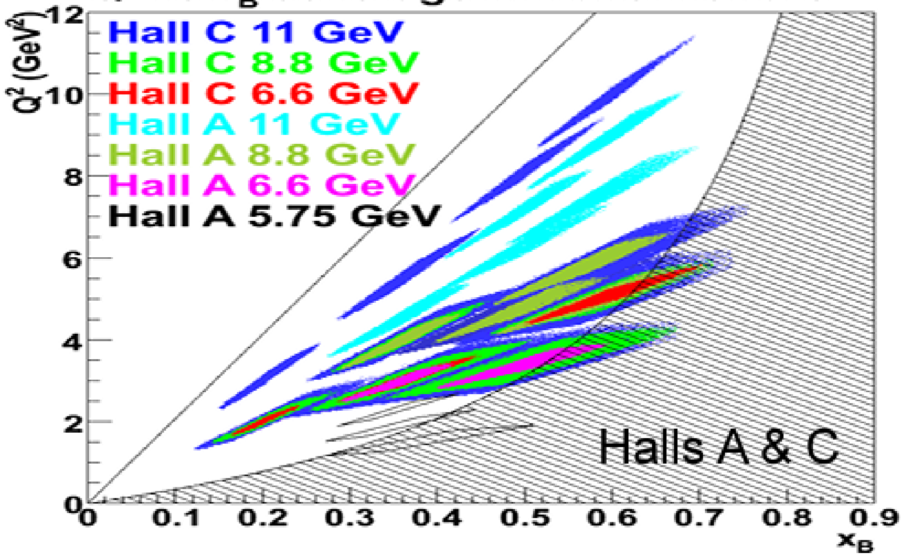
- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \mathrm{Re}\big[\underbrace{DVCS^{\perp}\ BH}_{\sim E^2_{beam}}\big] + \underbrace{|DVCS|^2}_{\sim E^3_{beam}}$$

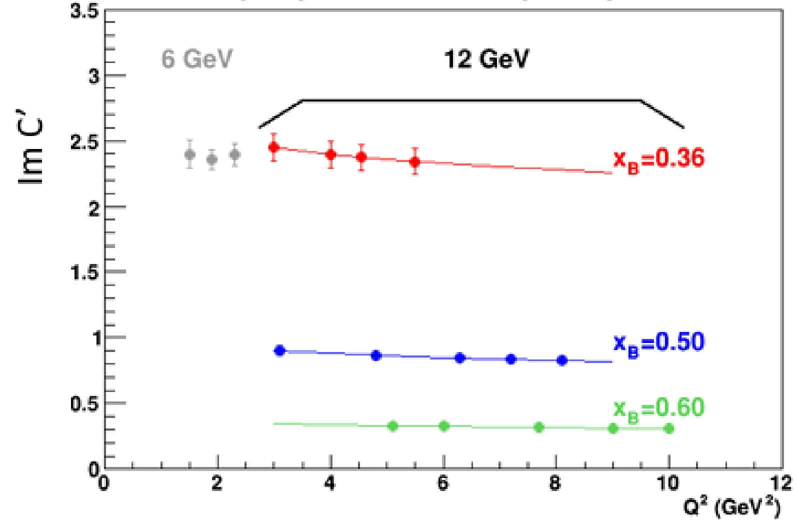
- L/T separation of $\pi^0$ production




Hall A data for Compton form factor (over *limited* $Q^2$ range) agree with hard-scattering



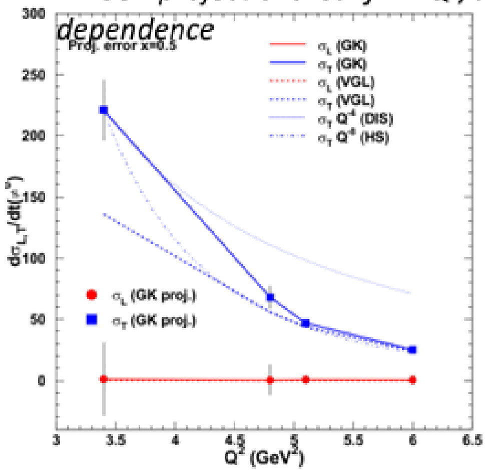

***12 GeV projections: confirm formalism***




**$\pi^0$ Exclusive Cross Sections**

- Relative L/T contribution to $\pi^0$ cross section important in probing transversity
- Results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in $\pi^0$ production is non-zero up to $Q^2$=2 GeV$^2$

*12 GeV projections: confirm $Q^2$/t dependence*



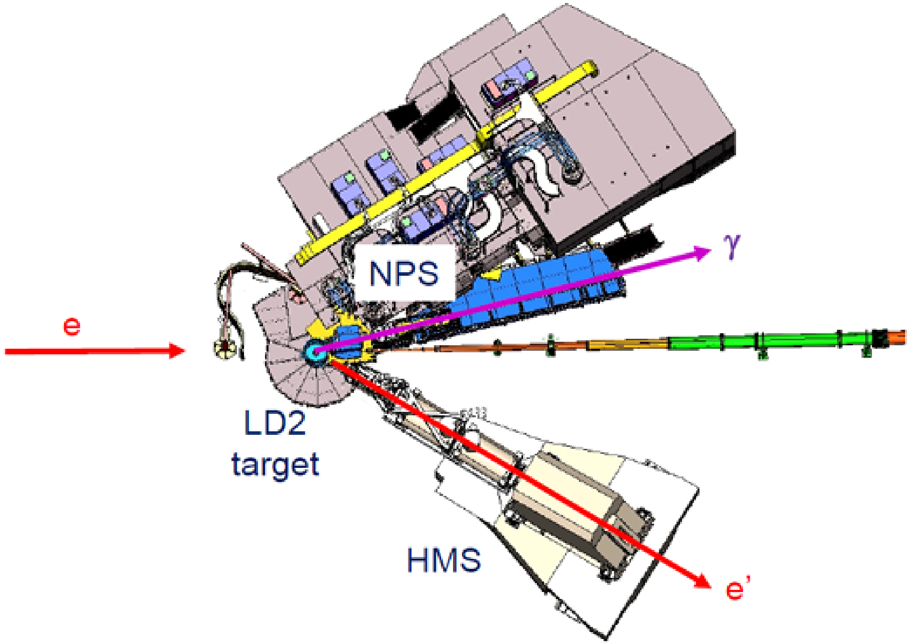

E12-13-010 provides also data on $\sigma_T$ and $\sigma_L$ at higher $Q^2$ for reliable interpretation of 12 GeV GPD data

Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies (DVCS$^2$–Interference separation)

# E12-22-006: DVCS off the Neutron

Probe flavor dependence of GPDs with precision nDVCS cross sections

Measurement of the $N \rightarrow e'\gamma X$ reaction (N=p, n, d) using an $LD_2$ target in Hall C




With NPS and HMS in Hall C reach ~x2-12 better nDVCS & dDVCS separation than previous 6 GeV experiment

*Projected Impact on flavor dependence of CFFs*

- *Simultaneous fit of E12-13-010 (p) and E12-22-006 (n)*
- *Real and imaginary parts of CFFs H and $\widetilde{H}$ and E (u & d) as free parameters (nDVCS not sensitive to $\tilde{E}$)*