Experiment E12-06-114 in Hall A

$ep \rightarrow ep\gamma$

Deep Virtual Compton Scattering (DVCS)

$ep \rightarrow ep\pi^0 \rightarrow ep\gamma\gamma$

Deep exclusive π^0 production

Generalized Parton Distributions (GPDs)
3D nucleon imaging

Hall A/C collaboration meeting
16 July 2020

Bishnu Karki
Duke University, North Carolina

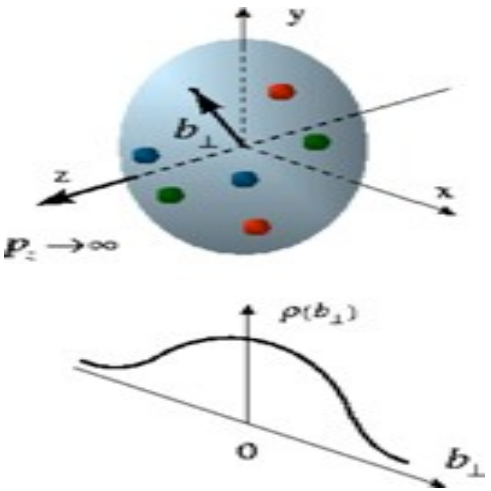
On behalf of DVCS collaboration

Award # 1913170

Nucleon structure

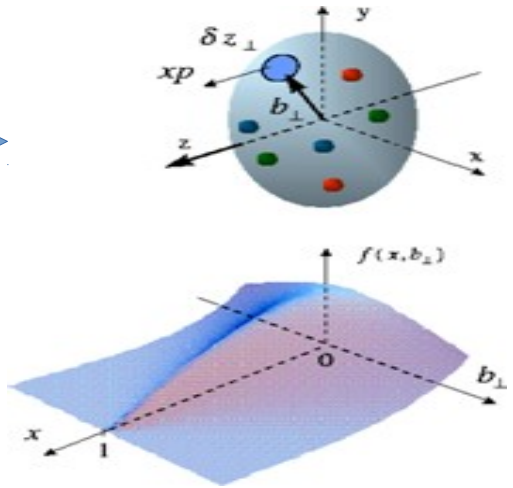
beyond FFs and PDFs

Elastic scattering



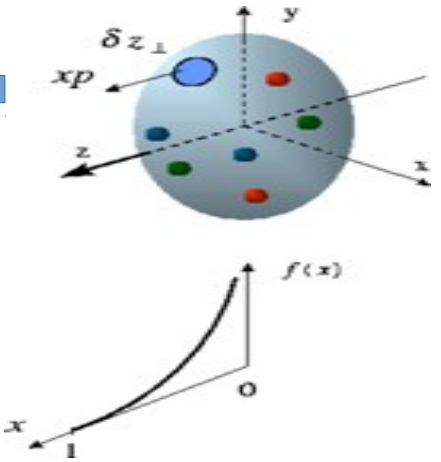
- **F**orm **F**actors **(FFs)**
  - ✔ Spatial distribution
  - ✗ Momentum distribution

Deep exclusive processes



- **G**eneralized **P**arton **D**istributions **(GPDs)**
  - ✔ Spatial distribution
  - ✔ Longitudinal momentum distribution

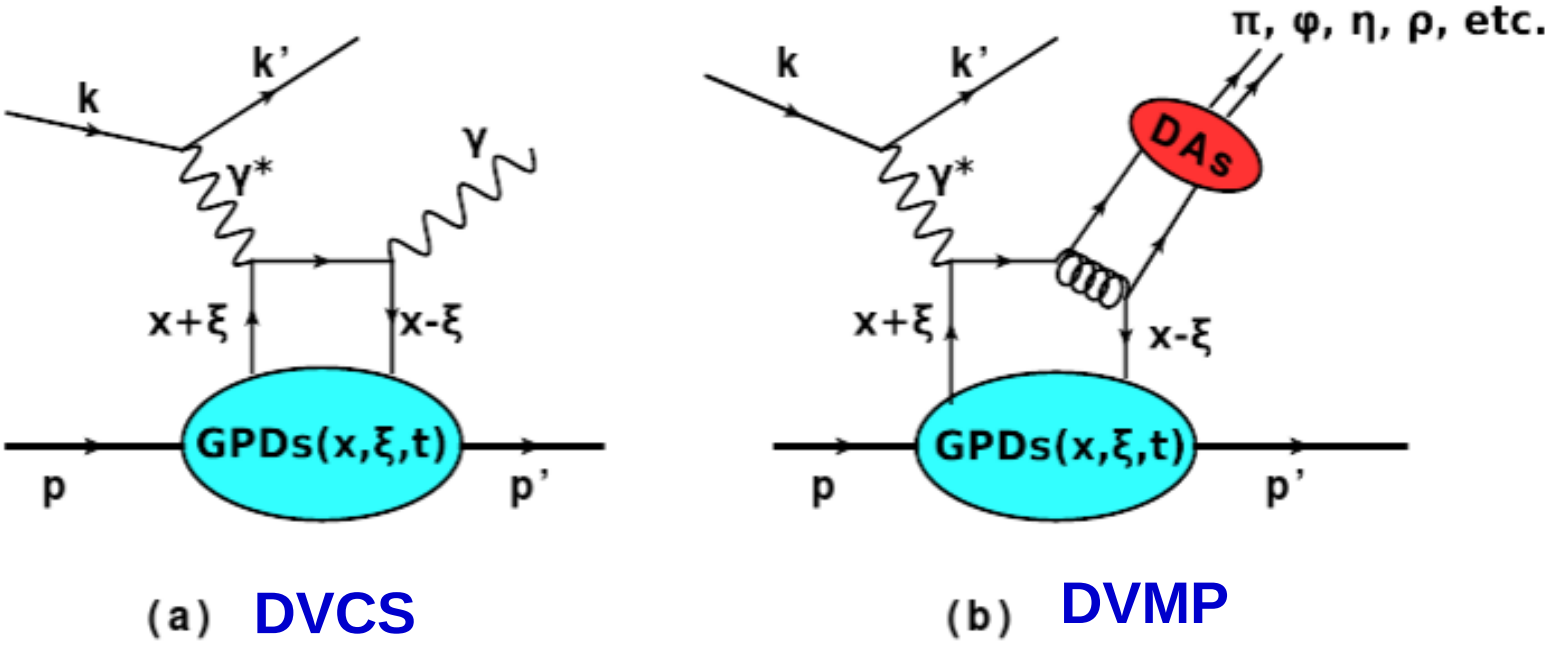
Deep inelastic scattering



- **P**arton **D**istribution **F**unctions **(PDFs)**
  - ✔ Longitudinal momentum distribution
  - ✗ Spatial distribution

GPDs allows to access a 3D structure of nucleon

Access to GPDs: Deep exclusive processes



(a) **DVCS** (b) **DVMP**

Nucleon can be described by

- 4 chiral even GPDs **: Quark Helicity** (**DVCS/DVMP**) **conserved**

$$H^q, \widetilde{H}^q, E^q, \widetilde{E}^q$$

- 4 chiral odd GPDs **: Quark Helicity** **(DVMP)** **not conserved**

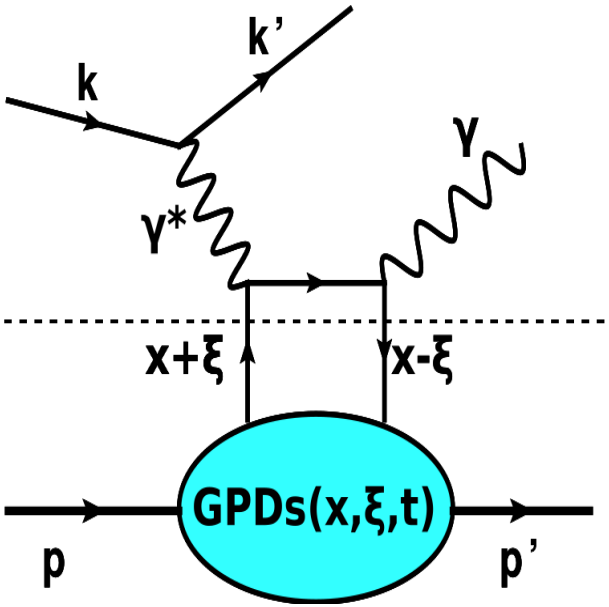
$$H_T^q, \widetilde{H}_T^q, E_T^q, \widetilde{E}_T^q$$

	Nucleon helicity	
	Conserving	Non-cons.
Unpolarized	H	E
polarized	$\widetilde{H}$	$\widetilde{E}$

Access to GPDs: QCD factorization

In Bjorken limit: $Q^2 = -q^2 \to \infty$, $\nu \to \infty$ } **At fixed** $x_B = Q^2 / 2M\nu$

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)



Or π, ϕ

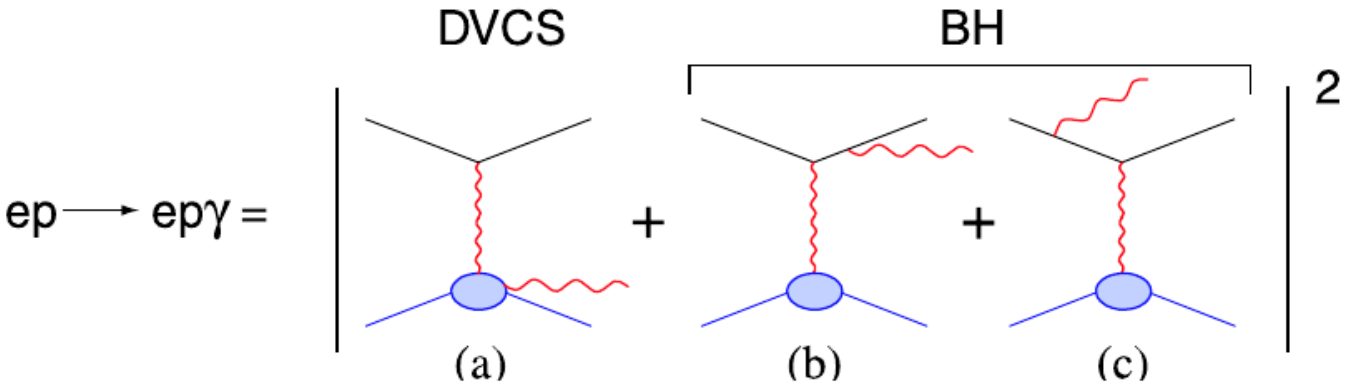
Hard/perturbative Part:
Calculable

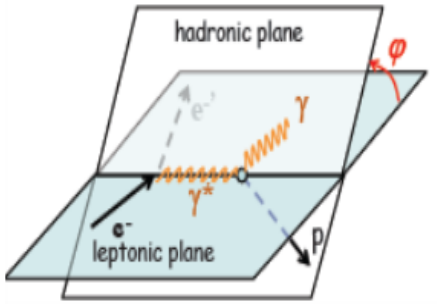
Soft/non-perturbative Part:
Nucleon structure is parametrized by GPDs

Definition of variables:
x: longitudinal momentum fraction carried by struck quark
ξ: longtitudinal momentum transfer ≈ x_B / (2- x_B)
t: four momentum transfer related to $b_\perp$ via Fourier transform

- **Minimum Q^2 at which factorization holds must be tested through experiments**
- **Factorization is only proven for longitudinally polarized virtual photons for DVMP**

Measuring DVCS cross-section





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

Known from FFs

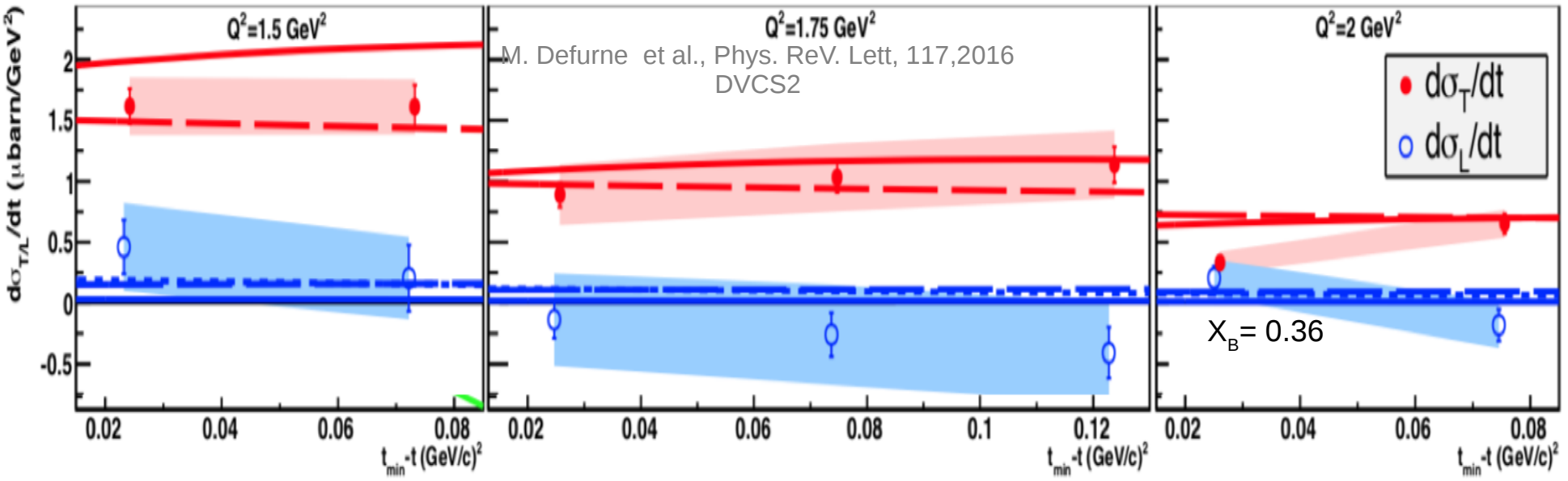
Bilinear combination of GPDs

Linear combination of GPDs and FFs

P_l : beam or target polarization

e_l : charge of lepton beam

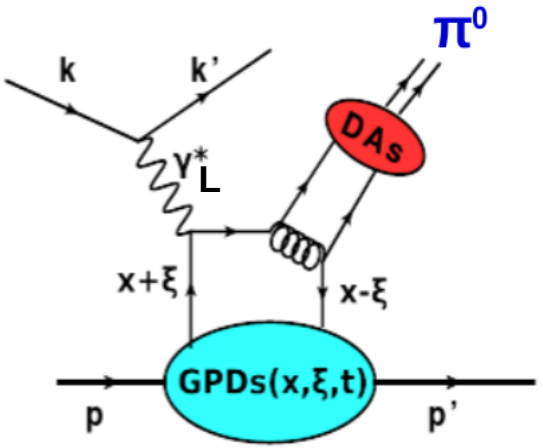
Exclusive π^0 production



M. Defurne et al., Phys. ReV. Lett, 117,2016
DVCS2

- Factorization only for longitudinally polarized virtual photon
- Leading twist handbag approach predicts: $\sigma_L \sim Q^{-6}$ & $\sigma_T \sim Q^{-8}$ **i.e.** $(\sigma_L >> \sigma_T)$
- Data from deviates from prediction
- Transversity GPDs models

S. V. Goloskokov and P. Kroll, Eur. Phys.J. C65:137,2010
G.R Goldstein, J.O Hernandez S. Liuti Phys. Rev. D84 (2011)



Exploring for the first time the high x_B region
(E12-06-114)

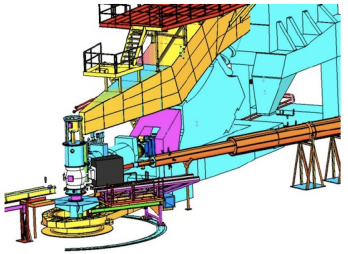
DVCS

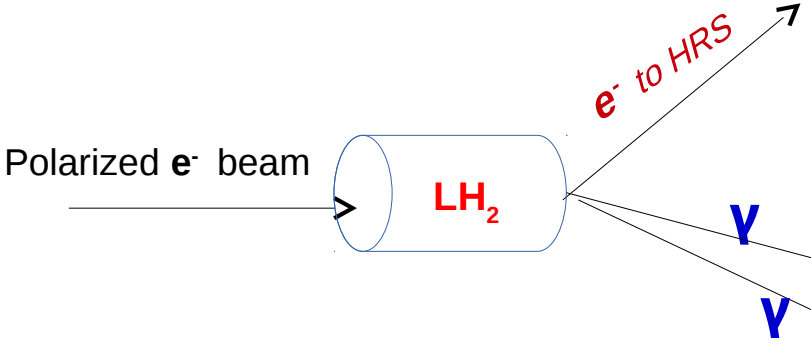
$$ep \rightarrow ep\gamma$$

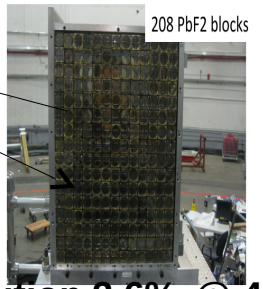
π^0 production

$$ep \rightarrow ep\pi^0 \rightarrow ep\gamma\gamma$$

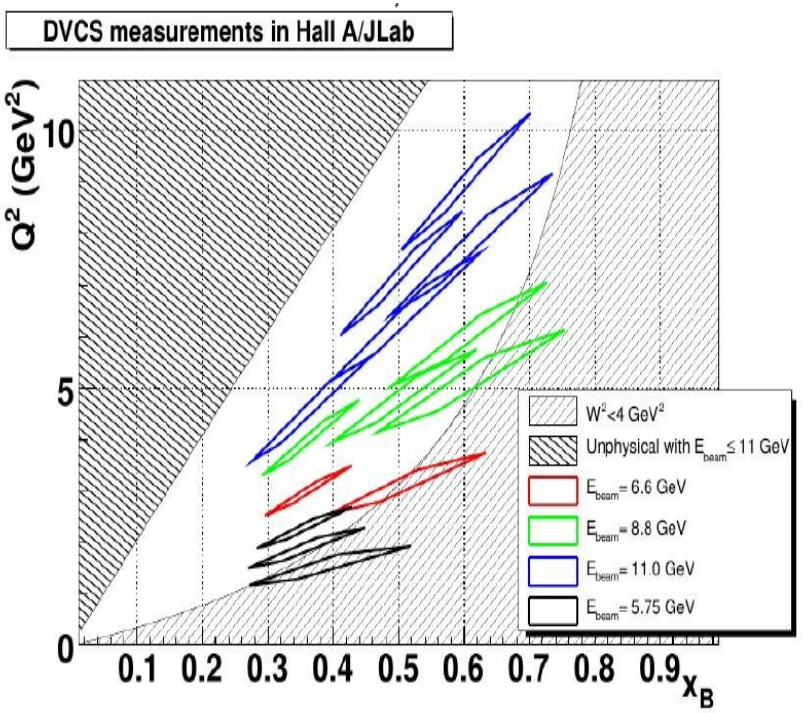
δP/P Resolution 10^{-4} @ 4.3 GeV



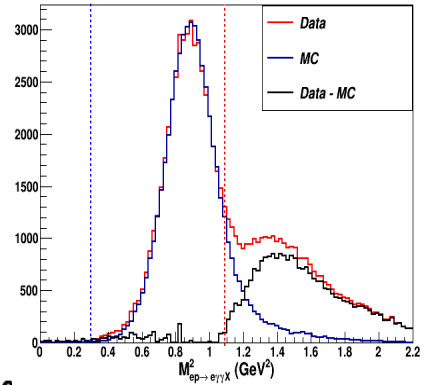




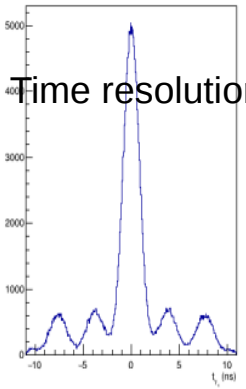
E resolution 3.6% @ 4.2 GeV



Recoil proton (missing mass)



$$M^2_{ep\rightarrow e'\gamma\gamma X} = (e + p - e' - \gamma_1 - \gamma)^2_2$$



Time resolution ~1ns

- **Ran between 2014-2016**
- **Beam energy between 8.5 to 11 GeV**
- **Completed ~50% of allocated 100 PAC days**
- **Missing PAC days reallocated in Hall C**

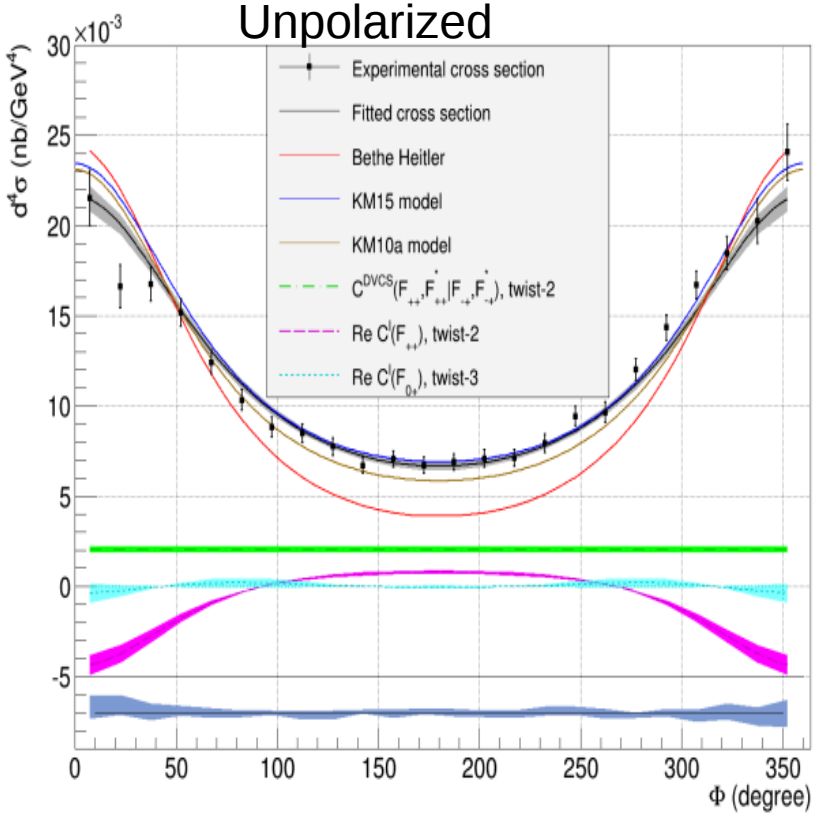
DVCS results

Unpolarized/Polarized cross-section

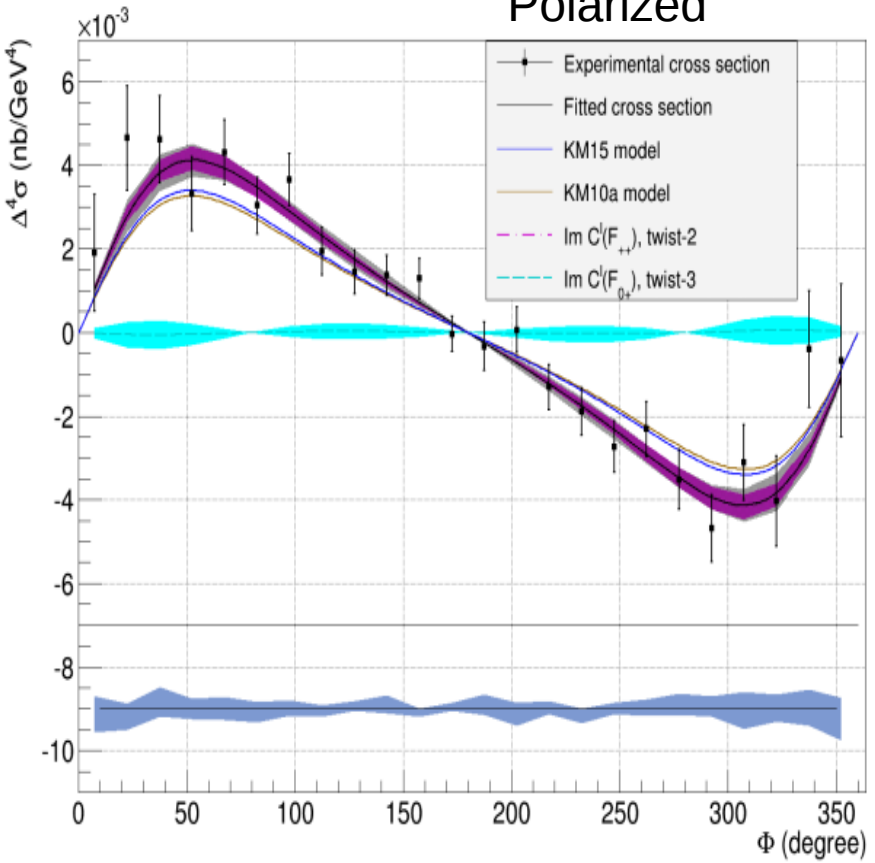
F. Georges, A. Johnson, H. Rashad

E=8.5, Q^2 = 3.6, x_B=0.36, t – t_{min} [-0.186, -0.124]

Unpolarized



Polarized



- Results ready for 9 different kinematics
- Twist 2 dominance
- Small contribution from twist 3
- DVCS paper is in preparation

K. Kumericki and D. Muller EPJ Web of conference 112, 2015
K. Kumericki, S. Liuti, and H. Moutarde Eur. Phys. J. A. 52, 2016

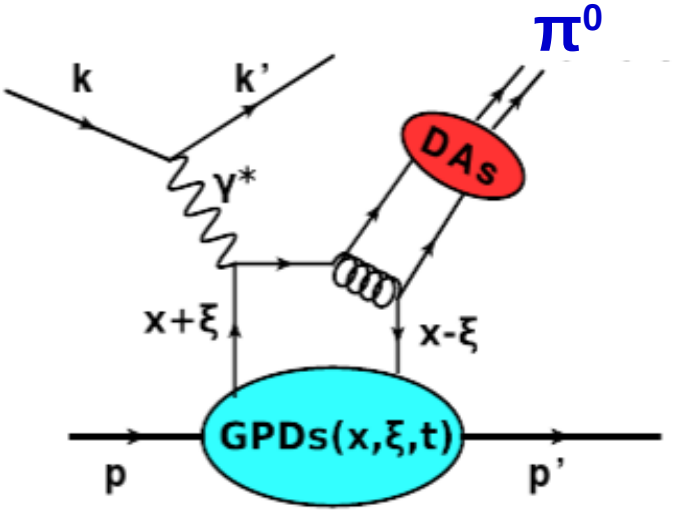
π^0 production

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

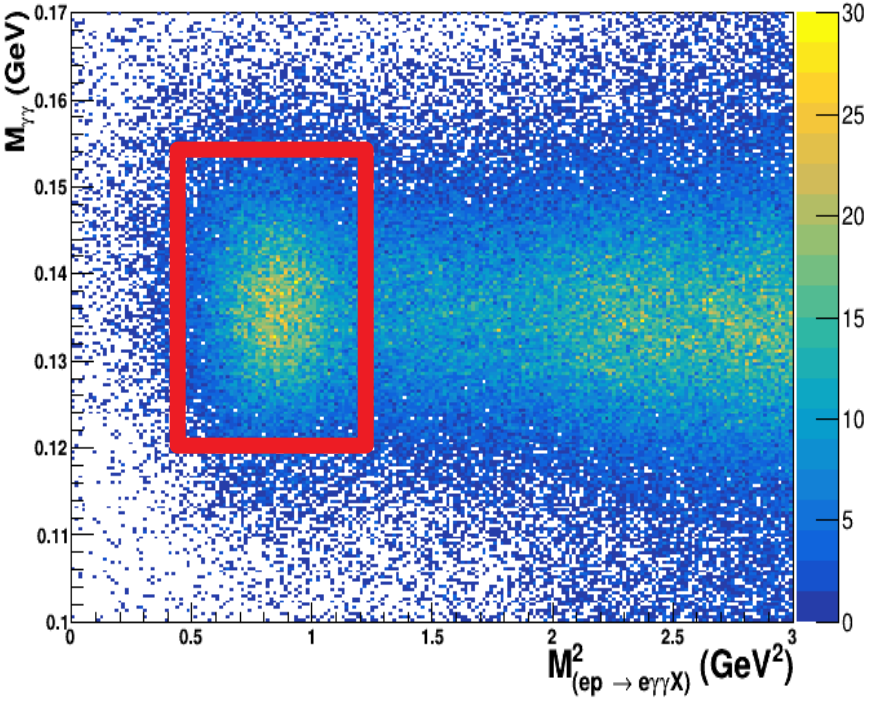
Unpolarized $\quad \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}, \quad \frac{d\sigma_{TL}}{dt}, \quad \frac{d\sigma_{TT}}{dt}$

- L/T not separable in this experiment

Polarized $\quad \frac{1}{2}\left(\sigma^+ - \sigma^-\right) \rightarrow \frac{d\sigma_{LT'}}{dt}$

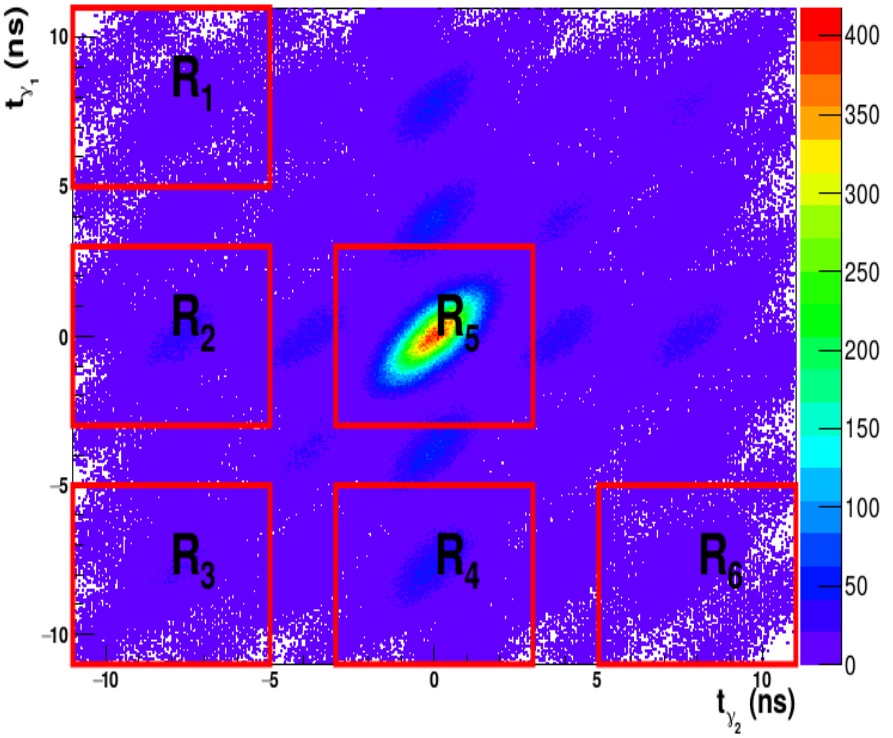


π^0 event selection



$ep \to e'p'\pi^0$

$\pi^0 \to \gamma\gamma$



$$M^2_{ep\to e'\gamma\gamma X} = (e + p - e' - \gamma_1 - \gamma_2)^2$$

- Signal : coincidence window [-3, 3] ns

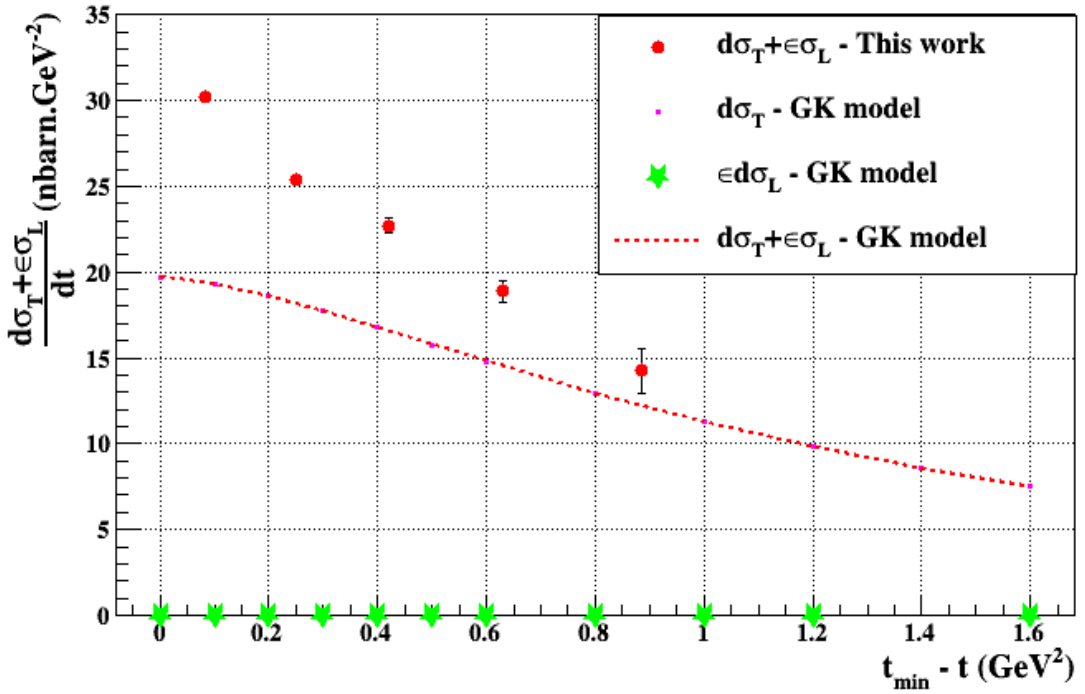
- Major source of background are accidentals
- SIDIS: ep ----►e'p'π^0**x** (different missing mass cut)

Unpolarized cross-section parameters

E0=10.59 GeV, x_B= 0.60, Q^2 = 8.4 GeV^2

M.Dlamini, S. Ali, Po-Ju Lin, Ho-San Ko, B. Karki

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



Source	Value (%)
DIS (e^-)	3.5
Exclusive cuts	0.5
Energy Thresh.	2
Clust. Thresh.	0.5
Total (Unpol)	**4.1**
Beam Pol.	1
Total (Pol.)	**4.2**

- Results available for three different x_B (0.36, 0.48, 0.60), total 9 different kinematics
- These data will improve the parametrization of the GPDs
- First time this model confronted to high x_B and t, GK predictions are promising
- S. Liuti et. al calculations on progress

Unpolarized cross-section parameters

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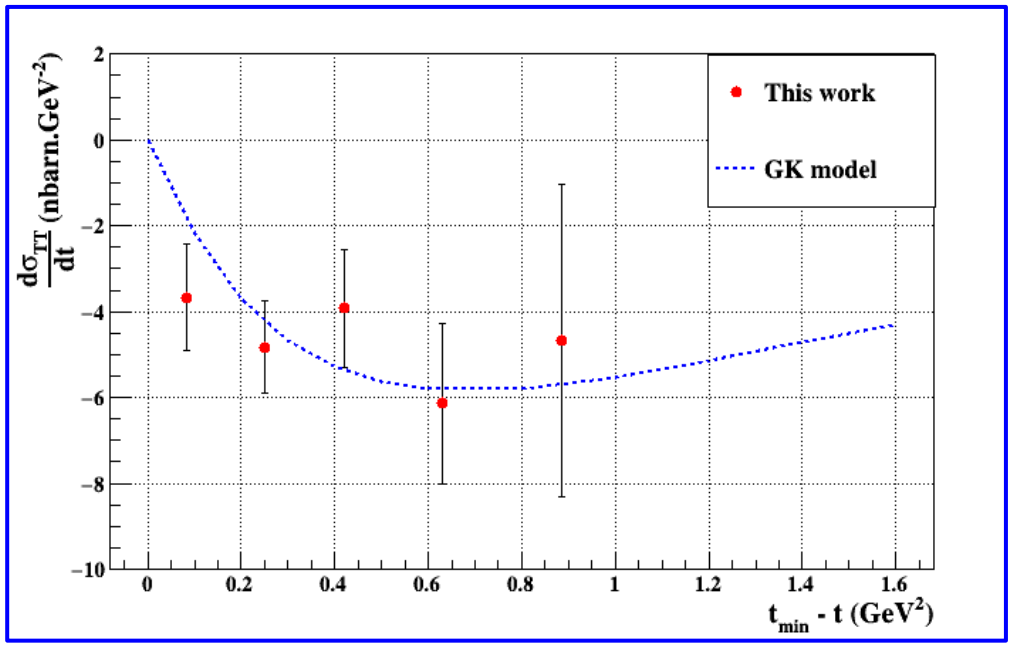
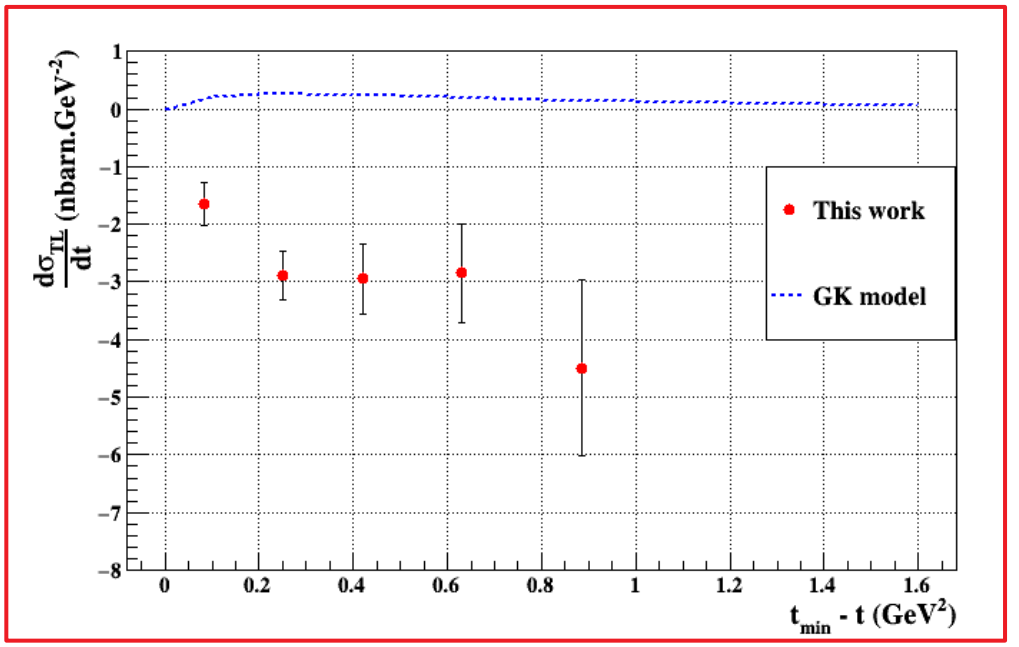
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma_\gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)\right]$$





- Larger value of σ_{TT} and σ_{TL}
- Hint for dominance of transversely polarized photon

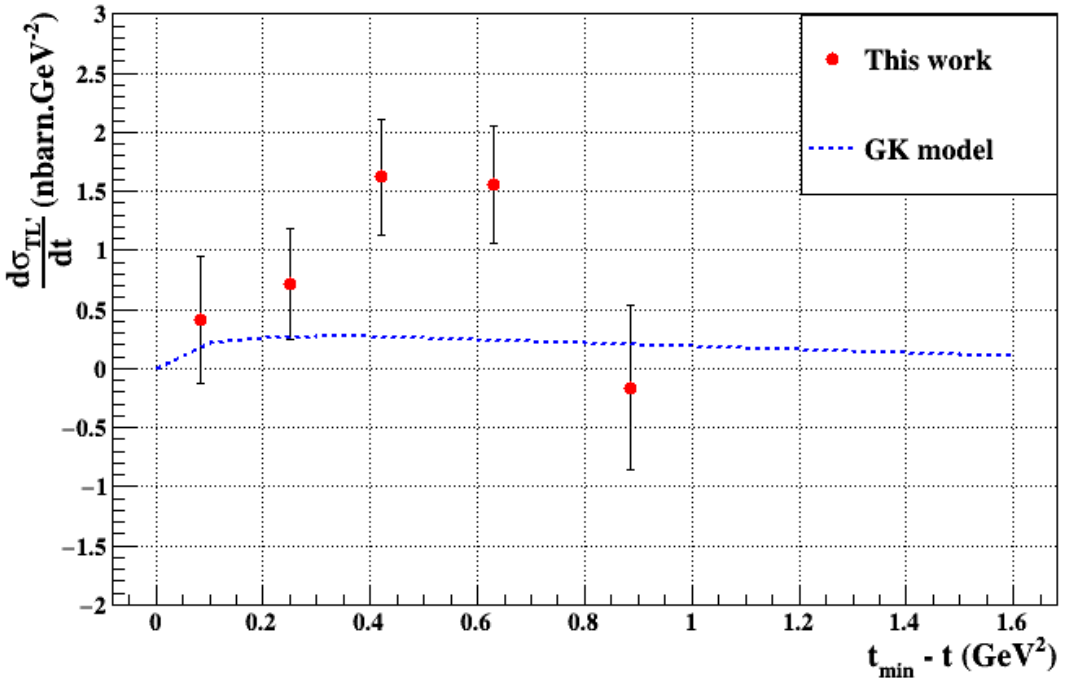
Polarized cross-section parameter

E0=10.59 GeV, E0=10.59 GeV, x_B= 0.60, Q^2 = 8.4 GeV^2

M.Dlamini, S. Ali, Po-Ju Lin, Ho-San Ko, B. Karki

Polarized

$$\frac{1}{2}\left(\sigma^{+}-\sigma^{-}\right) \rightarrow \frac{d\sigma_{LT'}}{dt}$$



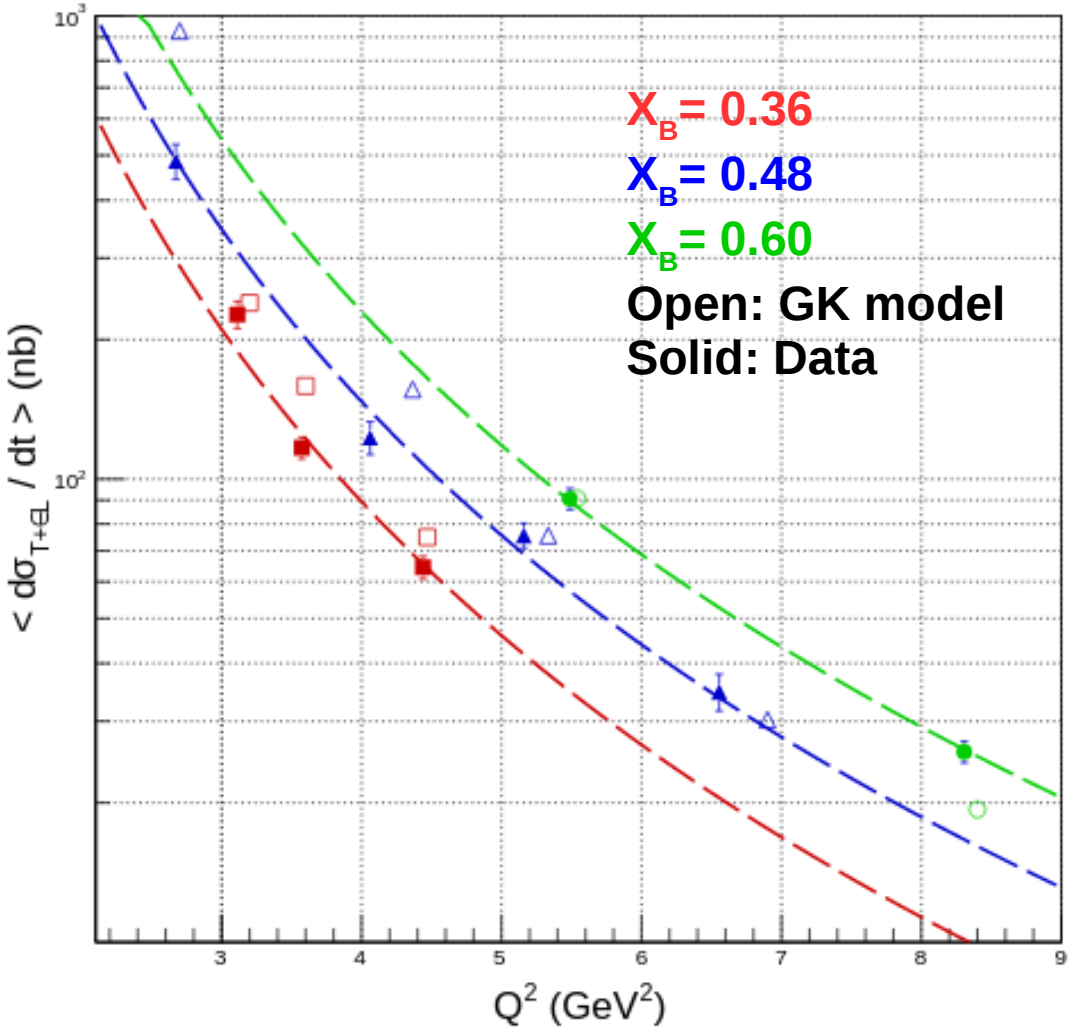
Small beam asymmetry with large error bar

Q^2 dependence study

Unpolarized cross-section ($d\sigma_T + \varepsilon\, d\sigma_L$)

M.Dlamini, S. Ali, Po-Ju Lin, Ho-San Ko, B. Karki

At fixed $t_{min} - t = 0.1$ GeV^2

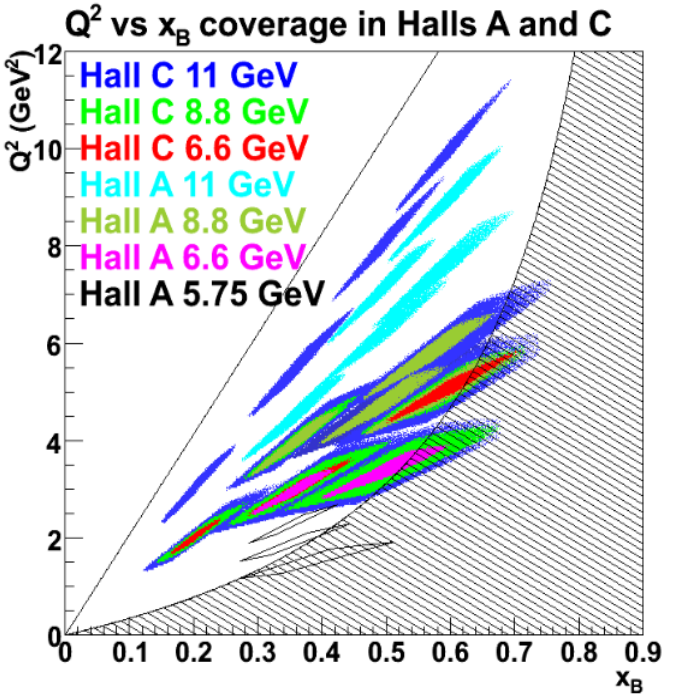


$$\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} = C_0(Q^2)^{\alpha}$$

Model independent feature: Cross-section falls as Q^{-6}

Conclusion and outlook

- **Dominance of transversly polarized virtual photons**
  - ✓ To interpret these data transversity GPDs model required
  - ✓ Model need to be improved
- **If σ_L is sufficiently large then GPDs can be extracted with regular QCD factorization**



- π^0 results can improve the GPDs parametrizations
- π^0 paper on progress
- DVCS leading twist dominance, small higher twist contribution
- DVCS paper in preparation

Outlook

- Extension to higher Q^2 and low x_B
- Energy separation of DVCS cross-section
- Separation of σ_T and σ_L for π^0 production

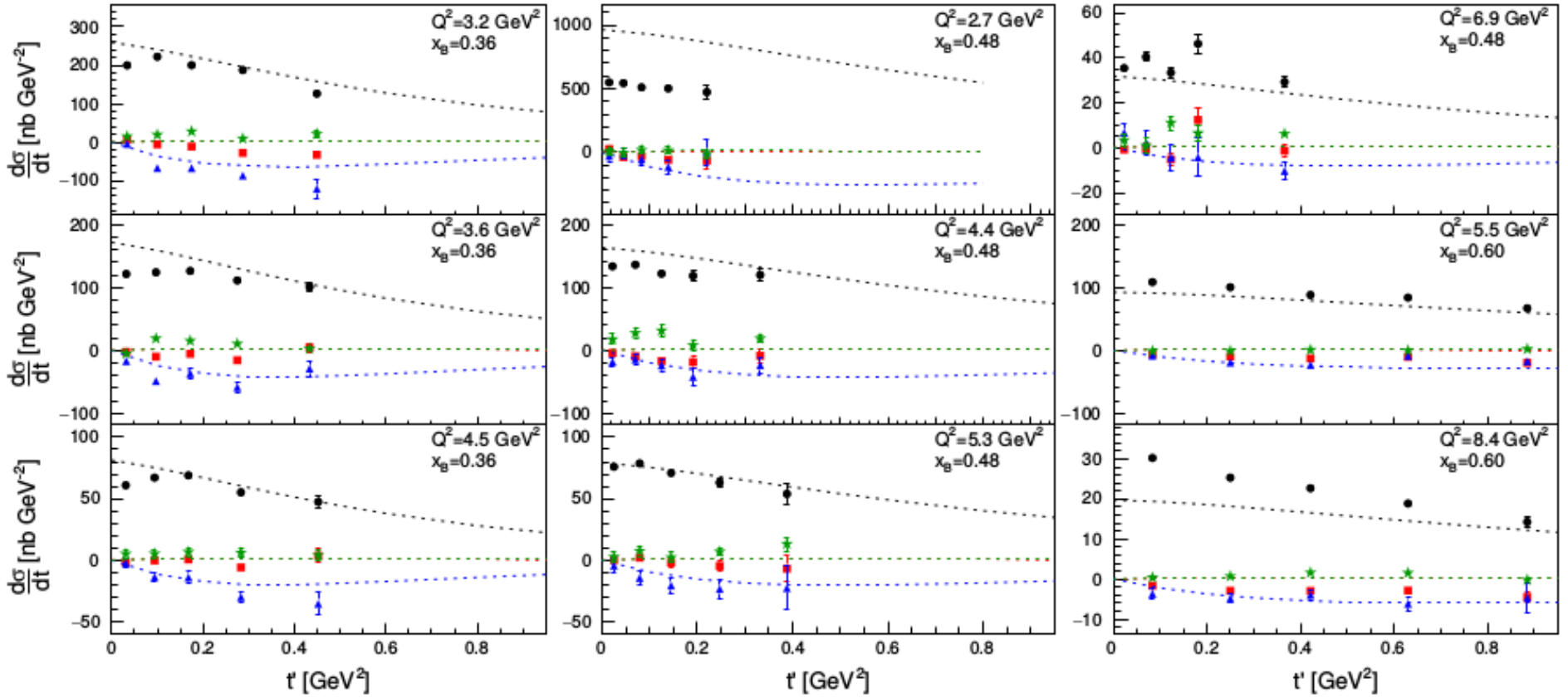
Acknowledgments:

Hall A DVCS Collaboration
Hall A Collaboration
Hall A technical staff
Accelerator staff
K. Kumericki and D. Müller
S.V. Goloskokov and P. Kroll

THANK YOU !

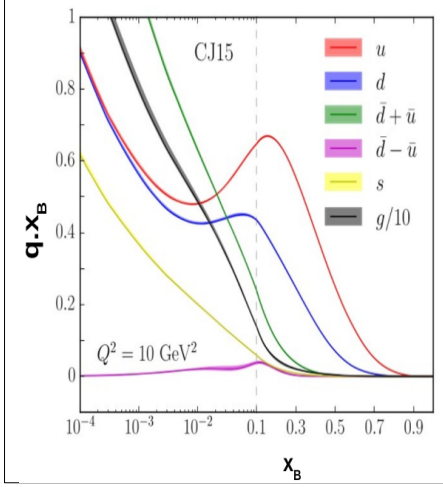
Unpolarized cross-section parameters

S. Ali, Po-Ju Lin, Ho-San Ko, B. Karki



GPDs and their exciting properties

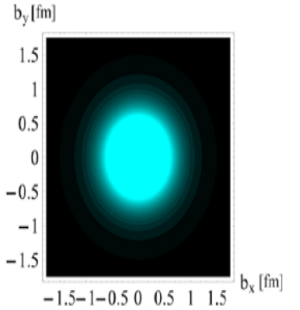
forward limit



$$H^q, \widetilde{H}^q, E^q, \widetilde{E}^q \quad (x,\xi,t)$$

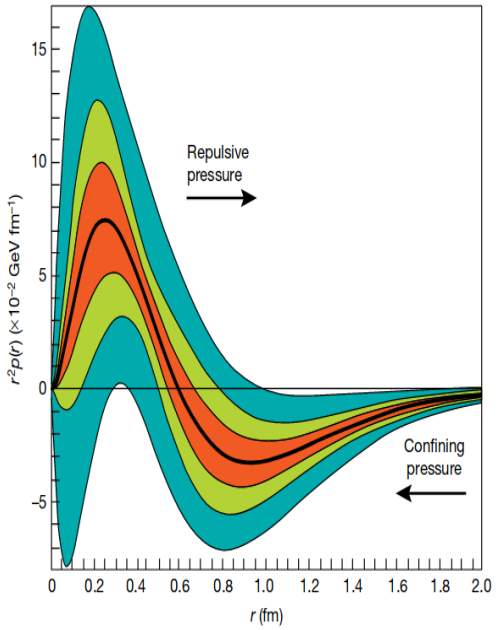
GPDs

First moments → FFs



Pressure inside proton

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$



V.D. Burkert,et.al Nature 557,2018

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

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

Ji's sum rule

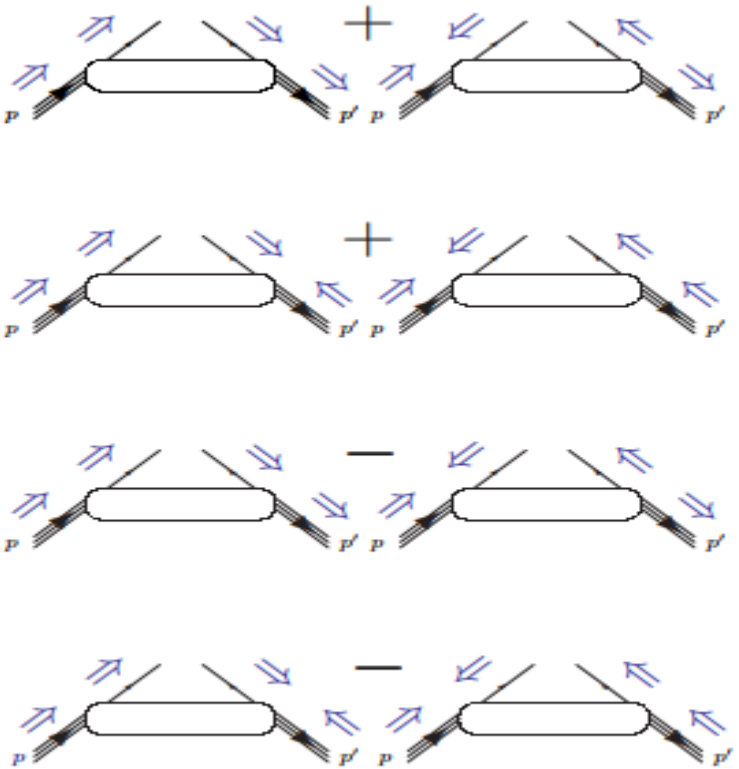
- **Access to orbital angular momentum of quarks**
- **Related to mechanical properties of nucleon**

GPDs

Quarks helicity and nucleon spin orientation

Nucleon helicity conserving

Nucleon helicity non-conserving



Average over quark helicity
Unpolarized

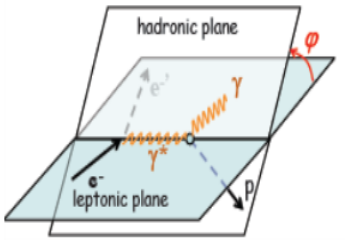
Difference of quark helicity
Polarized

M. Guidal et al 2013 Rep. Prog. Phys. **76** 066202

Unfolding cross-section components

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

A.V Belitsky, D. Meller, A. Kirchner Phys. Rev D **82**



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

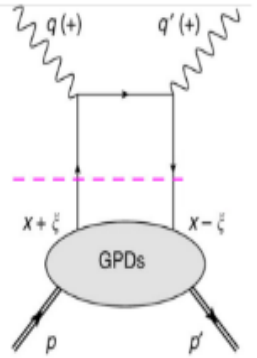
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

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

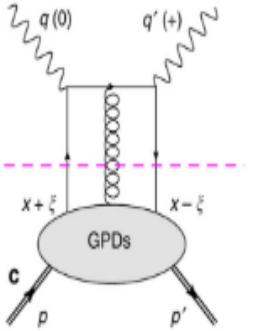
$$Re\,I \propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi$$

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

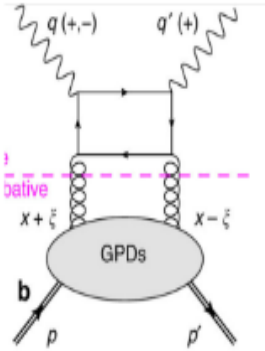
LT/LO



HT



NLO



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

Harmonics (c's and s's) ⟶ GPDs/CFFs