Experiment E12-06-114 in Hall A

$ep \longrightarrow ep\gamma$

Deep Virtual Compton Scattering (DVCS)

$ep \longrightarrow ep\pi^0 \longrightarrow ep\gamma\gamma$

Deep exclusive π^0 production

Generalized Parton Distributions (GPDs)
3D nucleon imaging

Hall A collaboration meeting
30 January 2020

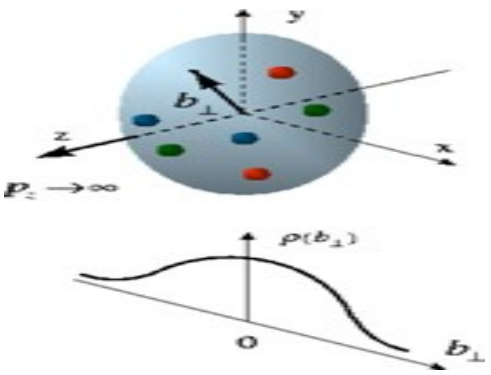
Bishnu Karki
Ohio University, Athens, Ohio

On behalf of DVCS collaboration

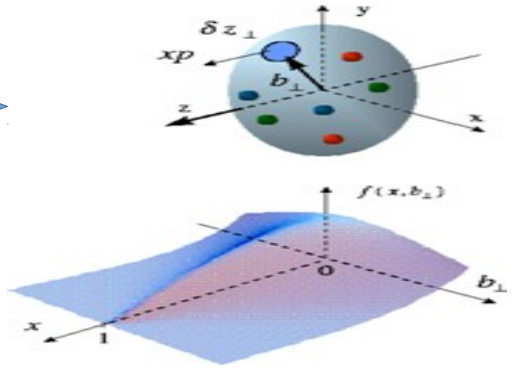
Award # 1913170

Beyond FFs and PDFs (GPDs)

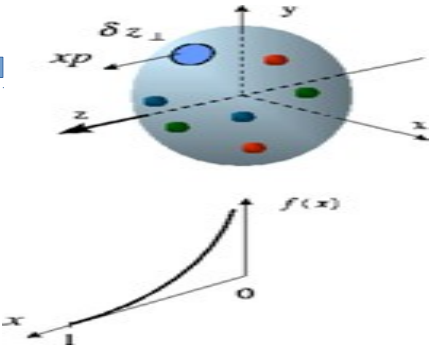
Elastic scattering



Deep exclusive processes



Deep inelastic scattering



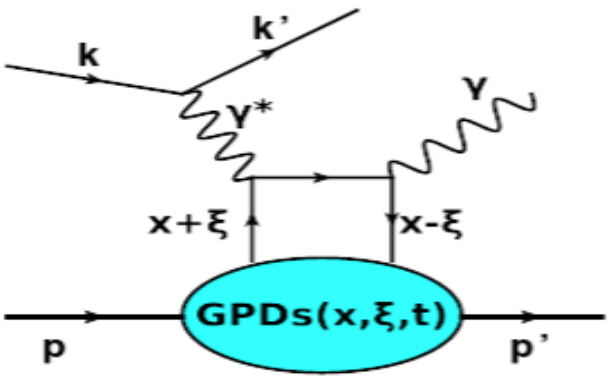
- **F**orm **F**actors **(FFs)**
  - ✔ Spatial distribution
  - ✗ Momentum distribution

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

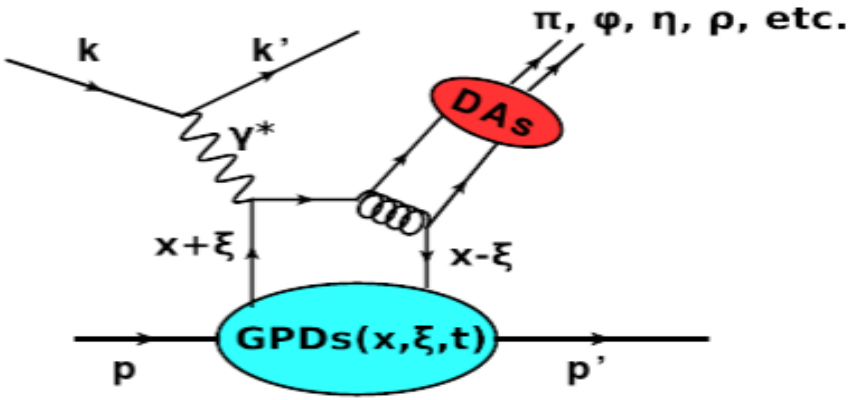
- **P**arton **D**istribution **F**unctions **(PDFs)**
  - ✔ Longitudinal momentum distribution
  - ✗ Spatial distribution

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**

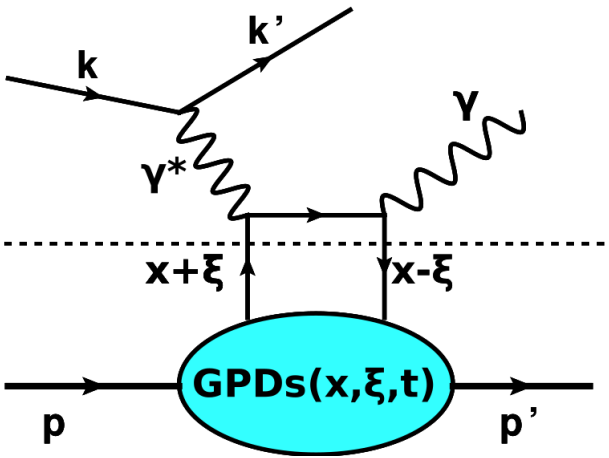
$$H_T^q, \widetilde{H}_T^q, E_T^q, \widetilde{E}_T^q$$

	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

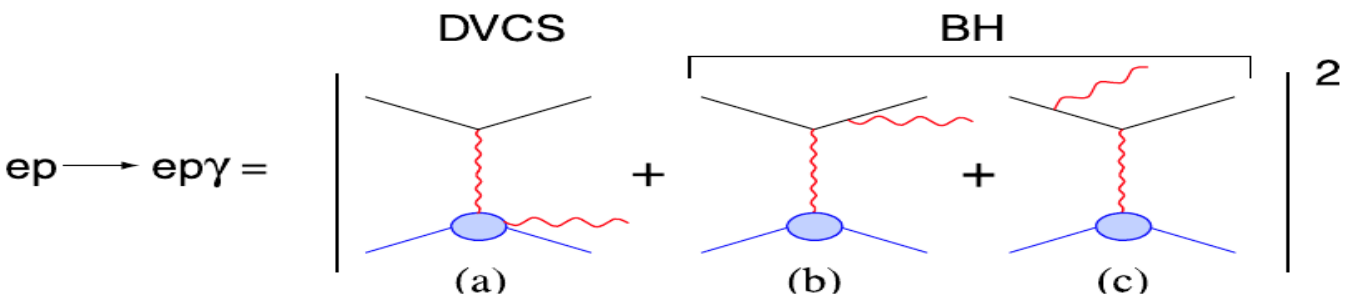
Hard/perturbative Part:
Calculable

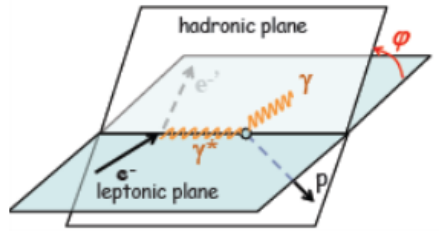
Soft/non-perturbative Part:
Nucleon structure is parametrized by GPDs

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

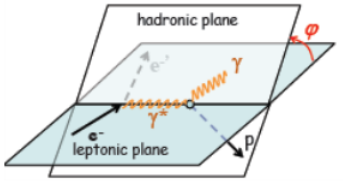
Linear combination of GPDs and FFs

P_l : beam or target polarization

e_l : charge of lepton beam

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**

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

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

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

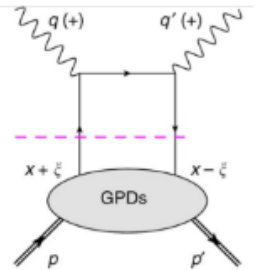
$$Re\,I \propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi$$

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

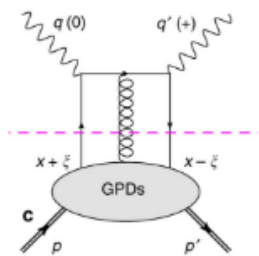
$$s_1^I = F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}$$

Harmonics (c's and s's) ⟶ GPDs/CFFs

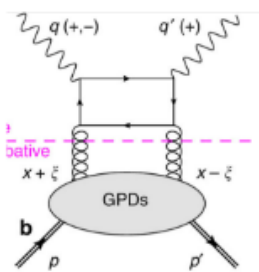
LT/LO



HT

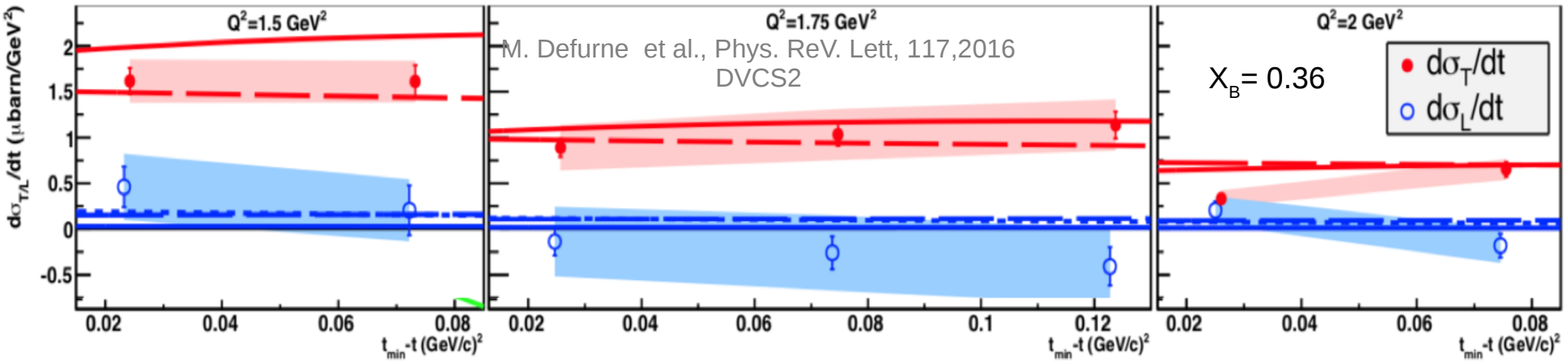


NLO



Exclusive π^0 production

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



- Factorization for longitudinally polarized virtual photon
- Prediction: ($\sigma_L >> \sigma_T$)
- 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)

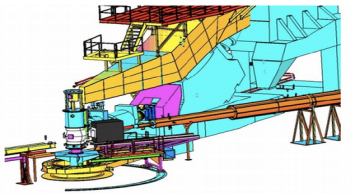
Exploring for the first time the high x_B region
(E12-06-114)

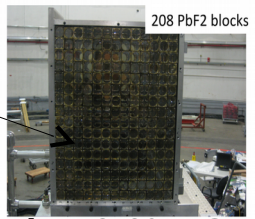
DVCS $ep \longrightarrow ep\gamma$

π^0 production $ep \longrightarrow ep\pi^0 \longrightarrow ep\gamma\gamma$

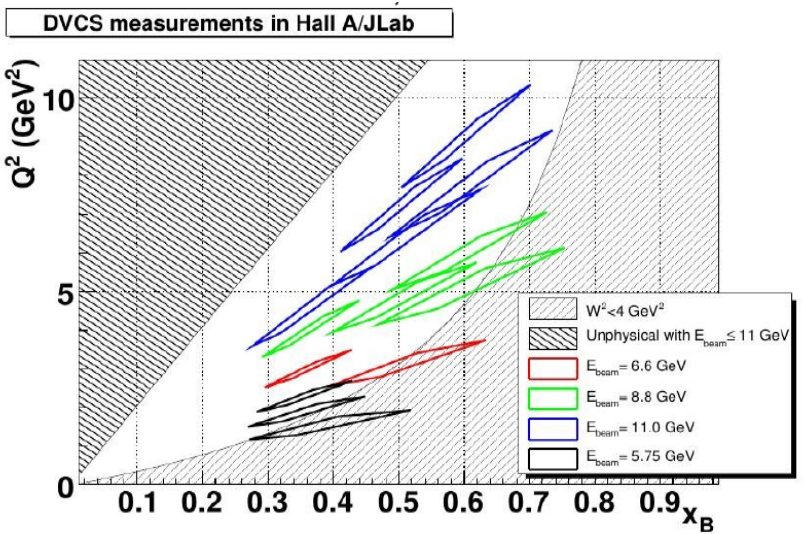
Polarized **e**$^-$ beam → LH_2 → **e**$^-$ to HRS, **γ**

δP/P Resolution 10^{-4} @ 4.3 GeV

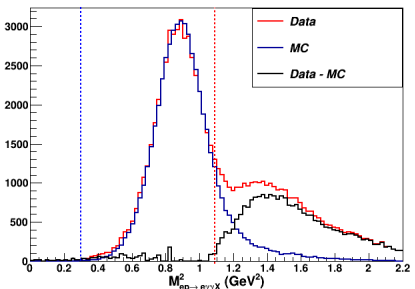




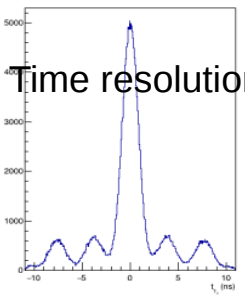
E resolution 3.6% @ 4.2 GeV



Recoil proton (missing mass)



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



Time resolution ~1ns

- **Ran between 2014-2016**
- **Completed ~50% of allocated 100 PAC days**
- **Missing PAC days reallocated in Hall C**

Deep Inelastic Cross-section Normalization study

Kin	Run period	E_{beam} (GeV)	P_0 (GeV)	θ_{HRS} (deg)	Q1 status	$(\sigma_M/\sigma_D)_{OU}$	$(\sigma_M/\sigma_D)_E$	$(\sigma_M/\sigma_D)_A$	Average
481	Sp '16	4.48	1.48	37.14	Unsat.	1.03	1.06	1.00	1.03
361	F '14	7.38	2.71	22.83	Unsat.	0.95	0.97	0.99	0.97
362	F '16	8.52	3.19	20.98	SOS (1%)	1.04	1.06	1.06	1.05
363	F'16	10.62	3.99	18.67	SOS (7%)	1.04	1.07	1.06	1.06
601	F '16	8.52	3.59	24.56	SOS (4%)	1.01	1.06	1.06	1.04
603	F '16	10.62	3.15	29.00	SOS (1%)	0.98	1.02	1.03	1.01
482	Sp '16	8.82	3.996	26.27	detuned	1.06	--	1.06	1.06
483	Sp '16	8.82	2.920	26.27	detuned	1.06	--	1.09	1.06
484	Sp '16	10.97	3.360	24.92	detuned	1.09	--	1.09	1.09
Average						**1.03±0.04**	**1.04±0.04**	**1.05±0.03**	**1.04±0.04**

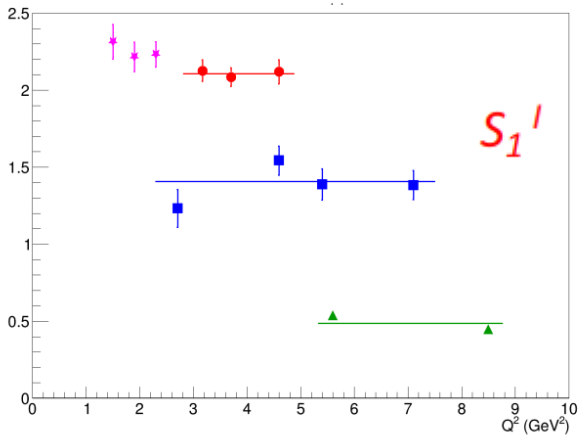
$$\frac{d^2\sigma}{dxB\,dQ^2} = \frac{N_{DIS}}{\mathcal{L}} \times \frac{1}{\eta_{Tracking} \times \eta_{S2} \times \eta_{CER} \times LT} \times \frac{1}{\eta_{virt}} \times \frac{1}{\alpha(xB, Q^2) \times \Gamma_{DIS}(xB, Q^2)}$$

- Reference cross-section from M. E. Christy and P. E. Bosted, Phys. Rev. C, 81 2010
- Deviation from world data is due to trigger inefficiency
- 4% systematic uncertainty (radiative correction + phase space + luminosity...)

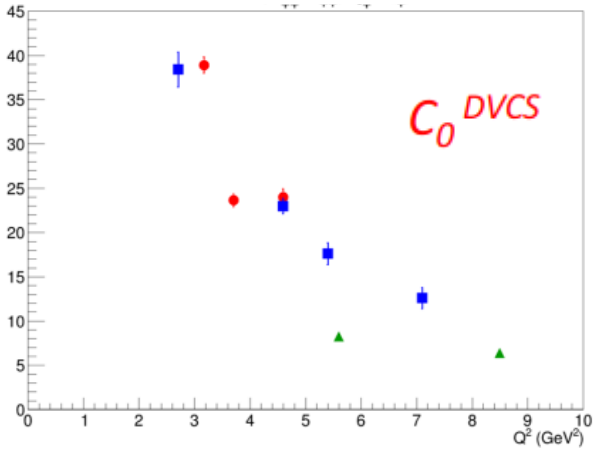
DVCS results

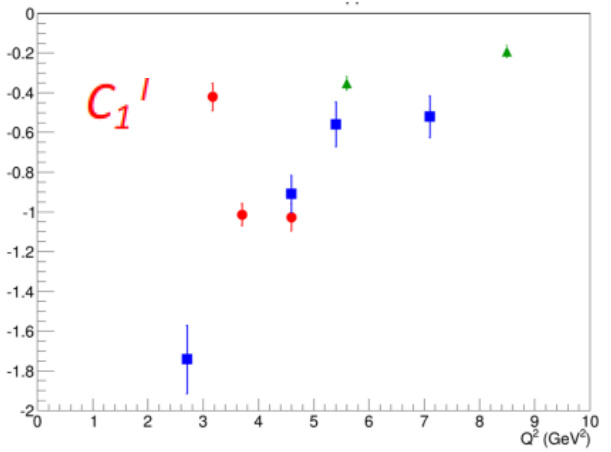
Twist 2 terms

F. Georges, A. Johnson, H. Rashad



Helicity dependent analysis





Helicity independent analysis

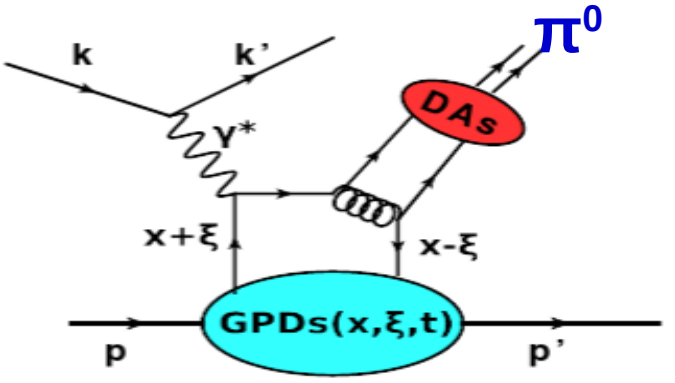
X_B = 0.36, <t> = -0.35 X_B = 0.60, <t> = -1.06

X_B = 0.48, <t> = -0.47 X_B = 0.36, <t> = -0.27

- Interpretation of harmonic coefficients in terms of twist and is complicated

π^0 production

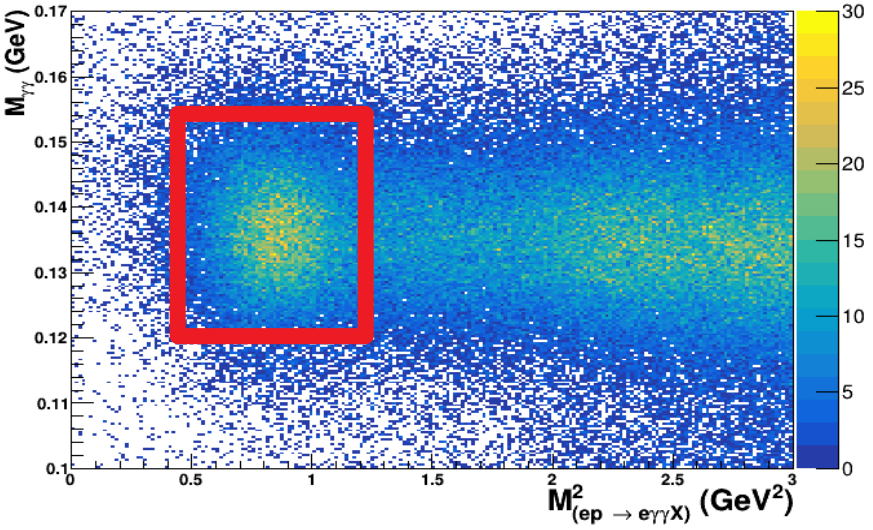
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma_\gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{TL'}}{dt}\sin(\phi)\right]$$



(b)

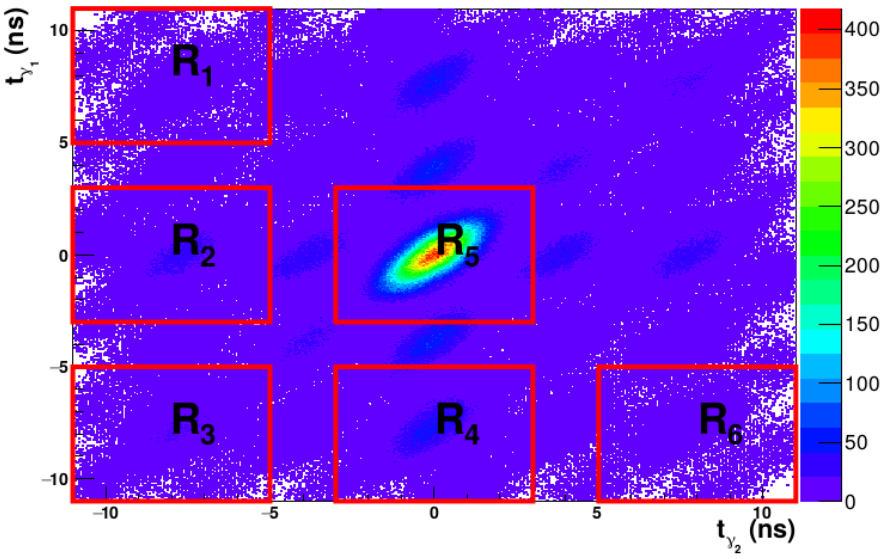
- Not separable through this experiment
- Rosenbluth type of separation (different E_{beam} at fixed Q^2 and x_B)

π^0 event selection



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

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



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

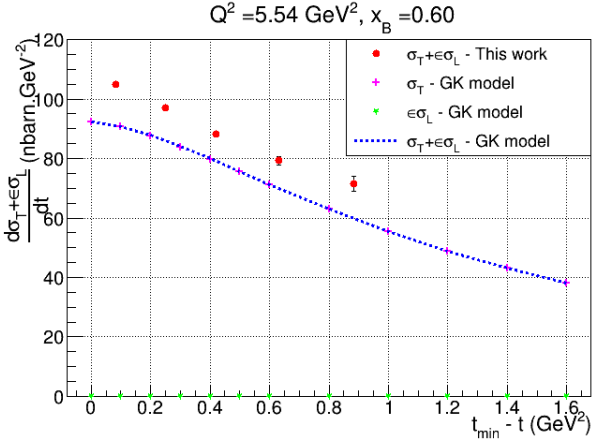
- Signal : coincidence window [-3, 3] ns

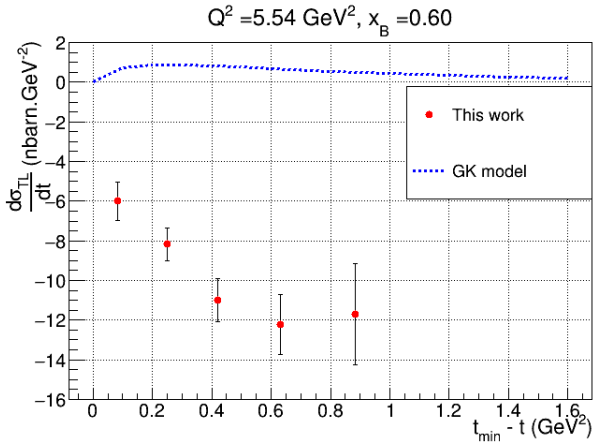
- Major source of background are accidentals
- SIDIS: ep----► e'p'π^0**x** (different missing mass cut)

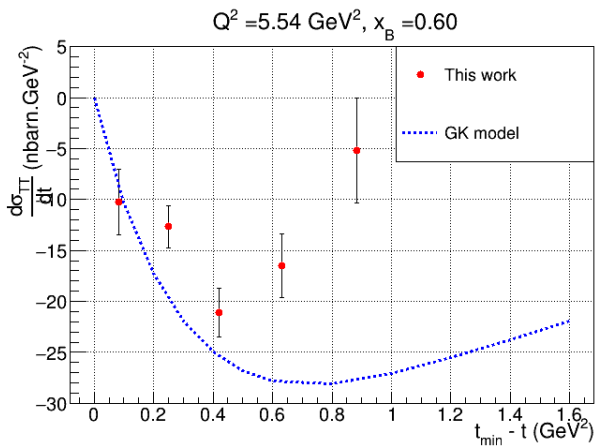
Cross-section parameters

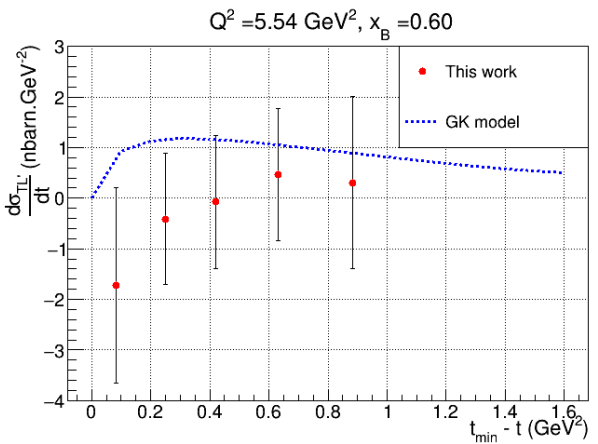
Kin 601 (E0=8.52 GeV)

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









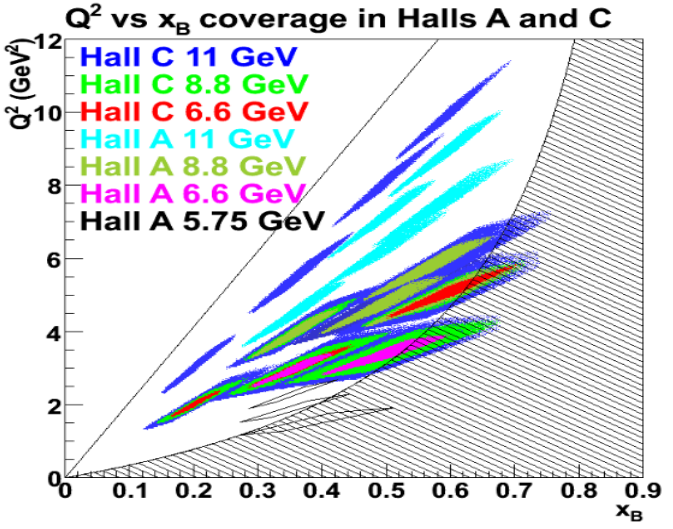
- Results available for 9 different kinematics
- Preliminary results from GK model
- Waiting the result another model (G.R Goldstein, and S. Liuti)
- These data will improve the parametrization of the GPDs

Source	Contribution
Lum + radi + ..	4%
Exclusive cuts	0.5%
E cut	< 1 %
Beam Pol.	1%
Total	**~ 5%**

Conclusion and outlook

- For DVCS sizable higher twist contribution
- Interpretation of harmonic coefficients not straightforward
- First draft for DVCS paper is being written

- π^0 results are finalized, soon start writing paper
- Sizable σ_T contribution
- π^0 results can improve the GPDs parametrizations



Outlook

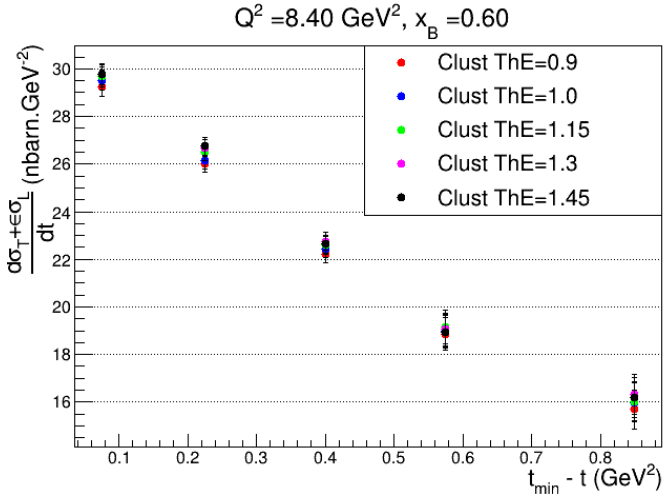
- Remaining PAC days will run in Hall C with NPS
- Extension to higher Q^2 and low x_B
- Energy separation of DVCS cross-section
- Separation of σ_T and σ_L for π^0 production

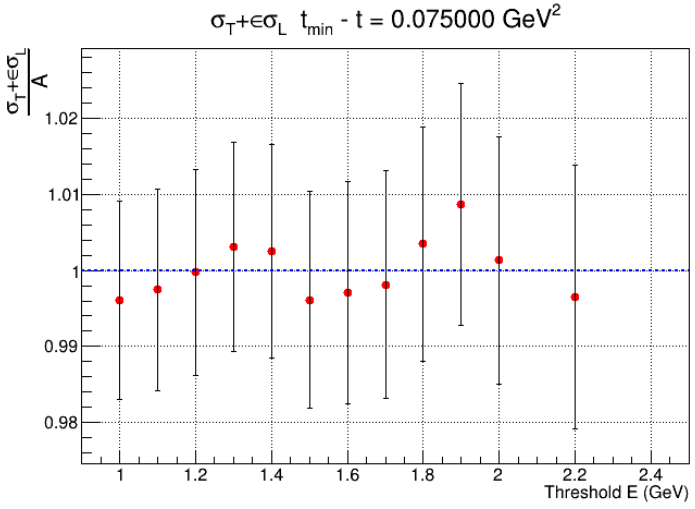
Acknowledgments:

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 !

Systematic study
Clustering threshold and photon E cut
Kin 603





Source	Contribution
DIS (e^-)	4%
Exclusive cuts	0.5%
E cut	< 1 %
Beam Pol.	1%
Total	**~ 5%**

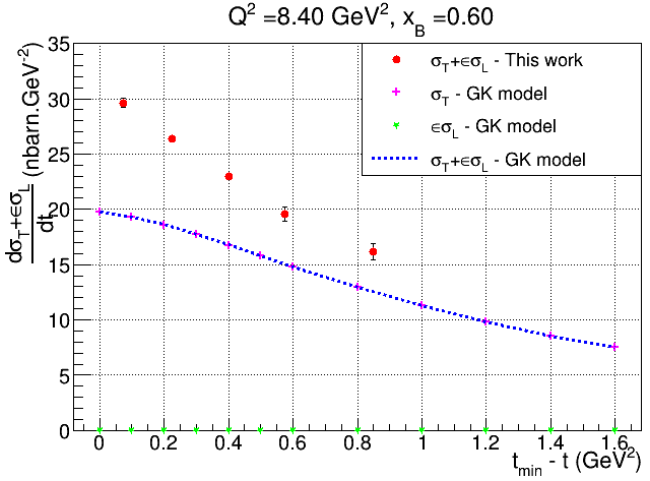
- Calorimeter analysis: threshold is set for clustering
- During analysis to avoid accidentals we apply cut on photon E

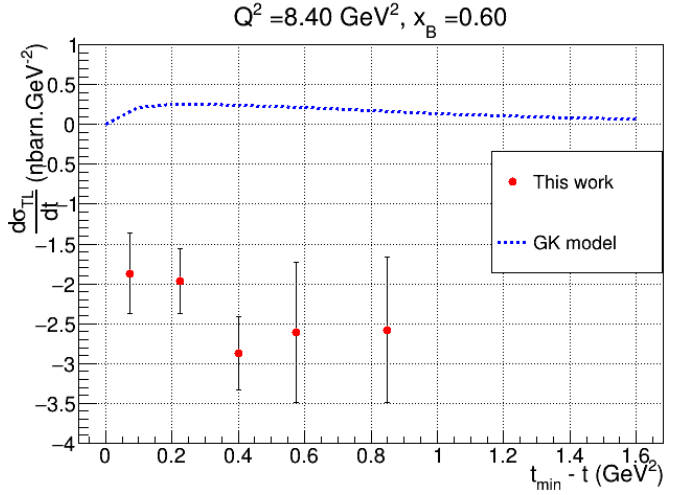
➔ Only $\sigma_T + \varepsilon\sigma_L$ is sensitive

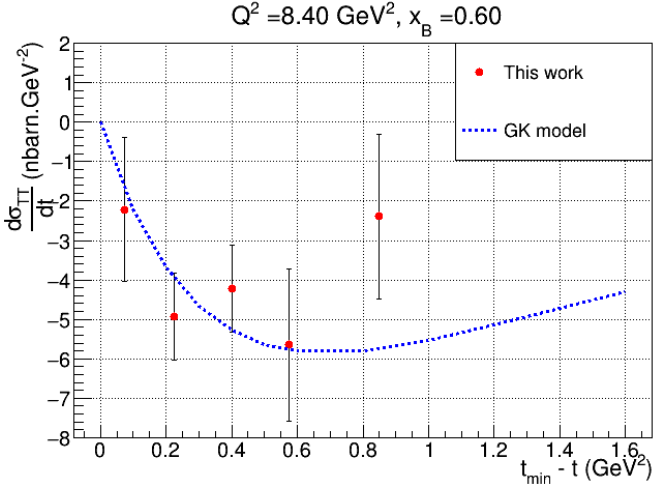
➔ Cross-section is consistent

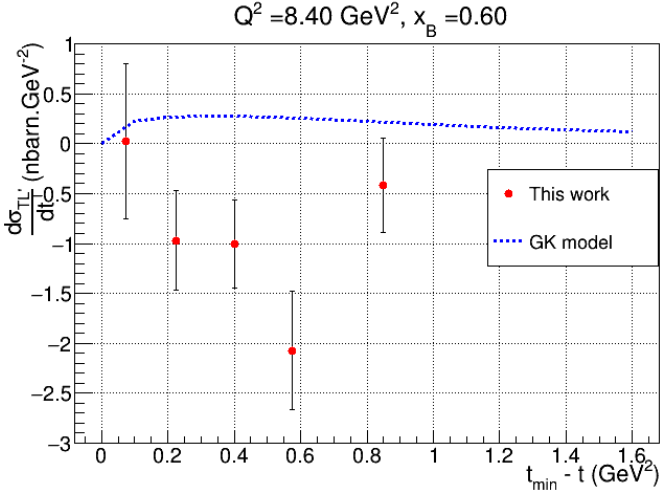
Cross-section parameters

Kin 603 (E0=10.59 GeV)





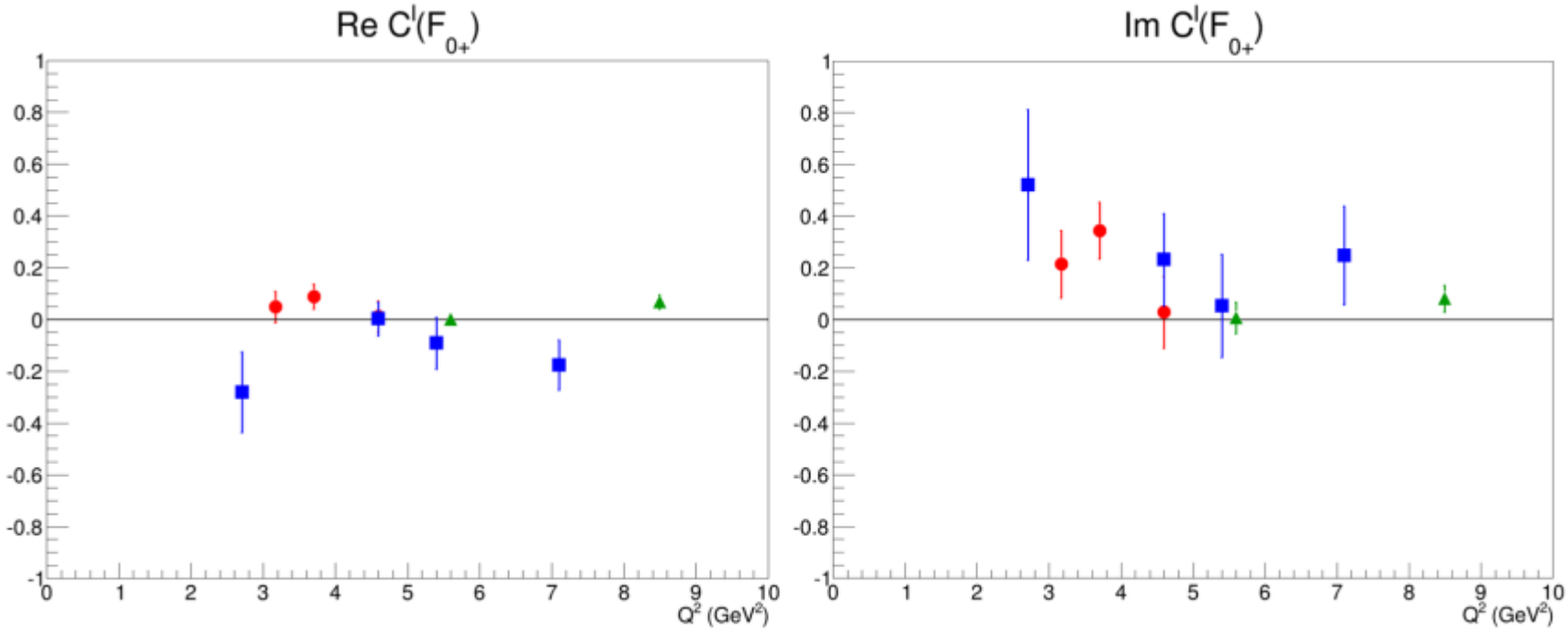




Preliminary DVCS results

Twist 3 terms

F. Georges



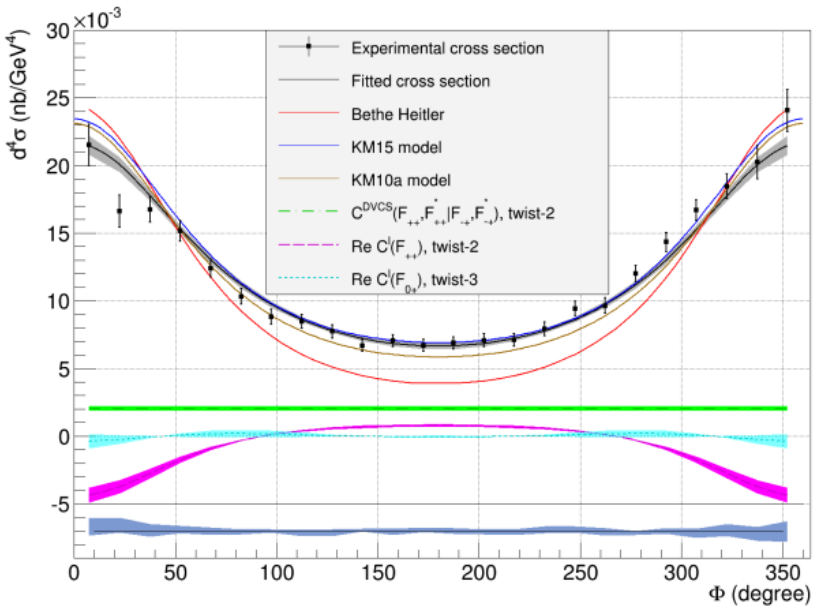
Twist 3 terms are small but not necessarily 0

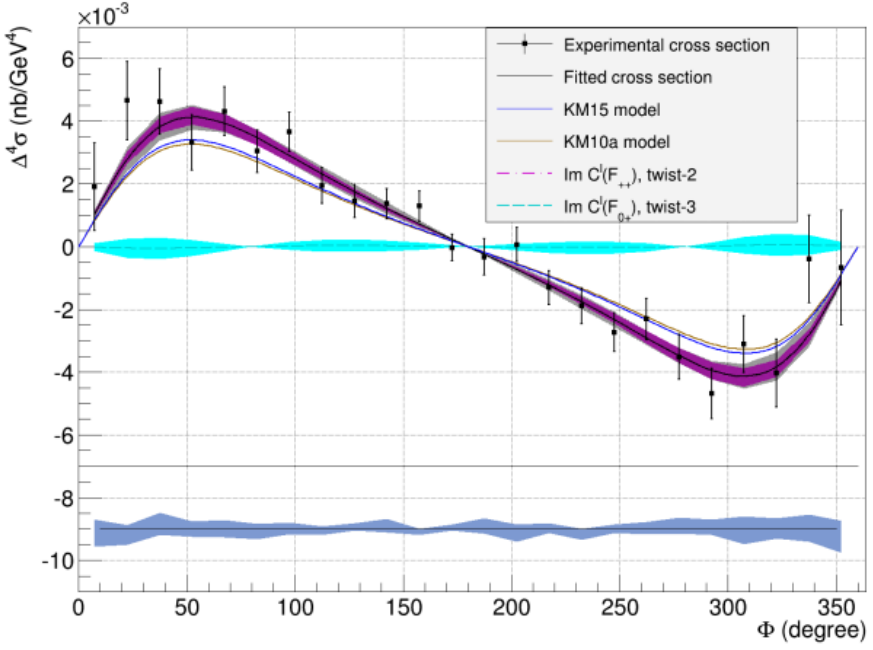
DVCS results

Unpolarized/Polarized cross-section

F. Georges

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

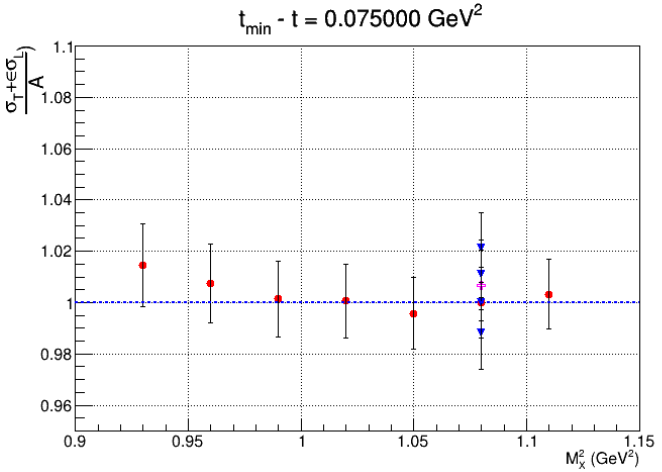


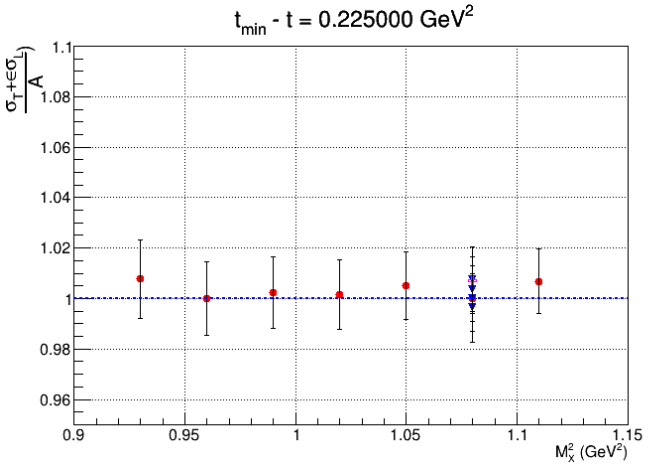


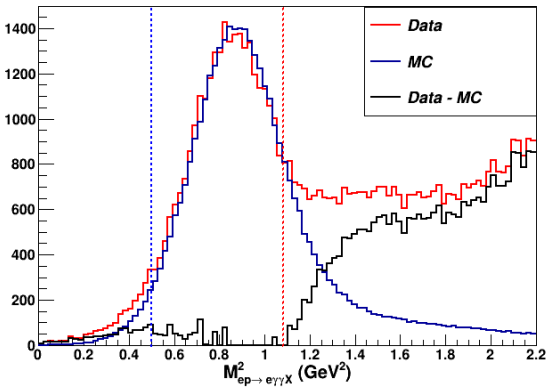
- Results ready for 9 different kinematics
- Twist 2 dominance
- Small contribution from twist 3

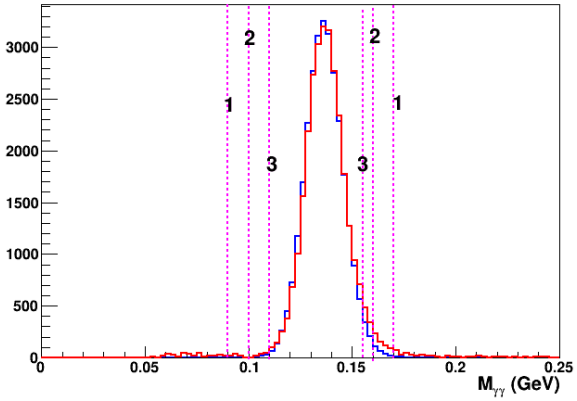
K. Kumericki and D. Muller EPJ Web of conference 112, 2015
K. Kumericki, S. Liuti, and H. Moutarde Eur. Phys. J. A. 52, 2016

Systematic study (Exclusive cut)
Kin 603









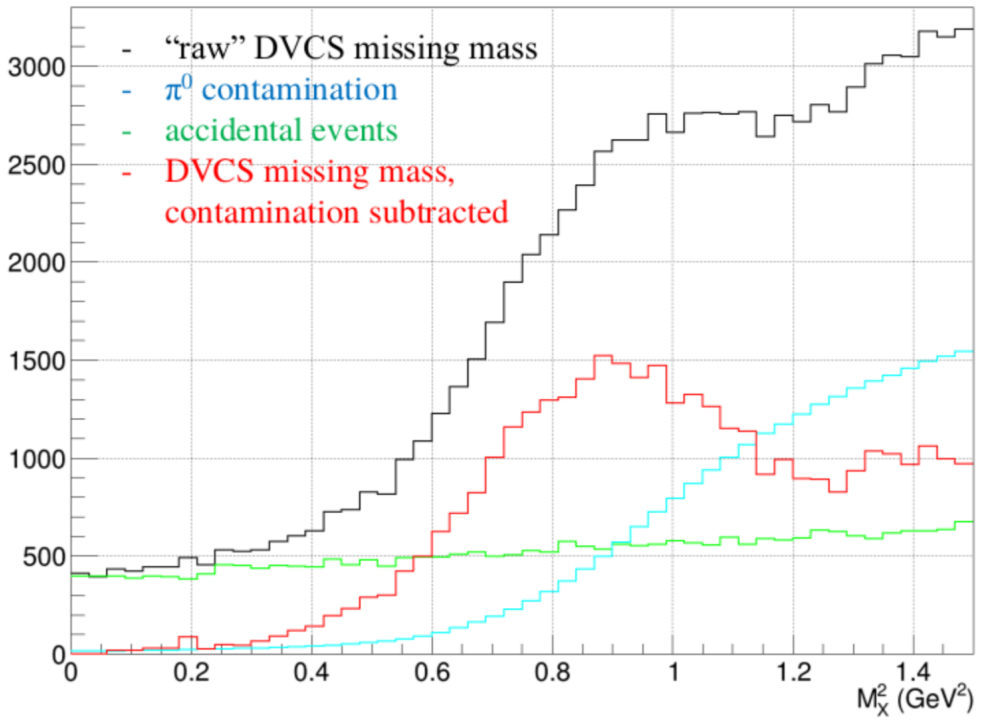
Minv fixed at "2" (3σ)
M² high end fixed
M² low end at different position

M² fixed
Minv at different spot "1" and "3"

Minv fixed at "2" (3σ)
M² low end fixed
M² high end at different position

Cross-section is consistent with different choices of exclusive cuts

Experimental Setup (E12-06-114)



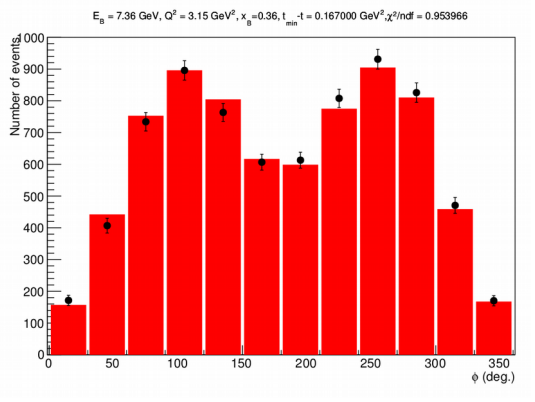
Period	Kinematic	Q^2	x_B	% target Charge
F '14	361	3.20	0.36	100.0
F '16	362	3.60	0.36	100.0
F '16	363	4.47	0.36	100.0
Sp '16	481	2.7	0.48	100.0
Sp '16	482	4.37	0.48	56.6
Sp '16	483	5.33	0.48	76.4
Sp '16	484	6.90	0.48	53.0
F '16	601	5.54	0.60	100.0
F '16	**602**	**6.10**	**0.60**	**0.0**
F '16	603	8.40	0.60	100.0
F '16	**604**	**9.00**	**0.60**	**0.0**

Cross-section extraction formalism (π^0 production)

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

$$\chi^2 = \sum_{r=0}^{N}\left(\frac{N_r^{exp} - N_r^{MC}}{\sigma_r^{exp}}\right)^2 \qquad N_r^{MC} = \sum_{v=0}^{V}\sum_{n=0}^{N} K_{rv}^n X_v^n \qquad K_{rv}^n = \sum_{i\epsilon r\cap v}\Gamma_n(E, Q^2, x_B, \phi)\frac{\Gamma_{MC}^i}{N_{gen}}$$

$$\overline{X}^n = \sum_{v'=1}^{V}\sum_{n'=1}^{N}[A^{-1}]_{v,v'}^{n,n'} \cdot B_{v'}^{n'}$$

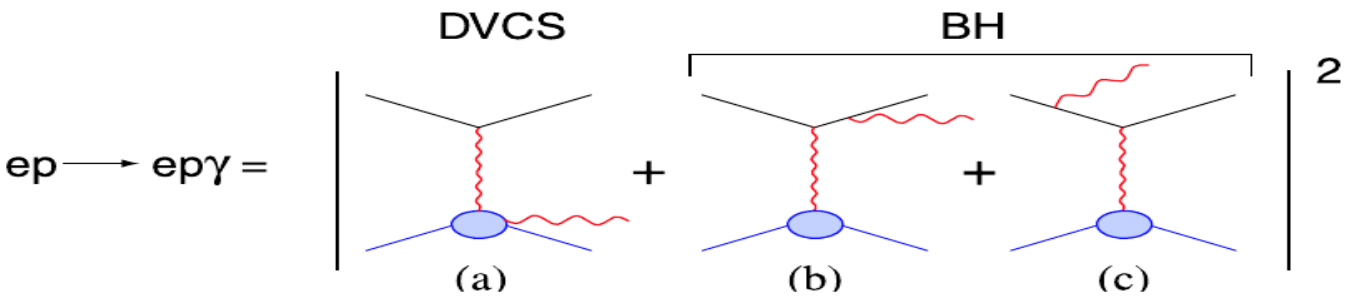


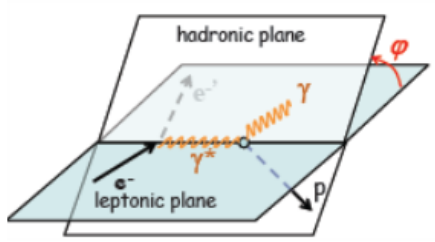
K_{rv} : Bin migration probability

σ^{exp} : Error in data (accidental subtraction considered)

For helicity dependent term $N_r^{exp} = N^+ - N^-$

DVCS and Bethe-Heitler (BH)





Combination of GPDs

$$d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma} = \mathcal{T}_{\mathcal{BH}}.Im(\mathcal{T}_{\mathcal{DVCS}})$$

$$d^4\overrightarrow{\sigma} + d^4\overleftarrow{\sigma} = |\mathcal{T}_{\mathcal{DVCS}}|^2 + |\mathcal{T}_{\mathcal{BH}}|^2 + \mathcal{T}_{\mathcal{BH}}.Re(\mathcal{T}_{\mathcal{DVCS}})$$

Known from FFs

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

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

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

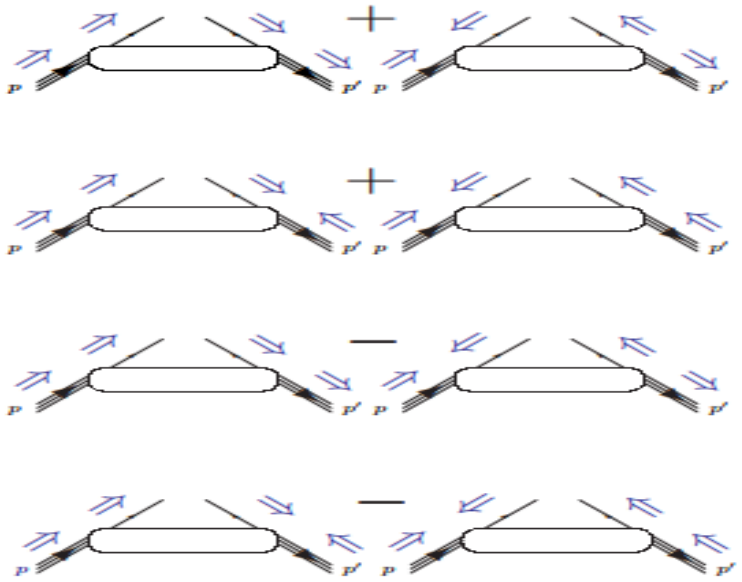
Interference with BH gives access to Re and Im part of DVCS amplitude.

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