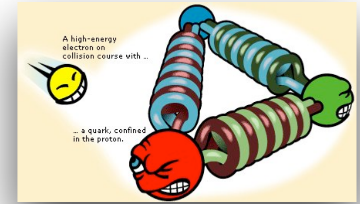
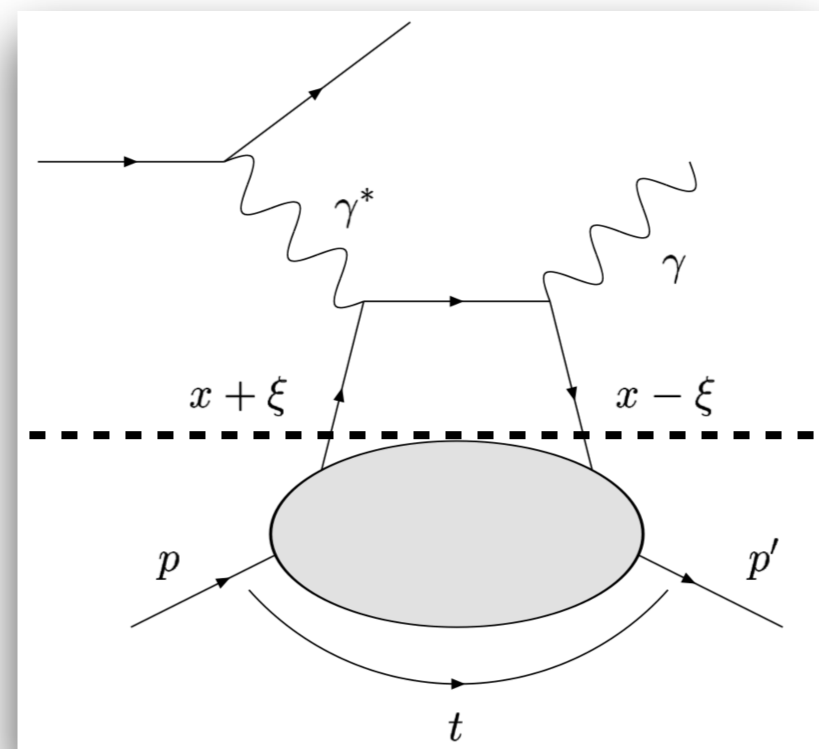
E12-06-114



$eP \rightarrow eP\gamma$

DEEPLY VIRTUAL COMPTON SCATTERING (DVCS)



Hashir Rashad

<O|D̂|U>

On behalf of Hall A DVCS Collaboration

01/30/2019

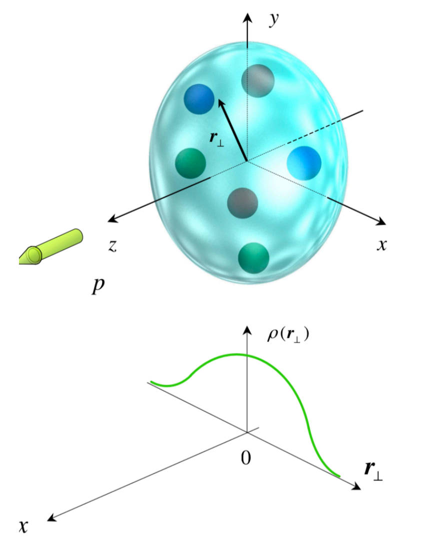
Hall A Winter Collaboration Meeting

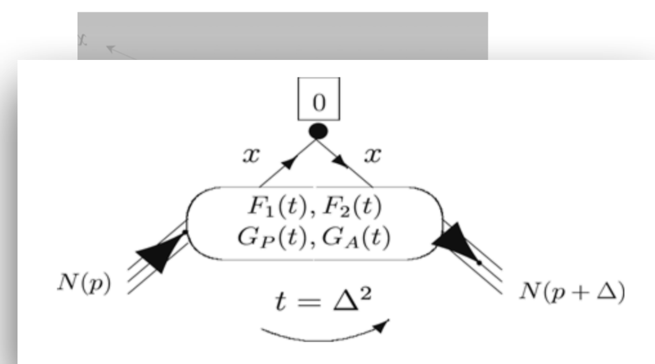
Thomas Jefferson National Accelerator Facility

3D Picture of a Proton

$$< P'|\bar{\psi}_q(y)\mathcal{O}\psi_q(0)|P >$$

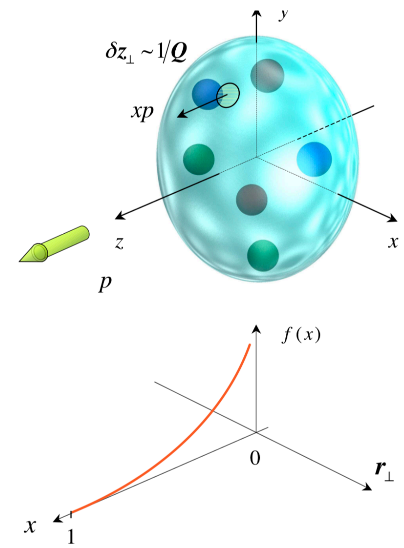
Elastic Scattering

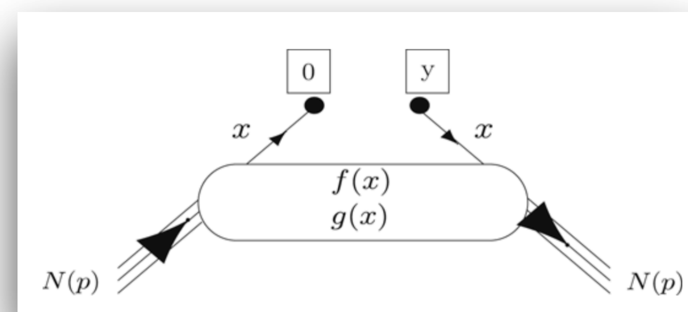




- Form Factors
- Local - non - Forward Matrix Elements
- Spacial Distribution

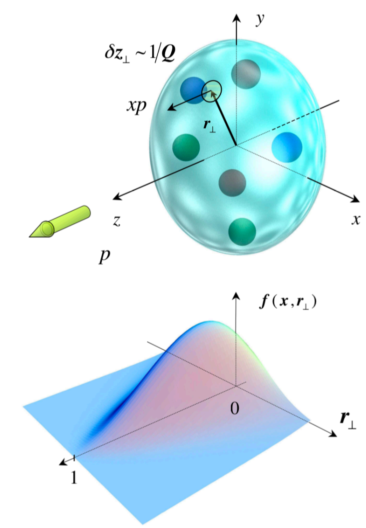
Deep Inelastic Scattering

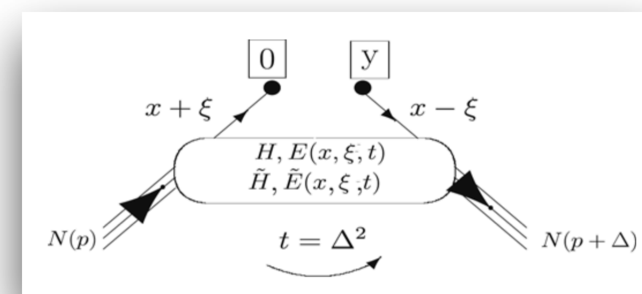




- Parton Distributions
- Non local - Forward Matrix Elements
- (Longitudinal) Momentum Distributions

Hard Exclusive Scattering





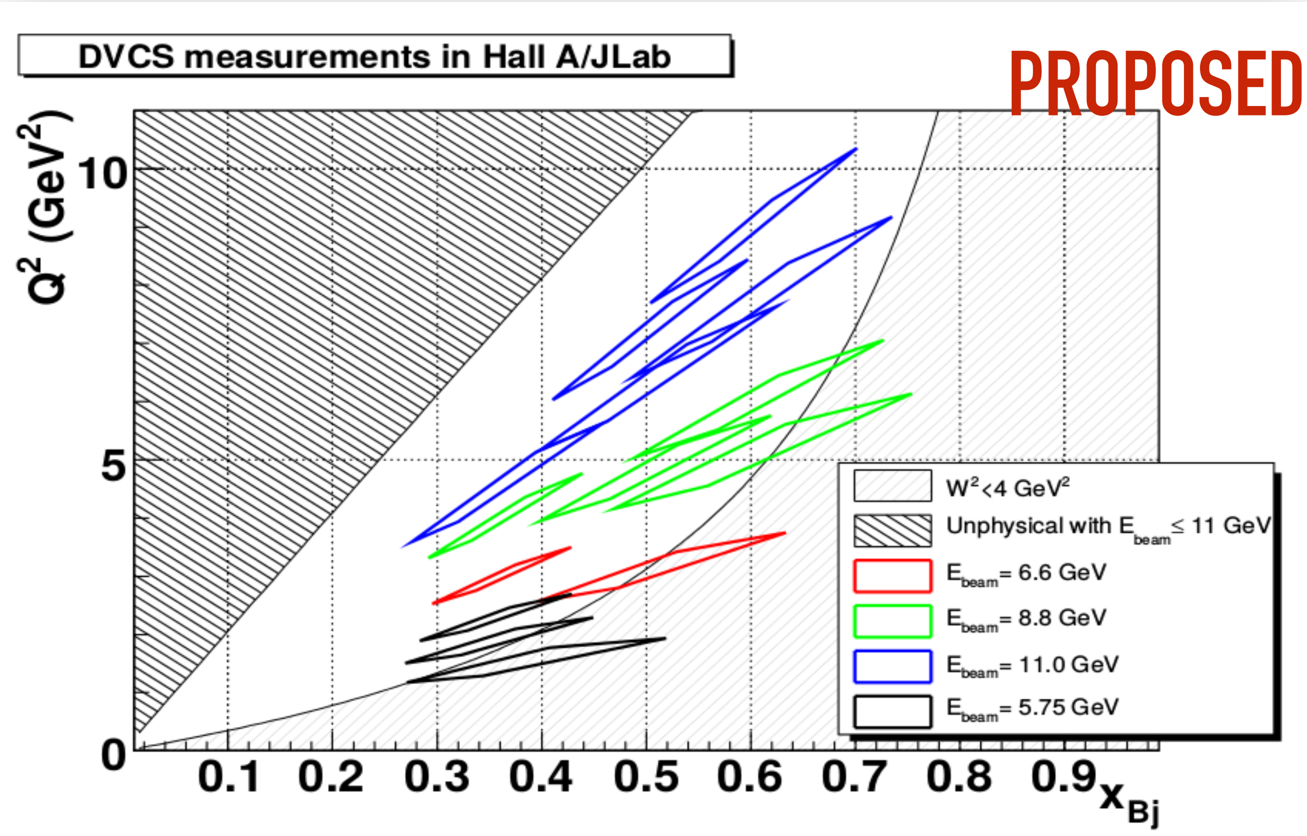
- Generalized Parton Distributions (GPD)
- Non local - Non -Forward Matrix Elements
- Relates spacial and momentum distributions
- Can shed light on quark orbital angular momentum

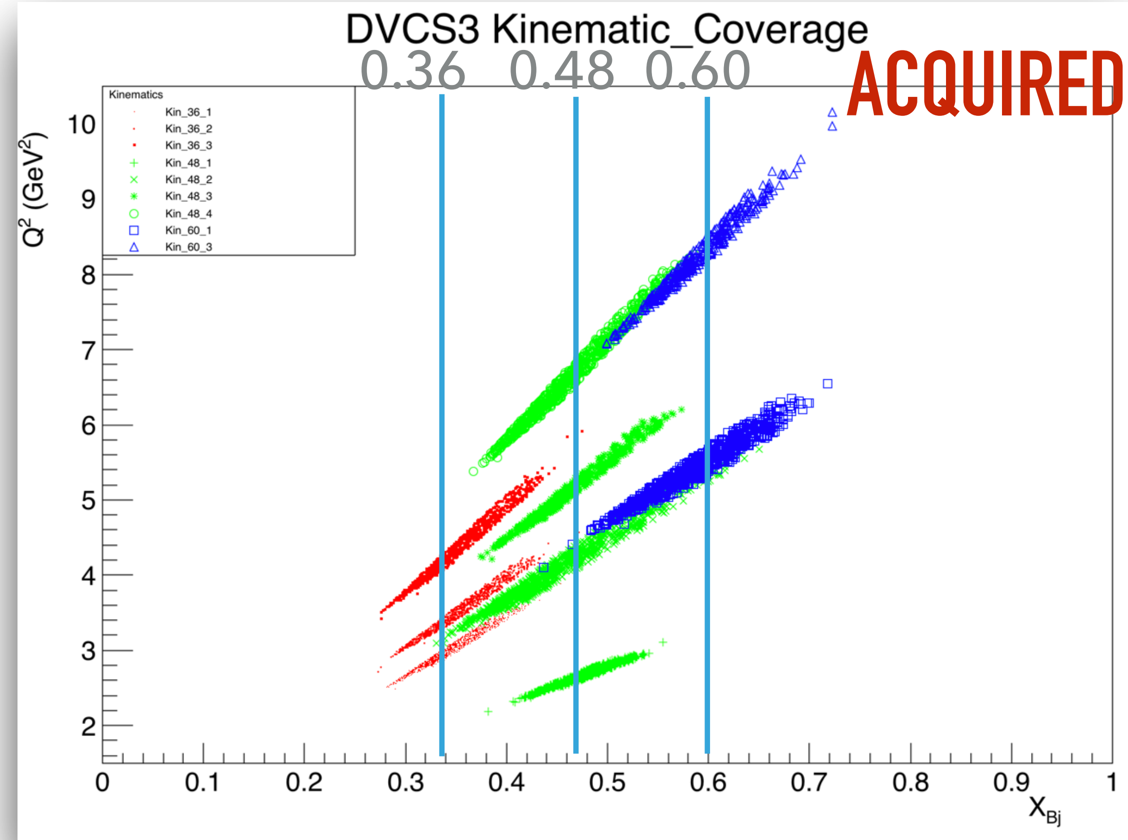
DVCS at Hall A

- 3 Generation of Experiments so far
- 2004 (Gen 1)
  - Scaling : (Q^2 dependence of GPD's/Angular Harmonics)
  - χ_b=0.36, Q^2 = 1.5, 1.9, 2.3 GeV^2
  - First measurement of DVCS Cross Section (5 Thesis and 4 peer reviewed papers)
- 2010 (Gen 2)
  - Rosenbluth like separation of Pure DVCS and Interference using beam energy dependence
  - χ_b=0.36, Q^2 = 1.5, 1.75, 2.0 GeV^2
  - Electron Beam 5.5 and 4.5 GeV
  - 3 Thesis, 2 publication in PRL, 1 in Nature Communications

E1206-114 : DVCS3

Goal : Scaling Test | **~50% of the approved PAC Days**

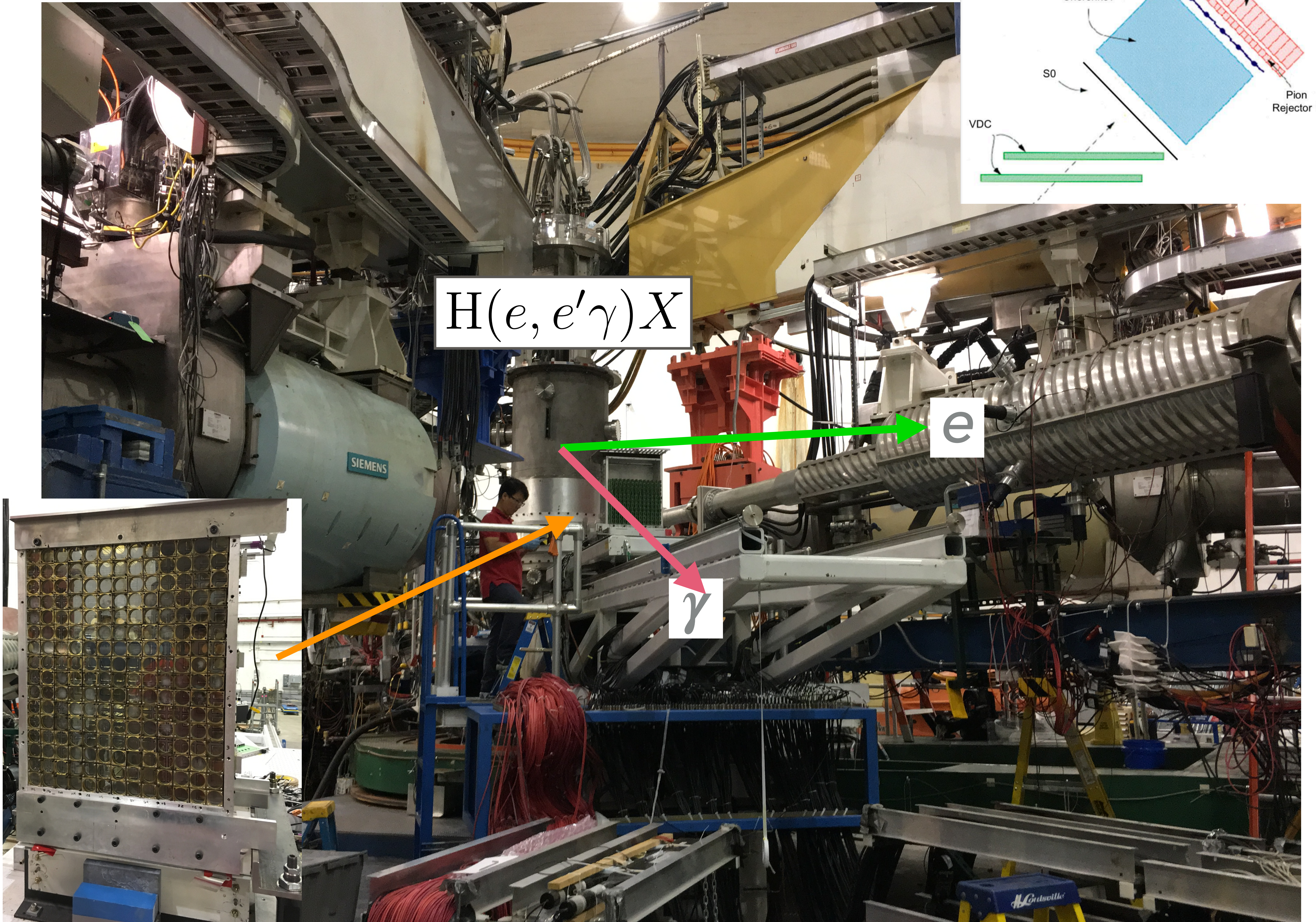




Run Period	Kinematics	χ_b	$Q^2(GeV^2)$
Fall 2014	36_1	0.36	3.20
Fall 2016	36_2	0.36	3.60
Fall 2016	36_3	0.36	4.47
Spring 2016	48_1	0.48	2.7
Spring 2016	48_2	0.48	4.36
Spring 2016	48_3	0.48	5.34
Spring 2016	48_4	0.48	6.90
Fall 2016	60_1	0.60	5.54
No Data	60_2	0.60	6.1
Fall 2016	60_3	0.60	8.4
No Data	60_4	0.60	9.0

- **Fall 2014** : Q1 Magnet with full field - Old RFunctions
- **Spring 2016** : Magnet couldn't run with full field for the entire run period. This resulted in detuning.
  - **48_1** : 100% tuned
  - **48_2** : 62% tuned
  - **48_3** : 85% tuned
  - **48_4** : 74% tuned
- **Fall 2016** : Replaced magnets, discovered to be saturating at higher current
  - **36_2** : 0.8% saturated
  - **36_3** : 6.4% saturated
  - **60_1** : 3.0% saturated
  - **60_3** : 0.7% saturated

DVCS3 Installation in Hall A

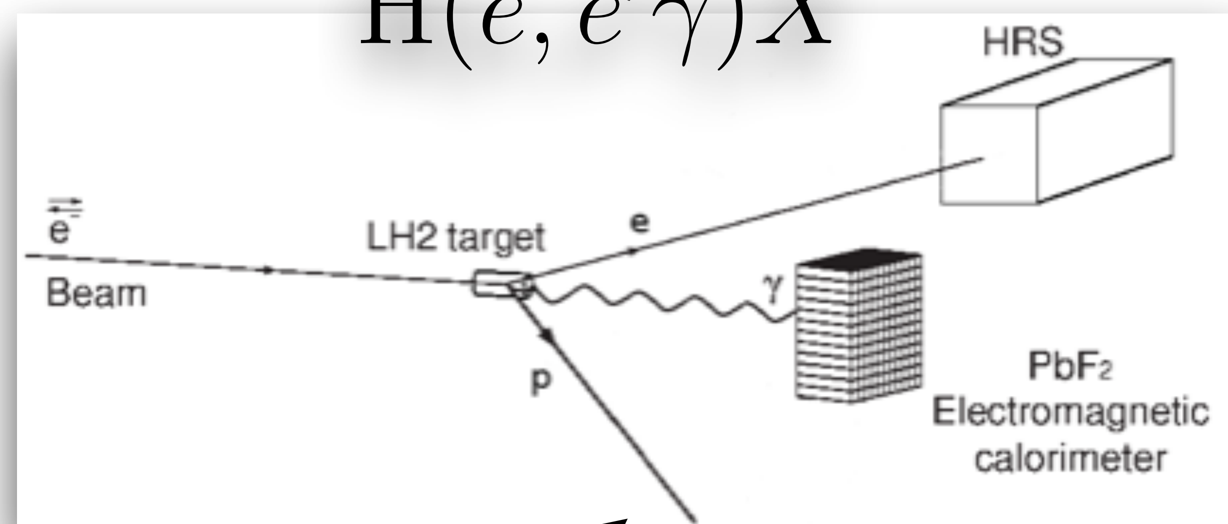


Counting the numbers:

- Beam Studies
  - Beam Energy Measurement
  - Polarization Measurement
  - BCM Calibration
  - Raster/BPM Calibration

- HRS- Electron Selection
  - Optics Calibration
  - Electron Identification
  - Acceptance Studies
  - Electronic Dead Time
  - Trigger Efficiency
  - Tracking Correction

$$\mathrm{H}(e, e'\gamma)X$$



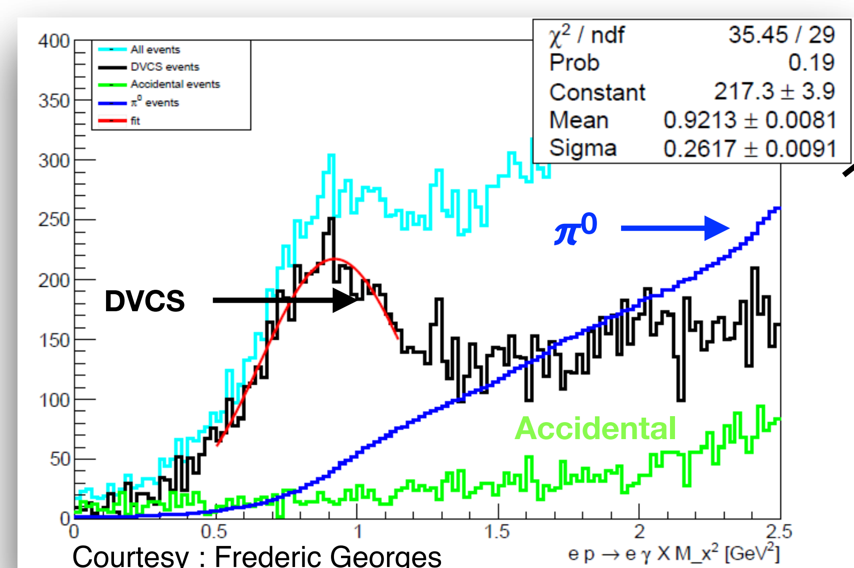
Exclusive DVCS

$$ep \longrightarrow ep\gamma$$

$$M_X^2 \leq (M + m_\pi)^2$$

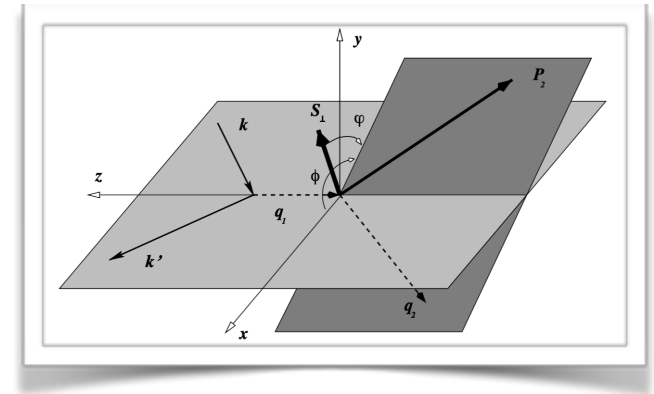
Associated DVCS

$$e + p \longrightarrow e + \gamma + N\pi$$



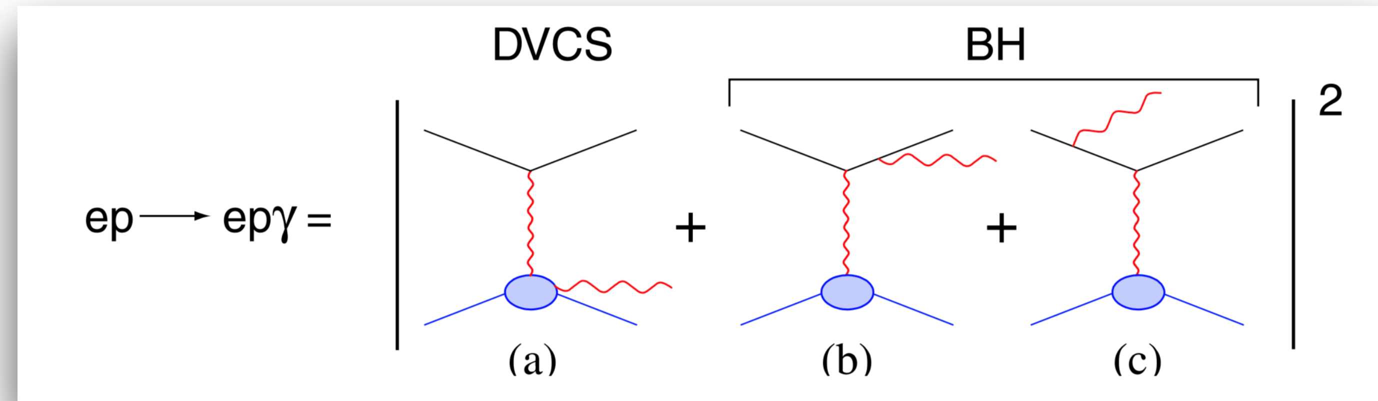
- PbF_2 (DVCS) Calorimeter - Photon Selection
  - Elastic and π_0 Calibration
  - Waveform Analysis
  - Coincidence Time Correction
  - Π^0 Subtraction
  - Accidental Subtraction

From Cross Section to GPD's



$$\frac{d\sigma}{dx_{\rm B}dyd|\Delta^2|d\phi d\varphi} = \frac{\alpha^3 x_{\rm B} y}{16\,\pi^2\,\mathcal{Q}^2\sqrt{1+\epsilon^2}} \left|\frac{\mathcal{T}}{e^3}\right|^2$$

DVCS - BH Interference



$$\mathcal{T}^2 = |\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2 + \mathcal{I}$$

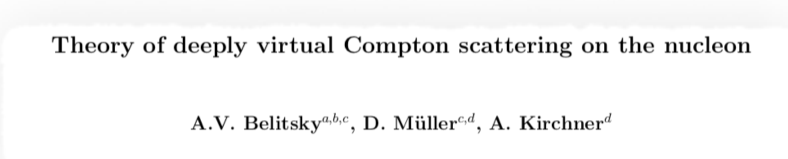
QED : Known

$$\mathcal{I} = \mathcal{T}_{\rm DVCS}\mathcal{T}^*_{\rm BH} + \mathcal{T}^*_{\rm DVCS}\mathcal{T}_{\rm BH}\,,$$

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{x_{\rm B}^2 y^2 (1+\epsilon^2)^2 \Delta^2\,\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH}\,\cos(n\phi) + s_1^{\rm BH}\,\sin(\phi) \right\}$$

$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6}{y^2\mathcal{Q}^2}\left\{ c_0^{\rm DVCS} + \sum_{n=1}^{2}\left[c_n^{\rm DVCS}\cos(n\phi) + s_n^{\rm DVCS}\sin(n\phi)\right]\right\}\,,$$

$$\mathcal{I} = \frac{\pm e^6}{x_{\rm B} y^3 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)\Delta^2}\left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\}\,,$$


Theory of deeply virtual Compton scattering on the nucleon

A.V. Belitsky[a,b,c], D. Müller[c,d], A. Kirchner[d]

C_n, S_n **Compton Form Factors**

From Numbers to cross section

$$d\sigma = d\sigma_{BH} + \sum_{j \in CFF_{termsc_j}} K_j(E, Q^2, \chi_B, t, \phi_{\gamma\gamma}, \phi_e) \times c_j(t)$$

← **Parameter**

↑ **Kinematic**

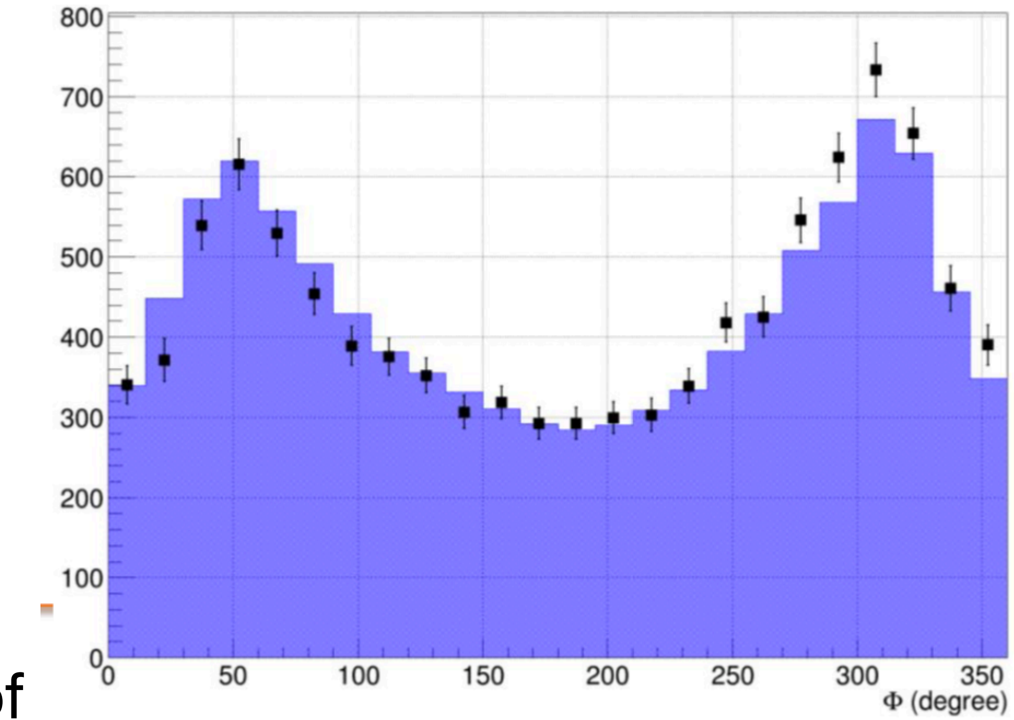
Compton Form Factors

$$Cj \in \left\{ C_n^T, S_n^T \,\middle|\, T = DVCS, BH, \mathcal{I};\ n = 0...3 \right\}$$

Use a fit method to extract the parameters and reconstruct the cross section by minimizing

$$\chi^2 = \sum_{k=1}^{N_{bin}} \left(\frac{N_k^{exp} - N_k^{sim}}{\sigma_k} \right)^2$$

Extracted cross sections are independent of choice of fit parameter



Simulated events Vs Fitted Events : Frederic Georges

For each setting in (X_B, Q^2), define 24 bins in $\phi_{\gamma\gamma}$ and ~5 bins in t (t-t_{min})

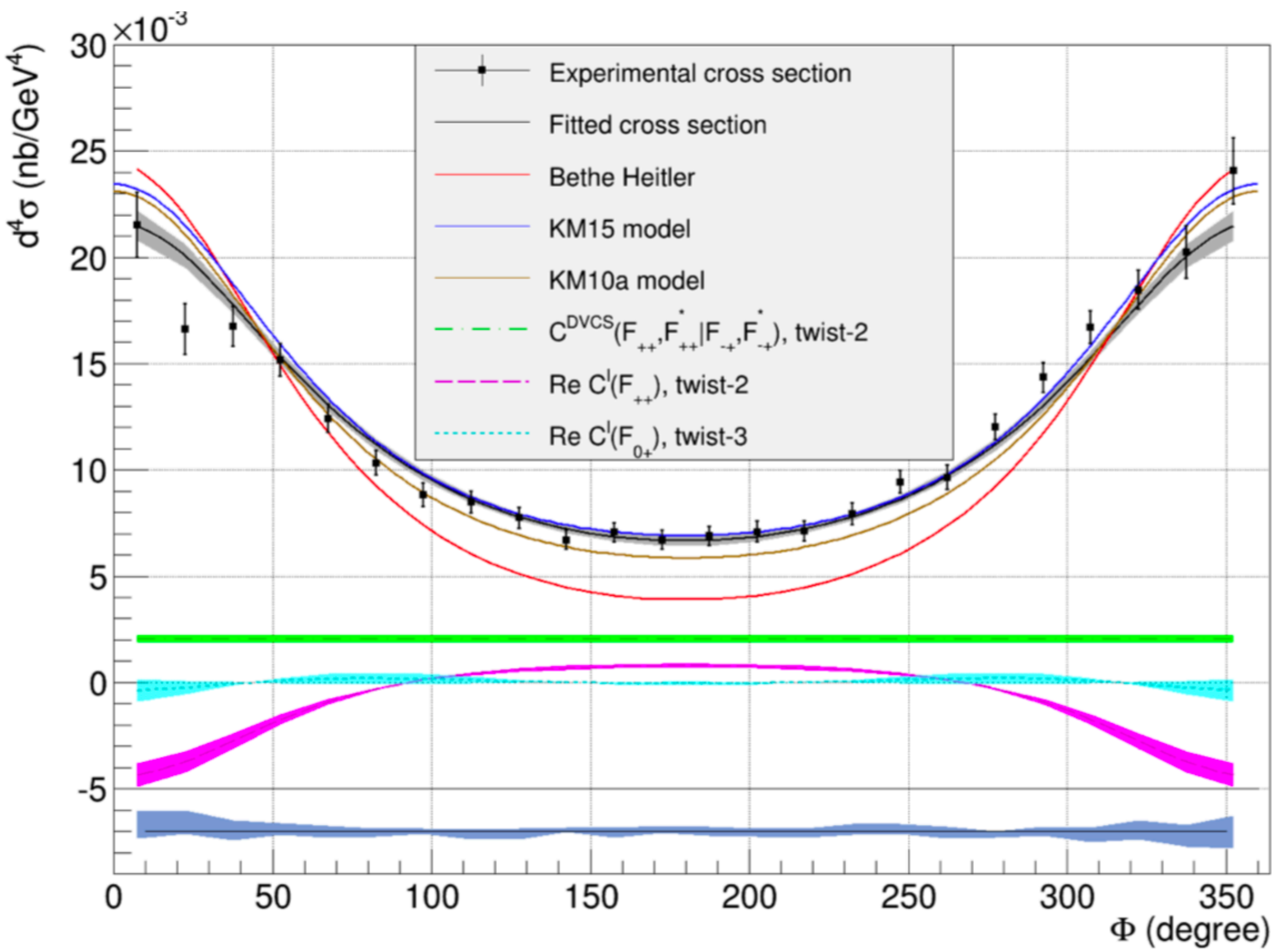
Assumption : $c_j(k)$ is constant over the phase-space within bin

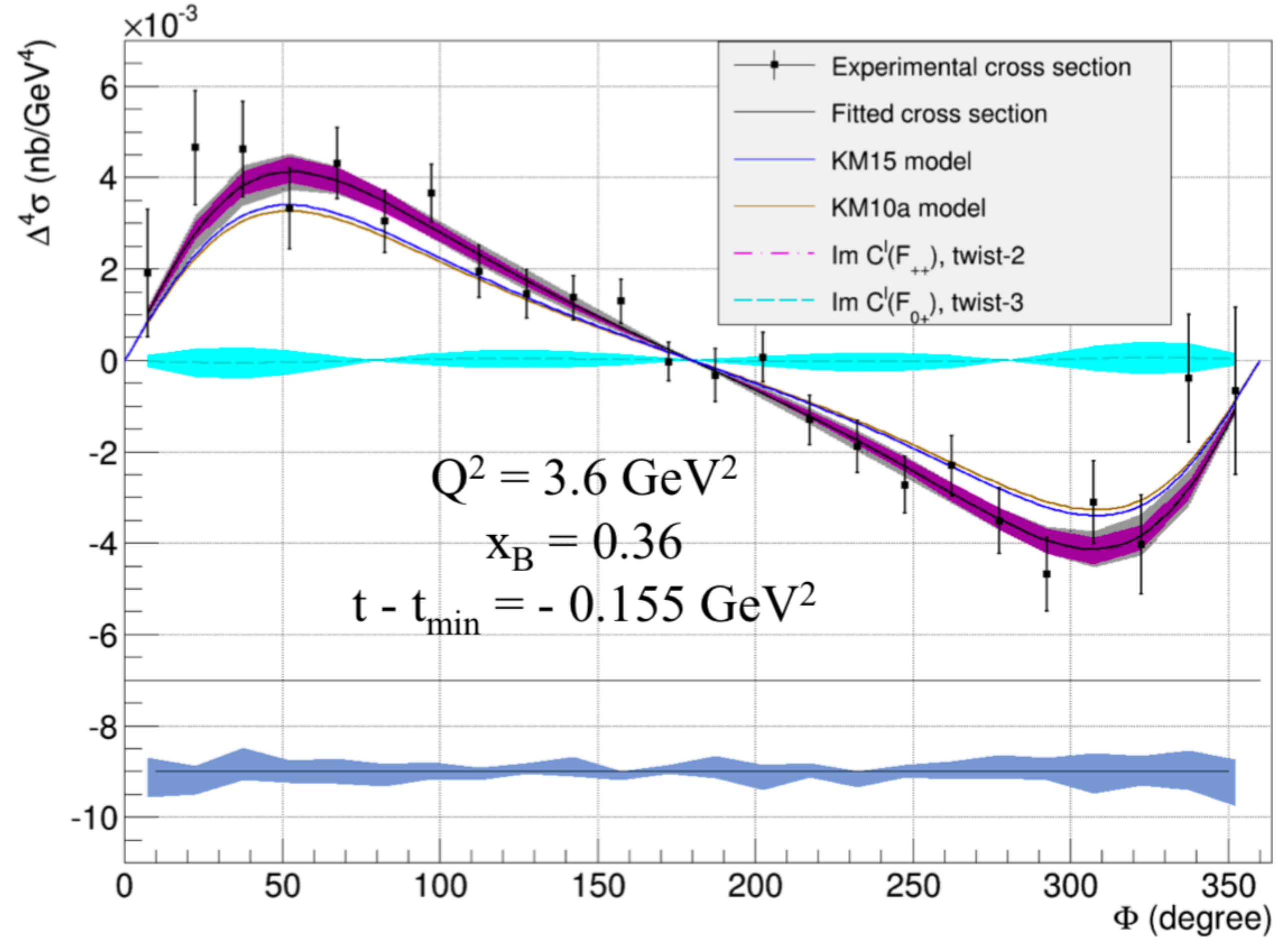
$$N_k^{sim} = \mathcal{L} \sum_{j \in CFF_{termsc_j}} c_j(k) \times \int_k K_j(E, Q^2, x_{Bj}, t, \phi_e, \phi\gamma\gamma)$$

Preliminary DVCS Cross Sections - Frederic Georges

$$d^4\sigma = \frac{d^4\overrightarrow{\sigma} + d^4\overleftarrow{\sigma}}{2} = |T_{BH}|^2 + |T_{DVCS}|^2 + \Re(\mathscr{T})$$

$$\Delta^4\sigma = \frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{2} = \Im(\mathscr{T})$$





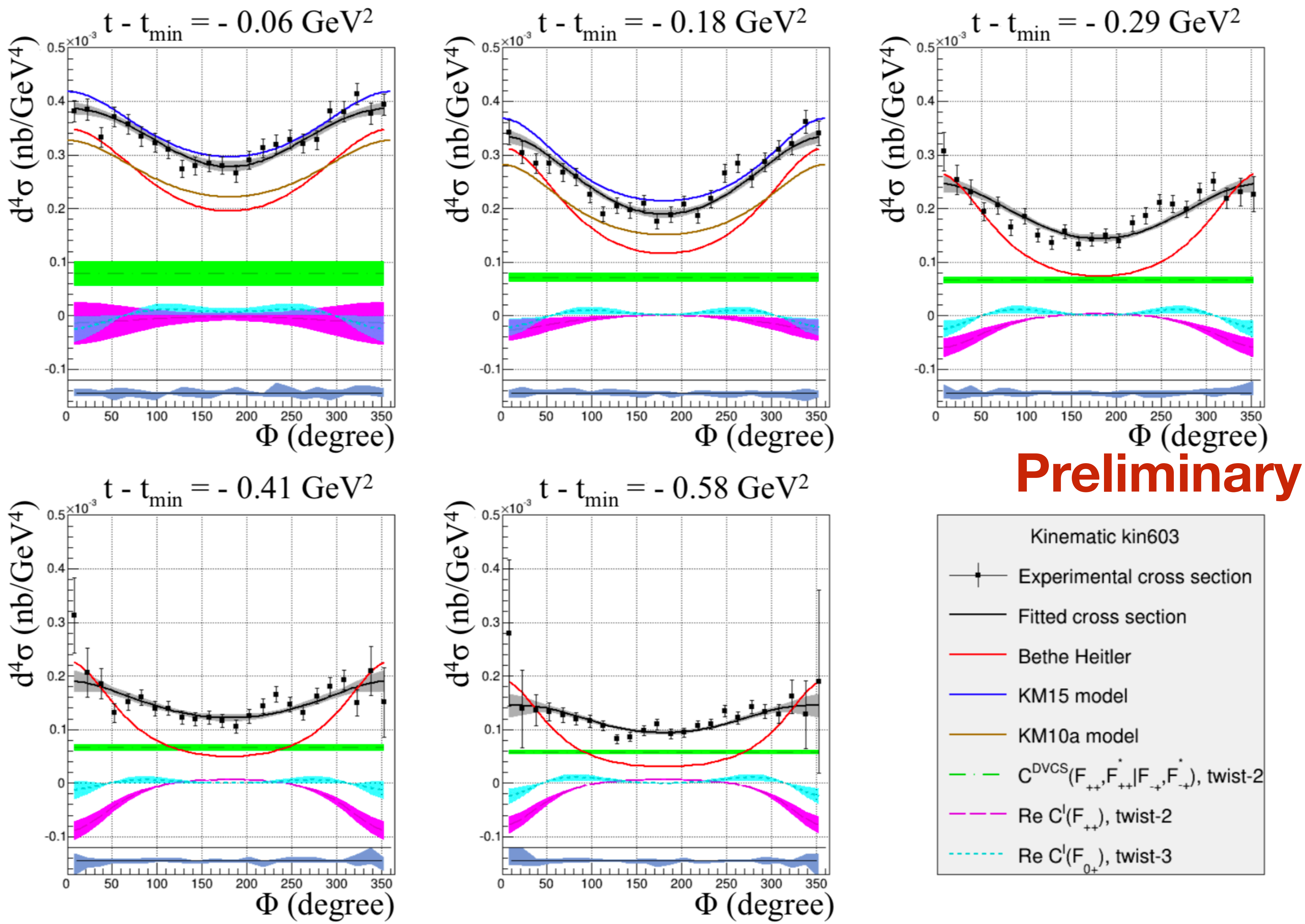
- KM10a & KM15: global fits to DVCS data.
- KM10a: does not use Hall A data.
- KM15: use Hall A and CLAS data up to 2015.

K. Kumerički, S. Liuti, and H. Moutarde. GPD phenomenology and DVCS fitting. *Eur. Phys. J. A. 52, 157*, 2016. arXiv:1602.02763.

K. Kumerički and D. Müller. Description and interpretation of DVCS measurements. *EPJ Web of Conferences 112, 01012*, 2015. arXiv:1512.09014.

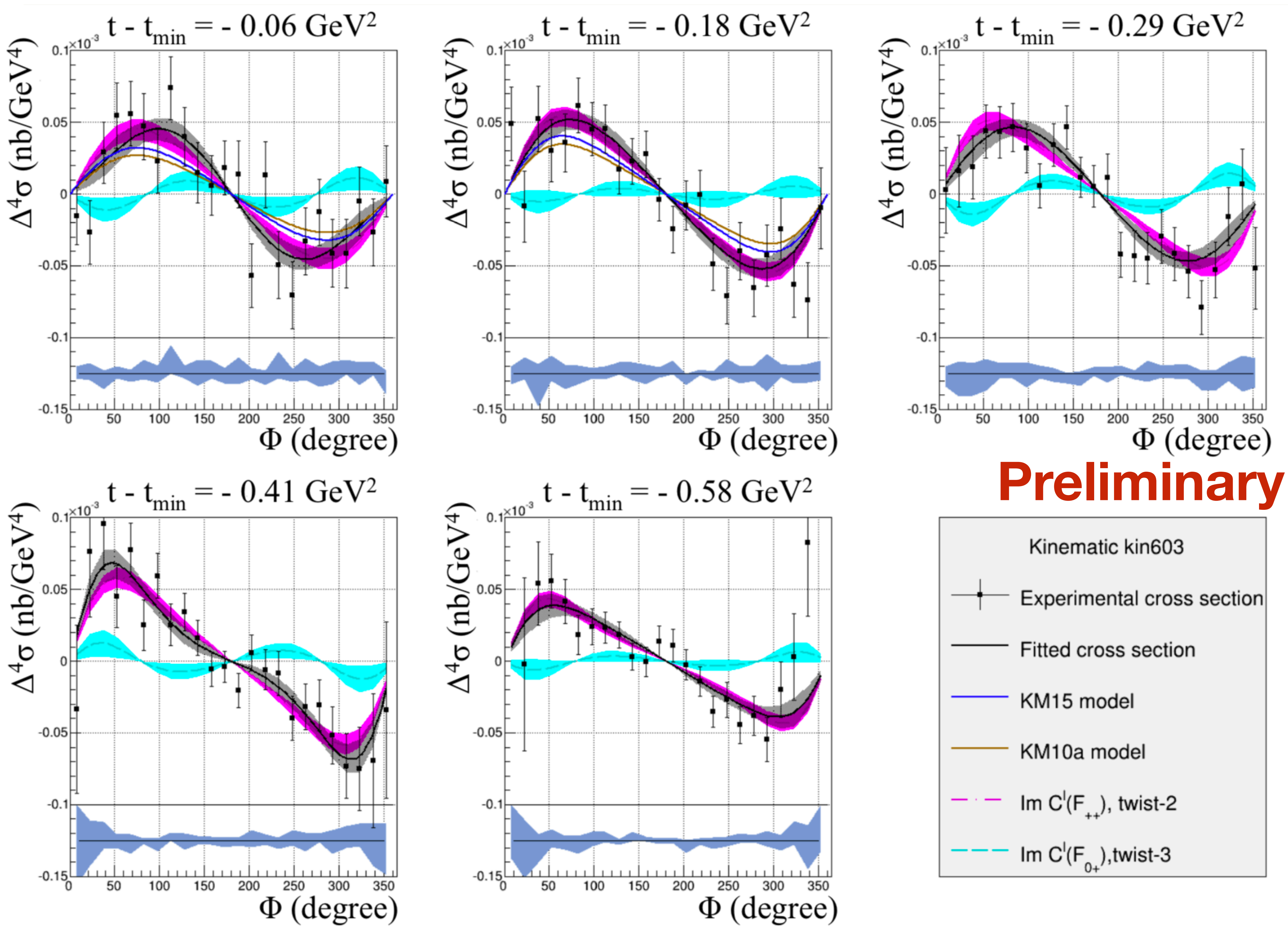
5 t-bins total,
Also Q^2 =3.2 and 4.5

Preliminary Helicity Independent cross section for $X_B = 0.60$ and $Q^2 = 8.4$ GeV^2 in all t bins (also Q^2=5)



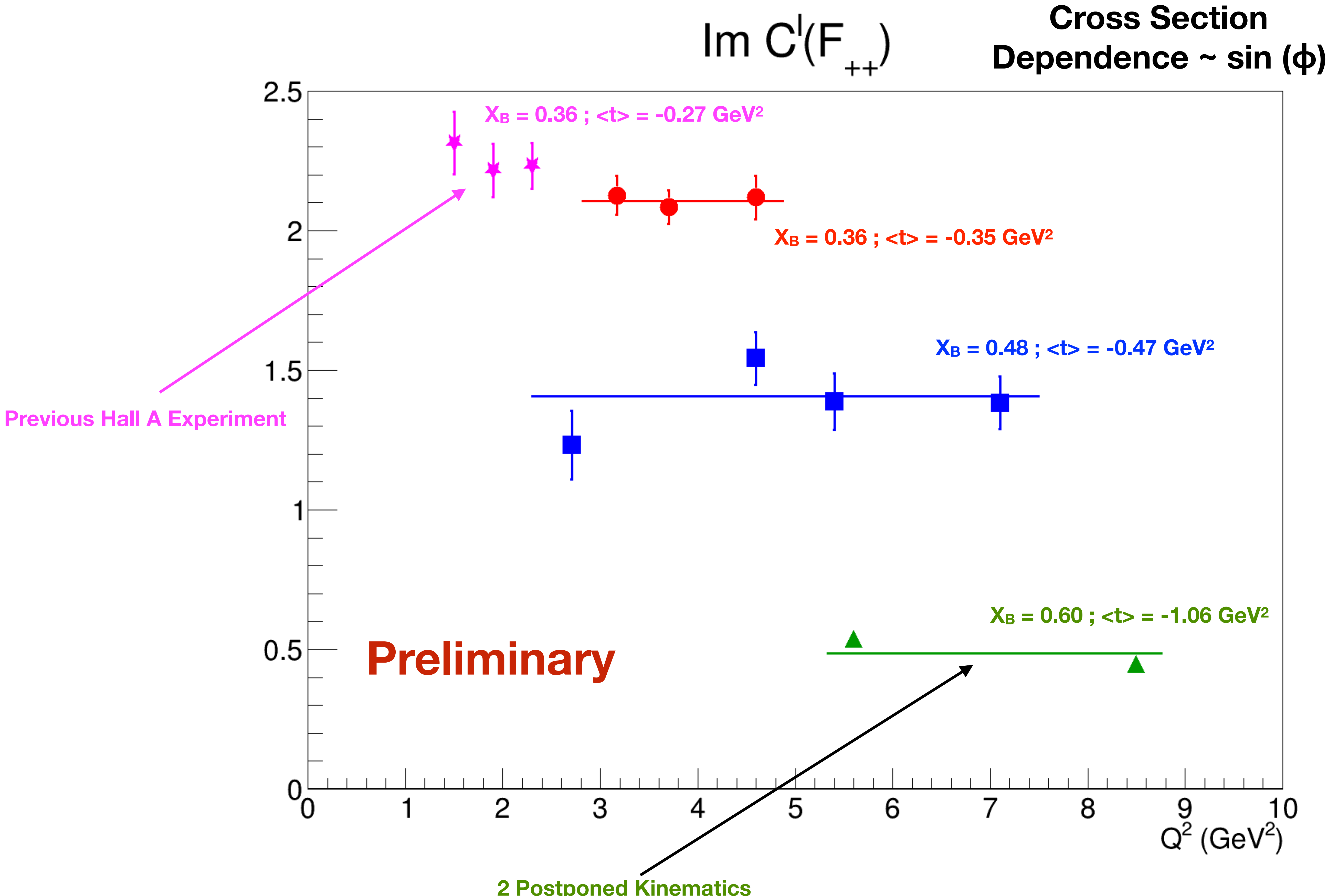
Frederic Georges

Preliminary Helicity Dependent cross section for $X_B = 0.60$ and $Q^2 = 8.4$ GeV^2 in all t bins (also Q^2=5)



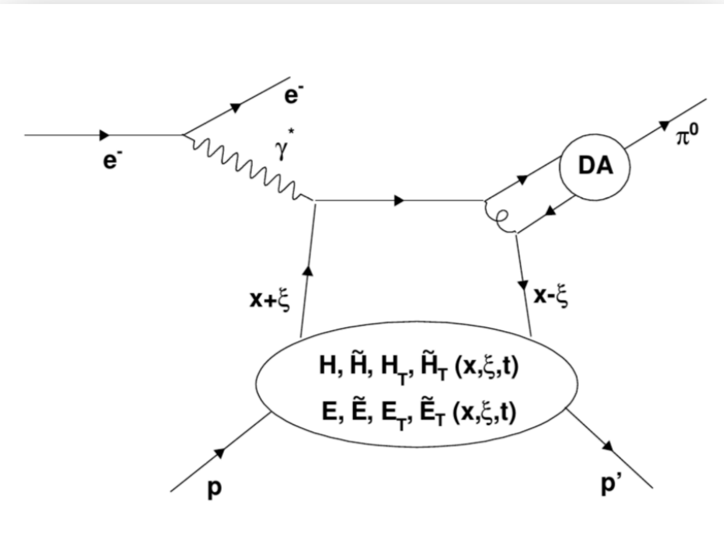
Frederic Georges

Q^2 Dependence (Scaling) - Twist 2 Im(CFF)



Frederic Georges

π^0 Cross Section - Mongi Dlamini



$$\frac{d^5\sigma}{dQ^2 d\chi_B dt d\phi_e d\phi_\pi} = \Gamma \frac{d\sigma^2}{dt d\phi}$$

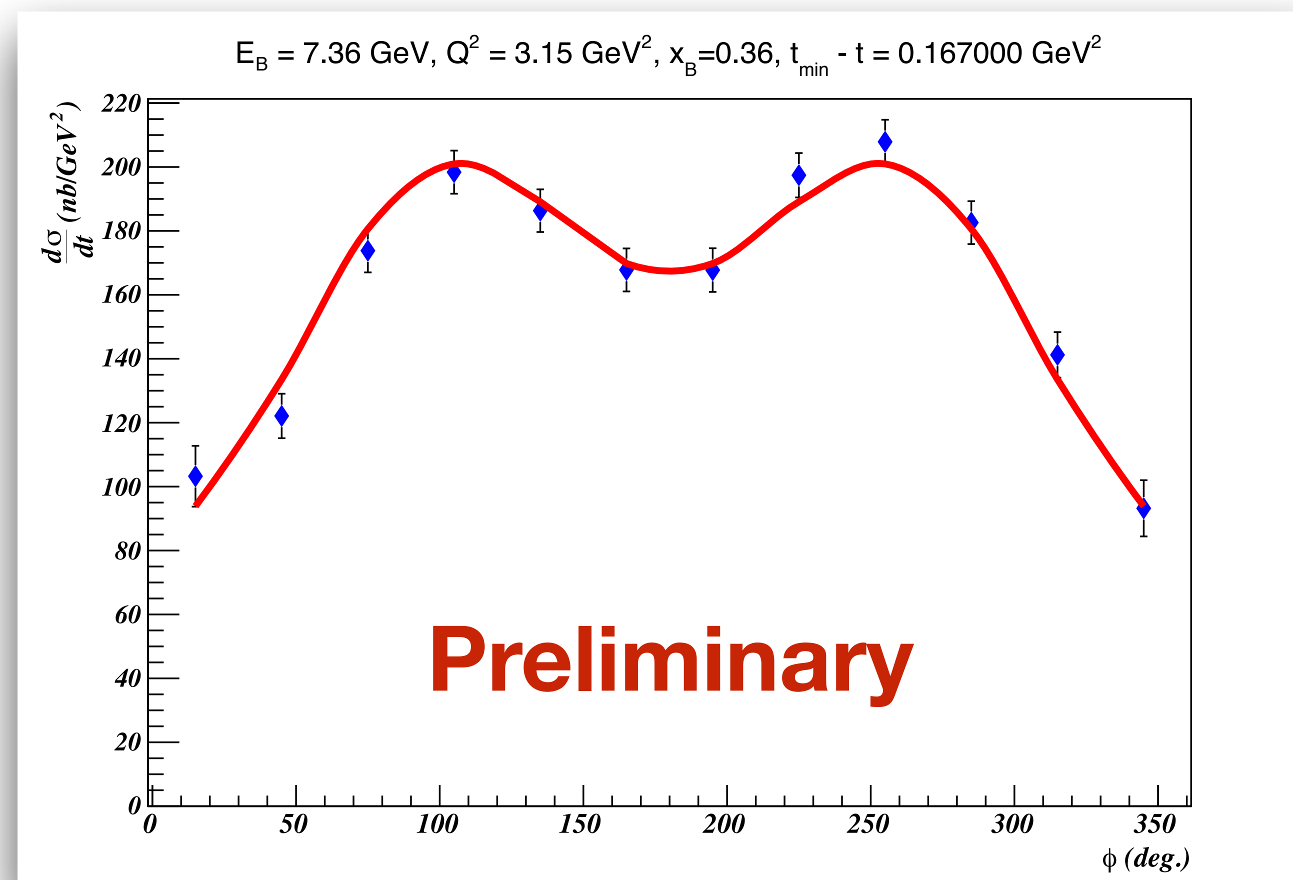
$$\frac{d^2\sigma}{dt d\phi_\pi} = \frac{d^2\sigma_T}{dt d\phi_\pi} + \epsilon \frac{d^2\sigma_L}{dt d\phi_\pi} + \sqrt{2\epsilon(1+\epsilon)} \frac{d^2\sigma_{LT}}{dt d\phi_\pi} \cdot cos(\phi_\pi)$$
$$+\epsilon \frac{d^2\sigma_{TT}}{dt d\phi_\pi} \cdot cos(2\phi_\pi) + h\sqrt{2\epsilon(1-\epsilon)} \frac{d^2\sigma_{LT'}}{dt d\phi_\pi} \cdot sin(\phi_\pi)$$

D. Dreschsel and L. Tiator, J. Phys. G: Nucl. Part. Phys. 18 449 (1992)

Same Electron Selection, But look for 2 photons in the DVCS Calorimeter corresponding to a pion signature

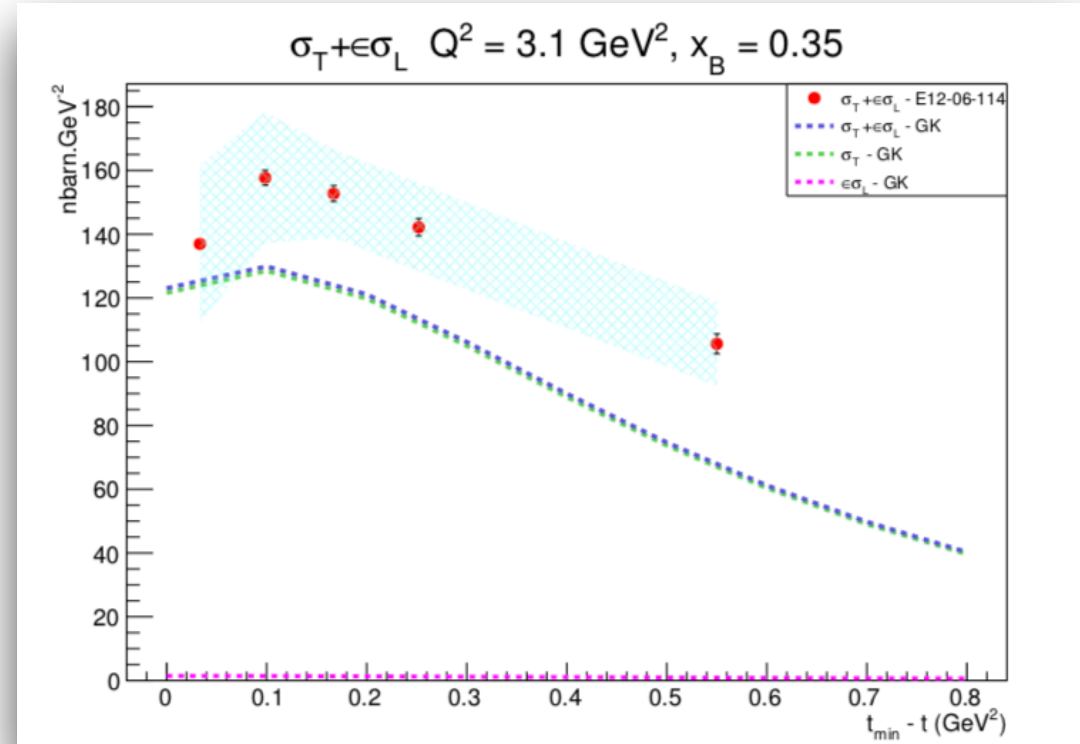
Similar Extraction Method to DVCS

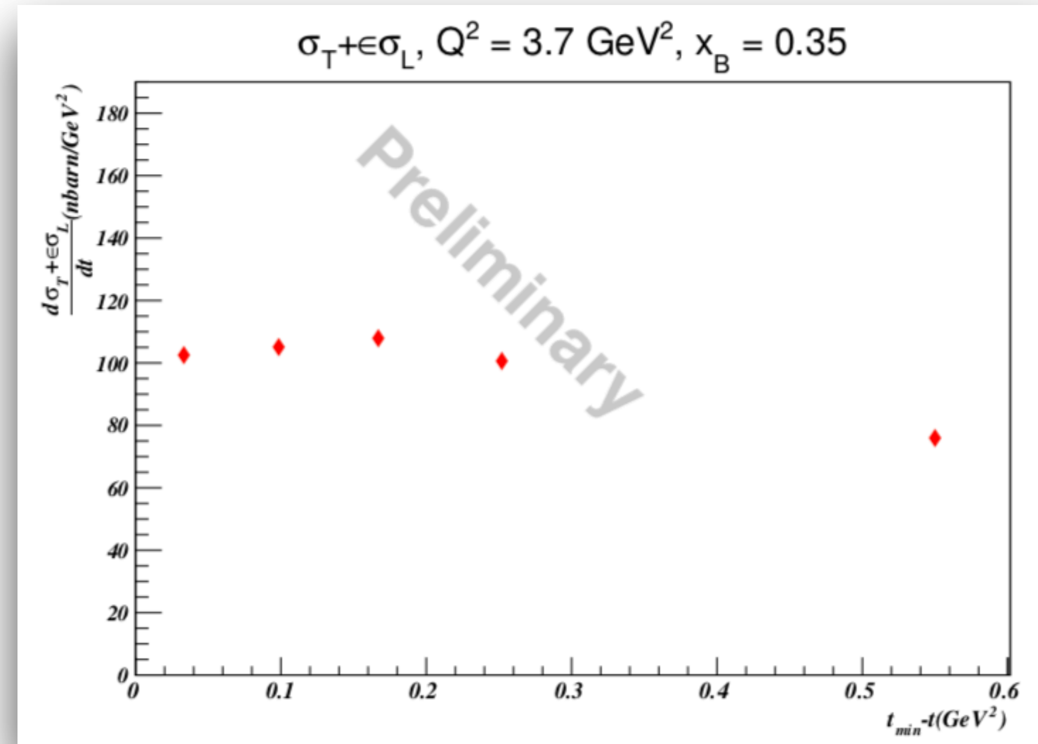
Extracted for X_B = 0.36 and Q^2 = 3.1 GeV^2, 3.7 GeV^2, 4.5 GeV^2

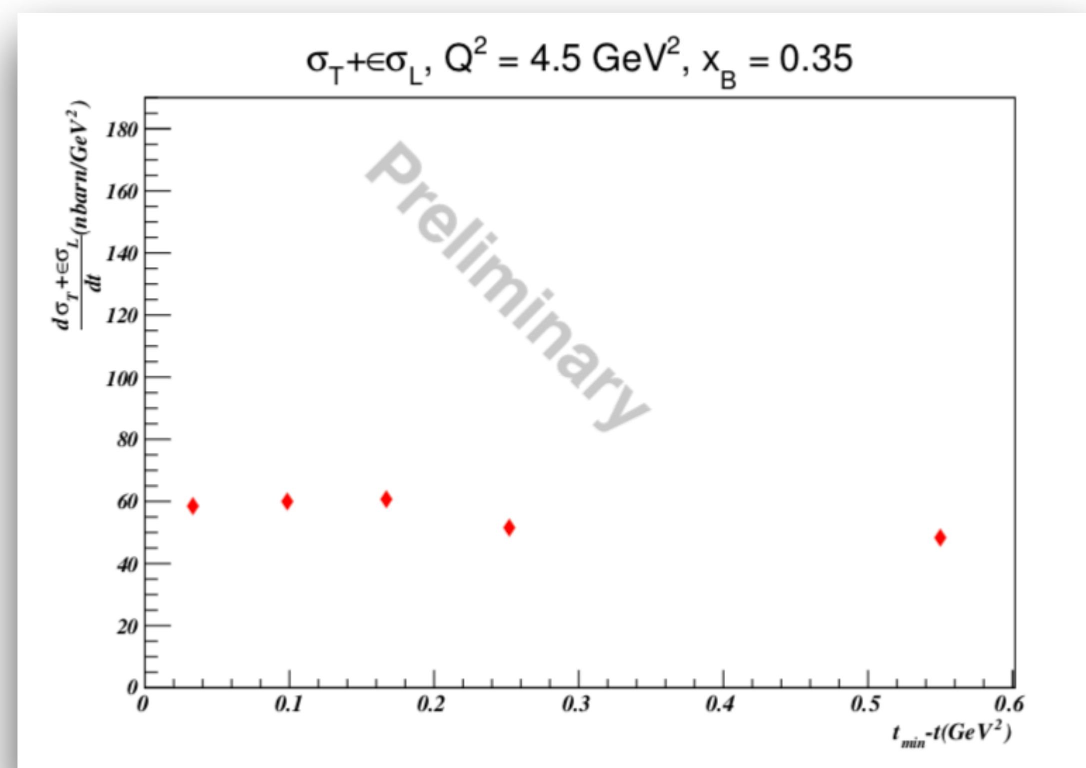


Extracted Structure Function $\sigma_T + \epsilon\sigma_L$

S. Goloskokov and P. Kroll, Eur.Phys.Jour.A 47:112 (2011)





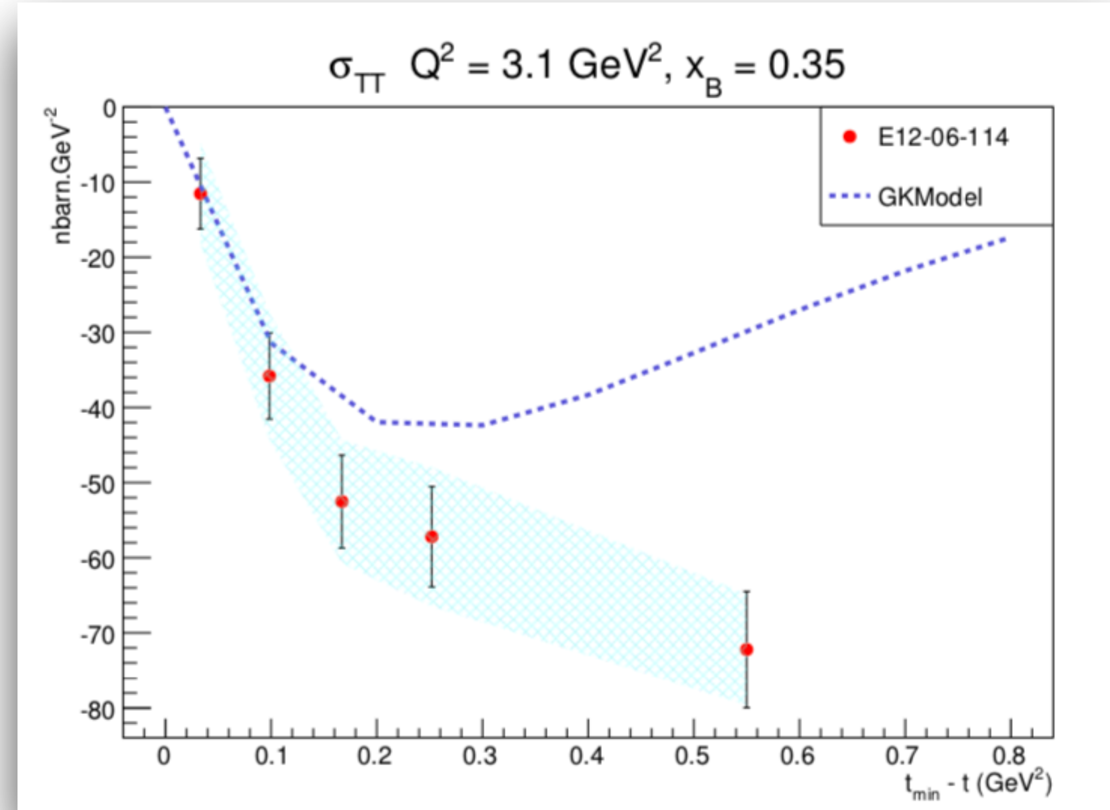


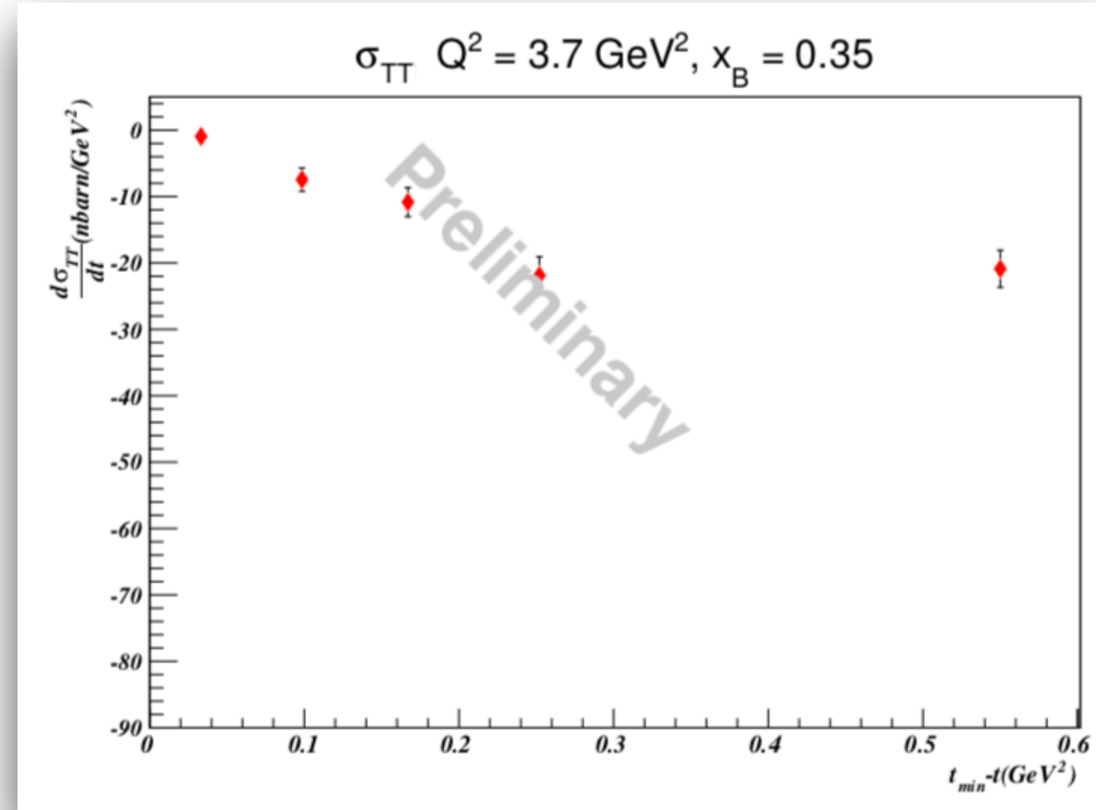
GK Dominated by $d\sigma_T$ - twist 3 transversely GPD

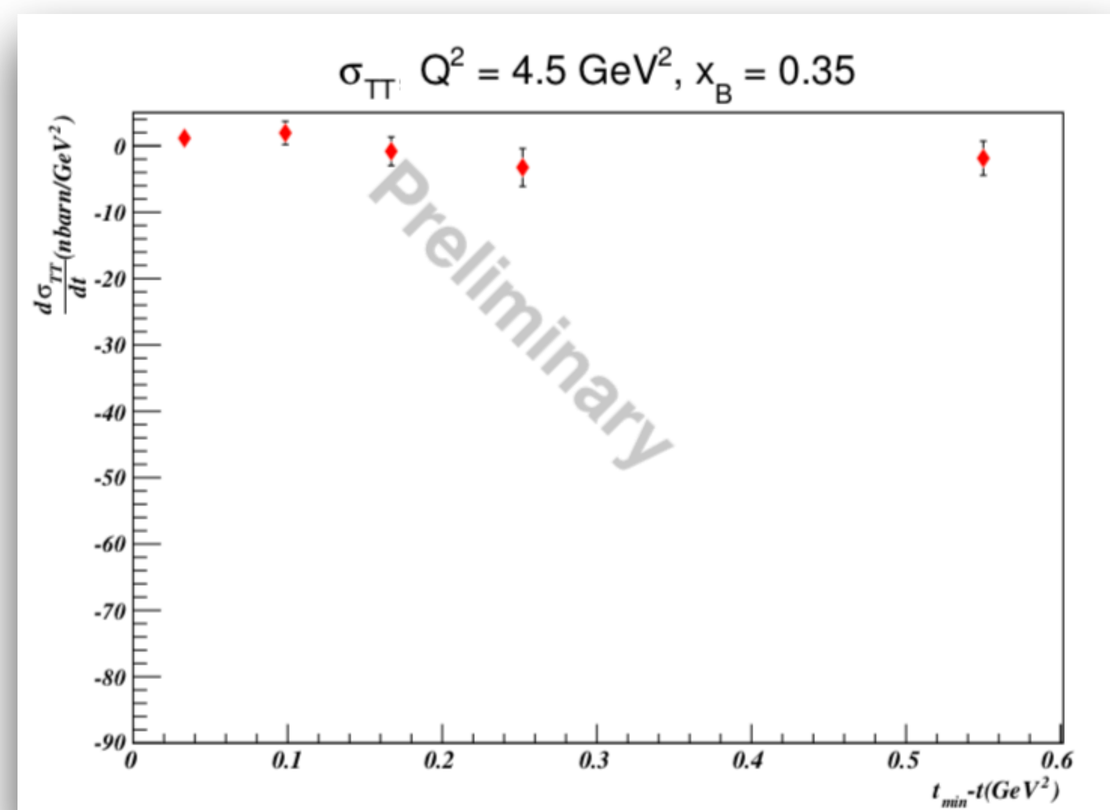
Strong Q^2 dependence

Mongi Dlamini

Extracted Structure Function σ_{TT}

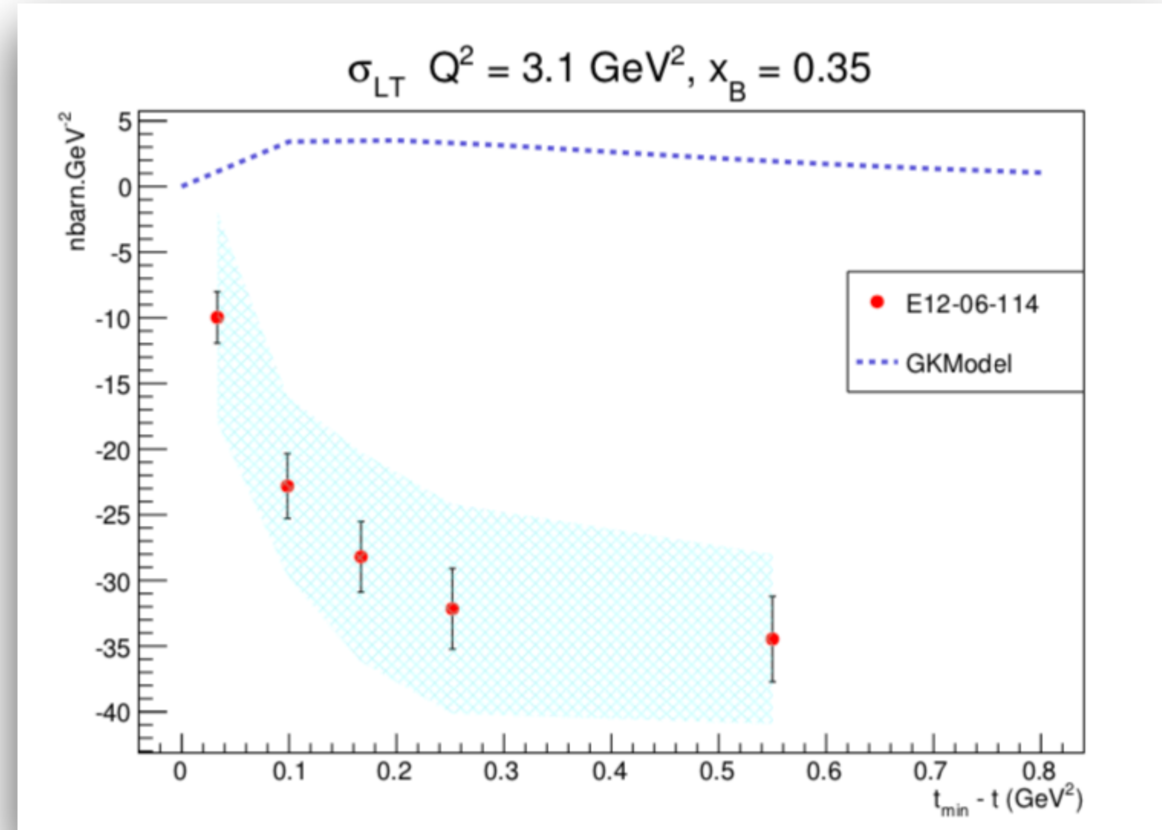


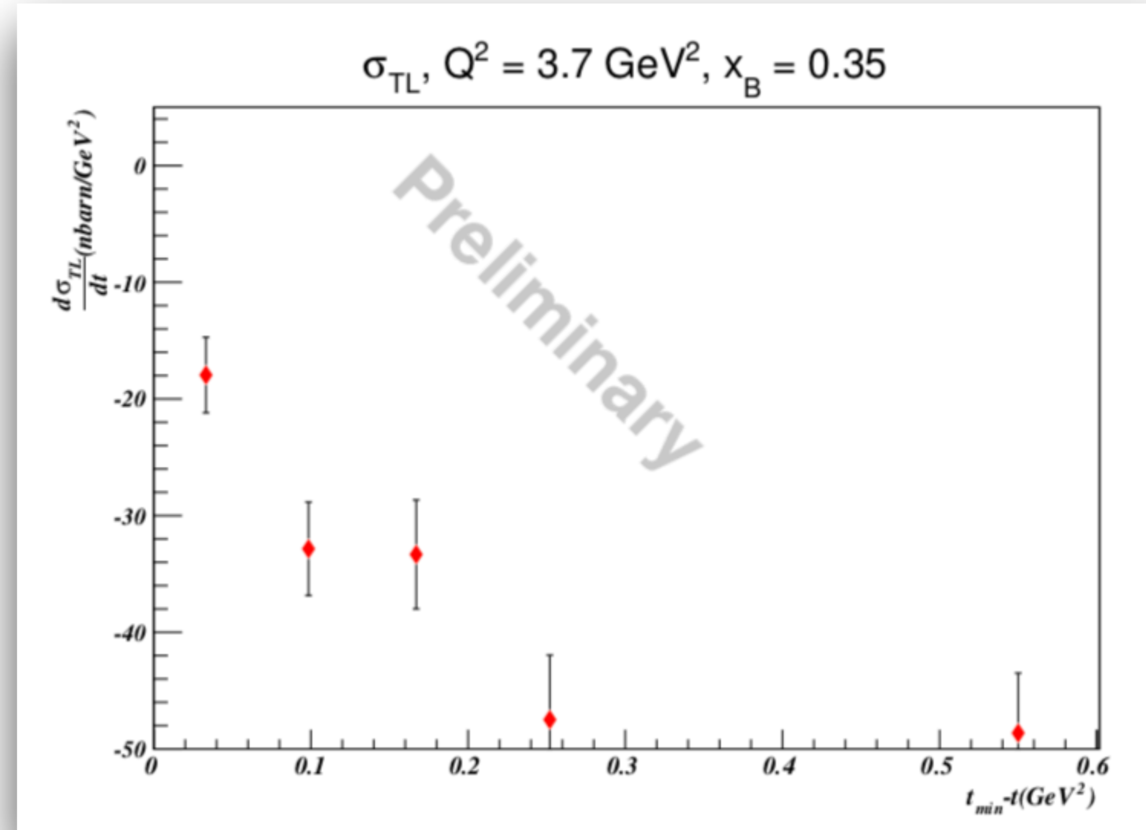


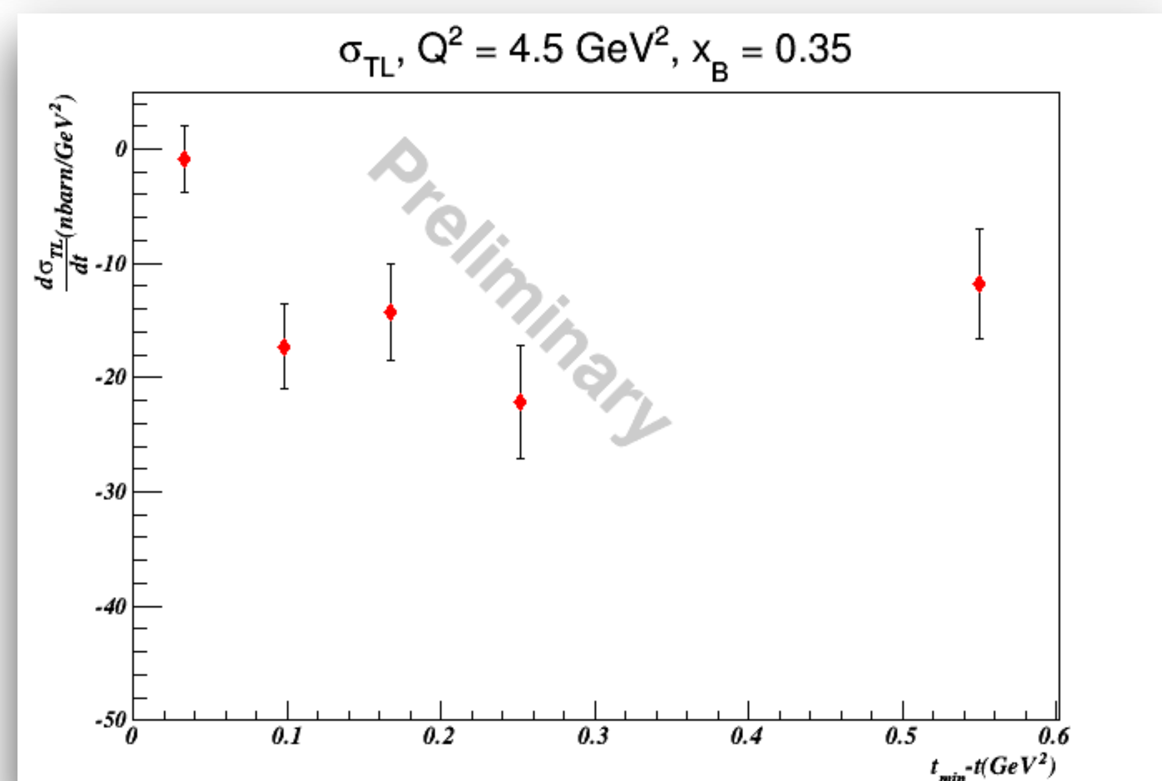


Mongi Dlamini

Extracted Structure Function σ_{LT}







Mongi Dlamini

Systematics and Corrections

Preliminary

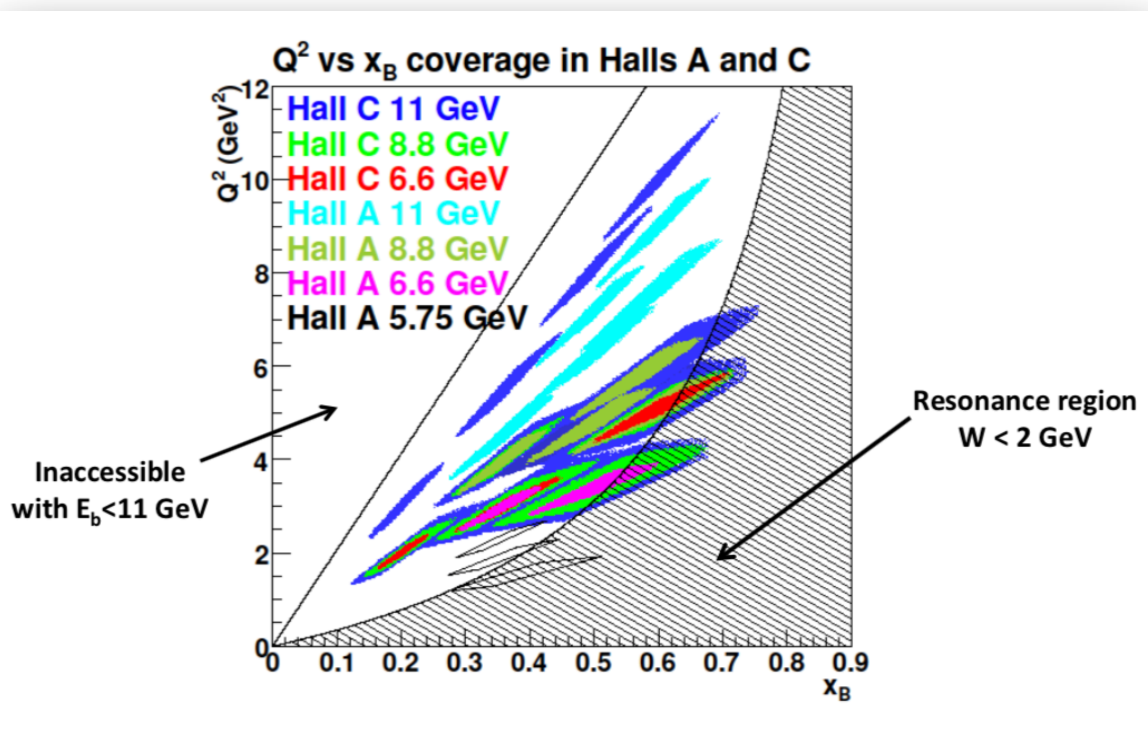
Uncertainty	Value (%)
CFF parametrization	1.0
Beam Polarization	1.0 (2.2)
Luminosity and Deadtime	1.6
HRS Electron ID *	0.5
HRS Multi Track *	0.5
HRS Acceptance (R-Function) *	1.0
Virtual Radiative Corrections *	2.0
Total (Helicity Independent)	3.0
Total (Helicity Dependent)	3.2 (3.7)

* Estimated from E00-110

Trigger Efficiency	99%
Beam Polarization	86%
Dead Time	2%-3% Correction
Spectrometer Tracking	4%-7% Correction
Calorimeter Multi Cluster	0.5% - 2% Correction

Summary and Future

- Preliminary results on DVCS and π^0 Cross Section - 2 Thesis
- 4 PhD students currently finalizing analyses
  - Including Normalization Studies
    - Updated Optics for Fall 2016, DIS Cross section is now within 4% of world data, down from ≤15% variation before.
    - Investigating a couple of leads for Spring 2016 DIS cross-section variation (Trigger labelling, detuned optics)
- Draft publications for summer 2019



Jeopardy 50 PAC Days + New Hall C

See : NPS Update, Charles Hyde, Hall C Collaboration Meeting

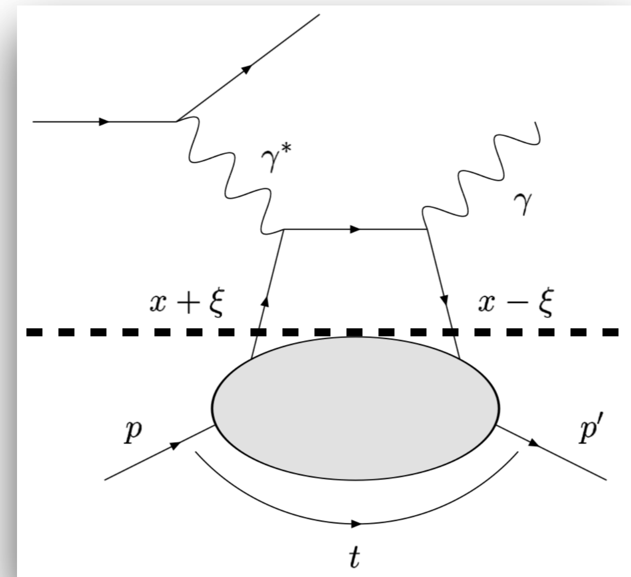
Thank You

Calibration updates…

- Updated Optics for Fall 2016 - Bishnu Karki
    - DIS Cross section is now within 4% of world data, down from ≤15% variation before.
    - Investigating a couple of leads for Spring 2016 DIS cross-section variation (Trigger labelling, detuned optics)
- Dead time correction - S. Ali
- Updated R-Function for Spring 2016 data - A. Johnson
- Raster Correction update for Fall 2014 - H. Rashad
- Updated Scattering chamber geometry for Geant4 simulation - Bill Henry

GPD's in Experiments - DVCS

$$\gamma^* P \rightarrow \gamma P$$
$$eP \rightarrow eP\gamma$$



Long Range
Perturbative

Factorization

Short Range
Non-Perturbative
(Parametrized by GPD's)

$$\chi_b = \frac{Q^2}{2P\,.\,q} = \frac{Q^2}{2M\nu}$$

$$\xi \sim \frac{\chi_b}{2-\chi_b}$$

$$Q^2 = -q^2 = 2EE'(1-cos\theta)$$

$$\nu = E - E' = q^2/2M$$

GPD's appears via Compton Form Factors (Complex Integrals)

$$\mathcal{F} = \int_{-1}^{+1} dx\, F(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right) \quad (F = H \text{ or } E)$$
$$\tilde{\mathcal{F}} = \int_{-1}^{+1} dx\, \tilde{F}(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} + \frac{1}{\xi + x - i\epsilon}\right) \quad (\tilde{F} = \tilde{H} \text{ or } \tilde{E})$$

Properties of GPD's

Connection to PDF's

$$H^q(x,0,0) = q(x)$$

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

Connection to Total angular Momentum

$$J_q = \frac{1}{2}\int_{-1}^{1} dx x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

$$J_q = \frac{\Delta\Sigma}{2} + L_q \longleftarrow \textbf{Orbital}$$

$$\uparrow$$

Spin

Connection to Form Factors

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

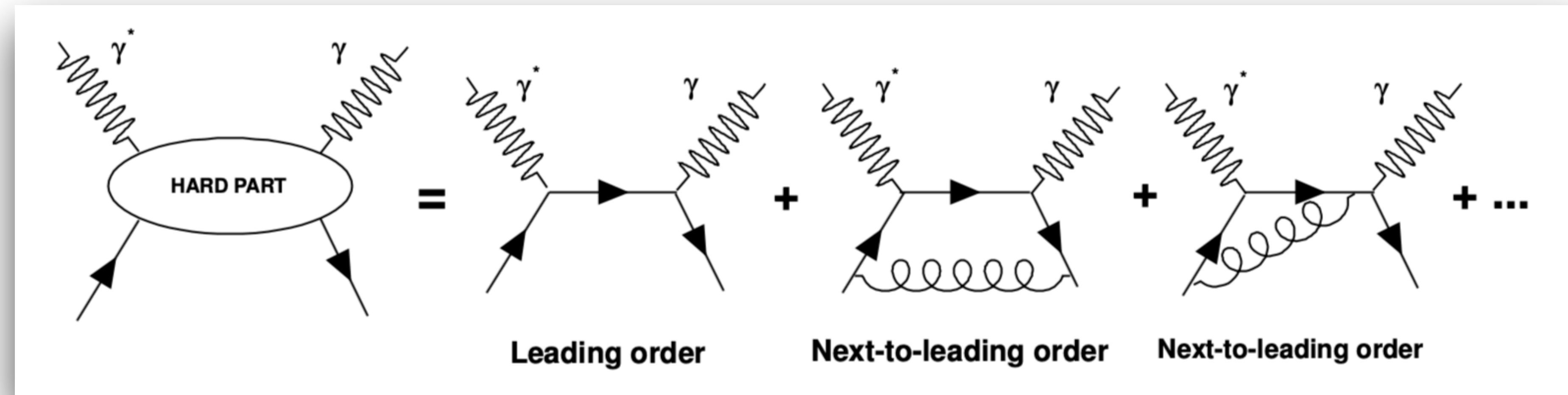
$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

$$\int_{-1}^{1} dx \tilde{H}^q(x,\xi,t) = G_A^q(t)$$

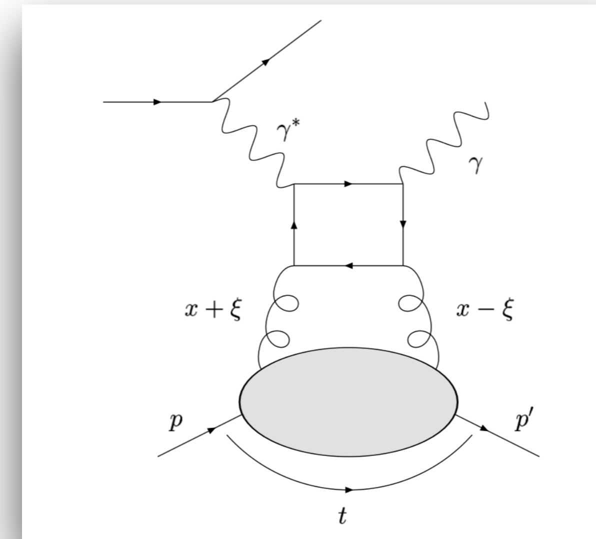
$$\int_{-1}^{1} dx \tilde{E}^q(x,\xi,t) = G_P^q(t)$$

Higher Order and Higher Twist

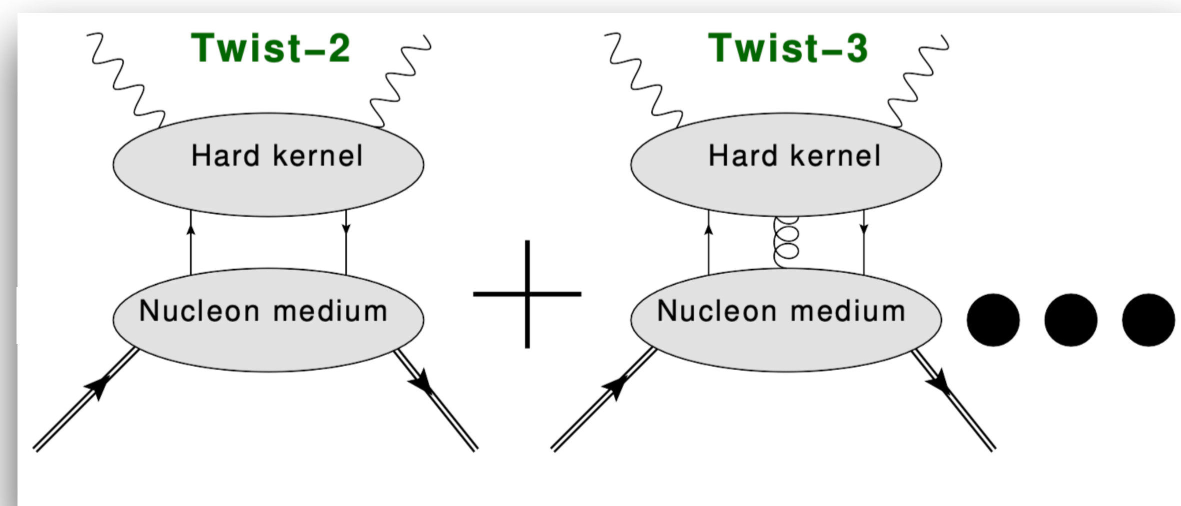
Higher Order



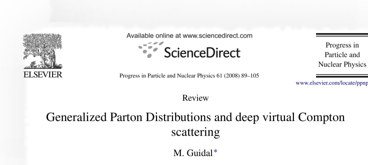
Gluon GPD's



Higher Twist



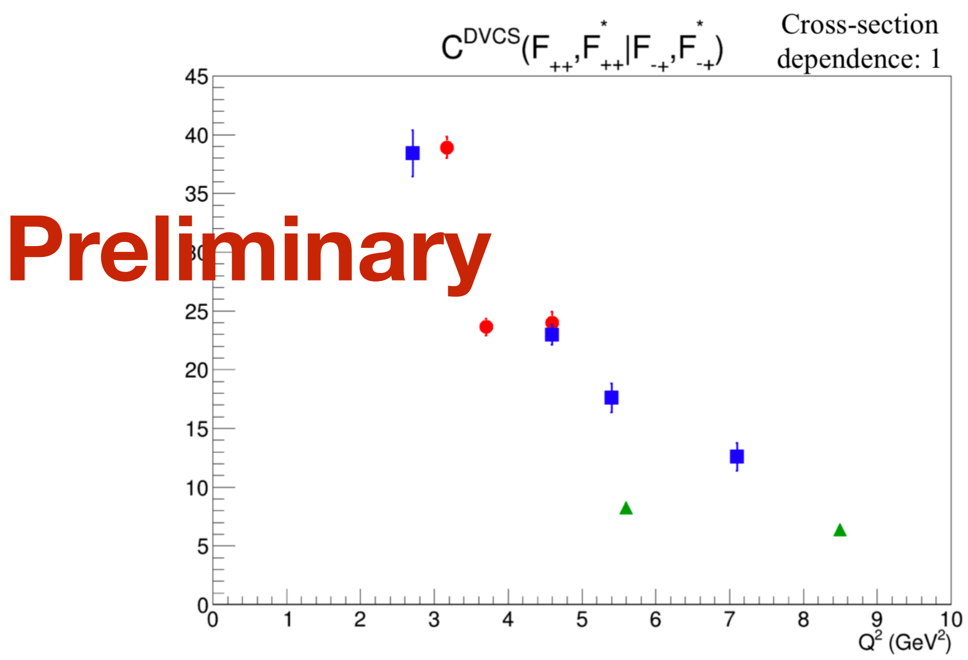
[1] The formal definition of *twist* is *dimension−spin*. For instance, a $\bar{\psi}\gamma^{\mu}\psi$ operator, that we will often meet in the following, where ψ is a spinor field and γ the standard Dirac matrix, has twist-2: since a spinor has dimension $\frac{3}{2}$, the operator has *dimension* 3 and, due to the γ^{μ} matrix which carries one Lorentz index μ, it is a spin 1 operator (i.e. *vector*). In a general fashion, *twist* allows to classify the order of terms in a $\frac{1}{Q}$ expansion. In other words, higher twists with respect to the leading twists are suppressed by $\frac{1}{Q}$.



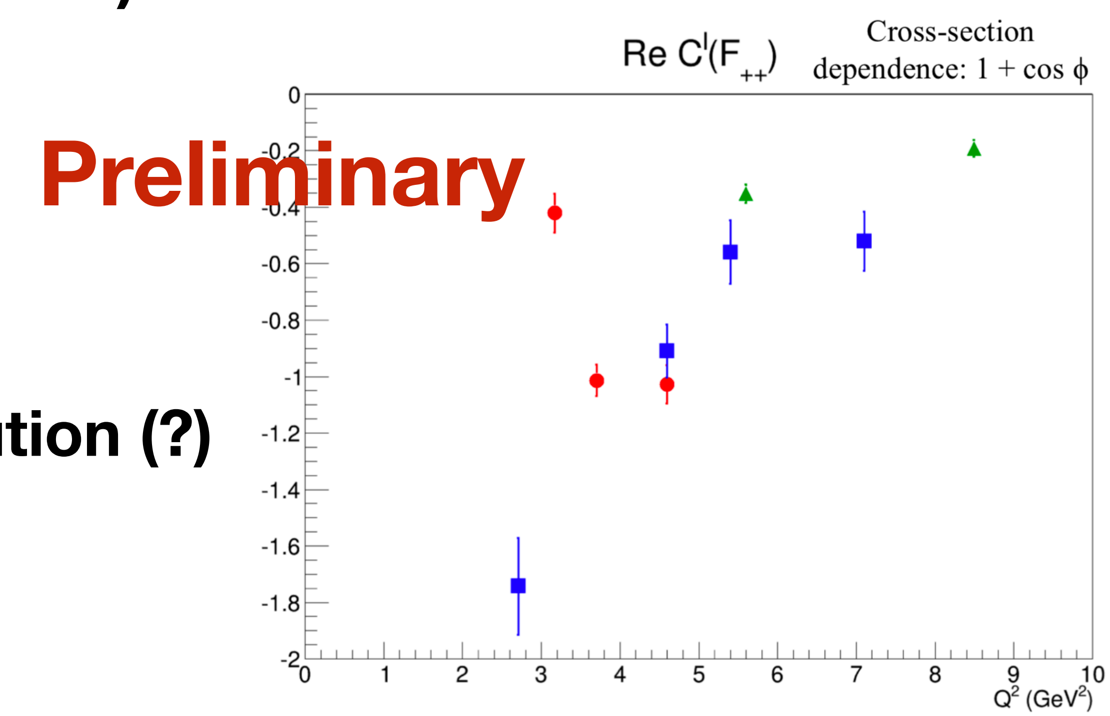
Q2 Dependency…

Frederic Georges

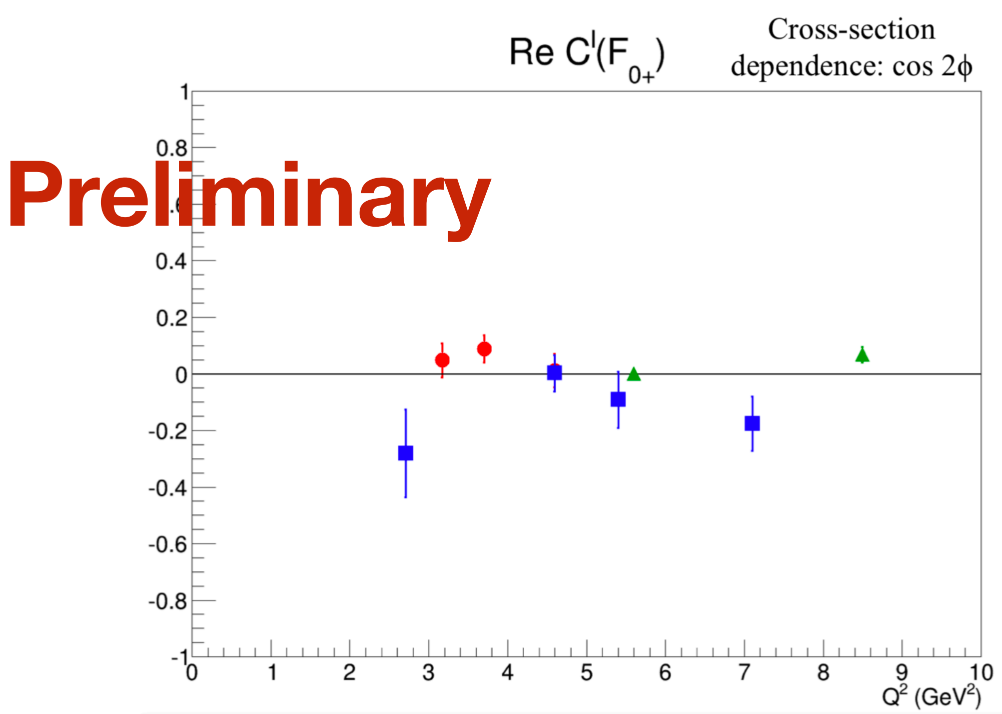
Twist 2 - Re(CFF)



Gluon Contribution (?)



Twist 3 - CFF



Small, but non-zero