Cross sections for deeply virtual Compton scattering with CLAS

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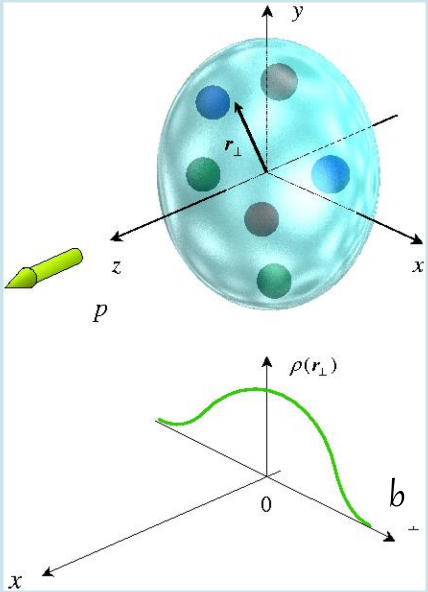
International Nuclear Physics Conference
Adelaide Convention Centre, Australia
11-16 September 2016

INPC 2016 - Adelaide Convention Centre, Australia - September 15, 2016

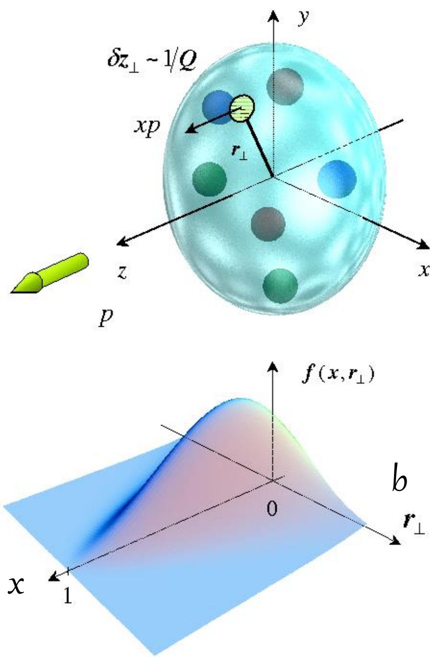
Generalized parton distributions (GPDs)



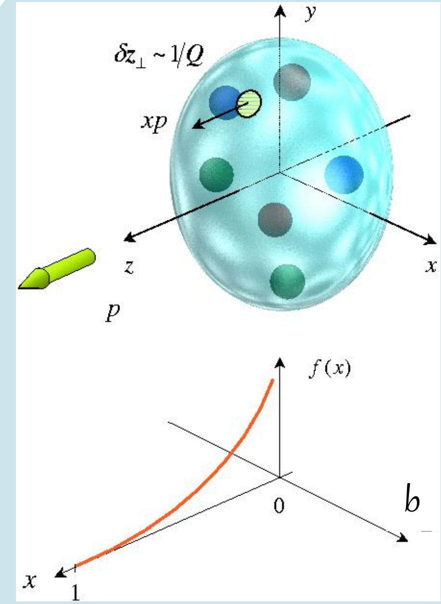
Form Factors (elastic scattering) :
Transverse position of the quarks in the nucleon

GPDs, accessibles via the measurement of exclusive reactions, provide a **correlation** between the transverse position and the longitudinal momentum of the quarks in the nucleon

Nucleon « tomography »



Transverse position (b) as a function of longitudinal momentum fraction x



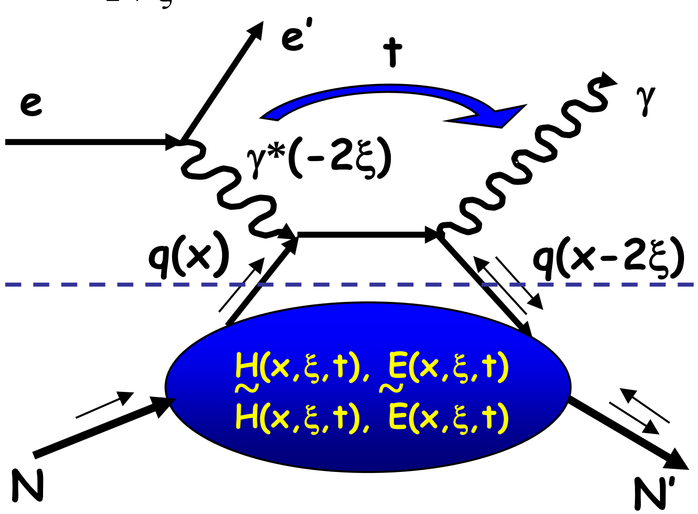
Parton Distribution Functions (Deep inelastic scattering) :
Longitudinal momentum of the quarks in the nucleon

Deeply Virtual Compton Scattering (DVCS)

"handbag" diagram (high Q^2, small t, fixed x_B)

$$x_B = \frac{2\xi}{1+\xi}$$

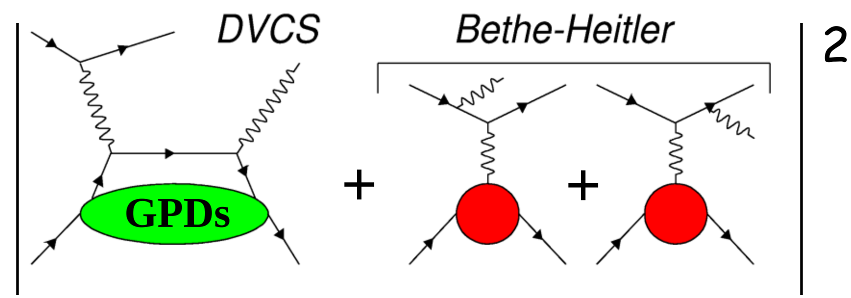
DVCS



DVCS is the key reaction allowing to access the GPDs → simplest interpretation in terms of GPDs

BH fully calculable in QED

$\sigma(eN \to eN\gamma) =$



DVCS and Bethe-Heitler (BH) experimentally undistinguishable

interference between the 2 processes

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Unpolarized Cross Section

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \approx \left|T^{DVCS} + T^{BH}\right|^2 = \left|T^{DVCS}\right|^2 + \left|T^{BH}\right|^2 + I$$

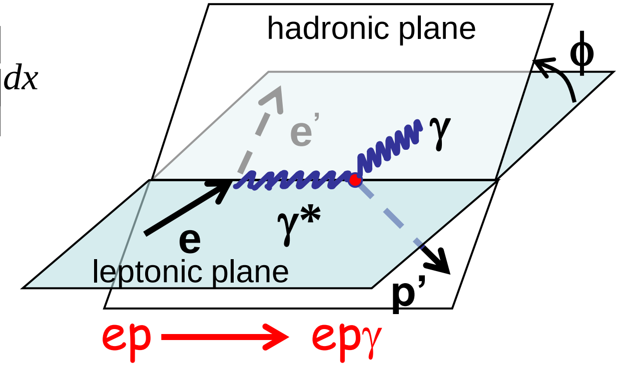
Beam-polarized Cross-Section difference

$$\frac{d^4\overrightarrow{\sigma}}{dQ^2 dx_B dt d\phi} - \frac{d^4\overleftarrow{\sigma}}{dQ^2 dx_B dt d\phi} \propto \mathrm{Im}(T_{DVCS}) \times T_{BH}$$

Extracting GPDs from DVCS observables

Compton Form Factors (CFFs)

$$\begin{cases} Re\,\mathcal{H}_q = e_q^2 P \int_0^{+1} \left(H^q(x,\xi,t) - H^q(-x,\xi,t)\right)\left[\frac{1}{\xi - x} + \frac{1}{\xi + x}\right]dx \\ Im\,\mathcal{H}_q = \pi e_q^2 \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right] \end{cases}$$



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

- Polarized beam, Unpolarized target

$$\boxed{\Delta\sigma_{LU} \sim \sin\phi\, Im\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi}$$

$\Rightarrow Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$

- Unpolarized beam, Longitudinally polarized target

$$\boxed{\Delta\sigma_{UL} \sim \sin\phi\, Im\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}} + \ldots\}d\phi}$$

$\Rightarrow Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$

- Unpolarized beam, Transversely polarized target

$$\boxed{\Delta\sigma_{UT} \sim \cos\phi\, Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi}$$

$\Rightarrow Im\{\mathcal{H}_p, \mathcal{E}_p\}$

- Polarized beam, Longitudinally polarized target

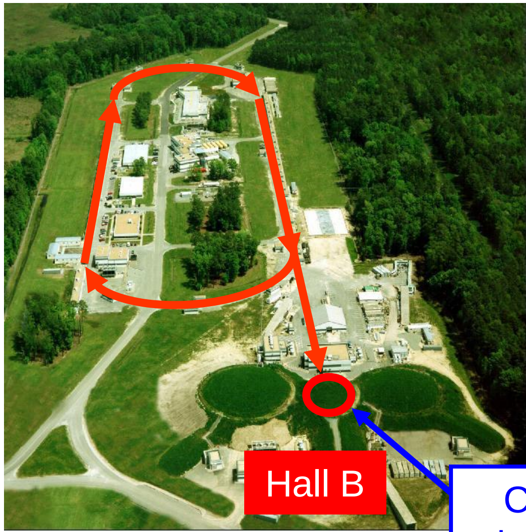
$$\boxed{\Delta\sigma_{LL} \sim (A+B\cos\phi)\, Re\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E})\ldots\}d\phi}$$

$\Rightarrow Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$

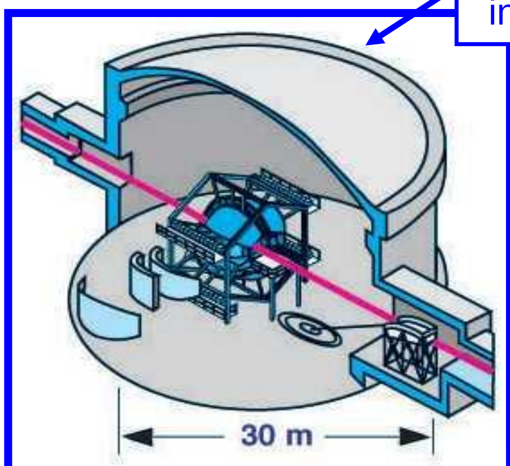
Jefferson Lab (Newport News, Virginia, USA)

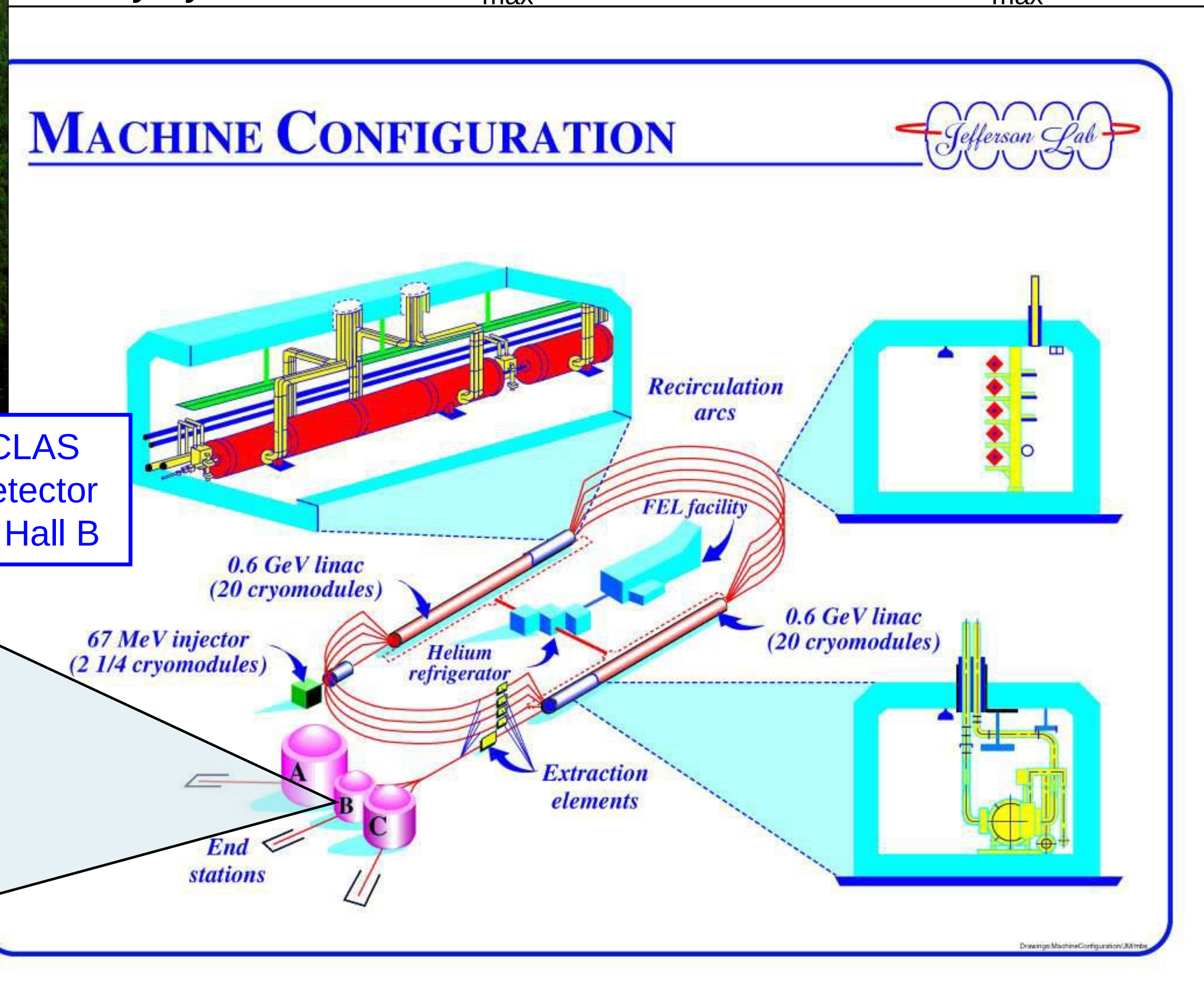
CEBAF : Continuous Electron Beam Accelerator Facility

Duty cycle~100% E_{max}~5.8 GeV $Polarization_{max}$~80%



CLAS detector in Hall B

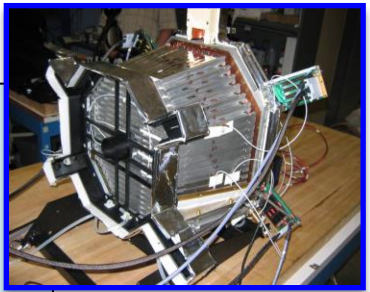


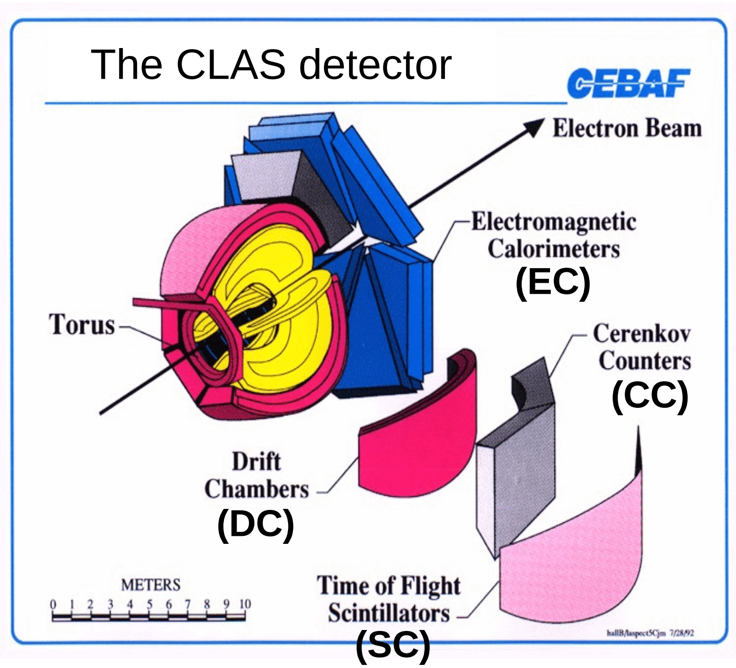


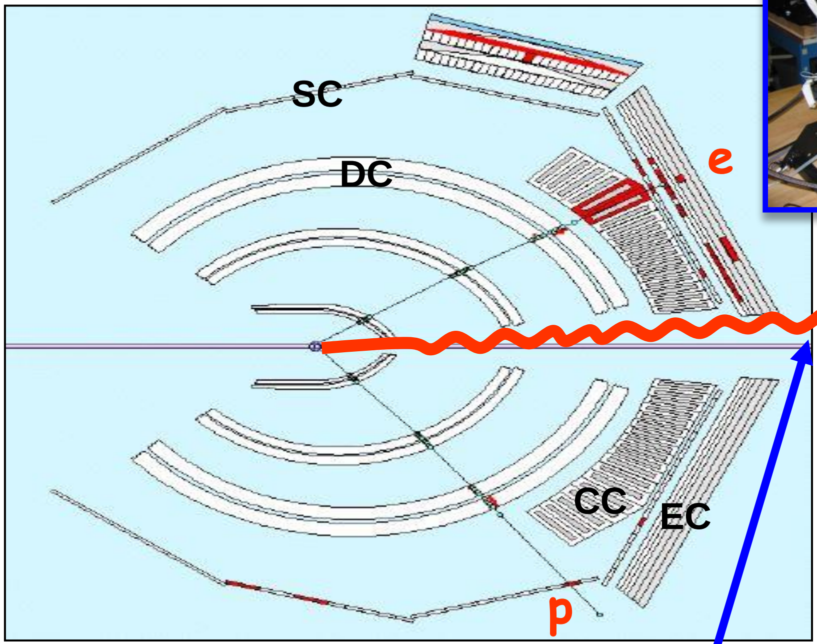
E1-DVCS experiment with CLAS

- Data taken in 2005 (L_{int} ~ 3.33 x 10^7 nb^{-1})
- CEBAF's polarized electron beam (E = 5.75 GeV, pol~80%) + LH_2 target
- Addition of an **electromagnetic calorimeter (IC)** to the standard setup of CLAS to detect the DVCS/BH photon of the reaction ep→epγ

IC



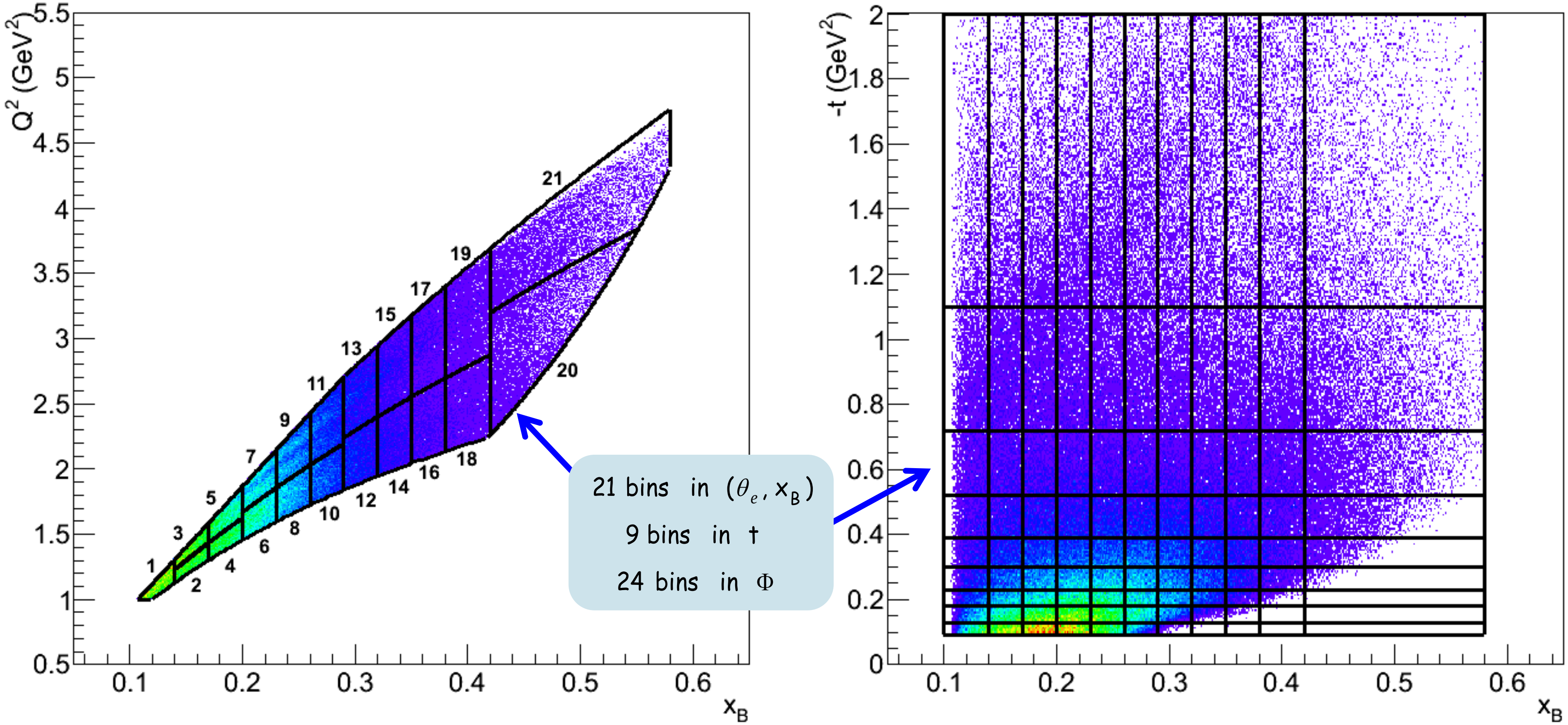




The DVCS/BH photon (mainly emitted to the forward angles) can hardly be detected with CLAS alone

E1-DVCS binning for cross sections analysis

$Q^2 > 1$, $0.1 < x_B < 0.58$, $21 < \theta_e < 45$, $p_e > 0.8$, $W > 2$



The cross section varies very quickly and is particularly sensitive to variations in x_B
$\rightarrow$ very small bins in x_B are necessary

Extraction of 4-fold cross sections

$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} \qquad \frac{1}{2}\left(\frac{d^4\vec{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} - \frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}\right)$$

Cross sections extracted for about **3000** (Q^2, x_B, t, ϕ) bins

DVCS cross section analysis

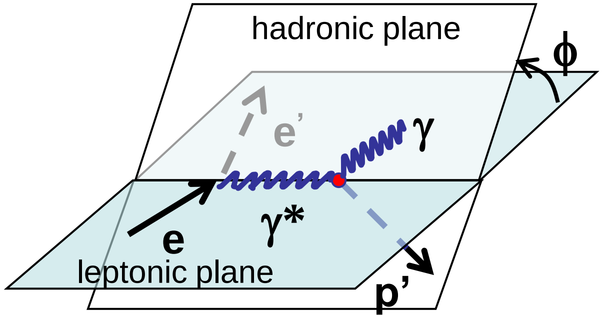
Extraction of 4-fold cross sections of the ep→epγ reaction

$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} = \frac{N_{ep\to ep\gamma} - N_{ep\to ep\pi^0\to ep\gamma(\gamma)}}{Lum\,.Acc\,.\Delta Q^2 \Delta x_B \Delta t \Delta\Phi\,.F_{vol}\,.F_{rad}\,.F_{eff}}$$

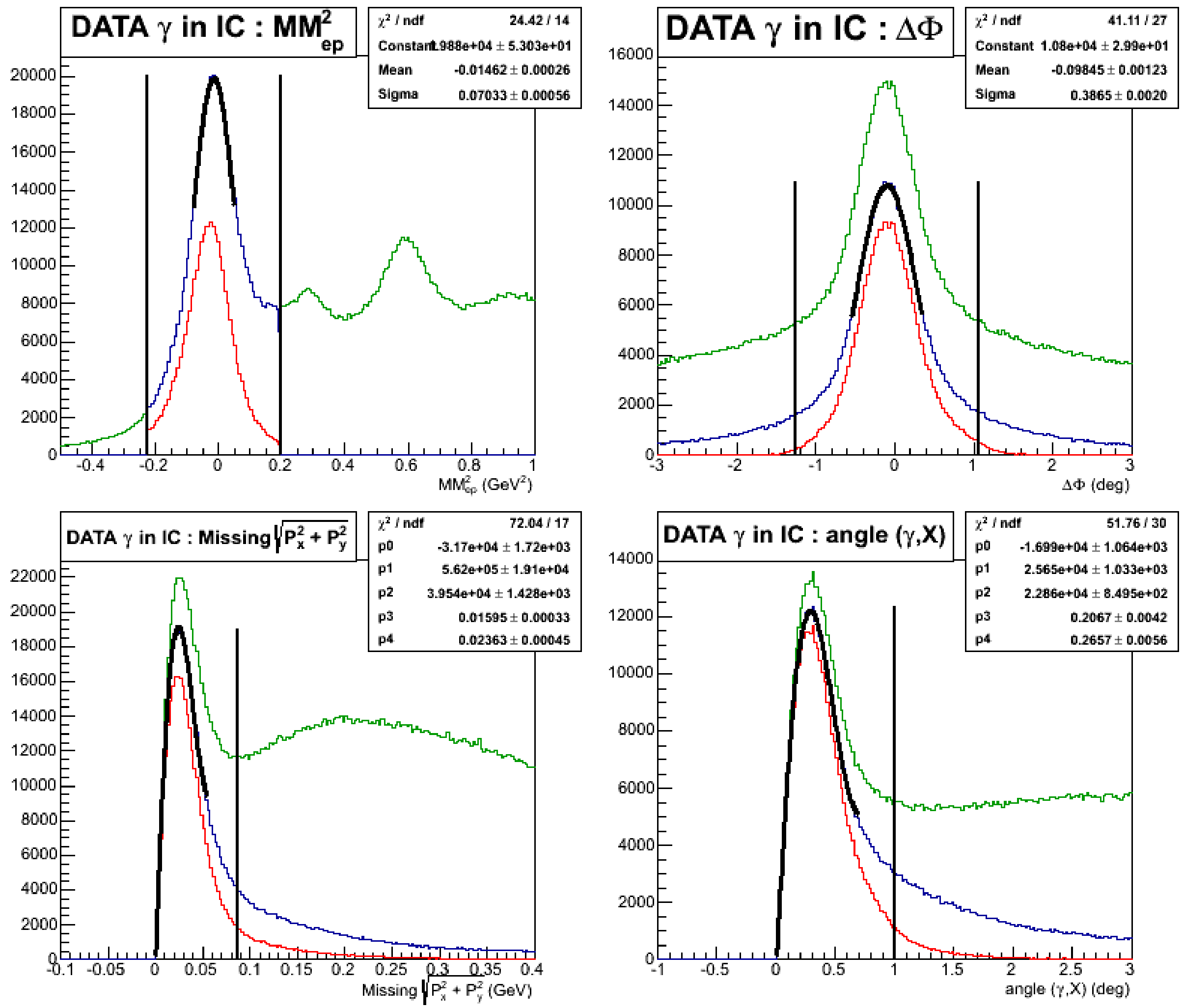
- Particle identification (e, p, γ) and selection of the ep→epγ events
- Subtraction of the background coming from the $ep\to ep\pi^0\to ep\gamma(\gamma)$ reaction: $N_{ep\to ep\gamma}$ - $N_{ep\to ep\pi 0\to ep\gamma(\gamma)}$
- Calculation of the integrated luminosity: Lum
- Calculation of the acceptance using Monte Carlo simulations: Acc
- Calculation of the bin volume correction: F_{vol} (bin volume = $\Delta Q^2 \Delta x_2 \Delta t \Delta \Phi$)
- Radiative corrections: F_{rad}
- Determination of various efficiencies: F_{eff}

The kinematics of the DVCS reaction is defined by 4 independent variables : Q^2, x_B, t and ϕ

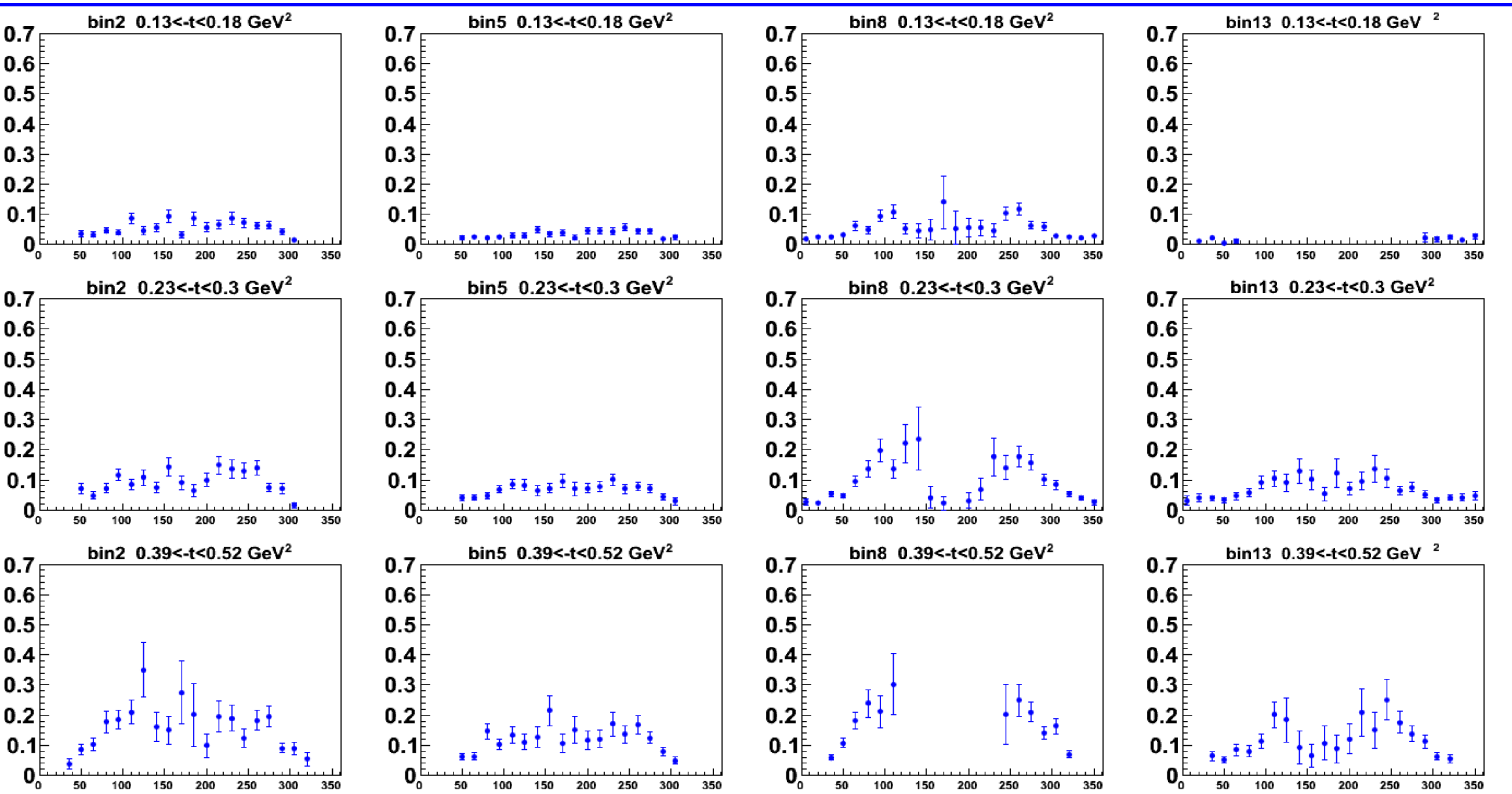
4-dimensional bins = (Q^2, x_B , -t, ϕ)



Selection of the ep→epγ events

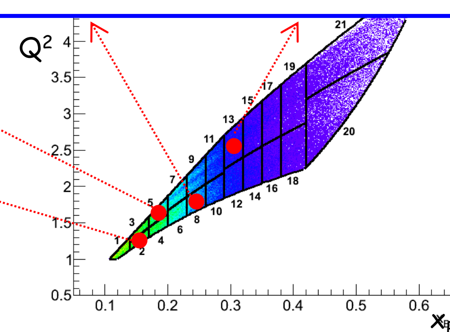


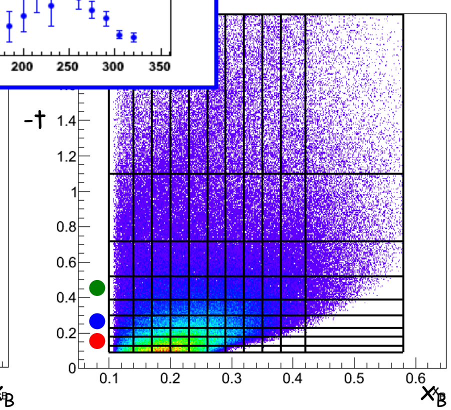
π^0 contamination fraction



$$\frac{N_{ep \to ep\pi^0 \to ep\gamma(\gamma)}}{N_{ep \to ep\gamma}}$$

with $N_{ep \to ep\pi^0 \to ep\gamma(\gamma)} = N_{\pi^0\ DATA} \times \dfrac{Acc^{1\gamma}_{\pi^0\ MC}}{Acc^{2\gamma}_{\pi^0\ MC}}$





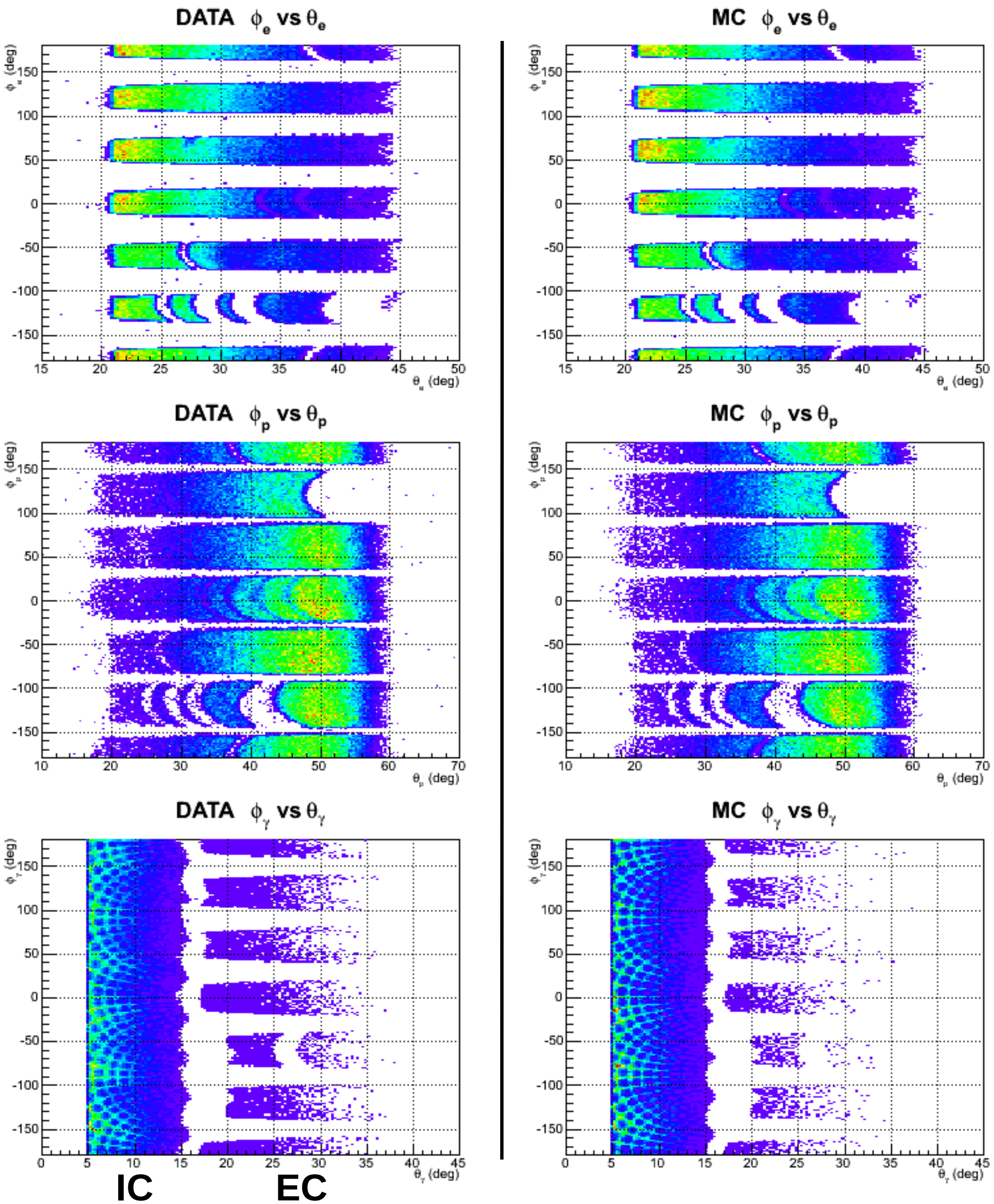
Averaged over all the bins,
π^0 contamination fraction is ~9%

Comparison between data and Monte Carlo simulations

electron

proton

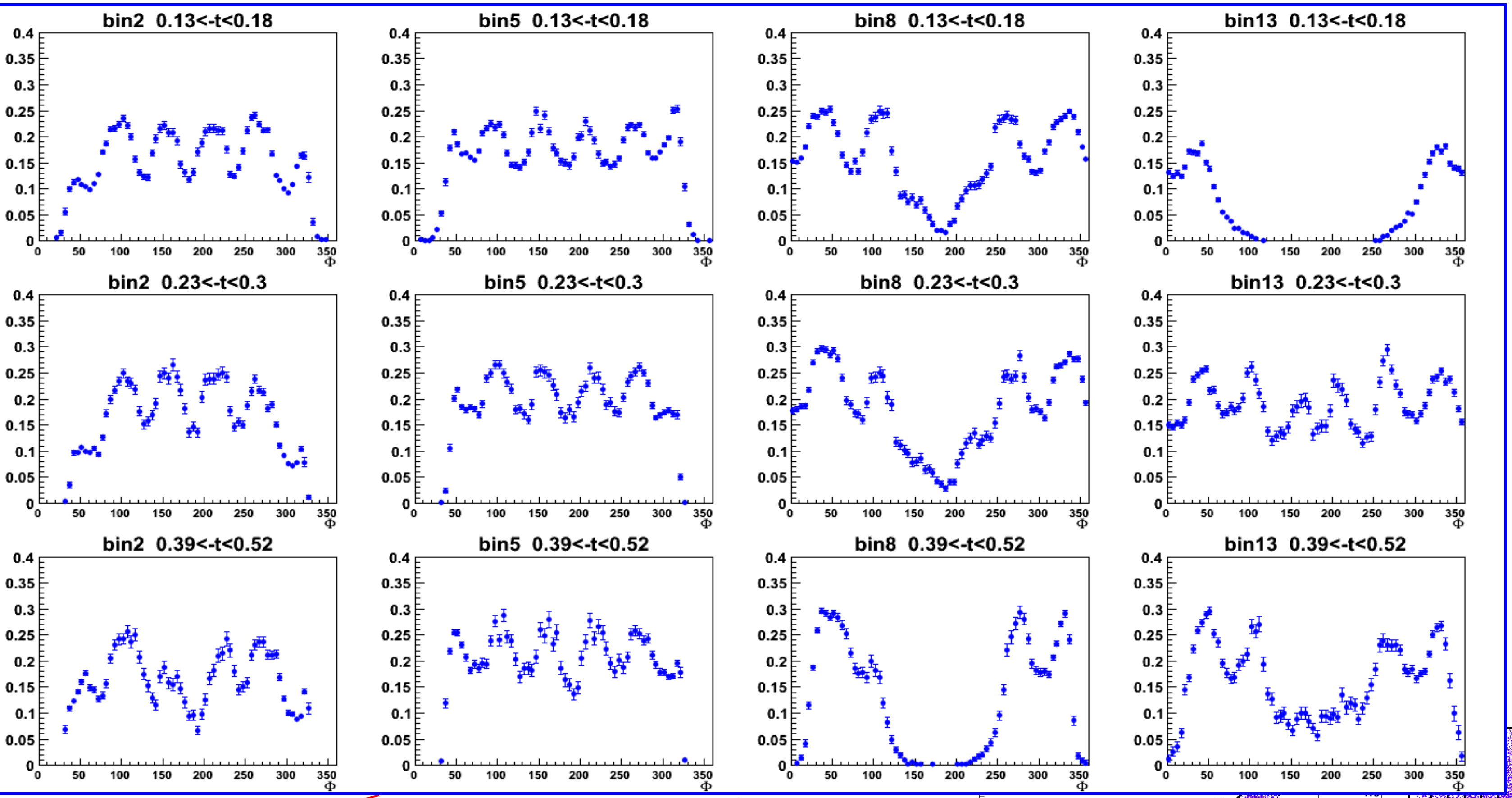
photon

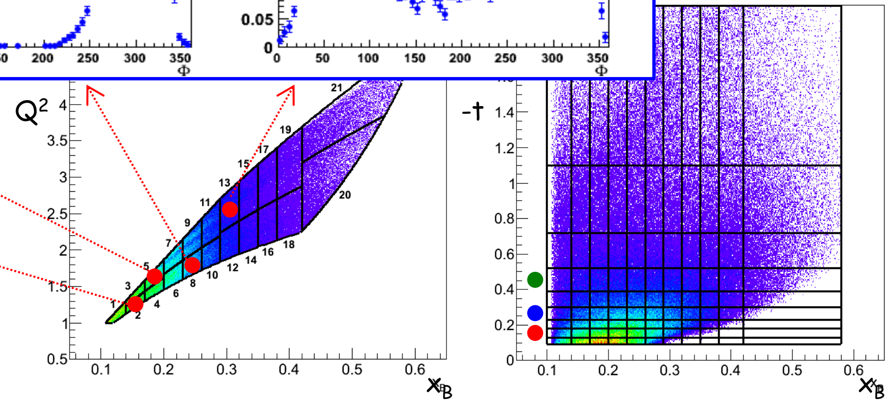


ϕ vs θ distributions for the three particles of the final state

Numerous fiducial cuts applied to reach good agreement between data and simulations

Acceptances: correction event by event with 72 bins in Φ

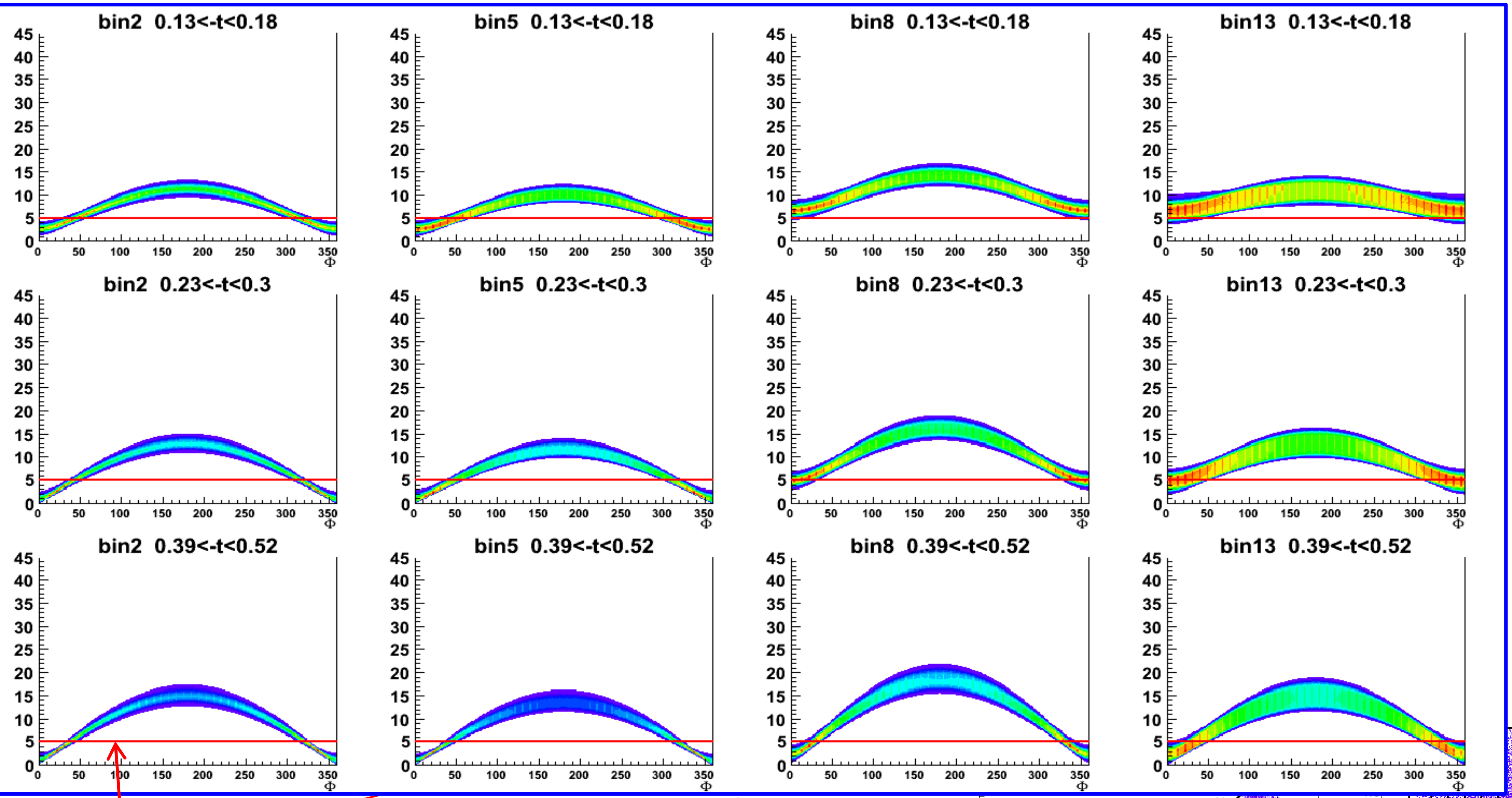




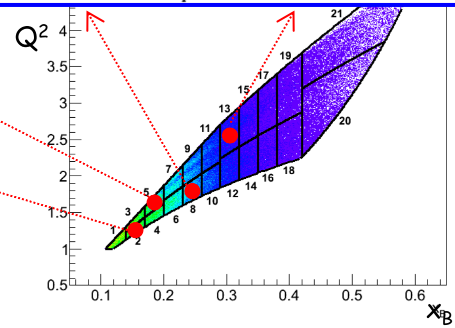
More than 200 million events simulated in total

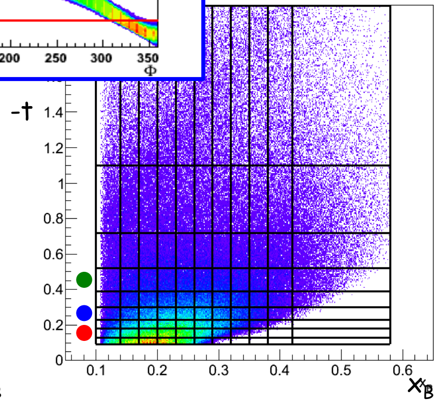
Averaged over all the bins, acceptance is ~14%

Correlation between the photon polar angle θ_γ and Φ



θ_γ vs Φ





Photon acceptance begins at θ_γ = 5 deg:
at certain kinematics, no data available at low Φ

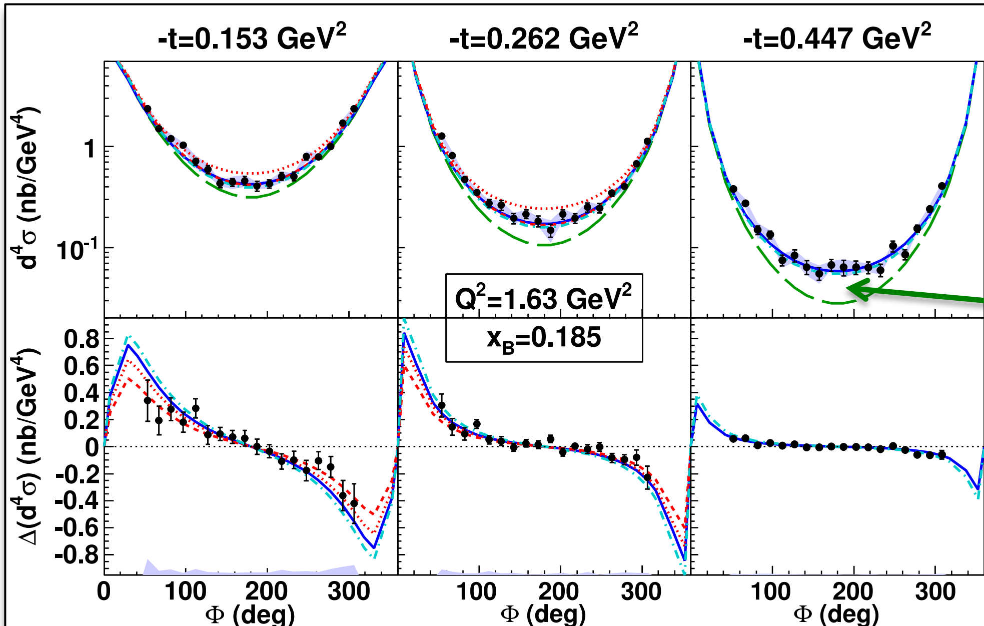
Systematic uncertainties

Systematic uncertainties are ~14% on average for the unpolarized cross section

Sources of uncertainties include among others:

- Acceptance calculation (using two different $ep \to ep\gamma$ event generators)
- Beam energy / kinematic corrections
- Exclusivity cuts (event selection)
- π^0 background subtraction (using two different $ep \to ep\pi^0$ event generators)

Unpolarized and beam-polarized cross sections

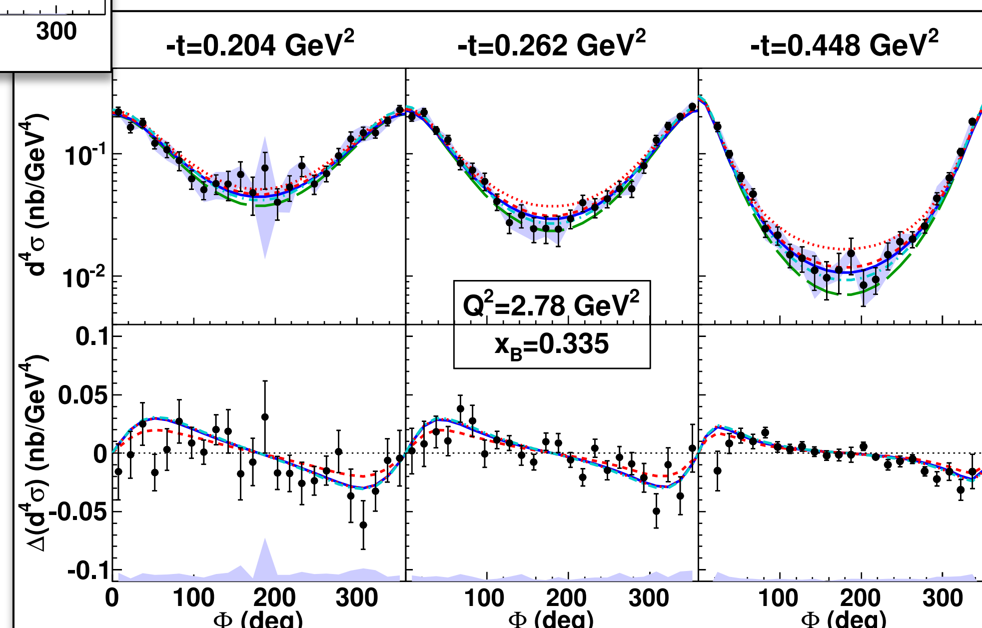


H.S. Jo *et al.* (CLAS Collaboration), Phys. Rev. Lett. 115, 212003 (2015)

$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}(nb/GeV^4)$$

DVCS + interference

$$\frac{1}{2}\left(\frac{d^4\overrightarrow{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} - \frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}\right)(nb/GeV^4)$$



BH
VGG (H only)
KMS
KM10
KM10a

VGG : Vanderhaeghen, Guichon, Guidal

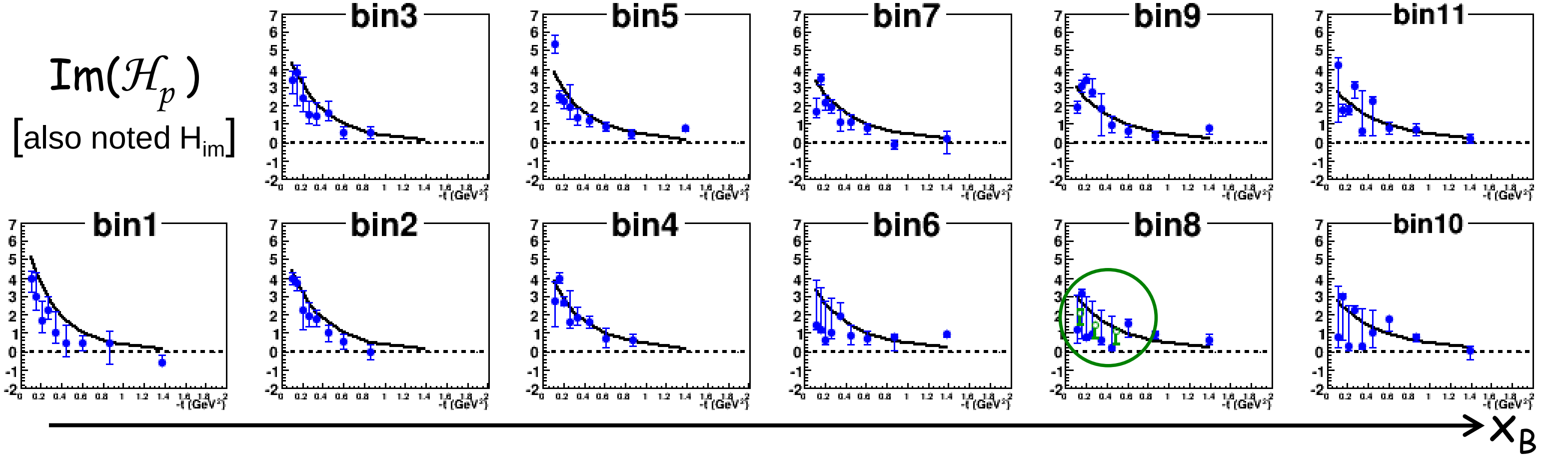
KMS : Kroll, Moutarde, Sabatie

KM : Kumericki, Mueller

Good agreement with standard GPD models (VGG, KMS, KM10a)

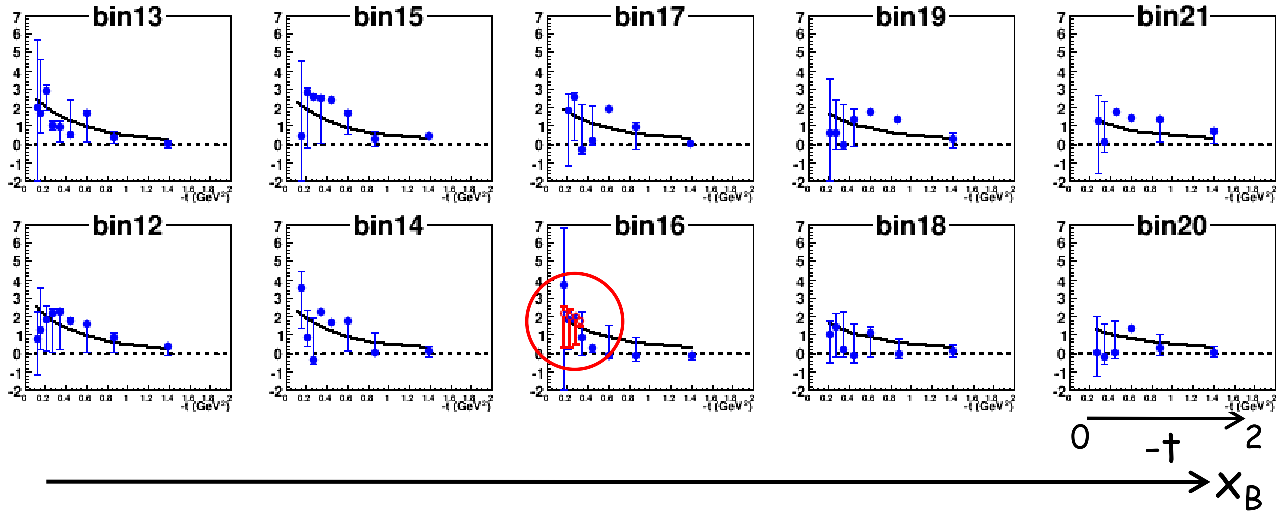
Extraction of CFFs from the cross sections

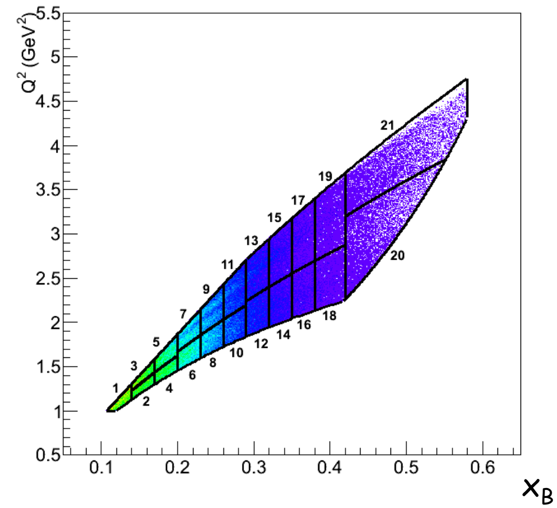
$\mathrm{Im}(\mathcal{H}_p)$
[also noted H_{im}]



CFF fits
(by M. Guidal)
using:
the results of this work
Hall A σ and Δσ
CLAS previous results

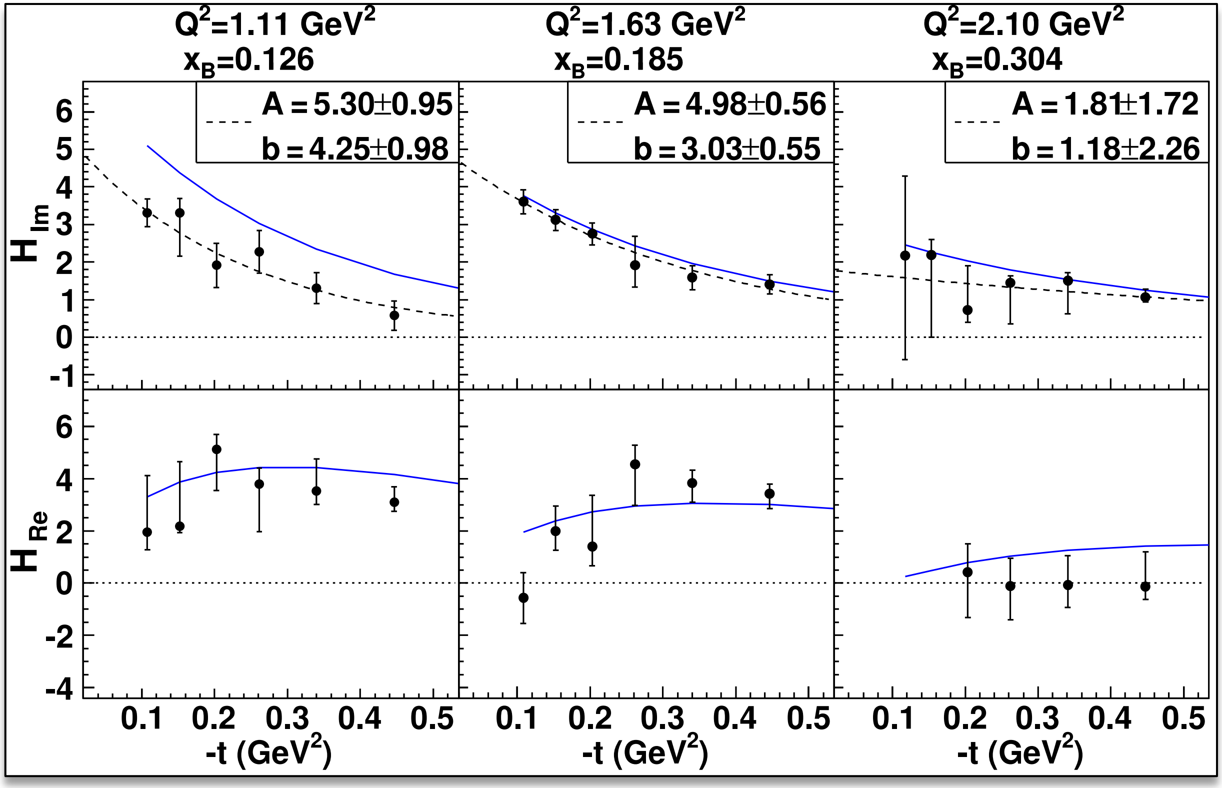
— VGG predictions





- The t-slope becomes flatter with increasing x_B
- The results of this work have a large impact in terms of kinematic coverage, statistics, and constraints provided to theoretical models

Interpretation of CFF fit results obtained from the cross sections



CFF fits by M. Guidal

b : transverse position of the quarks in the nucleon

- - - *Fits with function Ae^{bt}*

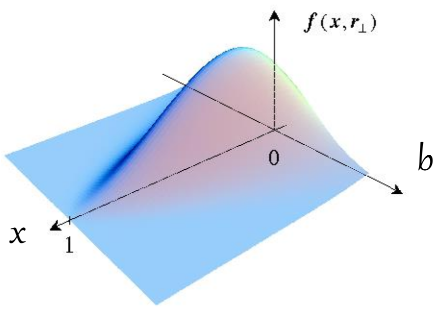
VGG predictions

H.S. Jo *et al.* (CLAS Collaboration), Phys. Rev. Lett. 115, 212003 (2015)

x_B

The transverse position *b* decreases with increasing x_B

The results tend to show that
valence quarks (high x) are at the heart of the nucleon
and sea quarks (low x) extend to its periphery



Summary

- Extraction of DVCS unpolarized and beam-polarized cross sections in the largest kinematic domain ever explored in the valence quark region
- Results are in good agreement with standard GPD model predictions (VGG, KM10a) and will provide strong constraints over a wide kinematic domain
- Extraction of Compton Form Factors by fitting simultaneously these unpolarized and beam-polarized cross sections gives a large set of results in a very wide kinematic domain
- Results suggest that the nucleon size increases at lower parton-momentum values, thus revealing from the experiment a “tomographic” image of the nucleon

Thank you