Deeply virtual Compton scattering cross sections with CLAS and generalized parton distributions

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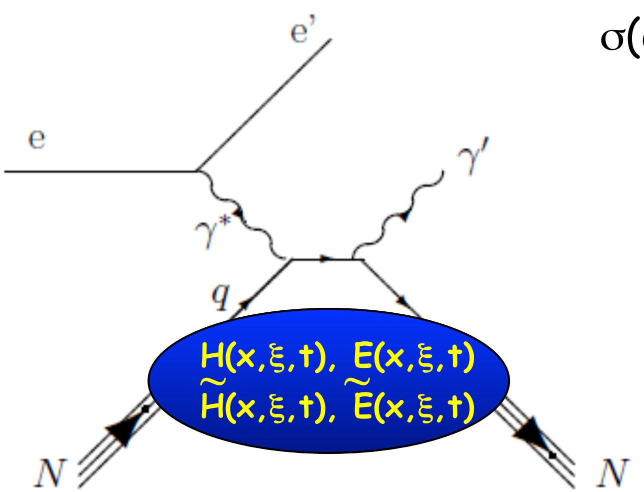
Deeply Virtual Compton Scattering (DVCS)

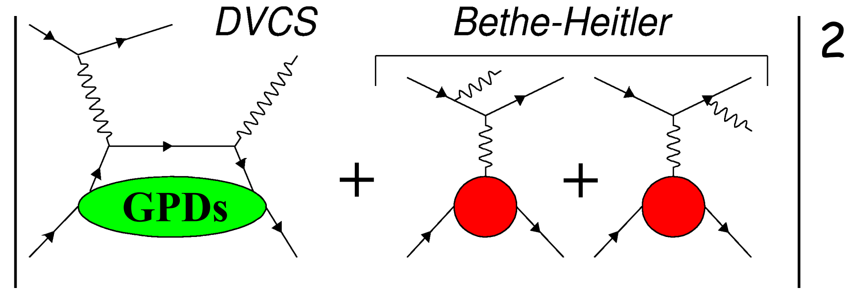
"handbag" diagram (high Q^2, small t, fixed x_B)

DVCS



BH fully calculable in QED

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



DVCS and Bethe-Heitler (BH) experimentally undistinguishable

interference between the 2 processes

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

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

Unpolarized Cross Section

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

Polarized Cross Section difference

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

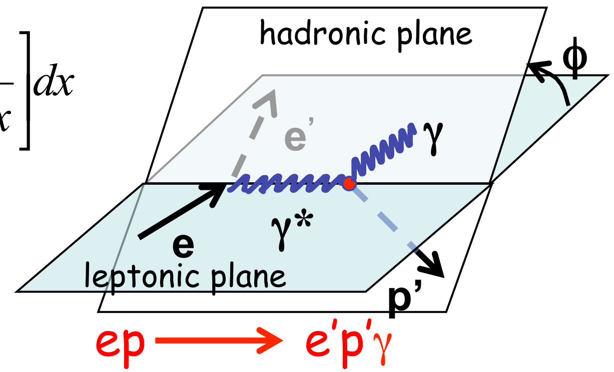
$\mathrm{Im}(T_{DVCS}) \rightarrow H(\pm\xi,\xi,t) + \ldots$, with $x = \pm\xi$

→ Linearly proportional to the imaginary part of the DVCS amplitude, and therefore to GPDs

Extracting GPDs from DVCS observables

Compton Form Factors (CFFs)

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



Beam Spin Asymmetry : $A_{LU} = \frac{d\vec{\sigma} - d\overleftarrow{\sigma}}{d\vec{\sigma} + d\overleftarrow{\sigma}} = \frac{\Delta\sigma_{LU}}{d\vec{\sigma} + d\overleftarrow{\sigma}}$

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

Proton	Neutron

- Polarized beam, Unpolarized target

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

- Unpolarized beam, Longitudinally polarized target

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

- Unpolarized beam, Transversely polarized target

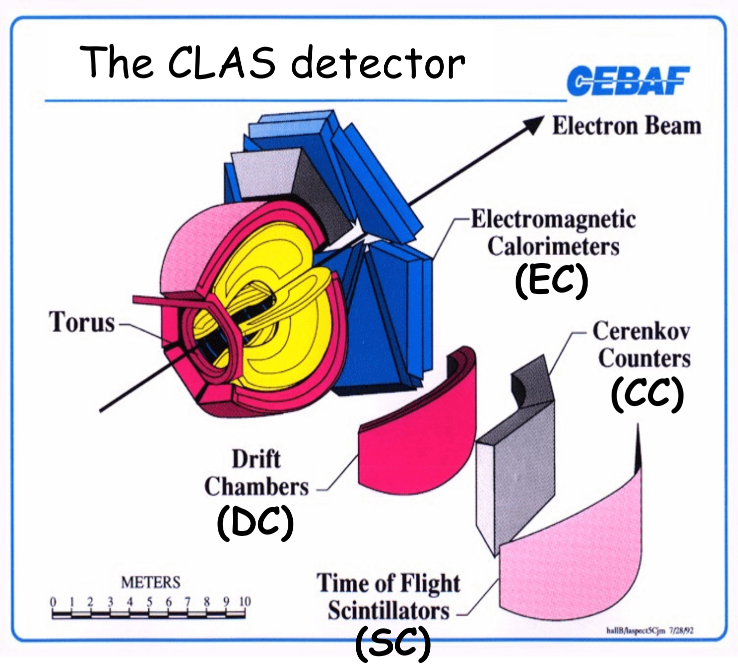
$\Delta\sigma_{UT} \sim \cos\phi\ Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

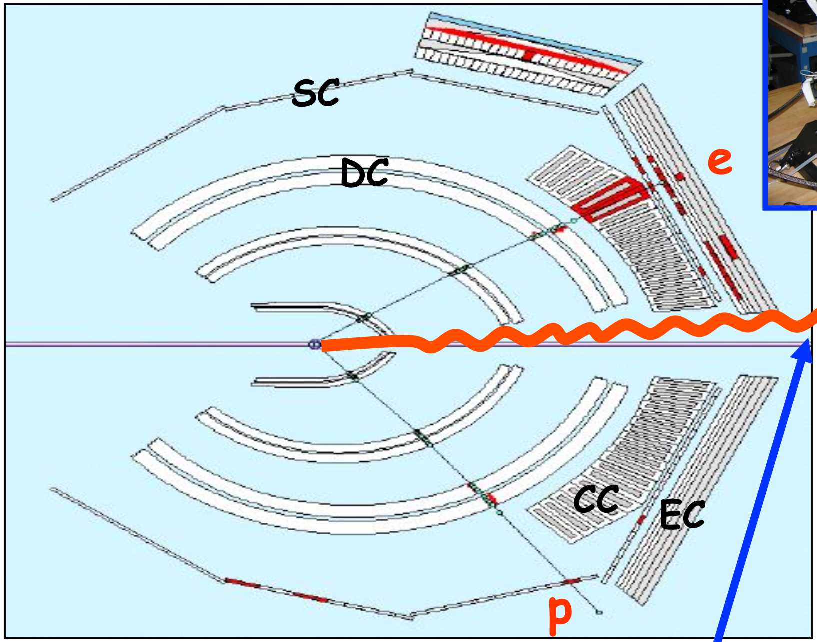
- Polarized beam, Longitudinally polarized target

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

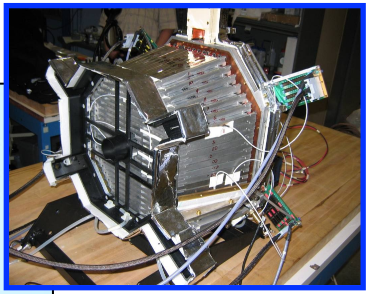
e1-DVCS-1 experiment

- Data taken from March to May 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

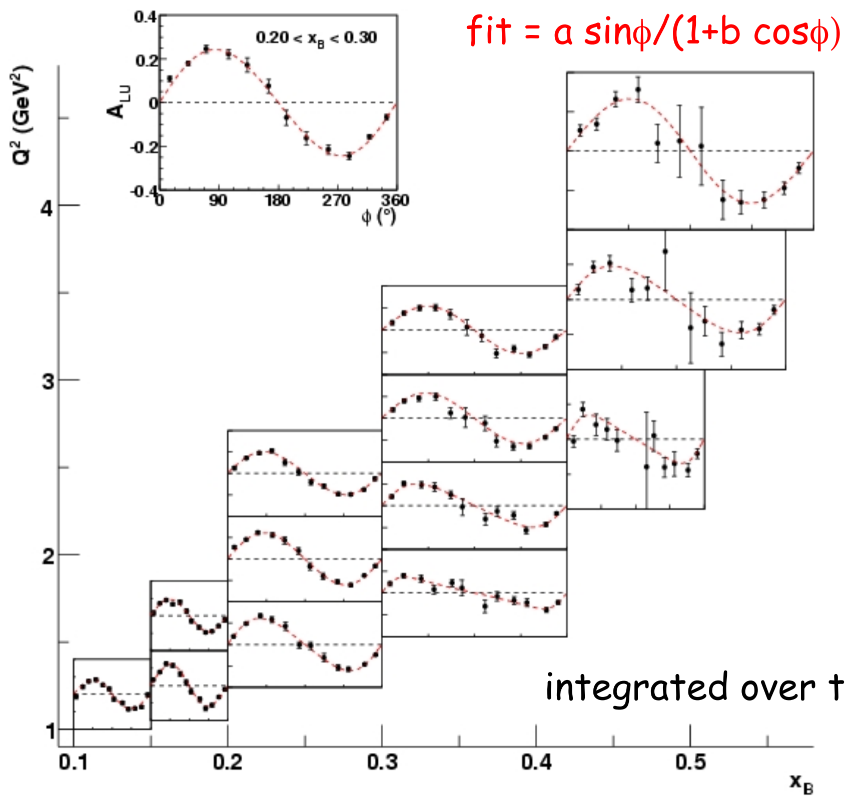


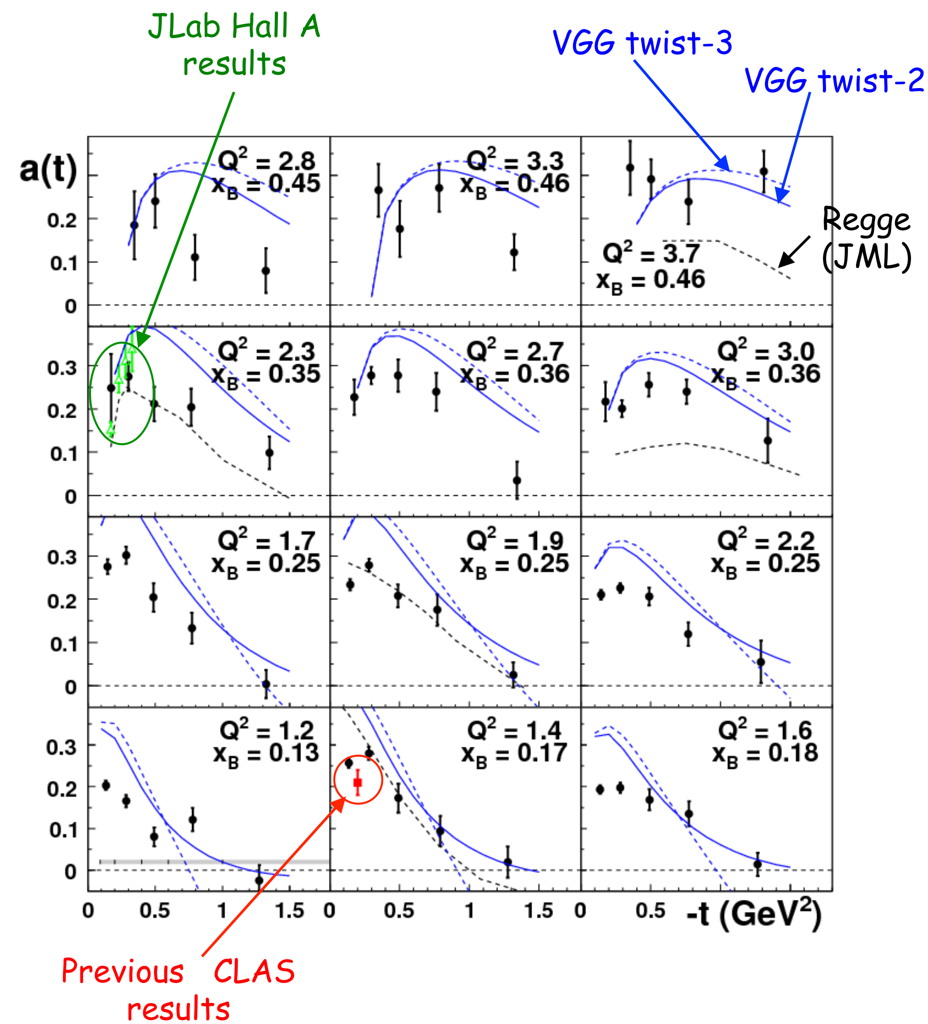
The DVCS/BH photon (mainly emitted to the forward angles) can hardly be detected with CLAS alone

e1-DVCS-1 : DVCS Beam Spin (A_{LU}) asymmetries

A_{LU} on the proton

fit = a sinϕ/(1+b cosϕ)





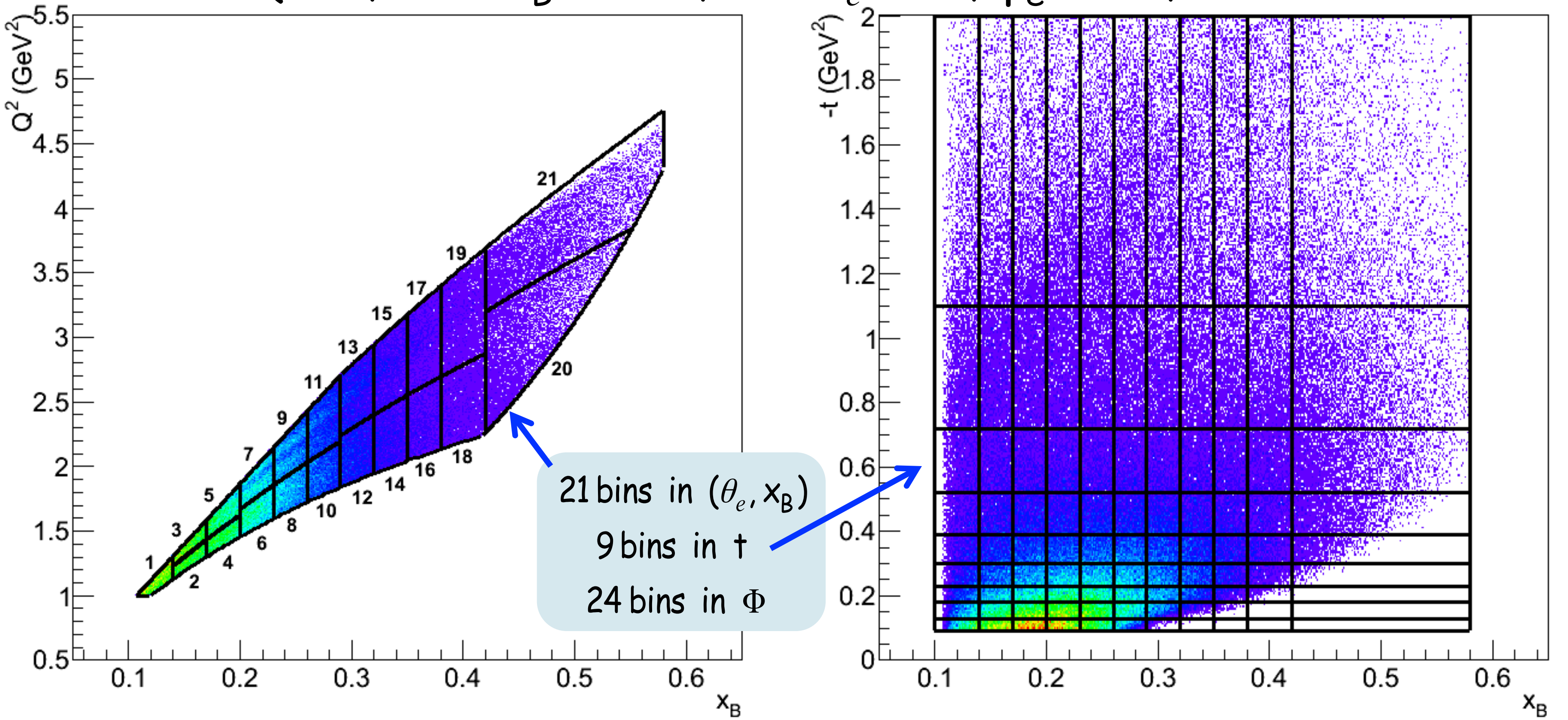
F.X. Girod *et al.* (CLAS Collaboration), Phys. Rev. Lett. 100, 162002 (2008)

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

VGG model: Vanderhaeghen,Guichon,Guidal

Kinematic coverage and observables

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



Extraction of 4-fold cross sections

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

DVCS cross section analysis

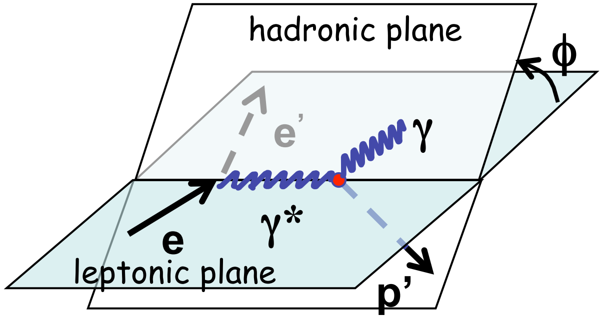
Extraction of 4-fold cross sections of the ep→epγ reaction

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

- Particle identification (e, p, γ) and selection of the ep→epγ events
- Subtraction of the background coming from the ep→epπ^0→epγ(γ) 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)



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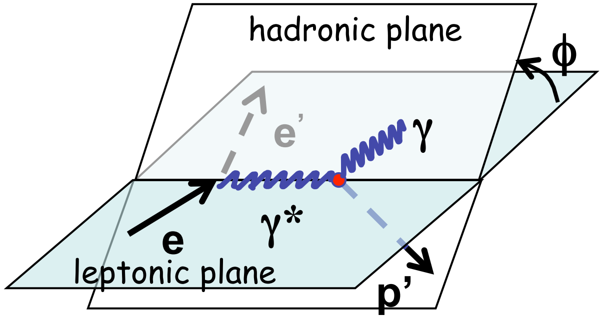
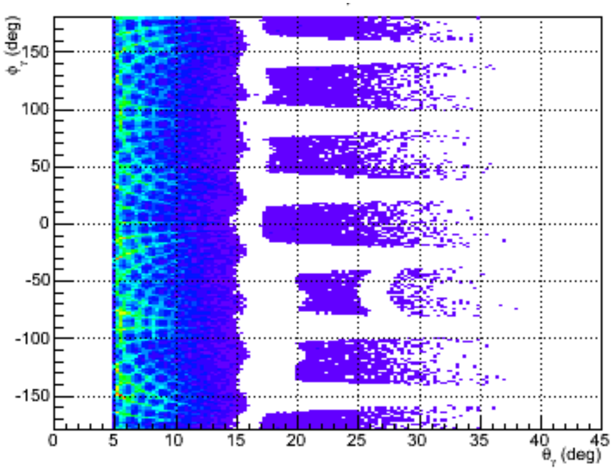


Selection of the ep→epγ events

Photon : θ vs φ

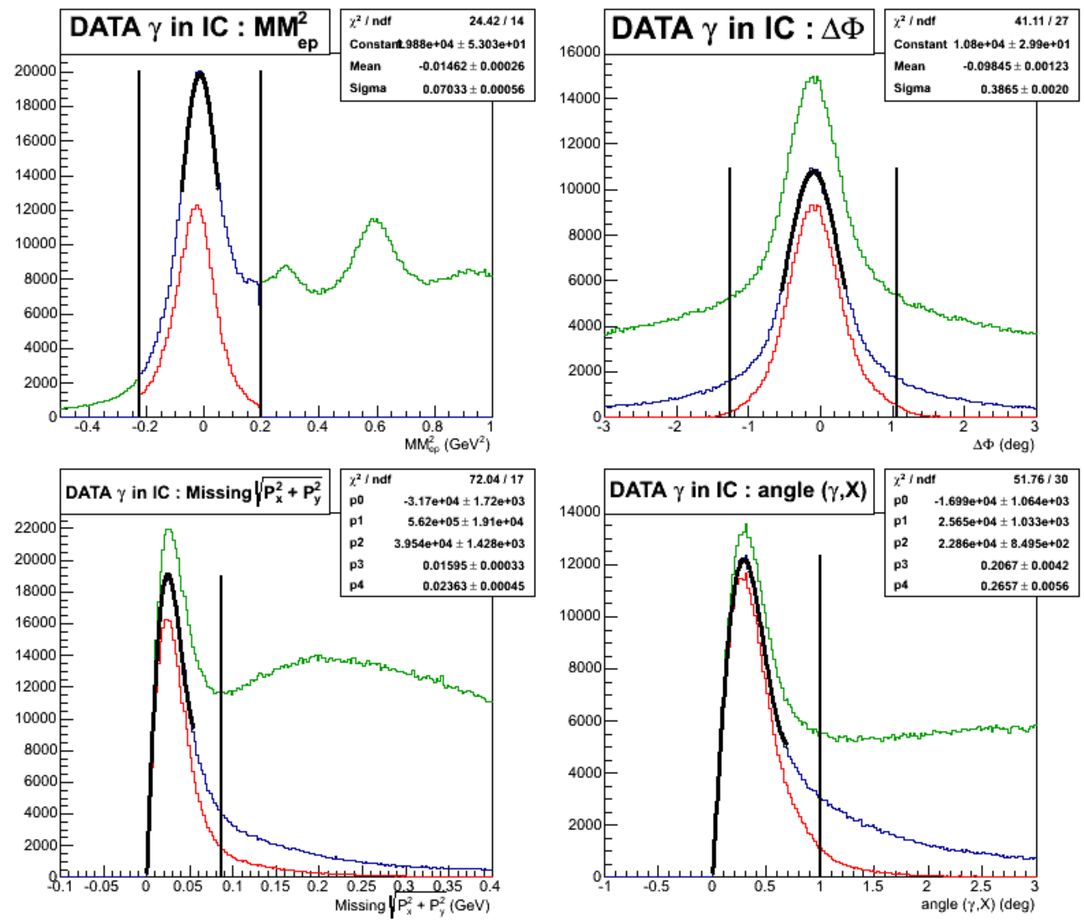


IC

~~EC~~

Discarded in this analysis because of too large uncertainties

ep→epγ exclusivity cuts in the case where the photon is detected in the IC



DVCS cross section analysis

Extraction of 4-fold cross sections of the $ep \rightarrow ep\gamma$ reaction

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

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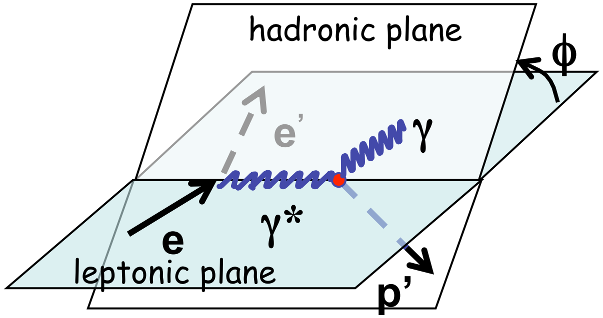
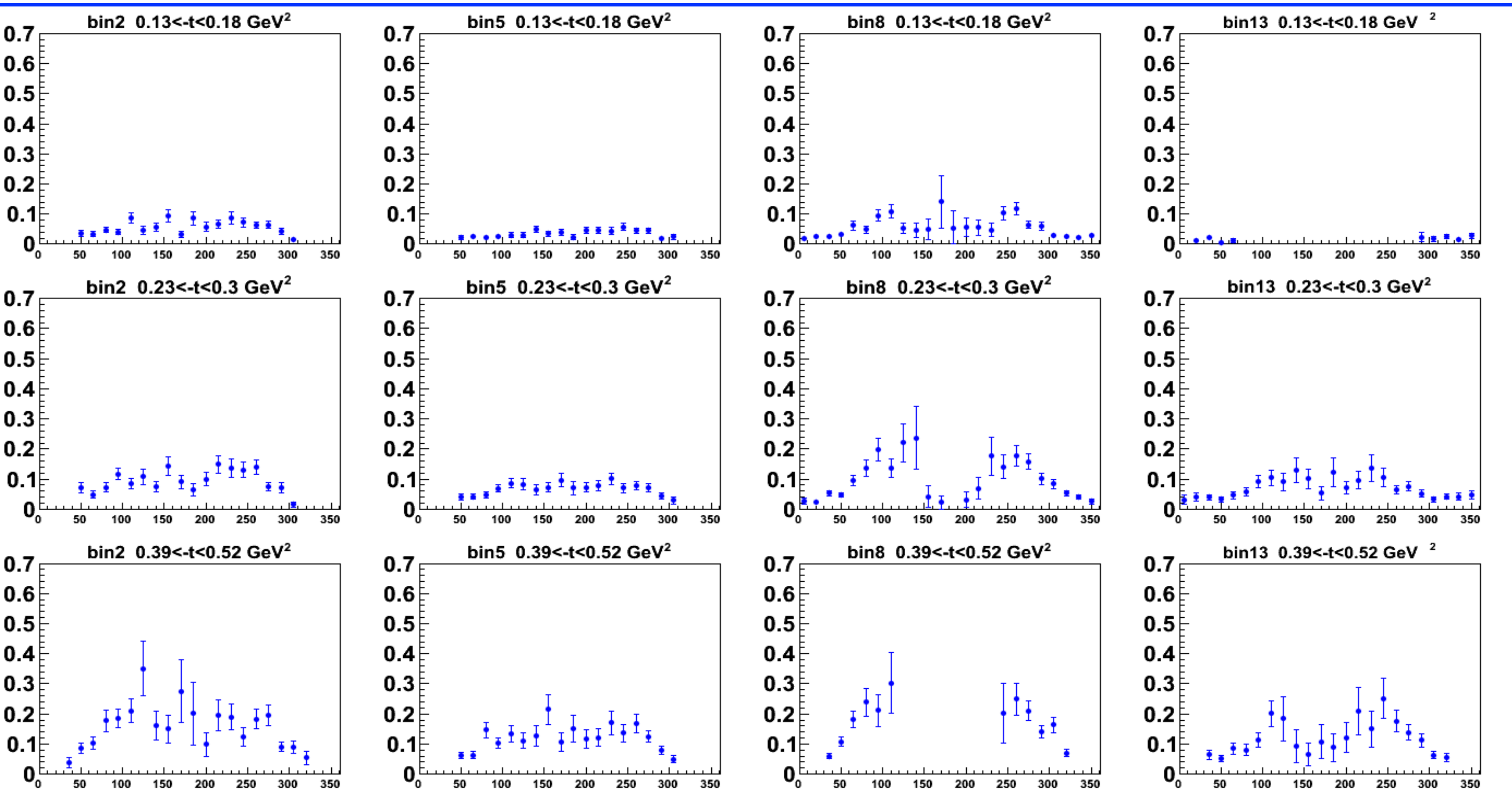
4-dimensional bins = (Q^2, x_B , -t, ϕ)

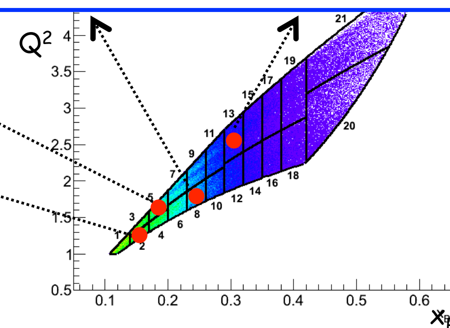


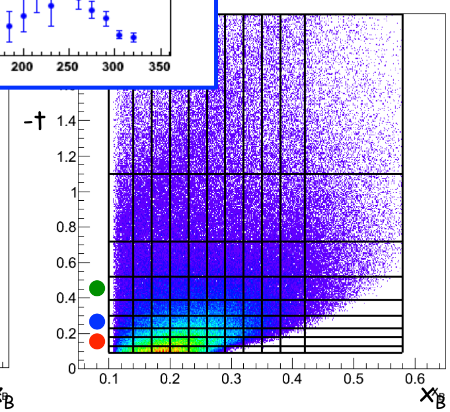
π^0 contamination fraction



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

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





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

DVCS cross section analysis

Extraction of 4-fold cross sections of the $ep \rightarrow ep\gamma$ reaction

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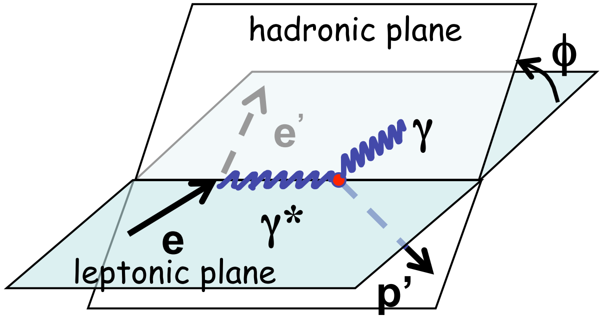
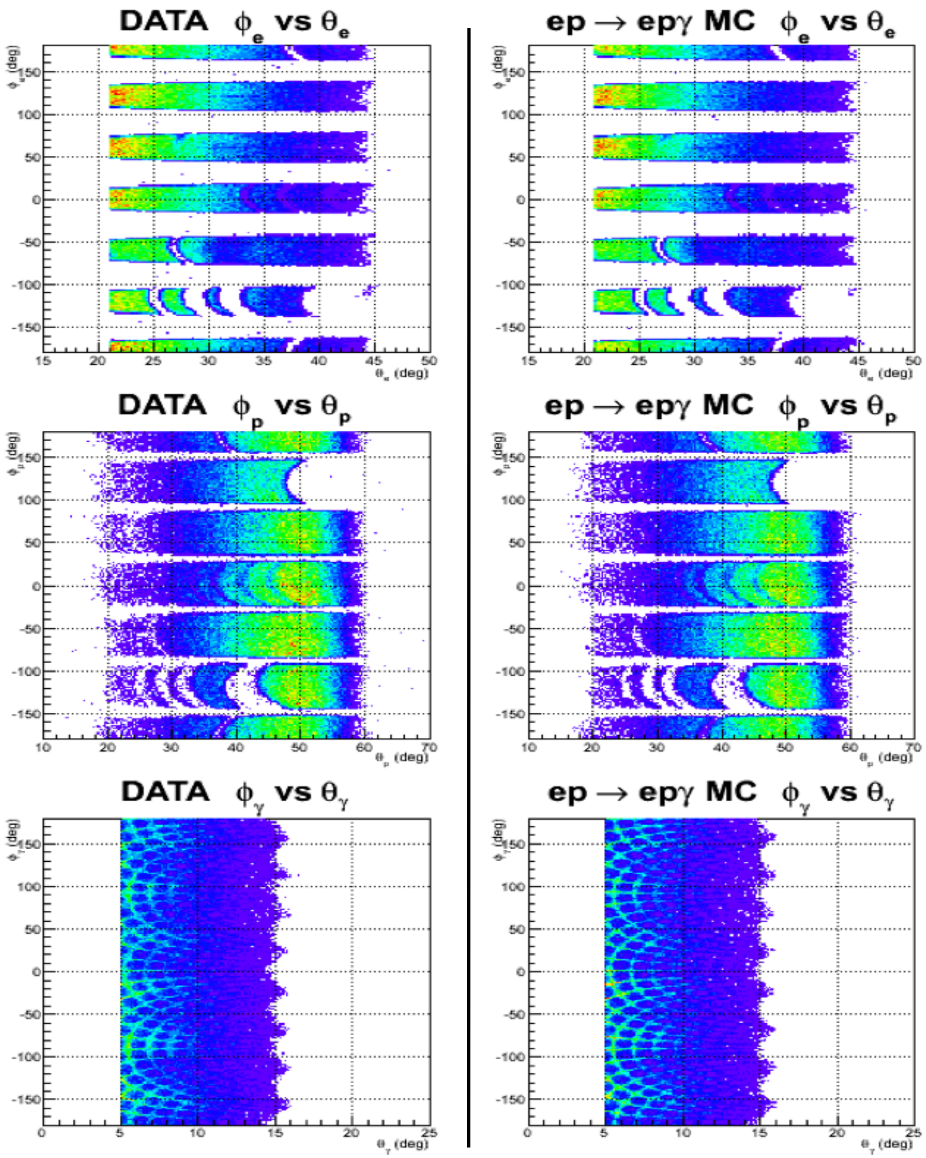


Comparison between data and Monte Carlo

electron

proton

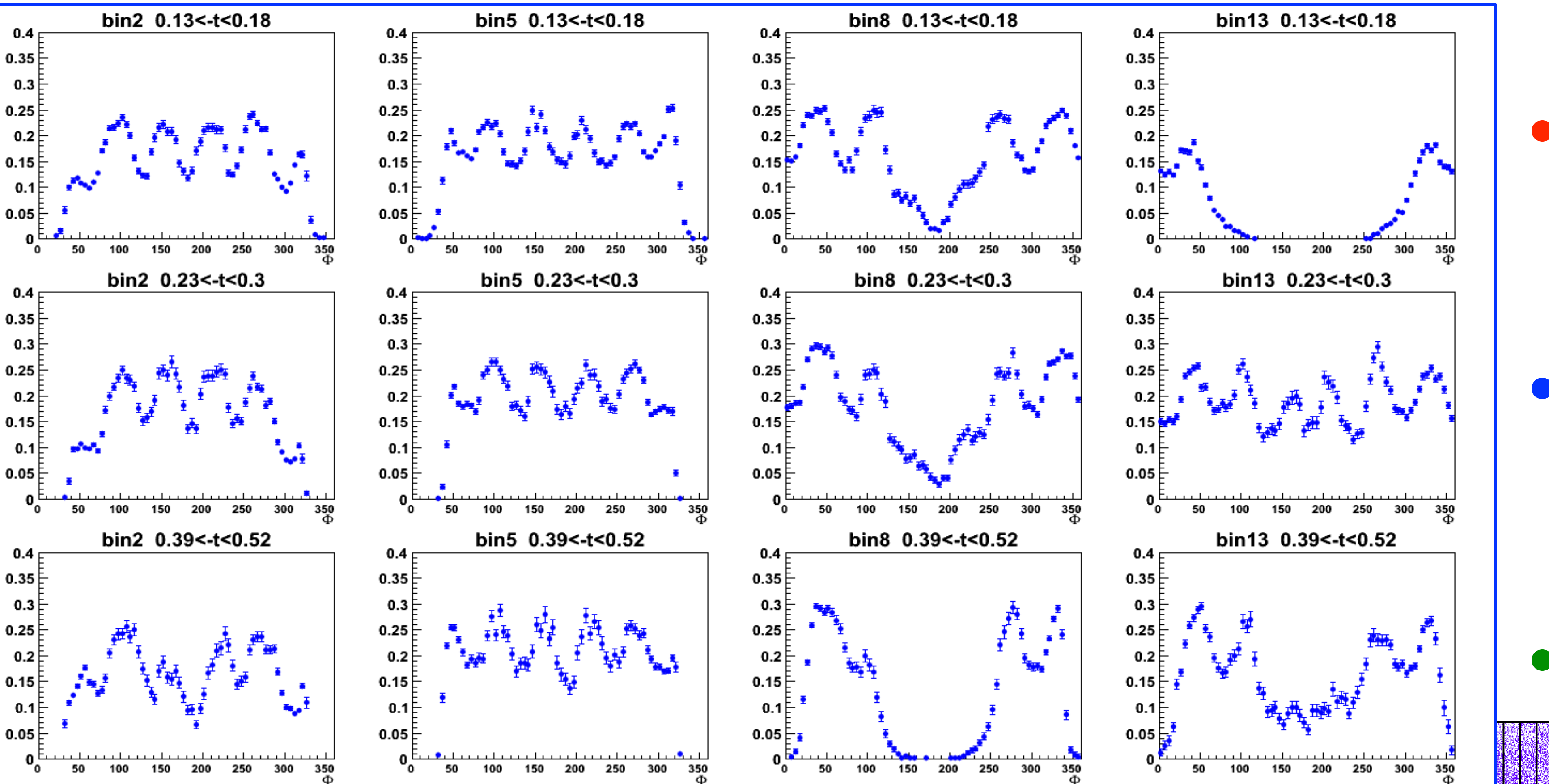
photon

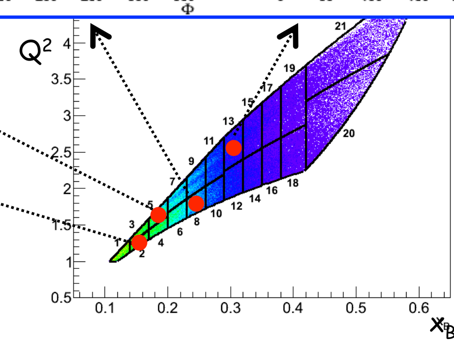


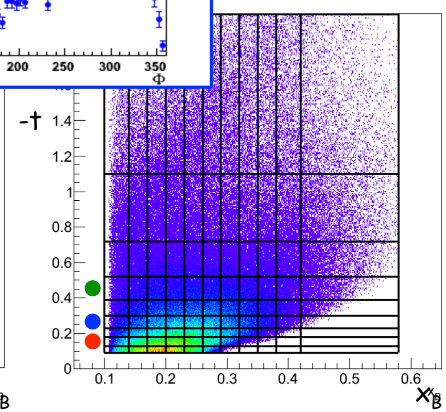
ϕ vs θ distributions for the three particles of the final state

Numerous fiducial cuts applied to reach good agreement between data and Monte Carlo

Acceptances : correction event by event with 72 bins in Φ

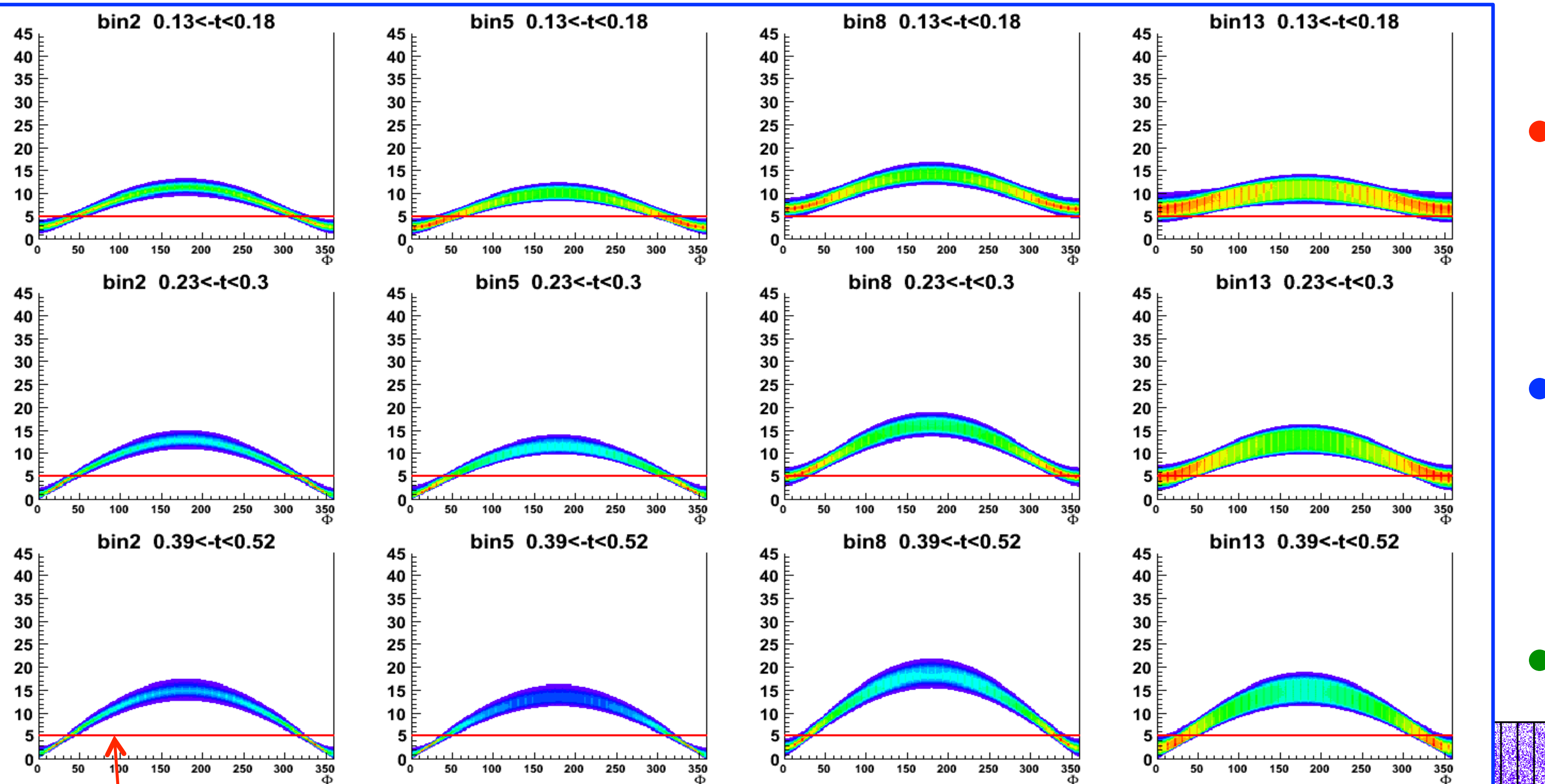




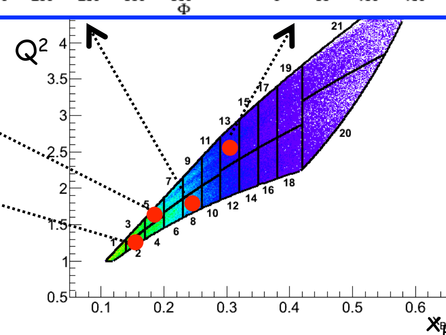


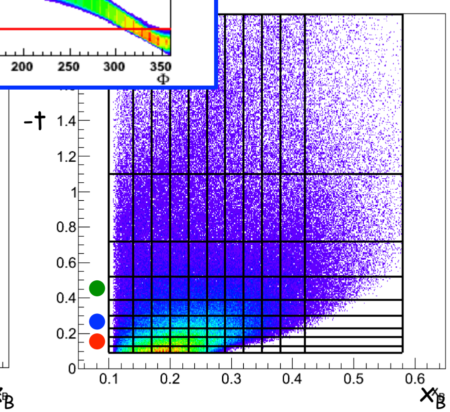
Averaged over all the bins, acceptance is ~17%

Correlation between the photon polar angle θ_γ and Φ



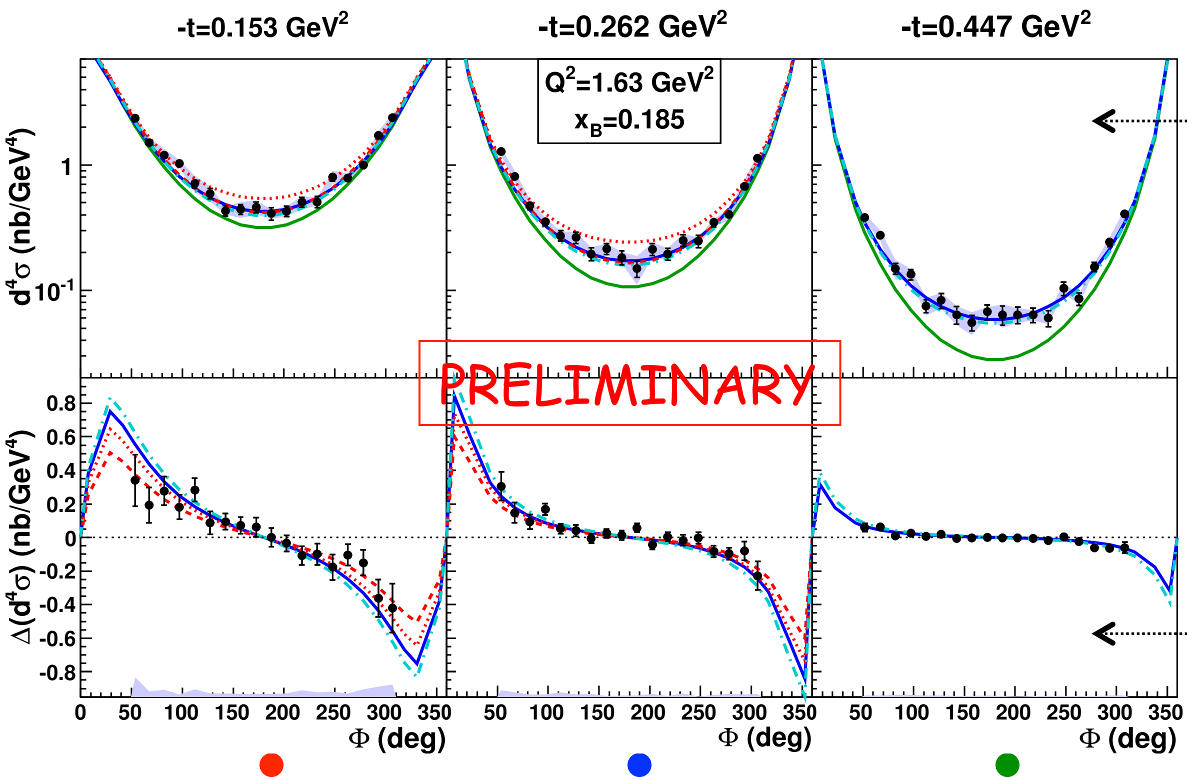
θ_γ vs Φ





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

Unpolarized cross sections and polarized cross-section differences (1)



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

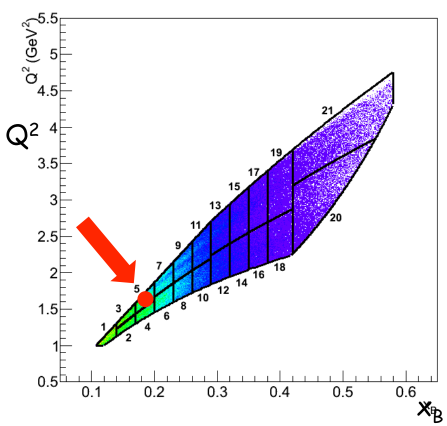
- BH
- VGG (H only)
- KMS
- KM10a
- KM10

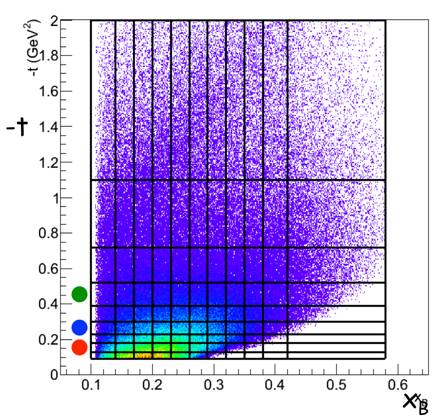
VGG : Vanderhaeghen, Guichon, Guidal

KMS : Kroll, Moutarde, Sabatié

KM : Kumericki, Mueller

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

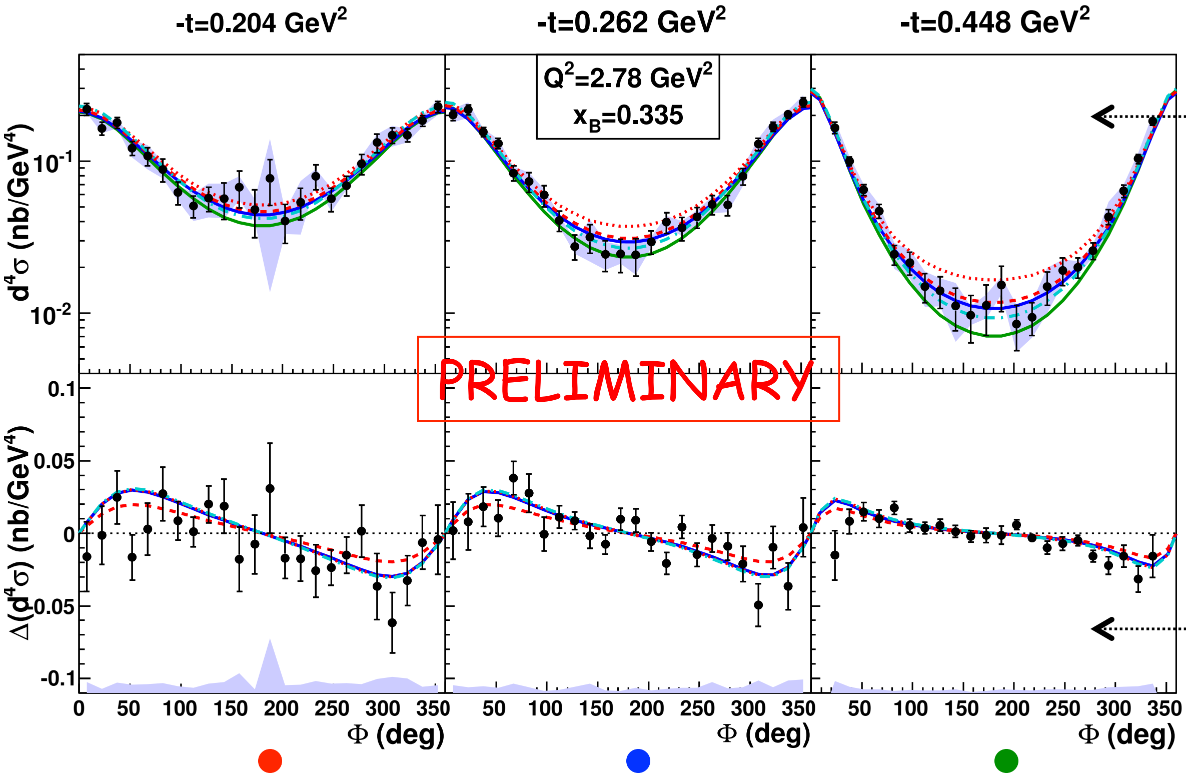




VGG, KMS, KM10a: standard GPD models, with the GPD H dominating in the cross section
KM10: addition of a very strong GPD $\tilde{H}$

The unpolarized cross-section results are in good agreement with the VGG, KMS, and KM10a predictions. Disagreement with KM10

Unpolarized cross sections and polarized cross-section differences (2)

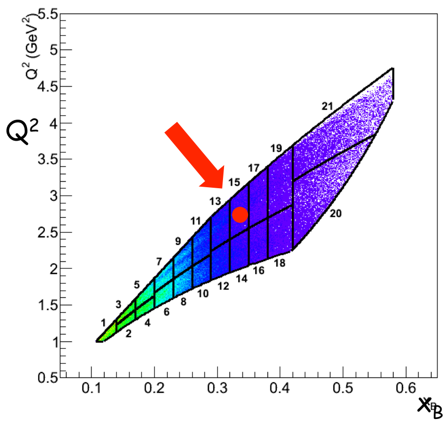


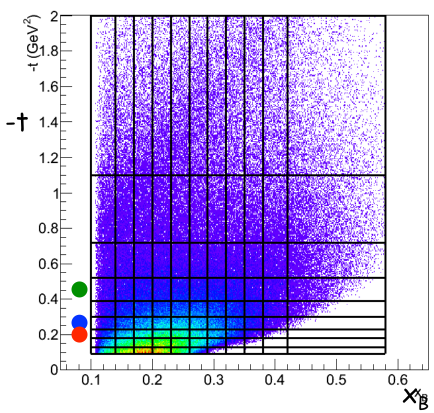
$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2dx_Bdtd\Phi}(nb/GeV^4)$$

- BH
- VGG (H only)
- KMS
- KM10a
- KM10

VGG : Vanderhaeghen, Guichon, Guidal
KMS : Kroll, Moutarde, Sabatié
KM : Kumericki, Mueller

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





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The unpolarized cross-section results are in good agreement with the VGG, KMS, and KM10a predictions. Disagreement with KM10

Systematic uncertainties

Averaged over all the bins, the total systematic uncertainties on the unpolarized cross section are ~14%

The sources of systematic uncertainties include:

- Particle selection ~1.6%
- Exclusivity cuts ~3.5%
- π^0 background subtraction ~1%
- Acceptance correction ~5.3%
- Beam energy and kinematic corrections ~5.7%
- Radiative corrections ~2.2%
- Efficiencies ~5%

Extraction of Compton Form Factors (CFFs)

$$\mathrm{Re}(\mathcal{H}) = P\int_0^1 dx\left[H(x,\xi,t) - H(-x,\xi,t)\right]C^+(x,\xi)$$

$$\mathrm{Re}(\mathcal{E}) = P\int_0^1 dx\left[E(x,\xi,t) - E(-x,\xi,t)\right]C^+(x,\xi)$$

$$\mathrm{Re}(\tilde{\mathcal{H}}) = P\int_0^1 dx\left[\tilde{H}(x,\xi,t) + \tilde{H}(-x,\xi,t)\right]C^-(x,\xi)$$

$$\mathrm{Re}(\tilde{\mathcal{E}}) = P\int_0^1 dx\left[\tilde{E}(x,\xi,t) + \tilde{E}(-x,\xi,t)\right]C^-(x,\xi)$$

$$\mathrm{Im}(\mathcal{H}) = H(\xi,\xi,t) - H(-\xi,\xi,t)$$

$$\mathrm{Im}(\mathcal{E}) = E(\xi,\xi,t) - E(-\xi,\xi,t)$$

$$\mathrm{Im}(\tilde{\mathcal{H}}) = \tilde{H}(\xi,\xi,t) - \tilde{H}(-\xi,\xi,t)$$

$$\mathrm{Im}(\tilde{\mathcal{E}}) = \tilde{E}(\xi,\xi,t) - \tilde{E}(-\xi,\xi,t)$$

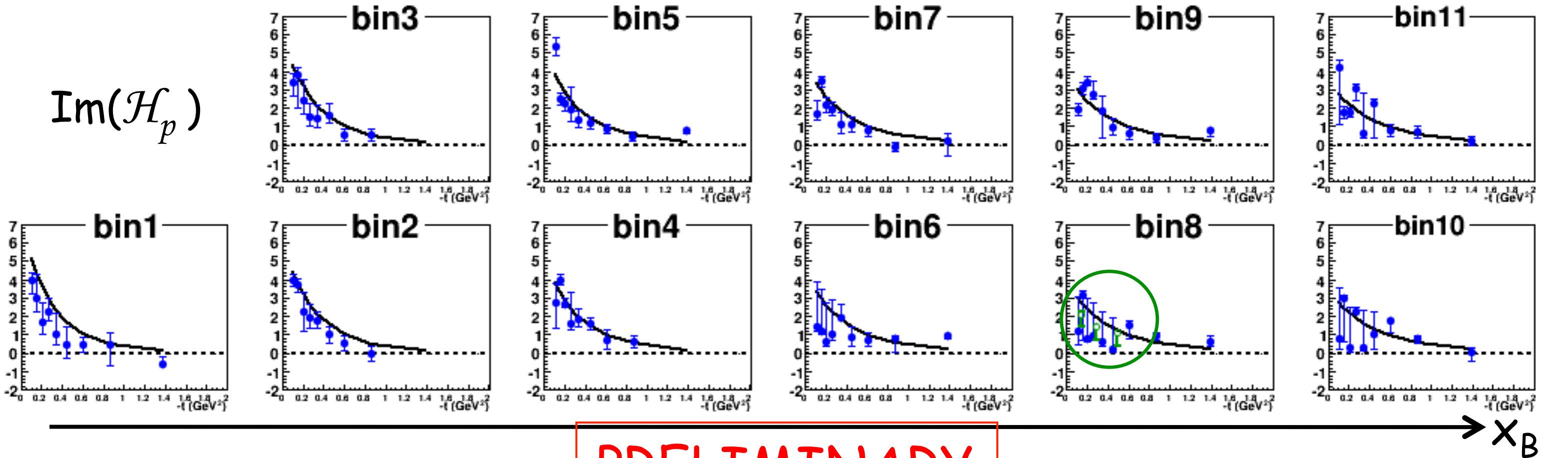
with $C^{\pm}(x,\xi) = \dfrac{1}{x-\xi} \pm \dfrac{1}{x+\xi}$

M. Guidal : model-independent local fit, at fixed Q^2, x_B and t of DVCS observables with MINUIT + MINOS

8 unknowns (the CFFs), non-linear problem, strong correlations

Bounding the domain of variation of the CFFs (5 x VGG)

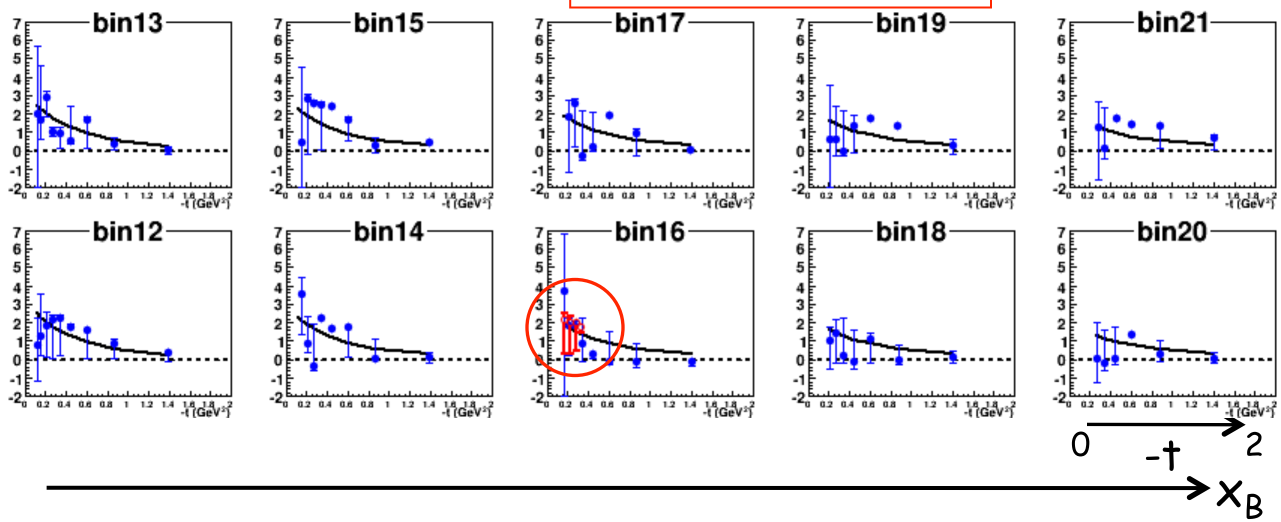
Extraction of CFFs from DVCS unpolarized and polarized cross sections

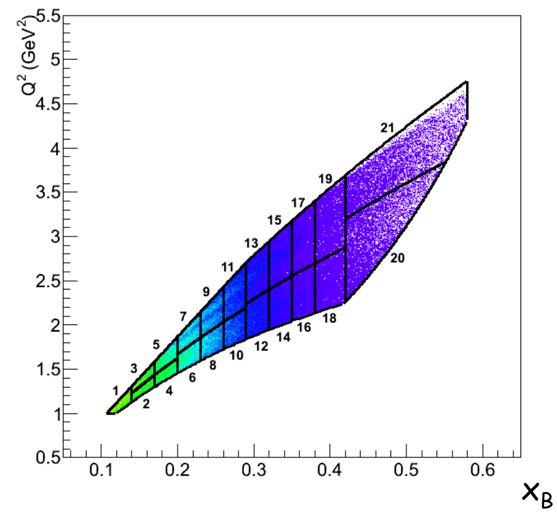


CFF fits (M. Guidal) using:
the results of this work
Hall A σ and $\Delta\sigma$
CLAS A_{LU} and A_{UL} (2006-2008)

— VGG predictions

PRELIMINARY





The t-slope becomes flatter with increasing x_B:
valence quarks (higher x_B) at the center of the nucleon and sea quarks (small x_B) at its periphery

Overview

- Extraction of DVCS unpolarized and polarized cross sections in the largest kinematic domain ever explored in the valence quark region

- Results are in good agreement with predictions from standard GPD models (VGG, KMS, KM10a), i.e., with a dominating GPD H, and will provide strong constraints over a wide kinematic domain

- Paper currently under collaboration review and to be submitted to journal in the upcoming weeks

- Extraction of Compton Form Factors by fitting simultaneously these unpolarized and polarized cross sections gives a large set of results in a very wide kinematic domain which provide a tomographic image of the nucleon (size as a function of parton momemtum)

Thank you