Transverse Extension of Partons in the Proton probed by DVCS

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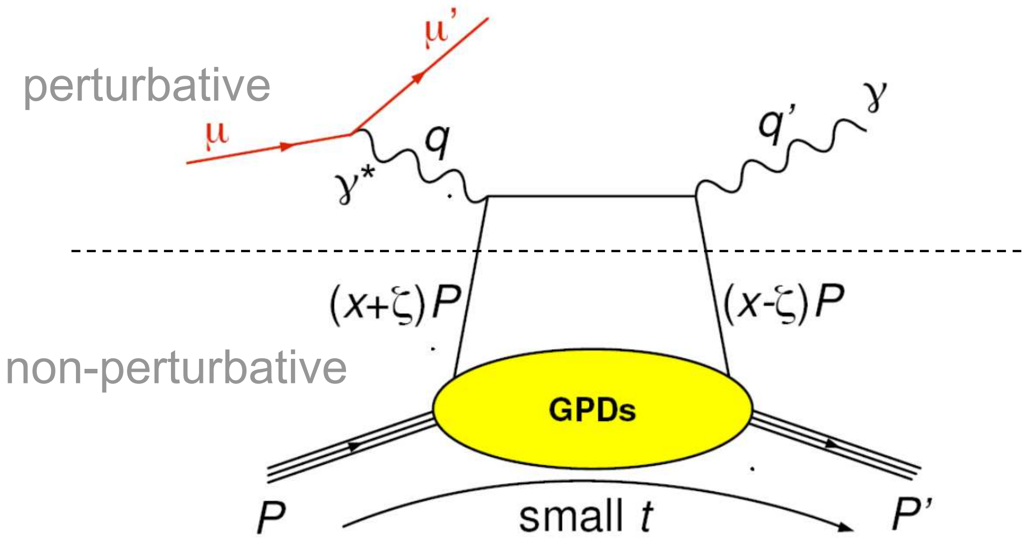
Contents

Generalised Parton Distributions (GPDs)

- Provide comprehensive description of 3-D partonic structure of the nucleon
  one of the central problems of non-perturbative QCD
- GPDs can be viewed as correlation functions between different partonic states
- 'Generalised' because they encompass 1-D descriptions by PDFs or by form factors

(the simplest) example: Deeply Virtual Compton Scattering (DVCS)

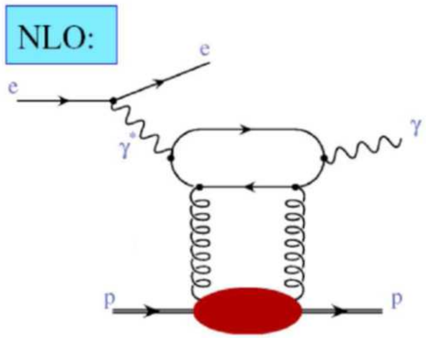


Factorisation for large Q^2 and | t | ‹‹ Q^2

4 GPDs for each quark flavour

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

for DVCS **gluons** contribute at higher orders in α_s

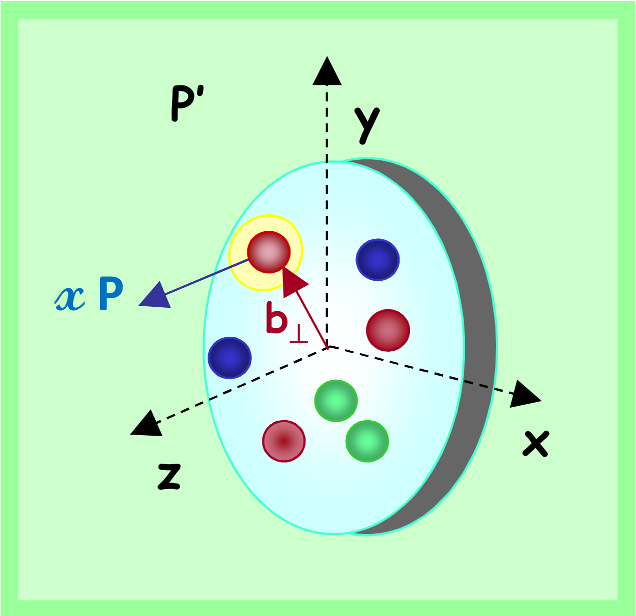


A ‘holy grail’ of GPDs - 3D tomography of the nucleon

- **3D tomography via GPD *H***

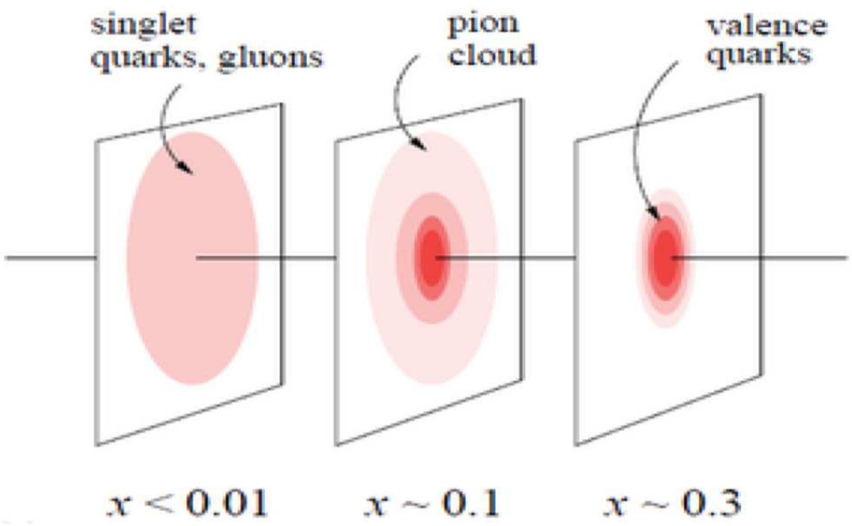
$$H(x, \xi{=}0, t) \;\rightarrow\; \sim \rho(x, b_\perp)$$

probability interpretation (Burkardt)



$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp} H^q(x, 0, -\mathbf{\Delta}_\perp{}^2)$$

(for $\xi = 0$ $\quad t = -\Delta_\perp^2$)



COMPASS experiment at CERN

Basic ingredients of versatile COMPASS experimental setup

- **unique secondary beam line M2 from the SPS**

  delivers:
  - high energy polarised μ^+ or μ^- beams
  - negative or positive hadron beams

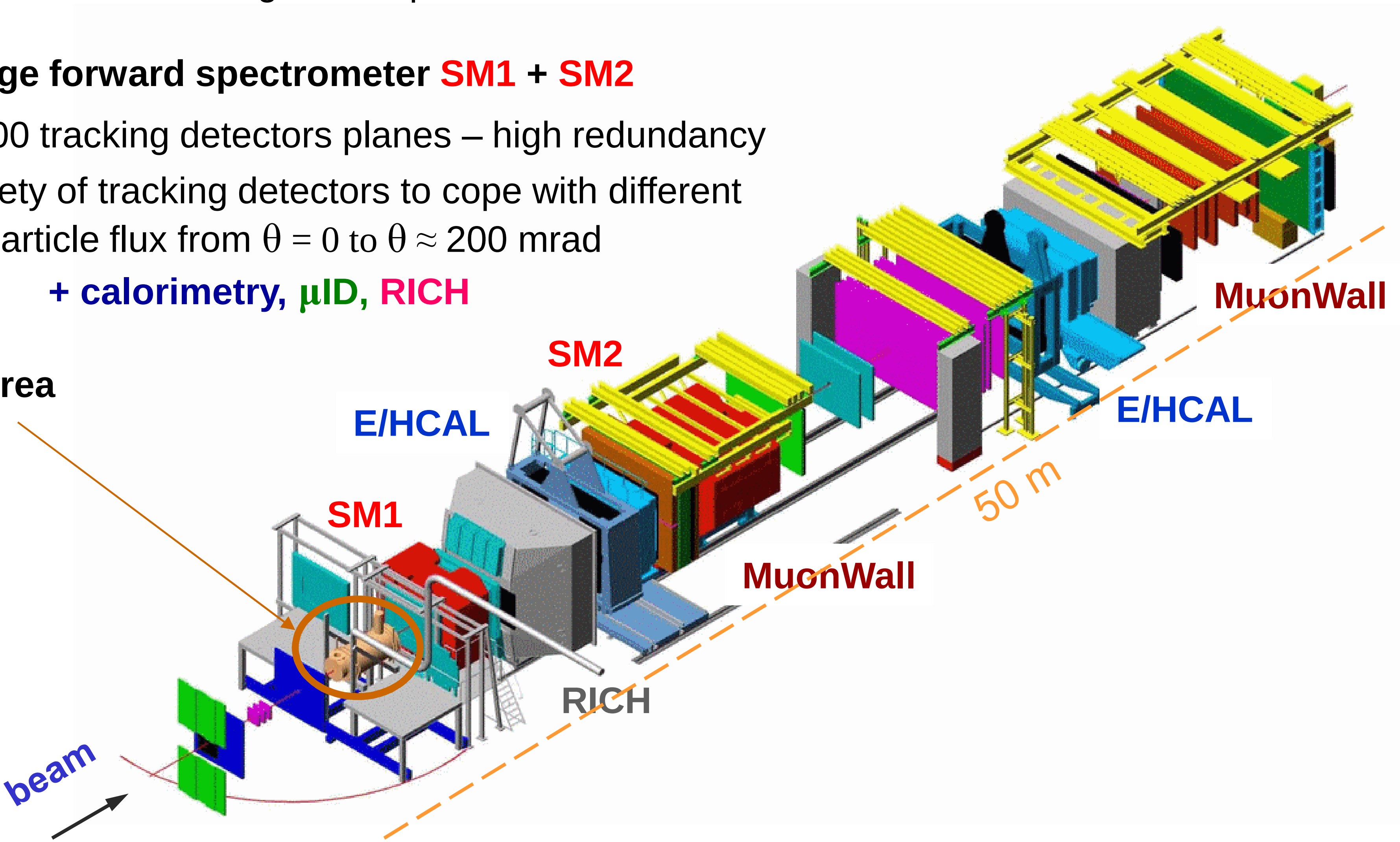
- **two-stage forward spectrometer SM1 + SM2**

  ≈ 300 tracking detectors planes – high redundancy

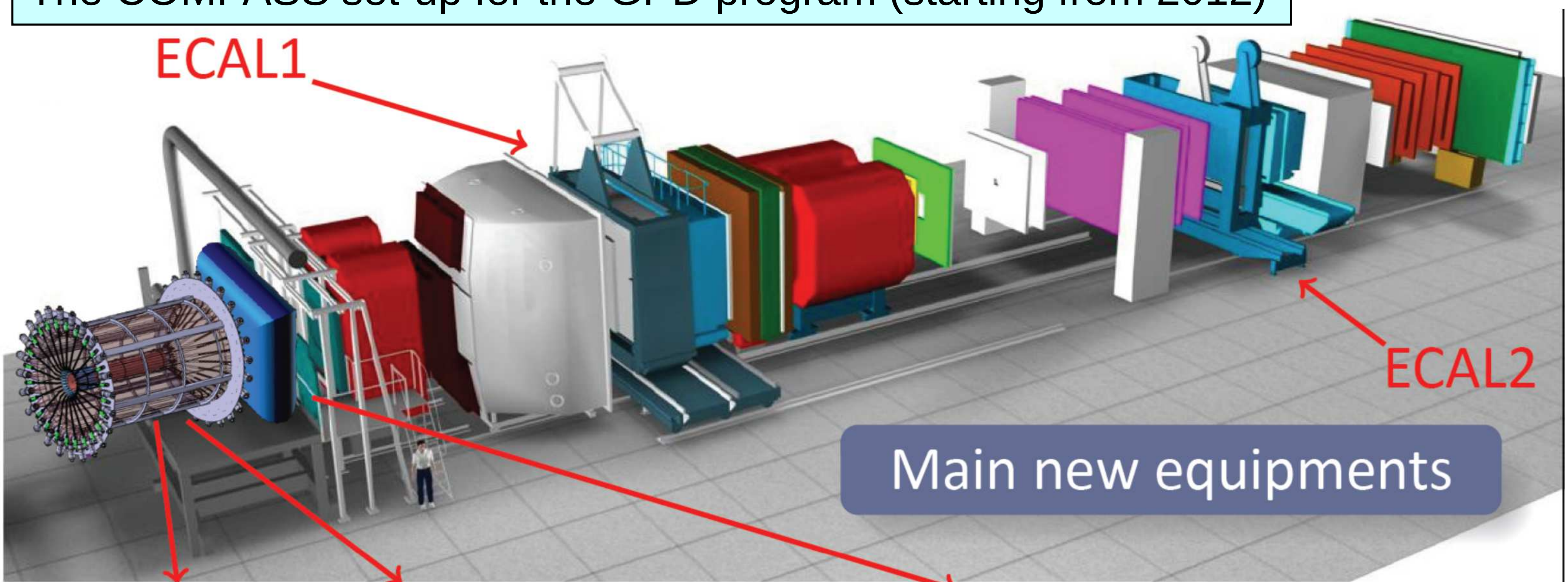
  variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

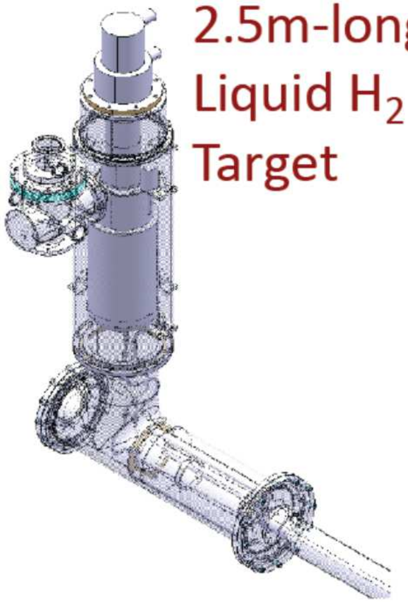
  + calorimetry, μID, RICH

- **target area**



The COMPASS set-up for the GPD program (starting from 2012)

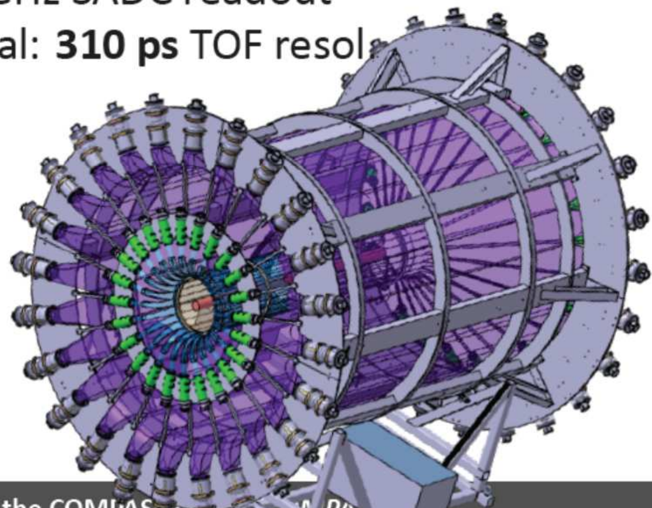




2.5m-long Liquid H_2 Target

Target TOF System

24 inner & outer scintillators
1 GHz SADC readout
goal: **310 ps** TOF resol



ECAL0 Calorimeter

Shashlyk modules + MAPD readout
$\sim 2 \times 2$ m^2, $\sim$2200 ch.

Mounting of Recoil Proton Detector ('CAMERA') in clean area at CERN

Selection of exclusive single photon events

Data collected in 4 weeks of 2012 pilot run

sample for t-slope dependence of DVCS cross section

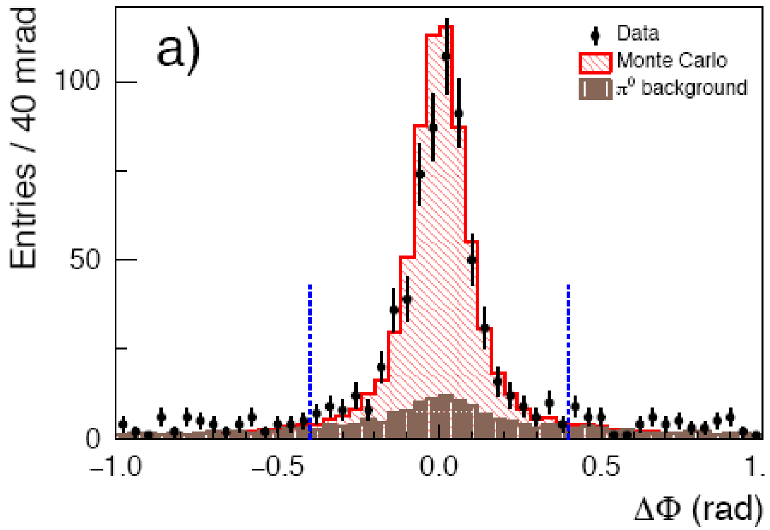
- μ, μ' and vertex in the target volume
- 1 GeV^2 < Q^2 < 5 GeV^2,   10 GeV < ν < 32 GeV
- 0.08 GeV^2 < | t | < 0.64 GeV^2
- 1 single photon with energy above DVCS threshold ← $E_{Ecal(0,1,2)}$ > (4,5,10) GeV

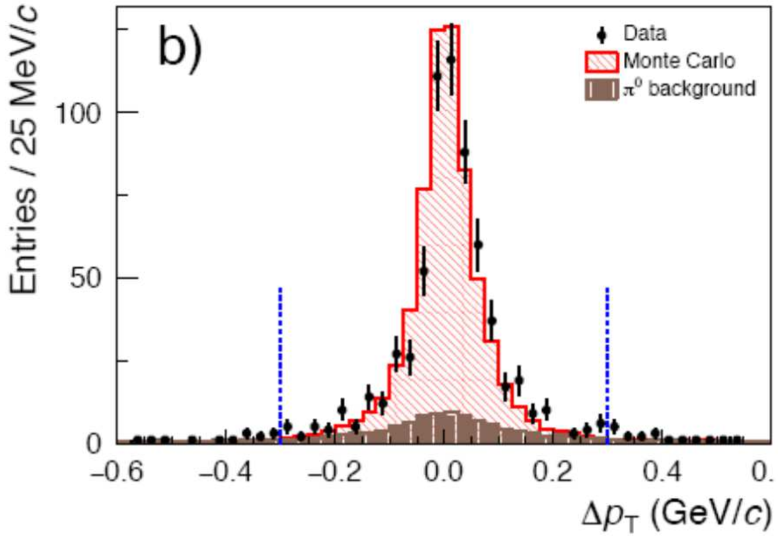
Overconstrained kinematics => a number of „exclusivity cuts" allows to select the exclusive sample

$$\Delta\Phi = \Phi^{p}_{meas} - \Phi^{p}_{pred}$$

$$\Delta p_T = p^{p}_{T,meas} - p^{p}_{T,pred}$$

Examples:



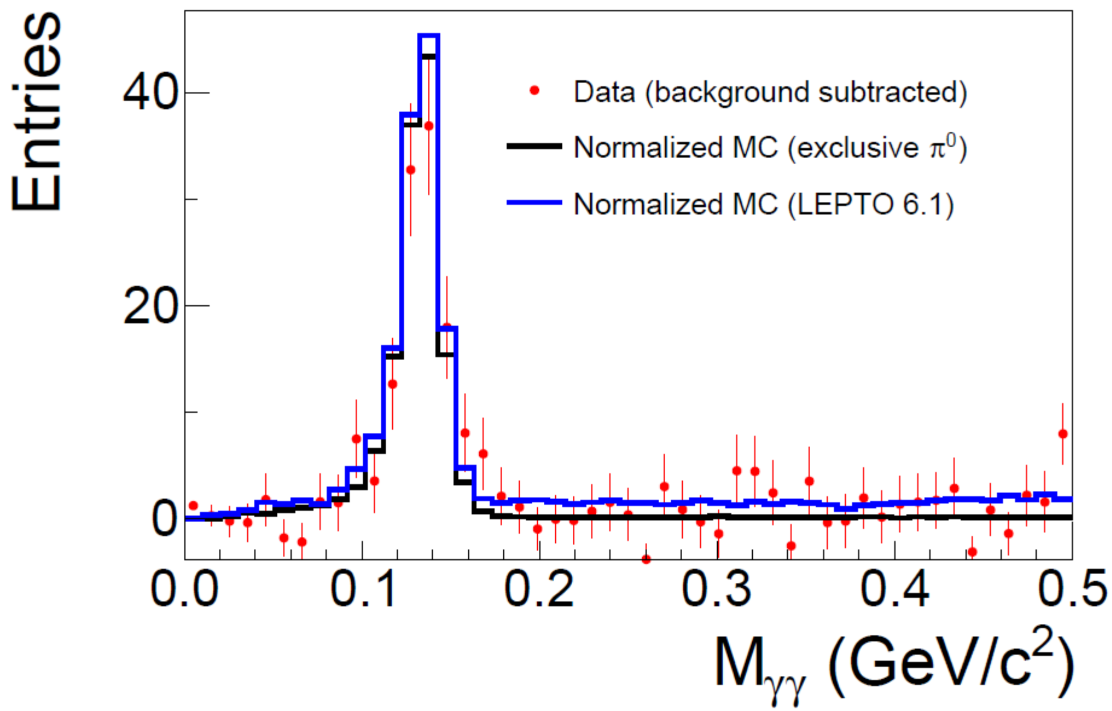


Estimate and subtraction of π^0 background

Major source of background for exclusive photon events

Two cases:

- Visible; detected second γ (below DVCS threshold) => events rejected from final sample
- Invisible; one γ lost => estimated from MC normalised to π^0 peak for 'visible' sample



'Visible' sample

Semi-inclusive (LEPTO MC) or exclusive

(HEPGEN MC based on Goloskokov-Kroll model)

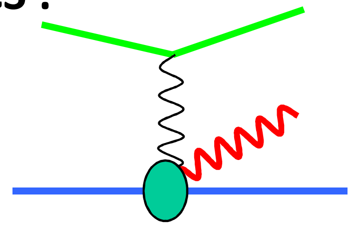
π^0 contribution normalised to $M_{\gamma\gamma}$ peak

'Invisible' sample

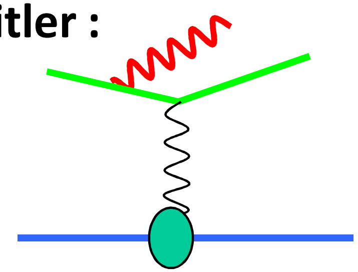
Relative contributions from both processes to π^0 background estimated from combined fits to the distributions of 'exclusivity variables' (M_X^2, $\Delta\phi$, Δp_T) and $E_{miss} = \nu - E_\gamma + t/(2m_p^2)$

Exclusive single photon production cross section

DVCS :



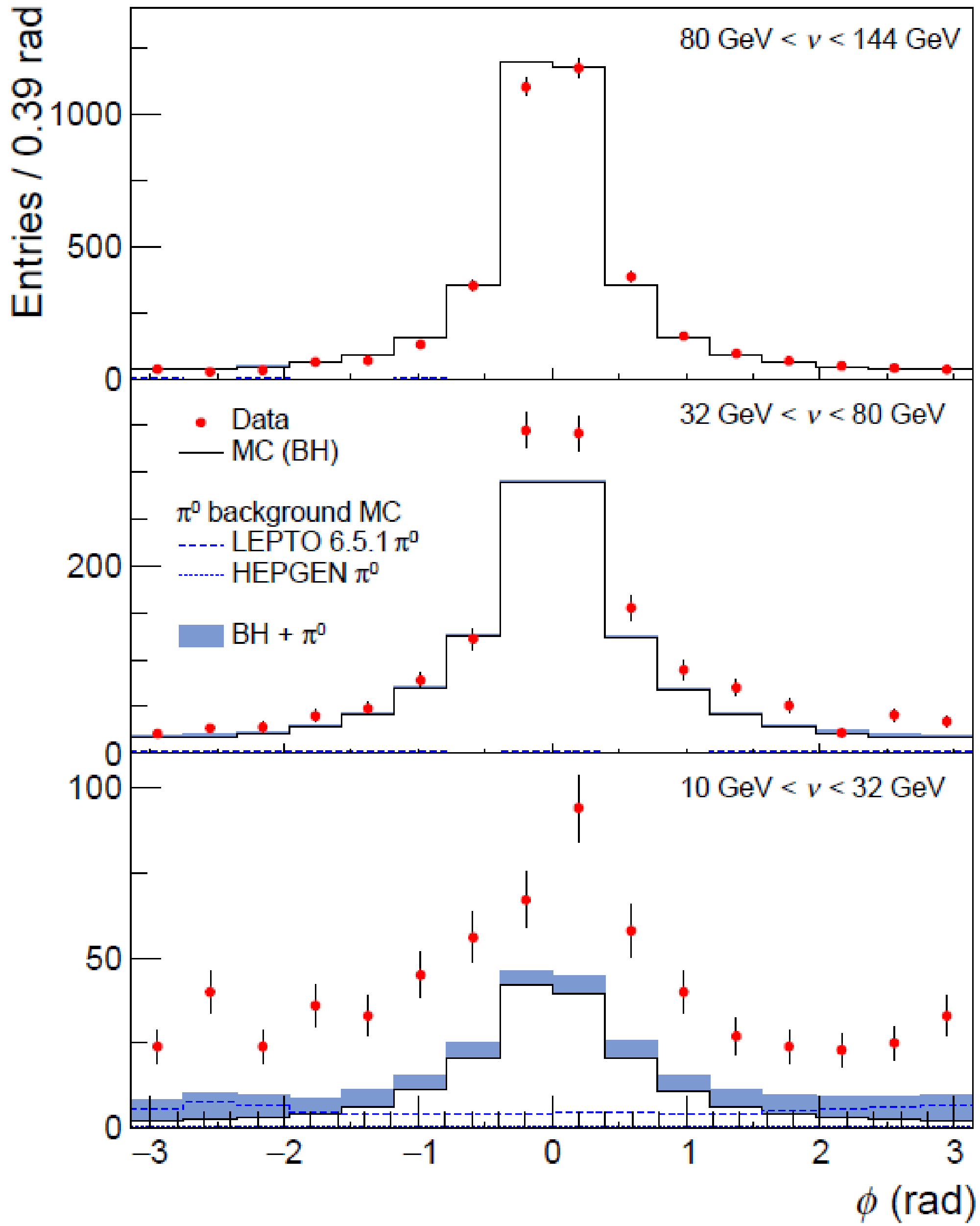
Bethe-Heitler :

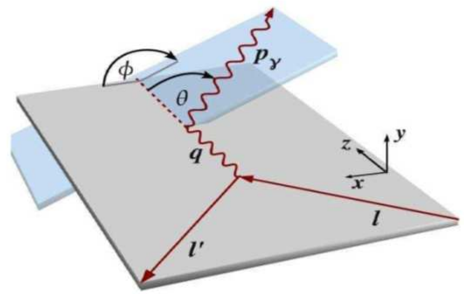


cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

$$d\sigma_{(\mu p\rightarrow\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} + e_\mu\, P_\mu\, a^{BH}\, \mathcal{I}m\, A^{DVCS}$$

Azimuthal distributions for single γ events





BH dominates

excellent reference yield

BH and DVCS at the same level

access to DVCS amplitude through the interference

DVCS dominates

study of $d\sigma^{DVCS}/dt$

Extraction of $d\sigma^{DVCS}/dt$

- measure $\mathrm{d}\sigma := \frac{\mathrm{d}^4\sigma^{\mu p}}{\mathrm{d}Q^2\mathrm{d}\nu\mathrm{d}t\mathrm{d}\phi}$ for μ^+ and μ^- beams

- sum of μ^+ and μ^- cross sections $2d\sigma \equiv d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2(d\sigma^{BH} + d\sigma^{DVCS} - |P_\mu| d\sigma^I)$

P_μ *beam polarisation*

$$\mathrm{d}\sigma^{DVCS} \propto \frac{1}{y^2Q^2}(c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi)$$

$$\mathrm{d}\sigma^I \propto \frac{1}{x_{\mathrm{Bj}}y^3tP_1(\phi)P_2(\phi)}(s_1^I\sin\phi + s_2^I\sin 2\phi)$$

- subtract calculable BH cross sections and integrate over ϕ

$$\frac{\mathrm{d}^3\sigma_{\mathrm{T}}^{\mu p}}{\mathrm{d}Q^2\mathrm{d}\nu dt} = \int_{-\pi}^{\pi}\mathrm{d}\phi\ (\mathrm{d}\sigma - \mathrm{d}\sigma^{BH}) \propto c_0^{DVCS}$$

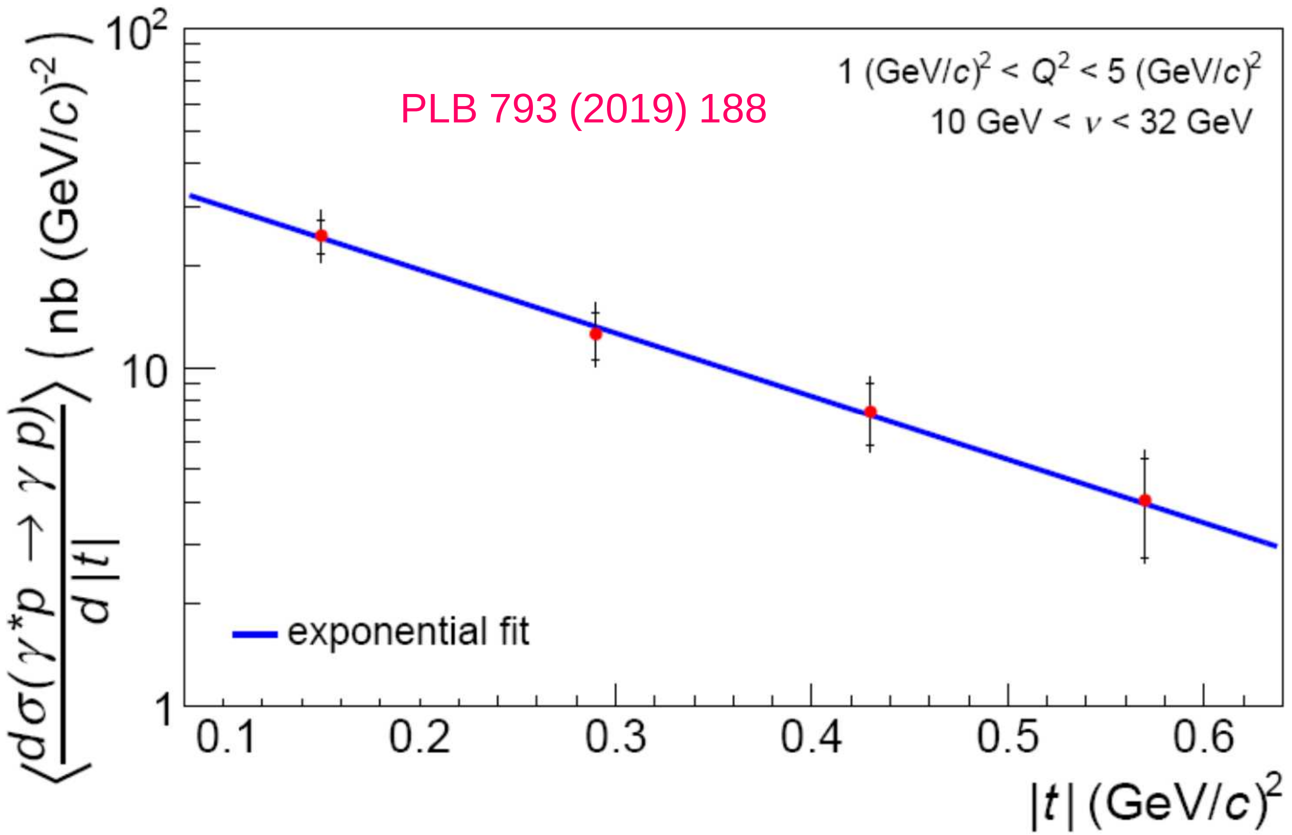
- convert into cross section for virtual-photon scattering

$$\frac{\mathrm{d}\sigma^{\gamma^* p}}{\mathrm{d}t} = \frac{1}{\Gamma(Q^2,\nu,E_\mu)}\frac{\mathrm{d}^3\sigma_{\mathrm{T}}^{\mu p}}{\mathrm{d}Q^2\mathrm{d}\nu dt}$$

Γ *transverse virtual photon flux*

DVCS cross section and t-slope

from 4 weeks of 2012 pilot run



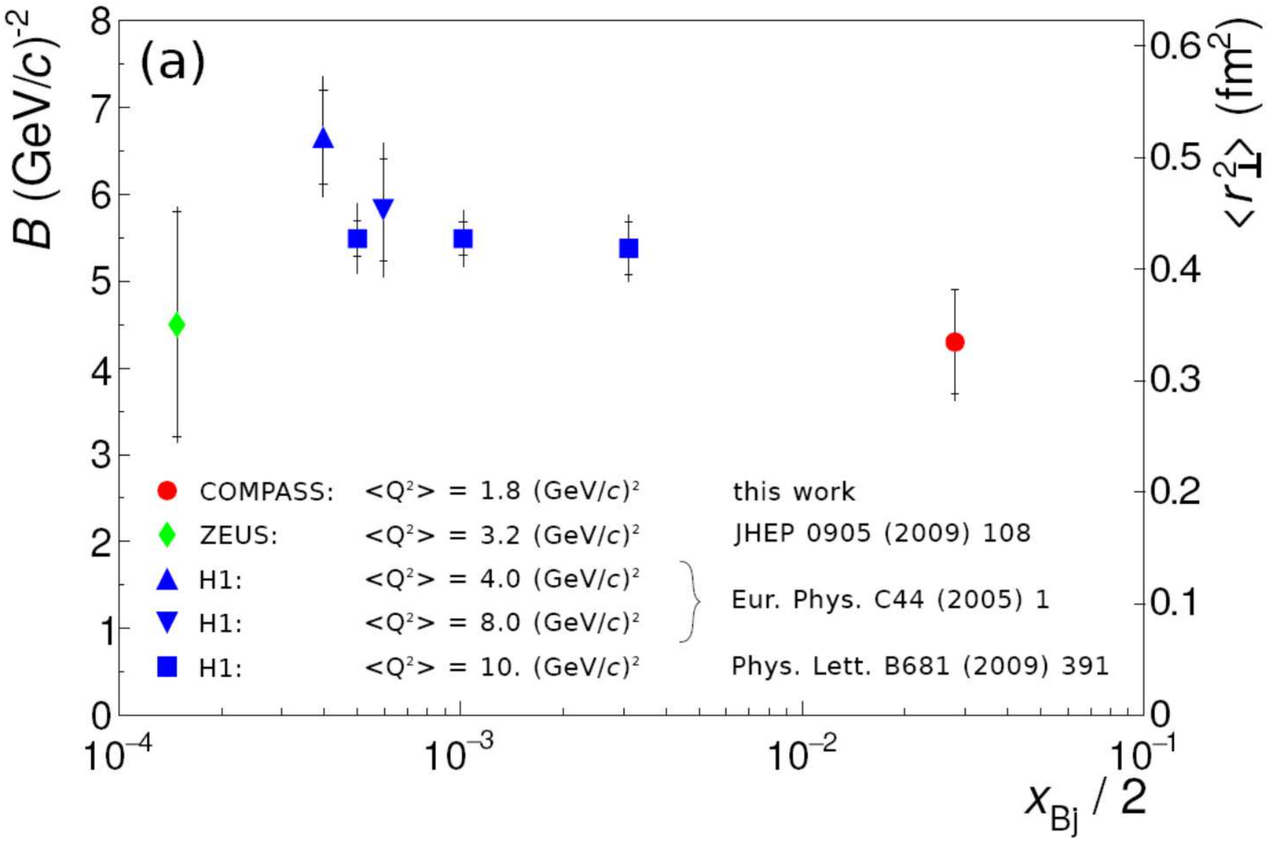
$$B = (4.3 \ \pm \ 0.6_{\rm stat} \ {}^{+\,0.1}_{-\,0.3}\big|_{\rm sys}) \ ({\rm GeV}/c)^{-2}$$

$$\langle r_\perp^2(x_{\rm Bj})\rangle \approx 2\langle B(x_{\rm Bj})\rangle \hbar^2$$

$$\sqrt{\langle r_\perp^2\rangle} = (0.58 \ \pm \ 0.04_{\rm stat} \ {}^{+\,0.01}_{-\,0.02}\big|_{\rm sys} \ \pm \ 0.04_{\rm model})\ {\rm fm}$$

$$\langle W\rangle = 5.8\,{\rm GeV}/c^2, \quad \langle Q^2\rangle = 1.8\,({\rm GeV}/c)^2 \ \text{and} \ \langle x_{\rm Bj}\rangle = 0.056$$

Comparison to HERA



a hint for shrinking with increasing x_{Bj}

what about Q^2 dependence of B ?

Transverse imaging of the proton using $d\sigma^{DVCS}/dt$

(*) $$\langle r_\perp^2(x_{Bj})\rangle \approx 2\langle B(x_{Bj})\rangle \hbar^2$$

how good is this approximation ?

Strict determination of $\langle r_\perp^2\rangle$ requires: (M. Burkardt)

i) measurement of t-dependence of the imaginary part of CFF $\mathcal{H}$

ii) skewness $\xi = 0$

spin- and ϕ-independent DVCS cross section $\propto c_0^{DVCS}$

for small x_{Bj} $$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$$ (BMK)

Systematic uncertainties on $\langle r_\perp^2\rangle$ when using (*) ('model' uncertainty)

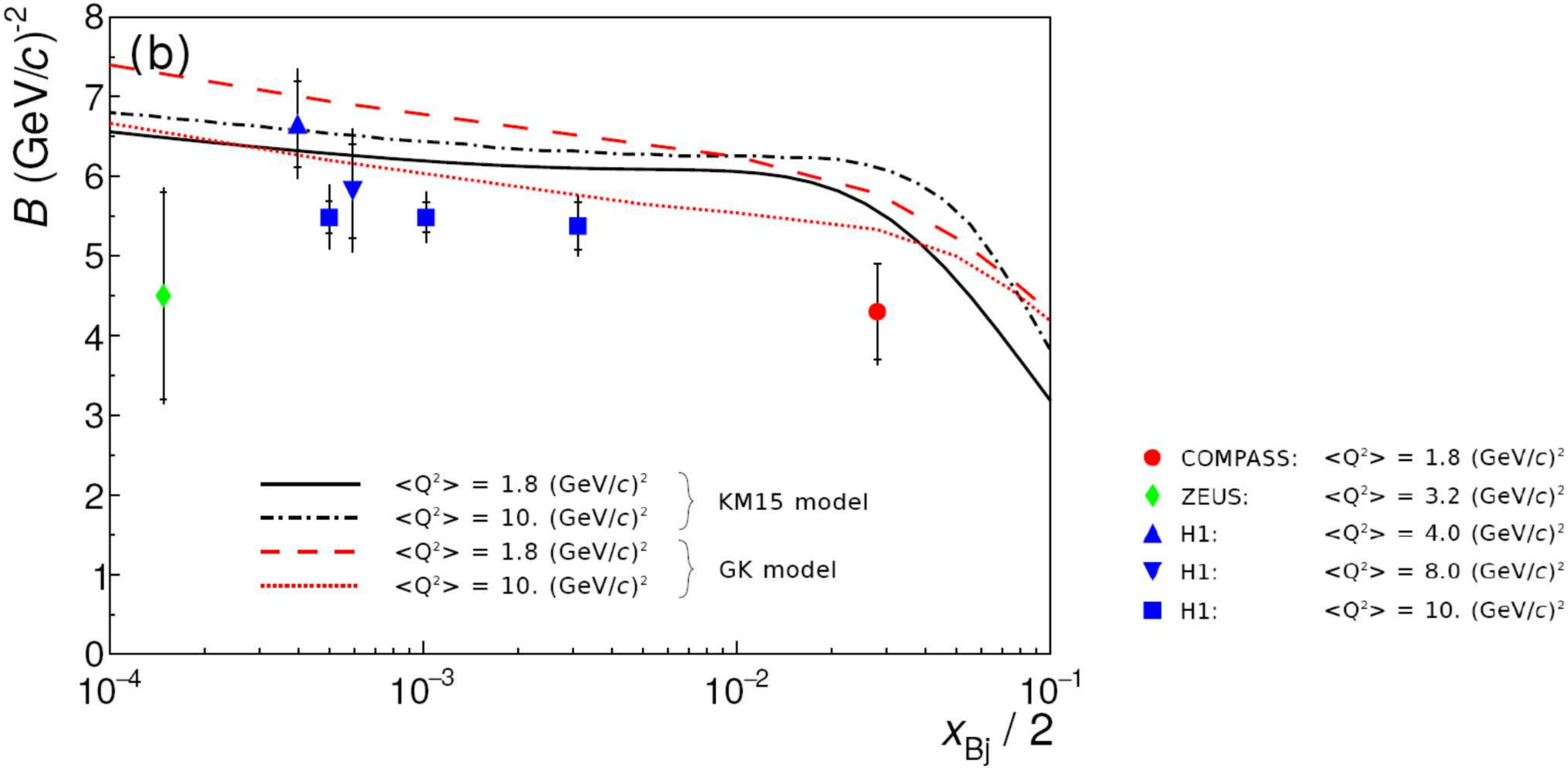
a) correction due to contributions of real part of $\mathcal{H}$ and other GPDs → ± 0.03

b) correction due to assumption ii) → ± 0.02

Estimates based on models:
- GK model in PARTONS framework
- Kumerički – Müller model

$$\sqrt{\langle r_\perp^2\rangle} = (0.58 \pm 0.04_{\rm stat}\ {}^{+\,0.01}_{-\,0.02}\Big|_{\rm sys} \pm 0.04_{\rm model})\ {\rm fm}$$

Comparison to model predictions



shrinking with increasing x_{Bj} similar to the one predicted by models

weak Q^2 dependence of B: (3 – 13)%

Extraction of Compton Form Factors

Dupré, Guidal, Vanderhaeghen, PRD95, 011501(R)(2017)
Dupré, Guidal, Nicolai, Vanderhaeghen, arXiv: 1704.07330

Results for CFF $\mathcal{H}_{\mathbf{Im}}(\xi, t)$ from 'local' fits

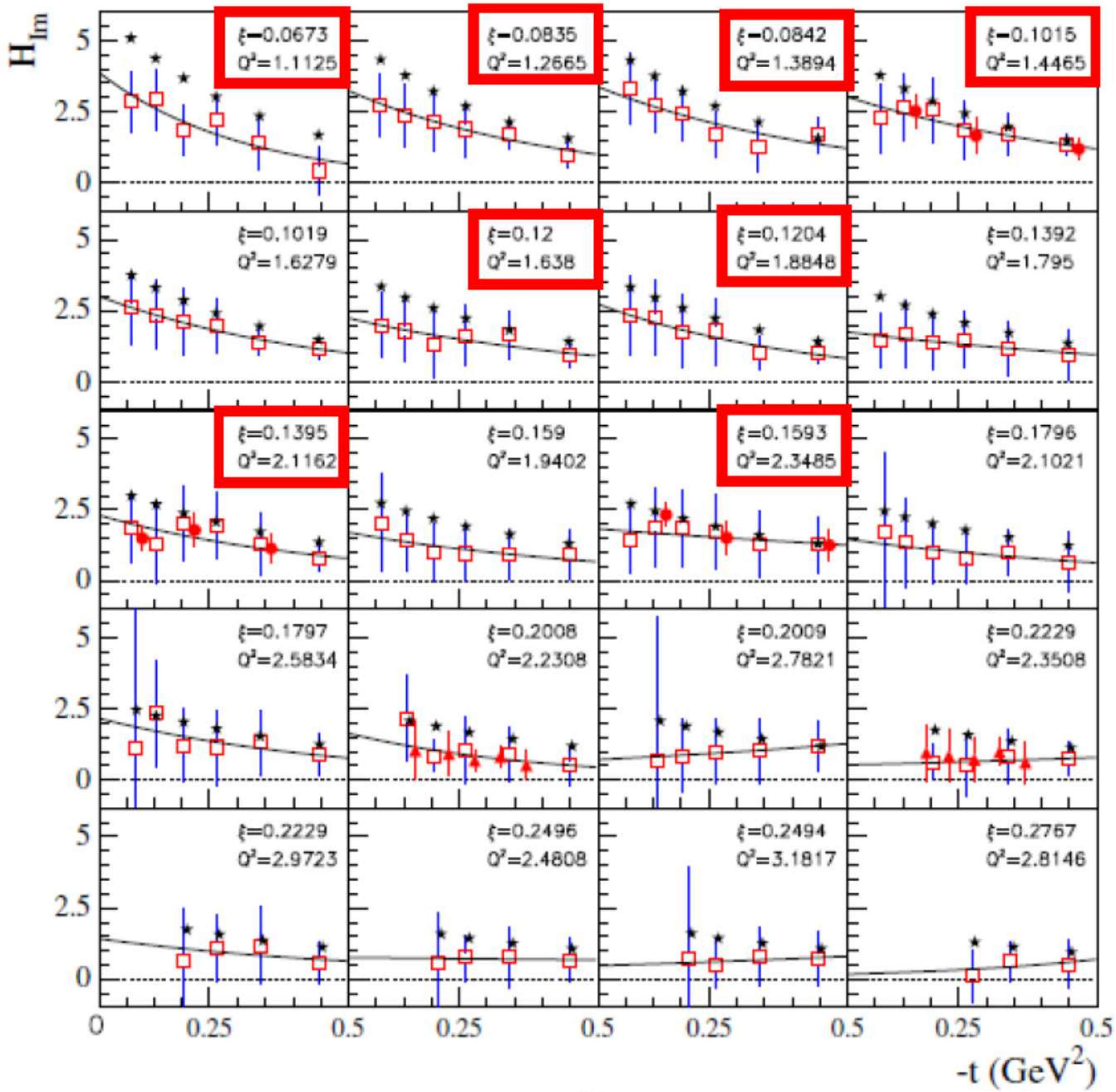
Experimental input

JLab measurements: DVCS cross sections and asymmetries as functions of ϕ in bins ($\mathbf{x_B}$, $\mathbf{Q^2}$, $\mathbf{t}$)

Fit of 8 CFFs at L.O and L.T.

- □ CLAS σ and $\Delta\sigma_{LU}$
- ▲ HallA σ and $\Delta\sigma_{LU}$
- ● CLAS σ, $\Delta\sigma_{LU}$, A_{UL} and A_{LL}
- ★ VGG model

—— Fit: $\mathcal{H}_{\mathbf{Im}}(\xi,t) = A(\xi)\, e^{B'(\xi)\, t}$



$$\xi \approx \frac{x_B}{2 - x_B}$$

Valence quark imaging at Jlab and HERMES

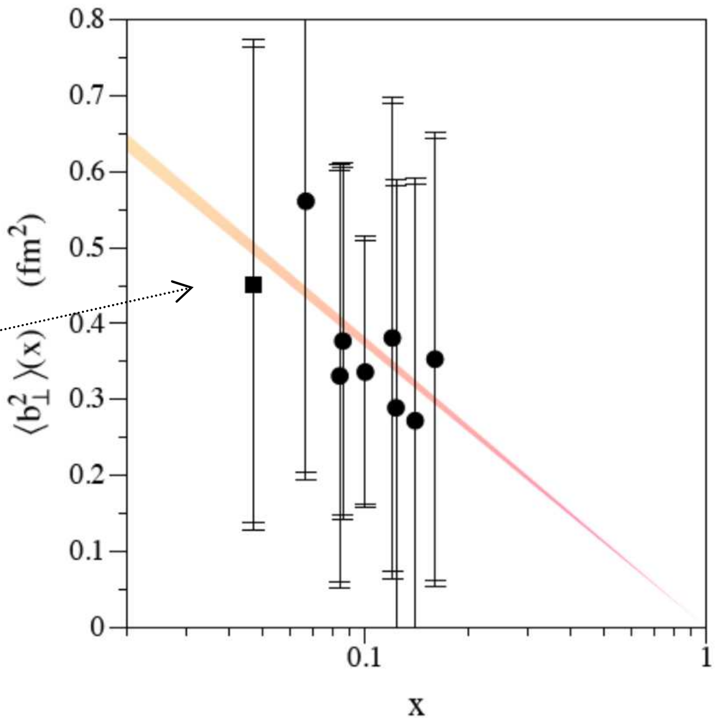
Note: $\mathcal{H}_{\mathbf{Im}}(\xi,t) \equiv H\,(x{=}\xi,\ \xi,\ t)$

interpolation

$$\rho\,(x,\mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp} H\,(x,0,-\mathbf{\Delta}_\perp{}^2)$$

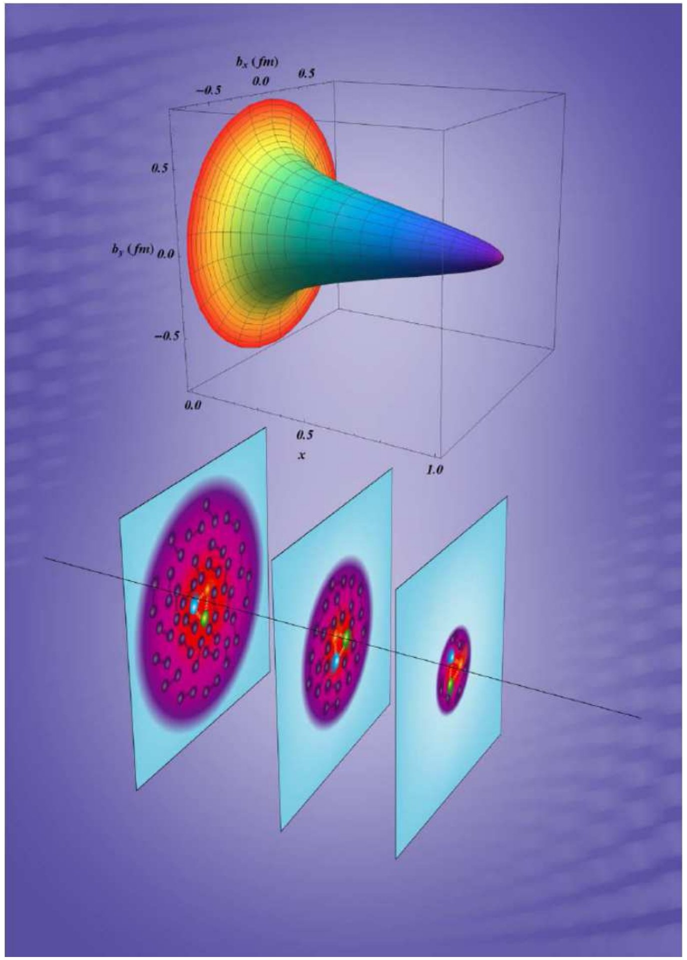
$$< b_\perp{}^2 > \;\approx\; 4\,B'$$

PHYSICAL REVIEW D **95**, 011501(R) (2017)



HERMES

+ 8 points from Jlab



What is the transverse size extracted in different analyses

HERA & COMPASS

$$d\sigma^{DVCS}/dt \sim \exp(-B\,|t|)$$

$$B(x_{Bj}) = 1/2\,\langle r_\perp^2(x_{Bj})\rangle$$

distance between the active quark and the centre of momentum of **spectators**

'Transverse size' of the nucleon

dominated mainly by $H(x = \xi, \xi, t)$

JLAB & HERMES

$$CFF\;H_{\mathrm{Im}} \sim \exp(-B'\,|t|)$$

$$B'(x_{Bj}) = 1/4\,\langle b_\perp^2(x_{Bj})\rangle$$

distance between the active quark and the centre of momentum of **the nucleon**

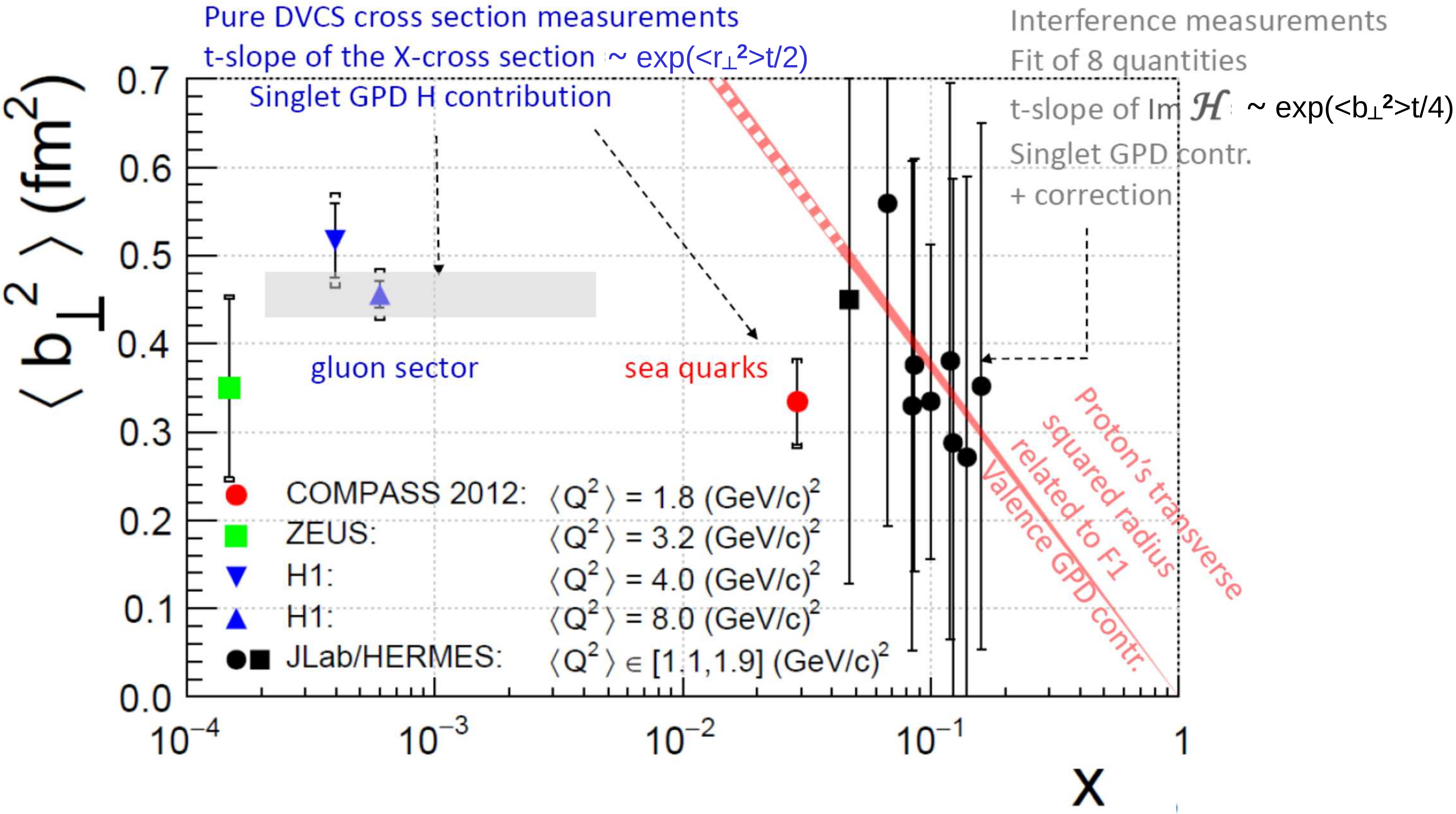
Impact parameter representation

$q\,(x, b_\perp) \leftrightarrow H\,(x, \xi = 0, t)$

$$\langle\, r_\perp \,\rangle \sim \langle\, b_\perp \,\rangle \,/\, (1\text{-}x)$$

Transverse proton extension via different extraction methods

$$\langle r_\perp^2(x)\rangle = 2B(x)$$



from Philipp Joerg and Nicole d'Hose

First insight into 2016 COMPASS data

Only 13% of 2016-17 data

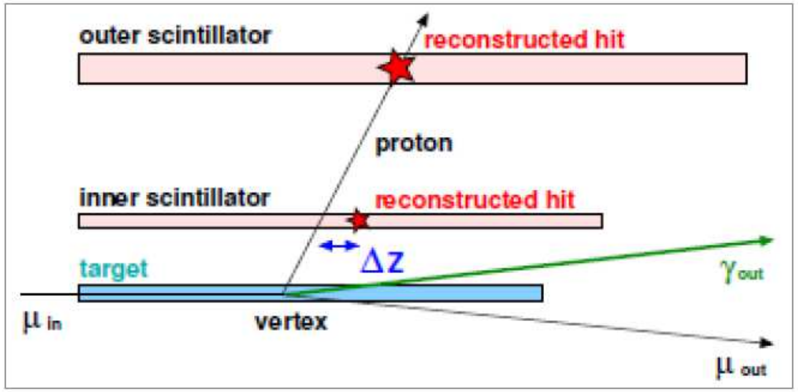
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

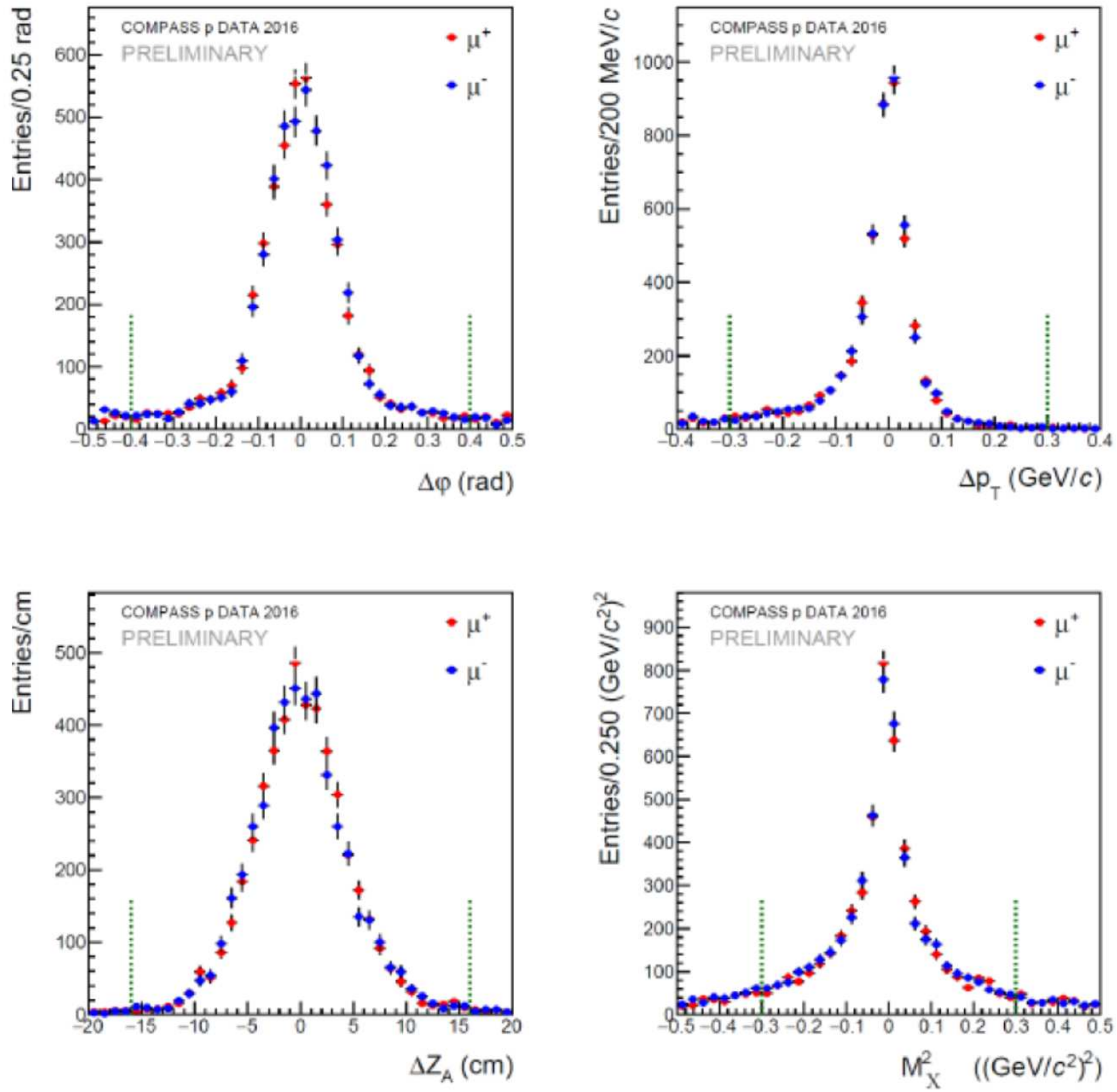
1) $\Delta p_T = p_T^{cam} - p_T^{spec}$

2) $\Delta\varphi = \varphi^{cam} - \varphi^{spec}$

3) $\Delta z_A = z_A^{cam} - z_A^{Z_B\ \text{and vertex}}$

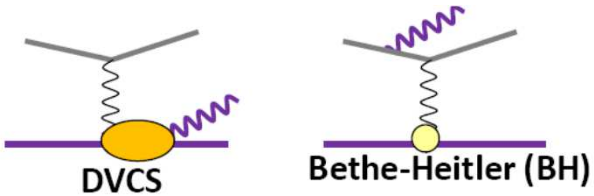
4) $M^2_X = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2$

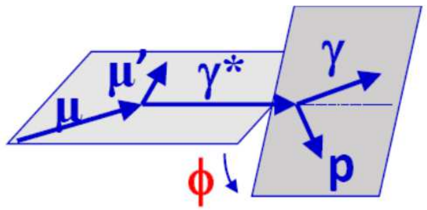




- All distributions obtained with μ^- are normalized to the same luminosity of the ones with μ^+
- Very good agreement between μ^+ and μ^- data observed.

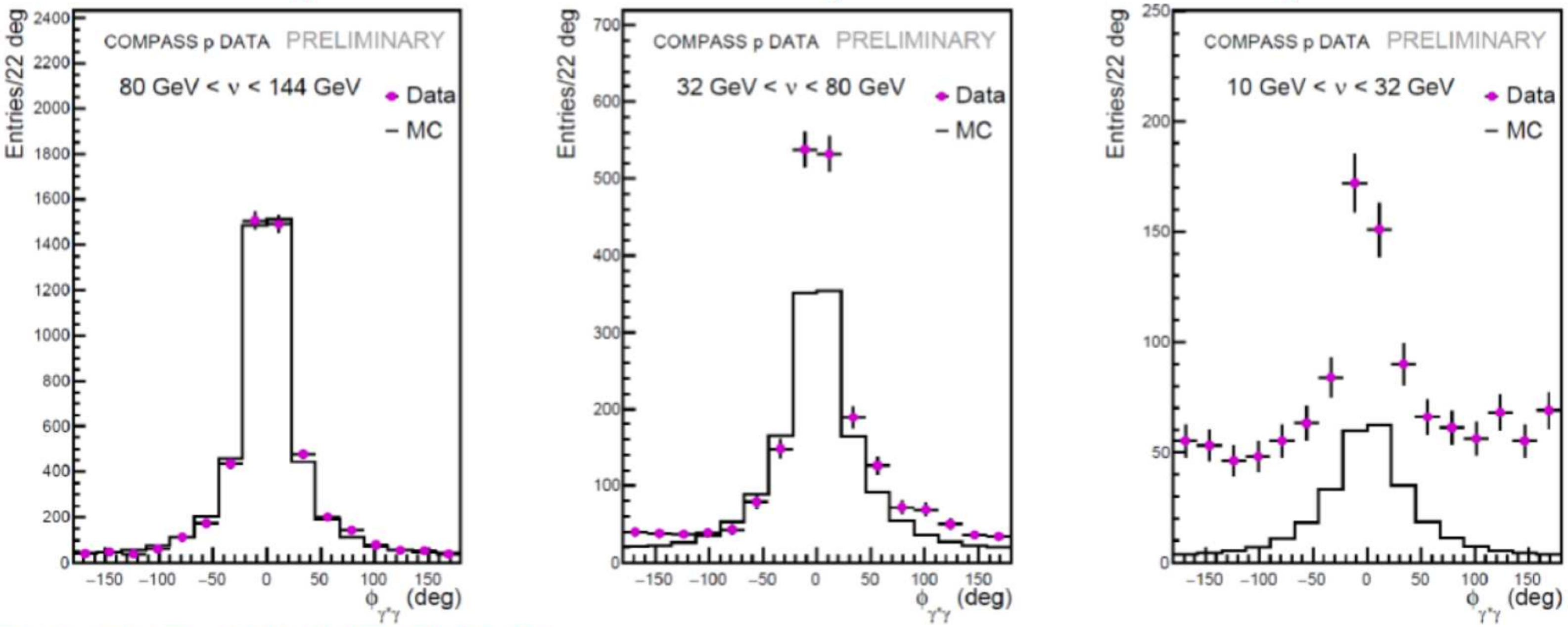
First insight into 2016 data (cont.)





Only 13% of 2016-17 data

$0.005 < x_{Bj} < 0.01$ | $0.01 < x_{Bj} < 0.03$ | $x_{Bj} > 0.03$



Bethe-Heitler MC

No π^0 subtraction.

DVCS contribution at high x_{Bj} will allow to perform re-analysis

$d\sigma^{DVCS}/dt = e^{-B'|t|}$

$= c_0^{DVCS}$

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from Antoine Vidon and Po-Ju Lin

Goals of the analysis of 2016-17 data

~ 10 times more statistics than in 2012

Extraction of DVCS cross section and amplitude

Beam Charge & Spin Sum

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) = 2(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu a^{BH}\, Im\, A^{DVCS})$$

$$c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \qquad s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi$$

$$c_0^{DVCS} \longrightarrow d\sigma^{DVCS}/dt$$

$$s_1^{Int} \rightarrow Im(F_1\mathcal{H})$$

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

Beam Charge & Spin Difference

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) = 2(e_\mu a^{BH}\, Re\, A^{DVCS} + P_\mu d\sigma^{DVCS}_{pol})$$

$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi \qquad s_1^{DVCS}\sin\phi$$

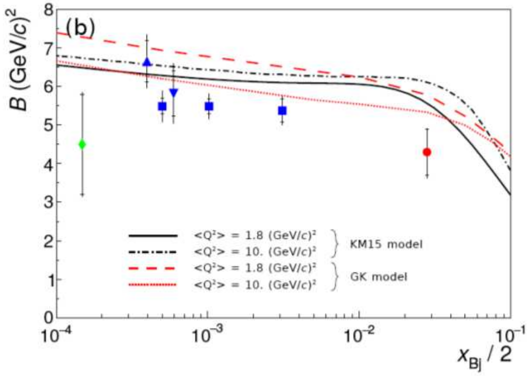
$$c_{0,1}^{Int} \rightarrow \mathcal{R}e(F_1\mathcal{H})$$

$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx\, \frac{H(x,x,t)}{x-\xi} + \mathcal{D}(t)$$

Summary and Outlook

➢ <u>first measurement of t-slope of DVCS cross section at intermediate x_{Bj}-region</u>

dominated by the sea quarks



indication of the decrease of the proton transverse radius with increasing x_{Bj}

in qualitative agreement with the trend observed for the valence region

➢ <u>results expected from the large data sample collected in 2016+2017</u>

with LH_2 target, RPD and wide-angle electromagneric calorimetry
collected statistic ~ 10 times larger than from 2012 pilot run

Deeply Virtual Compton Scattering:

- t-dependence of DVCS cross section vs. x_{Bj} („proton tomography”)
- mapping GPD H by measurments of real and imaginary parts of DVCS via ϕ-dependence the μ^+ and μ^- cross sections difference and sum