Results of DVCS measurement at COMPASS

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on behalf of the COMPASS collaboration

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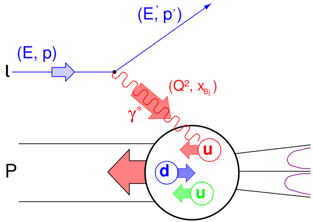
Introduction



γ^* **kinematics:**

- ν, Q^2: Energy, 4-momentum
- $x_{Bj} = Q^2/2m\nu$

Structure of the nucleon investigated by **Deep Inelastic Scattering (DIS)**

Described by **structure functions**:

$F_1(x_{Bj}, Q^2)$, $F_2(x_{Bj}, Q^2)$ (unpolarized)

$g_1(x_{Bj}, Q^2)$, $g_2(x_{Bj}, Q^2)$ (polarized)

Interpretation in quark-parton-model (QPM):

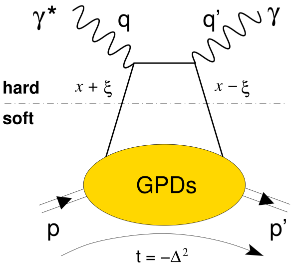
- Nucleon described as longitudinal beam of fast moving quarks
  $\rightarrow x_{Bj}$ interpreted as **longitudinal momentum fraction** of quark
- Assumptions of no transverse momentum

Structure functions $\propto$ **Parton Distribution Functions PDFs**

$\Rightarrow$ **incomplete picture** of the internal nucleon structure

Generalized Parton Distribution functions (GPDs)

$\Rightarrow$ describe the **3-dimensional structure** of the nucleon



Kinematic dependence:

- x: avg. longitudinal momentum fractions
- ξ: longitudinal momentum difference (related to x_{Bj})
- t: momentum transfer to nucleon squared ($t \ll Q^2$)
- Q^2

4 GPDs for each quark flavour in LO and leading twist

$$H^f(x,\xi,t) \qquad E^f(x,\xi,t)$$
$$\widetilde{H}^f(x,\xi,t) \qquad \widetilde{E}^f(x,\xi,t)$$

- Not allow nucleon spin flip
- Allow nucleon spin flip

GPDs not experimentally accessible
$\rightarrow$ related to **Compton Form Factors (CFFs)**

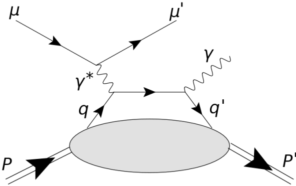
$$\mathcal{H} = \int_{-1}^{1} \frac{H(x,\xi,t)}{x-\xi+i\epsilon} dx$$

Exclusive single photon production:

$$\gamma^* N \rightarrow \gamma N$$

$\Rightarrow$ **Measure CFFs**

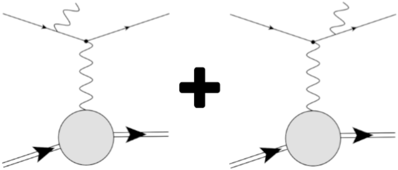
Exclusive photon production @ COMPASS



Deeply Virtual Compton Scattering (DVCS)

$$\mu + p \rightarrow \mu' + p' + \gamma$$

Bethe-Heitler (Bremsstrahlung)
$\rightarrow$ same final state



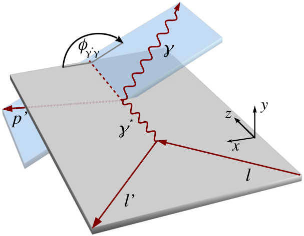
Cross section of exclusive photon production:

$$\sigma(\mu p \rightarrow \mu' \gamma p') = \sigma_{DVCS} + \sigma_{BH} + \sigma_{Int.}$$

Measurement @ COMPASS

Kinematic dependence:

- Q^2 : 4-momentum of γ^*
- ν : Energy of γ^*
- t : Momentum transfer to proton
- ϕ : Angle between scattering plane (γ^*) and production plane (γ)



$\Rightarrow$ Measure **angular distribution of real photon**

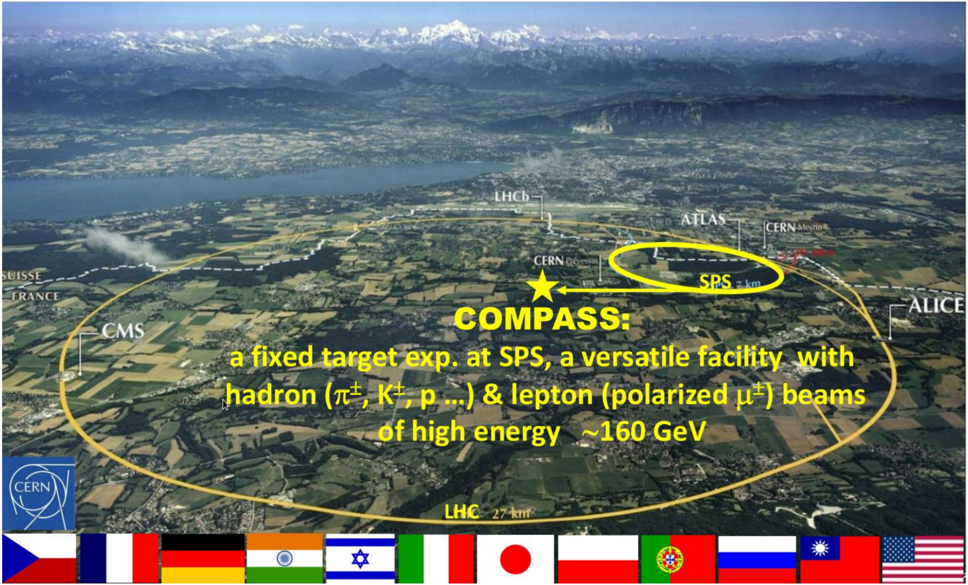
Identify exclusive single photon events:

Incoming muon
Scattered muon
Recoil proton
Real photon
} overconstrained

Data taking @COMPASS:

- 2012 pilot run for 4 weeks
  $\rightarrow$ Analysis finished and published
- Long runs dedicated to DVCS in 2016/17
  - 2×6 months
  - Analysis ongoing
    $\rightarrow$ preliminary results

The COMPASS experiment at CERN

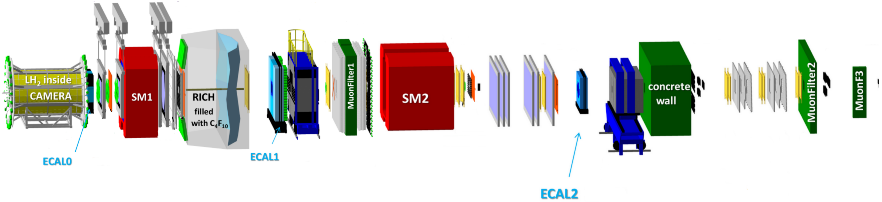


COMPASS spectrometer setup (2016/17)

Two stage forward spectrometer SM1 + SM2

- Liquid hydrogen target (2.5m, ∅4cm)
- Proton recoil detector (CAMERA)
- ECAL0, ECAL1 and ECAL2 (Photon detection)
- Muon trigger system (μID)

$\sim$ 300 tracking detector planes



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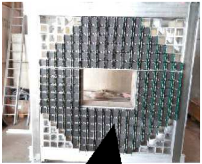
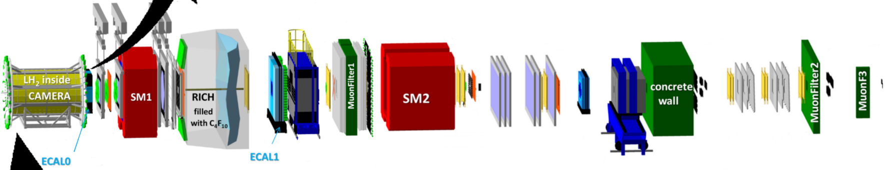
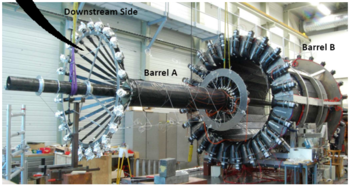


ECAL0:

Sampling calorimeter (lead scintillator sandwich)
$\sim$ 2 x 2 m^2, hole 60cm x 84cm
194 modules each consists of 9 cells (4 x 4 cm^2)





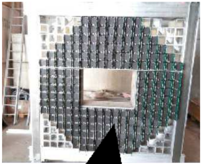
CAMERA:

Inner & outer ring (R_A=25cm, R_B=110cm)
each consisting of 24 scintillator slabs

TOF measurement:

δt=330 ps

COMPASS spectrometer setup (2016/17)



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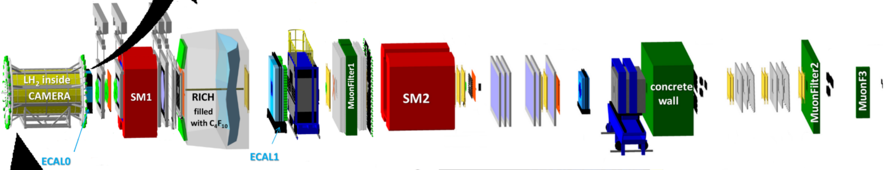
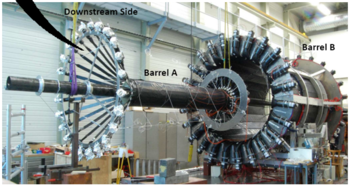
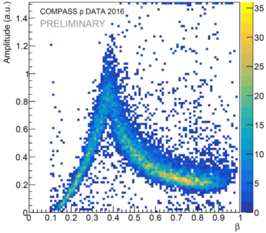






Energy loss of the proton in RingB as **function of** β

Selection of exclusive single photon events

Vertex candidates:

- Incoming muon
  - Use same selection as for muon flux
- Scattered muon

Real photon candidate:

- Photon energy above DVCS threshold in one ECAL
  - 4/5/10 GeV in ECAL0/1/2

Recoil proton candidates:

- CAMERA
- t_{min} =0.08 (GeV/c)^2

Additional conditions:

$\rightarrow$ use **overconstrain** of measurement

- Improve event selection by adding **"exclusivity conditions"**
- Perform a **kinematic fit**
  $\rightarrow$ **constrain on kinematic variables**
  - $\chi^2 < 10$
  - fit efficiency 98% for exclusive single photon events

Only events which have exactly one combination of :

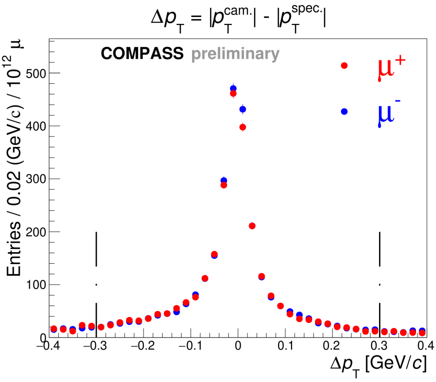
Vertex candidate $\times$ Proton candidate $\times$ γ candidate

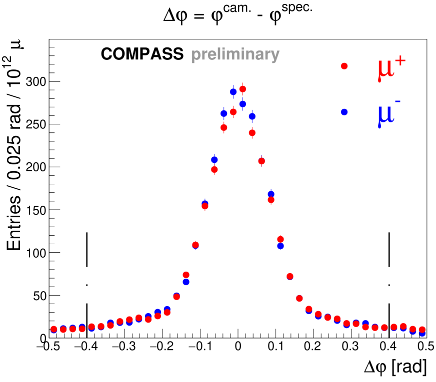
Exclusivity conditions for proton kinematics

Exclusivity variables

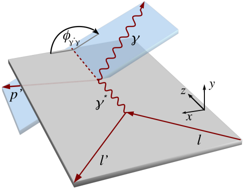
- **$\Delta\varphi$:** $\Delta\varphi = \varphi_{Cam} - \varphi_{Spec}$
- **Δp_t:** $\Delta p_t = p_{t,Cam} - p_{t,Spec}$
- **ΔZ_A:** $\Delta Z_A = Z_{A,Cam} - Z_{A,Spec}$
- **Missing mass:** $M_x^2 = (k + p - k' - q' - p')^2$

Spec: Lorentz Vector of proton calculated from 4-Momentum conservation
Cam: Lorentz Vector of proton by CAMERA measurement





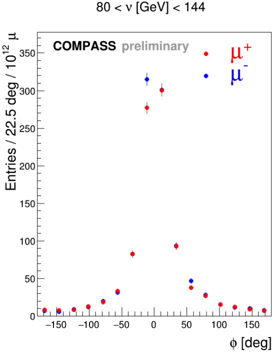
ϕ distribution



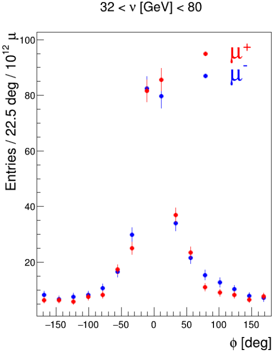
High beam energy (160 GeV)

- Choose 3 ν ranges
  $\rightarrow$ **different main contributions**

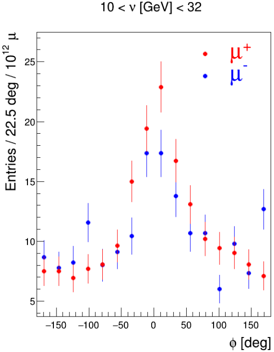
Bethe-Heitler dominant



Interference



DVCS dominant



The binned DVCS cross section

DVCS cross section in bins of t, ϕ, Q^2 and ν:

$$\left\langle \frac{d\sigma_{DVCS}}{d|t| d\phi dQ^2 d\nu} \right\rangle^{\pm}_{t_i \phi_j Q^2_k \nu_l} =$$

$$\frac{1}{\mathcal{L}^{\pm} \Delta t_i \Delta \phi_j \Delta Q^2_k \Delta \nu_l} \left[\left(a^{\pm}_{ijkl} \right)^{-1} \left(\text{data} - \text{BH}_{MC} - c^{\pm}_{\pi^0} \pi^0_{MC} \right) \right]$$

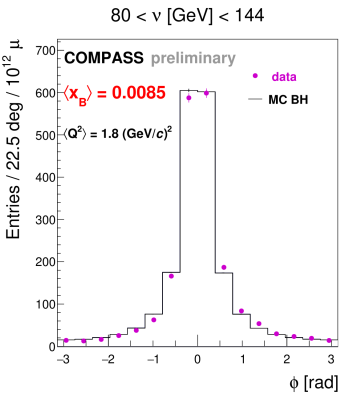
- BH_{MC}: exclusive single photon MC sample
- π^0_{MC}: π^0 MC sample (background estimation)
- c: Normalization factors
- $a^{\pm}_{ijkl}$: Acceptance

Contribution of Bethe-Heitler

- Contribution of BH process is **well known**
  → evaluated using **Monte-Carlo sample** for BH (HEPGEN generator)

Handling BH contribution:

- Kinematic range where **BH is dominant**
  → BH Monte-Carlo **normalized to data luminosity**
- **BH subtracted** from the data in the DVCS region



98.6±1% agreement between data and MC

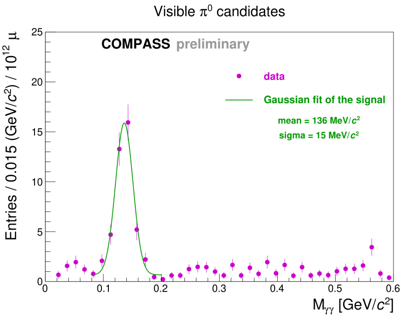
The π^0 background contribution

- Photons from π^0 **decay**
- **One photon identified as single exclusive photon event**

- **Visible** (both γ are detected) - substracted

  Combine the high energy photon candidate with all detected photons having energies below the DVCS energy thresholds

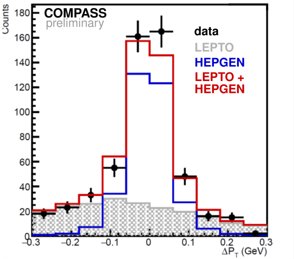
- **Invisible** (second γ lost) - estimated by MC
  - **Semi-inclusive:** LEPTO
  - **Exclusive:** HEPGEN π^0

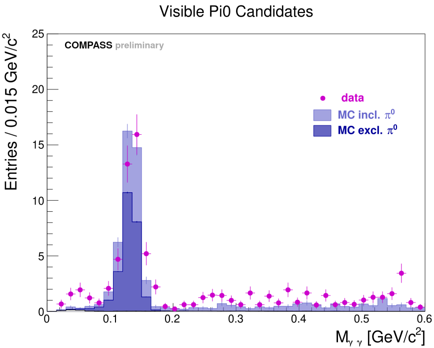


Monte-Carlo for invisible π^0 background estimation

- **HEPGEN** and **LEPTO** are both **individual normalized** to the π^0 peak in the $M_{\gamma\gamma}$ spectrum of the real data
  - General normalization factors $c^{\pm}_{HEPGEN,\pi^0}$ and $c^{\pm}_{LEPTO,\pi^0}$

- **Ratio between HEPGEN and LEPTO**:
  $\rightarrow$ Fit shape of "exclusivity" distributions to real data

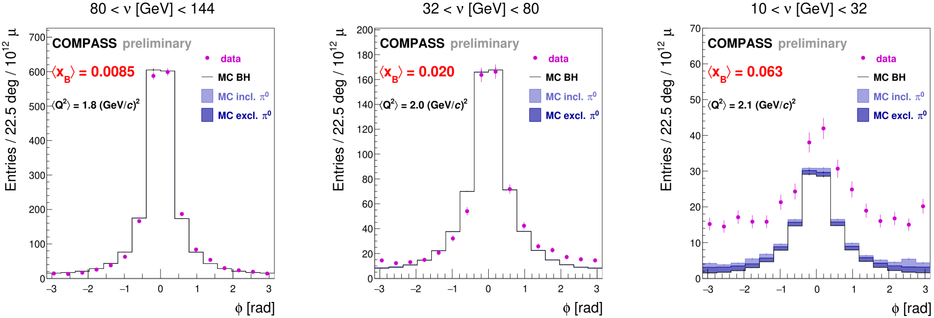




$\Rightarrow$ R **relative contribution of LEPTO 40±10%**

ϕ distribution of exclusive single photon events

- 2/3 of the 2016 data
- $1 < Q^2 < 10\ (\mathrm{GeV}/c)^2$



- 64% of events in data
- 24% of events in data
- 12% of events in data
- 37% BH contribution
- 10% inv.π^0 contribution

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DVCS cross section in bins of t, ϕ, Q^2 and ν:

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$$c^{\pm}_{\pi^0} \pi^0_{MC} = c^{\pm}_{HEPGEN} \cdot (1 - \text{R}) \cdot \pi^0_{HEPGEN} + c^{\pm}_{LEPTO} \cdot \text{R} \cdot \pi^0_{LEPTO}$$

- BH_{MC}: BH MC sample
- π^0_{HEPGEN}: exclusive π^0 MC sample
- π^0_{LEPTO}: semi-inclusive π^0 MC sample
- $c^{\pm}_{HEPGEN}$: normalization factor for HEPGEN π^0
- $c^{\pm}_{LEPTO}$: normalization factor for LEPTO π^0
- R: relative contribution of LEPTO
- $a^{\pm}$: Acceptance

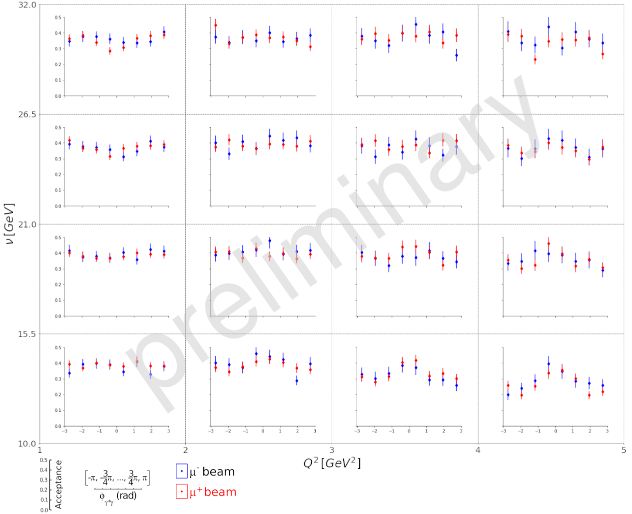
Binning and kinematic range:

- 4 bins in t $(\text{GeV/c})^2$: [0.08,0.136],]0.136,0.219],]0.219,0.36],]0.36,0.64]
- 4 bins in ν GeV: [10.0,15.5],]15.5,21.0],]21.0,26.5],]26.5,32.0]
- 4 bins in Q^2 $(\text{GeV/c})^2$: [1.0,2.0],]2.0,3.0],]3.0,4.0],]4.0,5.0]
- 8 bins in ϕ: equidistant $-\pi < \phi < +\pi$

Acceptance studies
→ limit to region with **mostly flat acceptance**
$1 < Q^2 < 5$ $(\text{GeV/c})^2$

Acceptance

- Exclusive single photon MC data sample
- In 4 dimensions: $acc(t, \phi, Q^2, \nu) = N_{rec}/N_{gen}$



Kinematic variables for reconstructed MC from **kinematic fit**
→ Includes bin migration

Average about 40%

Similar acceptance between μ^+ and μ^-

Calculate the t-dependence of the cross section

From μp to $\gamma^* p$:

$$\frac{d\sigma^{\mu p}}{dt d\phi dQ^2 d\nu} \rightarrow \frac{d\sigma^{\gamma^* p}}{dt d\phi dQ^2 d\nu}$$

by **weighting each event** in data and MC by the inverse **virtual photon flux**

$$\Gamma(Q^2,\nu) = \frac{\alpha_{EM}(1-Bj)}{2\pi Q^2 yE}\left[y^2\left(1-\frac{2m_\mu^2}{Q^2}\right)+\frac{2}{1+(\frac{Q^2}{\nu^2})}\left(1-y-\frac{Q^2}{4E^2}\right)\right]$$

t-dependence for μ^+ and μ^-:

$$\left\langle \frac{d\sigma_{DVCS}}{d|t|}\right\rangle_{t_i}^{\pm} = \frac{\sum_{k,l}\left\langle \frac{d\sigma_{DVCS}}{d|t|dQ^2 d\nu}\right\rangle_{t_i Q_k^2 \nu_l}^{\pm} \Delta Q_k^2 \Delta\nu_l}{\Delta Q^2 \Delta\nu}$$

$\rightarrow$ Integration over ϕ dependency **removes** **interference contribution**

$$\mathcal{S}_{CS,U} = d\sigma^{+\uparrow} + d\sigma^{-\downarrow} = 2[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi + s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi]$$

t-dependence of the cross section:

$$\left\langle \frac{d\sigma_{DVCS}}{d|t|}\right\rangle_{t_i} = \frac{1}{2}\left(\left\langle \frac{d\sigma_{DVCS}}{d|t|}\right\rangle_{t_i}^{+} + \left\langle \frac{d\sigma_{DVCS}}{d|t|}\right\rangle_{t_i}^{-}\right)$$

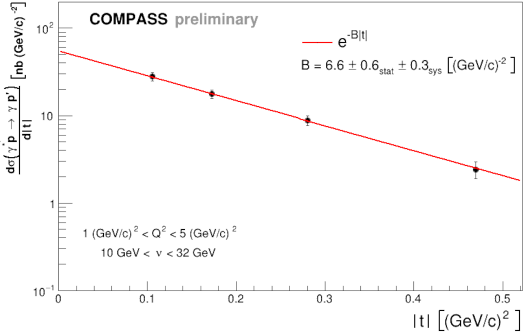
Analyse the cross section t-slope

$$d\sigma^{DVCS}/dt \propto e^{-B|t|} = c_0^{DVCS} \propto \mathcal{I}m\mathcal{H}$$

Perform **binned maximum Likelihood-fit**

$$B = (6.6 \pm 0.6_{stat} \pm 0.3_{sys})(\mathrm{GeV/c})^{-2}$$

Dominant source of systematic:
Normalisation to visible π^0



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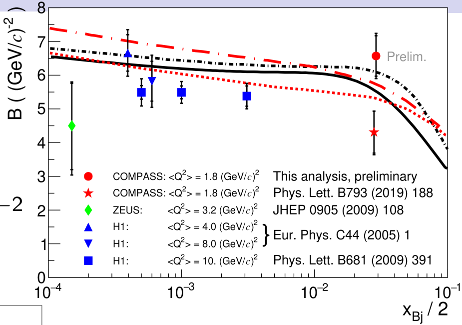

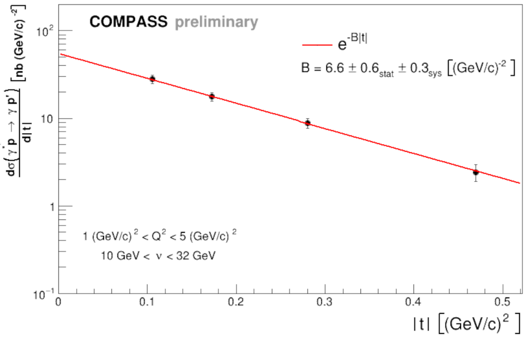

2012 results PLB 793 (2019) 188

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

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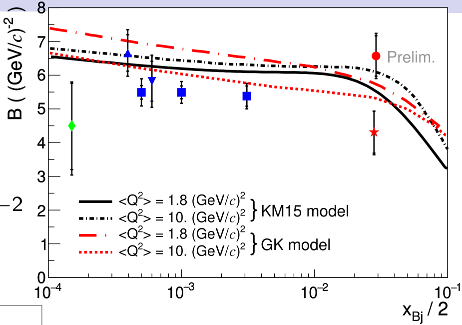

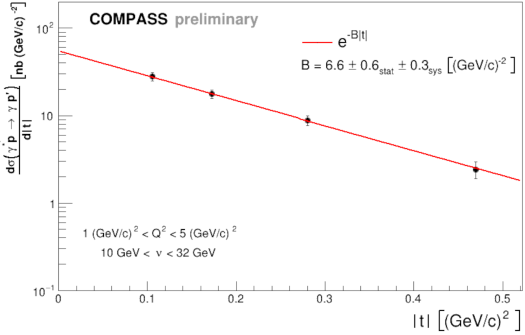

2012 results PLB 793 (2019) 188

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

Outlook

- More detailed studies of **systematic uncertainties**
- **Analyse full statistics** of 2016 and 2017 (about 3 times more than 2016)
  $\rightarrow$ Several x_{Bj} bins
- **Analyse the azimuthal distribution** of the cross section
  $\rightarrow$Determine c_0^{DVCS}, c_1^{DVCS}, c_2^{DVCS}, $s_1^{Int.}$ and $s_2^{Int.}$
- **Cross section difference** $\mathcal{D}_{CS,U} = d\sigma^{+\uparrow} - d\sigma^{-\downarrow}$

Thank you for your attention.