Deeply Virtual Compton Scattering at COMPASS

Anatolii Koval

on behalf of the COMPASS collaboration

September 10, 2022

Plan

1. Generalized Parton Distribution functions
2. Measurements at COMPASS and experimental setup
3. DVCS cross-section and steps for its extraction
4. Analysis of the cross section and its t-dependence

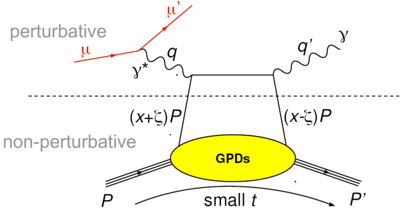
Generalized Parton Distribution functions (GPDs)

- Provide comprehensive description of 3-D partonic structure of the nucleon.
- Can be viewed as correlation functions between different partonic states.
- Allows to study decomposition of the total nucleon spin.

Generalized Parton Distribution functions (GPDs)

Deeply Virtual
Compton Scattering

$$\gamma^* + N \to \gamma + N'$$



$q = (p_\mu - p_{\mu'})$: 4-mom. of virt. photon
$Q^2 = -q^2$: virt. photon virtuality
$t = (p_P - p_{P'})^2$: mom. transfer to nucleon squared
x: avg. long. mom. fraction
ξ: half of long. mom. fraction transfer

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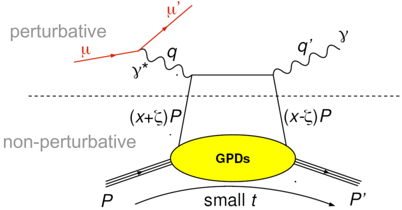

No nucleon spin flip
$H^f(x, \xi, t)$
$\tilde{H}^f(x, \xi, t)$

With nucleon spin flip
$E^f(x, \xi, t)$
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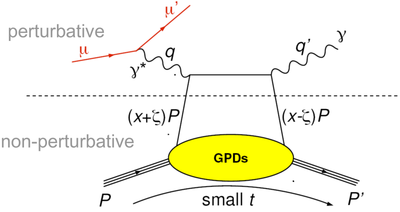

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GPDs are not experimentally accessible, but related to Compton Form Factors (CFFs)

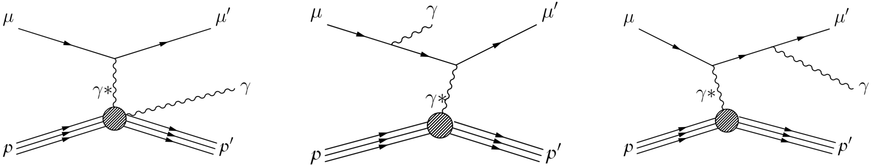
No nucleon spin flip
$H^f(x, \xi, t)$
$\tilde{H}^f(x, \xi, t)$

With nucleon spin flip
$E^f(x, \xi, t)$
$\tilde{E}^f(x, \xi, t)$

CFFs are observables in cross section measurements

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

$\mu p \to \mu' p' \gamma$ processes



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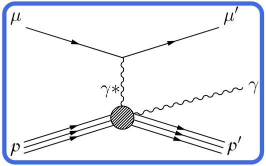

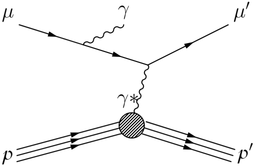

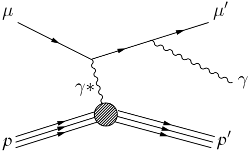

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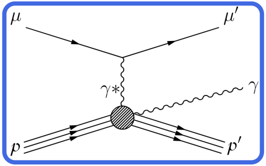

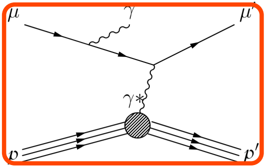

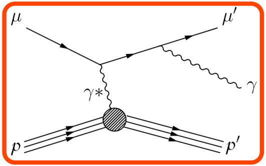

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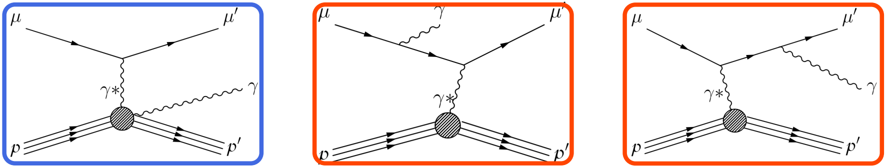


The observable products of these reactions are identical, therefore they can not be separated on per-event basis.

$$\sigma_\gamma \propto |A_{\texttt{DVCS}}|^2 + |A_{\texttt{BH}}|^2 + \texttt{Interference Term}$$

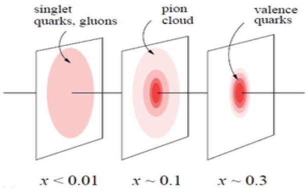
$\texttt{Interference Term} \equiv A_{\texttt{DVCS}} A_{\texttt{BH}}$ - allows to study DVCS on the amplitude level.

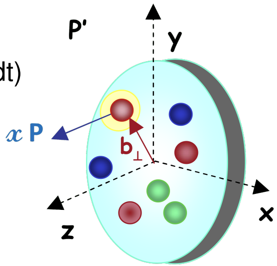
Most attractive goals

3D tomography via GPD H

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

probability interpretation (Burkardt)





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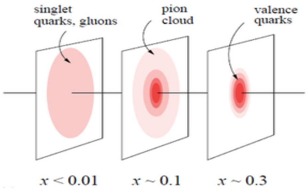
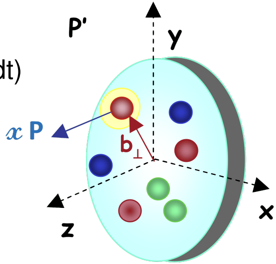
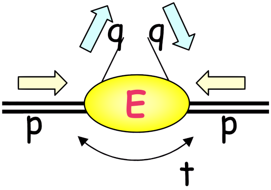




Contribution to the nucleon spin puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

by constraining GPD H and E



$$J^q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{+1} x \left[H^q(x, \xi, t) + E^q(x, \xi, t) \right] dx$$

GPD E related to the orbital angular momentum

Measurement at COMPASS

Diff. cross section $\dfrac{d\sigma^4}{dQ^2 d\nu d|t| d\phi}$

Kinematic dependence:
$Q^2 = -q^2$: virtual photon virtuality
$\nu = E_\mu - E_{\mu'}$: energy of virt. photon
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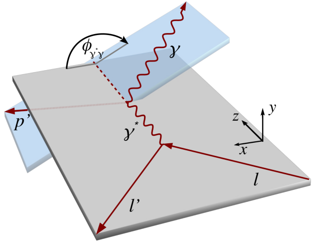
ϕ: angle between scattering and production planes



$\mu p \to \mu' p' \gamma$

Identify exclusive photon events:

- μ : beam muon
- μ' : scattered muon
- P' : recoil proton
- γ : real photon

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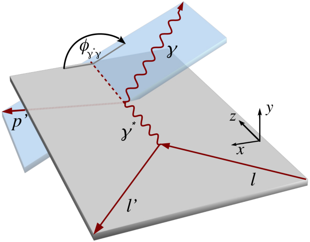

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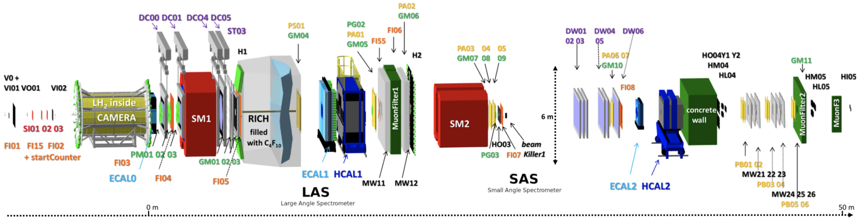
- **2012** pilot run for 4 weeks
  $\rightarrow$ analysis finished and published
- **2016/17** long runs (2 $\times$ 6 months) dedicated to DVCS
  $\rightarrow$ analysis ongoing, preliminary results

COMPASS experiment setup



COmmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

2.5m long Liquid Hydrogen target

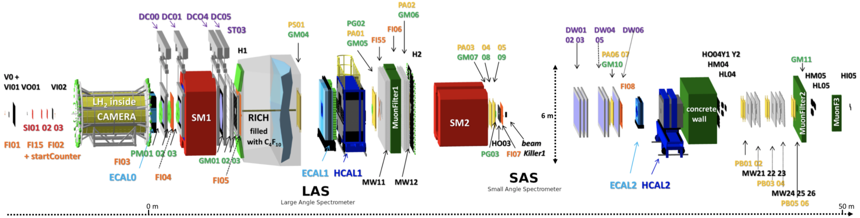
Beam energy is $140 - 180\texttt{GeV}$

Beam polarisations: $\mu^{+\downarrow}$ and $\mu^{-\uparrow}$

$\pi^+ \to \mu^+ + \nu_\mu \qquad P_{\mu^+} \approx -80\%$

$\pi^- \to \mu^- + \overline{\nu}_\mu \qquad P_{\mu^-} \approx +80\%$

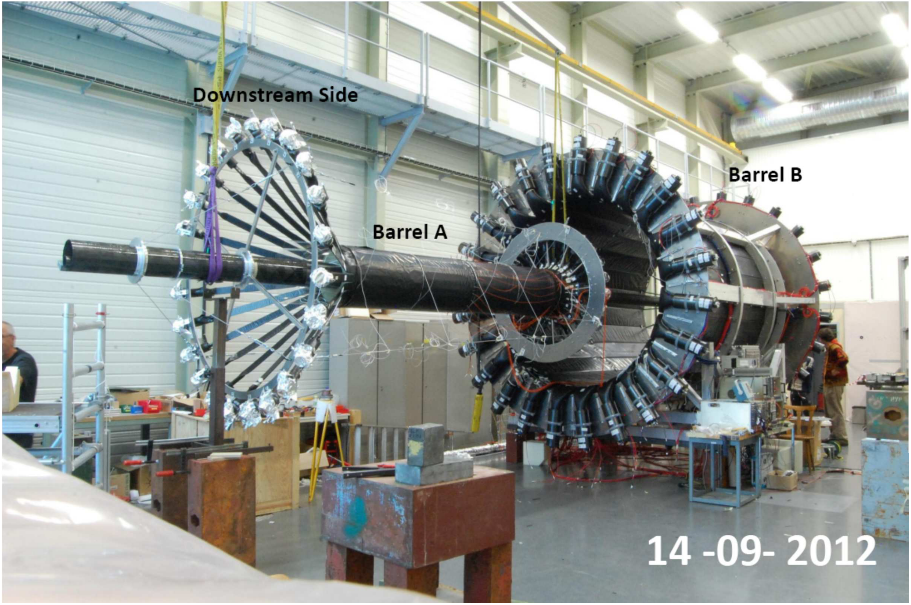
COMPASS experiment setup



Two stage forward spectrometer **SM1** + **SM2**

- Beam flux determined using true Random trigger, $\approx 1\%$ precission
- ECAL0, ECAL1 and ECAL2 for photon detection
- Muon trigger system ~ 300 tracking detector planes
- $\mu\mathtt{ID}$ for muon identification

CAMERA



Selection of events with a single γ topology

Vertex candidates:

μ Beam muon

μ' Scattered muon

Real photon candidate γ:
Single photon with the energy above DVCS threshold $E_\gamma > 4, 5, 10$ GeV in ECAL0, 1, 2

Recoil proton candidate P':
$|t|^{\mathrm{exp}}_{\mathrm{max}} = 0.64(\mathrm{GeV}/c)^2$

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Exclusivity selections:

- $|\Delta p_T| < 0.3\mathtt{GeV/c}$
- $|\Delta\phi| < 0.4\mathtt{rad}$
- $|\Delta z_A| < 16\mathtt{cm}$
- $|M^2_{\mathtt{Undet}}| < 0.3(\mathtt{GeV/c^2})^2$
- $0.08(\mathtt{GeV/c})^2 < |t_{\mathtt{fit}}| < 0.64(\mathtt{GeV/c})^2$

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Perform kinematic fit:

- constrain on kinematic variables $\chi^2 < 10$

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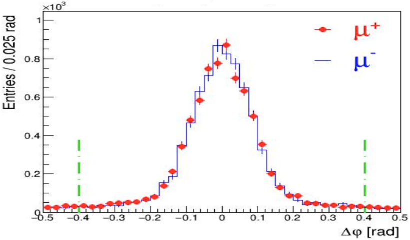
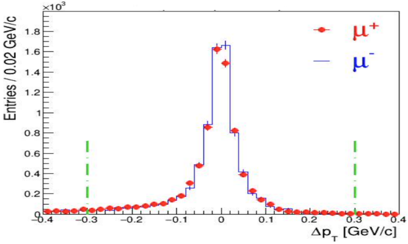
Only events with single valid combination
Vertex candidate $\times$ Real photon candidate $\times$ Recoil proton candidate

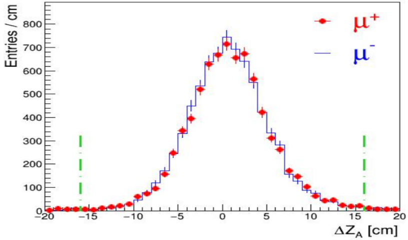
Exclusive selections (COMPASS 2016 preliminary results)



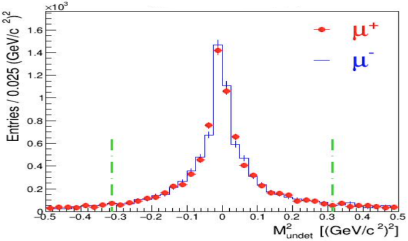
$$\Delta\phi = \phi^{\texttt{cam}} - \phi^{\texttt{spect}}$$



$$\Delta p_T = |p_T^{\texttt{cam}}| - |p_T^{\texttt{spect}}|$$



$$\Delta Z_A = Z_A^{\texttt{cam}} - Z_A^{\texttt{extrapolated}}$$



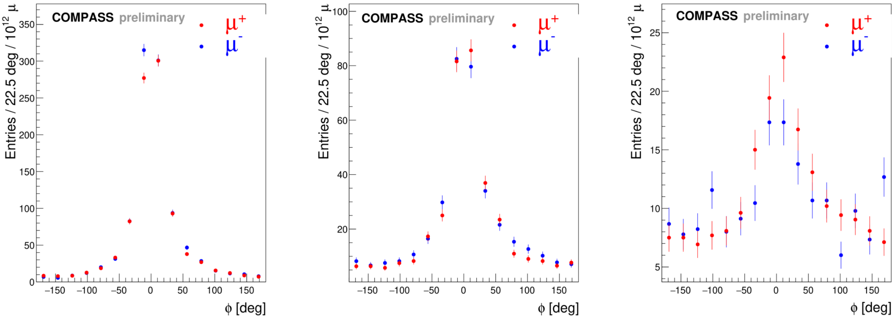
$$M^2_{\texttt{Undet}} = (p_\mu + p_P - p_{\mu'} - p_{P'} - p_\gamma)^2$$

ϕ distribution of single γ events at different ν

Bethe-Heitler dominant — 80 < ν [GeV] < 144

Interference — 32 < ν [GeV] < 80

DVCS dominant — 10 < ν [GeV] < 32

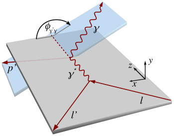


Number of reconstructed single-photon events as a function of angle ϕ.

left. $80\texttt{GeV} < \nu < 144\texttt{GeV}$ BH dominates, DVCS - negligible

middle. $32\texttt{GeV} < \nu < 80\texttt{GeV}$ BH and DVCS are comparable

right. $10\texttt{GeV} < \nu < 32\texttt{GeV}$ DVSC dominates BH



The binned DVCS cross section

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

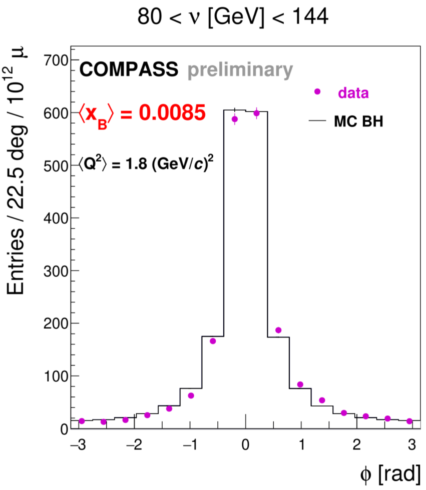
$$\left\langle \frac{d\sigma_{\texttt{DVCS}}}{d|t|d\phi dQ^2 d\nu} \right\rangle^{\pm}_{t_i \phi_j Q^2_k \nu_l} = \frac{1}{\mathcal{L}^{\pm} \Delta t_i \Delta\phi_j \Delta Q^2_k \Delta\nu_l} \left[\left(a^{\pm}_{ijkl} \right)^{-1} \left(\texttt{data} - \texttt{BH}_{\texttt{MC}} - \pi^0_{\texttt{MC}} \right) \right]$$

- $a^{\pm}_{ijkl}$ Acceptance
- $\texttt{BH}_{\texttt{MC}}$ Exclusive single photon MC sample
- $\pi^0_{\texttt{MC}}$ π^0 MC sample (background estimation)

The Bethe-Heitler contribution

Bethe-Heitler process is well known, pure QED
$\rightarrow$ evaluated using **Monte-Carlo sample** for BH

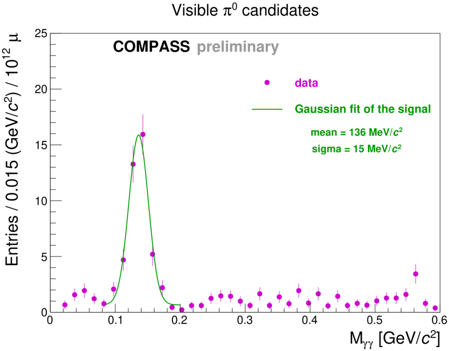
- Kinematic range where **BH is dominant**
  $\rightarrow$ **use data/MC luminosities for absolute normalization**
- **BH substracted** from the data in the DVCS region (small ν)



The π^0 background contamination

- Photons from π^0 decay
- One photon identified as exclusive photon event
  $\rightarrow$ above DVCS energy threshold in ECALs

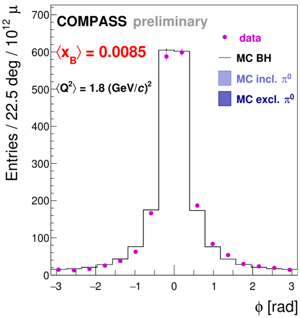
- **Visible** (both γ are detected)
  - *substracted*
  Combine $\gamma_{\mathtt{he}}$ and $\gamma_{\mathtt{le}}$ (below DVCS energy threshold)
- **Invisible** (second γ lost)
  - *estimated by MC*
  - **Inclusive**: LEPTO
  - **Exclusive**: HEPGEN π^0



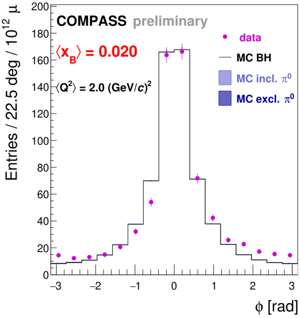
ϕ distribution of exclusive photon events

$1 < Q^2 < 10 (\mathrm{GeV}/c)^2$

80 < ν [GeV] < 144



32 < ν [GeV] < 80



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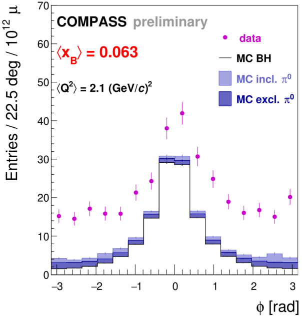

- 64% of events in data

- 24% of events in data

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

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$$\pi^0_{\mathrm{MC}} = (1 - R) \times \pi^0_{\mathtt{HEPGEN}} + R \times \pi^0_{\mathtt{LEPTO}}$$

- $\mathtt{BH}_{\mathrm{MC}}$: BH MC sample
- $\pi^0_{\mathtt{HEPGEN}}$: exclusive π^0 MC sample
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  - R: relative contrib. of LEPTO ($\approx 40\%$)
  - $a^{\pm}_{ijkl}$: acceptance

Acceptance studies limit to region with mostly flat acceptance
avg. acc. $\approx 40\%$, good agreement between μ^+ and μ^-

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Binning and kinematic range:

- 4 bins in $|t|$ between 0.08 and $0.64(\mathtt{GeV/c})^2$ (equistatistics)
- 4 bins ν between 10 and 32 $\mathtt{GeV}$ (equidistant)
- 4 bins Q^2 between 1 and $5(\mathtt{GeV/c})^2$ (equidistant)
- 8 bins ϕ between $-\pi$ and $+\pi$ (equidistant)

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Calculate the t-dependence of the cross section

From μp to $\gamma^* p$: $$\frac{d\sigma^{\mu p}}{dtdt\phi dQ^2 d\nu} = \Gamma\left(Q^2, \nu\right) \times \frac{d\sigma^{\gamma^* p}}{dtdt\phi dQ^2 d\nu}$$

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by **weighting each event** in data and MC by the inverse **flux of the transverse polarized photons**

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

Calculate the t-dependence of the cross section

From μp to $\gamma^* p$: $$\frac{d\sigma^{\mu p}}{dt dt\phi dQ^2 d\nu} = \Gamma\left(Q^2, \nu\right) \times \frac{d\sigma^{\gamma^* p}}{dt dt\phi dQ^2 d\nu}$$

by **weighting each event** in data and MC by the inverse **flux of the transverse polarized photons**

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

t-dependence for μ^+ and μ^-

$$\left\langle \frac{d\sigma_{\mathrm{DVCS}}}{d|t|} \right\rangle_{t_i}^{\pm} = \left(\Delta Q^2 \Delta\nu\right)^{-1} \Sigma_{k,l} \left\langle \frac{d\sigma_{\mathrm{DVCS}}}{d|t| dQ^2 d\nu} \right\rangle_{t_i Q_k^2 \nu_l}^{\pm} \Delta Q_l^2 \Delta\nu_l$$

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→ Integrating over ϕ dependence **removes interference and ϕ-dependent DVCS contribution**

$$\mathcal{S}_{CS,U} = d\sigma^{+\downarrow} + d\sigma^{-\uparrow} =$$
$$2\left[d\sigma^{\mathtt{BH}} + c_0^{\mathtt{DVCS}} + c_1^{\mathtt{DVCS}} cos\phi + c_2^{\mathtt{DVCS}} cos2\phi + s_1^{\mathtt{I}} sin\phi + s_2^{\mathtt{I}} sin2\phi\right]$$

Calculate the t-dependence of the cross section

From μp to $\gamma^* p$: $$\frac{d\sigma^{\mu p}}{dtdt\phi dQ^2 d\nu} = \Gamma\left(Q^2,\nu\right) \times \frac{d\sigma^{\gamma^* p}}{dtdt\phi dQ^2 d\nu}$$

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

t-dependence for μ^+ and μ^-

$$\left\langle\frac{d\sigma_{\text{DVCS}}}{d|t|}\right\rangle_{t_i}^{\pm} = \left(\Delta Q^2\Delta\nu\right)^{-1}\Sigma_{k,l}\left\langle\frac{d\sigma_{\text{DVCS}}}{d|t|dQ^2d\nu}\right\rangle_{t_iQ_k^2\nu_l}^{\pm}\Delta Q_l^2\Delta\nu_l$$

$\rightarrow$ Integrating over ϕ dependence **removes interference and ϕ-dependent DVCS contribution**

$$\mathcal{S}_{CS,U} = d\sigma^{+\downarrow} + d\sigma^{-\uparrow} =$$
$$2\left[d\sigma^{\text{BH}} + c_0^{\text{DVCS}} + c_1^{\text{DVCS}}cos\phi + c_2^{\text{DVCS}}cos2\phi + s_1^{\text{I}}sin\phi + s_2^{\text{I}}sin2\phi\right]$$

t-dependence of the cross section:

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

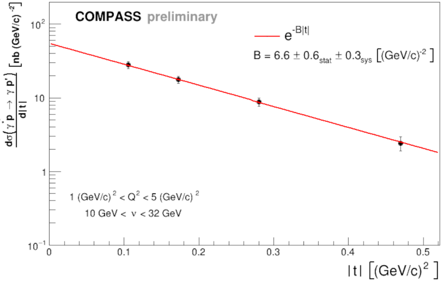
Analyse the cross section t-slope

$$d\sigma^{\texttt{DVCS}}/dt \sim e^{-B|t|} \propto c_0^{\texttt{DVCS}} = (Im\mathcal{H})^2$$

Perform binned maximum Likelyhood-fit.

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

Dominant source of systematics:
MC normalisation to visible π^0 in data.



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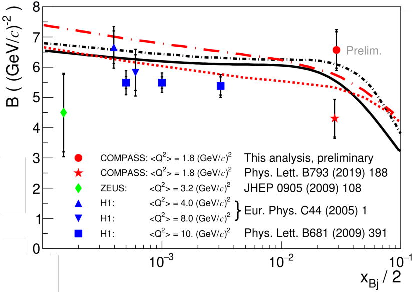

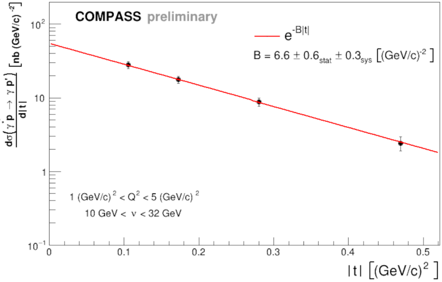

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$$B = \left(4.3 \pm 0.6_{\mathtt{stat}}{}^{+0.1}_{-0.3}|_{\mathtt{sys}}\right)(\mathtt{GeV/c})^{-2}$$

Outlook

- **Analyse full statistics** of 2016 and 2017 (3 times more data than 2016)
- More detailed studies of **systematic uncertainties**
- Cross section study in few x_{Bj} regions $\rightarrow$ tomography
- **Study the azimuthal dependence** of the cross section
  $\rightarrow$ Determine $c_0^{\mathtt{DVCS}}$, $c_1^{\mathtt{DVCS}}$, $c_2^{\mathtt{DVCS}}$, $s_1^{\mathtt{I}}$ and $s_2^{\mathtt{I}}$
- **Cross section difference** $\mathcal{D}_{CS,U} = d\sigma^{+\downarrow} - d\sigma^{-\uparrow}$
  $\rightarrow$ Access to $Re\mathcal{H}$

Thank you for your attention!

Backup

Cross section

$$d\sigma \quad \propto \quad |A_{\mathtt{BH}}|^2 \quad + \quad |A_{\mathtt{DVCS}}|^2 \quad + \quad \mathtt{Interference\ Term}$$

$$\frac{d^4\sigma(lp \to lp\gamma)}{dx_{Bj}dQ^2d|t|d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_l d\sigma^{DVCS}_{pol}\right) + \left(e_l ReI + e_l P_l ImI\right)$$

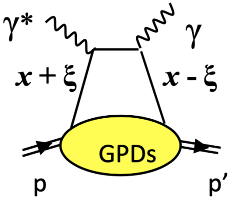
$$\mathcal{D}_{CS,U} = d\sigma^{+\downarrow} - d\sigma^{-\uparrow} = 2\left[e_\mu a^{BH} ReA^{DVCS} + |P_\mu| d\sigma^{DVCS}_{pol} + ReI\right]$$
$$= 2\left[s_1^{DVCS}\sin\phi + c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi\right]$$

$$\mathcal{S}_{CS,U} = d\sigma^{+\downarrow} + d\sigma^{-\uparrow} = 2\left[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} - |P_\mu| ImI\right]$$
$$= 2\left[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi + s_1^I\sin\phi + s_2^I\sin 2\phi\right]$$

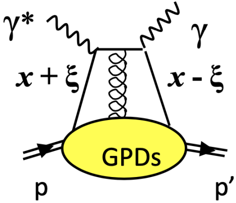
Cross section

$$\mathcal{S}_{CS,U} = d\sigma^{+\downarrow} + d\sigma^{-\uparrow} \qquad \mathcal{D}_{CS,U} = d\sigma^{+\downarrow} - d\sigma^{-\uparrow}$$

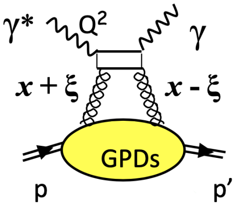
$$\begin{array}{llcl}
\mathcal{S}_{CS,U} & d\sigma^{BH} & \propto & c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
\mathcal{S}_{CS,U} & d\sigma^{DVCS}_{unpol} & \propto & c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
\mathcal{D}_{CS,U} & d\sigma^{DVCS}_{pol} & \propto & s_1^{DVCS}\sin\phi \\
\mathcal{D}_{CS,U} & ReI & \propto & c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \\
\mathcal{S}_{CS,U} & ImI & \propto & s_1^I\sin\phi + s_2^I\sin 2\phi
\end{array}$$



LO, Twist-2



LO, Twist-3



NLO, Twist-2