Deeply Virtual Compton Scattering and Hard Exclusive π^0 Muoproduction at COMPASS

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on behalf of the COMPASS collaboration
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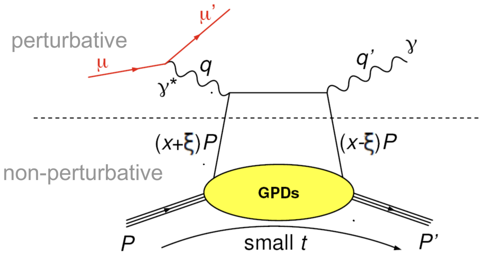
Plan

1. Generalized Parton Distribution functions
2. Measurements at COMPASS and experimental setup
3. DVCS cross-section extraction and its t-dependence
4. π^0 cross-section and its sensitivity to chiral-odd GPDs
5. Outlook and summary

Generalized Parton Distributions (GPDs)

Deeply Virtual Compton Scattering

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



- $q = (p_\mu - p_{\mu'})$: 4-momentum of virtual photon
- $Q^2 = -q^2$: virtual photon virtuality
- $t = (p_P - p_{P'})^2$: 4-momentum transfer to nucleon squared
- x: average longitudinal momentum fraction
- ξ: half of longitudinal momentum fraction transfer

No nucleon spin flip

$H^f(x, \xi, t)$

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

With nucleon spin flip

$E^f(x, \xi, t)$

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

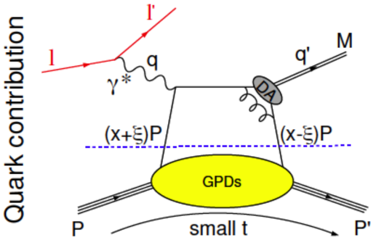
GPDs are not experimentally accessible, but related to Compton Form Factors (CFFs)

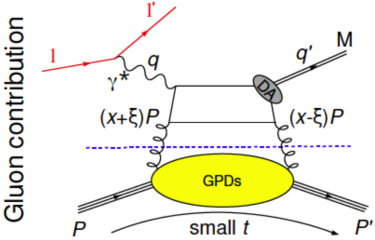
CFFs are observables in

cross section measurements

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

GPDs and Hard Exclusive Meson Production





Chiral-even GPDs
helicity of parton unchanged

$H^{q,g}$ $\tilde{H}^{q,g}$ $E^{q,g}$ $\tilde{E}^{q,g}$

Chiral-odd GPDs
helicity of parton changed

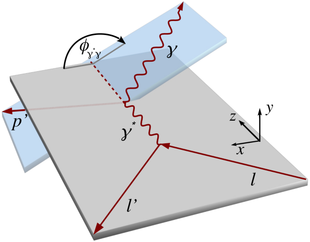
H_T^q $\tilde{H}_T^q$ E_T^q $\tilde{E}_T^q$

- factorisation proven only for σ_L, σ_T suppressed by $1/Q^2$
- wave function of meson (DA) additional non-perturbative term

Measurement at COMPASS

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

Kinematic dependence:
$Q^2 = -q^2$: virtual photon virtuality
$\nu = E_\mu - E_{\mu'}$: energy of virt. photon
$t = (p_P - p_{P'})^2$: 4-mom. transfer to nucleon squared
ϕ: angle between scattering and production planes



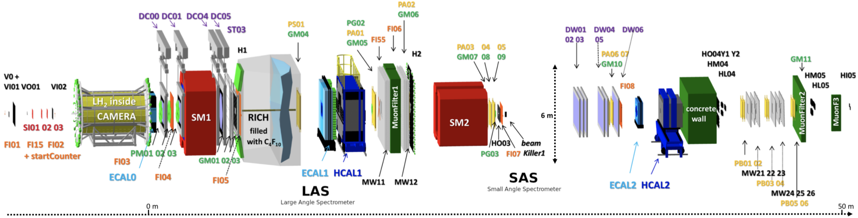
$\mu p \rightarrow \mu' p' \gamma$

Measured quantities:

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

- **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

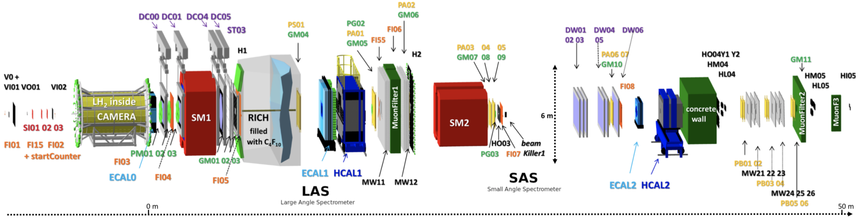
Beam energy is $160\ \mathrm{GeV}$

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

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

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

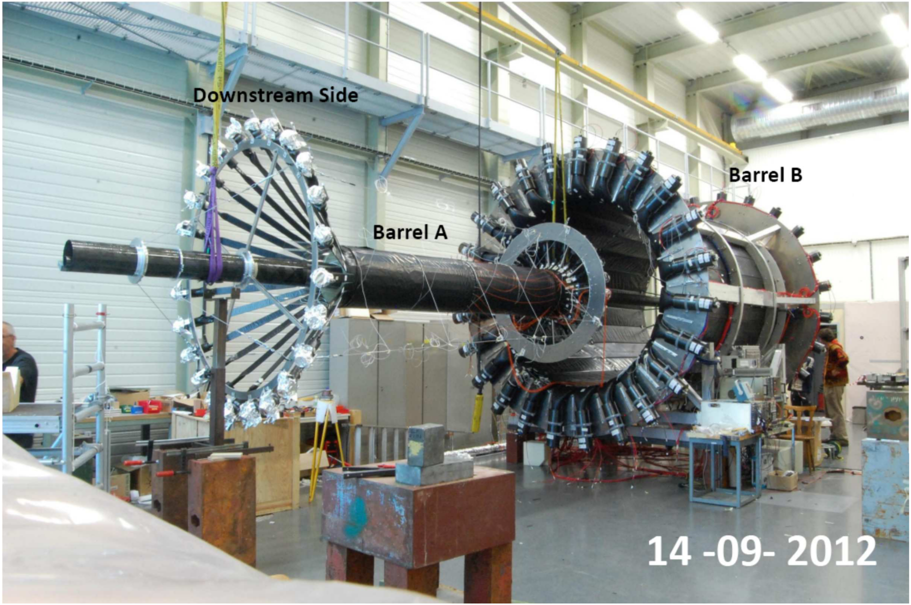
COMPASS experiment setup



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

- Beam flux determined with $\approx 1\%$ precision
- ECAL0, ECAL1 and ECAL2 for photon detection
- 300 tracking detector planes, muon trigger system
- Muon identification system
- CAMERA for recoil proton detection

CAMERA

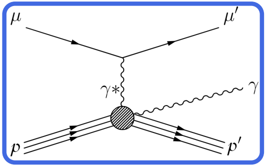


Deeply Virtual Compton Scattering

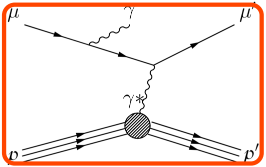
$\mu p \to \mu' p' \gamma$ process

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

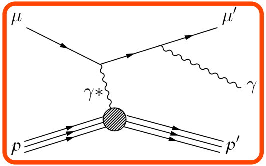
DVCS



BH



BH



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

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

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

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':
$|t|^{\mathtt{exp}}_{\mathtt{max}} = 0.64(\text{ GeV}/c)^2$

Exclusivity selections:

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

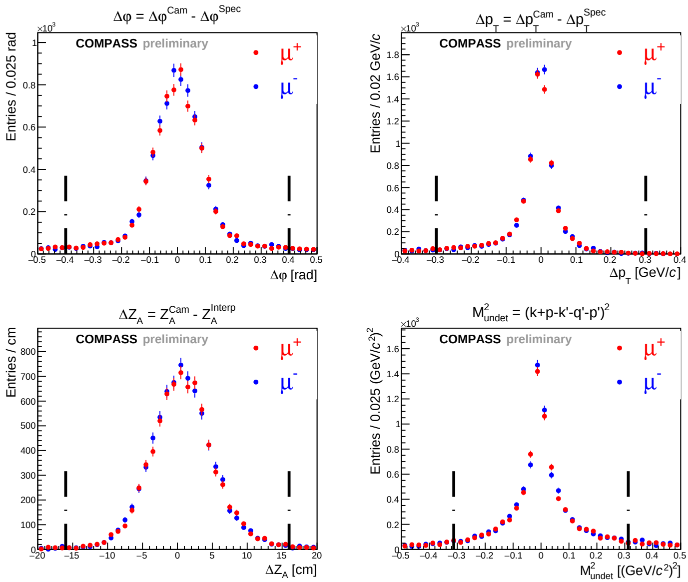
Perform kinematic fit:

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

Only events with single valid combination

Vertex candidate $\times$ Real photon candidate $\times$ Recoil proton candidate

Exclusive selections (COMPASS 2016 preliminary results)



The binned DVCS cross section

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

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

$a^{\pm}_{ijkl}$ Acceptance

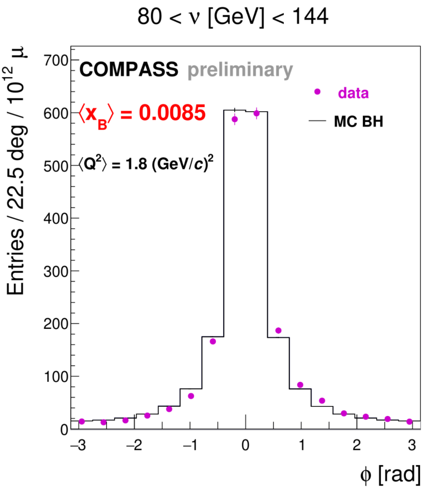
BH_{MC} Exclusive single photon MC sample

π^0_{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

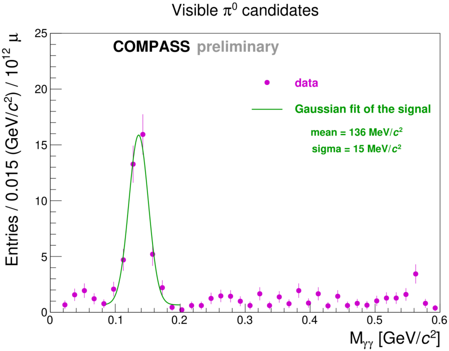
- Kinematic range where **BH is dominant**
  $\rightarrow$ The BH contribution is evaluated for the experimental integrated luminosity
- **BH substracted** from the data in the DVCS region (small ν)
- data / BH $= (98.6 \pm 1 \pm 4)\%$ (for this bin)



The π^0 background contamination

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

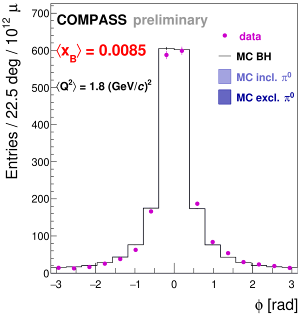
- **Visible** (both γ are detected)
  - substracted
  Combine $\gamma_{\mathtt{he}}$ and $\gamma_{\mathtt{le}}$ (below DVCS energy threshold)
- **Invisible** (second γ lost)
  - estimated by MC
  - **Inclusive**: LEPTO
  - **Exclusive**: HEPGEN π^0



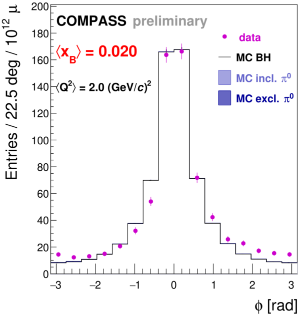
ϕ distribution of exclusive photon events

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

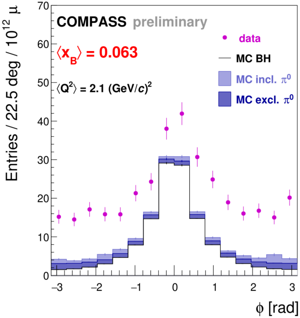
80 < ν [GeV] < 144



32 < ν [GeV] < 80



10 < ν [GeV] < 32



- **BH dominates**
  DVCS negligible
- 64% of events in data

- **BH and DVCS are comparable**
- 24% of events in data

- **DVCS dominates BH**
- 12% of events in data, where:
  - 37% BH contribution
  - 10% inv. π^0 contribution

The binned DVCS cross section

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

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

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

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

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

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)

Accessing the t-dependence of the cross section

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

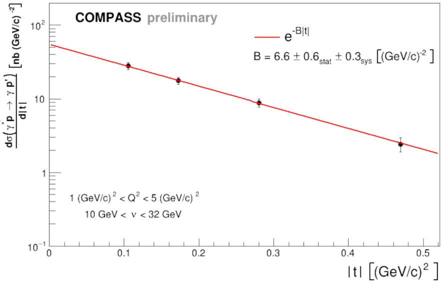
by **weighting each event** in data and MC by the inverse **flux of the transverse polarized photons**

$\rightarrow$ Integrate over Q^2 and ν and average over μ^+/μ^-, then t-dependence of the cross section:

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

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

Analyse the cross section t-slope



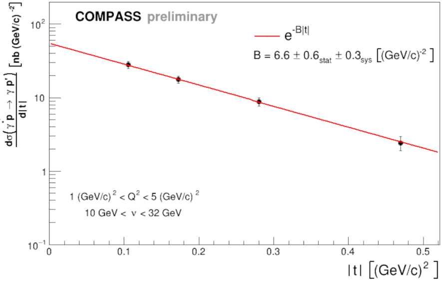
$$d\sigma^{\mathrm{DVCS}}/dt \sim e^{-B|t|} \propto c_0^{\mathrm{DVCS}} = (Im\mathcal{H})^2$$

Perform binned maximum Likelyhood-fit.

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

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

Analyse the cross section t-slope



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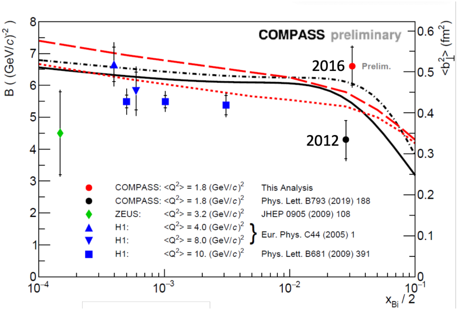
t-slope ⇒ proton trans. ext.

$$\langle b_\perp^2(x_{Bj})\rangle = 2\,\langle B(x_{Bj})\rangle\,\hbar^2$$



2012 results PLB 793 (2019) 188

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

Hard Exclusive π^0 Meson Production

$\mu p \rightarrow \mu' p' \pi^0$ process

Selection of events with π^0 topology

Vertex candidates:

μ Beam muon

μ' Scattered muon

2-γ candidate:
from π^0 decay, with invariant mass $M_{\gamma\gamma}$ cut

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

Exclusivity selections:

- $|\Delta p_T| < 0.3\mathtt{GeV/c}$
- $|\Delta\phi| < 0.4\mathtt{rad}$
- $|\Delta z_A| < 16\mathtt{cm}$
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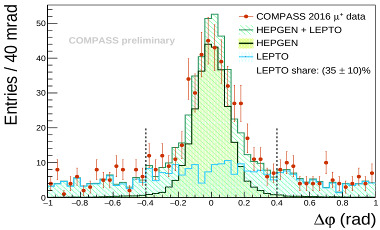
Perform kinematic fit:

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

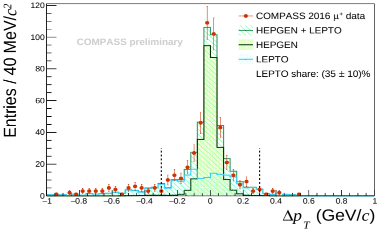
Only events with single valid combination

Vertex candidate $\times$ 2-γ candidate $\times$ Recoil proton candidate

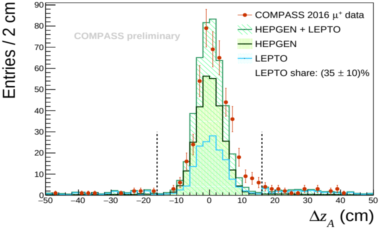
Exclusive selections (COMPASS 2016 preliminary results)



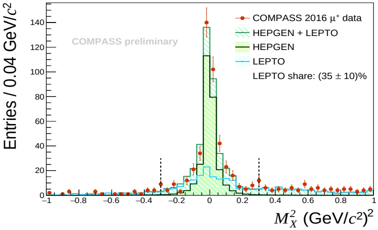
$$\Delta\phi = \phi^{\texttt{cam}} - \phi^{\texttt{spect}}$$



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



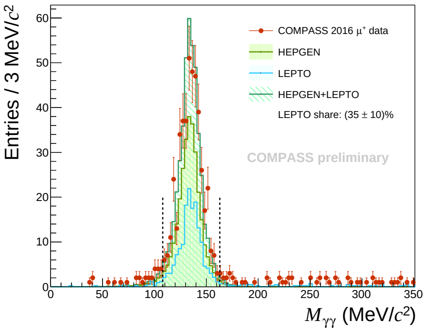
$$\Delta Z_A = Z_A^{\texttt{cam}} - Z_A^{\texttt{extrapolated}}$$



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

Exclusive π^0 production: SIDIS background estimation

- Main background of π^0 production $\Rightarrow$ non-exclusive DIS process
- 2 MC simulations with the same π^0 selection criteria:
  - LEPTO for the non-exclusive background
  - HEPGEN++ shape of distributions of exclusive π^0 production (signal contribution)
- Search for best description of data fitting by mixture of both MC



- Non-exclusive background fraction is $(35 \pm 10)\%$
- Background fit method is the main source of systematic uncertainty

Exclusive π^0 cross section

$$\frac{d^2\sigma}{dtd\phi} = \frac{1}{2\pi}\left[\left(\epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt}\right) + \epsilon\cos 2\phi\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon\left(1+\epsilon\right)}\cos\phi\frac{d\sigma_{LT}}{dt}\right]$$

Factorization proven for σ_L, not for σ_T which is expected to be suppressed by a factor $1/Q^2$ BUT large contributions are observed at JLab.

$$\frac{d\sigma_L}{dt} \sim \left|\left\langle\tilde{H}\right\rangle\right|^2 - \frac{t'}{4m^2}\left|\left\langle\tilde{E}\right\rangle\right|^2$$

$$\frac{d\sigma_T}{dt} \sim \left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\overline{E}_T\rangle\right|^2$$

$$\frac{d\sigma_{TT}}{dt} \sim \frac{t'}{16m^2}\left|\langle\overline{E}_T\rangle\right|^2$$

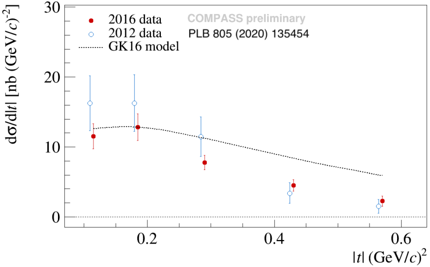
$$\frac{d\sigma_{LT}}{dt} \sim \frac{\sqrt{-t'}}{2m}Re\left[\left\langle\tilde{H}\right\rangle\left\langle\tilde{E}\right\rangle\right]$$

$t' = t - t_{min}$, where $|t_{min}|$ is minimum value of $|t|$

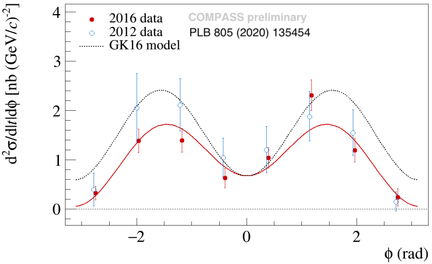
Impact of $\overline{E}_T$ should be visible in $\frac{d\sigma_{TT}}{dt}$, and also a dip at small t of $\frac{d\sigma_T}{dt}$

Exclusive π^0 cross section

as a function of t



as a function of ϕ



- **GK 16:** Goloskokov Kroll (2016)
- **other models:** Golstein Gonzalez Liuti PRD91 (2015)

Outlook and summary

- **Analyse full statistics** of 2016 and 2017 (3 times more data than 2016)
- DVCS
  - Cross section study in few x_{Bj} regions $\rightarrow$ tomography
  - More detailed studies of **systematic uncertainties**
  - **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 $Re\mathcal{H}$ and quark preassure distribution in the nucleon
- Exclusive π^0
  - New, preliminary results of 2016 COMPASS measurement at $\langle x_{Bj} \rangle = 0.096 \Rightarrow$ constraining phenomenological models (e.g. Goloskokov and Kroll; Goldstein, Gonzales and Liuti, etc.)

Thank you for your attention!

Backup

Cross section

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

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

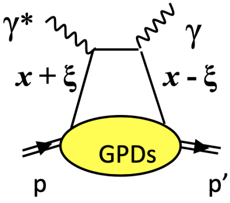
$$\mathcal{D}_{CS,U} = d\sigma^{+\downarrow} - d\sigma^{-\uparrow} = 2\left[e_\mu a^{BH} ReA^{DVCS} + |P_\mu| d\sigma^{DVCS}_{pol} + ReI\right]$$
$$= 2\left[s_1^{DVCS}\sin\phi + c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi\right]$$

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

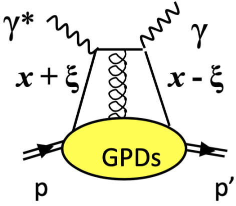
Cross section

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

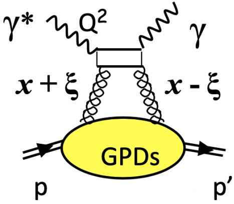
$$
\begin{array}{llll}
\mathcal{S}_{CS,U} & d\sigma^{BH} & \propto & c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
\mathcal{S}_{CS,U} & d\sigma^{DVCS}_{unpol} & \propto & c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
\mathcal{D}_{CS,U} & d\sigma^{DVCS}_{pol} & \propto & s_1^{DVCS}\sin\phi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



LO, Twist-2



LO, Twist-3



NLO, Twist-2

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