Results of DVCS measurement at COMPASS

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on behalf of the COMPASS collaboration

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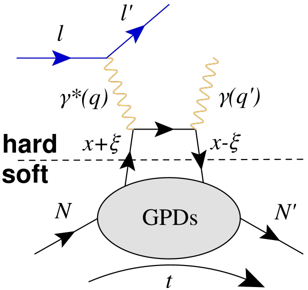
Generalized Parton Distribution functions (GPDs)



Kinematic dependence:

- q : 4-mom. of virtual photon
  $q = (\nu, \vec{q})$ ($Q^2 = -q^2$)
- $x_{Bj} = Q^2/2m_N\nu$
- x: avg. longitudinal momentum fractions
- ξ: longitudinal momentum difference (related to x_{Bj})
- t: momentum transfer to nucleon squared

- Parameterize nucleon structure in **hard exclusive reactions** e.g.
  - Deeply Virtual Compton Scattering (DVCS)

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

4 (chiral-even) GPDs for each quark flavour
in LO and leading twist

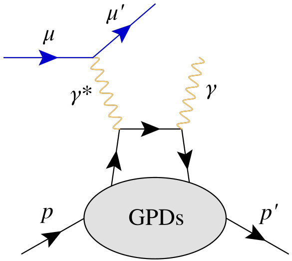
$$H^f(x,\xi,t) \qquad E^f(x,\xi,t)$$
$$\widetilde{H}^f(x,\xi,t) \qquad \widetilde{E}^f(x,\xi,t)$$

- No nucleon spin flip
- With nucleon spin flip

GPDs not experimentally accessible
→ Related to **Compton Form Factors (CFFs)**

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

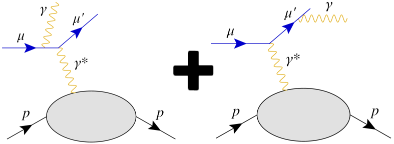
⇒ **CFFs** are observables
in **cross section measurements**



Deeply Virtual Compton Scattering (DVCS)

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

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



Cross section of exclusive photon production:

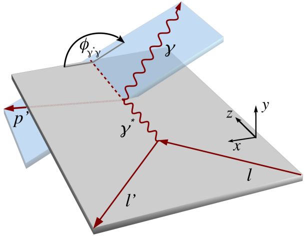
$$\sigma(\mu p \rightarrow \mu' p' \gamma) = \sigma_{DVCS} + \sigma_{BH} + \sigma_{Int.}$$

Measurement @ COMPASS

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

Kinematic dependence:

- Q^2 : 4-momentum squared 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 photon events:

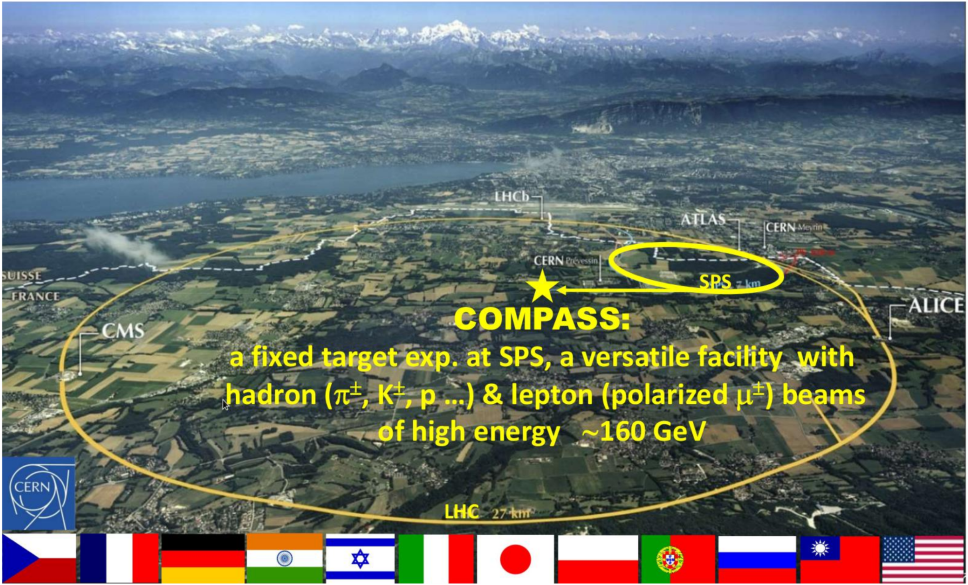
Incoming muon
Scattered muon
Recoil proton
Real photon

} overconstrained

Data taking @COMPASS:

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

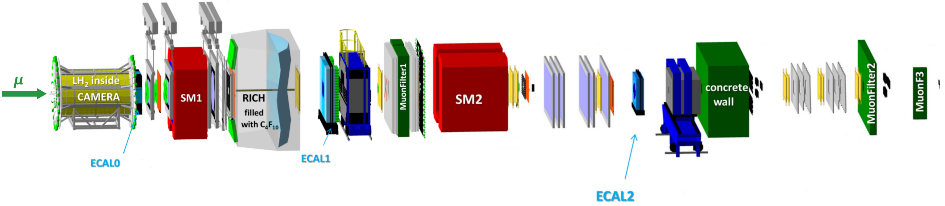
The COMPASS experiment at CERN



COMPASS spectrometer (2016/17)

Two stage forward spectrometer SM1 + SM2

- Beam flux determined using true Random Trigger
  $\sim$ 1% precision
- ECAL0, ECAL1 and ECAL2 (Photon detection)
- Muon trigger system (μID)
  $\sim$ 300 tracking detector planes



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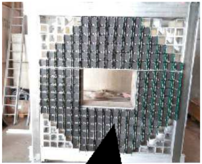
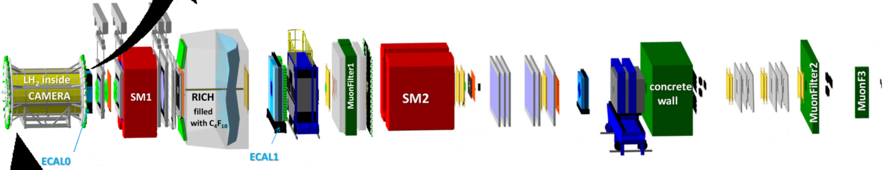


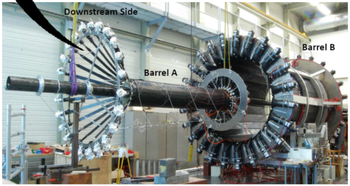
ECAL0 **(increase angular acceptance of photons):**

Sampling calorimeter (scintillator-lead-sandwich)

$\sim$ 2 x 2 m^2, hole 60 cm x 84 cm

194 modules each consists of 9 cells (4 x 4 cm^2)





Liquid hydrogen target (2.5 m, ∅4 cm)

Proton Recoil Detector:

Inner & outer ring (R_A=25 cm, R_B=110 cm)

each consisting of 24 scintillator slabs

TOF measurement:

δt=330 ps

Selection of exclusive photon events

Vertex candidates:

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

Real photon candidate:

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

Recoil proton candidates:

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

Additional conditions:

→ use **overconstrain** of measurement

- Improve event selection by adding **"exclusivity conditions"**
- Perform a **kinematic fit**
  → **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 × γ candidate × **Proton candidate**

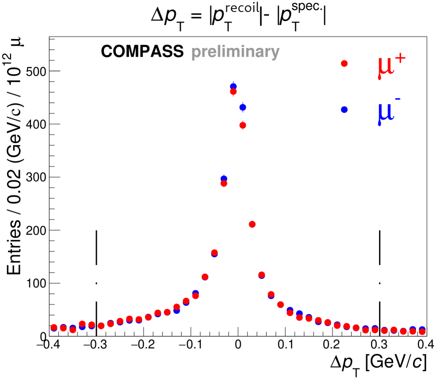
Exclusivity conditions for proton kinematics

Exclusivity variables

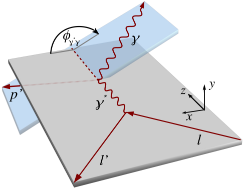
- **$\Delta\varphi$:** $\Delta\varphi = \varphi^{recoil} - \varphi^{spec.}$
- **Δp_T:** $\Delta p_T = |p_T^{recoil}| - |p_T^{spec.}|$
- **ΔZ_A:** $\Delta Z_A = Z_A^{recoil} - Z_A^{spec.}$
- **Missing mass:** $M_x^2 = (k + p - k' - q' - p')^2$

spec.: Lorentz Vector of proton calculated from 4-Momentum conservation

recoil: Lorentz Vector of proton by measurement of recoil detector



ϕ distribution

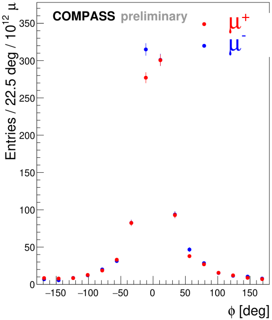


High beam energy (160 GeV)

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

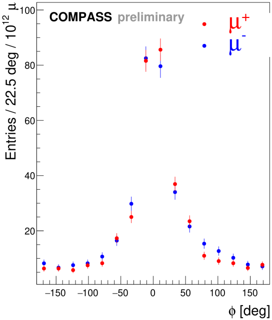
Bethe-Heitler dominant

$80 < \nu$ [GeV] < 144



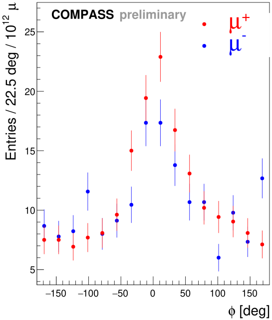
Interference

$32 < \nu$ [GeV] < 80



DVCS dominant

$10 < \nu$ [GeV] < 32



The binned DVCS cross section

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

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

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

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

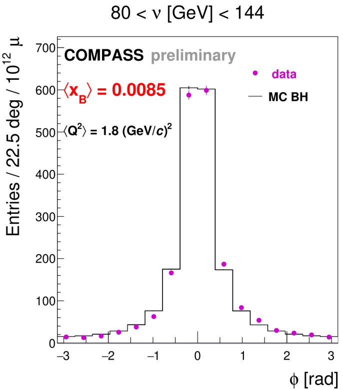
The Bethe-Heitler contribution

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

- **HEPGEN generator** for simulating exclusive events

Handling BH contribution:

- Kinematic range where **BH is dominant**
  $\rightarrow$ **use data luminosity as absolute normalization**
- **BH subtracted** from the data in the DVCS region (small ν)



98.6±1% agreement between data and MC

The π^0 background contamination

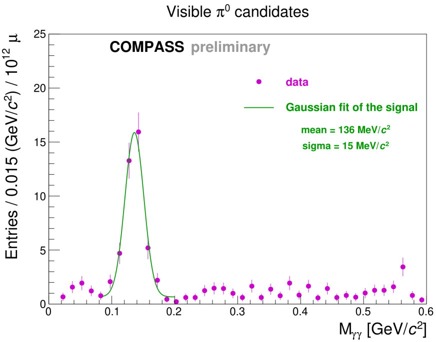
- Photons from π^0 **decay**
- **One photon identified as exclusive photon event**
  $\rightarrow$ above DVCS energy threshold in ECALs

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

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

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

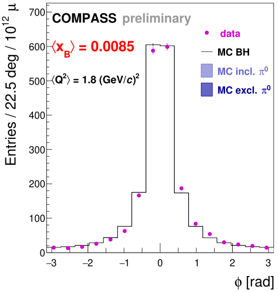
$\rightarrow$ MC samples **normalized to vis. π^0 in data**



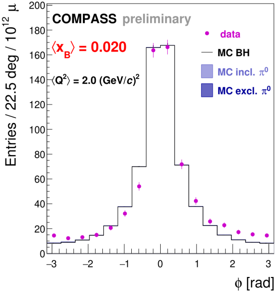
ϕ distribution of exclusive photon events

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

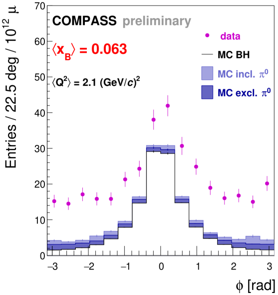
80 < ν [GeV] < 144



32 < ν [GeV] < 80



10 < ν [GeV] < 32



- 64% of events in data

- 24% of events in data

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

The binned DVCS cross section

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

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

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

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

- BH_{MC}: BH MC sample
- π^0_{HEPGEN}: exclusive π^0 MC sample
- π^0_{LEPTO}: inclusive π^0 MC sample

- R: Relative contribution of LEPTO (∼40%)
- $a^{\pm}$: Acceptance

Binning and kinematic range:

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

Acceptance studies
→ limit to region with **mostly flat acceptance**

avg. acc. ∼40%,
good agreement
between μ^+ and μ^-

Calculate the t-dependence of the cross section

From μp to $\gamma^* p$:

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

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

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

t-dependence for μ^+ and μ^-:

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

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

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

t-dependence of the cross section:

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

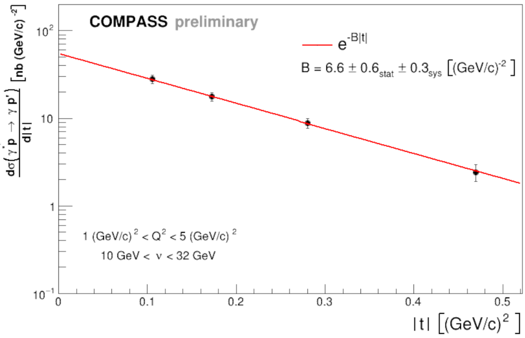
Analyse the cross section t-slope

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

Perform **binned maximum Likelihood-fit**

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

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



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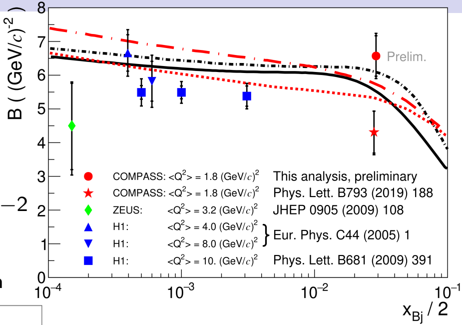
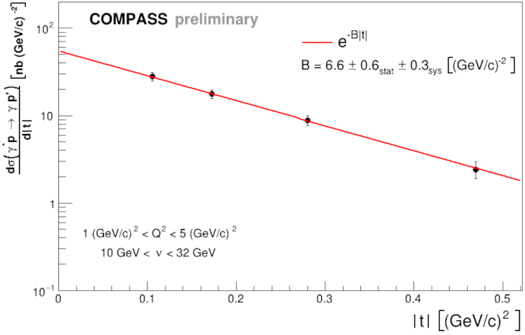




2012 results PLB 793 (2019) 188

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

Outlook

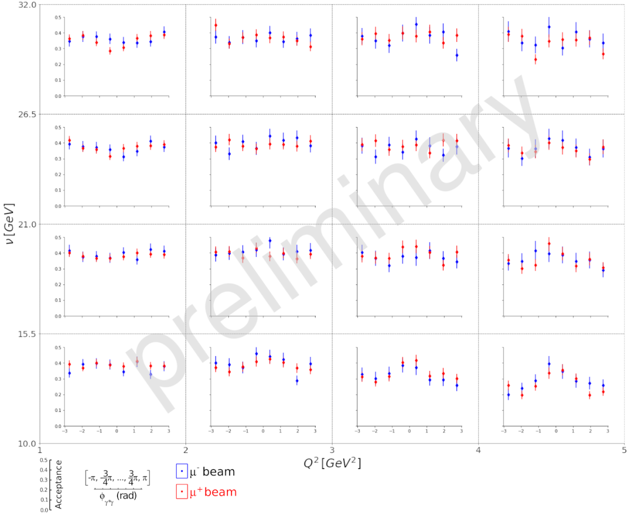
- **Analyse full statistics** of 2016 and 2017 (about 3 times more than 2016)
- More detailed studies of **systematic uncertainties**
- Cross section study in several x_{Bj} regions
- **Study the azimuthal dependence** of the cross section
  $\rightarrow$Determine c_0^{DVCS}, c_1^{DVCS}, c_2^{DVCS},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

Thank you for your attention.

Backup

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^-