The DVCS Physics Program at COMPASS

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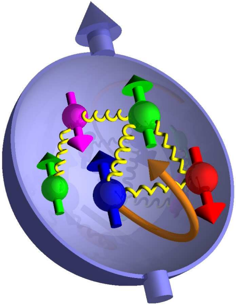
for the COMPASS Collaboration

PHOTON2015 - Novosibirsk, 15-19/06/2015

Where does the spin of the nucleons come from?

Proton spin sum rule: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

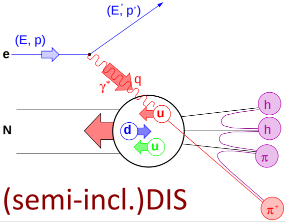


The ``proton spin crisis'':

$$\Delta\Sigma \rightarrow \begin{cases} \text{Static quark model}: \ \Delta\Sigma = 1 \\ \text{Weak baryon decays}: \ \Delta\Sigma \simeq 0.58 \\ \text{Experiments}: \ \Delta\Sigma \simeq 0.3 \end{cases}$$

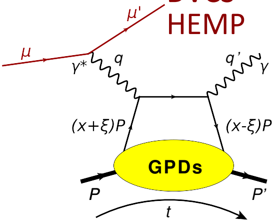
$\Delta G = ??$ $\quad L_{q,g} = ??$

COMPASS experimental tools:

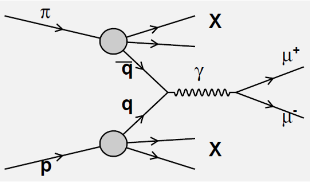


(semi-incl.)DIS

DVCS
HEMP



Pol. Drell-Yan



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This talk:

COMPASS experimental tools:

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DVCS

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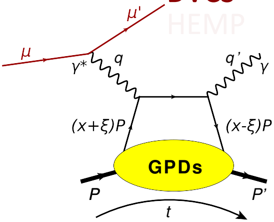
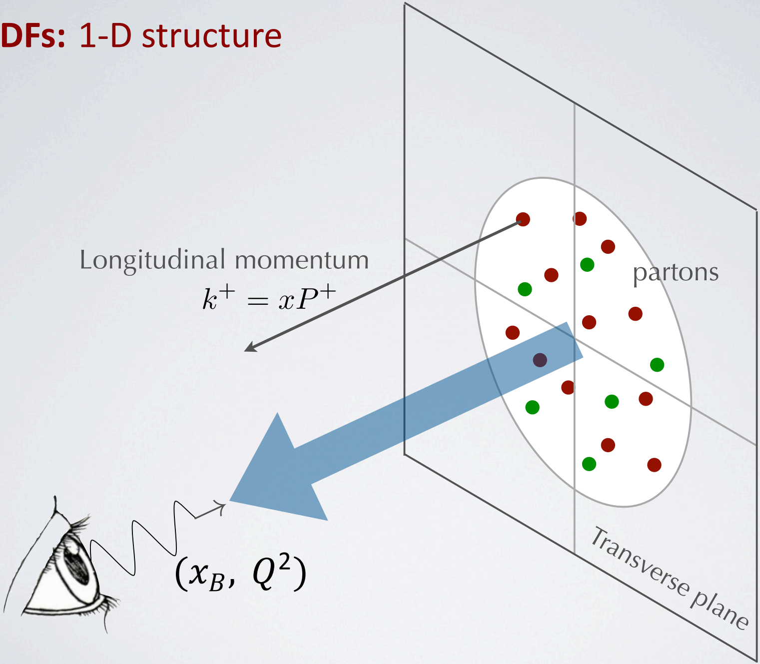


Pol. Drell-Yan

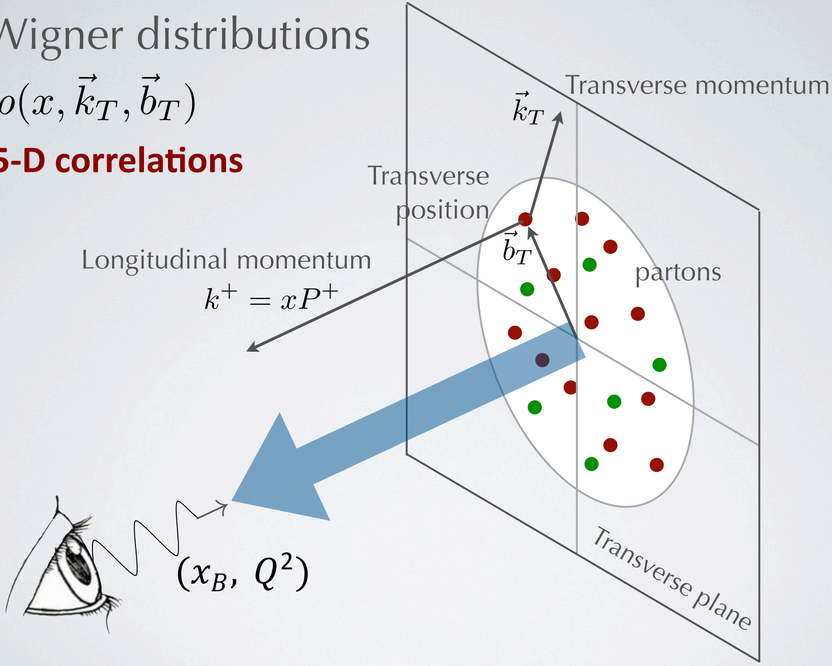
PDFs: 1-D structure



Wigner distributions

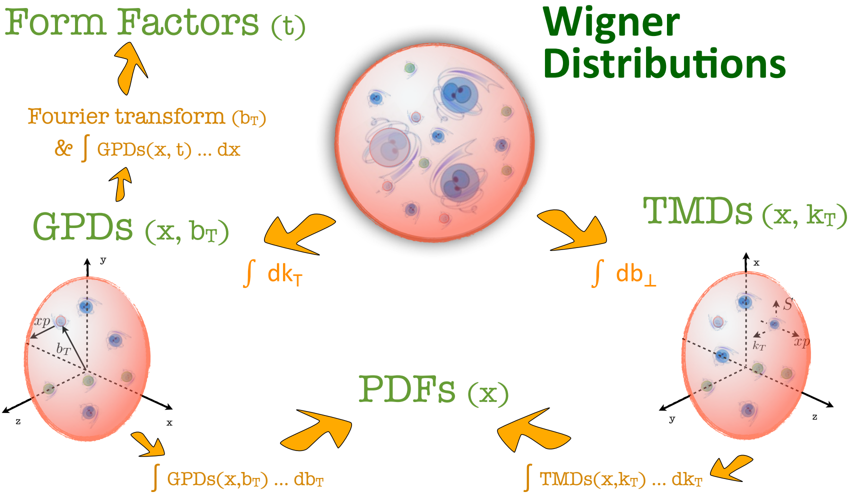
$$\rho(x, \vec{k}_T, \vec{b}_T)$$

5-D correlations



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Towards a 3D Picture of the Nucleon…

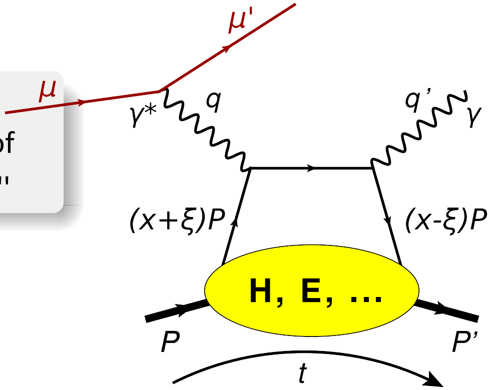


PDFs → $\Delta\Sigma$, ΔG

TMDs, GPDs → { nucleon"tomography" ; $L_{q,g}$ }

Introduction to GPDs

``GPDs are **non-perturbative** objects entering the description of **hard exclusive** electroproduction''



Definition of variables:

- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2-x_B)$
- t: four-momentum transfer
  related to $b_\perp$ via Fourier transform

Introduction to GPDs

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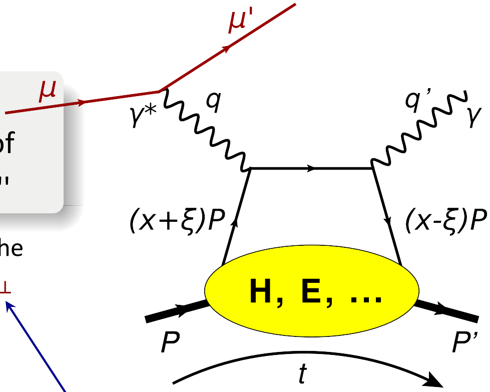
They encode **CORRELATIONS** between the long. mom. $\mathbf{x}$ and the transv. position $\mathbf{b}_\perp$ of partons



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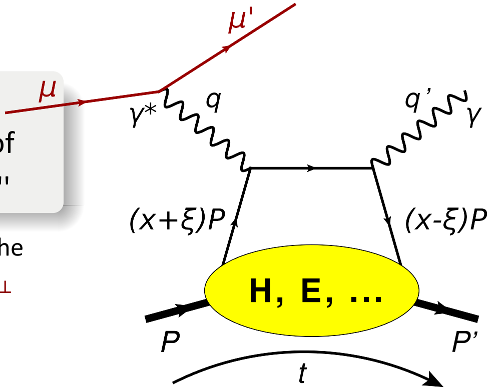

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Experimentally accessible through Compton Form Factors (CFFs):

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

$$\mathbf{Re}\mathcal{H}(\xi, \mathbf{t}) = \int \frac{\mathbf{dx\, H(x, x, t)}}{(\mathbf{x} - \xi)} + \mathbf{Dterm}$$

Definition of variables:

- x: average long. momentum - NOT ACCESSIBLE
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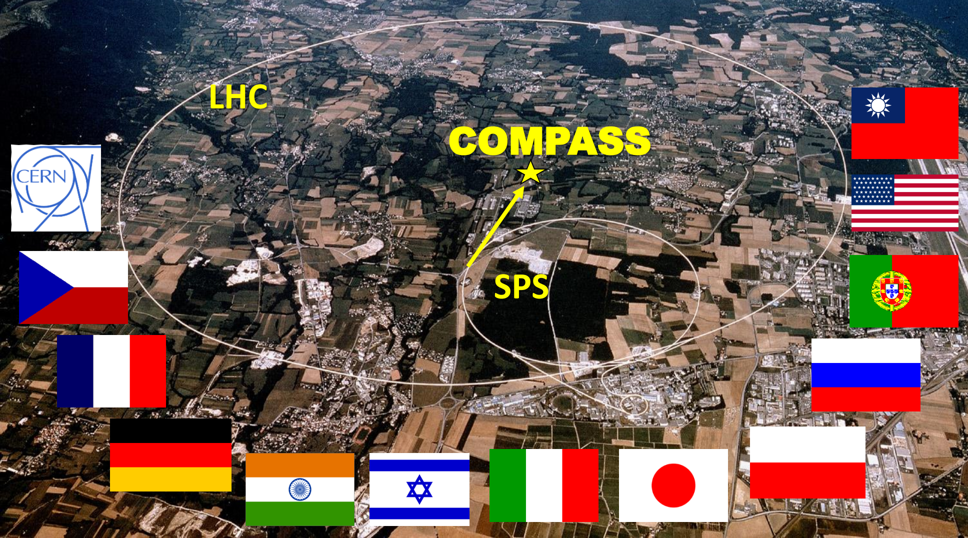
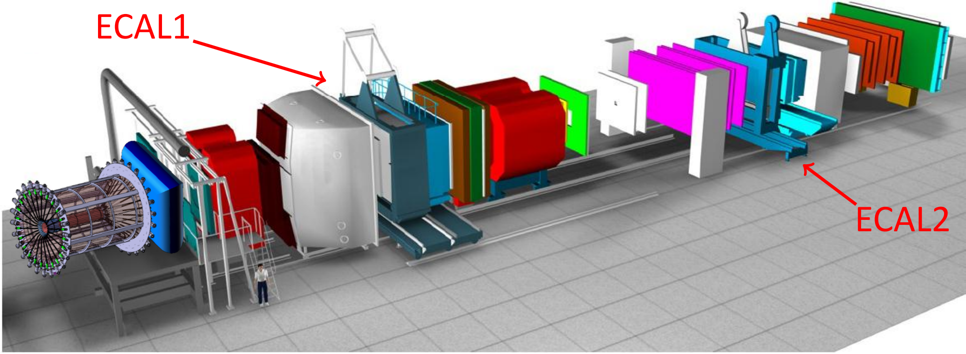
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

COMPASS: Versatile facility to study QCD with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) and lepton (polarized $\mu^{\pm}$) beams of ~200 GeV for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP…



The COMPASS set-up for the GPD program

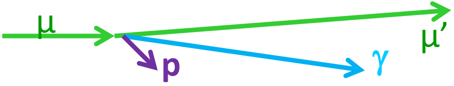


Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

- Ring Imaging Cerenkov Detector
- Electromagnetic calorimeters (**ECAL0**, **ECAL1** & **ECAL2**)
- Hadronic calorimeters
- Muon absorbers

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



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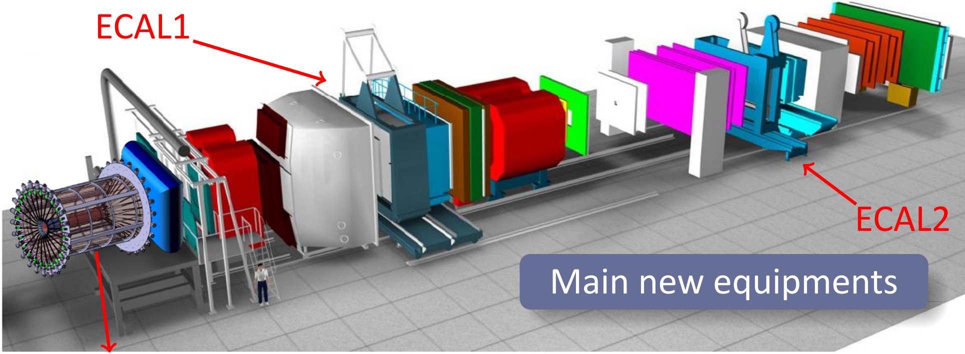

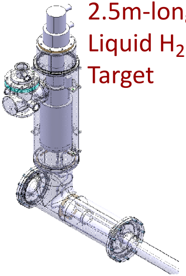

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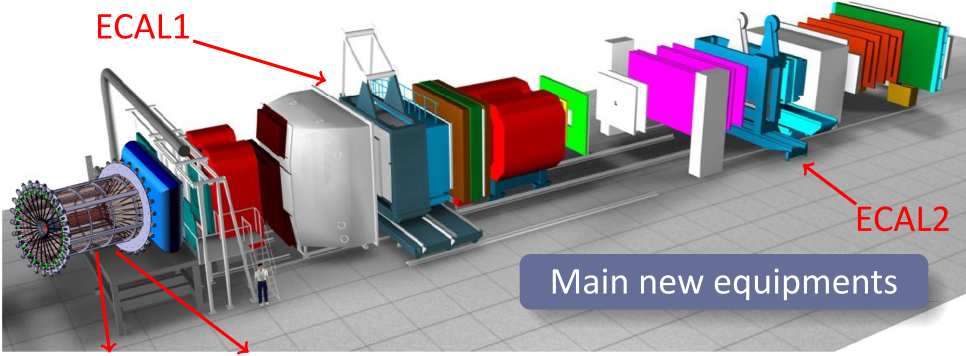
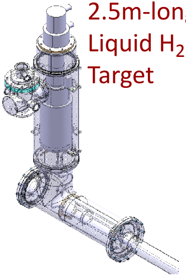
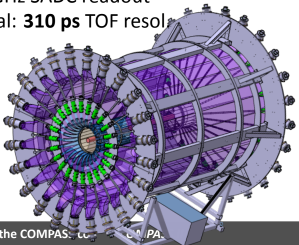




2.5m-long
Liquid H_2
Target

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



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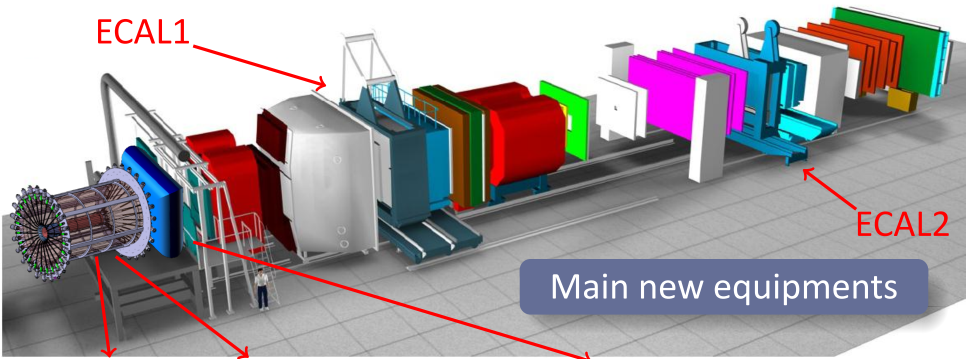
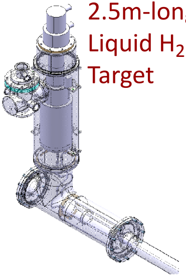
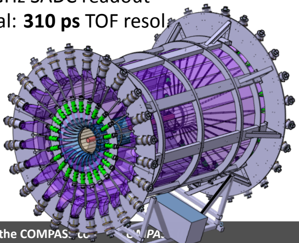




2.5m-long Liquid H_2 Target

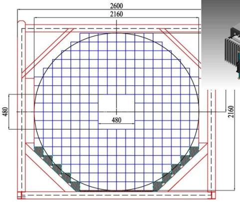
Target TOF System

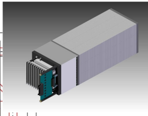
24 inner & outer scintillators
1 GHz SADC readout
goal: **310 ps** TOF resol.



ECAL0 Calorimeter

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





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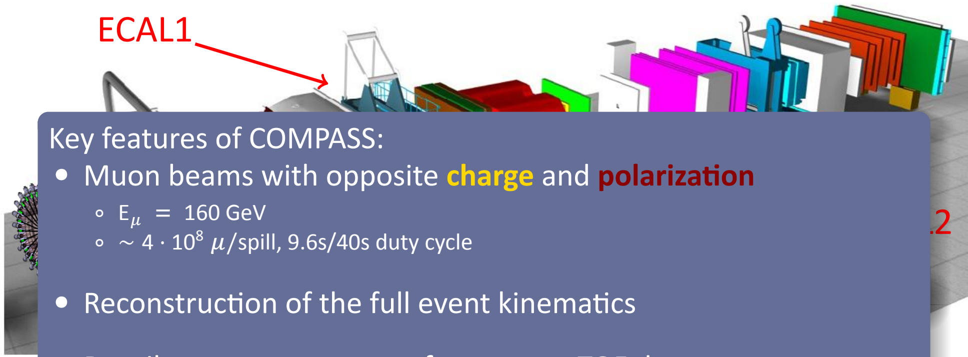
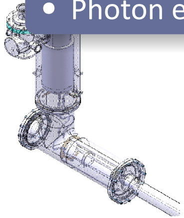
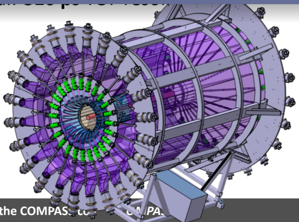
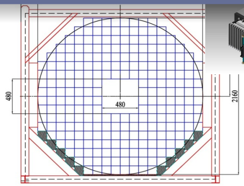


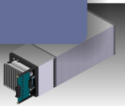
Key features of COMPASS:

- Muon beams with opposite **charge** and **polarization**
  - $E_{\mu} = 160$ GeV
  - $\sim 4 \cdot 10^{8}$ μ/spill, 9.6s/40s duty cycle
- Reconstruction of the full event kinematics
- Recoil proton momentum from target TOF detector
- Photon energy and angle from ECALs









The GPD Physics Program at COMPASS

2008: Very short test run, short LH_2 target

- Observation of exclusive photon production
- Confirmed the global efficiency $\simeq$ 10% used for projections

2009: **10 days**, short LH_2 target

- Coarse binning in x_B
- First hint of DVCS at large x_B

2004-10: Exclusive ρ^0 and ω^0 meson production on a **transv. pol. target** and **no recoil detector**

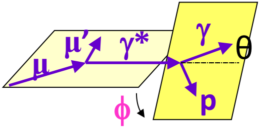
2012: **4 weeks**, full-scale LH_2 target and recoil detector

2016-7: **2 x 6 months** with LH_2 target and recoil det. → **GPD $\mathbf{H}$**

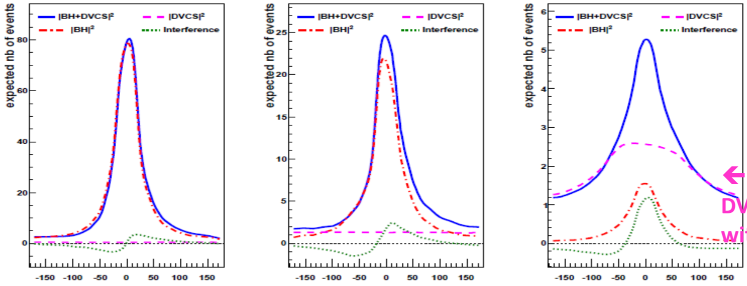
>2018: DVCS with **transv. pol. target** and **recoil detector** → **GPD $\mathbf{E}$**
Future addendum to COMPASS-II proposal

The DVCS Process at COMPASS Kinematics

Deep VCS Bethe-Heitler



$d\sigma \propto |T^{BH}|^2$ + Interference Term + $|T^{DVCS}|^2$



$0.005 < x_B < 0.01$ $0.01 < x_B < 0.03$ $0.03 < x_B$

Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

← Missing DVCS acceptance without ECAL0

BH dominates

excellent reference yield

study of Interference

→ Re T^{DVCS} or Im T^{DVCS}

DVCS dominates

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

→ Transverse Imaging

Measurements of DVCS and BH Cross-sections

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

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

Charge & Spin Difference and Sum:

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int} \cos\phi \quad \text{and} \quad c_{0,1}^{Int} \sim F_1 \, \mathcal{R}e \, \mathcal{H}$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int} \sin\phi \quad \text{and} \quad s_1^{Int} \sim F_1 \, \mathcal{I}m \, \mathcal{H}$$

$$c_1^{Int} \propto \mathcal{R}e \left(F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - t/4m^2 F_2 \mathcal{E} \right)$$

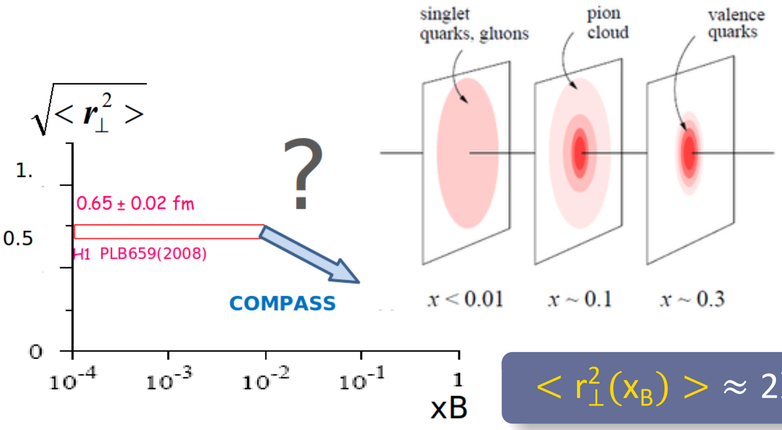
NOTE: ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics
✓ only leading twist and LO

Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin **SUM**:

$$\mathbf{S_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K s_1^{Int} \sin\phi}$$

Integration over ϕ and BH subtraction → $\mathbf{d\sigma^{DVCS}/dt \sim \exp(-B|t|)}$



$$< r_\perp^2(x_B) > \approx 2B(x_B)$$

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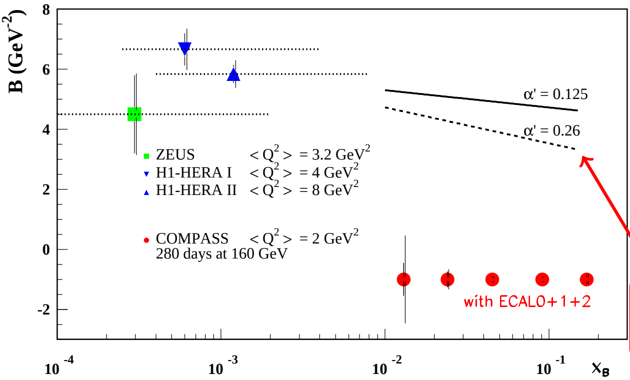

expected statistical and systematic uncertainties are shown

2 x 6 months of data in 2016-2017

2.5 m LH_2 target

ε_{global} = 10%

Ansatz at small x_B:
$B(x_B) \simeq B_0 + 2\alpha' \ln(x_0/x_B)$

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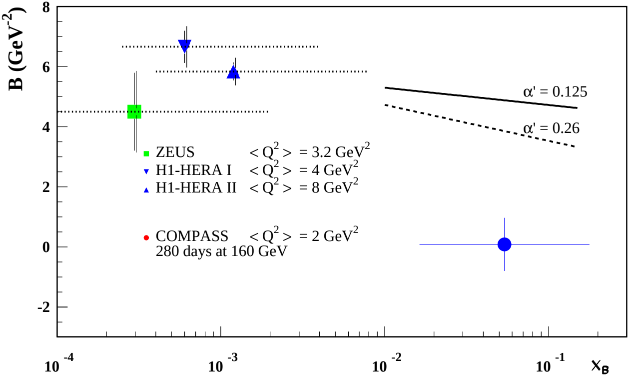
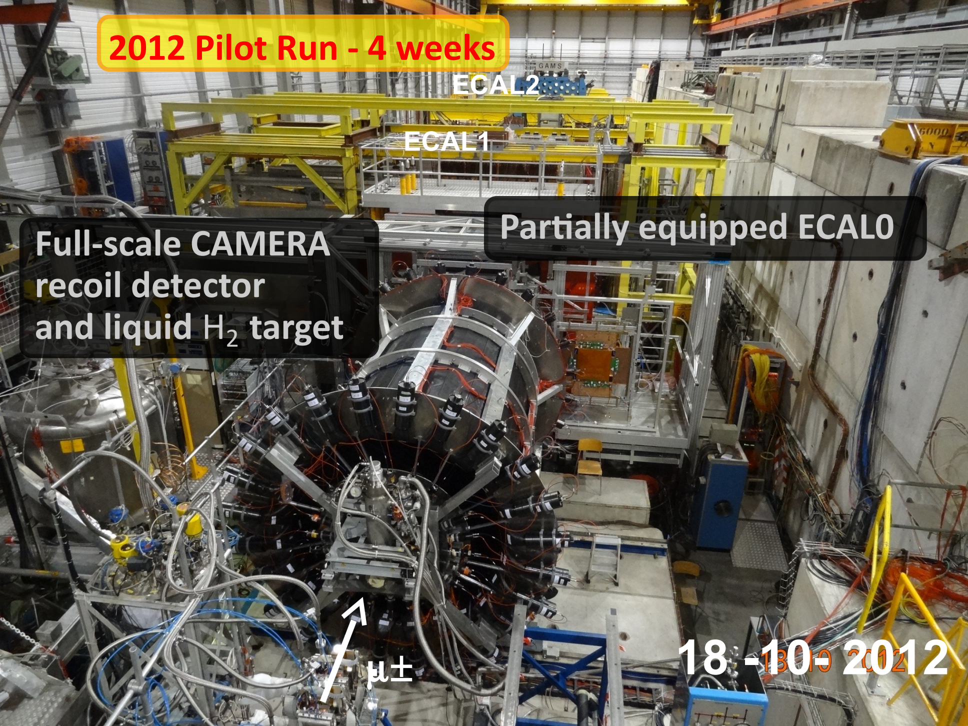


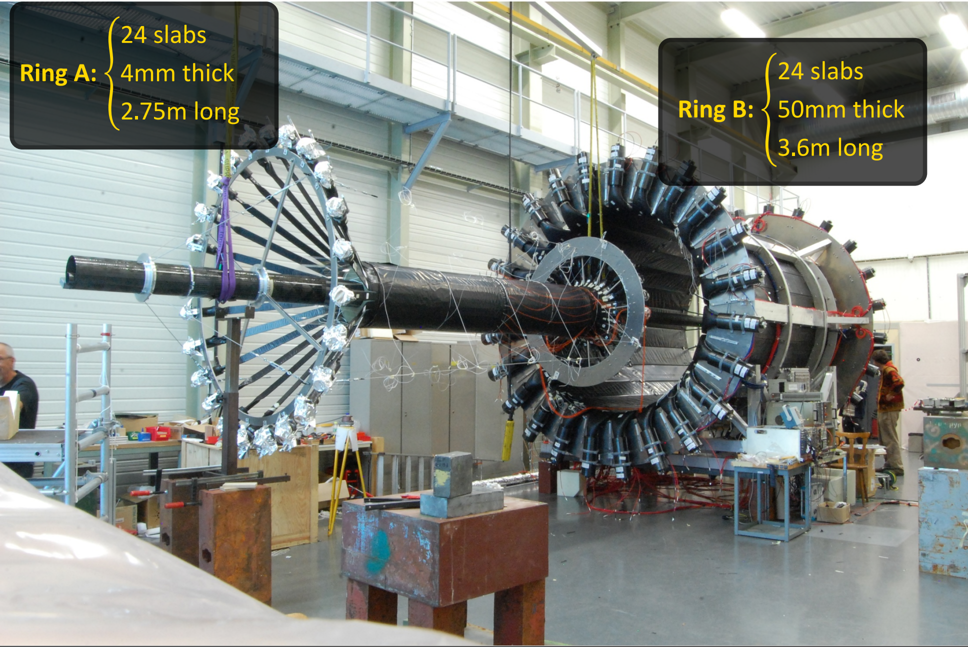
4 weeks in 2012

2.5 m LH_2 target

2012: **we can expect one mean value of B in the COMPASS kinematic range**


2012 Pilot Run - 4 weeks
ECAL2
ECAL1
Full-scale CAMERA
recoil detector
and liquid H_2 target
Partially equipped ECAL0
μ±
18 -10- 2012

The Recoil TOF Detector CAMERA

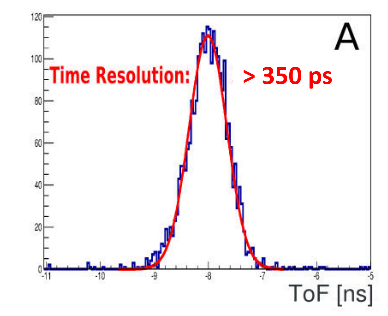


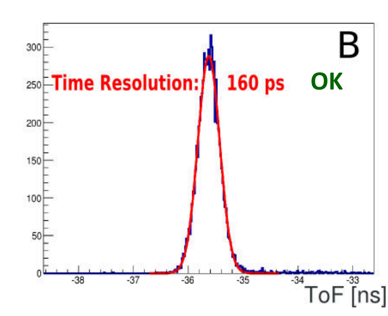
The Recoil TOF Detector CAMERA

Ring A:
- 24 slabs
- 4mm thick
- 2.75m long

Ring B:
- 24 slabs
- 50mm thick
- 3.6m long

Time resolution measurement with cosmics





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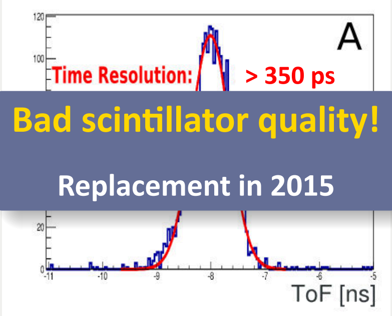
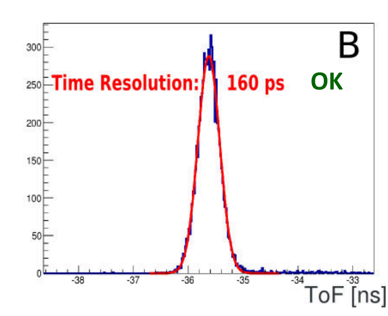


Bad scintillator quality!

Replacement in 2015



Exclusive Photon Events Selection

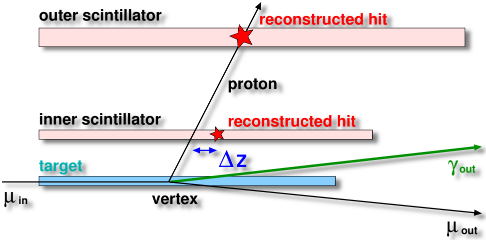
Reconstructed interaction vertex in **target volume**

One single photon above DVCS production threshold

$Q^2 > 1\ (\mathrm{GeV}/c)^2$, $0.05 < y < 0.9$, $0.06\ (\mathrm{GeV}/c)^2 < t < 0.64\ (\mathrm{GeV}/c)^2$

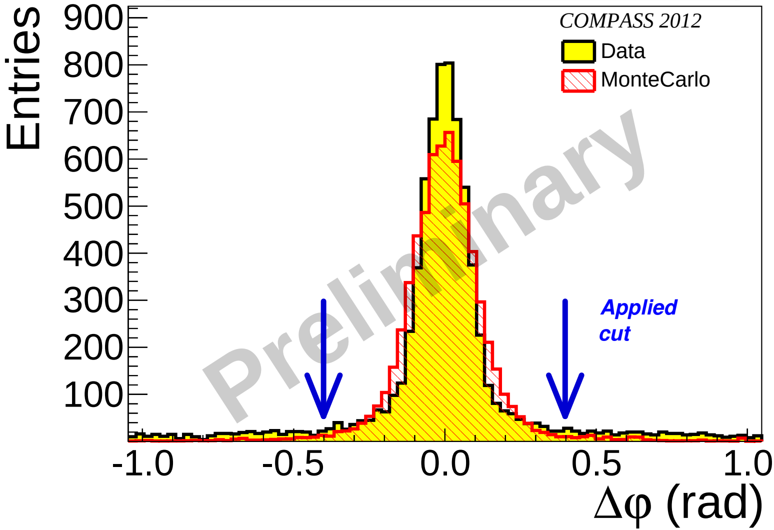
Exclusivity conditions:

- $\Delta\varphi = \varphi^{\mathrm{proton}}_{\mathrm{meas}} - \varphi^{\mathrm{proton}}_{\mathrm{reco}}$
- Vertex pointing (ΔZ)
- Transv. momentum balance:
  $\Delta p_\perp = p^{\mathrm{proton}}_{\perp,\mathrm{meas}} - p^{\mathrm{proton}}_{\perp,\mathrm{reco}}$
- Four-momentum balance:
  $M_X^2 = (p_{\mu_{\mathrm{in}}} + p_{p_{\mathrm{in}}} - p_{\mu_{\mathrm{out}}} - p_{p_{\mathrm{out}}} - p_\gamma)^2$
- Missing energy: $((p_{\mu_{\mathrm{in}}} + p_{p_{\mathrm{in}}} - p_{\mu_{\mathrm{out}}} - p_\gamma)^2 - M_p^2)/2M_p$

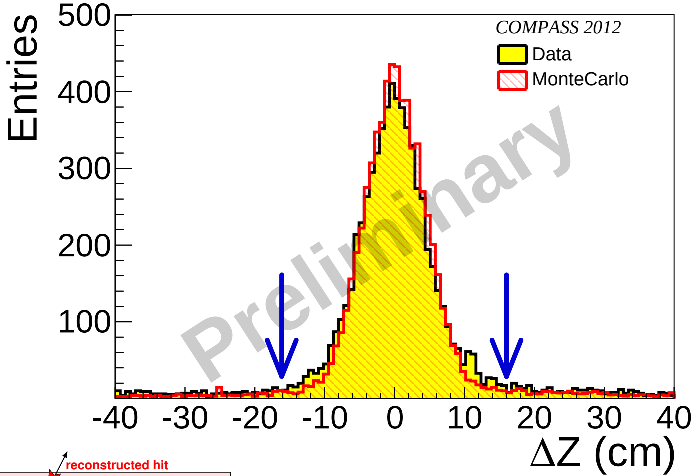


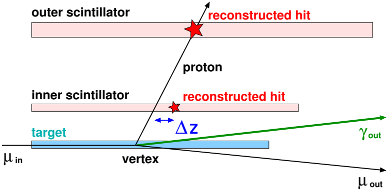
Exclusivity Variables: $\Delta\varphi$

$$\Delta\varphi = \varphi_{\text{meas}}^{\text{proton}} - \varphi_{\text{reco}}^{\text{proton}}$$



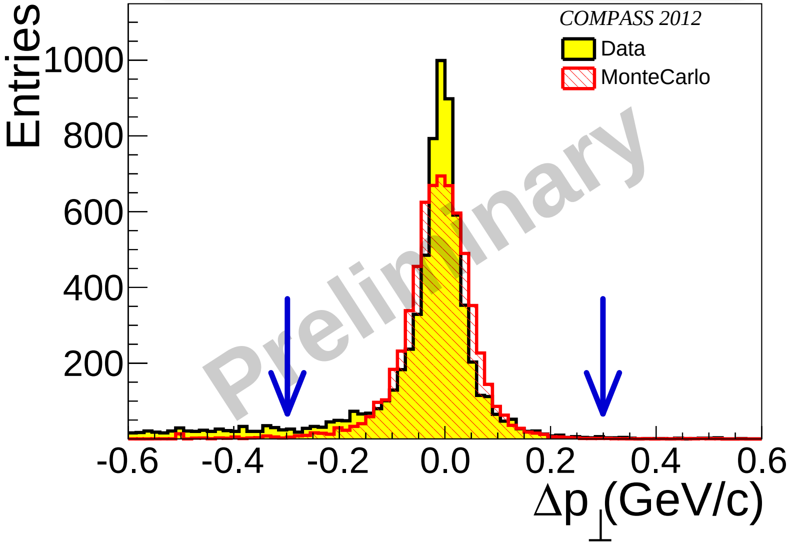
Exclusivity Variables: ΔZ





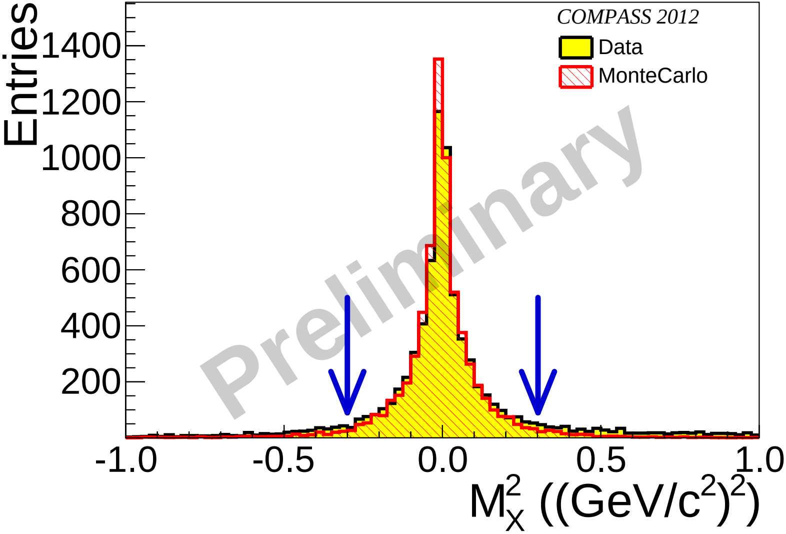
Exclusivity Variables: $\Delta p_\perp$

$$\Delta p_\perp = p_{\perp,meas}^{proton} - p_{\perp,reco}^{proton}$$



Exclusivity Variables: M_X^2

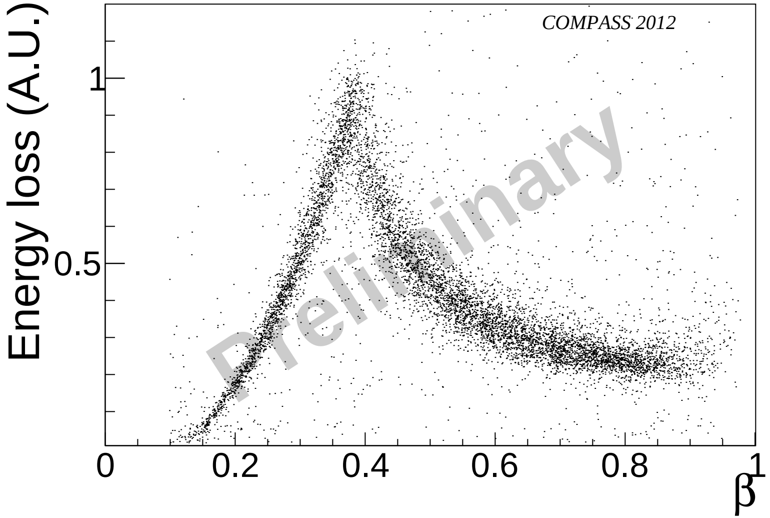
$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2$$



Proton Signal in Recoil Detector

Signal amplitude in outer scintillators vs. **beta** of recoiling particle

Proton signature clearly visible after all exclusivity conditions



π^0 Background Estimation

π^0s are one of the main backgroud sources for exclusive photon events

Two possible cases:

- **visible** (both γ detected, easy to reject)
- **invisible** (one γ ``lost'', only estimated with MC)

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``Invisible'' part estimate via **MC simulations**:

- **Semi-inclusive** contribution from LEPTO
- **Exclusive** contribution from HEPGEN/π^0 (Goloskokov-Kroll model)
- MC samples normalized to the ``visible'' π^0 in real data
- Two extreme cases considered:
  1. Fully **semi-inclusive** background
  2. Fully **exclusive** background

  $\rightarrow$ Gives **lower** and **upper** limits

π^0 Background Estimation

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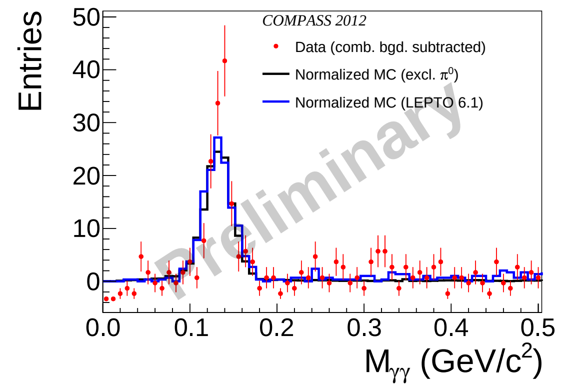
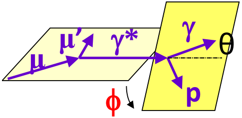
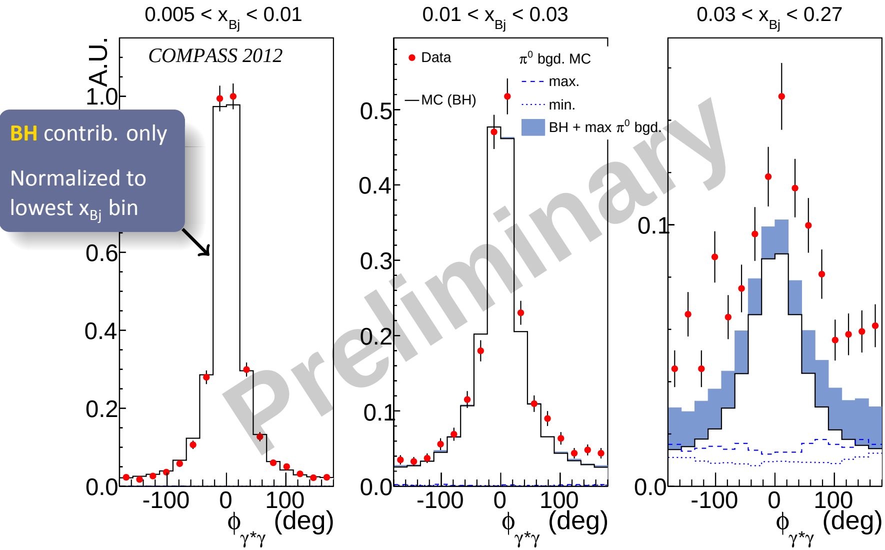


$M_{\gamma_{excl}\gamma_{bgd}}$ distribution (``Visible'' π^0)

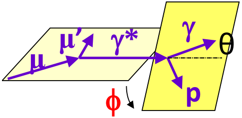
LEPTO and HEPGEN/π^0 MC normalized to $M_{\gamma_{excl}\gamma_{bgd}}$ peak from real data

Exclusive γ Azimuthal Distribution in 3 x_{Bj} Bins





Exclusive γ Azimuthal Distribution in 3 x_{Bj} Bins

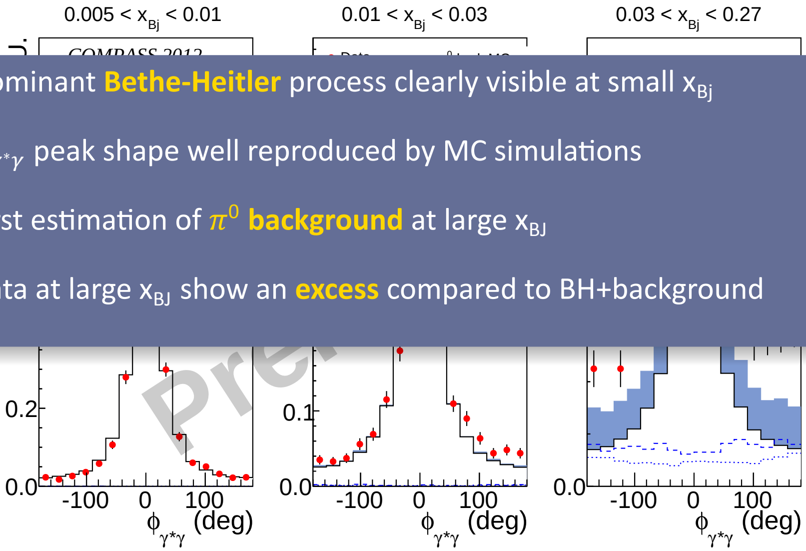


Dominant **Bethe-Heitler** process clearly visible at small x_{Bj}

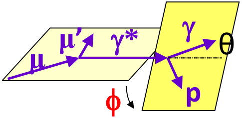
$\phi_{\gamma^*\gamma}$ peak shape well reproduced by MC simulations

First estimation of π^0 **background** at large x_{BJ}

Data at large x_{BJ} show an **excess** compared to BH+background



Exclusive γ Azimuthal Distribution in 3 x_{Bj} Bins



$0.005 < x_{Bj} < 0.01$ | $0.01 < x_{Bj} < 0.03$ | $0.03 < x_{Bj} < 0.27$

Dominant **Bethe-Heitler** process clearly visible at small x_{Bj}

$\phi_{\gamma^*\gamma}$ peak shape well reproduced by MC simulations

First estimation of **π^0 background** at large x_{BJ}

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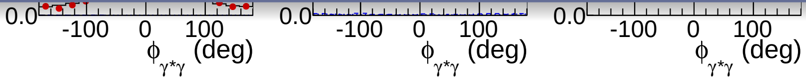
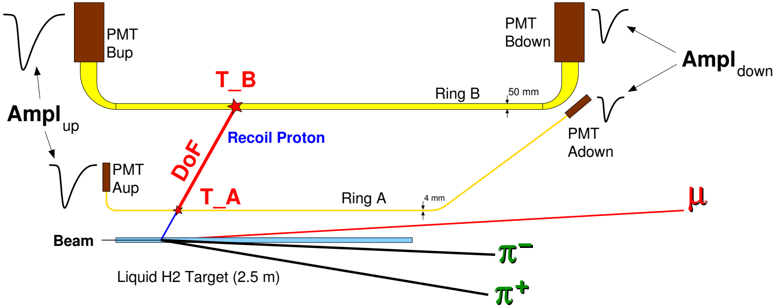
Next steps:

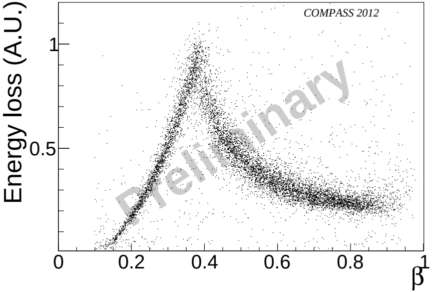
- **cross-section** extraction and **beam charge difference**
- **t-slope** extraction and nucleon tomography



Backup Slides

Recoil particle Measurement in CAMERA





$E_{loss} \sim \sqrt{Ampl_{up} * Ampl_{down}}$

TOF $\rightarrow (t_{up} + t_{down})_{A,B}$

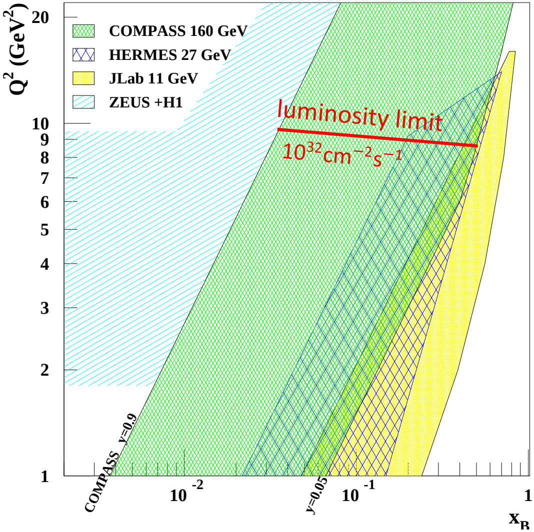
z $\rightarrow t_{up} - t_{down}$

Count rates: > 5 MHz in ring A

~1 MHz in ring B

What Makes COMPASS Unique?

COMPASS covers the unexplored region between collider (H1+Zeus) and low-energy fixed target (Hermes+JLab) experiments



- μ^+ and μ^- beams
- momentum: 100 – 190 GeV/c
- beam polarization: 80 %

  opposite for μ^+ and μ^-

- coverage of intermediate x_B

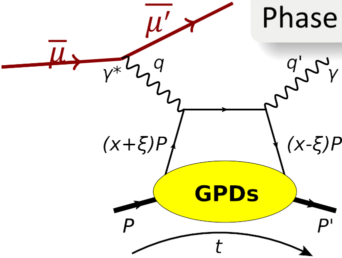
  → low x_B: **pure BH**

  useful for normalization

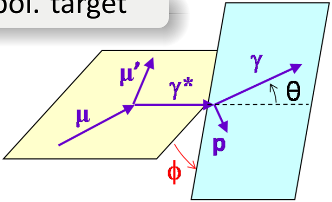
  → high x_B: **DVCS predominance**

⇝ **unexplored region between ZEUS+H1 and HERMES+JLab**

DVCS: What Can We Learn?



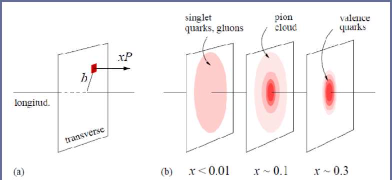
Phase 1: Polarized beam, unpol. target



DVCS dominance at large x_B

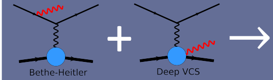
BH/DVCS interf. at intermediate x_B

x_B-dependent transv. size of nucleon



$r_\perp$ parameter from slope of $d\sigma^{DVCS}/dt$

Interference between BH and DVCS



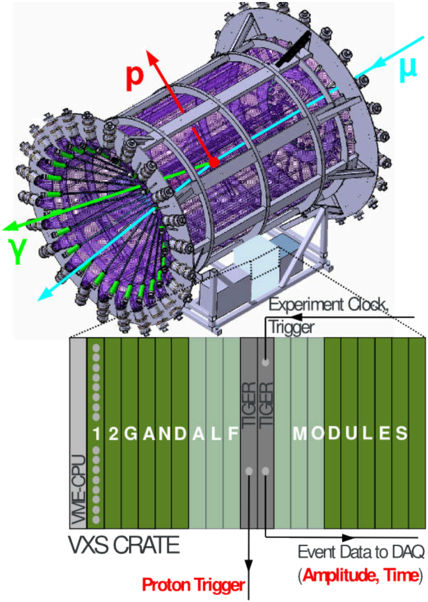
"Boost" of DVCS through int. term

Measurement of $\mathrm{Re}\mathcal{H}(\xi,t)$ and $\mathrm{Im}\mathcal{H}(\xi,t)$ via ϕ-modulation of cross section

- $\mathrm{Re}\mathcal{H}(\xi,t) = P\int dx\, H(x,\xi,t)/(x-\xi)$
- $\mathrm{Im}\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$

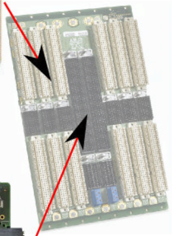
Exp. constrain to GPD H

CAMERA Readout



GANDALF

Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution



TIGER

Virtex-6 VLX365
onBoard GPU
2x SFP+
COM Express

Past, Present and Future GPD Experiments