COMPASS GPD Program

A. Ferrero (CEA-Saclay/IRFU/SPhN)

for the COMPASS Collaboration

Hadron 2015 Workshop - Kunshan, 3-7/8/2015

Outline

Introduction

The Quest of GPDs at COMPASS

Access to **GPD** H through **DVCS**

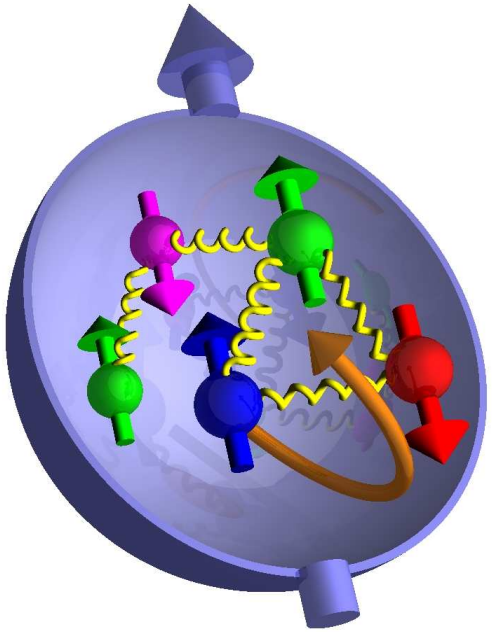
Hard Exclusive Meson Production

Conclusions and Outlook

Outline

Where does the spin of the nucleons come from?

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

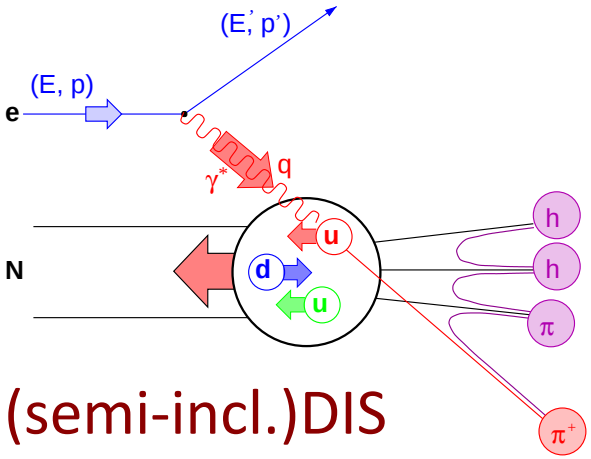


The ``proton spin crisis'':

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

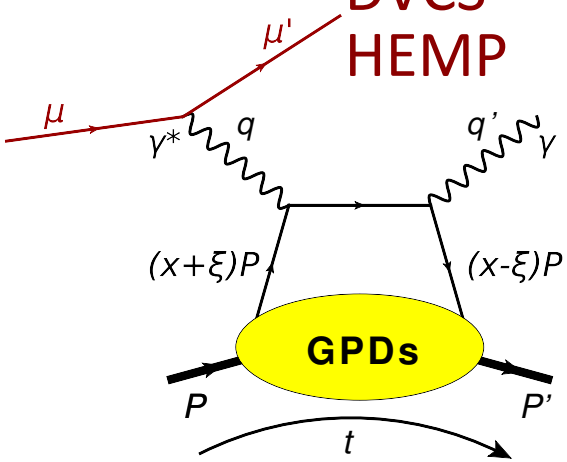
ΔG = ?? $L_{q,g}$ = ??

COMPASS experimental tools:

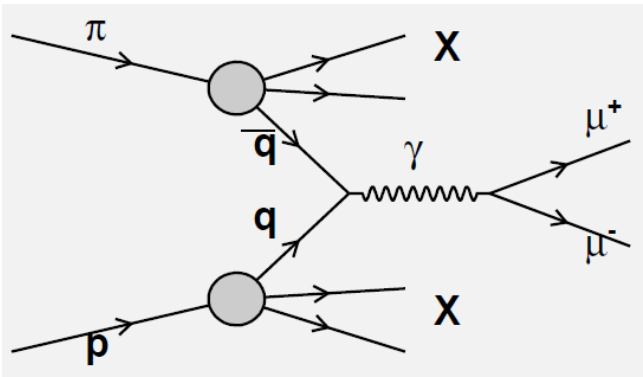


(semi-incl.)DIS

DVCS
HEMP



Pol. Drell-Yan



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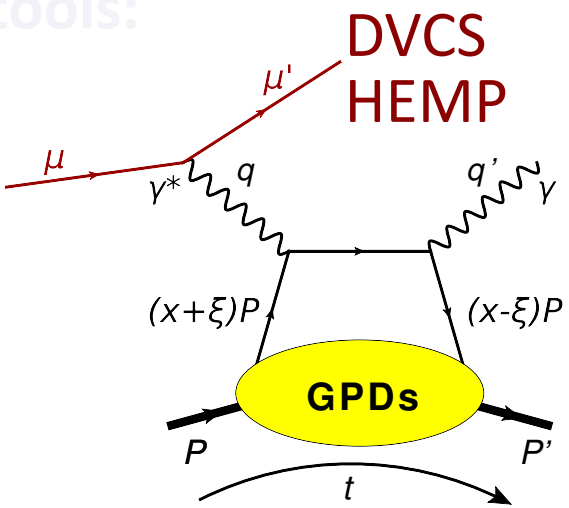
$\Delta G = ??$ $L_q + L_g = ??$

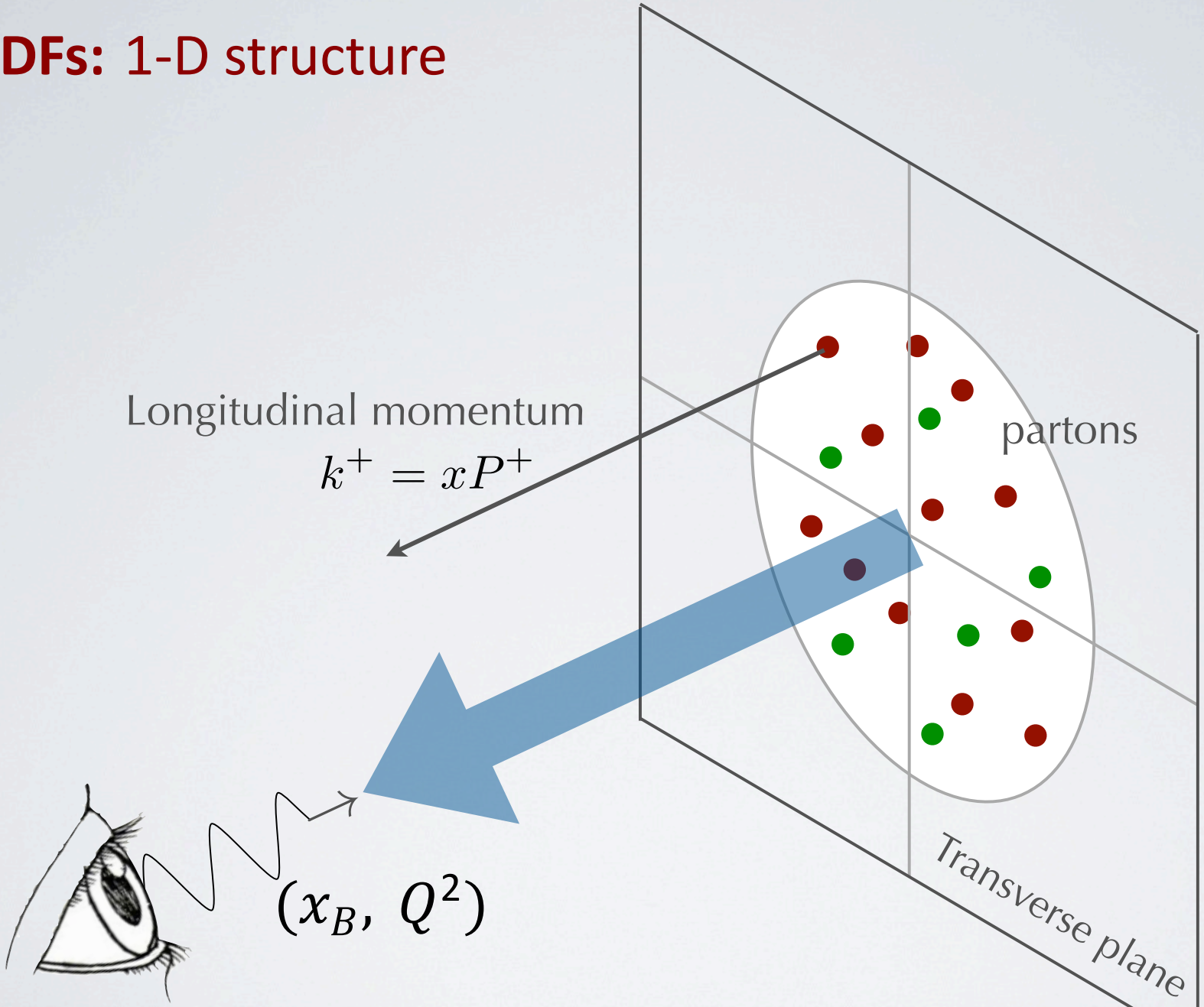
This talk:

COMPASS experimental tools:



Pol. Drell-Yan

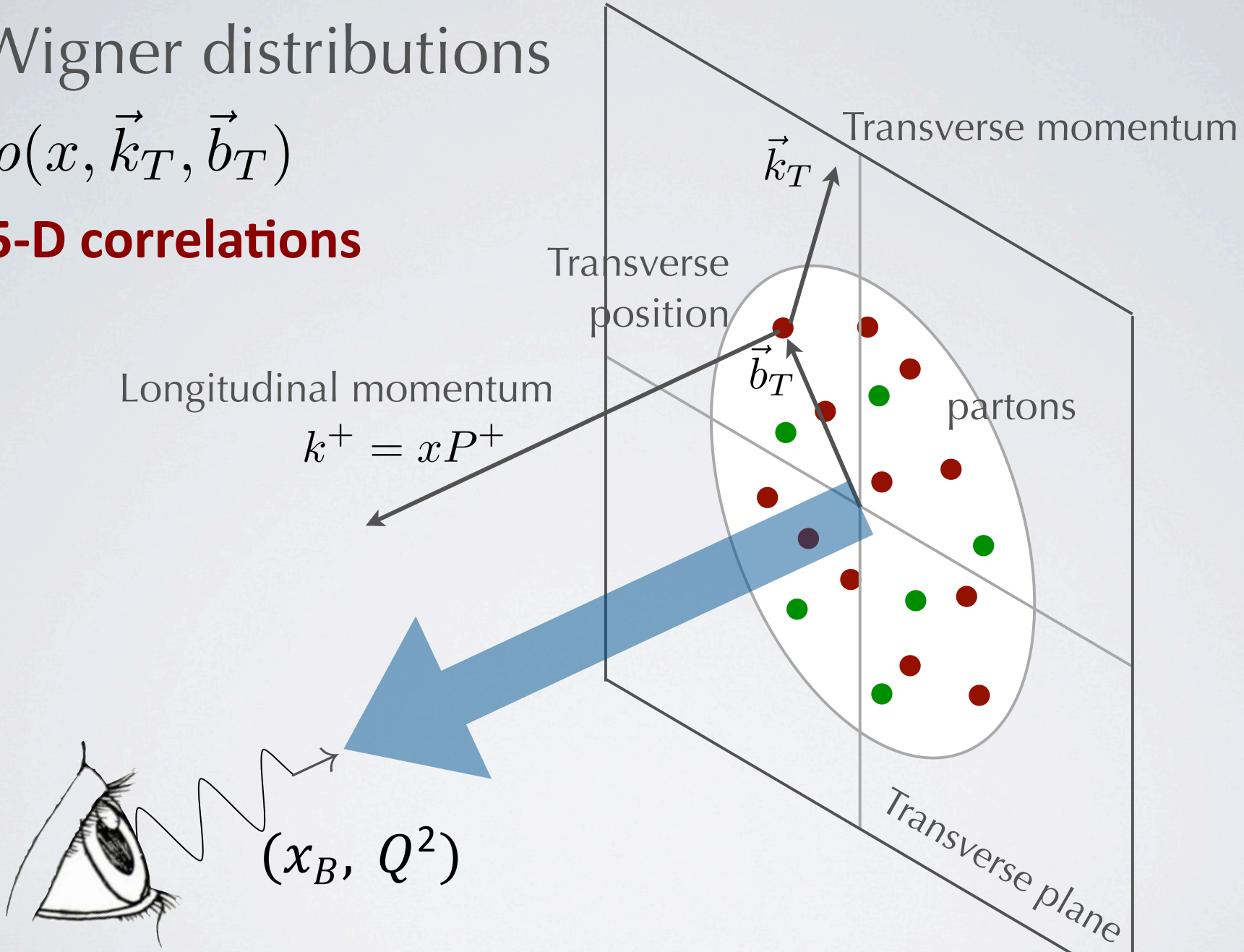
PDFs: 1-D structure



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)

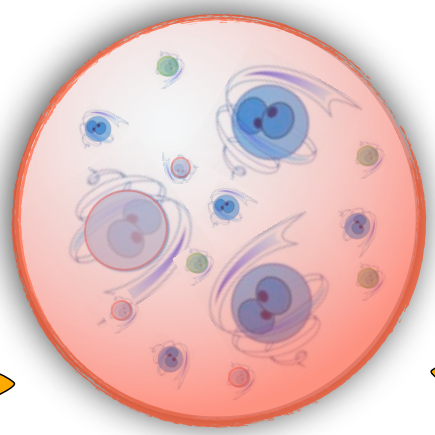
Towards a 3D Picture of the Nucleon…

Form Factors (t)

Fourier transform (b_T)
& $\int$ GPDs(x, t) … dx

GPDs (x, b_T)

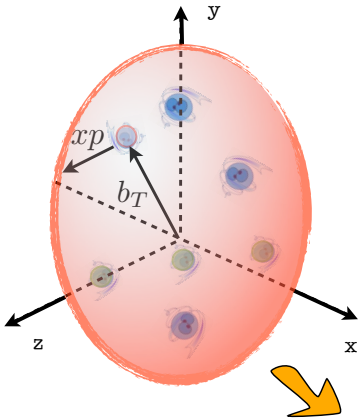
Wigner Distributions

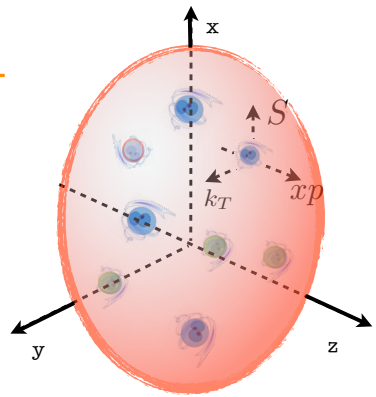


$\int dk_T$

$\int db_\perp$

TMDs (x, k_T)





PDFs (x)

$\int$ GPDs(x,b_T) … db_T

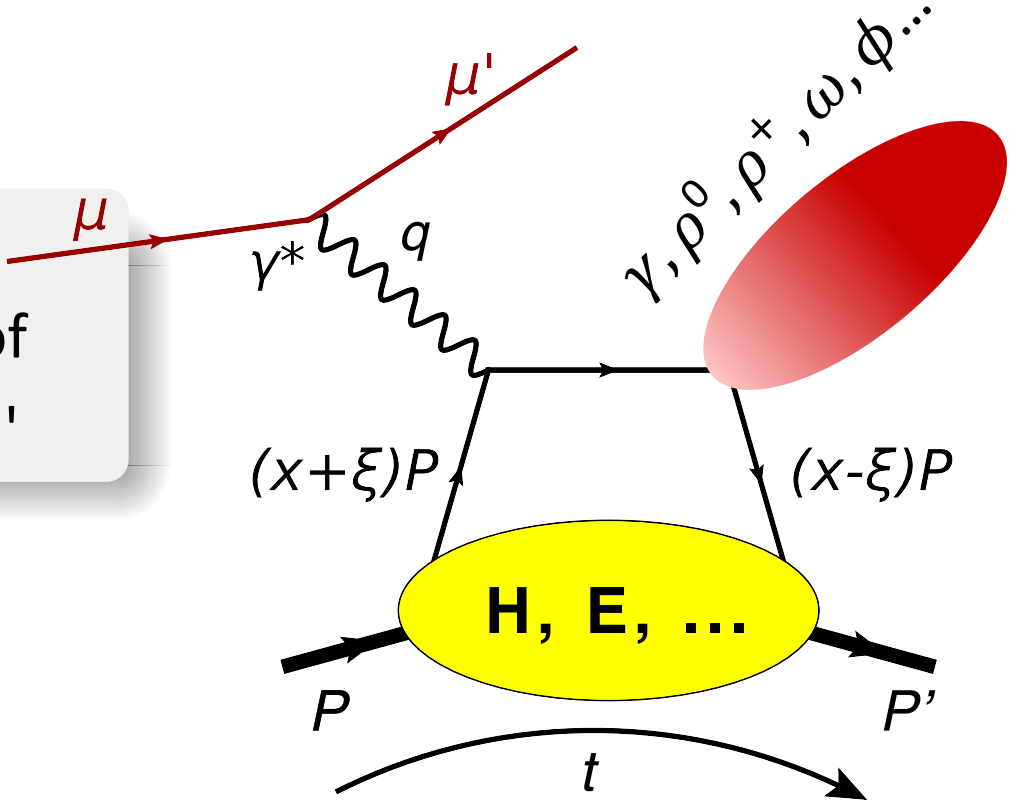
$\int$ TMDs(x,k_T) … dk_T

PDFs → ΔΣ, 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

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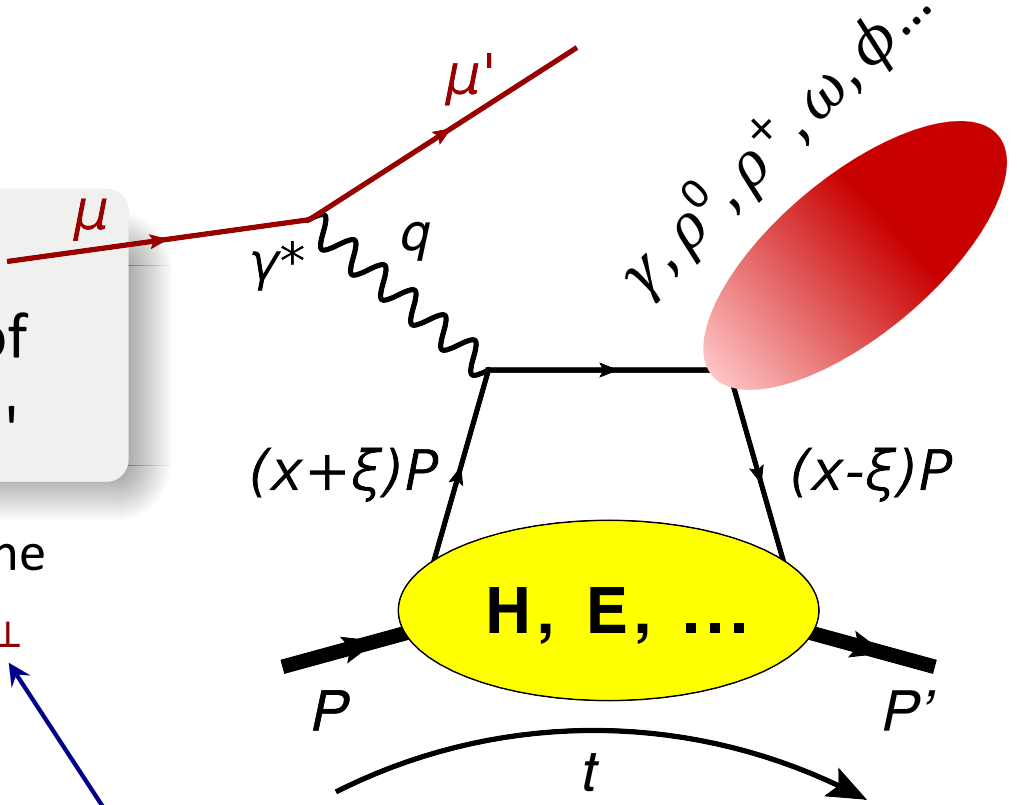
They encode **CORRELATIONS** between the long. mom. **x** and the transv. position $\mathbf{b}_\perp$ of partons



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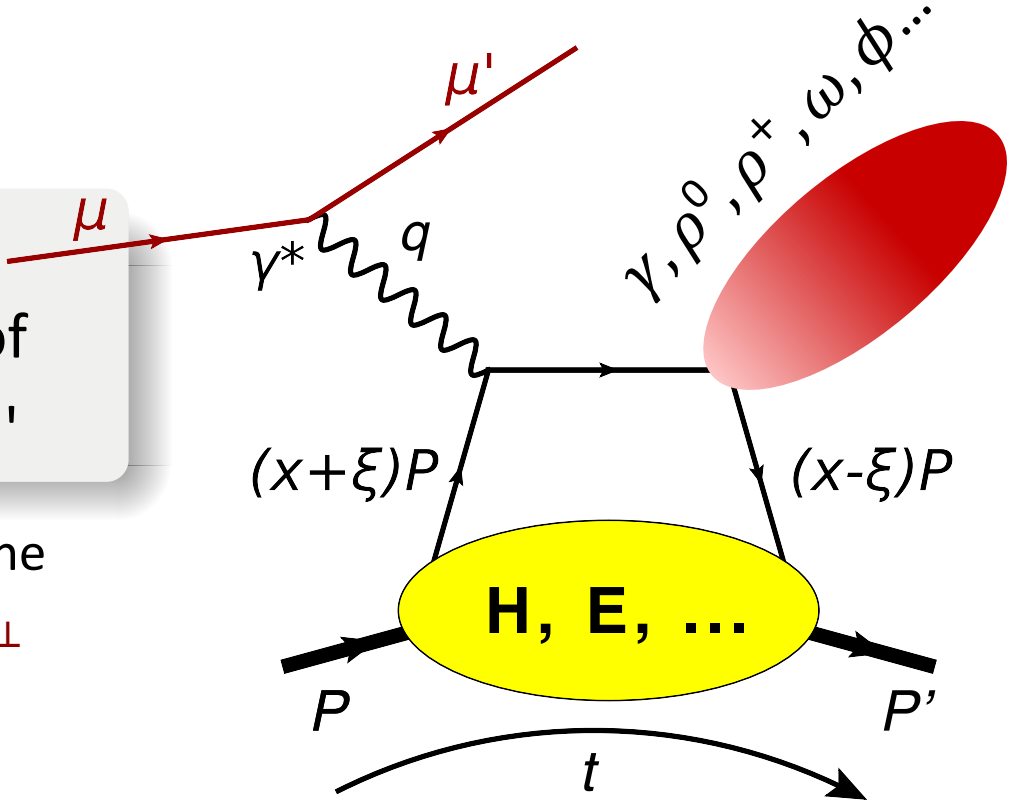

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Experimentally accessible through Compton Form Factors (CFFs):

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

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

Definition of variables:

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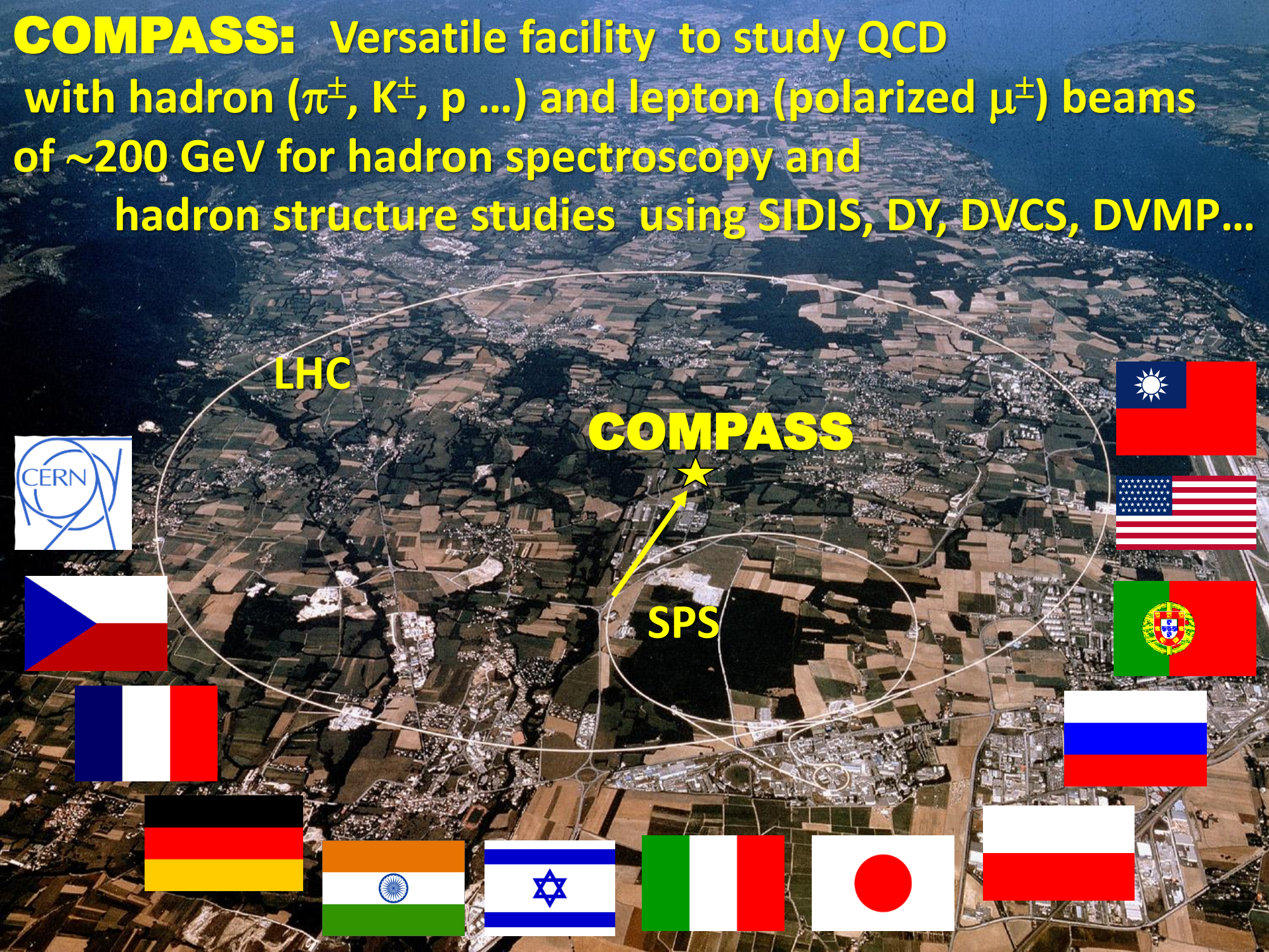
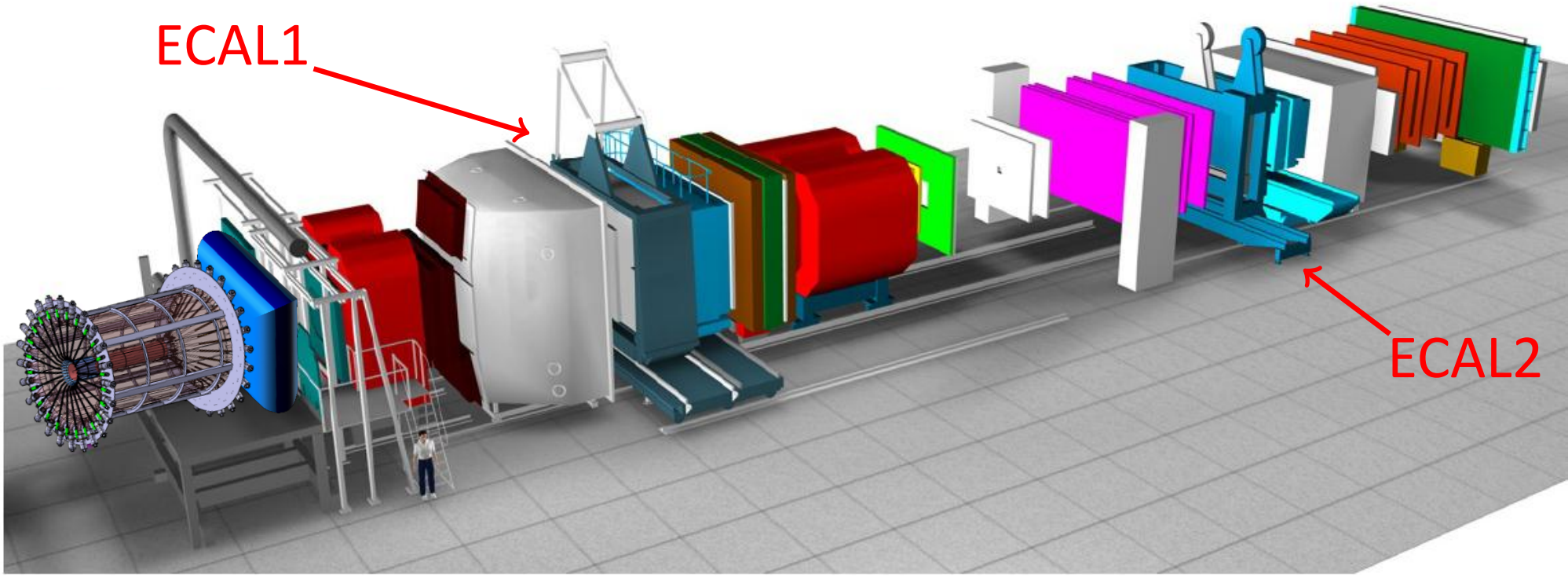

COMPASS: Versatile facility to study QCD
with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) and lepton (polarized $\mu^{\pm}$) beams
of ~200 GeV for hadron spectroscopy and
hadron structure studies using SIDIS, DY, DVCS, DVMP…
LHC
COMPASS
SPS
CERN

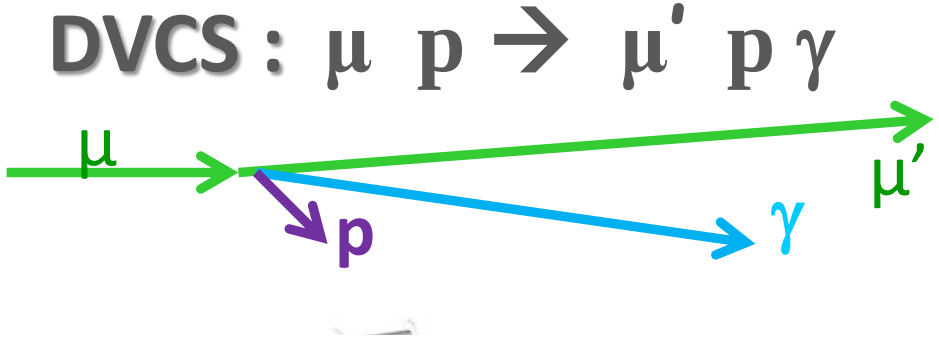
The COMPASS set-up for the GPD program



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

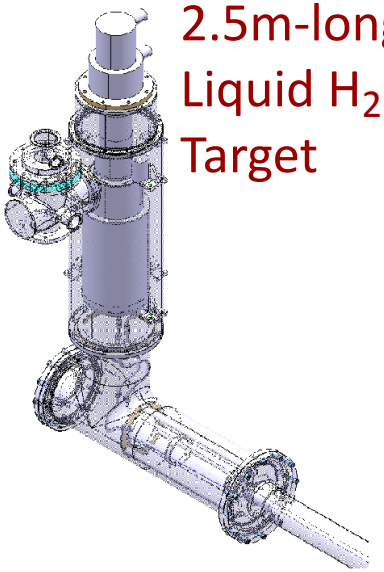


The COMPASS set-up for the GPD program

ECAL1

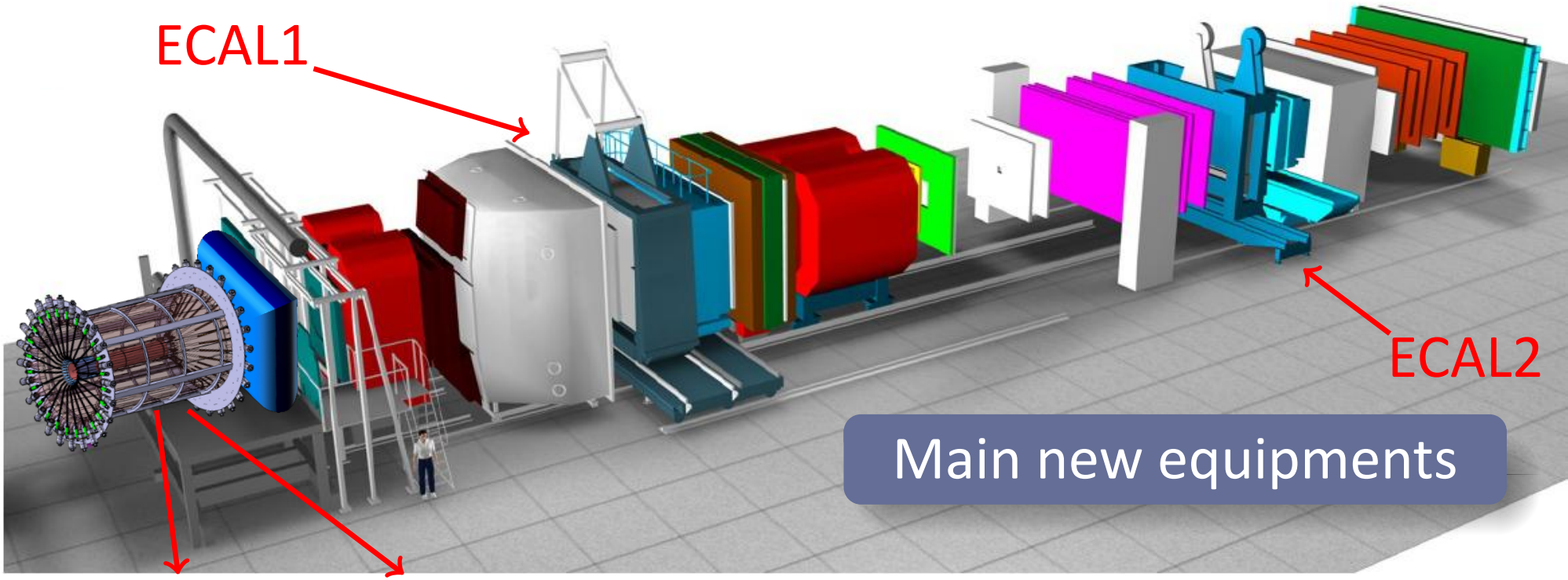
ECAL2

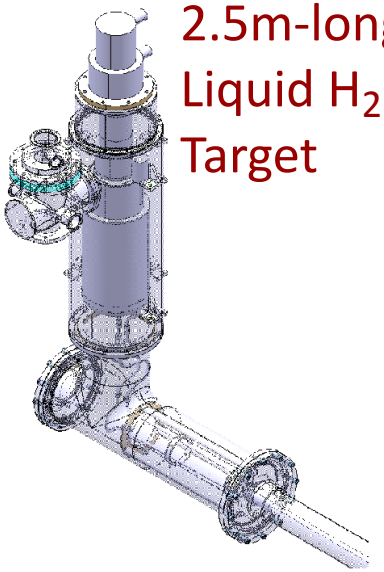
Main new equipments



2.5m-long
Liquid H_2
Target

The COMPASS set-up for the GPD program





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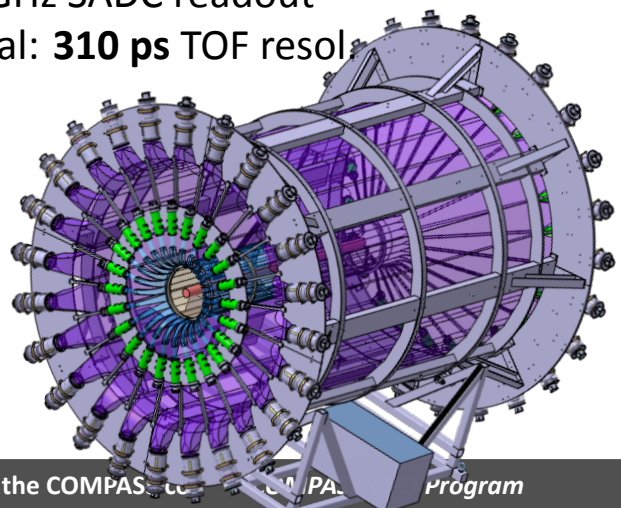
Target TOF System

24 inner & outer scintillators

1 GHz SADC readout

goal: **310 ps** TOF resol



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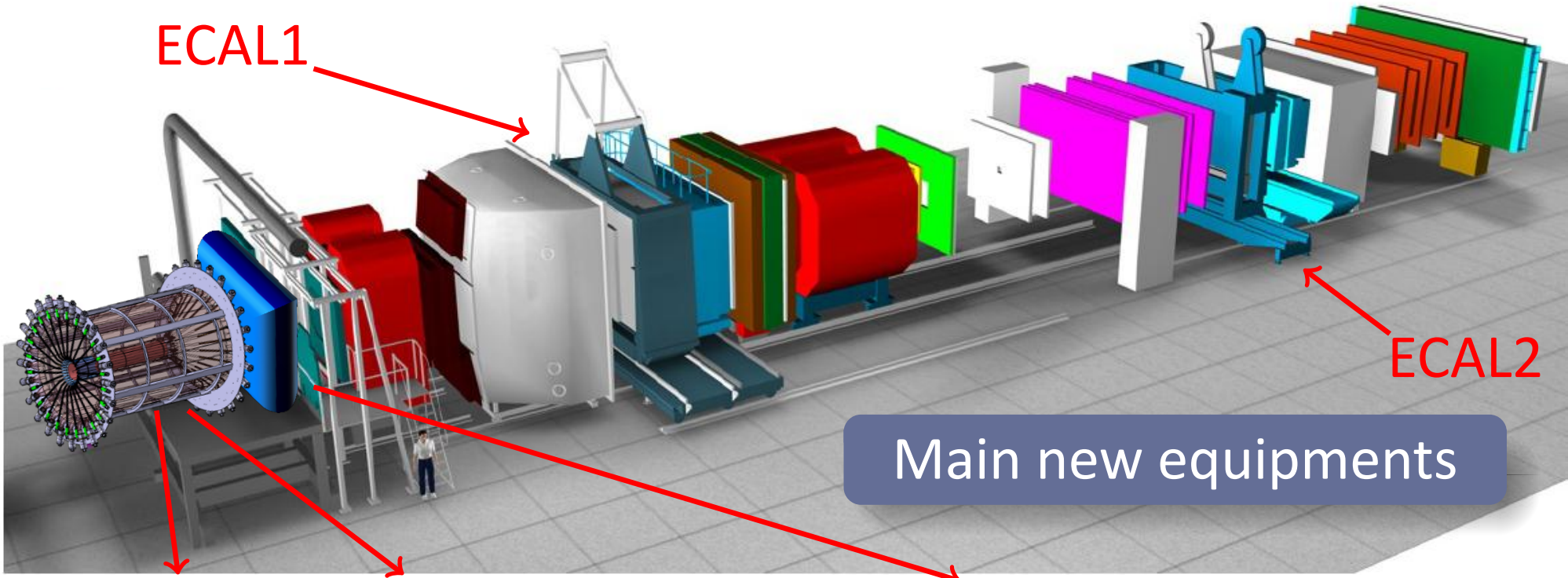

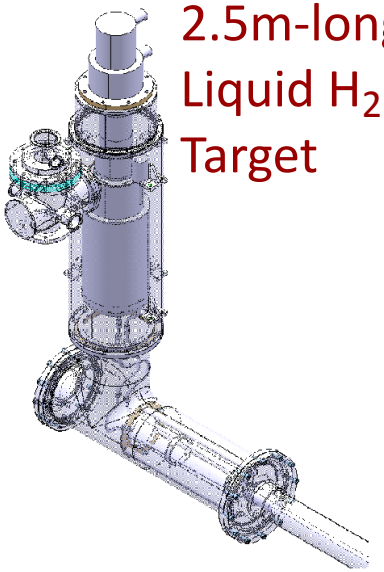

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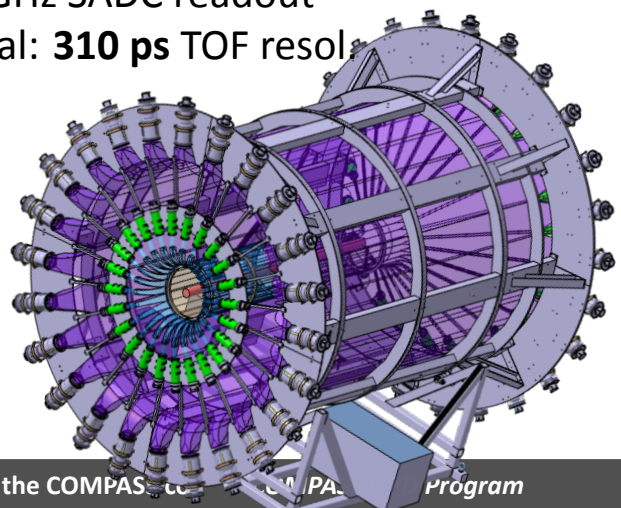
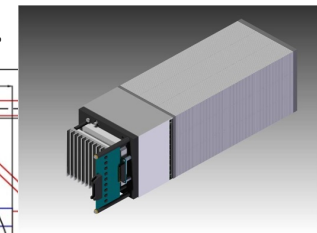
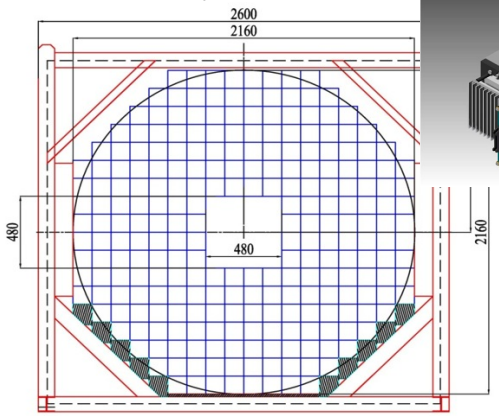


ECAL0 Calorimeter

Shashlyk modules + MAPD readout
~ 2 × 2 m^2, ~2200 ch.





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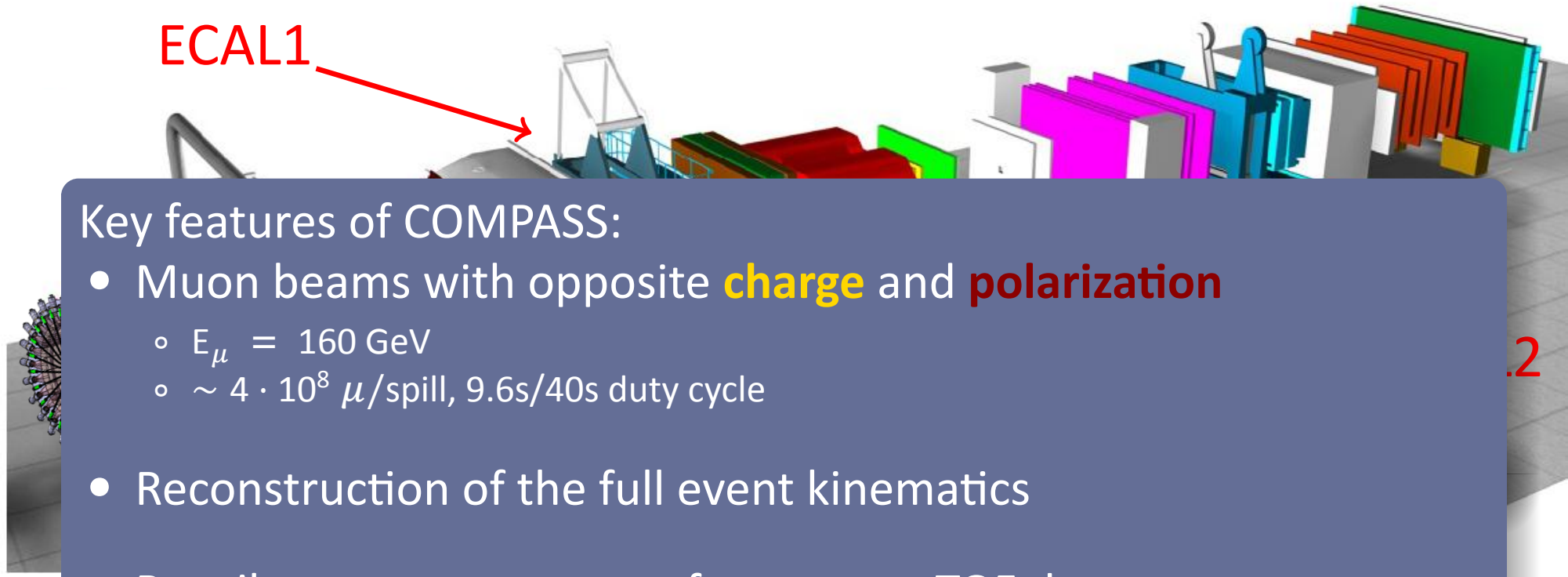
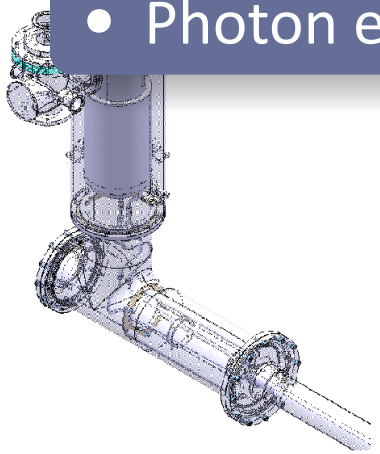
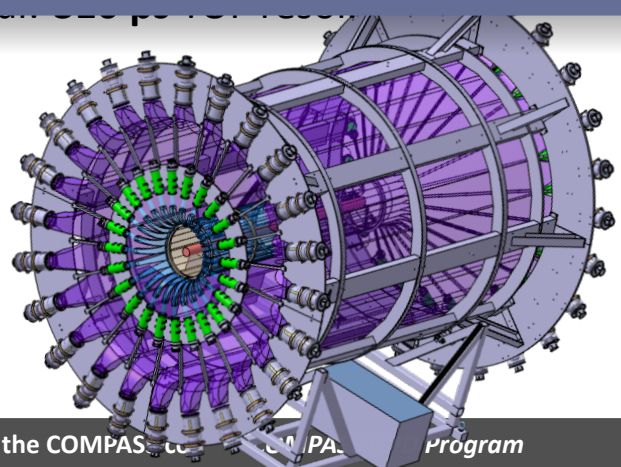
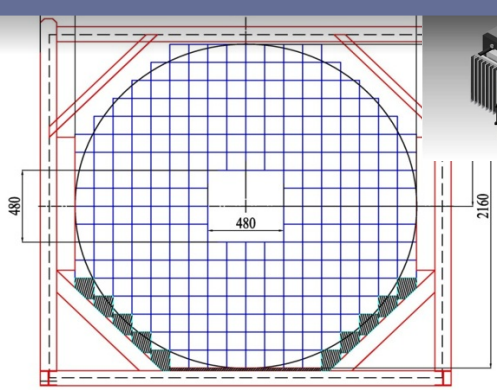


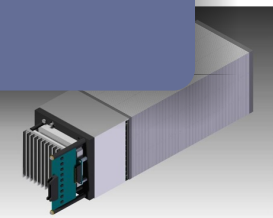
Key features of COMPASS:

- 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

2003-10: 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 H**

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

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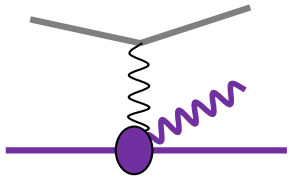
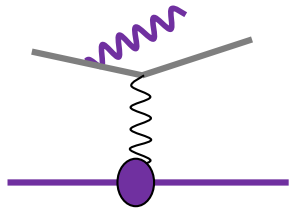
Hard Exclusive Meson Production

Conclusions and Outlook

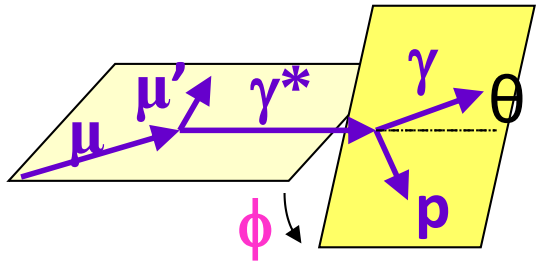
The DVCS Process at COMPASS Kinematics



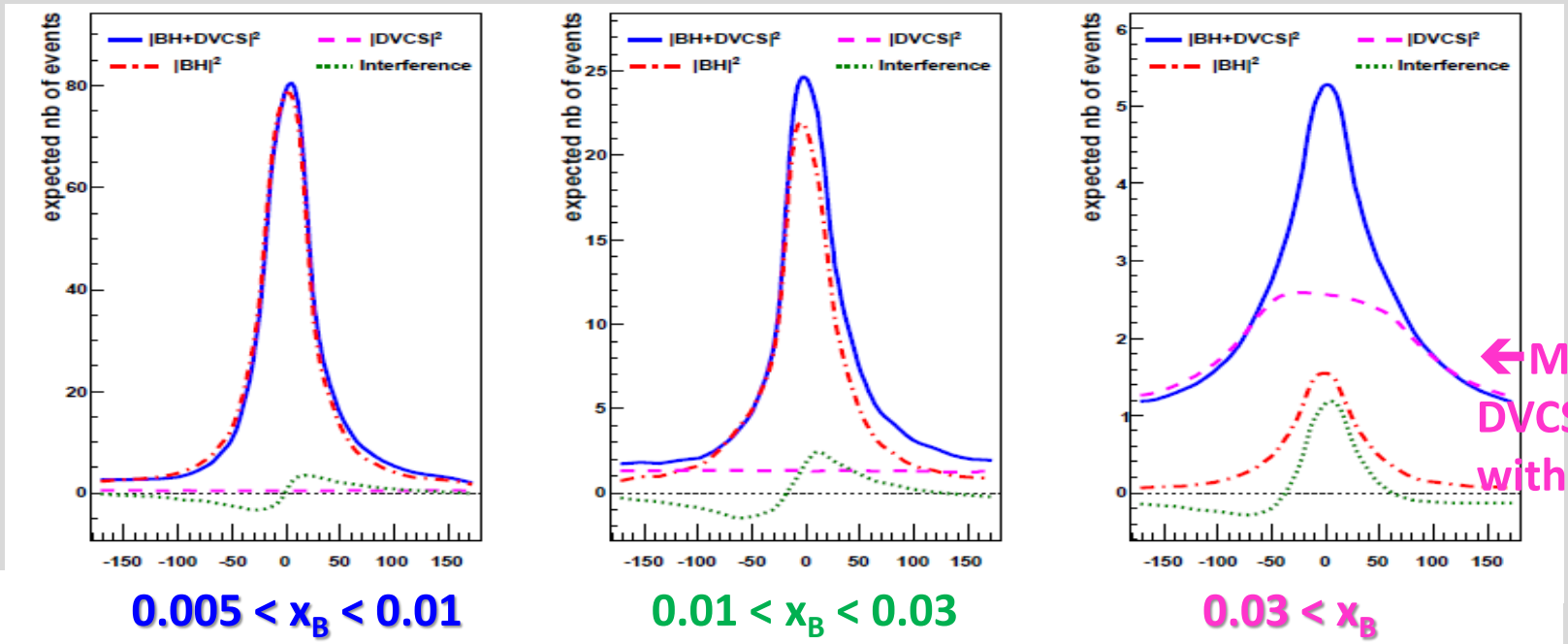
Deep VCS



Bethe-Heitler



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



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

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

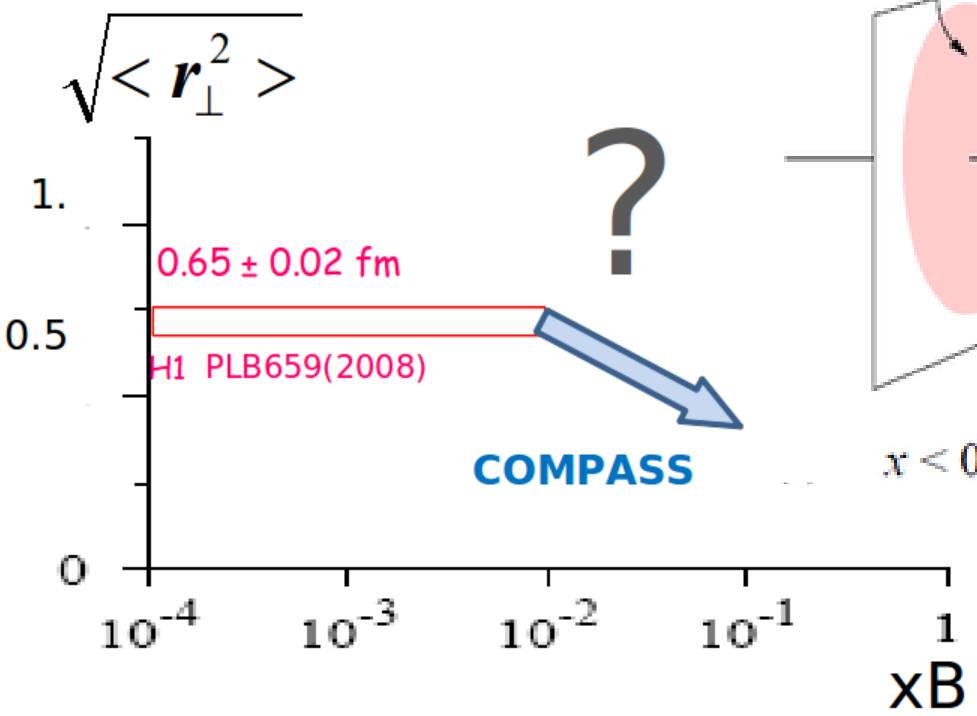
✓ only leading twist and LO

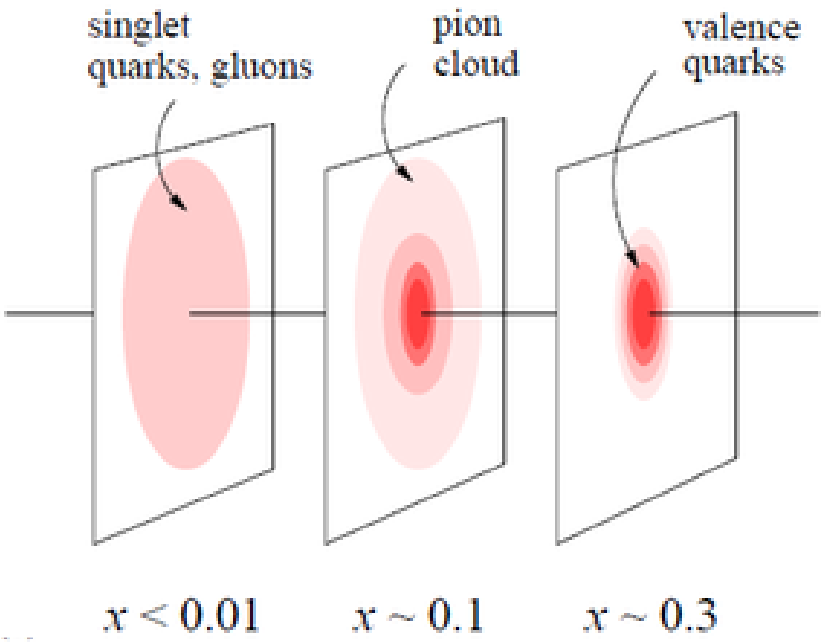
Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin **SUM**:

$$\mathbf{S_{CS,U}} \equiv \mathbf{d\sigma}(\boldsymbol{\mu}^{+\leftarrow}) + \mathbf{d\sigma}(\boldsymbol{\mu}^{-\rightarrow}) \propto \mathbf{d\sigma^{BH}} + \mathbf{d\sigma^{DVCS}_{unpol}} + \mathbf{Ks_1^{Int}} \sin\boldsymbol{\phi}$$

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





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

Transverse Nucleon Imaging at COMPASS

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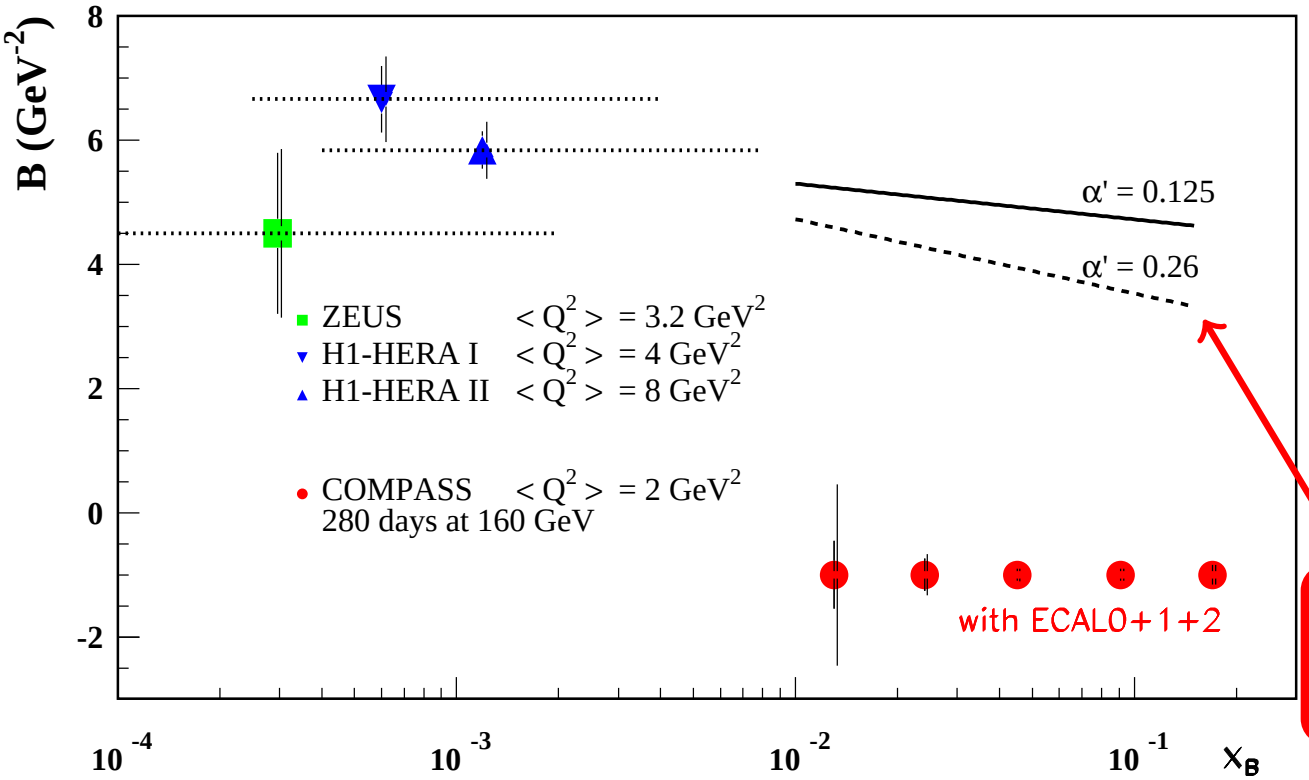

2 x 6 months of data in 2016-2017

2.5 m LH_2 target

ε_{global} = 10%

Ansatz at small x_B:

$$B(x_B) \simeq B_0 + 2\alpha' \ln(x_0/x_B)$$

expected statistical and systematic uncertainties are shown

Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin **SUM**:

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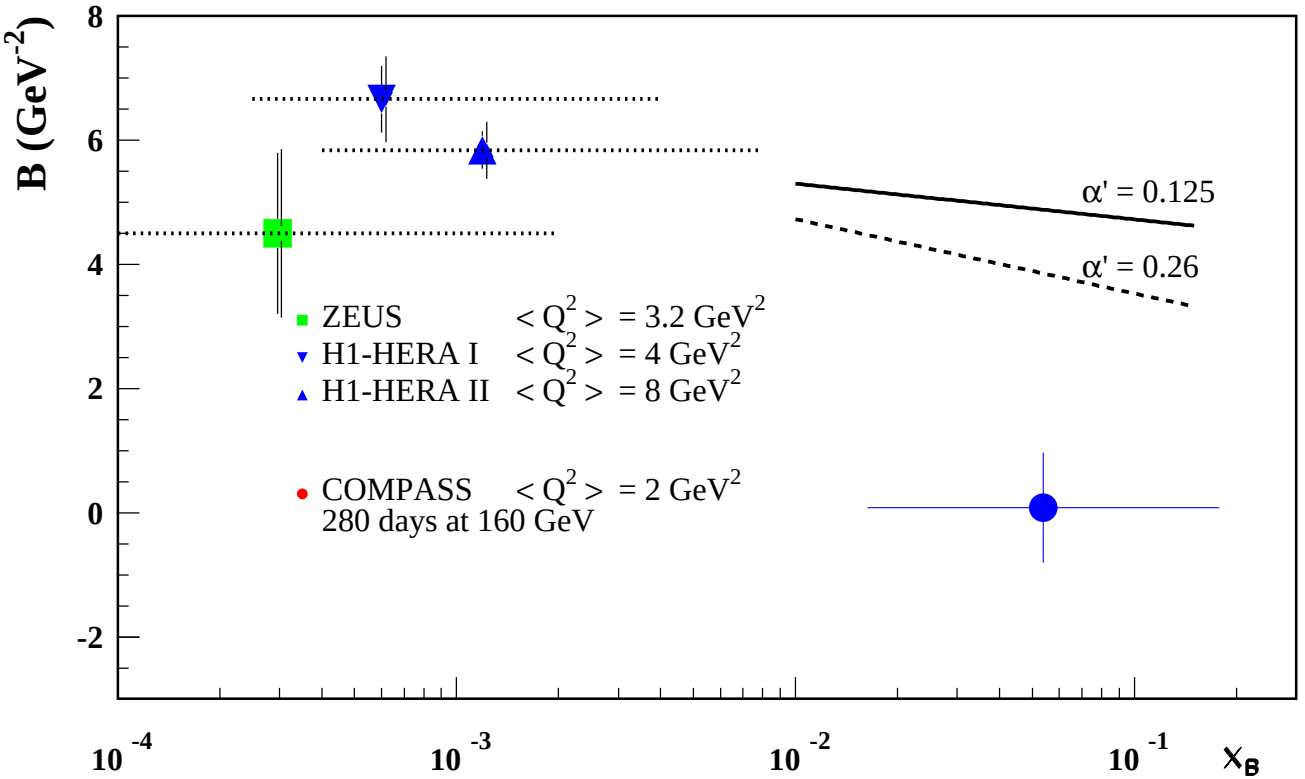


4 weeks in 2012

2.5 m LH_2 target

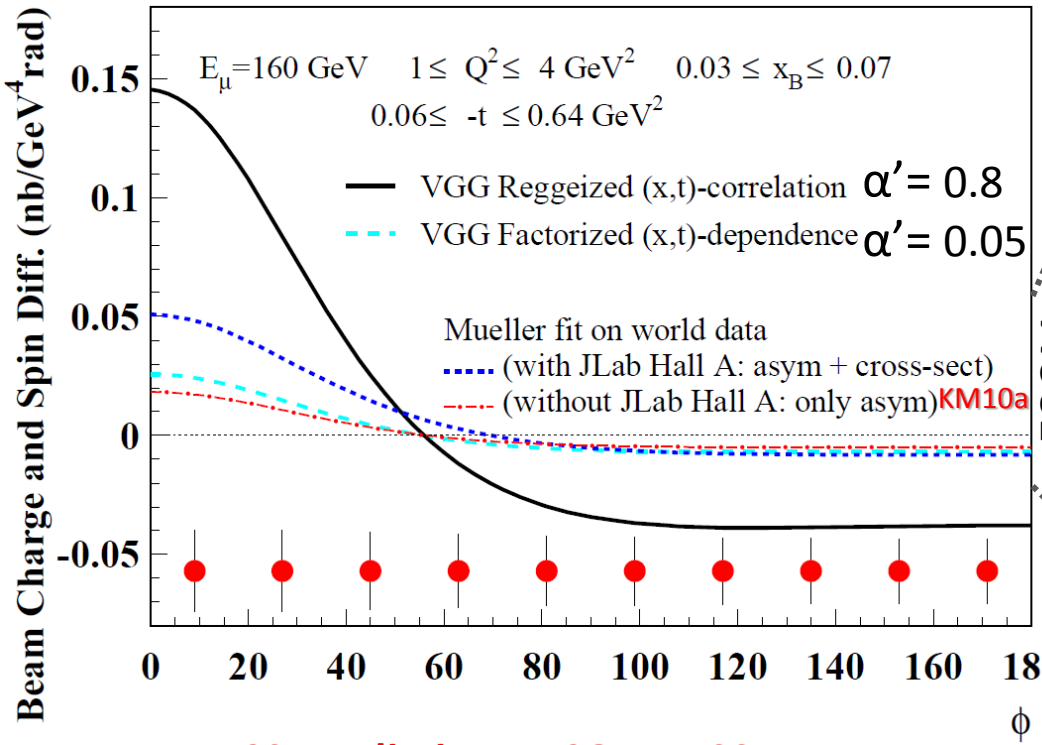
2012: **we can expect one mean value of B in the COMPASS kinematic range**

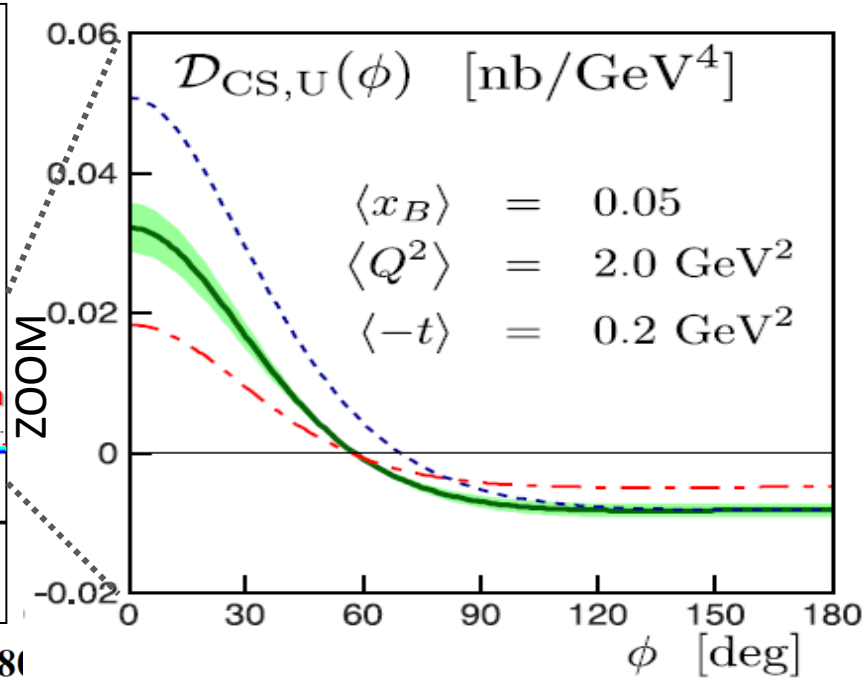
Beam Charge and Spin Difference

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} = 2[d\sigma^{DVCS}_{pol} + \mathrm{Re}\, I] \xrightarrow{L.T.} c_0^I + c_1^I \cos\phi$$

$$c_1^I = Re\, F_1 \mathcal{H}$$

Comparison to different models



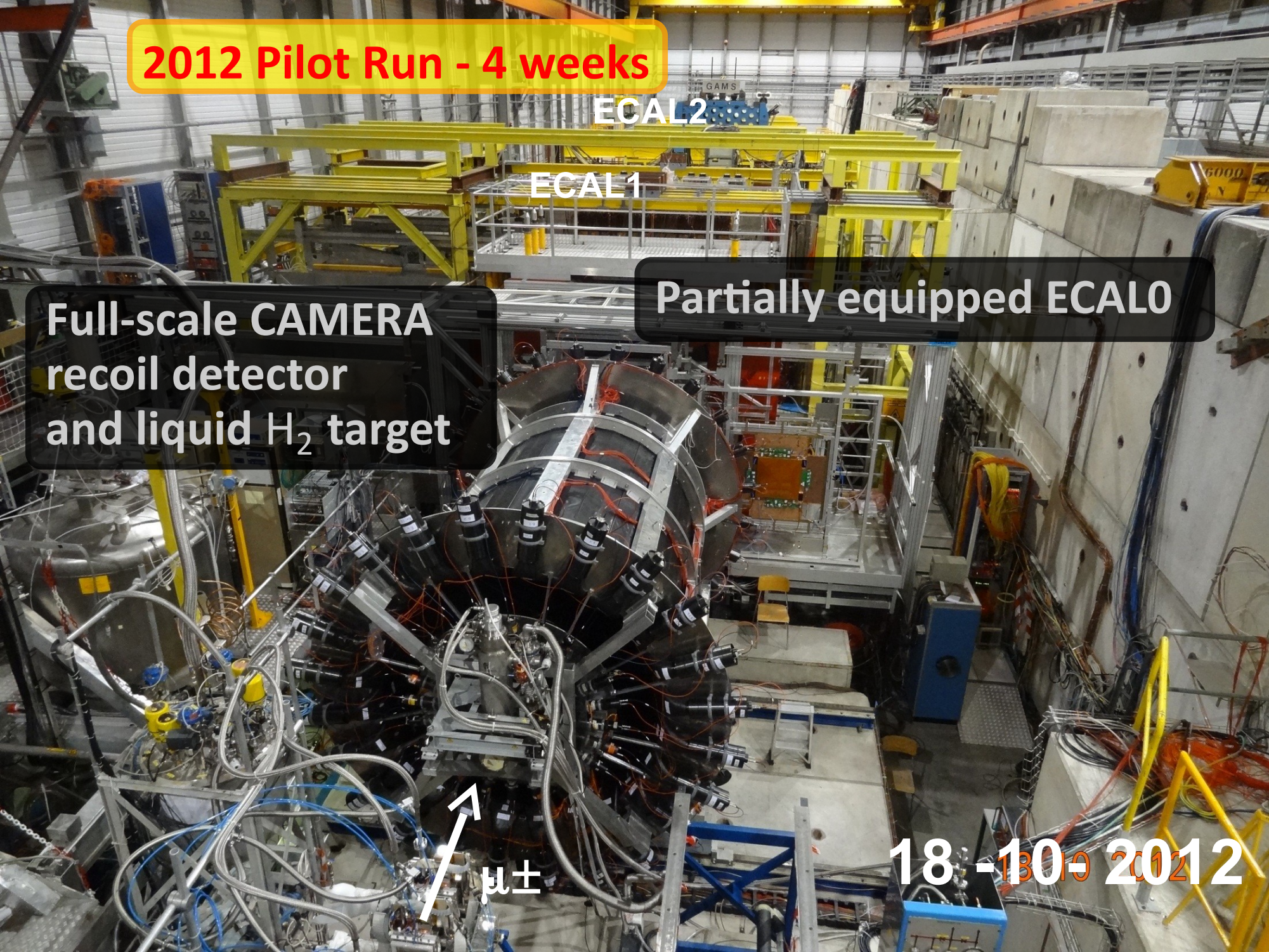


DVCS Prediction at COMPASS
For 2 × 6months in 2016-17

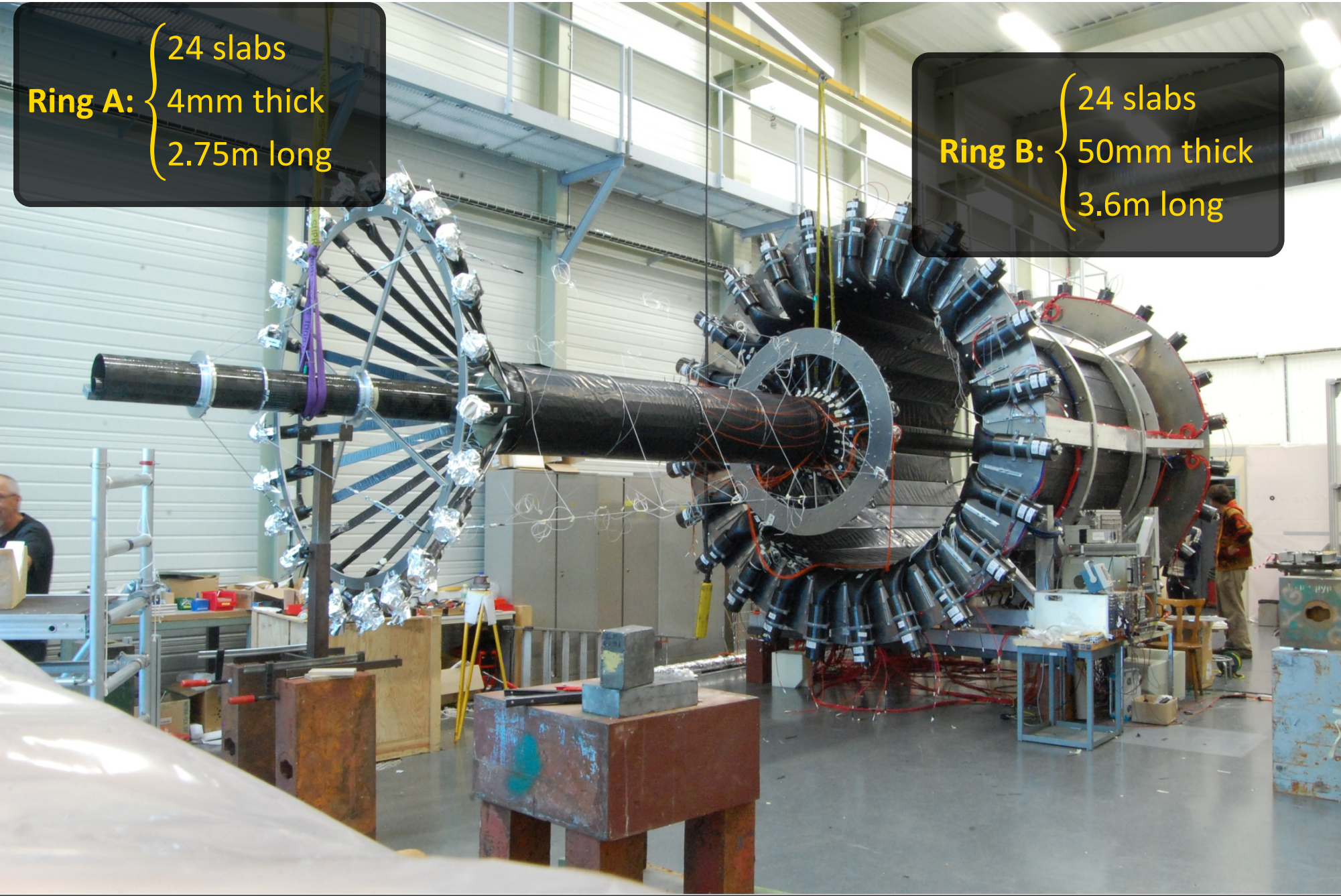
KMS12: Kroll, Moutarde, Sabatié
EPJC 73 (2013) 2278

KM10a (without Hall A)

KM10b


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

The Recoil TOF Detector CAMERA

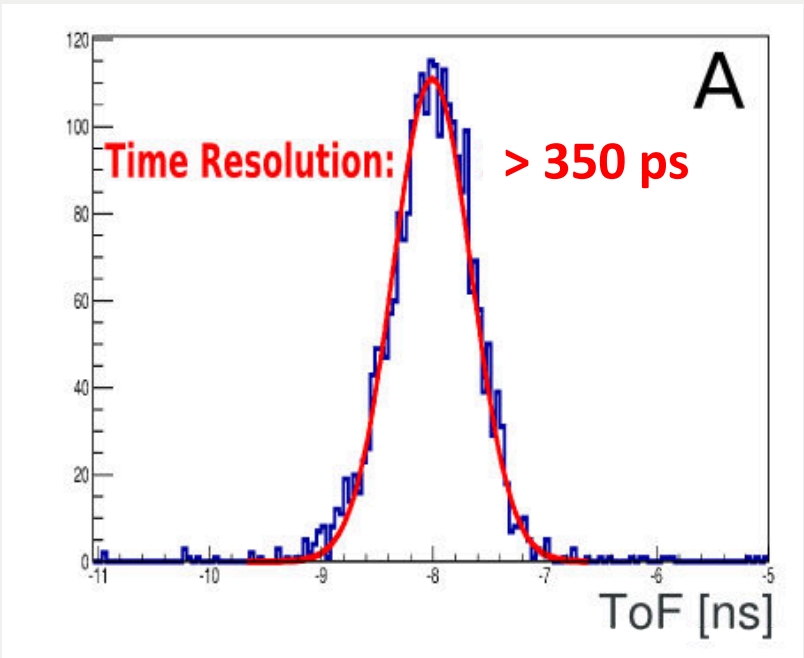


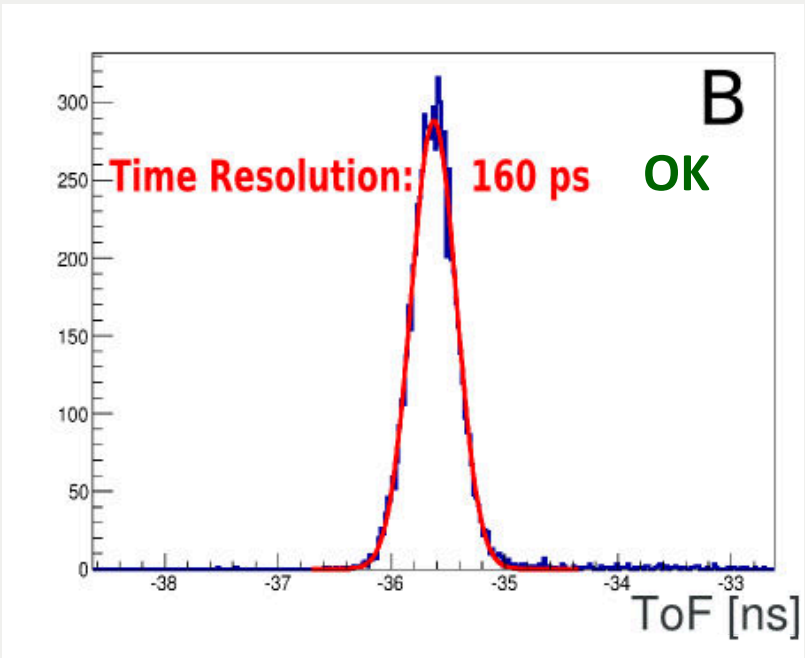
The Recoil TOF Detector CAMERA

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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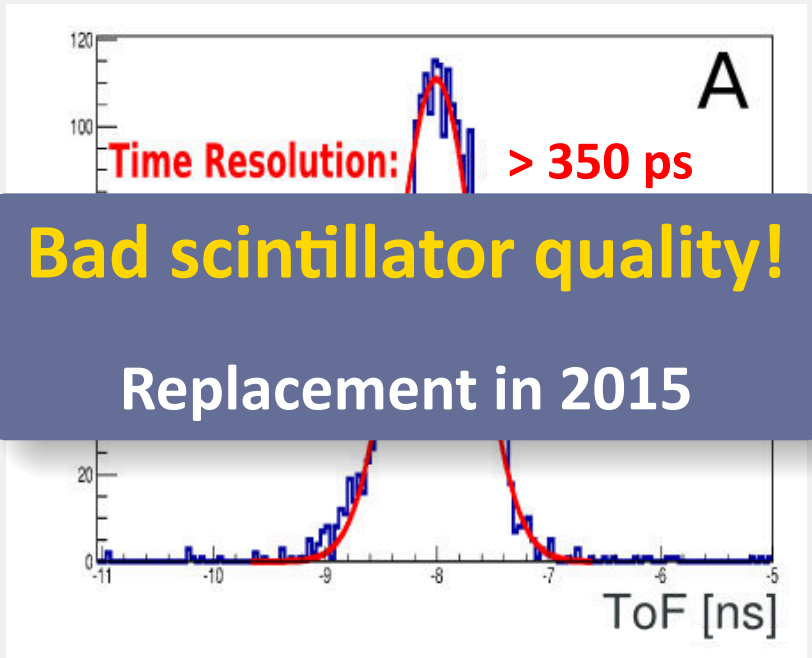
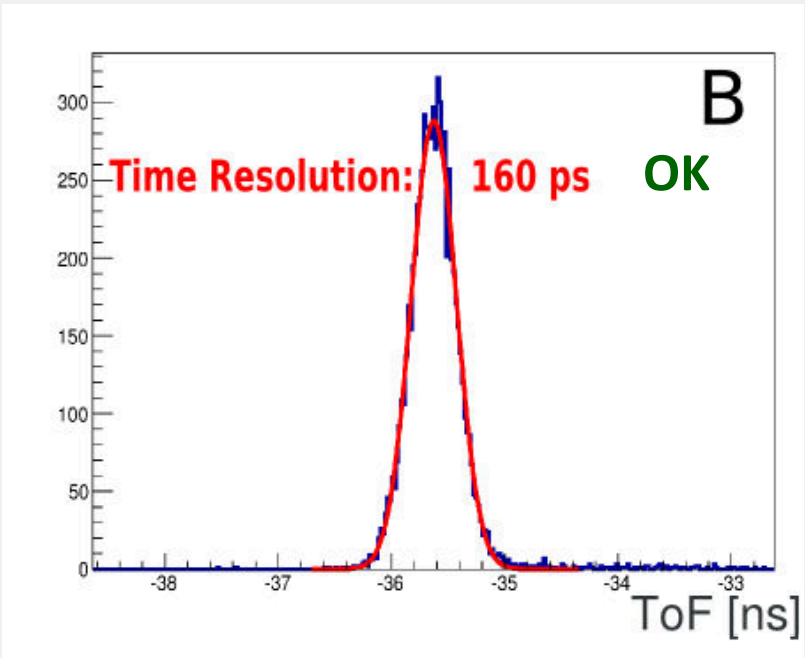


Bad scintillator quality!

Replacement in 2015



Exclusive Photon Events Selection

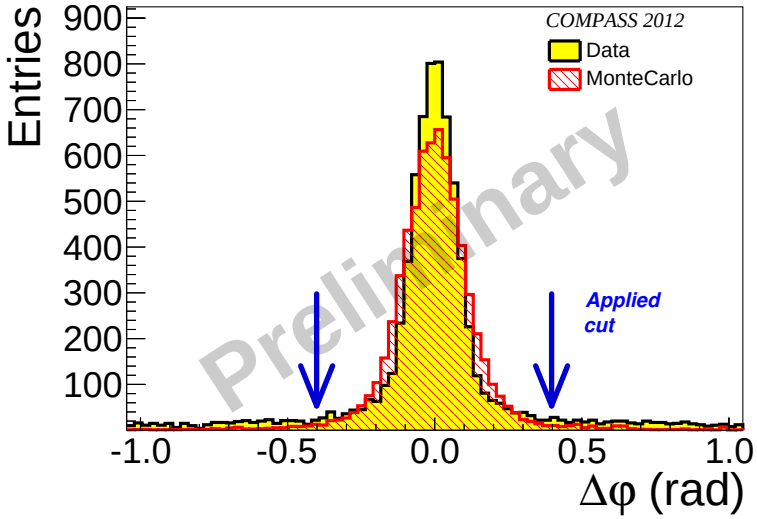
Reconstructed interaction vertex in **target volume**

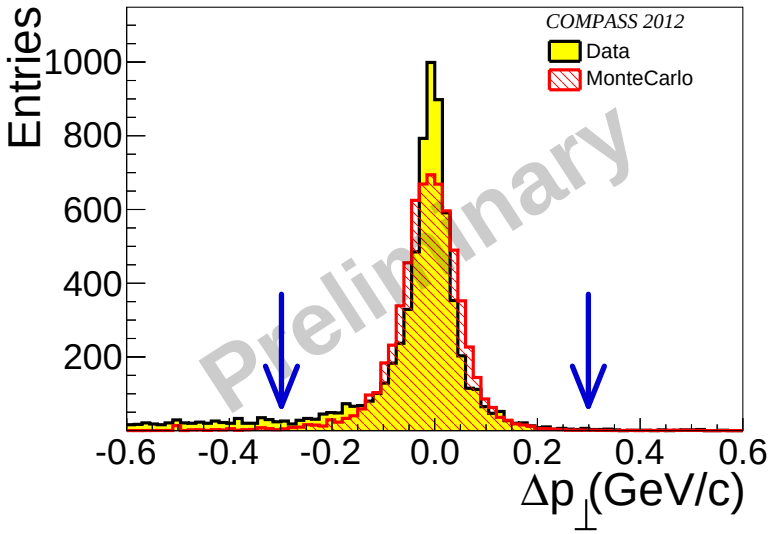
One single photon above DVCS production threshold

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

Exclusivity conditions:

- $\Delta\varphi = \varphi^{proton}_{meas} - \varphi^{proton}_{reco}$
- Vertex pointing (ΔZ)
- Transv. momentum balance
- Four-momentum balance
- Missing energy

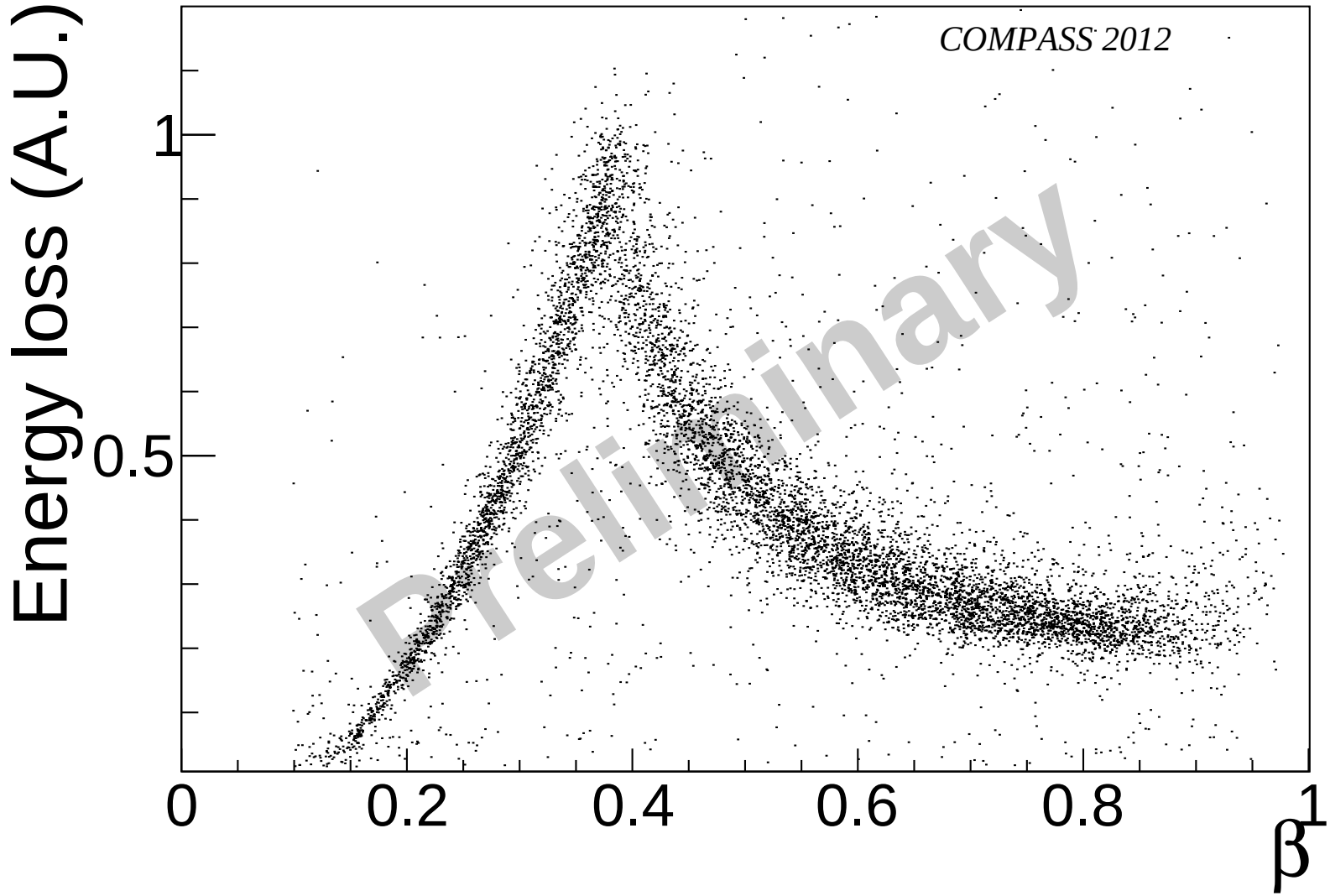




Proton Signal in Recoil Detector

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 **background sources** for excl. photon events

Two possible cases:

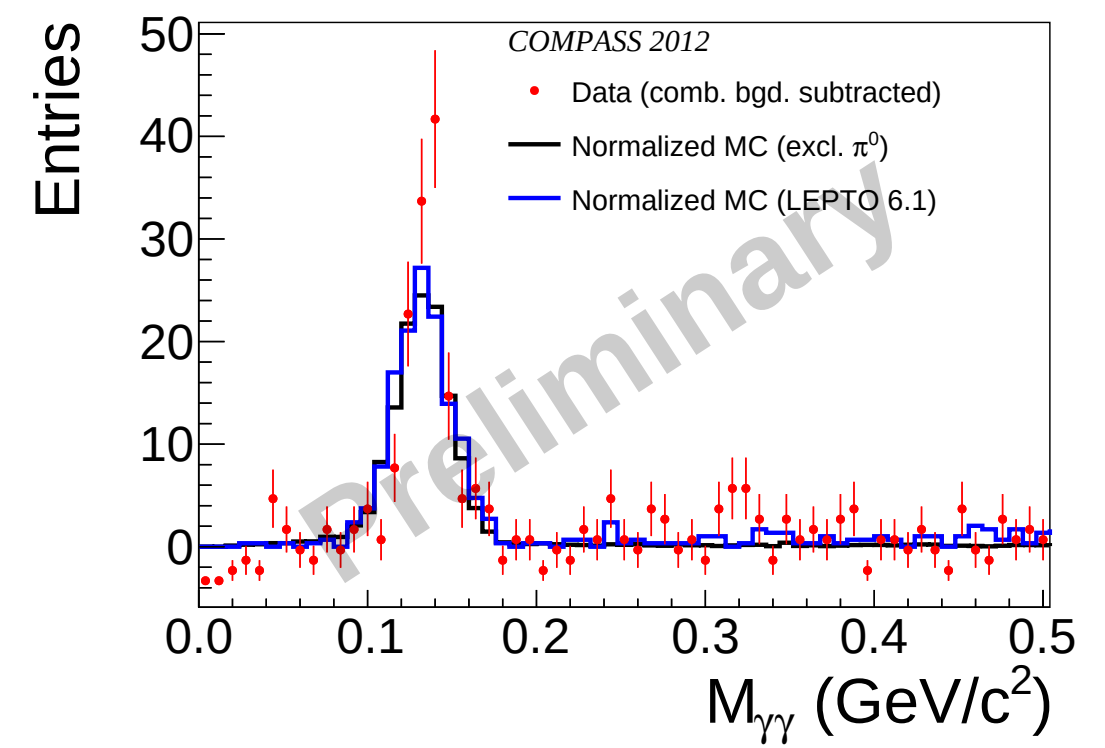
- **visible** (both γ detected, **subtracted**)
- **invisible** (one γ ``lost'', **estimated with MC**)
  - **Semi-inclusive** $\rightarrow$ LEPTO
  - **Exclusive** $\rightarrow$ HEPGEN/π^0 (Goloskokov-Kroll model)

MC samples normalized on ``visible'' π^0 signal

π^0 Background Estimation

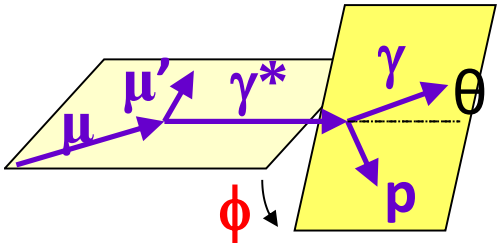
π^0s are one of the main **background sources** for excl. photon events

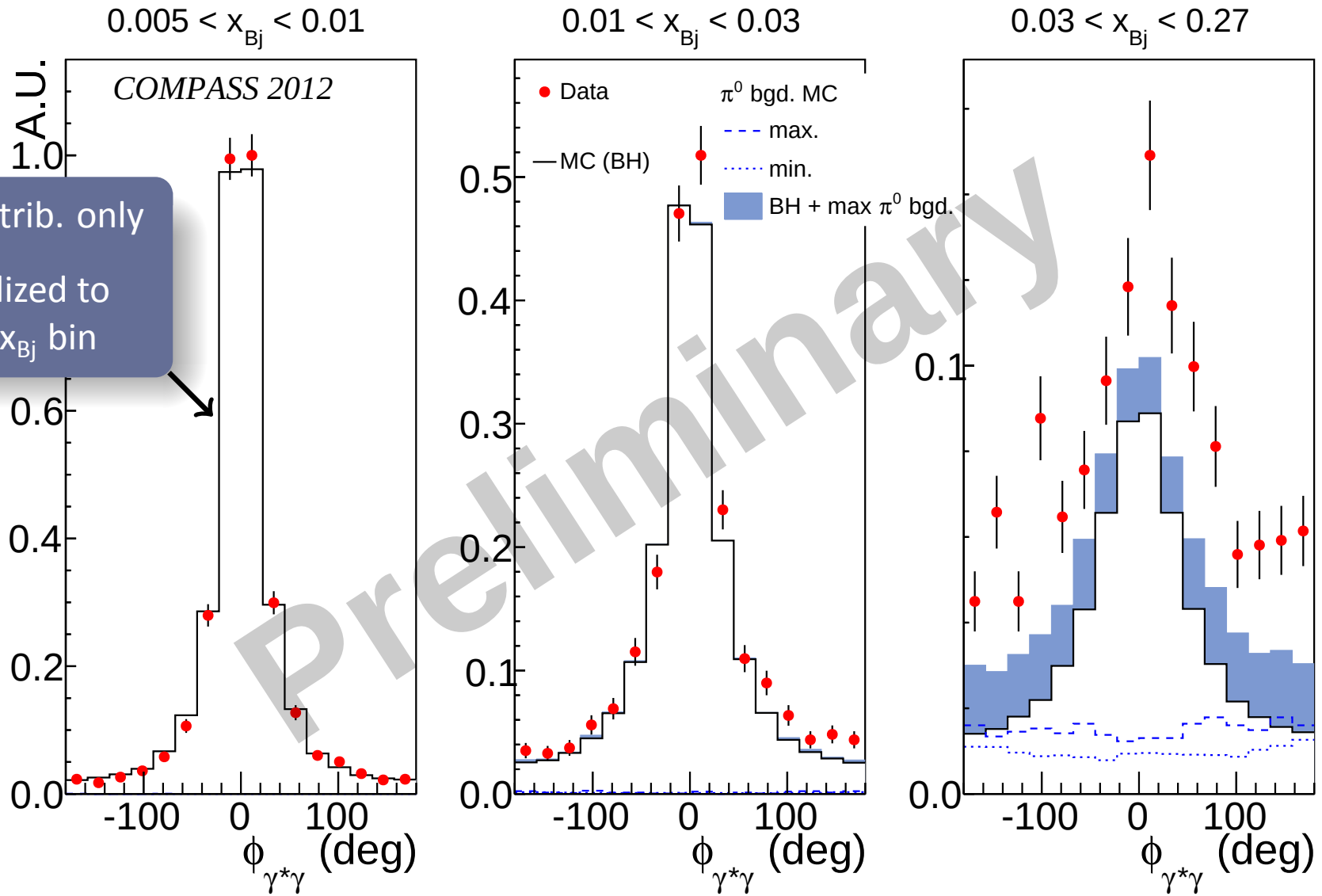
$M_{\gamma_{excl}\gamma_{bgd}}$ distribution (``visible'' π^0)



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





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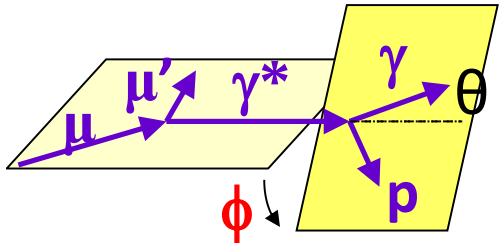
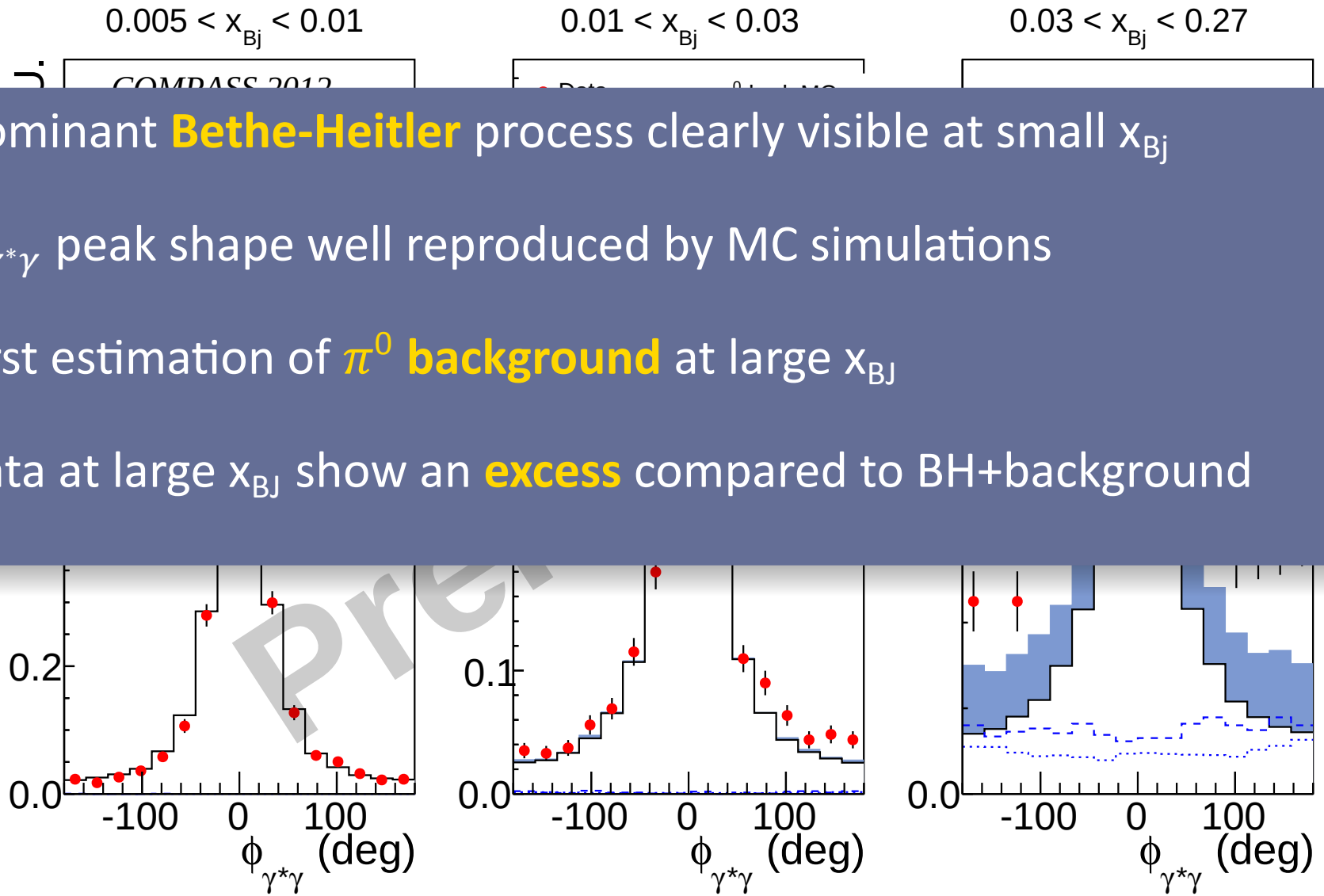




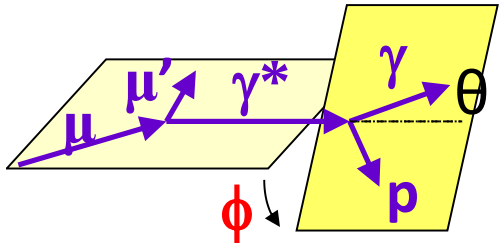
Dominant **Bethe-Heitler** process clearly visible at small x_{Bj}

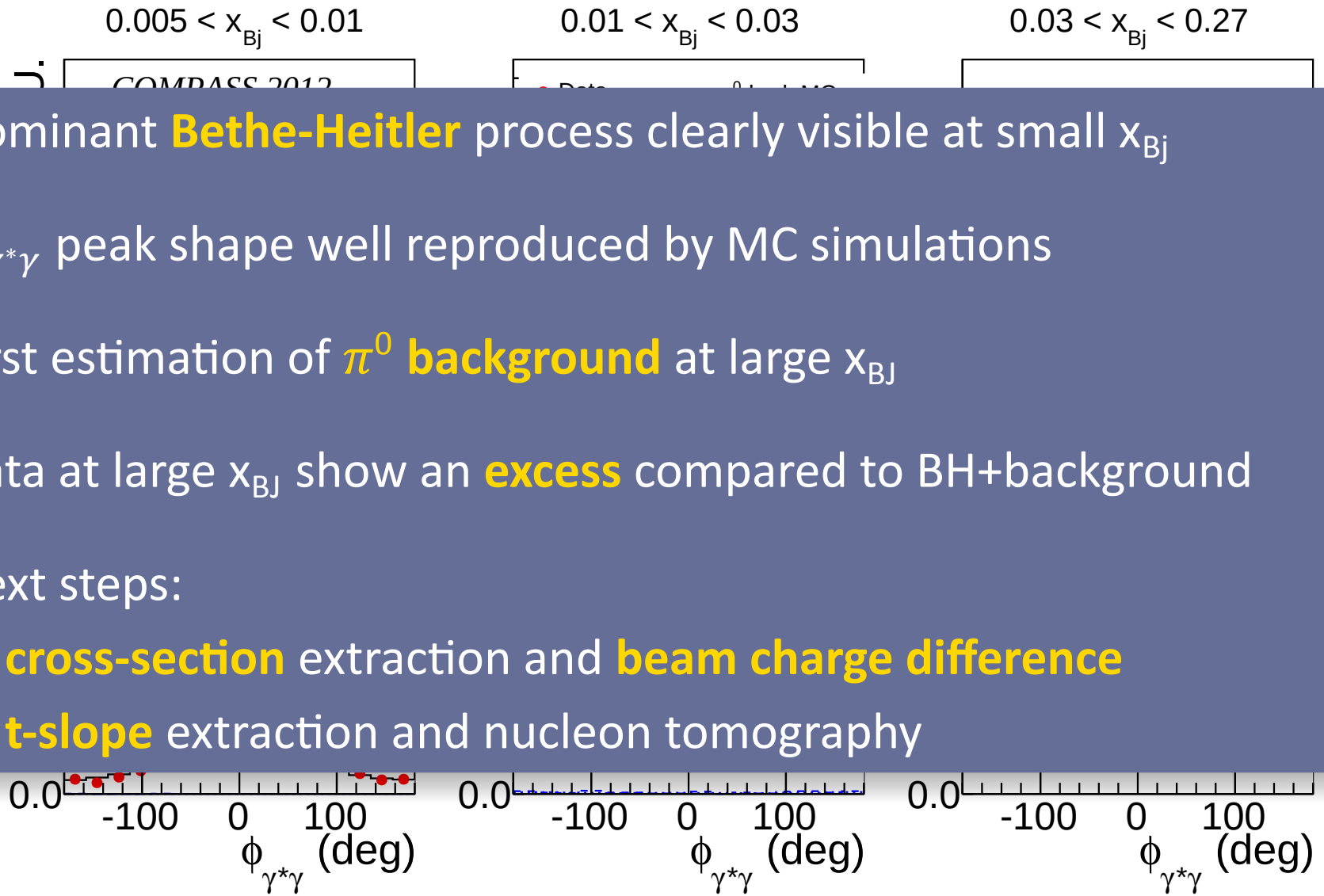
$\phi_{\gamma^*\gamma}$ peak shape well reproduced by MC simulations

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





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

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

Next steps:

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

Outline

Introduction

The Quest of GPDs at COMPASS

Access to **GPD** H through **DVCS**

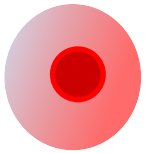
Hard Exclusive Meson Production

Conclusions and Outlook

Other GPDs (ex. in excl. ρ^0 production)

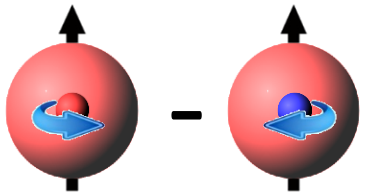
Chiral-even

$H \longleftrightarrow q$



$\gamma^*_L\ p^\uparrow \rightarrow \rho^0_L\ p^\uparrow \quad L=0$

"Elusive" $E \longleftrightarrow f_{1T}^{\perp}$



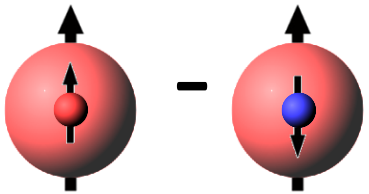
$\gamma^*_L\ p^\uparrow \rightarrow \rho^0_L\ p^\downarrow \quad L=1$

Ji: $2J^q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$

Sivers: quark k_T & nucleon transv. Spin

Chiral-odd

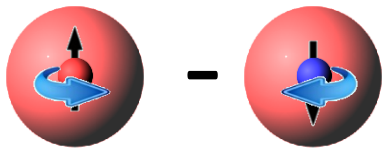
$H_T \longleftrightarrow h_1$



$\gamma^*_T\ p^\uparrow \rightarrow \rho^0_L\ p^\downarrow \quad L=0$

Transversity: quark spin & nucleon transv. spin

$\bar{E}_T = 2\tilde{H}_T + E_T \longleftrightarrow h_1^{\perp}$



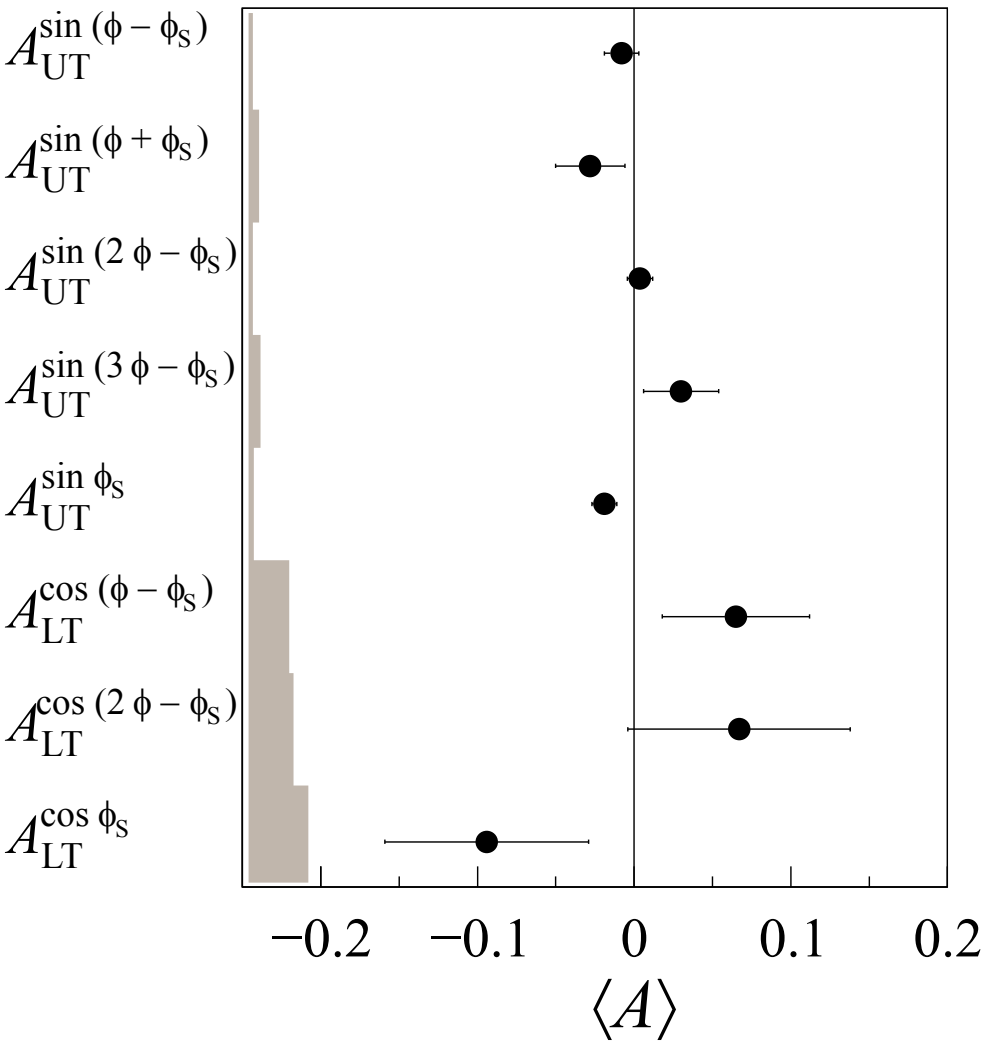
$\gamma^*_T\ p^\uparrow \rightarrow \rho^0_L\ p^\uparrow \quad L=1$

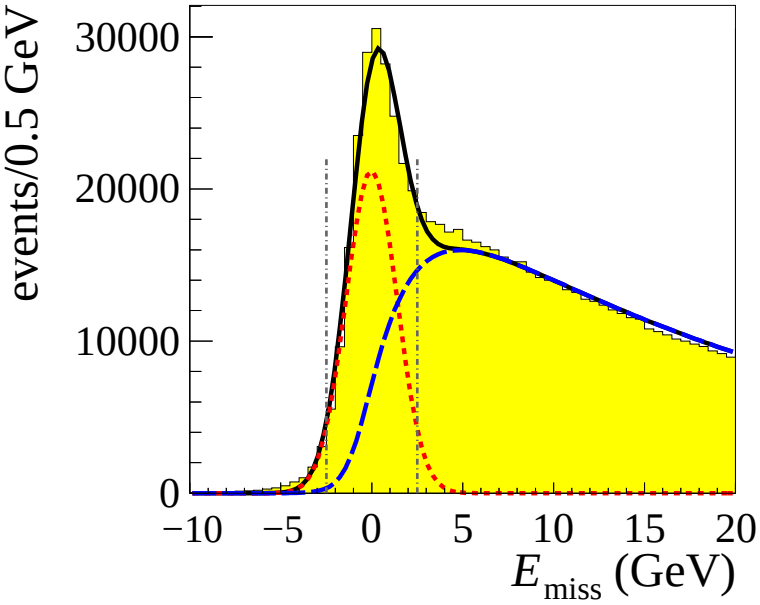
Boer-Mulders: quark k_T & quark transverse spin

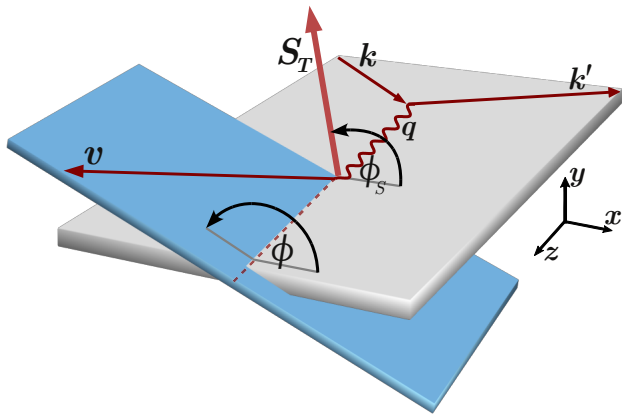
Excl. ρ^0 Production with Transv. Pol. Target

$$\mu\ p \rightarrow \mu'\ +\ \rho^0\ +\ p_{\text{non détecté}}$$
$$\hookrightarrow \pi^+\pi^-$$

COMPASS 2007-2010,without recoil detector







Excl. ρ^0 Production with Transv. Pol. Target

$\mu\ p \rightarrow \mu'\ +\ \rho^0\ +\ p_{\text{non détecté}}$
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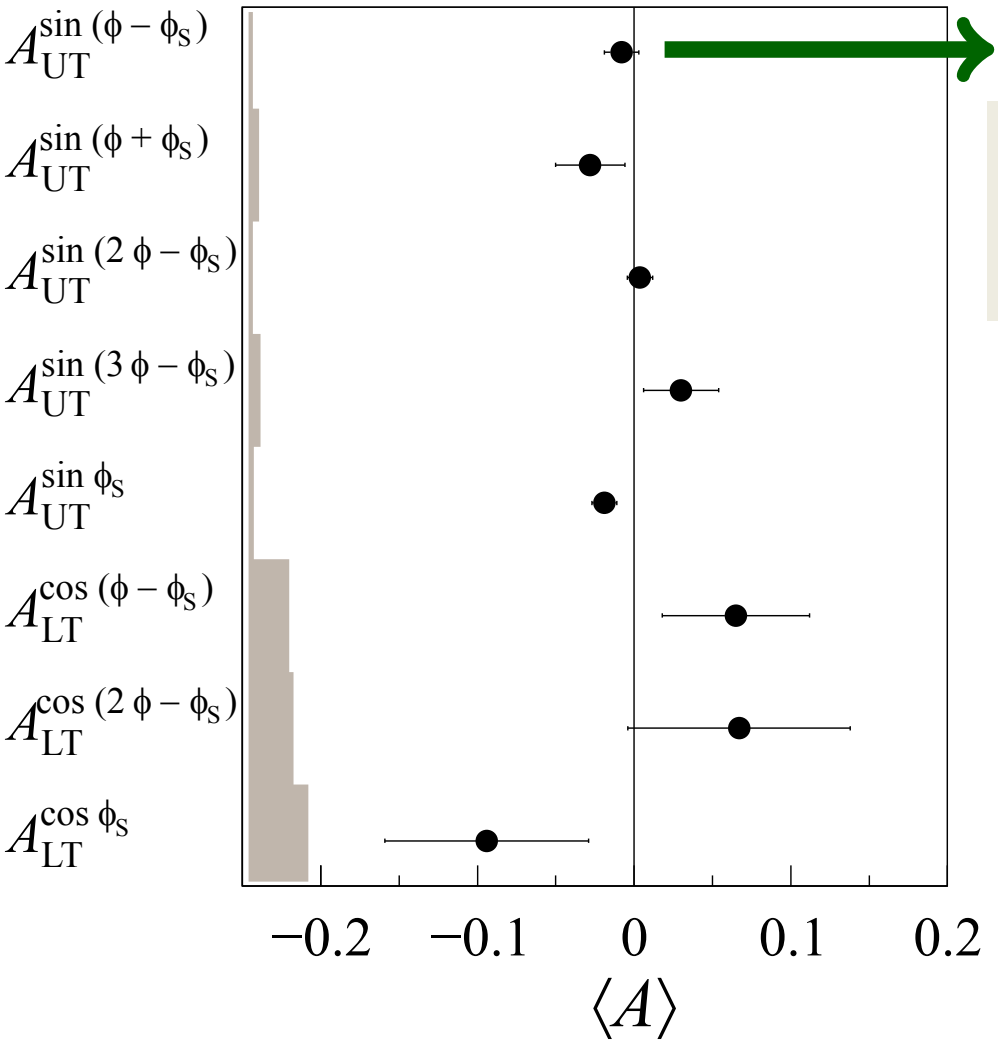
COMPASS 2007-2010,without recoil detector



$\propto\ \mathrm{Im}(\mathcal{E}^*\mathcal{H})$

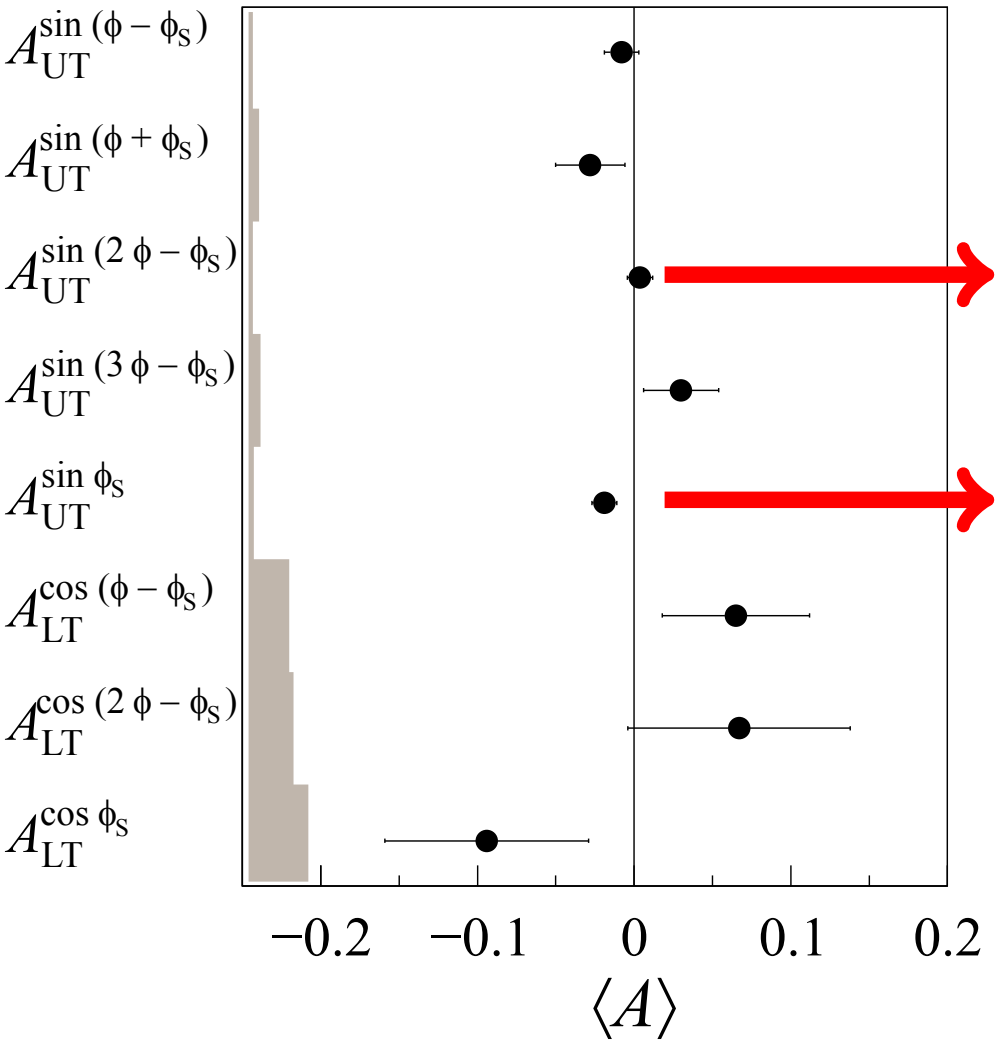
$E\rho^0 \propto$ 2/3 E^u + 1/3 E^d + 3/8 E^g
Cancellation between gluon and sea contributions and **$E^{u\ val} \sim -E^{d\ val}$**

COMPASS, NPB865 (2012) 1-20

Excl. ρ^0 Production with Transv. Pol. Target

$\mu\ p \rightarrow \mu'\ +\ \rho^0\ +\ p_{\text{non détecté}}$
$\hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,without recoil detector



$\propto\ \mathrm{Re}(\mathcal{E}^*\overline{\mathcal{E}}_{\mathcal{T}})$

$\propto\ \mathrm{Im}(\mathcal{E}^*\overline{\mathcal{E}}_{\mathcal{T}} - \mathcal{H}^*\mathcal{H}_{\mathcal{T}})$

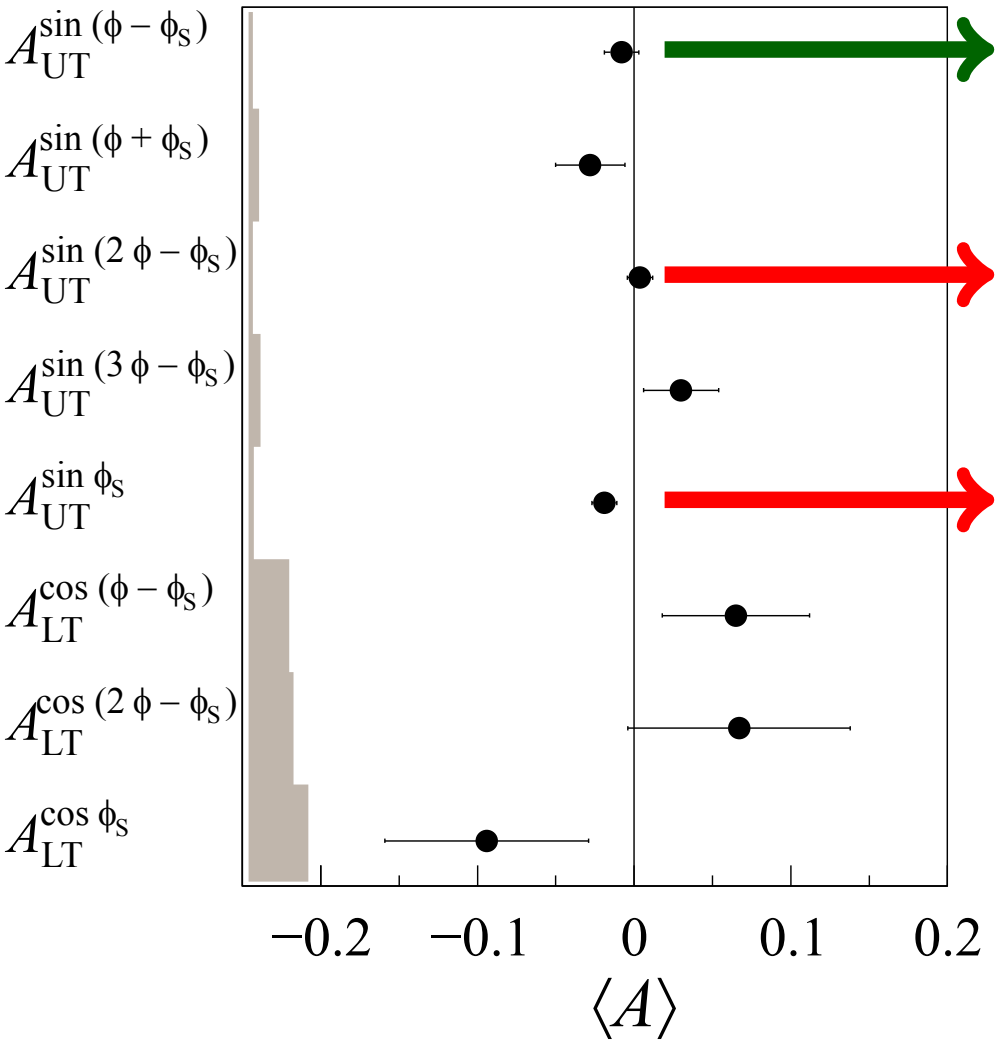
$\mathcal{H}_{\mathcal{T}}$ appears not be small

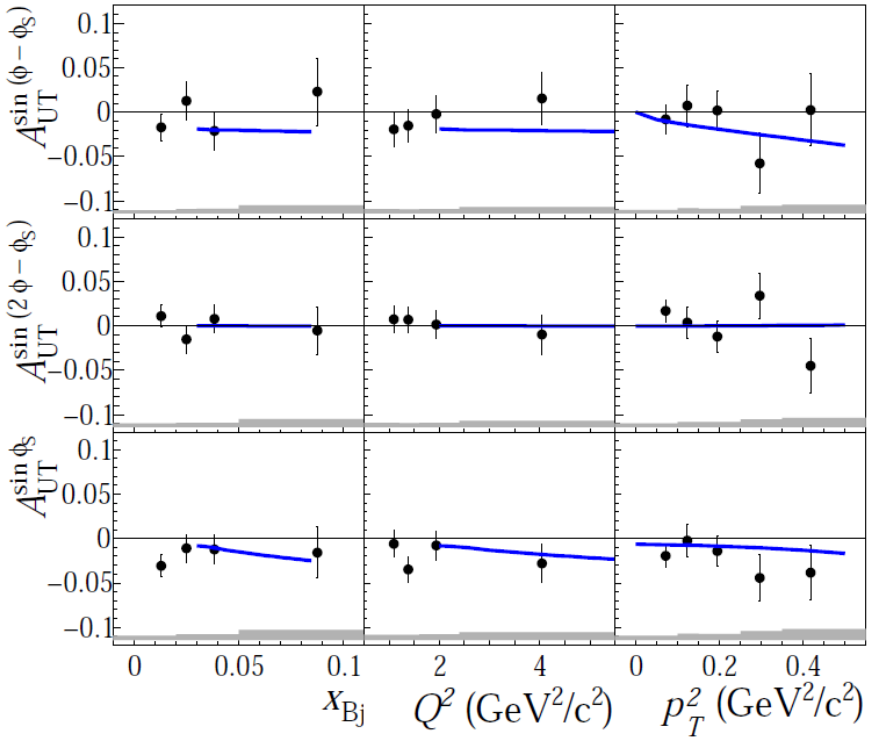
COMPASS, PLB B731 (2014) 19

Excl. ρ^0 Production with Transv. Pol. Target

$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non détecté}}$
$\hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,without recoil detector

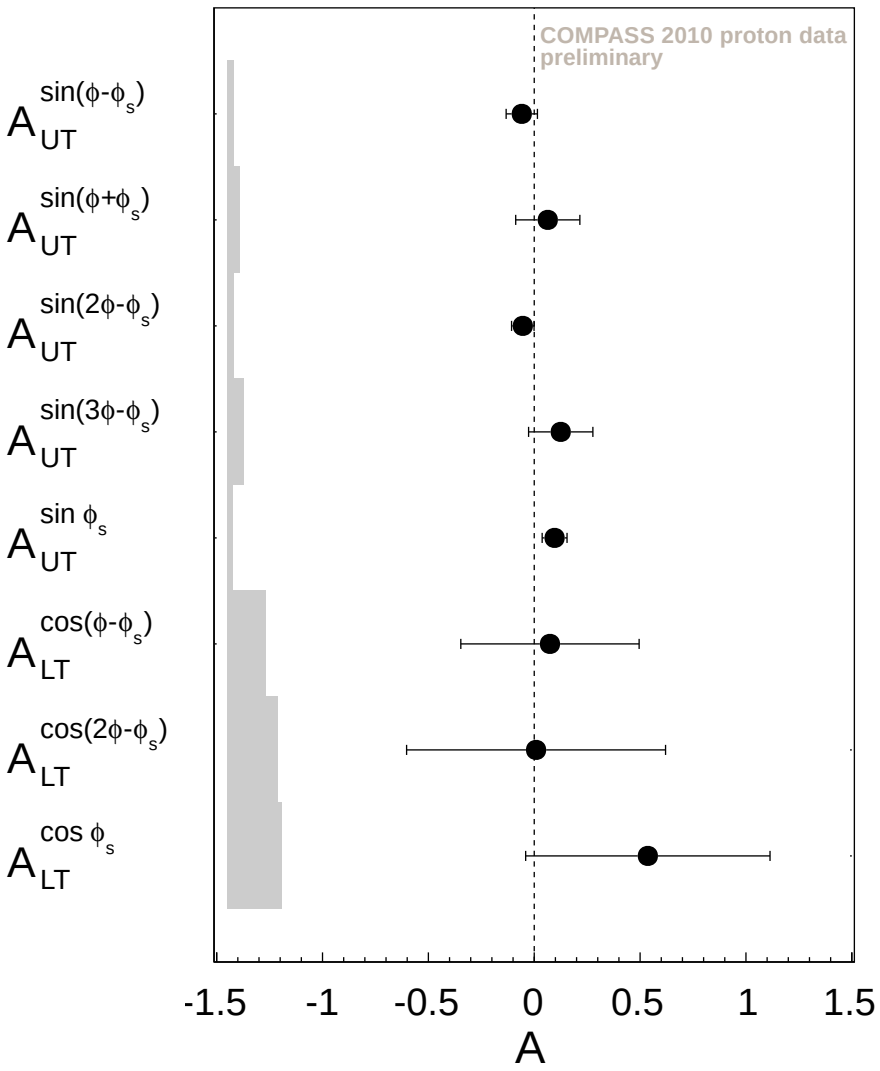




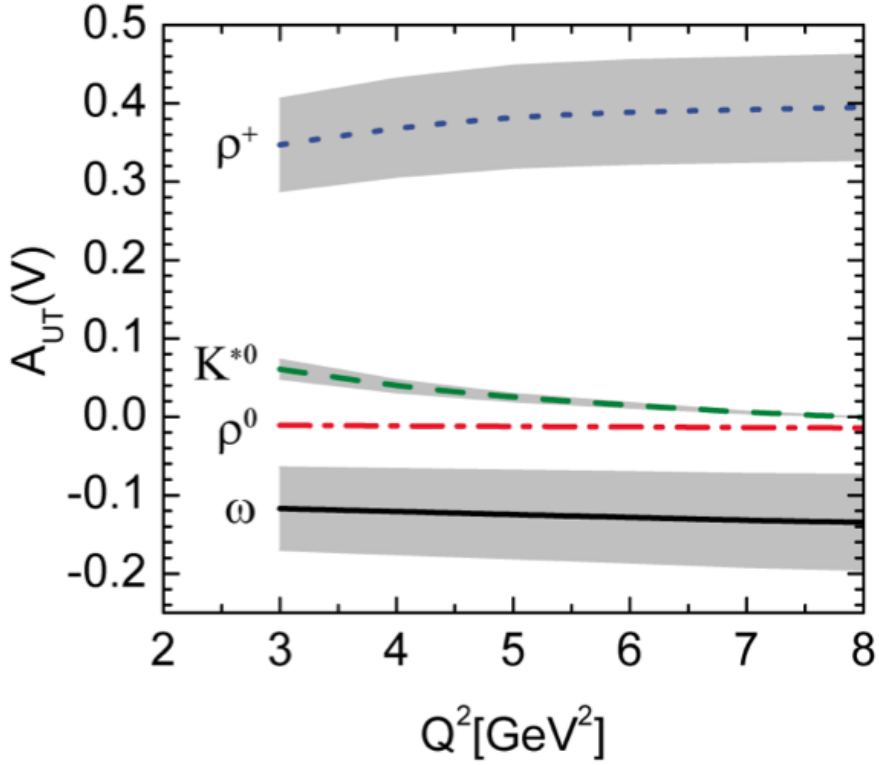
Model prediction:
Goloskokov-Kroll, EPJ C74 (2014) 2725

Excl. ω Production with Transv. Pol. Target

$$\mu\, p \rightarrow \mu' + \omega + p_{undet.}$$
$$\hookrightarrow \pi^+\pi^-\pi^0$$



Goloskokov and Kroll
(EPJC 59 (2009) 809)



$$E^{\omega} \propto 2/3E^u - 1/3E^d + 3/8E^g$$

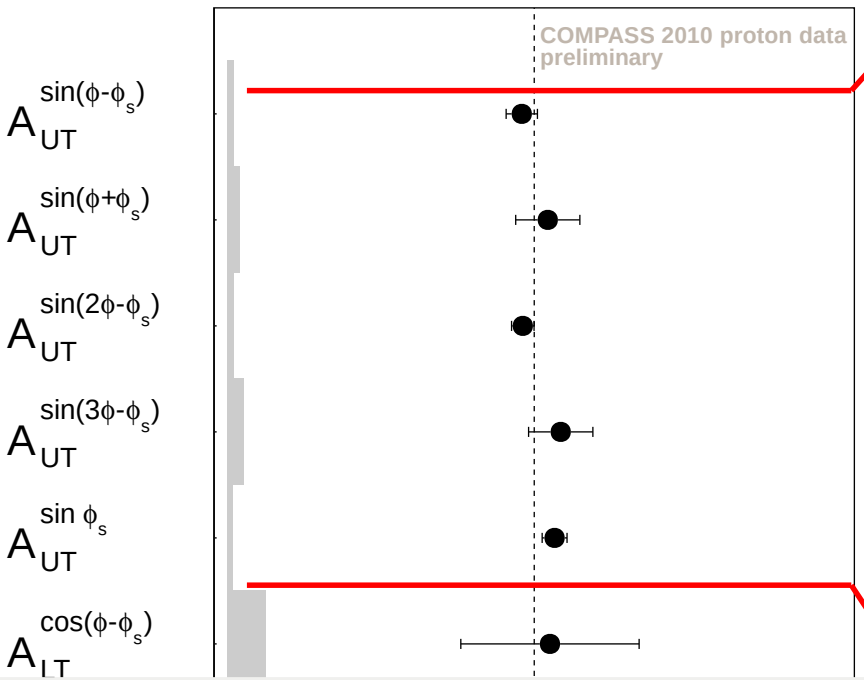
→ *NO CANCELLATION*

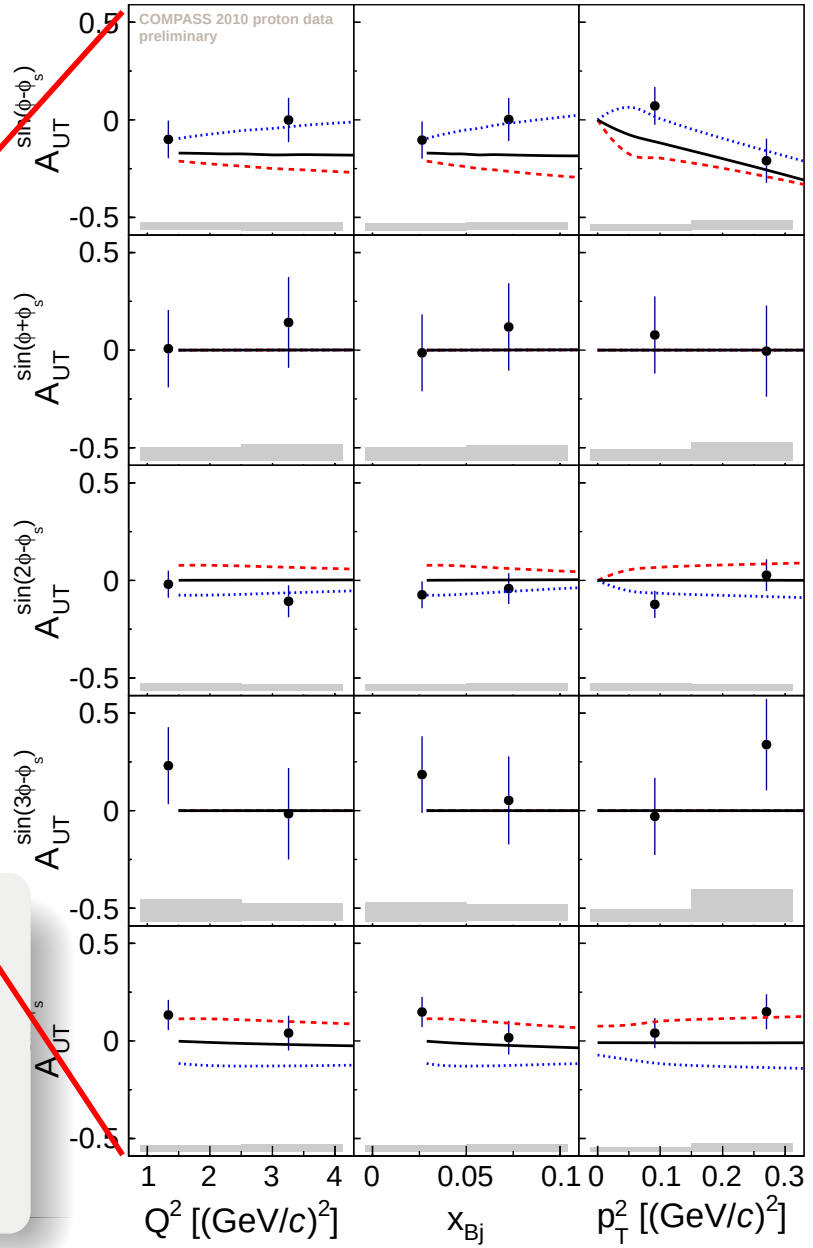
Remember:

$$E^{\rho} \propto 2/3E^u + 1/3E^d + 3/8E^g$$

Excl. ω Production with Transv. Pol. Target

$$\mu\, p \rightarrow \mu' + \omega + p_{undet.}$$
$$\hookrightarrow \pi^+\pi^-\pi^0$$





GK model predictions
(EPJ A50 (2014) 9 + *private comm.*):
- - - positive $\pi\omega$ trans. form factor
--- no pion pole
⋯ negative $\pi\omega$ trans. form factor

Outline

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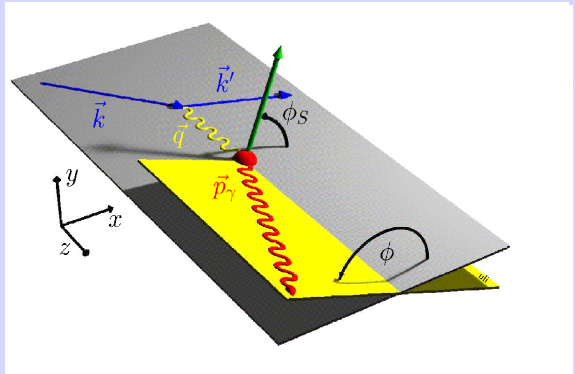
Beyond 2018: DVCS on Transv. Pol. Target at COMPASS?

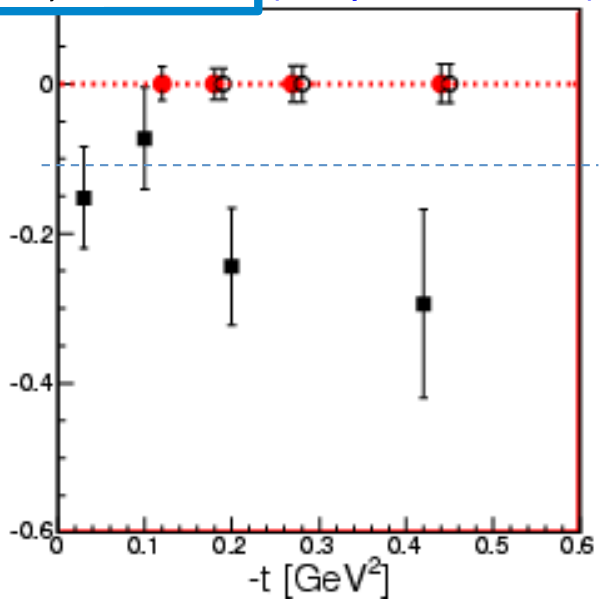
with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam and **transversely** polarized NH3 (proton) target

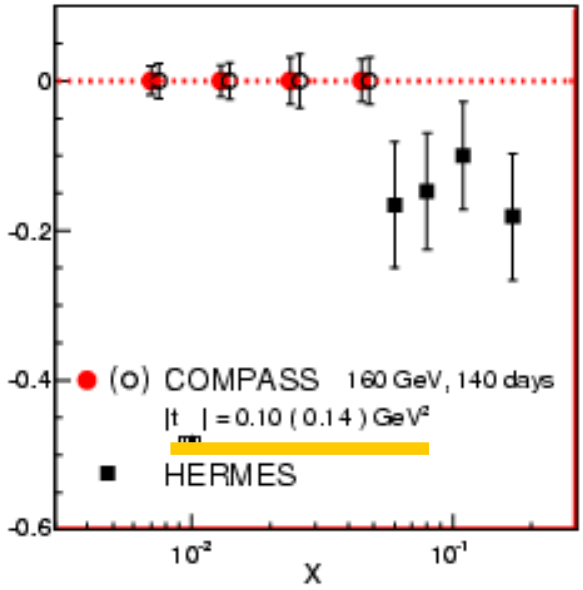
$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow}) \propto Im(F_2\mathcal{H} - F_1\mathcal{E})\sin(\phi-\phi_s)\cos\phi$$

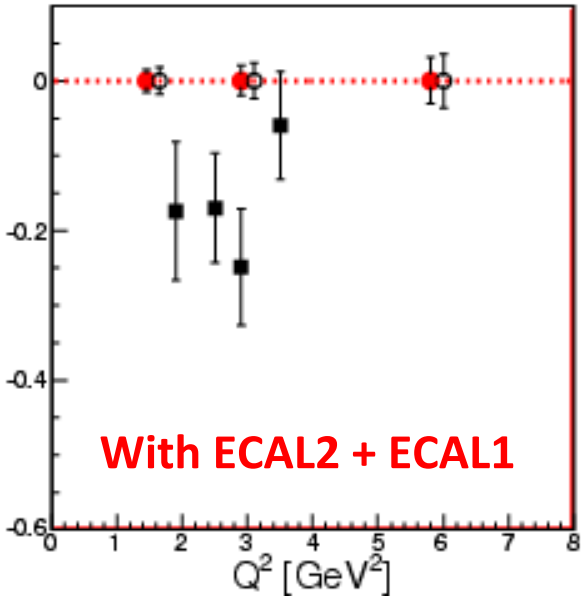


$A_{CS,T}^{\sin(\phi-\phi_s)\cos\phi}$ **related to H and E**
(only stat .error)

2 years of data 160 GeV muon beam
1.2 m polarised NH_3 target $\varepsilon_{global} = 10\%$







Conclusions

Great potential for hard exclusive processes studies:

- Complete event reconstruction
- Unique high-energy μ beams with **opposite charge and polarizations**
- Kin. coverage **complementary** to JLab 12 GeV, Hermes, Hera and future EIC

DVCS and HEMP on unpol. proton target:

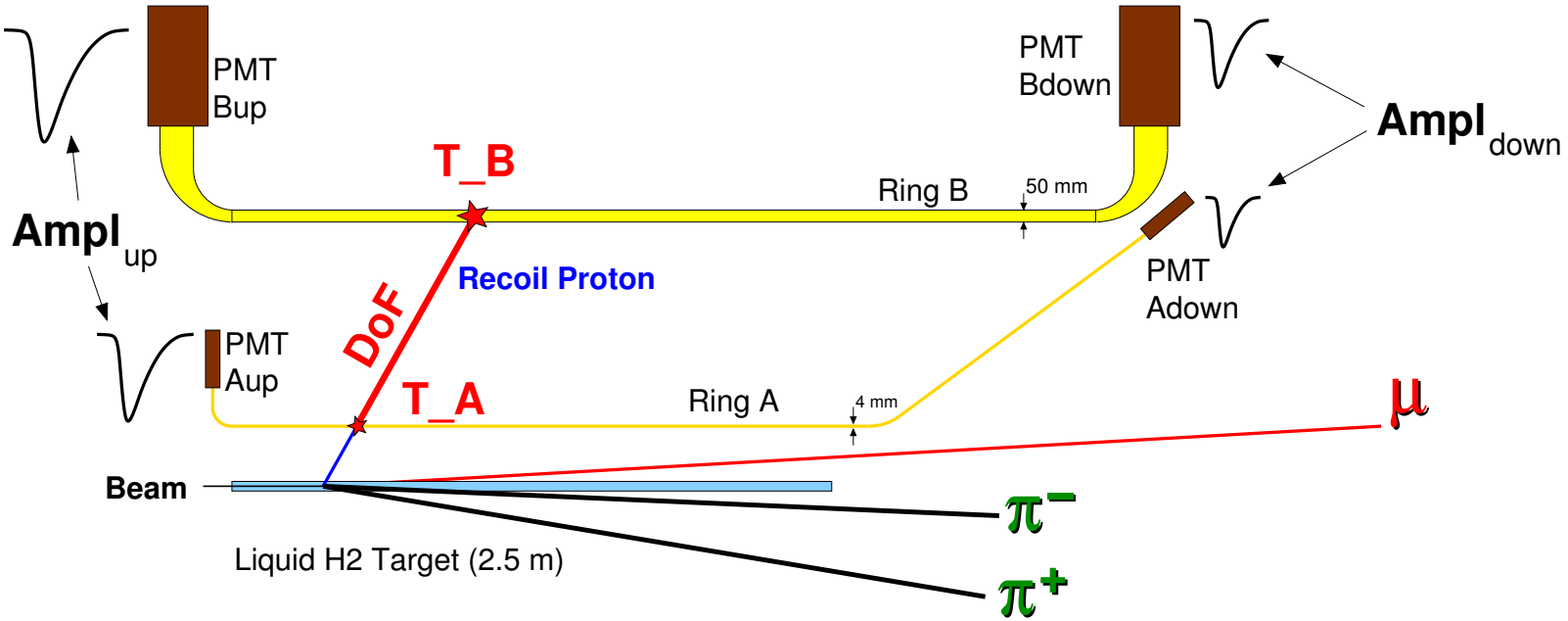
- t-slope of DVCS and HEMP cross sections as function of x_{Bj}
  → **transverse size** of the nucleon
- Beam Charge&Spin sum and difference of DVCS cross section
  → constraints on **GPD H**
- Exclusive meson production in parallel to DVCS
  → **flavour separation** of GPD H and sensitivity to **other GPDs**

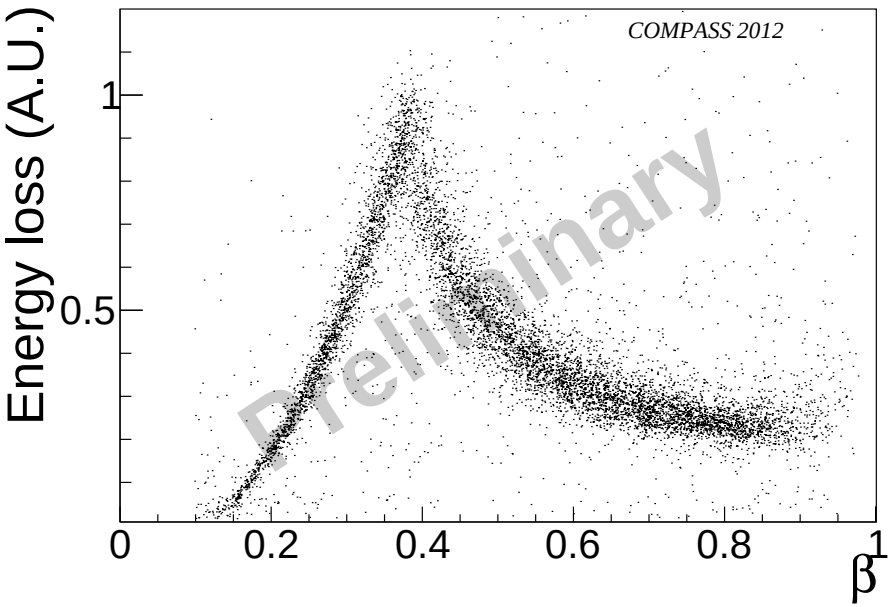
Exclusive ρ and ω production from existing transv. pol. target data:

- No detection of recoil protons
- **5 SSA** $A_{UT,p}$ and **3 DSA** $A_{LT,p}$ measured → indications of **non-zero** H_T
- ρ results published, ω results to be published soon

Backup Slides

Recoil particle Measurement in CAMERA





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

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

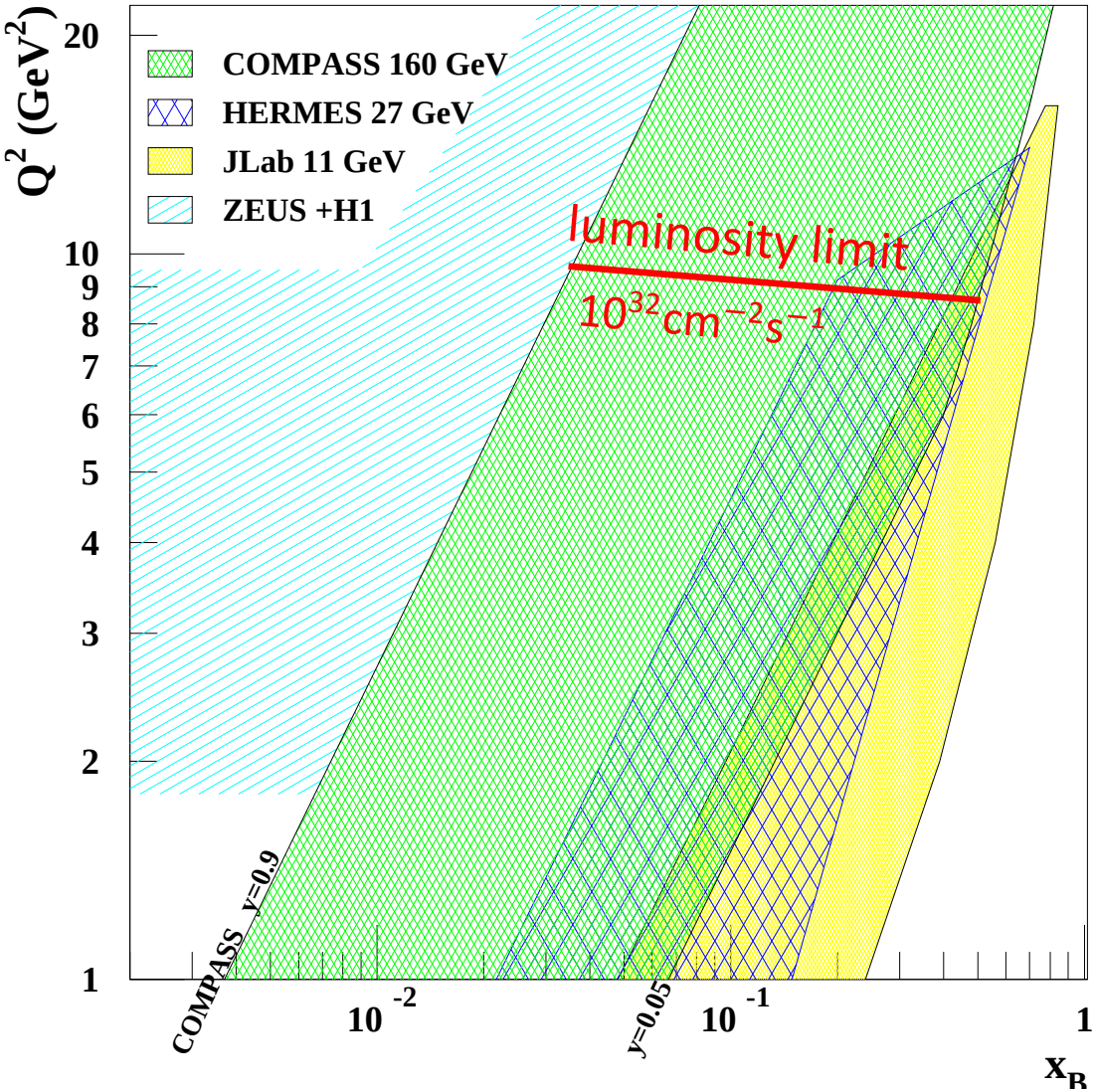
$$\textbf{z} \rightarrow t_{up} - t_{down}$$

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

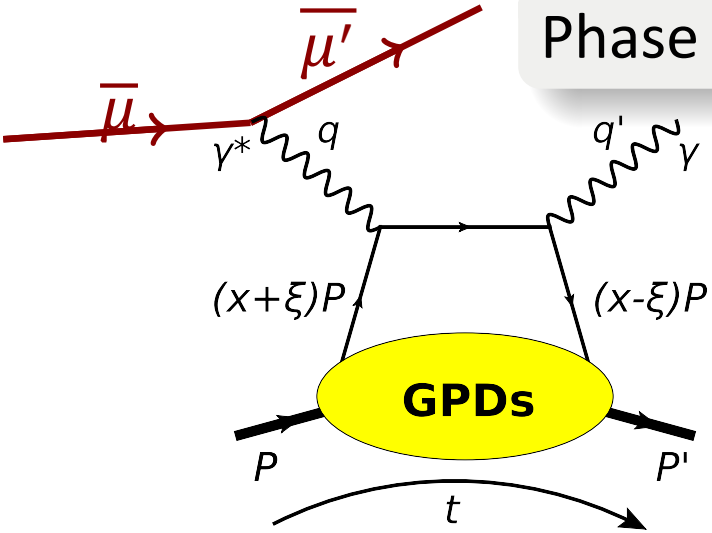


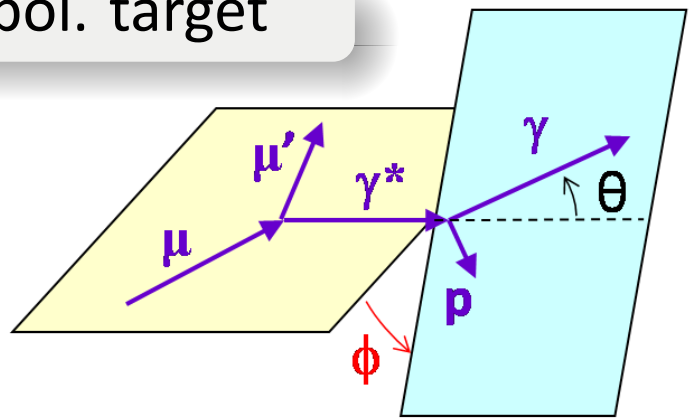
- μ^+ and μ^- beams
- momentum: 100 – 190 GeV/c
- beam polarization: 80 %
  opposite for μ^+ and μ^-
- coverage of intermediate x_B
  → low x_B: **pure BH**
  useful for normalization
  → high x_B: **DVCS predominance**

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

DVCS: What Can We Learn?

Phase 1: Polarized beam, unpol. target

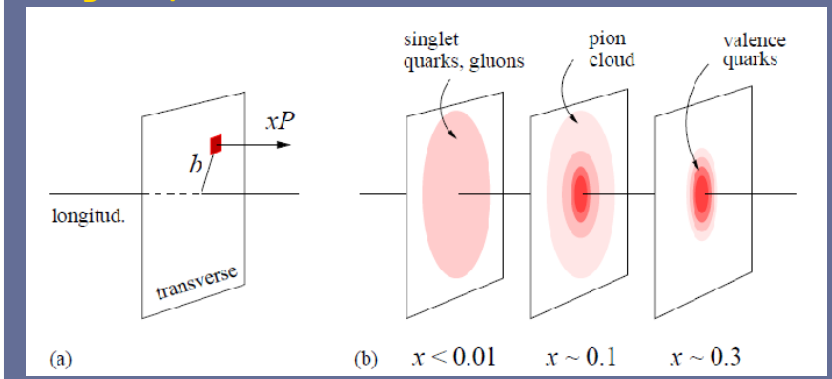




DVCS dominance at large x_B

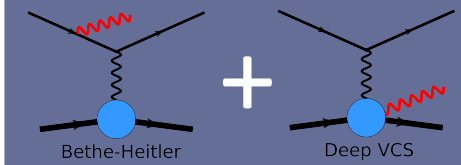
BH/DVCS interf. at intermediate x_B

x_B-dependent transv. size of nucleon



$\mathbf{r}_\perp$ parameter from slope of $d\sigma^{DVCS}/dt$

Interference between BH and DVCS



→ "Boost" of DVCS through int. term

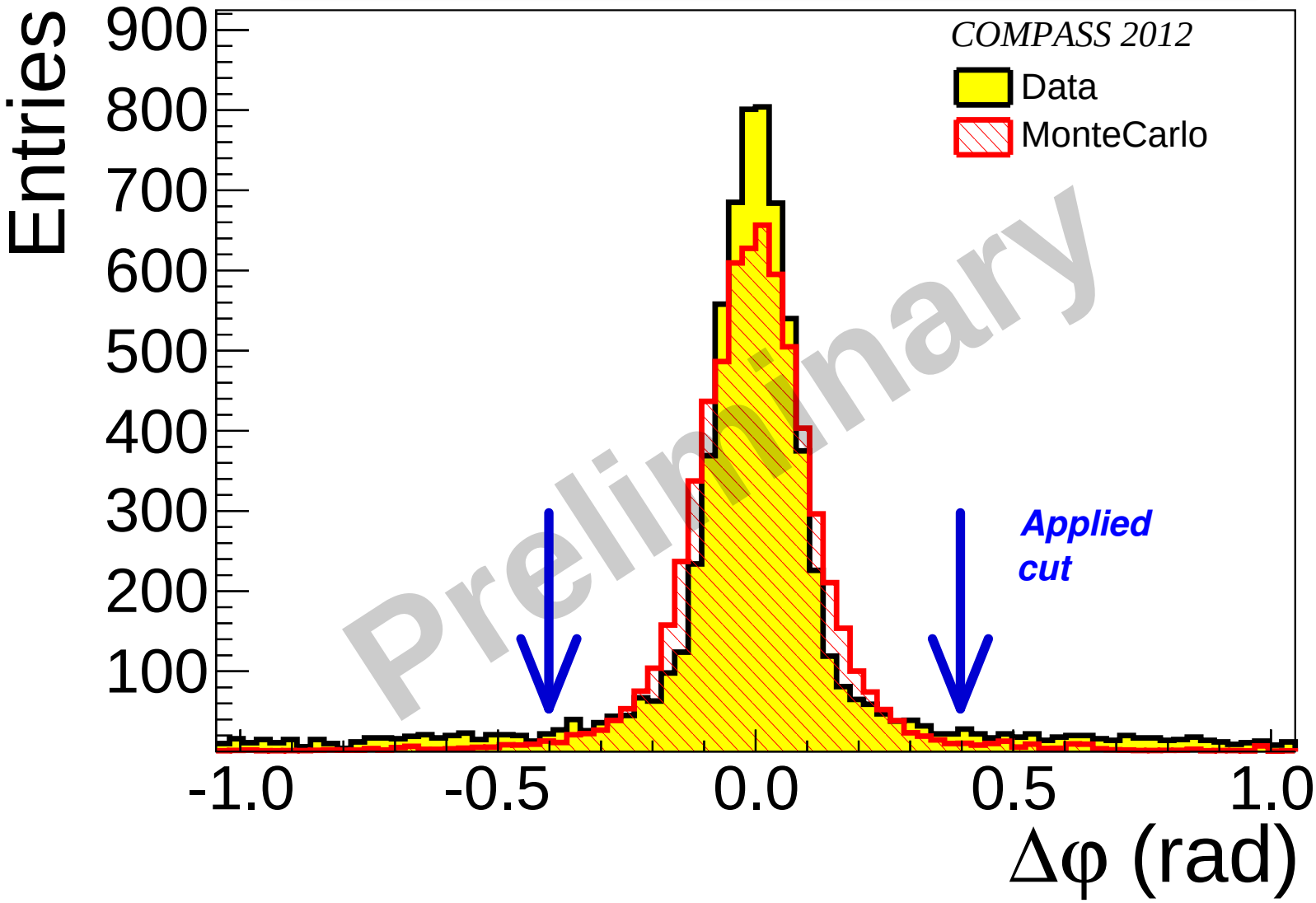
Measurement of $\mathrm{Re}\mathcal{H}(\xi,t)$ and $\mathrm{Im}\mathcal{H}(\xi,t)$ via ϕ-modulation of cross section

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

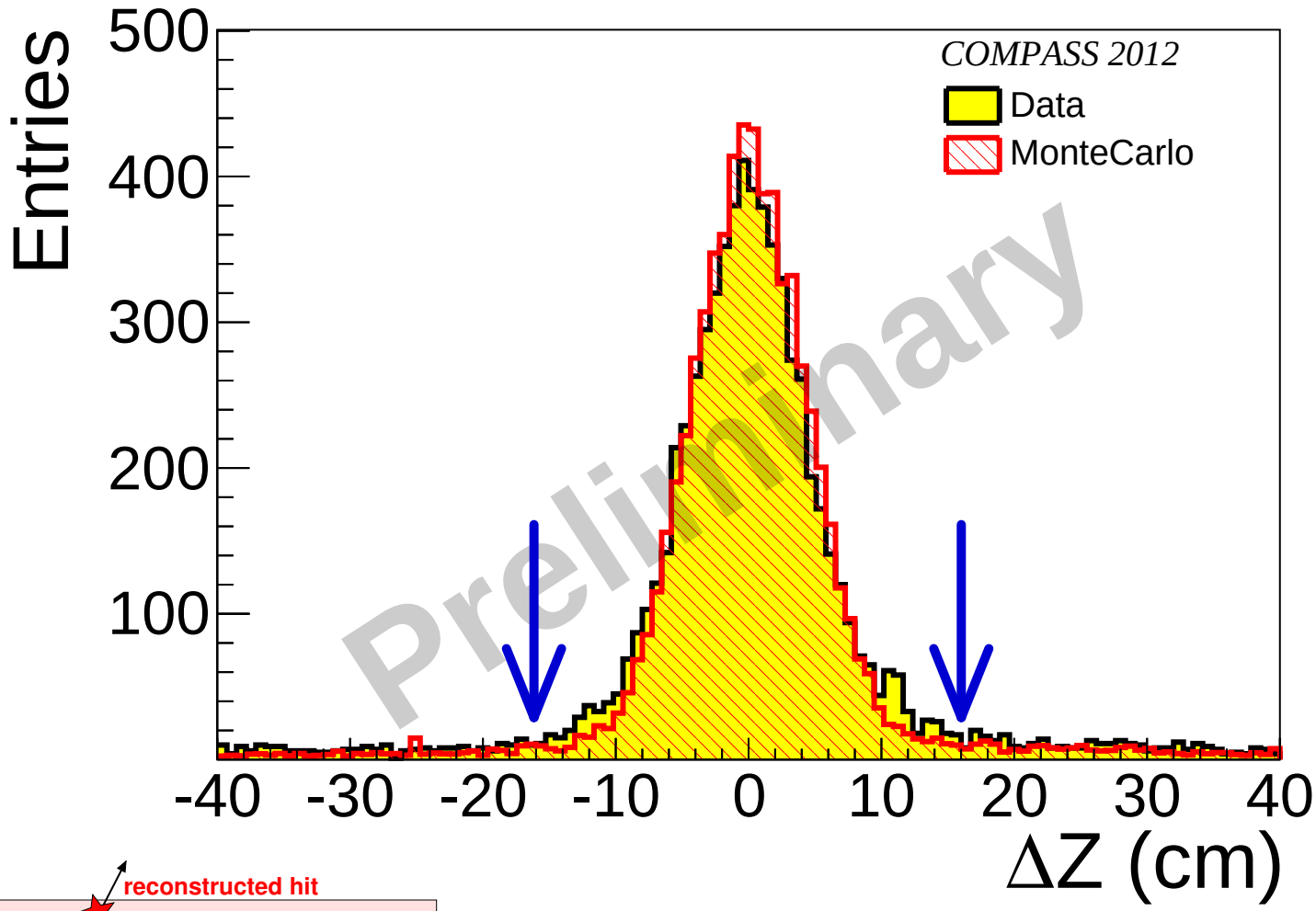
Exp. constrain to GPD H

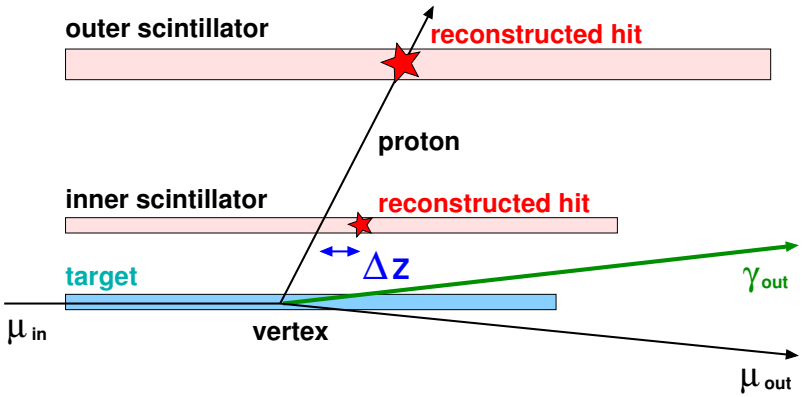
Exclusivity Variables: $\Delta\varphi$

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



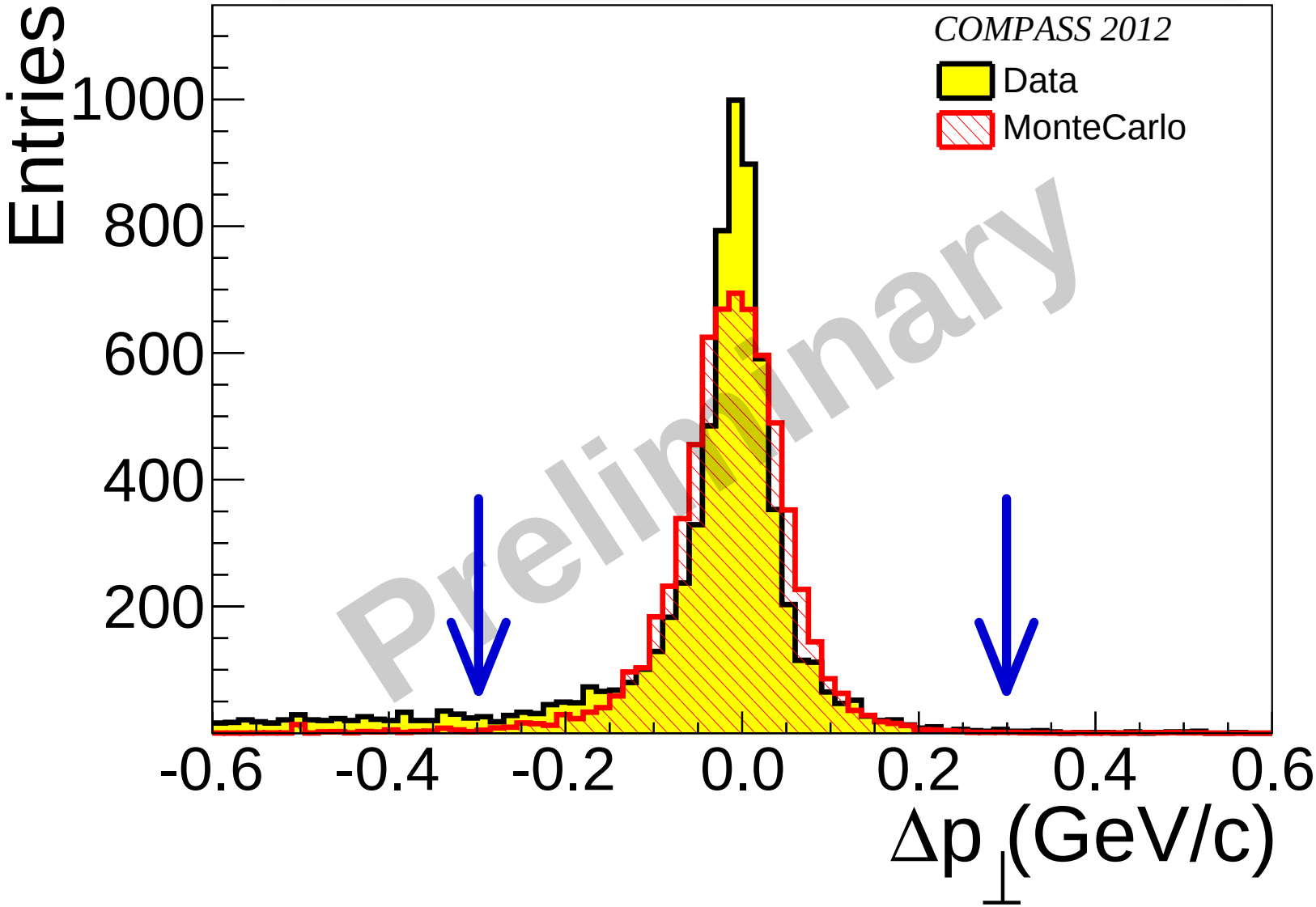
Exclusivity Variables: ΔZ





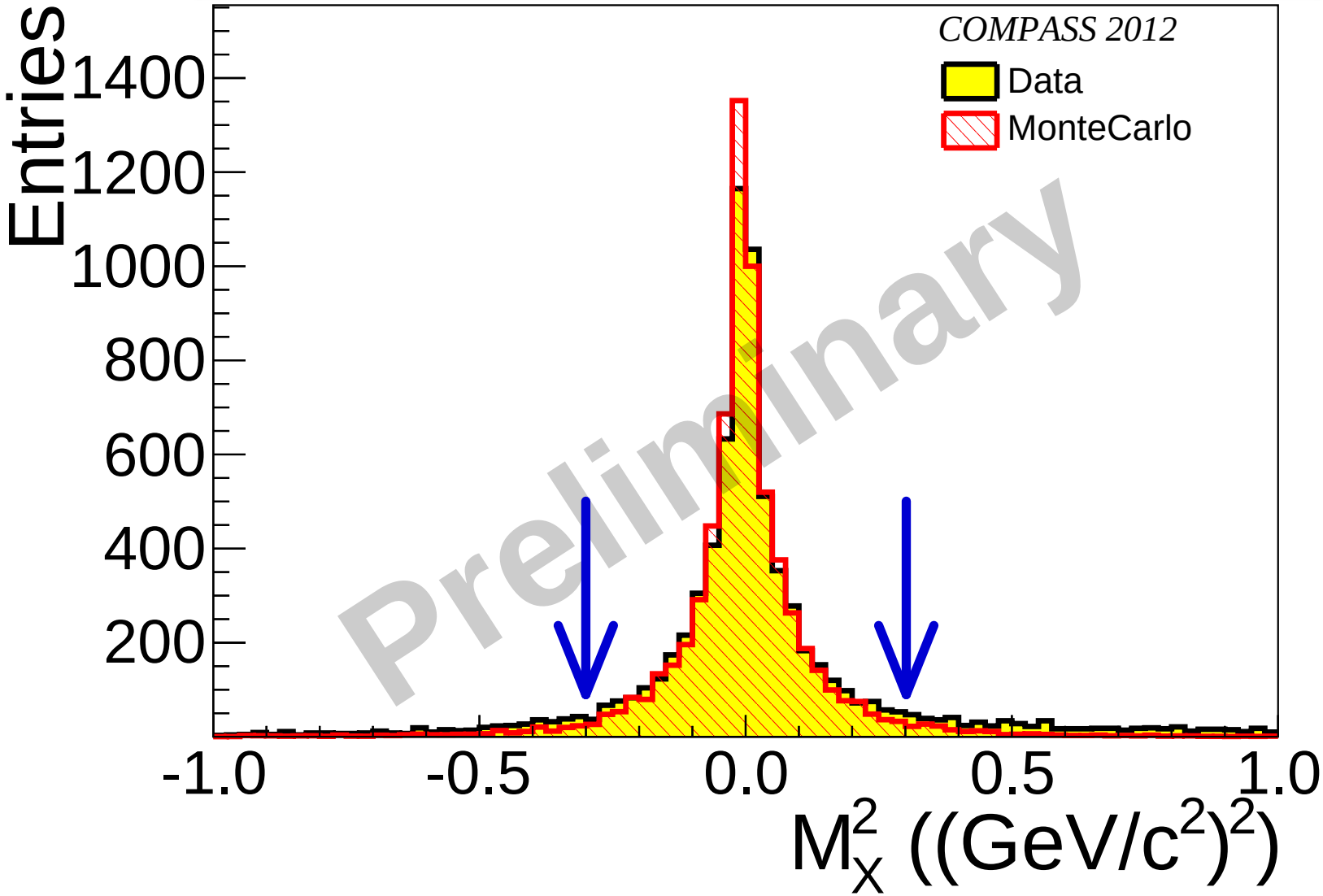
Exclusivity Variables: $\Delta p_\perp$

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

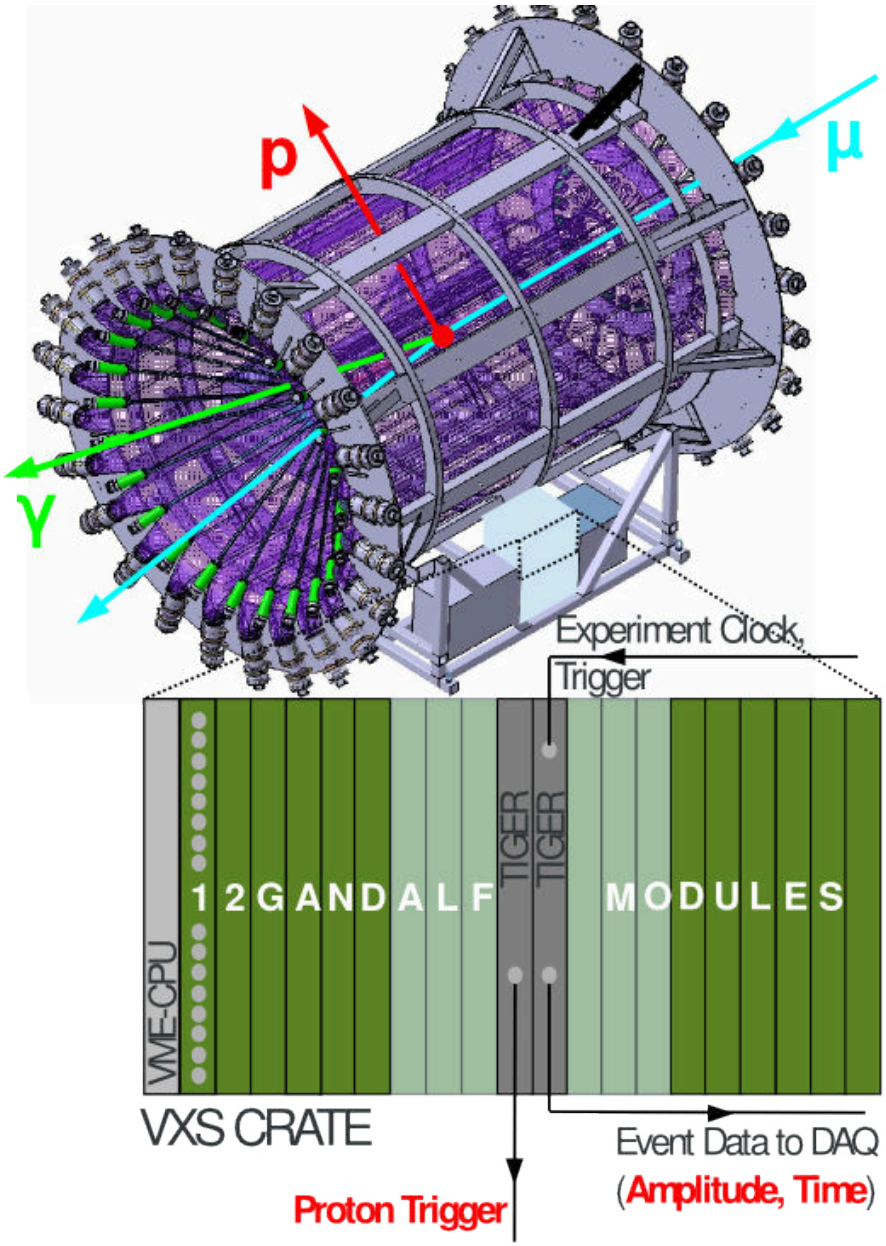


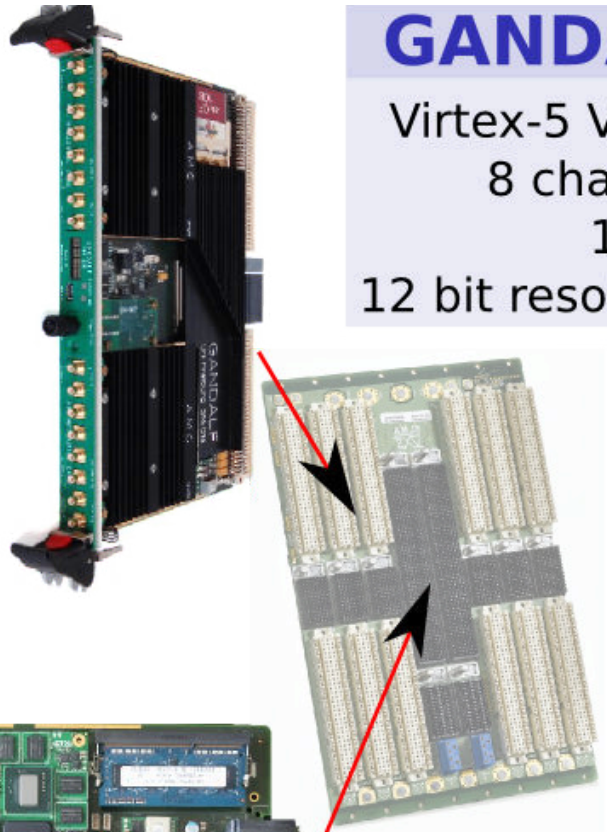
Exclusivity Variables: M_X^2

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



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