GPD Studies at COMPASS

Nicole d'Hose, CEA-Saclay
For the COMPASS Collaboration
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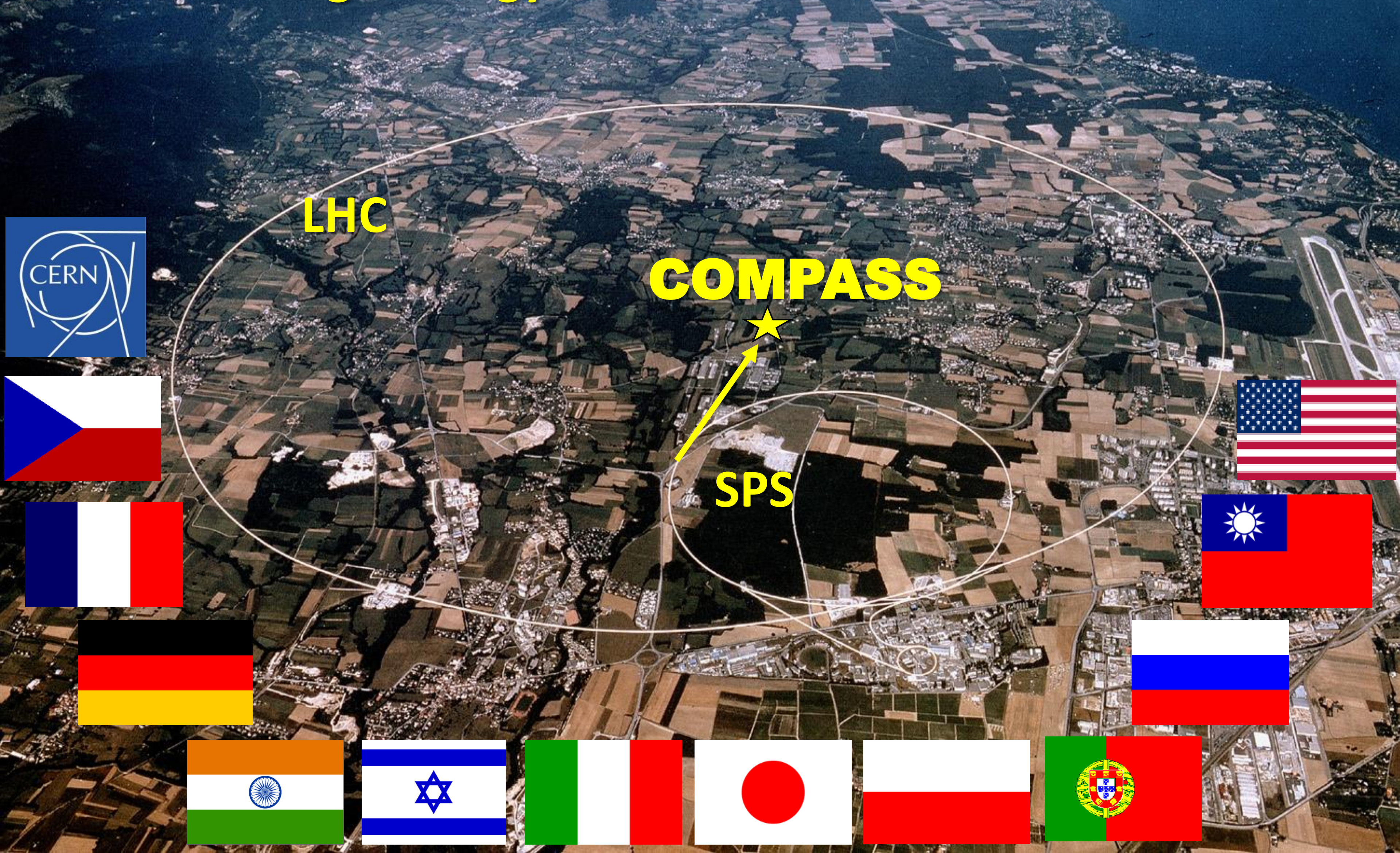
COMPASS: Versatile facility with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams of high energy ~200 GeV



COMPASS: a Facility to study QCD

a fixed target experiment at the CERN SPS

~ 220 physicists from 25 Institutes of 13 Countries

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

COMPASS

Hadron Spectroscopy & **Test of ChPT** with **π, K, p** beams on nuclei **2008-9-12**

Nucleon Structure

SIDIS with $\vec{\mu}$ beams with Long or Trans. Polarized Targets

Long. and Transv. Spin structure

PDFs, FFs and TMDs

	Polar. Deuteron (Li^6D)	Polar. Proton (NH_3)
Long.	**2002-3-4-6**	**2007-11**
Transv.	**2002-3-4**	**2007-10**

Drell-Yan with **π** beams with Transv. Pol. NH_3 target

TMDs

2009-12-14 (tests) and **2015**

Exclusive DVCS & DVMP +SIDIS with $\vec{\mu}$ beams with LH_2 target

GPDs + TMDs, FFs

2008-09-2012 (tests) and **2016-17**

GPD Studies at COMPASS
Exclusive Measurements

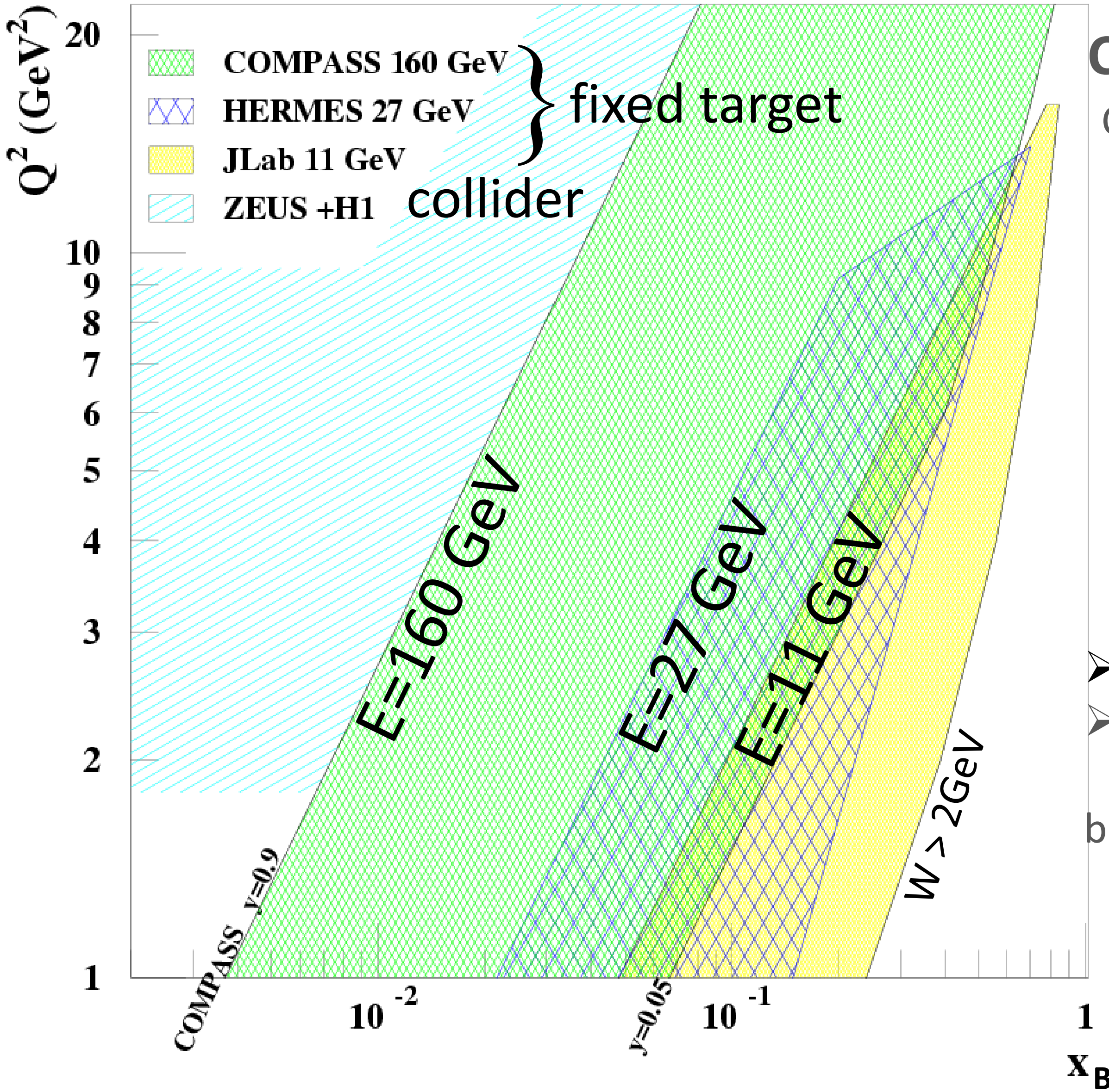
Deeply Virtual Compton Scattering and Exclusive Meson Production with LH2 target and Recoil detection

- pilot runs (2008-9 and 2012) .... PRELIMINARY RESULTS
- 2 years (2016-17) .... PLANNED MEASUREMENTS

Transverse target asymetries without recoil detection for exclusive ρ and ω production

- with polarized Li_6D (2002-3-4)..........RESULTS FOR ρ
- with polarized NH_3 (2007-10) ....RESULTS FOR ρ and ω

Kinematic domain (Q^2, x_B) for GPDs



COMPASS assets for GPDs

CERN High energy muon beam

✓ 100 - 190 GeV

✓ **$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ available**

✓ 80% Polarisation with opposite polarization

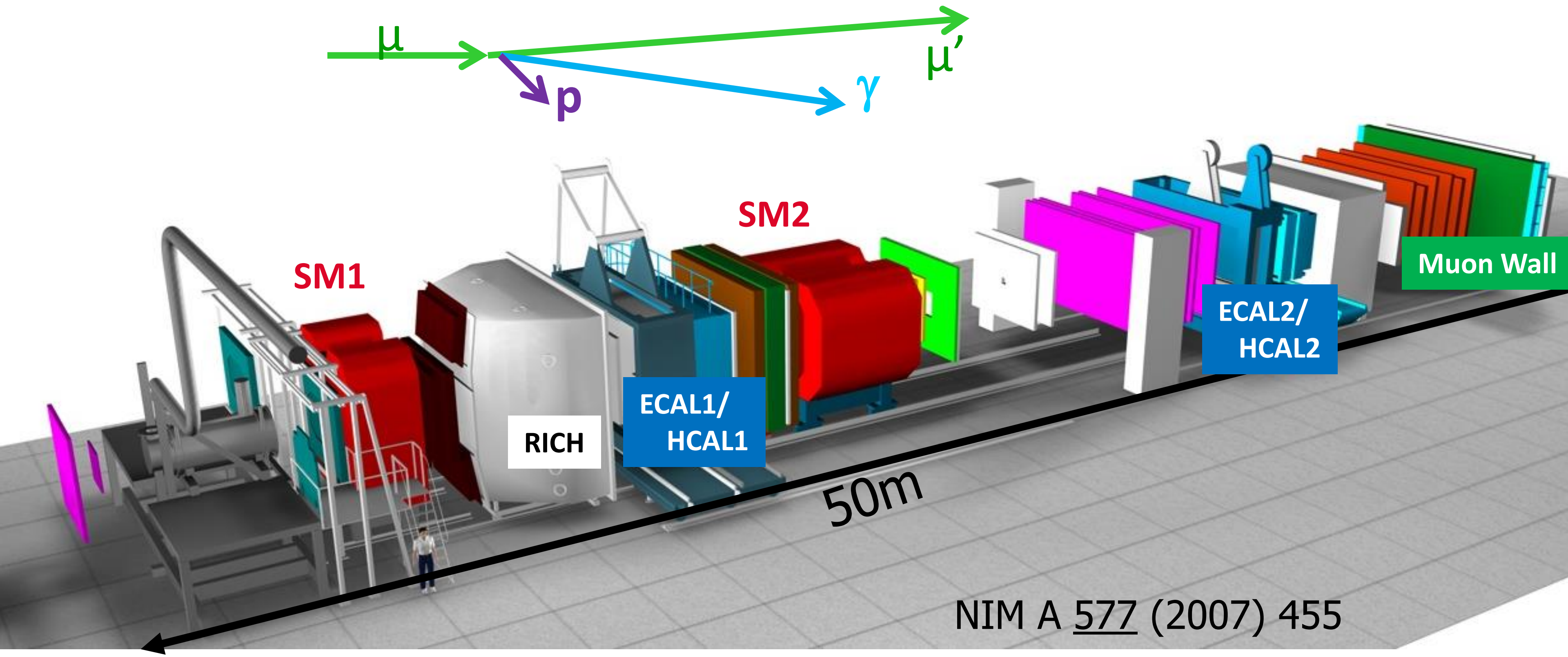
✓ 4.6 10^8 μ^+ /spill

➔ Lumi= 10^{32} cm^{-2} s^{-1} with 2.5m LH2 target

- Explore the intermediate x_{Bj} region
- Uncovered region between ZEUS+H1 & HERMES **+ JLab** before new colliders may be available

The DVCS experiment at COMPASS

DVCS : μ p → μ' p γ



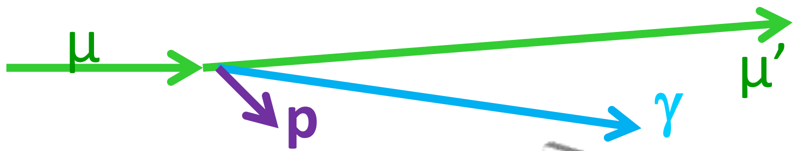
Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

- Ring Imaging Cerenkov Counter
- Electromagnetic calorimeters (**ECAL1** and **ECAL2**)
- Hadronic calorimeters
- Hadron absorbers

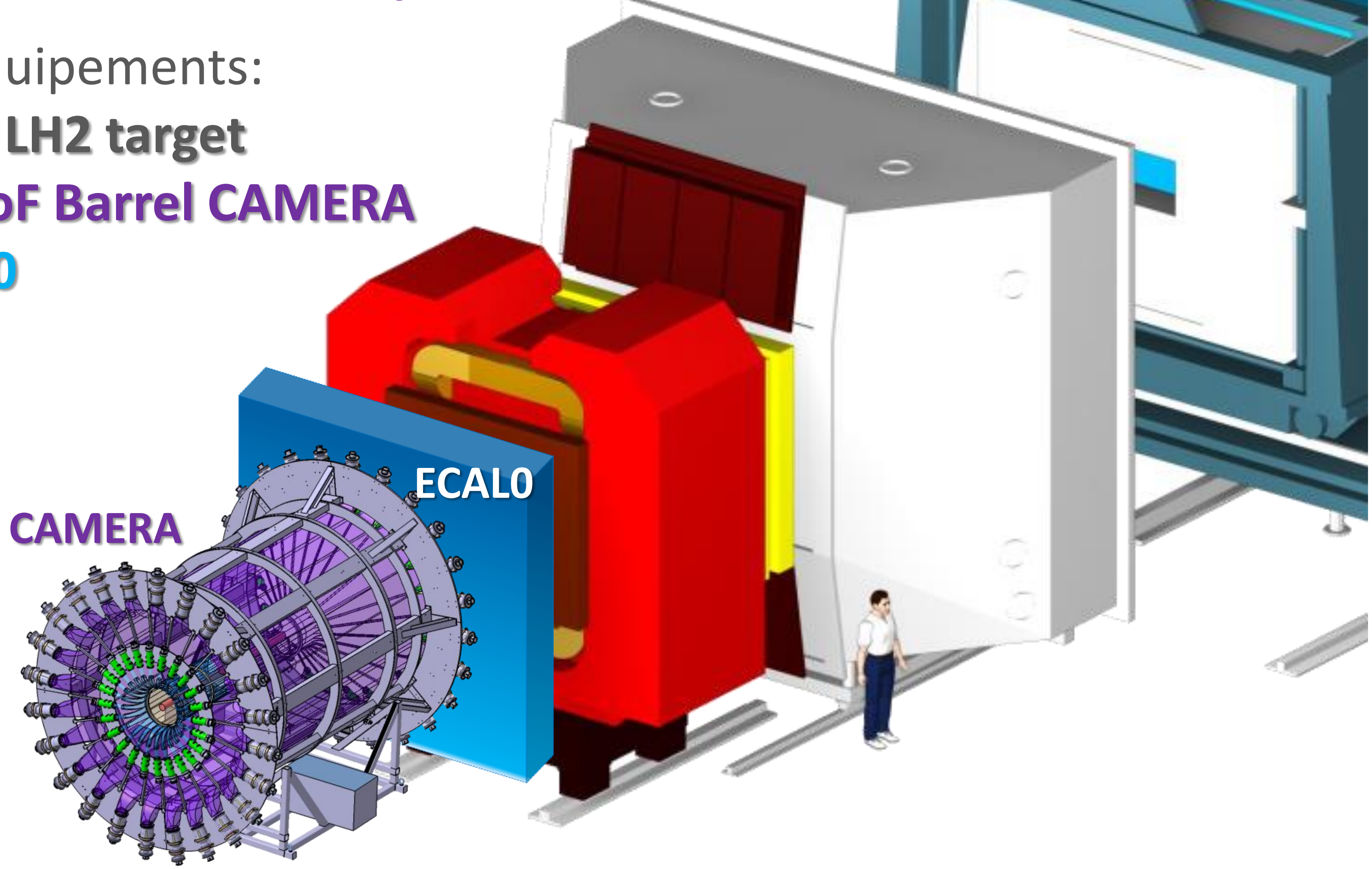
The DVCS experiment at COMPASS

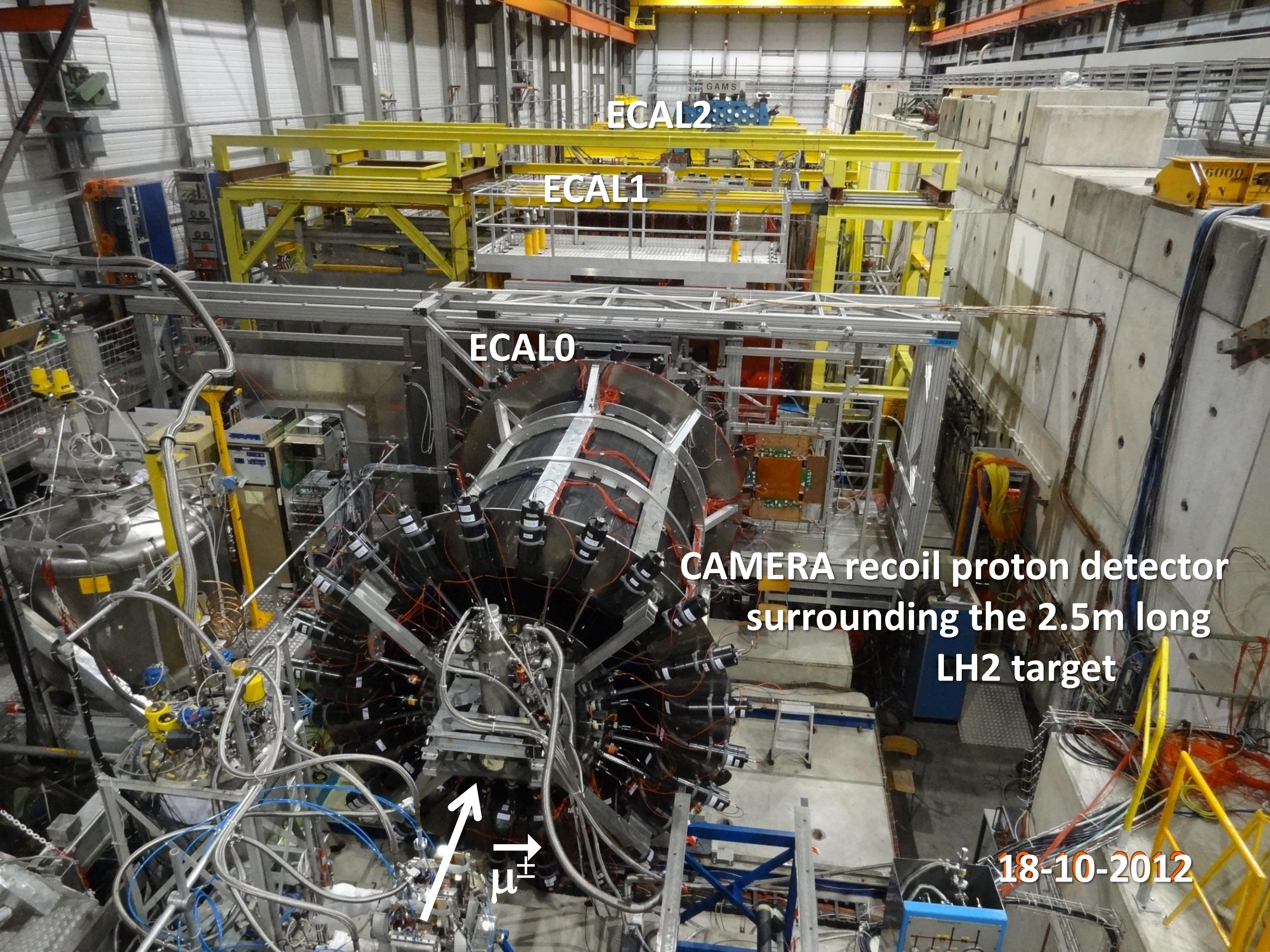
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$



New equipements:

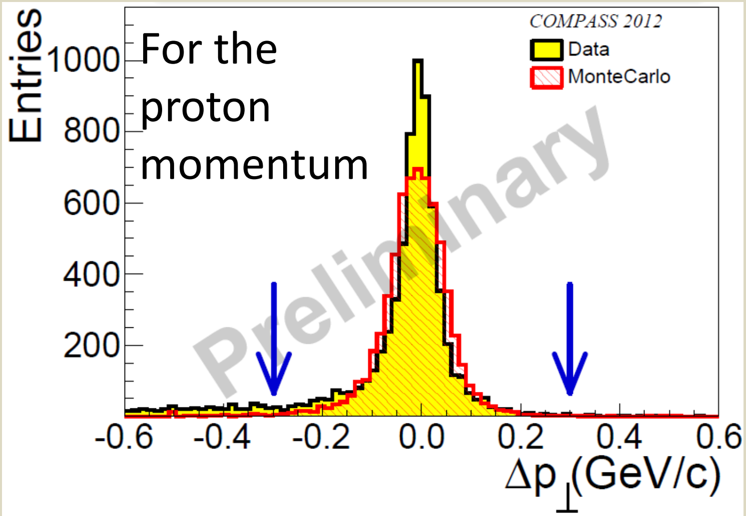
- **2.5m LH2 target**
- **4m ToF Barrel CAMERA**
- **ECAL0**

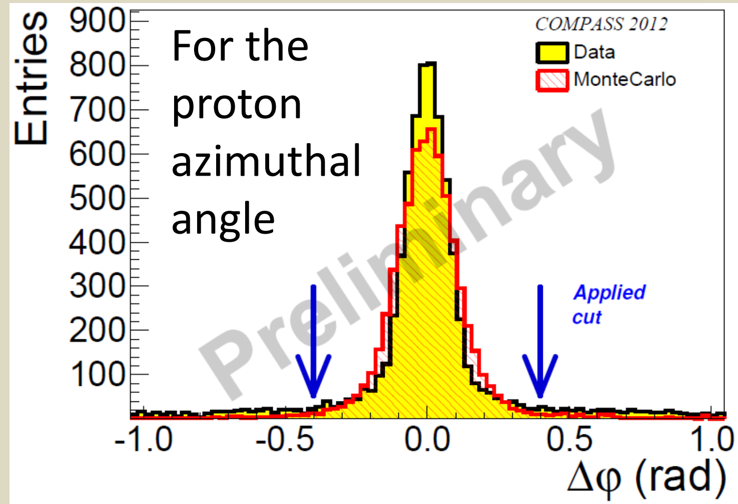


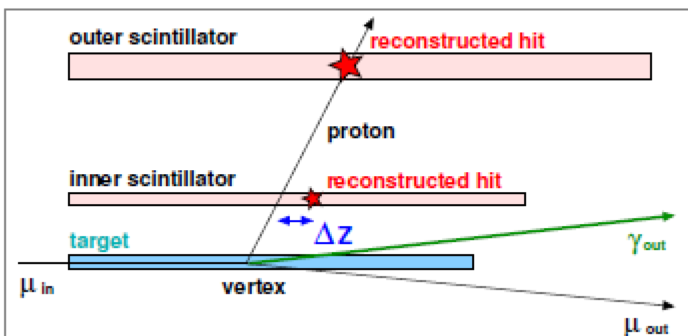

ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\vec{\mu}^{\pm}$
18-10-2012

Selection of exclusive evts with recoil detection
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

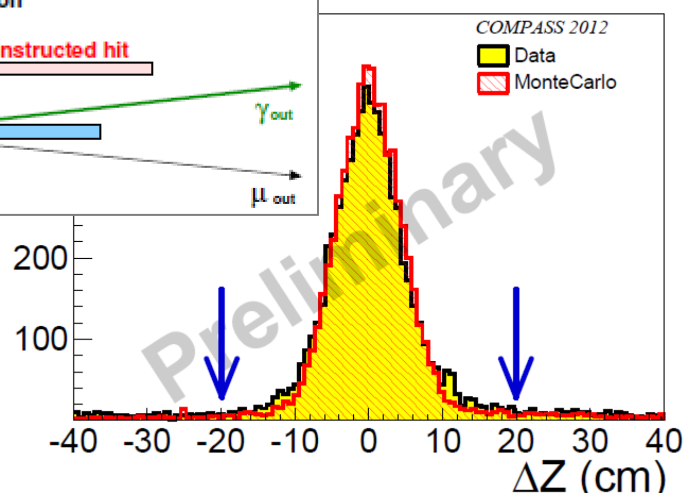
Comparison between the observables given by the spectro or by CAMERA





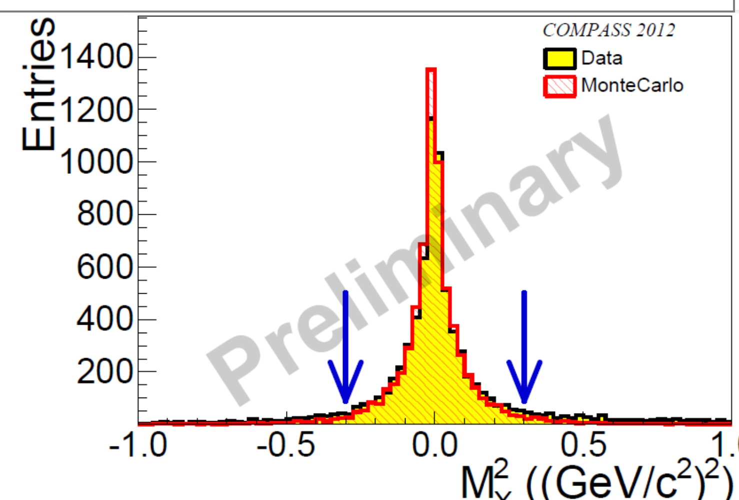


For the proton track

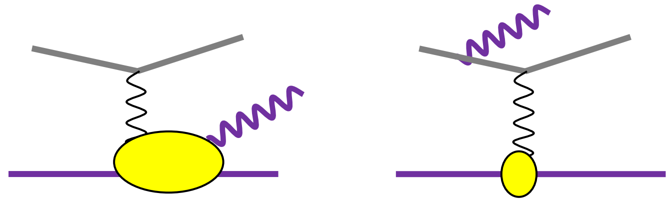


Four-momentum balance:

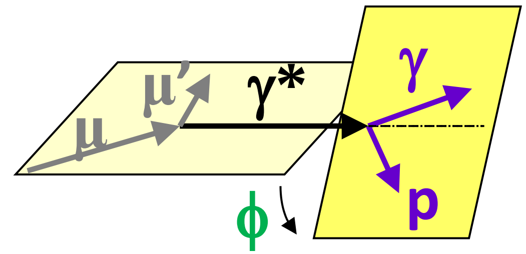
$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\gamma})^2$$



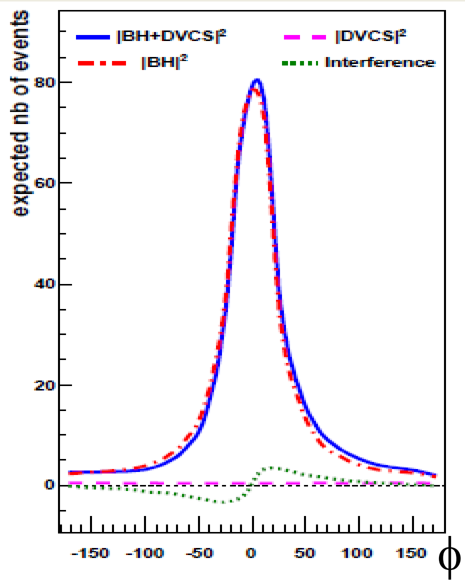
Contributions of DVCS and BH at E_μ=160 GeV



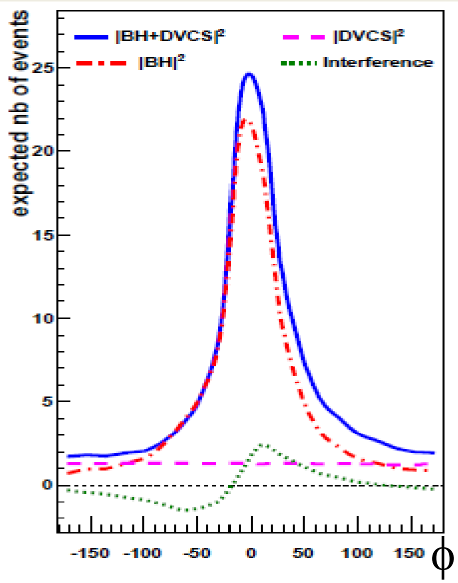
Deep VCS   Bethe-Heitler



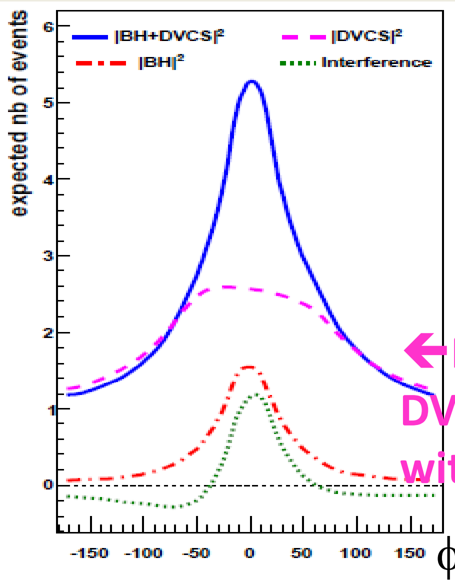
$d\sigma \, \alpha \; |T^{BH}|^2$ + Interference Term + $|T^{DVCS}|^2$



$0.005 < x_B < 0.01$



$0.01 < x_B < 0.03$



$0.03 < x_B$

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

← Missing DVCS acceptance without ECAL0

BH dominates

excellent reference yield

study of Interference

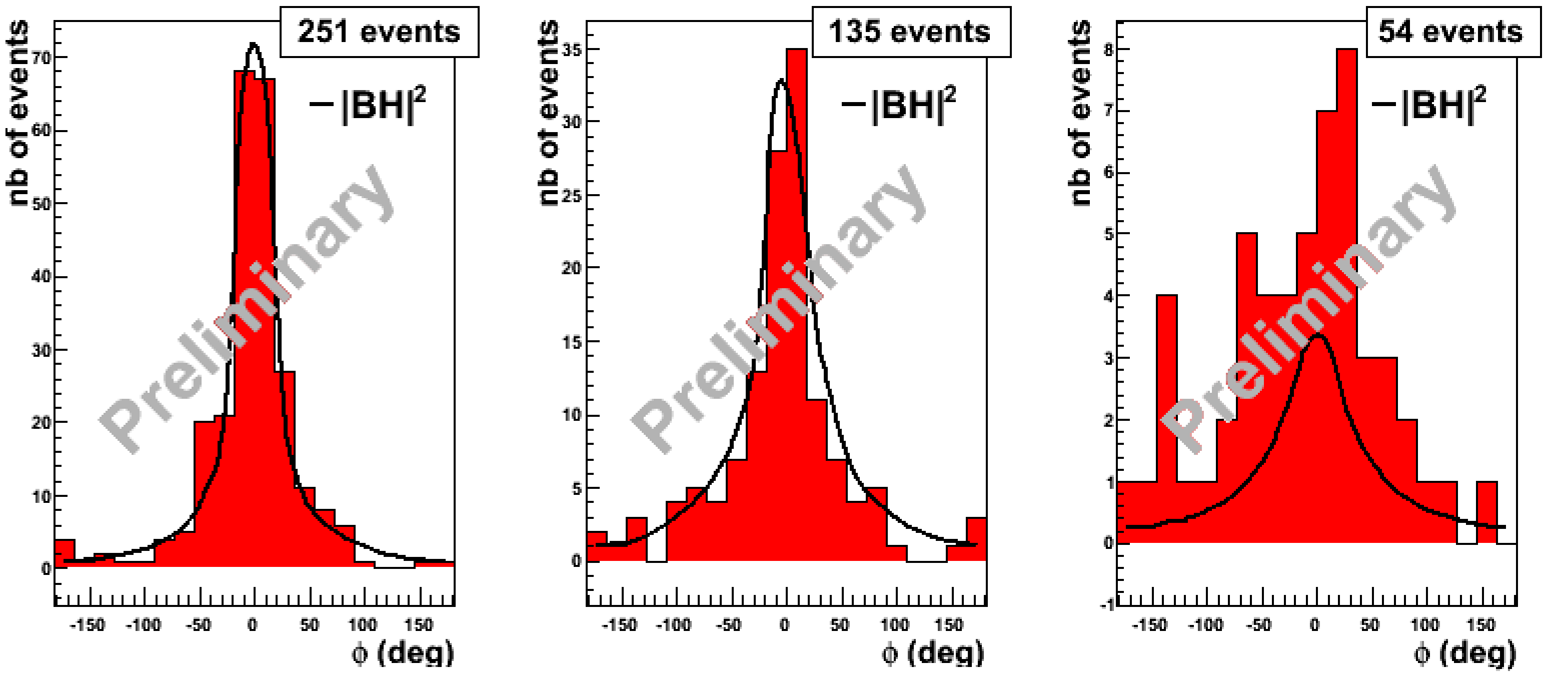
→ Re T^{DVCS} or Im T^{DVCS}

DVCS dominates

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

→ Transverse Imaging

2009 DVCS test run (10 days, short RPD + target)



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

$\varepsilon_{\mu p \rightarrow \mu' \gamma p} \approx 35\%$

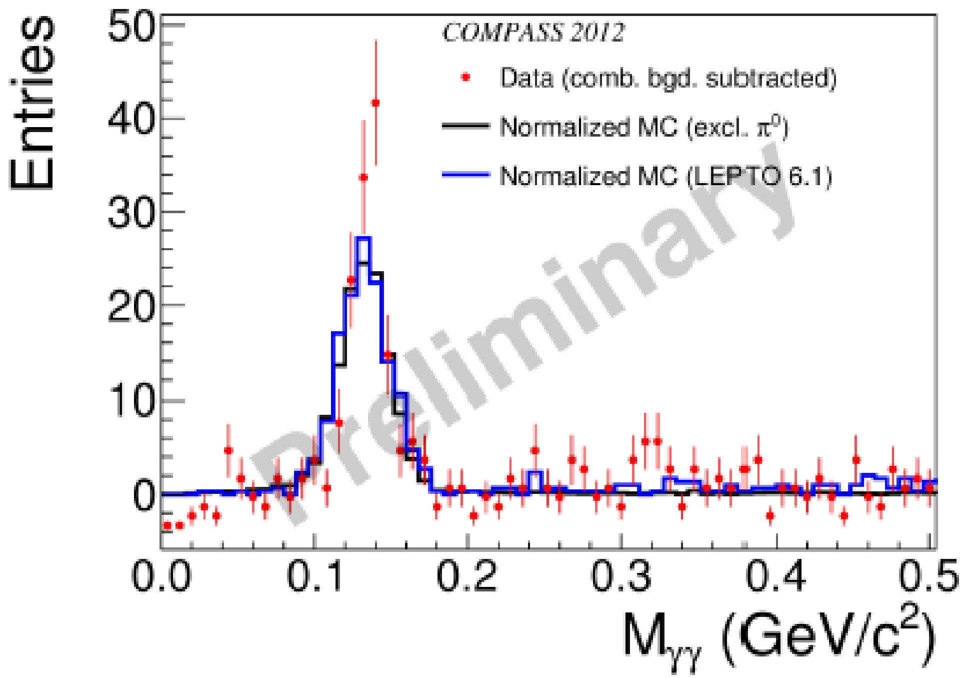
$\times (0.8)^4$ for SPS + COMPASS avail. + trigger eff + dead time

$\varepsilon_{global} \approx 0.14$ confirmed $\varepsilon_{global} = 0.1$
as assumed for COMPASS-II predictions

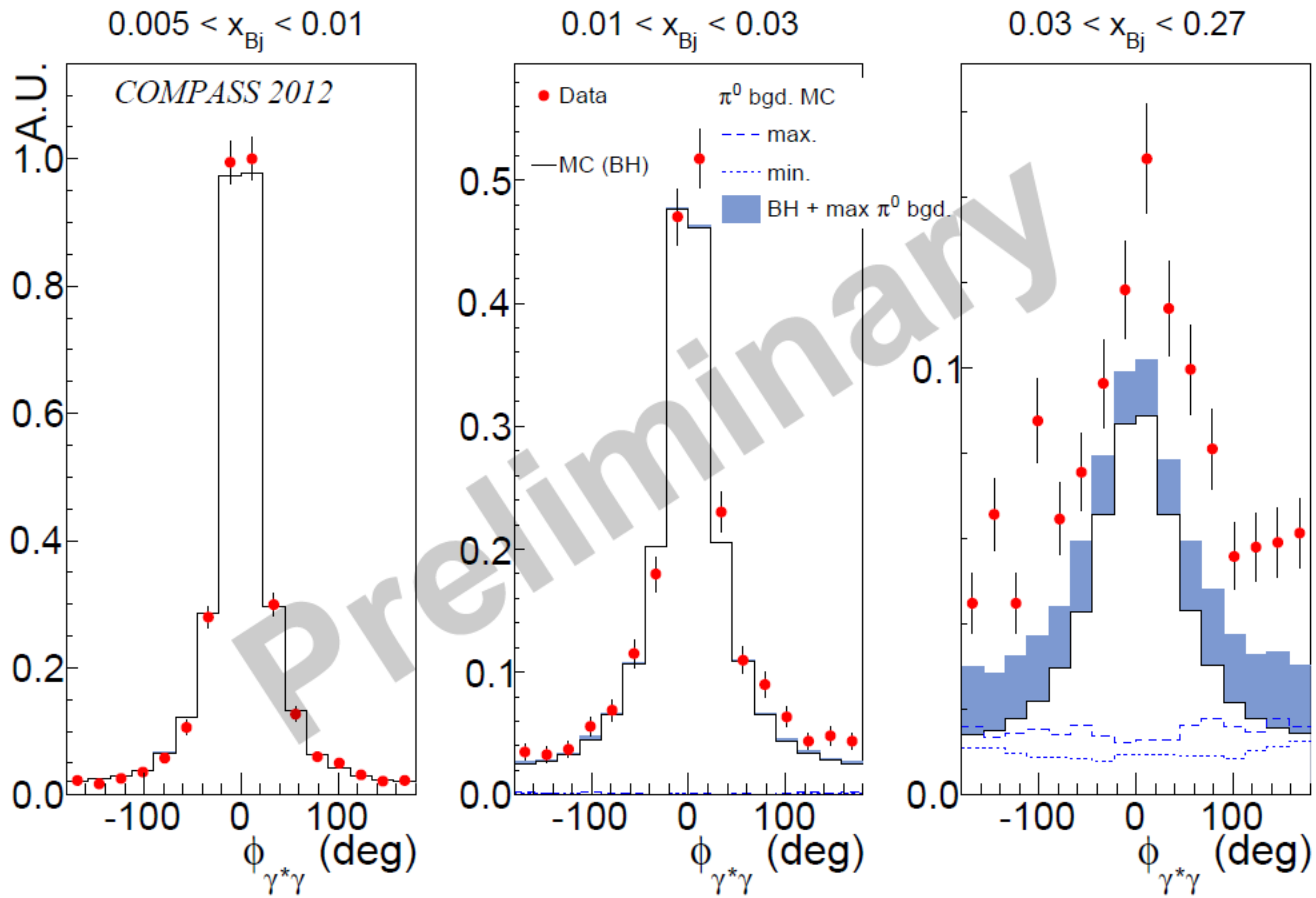
54 evts = 20 BH
\+ a significant DVCS contri.
which can be polluted
by γ from π^0 decay

2012 DVCS test run: π^0 background estimation

- Two possible cases:
  - visible: both γ detected { one γ of high energy > 4/5/10 GeV in ECAL0/1/2 + one γ of low energy < Thresholds
  - invisible: one γ lost $\rightarrow$ estimate with MC
- Consider limits (for the invisible part):
  - Fully semi-inclusive Background $\rightarrow$ estimate with LEPTO
  - Fully exclusive Background $\rightarrow$ HEPGEN/π^0 (GK model)
  - $\rightarrow$ Gives lower and upper limits
- LEPTO&HEPGEN/π^0 MC normalized to $M_{\gamma_{excl}\gamma_{bgd}}$ peak fom real data (visible π^0)



2012 DVCS test run (4 weeks, CAMERA + 2.5m long target)



- ✓ Dominant Bethe-Heitler process clearly visible at small x_{Bj}
- ✓ $\phi_{\gamma^*\gamma}$ peak shape well reproduced by MC simulations
- ✓ Maximum π^0 background at large x_{Bj} estimated in blue
- ✓ The data at large xBj show an excess compared to BH+Background (for pure DVCS)

Deeply Virtual Compton Scattering

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

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

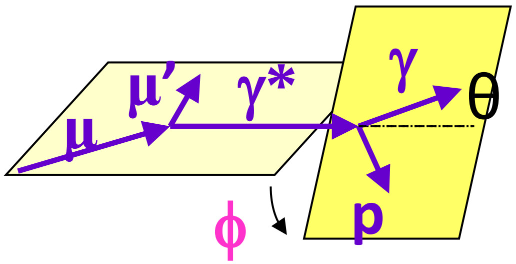
Charge & Spin Sum:

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

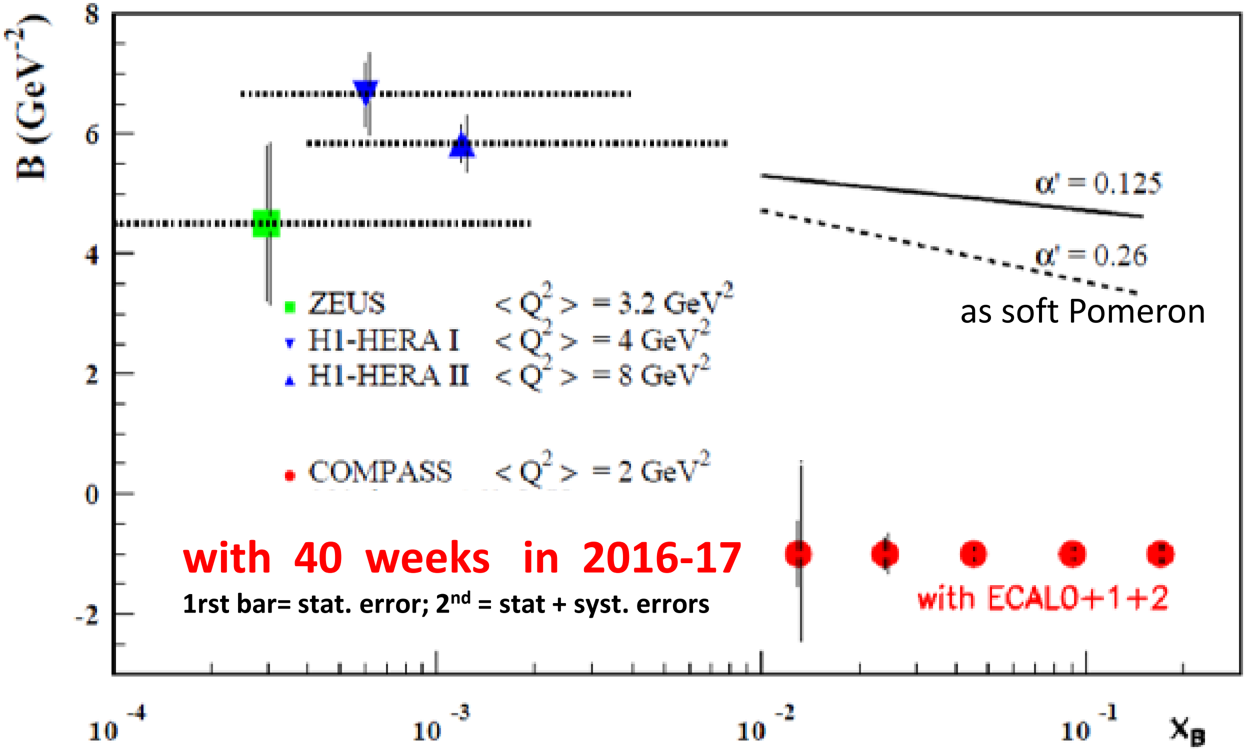
Using $S_{CS,U}$ and BH subtraction

and integration over ϕ

$$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$



Transverse imaging at COMPASS
$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$

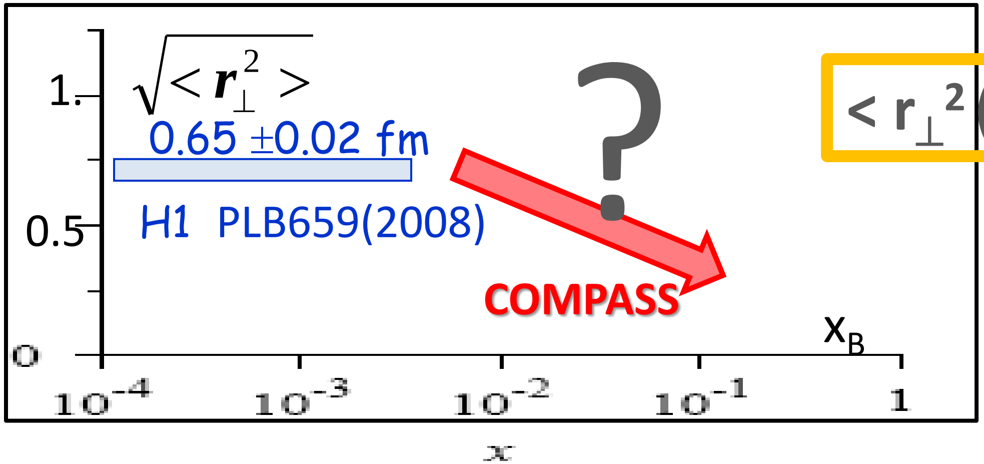


2 years of data = 40 weeks
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

ansatz at small x_B
inspired by
Regge Phenomenology:

$B(x_B) = b_0 + 2\,\alpha' \ln(x_0/x_B)$

α' slope of Regge traject



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

Deeply Virtual Compton Scattering

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

Deeply Virtual Compton Scattering

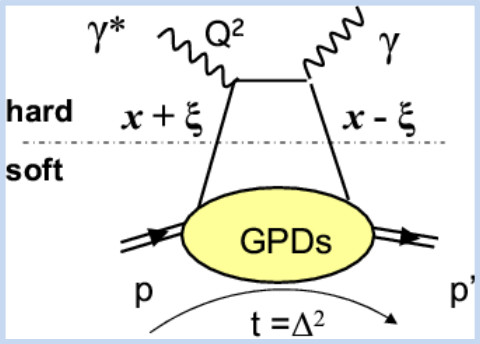
cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

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

Charge & Spin Difference and Sum:

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

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



$\xi \sim x_B / (2-x_B)$

$$\mathcal{I}m\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$$

$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx\, \frac{H(x,x,t)}{x-\xi} + \mathcal{D}(t)$$

Re part of the *Compton Form Factors* linked to the *D term*

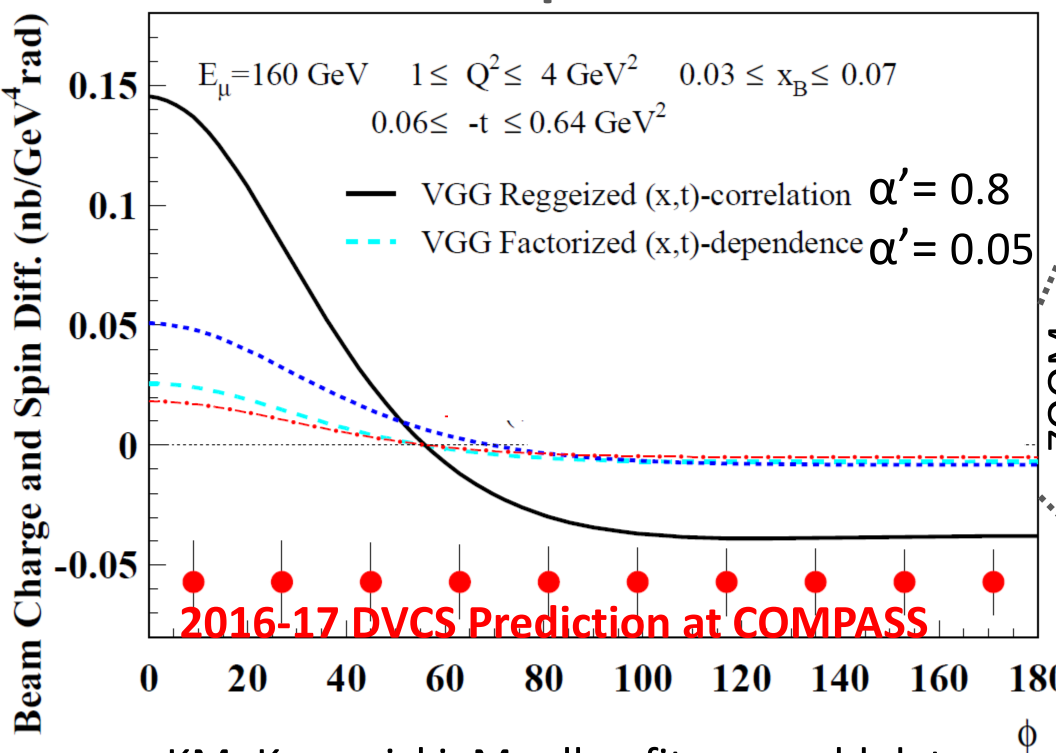
Energy-Momentum Tensor : Polyakov, PLB 555 (2003) 57-62

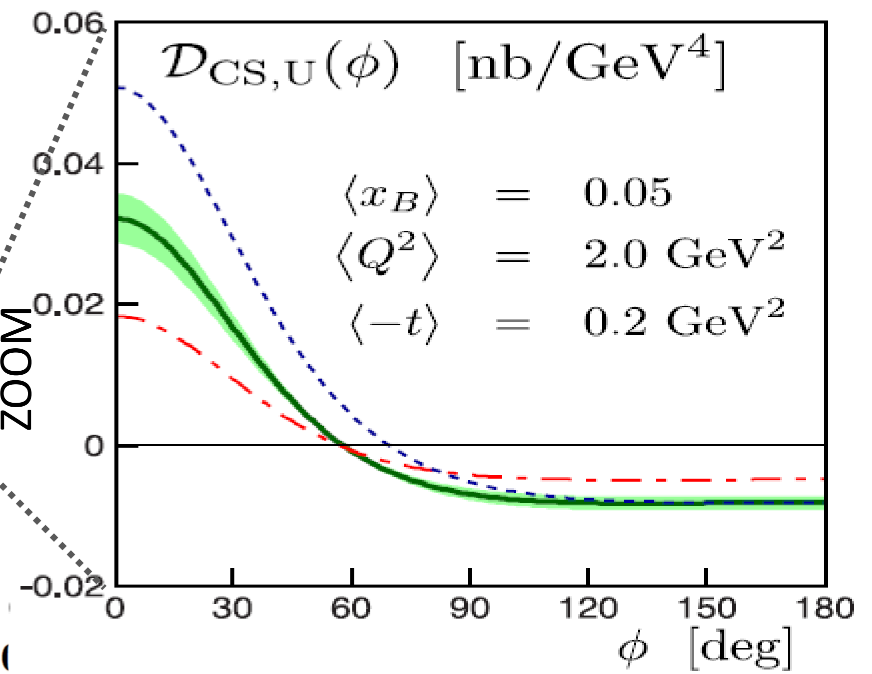
Beam Charge and Spin Difference (using $\mathcal{D}_{CS,U}$)

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

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

Comparison to different models





KM: Kumericki, Mueller, fit on world data

KM10a (without Jlab Hall A)

KM10b (with Jlab Hall A
BUT superseded by new results arXiv:1504.05453)

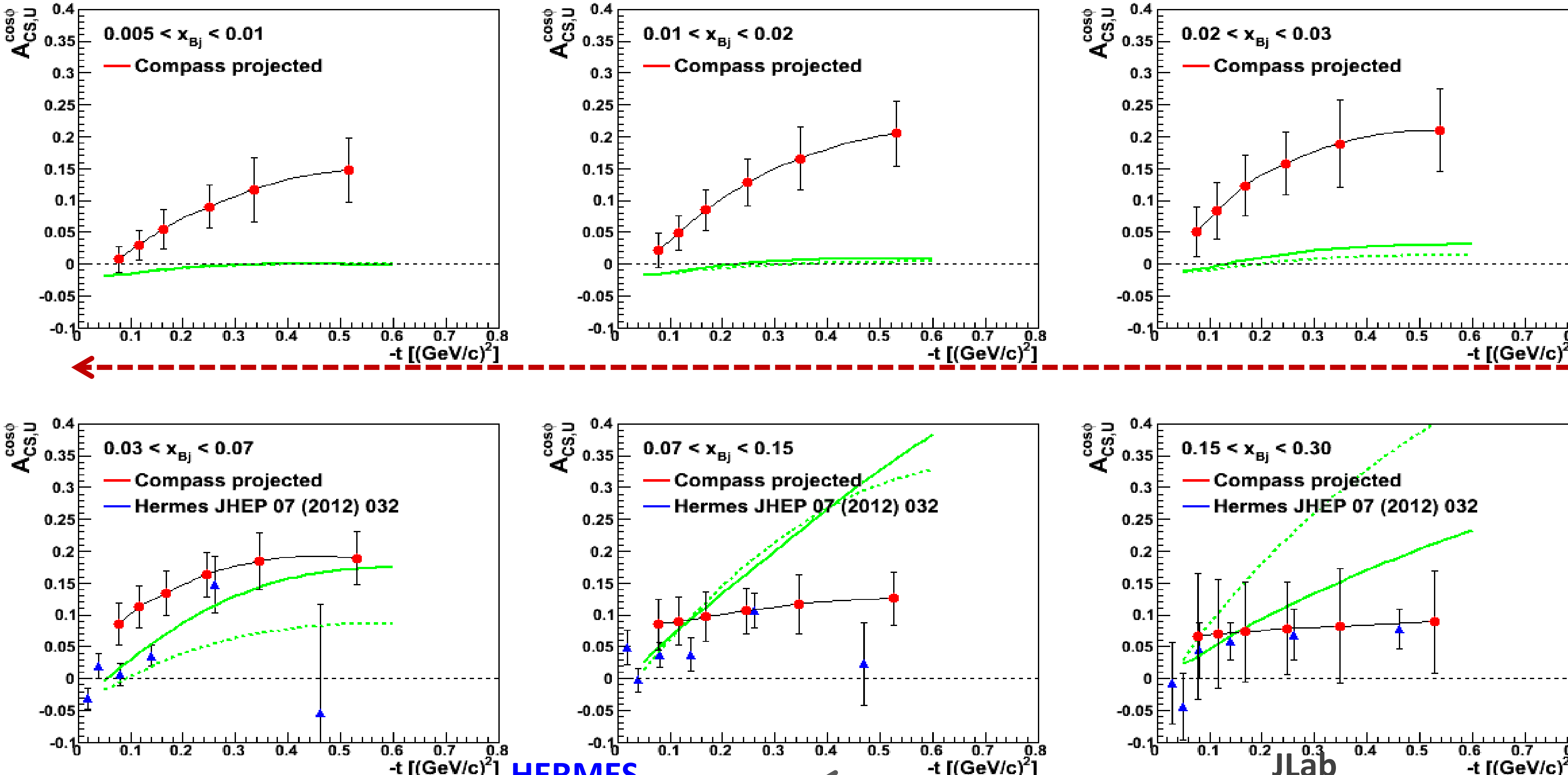
KMS12: Kroll, Moutarde, Sabatié
EPJC 73 (2013) 2278

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

$A_{CS,U}^{\cos\phi}$ related to c_1^{Int}

Predictions with **VGG** and **D.Mueller (KM10a)**

$\mathcal{R}e\,\mathcal{H}$ > 0 at H1
< 0 at HERMES/JLab
Value of x_B for the node?

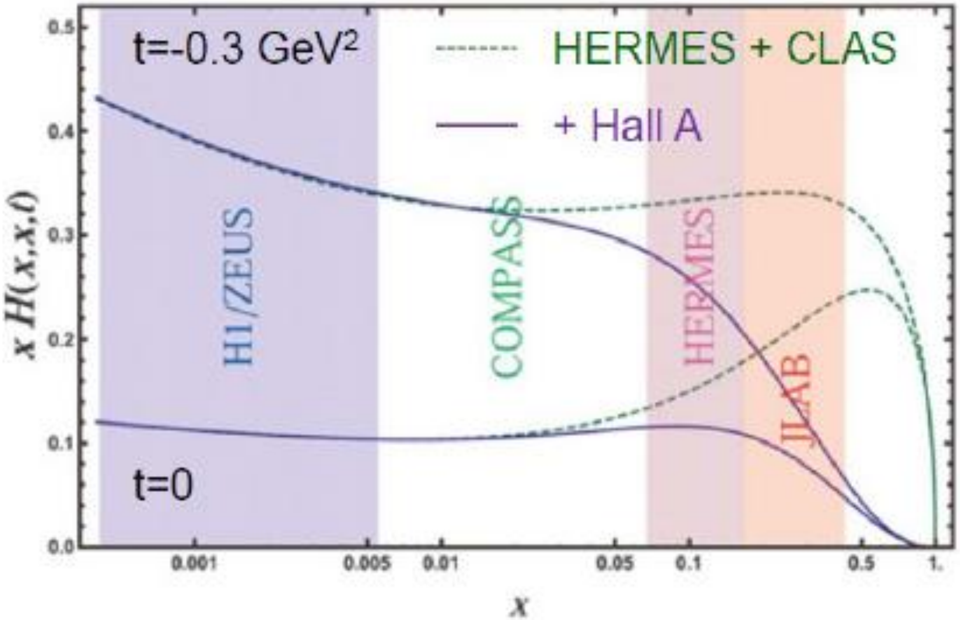


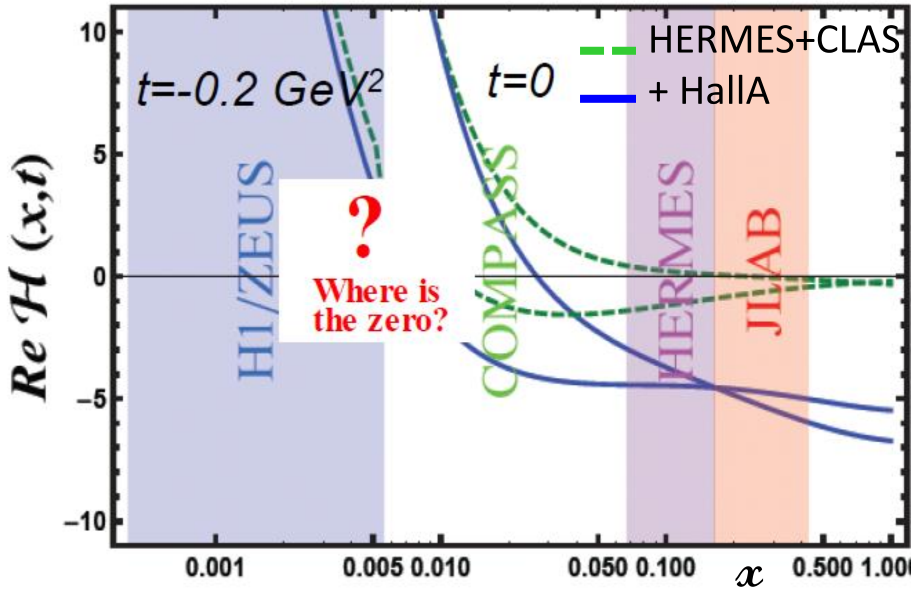
COMPASS 2 years of data E_μ = 160 GeV 1 < Q^2 < 8 GeV^2 with ECAL2 + ECAL1 + ECAL0

Impact of DVCS @ COMPASS in global analysis ?

Im $\mathcal{H}$ is rather well known

Re $\mathcal{H}$ linked to the $\mathcal{D}$ *term* is still poorly constrained





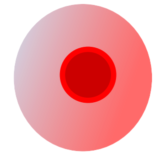
- From Müller, COMPASS workshop, Venise, 2010
- Kumericki, Müller, NPB 841 (2010) 1-58
- Müller, Lautenschlager, Passek-Kumericki, Schaefer, arXiv:1310.5394, 125p

- Note: Jlab Hall A superseded by new results arXiv:1504.05453
- And new results from CLAS: arXiv: 1504.02009 and PRL114 (2015), PRD91 (2015)

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

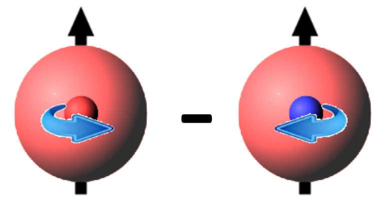
Chiral-even

$H \longleftrightarrow q$



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

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



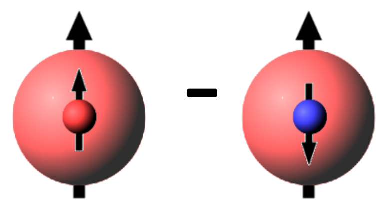
Sivers: quark k_T & nucleon transv. Spin

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

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

Chiral-odd

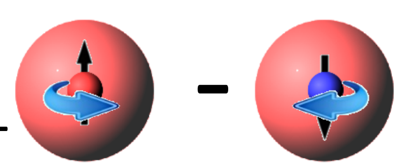
$H_T \longleftrightarrow h_1$



Transversity: quark spin & nucleon transv. spin

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

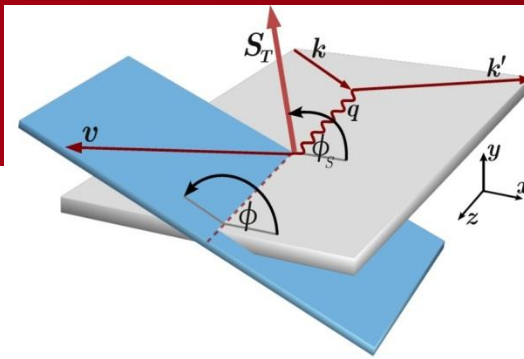
$\bar{E}_T = 2\tilde{H}_T + E_T \longleftrightarrow h_1^{\perp}$



Boer-Mulders: quark k_T & quark transverse spin

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

Exclusive ρ^0 production



$$\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\varepsilon}\frac{1-x_B}{x_B}\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_{Bj}\,dQ^2\,dt\,d\phi\,d\phi_s}$$

$$= \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}-\varepsilon\cos(2\phi)\,\mathrm{Re}\,\sigma_{+-}^{++}-\sqrt{\varepsilon(1+\varepsilon)}\cos\phi\,\mathrm{Re}\left(\sigma_{+0}^{++}+\sigma_{+0}^{--}\right)$$

$$-P_\ell\sqrt{\varepsilon(1-\varepsilon)}\sin\phi\,\mathrm{Im}\left(\sigma_{+0}^{++}+\sigma_{+0}^{--}\right)$$

$$-S_T\left[\sin(\phi-\phi_S)\,\mathrm{Im}\left(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-}\right)+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{-+}\right.$$
$$\left.+\sqrt{\varepsilon(1+\varepsilon)}\sin\phi_S\,\mathrm{Im}\,\sigma_{+0}^{+-}+\sqrt{\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+0}^{-+}\right]$$

transv. polar. target

$$+S_T P_\ell\left[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)\,\mathrm{Re}\,\sigma_{++}^{+-}\right.$$
$$\left.-\sqrt{\varepsilon(1-\varepsilon)}\cos\phi_S\,\mathrm{Re}\,\sigma_{+0}^{+-}-\sqrt{\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S)\,\mathrm{Re}\,\sigma_{+0}^{-+}\right]$$

transv. polar. target + long. polar. beam

σ ^{ij} for nucleon helicity, $_{mn}$ for photon helicity

Dominant interference terms:

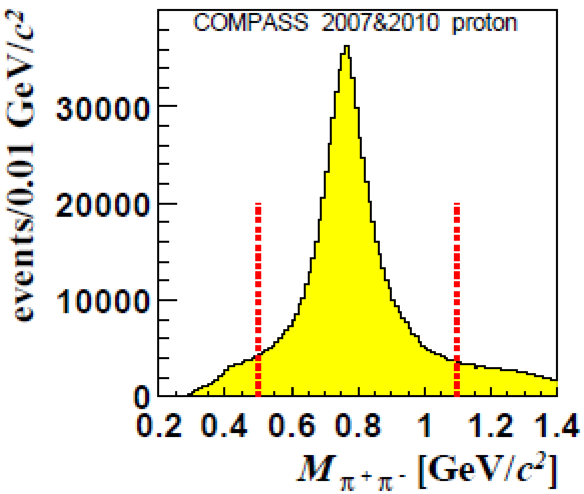
LL $\gamma^*_L \to \rho^0_L$

then LT $\gamma^*_T \to \rho^0_L$

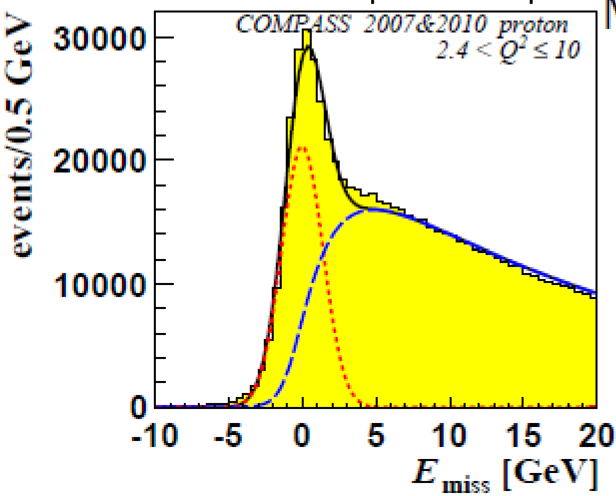
Selection of exclusive evts without recoil detection

$\mu\ p_{\text{in NH3}} \rightarrow \mu'\ V\ p_{\text{non detected}}$

V= $\rho^0 \rightarrow \pi^+\pi^-$



$E_{miss}=(M^2_X-M_p^2)/2M_p$



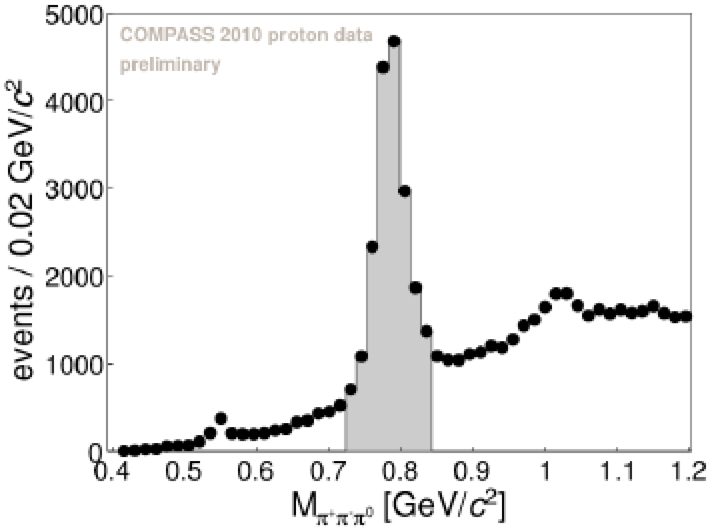
$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_V)^2$$

$-2.5 < E_{miss} < 2.5$ GeV

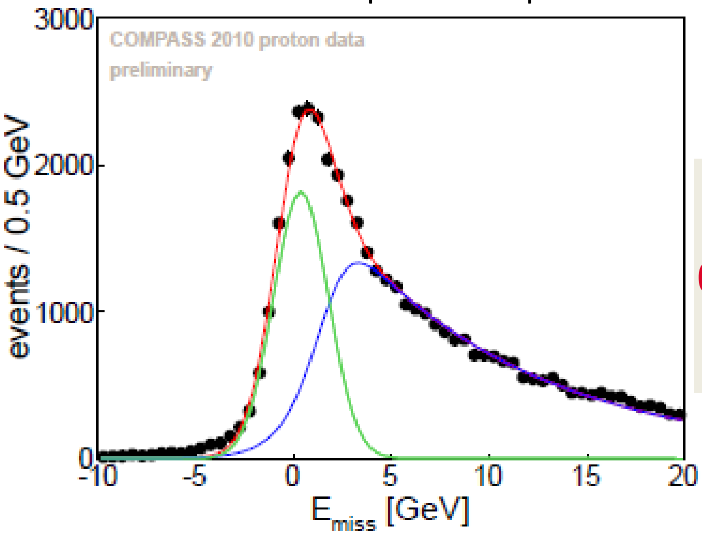
$0.1 < p_T^2 < 0.5$ GeV²

Background ~22%

V= $\omega \rightarrow \pi^+\pi^-\pi^0$ BR=89%



$E_{miss}=(M^2_X-M_p^2)/2M_p$



$-3 < E_{miss} < 3$ GeV

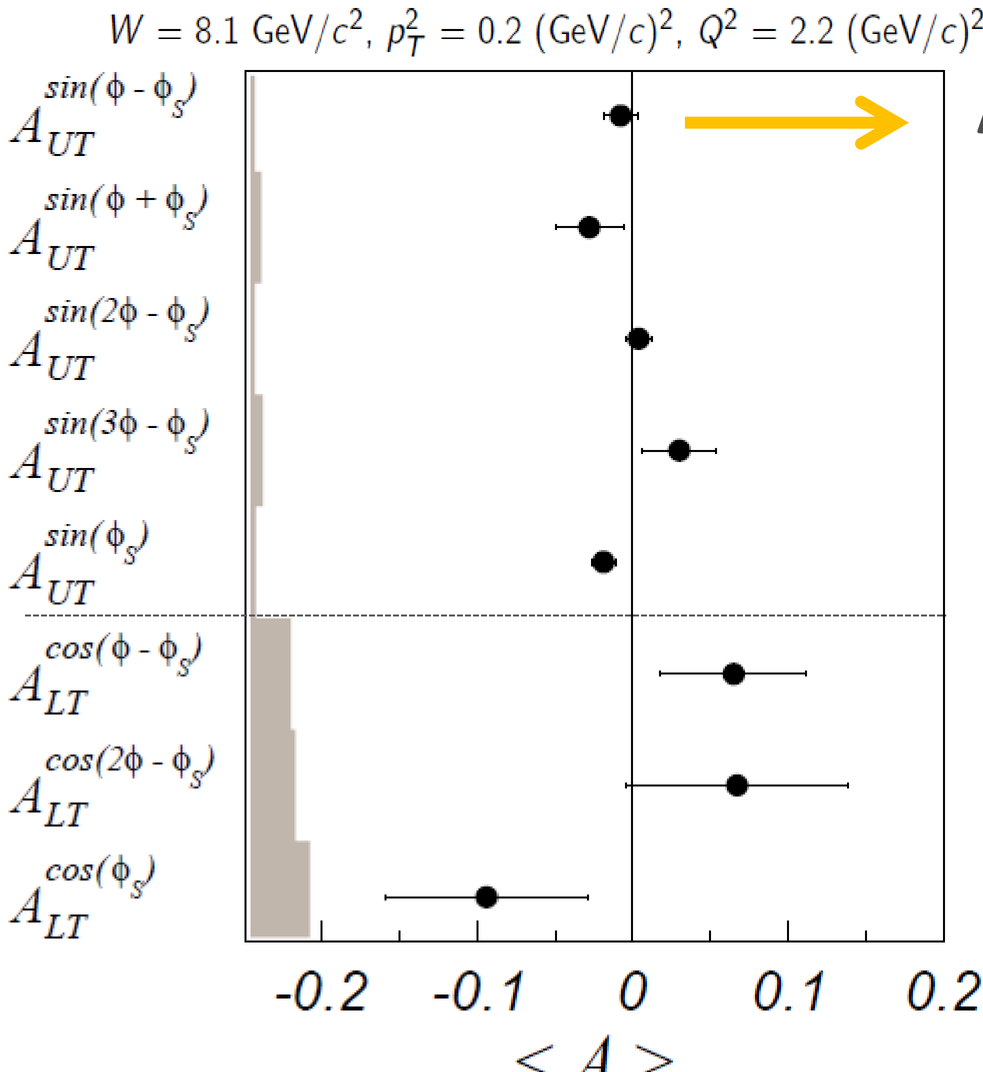
$0.05 < p_T^2 < 0.5$ GeV²

Background ~34%

exclusive ρ^0 production with Transv. Polar. Target

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

COMPASS 2007-2010,without recoil detector



$A_{UT}^{\sin(\phi - \phi_S)} \propto Im(\mathcal{E}^* \mathcal{H})$

$E\rho^0 \propto 2/3\ E^u + 1/3\ E^d + 3/8\ E^g$

- ✓ Cancellation between gluon and sea contributions
- ✓ $E^{u\ val} \sim -E^{d\ val}$

COMPASS, NPB 865 (2012) 1-20

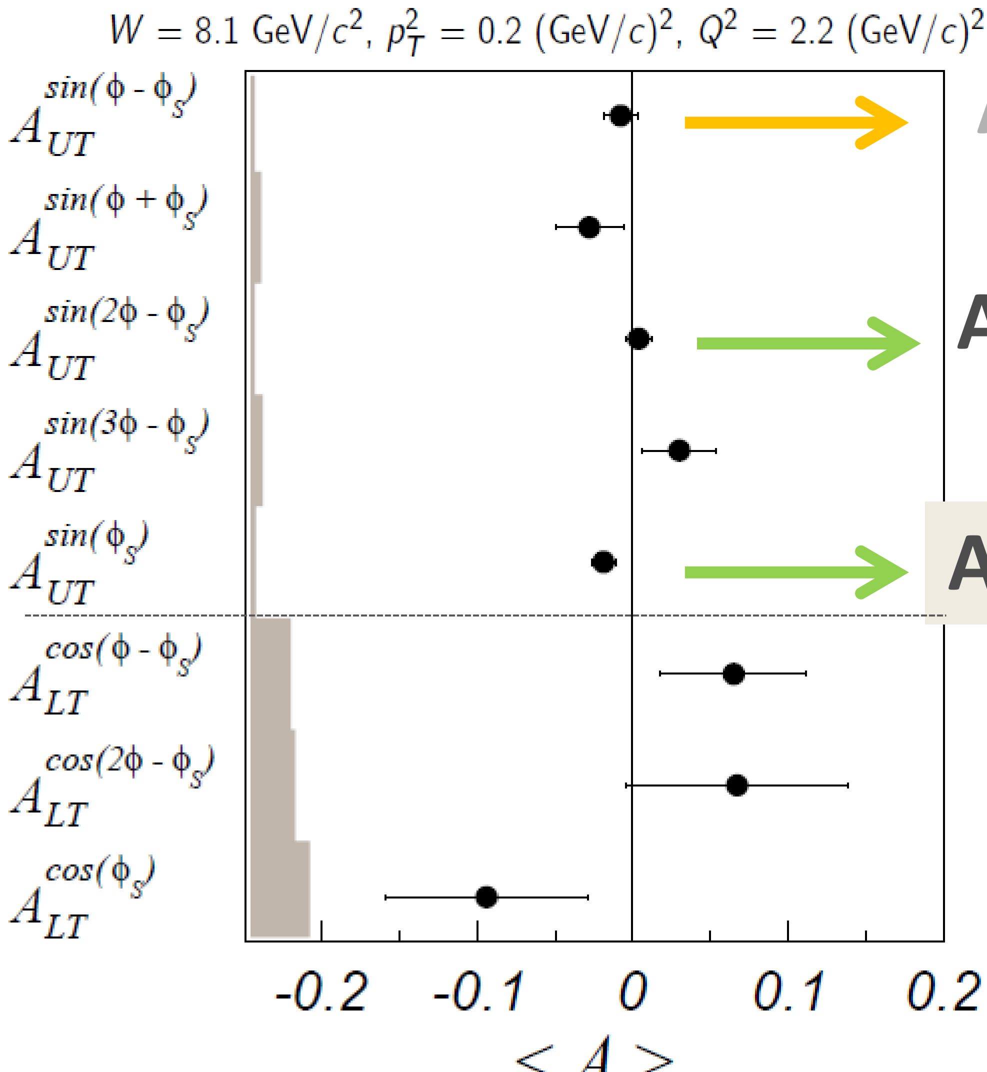
ω production very interesting

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

exclusive ρ^0 production with Transv. Polar. Target

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

COMPASS 2007-2010,without recoil detector



$A_{UT}^{\sin(\phi-\phi_S)} \propto Im(E^* H)$

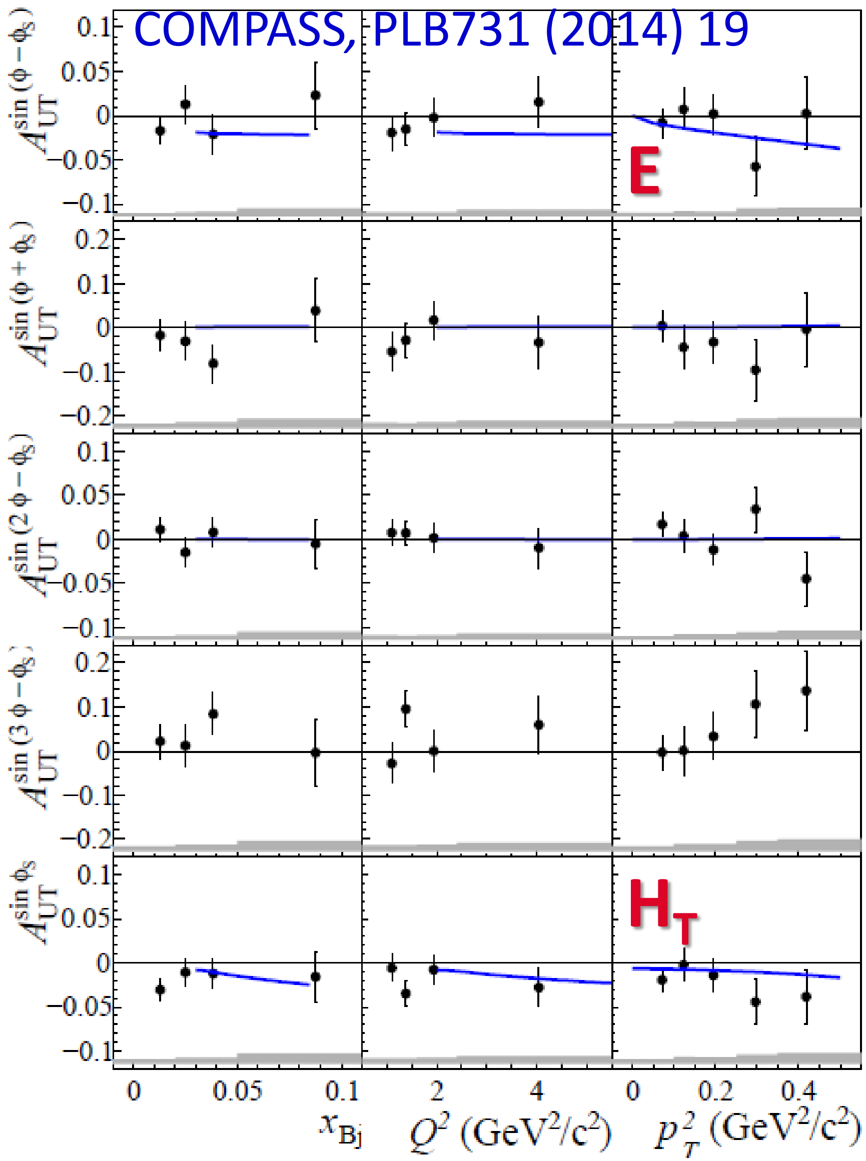
$A_{UT}^{\sin(2\phi-\phi_S)} \propto Im(E^* \bar{E}_T)$

$A_{UT}^{\sin(\phi_S)} \propto Im(E^* \bar{E}_T - H^* H_T)$

➔ H_T **should not be small**

COMPASS, PLB731 (2014) 19

exclusive ρ^0 production with Transv. Polar. Target



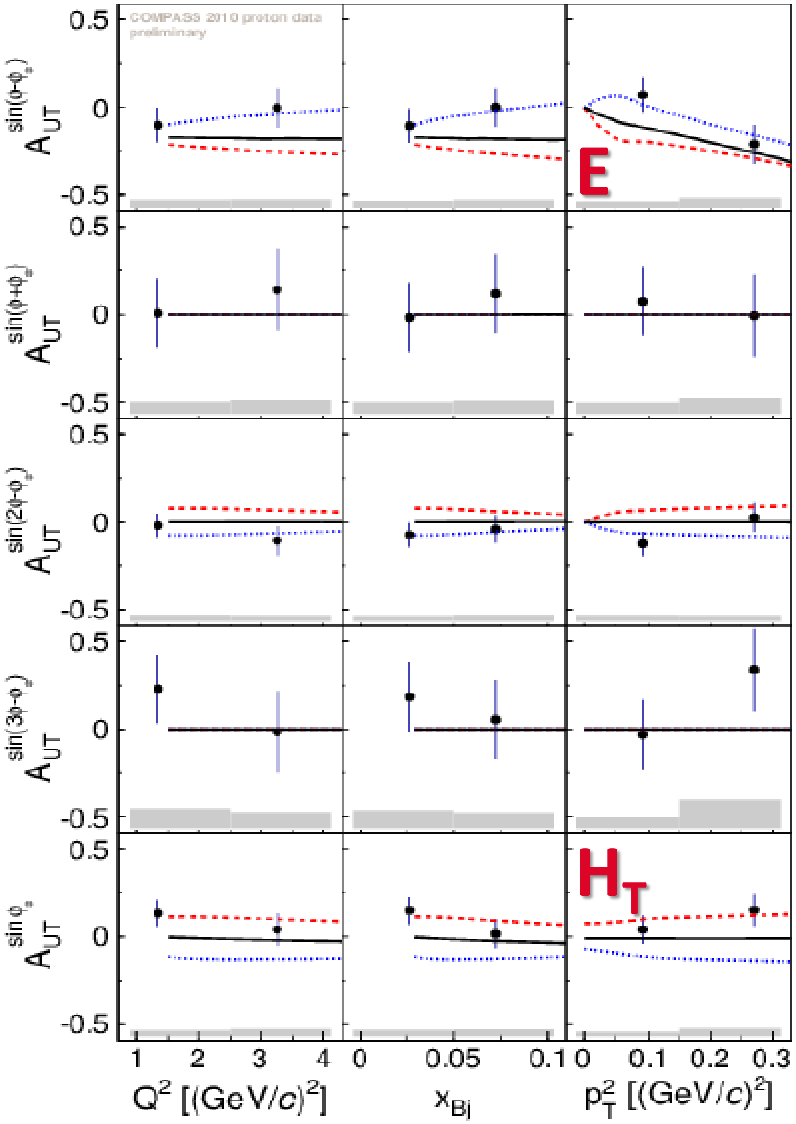
$\langle x_{Bj} \rangle \approx 0.039$, $\langle Q^2 \rangle \approx 2.0$ GeV^2, $\langle p_T^2 \rangle \approx 0.18$ GeV^2

Comparison with a phenomeno-logical GPD-based model

- Blue line: Model from Goloskokov and Kroll (EPJ C74 (2014))
- Phenomenological 'handbag' approach
- Includes twist-3 ρ^0 meson wave functions
- Includes contributions from γ_L^* and γ_T^*

Large contribution of the GPDs E and H_T

exclusive ω production with Transv. Polar. Target

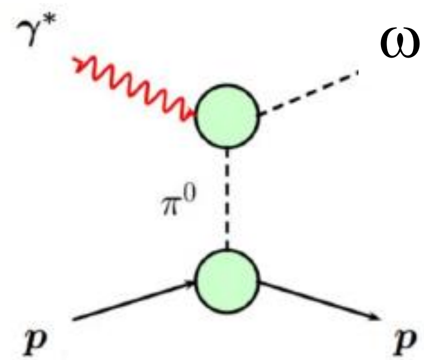


$\langle x_{Bj} \rangle \approx 0.049$, $\langle Q^2 \rangle \approx 2.2$ GeV^2
$\langle p_T^2 \rangle \approx 0.17$ GeV^2, $\langle W \rangle \approx 7.1$ GeV^2

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

GK model predictions (EPJ A50 (2014)) including all the GPDs and transverse GPDs

+ the pion pole exchange which is large for ω production



- positive $\pi\omega$ form factor
- no pion pole
- negative $\pi\omega$ form factor

no unambigous determination of the sign

Summary and Outlook

Exclusive ρ^0 and ω prod on transv. polar. protons w/o recoil detection

5 asym A_{UT} and 3 asym A_{LT}

Sensitivity to **GPD E** $\rightarrow$ orbital angular momentum

GPD H_T $\rightarrow$ transversity

2016-17 Exclusive **single photon** and **meson** on LH2 with recoil detection

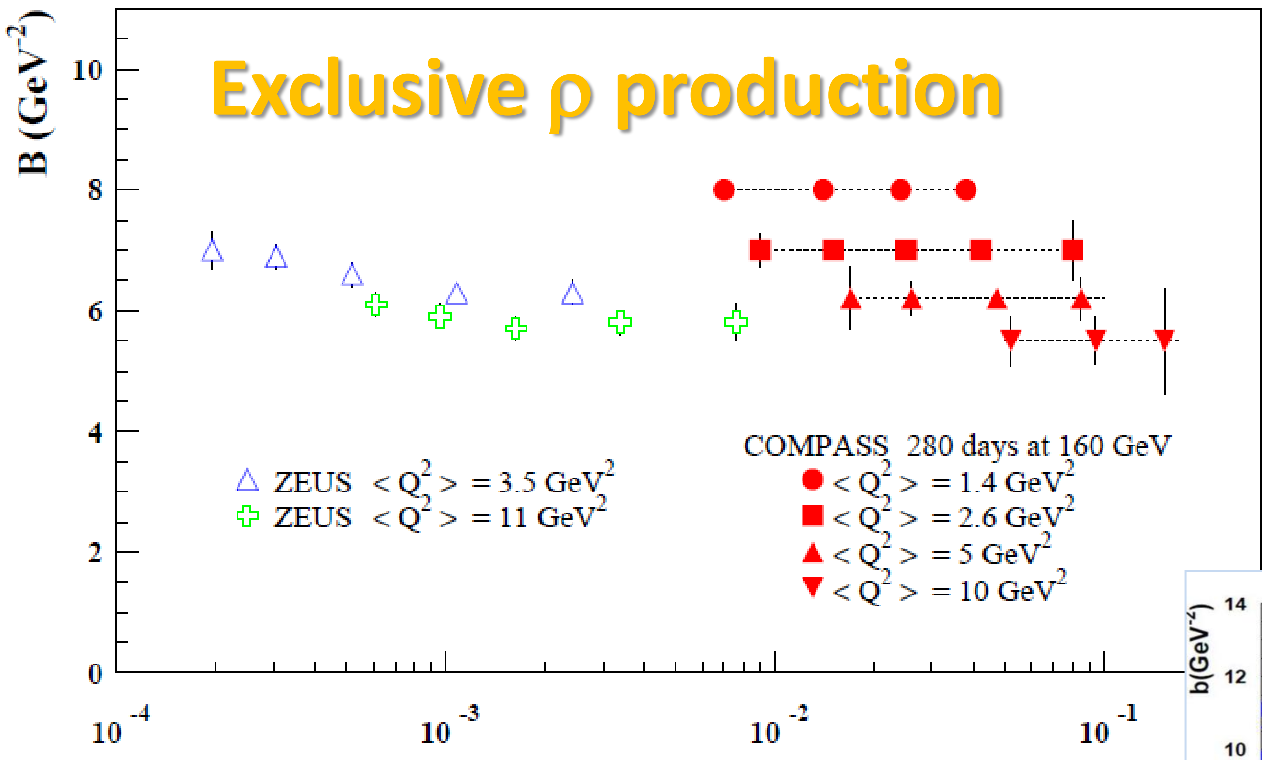
Sensitivity to **GPD H**

and to the **real part of the CFF** (thanks to $\overleftarrow{\mu}$+ and $\overrightarrow{\mu}$- beam)

LONG-TERM FUTURE recoil detection with a transv. polar. target

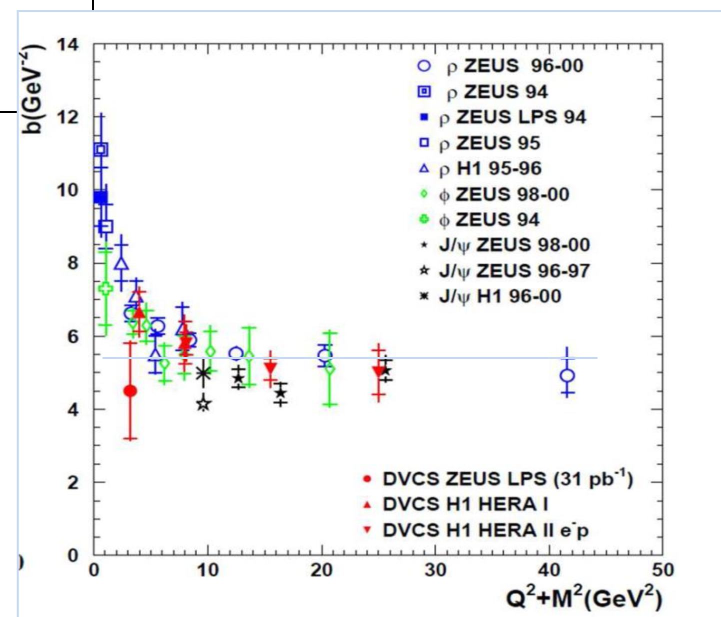
DVCS, π, ρ, ω, ϕ, J/ψ

Transverse imaging at COMPASS
$d\sigma^{excl.\ \rho}/dt \sim \exp(-B|t|)$



2 years of data = 40 weeks
160 GeV muon beam
2.5m LH_2 target
$\varepsilon_{global} = 10\%$

model developed by Sandacz renormalised according Goloskokov and Kroll prediction



sensitivity
to the nucleon transverse size
+ to the meson transverse size