GPD program at COMPASS

Transverse target asymetry for exclusive ρ production (2007-2010 data)
with polarized NH3 target without recoil detection - NEW RESULTS

The first DVCS pilot run (one month November 2012)
with LH2 target and with recoil detection - ANALYSIS ONGOING

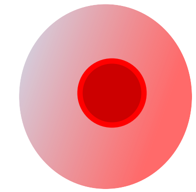
Outlook for the complete program (2016-17)

Nicole d'Hose (CEA-Saclay)
On behalf of the COMPASS Collaboration

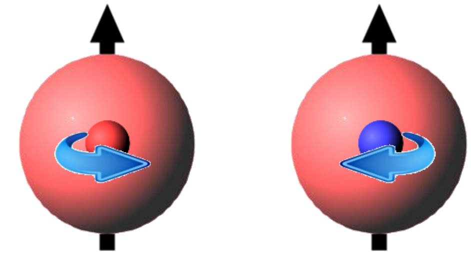
With DVCS and exclusive ρ production

Chiral-even GPDs

σ $\quad H \rightarrow q$



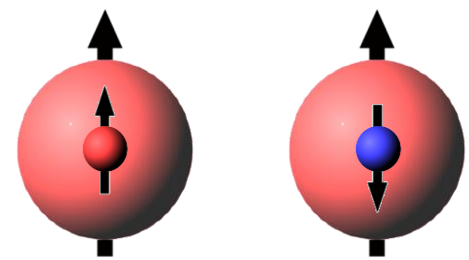
$A_{UT}^{\sin(\phi - \phi_S)}$ $\quad E \longleftrightarrow f_{1T}^{\perp}$



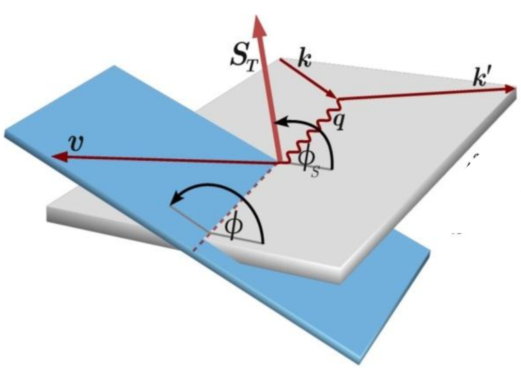
Sivers correlates
quark k_T and nucleon spin (transv. pol. N)

Chiral-odd GPDs

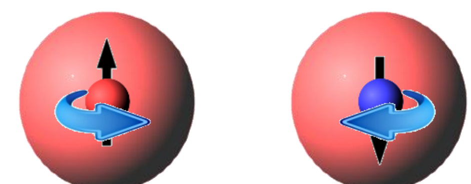
$A_{UT}^{\sin(\phi_S)}$ $\quad H_T \longleftrightarrow h_1$



Transversity correlates
quark spin and nucleon spin (transv. pol. N)

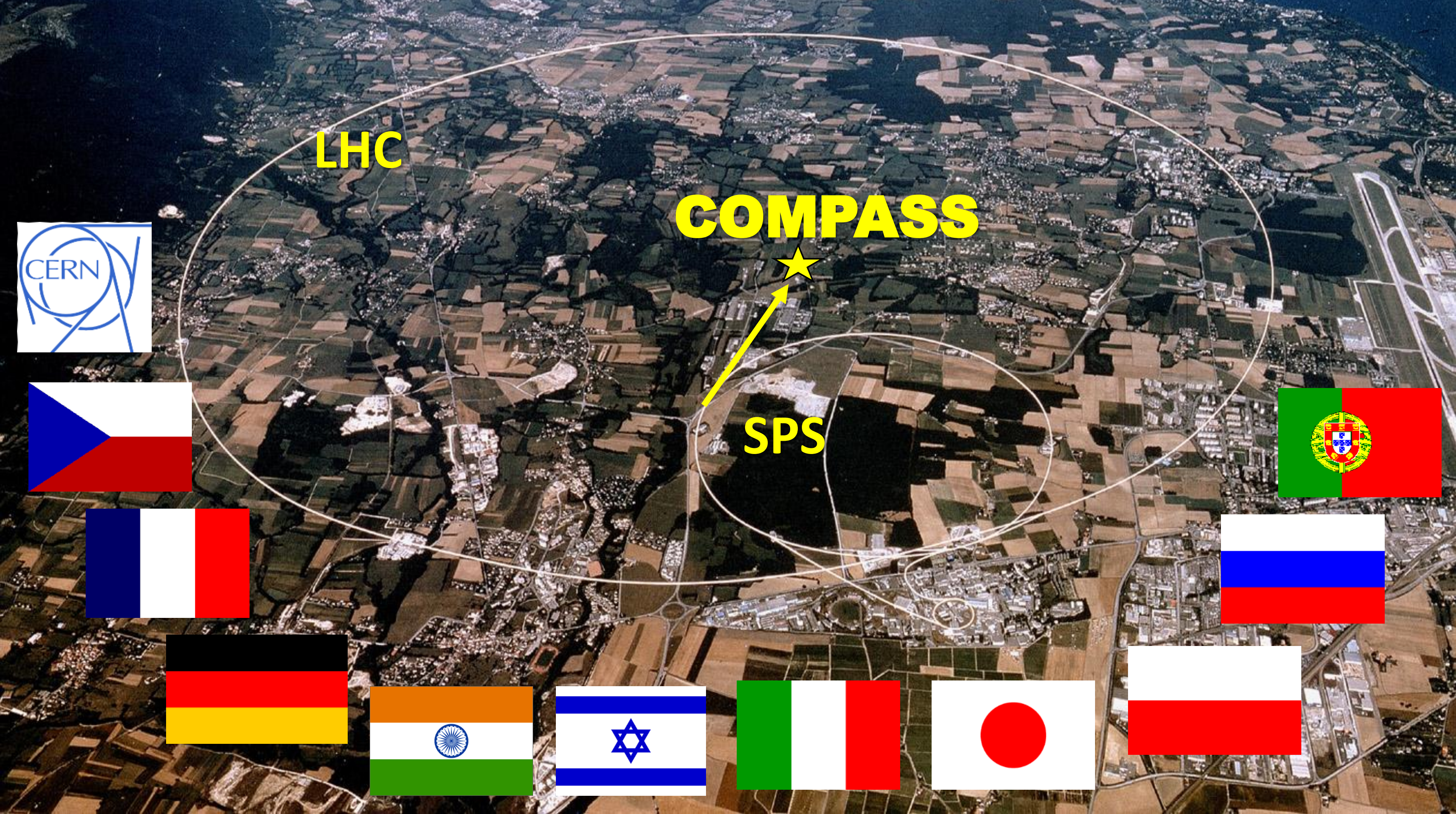


$$\bar{E}_T = 2\tilde{H}_T + E_T \longleftrightarrow h_1^{\perp}$$

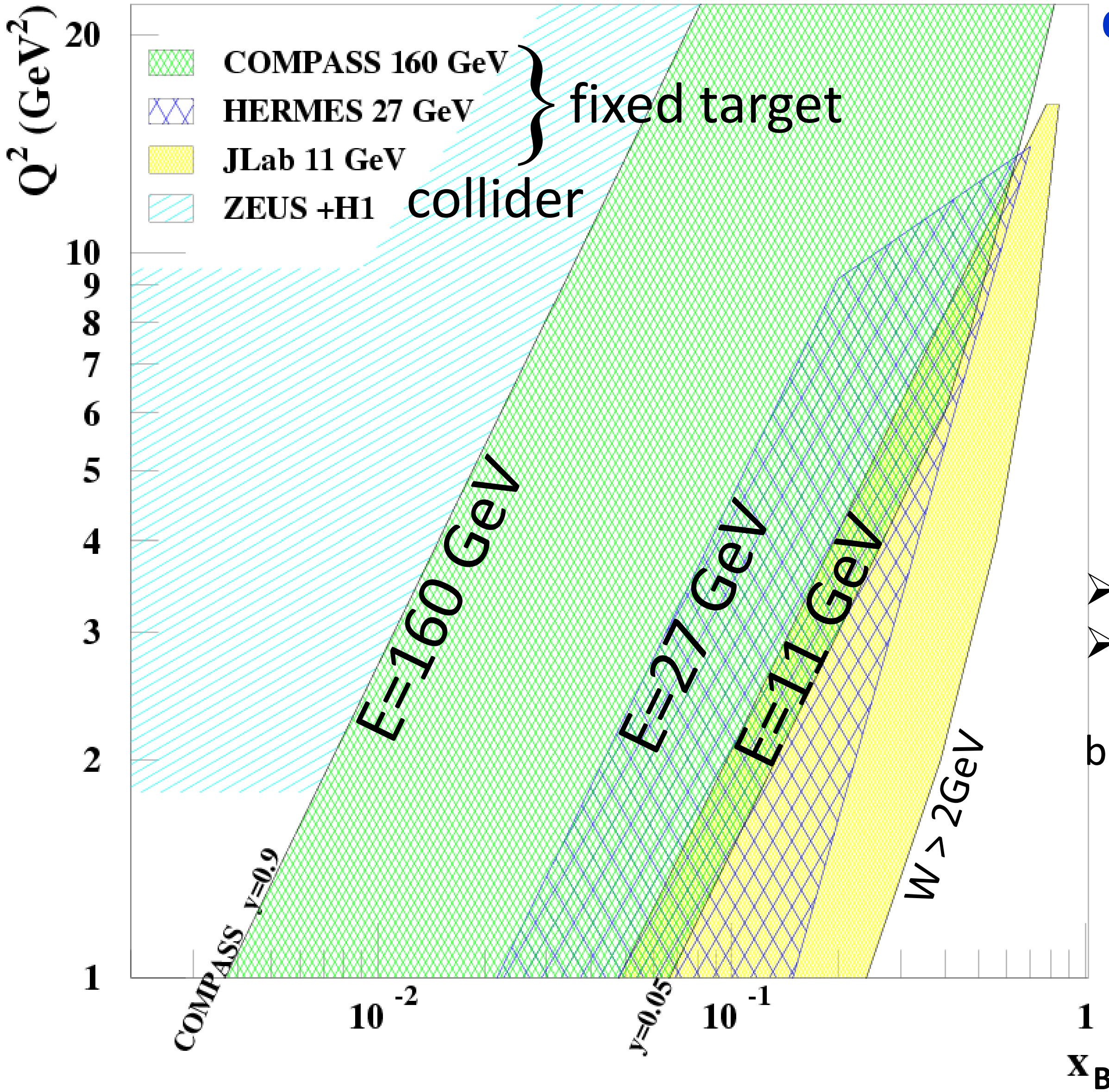


Boer-Mulders correlates
quark k_T and quark transverse spin (unpol N)

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



Kinematic domain (Q^2, x_B) for GPDs



COMPASS unique 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^+**

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

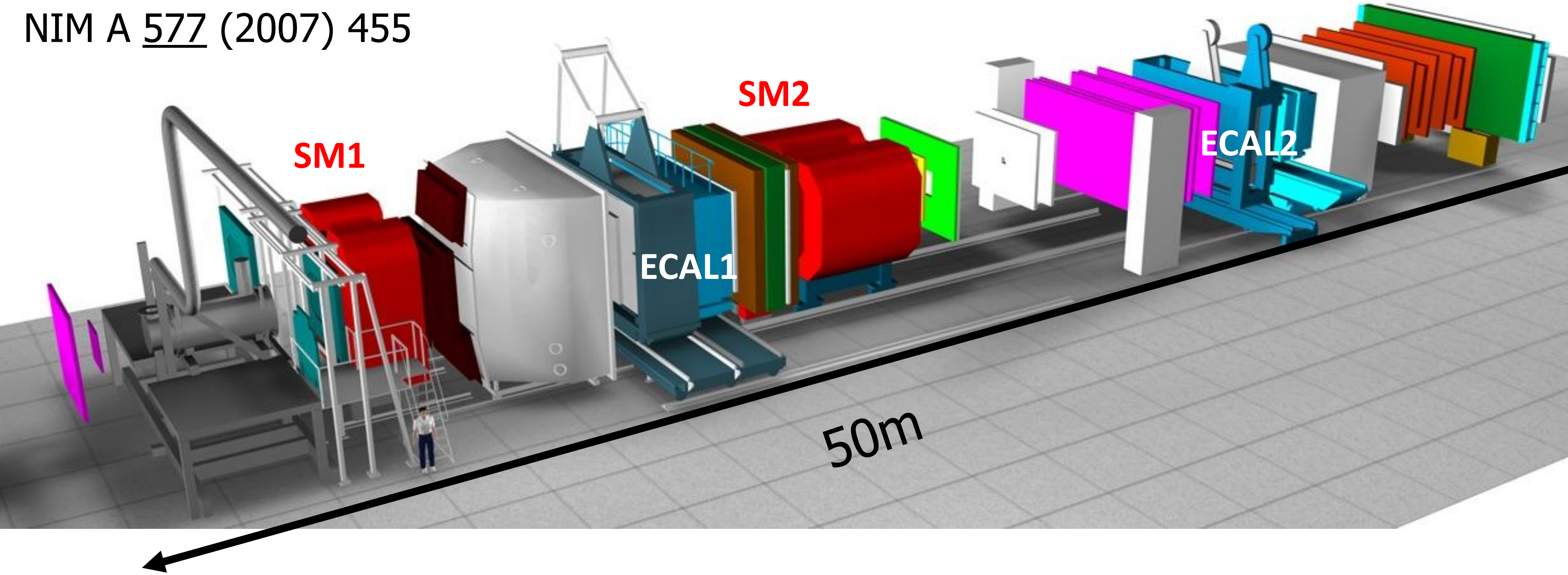
- Explore the intermediate x_{Bj} region
- Uncovered region between ZEUS+H1 & HERMES **+ Jlab** before new colliders may be available

It's time to show the impact of COMPASS

=> goal of the 2012 DVCS pilot run

The COMPASS experiment at CERN

NIM A 577 (2007) 455



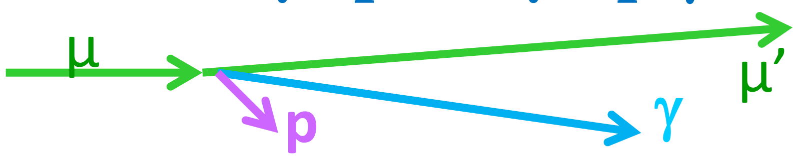
Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

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

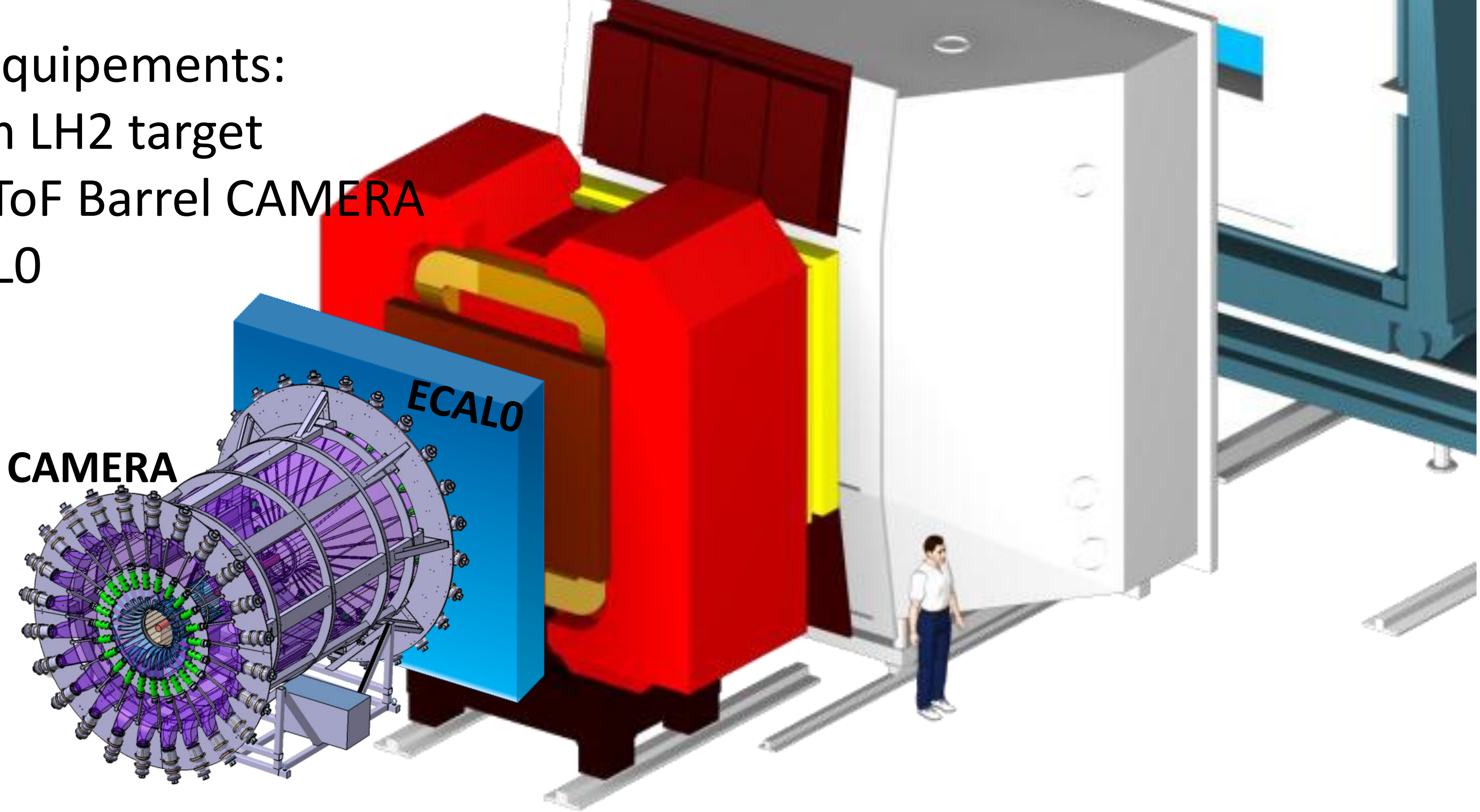
Upgrades of COMPASS spectrometer

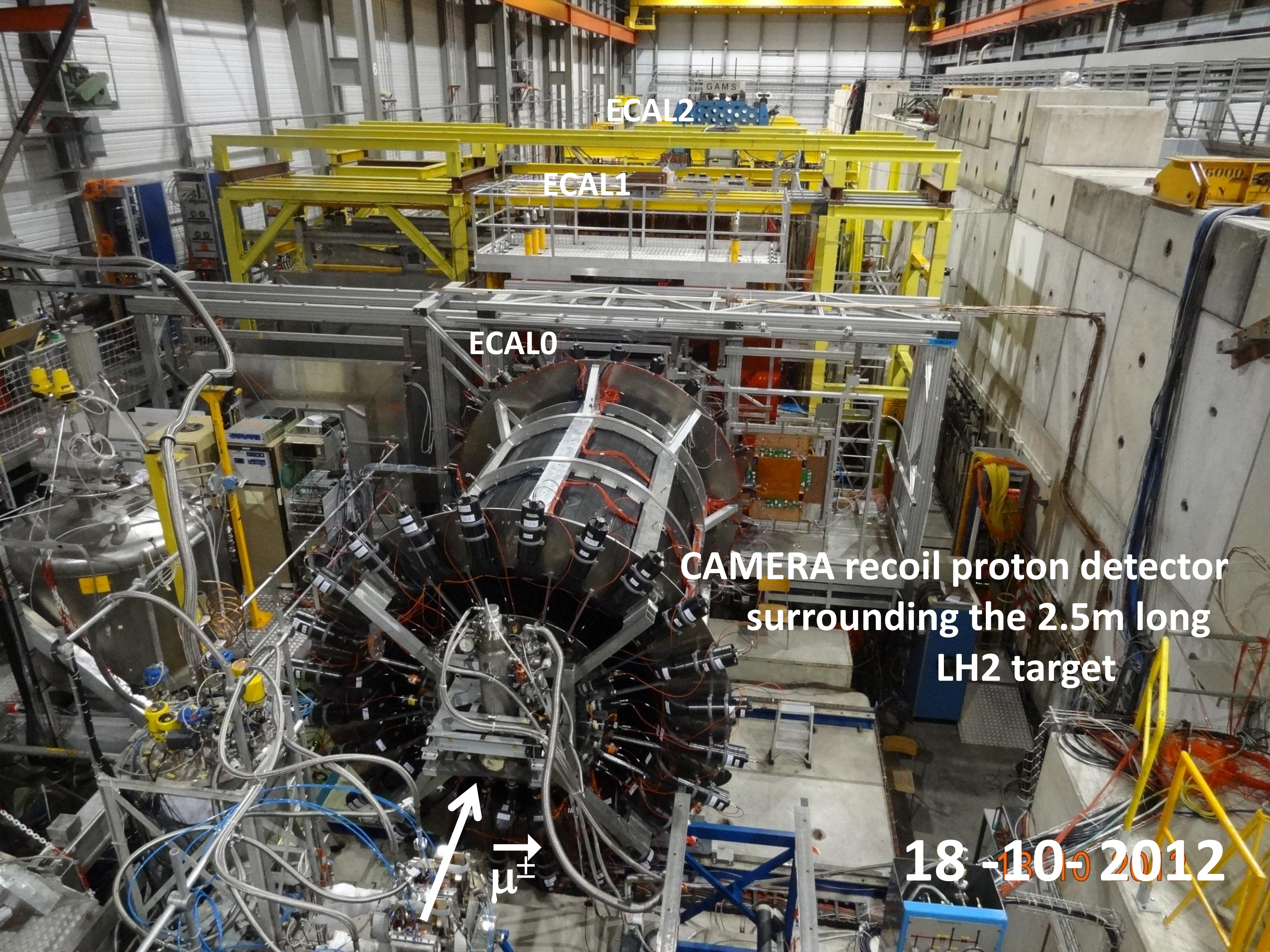
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$



New equipements:

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



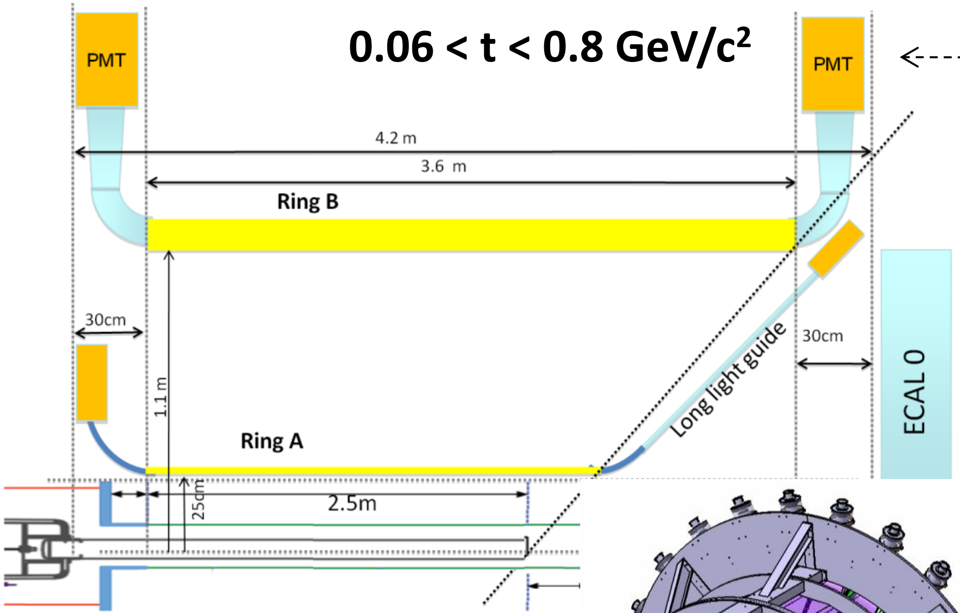

ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\vec{\mu}^{\pm}$
18 -10- 2012

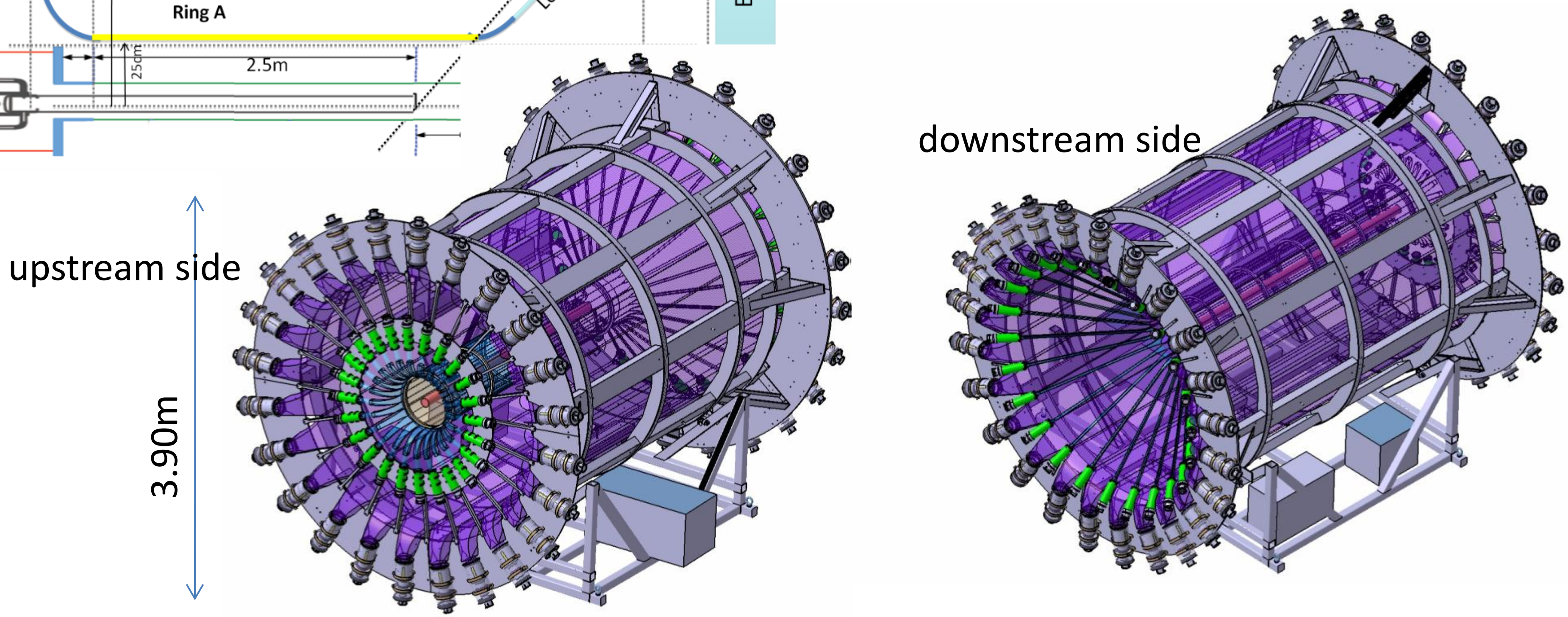
Recoil Proton Detector CAMERA

ToF between 2 rings of scintillators $\sigma(ToF) < 300ps$

1 GHz digitization of the PMT signal to cope with high rate

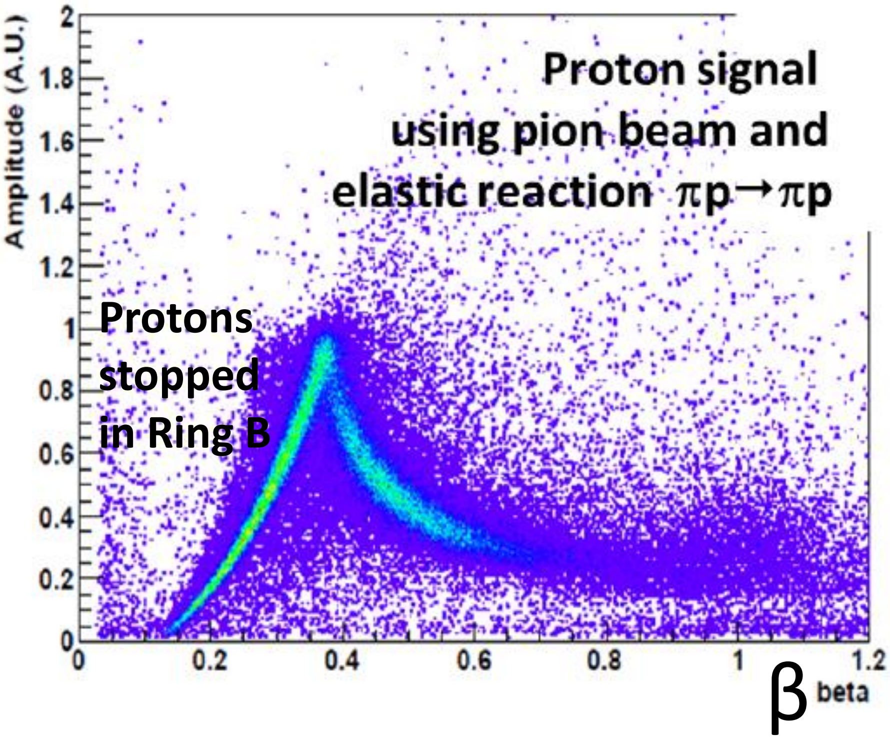
GANDALF boards ➔ First level trigger



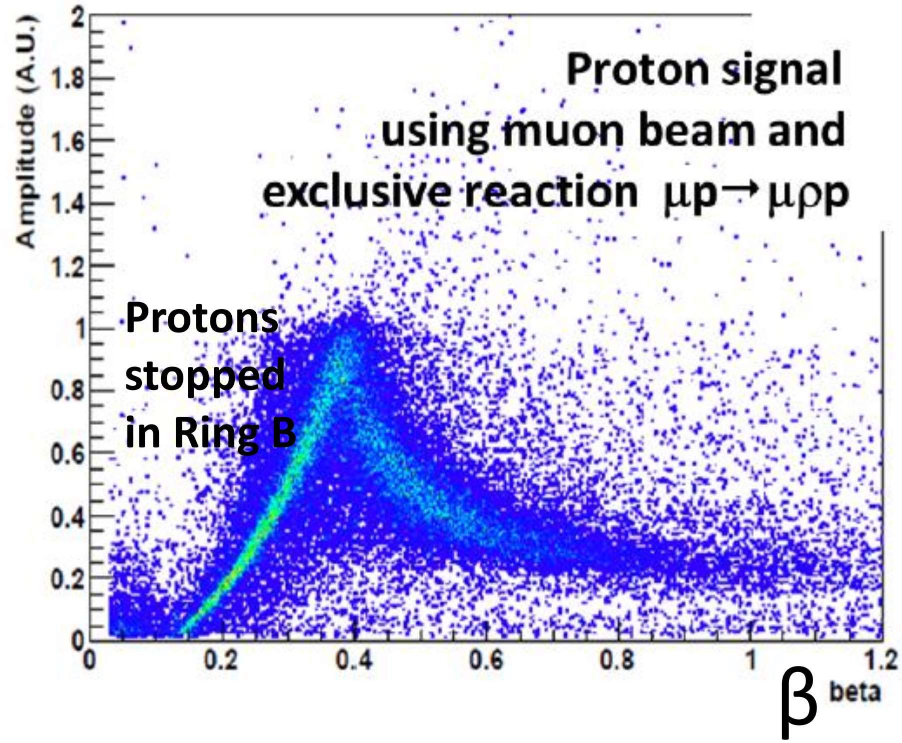


calibration of CAMERA

Energy lost in Ring B



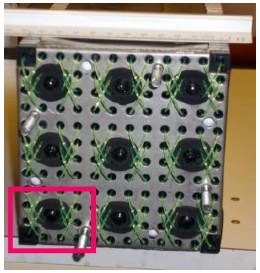
Energy lost in Ring B

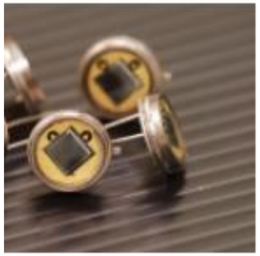


ECAL0 to enlarge the angular coverage

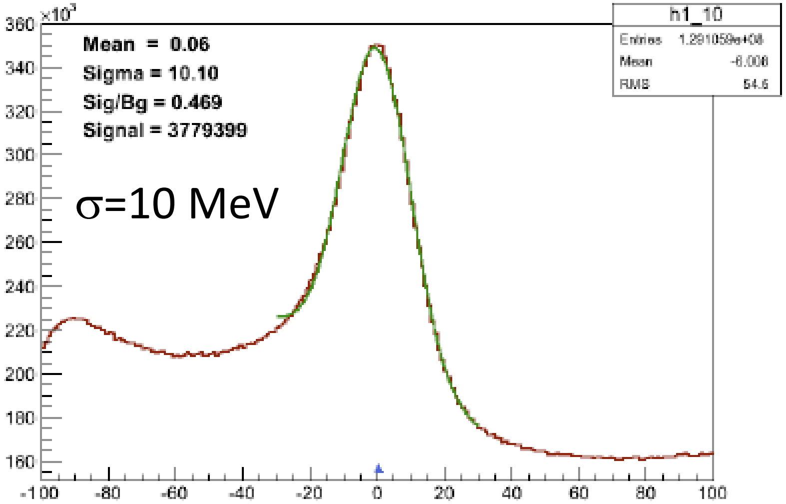
ECAL0 made of 200 modules (12 × 12 cm²) of 9 cells read by 9 MAPDs

56 Modules are available for the 2012 setup
They are already calibrated (24 Oct 2012)





Invariant γγ mass spectra
for π⁰ production using pion beam

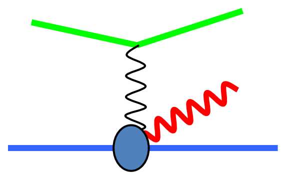


Constraints on the GPD H

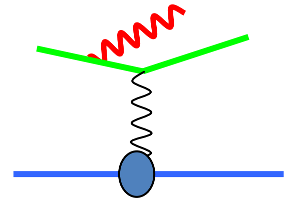
with recoil proton detection and hydrogen target

- ❖Very first tests in 2008-9
- ❖1 month in november 2012
- ❖2 years 2016-17

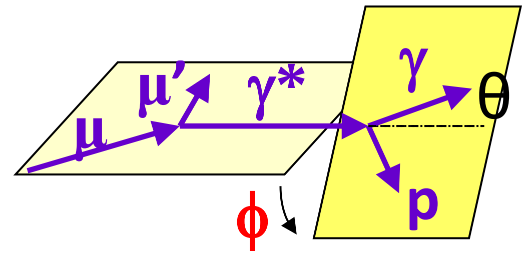
Contributions of DVCS and BH at E_μ=160 GeV



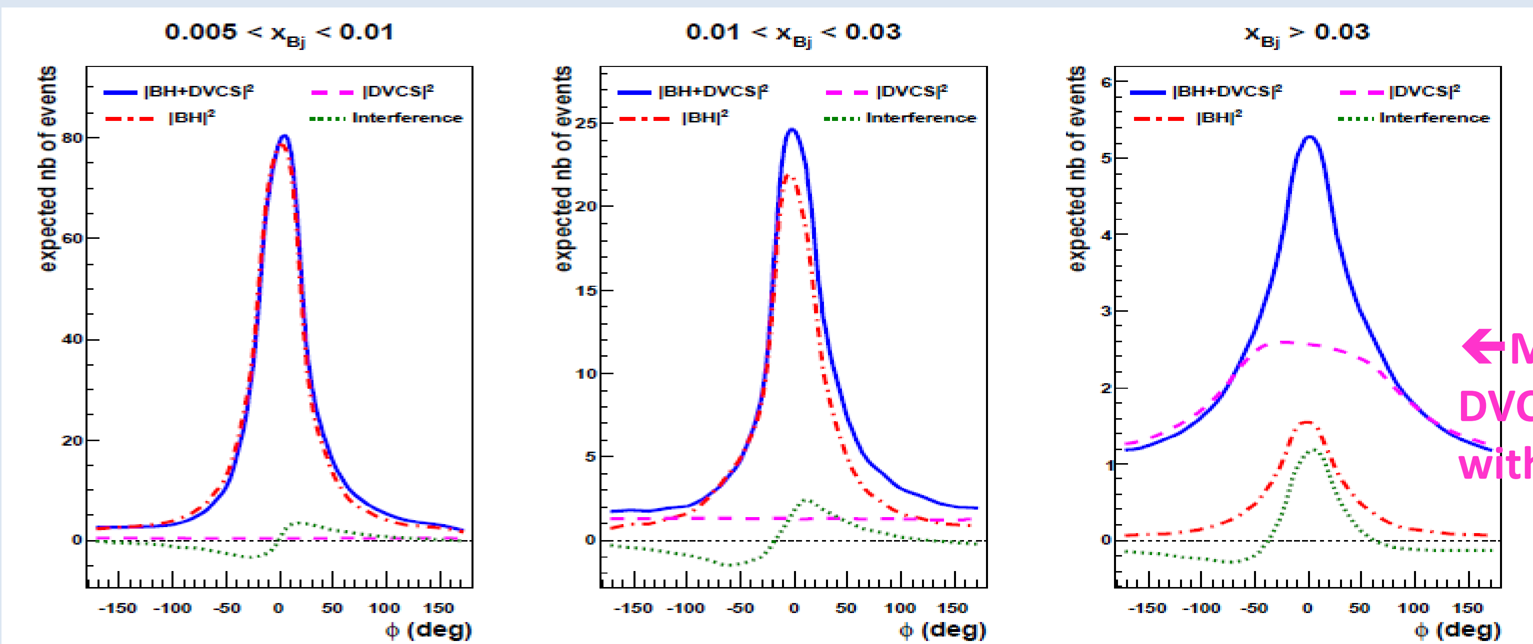
Deep VCS



Bethe-Heitler



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



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}

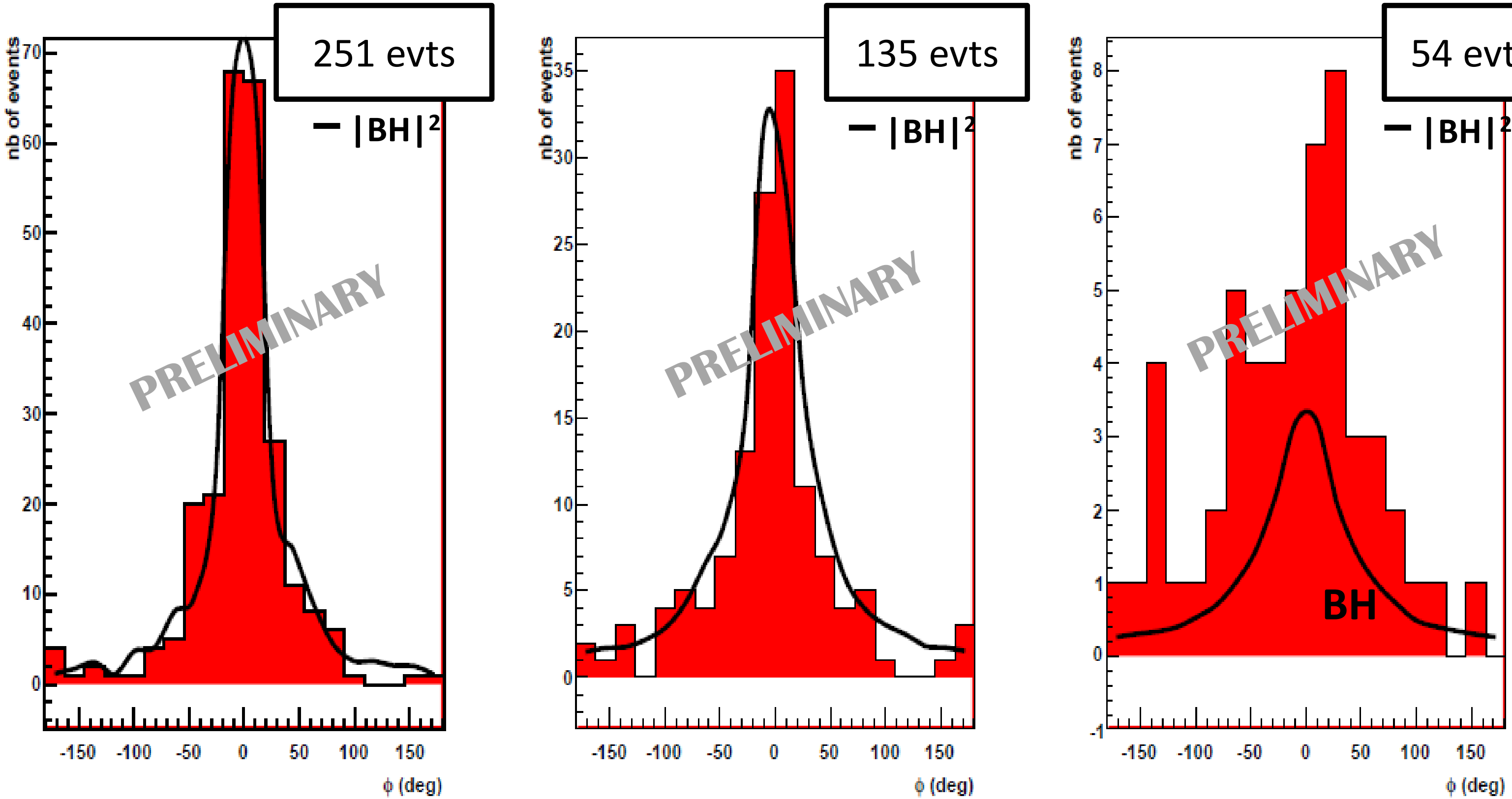
or Im T^{DVCS}

DVCS dominates

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

→ Transverse Imaging

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



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

$\epsilon_{\mu p \to \mu' \gamma p} \approx 35\%$

$\times (0.8)^4$ 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
+ 22 DVCS
+ about 12 γ from π^0

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol}$$

$$+ e_\mu\, a^{BH}\, \mathcal{Re}\, A^{DVCS} \qquad + e_\mu\, P_\mu\, a^{BH}\, \mathcal{Im}\, A^{DVCS}$$

Phase 1: DVCS experiment to study the transverse imaging

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

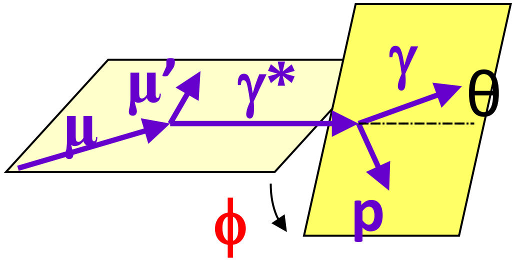
$$S_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K.s_1^{Int} \sin\phi$$

↓

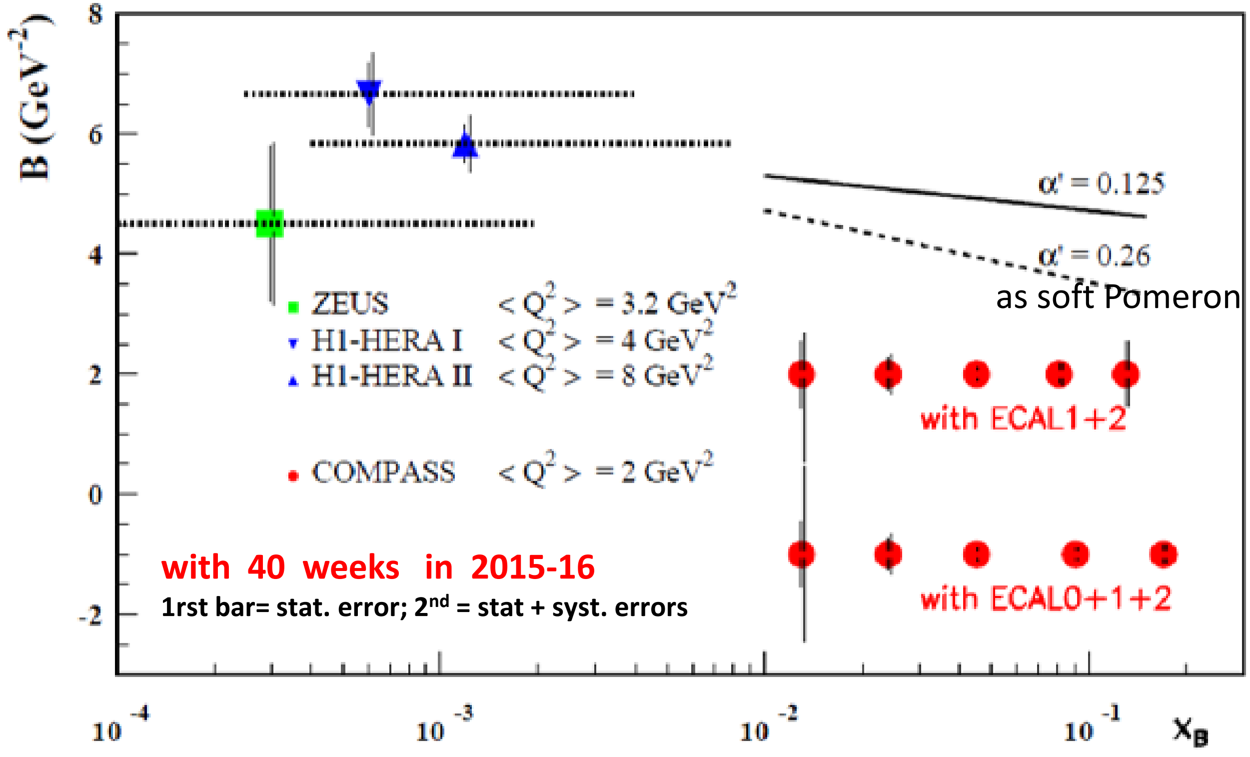
$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$

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

and integration over ϕ



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



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

ansatz at small x_B
inspired by
Regge Phenomenology:

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

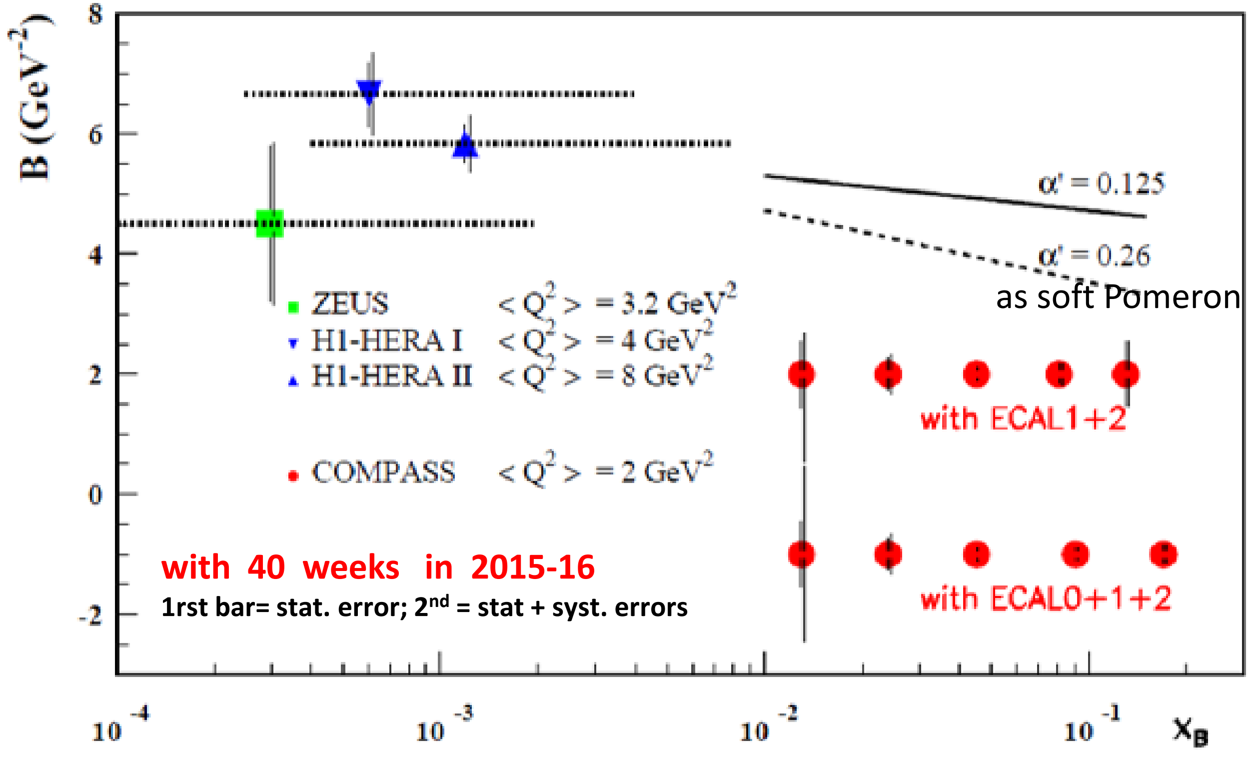
α' slope of Regge traject

for valence quark $\alpha' \sim 1$ GeV^{-2} to reproduce FF ≅ meson Regge traj.

for gluon $\alpha' \sim 0.164$ GeV^{-2} (J/Ψ at Q^2=0) << $\alpha' \sim 0.25$ GeV^{-2}
$\alpha' \sim 0.02$ GeV^{-2} (J/Ψ at Q^2=2-80 GeV^2) for soft Pomeron

Transverse imaging at COMPASS

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



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

α' slope of Regge traject

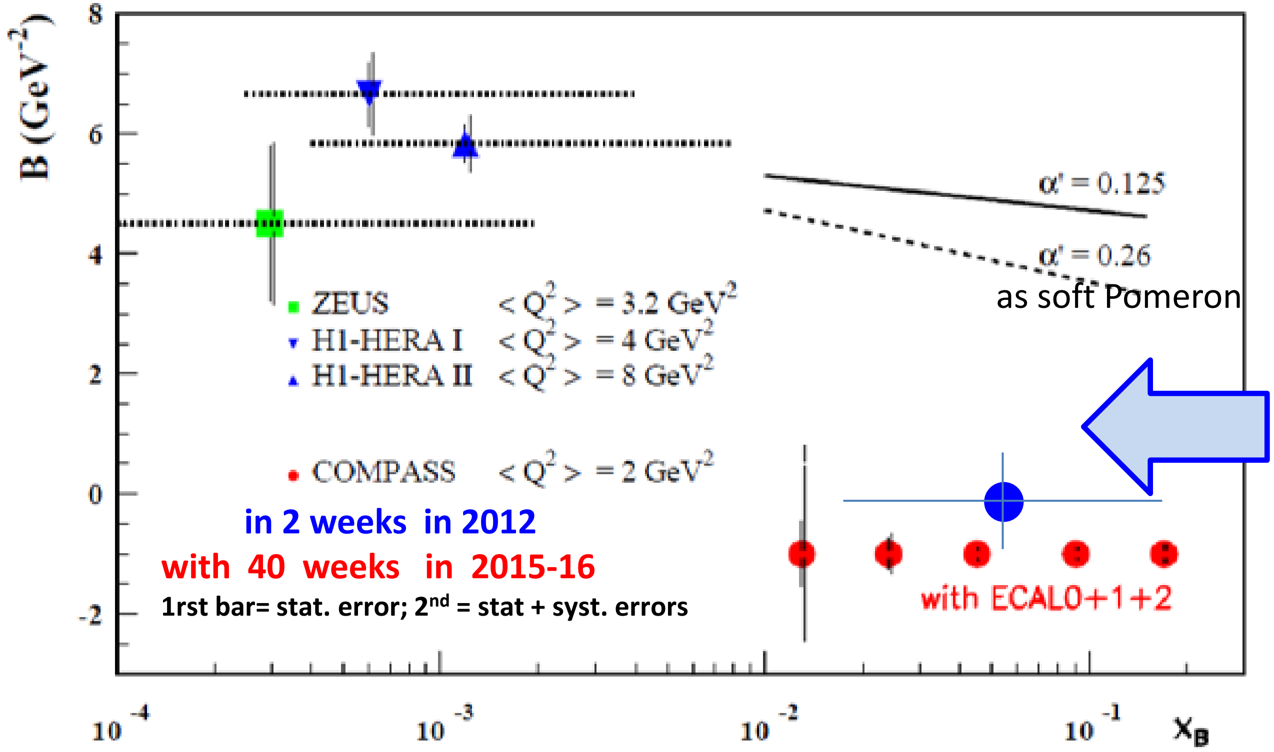
without any model we can extract $B(x_B)$

$$B(x_B) = \frac{1}{2} < r_\perp^2 (x_B) >$$

$r_\perp$ is the transverse size of the nucleon

Accuracy > 2.5 σ if α' = 0.125 and full ECALS

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



DVCS test in 2012

With **2 weeks**
Using the 4m long RPD
+ the 2.5m long LH2 target

1/20 of the complete statistics

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

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol}$$

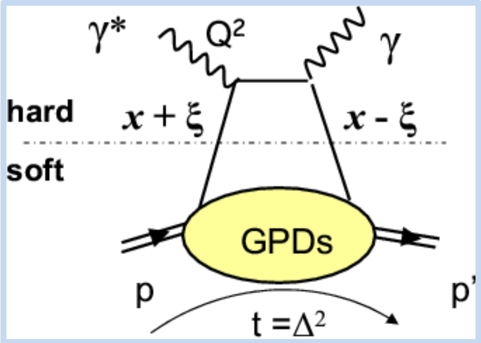
$$+\, e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} + e_\mu\, P_\mu\, a^{BH}\, \mathcal{I}m\, A^{DVCS}$$

Phase 1: DVCS experiment to constrain GPD H

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

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

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



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

- $\mathcal{I}m\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$
- $\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, H(x,\xi,t)/(x-\xi)$

Note: dominance of H at COMPASS kinematics

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol}$$

$$+ e_\mu\, a^{BH}\, \mathcal{Re}\, A^{DVCS} + e_\mu\, P_\mu\, a^{BH}\, \mathcal{Im}\, A^{DVCS}$$

Phase 1: DVCS experiment to constrain GPD H

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

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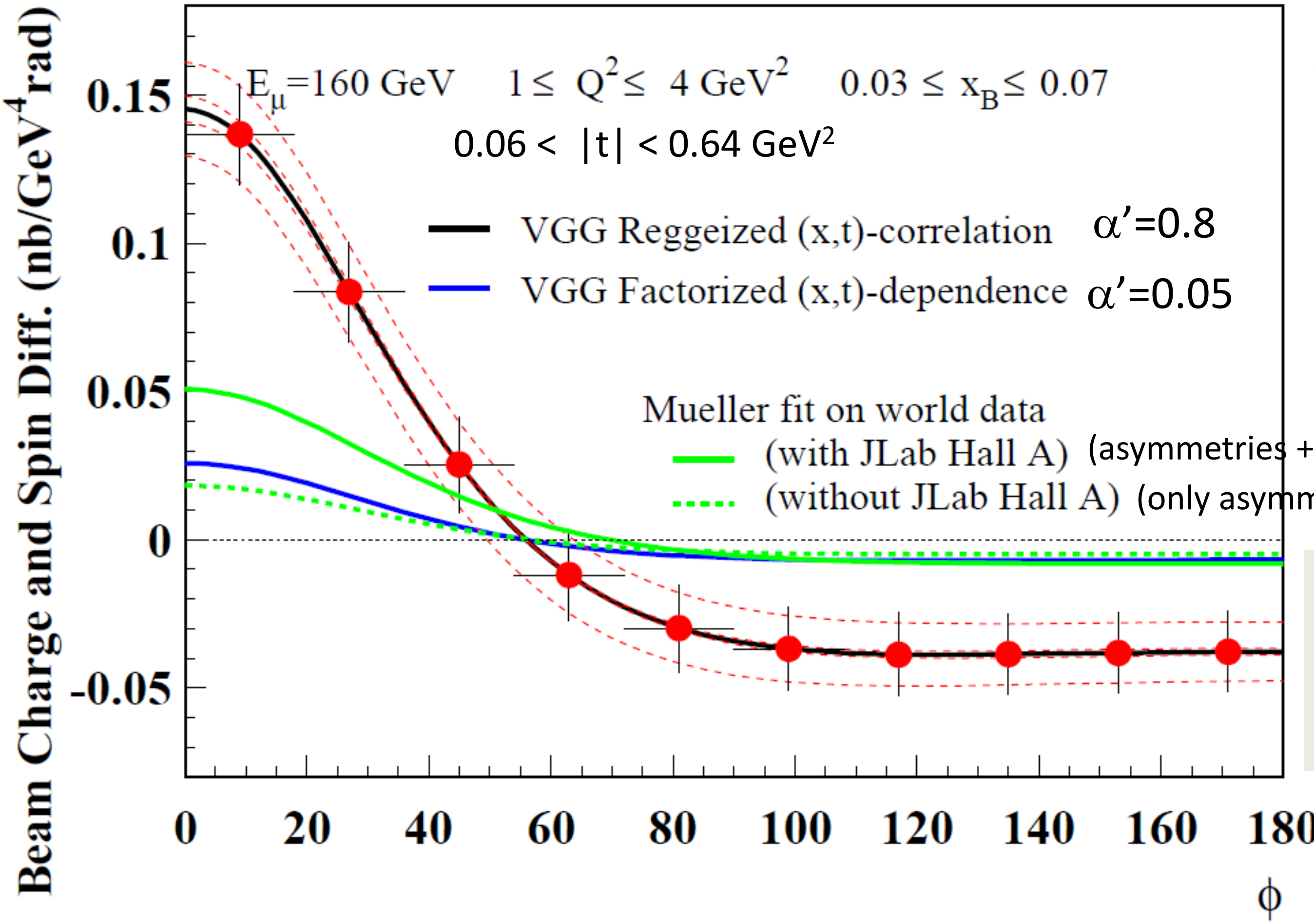
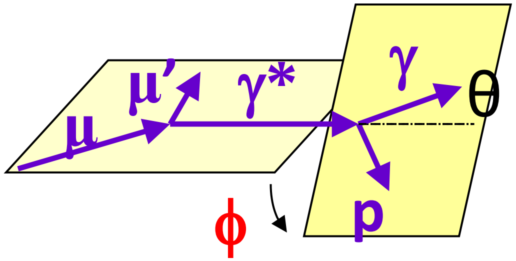
$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int} \sin\phi \quad \text{and} \quad s_1^{Int} \sim \mathcal{Im}(F_1 \mathcal{H})$$

Angular decomposition of **sum** and **diff** of the **DVCS cross section** will provide umambiguous way to separate the *Re* and *Im* of the *Compton Form Factors* from higher twist contributions

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

Comparison to different models





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

Note: Kroll, Moutarde, Sabatié predictions are of the same order of magnitude than Mueller predictions

High precision beam flux and acceptance determination
Systematic error bands assuming a 3% charge-dependent effect between μ+ and μ- (control with inclusive evts, BH…)

Beam Charge and Spin Difference over the kinematic domain

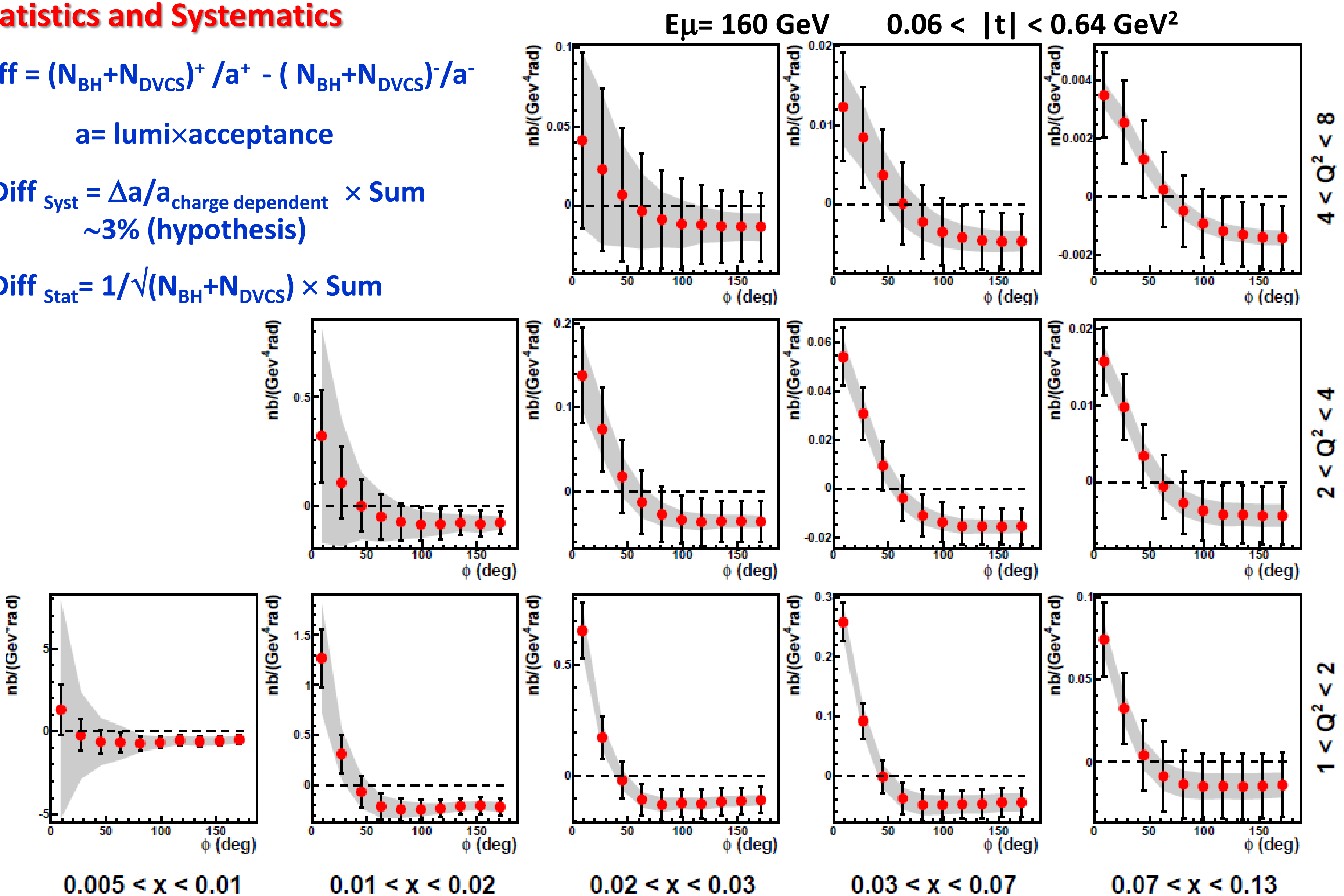
Statistics and Systematics

$\text{Diff} = (N_{BH}+N_{DVCS})^{+}/a^{+} - (N_{BH}+N_{DVCS})^{-}/a^{-}$

$a = \text{lumi}\times\text{acceptance}$

$\Delta\text{Diff}_{Syst} = \Delta a/a_{\text{charge dependent}} \times \text{Sum}$
$\sim 3\%$ (hypothesis)

$\Delta\text{Diff}_{Stat} = 1/\sqrt{(N_{BH}+N_{DVCS})} \times \text{Sum}$

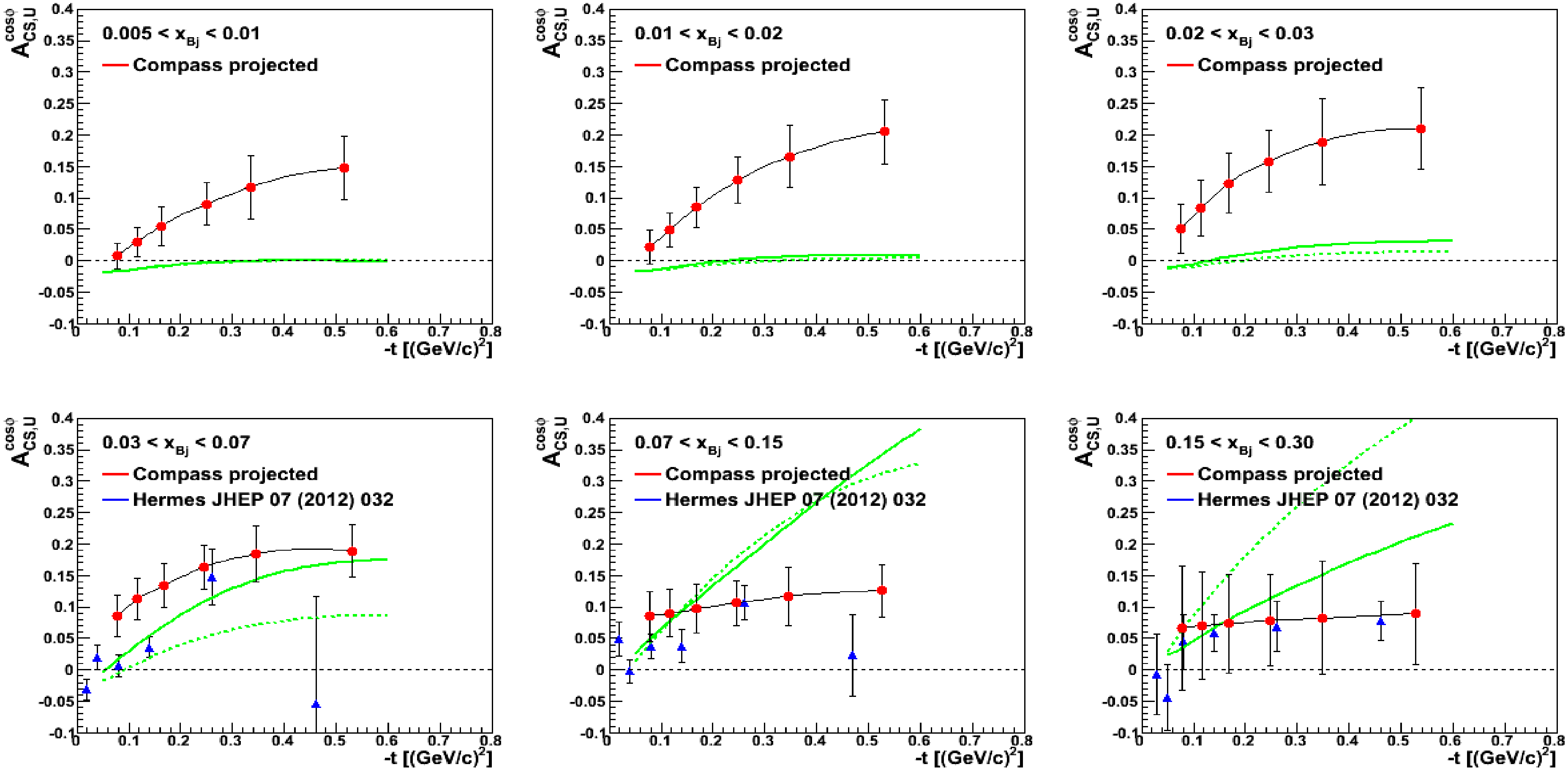


$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int}\cos\phi \quad \text{and} \quad c_{0,1}^{Int} \sim \mathcal{R}e(F_1\mathcal{H})$$

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

Predictions with
VGG and D.Mueller

$\mathcal{R}e(F_1\mathcal{H})$ > 0 at H1
< 0 at HERMES/JLab
Value of x_B for the node?



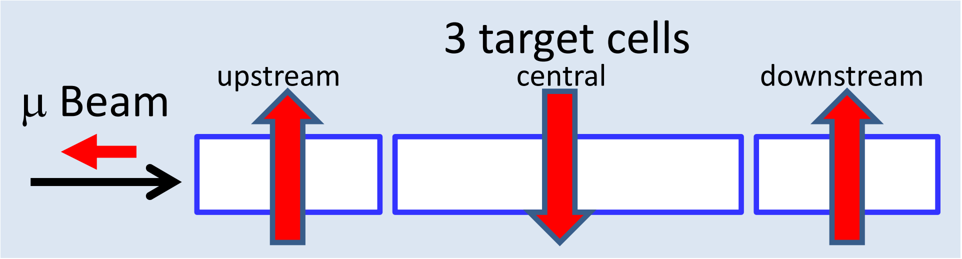
2 years of data

$E\mu$ = 160 GeV $1 < Q^2 < 8$ GeV^2 With ECAL2 + ECAL1 + ECAL0

with transversely polarized protons (NH3 target)

1) without recoil detection (2007 & 10)

2) with recoil detection **Phase 2** (in a future addendum)



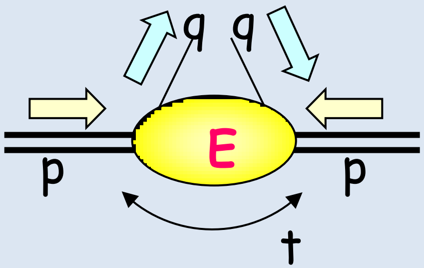
Constraints on the 'elusive' chiral-even GPD E

the GPD **E** allows nucleon helicity flip

so it is related to the angular momentum

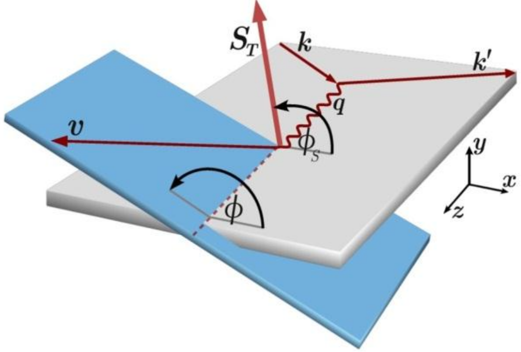
Ji sum rule: $2J^q = \int x\, (H^q(x,\xi,0) + E^q(x,\xi,0))\, dx$

The GPD E is the 'Holy-Grail' of the GPD quest



Constraints on the chiral-odd GPDs H_T and $\bar{E}_T$

exclusive ρ^0 production



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

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

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

transv. polar. target

$$-S_T\Big[\sin(\phi-\phi_S)\,\mathrm{Im}\,(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-})+\frac{\varepsilon}{2}\sin(\phi+\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{\varepsilon}{2}\sin(3\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+-}^{-+}$$

$$+\sqrt{\varepsilon(1+\varepsilon)}\sin\phi_S\,\mathrm{Im}\,\sigma_{+0}^{+-}+\sqrt{\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)\,\mathrm{Im}\,\sigma_{+0}^{-+}\Big]$$

transv. polar. target + long. Polar. beam

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

$$-\sqrt{\varepsilon(1-\varepsilon)}\cos\phi_S\,\mathrm{Re}\,\sigma_{+0}^{+-}-\sqrt{\varepsilon(1-\varepsilon)}\cos(2\phi-\phi_S)\,\mathrm{Re}\,\sigma_{+0}^{-+}\Big]$$

σ	i j	for nucleon helicity
	mn	for photon helicity

exclusive ρ^0 production

Leading twist contribution for ρ^0 produced by longitudinal photons

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

chiral-even GPDs

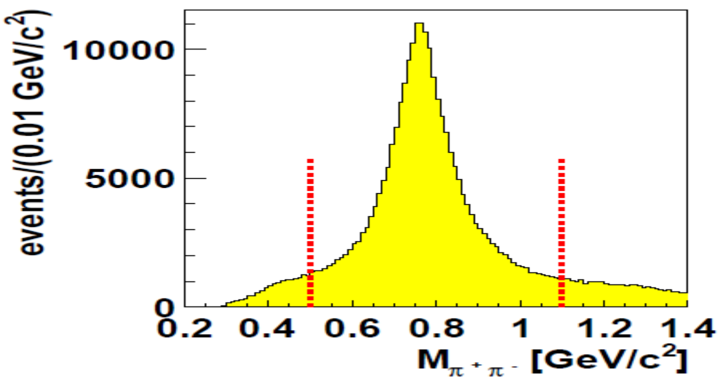
Subleading twist contribution for ρ^0 including transverse photons

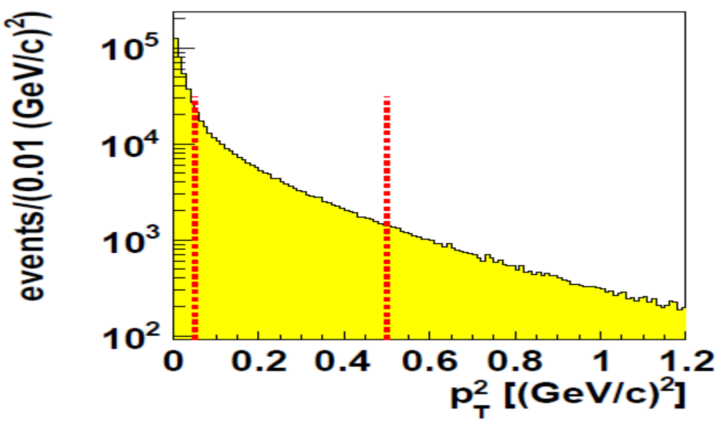
$$A_{UT}^{\sin(\phi_S)} \propto Im(\mathcal{E}^* \overline{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$$

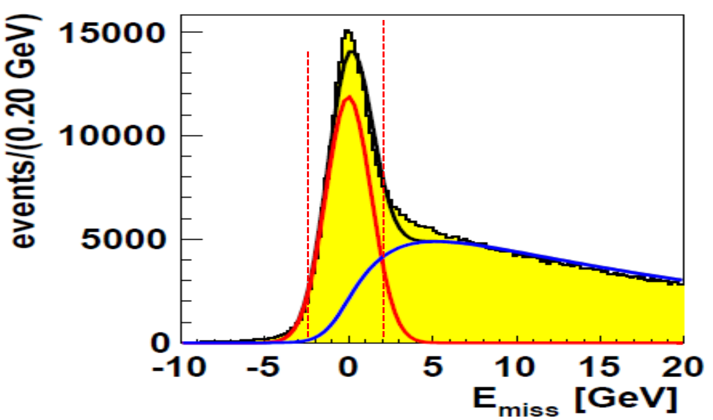
chiral-odd GPDs

Selection of Exclusive ρ° Production: μ p → μ′ ρ° p

without RPD







$1 < Q^2 < 10\ GeV^2$ $0.1 < y < 0.9$ $W > 4$ GeV $E_\rho > 15$ GeV

1- Assuming both hadrons are π

$0.5 < M_{\pi\pi} < 1.1$ GeV

To maximize the purity of the sample of ρ° / non resonant $\pi^+\pi$

2- Suppression of incoherent production on quasi-free protons in NH_3 polarized target

+ Suppression of SIDIS background

$0.05 < p_t^2 < 0.5\ GeV^2$

Contamination of about a 5% coherent production

3- Exclusivity of the reaction

$$E_{\text{miss}} = \frac{M_X^2 - M_P^2}{2 \cdot M_P} = E_{\gamma^*} - E_{\rho^0} + t/(2 \cdot M_P)$$

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

Diffractive dissociation contamination ~14%

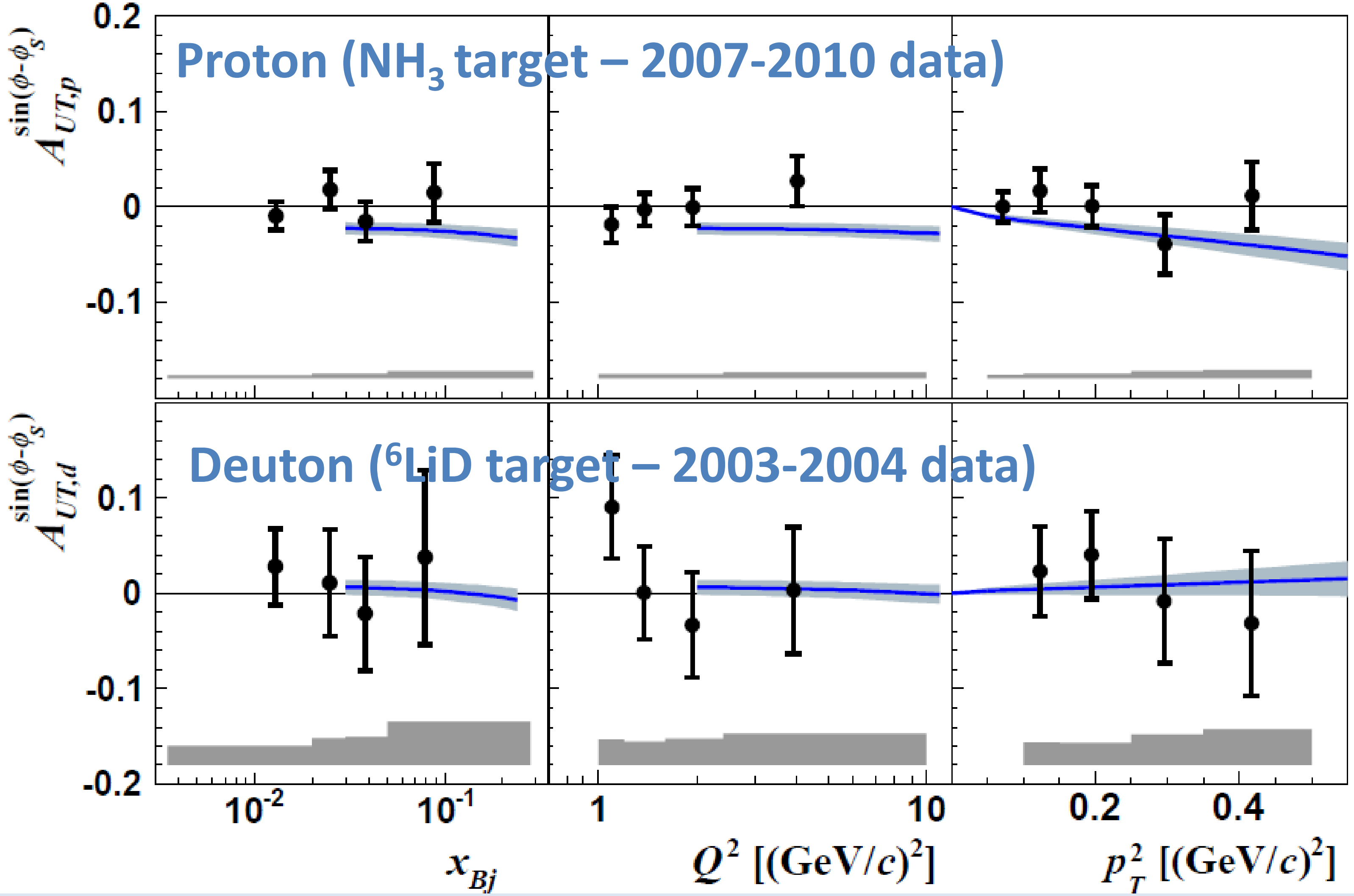
No attempt to remove it(motivated by HERA)

→correction for SIDIS background (5 to 40%) in each bin (x_{Bj}, Q^2, p_T^2, cell and polar. State)

Bins in $\Phi - \Phi_S$

asymmetry extraction
using a **1D** binned maximum likelihood fit
after subtracting the SIDIS background

Exclusive ρ° production on transerve polar. target
without Recoil Detection

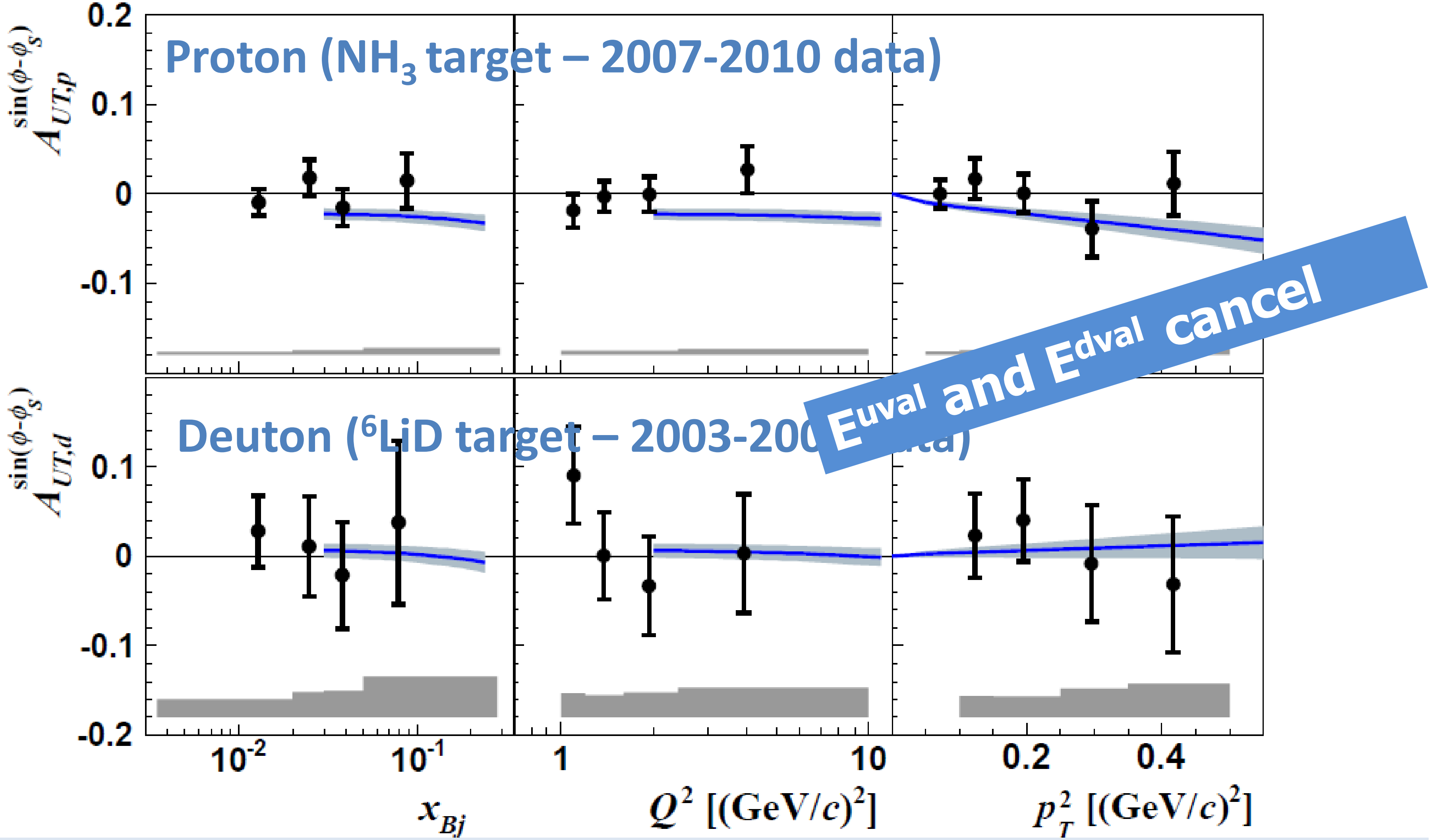


COMPASS (NPB 865 1- July 2012) and predictions by

Goloskokov & Kroll, EPJ C59 (2009)

Exclusive ρ° production on transerve polar. target

without Recoil Detection



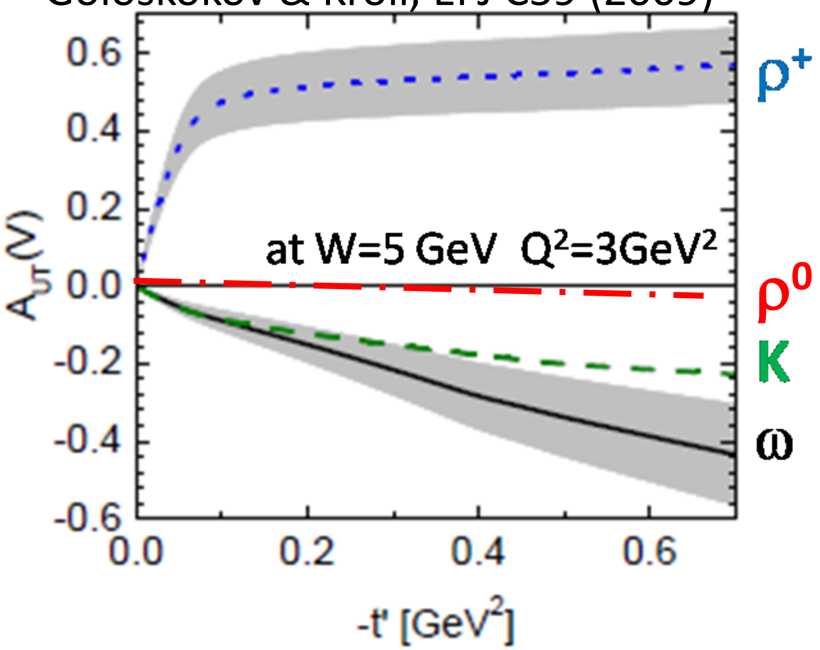
COMPASS (NPB 865 1- July 2012) and predictions by

Goloskokov & Kroll, EPJ C59 (2009)

Hard Exclusive Vector Meson Production

$$A_{UT}(\rho^0_L) \propto \sqrt{|-t'|}\, Im(\mathcal{E}^* \mathcal{H}) \,/\, |\mathcal{H}|^2$$

Goloskokov & Kroll, EPJ C59 (2009)



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

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

$E\rho^+ \propto\ E^u - E^d\ - 3/8\ H^g$

Cancellation between gluon and sea contributions

$\kappa^q = \int e^q(x)\ dx$

➔ $E^{uval} \sim -E^{dval}$

$A_{UT}(\rho^0)$ very small

$A_{UT}(\omega)$ and $A_{UT}(\rho^+)$ should be more promising

analysis on going for ω, ρ⁺, ϕ and γ

New Analysis

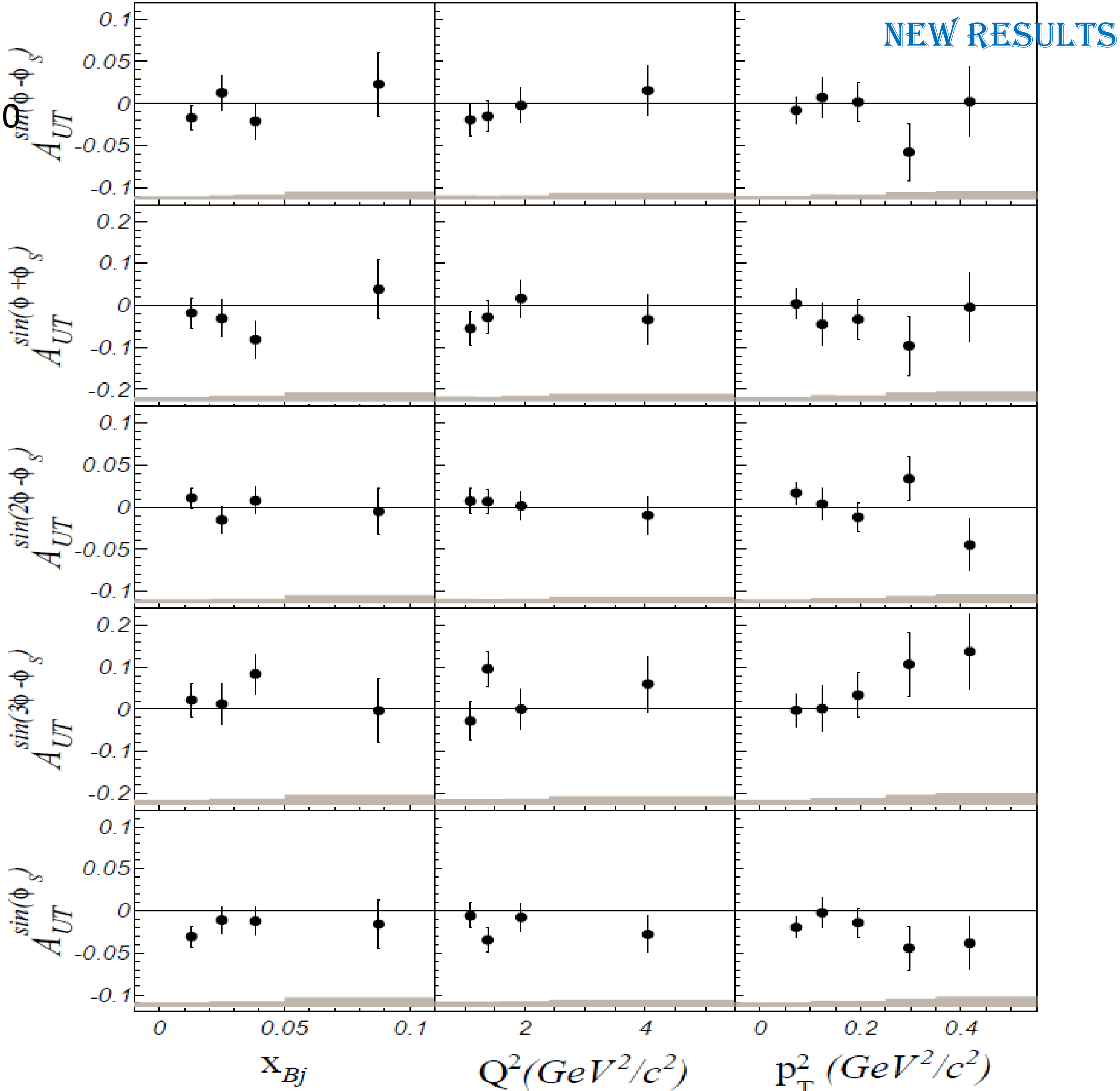
Bins in Φ and Φ_S

asymmetry extraction
using a **2D** binned maximum likelihood fit
After subtracting the SIDIS background

transv. pol. Protons

NH3 target 2007-2010

A_{UT}

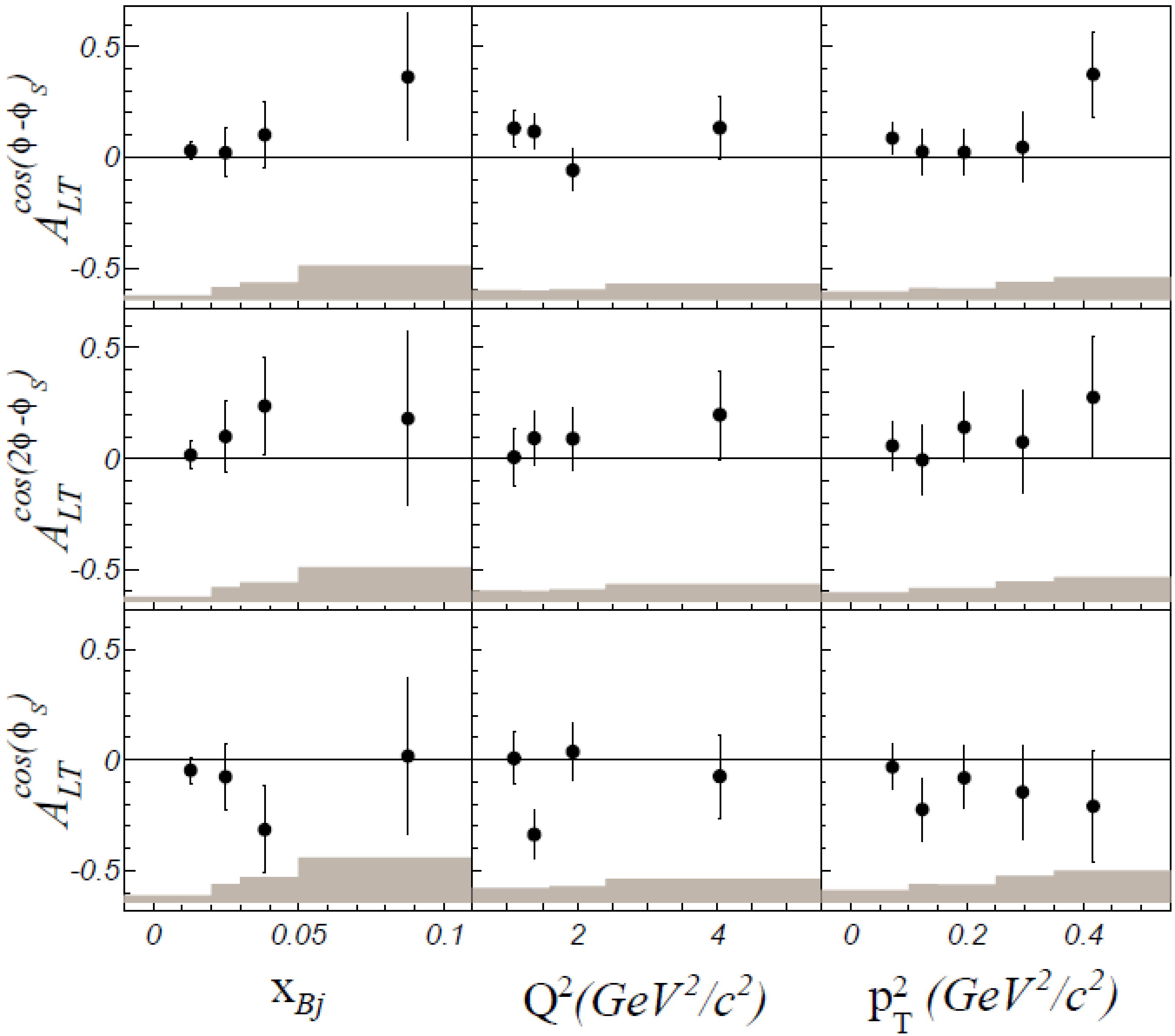


NEW RESULTS

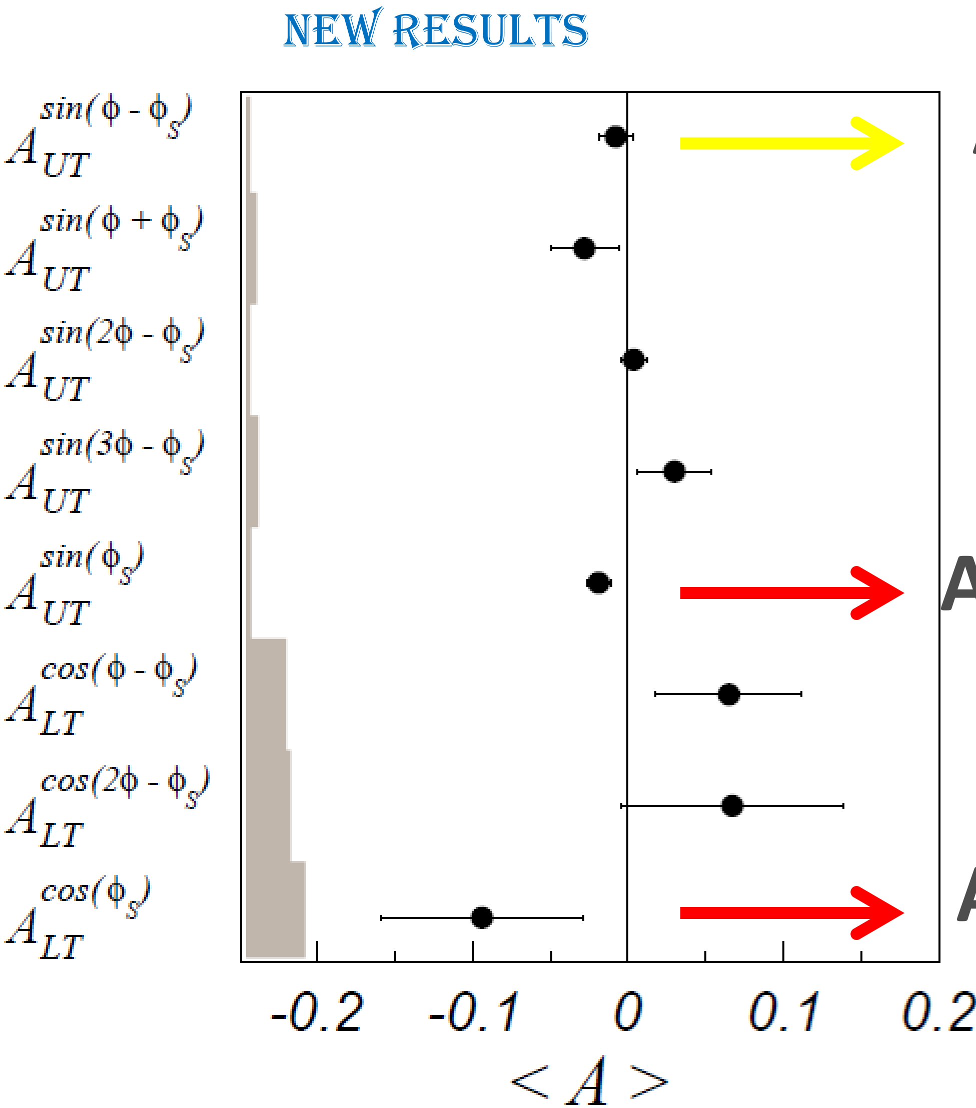
transv. pol. Protons

NH3 target 2007-2010

A_{LT}



exclusive ρ^0 production –Transv. Polar. target



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

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

$A_{LT}^{\cos(\phi_S)} \propto Re(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$

H_T could be not small

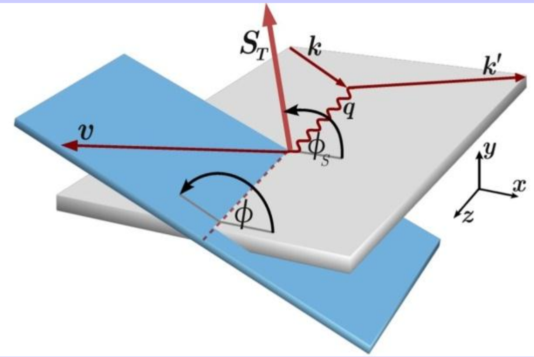
$W = 8.1$ GeV$/c^2$, $p_T^2 = 0.2$ (GeV$/c)^2$, $Q^2 = 2.2$ (GeV$/c)^2$

Deeply Virtual Compton Scattering

Phase 2 (in future): DVCS experiment to constrain GPD E

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

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

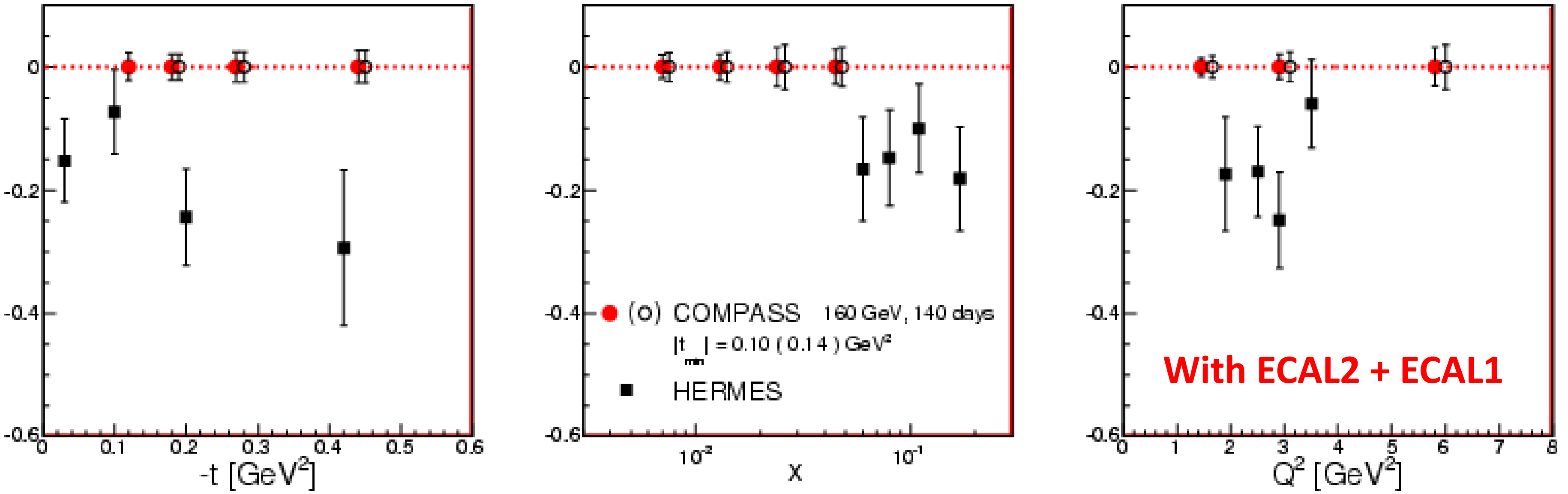


$\mathcal{D}_{CS,T}$ and Transverse Target Asymmetry

Prediction for phase 2 (in future)
With a transversely polarized NH3 (proton) target:

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

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



Summary for GPD @ COMPASS

GPDs investigated with Hard Exclusive Photon and Meson Production

$\mu^{+\downarrow}$, $\mu^{-\uparrow}$ 160 GeV

COMPASS-II 2016-17: with LH_2 target + RPD (phase 1)

✓ the t-slope of the DVCS and HEMP cross section
→ transverse distribution of partons

✓ the Beam Charge and Spin Sum and Difference
→ $\mathcal{Re}\, T^{DVCS}$ and $\mathit{Im}\, T^{DVCS}$ for the GPD H determination

✓ Vector Meson ρ^0, ρ^+, ω, Φ

✓ Pseudo-saclar π^0

Using the 2007-10 data: transv. polarized NH_3 target without RPD
In a future addendum > 2017: transv. polarised NH_3 target with RPD (phase 2)

✓ the Transverse Target Spin Asymm
→ GPD E and chiral-odd (transverse) GPDs

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

$B(x_B) = ½ < r_\perp^2(x_B) >$

distance between the active quark
and the center of momentum of spectators

Transverse size of the nucleon

mainly dominated by $H(x, \xi = x, t)$

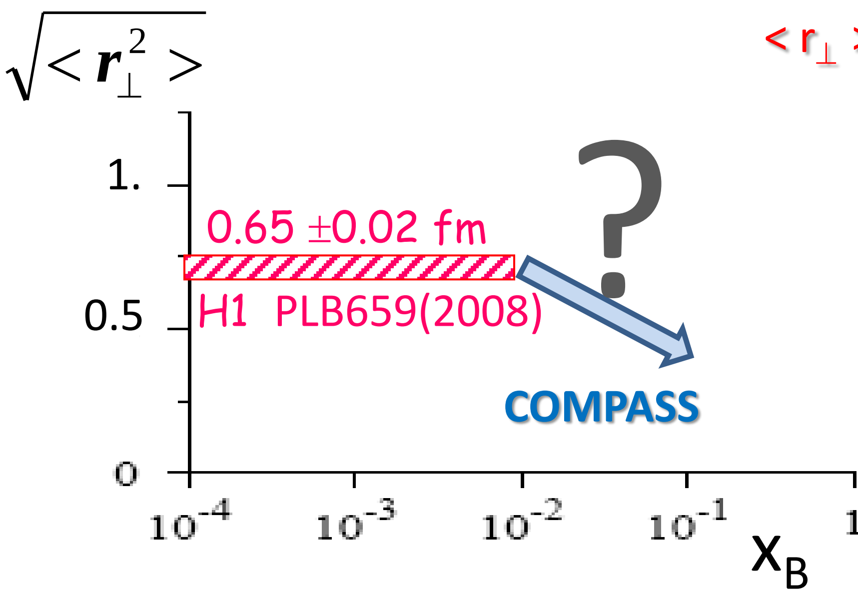
related to $½ < b_\perp^2(x_B) >$

distance between the active quark
and the center of momentum of the nucleon

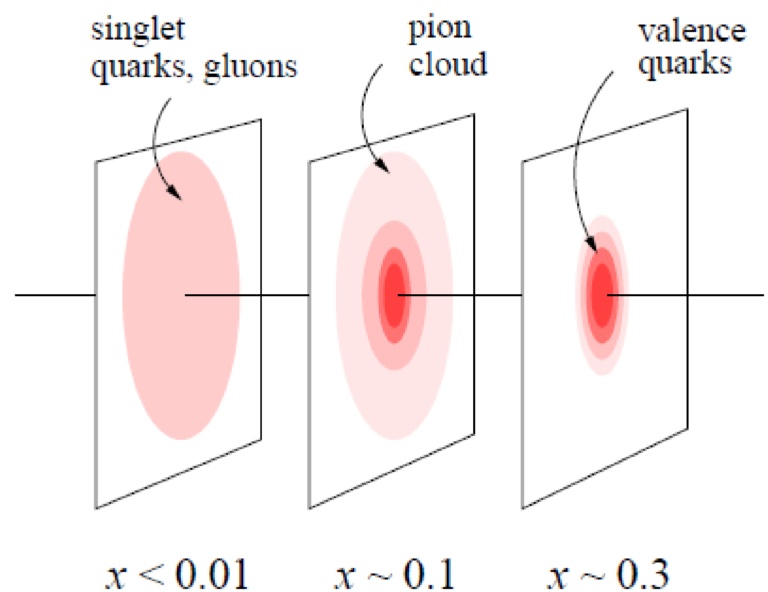
Impact Parameter Representation

$q(x, b_\perp) \leftrightarrow H(x, \xi=0, t)$

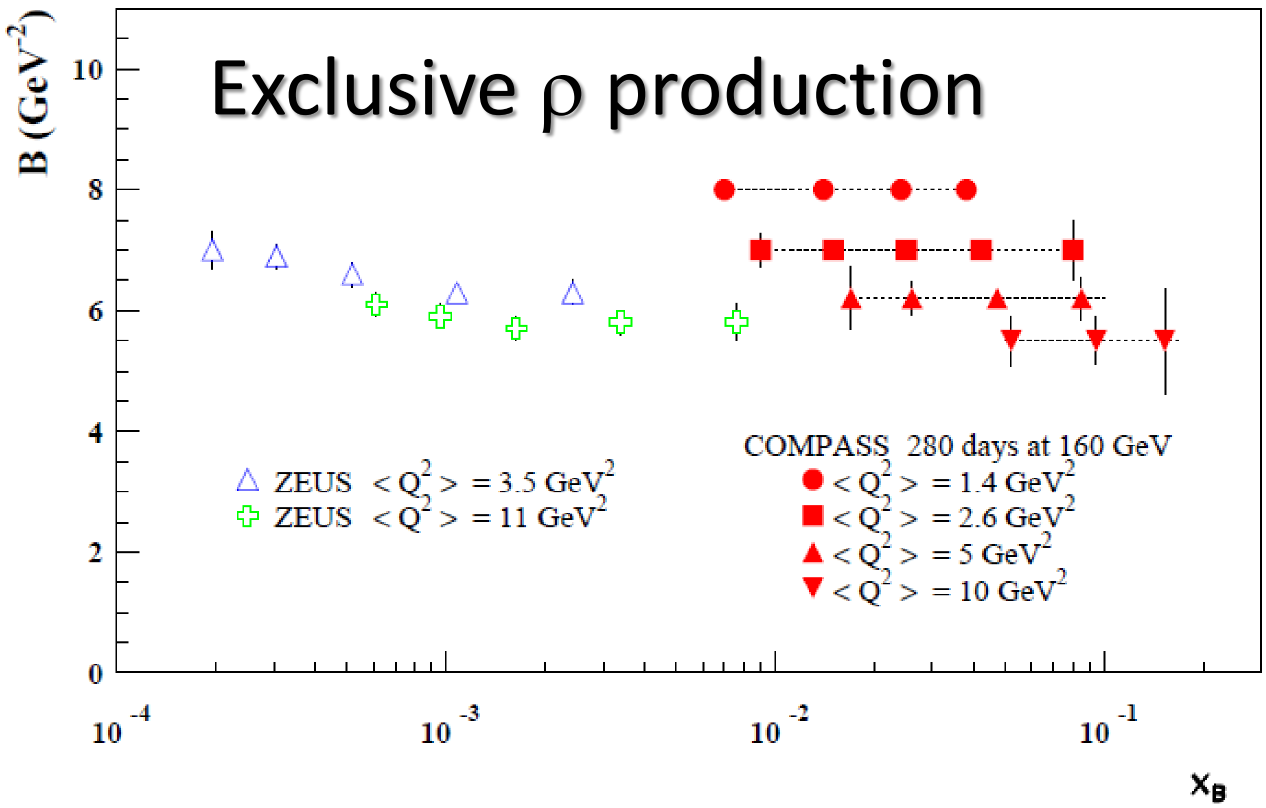
$< r_\perp > \sim < b_\perp > / (1-x)$



Note 0.65 fm $= \sqrt{2/3} \times 0.8$ fm



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

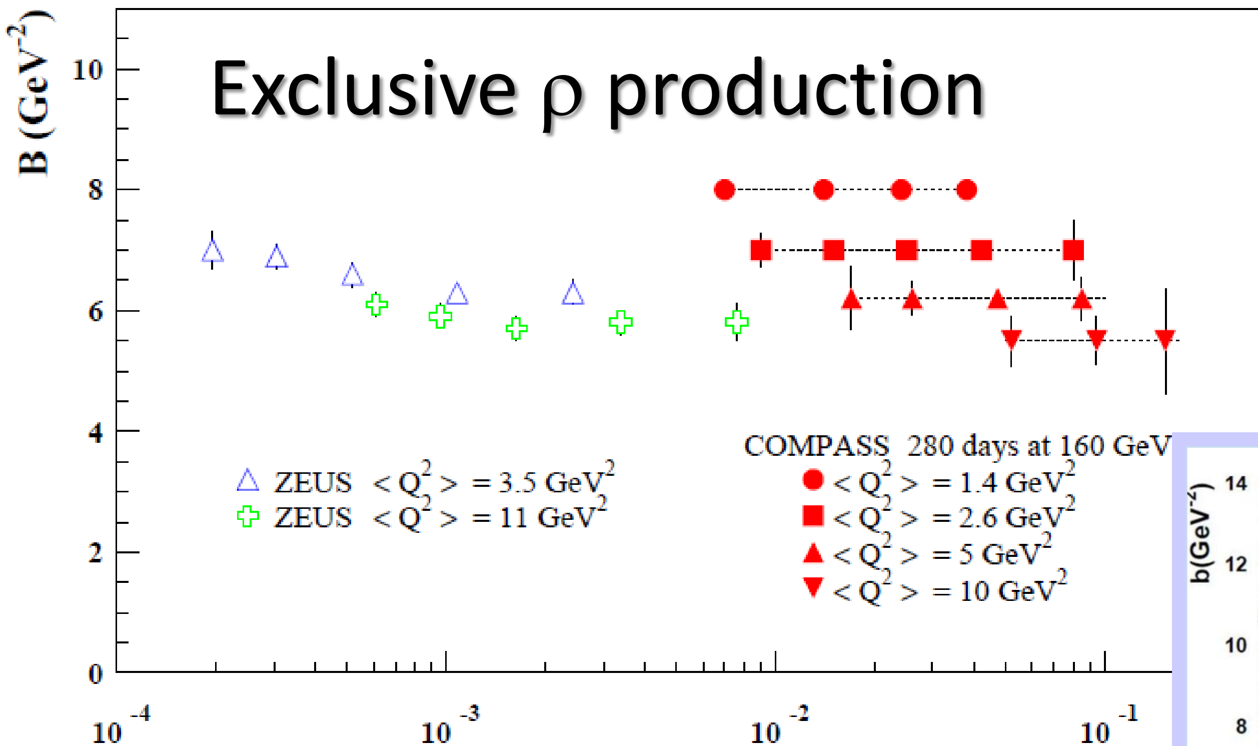


2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

model developed by Sandacz
renormalised according
Goloskokov and Kroll prediction

Transverse imaging at COMPASS

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



2 years of data
160 GeV muon beam
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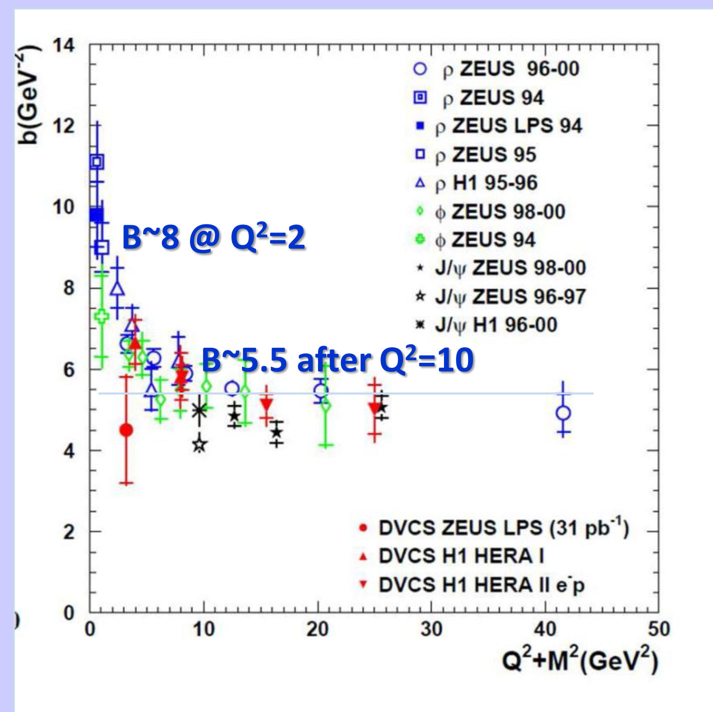

We are sensitive
to the nucleon transverse size
+ to the meson transverse size

Mounting in clean room at CERN