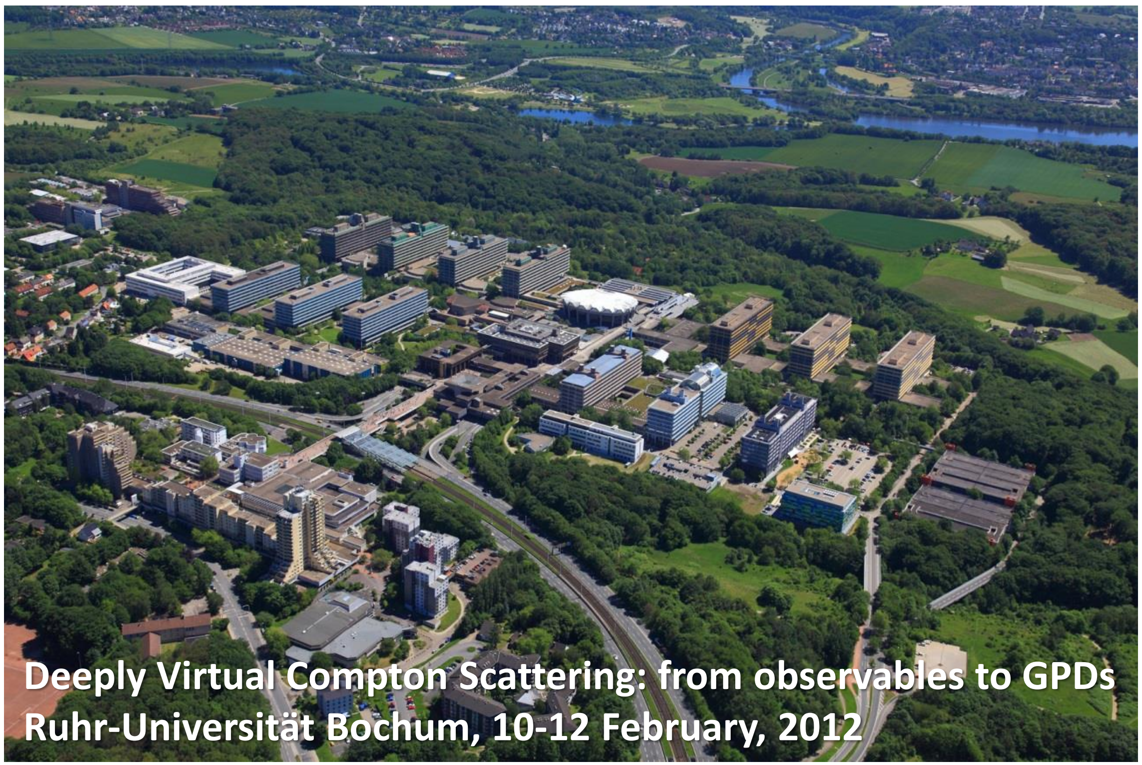
DVCS & DVMP measurements at COMPASS

DVCS and DVMP with LH2 target and Recoil detection

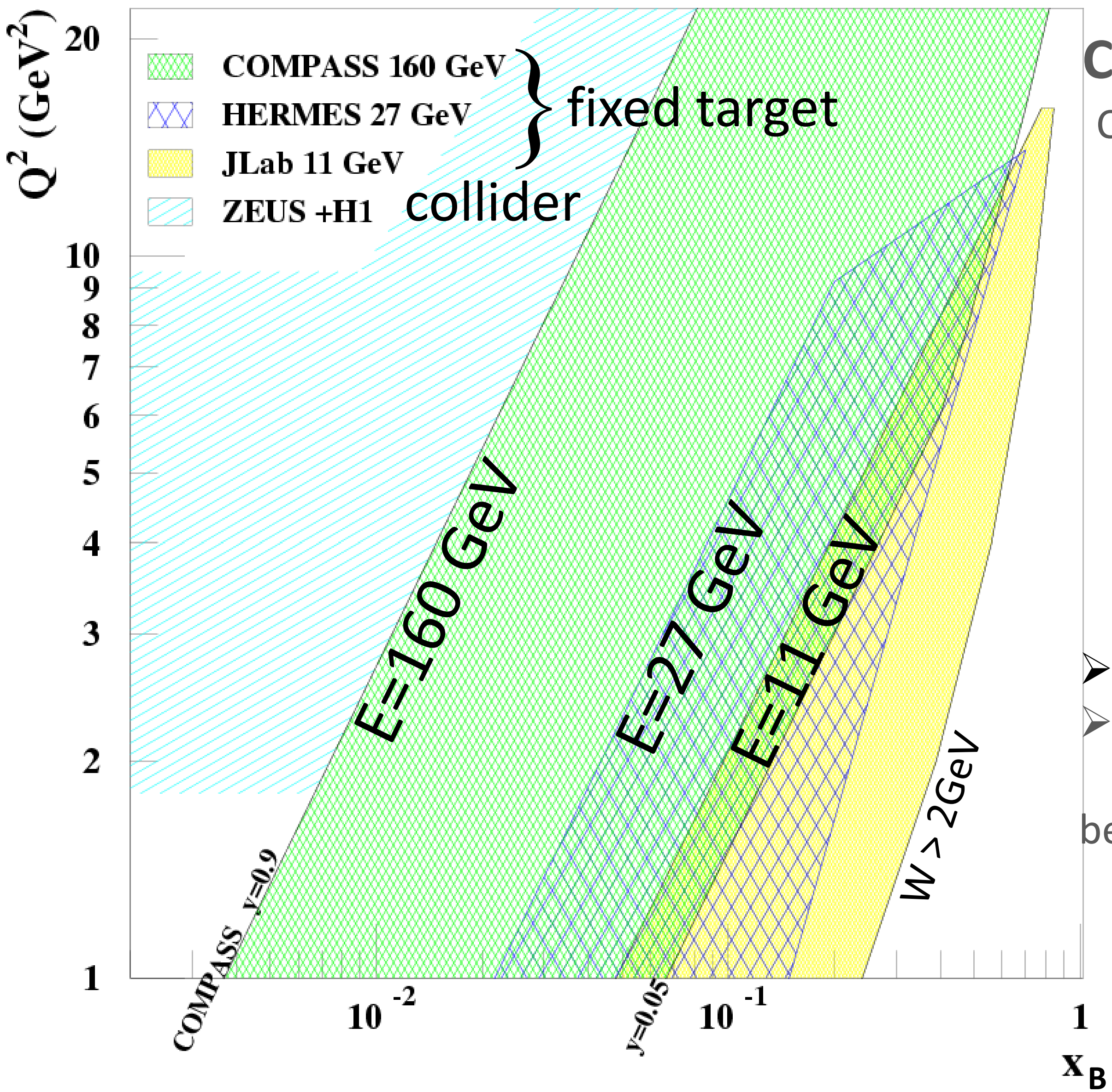
- pilot runs (2008-9 and 2012)
- 2 years (2016-17) - PLANNED MEASUREMENTS

Transverse target asymetries for exclusive ρ production (2007-10)
with polarized NH3 target without recoil detection - NEW RESULTS

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



Kinematic domain (Q^2, x_B) for GPDs



COMPASS assets for GPDs

CERN High energy muon beam

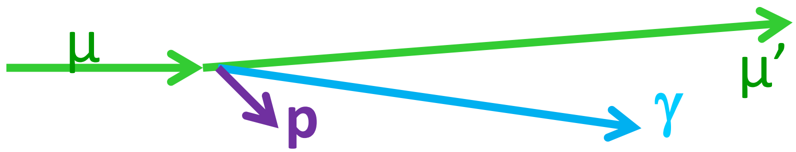
- ✓ 100 - 190 GeV
- ✓ **$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ available**
- ✓ 80% Polarisation with opposite polarization
- ✓ 4.6 10^8 μ^+ /spill

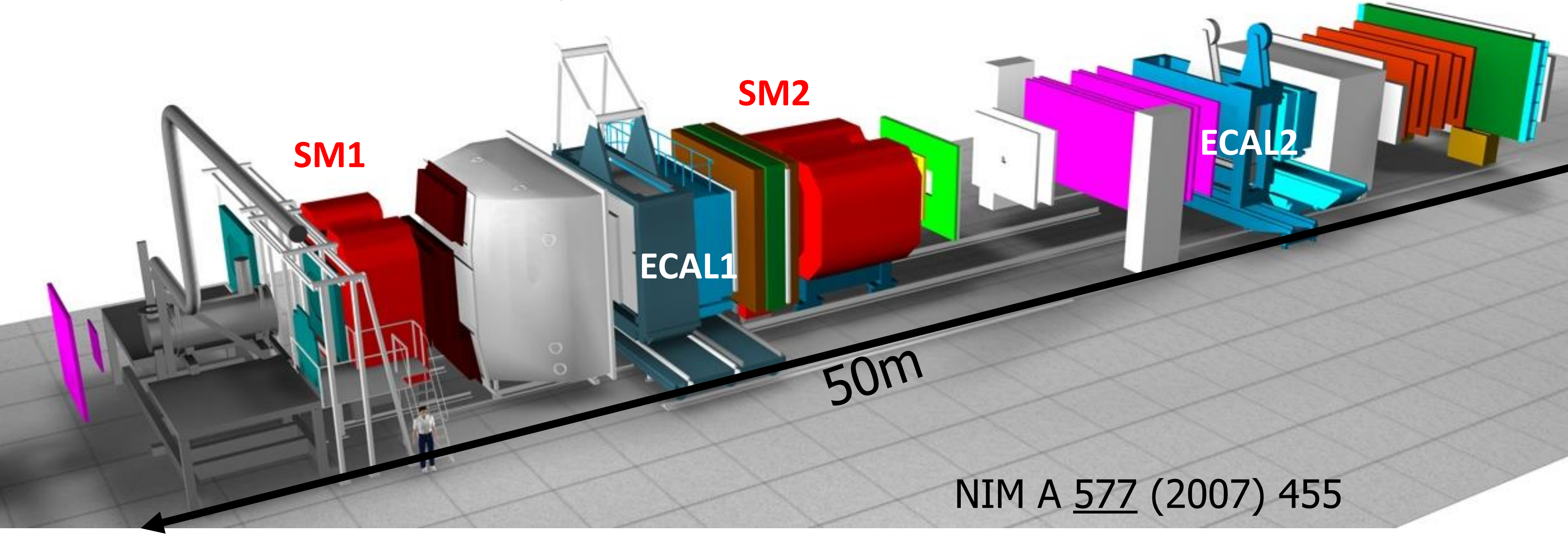
➔ Lumi= 10^{32} cm^{-2} s^{-1} with 2.5m LH2 target

- ➢ 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 : $\mu\ p \rightarrow \mu'\ p\ \gamma$





NIM A 577 (2007) 455

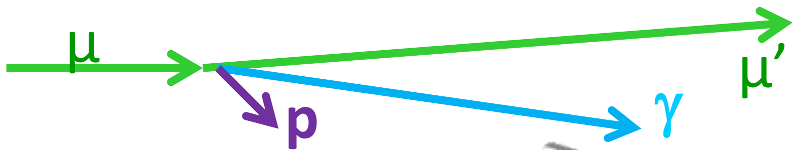
Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

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

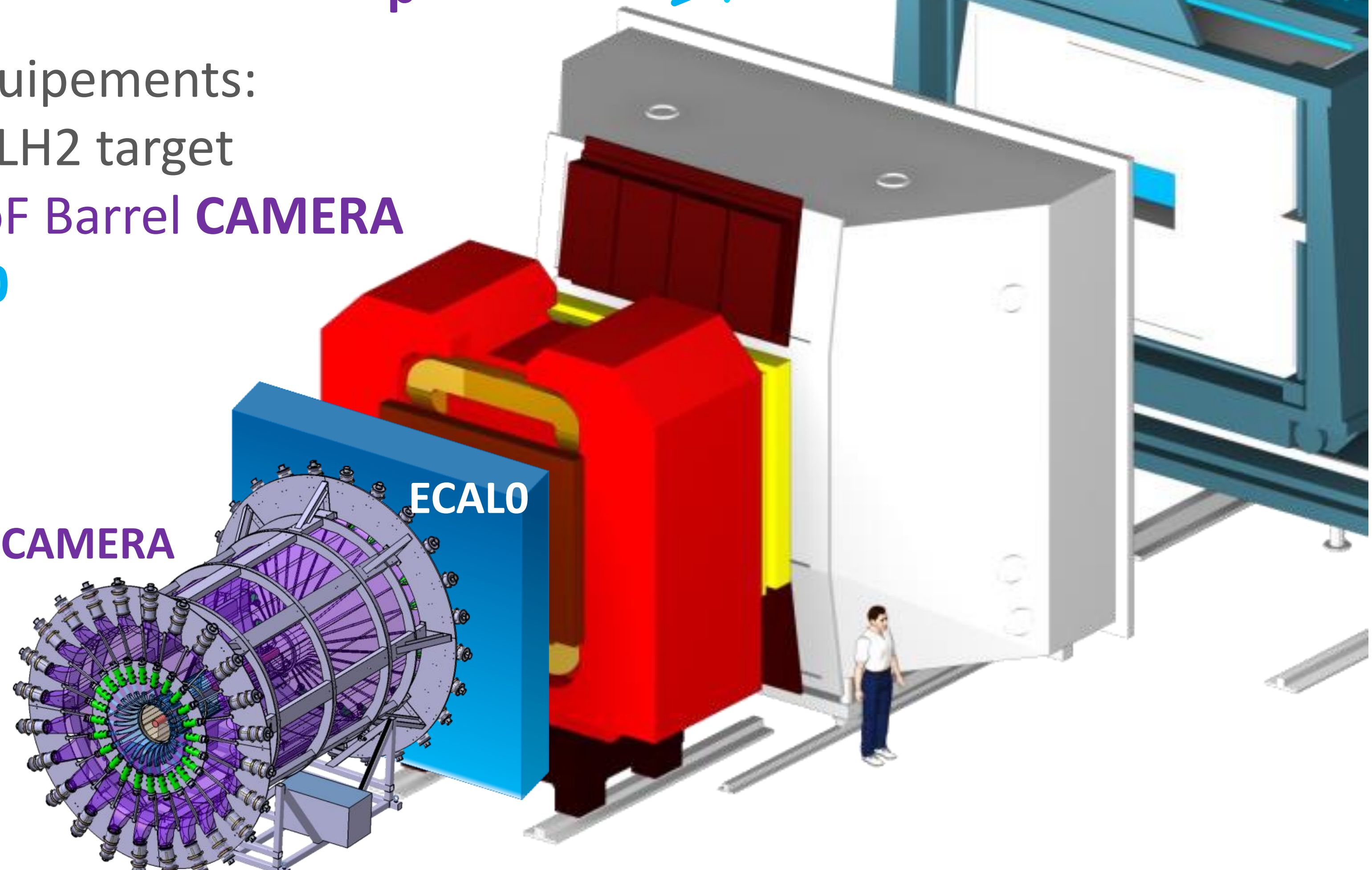
The DVCS experiment at COMPASS

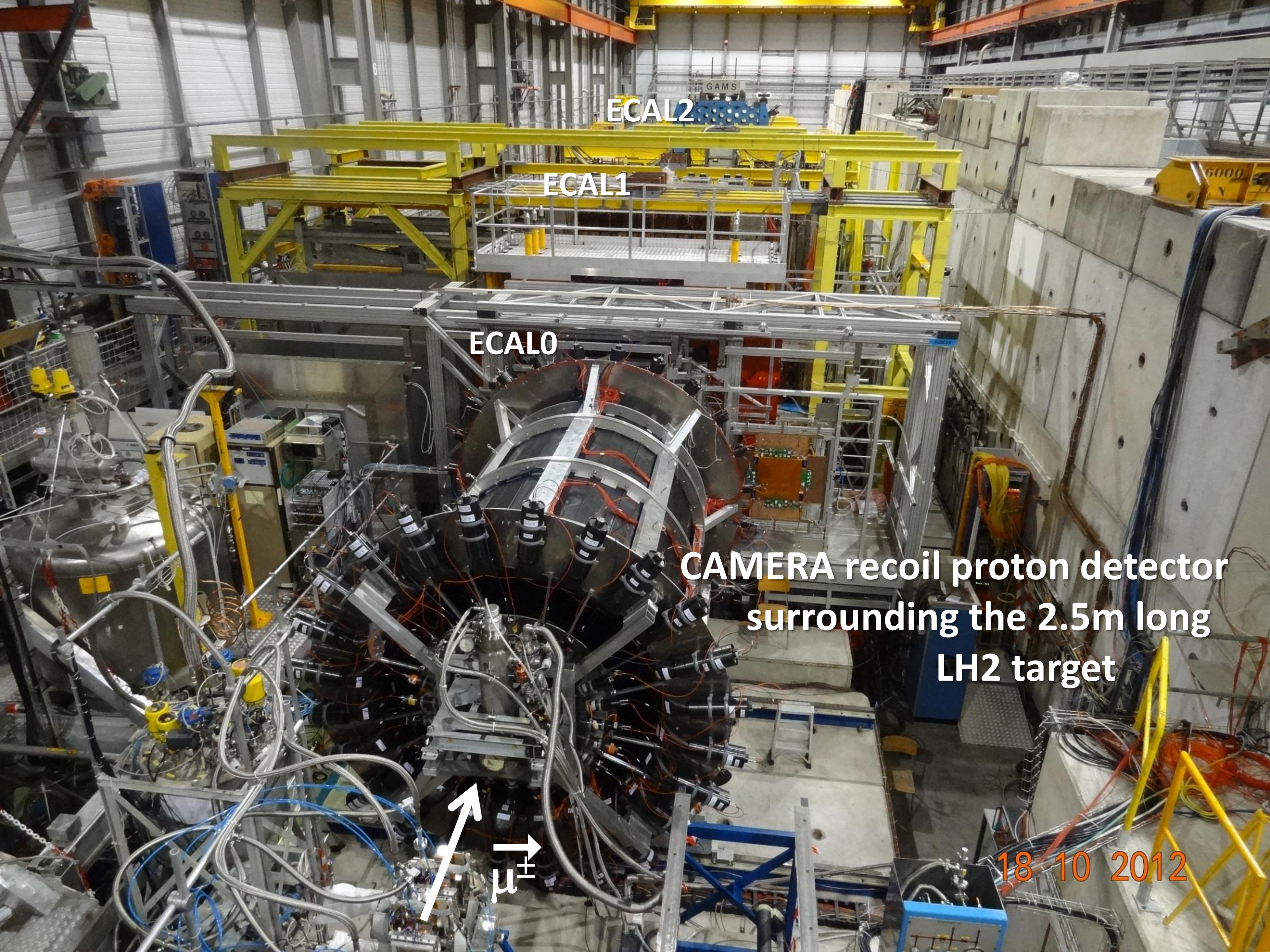
DVCS : $\mu \; p \rightarrow \mu' \; p \; \gamma$



New equipements:

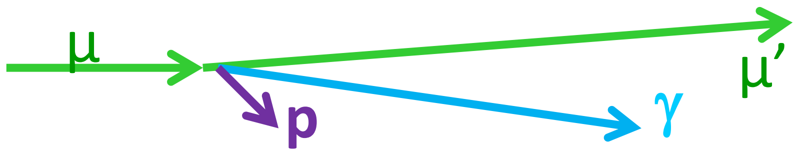
- 2.5m LH2 target
- 4m ToF Barrel **CAMERA**
- **ECAL0**




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

The experimental method to select DVCS

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



Comparison energy-momentum balance between Spectro and Recoil Detector

$P_{spectro} = P\mu - P\mu' - P\gamma$ and $P_{RPD} = Pp$

In the transverse plane: $\Delta p_{\perp} = |P^{\perp}_{spectro}| - |P^{\perp}_{RPD}|$

$\Delta\Phi = \Phi_{spectro} - \Phi_{RPD}$

$E_{miss} = E\mu - E\mu' - E\gamma - Ep$

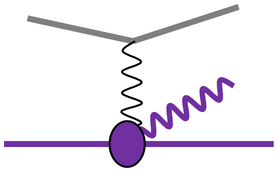
$M_{miss}^{2} = (P\mu - P\mu' - P\gamma - Pp)^{2}$

➔ a kinematical fit

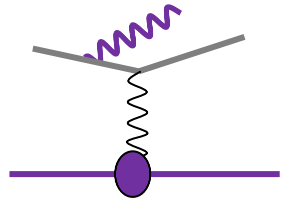
It is necessary to evaluate the maximum energy of a non identified radiative photon

- Real Radiative Corrections in $\ln(1/m_{lepton}^{2})$ ➔ corr(muon) $\sim$ ¼ corr(electron)
- Difference between μ^{+} and μ^{-} due to 2 photon exchange

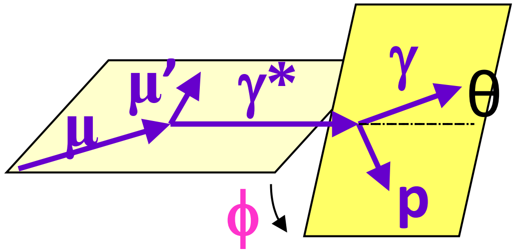
Contributions of DVCS and BH at E_μ=160 GeV



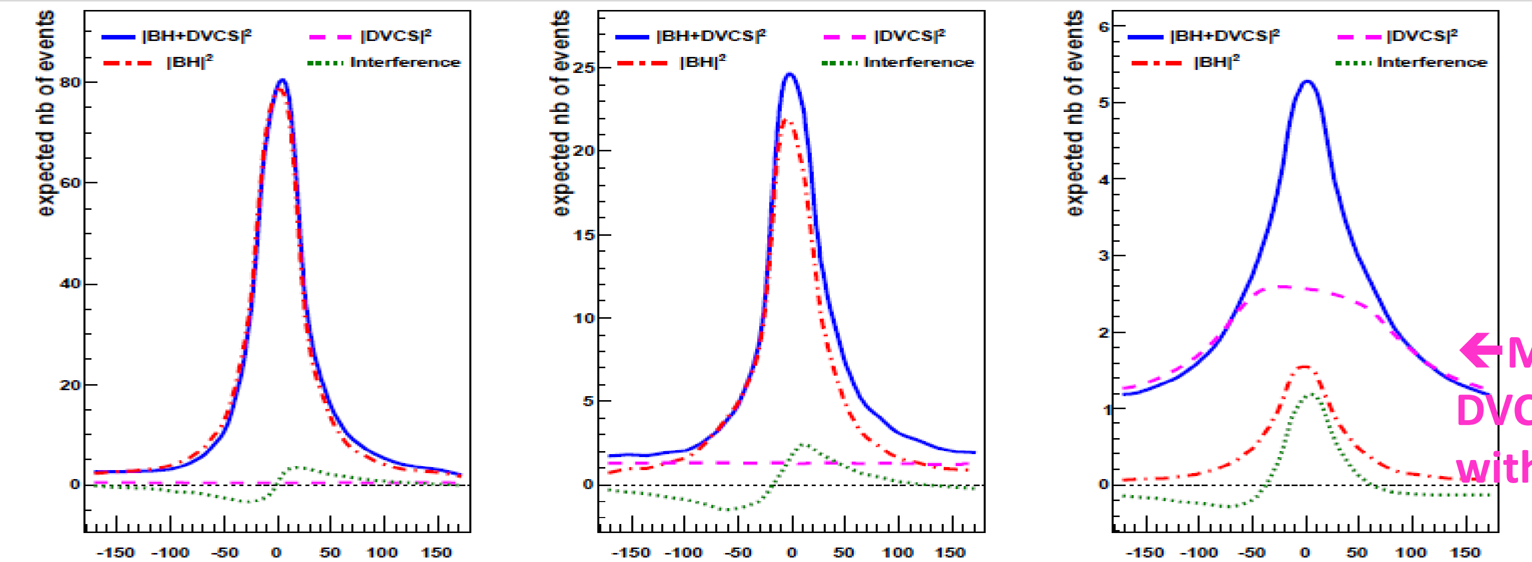
Deep VCS



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}

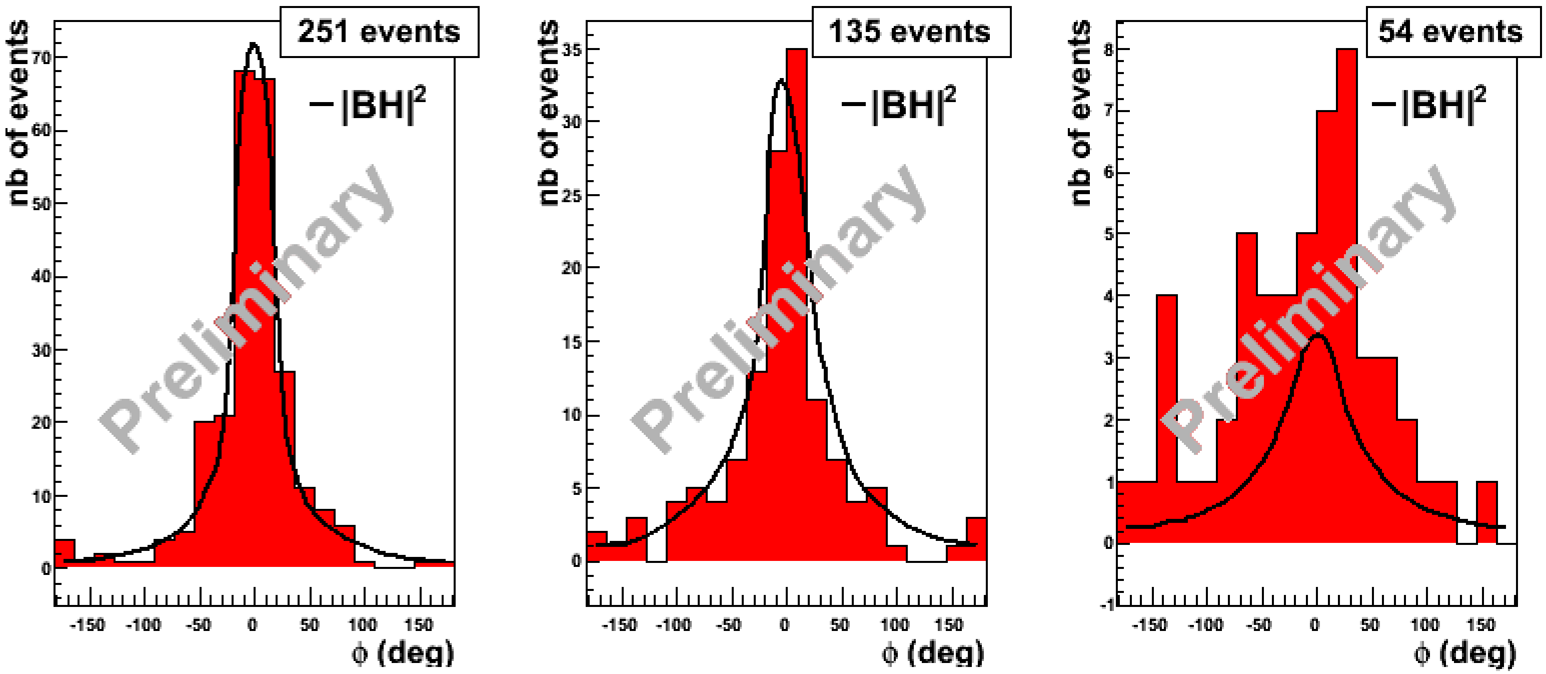
or Im T^{DVCS}

DVCS dominates

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

→ Transverse Imaging

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



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

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

× $(0.8)^4$ 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

Deeply Virtual Compton Scattering

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

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

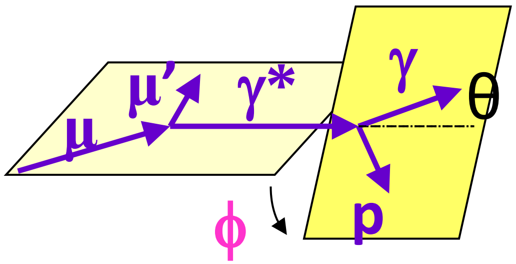
Charge & Spin Sum:

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

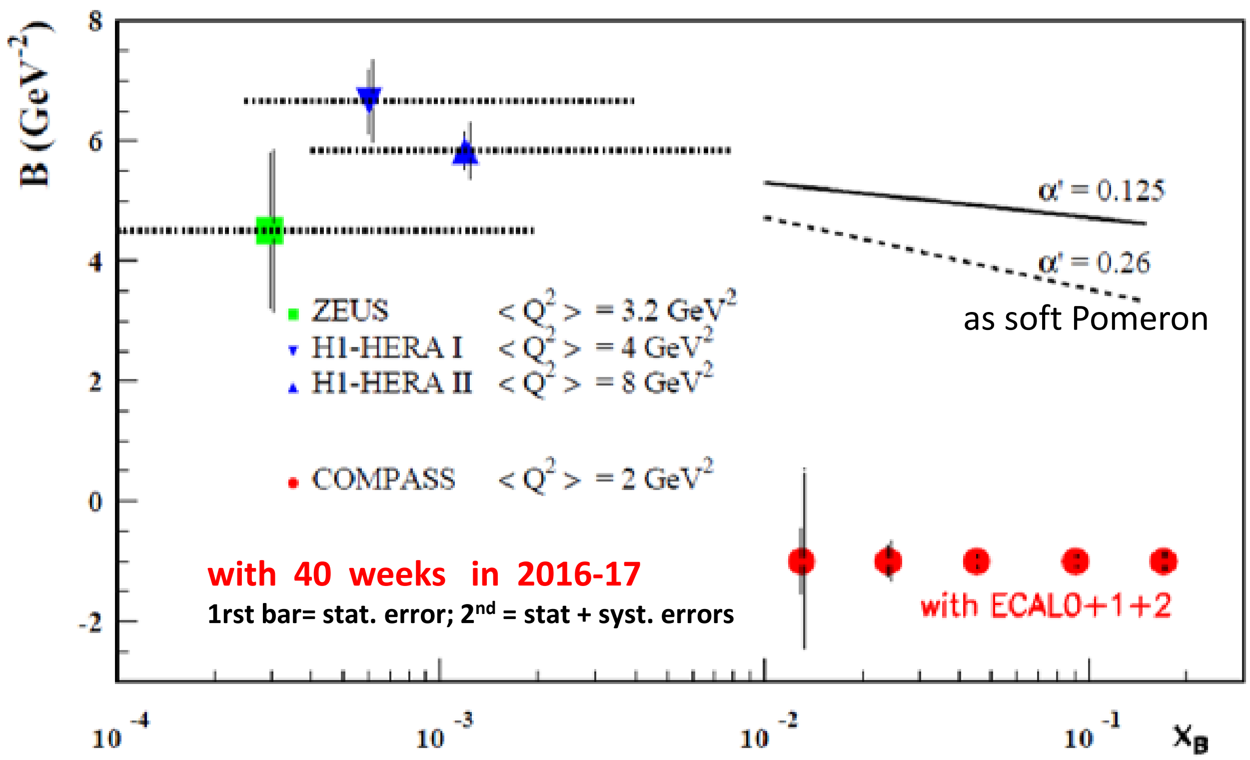
↓

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

Using $S_{CS,U}$ and BH subtraction and integration over ϕ

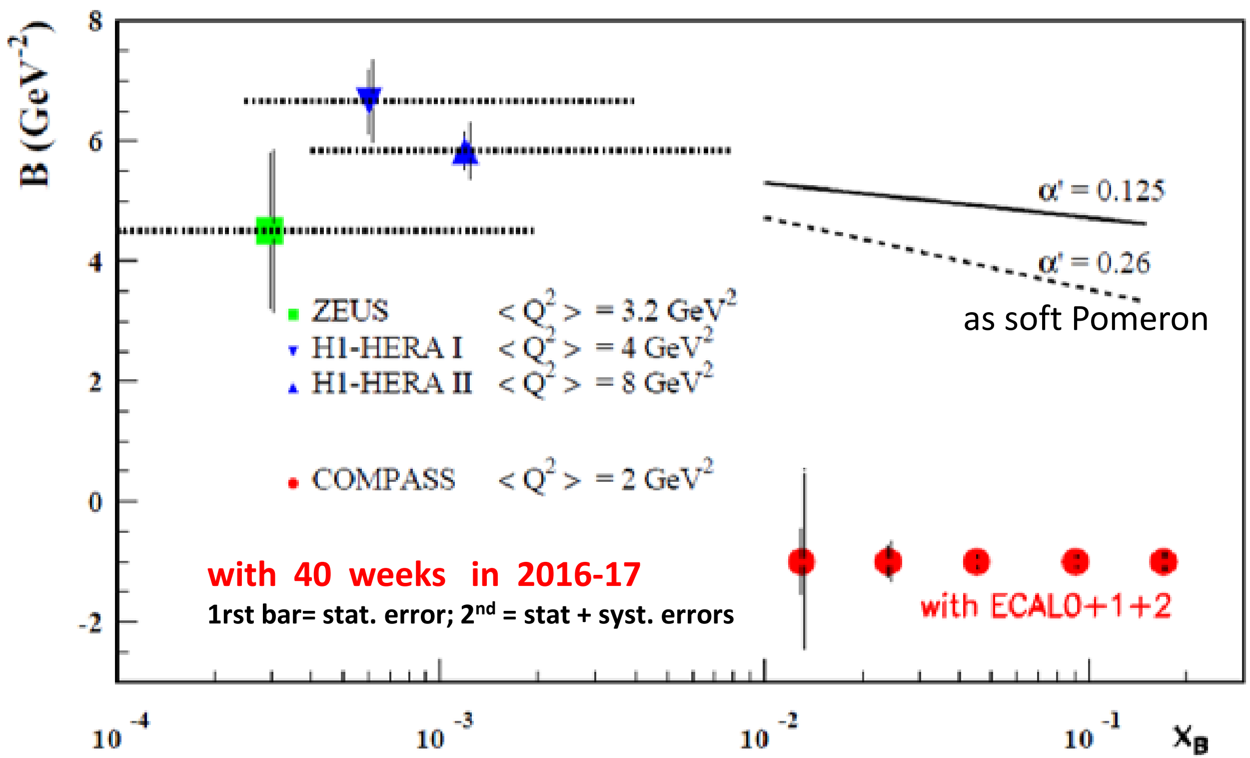


Transverse imaging at COMPASS
$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$



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

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



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

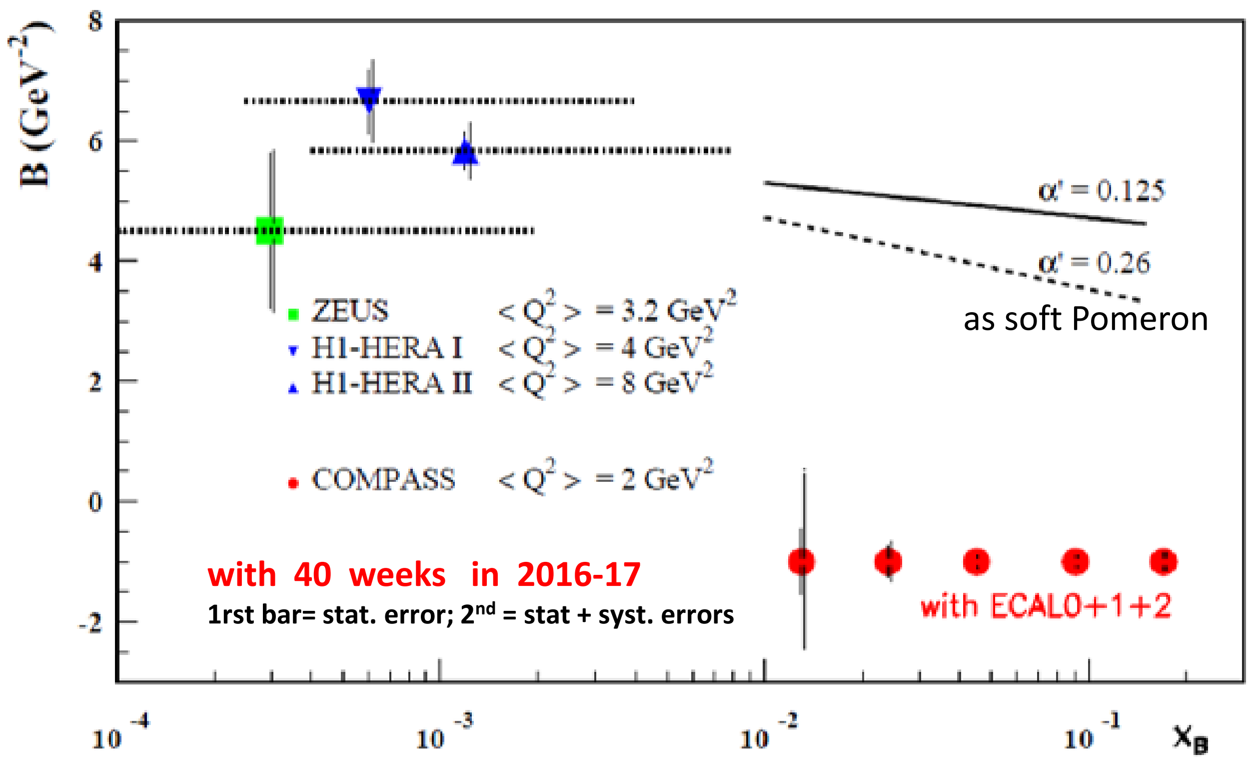
for valence quark $\alpha' \sim 1$ GeV^{-2} to reproduce FF $\cong$ meson Regge traj.

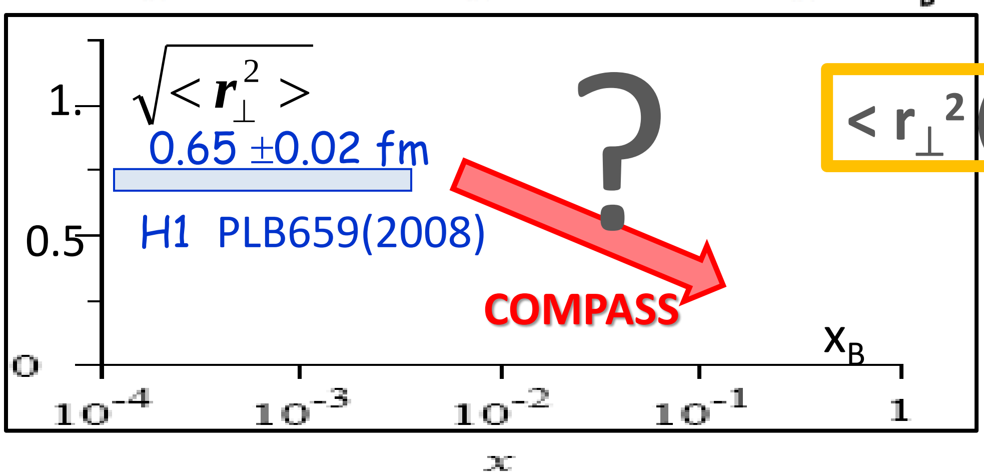
for gluon $\alpha' \sim 0.164$ GeV^{-2} (J/Ψ at Q^2=0)
$\alpha' \sim 0.02$ GeV^{-2} (J/Ψ at Q^2=2-80 GeV^2)

<< $\alpha' \sim 0.26$ GeV^{-2} for soft Pomeron

Transverse imaging at COMPASS

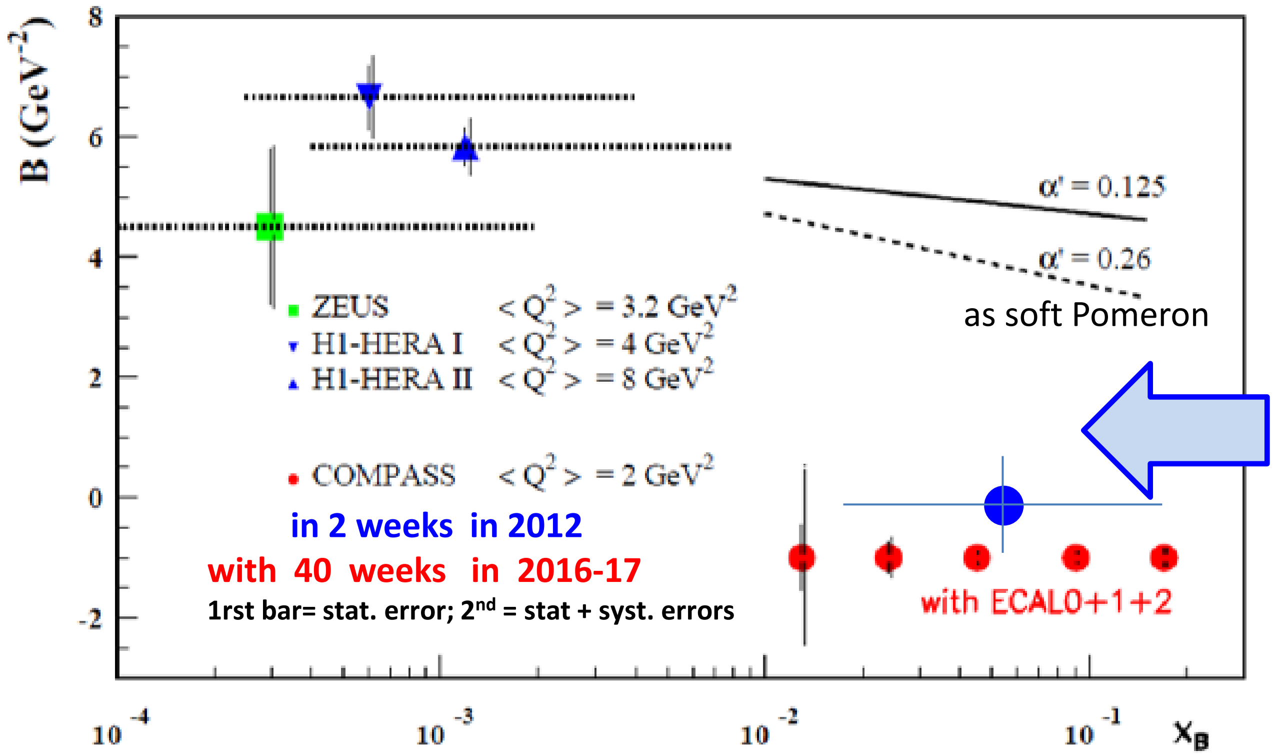
$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$





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

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



DVCS test in 2012

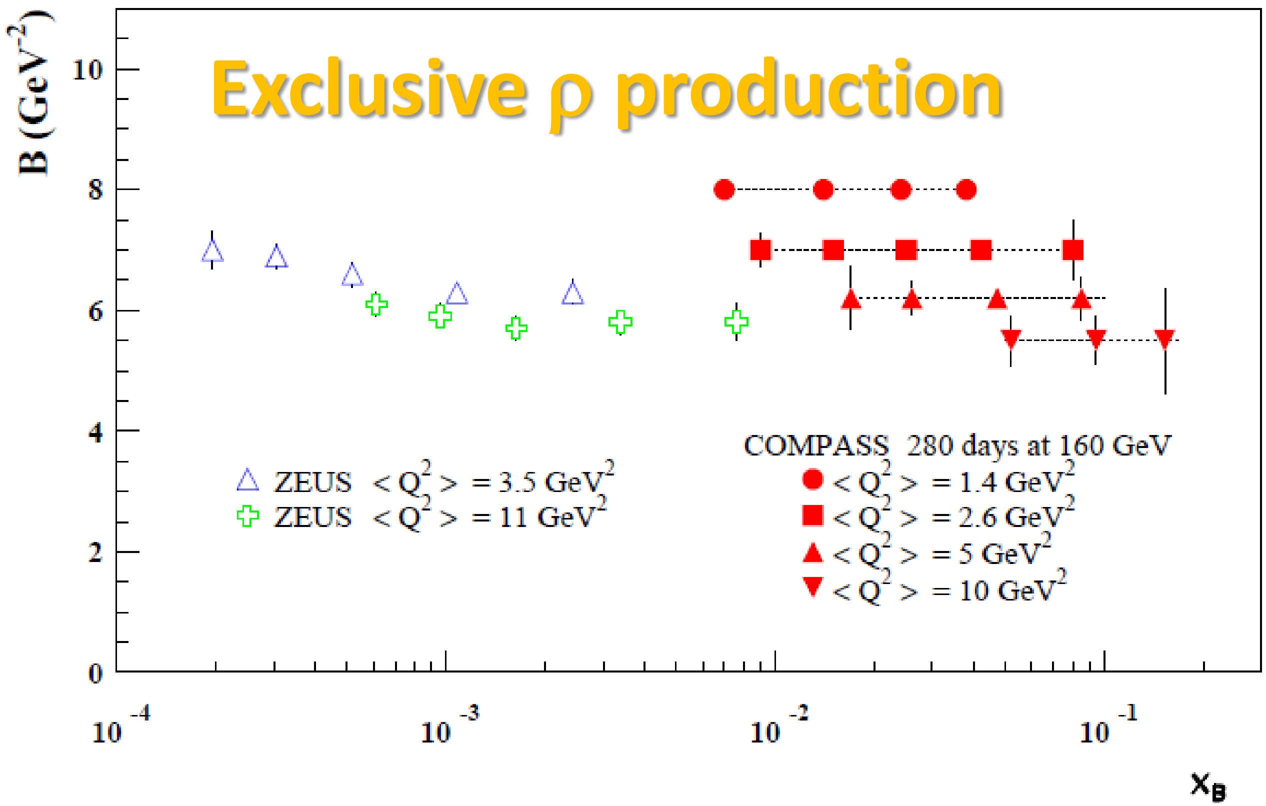
With 2 weeks
Using the 4m long RPD
+ the 2.5m long LH2 target

1/20 of the complete statistics

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

Transverse imaging at COMPASS

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

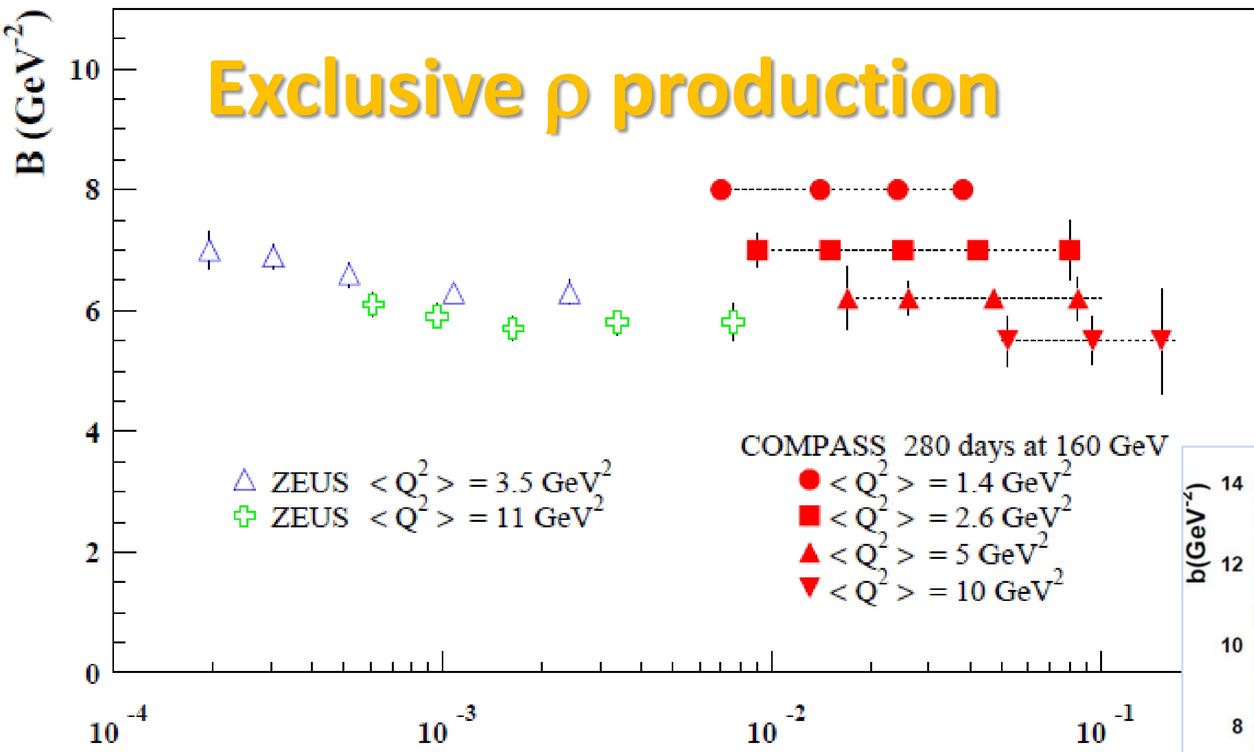


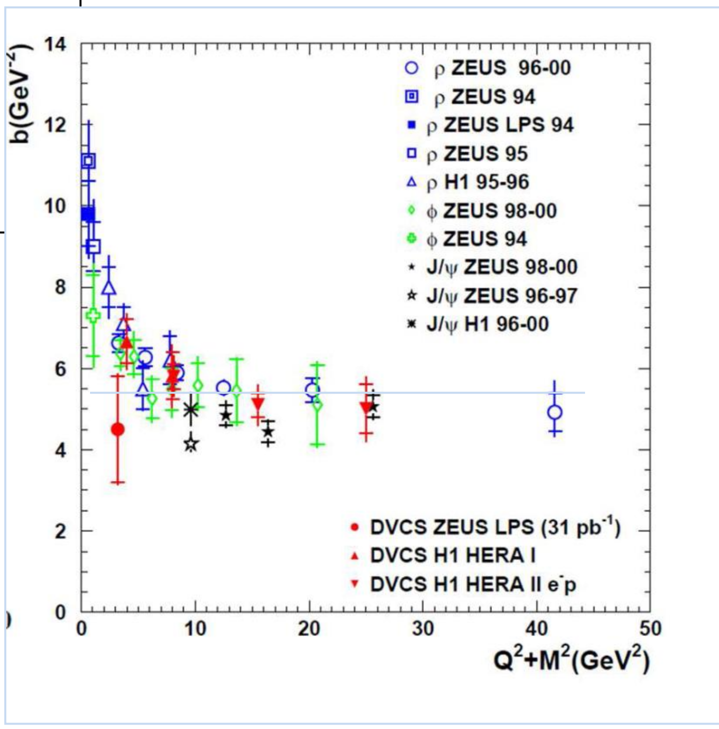
2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

model developed by Sandacz
renormalised according
Goloskokov and Kroll prediction

Transverse imaging at COMPASS

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





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

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:

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

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

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Charge & Spin Difference and Sum:

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

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

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)

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

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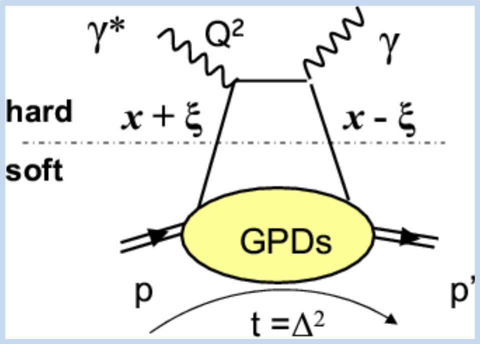
$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int} \sin\phi \quad \text{and} \quad s_1^{Int} \sim F_1\, \mathcal{Im}\, \mathcal{H}$$



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

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

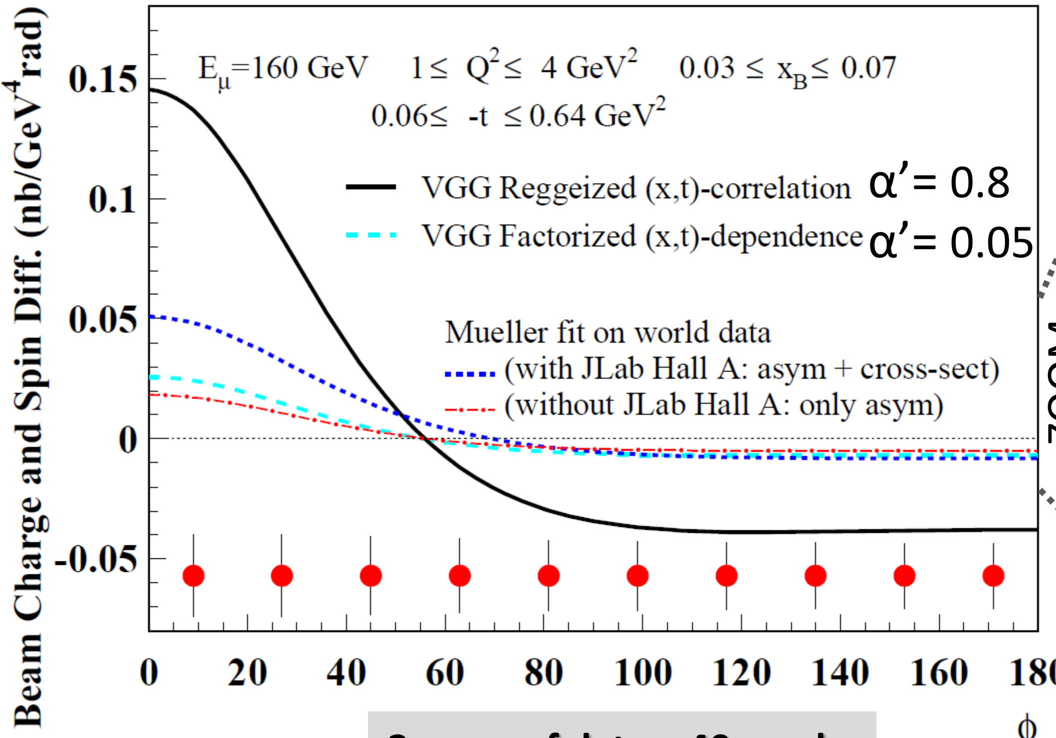
$$\mathcal{Re}\, \mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{H(x,\xi,t)}{x-\xi} = \mathcal{P}\int dx\, \frac{H(x,x,t)}{x-\xi} + \mathcal{D}(t)$$

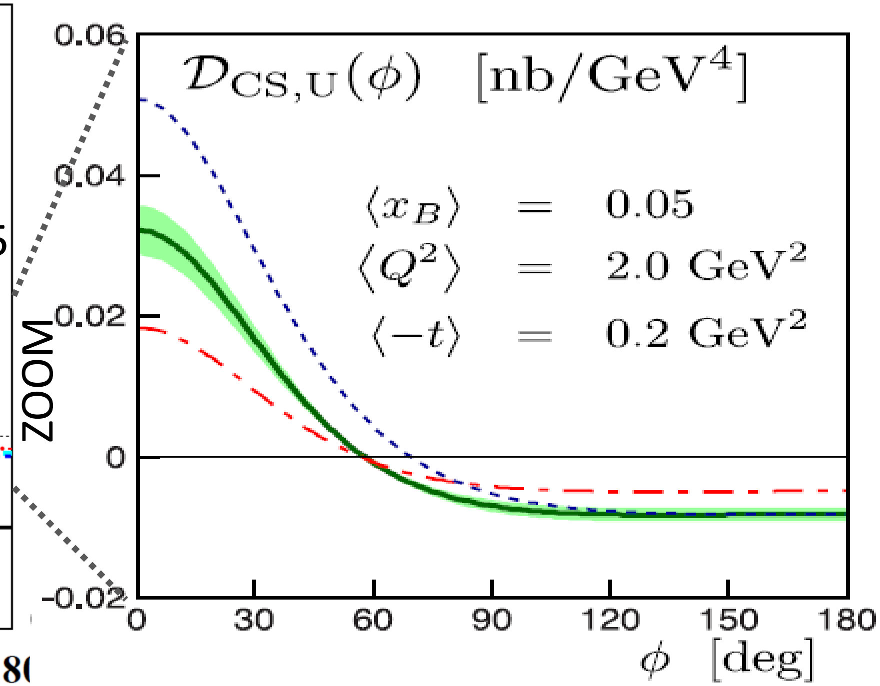
Re part of the *Compton Form Factors* linked to the *D term*

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

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

Comparison to different models





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

Kroll, Moutarde, Sabatié
EPJC 73 (2013) 2278

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

Statistics and Systematics

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

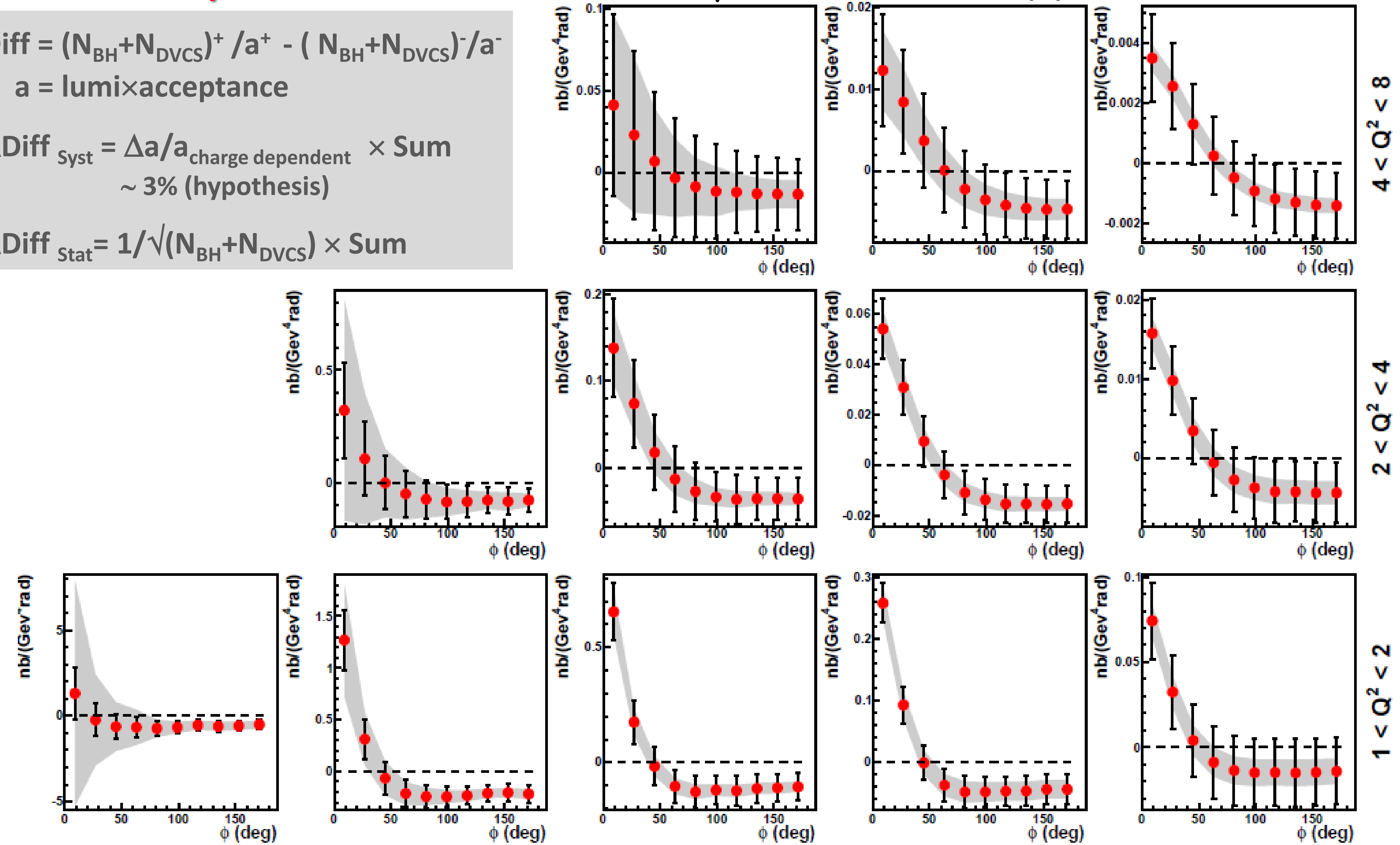
a = lumi×acceptance

$$\Delta\text{Diff}_{Syst} = \Delta a/a_{\text{charge dependent}} \times \text{Sum}$$

~ 3% (hypothesis)

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

Eμ= 160 GeV 0.06 < |t| < 0.64 GeV²

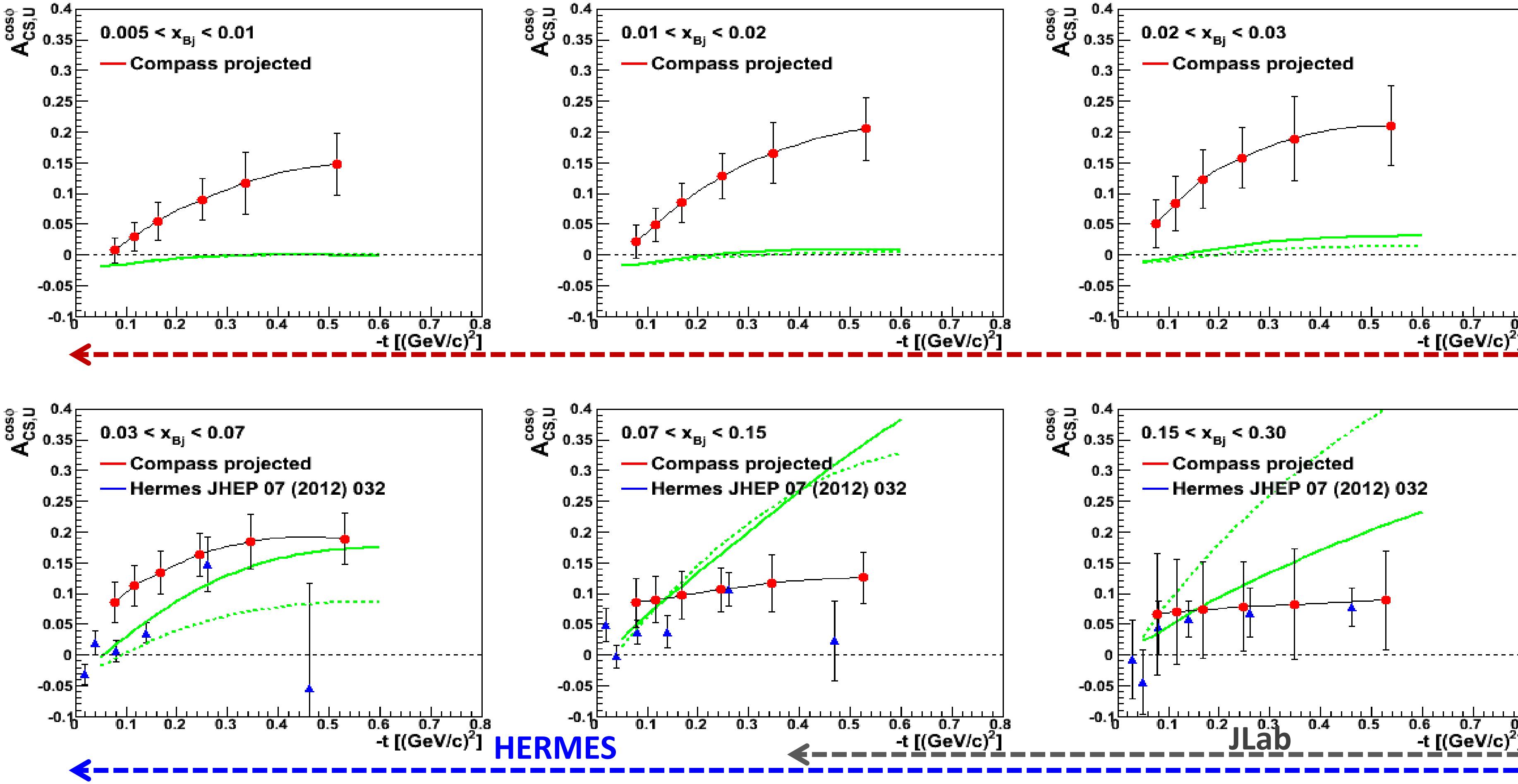


$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int} \cos\phi$ and $c_{0,1}^{Int} \sim F_1 \, \mathcal{Re}\,\mathcal{H}$

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

Predictions with
VGG and **D.Mueller**

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

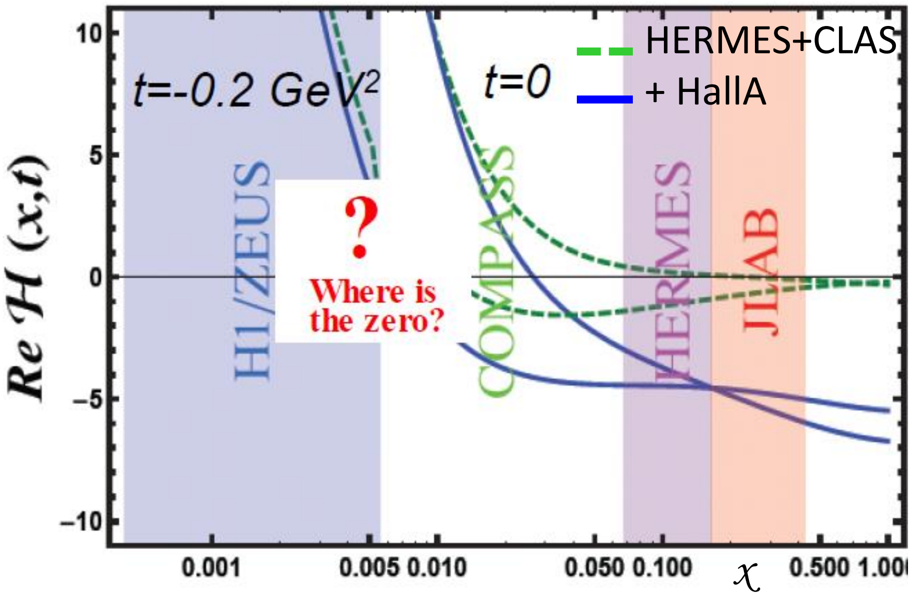


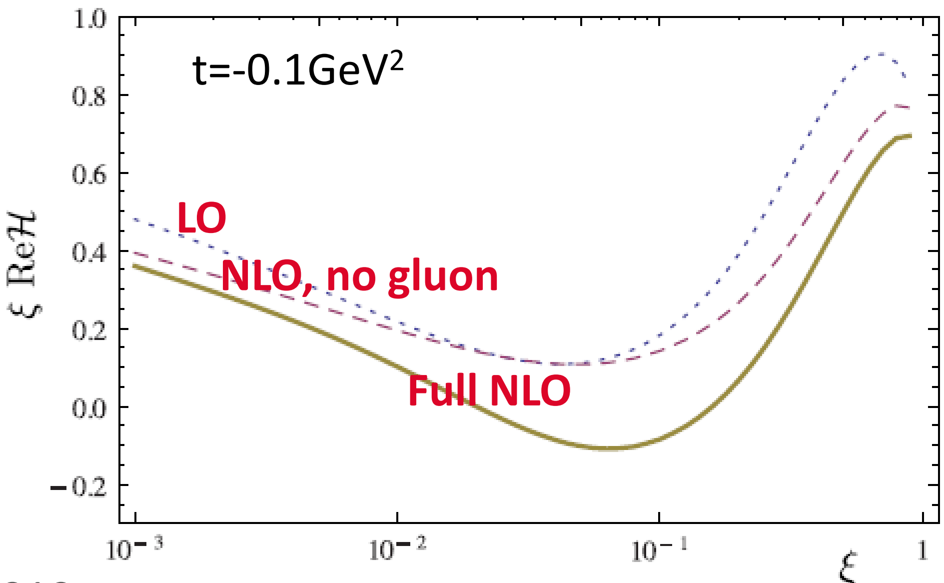
COMPASS 2 years of data E_μ = 160 GeV 1 < Q^2 < 8 GeV^2 with ECAL2 + ECAL1 + ECAL0

Impact of DVCS @ COMPASS in global analysis ?

Beam Spin and Charge Diff. and Sum (Cross section measurement)
dominance of $\mathcal{H}$ on a proton target at COMPASS

Sensitivity to the $Re\,\mathcal{H}$ linked to the $\mathcal{D}$ term





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

- Moutarde, Pire, Sabatié, Szymanowski, Wagner,PRD87(2013) 054029, 15p

beyond the dominant GPD H

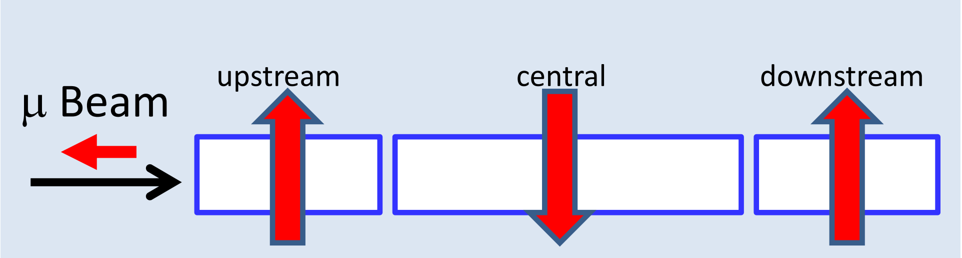
DVCS but also exclusive meson productions:

- ✓ Pseudo scalar mesons: π^0 (channel associated to DVCS), π^+...
- ✓ Vector mesons: **ρ^0**, ρ^+, ω , Φ ...

with transversely polarized protons (NH3 target)

1) without recoil detection (2007 & 10)

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

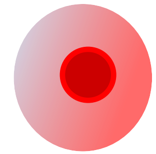


3 target cells

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

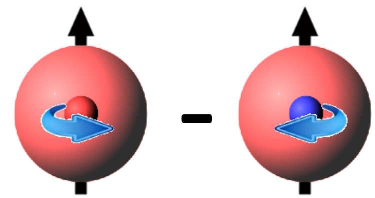
Chiral-even

$H \leftrightarrow q$



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

"Elusive" $E \leftrightarrow f^\perp_{1T}$



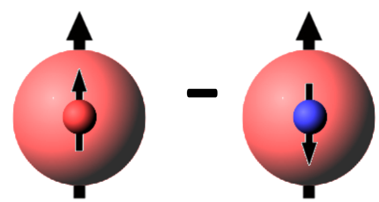
Sivers: quark k_T
& nucleon transv. Spin

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

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

Chiral-odd

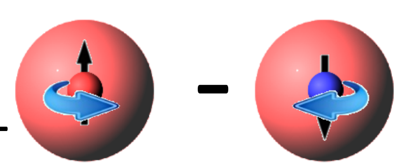
$H_T \leftrightarrow h_1$



Transversity: quark spin
& nucleon transv. spin

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

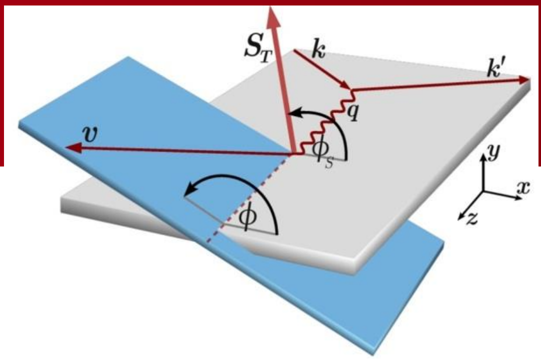
$\bar{E}_T = 2\tilde{H}_T + E_T \leftrightarrow h^\perp_1$



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



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

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

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

transv. polar. target

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

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

transv. polar. target + long. Polar. beam

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

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

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

Dominant interference terms:

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

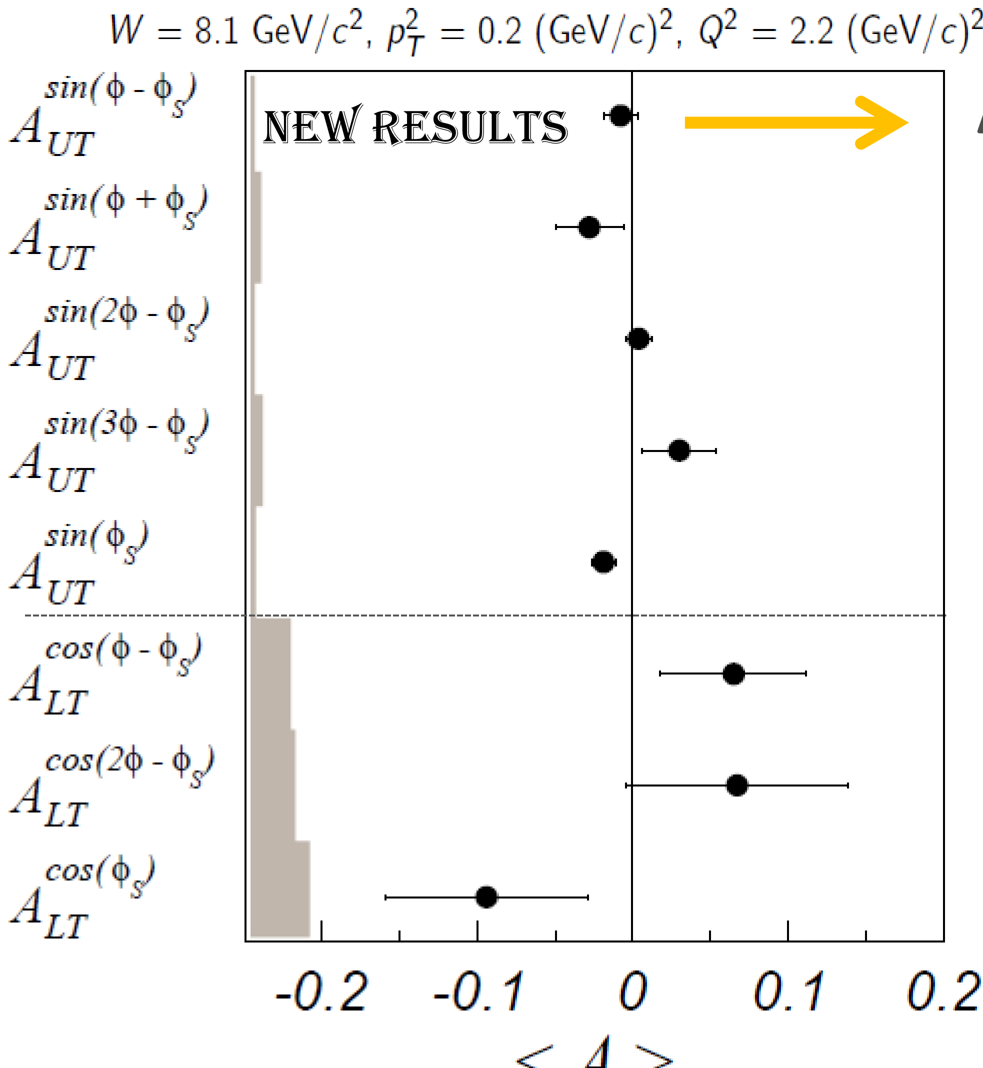
then LT $\gamma^*_T \rightarrow \rho^0_L$

exclusive ρ^0 production with Transv. Polar. Target

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

$\hookrightarrow \pi^+\pi^-$

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 and **$E^{u\ val} \sim -E^{d\ val}$**

COMPASS, NPB865 (2012) 1-20

ω production very interesting

analysis on going

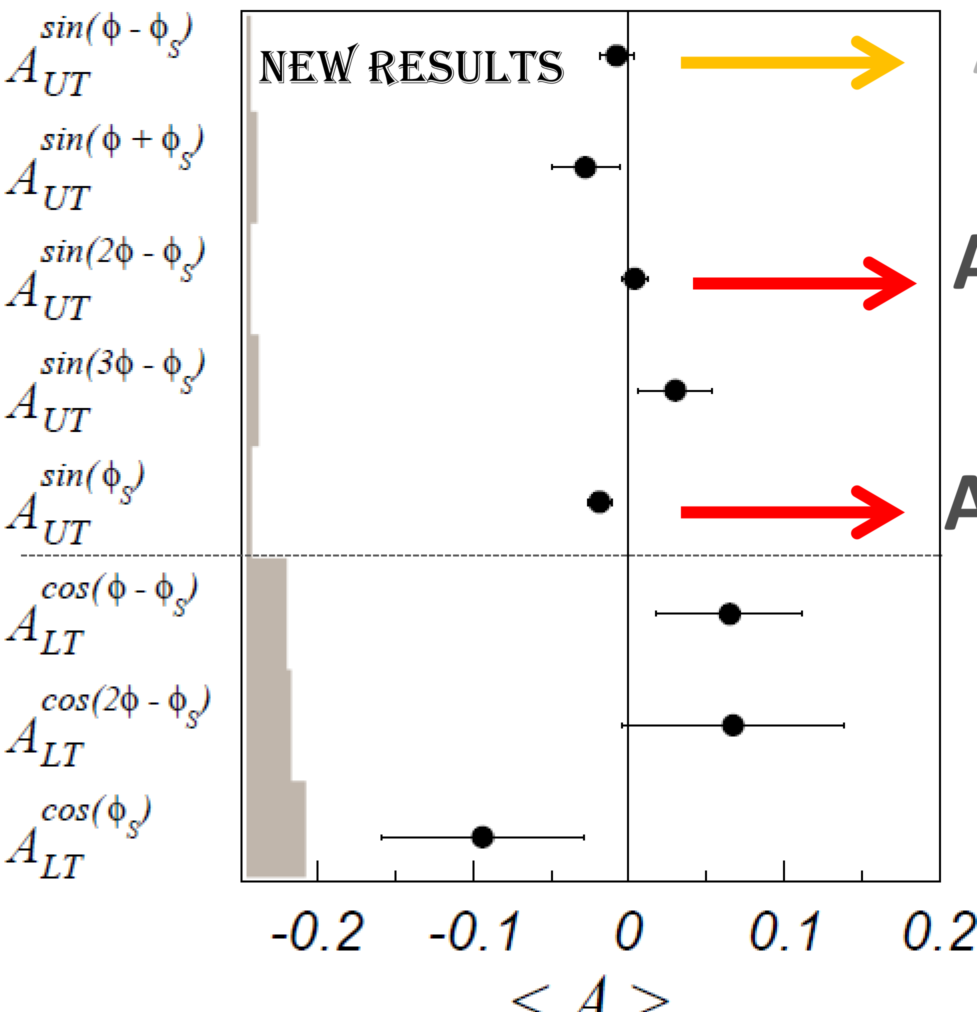
exclusive ρ^0 production with Transv. Polar. Target

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

$\hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,without recoil detector

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



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

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

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

➔ H_T **should not be small**

Publication accepted in PLB (4 Feb 2014)

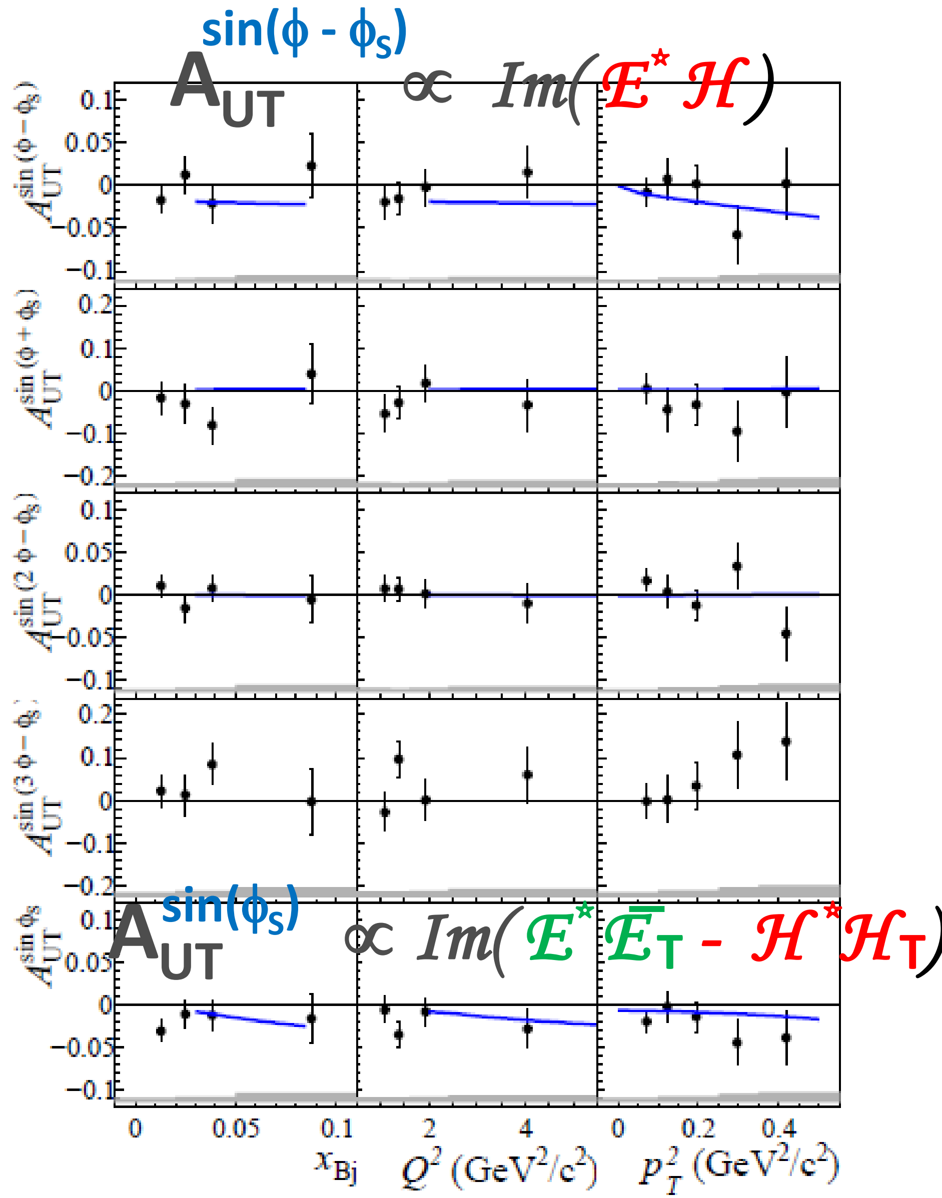
exclusive ρ^0 production with Transv. Polar. Target

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

Publication accepted in PLB (4 Feb 2014)

Curves from:
Goloskokov, Kroll, accepted for EPJ (Dec 2013)

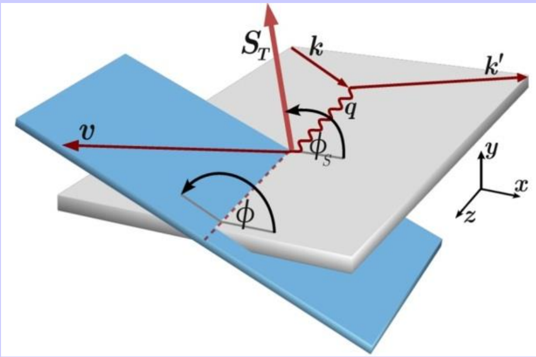
COMPASS 2007-2010,without recoil detector



Plan for DVCS after 2018 with Transv. Polarized target

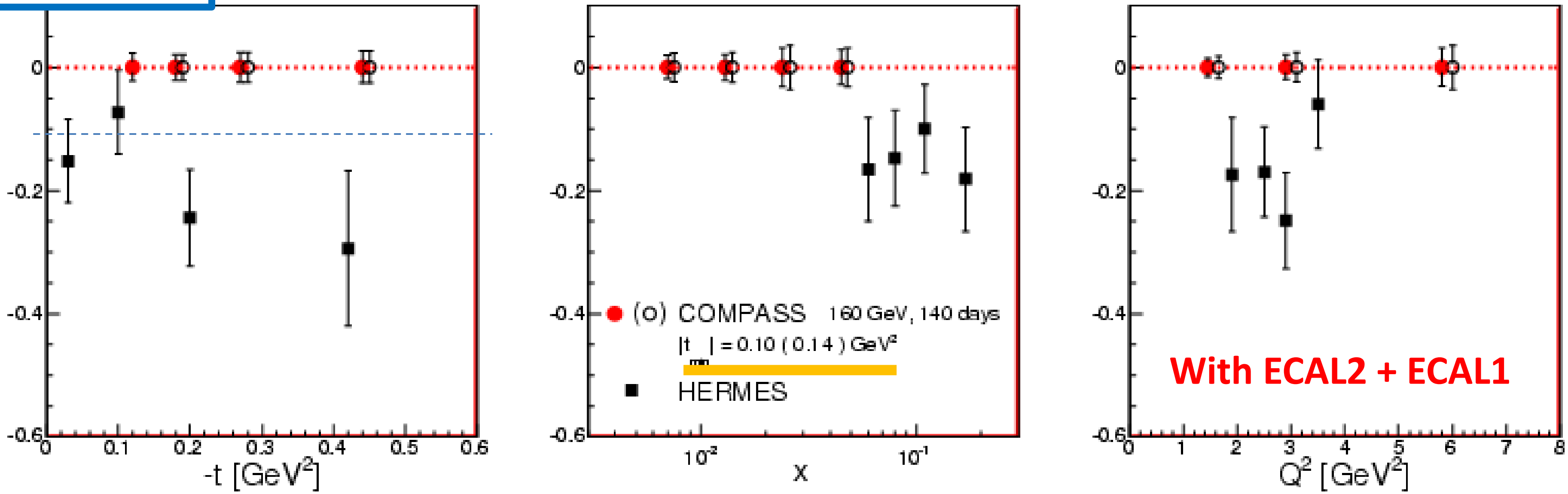
with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam and **transversely** polarized NH3 (proton) target

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



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

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



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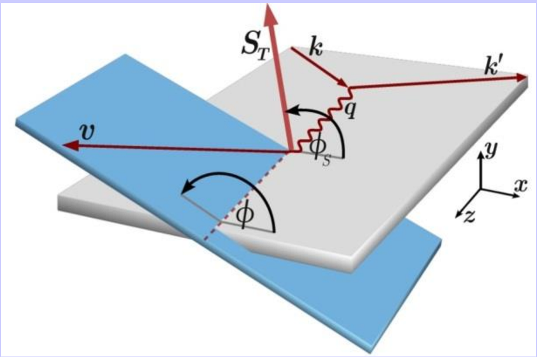

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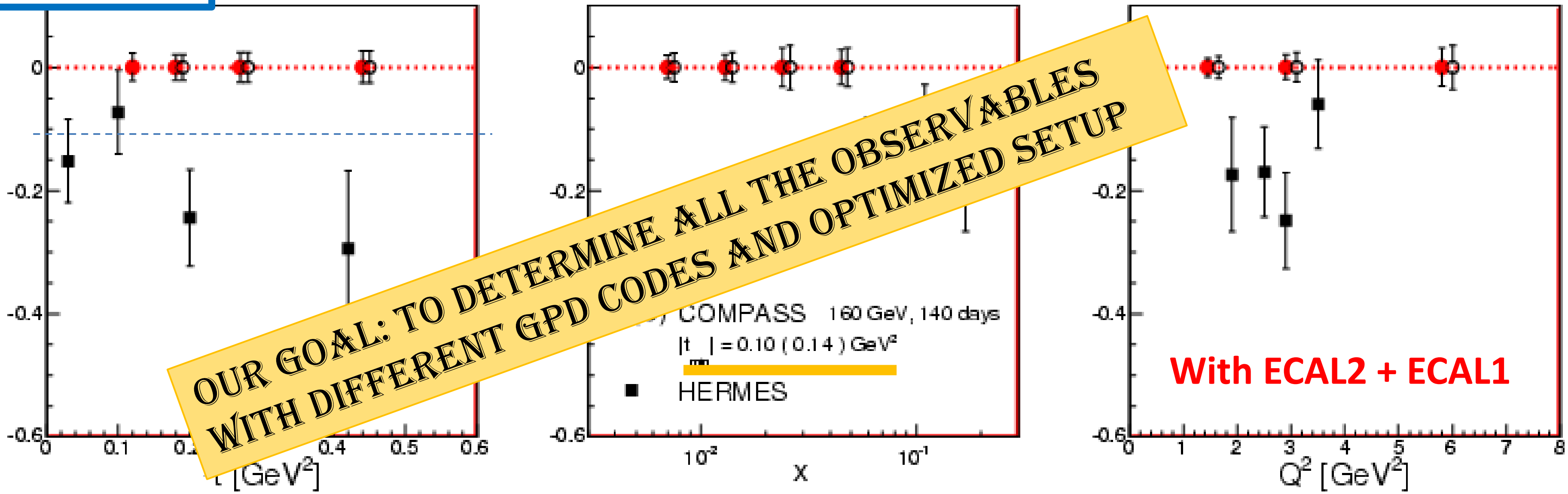
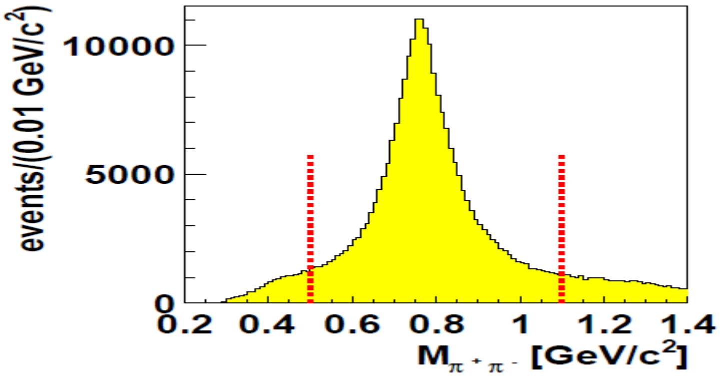
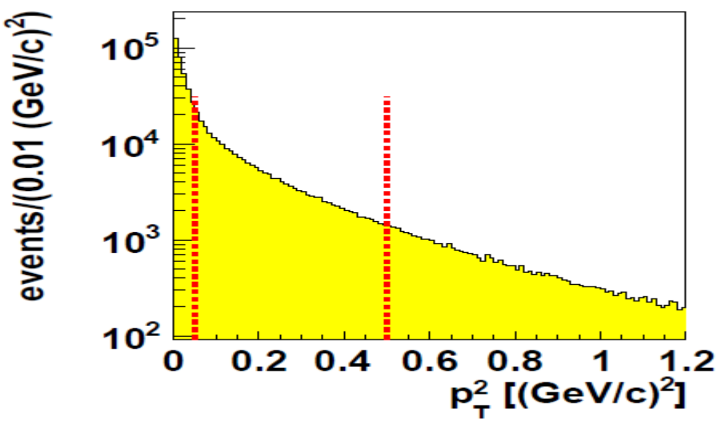
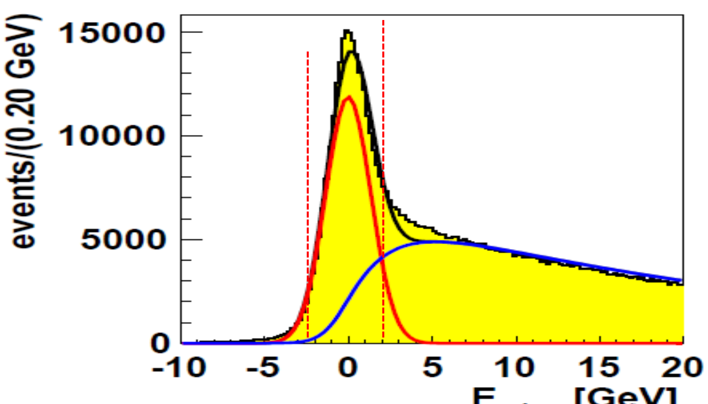


Selection of Exclusive ρ° Production: μ p → μ' ρ° p

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 $\rho°$ / 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)

NEW ANALYSIS

Bins in **Φ** and **Φ_S**

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

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 $H(x, \xi=x, t)$

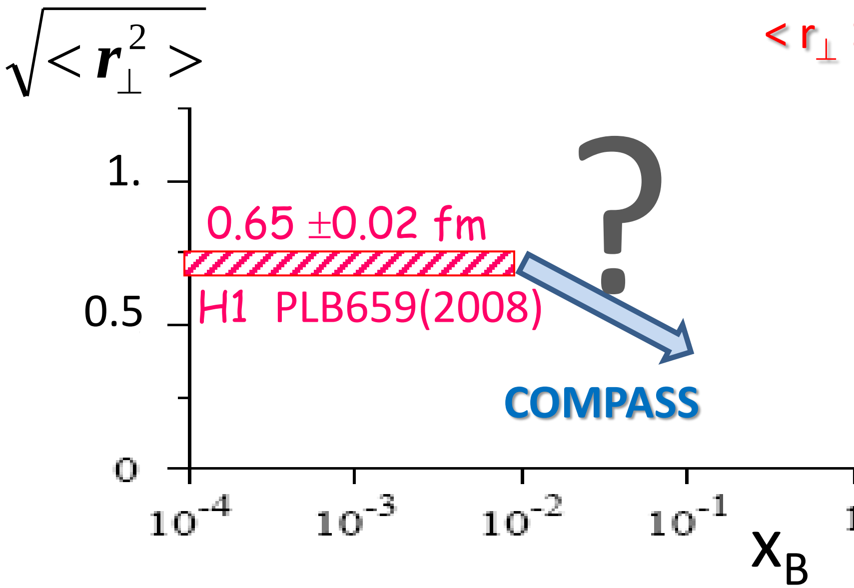
related to $½ < b_\perp^2(x_B) >$

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

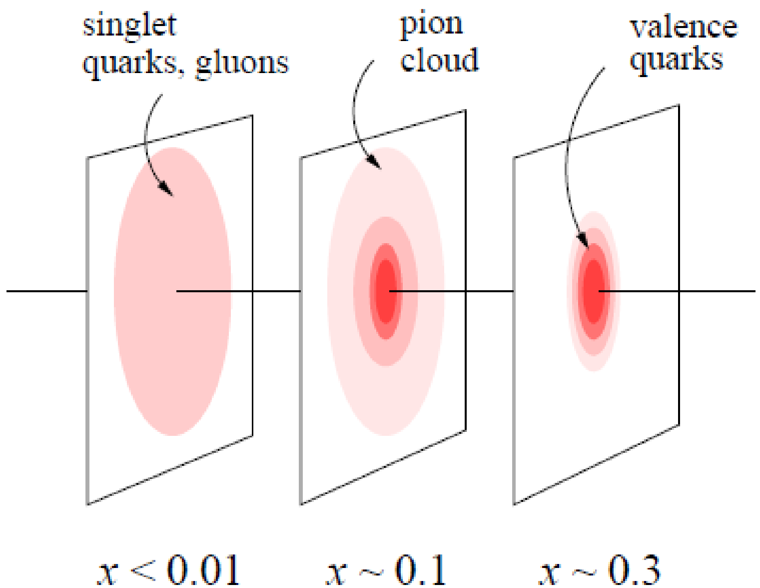
Impact Parameter Representation

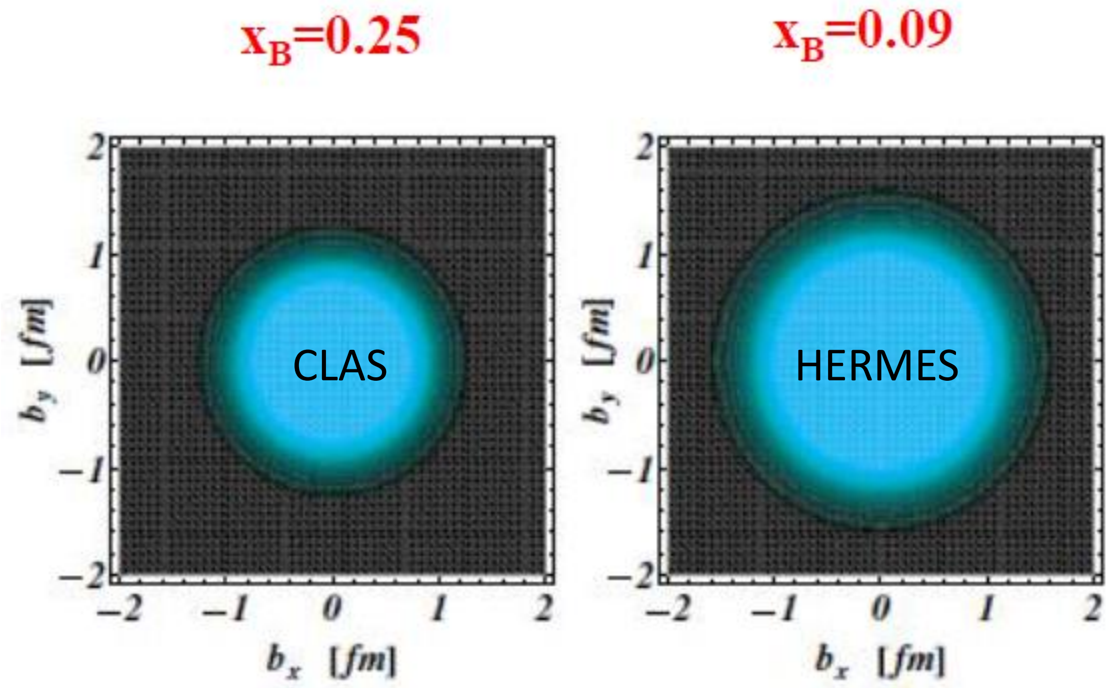
$q(x, b_\perp) \leftrightarrow H(x, \xi=0, t)$

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

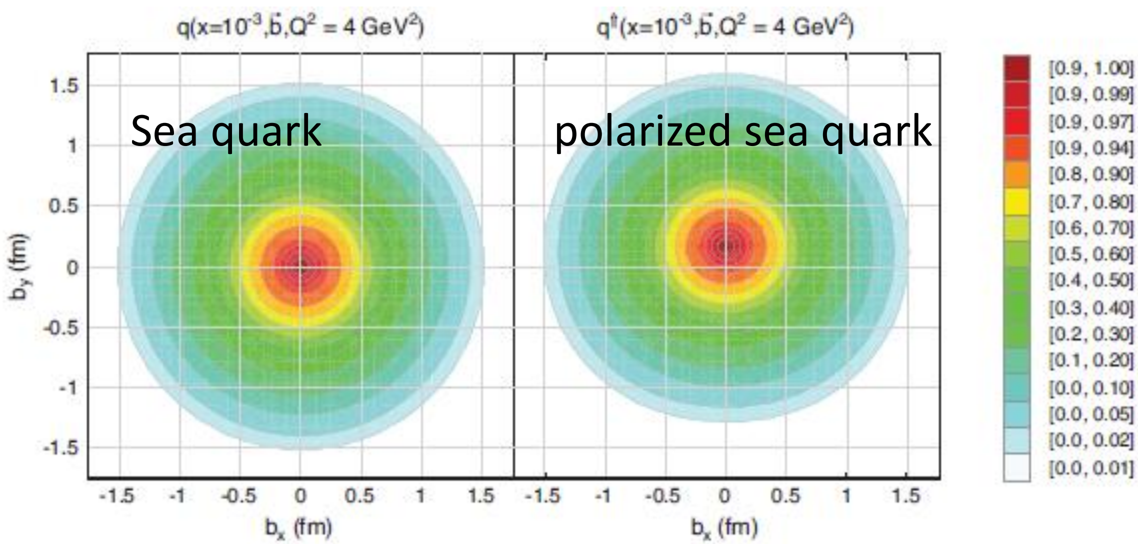


Note 0.65 fm = $\sqrt{2/3} \times 0.8$ fm

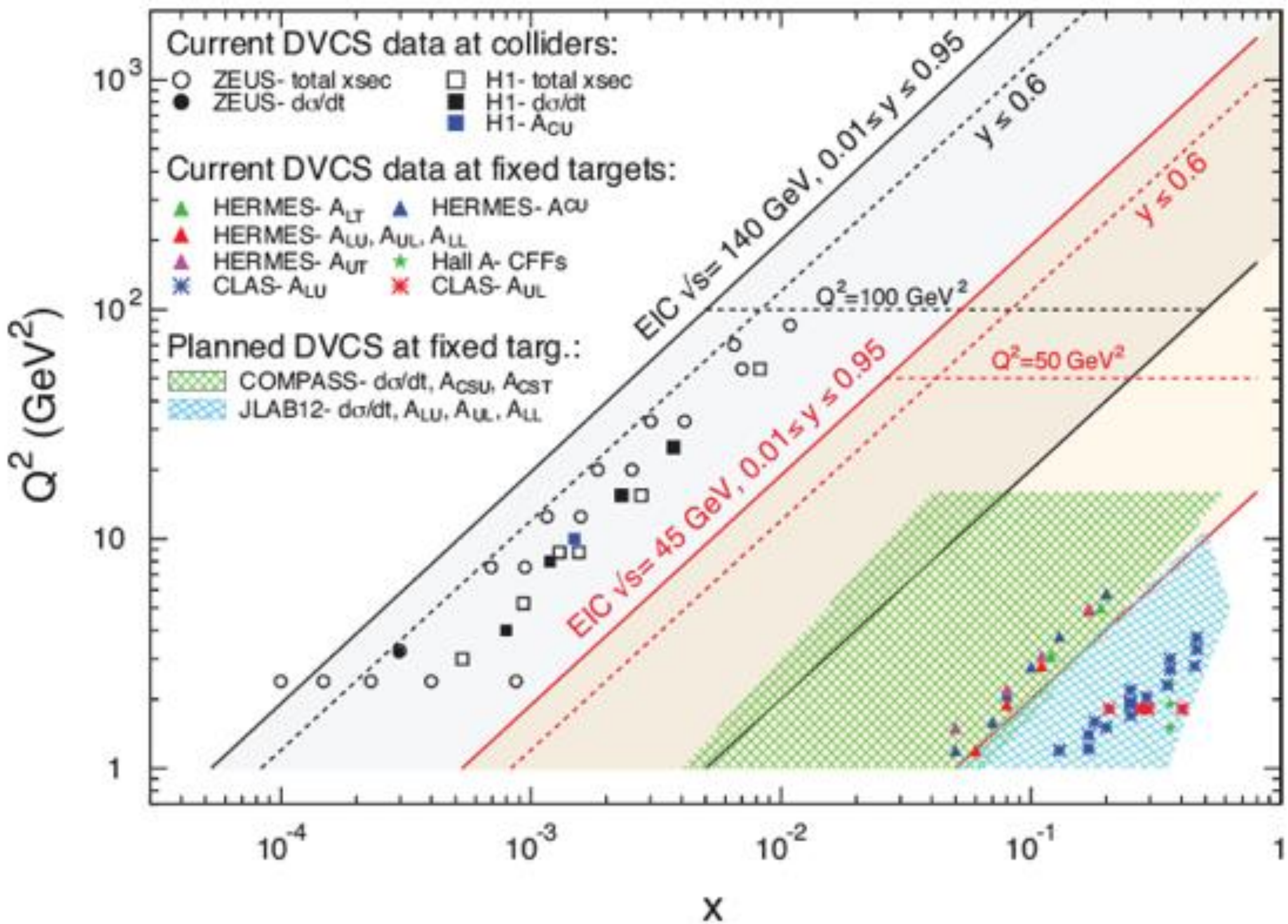




Guidal, Moutarde,
Vanderhaeghen,
Rept. Prog. Phys. 76 (2013) 066202



Mueller, 2011



Current DVCS data at colliders:
ZEUS- total xsec
ZEUS- dσ/dt
H1- total xsec
H1- dσ/dt
H1- A_CU
Current DVCS data at fixed targets:
HERMES- A_LT
HERMES- A_CU
HERMES- A_LU, A_UL, A_LL
HERMES- A_UT
Hall A- CFFs
CLAS- A_LU
CLAS- A_UL
Planned DVCS at fixed targ.:
COMPASS- dσ/dt, A_CSU, A_CST
JLAB12- dσ/dt, A_LU, A_UL, A_LL
EIC √s= 140 GeV, 0.01≤ y ≤ 0.95
y ≤ 0.6
EIC √s= 45 GeV, 0.01≤ y ≤ 0.95
y ≤ 0.6
Q²=100 GeV²
Q²=50 GeV²
Q² (GeV²)
x
10³
10²
10
1
10⁻⁴
10⁻³
10⁻²
10⁻¹
1