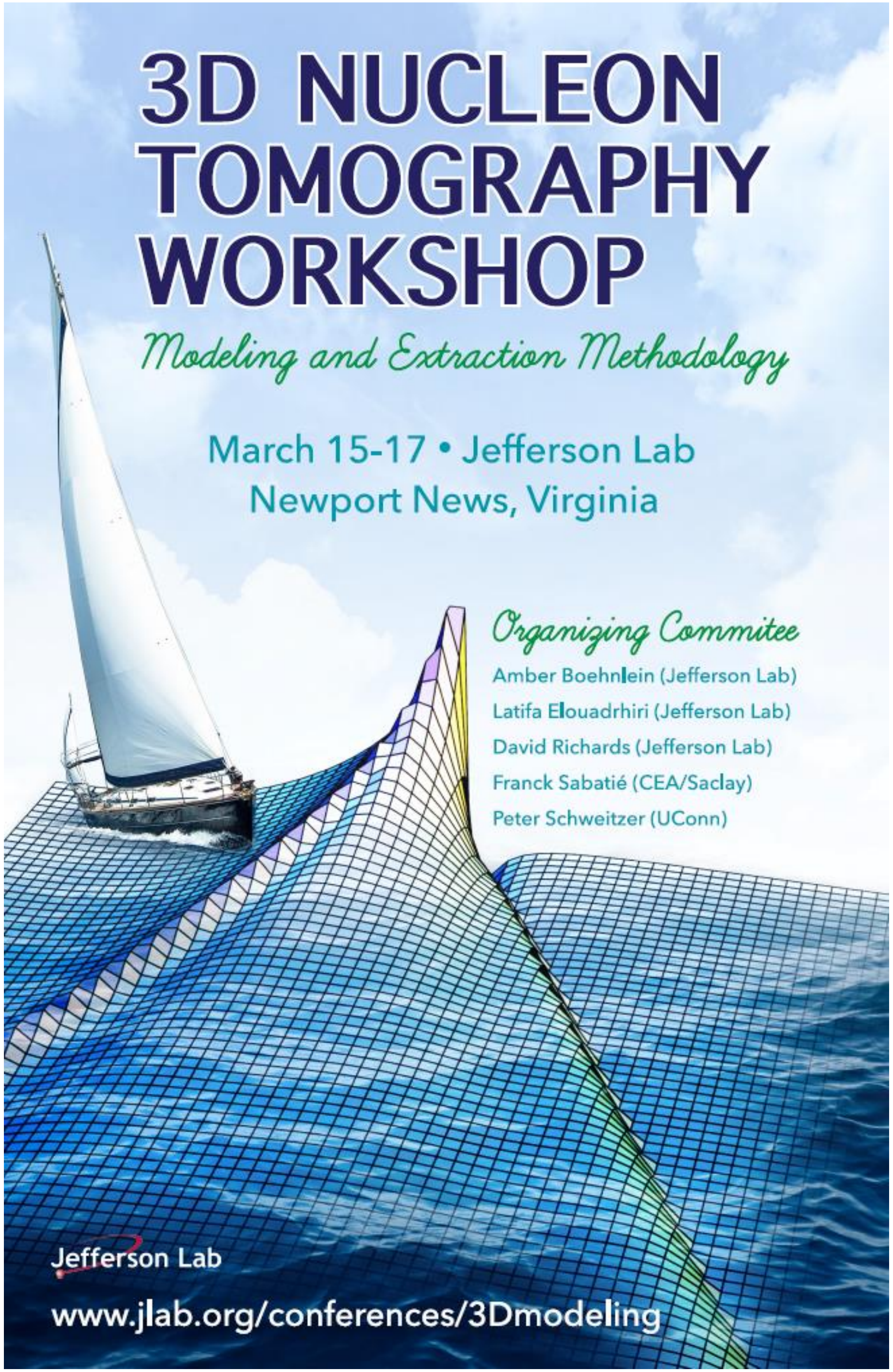


GPD/DVCS at COMPASS status and plan

DVCS with a recoil detector + an unpolarized proton target

one month in 2012

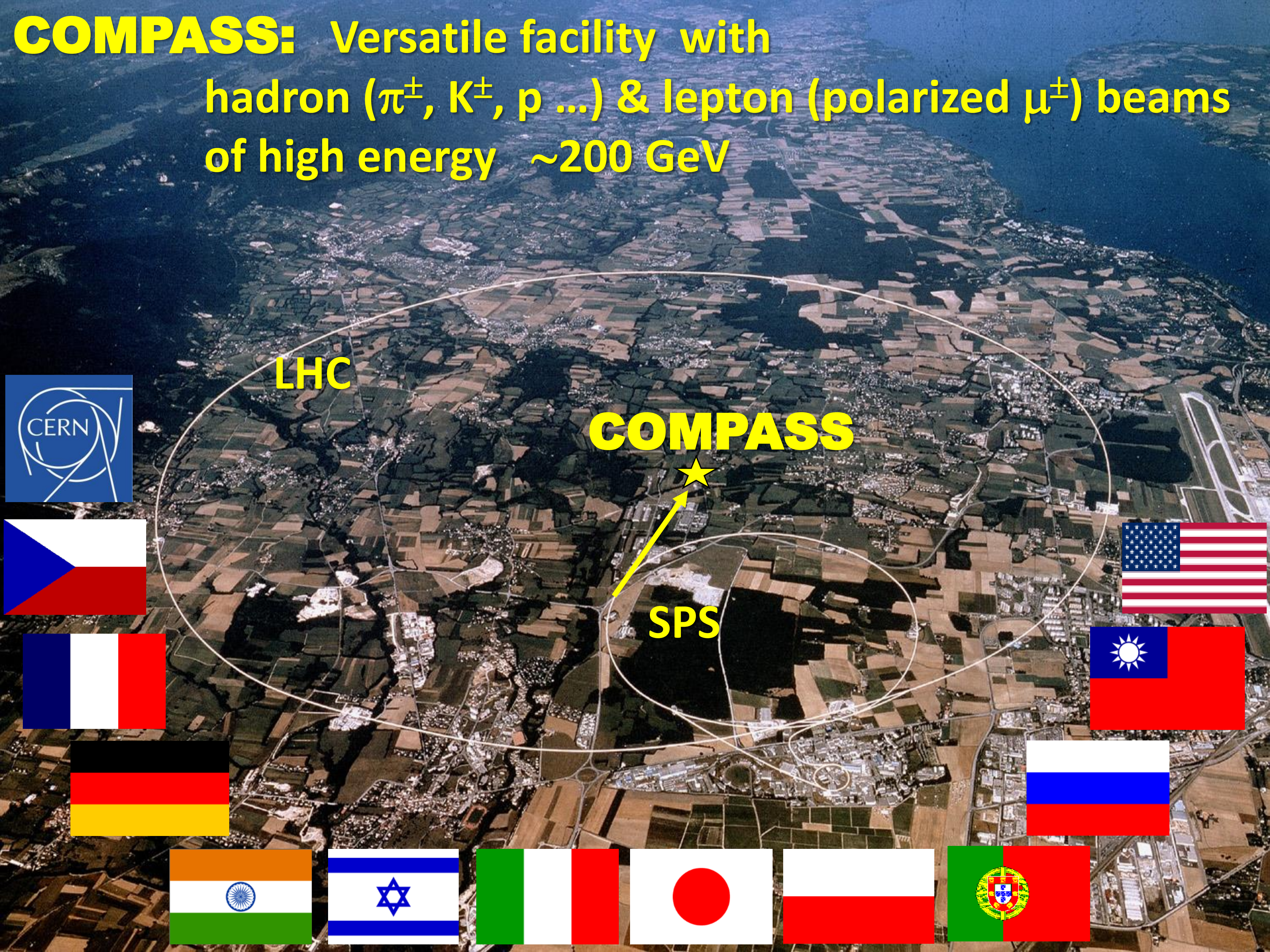
6 months in 2016

5 months in 2017

Plan or idea for future with a polarized target

Nicole d'Hose – CEA Saclay
for the COMPASS Collaboration

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

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 **2105-18**

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

GPDs + TMDs, FFs **2008-9-2012** (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 **DVCS** AND π^0
- 2 years (2016-17) ……………………. MEASUREMENTS ONGOING

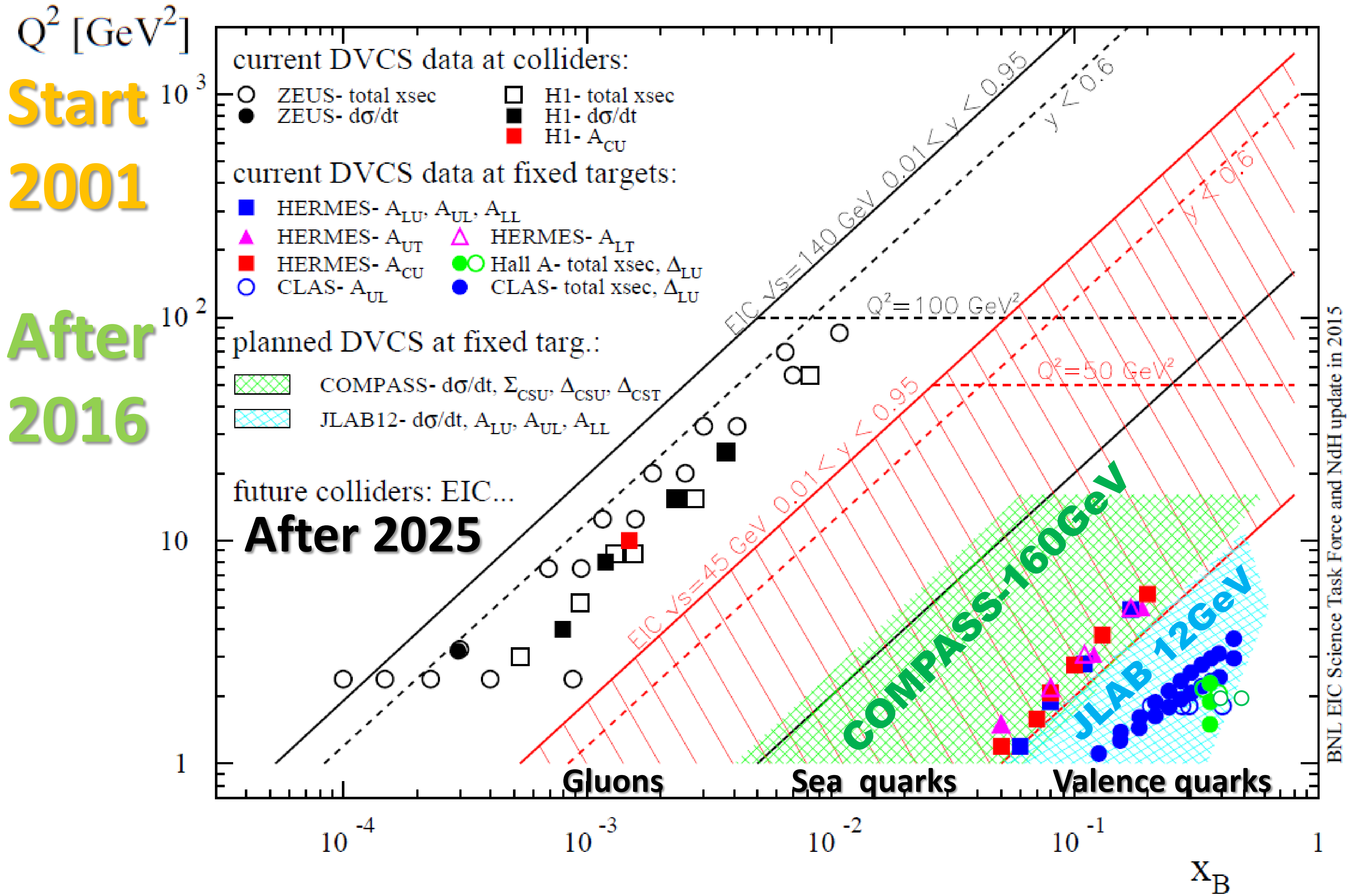
Transverse target asymetries without recoil detection for exclusive ρ and ω production

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

Plan/idea for Transverse target and recoil detection

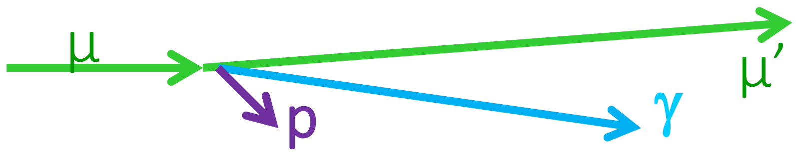
- After 2020

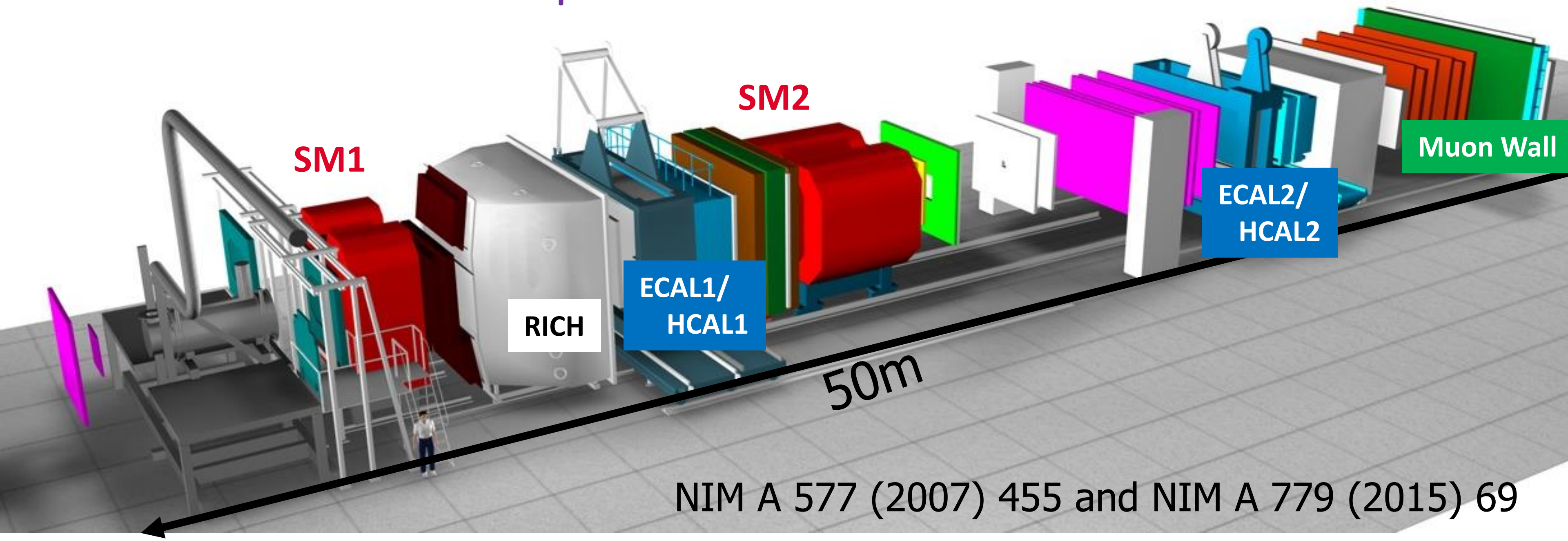
The past and future DVCS experiments



The DVCS experiment at COMPASS

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





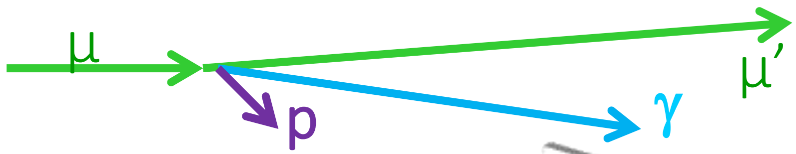
Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

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

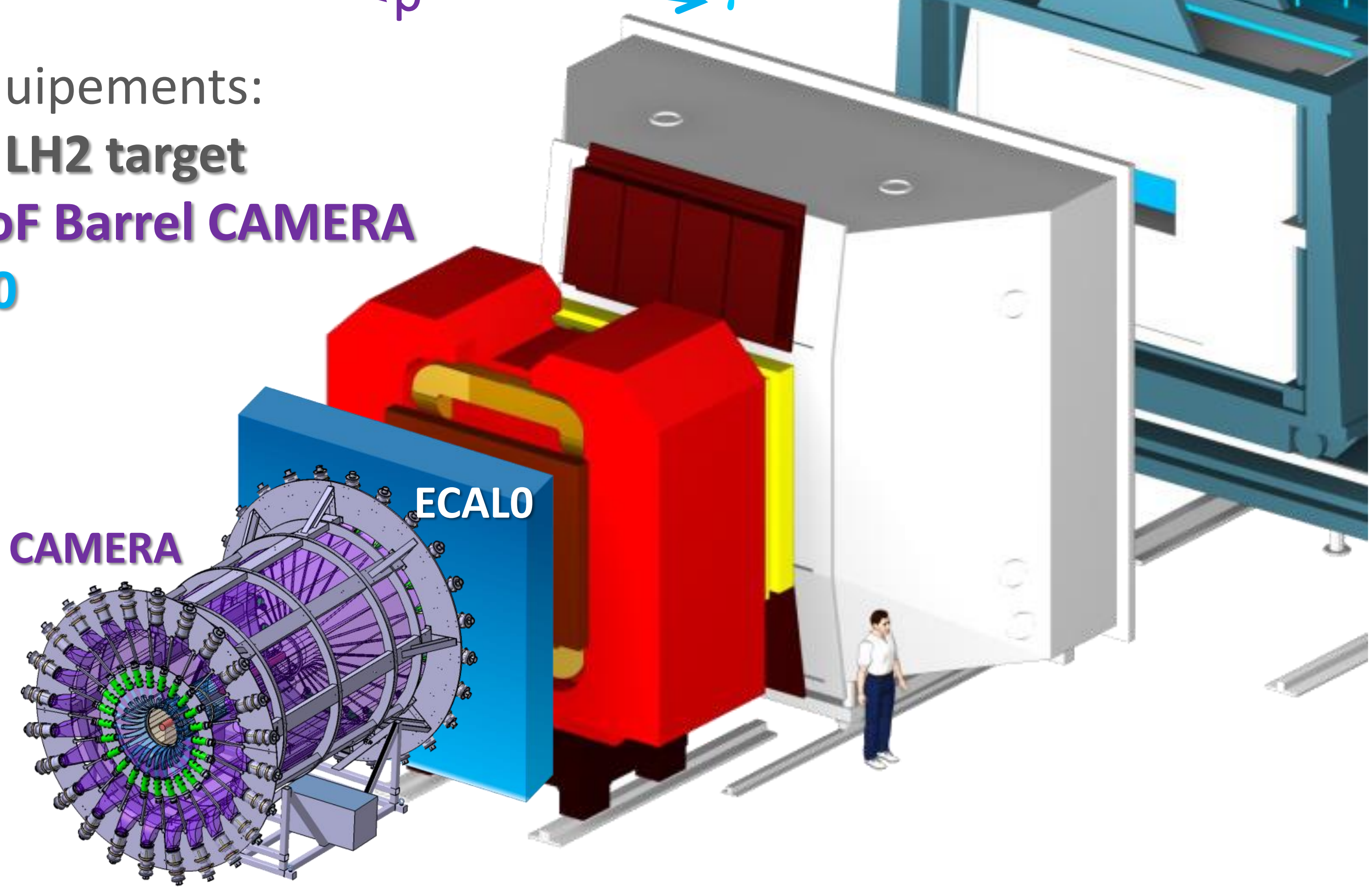
The DVCS experiment at COMPASS

DVCS : μ p → μ' p γ



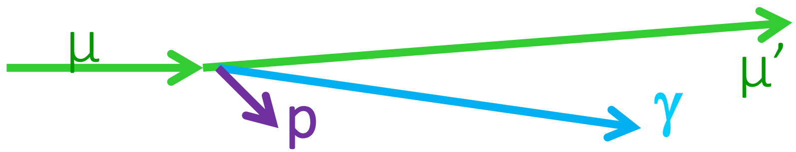
New equipements:

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



The DVCS experiment at COMPASS

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



New equipements:

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

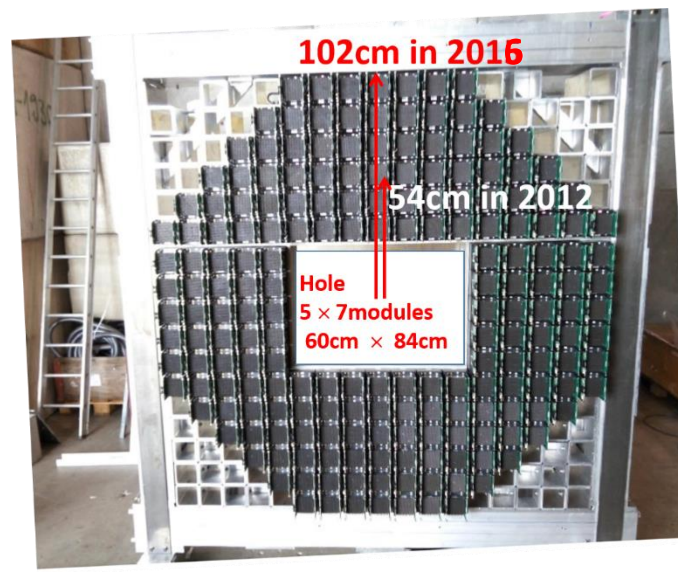
CAMERA

L=4m

∅=2m

24 inner & outer scintillators separated by about 1m

1 GHz SADC readout, 330ps ToF resolution

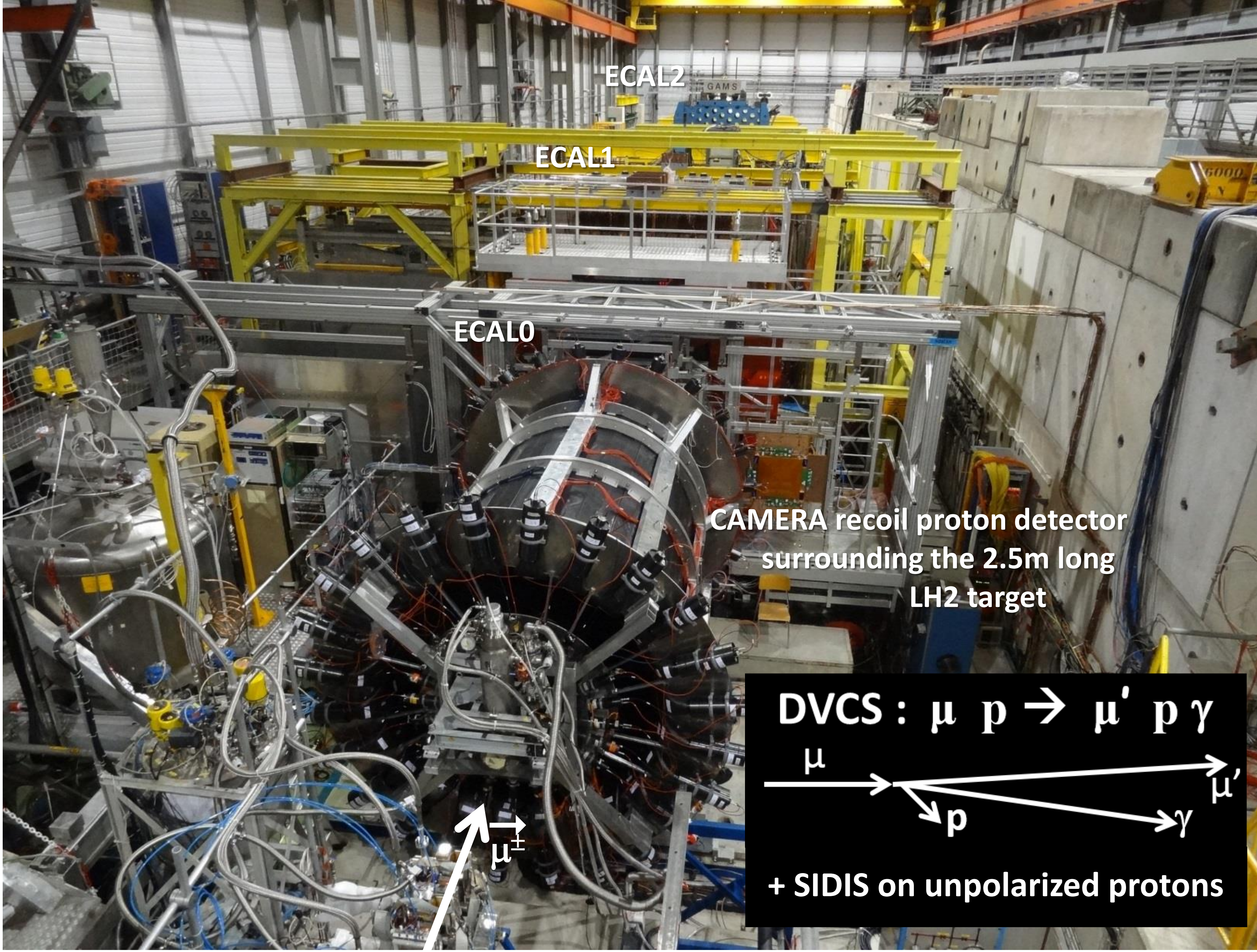


ECAL0: 2 × 2 m2

Shashlyk modules + MAPD readout

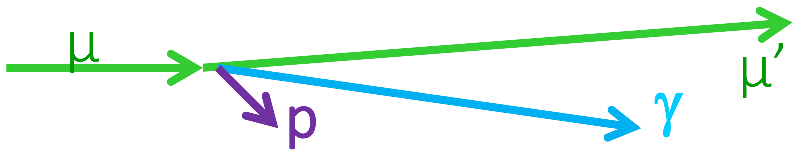
one module is made of 9 cells (4×4 cm^2)

= 194 modules or 1746 cells


ECAL2
GAMS
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
DVCS : μ p → μ' p γ
μ
μ'
p
γ
$\mu^{\pm}$
+ SIDIS on unpolarized protons

The DVCS experiment at COMPASS

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



Muon beams with oppositive charge and polarization

max intensity in 2012: 4.6 10^8 μ^+ /spill (in 9.6s each 48s)
$\rightarrow$ Lumi= 10^{32} cm^{-2} s^{-1} with 2.5m LH2 target

Recoil Proton momentum from ToF detector

Photon energy and angle from ECALs

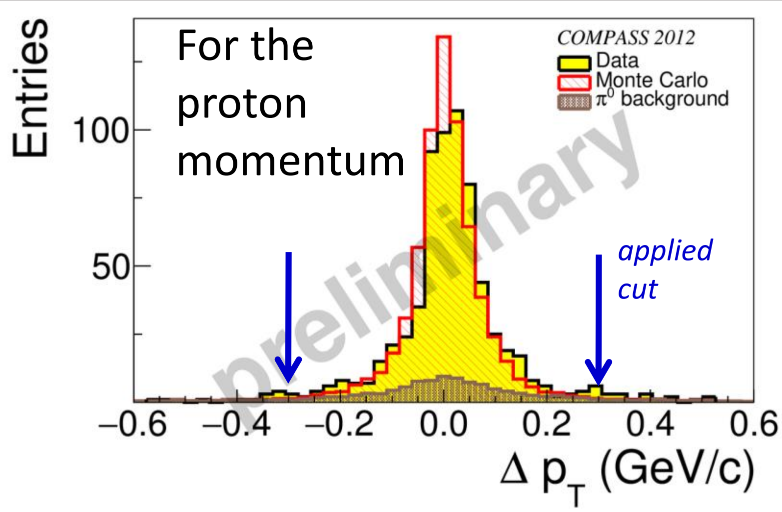
Reconstruction of the full event kinematics (+ kinematic fit)

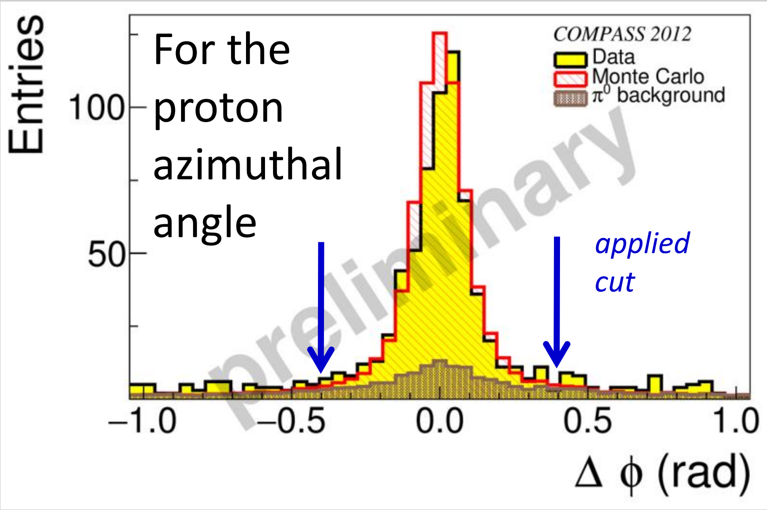
$Q^2 > 1$ GeV^2 $\quad 0.05 < y < 0.9 \quad 0.08 < t < 0.64$ GeV^2

Selection of exclusive evts with recoil detection

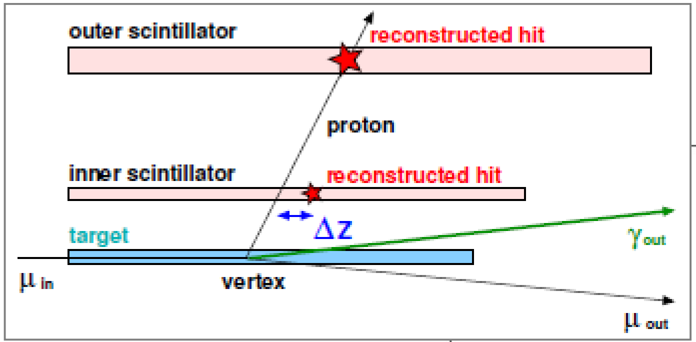
DVCS : μ p → μ' p γ

Comparison between the observables given by the spectro or by CAMERA

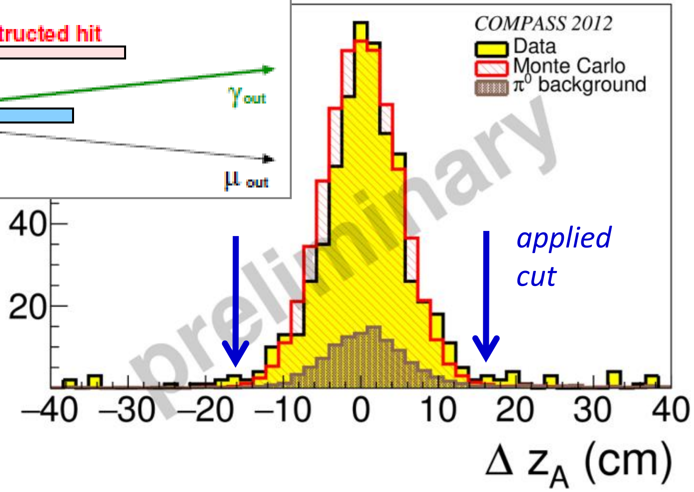




one of the 3 bins
$x_B > 0.03$
$10 < \upsilon < 32$GeV
with π^0 contamination

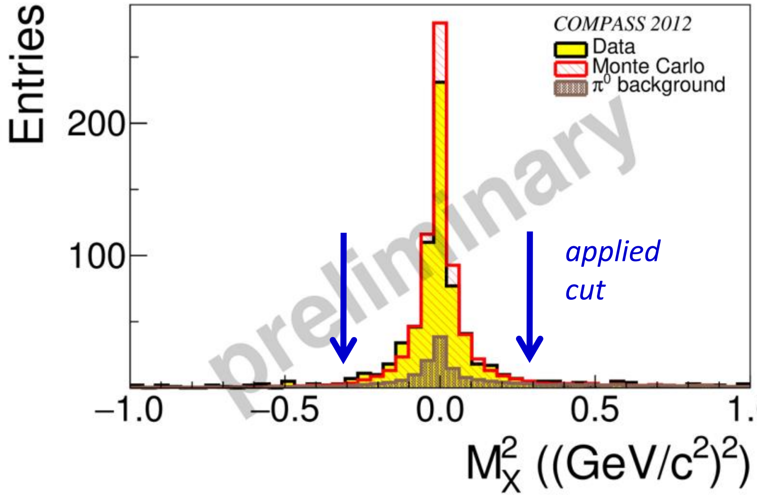


For the proton track



Four-momentum balance:

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



π^0 background estimation

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

Two possible case:

- **Visible** (both γ detected ➔ subtracted)

  the DVCS photon after all exclusivity cuts is combined with all detected photons below the DVCS threshold: 4,5,10 GeV in ECAL0, 1, 2

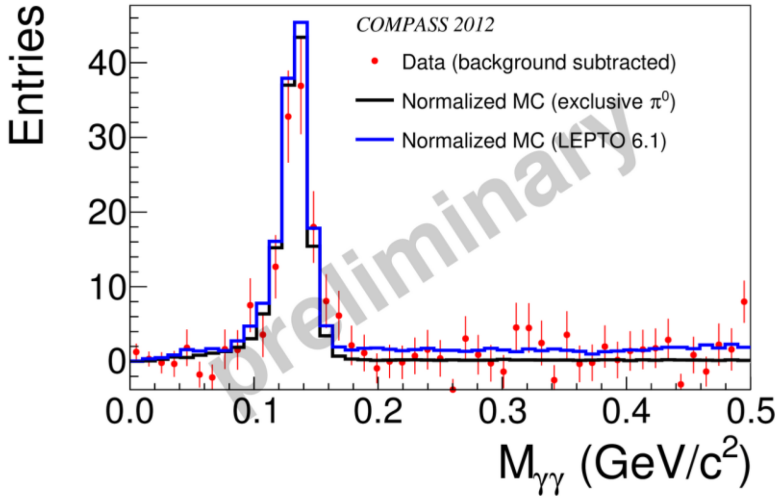
- **Invisible** (one γ lost ➔ estimated by MC)

  - **Semi-inclusive LEPTO 6.1**
  - **Exclusive HEPGEN π^0** (Goloskokov-Kroll model)

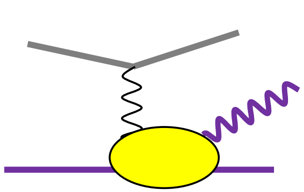
  gives lower and upper limit

  LEPTO and HEPGEN samples normalized to $M_{\gamma\gamma}$ peak in real data

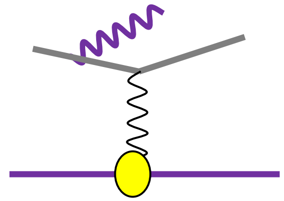
Visible leaking π^0 in the data



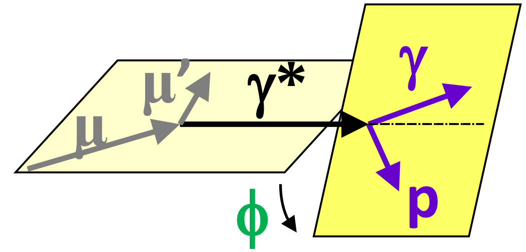
Contributions of DVCS and BH at E_μ=160 GeV



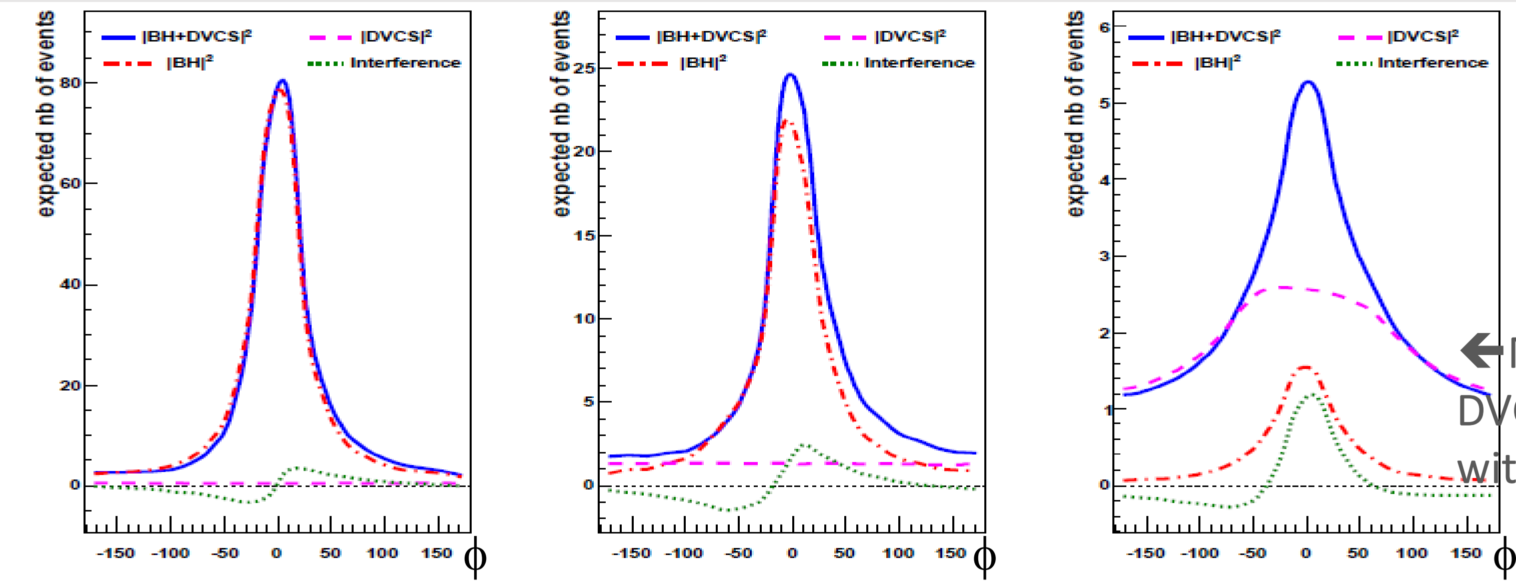
Deep VCS



Bethe-Heitler



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



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

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

← Missing DVCS acceptance without ECAL0

BH dominates

excellent reference yield

study of Interference

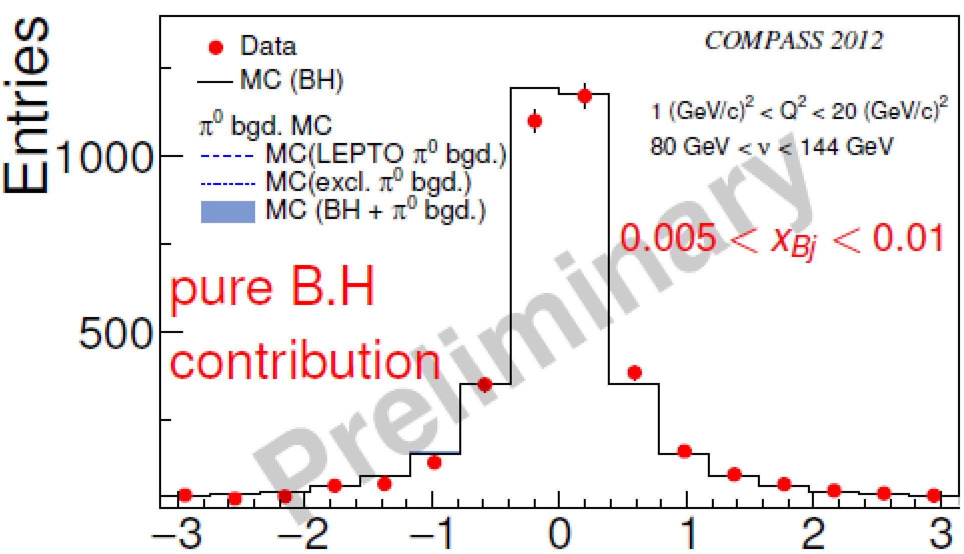
→ Re T^{DVCS} or Im T^{DVCS}

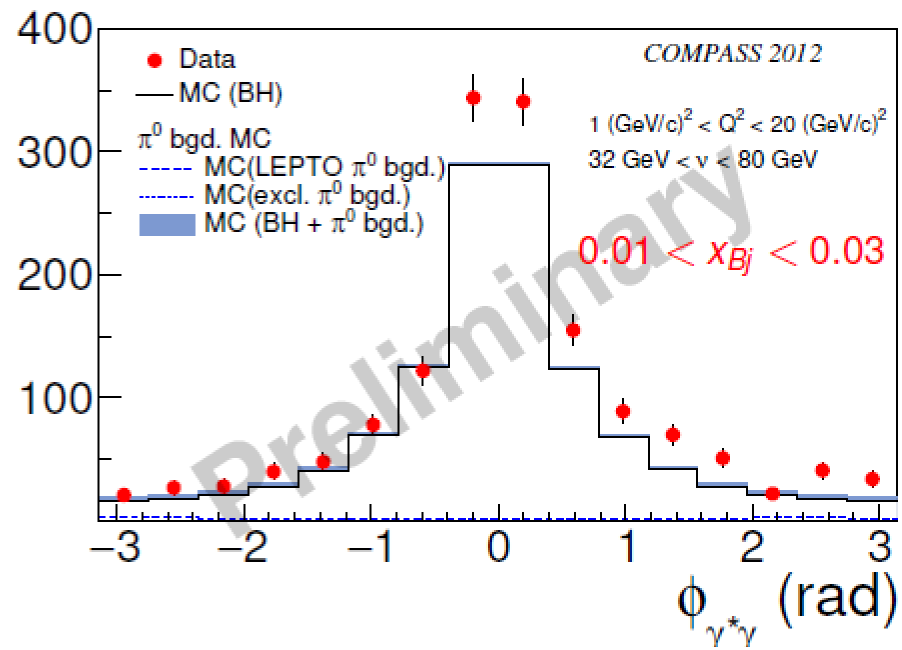
DVCS dominates

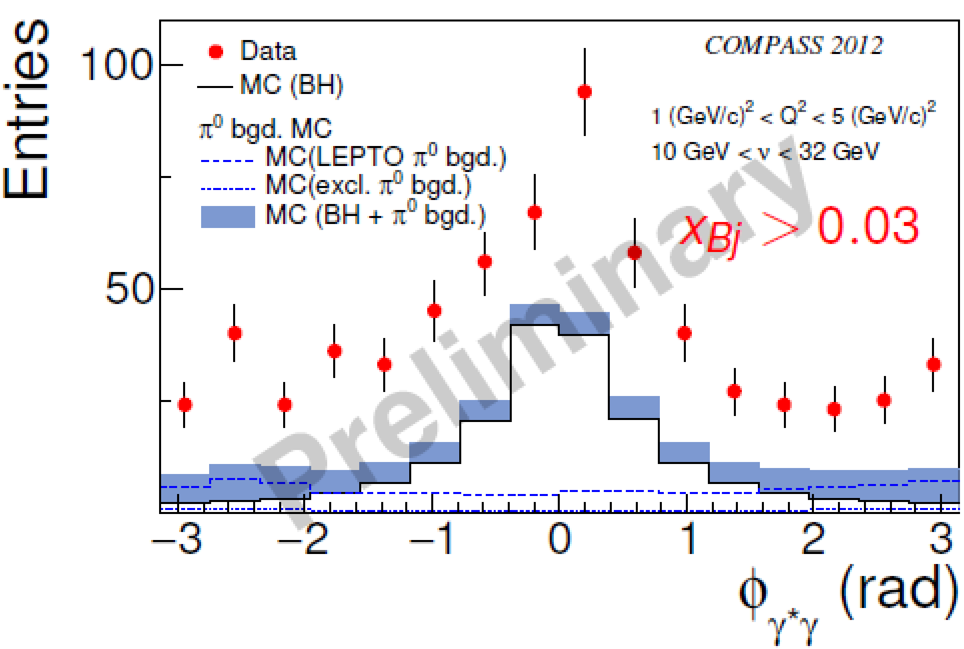
study of $d\sigma^{DVCS}/dt$

→ Transverse Imaging

Contributions of DVCS and BH at E_μ=160 GeV







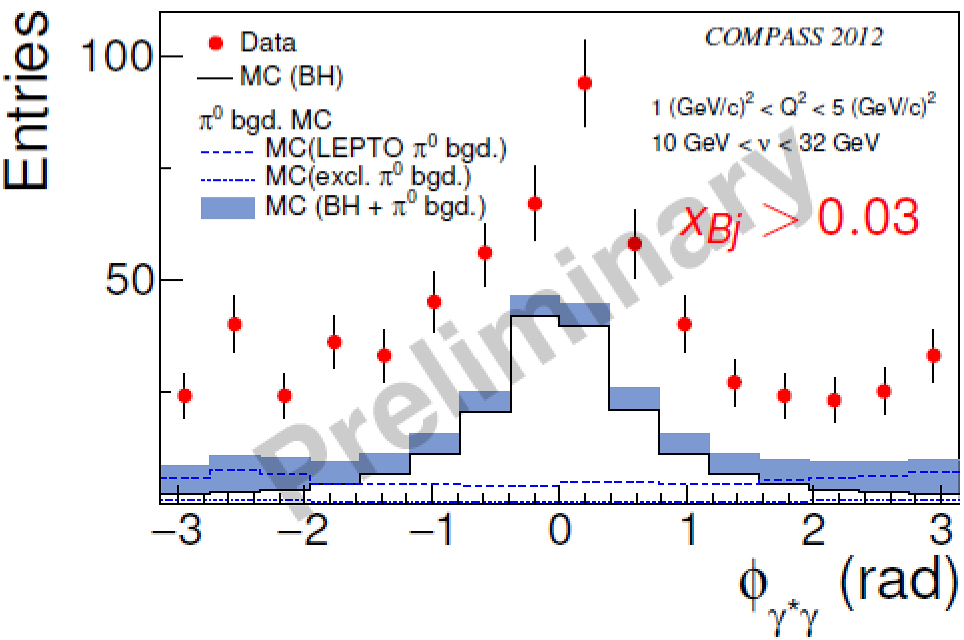
- BH MC normalisation based on Integrated luminosity
- BH process dominant at small x_{Bj}
- π^0 background contributing at large x_{Bj}
- Clear excess of DVCS at large x_{Bj}

Contributions of DVCS and BH at E_μ=160 GeV

In the bin at large x_{Bj}

- Subtract π^0 background
- Subtract BH contribution
- Kinematic fit for a better t determination
- Experimental acceptance corrections

➔ Study of t-dependence of the DVCS x-section (γ^* p → γ p)



- BH MC normalisation based on Integrated luminosity
- BH process dominant at small x_{Bj}
- π^0 background contributing at large x_{Bj}
- Clear excess of DVCS at large x_{Bj}

DVCS and BH at COMPASS

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

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

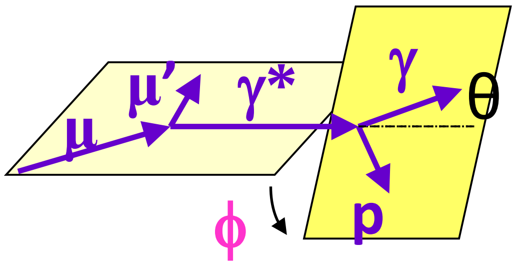
Charge & Spin Sum:

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

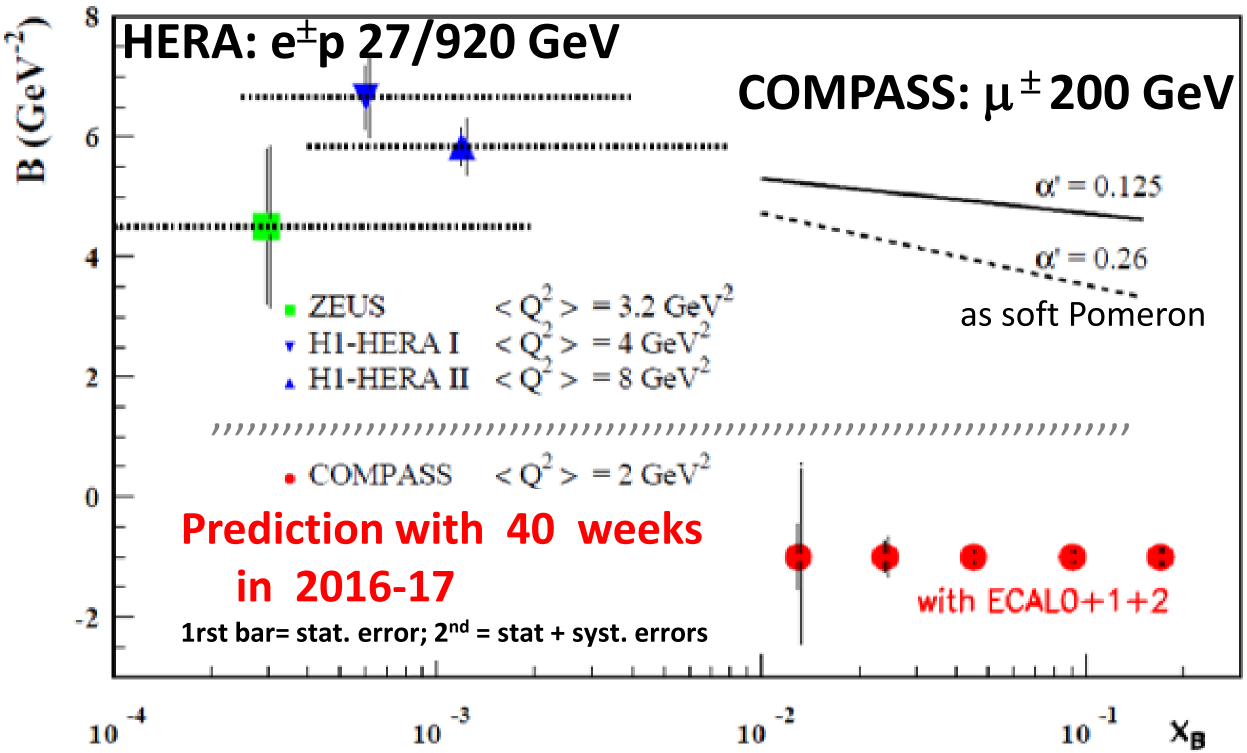
Using $S_{CS,U}$ and BH subtraction

and integration over ϕ

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



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

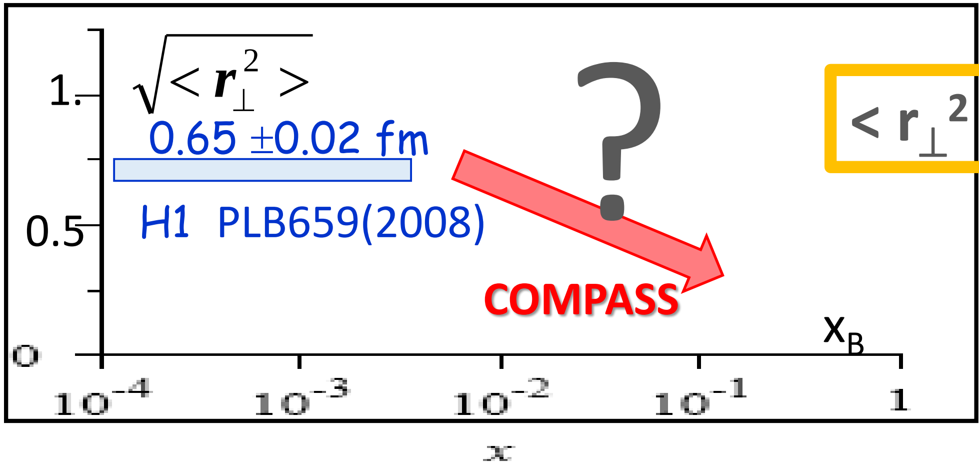


2 years of data = 40 weeks
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

ansatz at small x_B
inspired by
Regge Phenomenology:

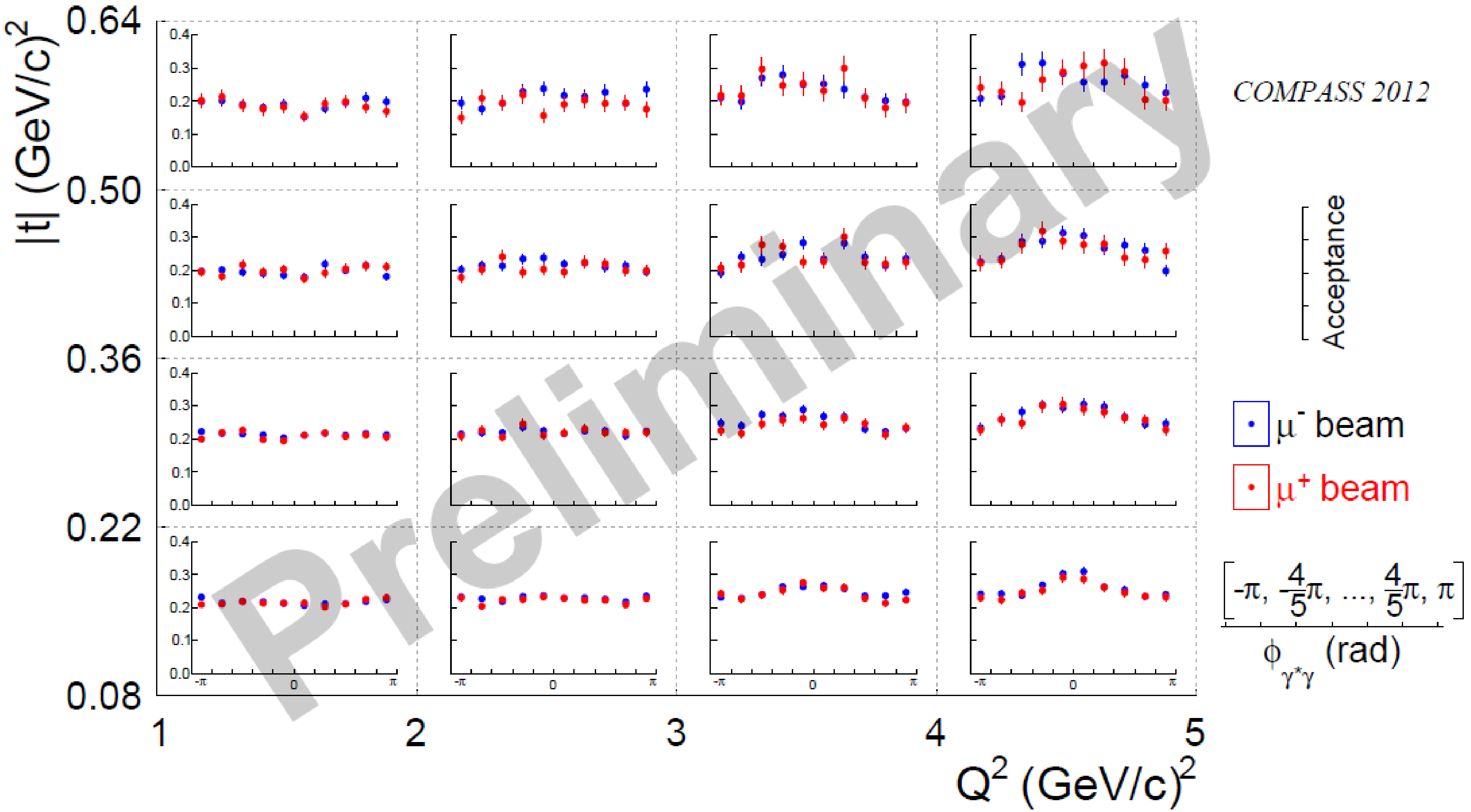
$B(x_B) = b_0 + 2\,\alpha' \ln(x_0/x_B)$

α' slope of Regge traject



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

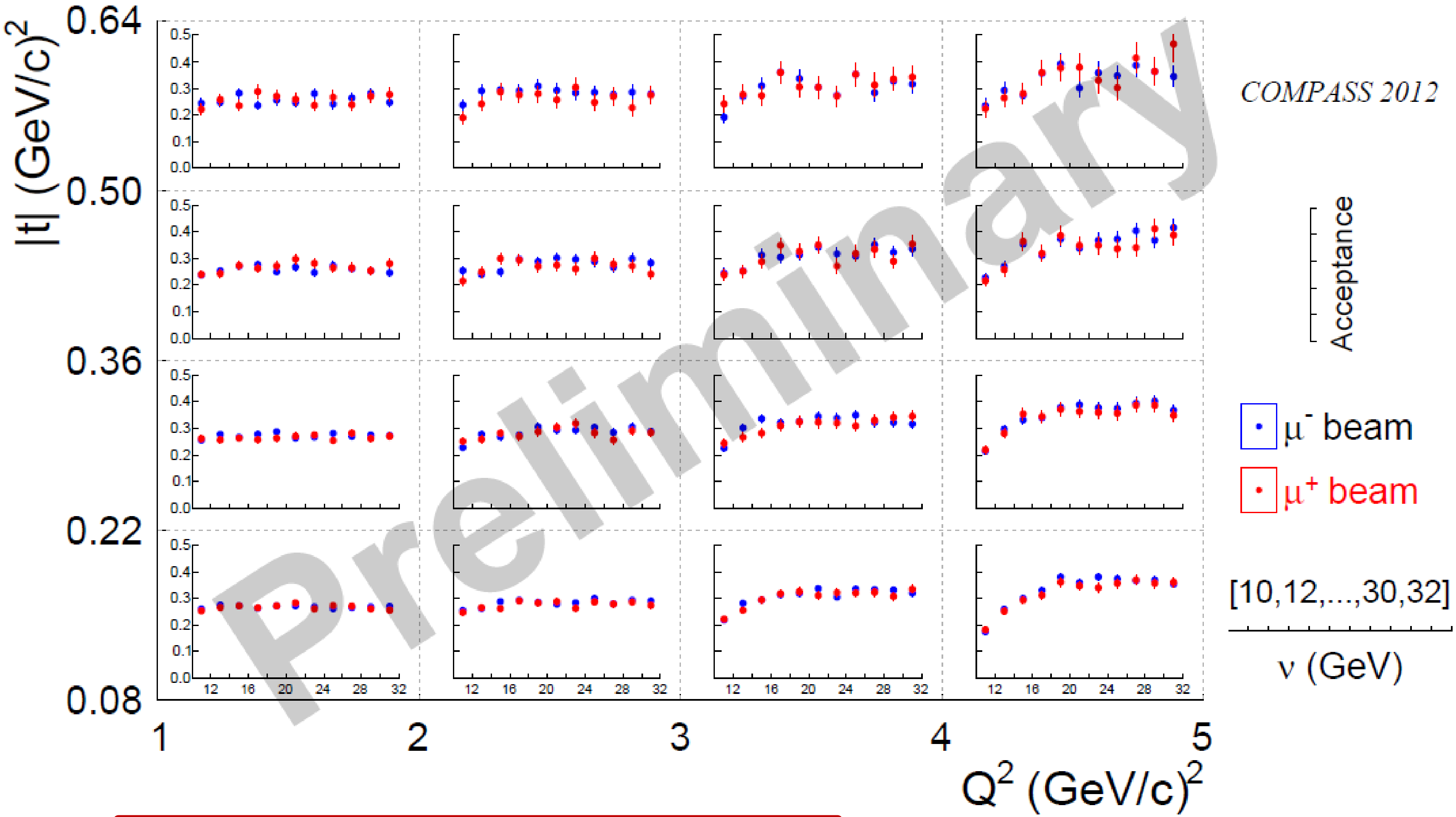
COMPASS acceptance for DVCS (2012)



Symmetric acceptance in $\phi_{\gamma\gamma}$

Size of ECAL0 limited in 2012

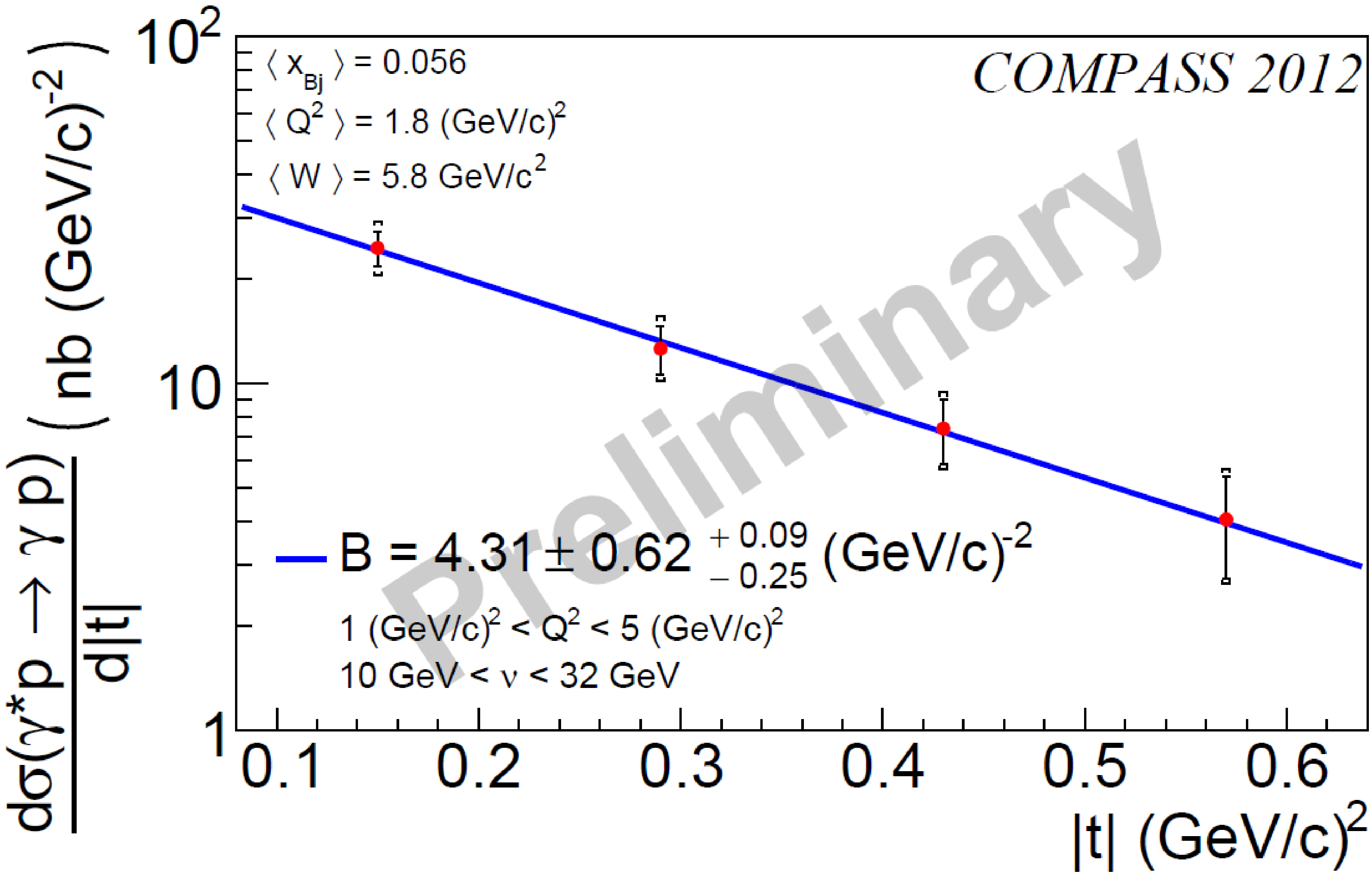
COMPASS acceptance for DVCS (2012)



$$\frac{d^3\sigma^{\mu p}}{dQ^2 d\nu dt} = \Gamma(1+\varepsilon R)\frac{d\sigma^{\gamma^* p}}{dt}$$

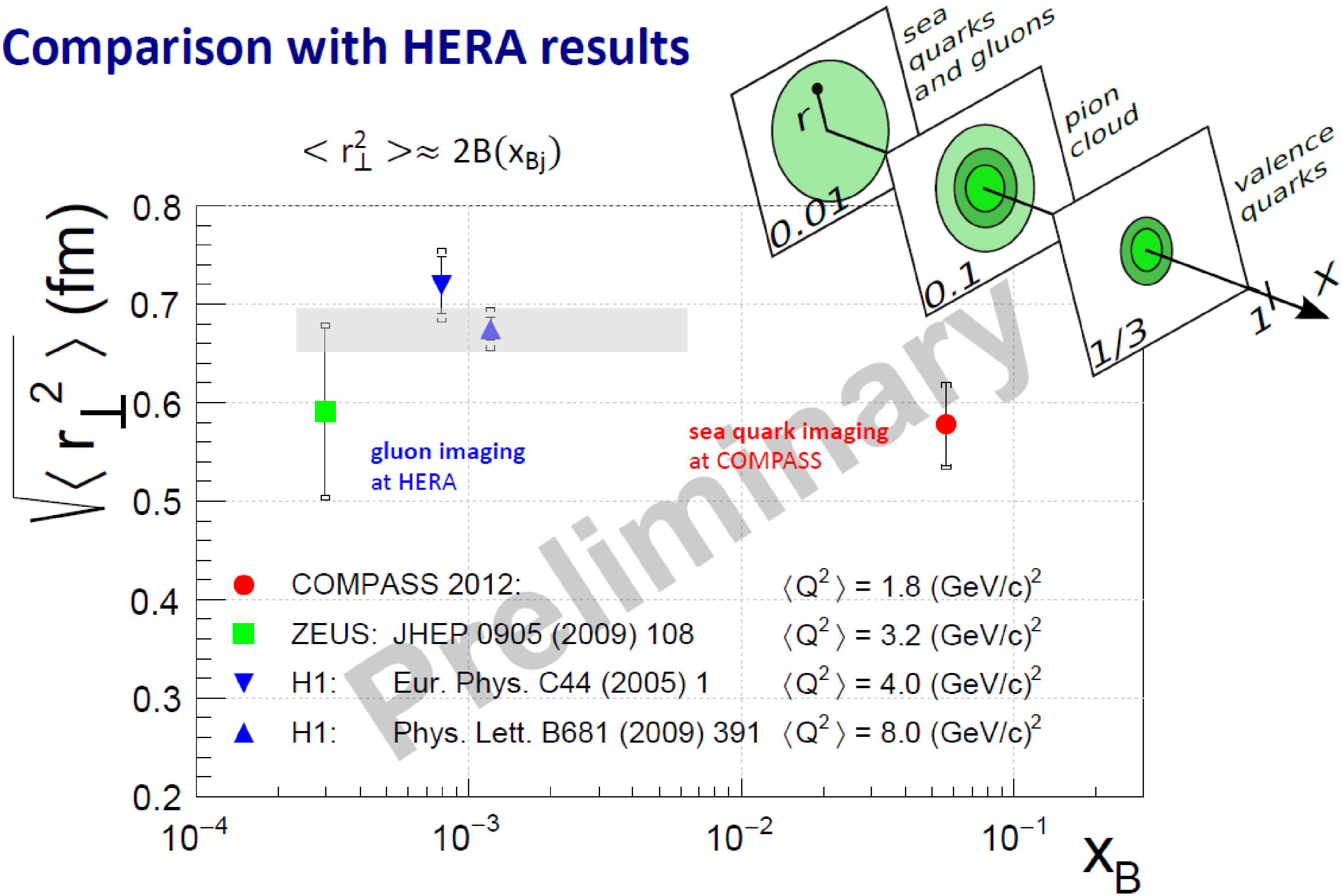
virtual photon flux $\Gamma = \Gamma(Q^2, \nu)$

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



Proton « radius » measured at COMPASS

Comparison with HERA results



$\sqrt{< r_\perp^2 >}$ to be compared to $\sqrt{4 \frac{d}{dt} F_1^p}\Big|_{t=0} = 0.66 \pm 0.01$ fm $\neq \sqrt{4 \frac{d}{dt} G_E^p}\Big|_{t=0} = 0.72 \pm 0.01$ fm

$+\sqrt{\kappa / m_p^2}$ $\quad r_p = 0.88$ fm

Proton « radius » measured at JLab

Fit of 8 CFFs at L.O and L.T.

Dupré, Guidal, Vanderhaeghen, PRD95, 011501(R)(2017)

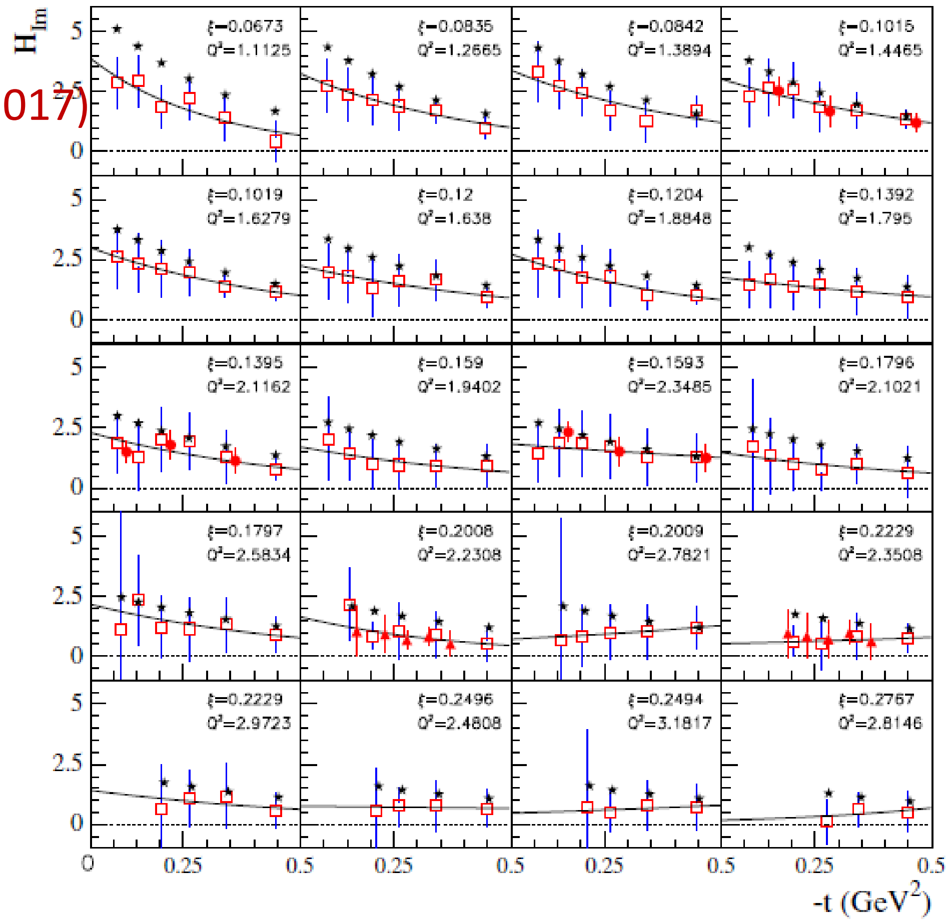
$s_1^I = Im\, F_1 \mathcal{H}$

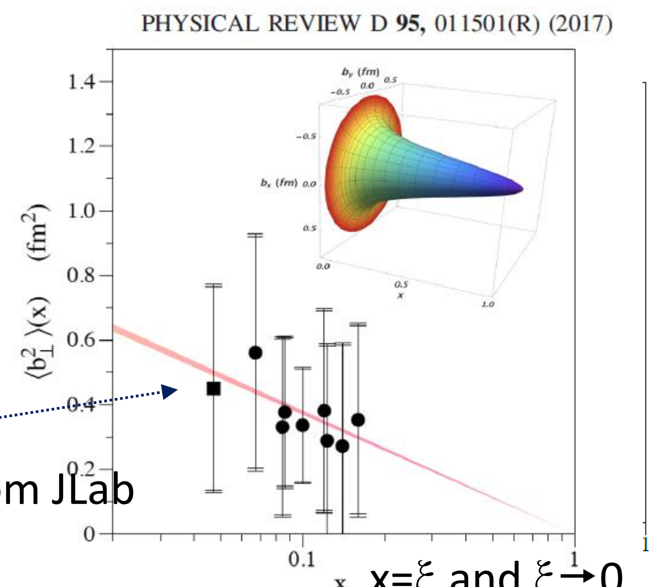
- □ CLAS σ and Δσ
- ▲ HallA σ and Δσ
- ● CLAS A_{UL} and A_{LL}

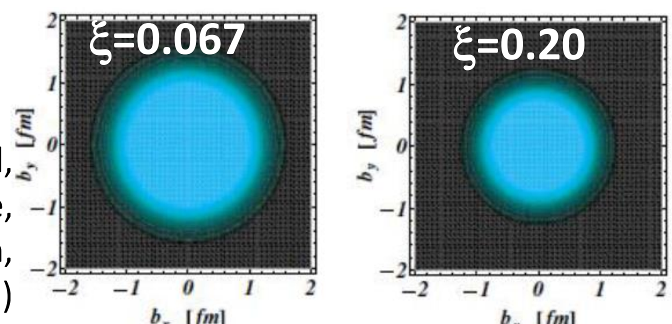
★ VGG model

— Fit $A\, e^{-B'|t|}$

$< b_\perp^2 > \approx 4 B'$

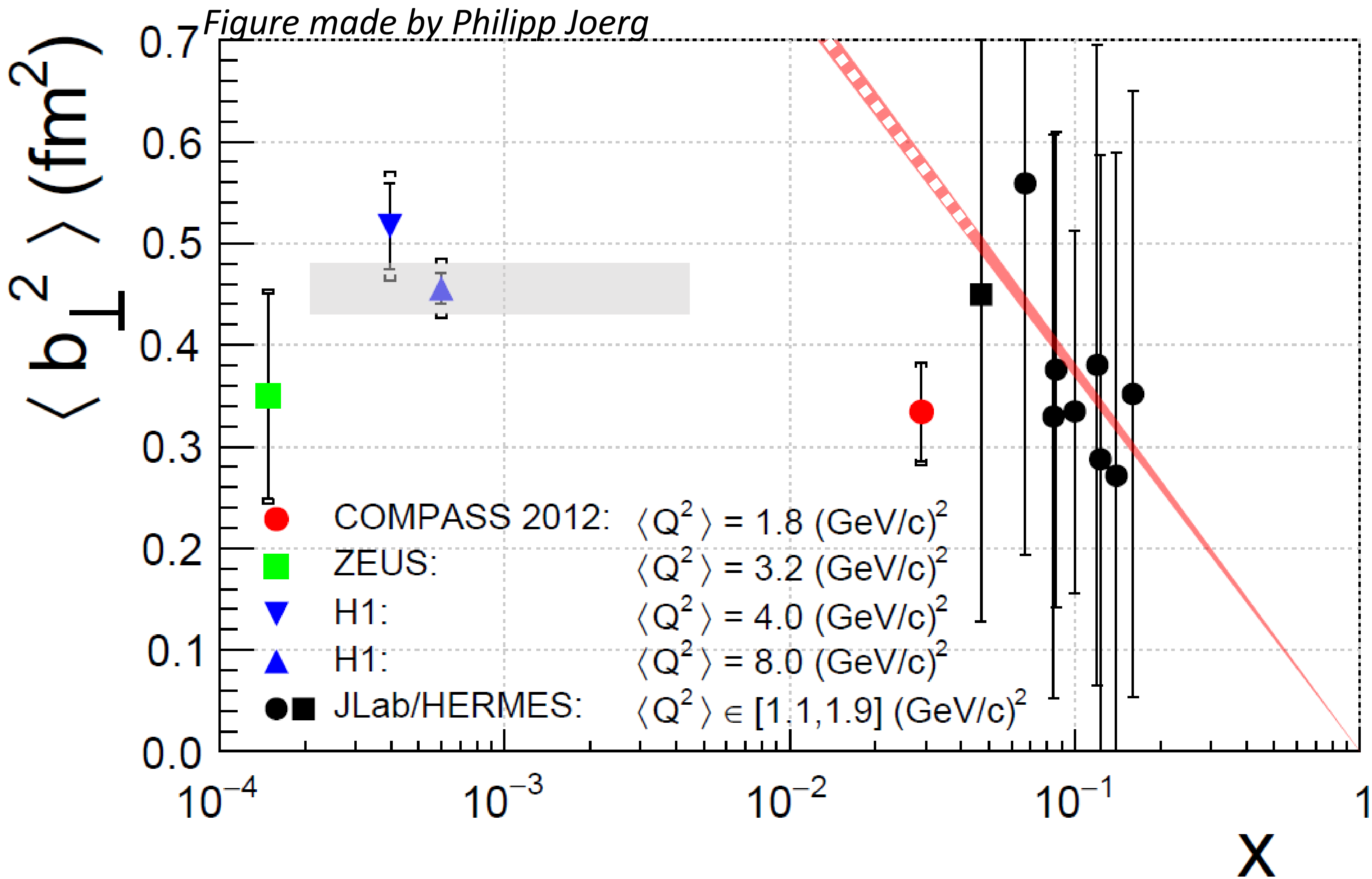




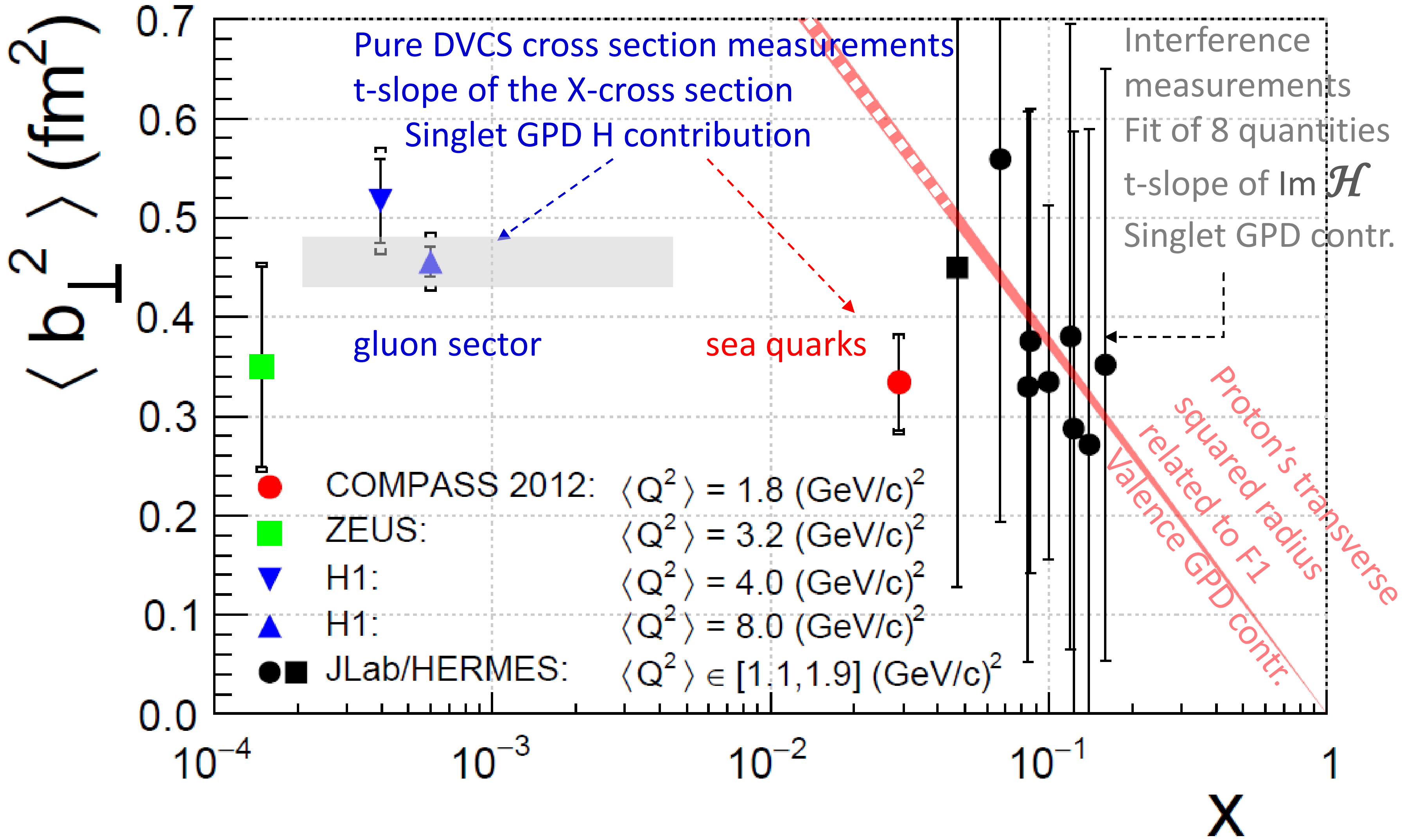


Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013)

Can we compare all the Proton « radii »?



Can we compare all the Proton « radii »?



Can we compare all the Proton « radii »?

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

$B(x_B) = ½ < r_\perp^2(x_B) >$

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

Transverse size of the nucleon

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

$A^{DVCS \text{ linked to } ImH} \sim \exp(-B'|t|)$

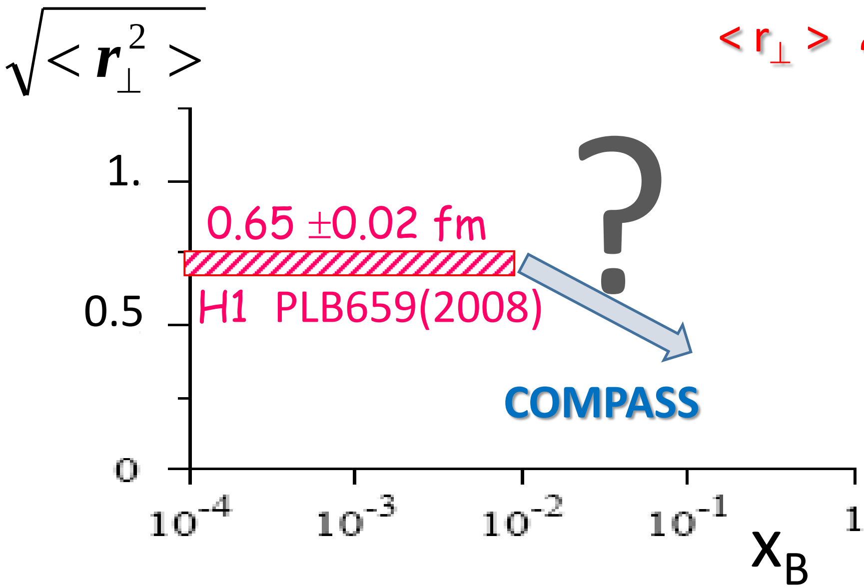
$B'(x_B) = 1/4 < b_\perp^2(x_B) >$

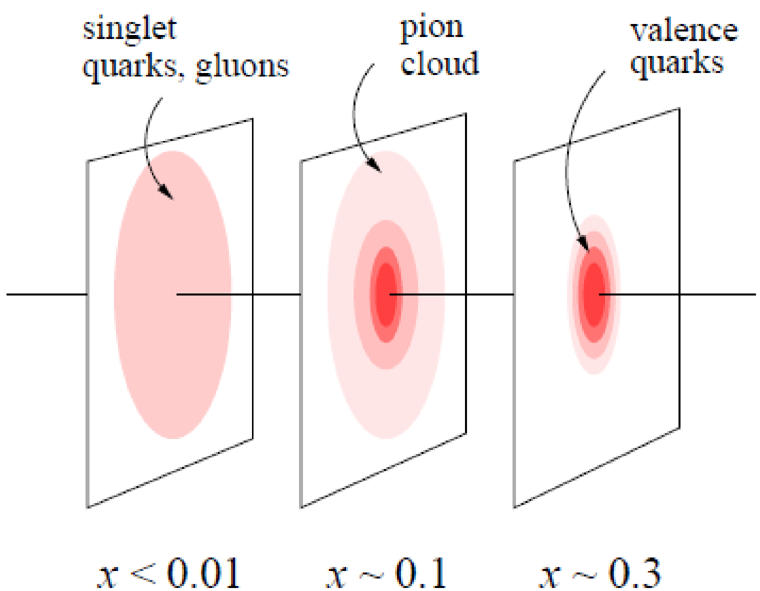
distance between the active quark
and the center of momentum of the nucleon

Impact Parameter Representation

$q(x, b_\perp) <-> H(x, \xi=0, t)$

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





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

DVCS and BH at COMPAS

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 Difference and Sum:

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

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

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

NOTE: ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics

✓only leading twist and LO

DVCS and BH at COMPAS

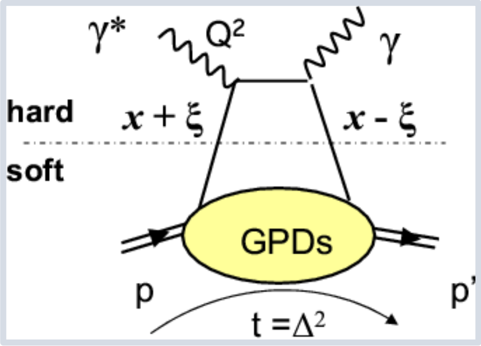
cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

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

Charge & Spin Difference and Sum:

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

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



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

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

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

$\mathcal{Re}$ part of the *Compton Form Factors* linked to the $\mathcal{D}$ *term*

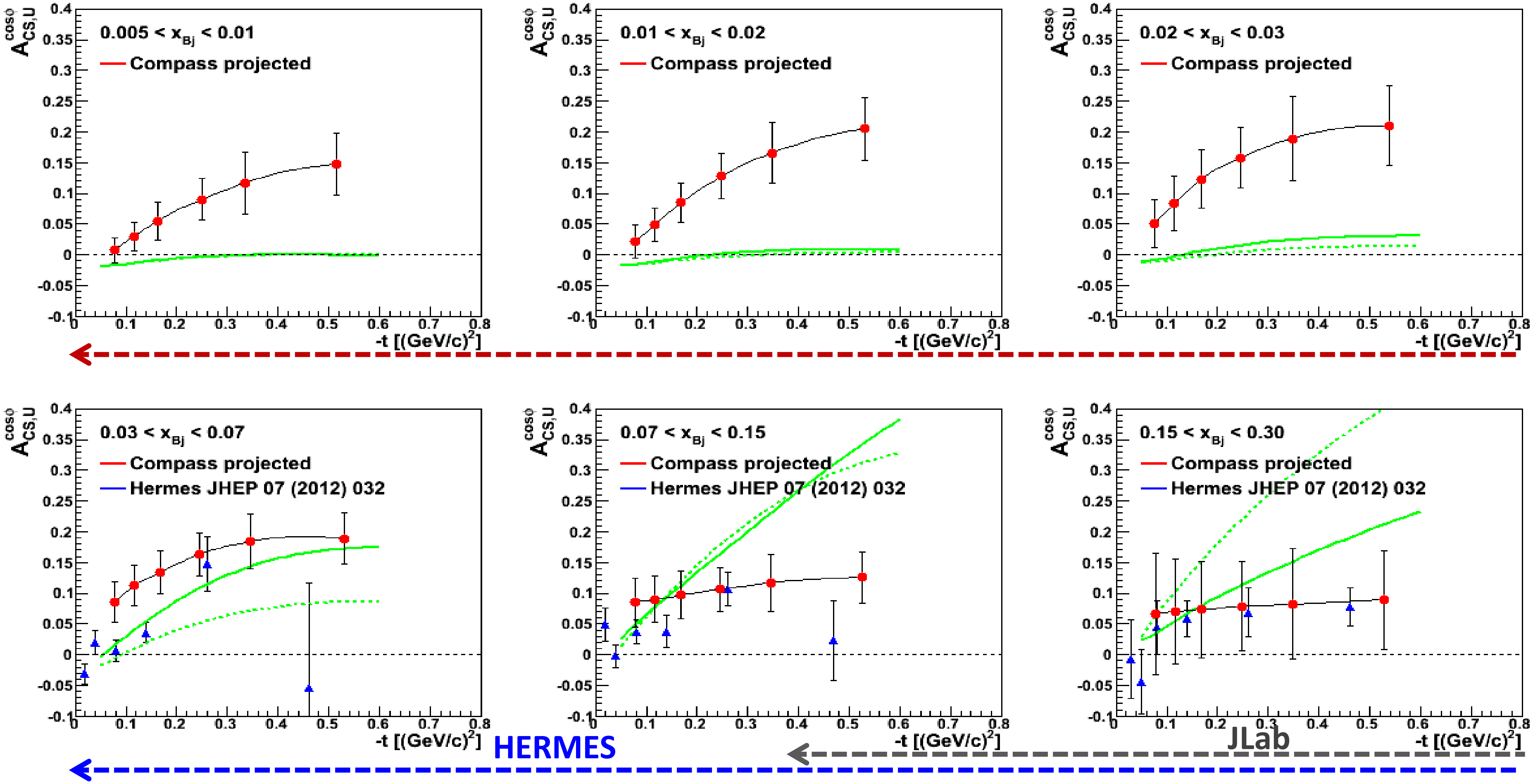
Energy-Momentum Tensor : Polyakov, PLB 555 (2003) 57-62

Beam Charge and Spin Diff. @ COMPASS

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

Predictions with
VGG and D.Mueller KM10

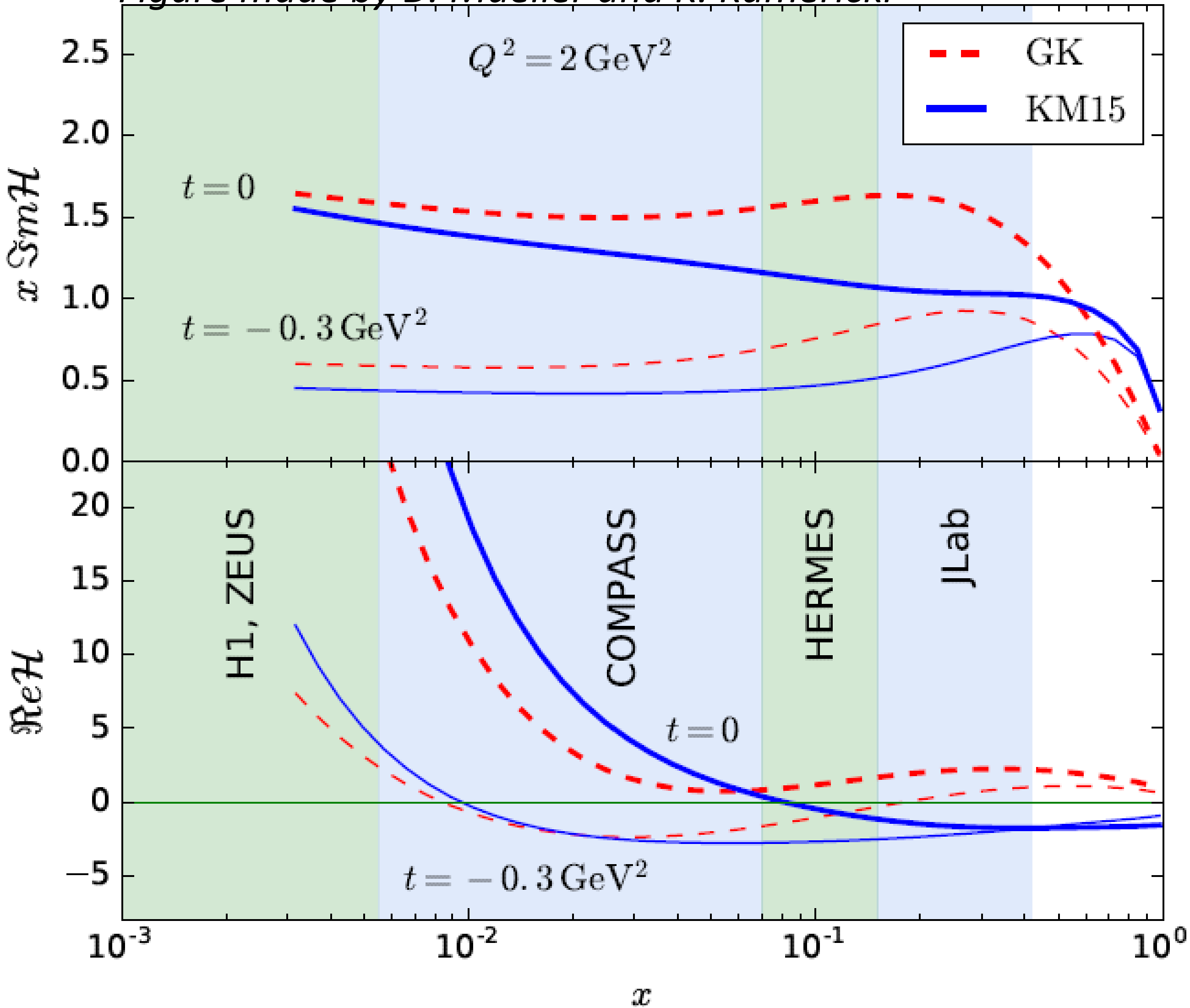
$\mathcal{R}e\, \mathcal{H}$ > 0 at H1
< 0 at HERMES
Value of x_B for the node?



COMPASS 2 years of data E_μ= 160 GeV $1 < Q^2 < 8$ GeV^2

Impact of DVCS @ COMPASS in global analysis ?

Figure made by D. Mueller and K. Kumericki



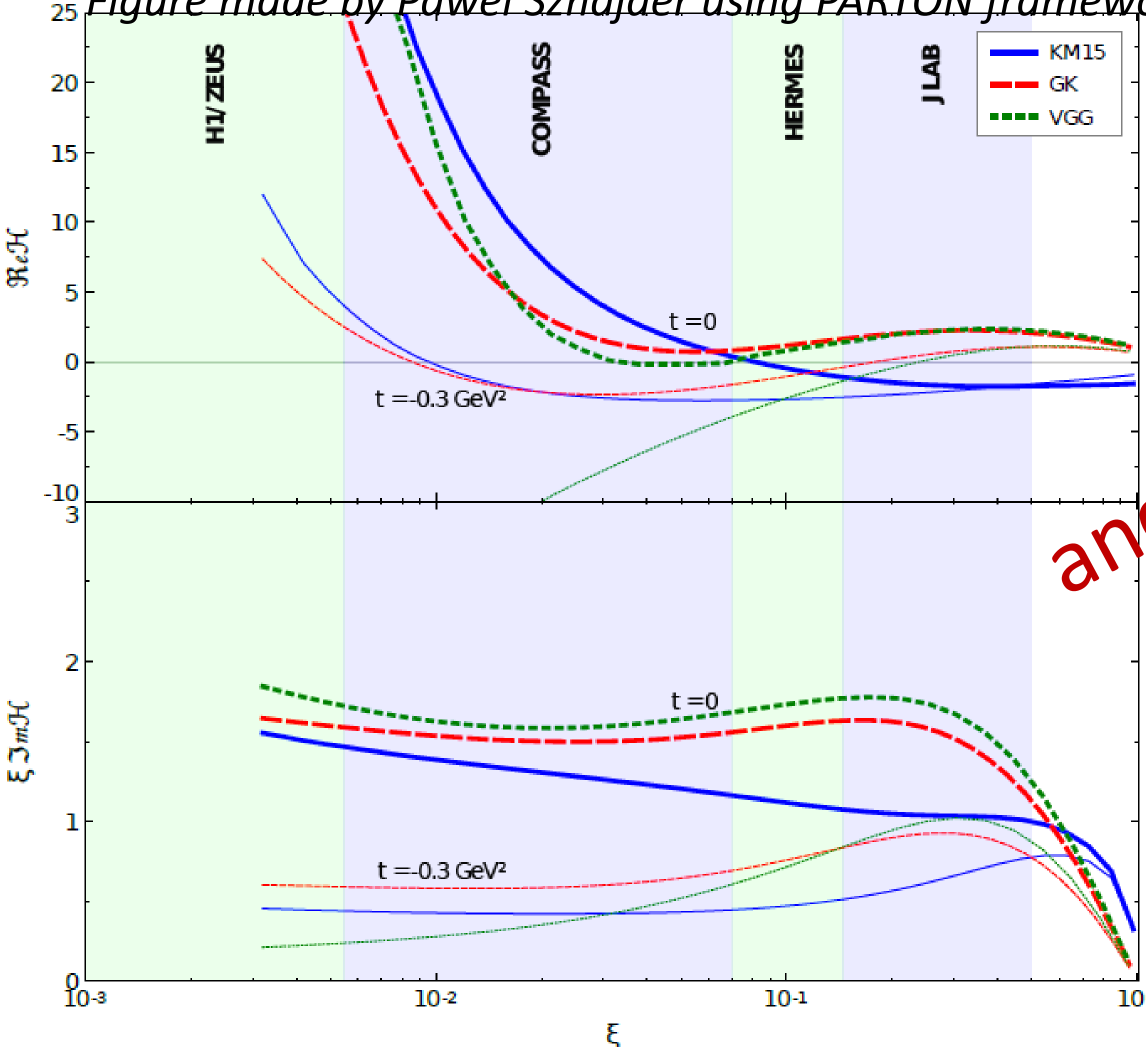
Im H
Is it rather well known ?

Re H linked to the *D term* is still poorly constrained

KM15 K Kumericki and D Mueller arXiv:1512.09014v1
GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)

Impact of DVCS @ COMPASS in global analysis ?

Figure made by Pawel Sznajder using PARTON framework



and for the GPD E?

question to our theoretician colleagues

KM15 K Kumericki and D Mueller NPB (2010) 841 and arXiv:1512.09014v1

GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)

VGG Vanderhaeghen, Guichon, Guidal PRL80(1998),PRD60(1999), PPNP47(2001), PRD72(2005

Exclusive π^0 production on unpolarized proton target

using 2012 data

Exclusive π^0 production on unpolarized proton

$e\,p \rightarrow e\,\pi^0\,p$

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

Leading twist should be dominant

but $\approx$ only a few % of $\frac{d\sigma_T}{dt}$

The other contributions arise from coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

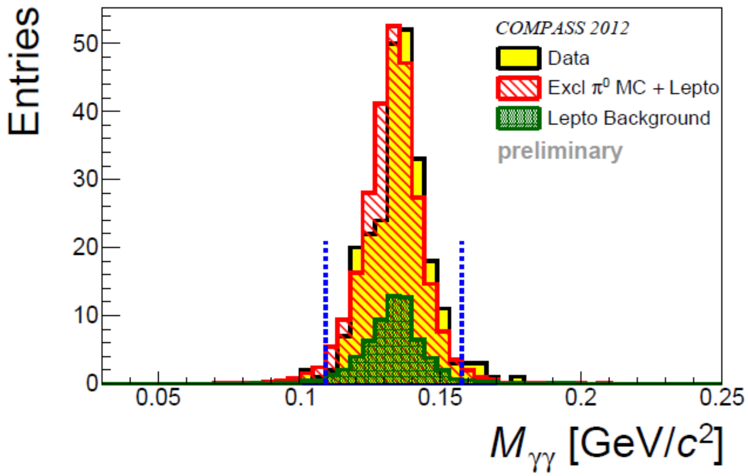
$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

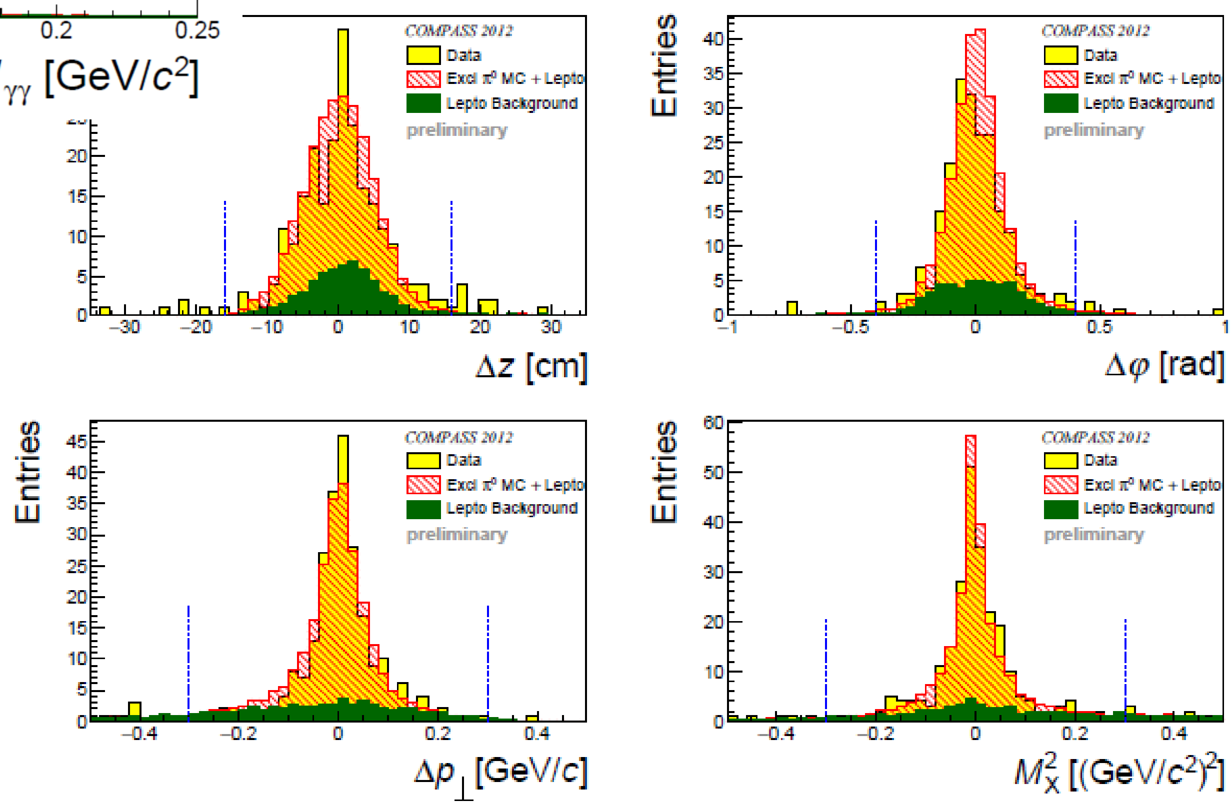
A large impact of $\bar{E}_T$
should be clearly visible in σ_{TT}
and in the dip at small t of σ_T

Exclusive π^0 production on unpolarized proton



Selection of exclusive events
Background of semi-inclusive LEPTO
+ Kinematic fit

all the cuts
are applied except
on the variable
which is shown
in each plot



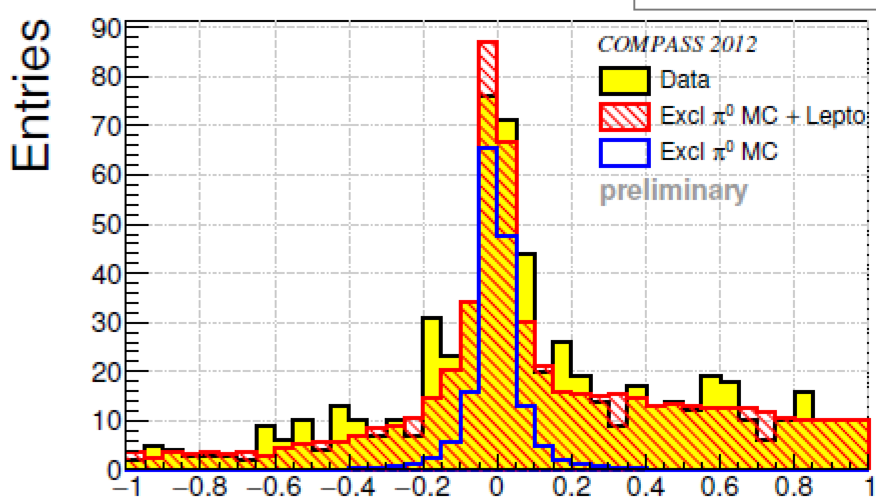
Exclusive π^0 production on unpolarized proton

SIDIS background estimation

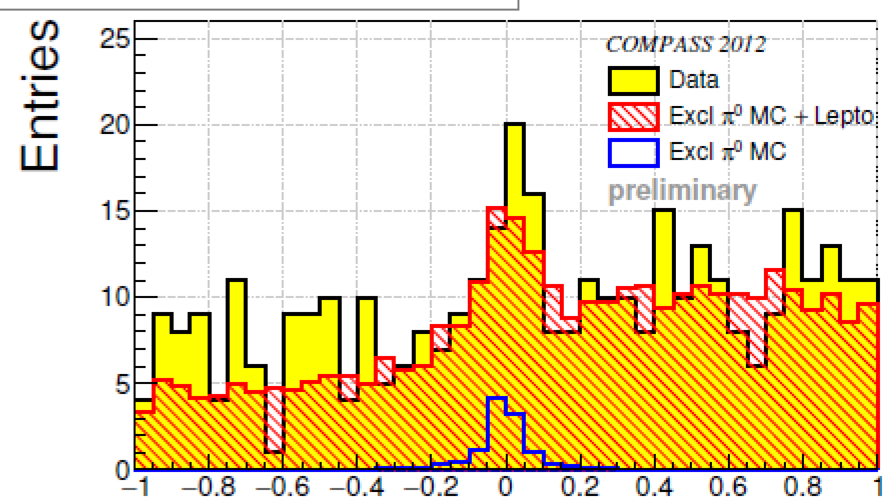
- use LEPTO MC to describe non exclusive background
- use exclusive π^0 MC to describe signal contribution
- find best description of data
  - in signal region (only two photon clusters)
  - in background region (more photon clusters)

Four-momentum balance:

$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$$



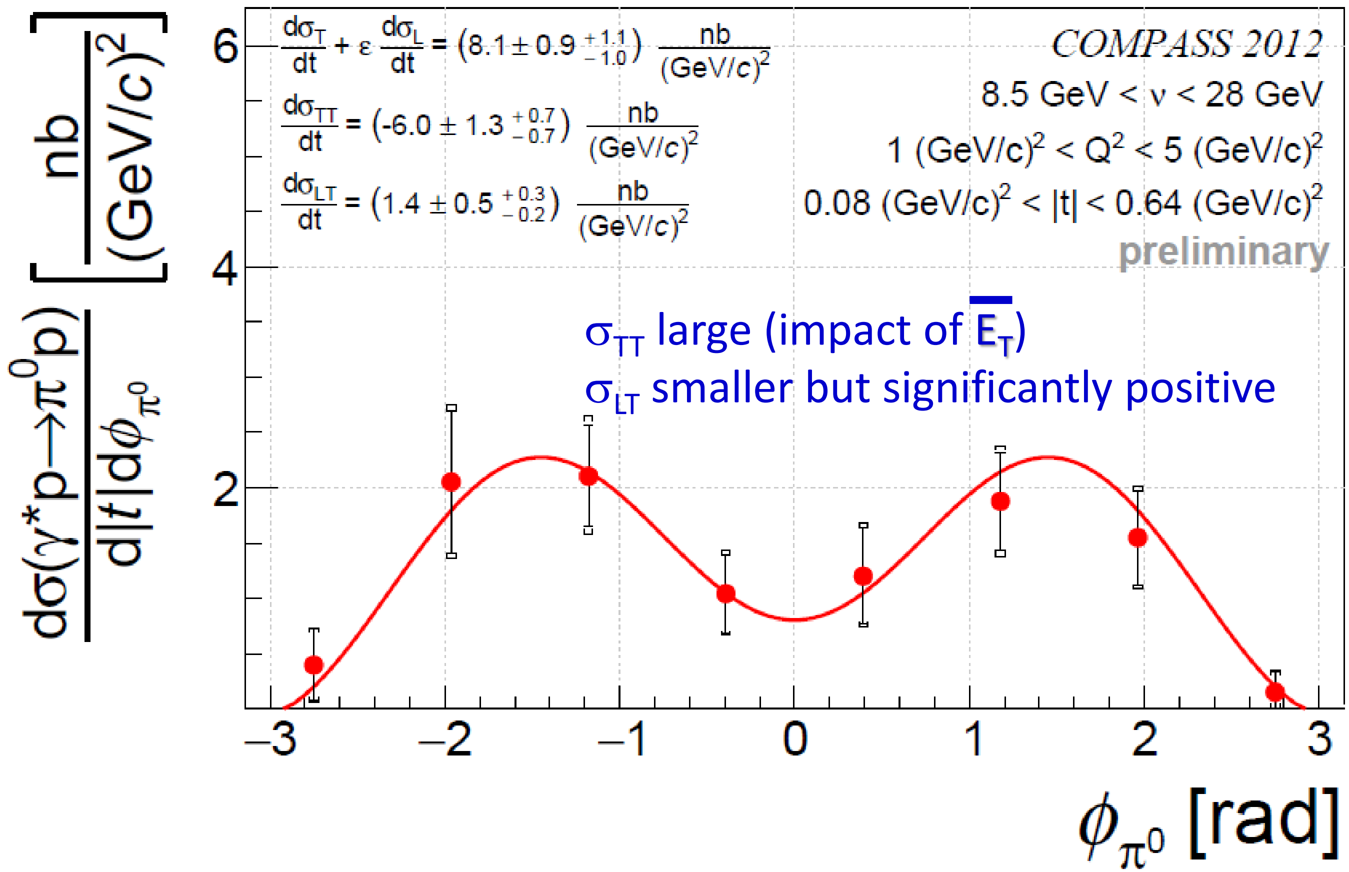
signal region M_X^2 [(GeV/c^2)^2]



background region M_X^2 [(GeV/c^2)^2]

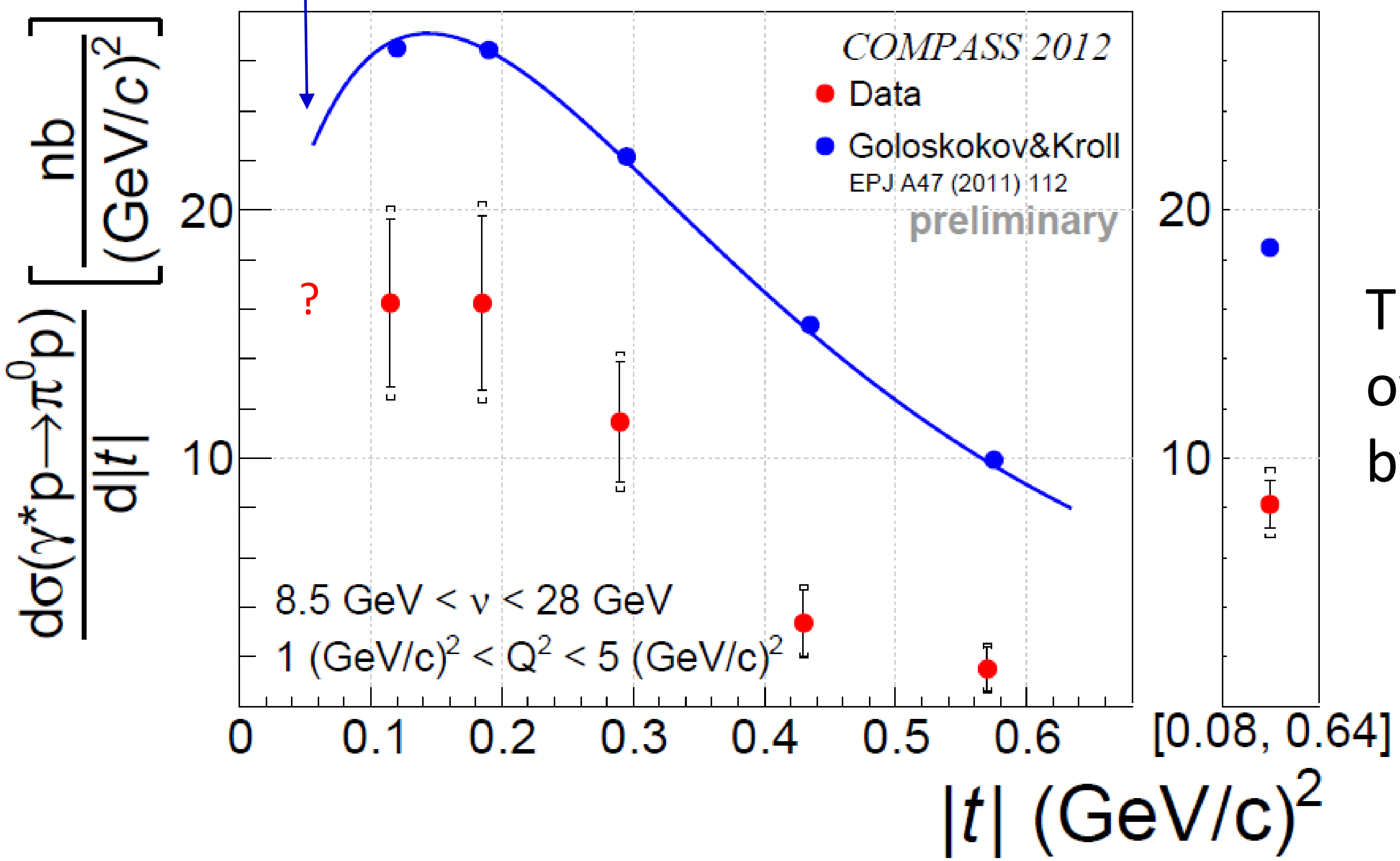
Exclusive π^0 production on unpolarized proton

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$



Exclusive π^0 production on unpolarized proton

The dip at small t
indicates the large impact of ETbar

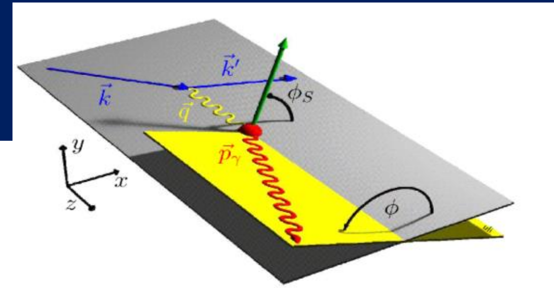


The GK model overestimates by a factor 2

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

using 2002-2010 data

Exclusive ρ^0 production



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

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

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

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

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

transsv. polar. target

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

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

transv. polar. target + long. polar. beam

σ — $i\,j$ for nucleon helicity, mn for photon helicity

Dominant interference terms:

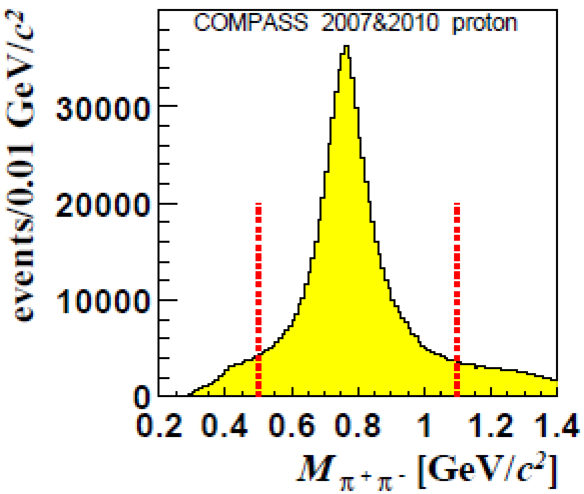
LL $\quad \gamma^*_L \to \rho^0_L$

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

Selection of exclusive evts without recoil detection

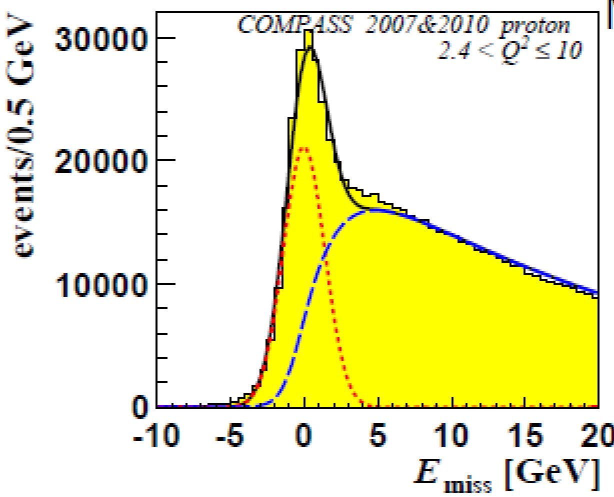
$\mu\ p_{\text{in NH3}} \rightarrow \mu'\ V\ p_{\text{non detected}}$

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



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

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

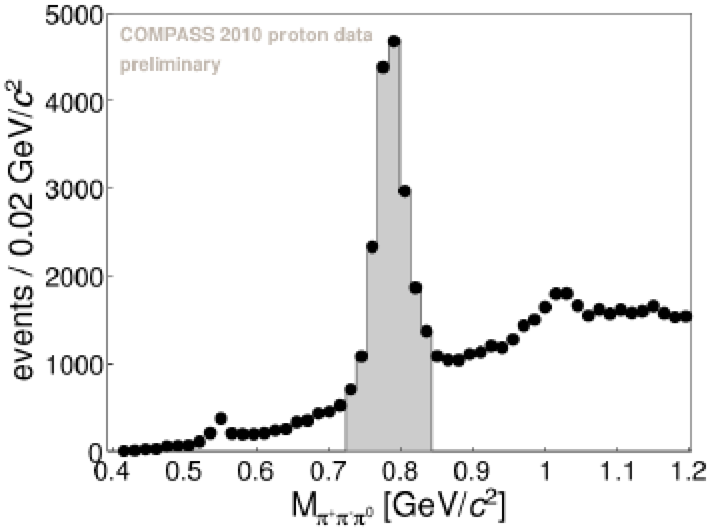


$-2.5 < E_{miss} < 2.5$ GeV

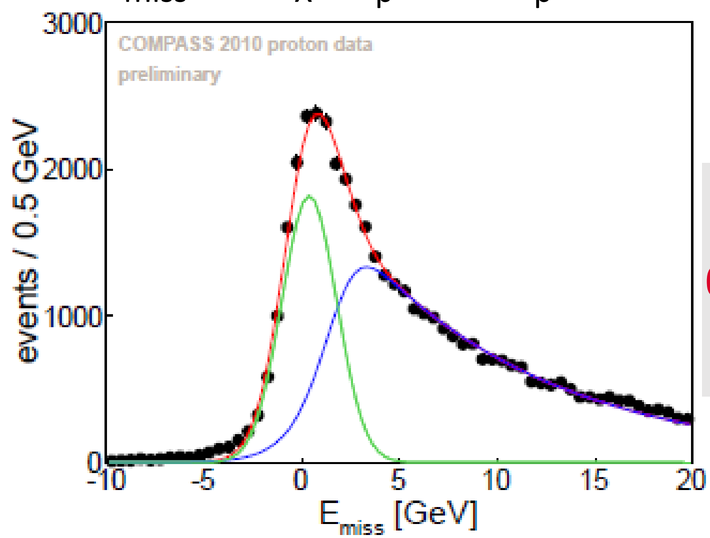
$0.1 < p_T^2 < 0.5$ GeV²

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

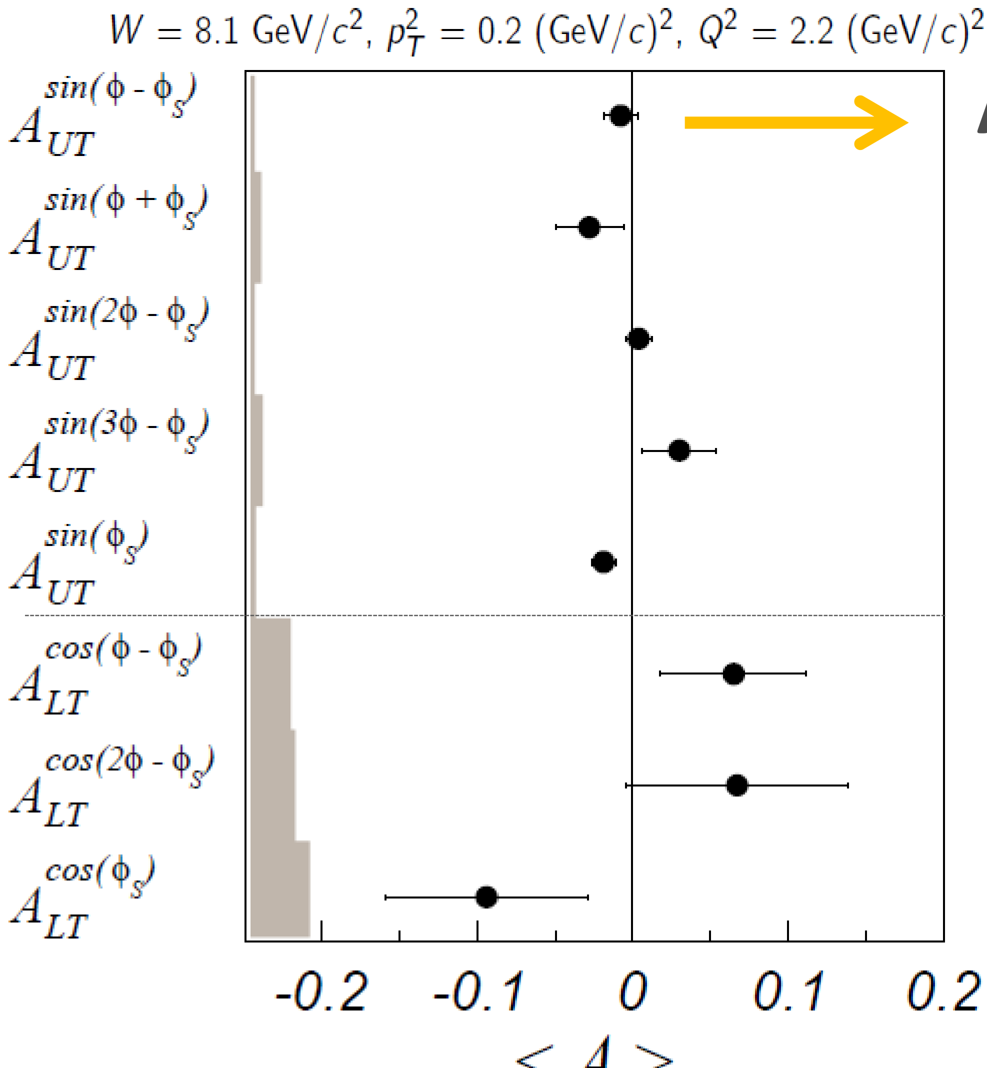
$0.05 < p_T^2 < 0.5$ GeV²

Background ~34%

exclusive ρ^0 production with Transv. Polar. Target

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

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

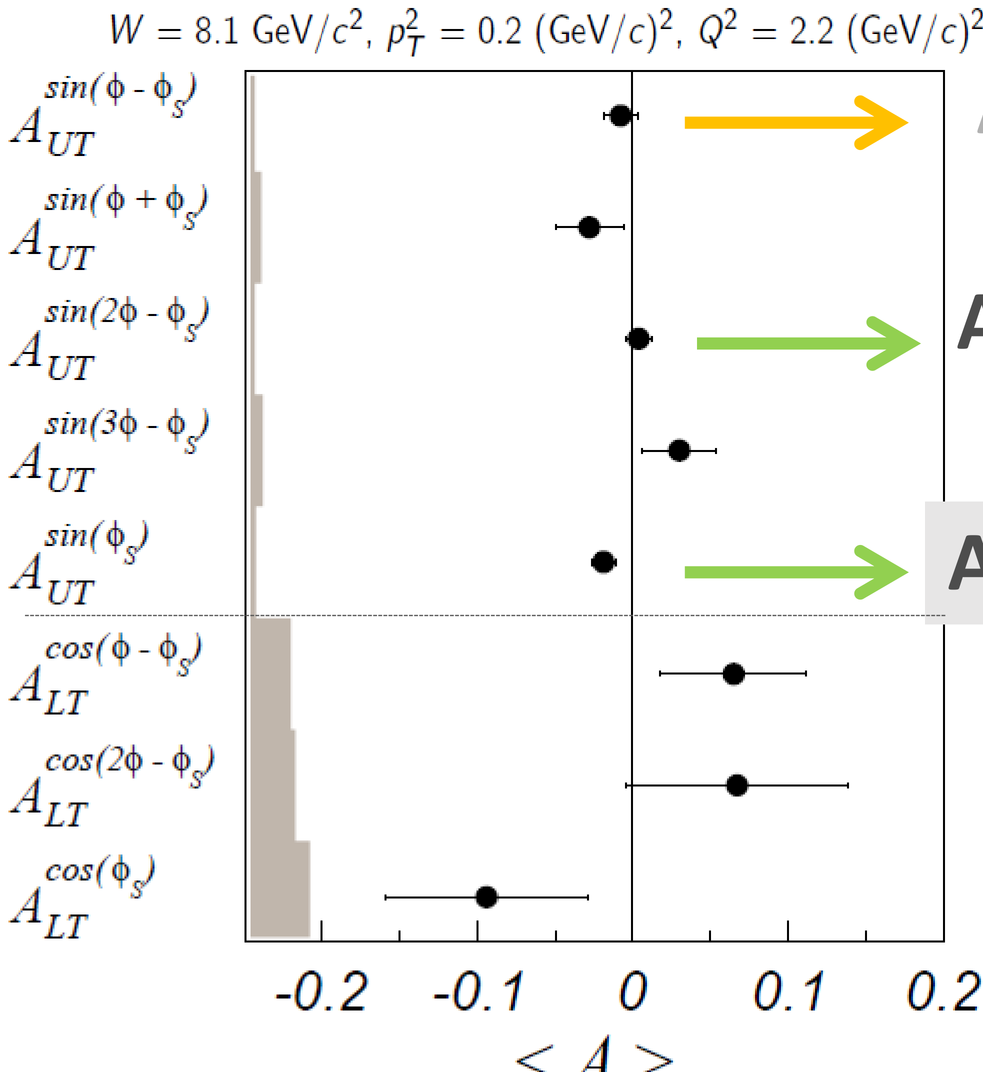
ω production should be powerful

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

exclusive ρ^0 production with Transv. Polar. Target

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

COMPASS 2007-2010,without recoil detector



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

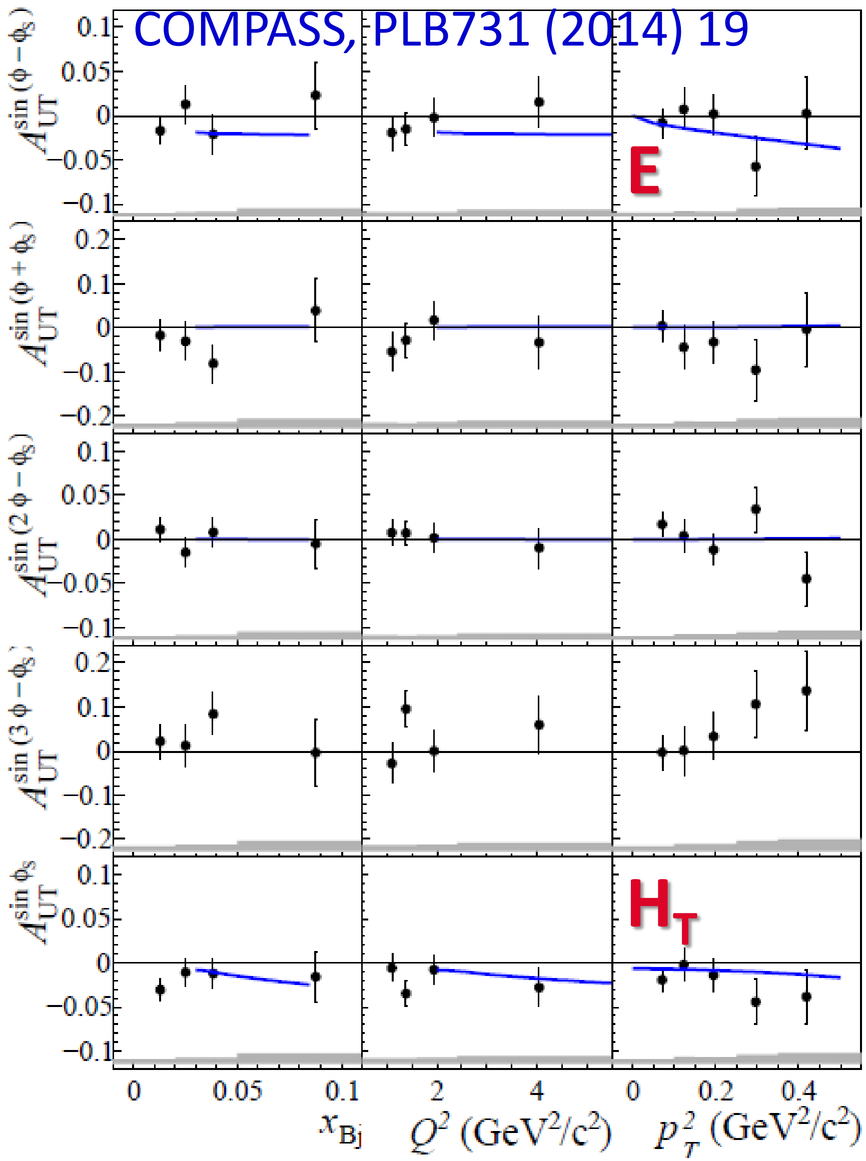
$A_{UT}^{\sin(2\phi - \phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T)$

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

➔ **H_T should not be small**

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

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

Comparison with a phenomeno-logical GPD-based model

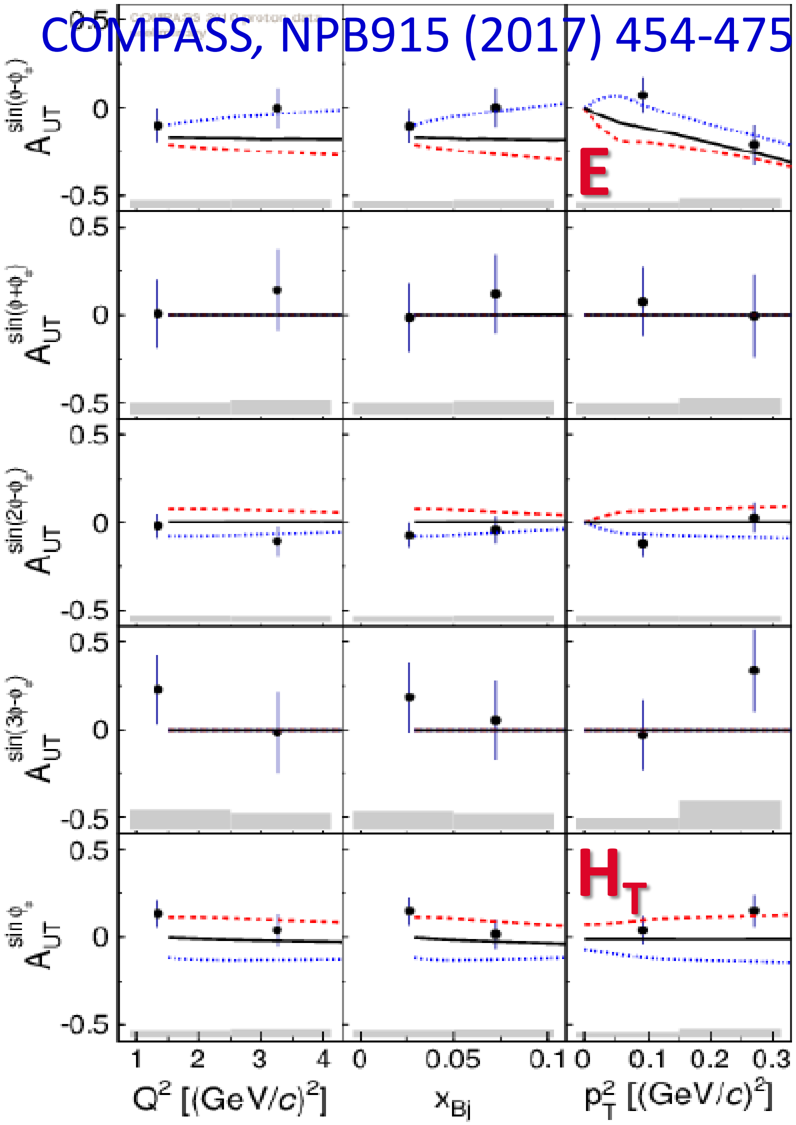
Goloskokov and Kroll (EPJ C74 (2014))

- 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

COMPASS, NPB915 (2017) 454-475

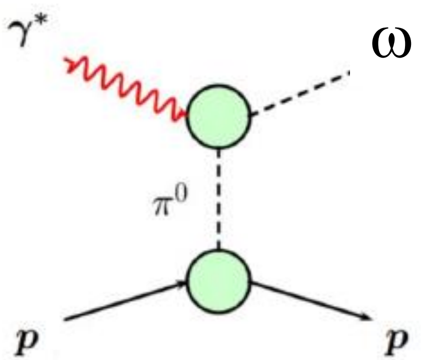


$\langle x_{Bj} \rangle \approx 0.049$, $\langle Q^2 \rangle \approx 2.2$ GeV^2
$\langle p_T^2 \rangle \approx 0.17$ GeV^2, $\langle W \rangle \approx 7.1$ GeV^2

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

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

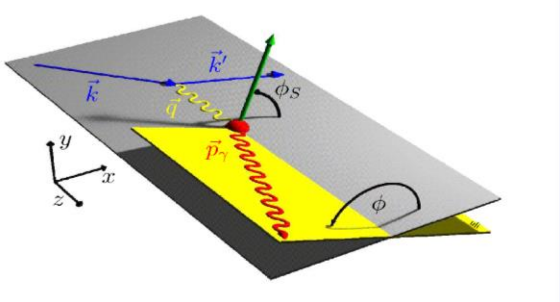
Future plan/idea with Transversely Polarized Target and Recoil Detection

after 2020

COMPASS + Transv. Pol. Target to constrain the GPD E

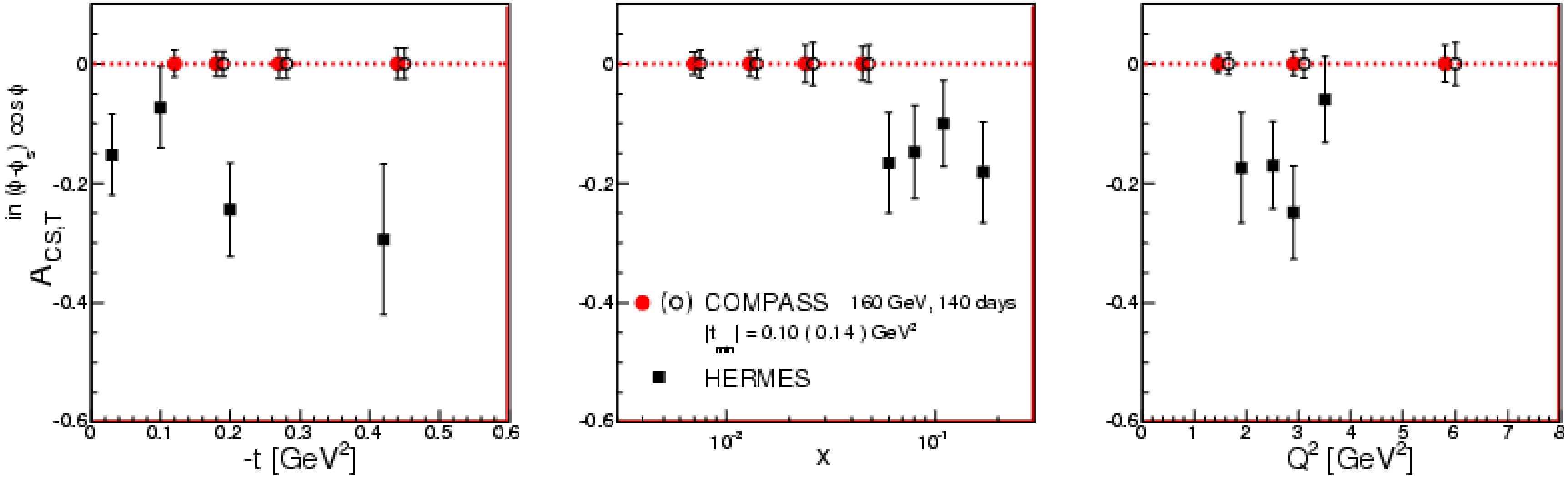
with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam and **transversely** polarized NH3 (proton) target

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



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

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



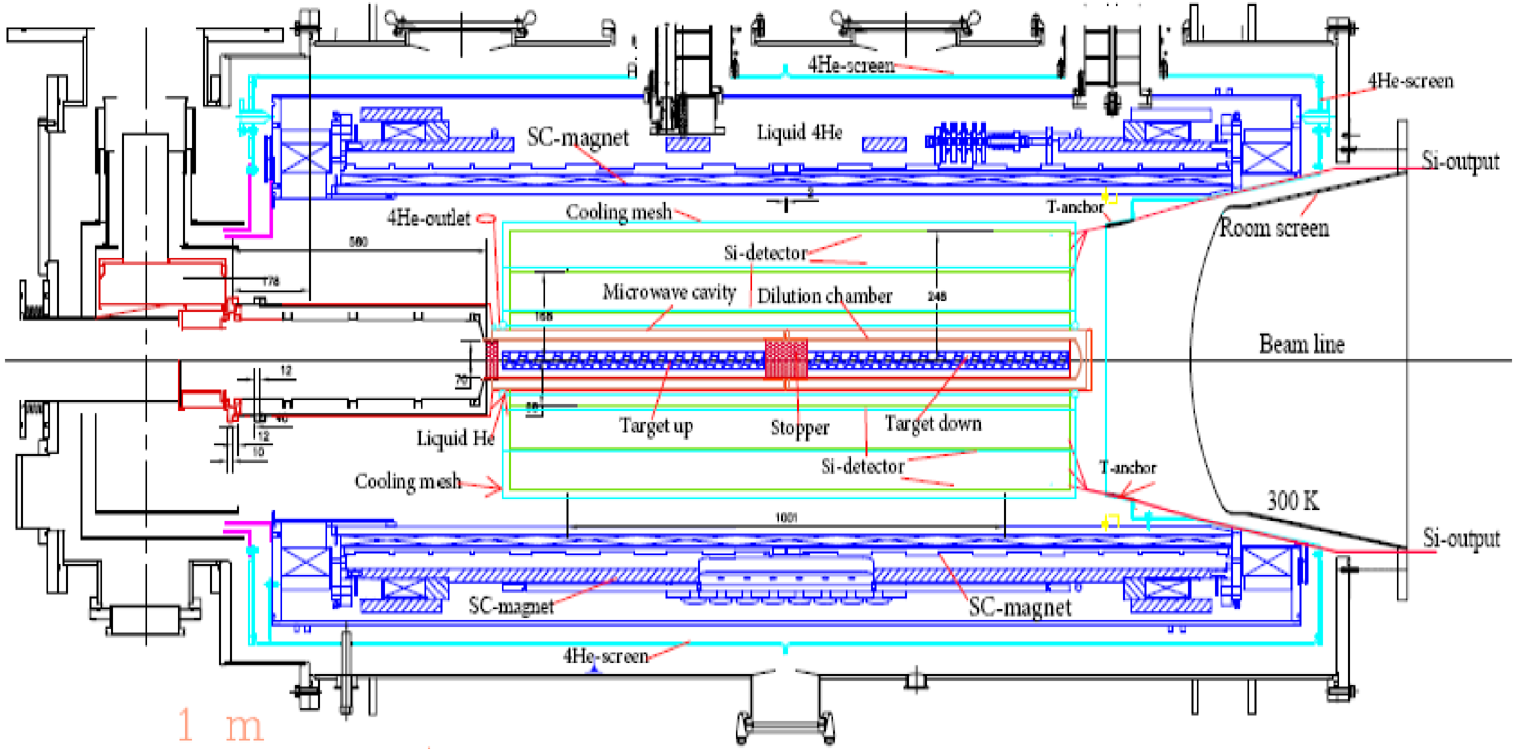
Questions: what is the impact of the CFF E measurement?
Impact on AOM of valence quarks? Or sea quarks? Or gluons?

How to realize such and experiment?

New design of the MW cavity of the present NH3 polarized target

Radial dimension of the free space outside of the MW ~180mm

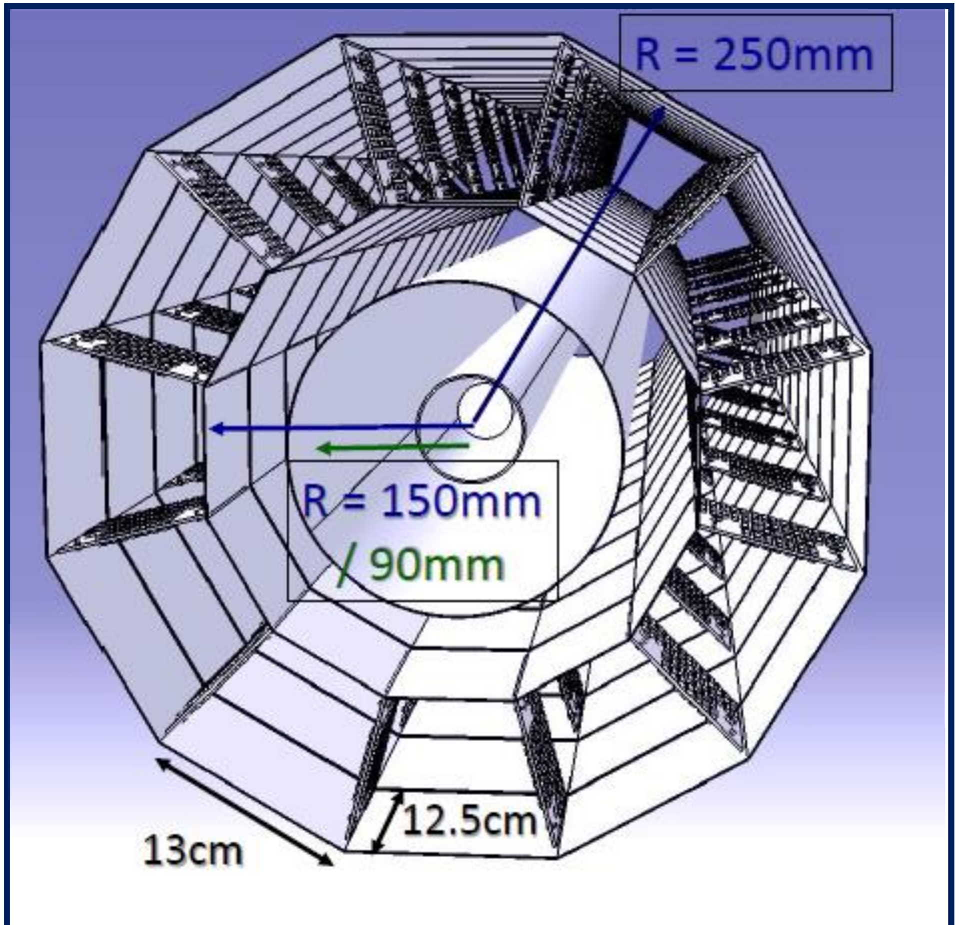
allow 3 concentric cylindrical layers of Silicon detectors (in green)



No possibility for ToF ➔ PID of protons/pions with dE/dx momentum and coordinates   (as for HERMES)

How to realize such and experiment?

First idea from Dubna, Munich, Illinois, Freiburg…



About 300 modules read by APV25

Major issues to overcome:

- number of Si strip
  for optimum position resolution
  about 1 to 2 cm (for $\Delta\phi=5°$)
  × 1 cm (for $\Delta z=3mm$)
- **Thermal load**
  very first estimate ~ 10 Watts
  Problem of cooling
- Access to a the **smallest minimum t**

Ring A 300µm Ring B 1000µm
Target radius 20mm
Cavity thickness 0.6mm
Cavity radius 100mm

TGEANT

t_{min}=0.0917 GeV2 P_{min}= 307MeV $\varepsilon_{\mu p\gamma}$=38.1%

Ex CAMERA t_{min}=0.0656 GeV2 P_{min}= 260MeV $\varepsilon_{\mu p\gamma}$=56.6%

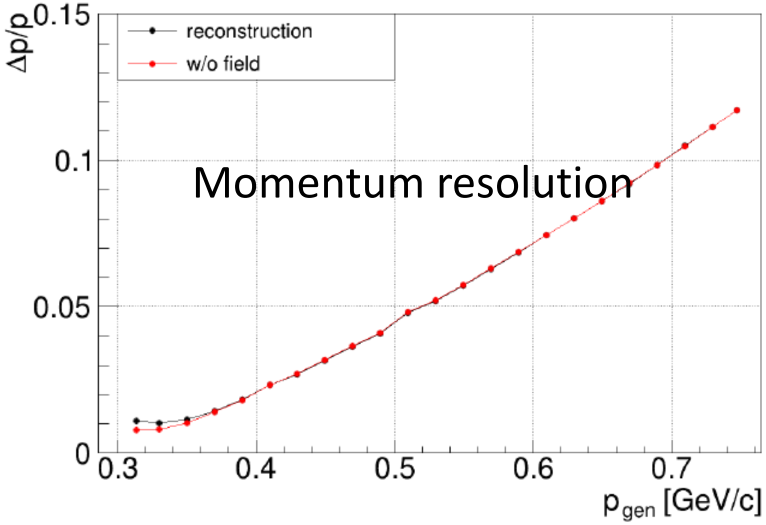
Reference: Ring A: 300 μm, Ring B: 1000 μm,
Target radius: 20 mm, Cavity thickness: 0.6 mm, Cavity radius: 100 mm

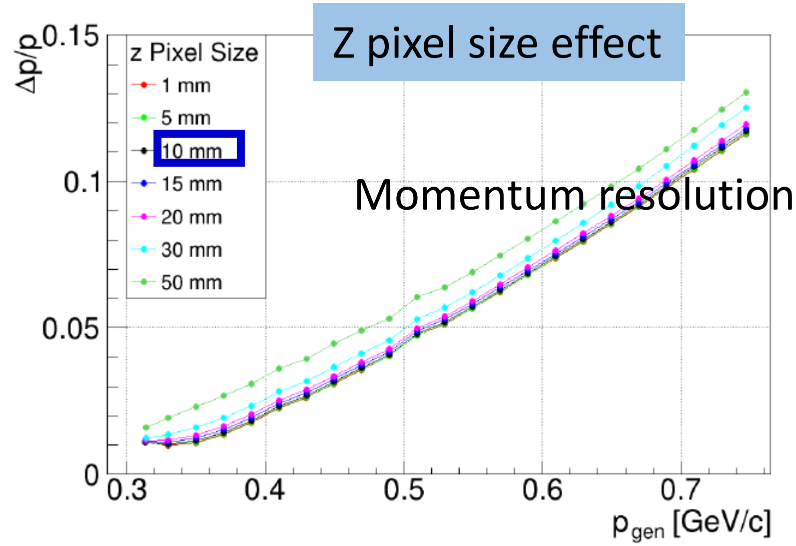
Setup changes w.r.t reference	$-t_{min}/(\mathrm{GeV}/c)^2$	Combined efficiency
Reference	0.0917	38.1%
NH3 target radius 15 mm	0.0817	34.4%
NH3 target radius 10 mm	0.0758	21.2%
Cu Cavity Thickness 0.5 mm	0.0907	38.6%
Cu Cavity Thickness 0.4 mm	0.0895	39.3%
Cu Cavity Thickness 0.3 mm	0.0876	39.7%
Cu Cavity Thickness 0.2 mm	0.0866	40.3%
Cu Cavity Radius 90 mm	0.0917	37.8%
Cu Cavity Radius 80 mm	0.0917	37.3%
Cu Cavity Radius 70 mm	0.0917	36.8%
Ring A Thickness 200 μm	0.0913	38.3%
Ring A Thickness 250 μm	0.0915	38.2%
Ring A Thickness 350 μm	0.0919	38.1%
CAMERA	0.0656	56.6%

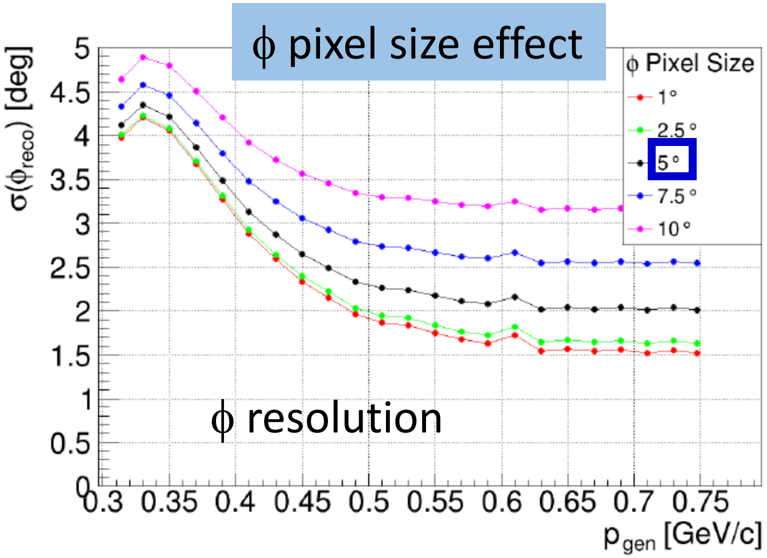
How to realize such and experiment?

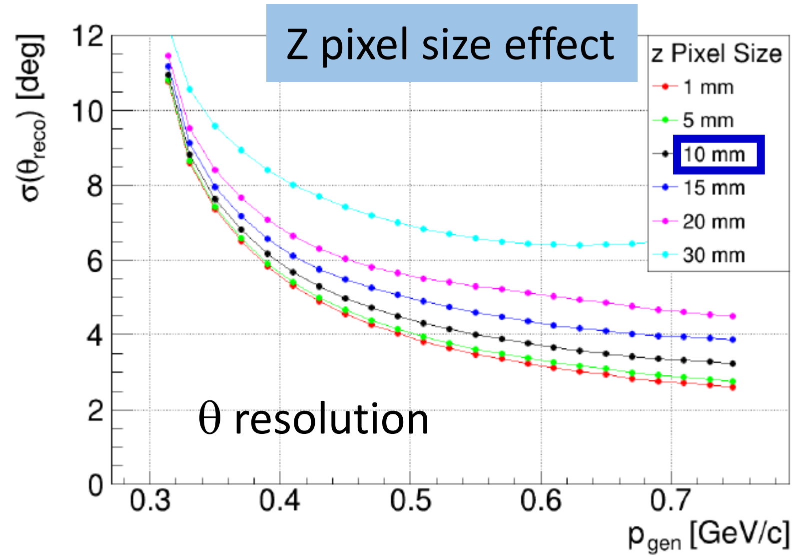
TGEANT

Comparison to Reference: 20 mm NH3, 0.6 mm Cu, 300 μm Ring A, 1000 μm Ring B









Only a major impact on the GPD E (and on OAM)

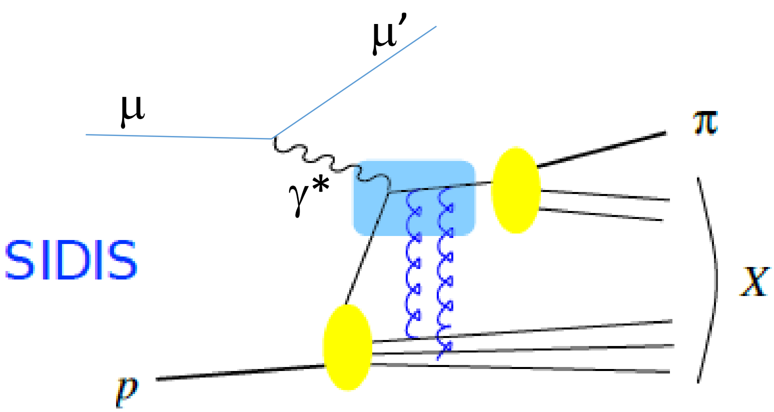
will deserve this challenging project

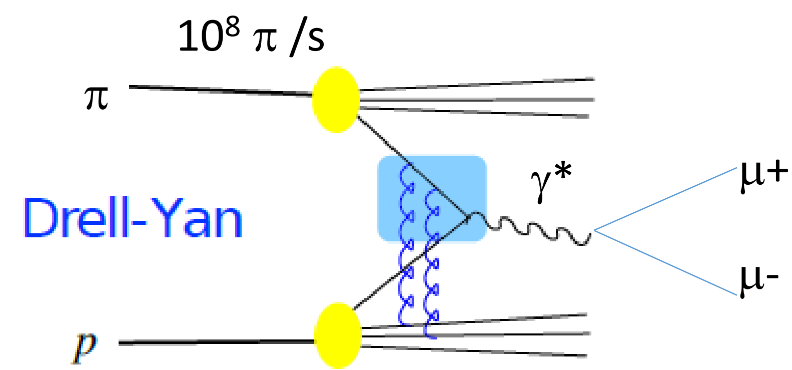
Quick overview on the COMPASS future
and on another major activity related to TMDs

For the global quest on 3D nucleon structure

SIDIS and DY programs at COMPASS for TMD studies

with transversely polarized NH3 target (2 cells of opposite polarisation)





SIDIS: spin asymmetry proportional to TMD (quarks) ⊗ FF (quark -> hadron)

DY: spin asymmetry proportional to TMD (quark) ⊗ TMD (antiquark)

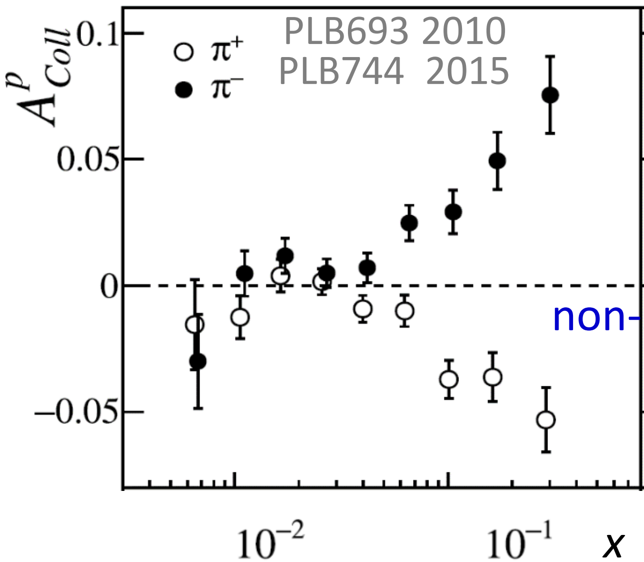
Expectation for the T-odd Sivers TMD :

$$\left(f_{1T}^{\perp}\right)_{\mathrm{SIDIS}} = -\left(f_{1T}^{\perp}\right)_{\mathrm{DY}}$$

Experimental check of this sign change is a crucial test of non-perturbative QCD

Polarized DY data taken in 2015, results expected soon

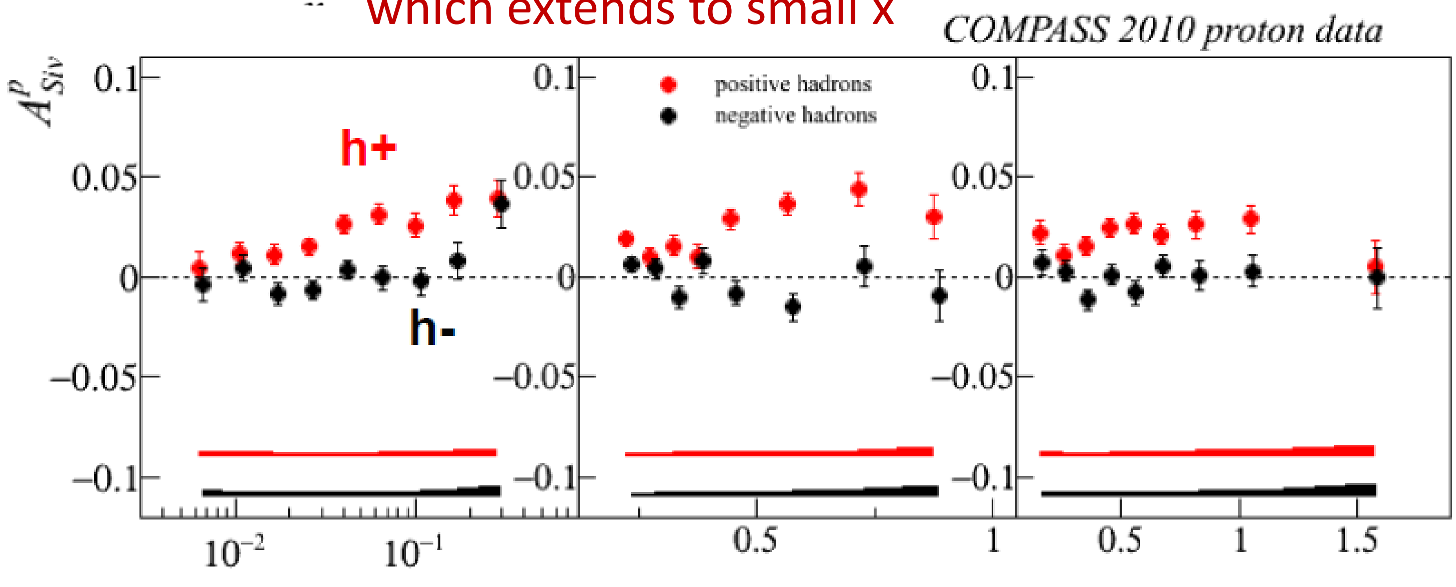
Major results for TMD studies in SIDIS



in the past 10 years, 2 of these new PDF's have been measured by COMPASS and HERMES and shown to be different from zero

non-zero Collins asymmetry on p

clear evidence for a positive signal for h^+ which extends to small x

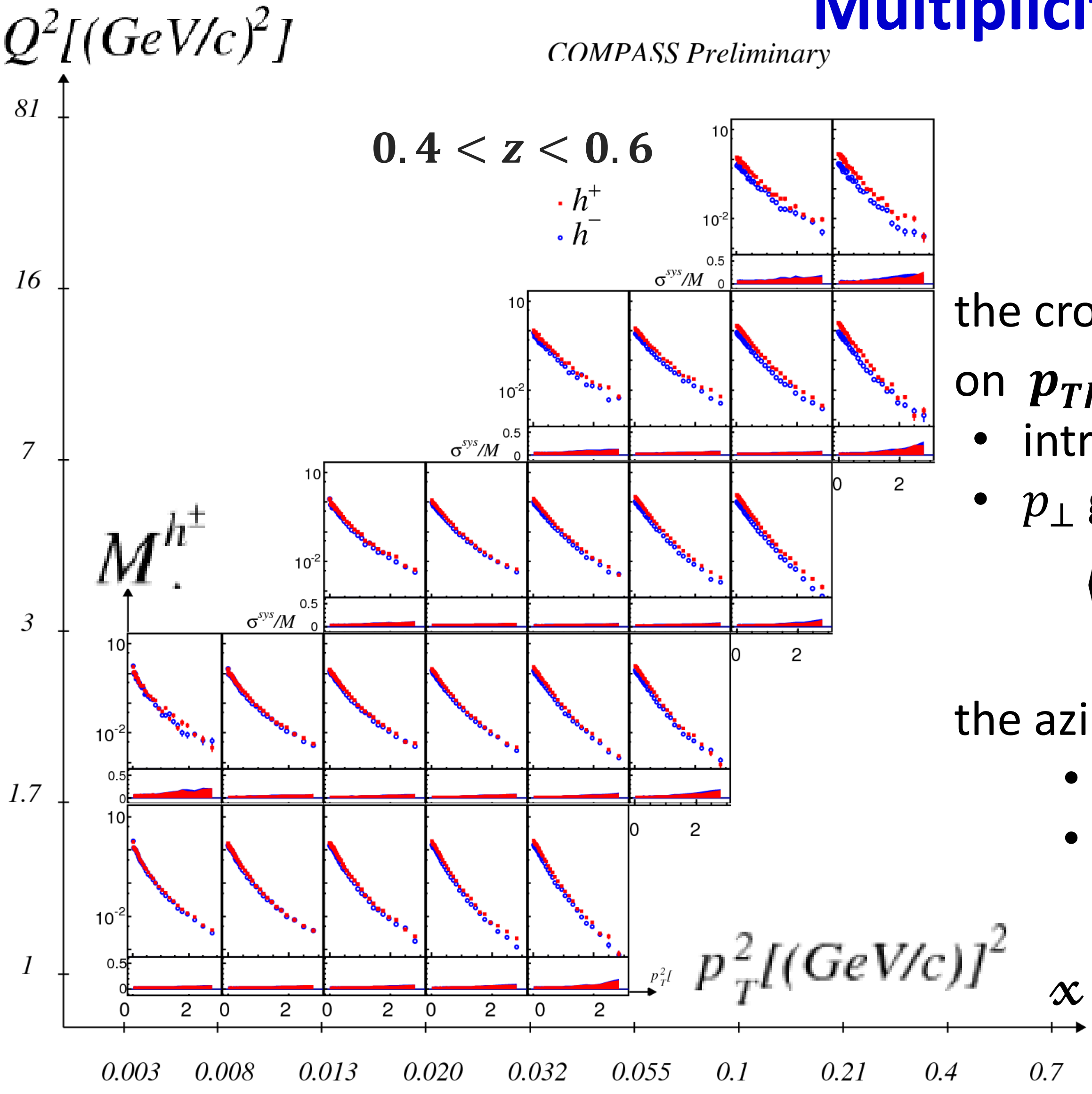


$\sigma_{syst} \sim 0.5\ \sigma_{stat}$

Plenty of data -> studies in (Q^2, x, z, p_{Th}) bins

Multiplicities in unpolarized SIDIS (on deuteron)

total: 4918 data points



the cross-section dependence on p_{Th} comes from:

- intrinsic k_T of the quarks
- $p_\perp$ generated in the quark fragment.

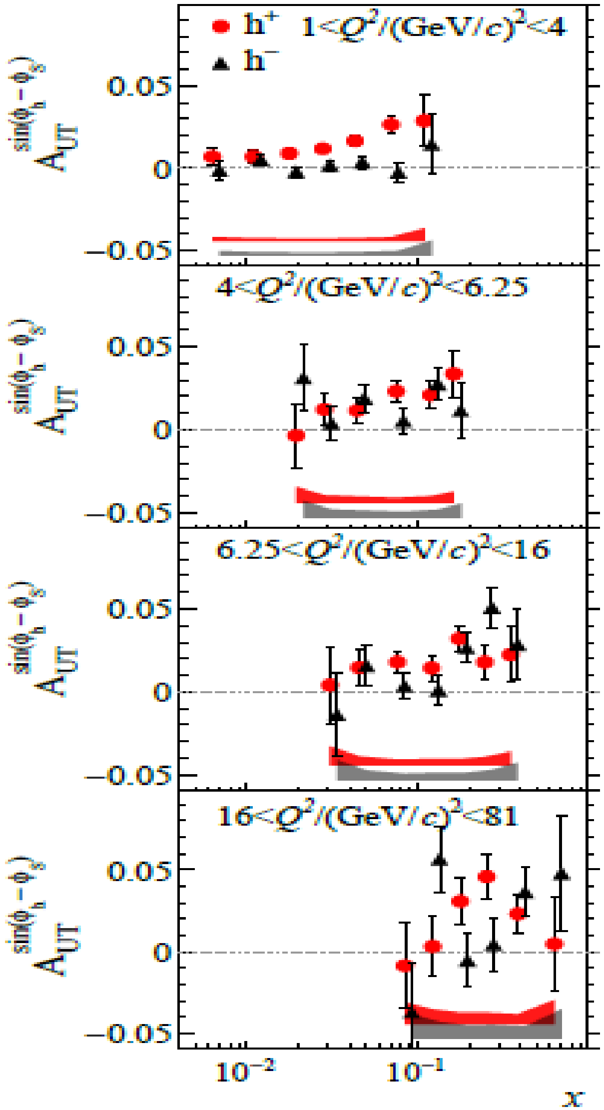
$$\left\langle p_{Th}{}^2 \right\rangle = \langle p_\perp{}^2 \rangle + z^2 \langle k_T{}^2 \rangle$$

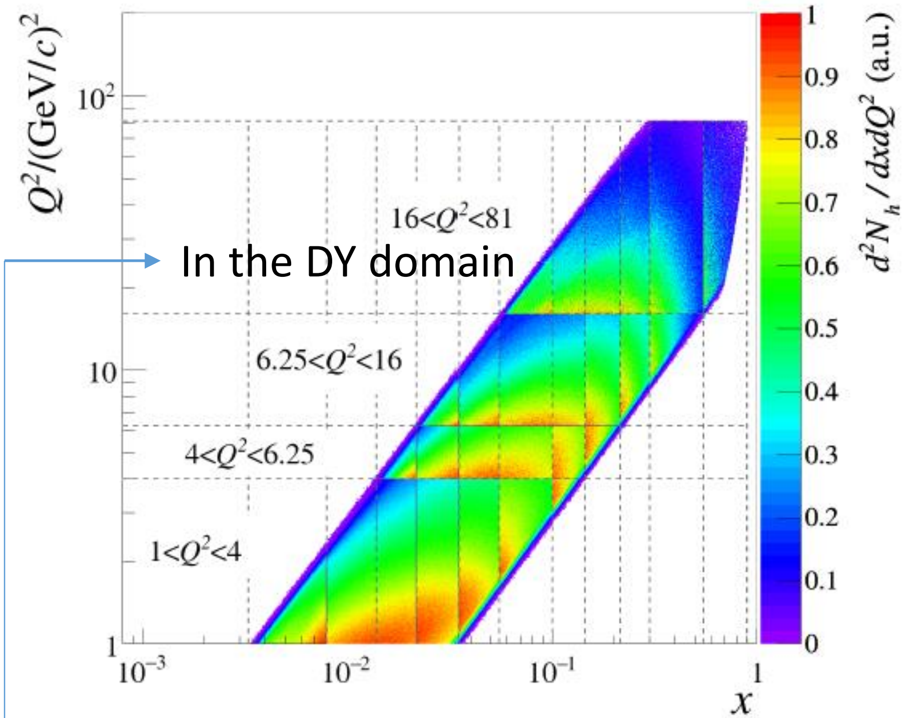
the azimuthal modulations comes from:

- intrinsic k_T of the quarks
- Boer-Mulders PDF

combined analysis to disentangle the different effects

COMPASS has measured TSA in the Q^2 range of the DY exp





Clearly positive

Test of change of sign feasible

COMPASS++: opportunities beyond 2020

COMPASS has joined the CERN ''Physics Beyond Colliders'' Working Group

Mid-range plans

- Exclusive DVCS and DVMP with transversely pol. proton target
- Semi-inclusive DIS with transv polarized deuteron target
- Pion DY
- Hadron spectroscopy

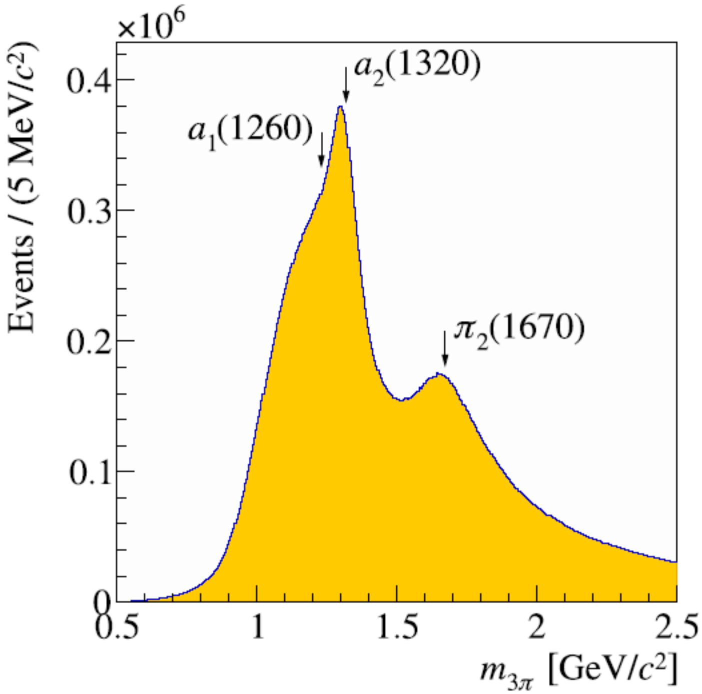
Long range focus on separated kaon and antiproton beams

up to 3.2×10^7 $\bar{p}$ /s (gain of 50) and 8×10^6 K /s (gain of 80)

- TMD parton distribution via DY
- Strange meson excitation spectrum
- Primakoff with kaon
- Direct photon production

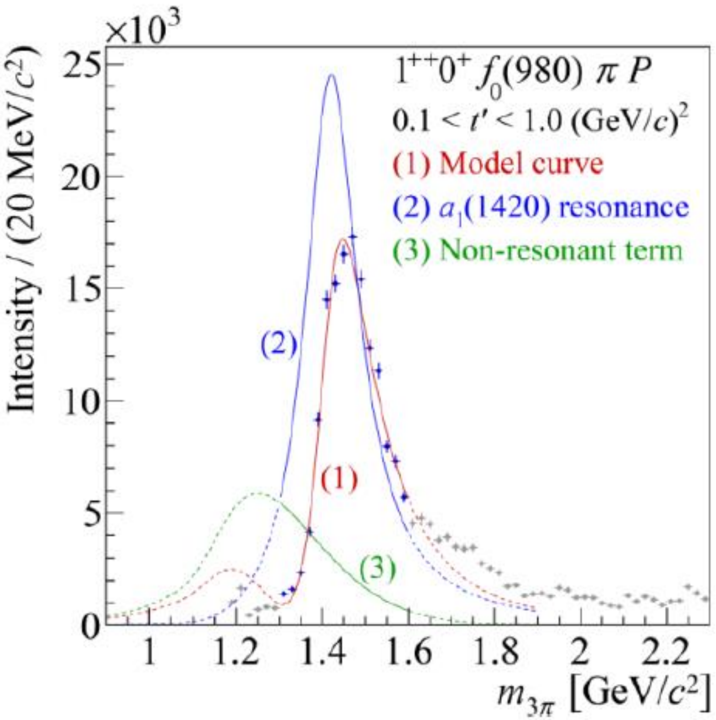
Just a look about meson spectroscopy

$\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$



46 million exclusive 3π events
(10 - 100 more than for previous experiments)
Partial-wave fit with 88 waves
in narrow 3π mass slides

A new axial-vector meson a1 (1420)



C. Adolph et al., COMPASS, PRL 115, 082001 (2015)

COMPASS results in the Part Data Group

2016 Review of Particle Physics.
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016).

π ELECTRIC POLARIZABILITY α_π

See HOLSTEIN 2014 for a general review on hadron polarizability.

VALUE (10^{-4} *fm*^{3})	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$2.0 \pm 0.6 \pm 0.7$	63k	[1] ADOLPH 2015A	SPEC	$\pi^- \gamma \to \pi^- \gamma$ Compton scatt.

[1] Value is derived assuming $\alpha_\pi = -\beta_\pi$.

C. Adolph at al., COMPASS, Phys. Rev. Lett. 114, 062002 (2015)

References

ADOLPH 2015A	PRL 114 062002	Measurement of the Charged-Pion Polarizability
HOLSTEIN 2014	ARNPS 64 51	

$a_1(1420)$ $I^G(J^{PC}) = 1^-(1^{++})$

$a_1(1420)$ MASS	1414^{+15}_{-13} MeV
$a_1(1420)$ WIDTH	153^{+8}_{-23} MeV

C. Adolph at al., COMPASS, Phys. Rev. Lett. 115, 082001 (2015)

Decay Modes

	Mode	*Fraction* (Γ_i/Γ)	*Scale Factor/ Confidence Level*	*P (MeV/c)*
Γ_1	$f_0(980)\pi$	seen		341

To do list after:

Christain Weiss:

- J/psi and t-slope

Marc Vanderhaeghen:

- 8 points from Jlab
- Meaning of F1 and improved theoretical t-slope
- Gluons/sea quarks…

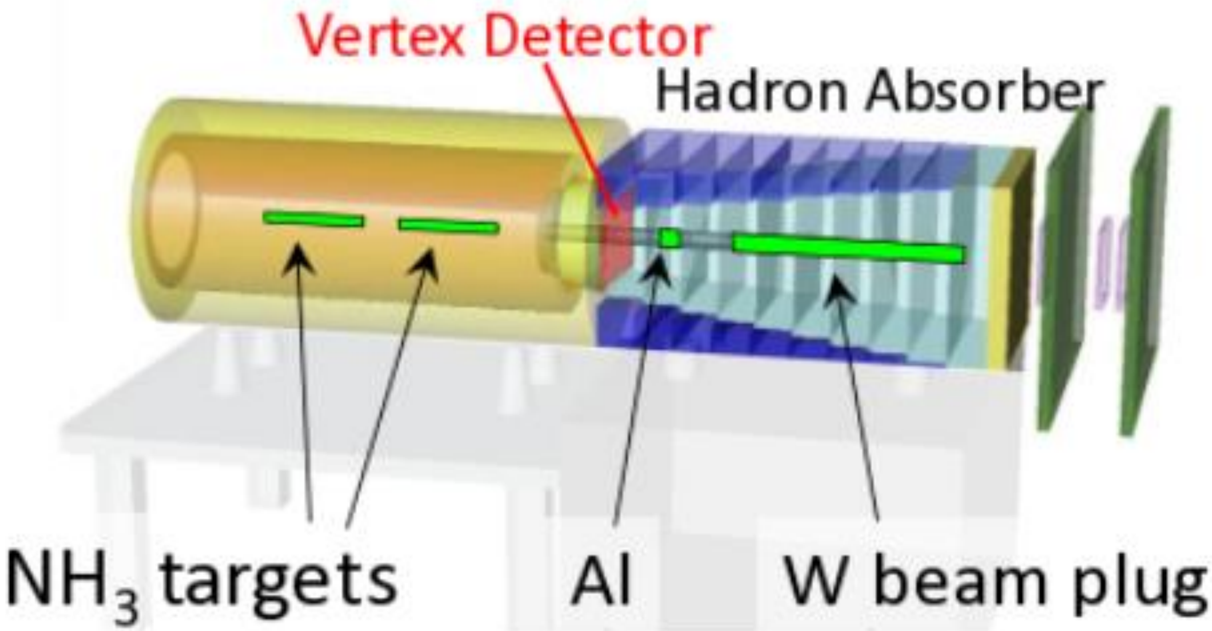
- Rad Corrections

Latifa and meeting in May

Kresimir GPD E

Pi0 RC in cosphi impact on Sigma_LT

D term to be extracted with ReH and Integrated ImH!

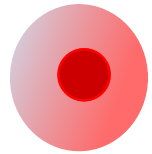


Vertex Detector
Hadron Absorber
NH3 targets
Al
W beam plug

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

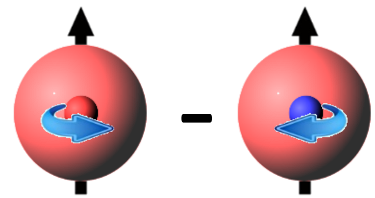
Chiral-even

$H \longleftrightarrow q$



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

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



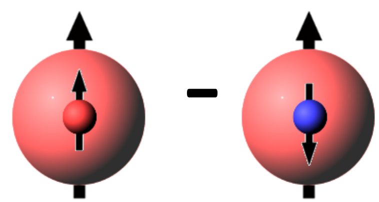
Sivers: quark k_T
& nucleon transv. Spin

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

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

Chiral-odd

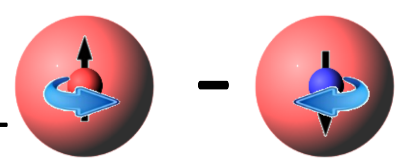
$H_T \longleftrightarrow h_1$



Transversity: quark spin
& nucleon transv. spin

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

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

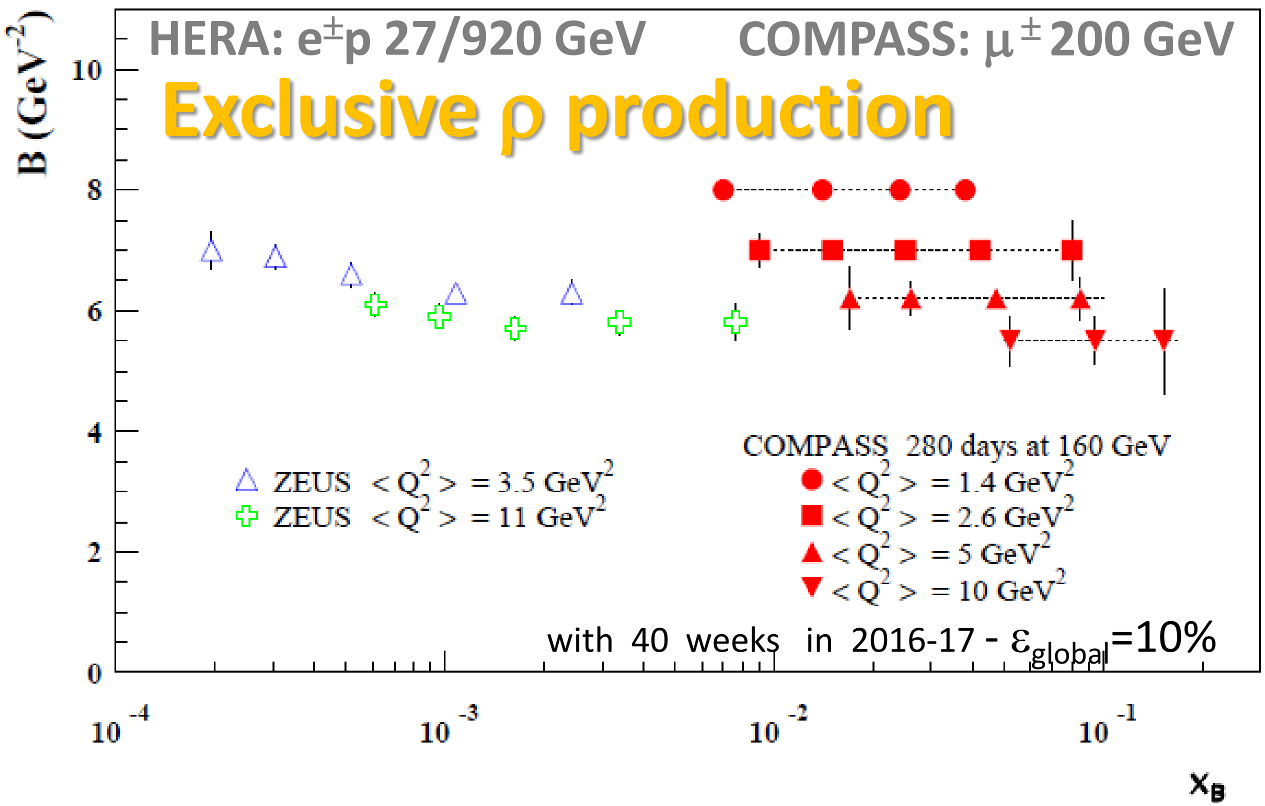


Boer-Mulders: quark k_T
& quark transverse spin

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

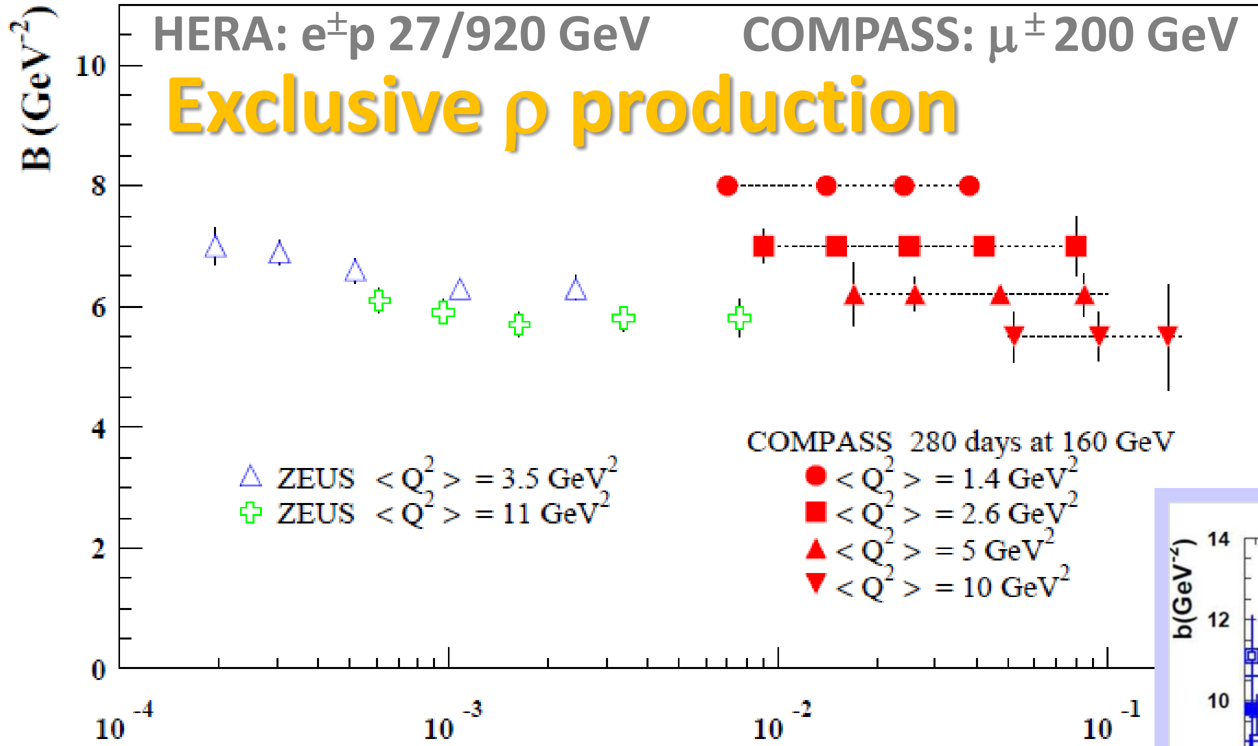
Transverse imaging at COMPASS

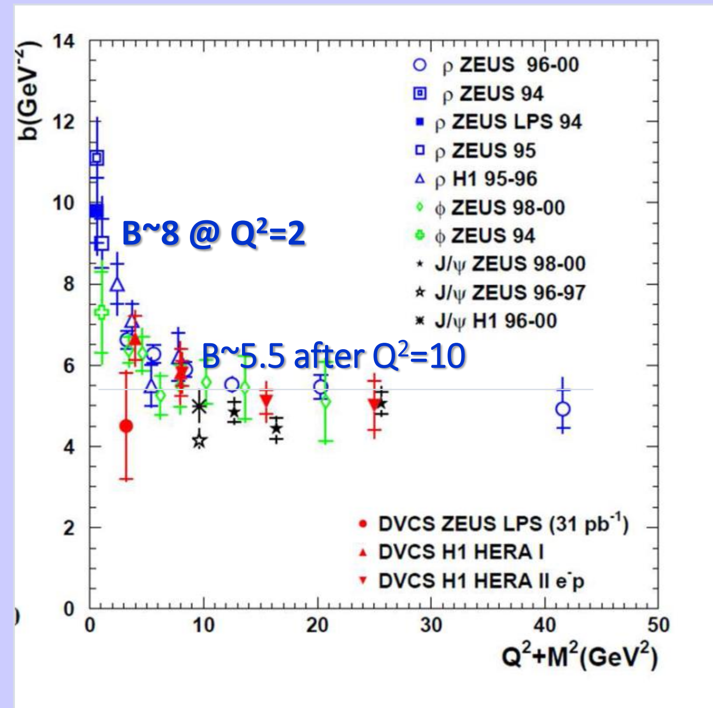
$d\sigma^{excl.\ \rho}/dt \sim \exp(-B|t|)$



model developed by Sandacz renormalised according Goloskokov and Kroll prediction

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

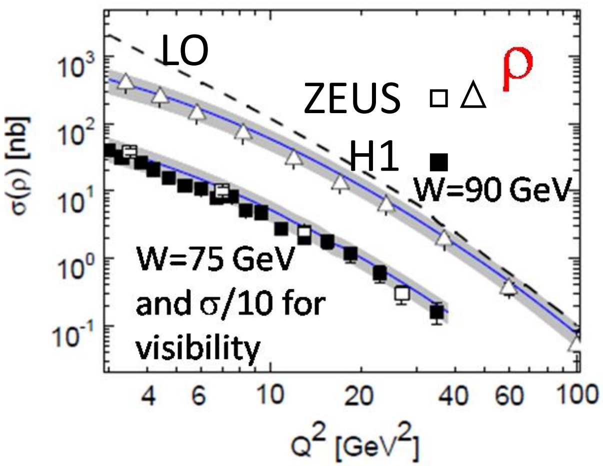


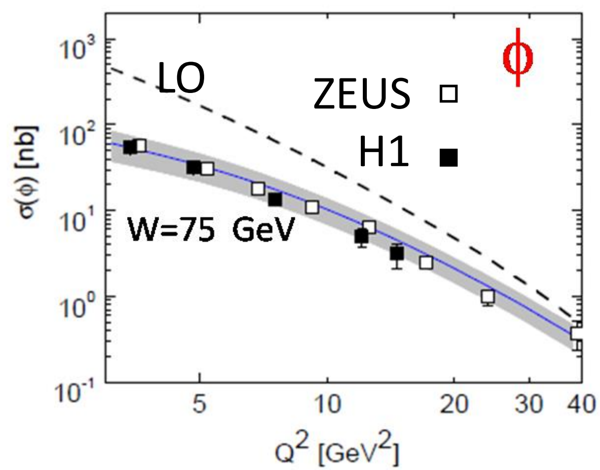


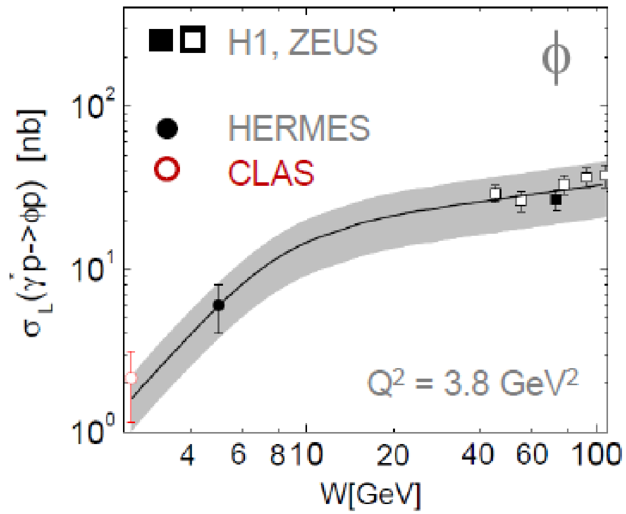
We are sensitive
to the nucleon transverse size
+ to the meson transverse size

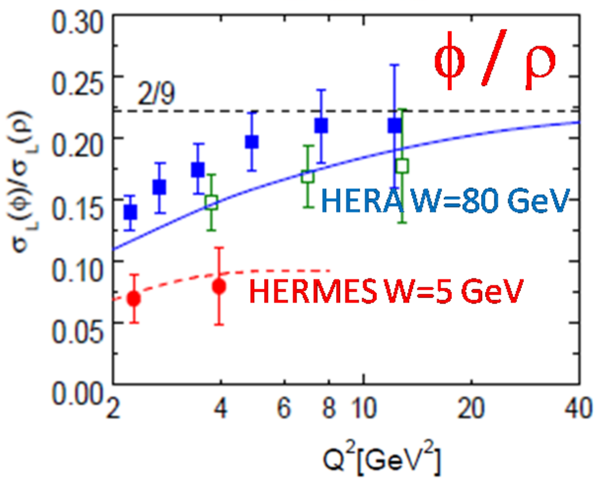
Predictions for mesons from GK model

GK model for GPDs (determined for mesons) including
dominant (longitudinal) $\gamma_L^* \, p \rightarrow \rho_L \, p$ and transv. polar. $\gamma_T^* \, p \rightarrow \rho_T p$
quark and gluon contributions and beyong leading twist









$$H\rho^0 = 1/\sqrt{2}\,(2/3\, H^u + 1/3\, H^d + 3/8\, H^g)$$
$$H\phi = -1/3\, H^s - 1/8\, H^g$$

Show strong violation of $\sigma_\phi/\sigma_\rho = 2/9$ at HERA energies and low Q^2 is caused by the flavor symmetry breaking $\bar{u}(x) = \bar{d}(x) = \kappa_s s(x)$

Q^2 dependence of σ_ϕ/σ_ρ at HERA is determined by κ_s factor completely.
At HERMES energies we have valence quarks contribution which gives additional suppression of σ_ϕ/σ_ρ ratio.