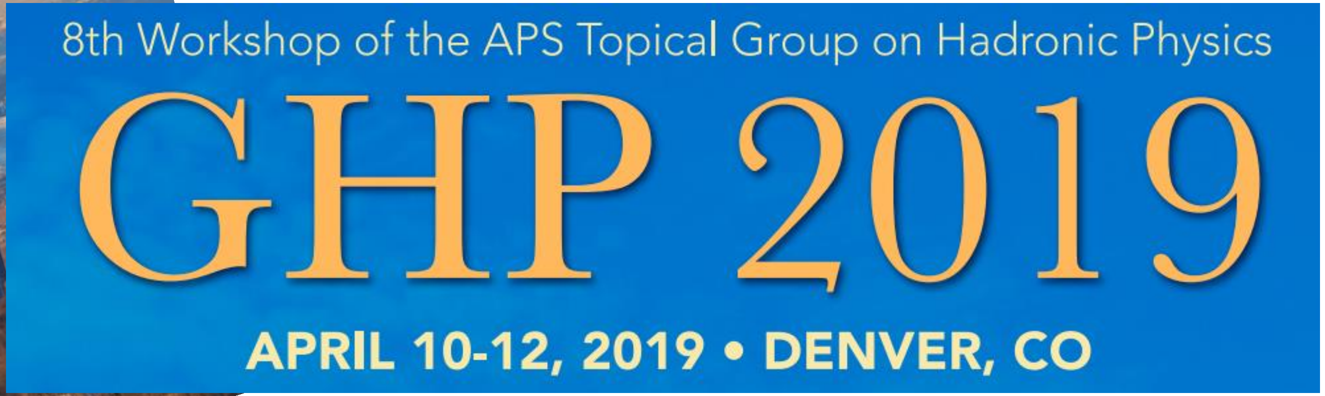
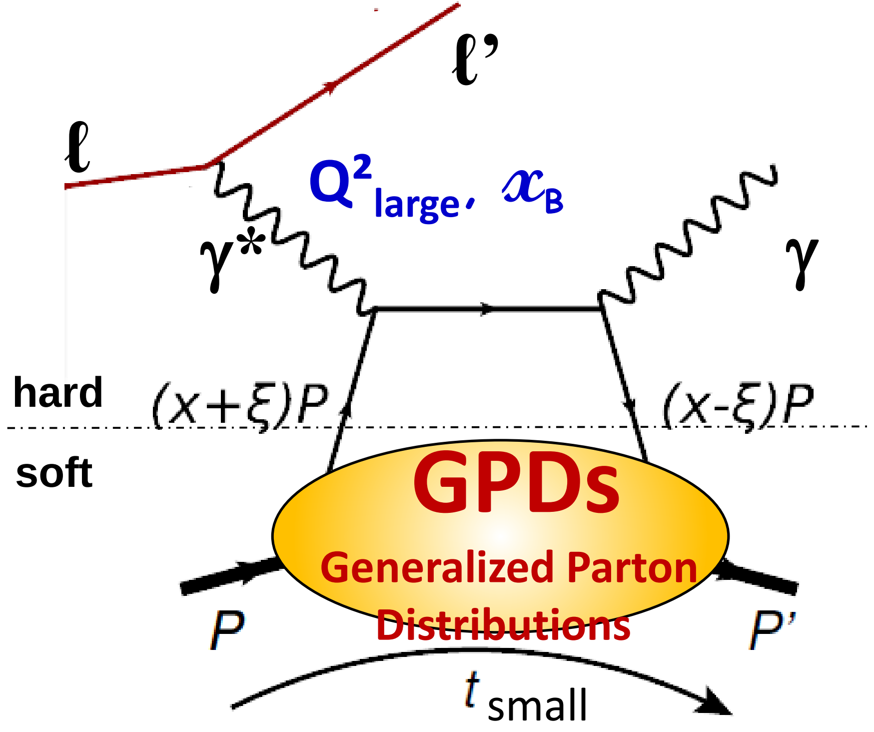


GPD at COMPASS at CERN

1- DVCS
2- HEMP

Nicole d'Hose – CEA – Université Paris-Saclay

Deeply virtual Compton scattering (DVCS)



D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

DVCS: **ℓp→ ℓ' p' γ**
the golden channel
because it interferes with
the Bethe-Heitler process

also meson production
ℓp→ ℓ' p' π, ρ, ω or **ϕ** or **J/ψ...**

The GPDs depend on the following variables:

x: average long. momentum

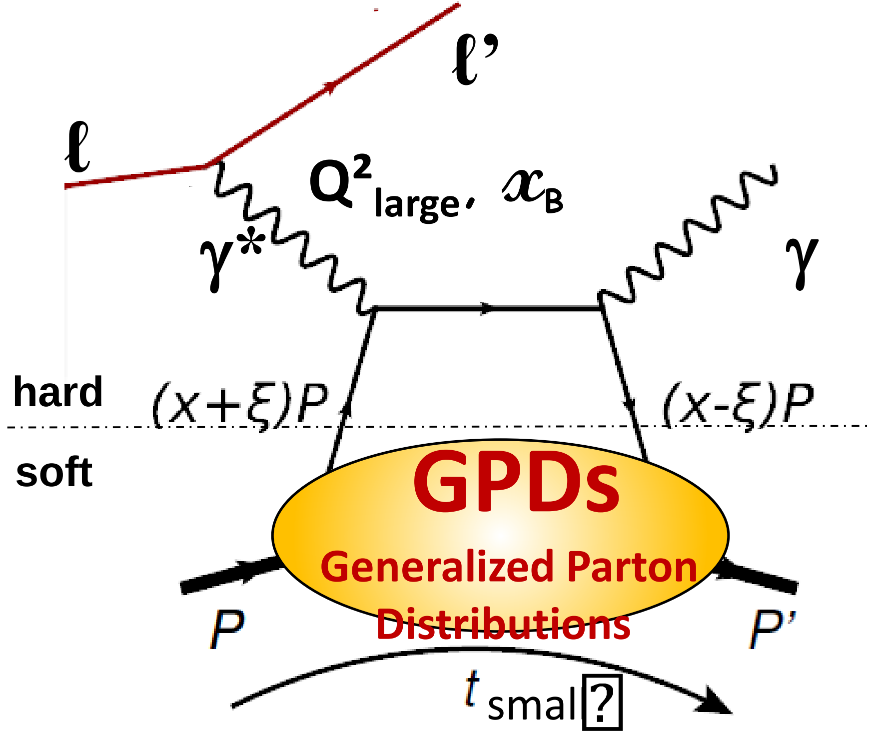
ξ: long. mom. difference

t: four-momentum transfer
related to $b_\perp$ via Fourier transform

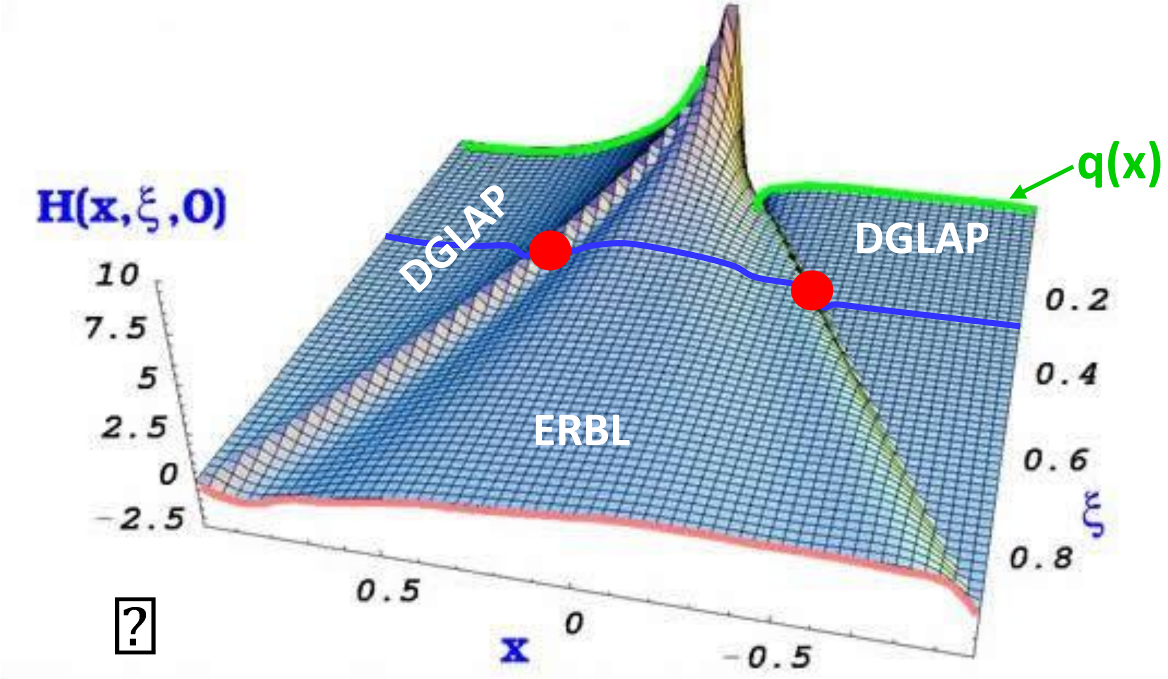
The variables measured in the experiment:

E_ℓ, Q^2, $x_B \sim 2\xi/(1+\xi)$,
t (or $\theta_{\gamma^*\gamma}$) and ϕ (ℓℓ' plane/γγ* plane)

Deeply virtual Compton scattering (DVCS)



From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



The amplitude DVCS at LT & LO in α_S (GPD **H**) :

Real part Imaginary part

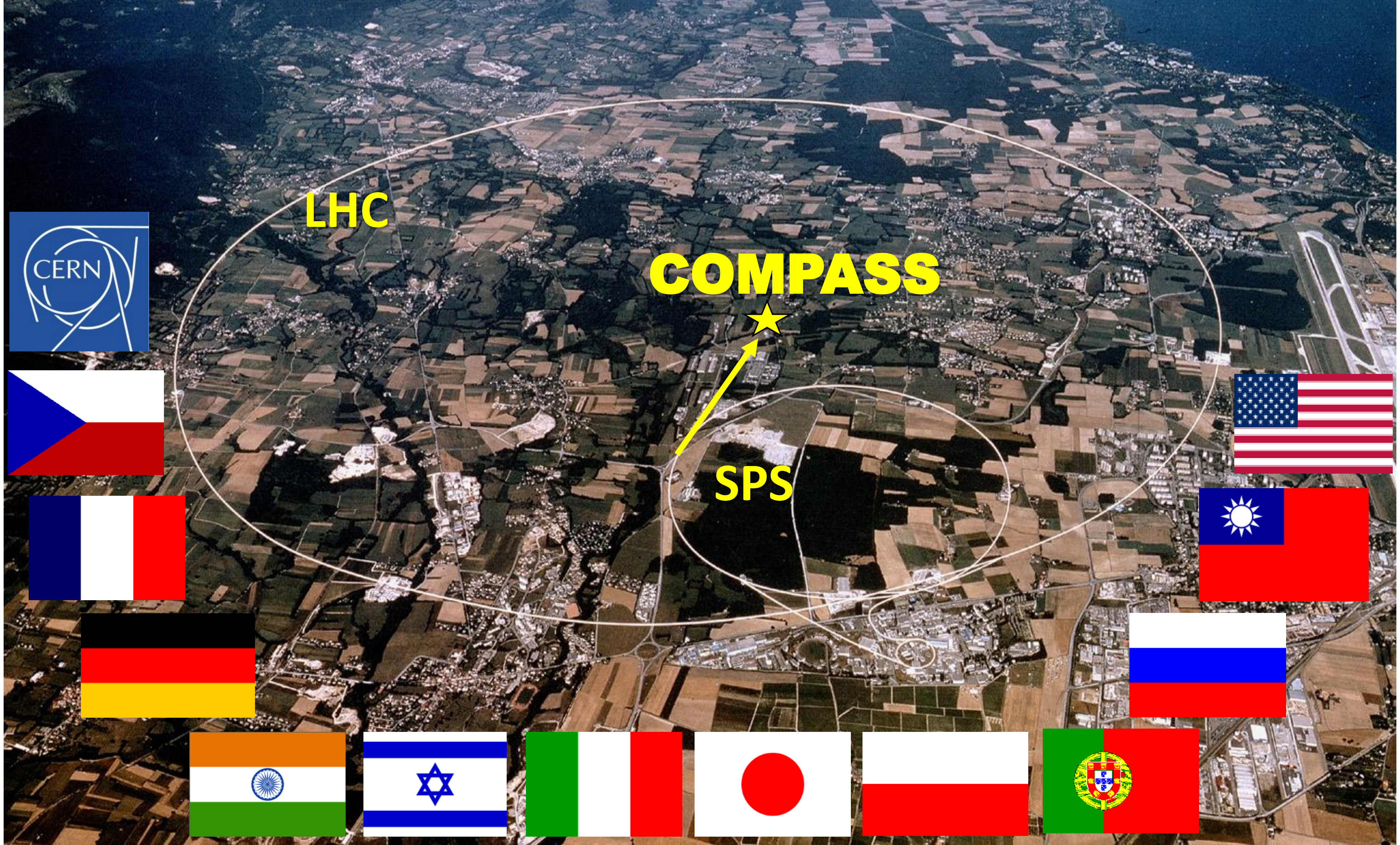
$$\underset{t,\,\xi\ \text{fixed}}{\mathcal{H}} = \int_{-1}^{+1} dx \, \frac{H(x,\ ,t)}{x- \ +i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \, \frac{H(x,\ ,t)}{x-} - i\,\pi\, H(x \pm \xi, x, t)$$

In an experiment we measure

Compton Form Factor $\mathcal{H}$

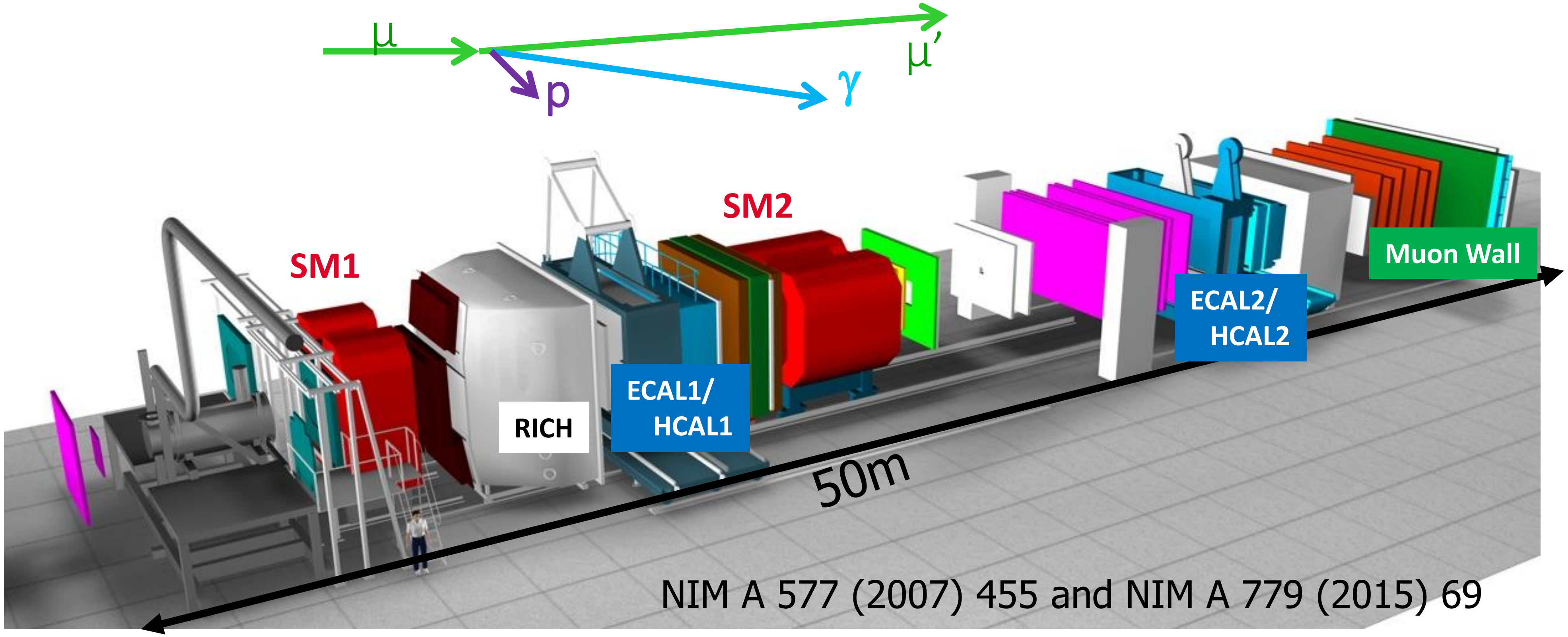
$$\mathcal{R}e\mathcal{H}(\xi,t) = \int dx \, \frac{Im\mathcal{H}(x,t)}{x-} + D(t)$$

COMPASS: Versatile facility with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams of high energy ~200 GeV



The DVCS experiment at COMPASS

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



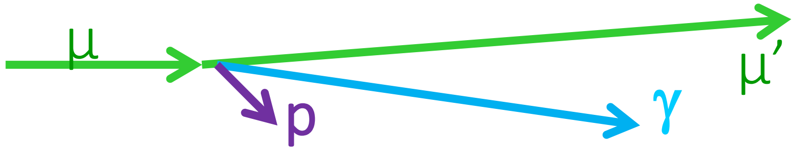
Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

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

The DVCS experiment at COMPASS

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



New equipements:

- **2.5m LH2 target**

- **4m ToF Barrel CAMERA**

24 inner & outer scintillators separated by ~1m

1 GHz SADC readout, 330ps ToF resolution

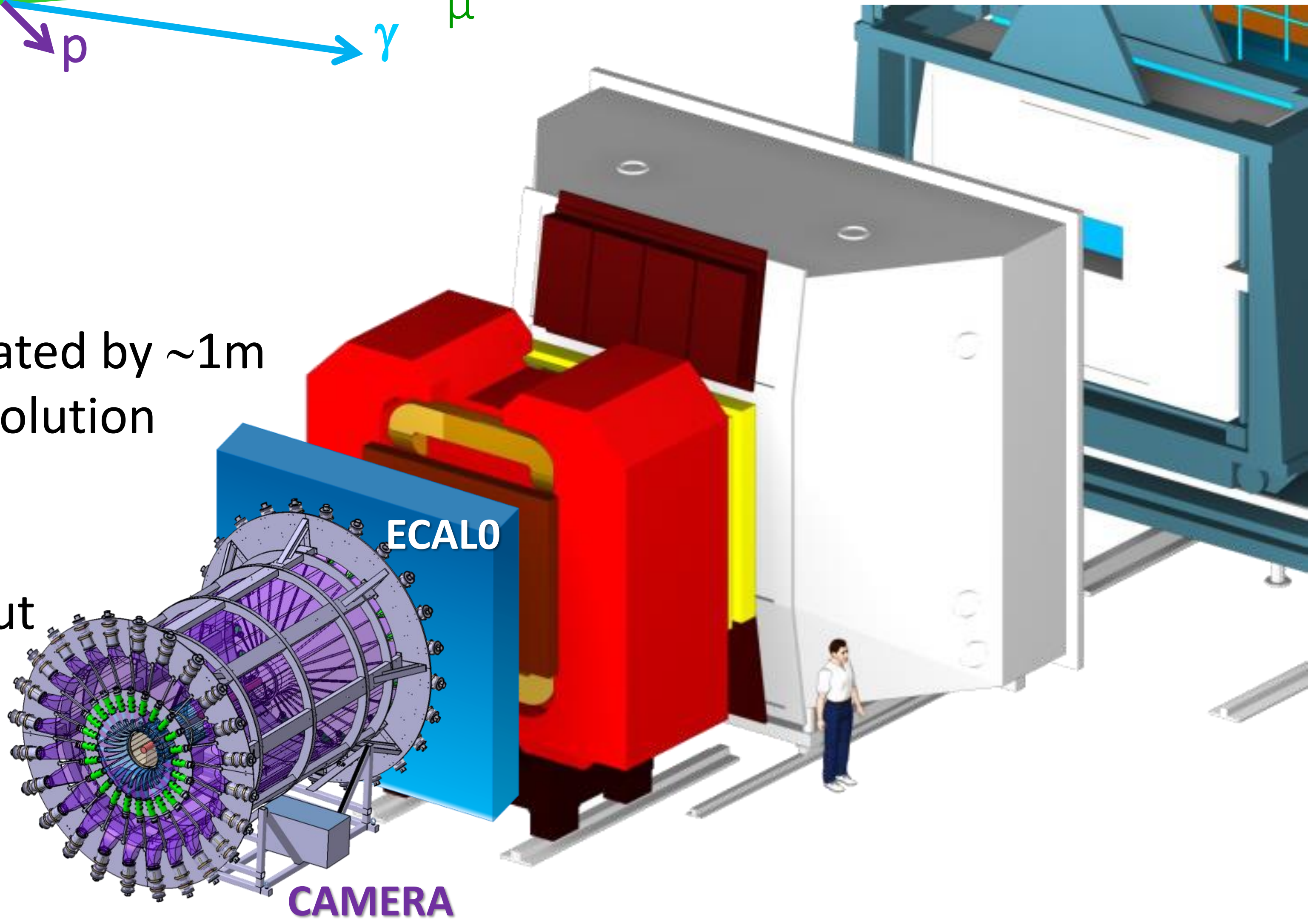
- **ECAL0 : 2 × 2 m2**

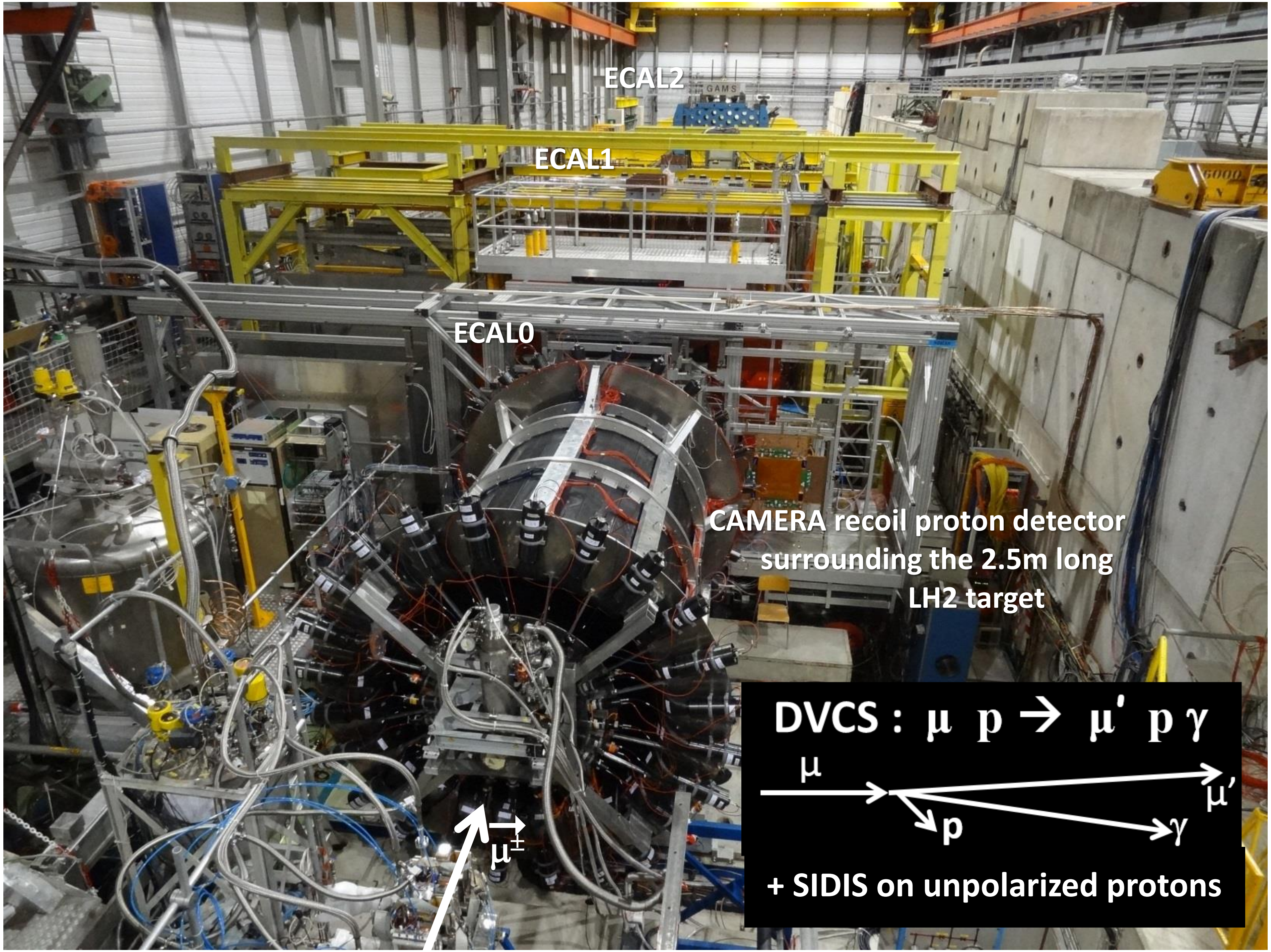
Shashlyk modules + MAPD readout

one module is made of

9 cells (4×4 cm^2)

= 194 modules or 1746 cells





2012: 1 month pilot run

2016 -17: 2 x 6 months data taking

COMPASS 2012 — Selection of exclusive evts with recoil detection

Comparison between the observables given by the spectro or by CAMERA

$x_{Bj} > 0.03$ $10 < \upsilon < 32$GeV
with π^0 contamination

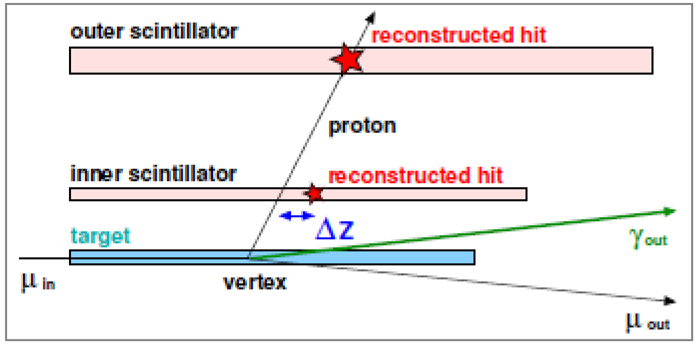
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

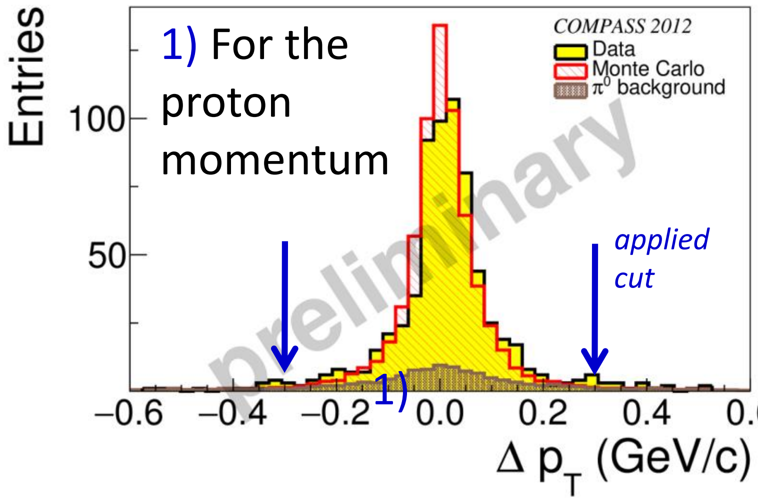
1) $\Delta p_T = p_T^{cam} - p_T^{spec}$

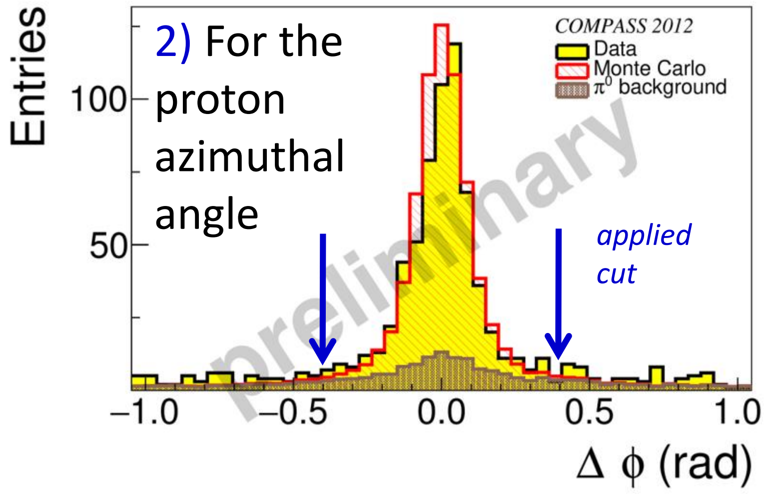
2) $\Delta\varphi = \varphi^{cam} - \varphi^{spec}$

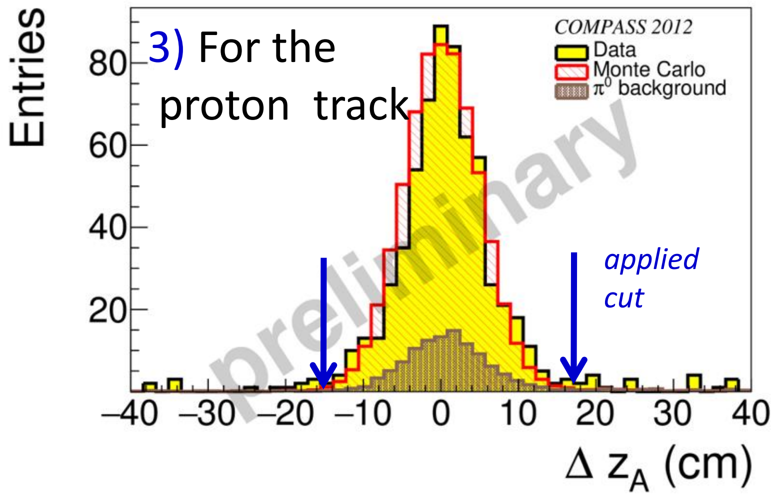
3) $\Delta z_A = z_A^{cam} - z_A^{Z_B \text{ and vertex}}$

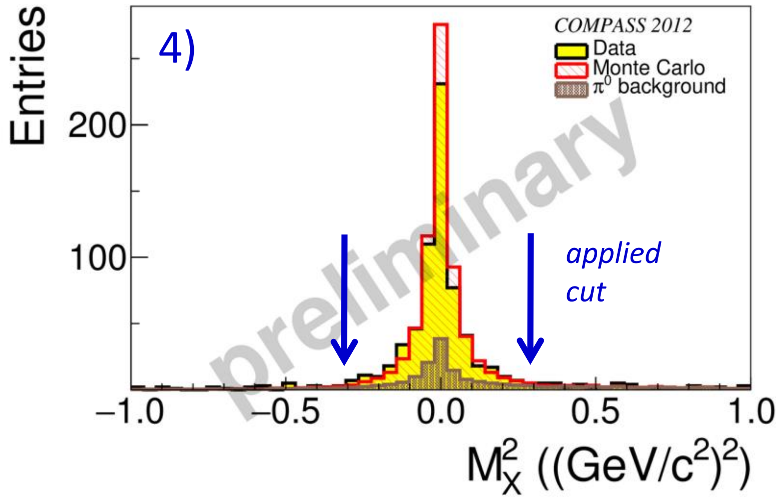
4) $M^2_{X=0} = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\gamma})^2$











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

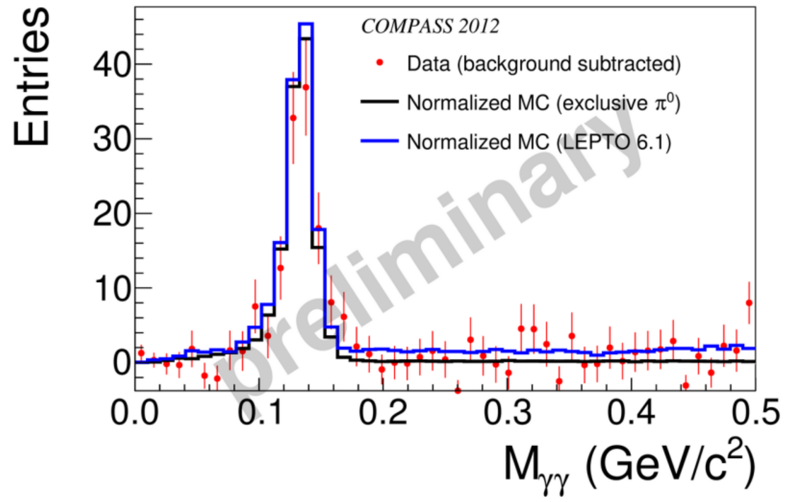
- **Invisible** (one γ lost ➔ estimated by MC)

  - **Semi-inclusive LEPTO 6.1**

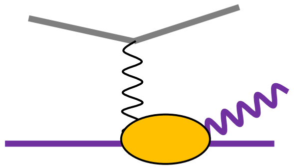
  - **Exclusive HEPGEN π^0** (Goloskokov-Kroll model)

Comparing the two components to the data allows the determination of their relative normalisation. The sum of the 2 components is normalized to the visible π^0 contamination in the $M_{\gamma\gamma}$ peak

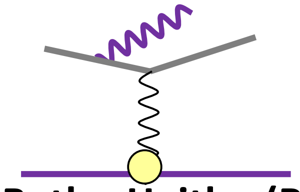
Visible leaking π^0 in the data



COMPASS 2012 DVCS cross section at Eμ=160 GeV

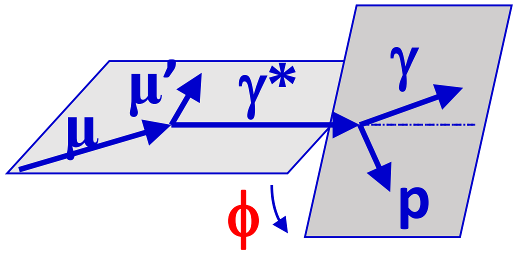


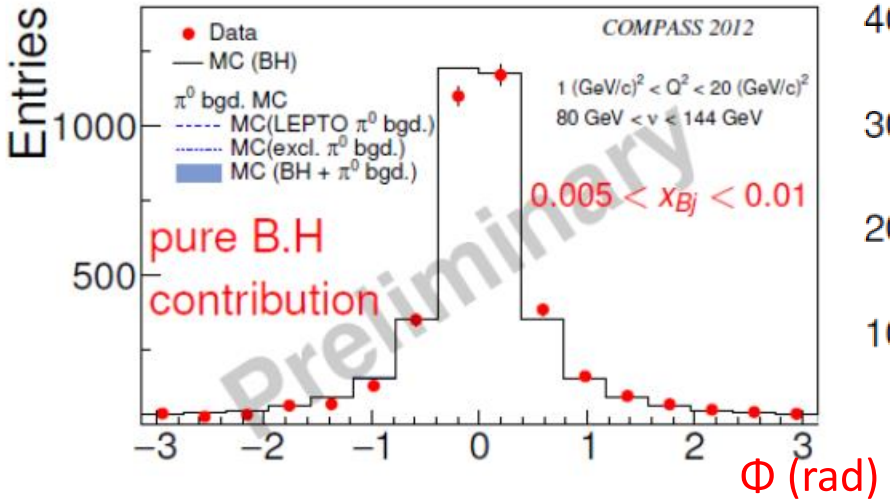
DVCS

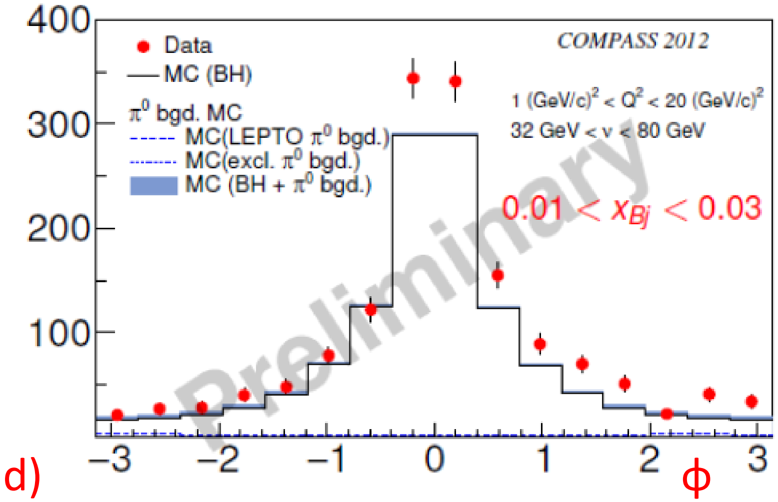


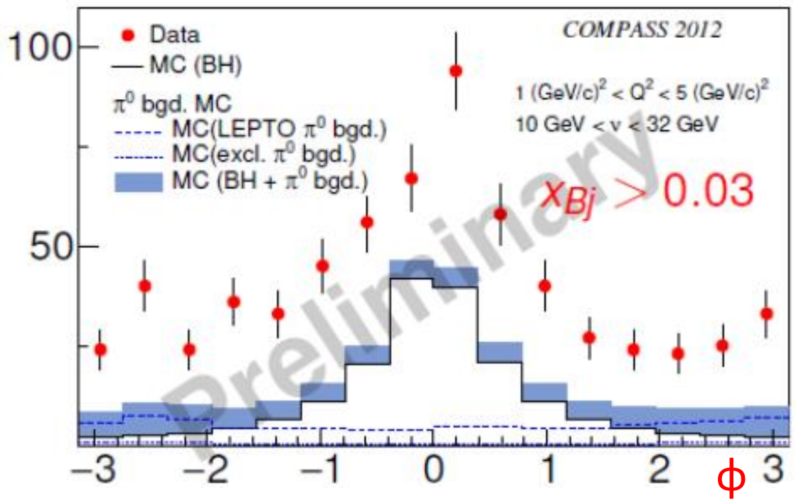
Bethe-Heitler (BH)

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

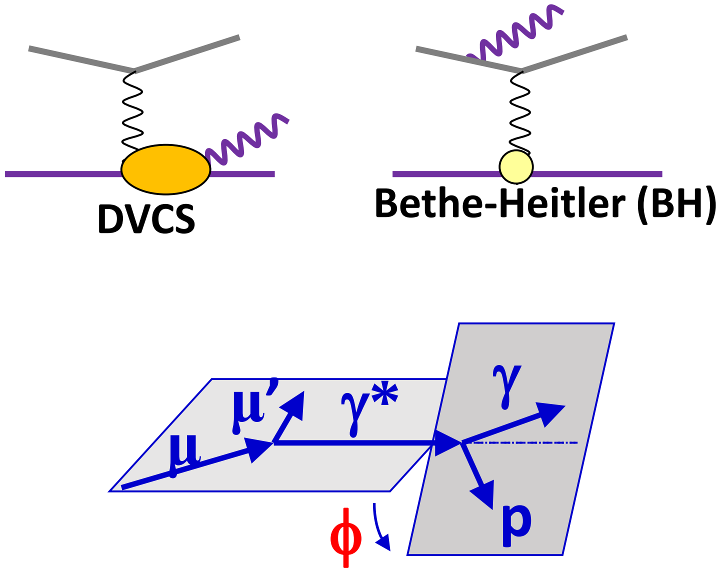




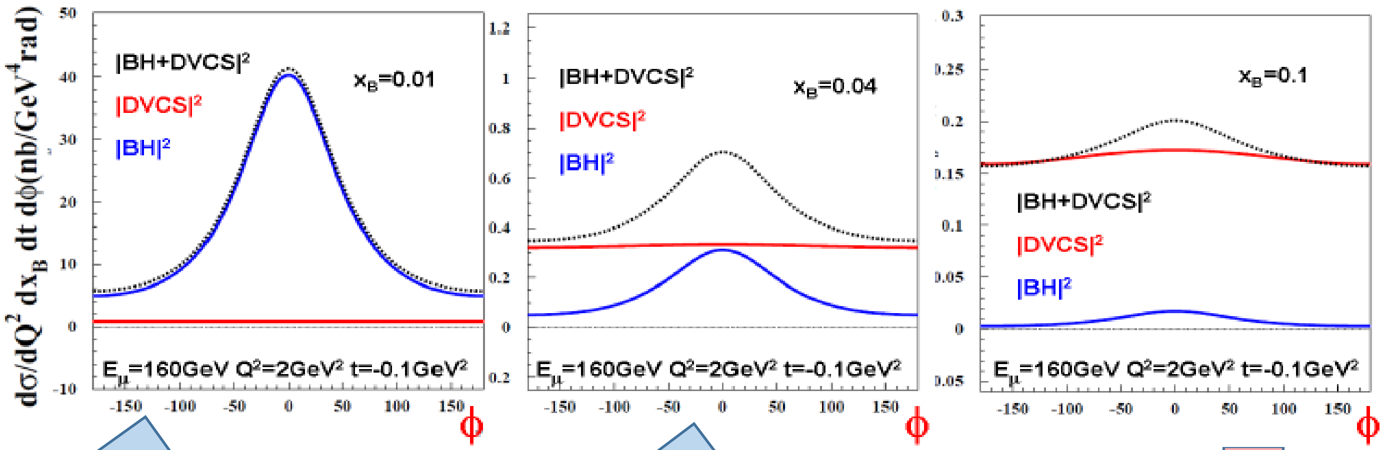




COMPASS 2012 DVCS cross section at Eμ=160 GeV



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



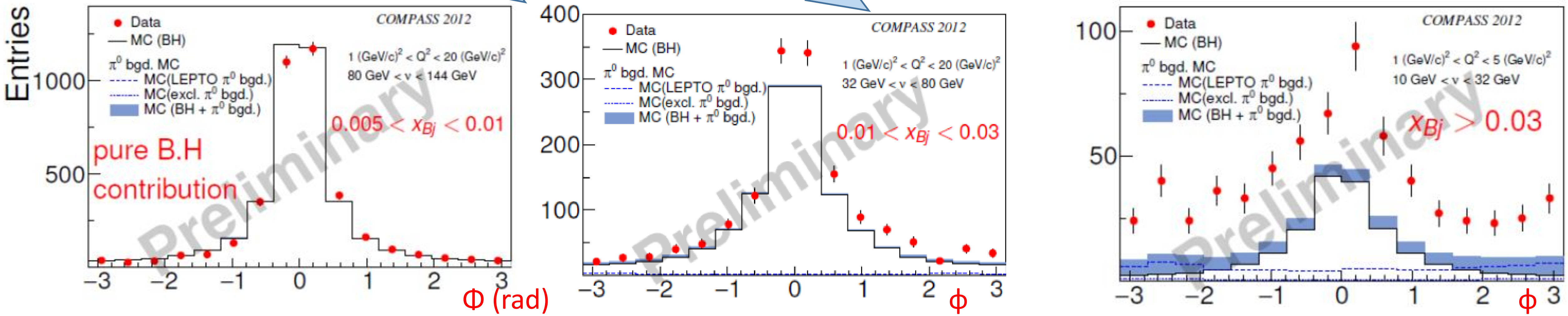
BH dominates
Reference yield

DVCS ampl. via interference

Jlab, HERMES,
H1, COMPASS

DVCS dominates - Study of $d\sigma^{DVCS}/dt$

Only for H1, ZEUS, COMPASS



COMPASS 2012 DVCS cross section at Eμ=160 GeV

when BH is not dominant

At COMPASS using polarized positive and negative muon beams:

$$S_{CS,U} \equiv \quad d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} \quad = \quad 2[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Im}\, I]$$

$$= \quad 2[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \quad + \quad s_1^I \sin\phi + s_2^I \sin 2\phi\ ]$$

calculable
can be subtracted

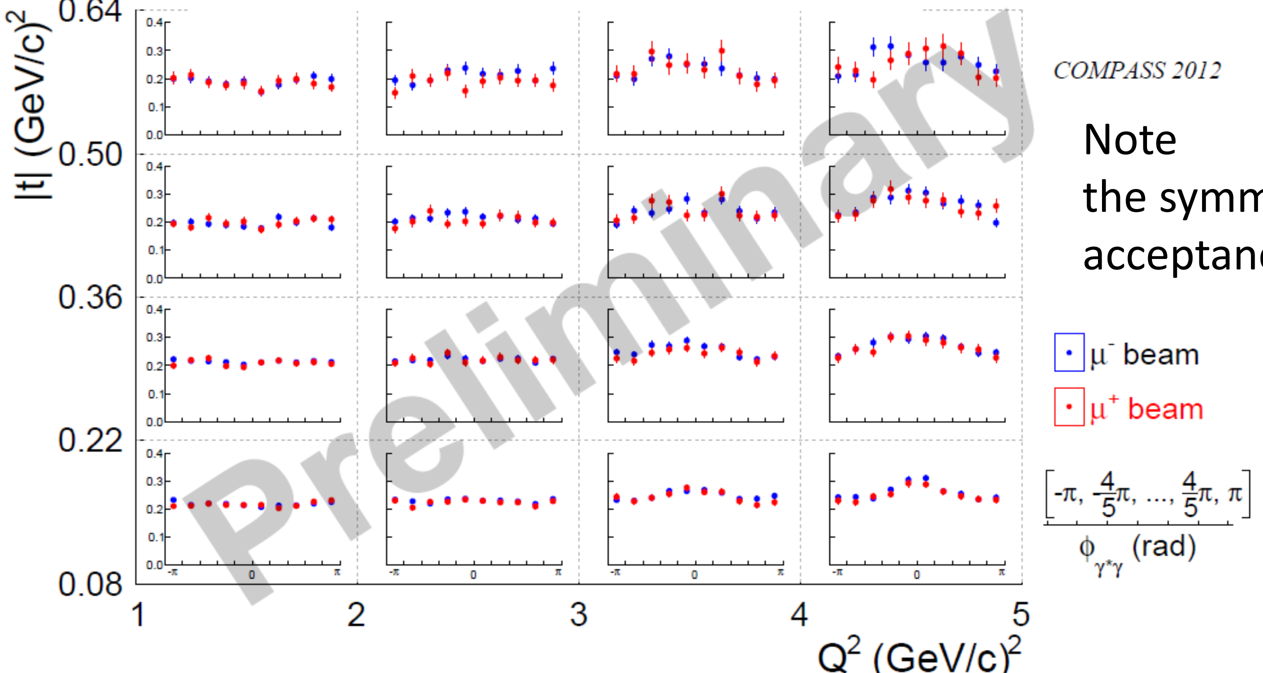
All the other terms are cancelled in the integration over ϕ

$$\frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt} = \int_{-\pi}^{\pi} d\phi\ (d\sigma - d\sigma^{BH}) \propto c_0^{DVCS}$$

$$\frac{d\sigma^{\gamma^* p}}{dt} = \frac{1}{\Gamma(Q^2, \nu, E_\mu)} \frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt}$$

Flux for transverse virtual photons

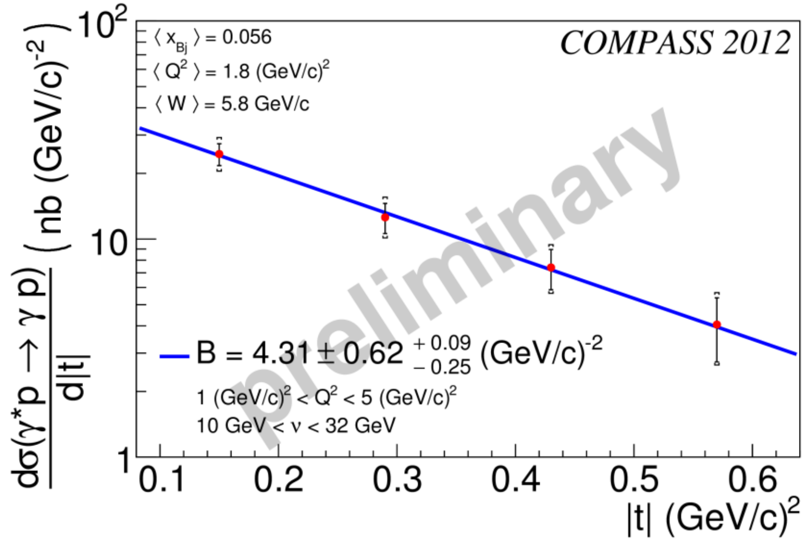
COMPASS acceptance for DVCS

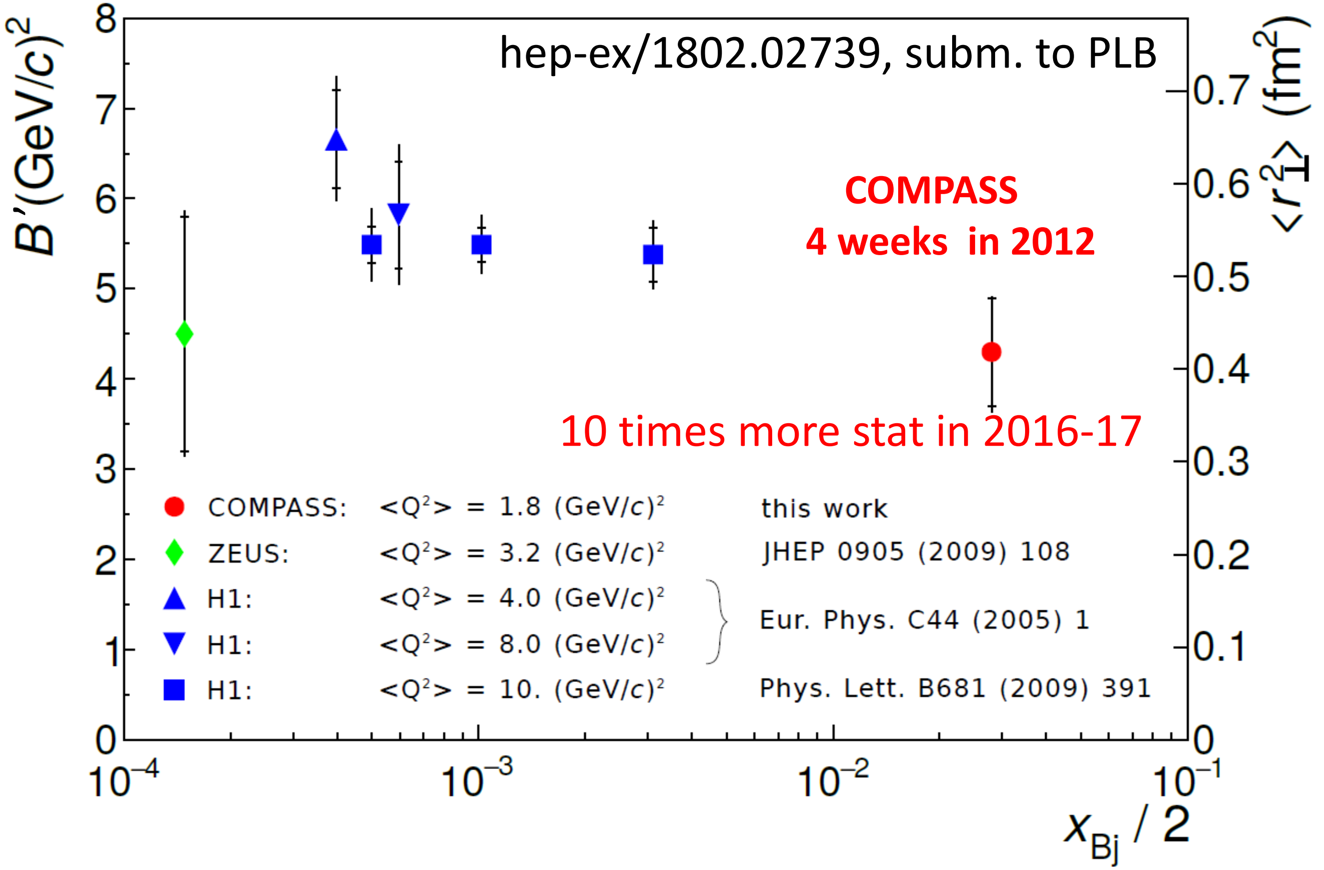


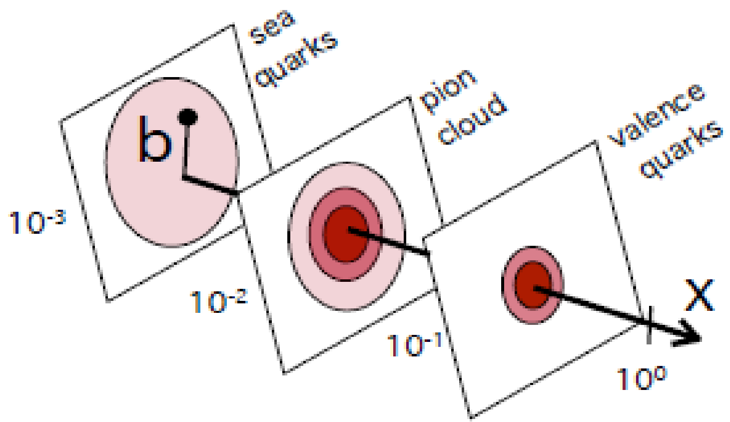
Note
the symmetric
acceptance

COMPASS 2012 Transverse extention of partons in the sea quark range

$$d\sigma^{DVCS}/dt = e^{-B'|t|} = c_0^{DVCS}$$







$$B = (4.3 \pm 0.6_{\text{stat}} \, {}^{+\,0.1}_{-\,0.3}\big|_{\text{sys}}) \; (\text{GeV}/c)^{-2}$$

COMPASS 2012 Transverse extention of partons in the sea quark range

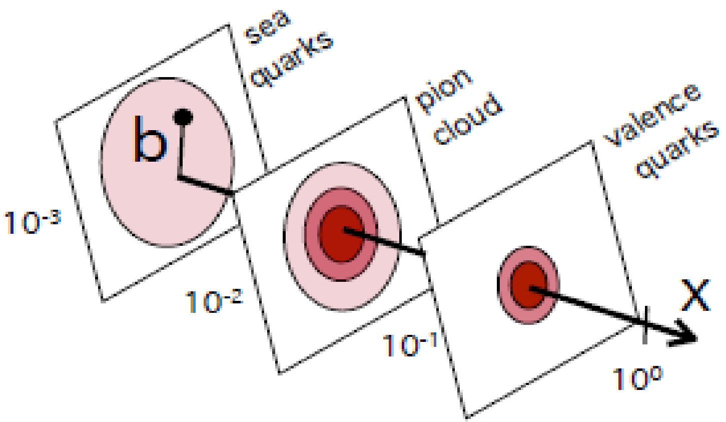
$d\sigma^{DVCS}/dt = e^{-B'|t|} = c_0^{DVCS}$

At COMPASS:
$\langle x_{Bj}\rangle=0.056$; $\langle Q^2\rangle=1.8\ \mathrm{GeV}^2$;
t varies from 0.08 to 0.64 GeV^2

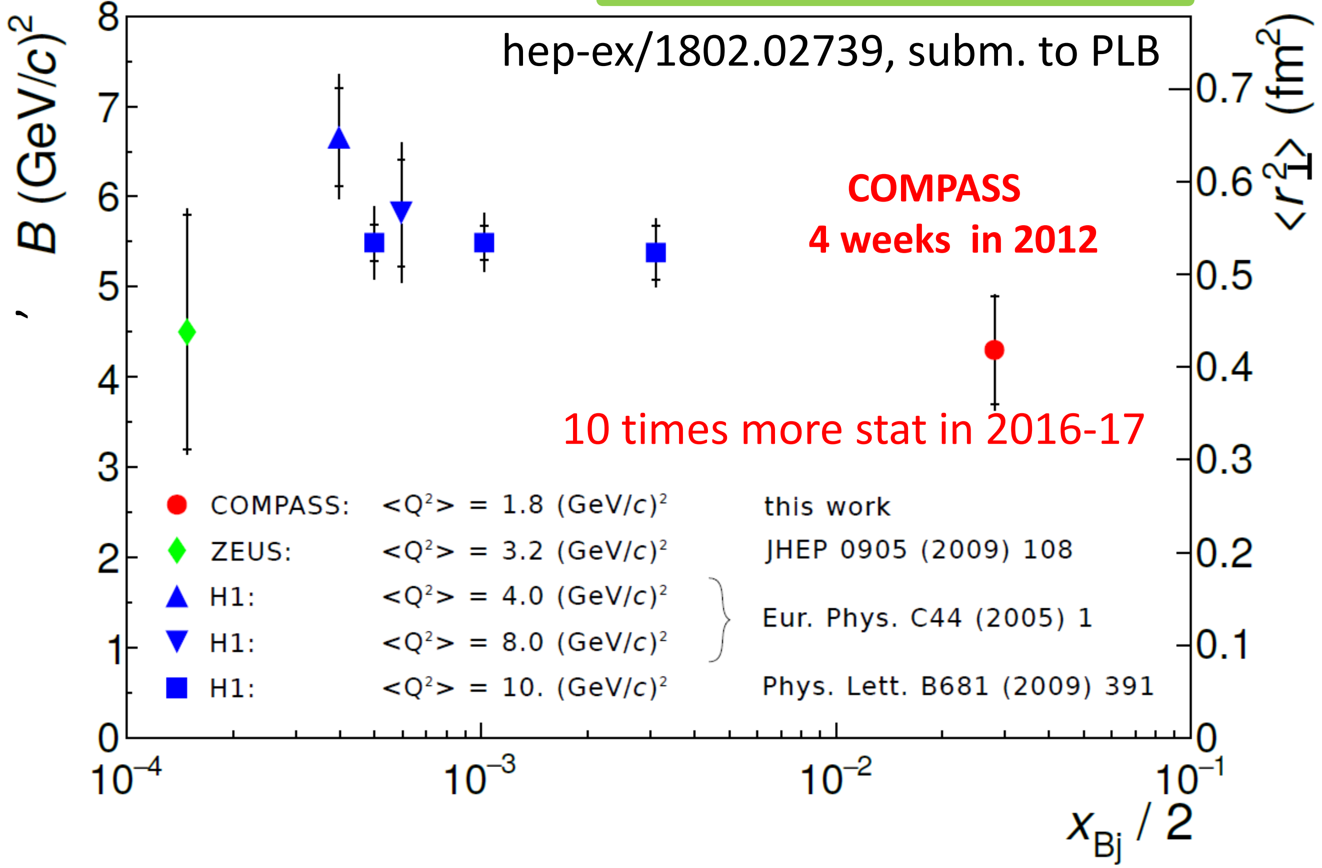
At small x_{Bj} and small t:

$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \cancel{\tilde{\mathcal{H}}\tilde{\mathcal{H}}^*}) - \cancel{\frac{t}{M^2}\mathcal{E}\mathcal{E}^*}$$

Dominance of $Im\mathcal{H}$
(with respect of $Re\mathcal{H}$ and other $\mathcal{CFF}$)



$\langle r_\perp^2(x_B)\rangle \approx 2B'(x_B)$



$$B = (4.3 \pm 0.6_{\mathrm{stat}}\ {}^{+0.1}_{-0.3}\big|_{\mathrm{sys}})\ (\mathrm{GeV}/c)^{-2}$$

$$\sqrt{\langle r_\perp^2\rangle} = (0.58 \pm 0.04_{\mathrm{stat}}\ {}^{+0.01}_{-0.02}\big|_{\mathrm{sys}}\ \pm 0.04_{\mathrm{model}})\ \mathrm{fm}$$

COMPASS 2012 Transverse extention of partons in the sea quark range

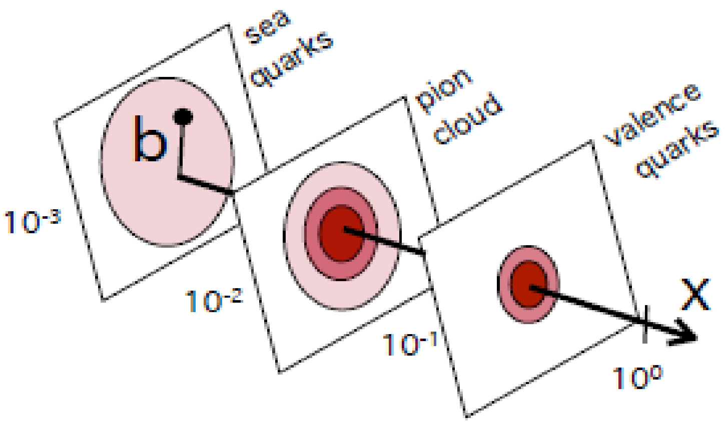
$$d\sigma^{DVCS}/dt = e^{-B'|t|} = c_0^{DVCS}$$

At COMPASS:
$\langle x_{Bj}\rangle=0.056$; $\langle Q^2\rangle=1.8$ GeV^2;
t varies from 0.08 to 0.64 GeV^2

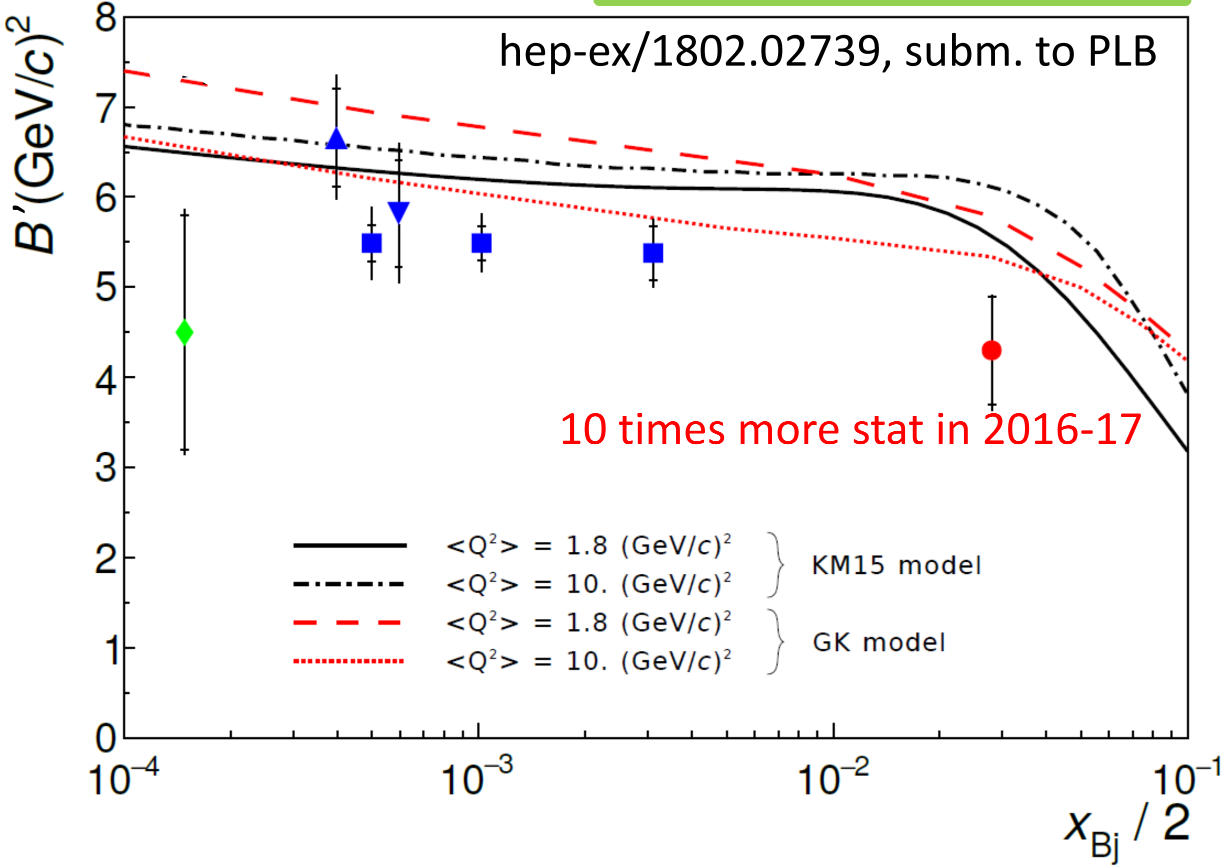
At small x_{Bj} and small t:

$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \cancel{\tilde{\mathcal{H}}\tilde{\mathcal{H}}^*}) - \cancel{\frac{t}{M^2}\mathcal{E}\mathcal{E}^*}$$

Dominance of *ImH*
(with respect of *ReH* and other *CFF*)



$$\langle r_\perp^2(x_B)\rangle \approx 2B'(x_B)$$



$$B = (4.3 \pm 0.6_{\text{stat}}\ {}^{+0.1}_{-0.3}\big|_{\text{sys}})\ (\text{GeV}/c)^{-2}$$

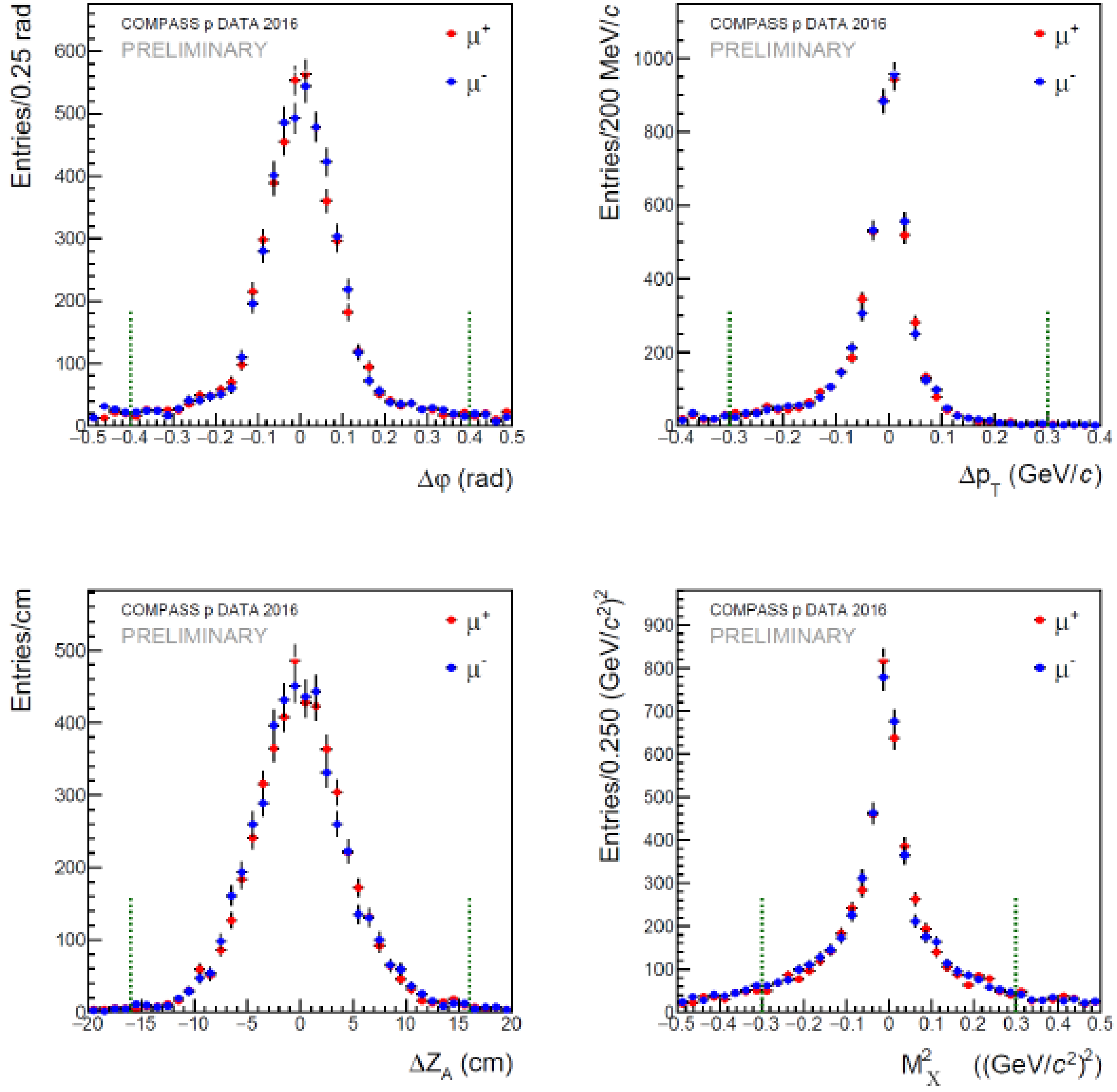
$$\sqrt{\langle r_\perp^2\rangle} = (0.58 \pm 0.04_{\text{stat}}\ {}^{+0.01}_{-0.02}\big|_{\text{sys}} \pm 0.04_{\text{model}})\ \text{fm}$$

COMPASS 2016-17 First insight Exclusivity variables

Comparison between the observables given by the spectro or by CAMERA

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

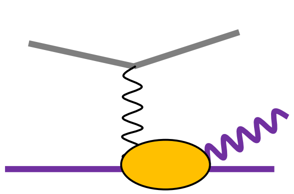
1) $\Delta p_T = p_T^{cam} - p_T^{spec}$
2) $\Delta\varphi = \varphi^{cam} - \varphi^{spec}$
3) $\Delta z_A = z_A^{cam} - z_A^{Z_B \text{ and vertex}}$
4) $M^2_{X=0} = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2$



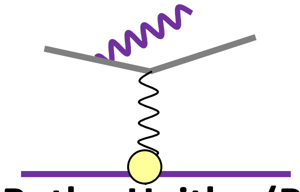
$d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$ *t-slope*

$d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$ *d-term*

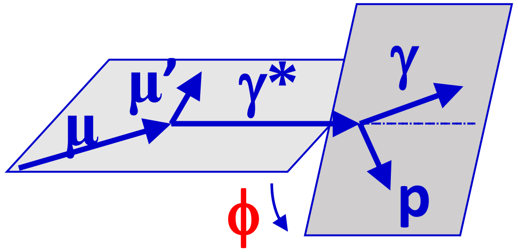
COMPASS 2016-17 First insight Distributions in ϕ



DVCS



Bethe-Heitler (BH)

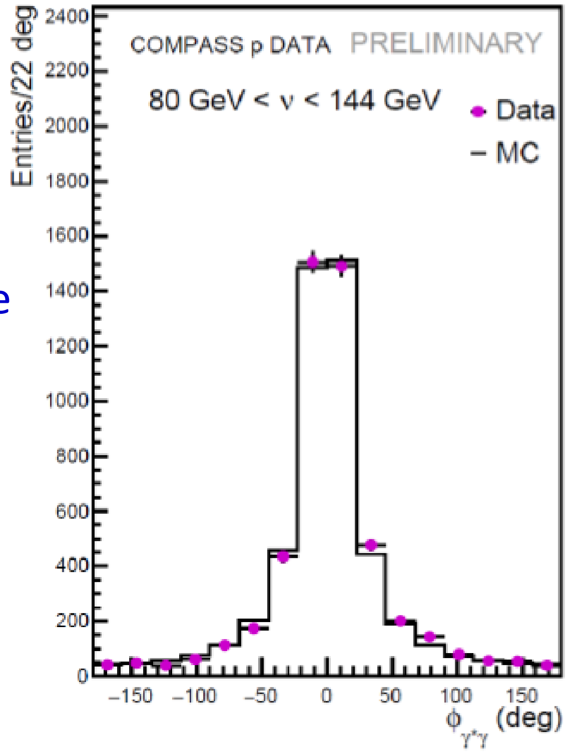


Only 13% of 2016-17 data

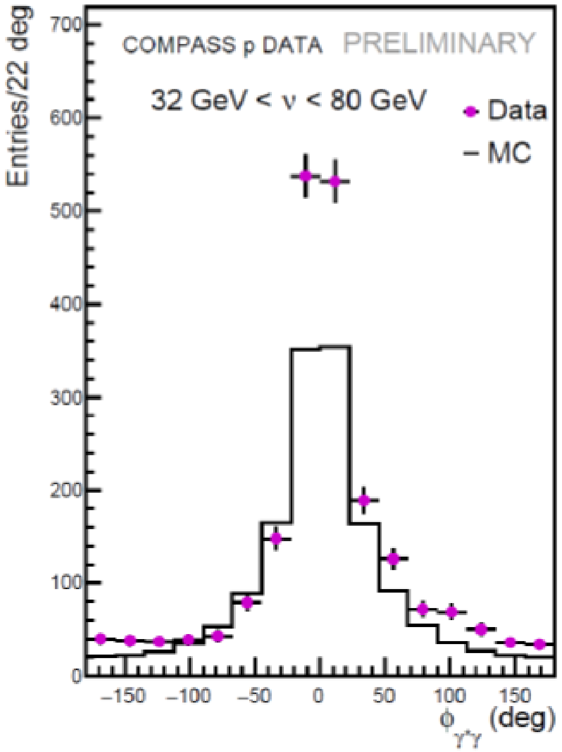
BH expected to contribute only

BH MC is normalized to this bin

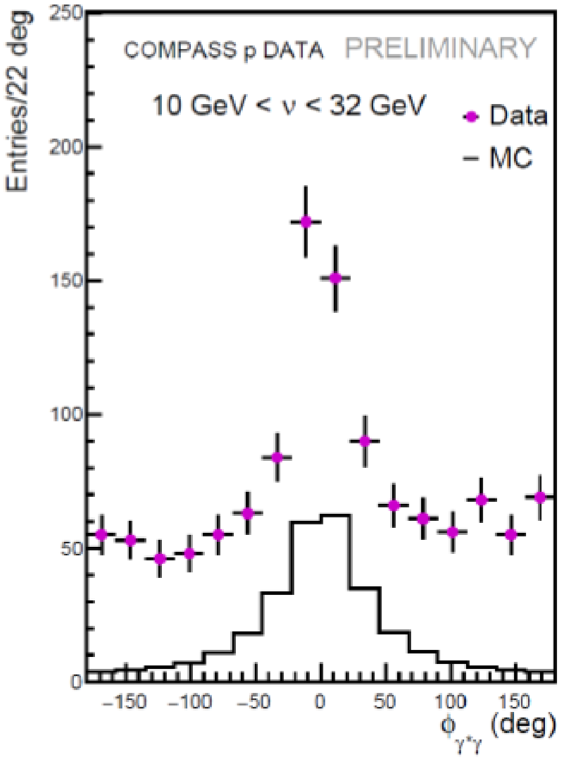
$0.005 < x_{Bj} < 0.01$



$0.01 < x_{Bj} < 0.03$



$x_{Bj} > 0.03$



No "invisible" π^0 still to be removed

a significant DVCS contribution will allow to study

$d\sigma^{DVCS}/dt = e^{-B'|t|}$

$= c_0^{DVCS}$

BLUE WATERS

This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications. This work is also part of the "Mapping Proton Quark Structure using Petabytes of COMPASS Data" PRAC allocation supported by the National Science Foundation (award number OCI 1713684).

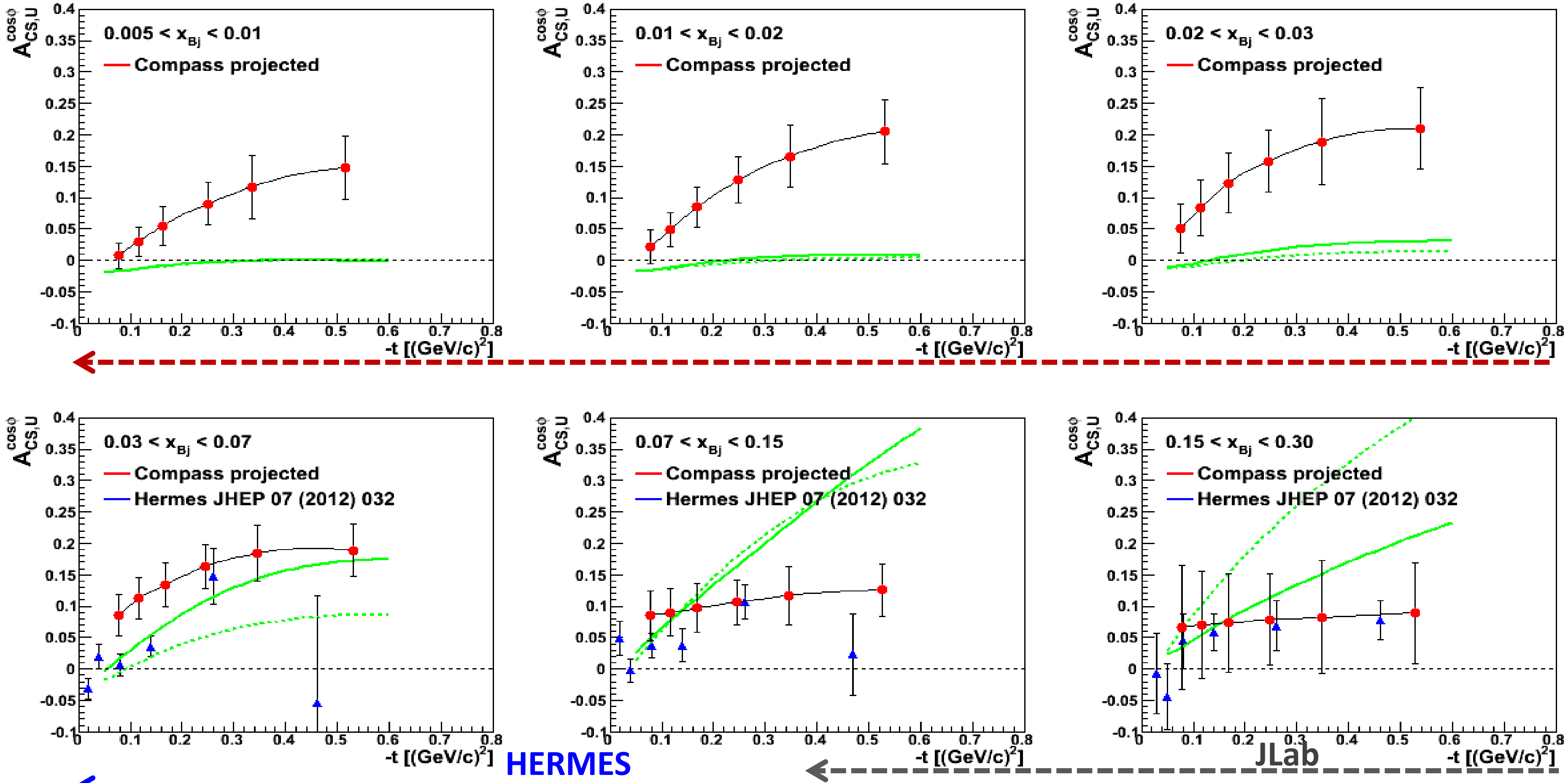
Beam Charge and Spin Diff. @ COMPASS

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

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

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

Predictions with
VGG
KM10

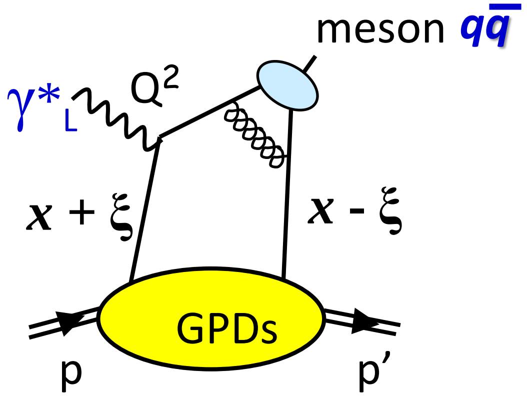


The knowledge of
$\mathrm{Re}\, F_1\mathcal{H}$ and $\mathrm{Im}\, F_1\mathcal{H}$
is essentiel to play with
the dispersion relation
to extract the D-term

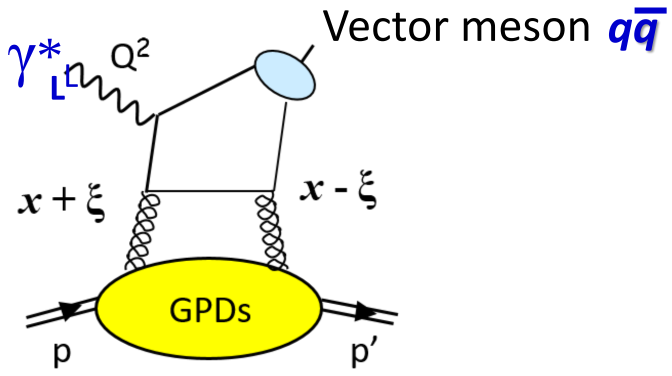
COMPASS 2 years of data $E\mu$= 160 GeV $1 < Q^2 < 8$ GeV^2

GPDs and Hard Exclusive Meson Production

Quark contribution



Gluon contribution at the same order in α_S



The meson wave function
Is an additional non-perturbative term

4 chiral-even GPDs: helicity of parton unchanged

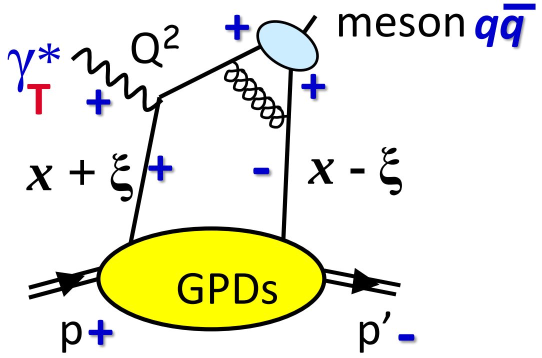
$H^q(x, \xi, t)$	$E^q(x, \xi, t)$	**For Vector Meson**
$\tilde{H}^q(x, \xi, t)$	$\tilde{E}^q(x, \xi, t)$	**For Pseudo-Scalar Meson**

+ 4 chiral-odd or transversity GPDs: helicity of parton changed
(not possible in DVCS)

$H^q_T(x, \xi, t)$	$E^q_T(x, \xi, t)$	$\bar{E}^q_T = 2\,\tilde{H}^q_T + E^q_T$
$\tilde{H}^q_T(x, \xi, t)$	$\tilde{E}^q_T(x, \xi, t)$	

Factorisation proven only for σ_L
σ_T is asymptotically suppressed by $1/Q^2$ but large contribution observed
model of σ_T with transversity GPDs - divergencies regularized by k_T of q and $\bar{q}$ and Sudakov suppression factor

$\mathfrak{M}_{0-,++}$ sensitive to H^q_T
and to a twist-3 meson wave function



COMPASS 2012 Exclusive π^0 production on unpolarized proton

e p → e π^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 ≈ 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

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

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

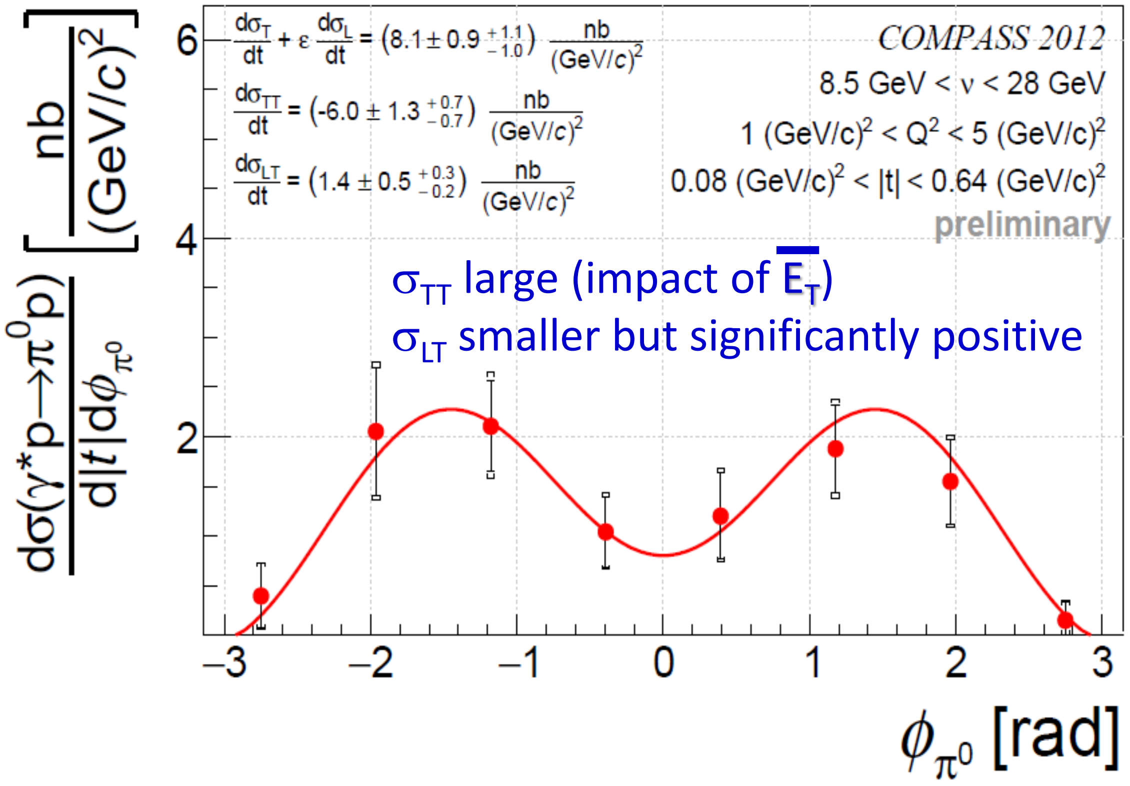
$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

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

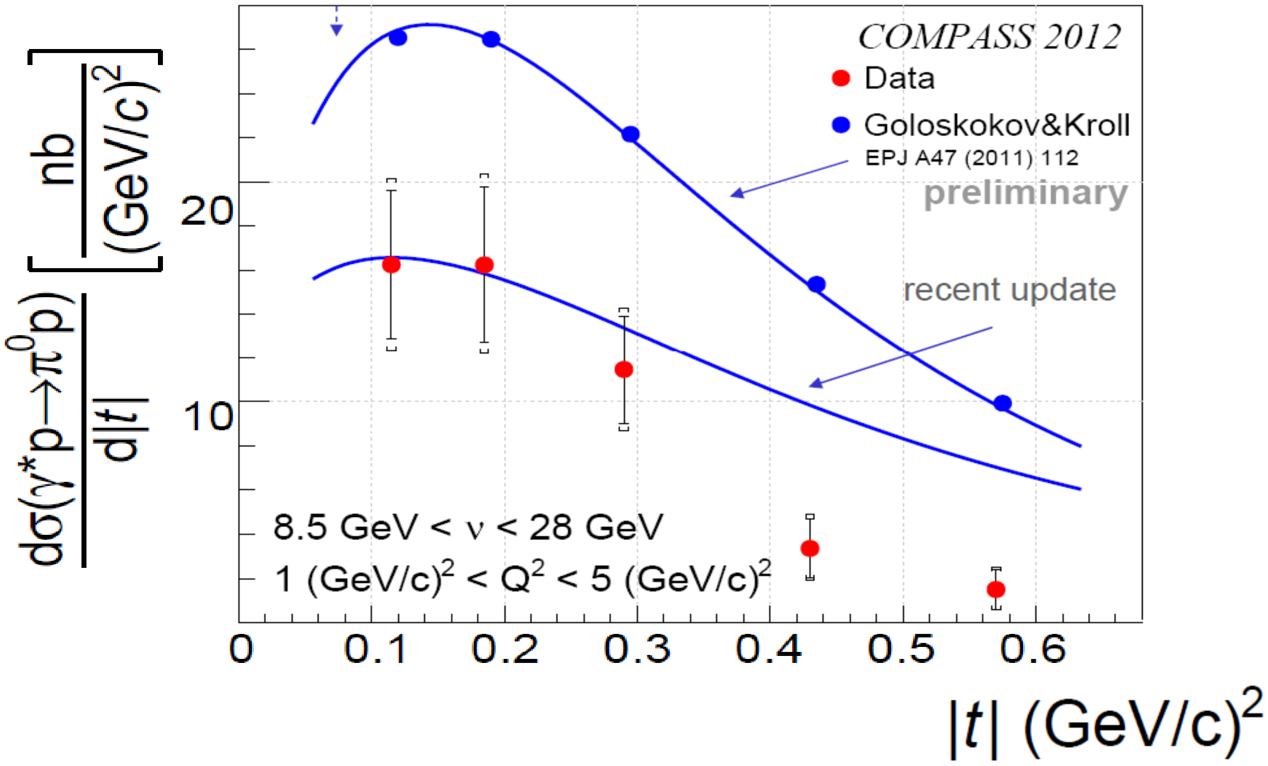
COMPASS 2012 Exclusive π^0 production on unpolarized proton

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

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



A dip at small t would indicate a large impact of $\bar{E}_T$



hep-ex/1903.12030, subm. to PLB

Exclusive ω production on unpolarized proton

SCHC ($\lambda_\gamma = \lambda_V$)

SCHC implies:

- $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$

  = - 0.010 ± 0.032 ± 0.047 OK

- $\mathrm{Re}\, r^5_{10} + \mathrm{Im}^6_{10} = 0$

  = 0.014 ± 0.011 ± 0.013 OK

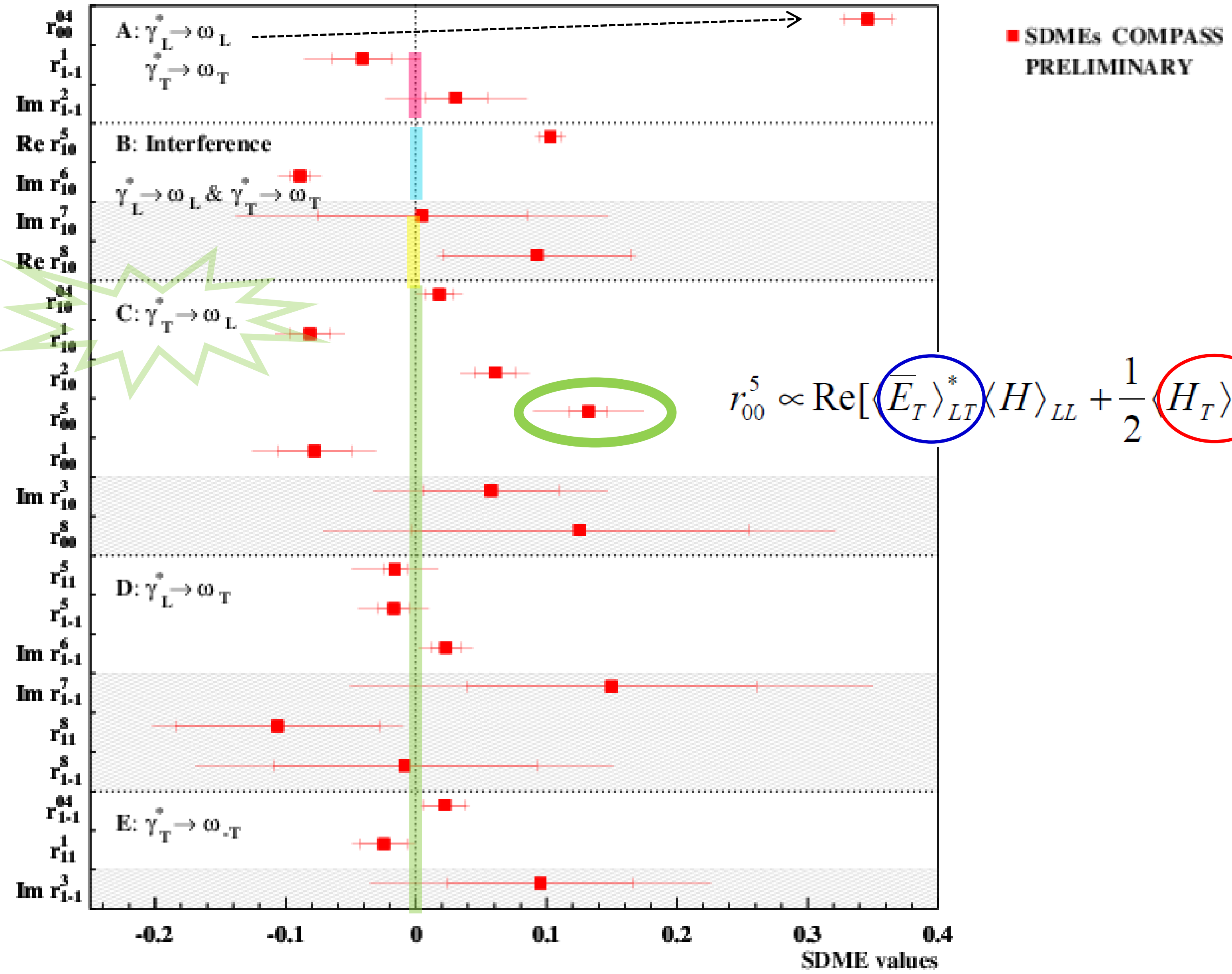
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

  = - 0.088 ± 0.110 ± 0.196 OK

- all elements of classes C, D, E should be 0

for $\gamma^*_L \to \omega_T$ and $\gamma^*_T \to \omega_{-T}$ OK within errors

not obeyed for transitions $\gamma^*_T \to \omega_L$



$$r^5_{00} \propto \mathrm{Re}[\langle \overline{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$$

Conclusions

From 2016-17 data

sum and difference of DVCS x-sections with polarized μ+ and μ-

- ➔ transverse extension of partons as a function of x_{Bj}
- ➔ Im$\mathcal{H}(\xi,t)$ and Re$\mathcal{H}(\xi,t)$ for D-term and pressure distribution

HEMP π^0, ρ, ω, ϕ, J/ψ ➔ universality of GPDs - transverse GPDs - flavor decomposition

COMPASS++/AMBER starting in 2022

Letter of Intent Draft 1.0: https://arXiv.org/abs/1808.00848

New collaborators are welcome: https://nqf-m2.web.cern.ch

A new QCD facility
at the M2 beam line of the CERN SPS

Letter of Intent - Draft 1.0: https://arXiv.org/abs/1808.00848

COMPASS++/AMBER starting in 2022

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware Additions
μp elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified PT magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
$\overline{p}$-induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^\pm, \overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Beam line unique with polarised μ+ and μ- and high intensity pion beam

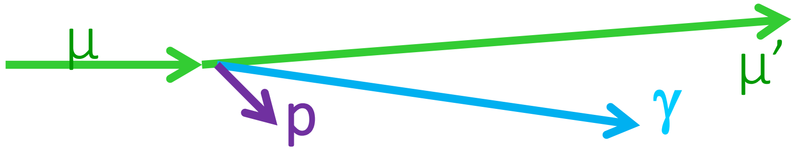
Possible RF separated beam for high intensity antiproton and K beams

Versatile apparatus (Upgrade ++)

Proton Radius
Meson PDF – gluon PDF
Proton spin structure
3D imaging (TMDs and GPDs)
Hadron spectroscopy
Anti-matter cross section

The DVCS experiment at COMPASS

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

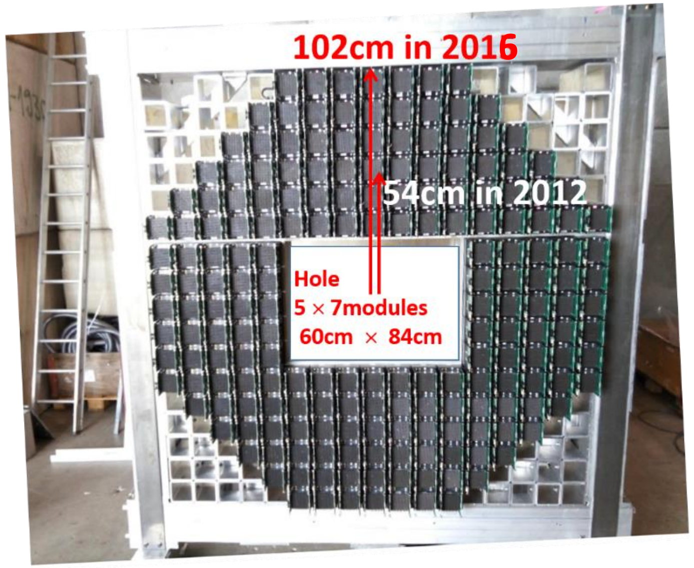


New equipements:

- **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

COMPASS 2012 Transverse extention of partons in the sea quark range

$$d\sigma^{DVCS}/dt = e^{-B'|t|} = c_0^{DVCS}$$

$$c_{0,\mathrm{unp}}^{\mathrm{DVCS}} = 2(2-2y+y^2)\mathcal{C}_{\mathrm{unp}}^{\mathrm{DVCS}}(\mathcal{F},\mathcal{F}^*)$$

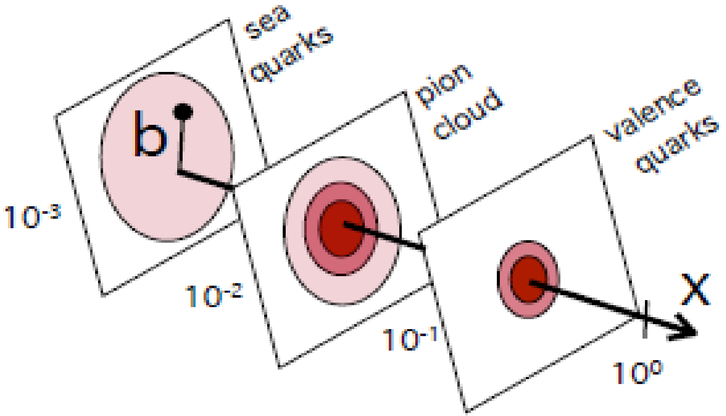
$$\mathcal{C}_{\mathrm{unp}}^{\mathrm{DVCS}}(\mathcal{F},\mathcal{F}^*) = \frac{1}{(2-x_{\mathrm{B}})^2}\Big\{4(1-x_{\mathrm{B}})\left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right) - x_{\mathrm{B}}^2\left(\mathcal{H}\mathcal{E}^* + \mathcal{E}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{E}}^* + \widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^*\right) - \left(x_{\mathrm{B}}^2 + (2-x_{\mathrm{B}})^2\frac{\Delta^2}{4M^2}\right)\mathcal{E}\mathcal{E}^* - x_{\mathrm{B}}^2\frac{\Delta^2}{4M^2}\widetilde{\mathcal{E}}\widetilde{\mathcal{E}}^*\Big\},$$

At COMPASS:

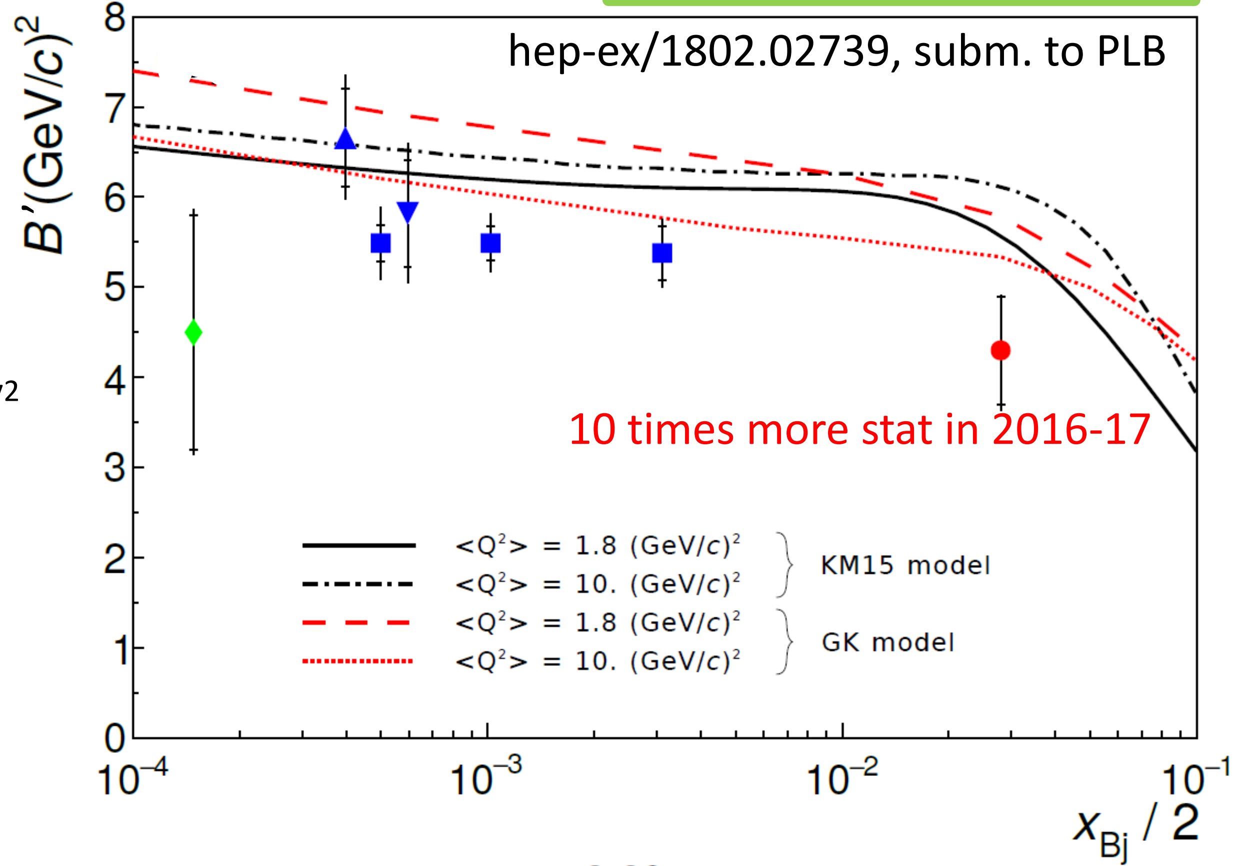
$\langle x_{Bj}\rangle$=0.056; $\langle Q^2\rangle$=1.8 GeV^2; t varies from 0.08 to 0.64 GeV^2

Due to the small value of x_{Bj} and t it remains only:

$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) - \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$$

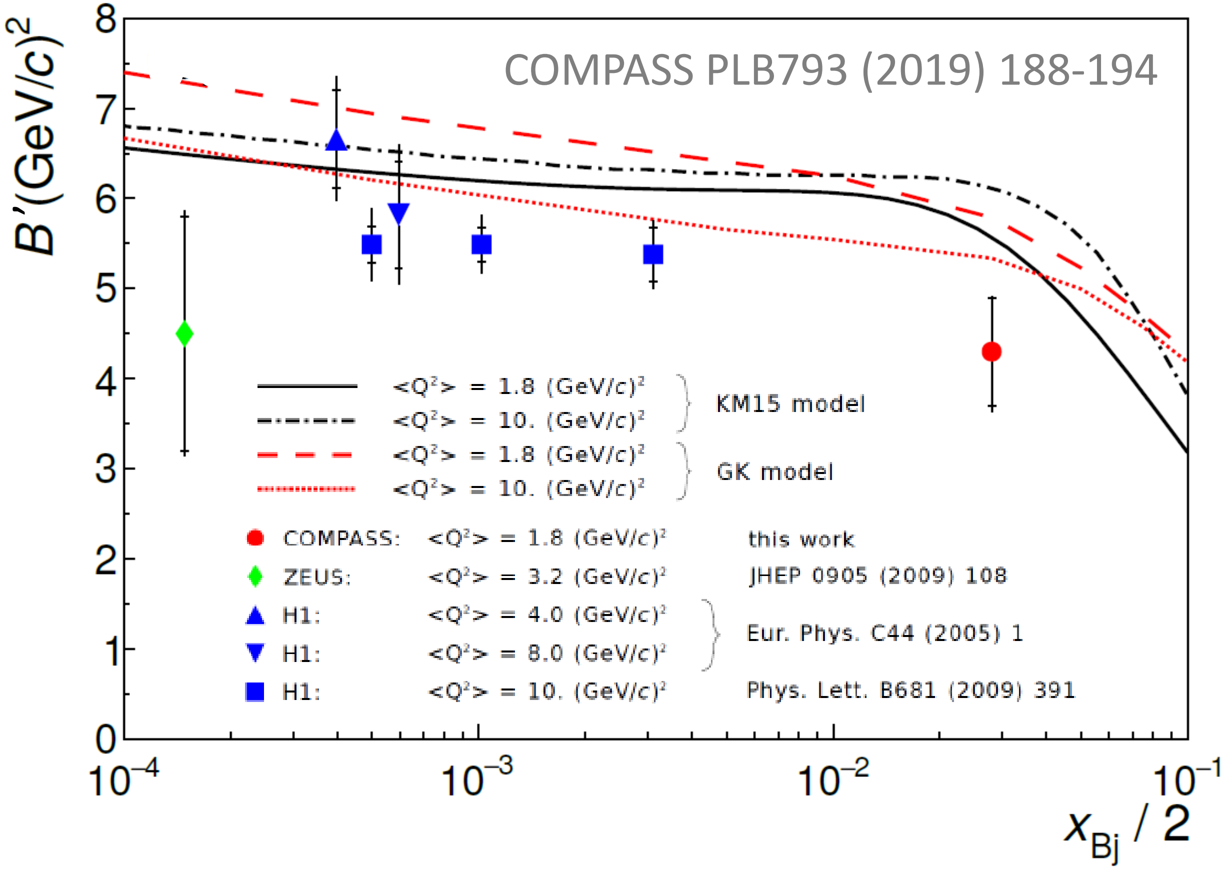


$$\langle r_\perp^2(x_B)\rangle \approx 2B'(x_B)$$



$$B = (4.31 \pm 0.62_{\mathrm{stat}}\ {}^{+0.09}_{-0.25}\big|_{\mathrm{sys}})\ (\mathrm{GeV}/c)^{-2}$$

$$\sqrt{\langle r_\perp^2\rangle} = (0.58 \pm 0.04_{\mathrm{stat}}\ {}^{+0.01}_{-0.02}\big|_{\mathrm{sys}})\ \mathrm{fm}$$



COMPASS PLB793 (2019) 188-194
$B'(\mathrm{GeV}/c)^2$
x_{Bj} / 2
$\langle Q^2 \rangle$ = 1.8 $(\mathrm{GeV}/c)^2$
$\langle Q^2 \rangle$ = 10. $(\mathrm{GeV}/c)^2$
KM15 model
$\langle Q^2 \rangle$ = 1.8 $(\mathrm{GeV}/c)^2$
$\langle Q^2 \rangle$ = 10. $(\mathrm{GeV}/c)^2$
GK model
COMPASS: $\langle Q^2 \rangle$ = 1.8 $(\mathrm{GeV}/c)^2$ this work
ZEUS: $\langle Q^2 \rangle$ = 3.2 $(\mathrm{GeV}/c)^2$ JHEP 0905 (2009) 108
H1: $\langle Q^2 \rangle$ = 4.0 $(\mathrm{GeV}/c)^2$
H1: $\langle Q^2 \rangle$ = 8.0 $(\mathrm{GeV}/c)^2$ Eur. Phys. C44 (2005) 1
H1: $\langle Q^2 \rangle$ = 10. $(\mathrm{GeV}/c)^2$ Phys. Lett. B681 (2009) 391

Dominance of $Im\mathcal{H}$ (with respect of $Re\mathcal{H}$ and other $\mathcal{CFF}$) at small x_B

Figure from Kumericki, Mueller

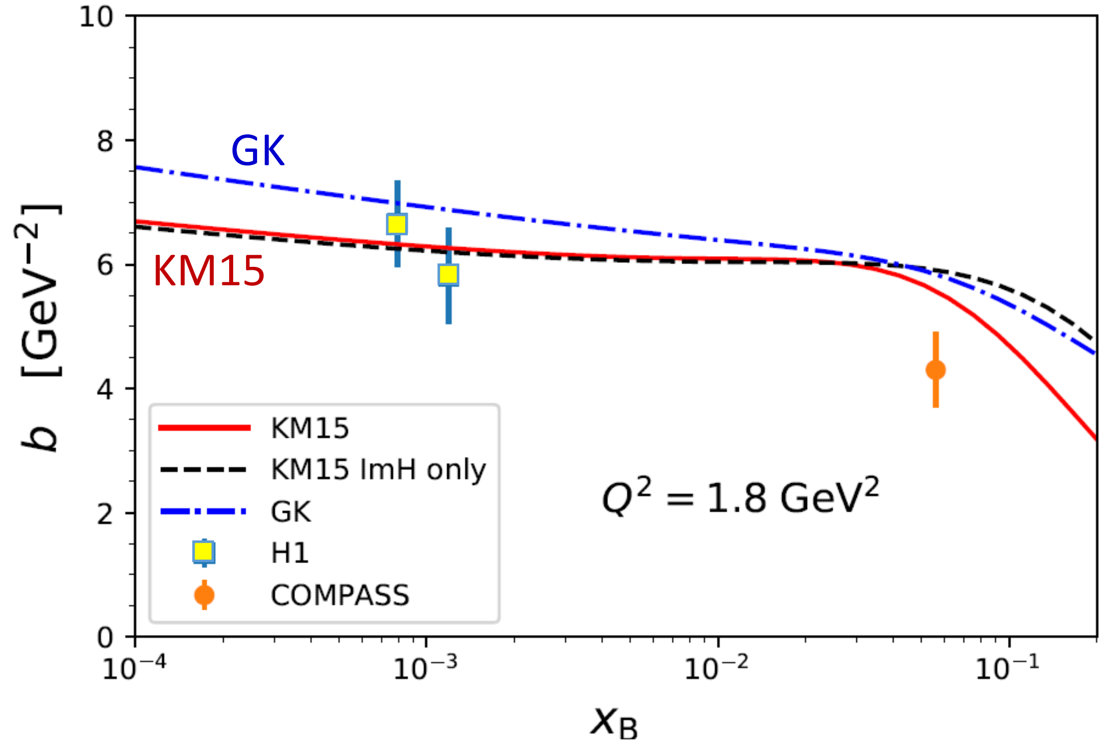
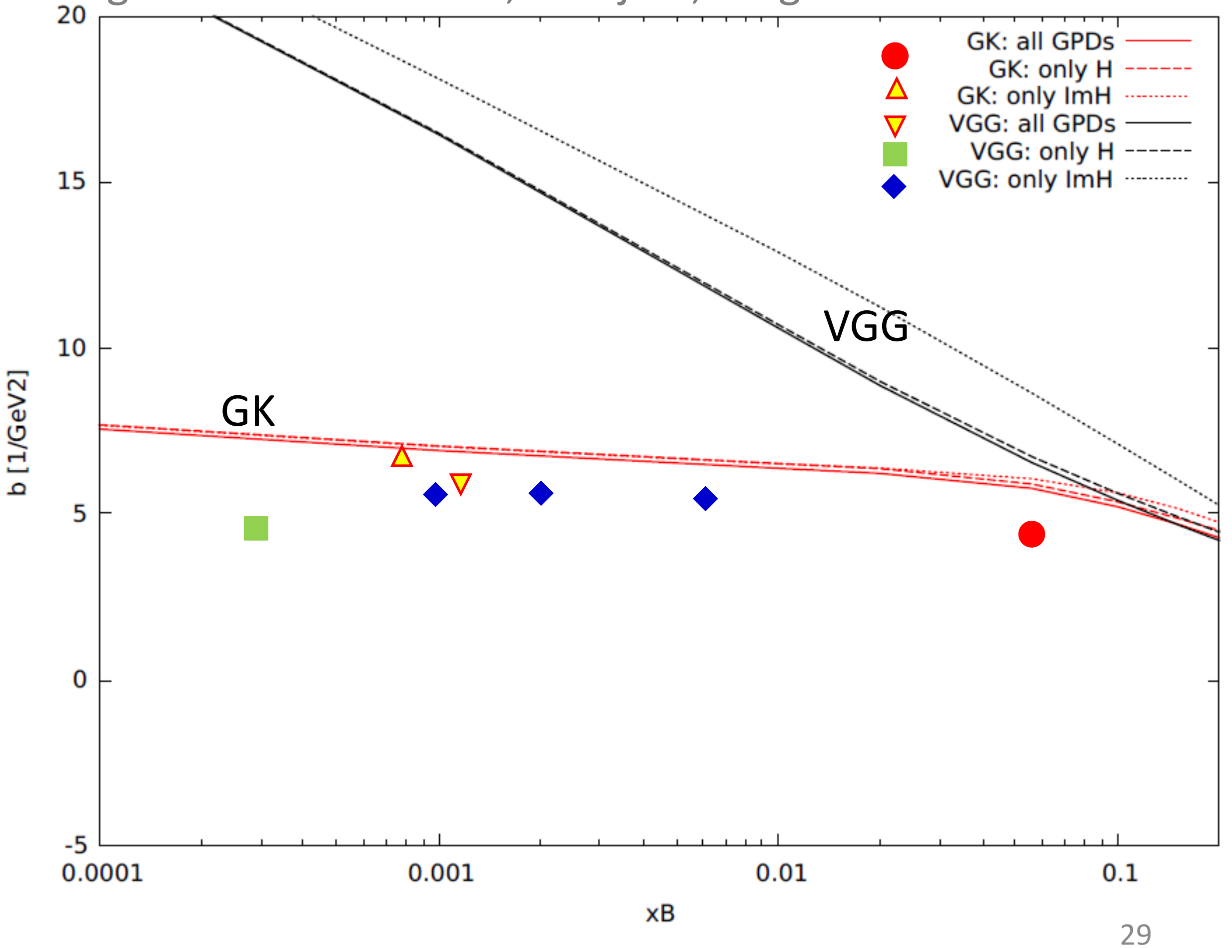


Figure from Moutarde, Sznajder, Wagner arXiv: 1807.07620



The past and future DVCS experiments