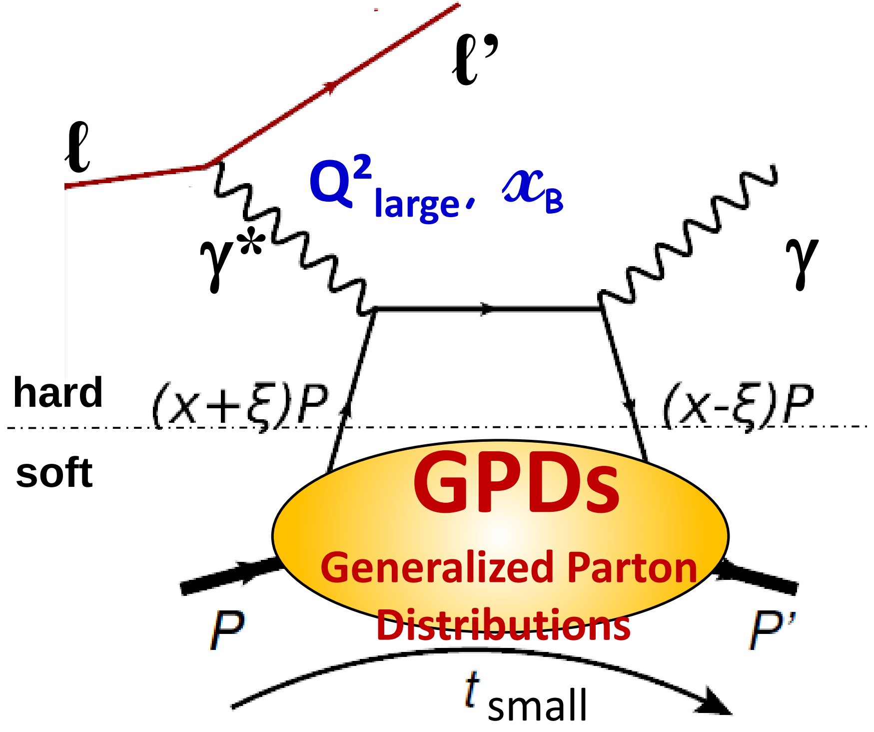
Correlations in Partonic and Hadronic Interactions 2020 (CPHI-2020)

GPD at COMPASS at CERN

1- DVCS
2- HEMP

Nicole d'Hose – CEA – Université Paris-Saclay
for the COMPASS Collaboration

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...**

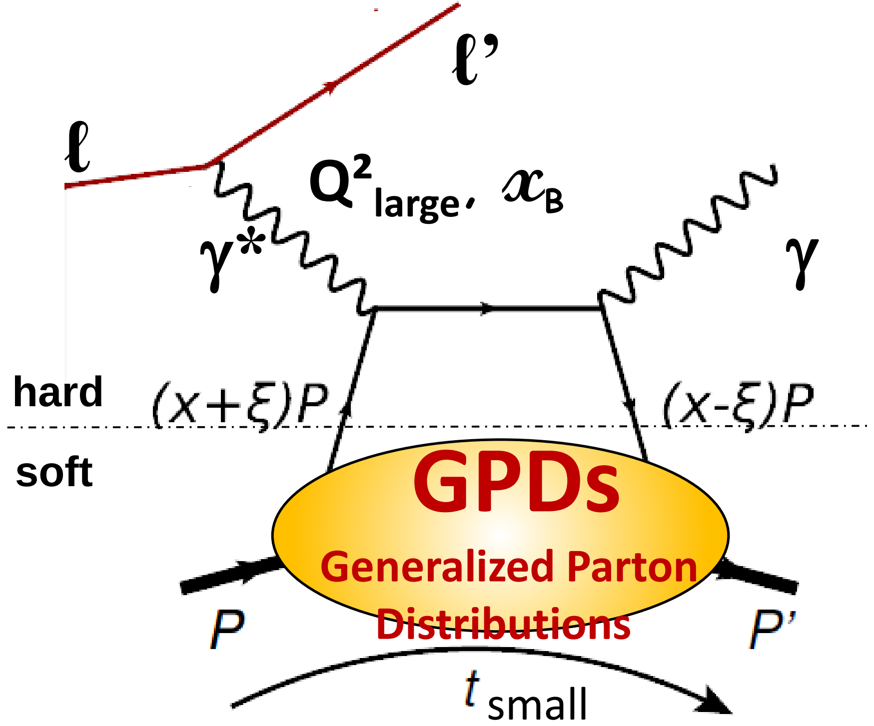
The GPDs depend on the following variables:

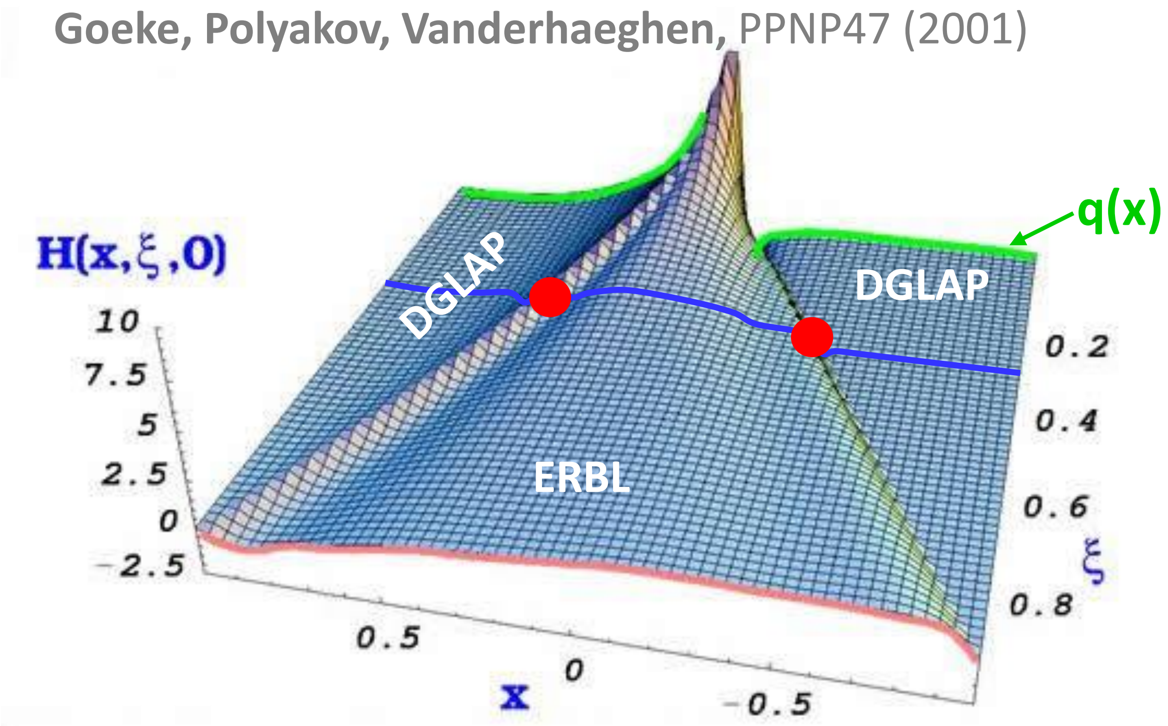
- x: average long. momentum
- ξ: long. mom. difference
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

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)





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

Real part Imaginary part

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

In an experiment we measure

Compton Form Factor $\mathcal{H}$

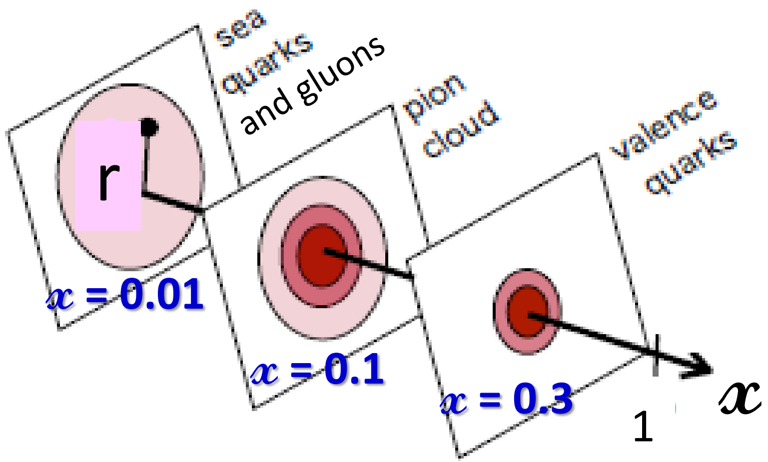
$$\mathcal{R}e\mathcal{H}(\xi,t) = \int dx\, \frac{Im\mathcal{H}(x,t)}{x-\xi} + D(t)$$

Deeply virtual Compton scattering (DVCS)

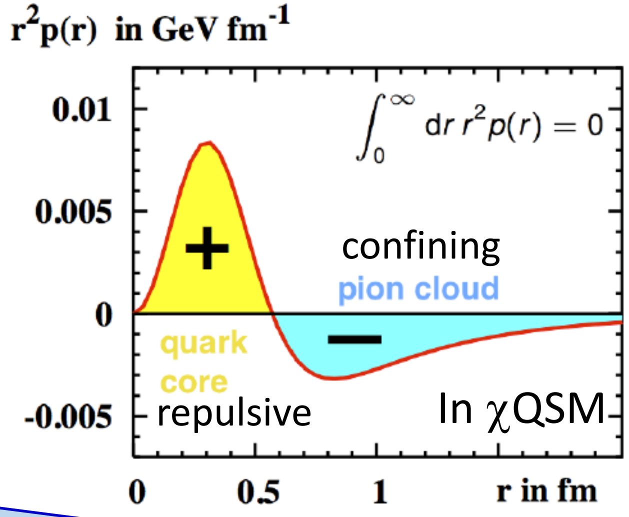
M. Burkardt, PRD66(2002)

M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

Mapping in the transverse plane



Pressure Distribution



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

Real part   Imaginary part

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

t, ξ fixed

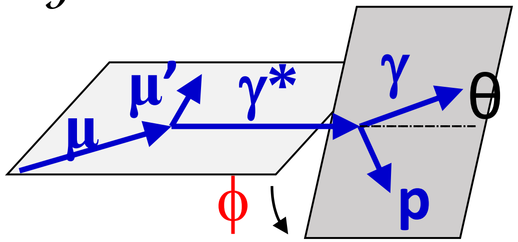
In an experiment we measure

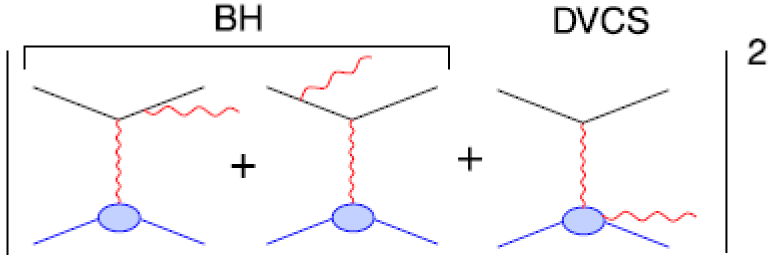
Compton Form Factor $\mathcal{H}$

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

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ, e_ℓ) and ϕ





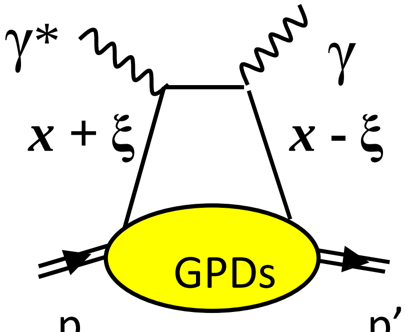
$$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2 + \text{Interference Term}$$

$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}\right) + (e_\ell \mathrm{Re}\, I + e_\ell P_\ell \mathrm{Im}\, I)$$

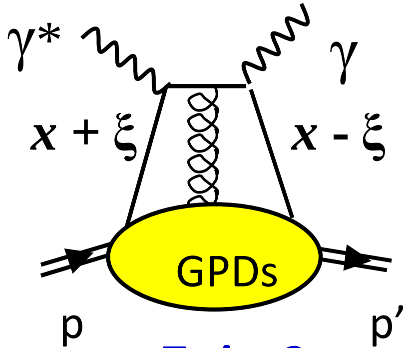
Well known

Σ	$d\sigma^{BH}$	$\propto$	$c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$
Σ	$d\sigma^{DVCS}_{unpol}$	$\propto$	$c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$
Δ	$d\sigma^{DVCS}_{pol}$	$\propto$	$s_1^{DVCS}\sin\phi$
Δ	$\mathrm{Re}\, I$	$\propto$	$c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$
Σ	$\mathrm{Im}\, I$	$\propto$	$s_1^I\sin\phi + s_2^I\sin 2\phi$

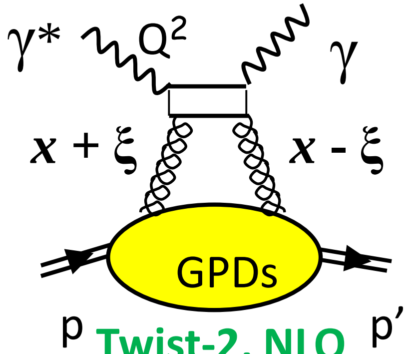
With both $\overleftarrow{\mu^+}$ and $\overrightarrow{\mu^-}$ beams we can build the Σ and Δ:



LO,Twist-2



Twist-3



Twist-2, NLO
double helicity flip

Deeply virtual Compton scattering (DVCS)

$$
\begin{array}{llll}
\Sigma & d\sigma^{BH} & \propto & c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
\Sigma & d\sigma^{DVCS}_{unpol} & \propto & c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
\Delta & d\sigma^{DVCS}_{pol} & \propto & s_1^{DVCS}\sin\phi \\
\Delta & \mathrm{Re}\, I & \propto & c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \\
\Sigma & \mathrm{Im}\, I & \propto & s_1^I\sin\phi + s_2^I\sin 2\phi
\end{array}
$$

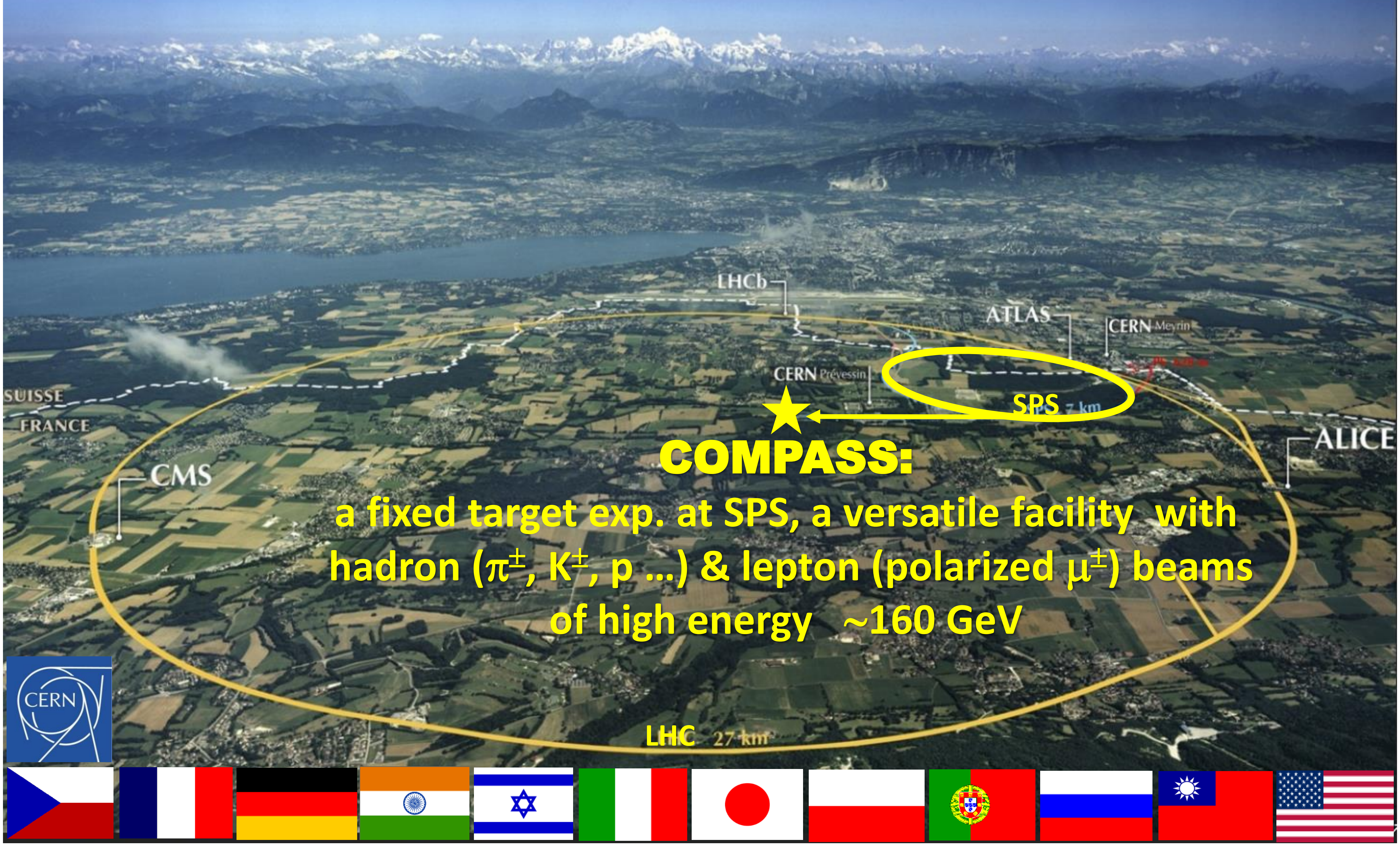
With both $\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ beams at COMPASS we can build the Σ and Δ:

$$\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} \;\Rightarrow\; s_1^{\,I} = Im\,\mathcal{F}$$

$$\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}} \;\Rightarrow\; c_1^{\,I} = Re\,\mathcal{F}$$

$$\mathcal{F} = F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} - t/4m^2\, F_2\mathcal{E} \;\xrightarrow{\text{for proton}}\; F_1\mathcal{H}$$

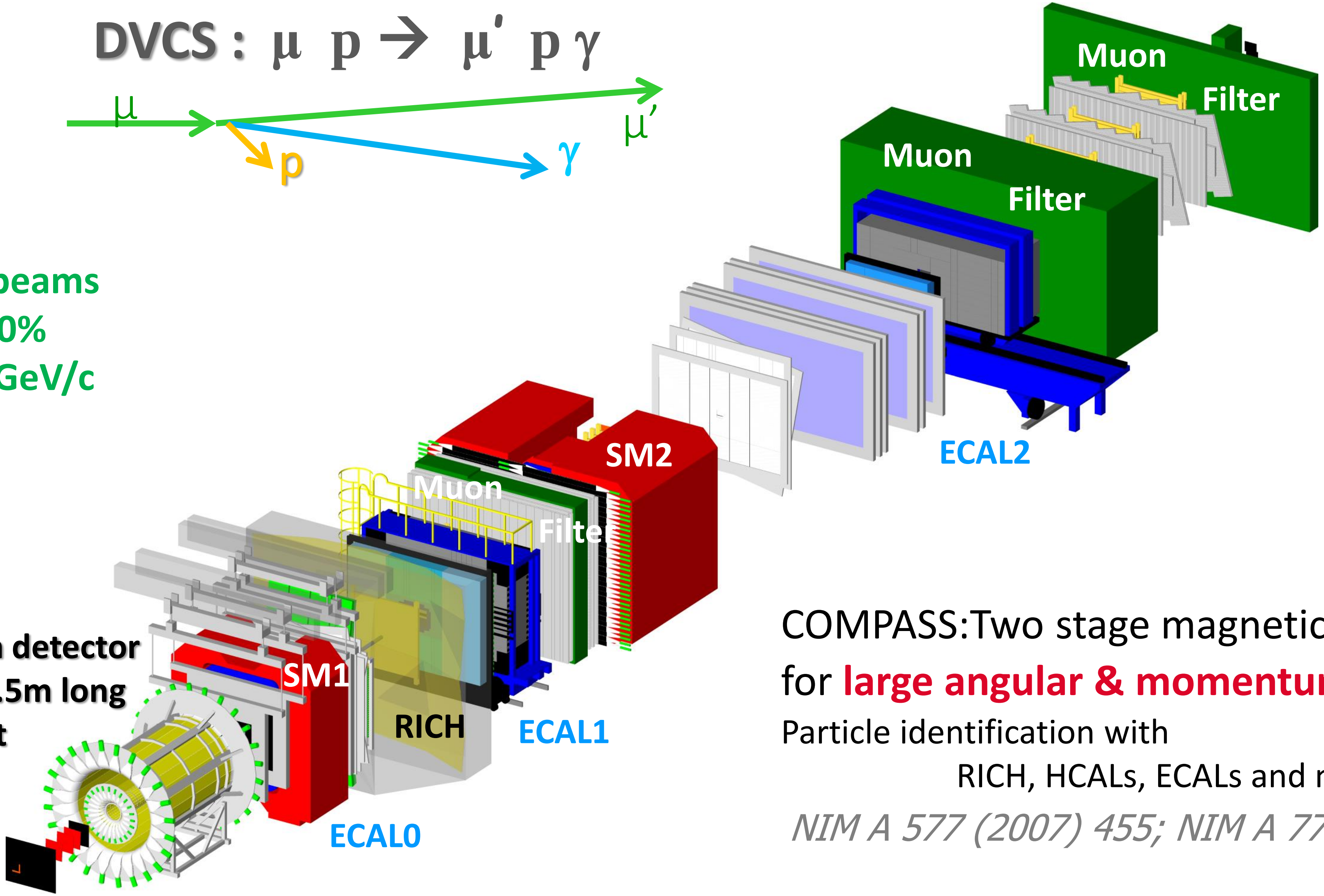
at small x_B
COMPASS domain


COMPASS:
a fixed target exp. at SPS, a versatile facility with
hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams
of high energy ~160 GeV
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km
CERN

The DVCS experiment at COMPASS

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

Both $\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ beams
Polarisation ~ ±80%
Momentum 160 GeV/c



CAMERA recoil proton detector surrounding the 2.5m long LH2 target

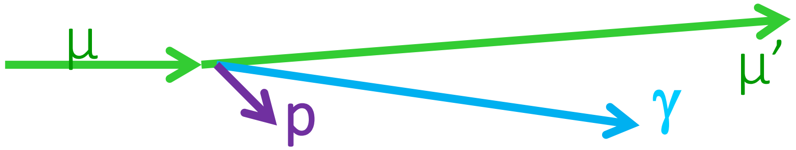
COMPASS:Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with RICH, HCALs, ECALs and muon filters

NIM A 577 (2007) 455; NIM A 779 (2015) 69

The DVCS experiment at COMPASS

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



New equipements:

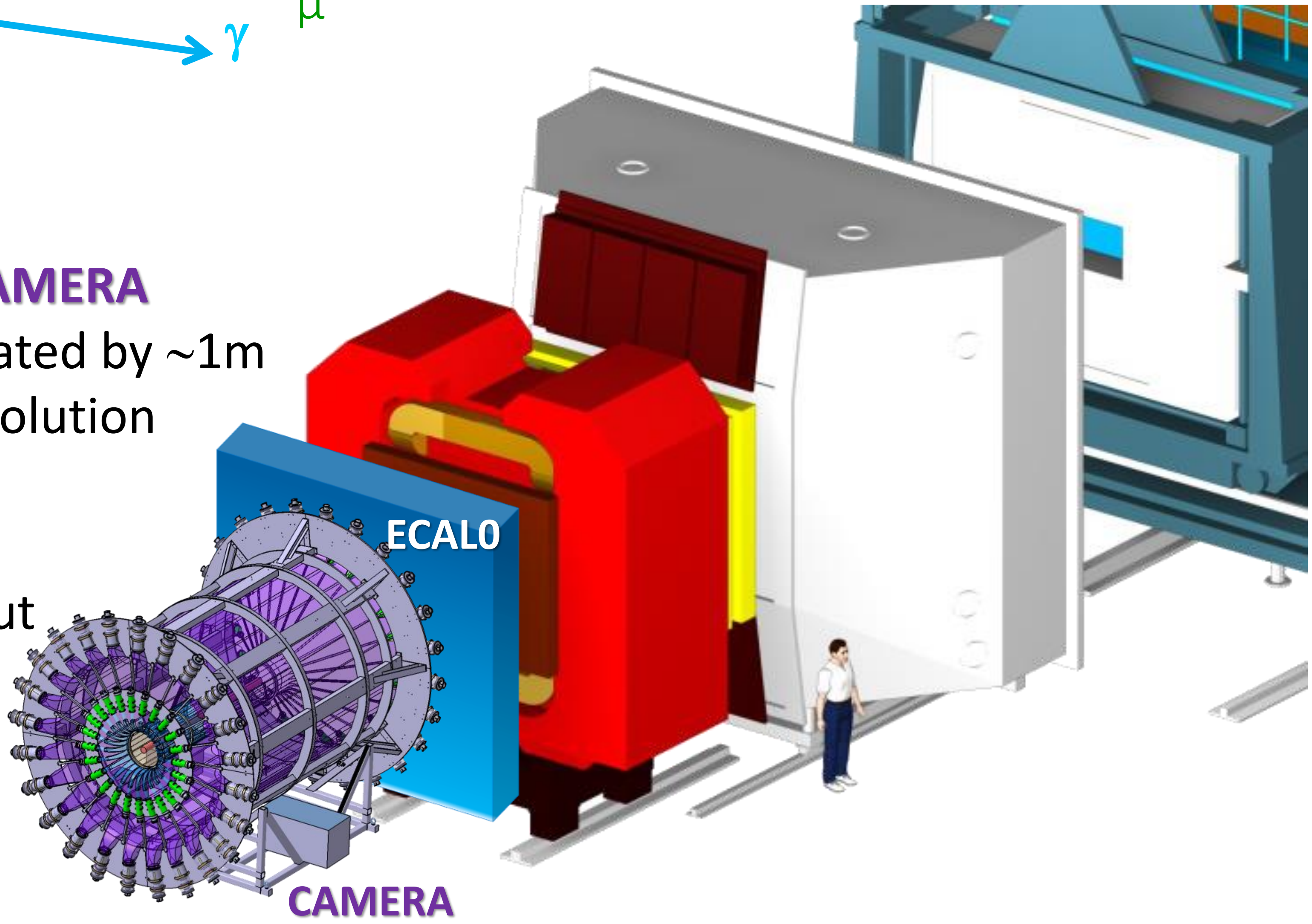
- **2.5m LH2 target**

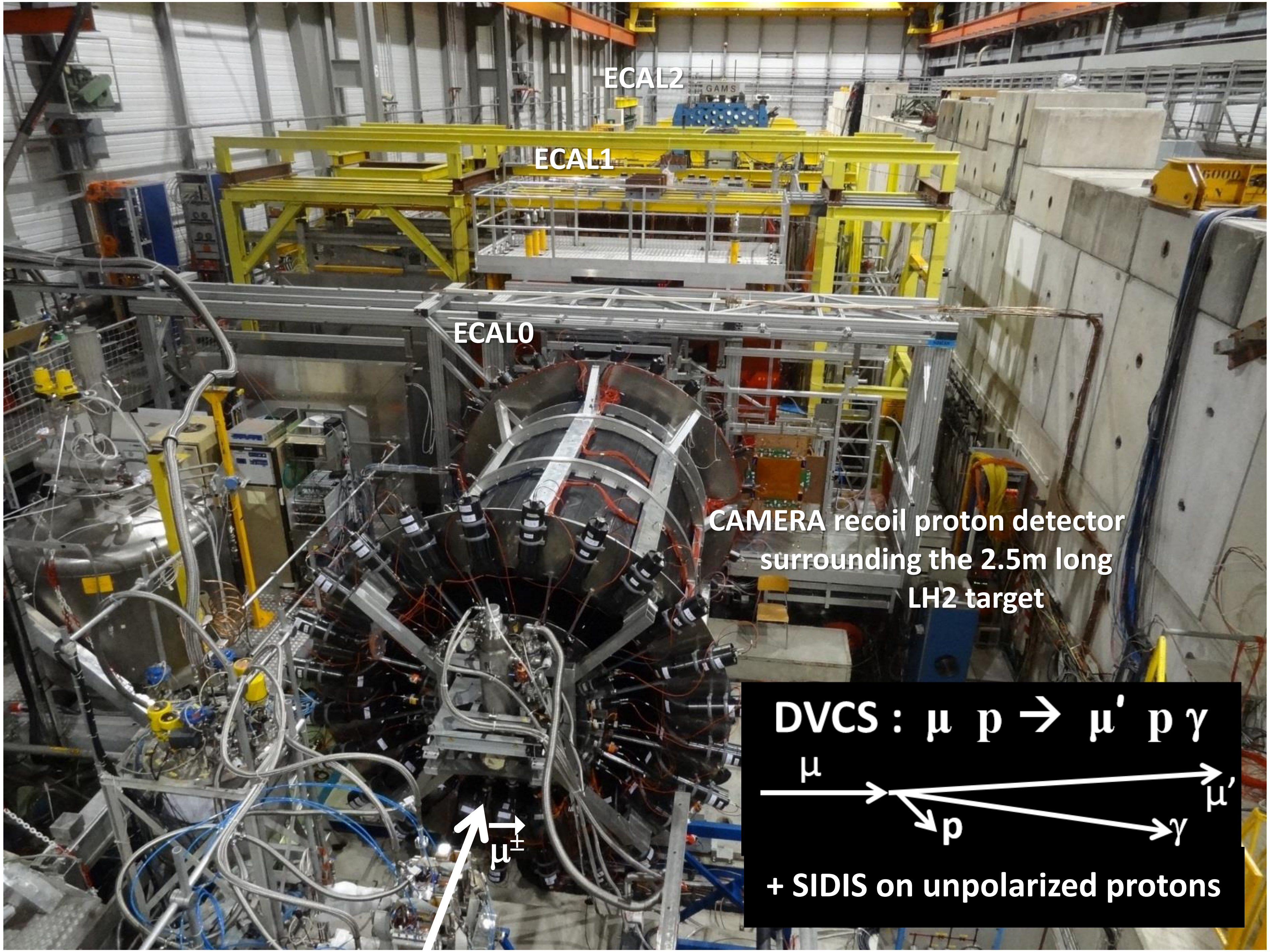
- **4m ToF recoil proton detector CAMERA**

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 month
data taking

COMPASS 2016-17 First insight Exclusivity variables

Comparison between the observables given by the spectro or by CAMERA

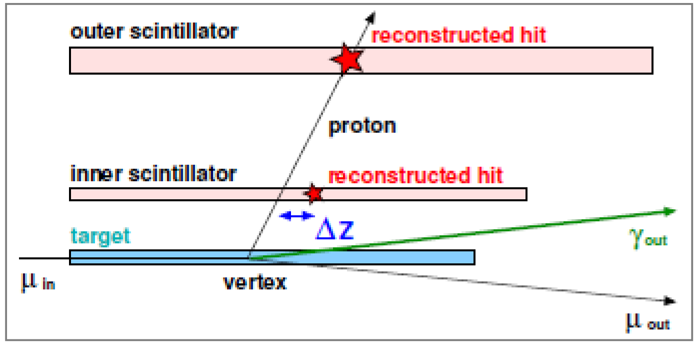
DVCS : μ p → μ' p γ

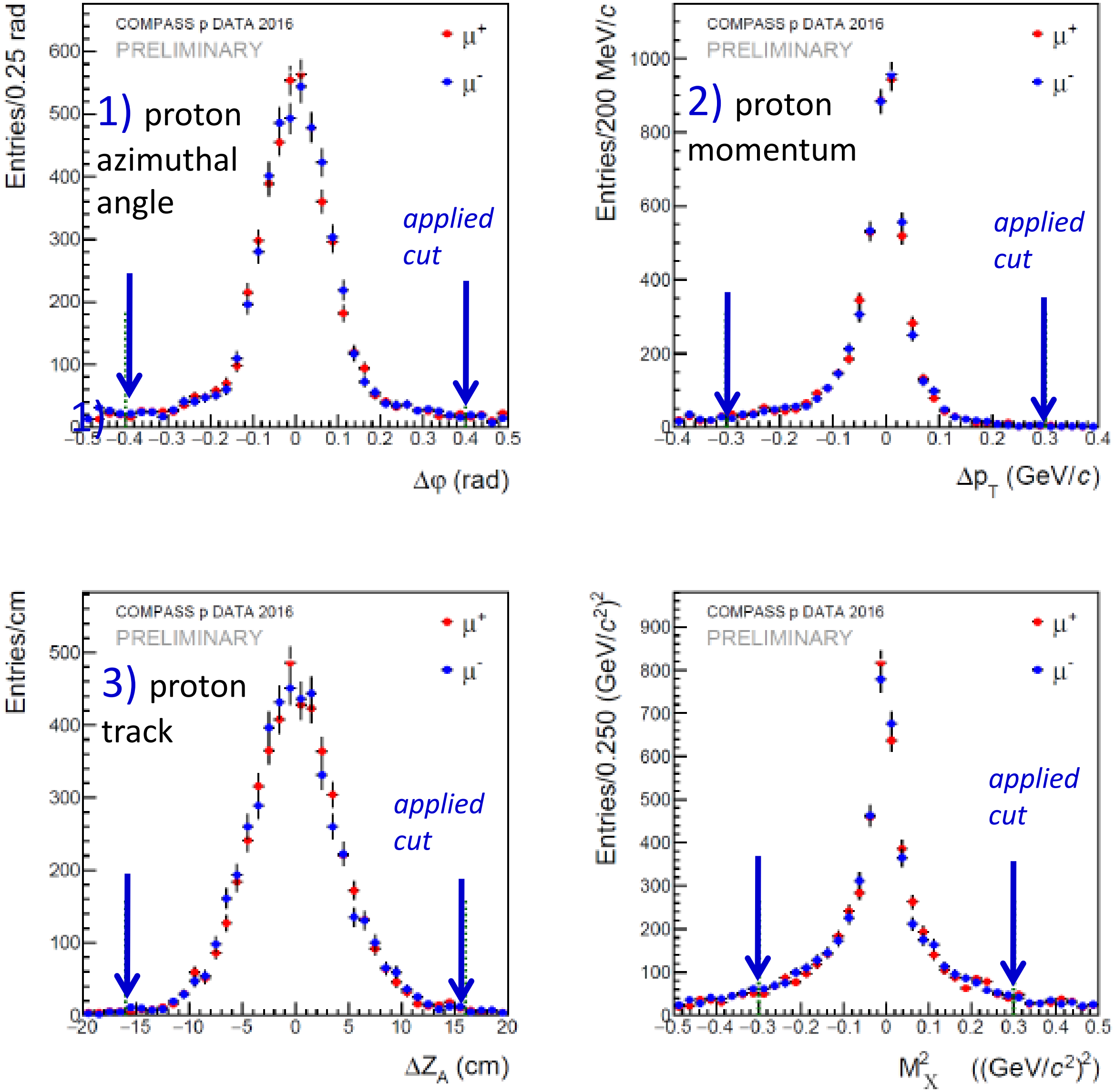
1) $\Delta\varphi = \varphi^{cam} - \varphi^{spec}$

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

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

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





COMPASS 2016-17 First insight Exclusivity variables

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

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

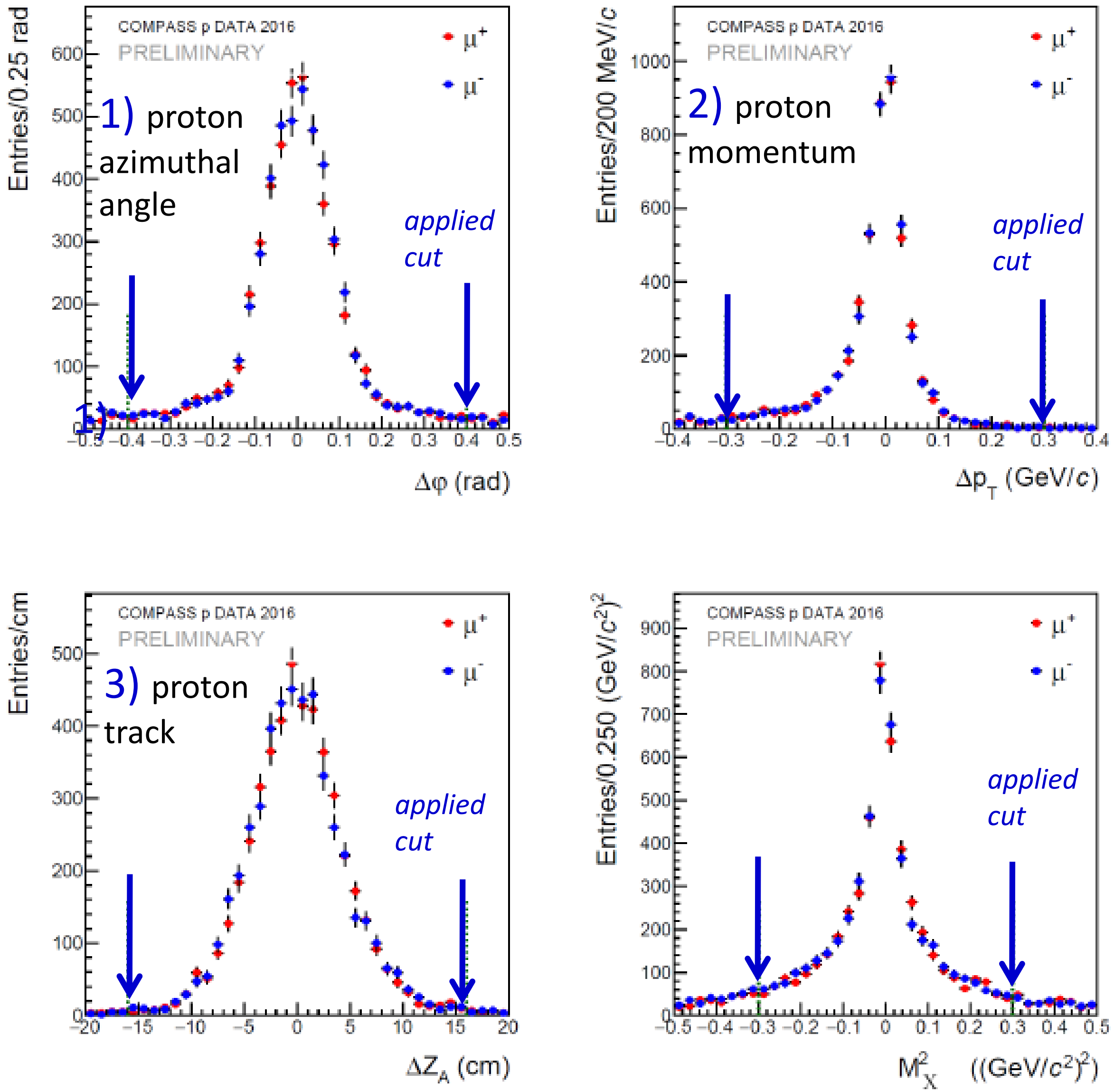
4) $M^2_{X=0} = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\gamma})^2$

Good agreement between $\overleftarrow{\mu^{+}}$ **and** $\overrightarrow{\mu^{-}}$ yields

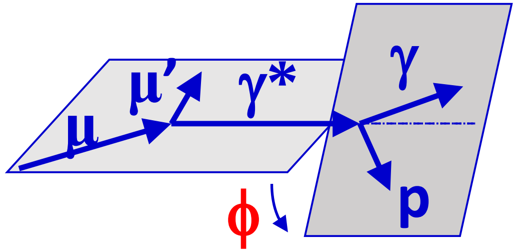
Important achievement for:

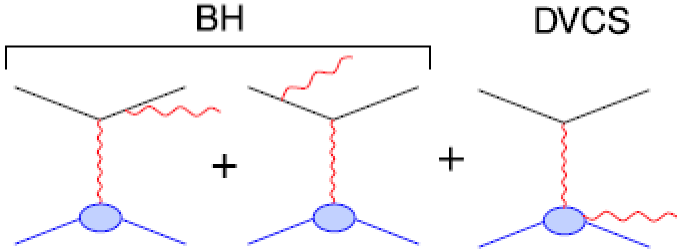
$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$$ Challenging

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$ Easier, done first



COMPASS DVCS cross section at Eμ=160 GeV



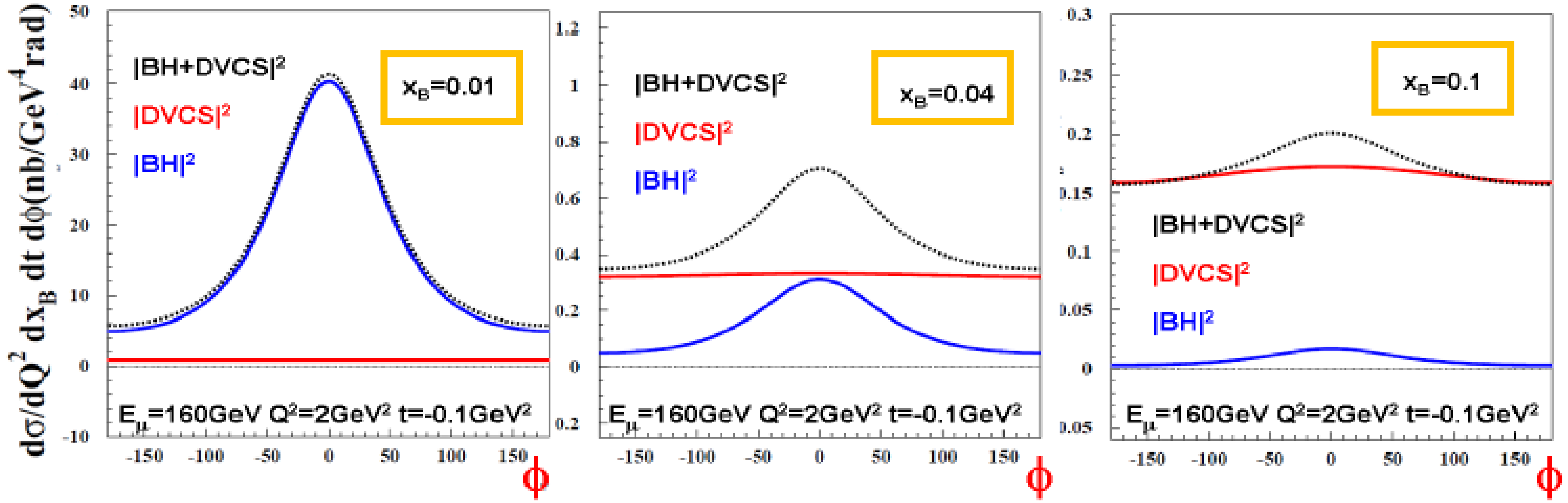


$$S_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

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

BH dominates

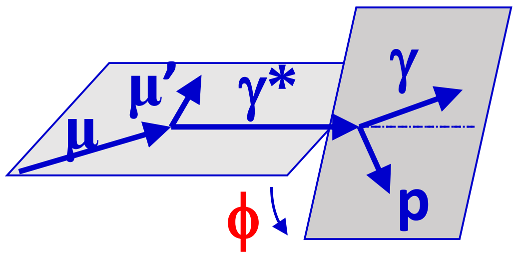
DVCS dominates

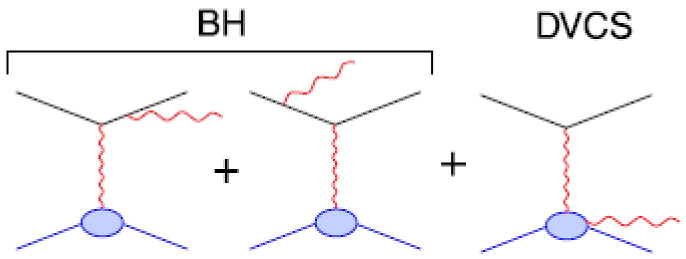


Study of DVCS amplitude via the interference

Study of DVCS cross section
Small BH contribution
which can be subtracted

COMPASS 2016-17 DVCS cross section at Eμ=160 GeV





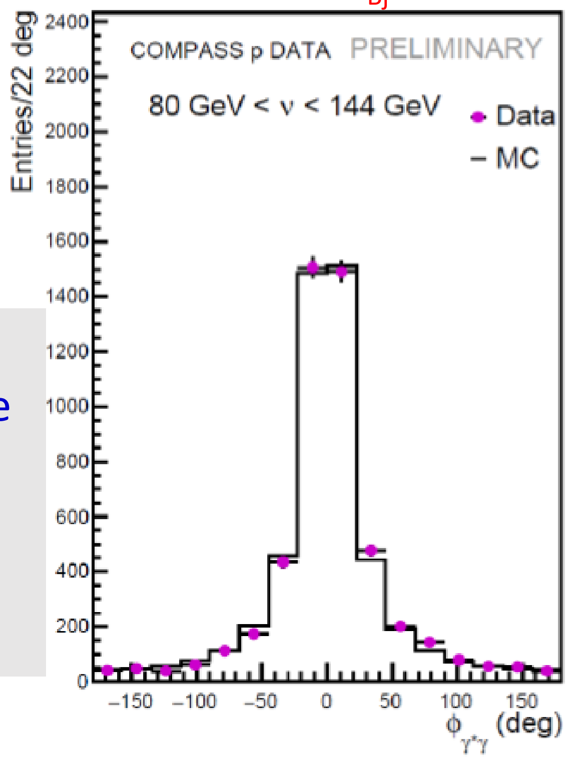
$$S_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

First insight
Only 13% of 2016-17 data

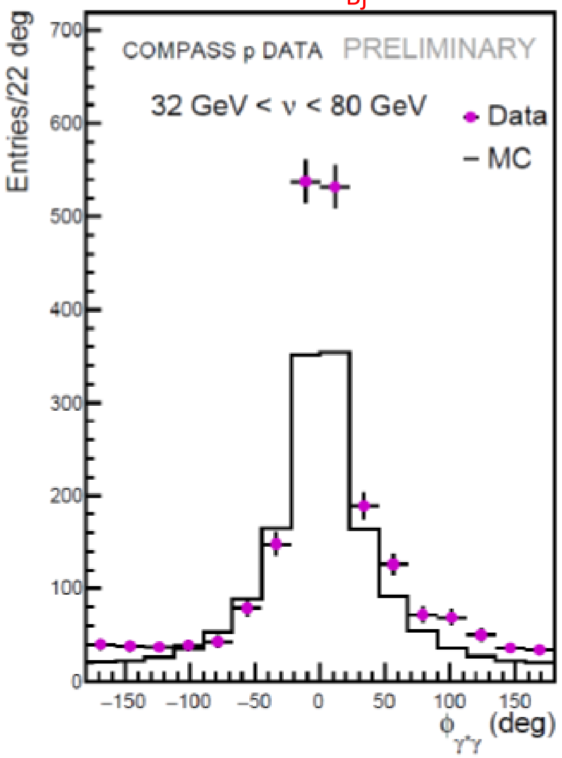
$$d\sigma \; \alpha \; |T^{BH}|^2 + \text{Interference Term} + |T^{DVCS}|^2$$

BH expected to contribute only.
BH MC is normalized to this bin

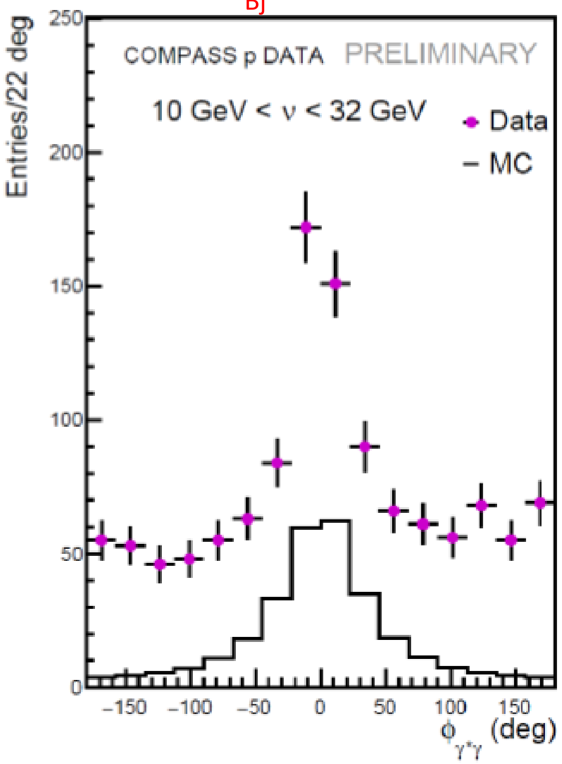
$0.005 < x_{Bj} < 0.01$



$0.01 < x_{Bj} < 0.03$



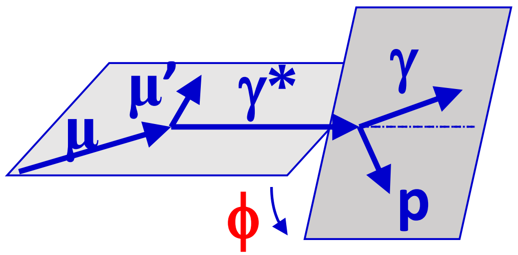
$x_{Bj} > 0.03$

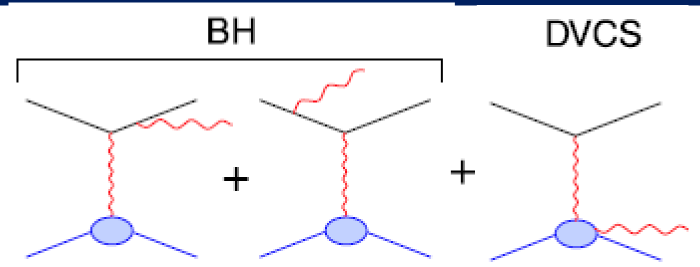


π^0 contamination to be removed
a significant DVCS contribution will allow to study $d\sigma^{DVCS}/dt = e^{-B|t|}$

Thanks to the BLUE WATERS sustained-petascale computing project (NSF and University of Illinois at Urbana-Champaign)

COMPASS 2012 DVCS cross section at Eμ=160 GeV

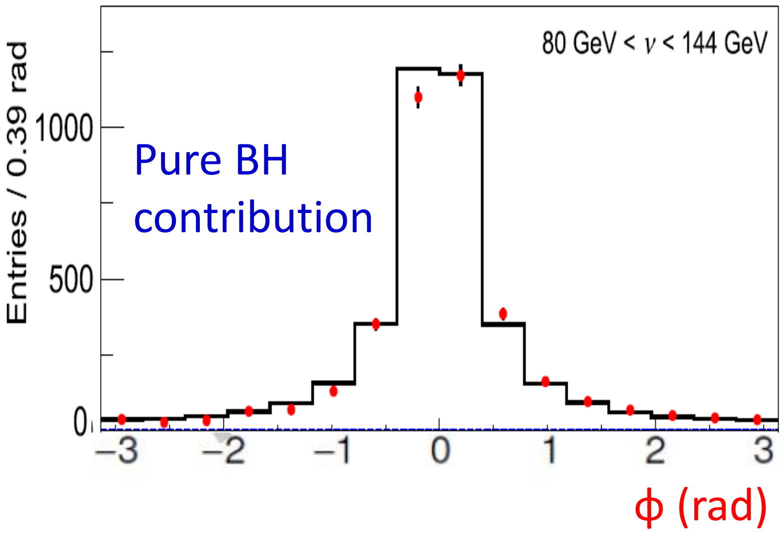




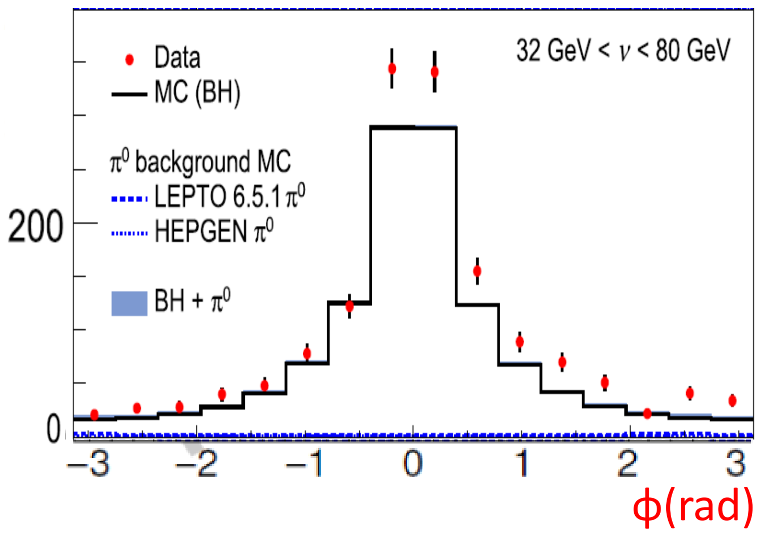
$$S_{CS,U} \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$$

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

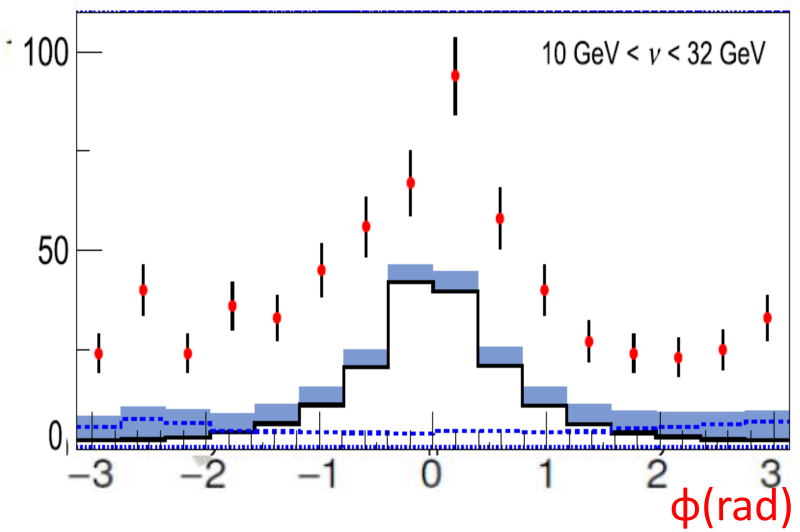
$0.005 < x_{Bj} < 0.01$



$0.01 < x_{Bj} < 0.03$



$x_{Bj} > 0.03$



MC: — BH normalisation based on integrated luminosity

π° background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

DVCS > BH

COMPASS PLB793 (2019) 188-194

COMPASS 2012 DVCS cross section at Eμ=160 GeV

when DVCS > BH

At COMPASS using polarized positive and negative muon beams:

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

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

calculable
can be subtracted

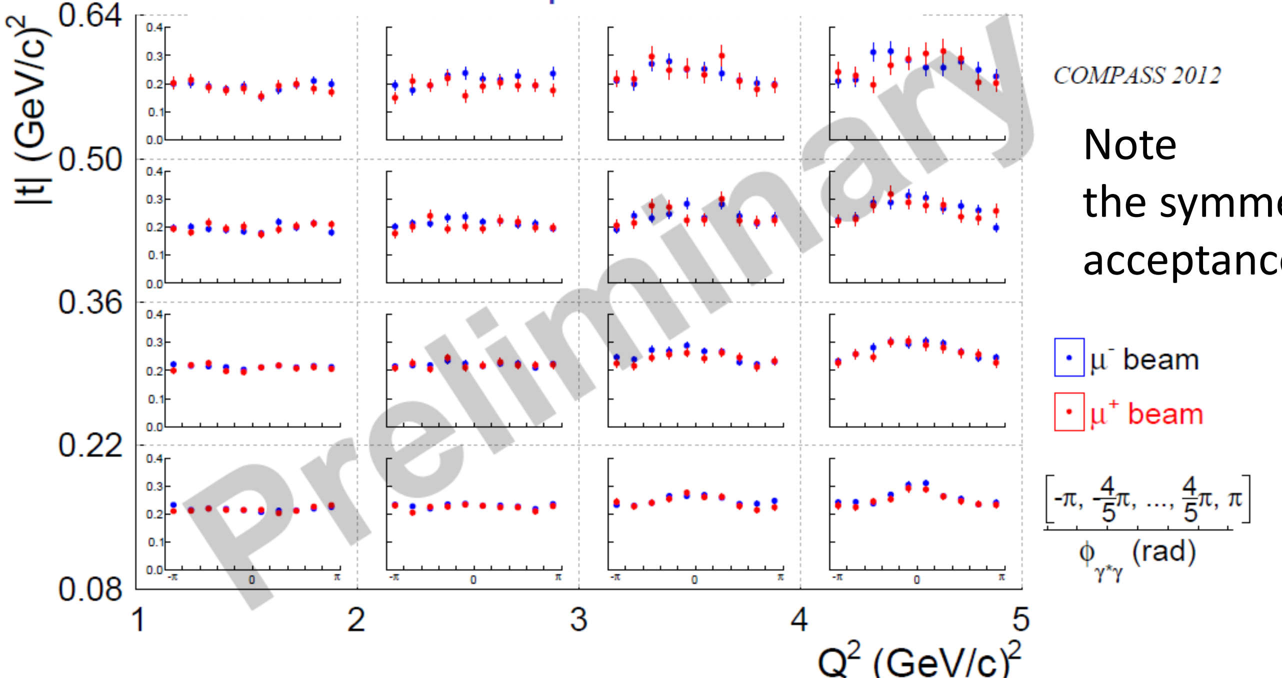
All the other terms are cancelled in the integration over ϕ

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

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

Flux for transverse virtual photons

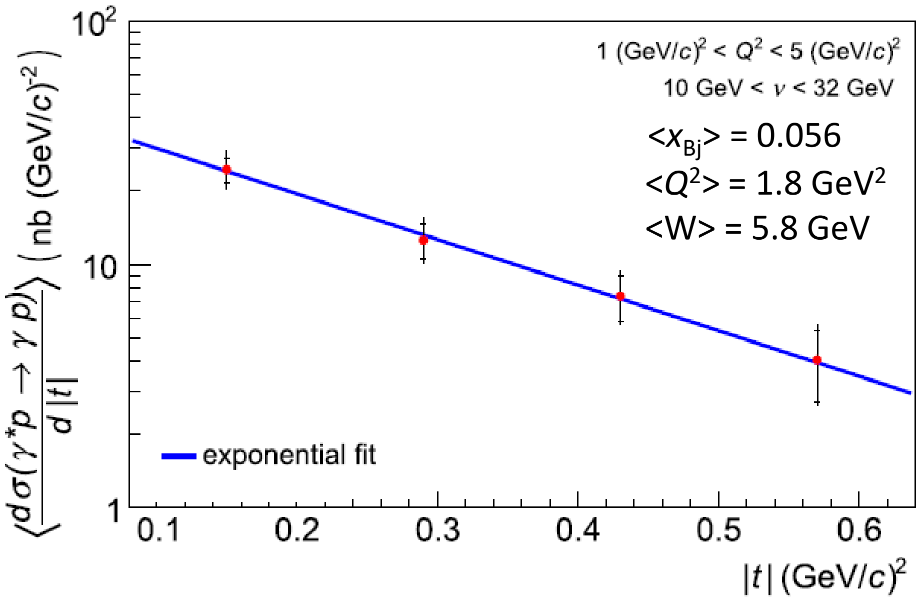
COMPASS acceptance for DVCS

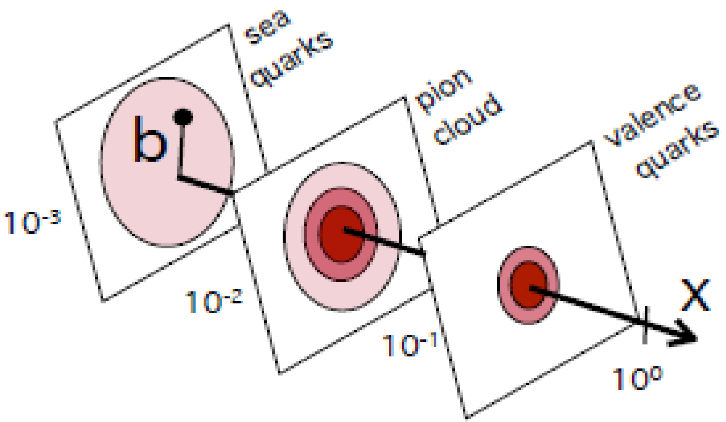


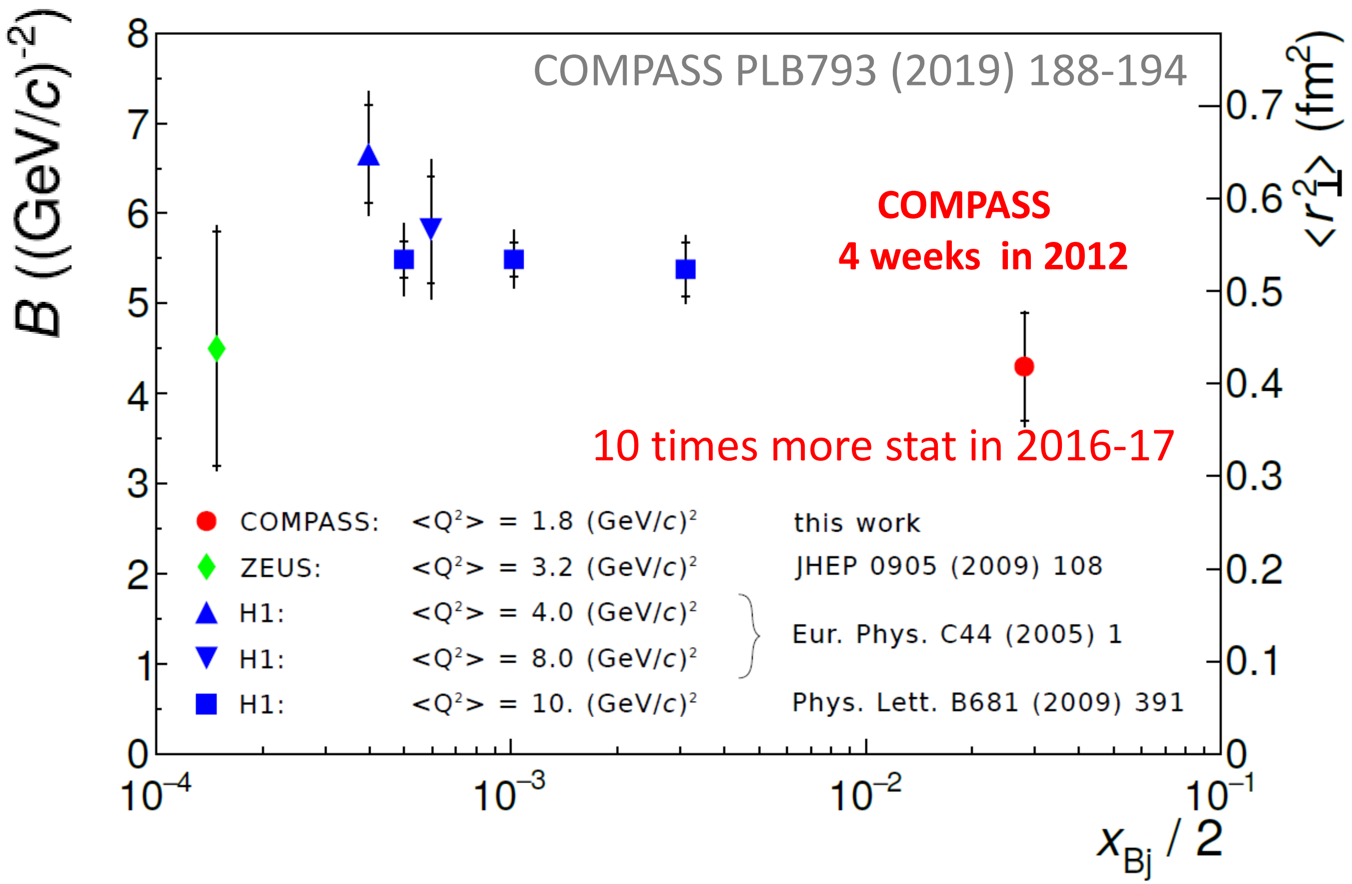
Note the symmetric acceptance

COMPASS 2012 Transverse extention of partons in the sea quark range

$$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS}$$







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

COMPASS 2012 Transverse extention of partons in the sea quark range

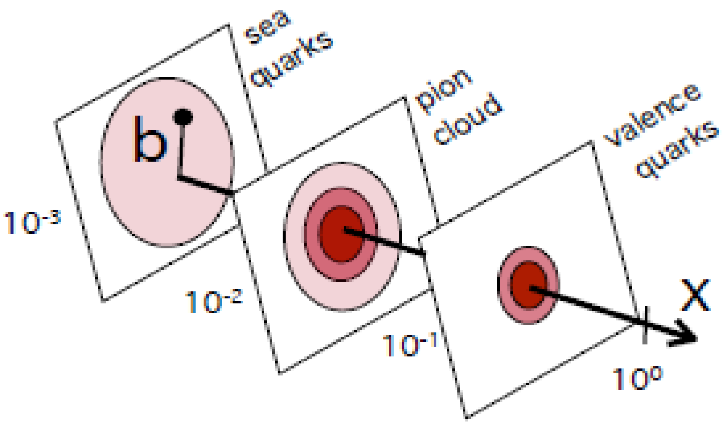
$$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS}$$

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

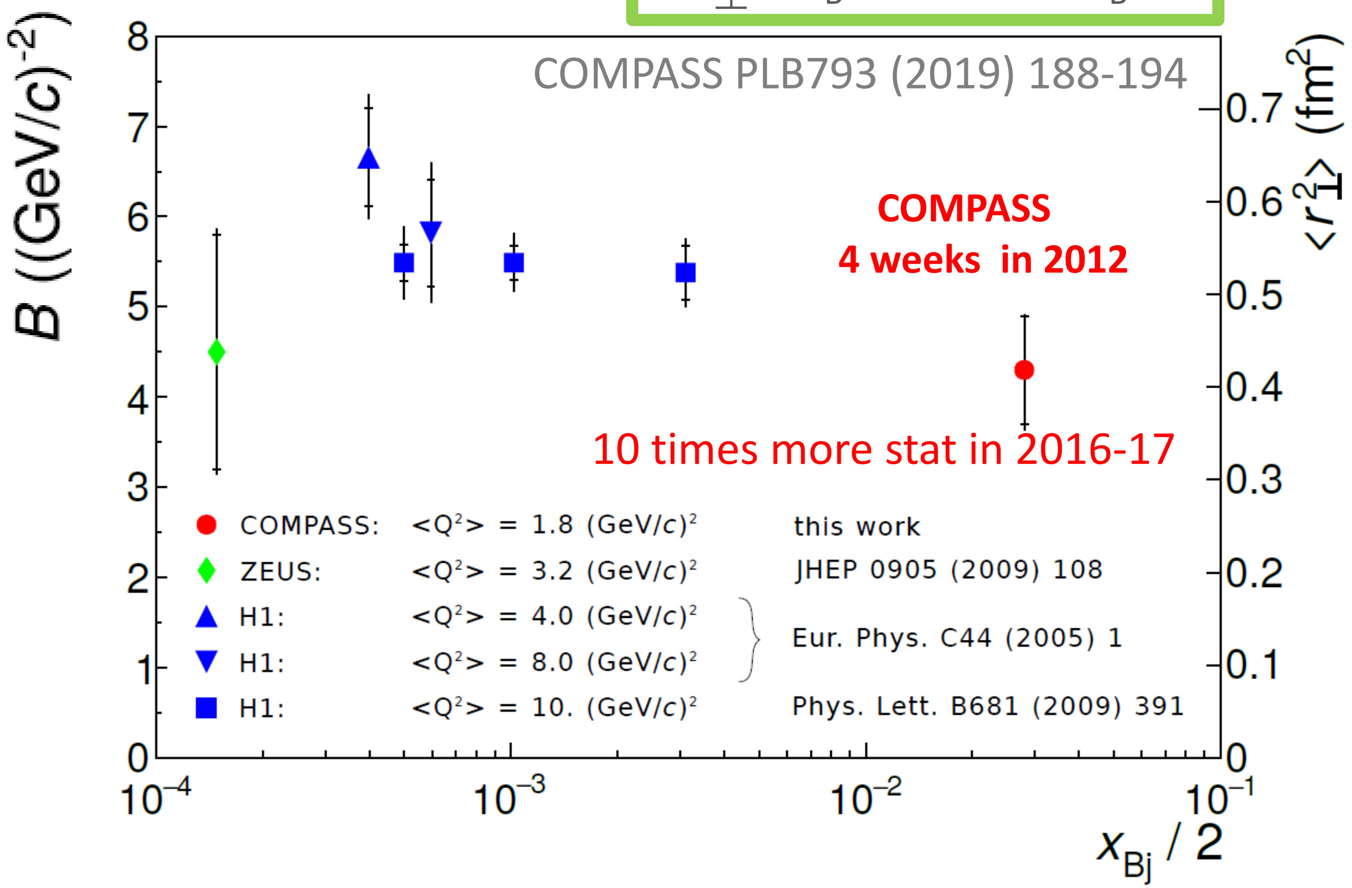
At small x_{Bj} and small t:

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

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 2012 Transverse extention of partons in the sea quark range

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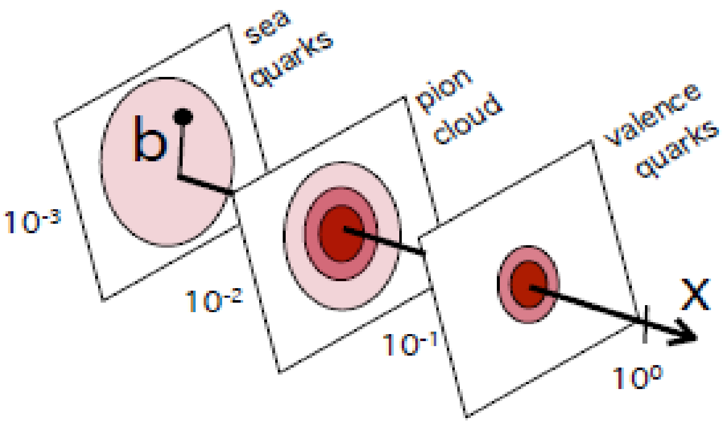
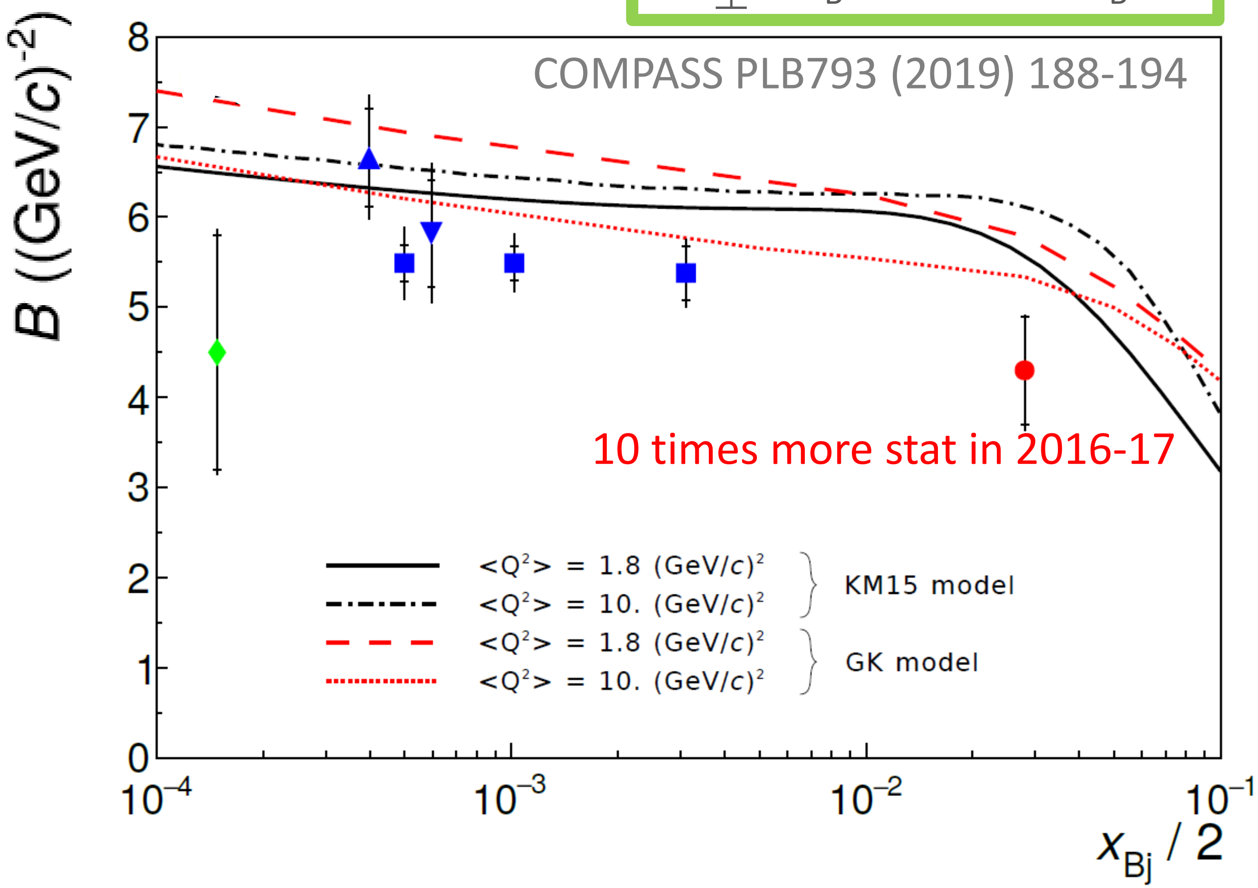
Dominance of *Im*$\mathcal{H}$
(with respect of *Re*$\mathcal{H}$ and other *CFF*)



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



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What will come next?

4 weeks in 2012

2 years of data in 2016-17 ➔ 10 times more stat

At COMPASS with polarized positive and negative muon beams:

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$$

The sum of DVCS x-sections at small x_B
mostly sensitive to $Im\mathcal{H}(\xi,t)$
➔ transverse extension of partons

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$$

The difference of DVCS x-section at small x_B
mostly sensitive to $Re\mathcal{H}(\xi,t)$

$Im\mathcal{H}(\xi,t)$ + $Re\mathcal{H}(\xi,t)$ ➔ D-term and pressure distribution

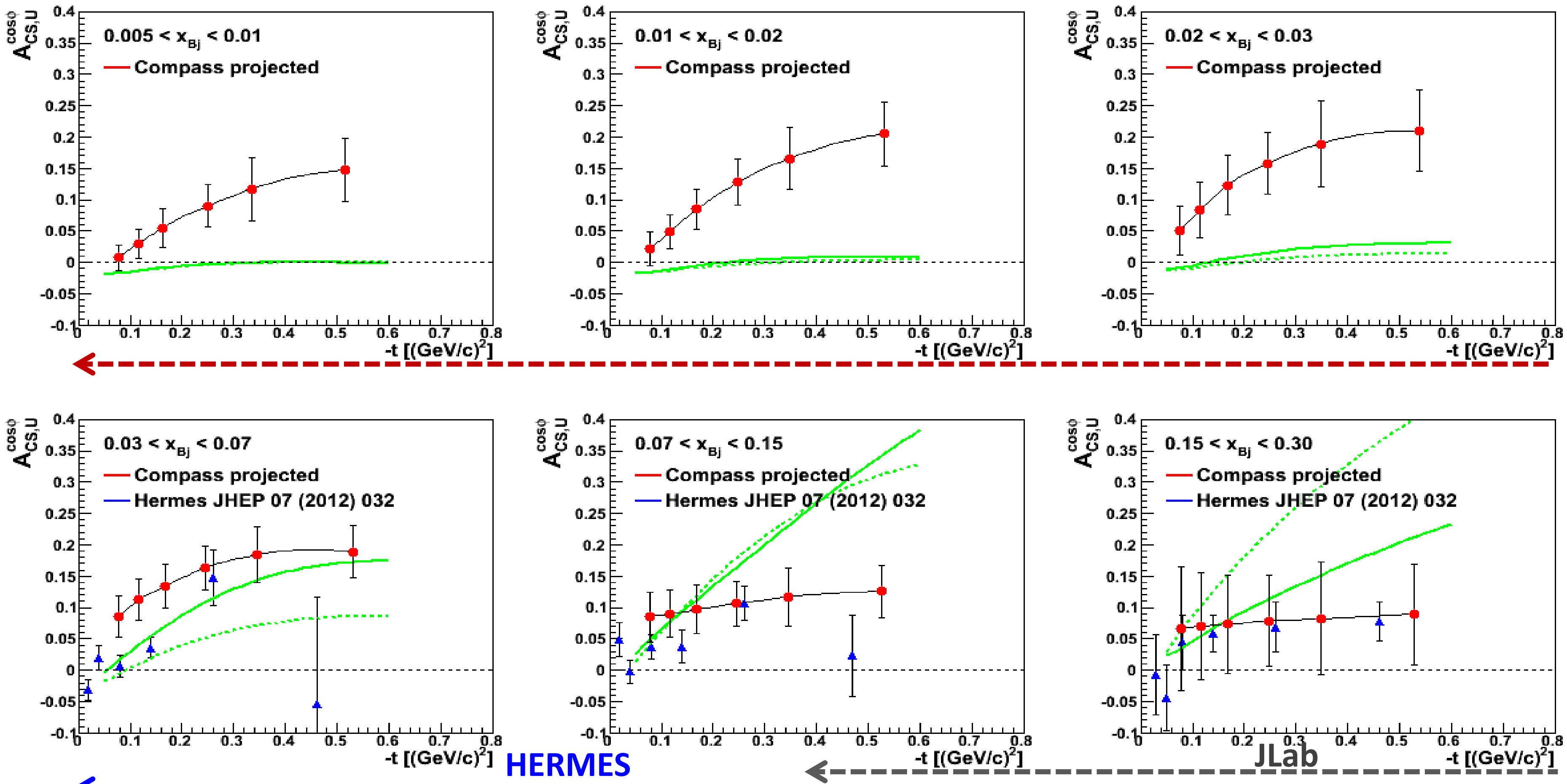
Beam Charge and Spin Diff. @ COMPASS

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

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

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

Predictions with
VGG
KM10



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

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

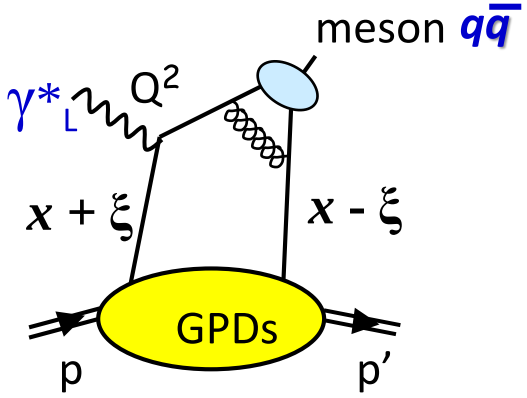
Now HEMP,

pseudo-scalar meson π^0

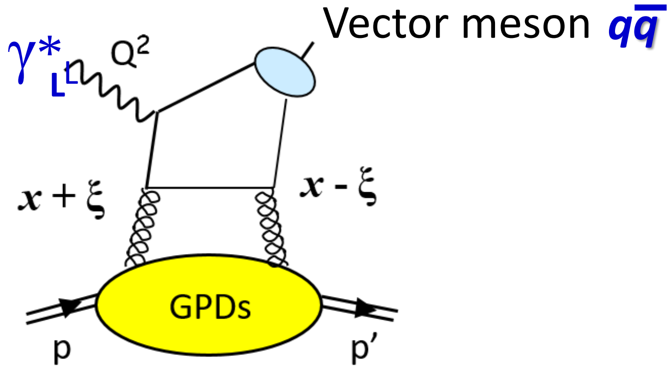
vector mesons ω, ρ, …

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

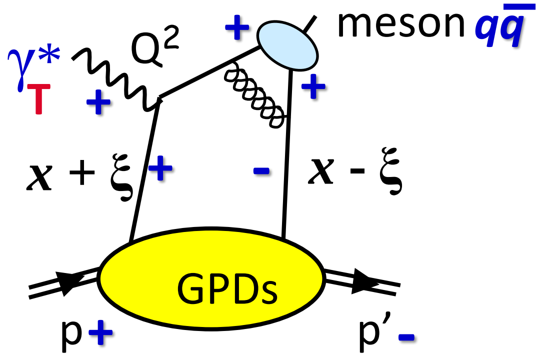
$H^q(x, \xi, t)$	$E^q(x, \xi, t)$	**For Vector Meson**
$\tilde{H}^q(x, \xi, t)$	$\tilde{E}^q(x, \xi, t)$	**For Pseudo-Scalar Meson**

+ 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

$\mathcal{M}_{0-,++}$ 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

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

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

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

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

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

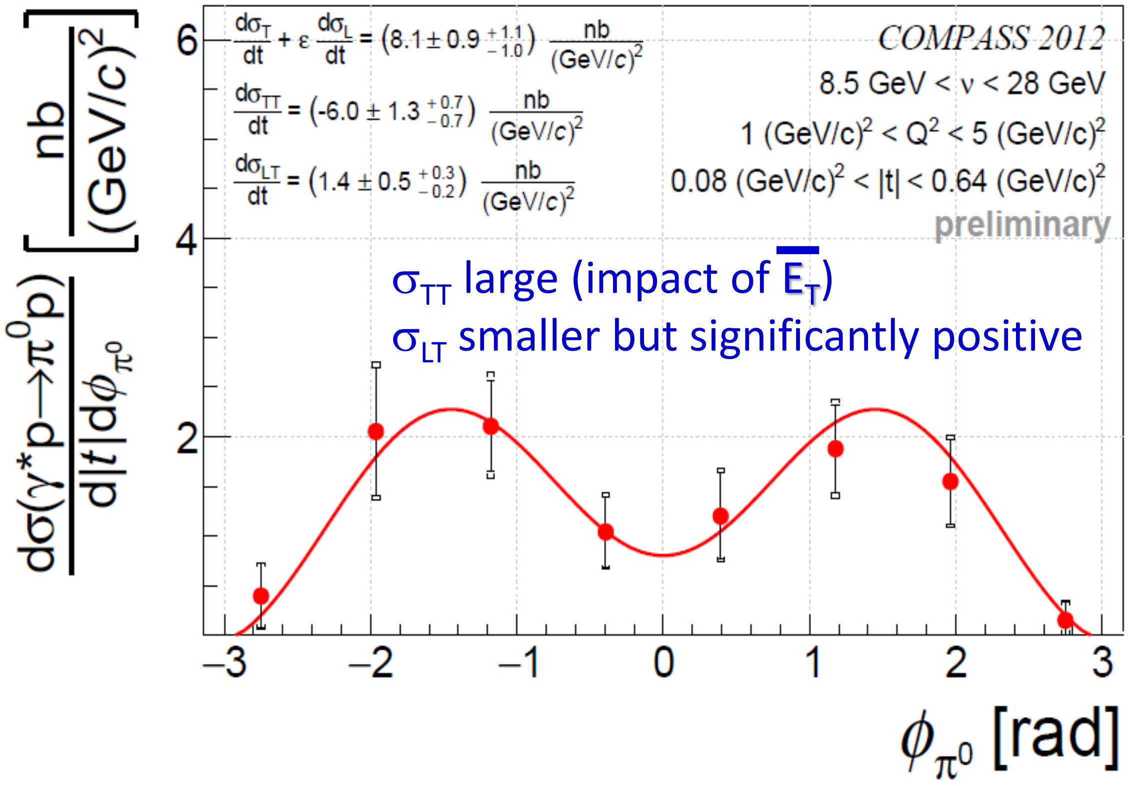
$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

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

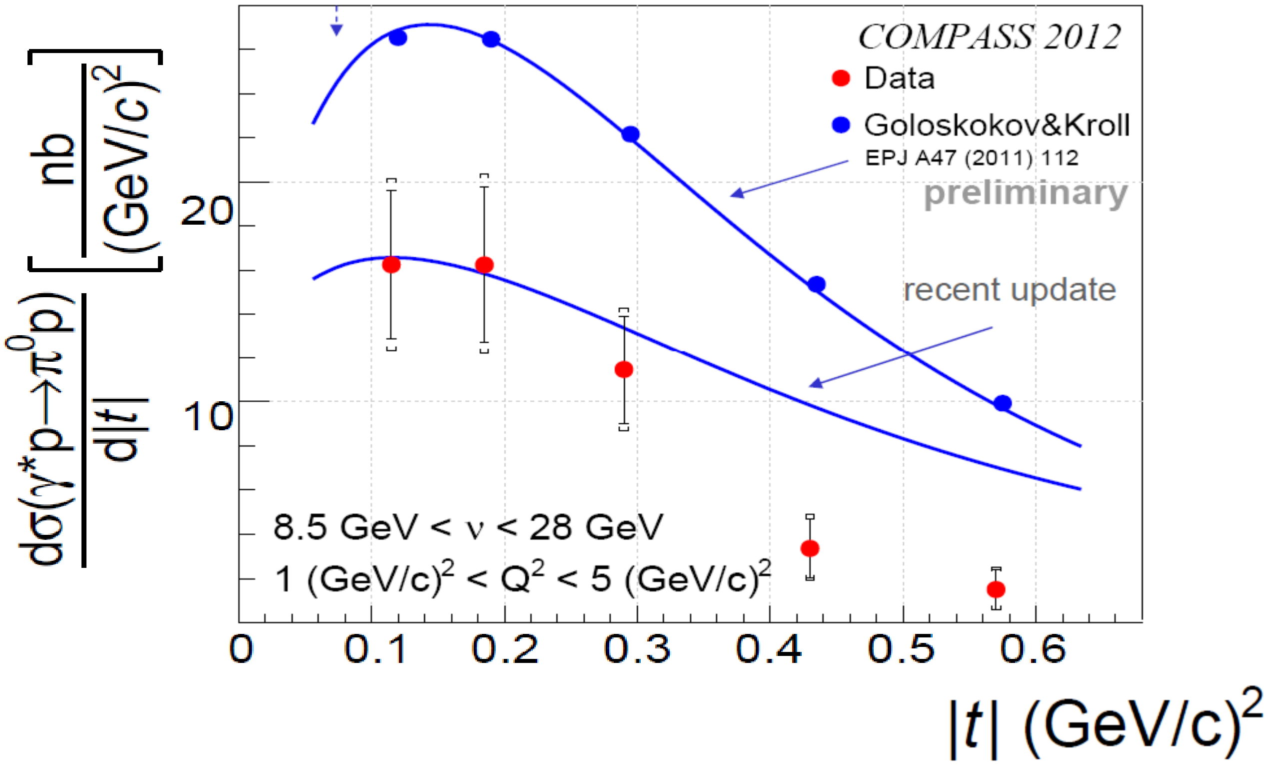
COMPASS 2012 Exclusive π^0 production on unpolarized proton

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

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

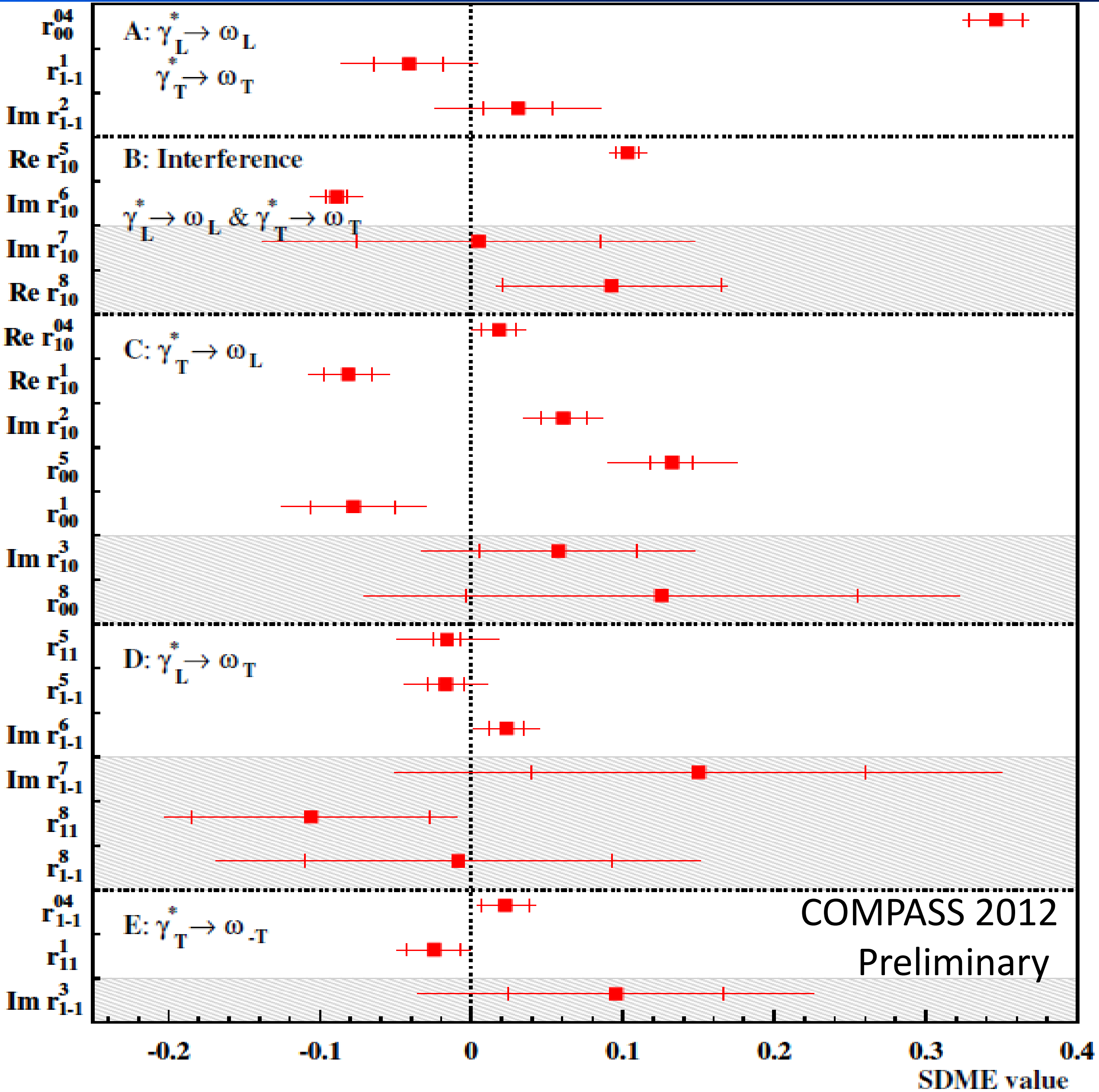


A dip at small t would indicate a large impact of $\bar{E}_T$



hep-ex/1903.12030, subm. to PLB

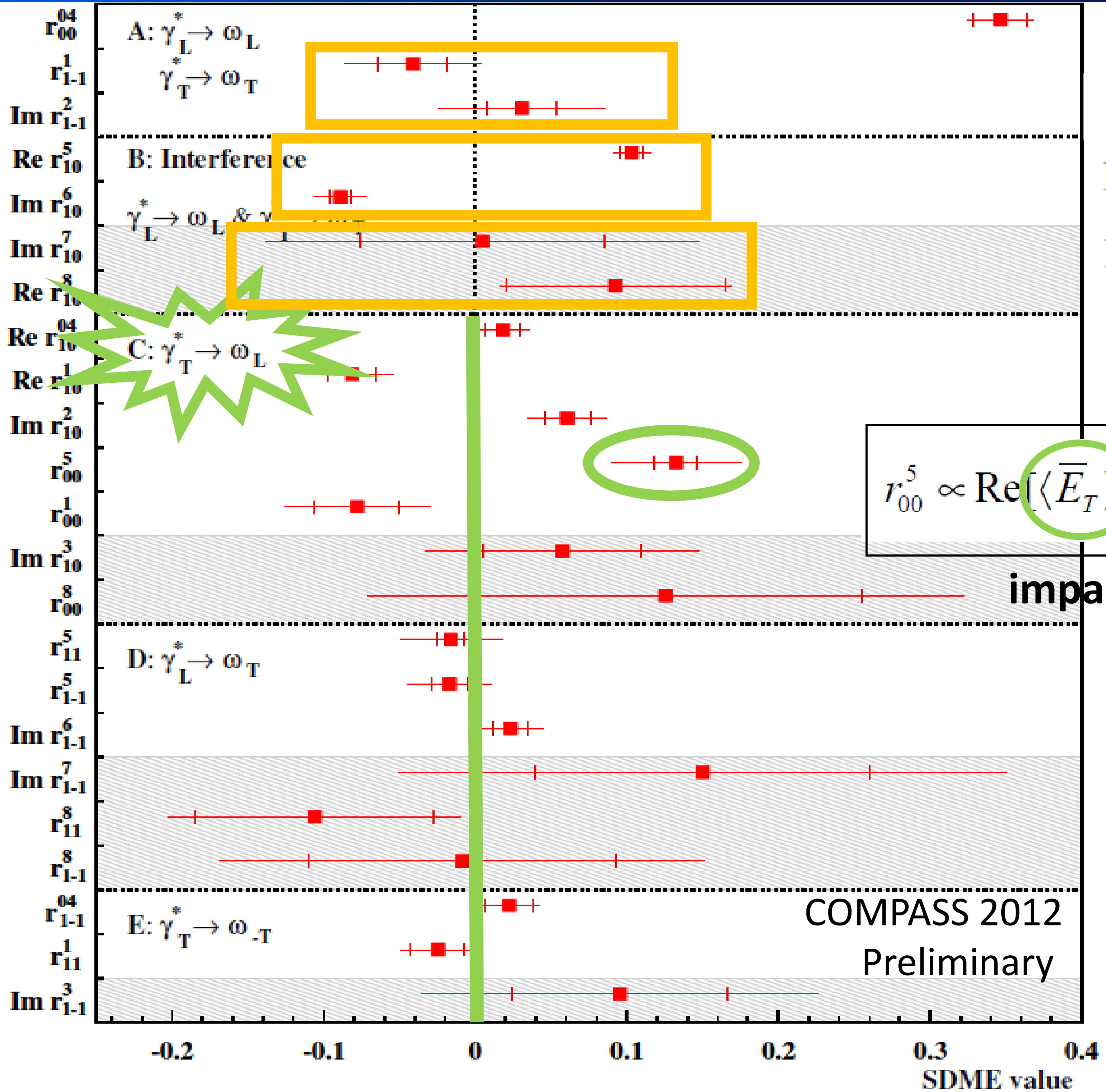
COMPASS 2012 Exclusive ω production on unpolarized proton



23 SDMEs in 5 classes A, B, C, D, E depending on helicity transitions

SDMEs dependent on beam polarisation
Shown within shaded areas

COMPASS 2012 Exclusive ω production on unpolarized proton



If sCHC ($\lambda_\gamma = \lambda_V$) measurements:

$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0 \quad = -0.010 \pm 0.032 \pm 0.047$$

$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0 \quad = 0.014 \pm 0.011 \pm 0.013$$

$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0 \quad = -0.088 \pm 0.110 \pm 0.196$$

All the other SDME in classes C,D, E should be 0

not observed for class C

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

From Goloskokov and Kroll, EPJC74 (2014) 2725

impact of $\bar{E}_T$ and H_T

Already clearly observed
in exclusive ρ^0, ω production
with transvers. polar. target
COMPASS 2004-7-10 data

COMPASS, NPB865 [2012) 1-20
COMPASS, PLB731 (2014) 19
COMPASS, NPB915 (2017) 454-475

Conclusions

From 2016-17 data
sum and difference of DVCS x-sections with polarized μ+ and μ-

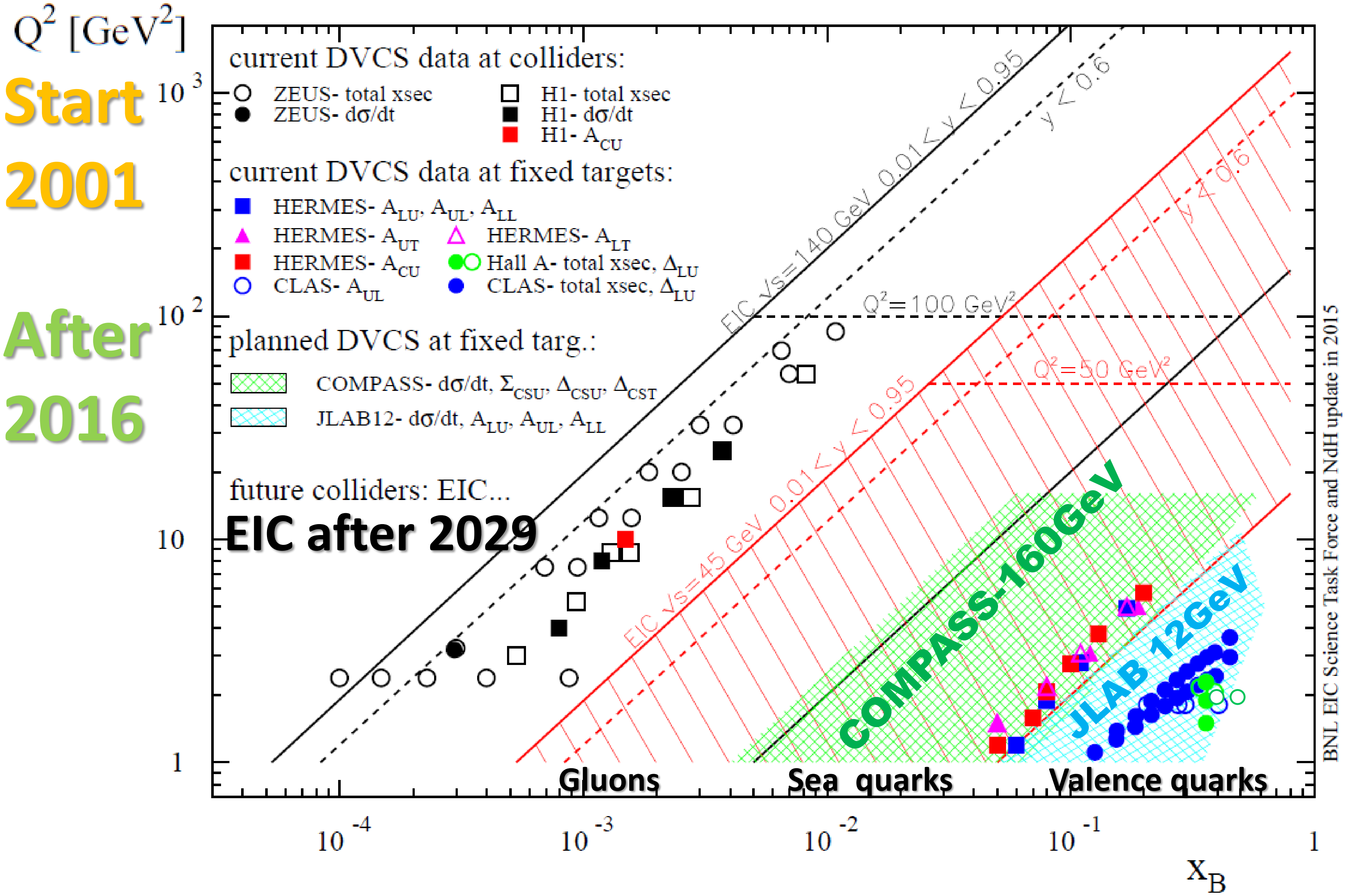
- ➔ transverse extension of partons as a function of x_{Bj}
- ➔ Im$\mathcal{H}(\xi,t)$ and Re$\mathcal{H}(\xi,t)$ for D-term and pressure distribution

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

The past and future DVCS experiments

Start 2001

After 2016



CERN 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

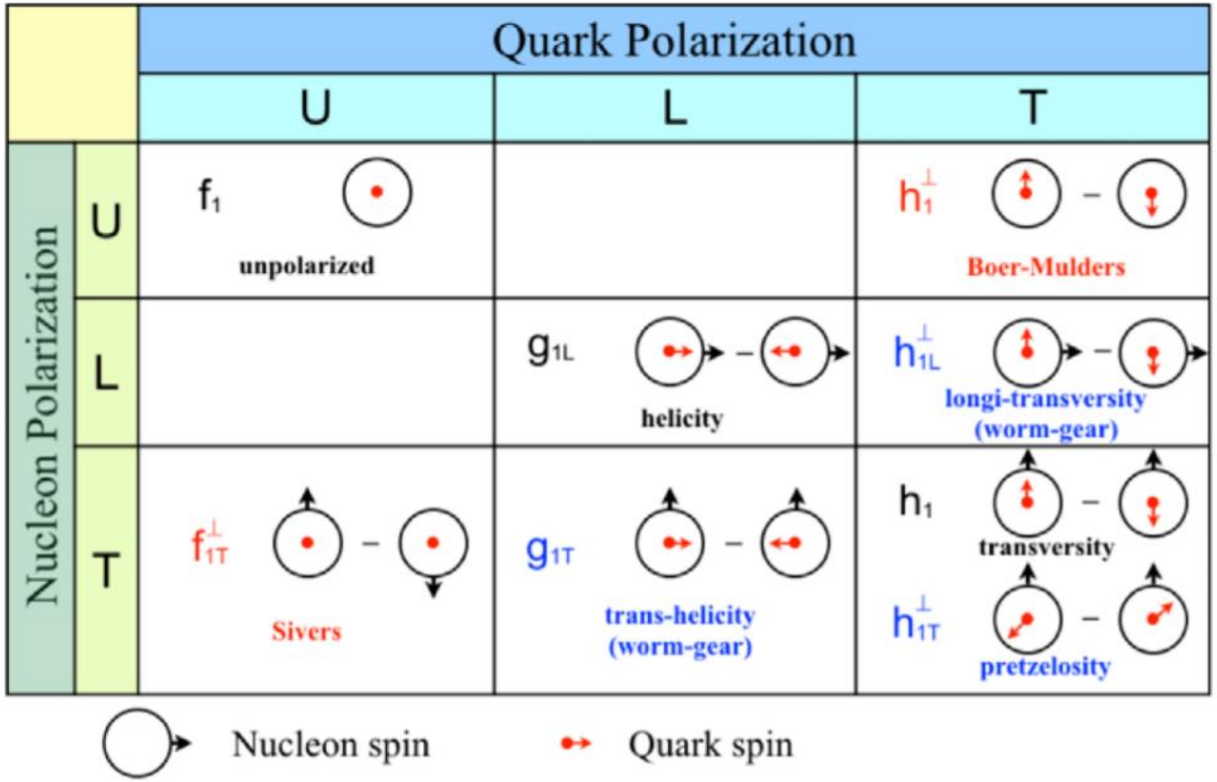
Possible RF separated beam for high intensity antiproton and K beams

Versatile apparatus (Upgrade ++)

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

Eight GPDs for quarks or gluons

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\widetilde{H}_T + E_T$
	L		$\widetilde{H}$	$\widetilde{E}_T$
	T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

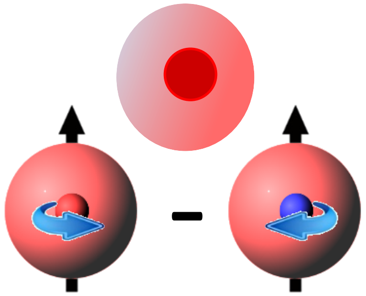


GPDs and TMDs

Chiral-even

$$H \longleftrightarrow q$$

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



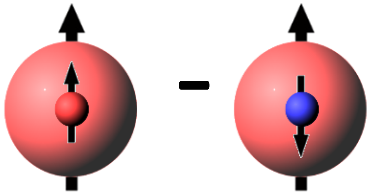
Sivers: quark k_T
and nucleon transv. Spin

the Holy Grail: to reveal OAM

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

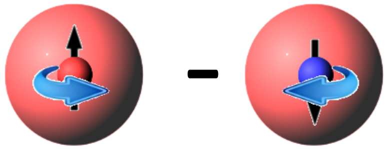
Chiral-odd

$$H_T \longleftrightarrow h_1$$



Transversity: quark spin
and nucleon transv. spin

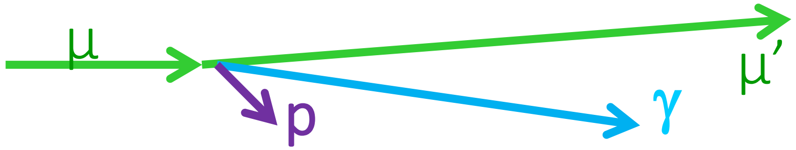
$$\bar{E}_T = 2\tilde{H}_T + E_T \longleftrightarrow h_1^{\perp}$$



Boer-Mulders: quark k_T
and quark transverse spin

The DVCS experiment at COMPASS

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

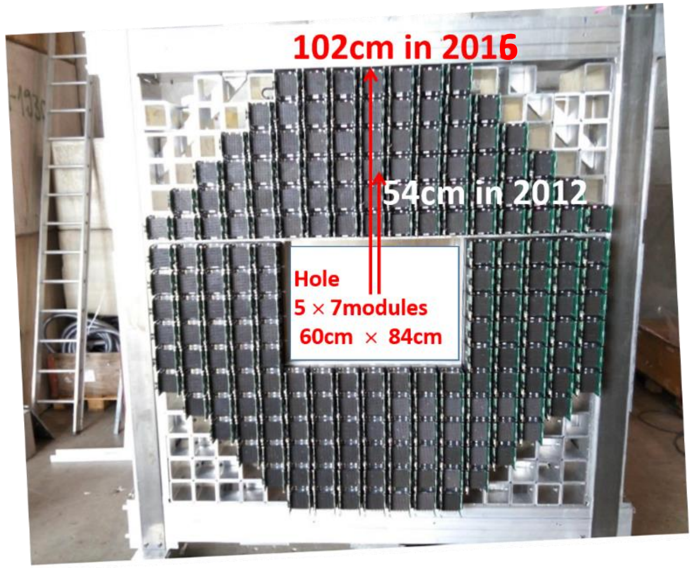


New equipements:

- ➢ **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

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

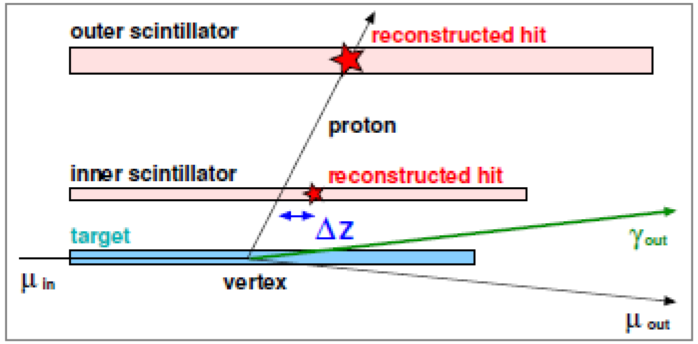
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

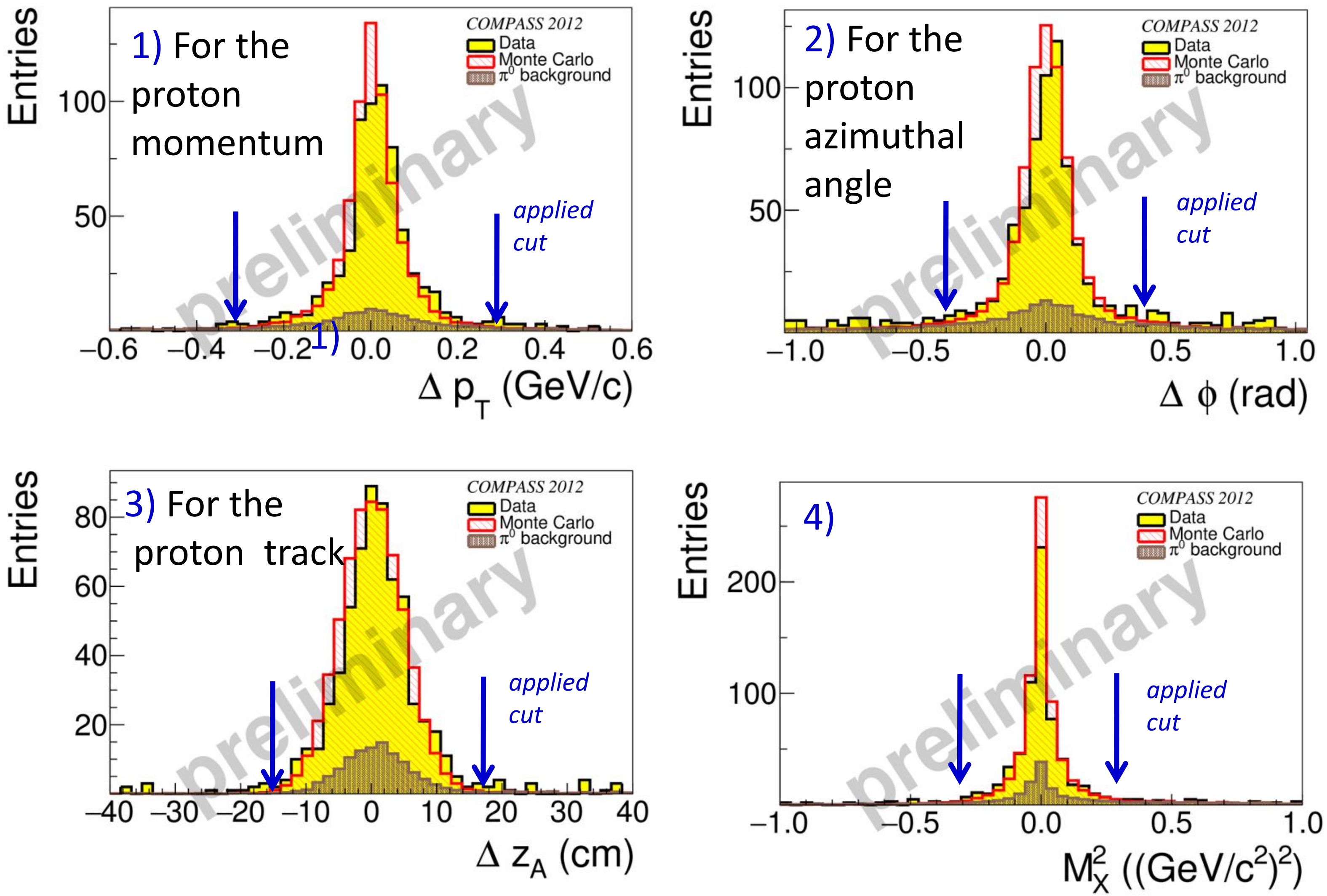
1) $\Delta p_T = p_T^{cam} - p_T^{spec}$

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

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

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





COMPASS 2012 — π^0 background estimation

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

Two possible case:

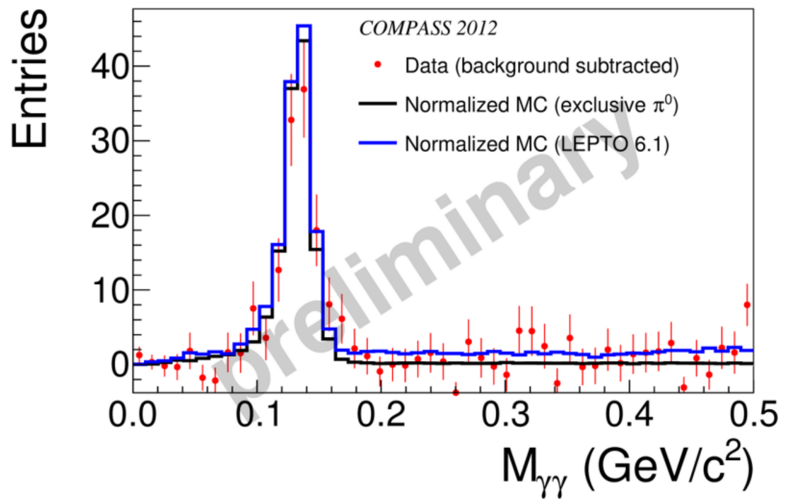
- **Visible** (both γ detected ➔ subtracted)

  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)

Visible leaking π^0 in the data



Releasing the cuts and 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

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

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

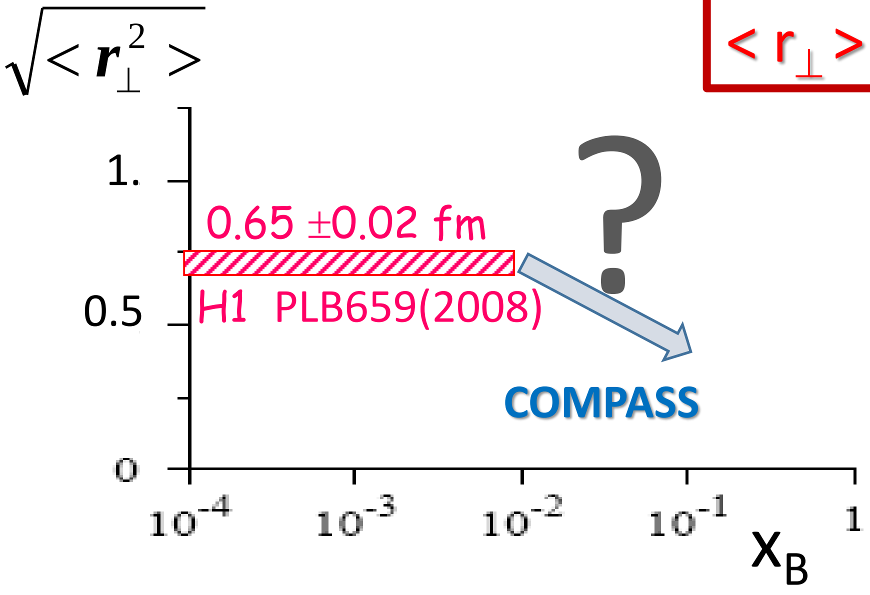
$B'(x_B) = 1/4 < b_\perp^2(x_B) >$

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

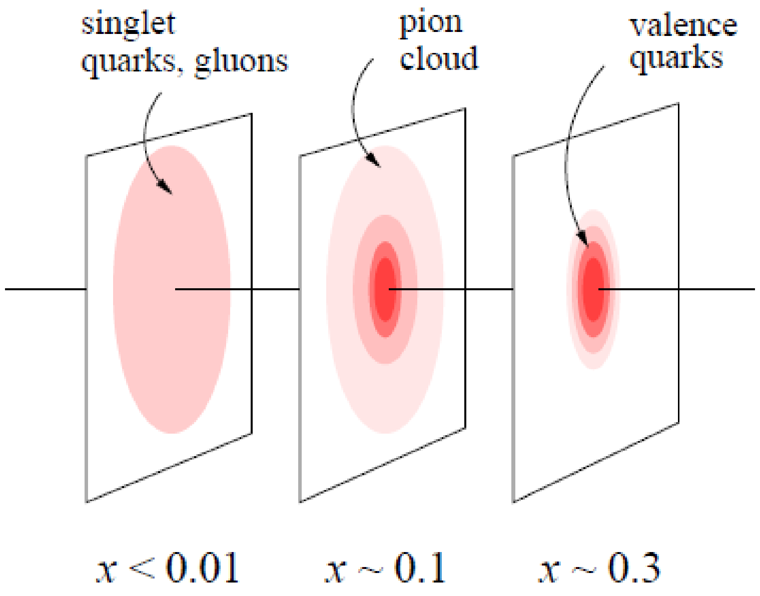
Impact Parameter Representation

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

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



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



COMPASS 2012 Transverse extention of partons in the sea quark range

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

$c_{0,\mathrm{unp}}^{\mathrm{DVCS}} = 2(2-2y+y^2)\mathcal{C}_{\mathrm{unp}}^{\mathrm{DVCS}}(\mathcal{F},\mathcal{F}^*)$ Belitsky, Mueller et al. 2020

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

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:

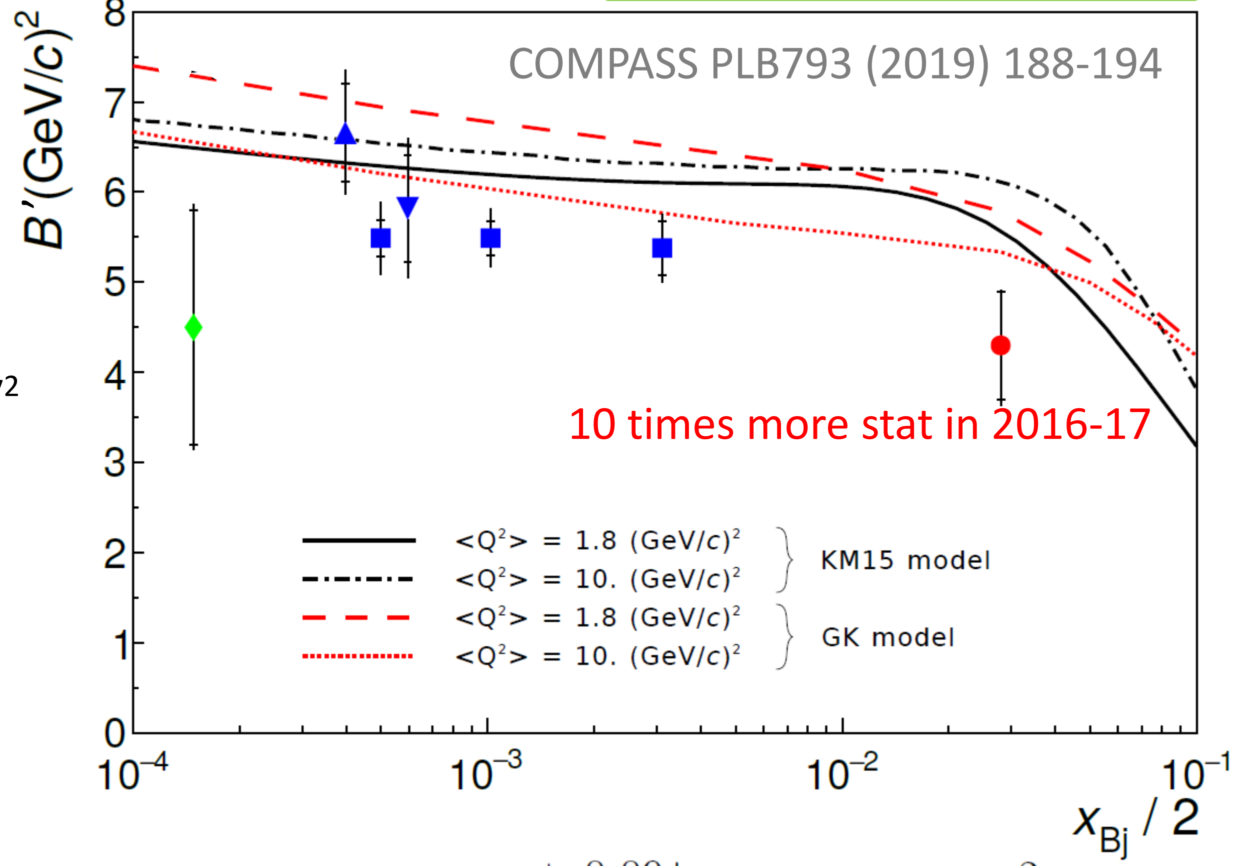
$$c_{0\,\mathrm{unp}}^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) - \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$$

Dominance of $Im\mathcal{H}$

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

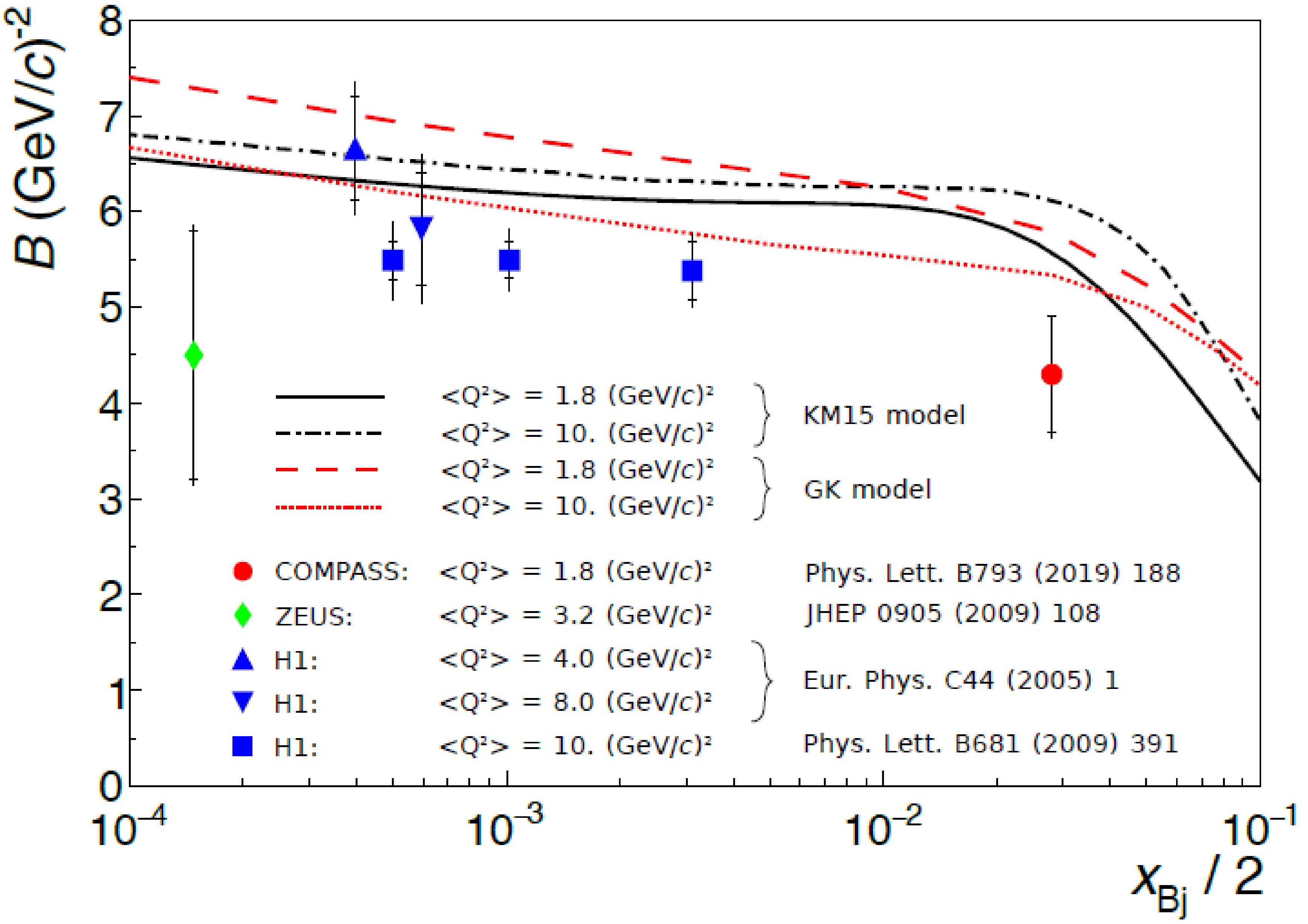
$x = \xi \sim x_{Bj}/2$

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

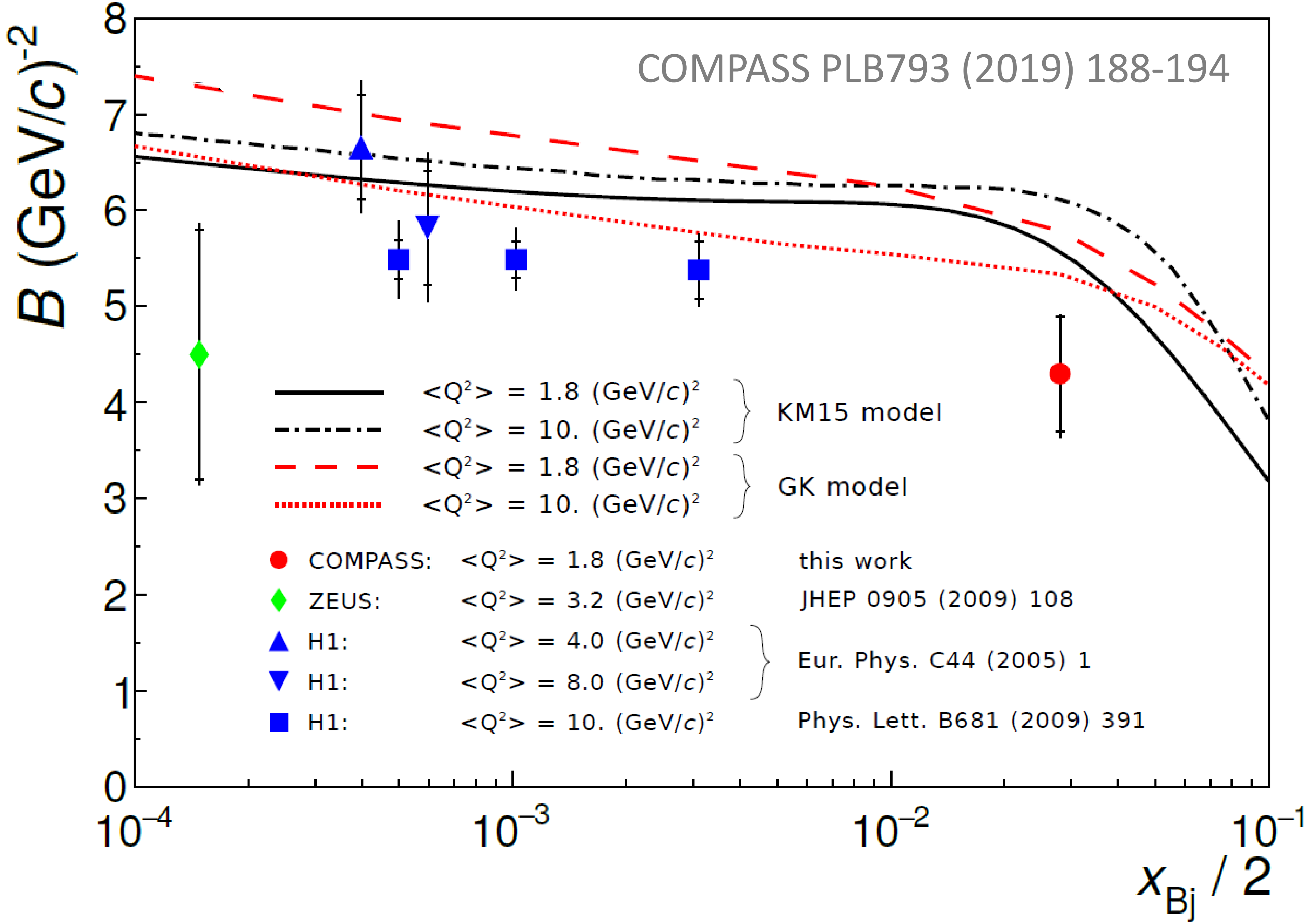


$$B = (4.31 \pm 0.62_{\mathrm{stat}}\ {}^{+0.09}_{-0.25}\big|_{\mathrm{sys}})\ (\mathrm{GeV}/c)^{-2}$$

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


B (GeV/c)^-2
8
7
6
5
4
3
2
1
0
10^-4
10^-3
10^-2
10^-1
x_Bj / 2
<Q²> = 1.8 (GeV/c)²
<Q²> = 10. (GeV/c)²
KM15 model
<Q²> = 1.8 (GeV/c)²
<Q²> = 10. (GeV/c)²
GK model
COMPASS: <Q²> = 1.8 (GeV/c)² Phys. Lett. B793 (2019) 188
ZEUS: <Q²> = 3.2 (GeV/c)² JHEP 0905 (2009) 108
H1: <Q²> = 4.0 (GeV/c)²
H1: <Q²> = 8.0 (GeV/c)²
Eur. Phys. C44 (2005) 1
H1: <Q²> = 10. (GeV/c)² Phys. Lett. B681 (2009) 391

Fait main!



COMPASS PLB793 (2019) 188-194
B (GeV/c)^-2
8
7
6
5
4
3
2
1
0
10^-4
10^-3
10^-2
10^-1
x_Bj / 2
<Q²> = 1.8 (GeV/c)²
<Q²> = 10. (GeV/c)²
KM15 model
<Q²> = 1.8 (GeV/c)²
<Q²> = 10. (GeV/c)²
GK model
COMPASS: <Q²> = 1.8 (GeV/c)² this work
ZEUS: <Q²> = 3.2 (GeV/c)² JHEP 0905 (2009) 108
H1: <Q²> = 4.0 (GeV/c)²
H1: <Q²> = 8.0 (GeV/c)²
Eur. Phys. C44 (2005) 1
H1: <Q²> = 10. (GeV/c)² Phys. Lett. B681 (2009) 391

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

Figure from Kumericki, Mueller

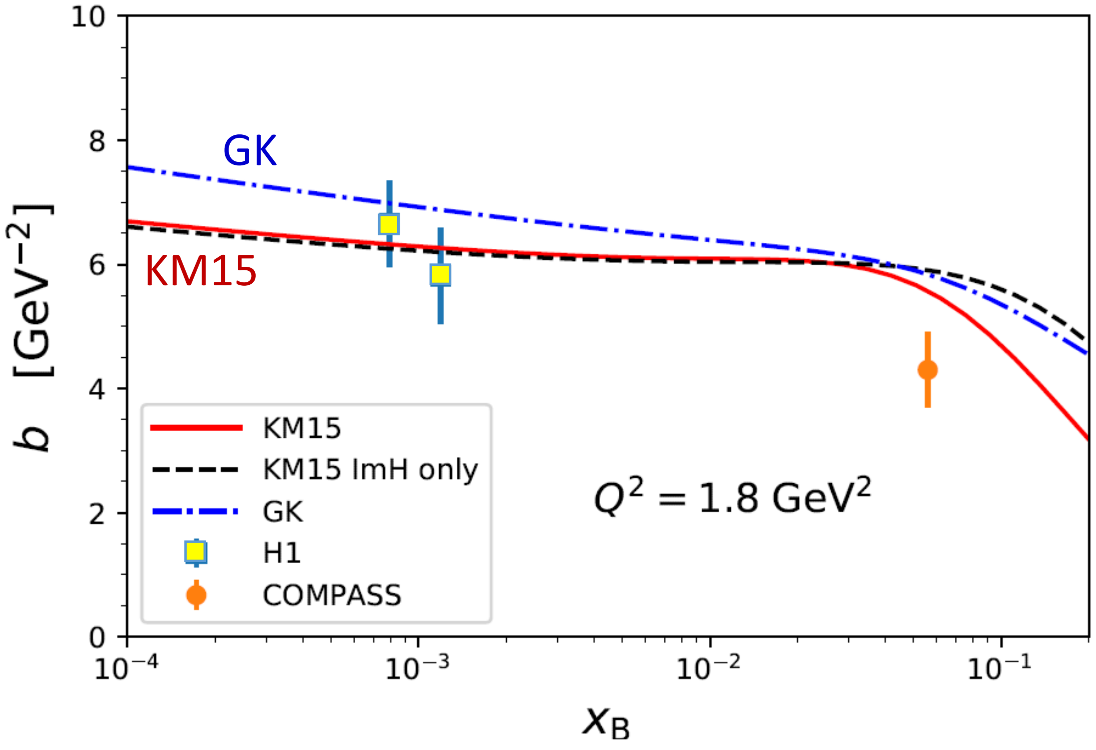


Figure from Moutarde, Sznajder, Wagner arXiv: 1807.07620