GPDs study at COMPASS

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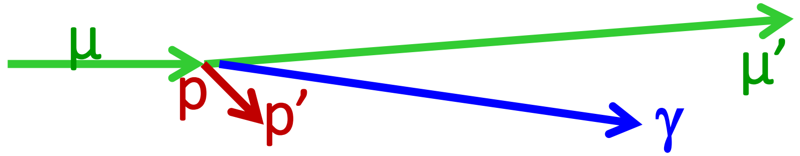
For the COMPASS Collaboration

Hard Exclusive Reactions at COMPASS at CERN

Exclusive photon (DVCS) and meson (HEMP) production at small transfer for GPD studies

Deeply Virtual Compton Scattering

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



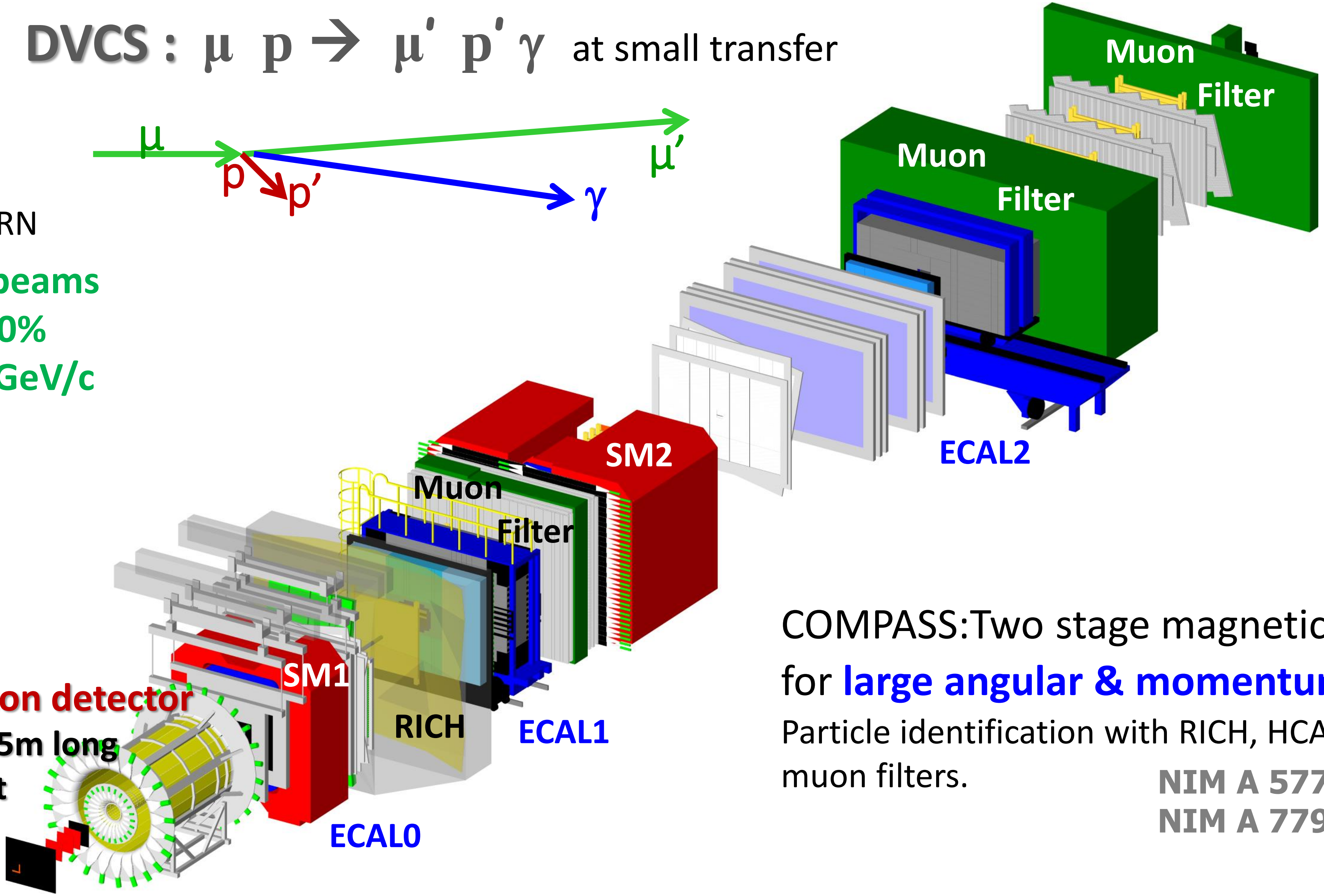
Pseudo-Scalar Meson : $\mu\ p \rightarrow \mu'\ p'\ \pi^0$

New results

Vector Meson : $\mu\ p \rightarrow \mu'\ p'\ \rho$ or ω

Measurement of exclusive cross sections at COMPASS

DVCS : $\mu\ p \rightarrow \mu'\ p'\ \gamma$ at small transfer



From the SPS at CERN

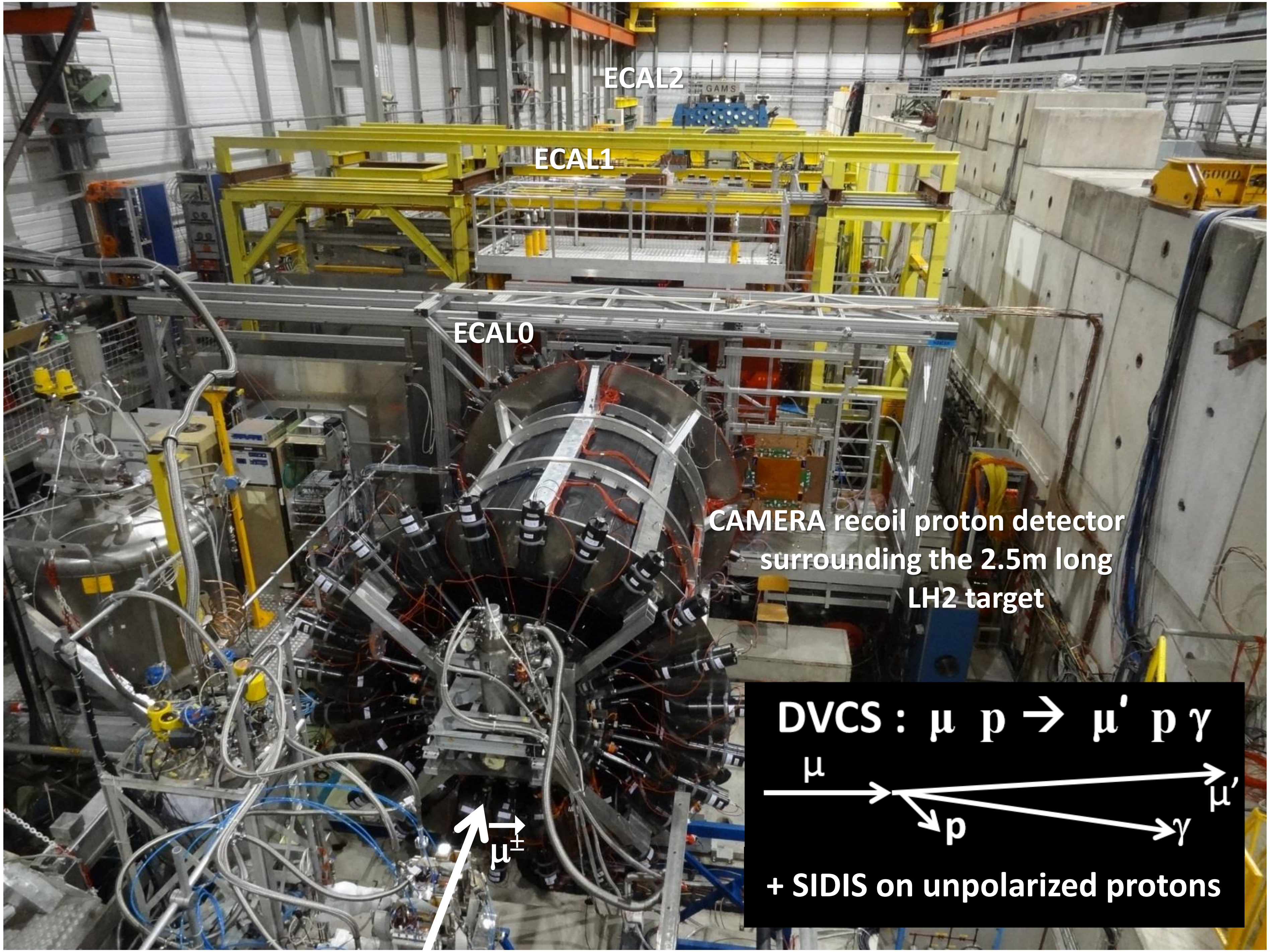
Both $\overleftarrow{\mu}^+$ and $\overrightarrow{\mu}^-$ beams
Polarisation ~ ±80%
Momentum 160 GeV/c

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.

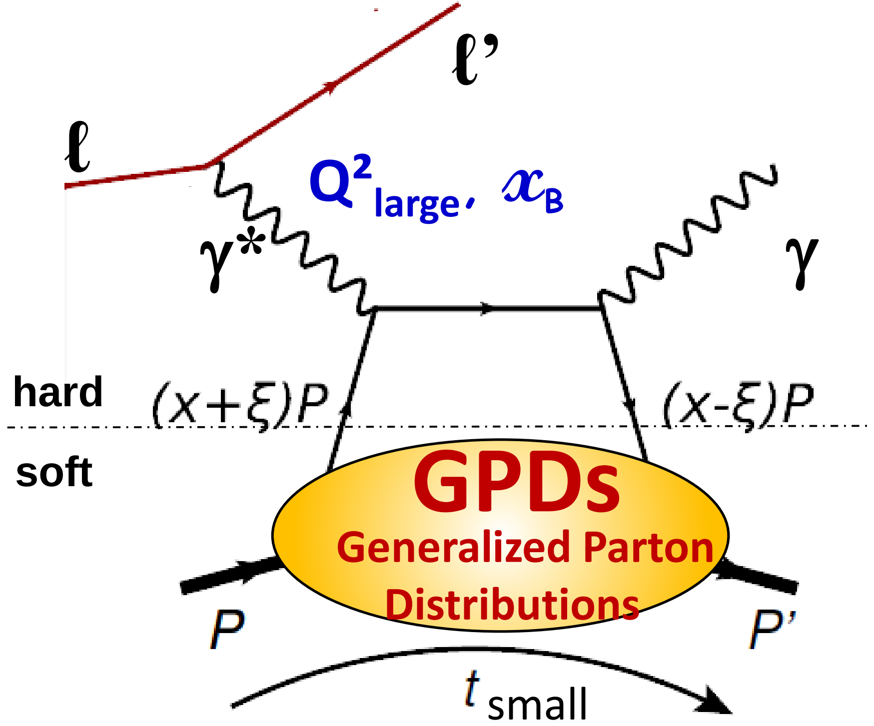
NIM A 577 (2007) 455
NIM A 779 (2015) 69



2012:
1 month pilot run

2016 -17:
2 x 6 month
data taking

Deeply virtual Compton scattering (DVCS)



x inside the loop: average longitudinal momentum fraction

$\xi \approx x_B/2$: transferred longitudinal momentum fraction

t: total proton momentum transfer squared related to $b_\perp$ via Fourier transform (when $\xi = 0$)

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

Real part **Imaginary part**

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

In an experiment we measure Compton Form Factor $\mathcal{H}$

$$\mathcal{R}e\mathcal{H}(\xi,t) = \pi^{-1}\int dx\, \frac{Im\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

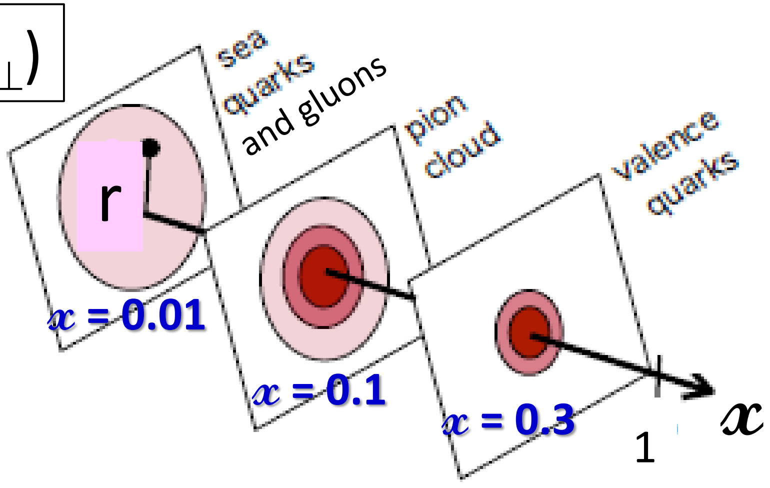
Deeply virtual Compton scattering (DVCS)

M. Burkardt, PRD66(2002)

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

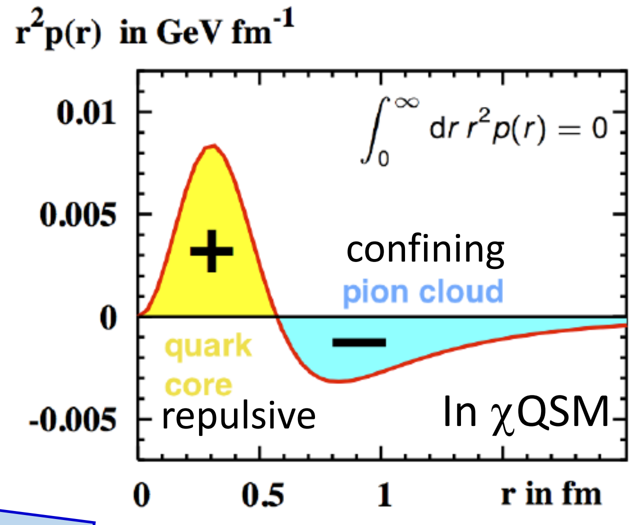
Mapping in the transverse plane

$q(x,b_\perp)$



FT of $H(x,\xi=0,t)$

Pressure Distribution



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

Real part **Imaginary part**

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

t, ξ fixed

In an experiment we measure

Compton Form Factor $\mathcal{H}$

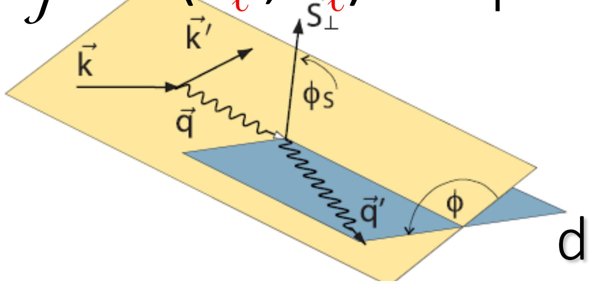
$$\mathcal{Re}\mathcal{H}(\xi,t) = \pi^{-1}\int dx \frac{Im\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

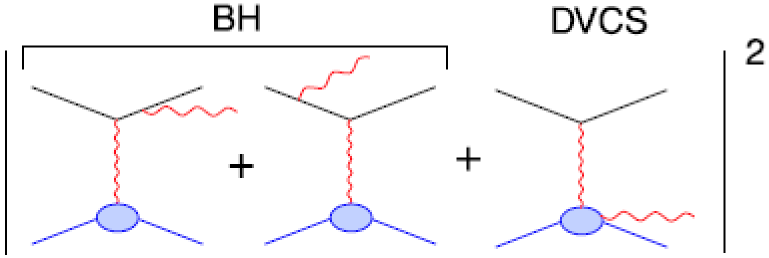
$d_1(t)$

D-term

Exclusive single photon production (BH + DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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

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

Well known

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

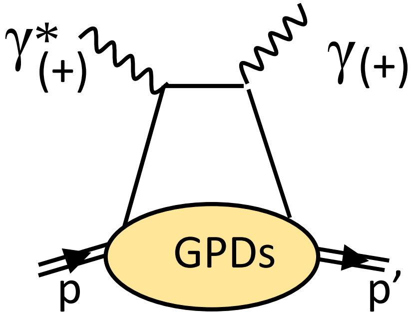
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

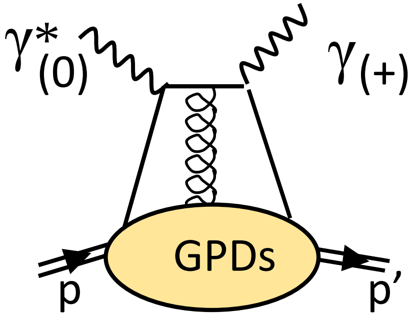
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$

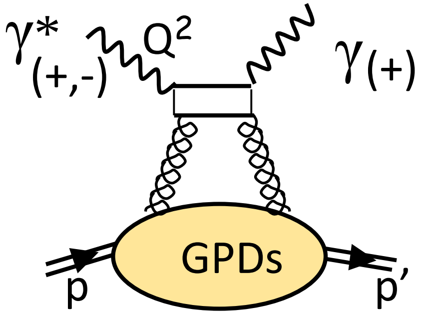


LO,Twist-2



HT,Twist-3

suppressed by 1/Q



NLO,Twist-2

double helicity flip

suppressed by α_S

Exclusive single photon production (BH + DVCS)

With both $\mu^{\overset{\leftarrow}{+}}$ and $\mu^{\overset{\rightarrow}{-}}$ beams we can build:

❶ beam charge-spin sum

$$\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} =$$

$$\begin{aligned} & d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\ + & d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\ + & \mathrm{Im}\, I \propto s_1^I \sin\phi + s_2^I \sin 2\phi \end{aligned}$$

❷ difference

$$\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}} =$$

$$\begin{aligned} & d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi \\ + & \mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \end{aligned}$$

$\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$ ➔ $s_1^I \propto \mathrm{Im}\,\mathcal{F}$

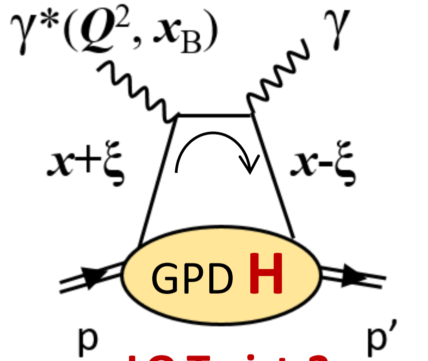
and $c_0^{DVCS} \propto (\mathrm{Im}\mathcal{H})^2$

$\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$ ➔ $c_1^I \propto \mathrm{Re}\,\mathcal{F}$

$$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - t/4m^2\, F_2\mathcal{E}$$

for proton target ➔ **at small x_B COMPASS domain** $F_1\mathcal{H}$

Compton Form Factor linked to the GPD **H**



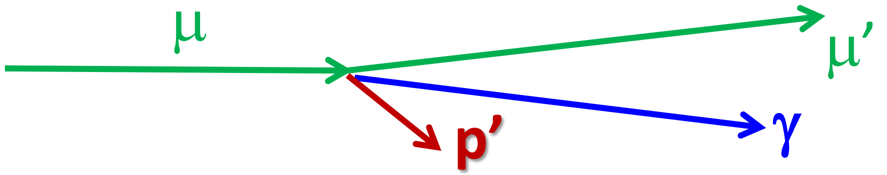
LO,Twist-2

$\xi \approx x_B/2$

x in the loop

COMPASS 2016 data Selection of exclusive single photon production

Comparison between the observables given by the spectro or by CAMERA



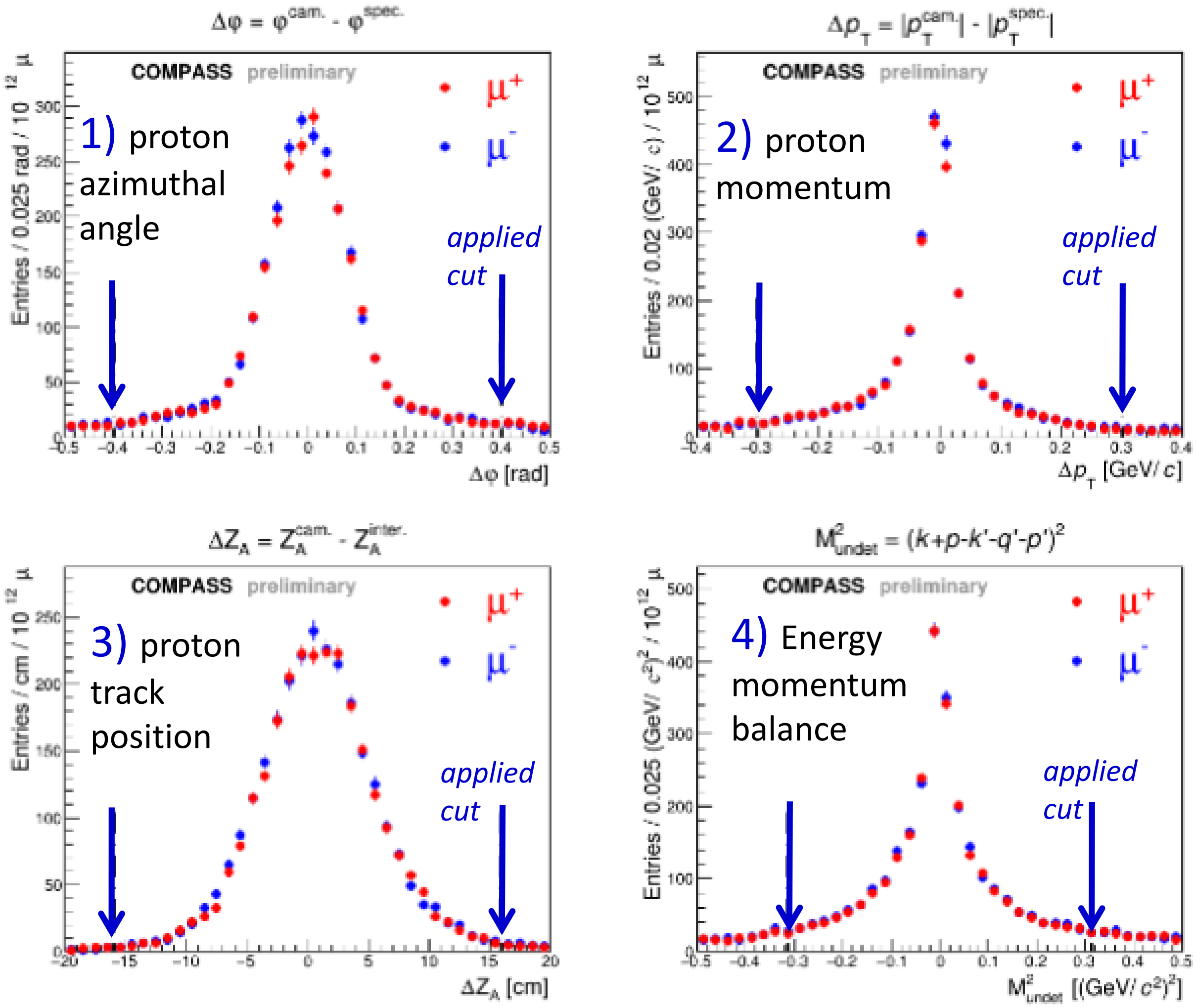
DVCS : μ p → μ' p γ

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

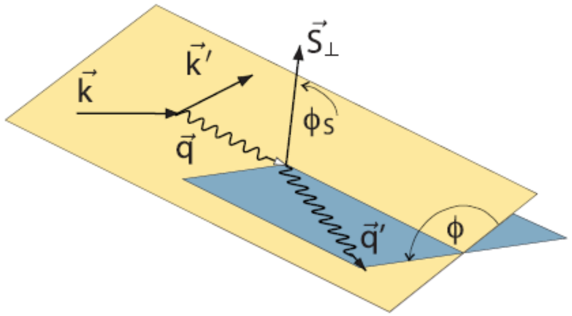


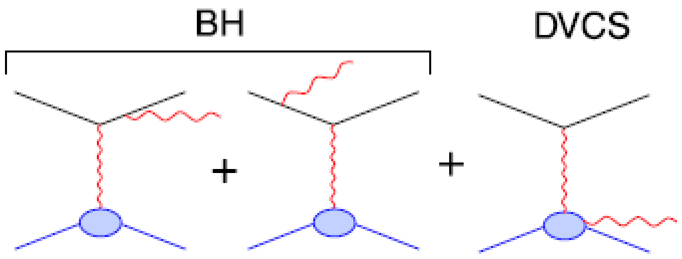
Good agreement between $\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ yields important achievement for:

❶ $\Sigma \equiv d\overset{+}{\overleftarrow{\sigma}} + d\overset{-}{\overrightarrow{\sigma}}$ **Easier, done first**
Mapping in Transverse plane

❷ $\Delta \equiv d\overset{+}{\overleftarrow{\sigma}} - d\overset{-}{\overrightarrow{\sigma}}$ **Challenging, but promising**
Related to EMT and pressure

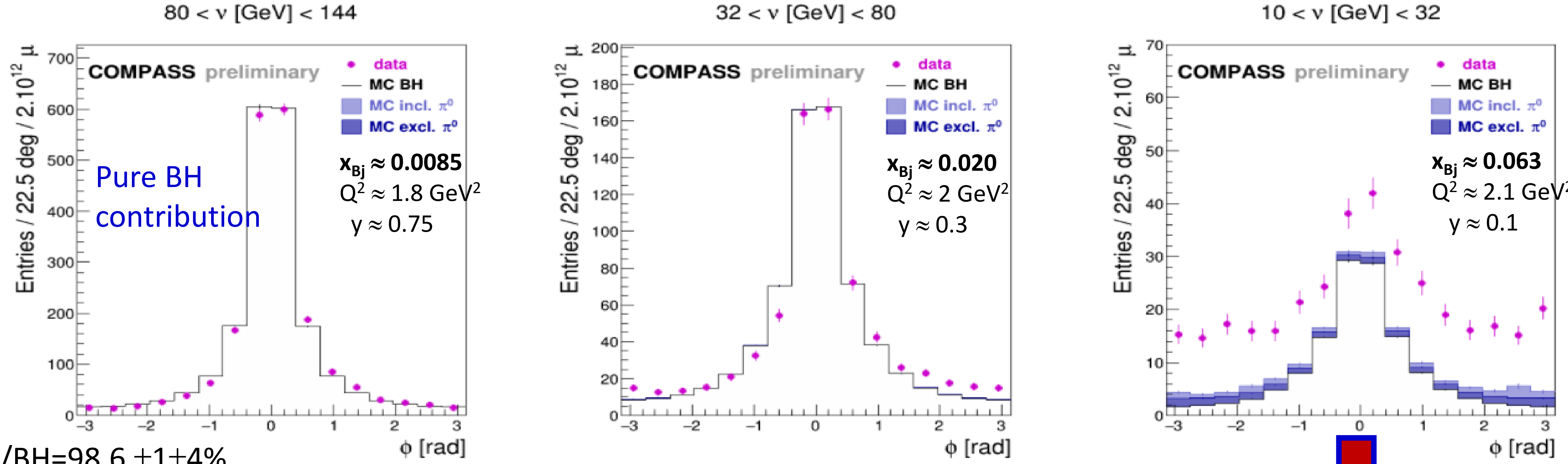
COMPASS 2016 data DVCS+BH cross section at $E\mu$=160 GeV





$$\Sigma = d\sigma(\overleftarrow{\mu^+}) + d\sigma(\overrightarrow{\mu^-})$$

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



Data/BH=98.6 ±1±4%

MC: BH contribution evaluated for the integrated luminosity
$\pi°$ background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

DVCS above the BH contrib.

COMPASS 2016 DVCS cross section for 10 < υ < 32 GeV

At COMPASS using polarized positive and negative muon beams:

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

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

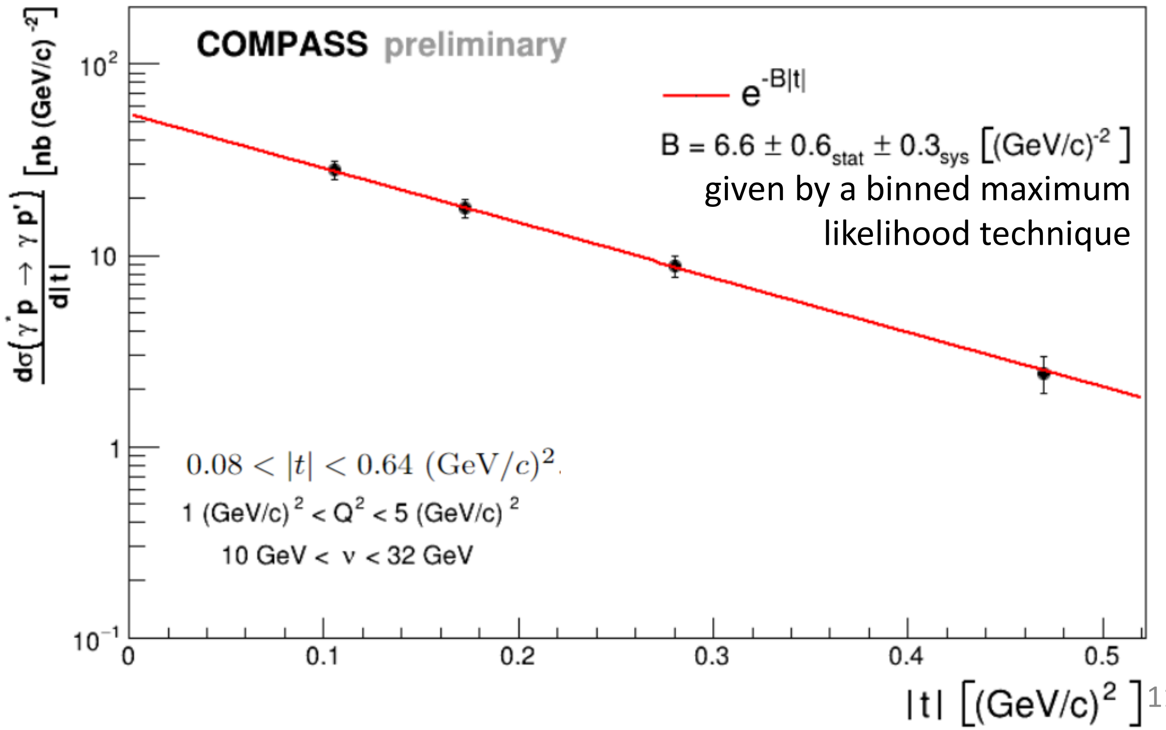
calculable
can be subtracted

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



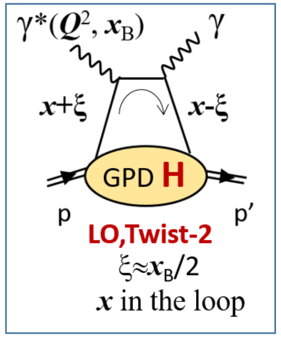
COMPASS 12-16 Transverse extention of partons in the sea quark range

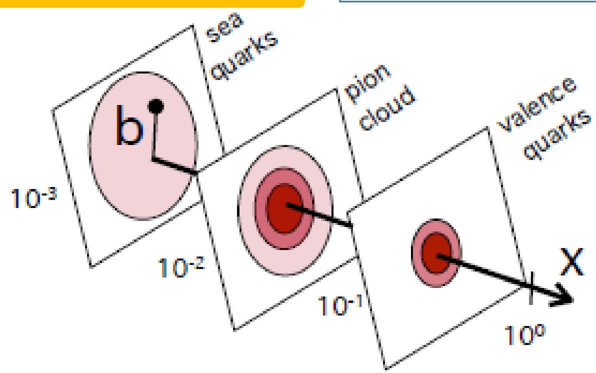
$$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS} \propto (Im\mathcal{H})^2$$

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

$x = \xi \approx x_B/2$ close to 0

$$\langle b_\perp^2(x)\rangle \approx 2B(\xi)$$

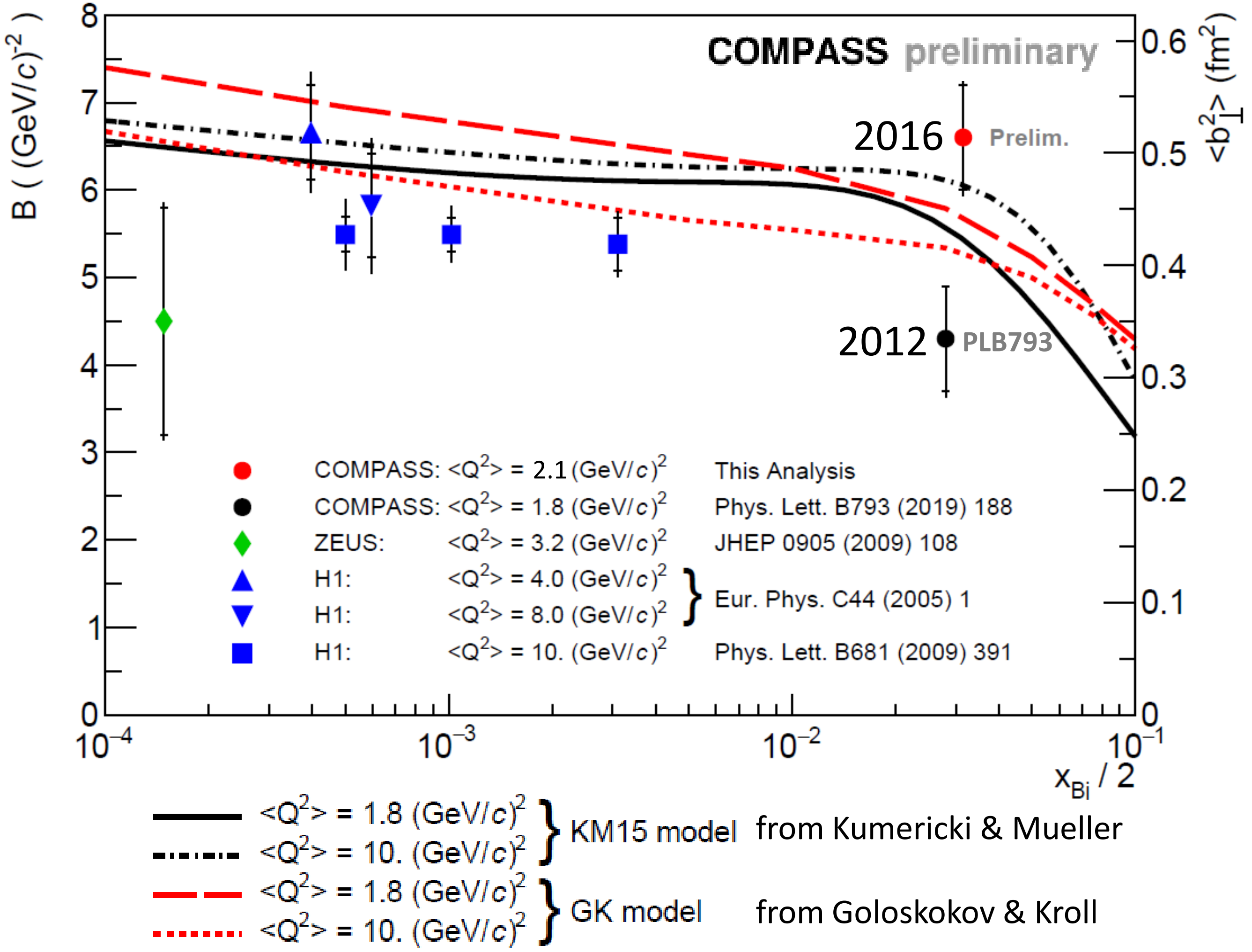




2012 statistics = Ref

2016 analysed statistics = 2.3 × Ref

2016+2017 expected statistics = 10 × Ref



Improvements in 2016 analysis compared to 2012

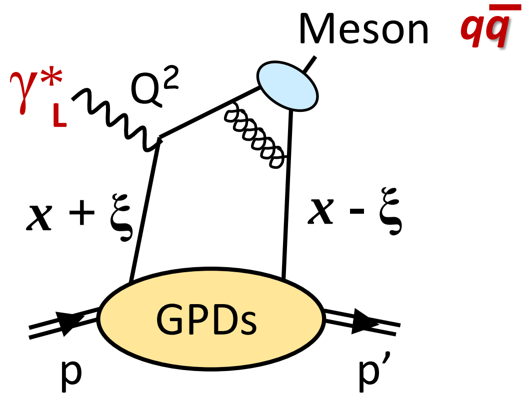
- same intensity with $\mu+$ and $\mu-$ beam in 2016
- more advanced analysis with 2016 data, still ongoing
- π^0 contamination with different thresholds
- better MC description of the evolution in ν
- binning with 3 variables (t,Q^2,ν) or 4 variables (t,ϕ,Q^2,ν)
- different binning in t

GPDs and Hard Exclusive Meson Production

Factorisation proven only for σ_L

The meson wave function is
an additional non-perturbative term

Quark contribution



For Pseudo-Scalar Meson, as π^0

chiral-even GPDs: helicity of parton unchanged

$\tilde{H}^q(x, \xi, t) \quad \tilde{E}^q(x, \xi, t)$

+ chiral-odd or transversity GPDs: helicity of parton changed

$H_T^q(x, \xi, t)$ (as the transversity TMD)

related in the forward limit to transversity and the tensor charge

$\bar{E}_T^q = 2\,\tilde{H}_T^q + E_T^q$ (as the Boer-Mulders TMD)

related to the distortion of the polarized quark distribution in the transverse plane for the unpolarized proton and to its transverse anomalous magnetic moment

σ_T should be asymptotically suppressed by $1/Q^2$ but large contribution observed
GK model: k_T of q and $\bar{q}$ and Sudakov suppression factor are considered
Chiral-odd GPDs with a twist-3 meson wave function

COMPASS 2016 — Exclusive π^0 production on unpolarized proton

$\mu^{\pm}\, p \rightarrow \mu^{\pm}\, \pi^0\, p$

$\mu^{\pm}$ beams with opposite polarization

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

COMPASS
$\langle x_B\rangle = 0.13$
ε close to 1

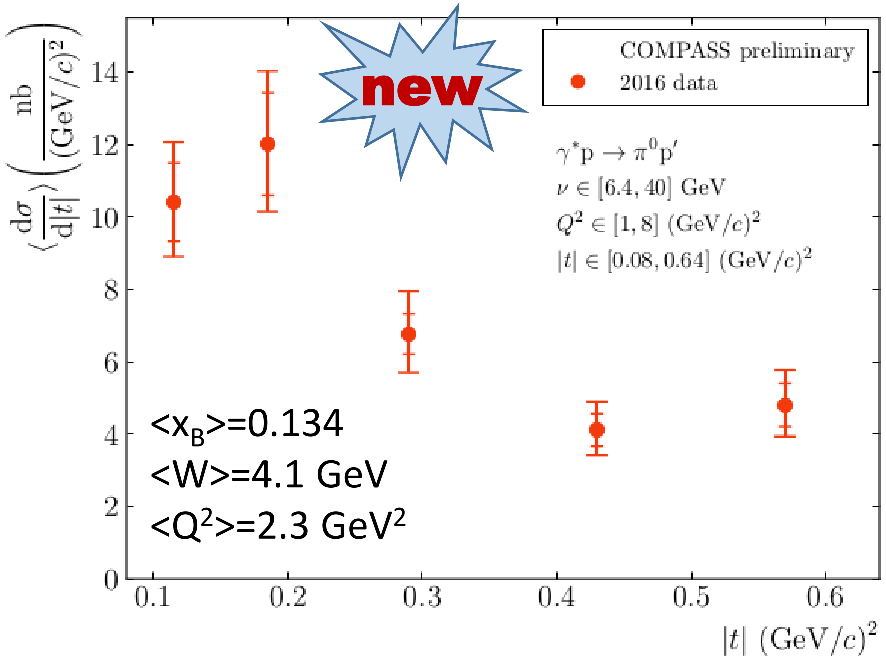
$$\frac{d\sigma_L}{dt}\propto\left|\langle\tilde{H}\rangle\right|^2-\frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

$$\frac{d\sigma_T}{dt}\propto\left|\langle H_T\rangle\right|^2-\frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

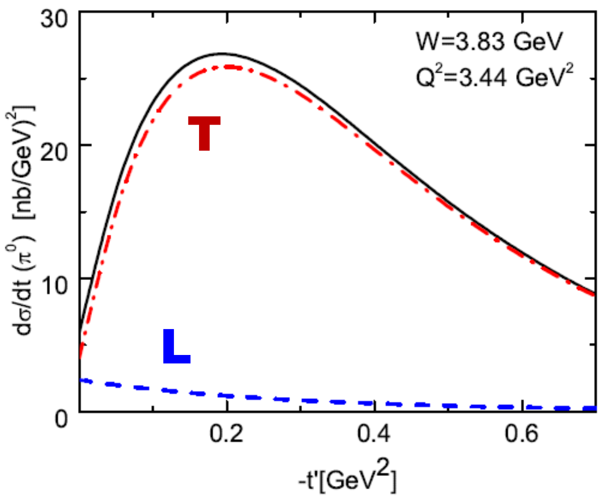
$$\frac{\sigma_{TT}}{dt}\propto\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\frac{\sigma_{LT}}{dt}\propto\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle+\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle\right]$$

$F_{\pi^0}=2/3F^u + 1/3\, F^d$ $(\tilde{H}^u\ \tilde{H}^d)$ $(\tilde{E}^u\ \tilde{E}^d)$ $(H^u_T\ H^d_T)$ of opposite sign $(\bar{E}^u_T\ \bar{E}^d_T)$ of **same** sign ➔ **clearly enhanced contribution**



S. Goloskokov, P. Kroll, EPJC47 (2011)



Typical dip of the cross section as a function of $-t' = -(t-t_0) \approx |t|$

$|t_0| \approx 10^{-2}$ GeV^2

COMPASS 2016 Exclusive π^0 production on unpolarized proton

$\mu^{\pm}\, p \rightarrow \mu^{\pm}\, \pi^0\, p$

$\mu^{\pm}$ beams with opposite polarization

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

COMPASS $\langle x_B\rangle = 0.13$, ε close to 1

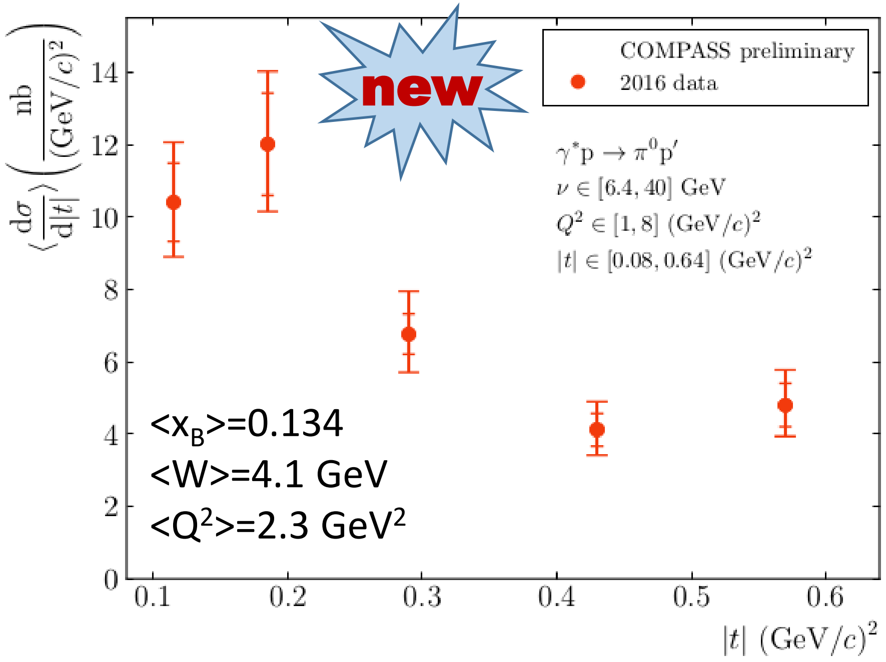
$$\frac{d\sigma_L}{dt}\propto\left|\langle\tilde{H}\rangle\right|^2-\frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

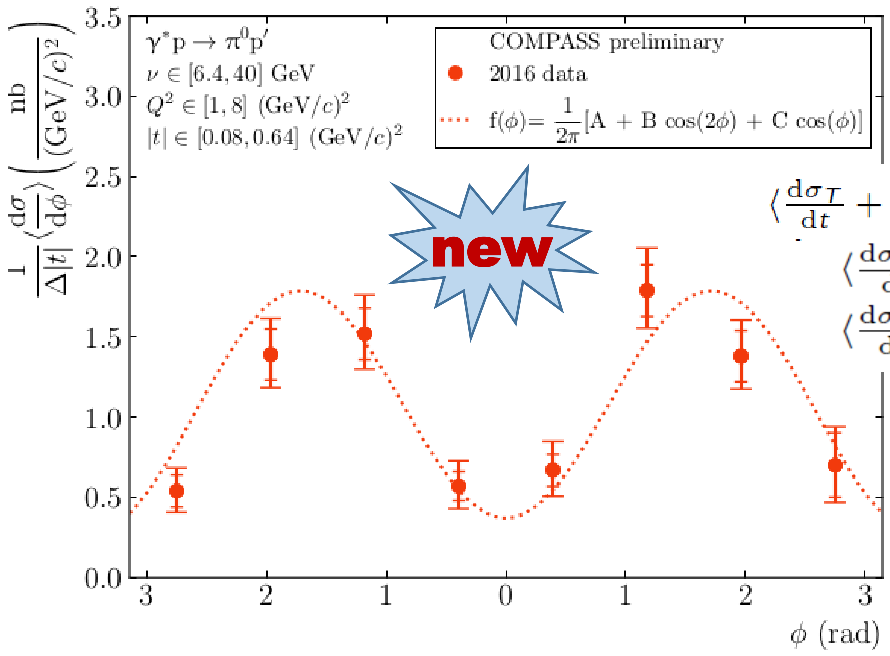
$$\frac{d\sigma_T}{dt}\propto|\langle H_T\rangle|^2-\frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\frac{\sigma_{TT}}{dt}\propto\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\frac{\sigma_{LT}}{dt}\propto\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle+\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle\right]$$

$F_{\pi^0} = 2/3 F^u + 1/3 F^d$ $(\tilde{H}^u\ \tilde{H}^d)$ $(\tilde{E}^u\ \tilde{E}^d)$ $(H^u_T\ H^d_T)$ of opposite sign $(\bar{E}^u_T\ \bar{E}^d_T)$ of **same** sign ➔ **clearly enhanced contribution**





$$\left\langle\frac{d\sigma_T}{dt}+\epsilon\frac{d\sigma_L}{dt}\right\rangle=\left(6.6\pm0.3_{stat}{}^{+\,0.9}_{-\,0.8}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

$$\left\langle\frac{d\sigma_{TT}}{dt}\right\rangle=\left(-4.6\pm0.5_{stat}{}^{+\,0.3}_{-\,0.3}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

$$\left\langle\frac{d\sigma_{LT}}{dt}\right\rangle=\left(0.2\pm0.2_{stat}{}^{+\,0.2}_{-\,0.2}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

$\langle\epsilon\rangle = 0.997$

$|\sigma_{TT}|$ almost as large as $\sigma_T + \varepsilon\,\sigma_L$

➔ impact of $\bar{E}_T$

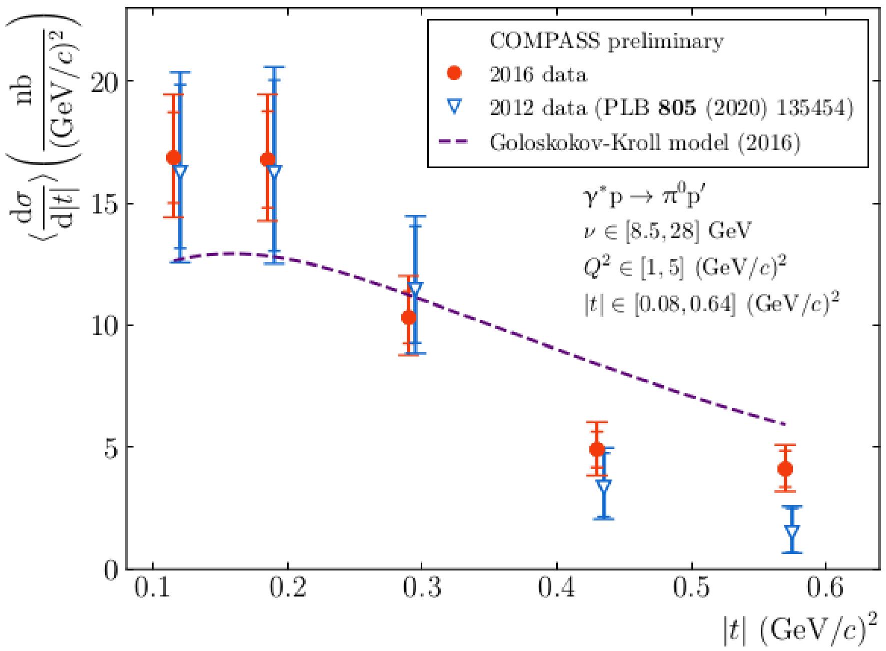
σ_{LT} rather small

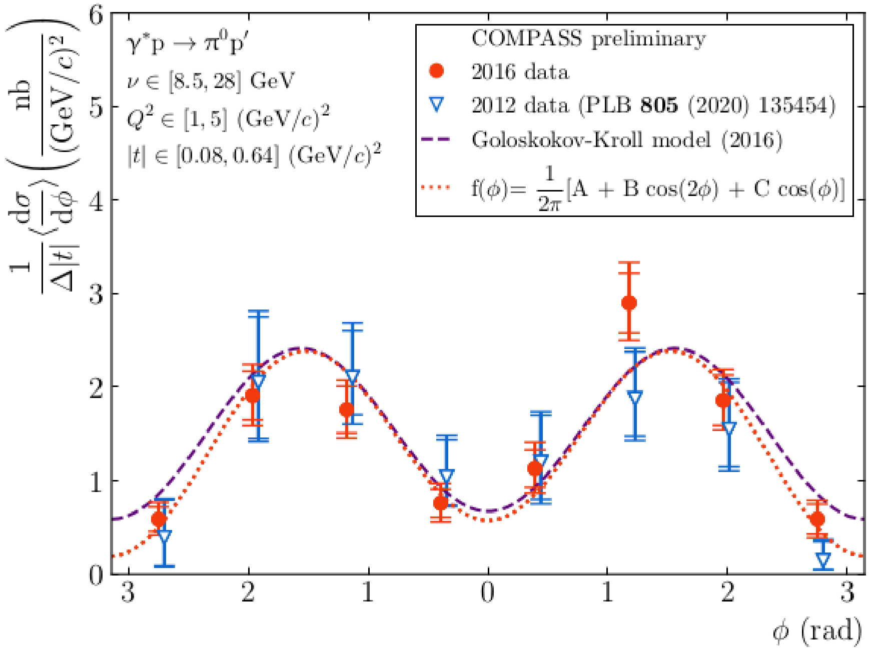
Cross section for $\upsilon \in [6.4, 40]$ GeV and $Q^2 \in [1, 8]$ GeV^2 $\langle x_B\rangle = 0.13$

COMPASS 2012-16 Exclusive π^0 production on unpolarized proton

2016 kinematic domain: Cross section for $\upsilon \in [6.4, 40]$ GeV and $Q^2 \in [1, 8]$ GeV^2 $\langle x_B \rangle = 0.13$

2012 kinematic domain for comparison: $\upsilon \in [8.5, 28]$ GeV and $Q^2 \in [1, 5]$ GeV^2 $\langle x_B \rangle = 0.10$





2012 data:

$$\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \rangle = (8.1 \pm 0.9_{stat} {}^{+\ 1.1}_{-\ 1.0}|_{sys}) \ \frac{nb}{(GeV/c)^2}$$

$$\langle \frac{d\sigma_{TT}}{dt} \rangle = (-6.0 \pm 1.3_{stat} {}^{+\ 0.7}_{-\ 0.7}|_{sys}) \ \frac{nb}{(GeV/c)^2}$$

$$\langle \frac{d\sigma_{LT}}{dt} \rangle = (1.4 \pm 0.5_{stat} {}^{+\ 0.3}_{-\ 0.2}|_{sys}) \ \frac{nb}{(GeV/c)^2}$$

$$\langle \epsilon \rangle = 0.996$$

2016 data:

$$\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \rangle = (8.7 \pm 0.5_{stat} {}^{+\ 1.0}_{-\ 1.0}|_{sys}) \ \frac{nb}{(GeV/c)^2}$$

$$\langle \frac{d\sigma_{TT}}{dt} \rangle = (-6.3 \pm 0.8_{stat} {}^{+\ 0.4}_{-\ 0.5}|_{sys}) \ \frac{nb}{(GeV/c)^2}$$

$$\langle \frac{d\sigma_{LT}}{dt} \rangle = (0.6 \pm 0.3_{stat} {}^{+\ 0.3}_{-\ 0.3}|_{sys}) \ \frac{nb}{(GeV/c)^2}$$

$$\langle \epsilon \rangle = 0.996$$

$|\sigma_{TT}|$ almost as large as $\sigma_T + \varepsilon\, \sigma_L$

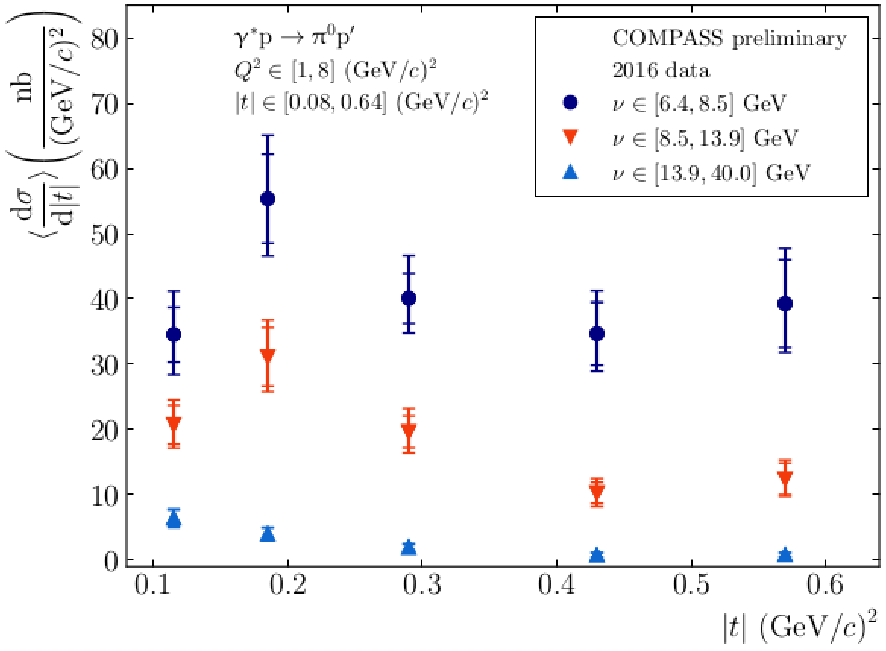
➔ impact of $\bar{E}_T$

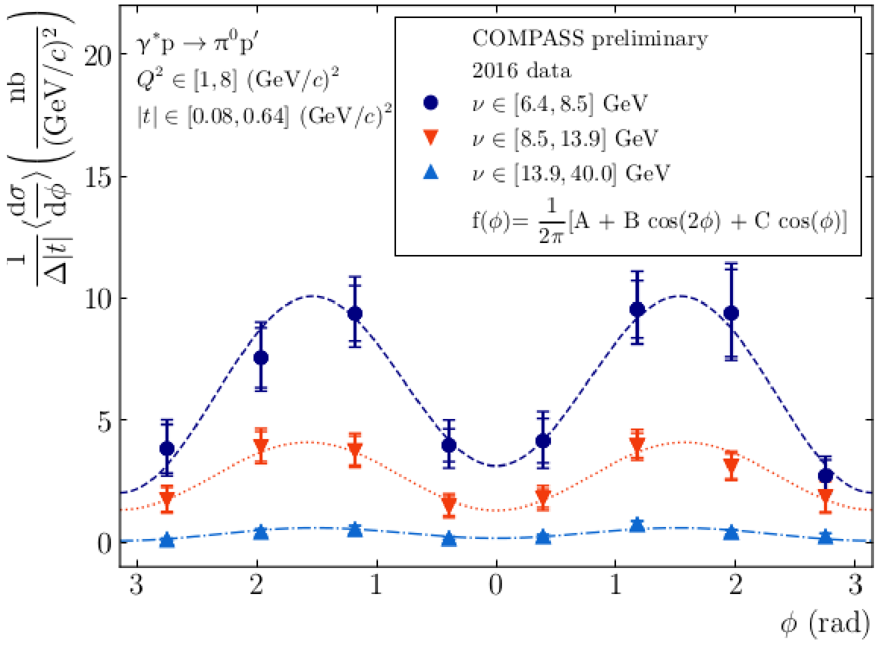
σ_{LT} rather small

COMPASS 2016 Exclusive π^0 production on unpolarized proton

Evolution of the cross section with υ: σ ↘ when υ ↗

new





➔ Extraction of

$\sigma_T + \varepsilon\, \sigma_L$

σ_{TT}

σ_{LT}

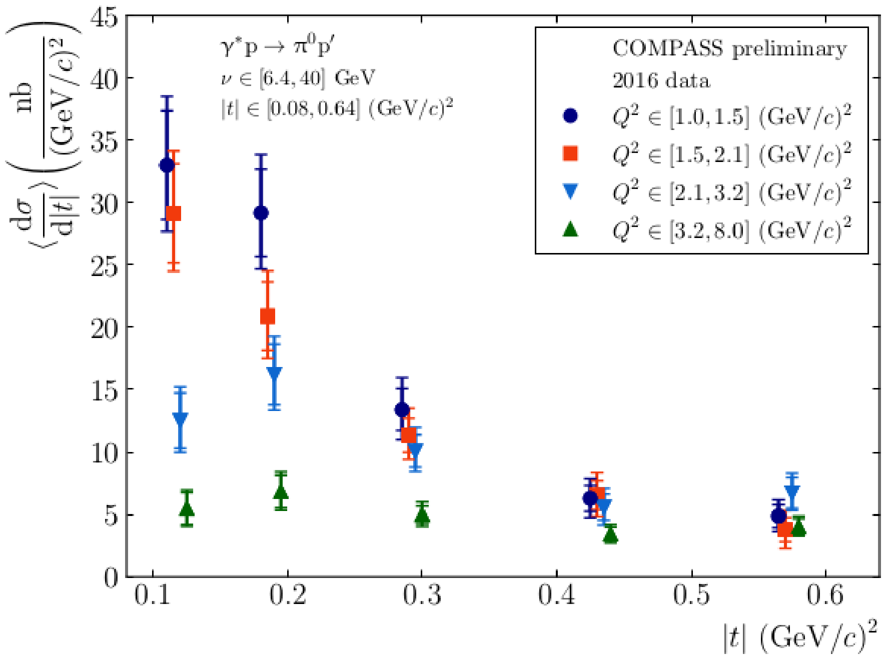
in 3 υ bins

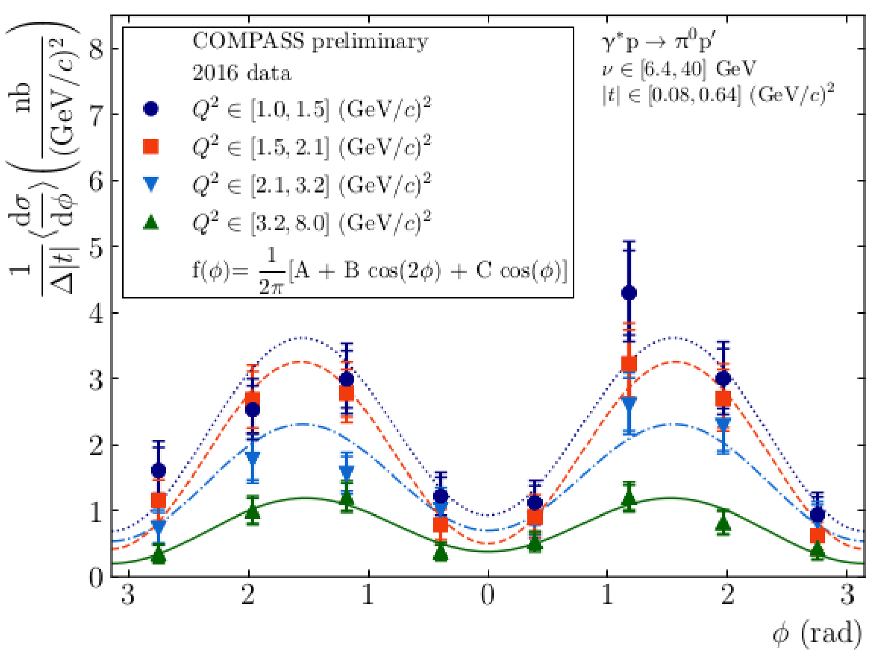
	$\langle \nu \rangle$ [GeV]	$\langle Q^2 \rangle$ [GeV$^2/c^2$]	$\langle x_B \rangle$	$\langle \epsilon \rangle$
$\nu \in [6.4, 8.5]$	7.35	2.15	0.156	0.999
$\nu \in [8.5, 13.9]$	10.32	2.50	0.131	0.998
$\nu \in [13.9, 40.0]$	21.08	2.09	0.057	0.989

COMPASS 2016 Exclusive π^0 production on unpolarized proton

Evolution of the cross section with Q^2 : $\sigma \searrow$ when $Q^2 \nearrow$

new





➔ Extraction of

$\sigma_T + \varepsilon \sigma_L$

σ_{TT}

σ_{LT}

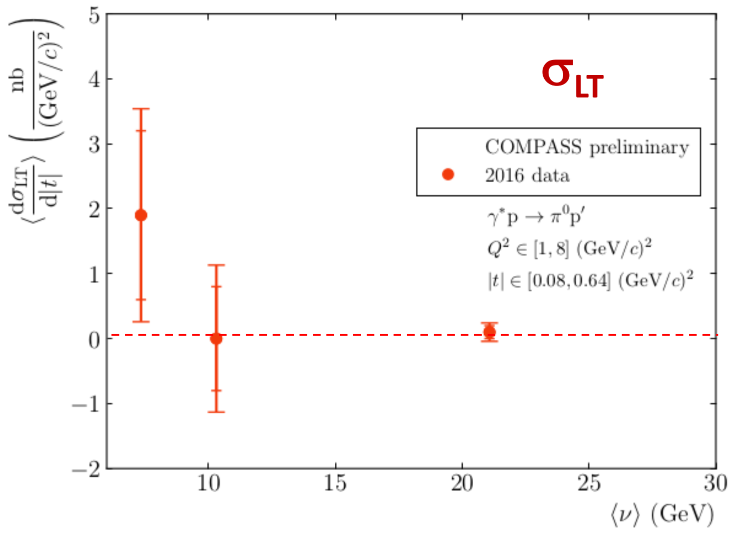
in 4 Q^2 bins

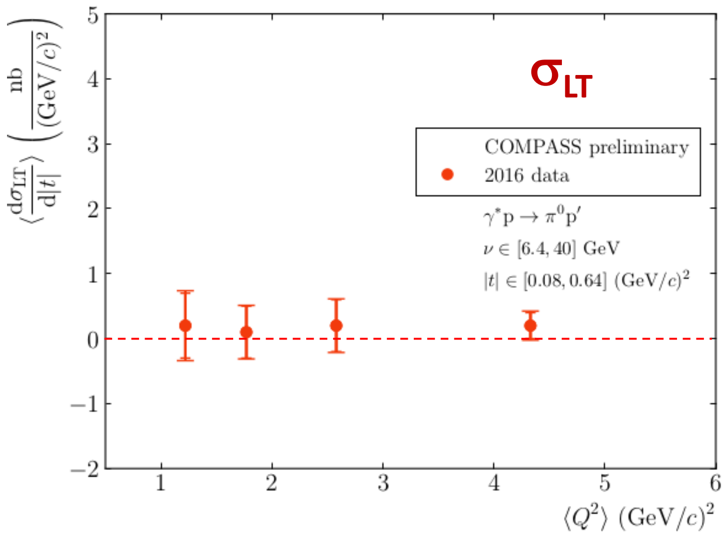
	$\langle Q^2 \rangle$ [GeV^2/c^2]	$\langle \nu \rangle$ [GeV]	$\langle x_B \rangle$	$\langle \epsilon \rangle$
$Q^2 \in [1.0, 1.5]$	1.22	10.54	0.072	0.997
$Q^2 \in [1.5, 2.1]$	1.77	9.81	0.109	0.997
$Q^2 \in [2.1, 3.2]$	2.58	9.82	0.157	0.997
$Q^2 \in [3.2, 8.0]$	4.33	10.39	0.247	0.997

Exclusive π^0 production on unpolarized proton

Evolution of the structure functions with υ and Q^2

new

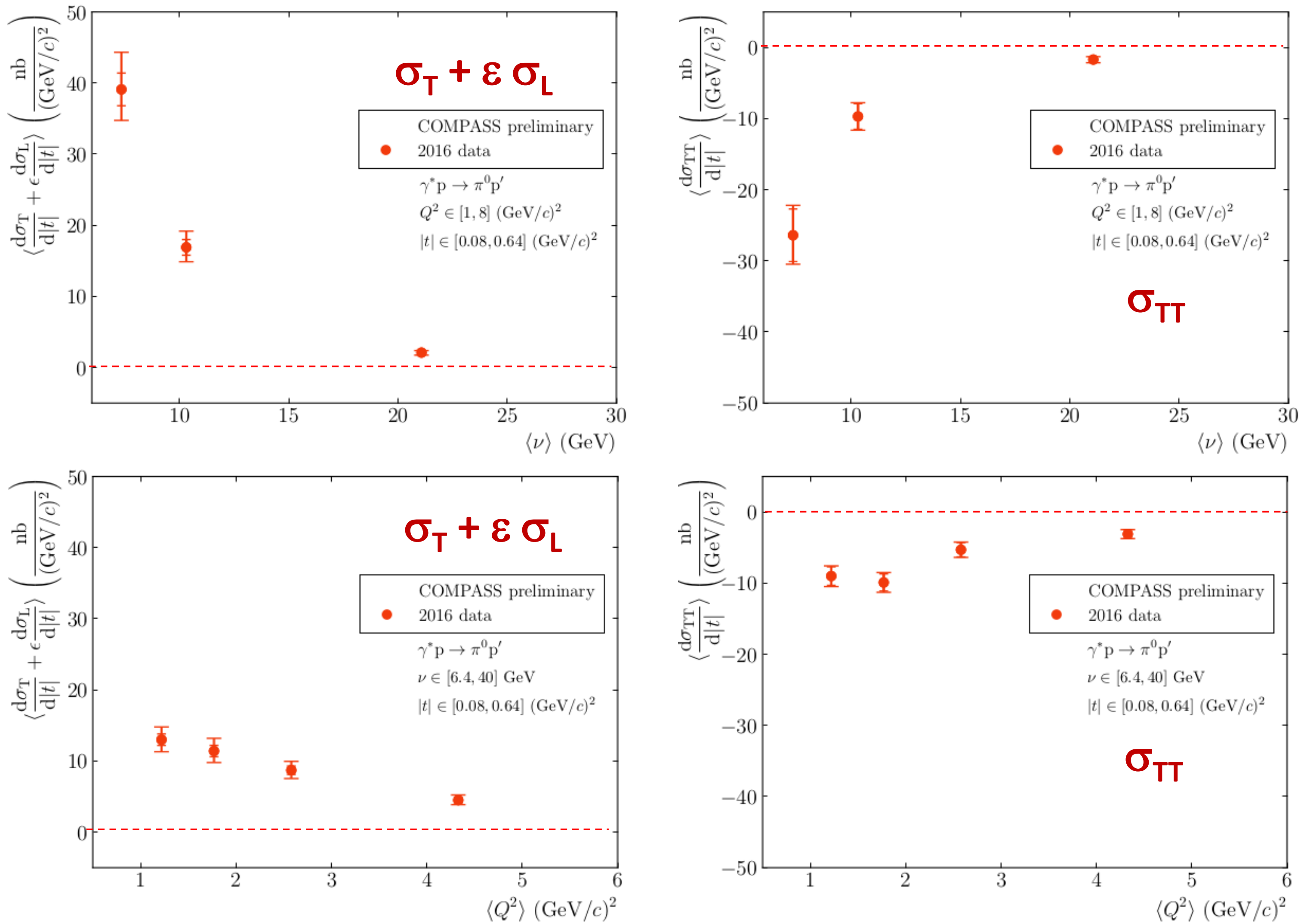




σ_{LT} close to 0

COMPASS 2016 Exclusive π^0 production on unpolarized proton

Evolution of the structure functions with υ and Q^2



Both $\sigma_T + \varepsilon\, \sigma_L$ and σ_{TT}
large evolution with υ
small evolution with Q^2

Impact of these data for modeling $\bar{E}_T$ (and other GPDs) contributions at twist-3 and NLO

Recent work on twist-3 contribution
G. Duplančić, P. Kroll and K. Passek-Kumerički, PRD109 (2024)

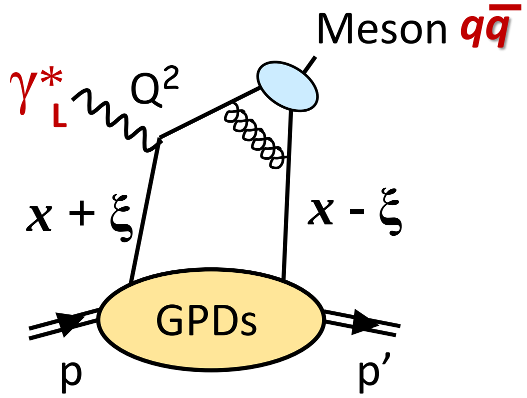
Also S. Golosgokov et al.
S. Liuti et al.

GPDs and Hard Exclusive Meson Production

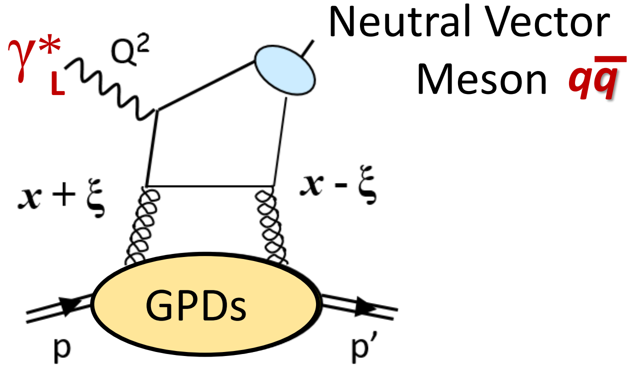
Factorisation proven only for σ_L

The meson wave function is
an additional non-perturbative term

Quark contribution



Gluon contribution at the same order in α_S



For Vector Meson, as ρ, ω, ϕ…

chiral-even GPDs: helicity of parton unchanged

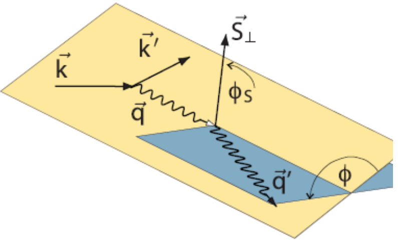
$\mathbf{H}^q(x, \xi, t)$ $\mathbf{E}^q(x, \xi, t)$

+ chiral-odd or transversity GPDs: helicity of parton changed

$\mathbf{H}^q_T(x, \xi, t)$ (as the transversity TMD)

$\bar{\mathbf{E}}^q_T = 2\,\tilde{\mathbf{H}}^q_T + \mathbf{E}^q_T$ (as the Boer-Mulders TMD)

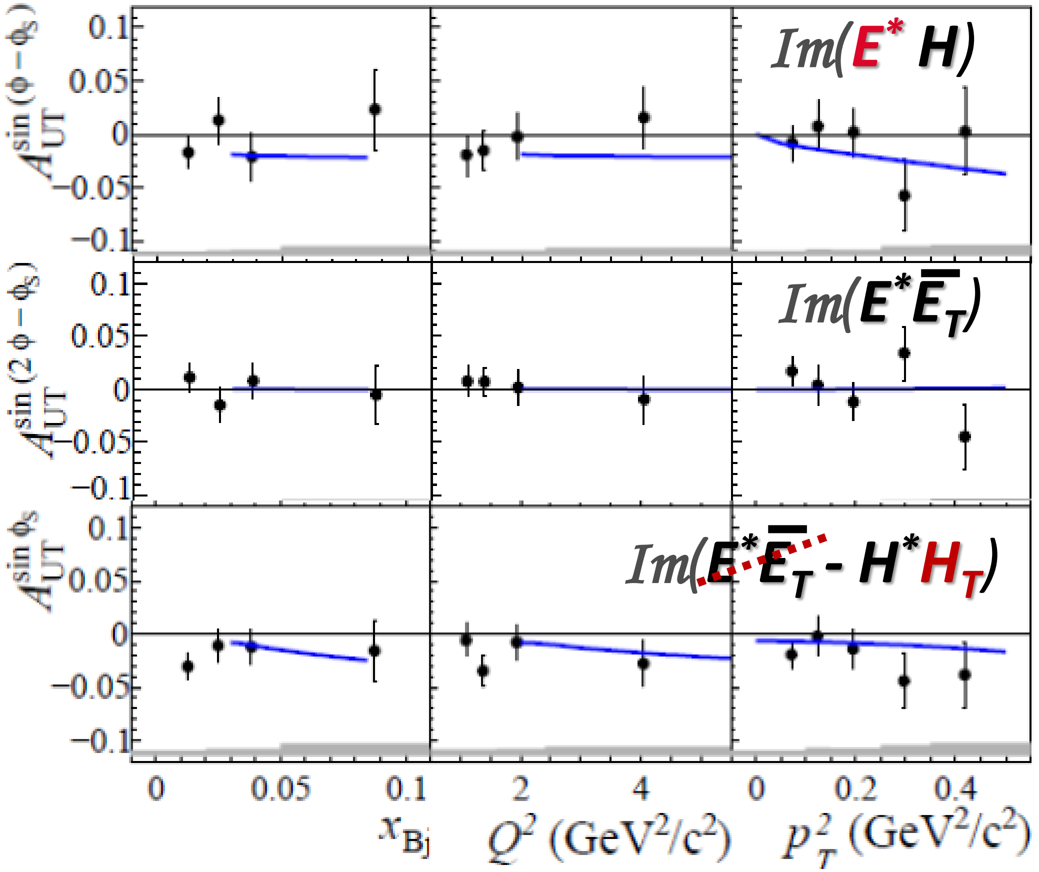
COMPASS 2010 2007 HEMP with Transversely Polarized Target without RPD



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

$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}\frac{E_g}{x}\right)$$

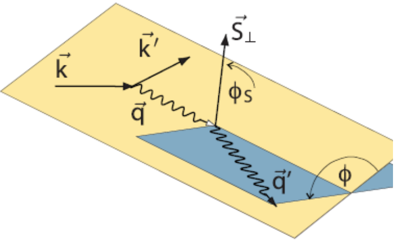
COMPASS, NPB 865 (2012) 1-20, PLB731 (2014) 19



Sensibility to E and H_T

GK model EPJC42,50,53,59,65,74

COMPASS 2010 2007 HEMP with Transversely Polarized Target without RD



$\rho^0 \to \pi^+\pi^-$

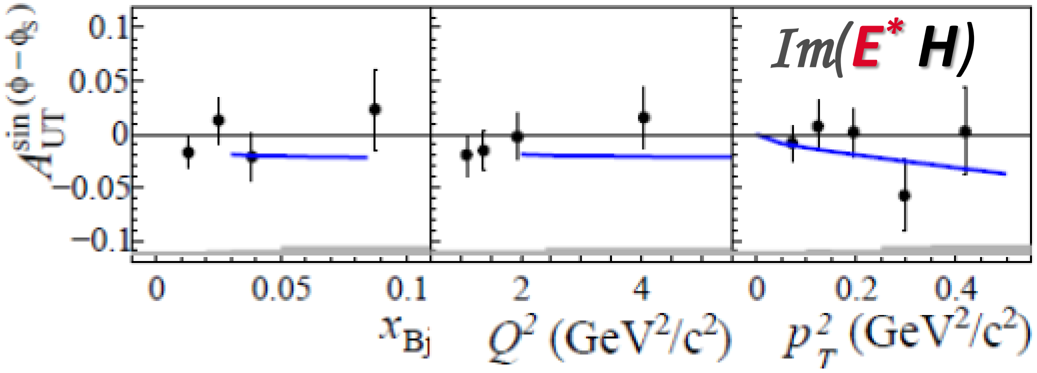
$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}\frac{E_g}{x}\right)$$

$\omega \to \pi^+\pi^-\pi^0$

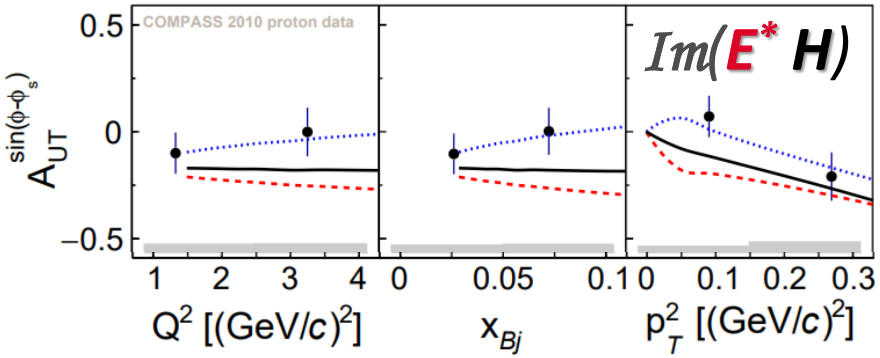
$$E_\omega = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}\frac{E_g}{x}\right)$$

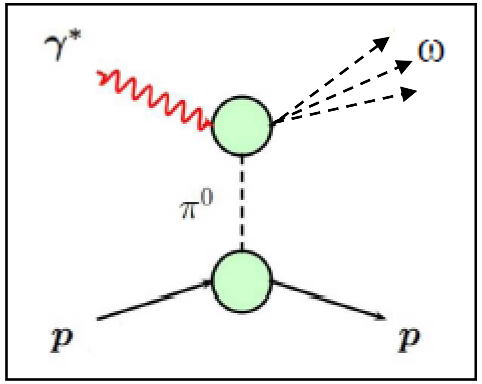
E^u and E^d of opposite sign

COMPASS, NPB 865 (2012) 1-20, PLB731 (2014) 19



COMPASS, NPB 915 (2017)





$\Gamma(\omega \to \pi^0\gamma) = 9\times\Gamma(\rho^0 \to \pi^0\gamma)$

Same for πω FF but sign unknown

- positive πω form factor
- no pion pole
- negative πω form factor

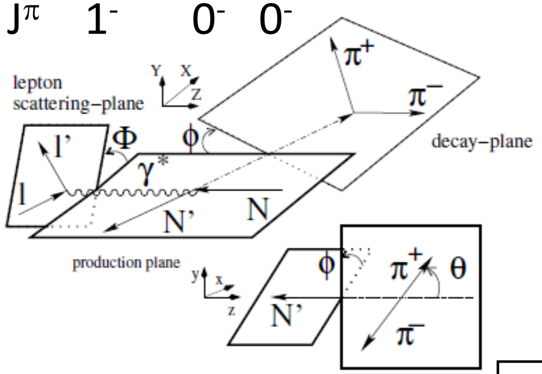
ω is more promising (see the larger scale)
but there is the inherent pion pole contribution

GK model EPJC42,50,53,59,65,74

COMPASS 2012-16 exclusive VM production with Unpolarised Target and SDME

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

J^π 1^- 0^- 0^-



experimental angular distributions:

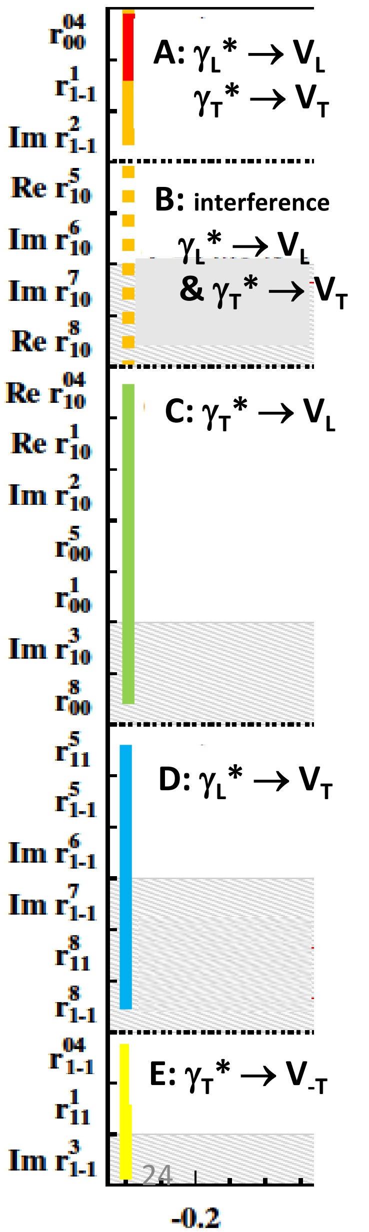
$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + P_b \mathcal{W}^{L}(\Phi,\phi,\cos\Theta)$$

15 'unpolarized' and 8 'polarized' SDMEs

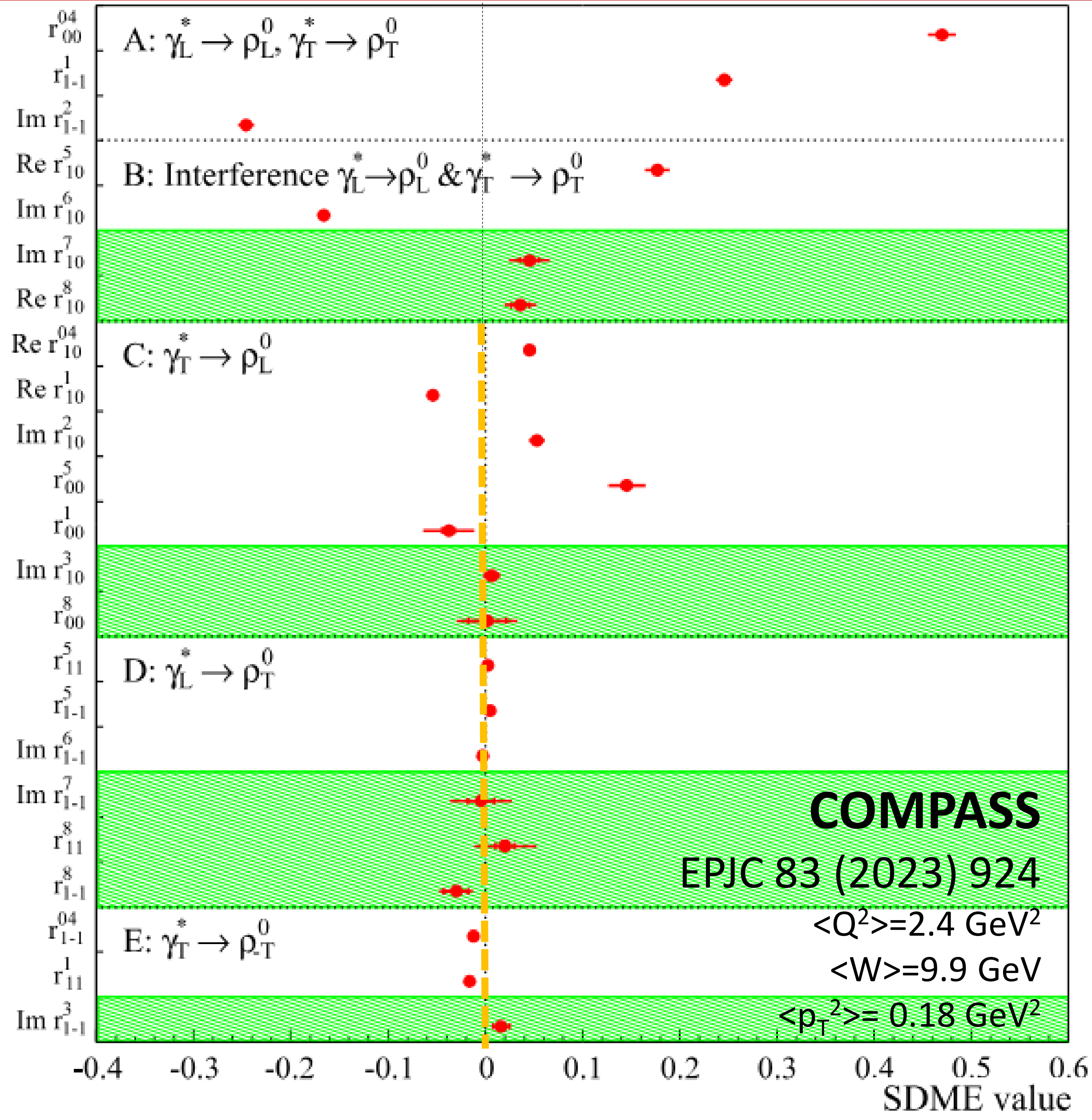
$$\mathcal{W}^U(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1-r_{00}^{04}) + \frac{1}{2}(3r_{00}^{04}-1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r_{10}^{04}\}\sin 2\Theta\cos\phi - r_{1-1}^{04}\sin^2\Theta \ \cos 2\phi$$
$$-\epsilon\cos 2\Phi\Big(r_{11}^{1}\sin^2\Theta + r_{00}^{1}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r_{10}^{1}\}\sin 2\Theta\cos\phi - r_{1-1}^{1}\sin^2\Theta\cos 2\phi\Big)$$
$$-\epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r_{10}^{2}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r_{1-1}^{2}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+\sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r_{11}^{5}\sin^2\Theta + r_{00}^{5}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r_{10}^{5}\}\sin 2\Theta\cos\phi - r_{1-1}^{5}\sin^2\Theta\cos 2\phi\Big)$$
$$+\sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r_{10}^{6}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r_{1-1}^{6}\}\sin^2\Theta\sin 2\phi\Big)\Bigg],$$

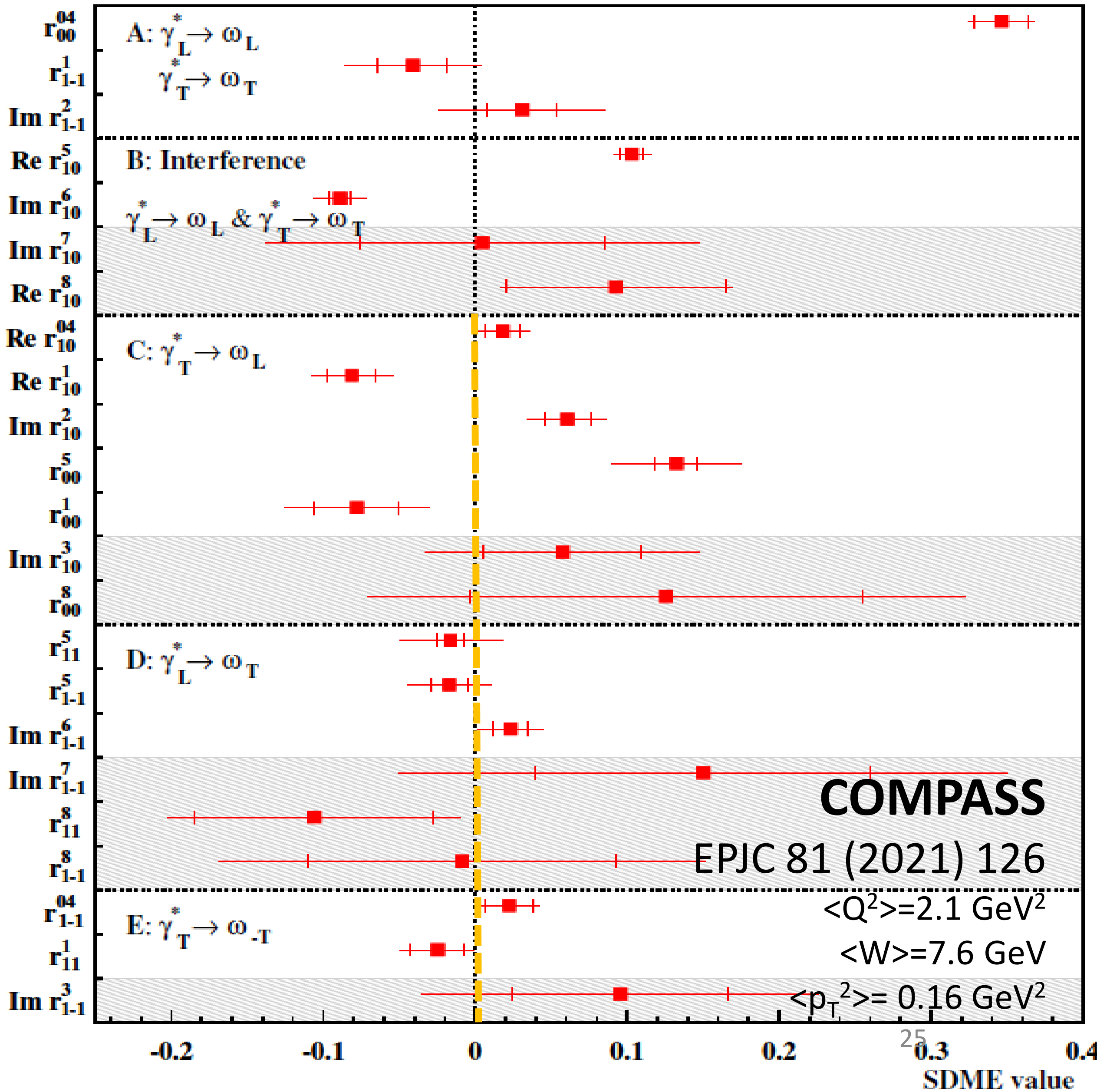
$$\mathcal{W}^L(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r_{10}^{3}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r_{1-1}^{3}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r_{10}^{7}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r_{1-1}^{7}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r_{11}^{8}\sin^2\Theta + r_{00}^{8}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r_{10}^{8}\}\sin 2\Theta\cos\phi - r_{1-1}^{8}\sin^2\Theta\cos 2\phi\Big)\Bigg]$$

ε close to 1,
small $\mathcal{W}^L$
no L/T separation

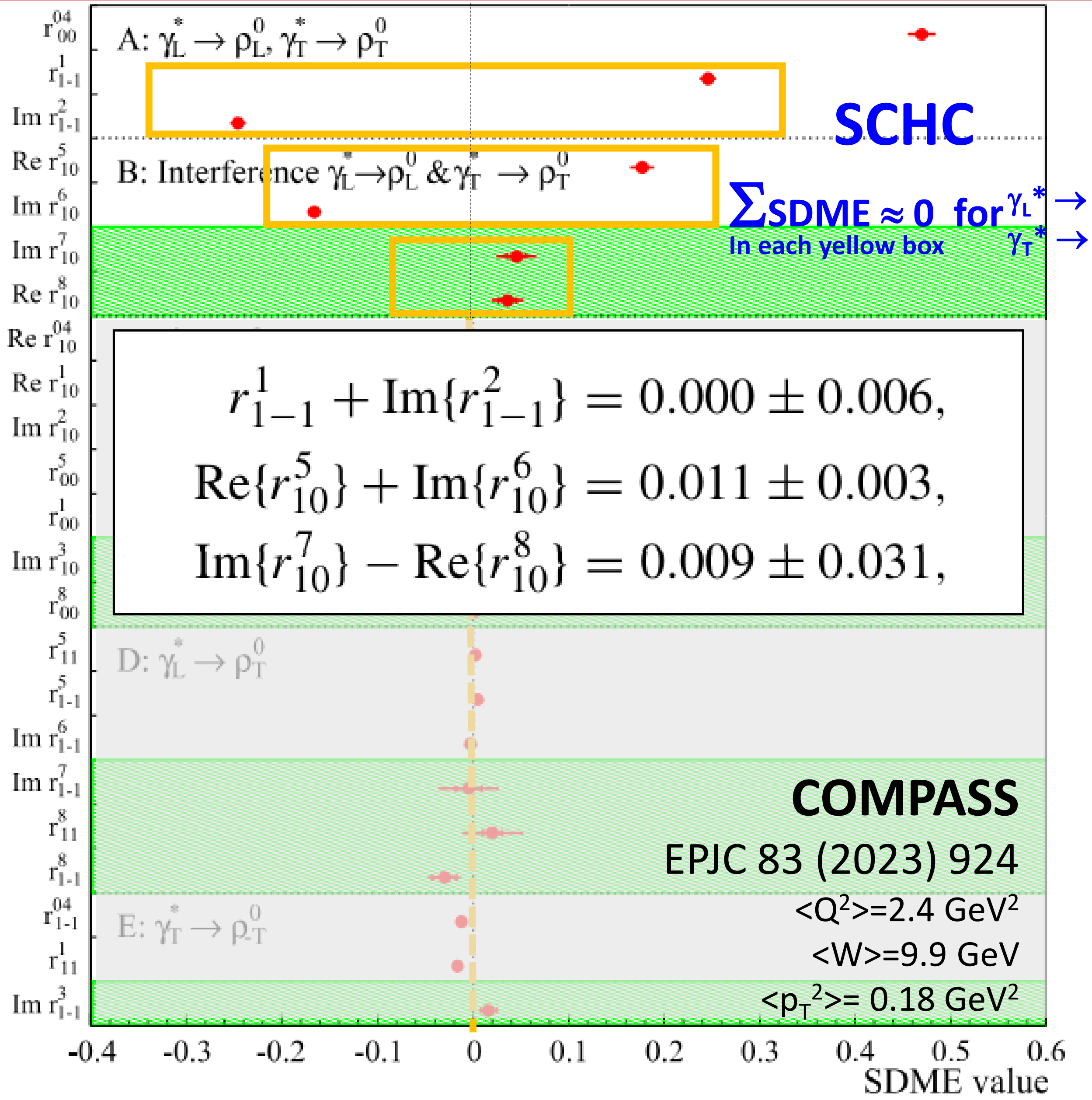


COMPASS 2012 Exclusive ρ^0 and ω production on unpolarized proton

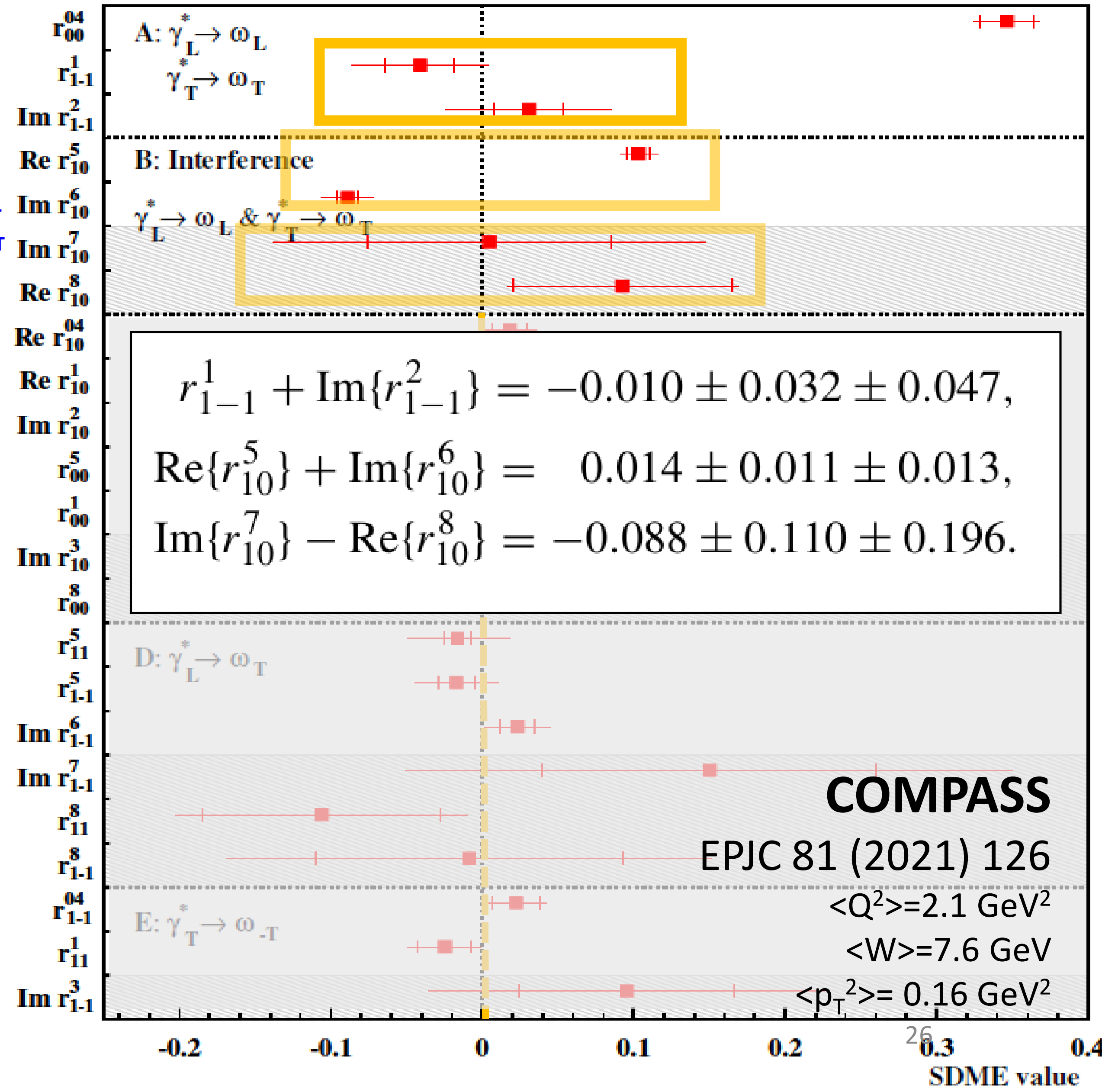




COMPASS 2012 Exclusive ρ^0 and ω production on unpolarized proton

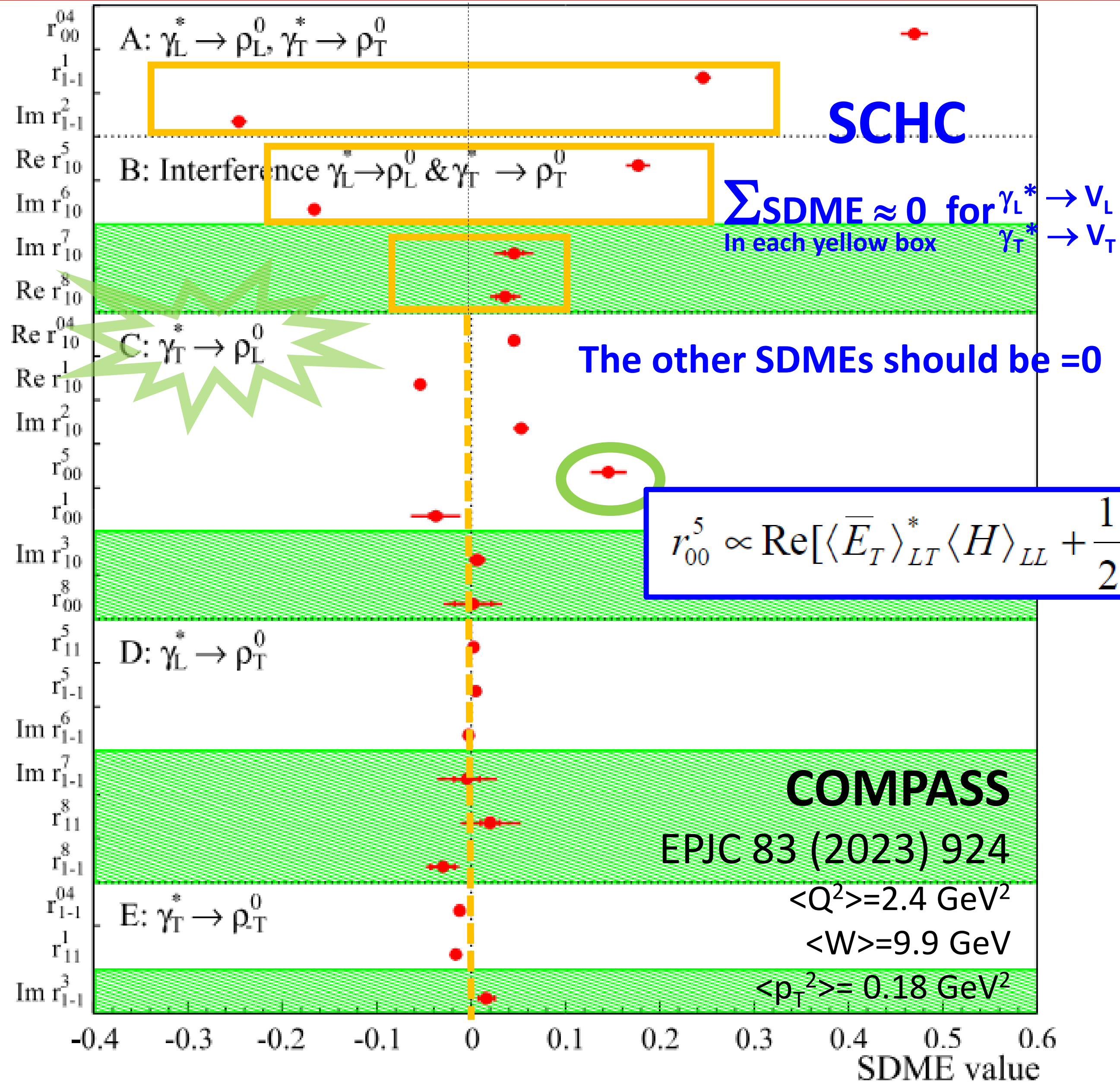


$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0.000 \pm 0.006,$$
$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0.011 \pm 0.003,$$
$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0.009 \pm 0.031,$$

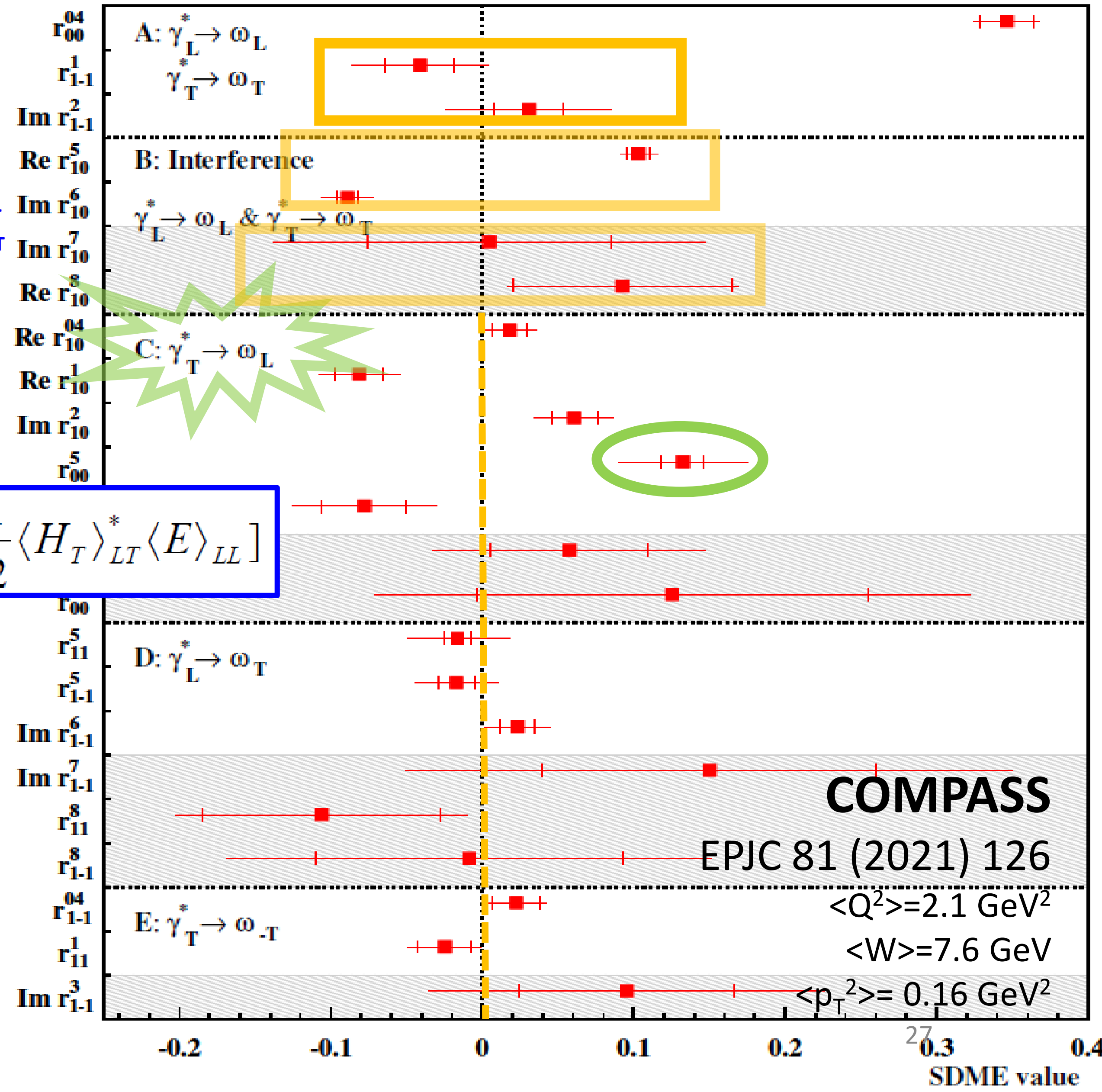


$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = -0.010 \pm 0.032 \pm 0.047,$$
$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0.014 \pm 0.011 \pm 0.013,$$
$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = -0.088 \pm 0.110 \pm 0.196.$$

COMPASS 2012 Exclusive ρ^0 and ω production on unpolarized proton



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

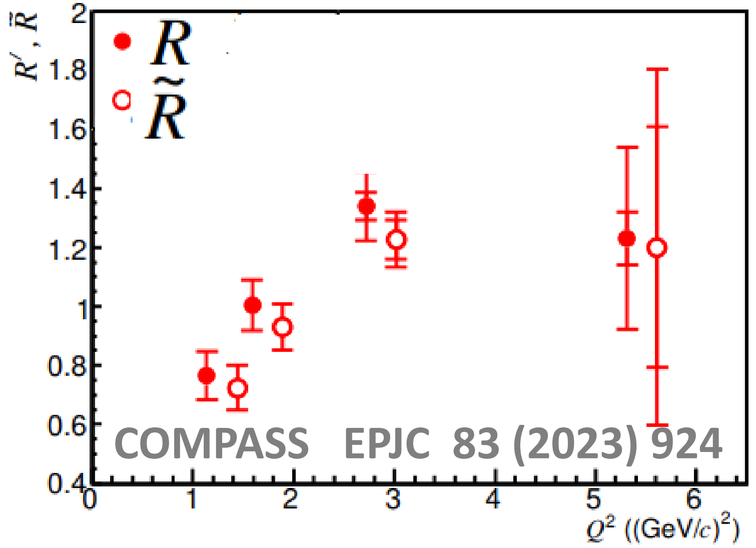


COMPASS 2012 $R = \sigma_L/\sigma_T$ for exclusive ρ^0 production

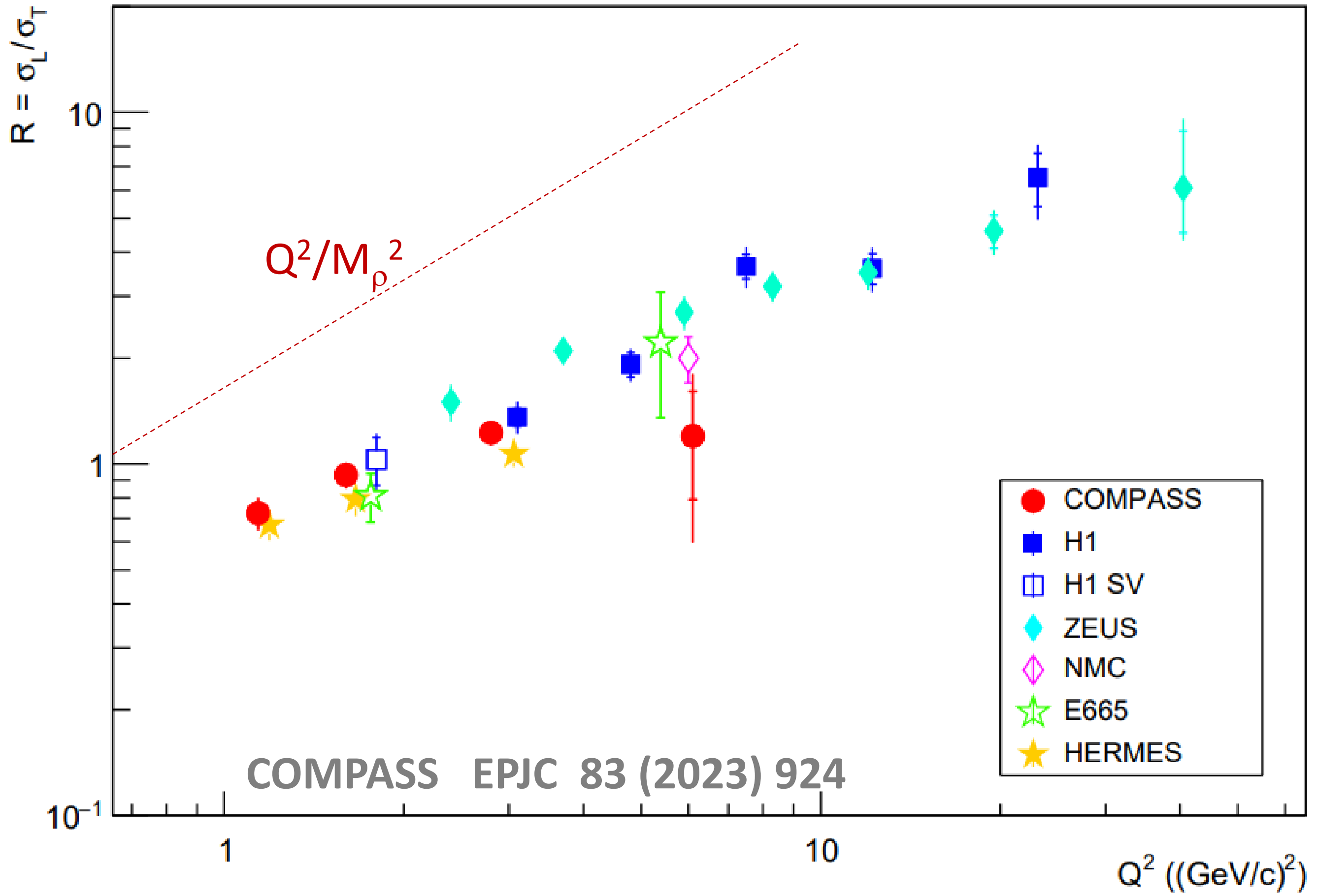
$$\mathbf{R} = \frac{\sigma_L(\gamma_L^* \to V)}{\sigma_T(\gamma_T^* \to V)}$$

$$\mathbf{R} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$ **only if SCHC**

In COMPASS domain evaluation of **R** and $\tilde{\mathbf{R}}$ considering violation of SCHC (but only NPE)



for all the experiments with $Q^2 > 1$ GeV^2



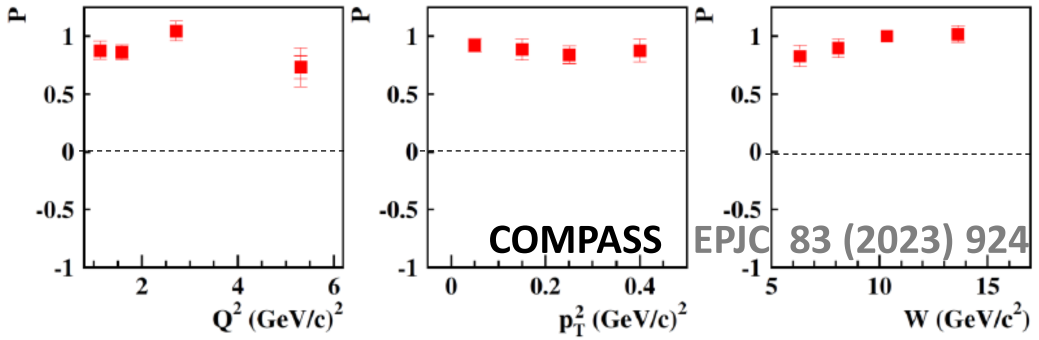
Deviations from the pQCD LO prediction in $Q^2/M_\rho^{\ 2}$ due to QCD evolution and q_T

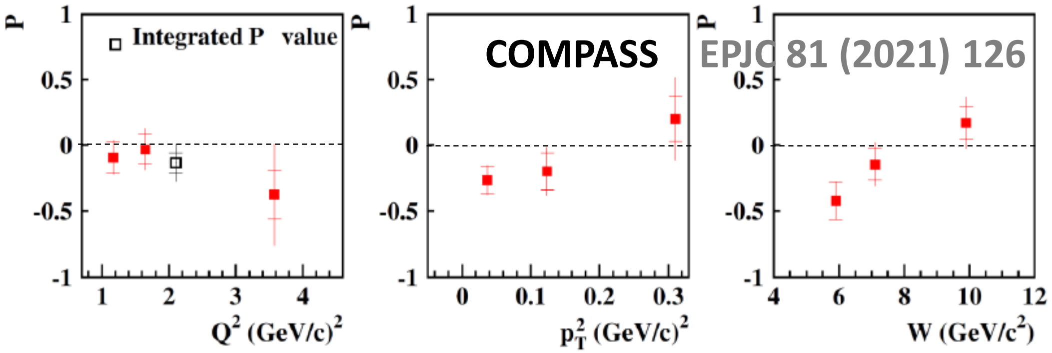
Transversize size effects of the meson smaller for $\boldsymbol{\sigma_L}$ than for $\boldsymbol{\sigma_T}$

Comparison ρ^0 and ω production

Natural (N) to Unatural (U) Parity Exchange for $\gamma_T^* \to V_T$

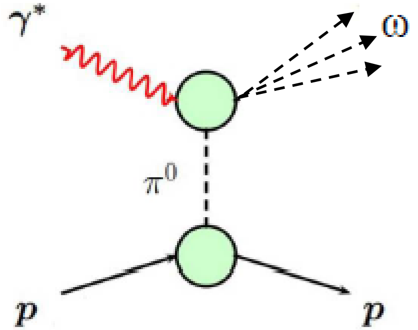
$$P = \frac{d\sigma_T^N(\gamma_T^* \to V_T) - d\sigma_T^U(\gamma_T^* \to V_T)}{d\sigma_T^N(\gamma_T^* \to V_T) + d\sigma_T^U(\gamma_T^* \to V_T)} \approx \frac{2r_{1-1}^1}{1 - r_{00}^{04} - 2r_{1-1}^{04}}$$



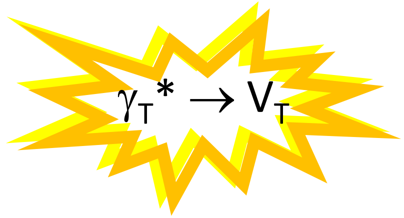


The pion pole exchange (UPE) is large for ω compared to ρ^0

$\Gamma(\omega \to \pi^0 \gamma) = 9 \times \Gamma(\rho^0 \to \pi^0 \gamma)$ as for π^0 Vector Meson FF



It plays an important role in ω production for:



ρ^0: P~1 ➔ NPE dominance P~1

NPE with GPDs H, E

ω: P~0 ➔ NPE ~ UPE

UPE dominance at small W and p_T^2

UPE with GPDs $\tilde{H}, \tilde{E}$ and the dominant pion pole

Summary and perspective using 2016 + 2017 data

- ✓ **DVCS** and the **sum** $\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$

  ➔ c_0 and s_1 and constrain on Im$\mathcal{H}$ and Transverse extension of partons

- ✓ **DVCS** and the **difference** $\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$

  ➔ c_1 and constrain on Re$\mathcal{H}$ (>0 as H1 or <0 as HERMES)

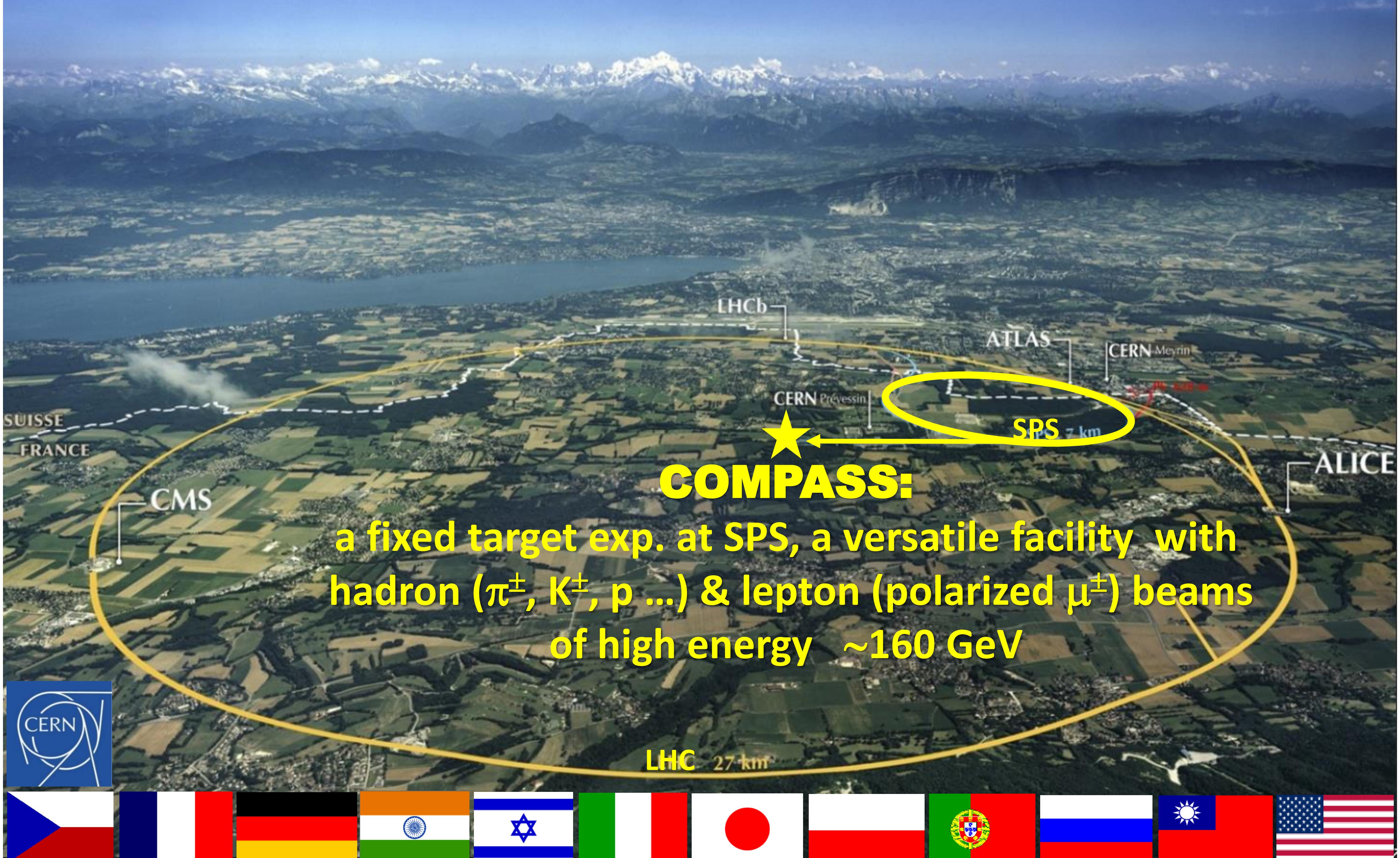
  for D-term and pressure distribution

- ✓ **Cross section** for π^0

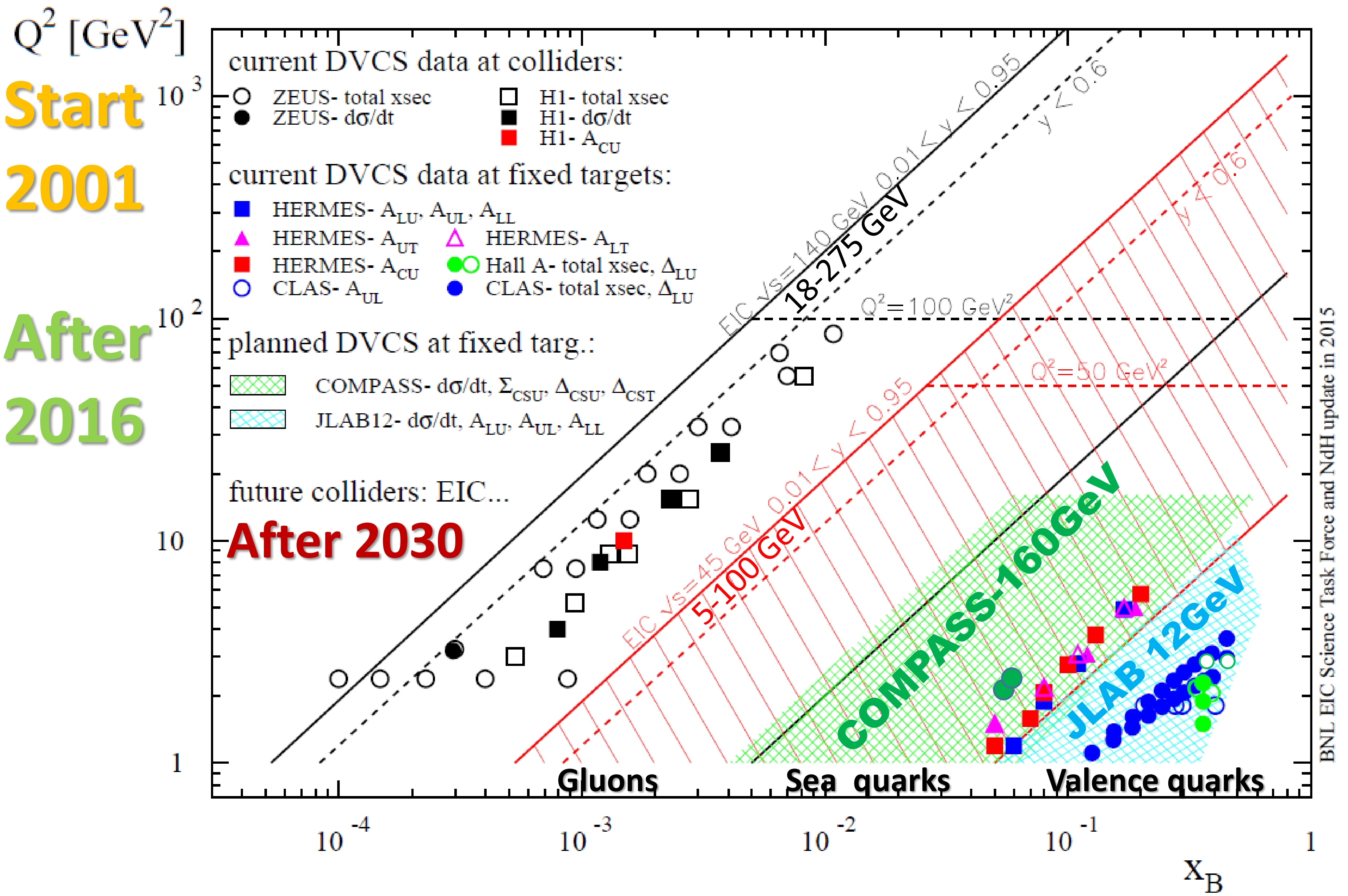
- ✓ **Cross section** and **SDME** for ρ^0, ω, ϕ, J/ψ

  - ✓ Transversity GPDs
  - ✓ Gluon GPDs
  - ✓ Flavor decomposition

THANK YOU FOR YOUR ATTENTION


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
COMPASS:
a fixed target exp. at SPS, a versatile facility with
hadron (π±, K±, p …) & lepton (polarized μ±) beams
of high energy ~160 GeV
CERN
LHC 27 km

Past and future experiments for DVCS ℓp⟶ ℓ’p’γ



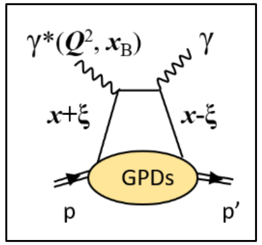
COMPASS 12-16 Transverse extention of partons in the sea quark range

$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS} \propto (Im\mathcal{H})^2$

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

In the COMPASS kinematics, $x_B \approx 0.06$, dominance of $Im\mathcal{H}$
97% (GK model) 94% (KM model)

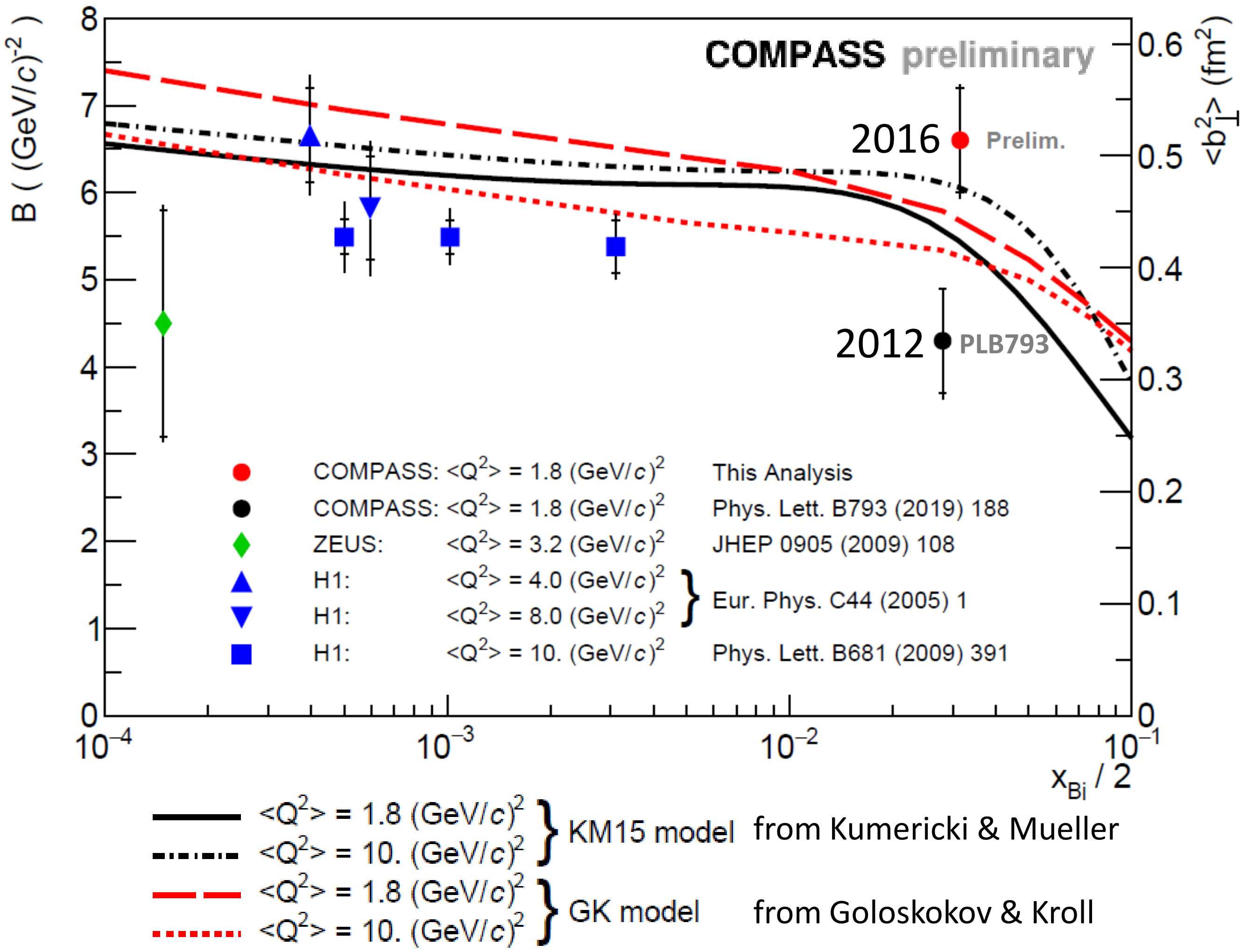
$Im\mathcal{H} = H(x=\xi, \xi, t)$
$x = \xi \approx x_B/2$ close to 0



$$q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp} H_-^q(x, 0, -\mathbf{\Delta}_\perp{}^2).$$

$$\langle b_\perp^2\rangle_x^f = \frac{\int d^2b_\perp b_\perp^2 q_f(x, b_\perp)}{\int d^2b_\perp q_f(x, b_\perp)} = -4\frac{\partial}{\partial t}\log H^f(x, \xi=0, t)\Big|_{t=0}$$

$$\langle b_\perp^2(x)\rangle \approx 2B(\xi)$$

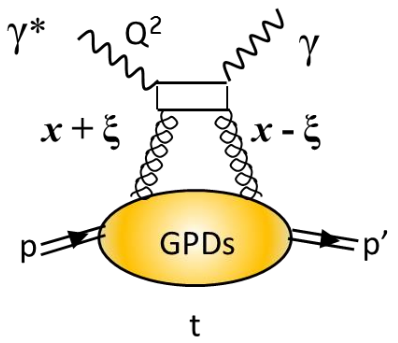


➔ nucleon tomography in the gluon domain at HERA

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

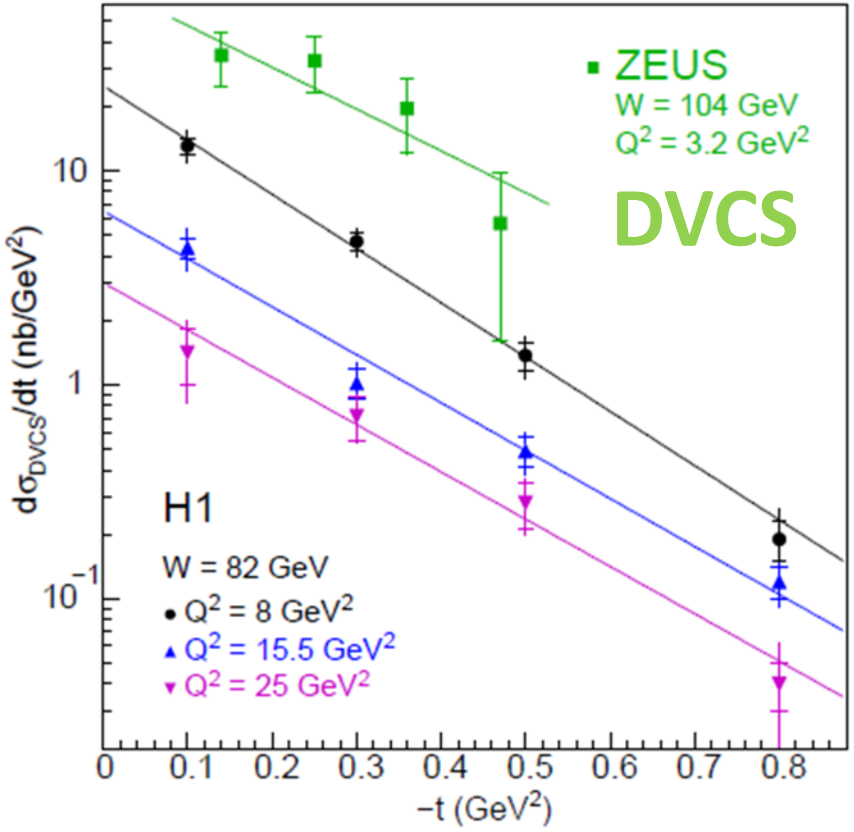
B is related to the transversed size of the scattering object

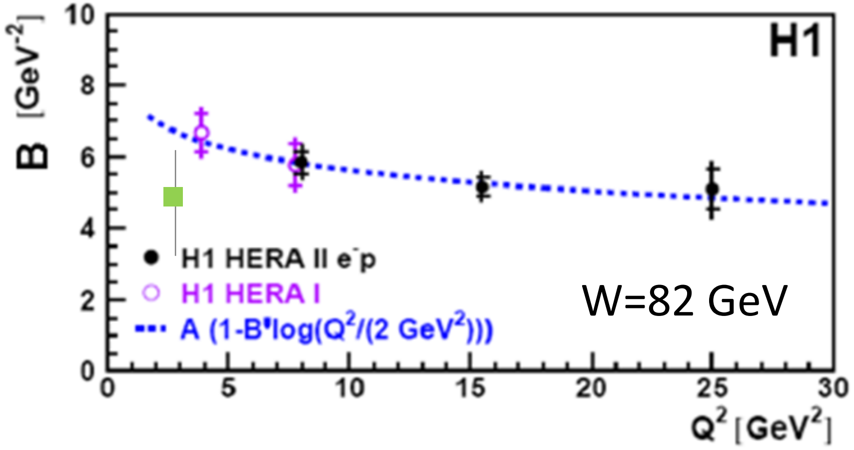
Dominance of *Im$\mathcal{H}$*

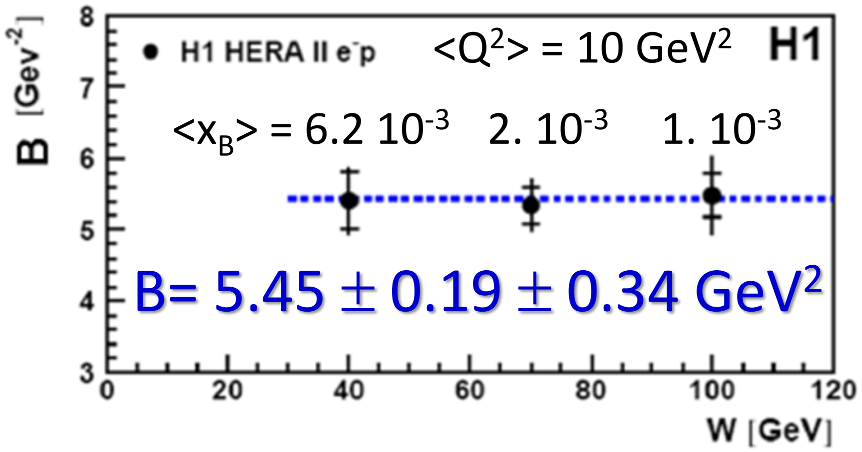


ZEUS-H1
Data collected
1995-2007

Aaron et al., H1 Coll, PLB659 (2008)







$\langle b_\perp^2(x)\rangle \approx 2B(\xi)$

$\sqrt{< b_\perp^2 >}$ = 0.65 ± 0.02 fm to be compared to $\sqrt{4\frac{d}{dt}F_1^p}\overset{t=0}{=}$ 0.67 ± 0.01 fm

COMPASS 2016 Exclusive π^0 production on unpolarized proton

$$\frac{d^2\sigma_{\gamma^* p}^{\leftrightarrows}}{dt d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\frac{d\sigma_{LT}}{dt} \mp |P_l|\sqrt{2\epsilon(1-\epsilon)}\sin\phi\frac{d\sigma'_{LT}}{dt}\right]$$

$$\frac{d\sigma_L}{dt} \propto \left[(1-\xi^2)|\langle\widetilde{H}\rangle|^2 - 2\xi^2\,\mathrm{Re}\left[\langle\widetilde{H}\rangle^*\langle\widetilde{E}\rangle\right] - \frac{t'}{4M^2}\xi^2|\langle\widetilde{E}\rangle|^2\right],$$

$$\frac{d\sigma_T}{dt} \propto \left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle\overline{E}_T\rangle|^2\right],$$

$$\frac{d\sigma_{TT}}{dt} \propto t'|\langle\overline{E}_T\rangle|^2,$$

$$\frac{d\sigma_{LT}}{dt} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\ \mathrm{Re}\left[\langle H_T\rangle^*\langle\widetilde{E}\rangle + \langle\overline{E}_T\rangle^*\langle\widetilde{H}\rangle\right],$$

$$\frac{d\sigma_{LT'}}{dt} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\ \mathrm{Im}\left[\langle H_T\rangle^*\langle\widetilde{E}\rangle + \langle\overline{E}_T\rangle^*\langle\widetilde{H}\rangle\right].$$

At COMPASS

$$|P_l|\sqrt{2\epsilon(1-\epsilon)} \simeq 0.06$$

Comparison ρ^0 SDMEs at COMPASS and HERMES

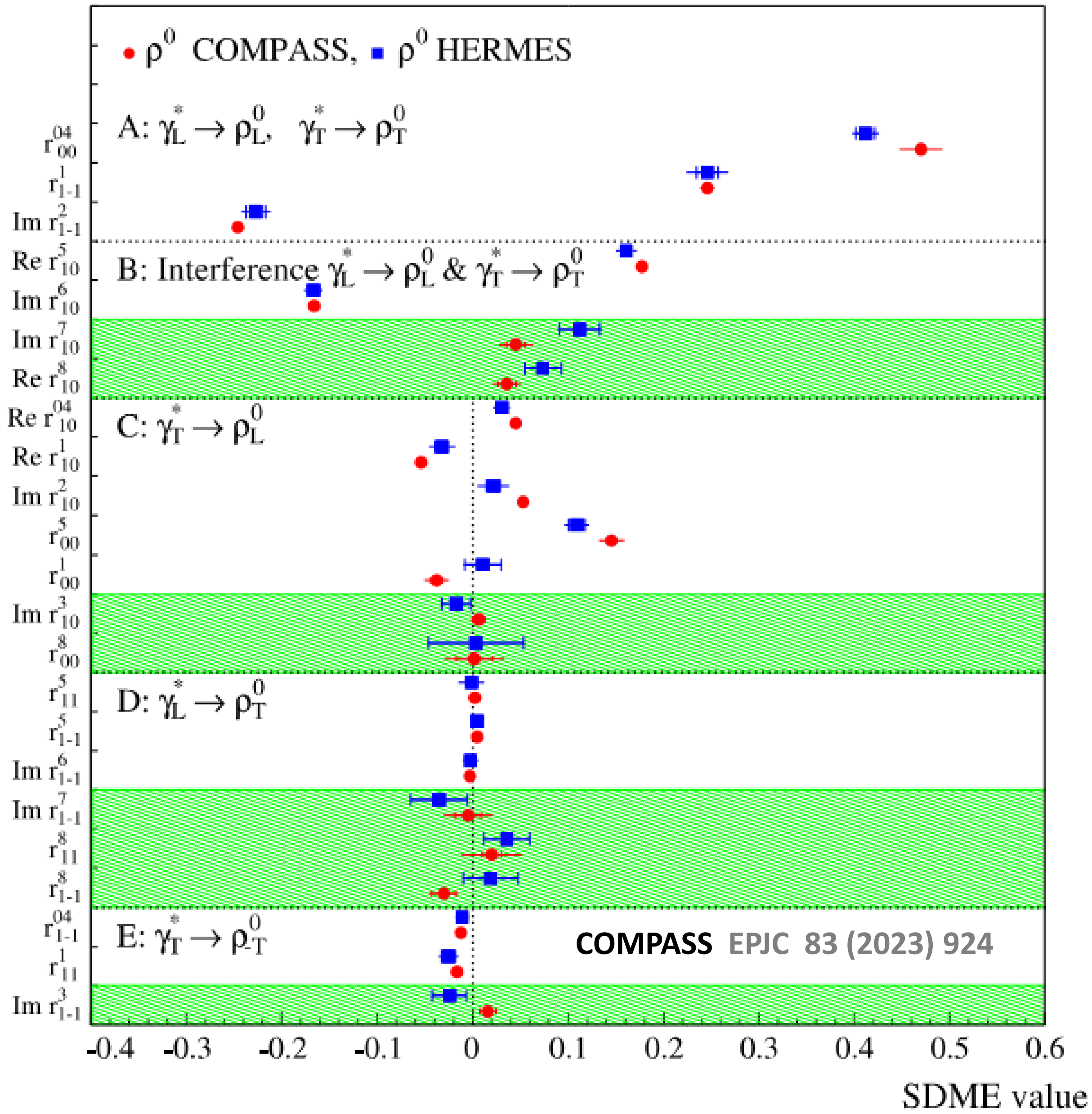


Fig. 12 Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2 \rangle = 1.96$ (GeV/c)^2, $\langle W \rangle = 4.8$ GeV/c^2, $\langle |t'| \rangle = 0.13$, while those for COMPASS are $\langle Q^2 \rangle = 2.40$ (GeV/c)^2, $\langle W \rangle = 9.9$ GeV/c^2, $\langle p_T^2 \rangle = 0.18$ (GeV/c)^2. Inner error bars represent statistical uncertainties and outer ones statistical and systematic uncertainties added in quadrature. Unpolarised (polarised) SDMEs are displayed in unshaded (shaded) areas