Transversity 2024
Trieste, 3-7 June 2024

GPDs studies at COMPASS

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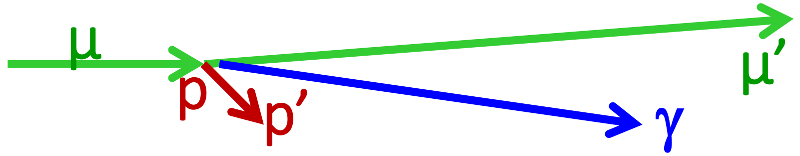
7th international workshop on
transverse phenomena in hard processes

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

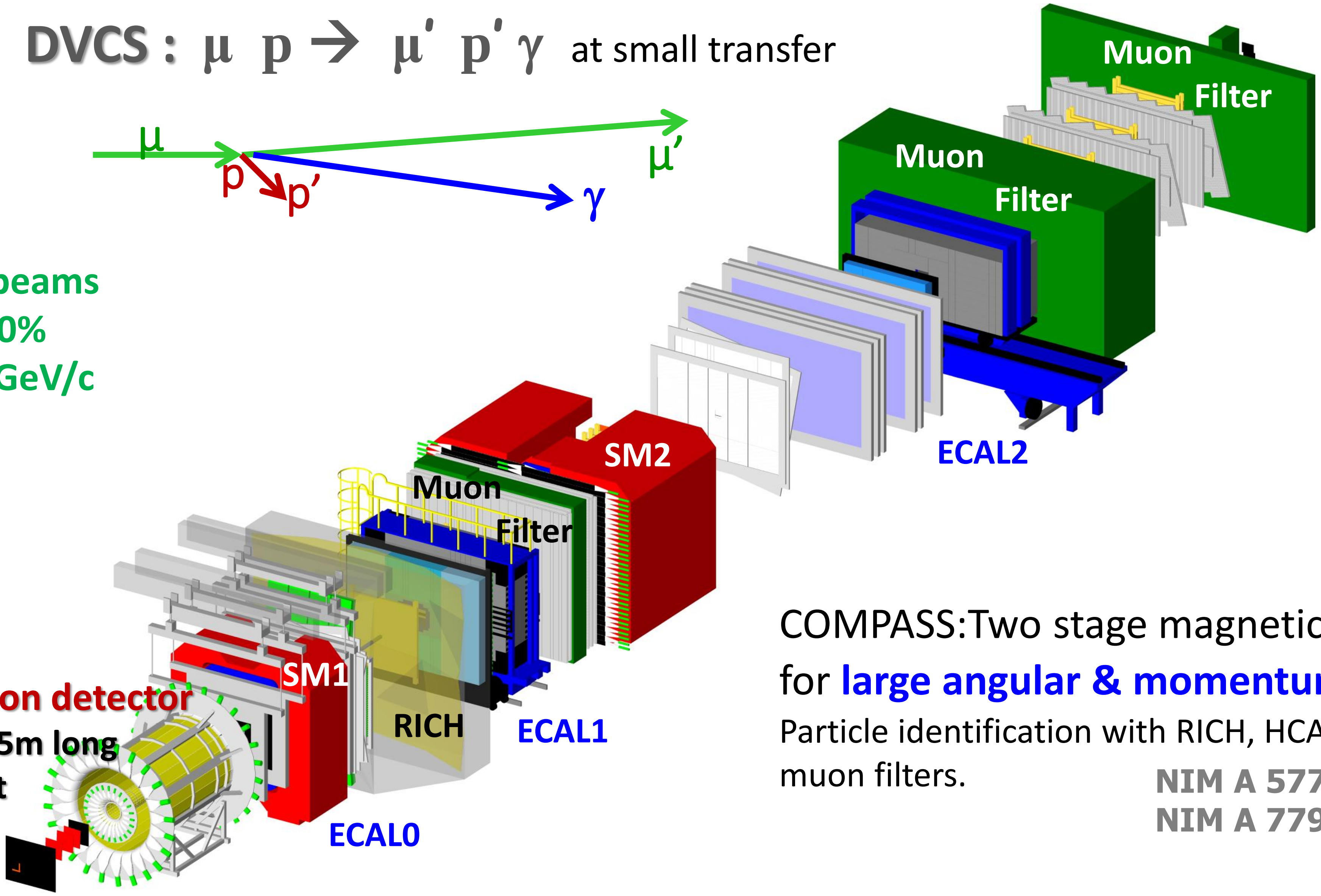


Pseudo-Scalar Meson : $\mu\ p \rightarrow \mu'\ p'\ \pi^0$

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



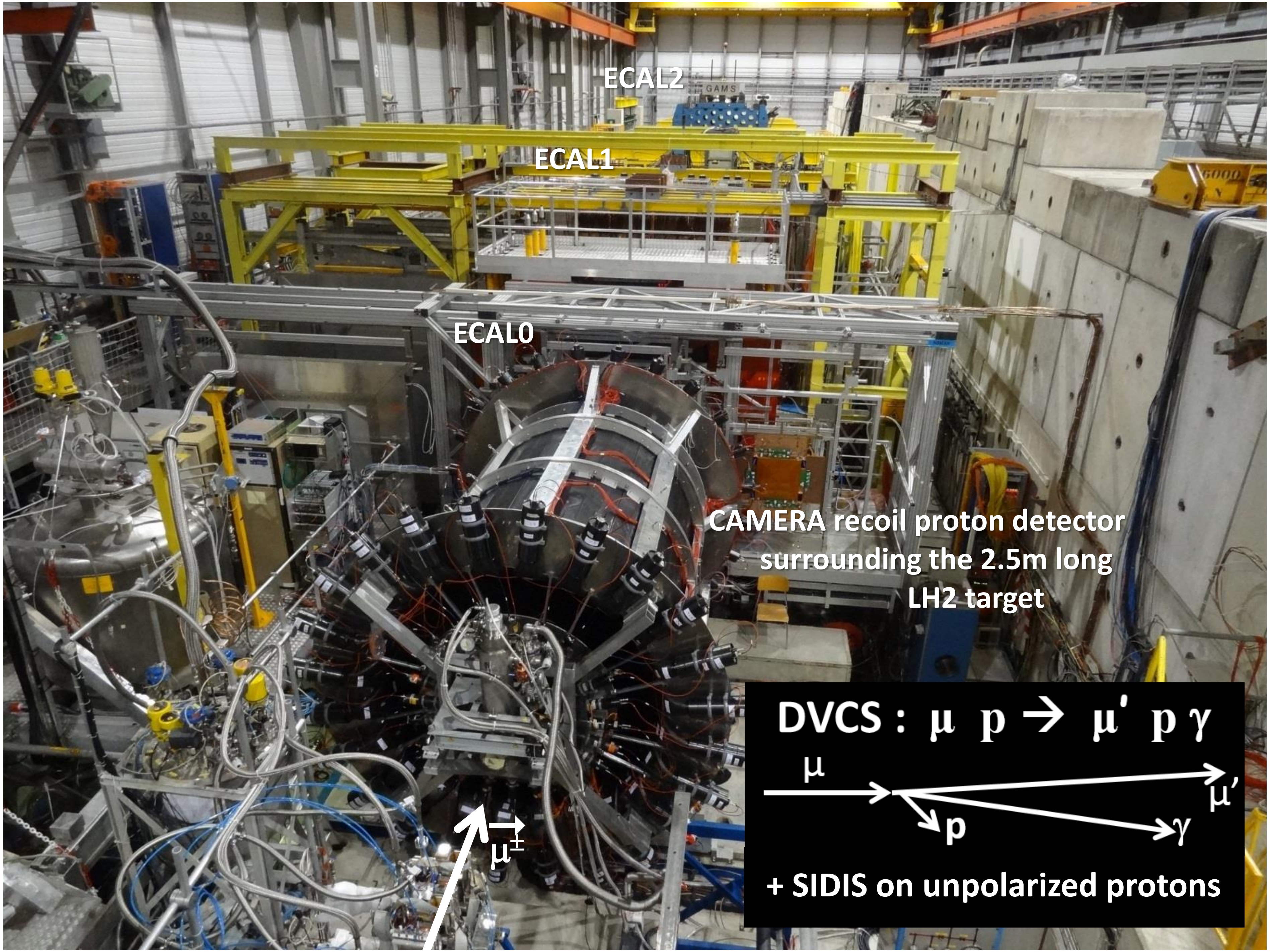
Both $\overleftarrow{\mu^+}$ and $\overrightarrow{\mu^-}$ beams
Polarisation ~ ±80%
Momentum 160 GeV/c

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:

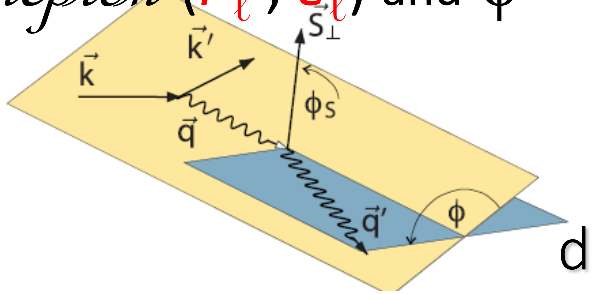
1 month pilot run

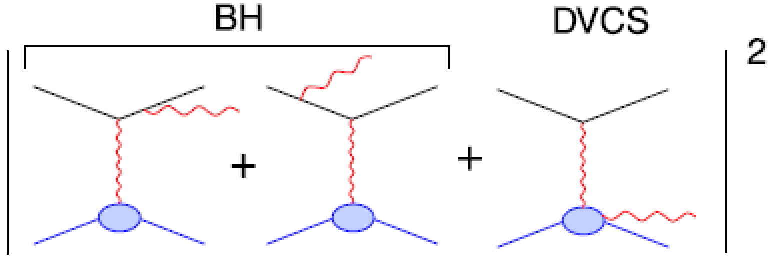
2016 -17:

2 x 6 month
data taking

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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

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

Well known

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

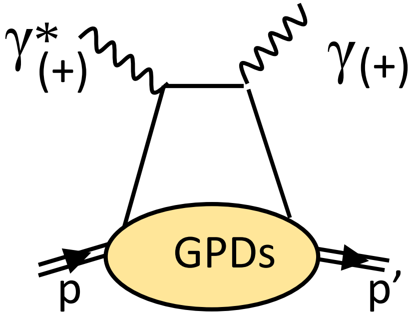
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

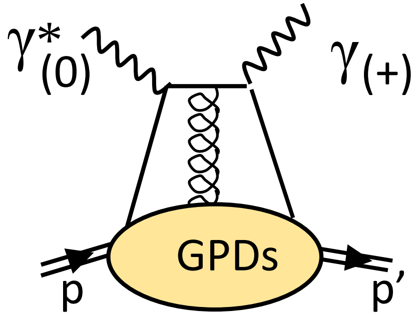
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

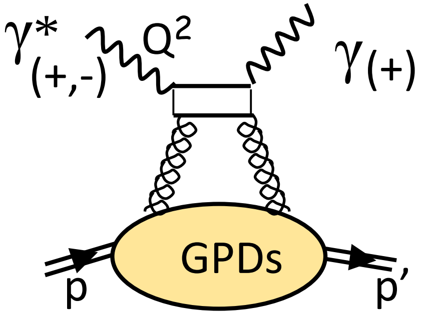
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



LO,Twist-2



HT,Twist-3
suppressed by 1/Q



NLO,Twist-2
double helicity flip
suppressed by α_S

Deeply virtual Compton scattering (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

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

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

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

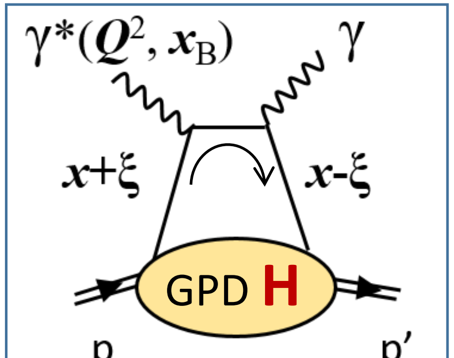
and $c_0^{DVCS} \propto (Im\mathcal{H})^2$

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

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

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

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



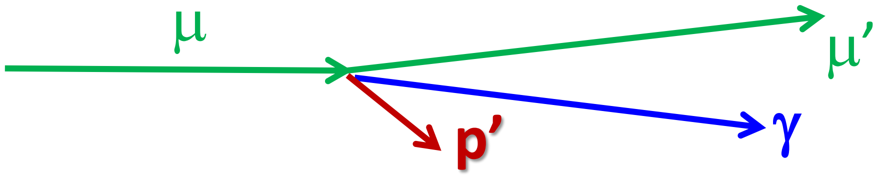
LO,Twist-2

$\xi \approx x_B/2$

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

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

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

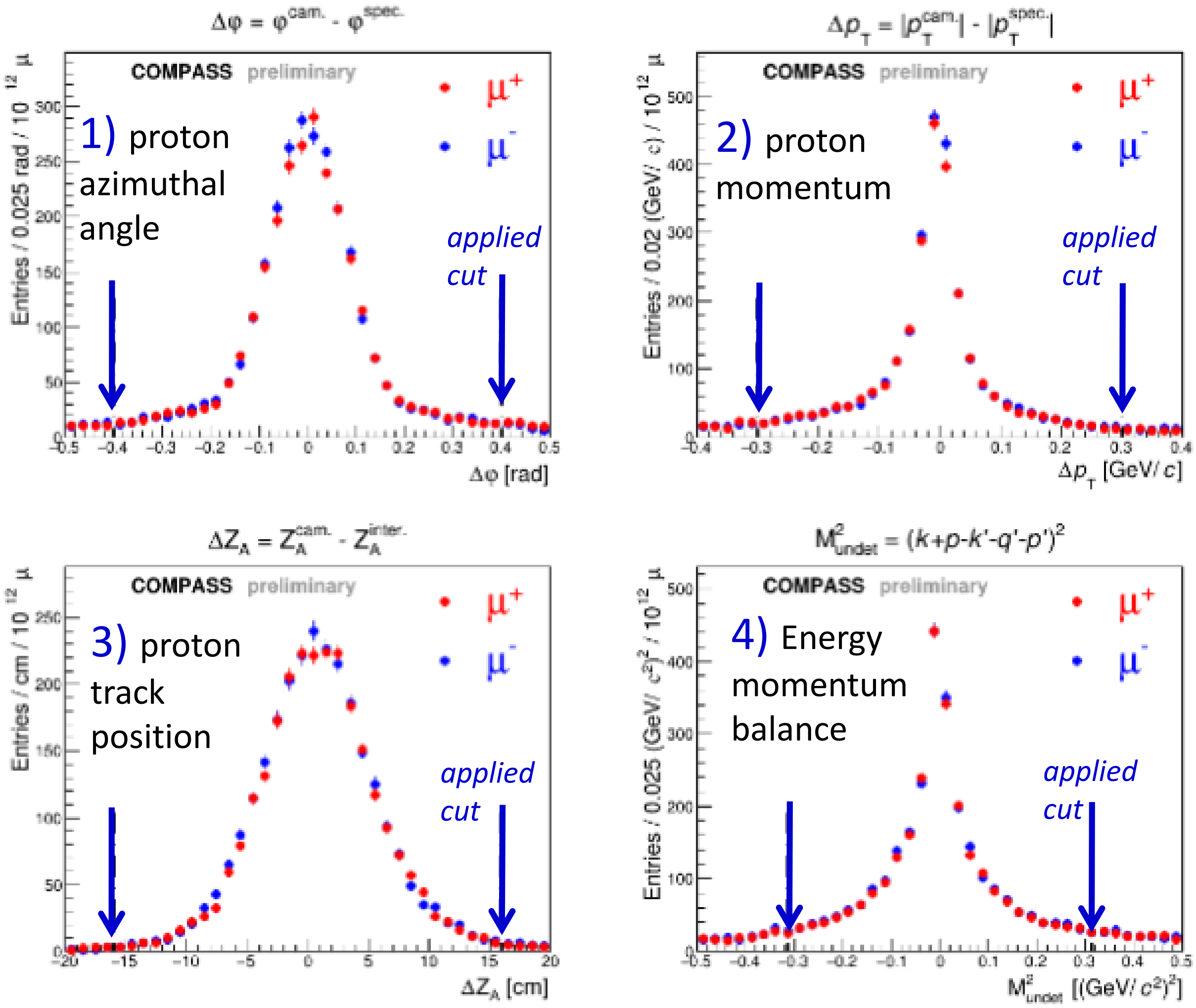
3) $\Delta z_A = z_A^{cam} - z_A^{Z_B \text{ and vertex}}$

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

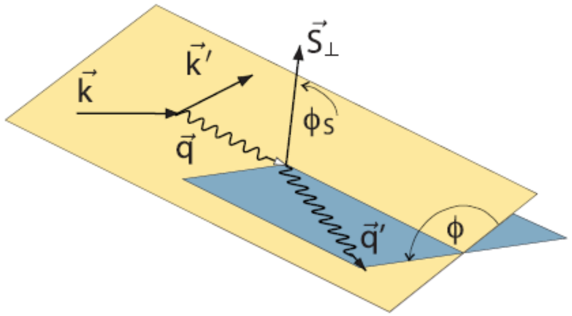
Good agreement between $\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ yields important achievement for:

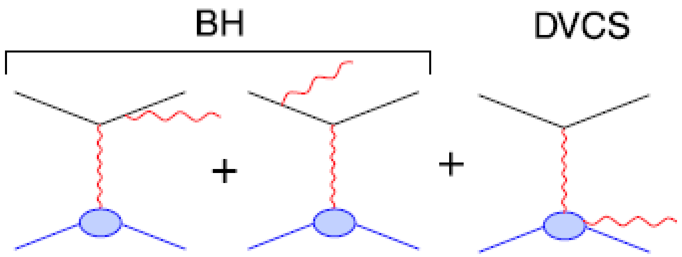
❶ $\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$ **Easier, done first**
Mapping in Transverse plane

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



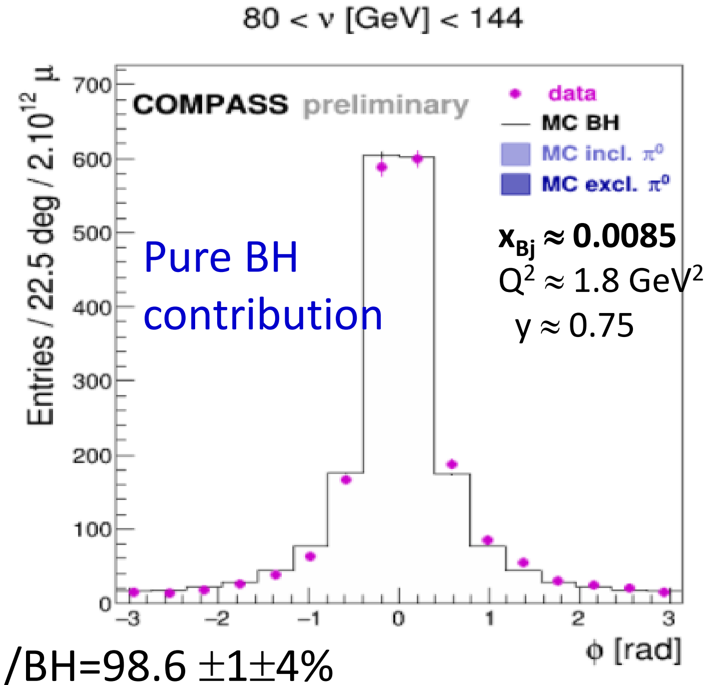
COMPASS 2016 data DVCS+BH cross section at Eμ=160 GeV

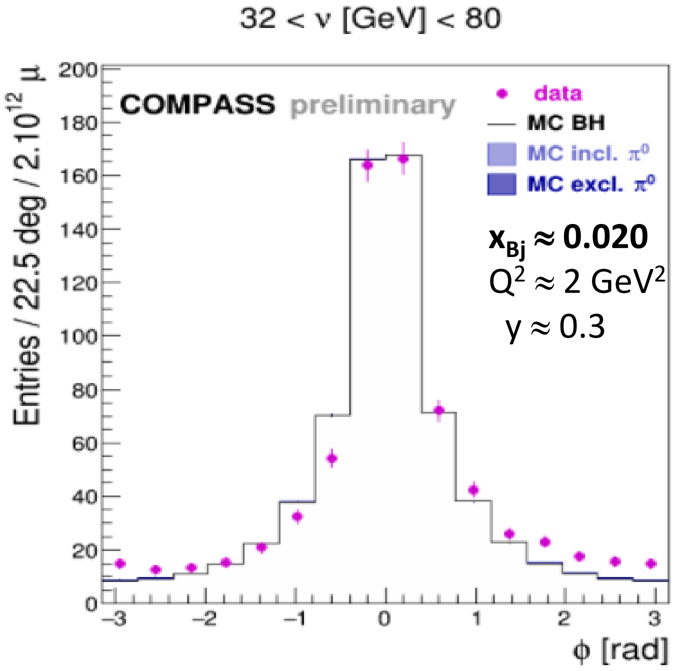


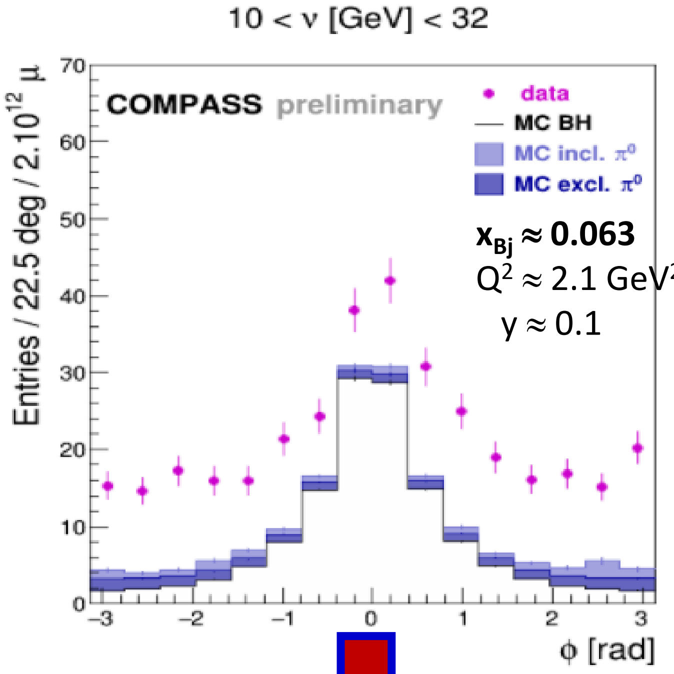


$$\Sigma = d\sigma(\overleftarrow{\mu^+}) + d\sigma(\overrightarrow{\mu^-})$$

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







Data/BH=98.6 ±1±4%

MC: BH contribution evaluated for the integrated luminosity
π° 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:

$$\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \text{Im}\, I]$$

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

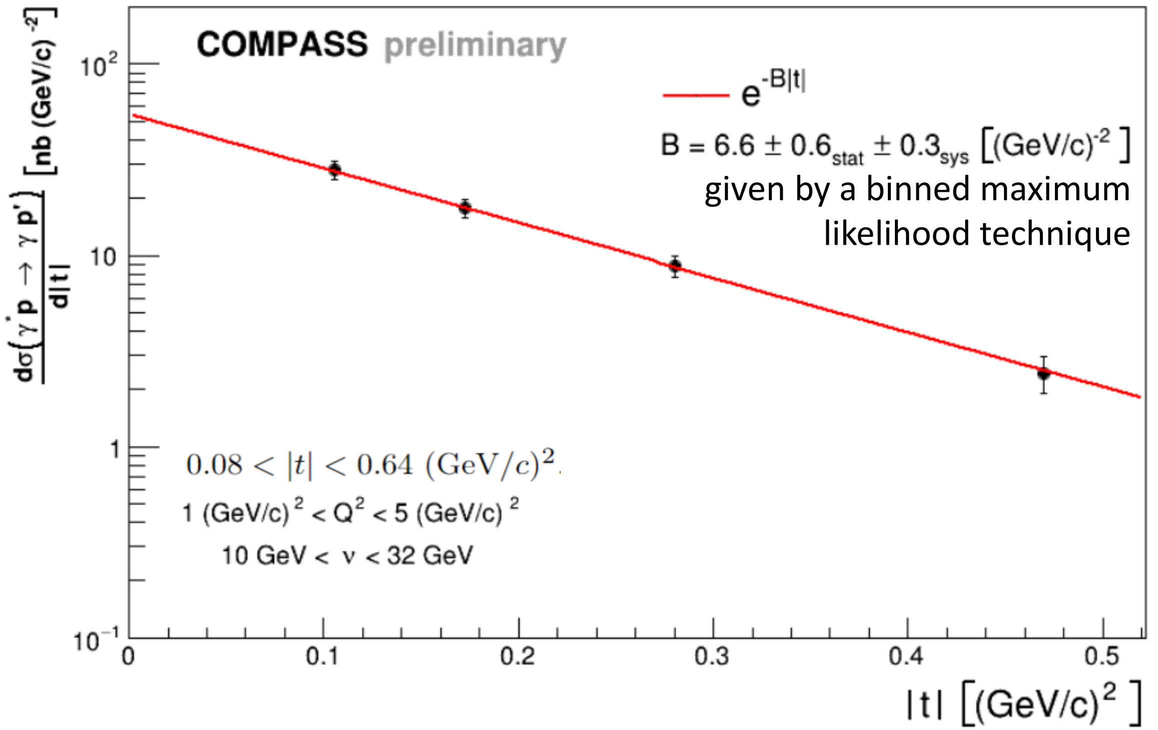
calculable
can be subtracted

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



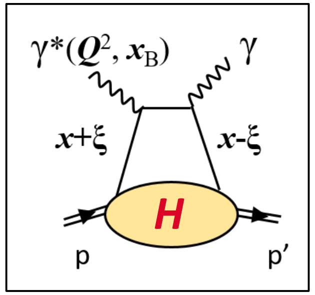
COMPASS 12-16 Transverse extention of partons in the sea quark range

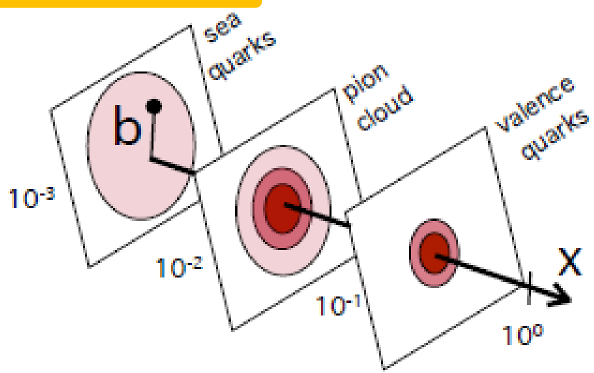
$$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS} \propto (Im\mathcal{H})^2$$

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

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

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

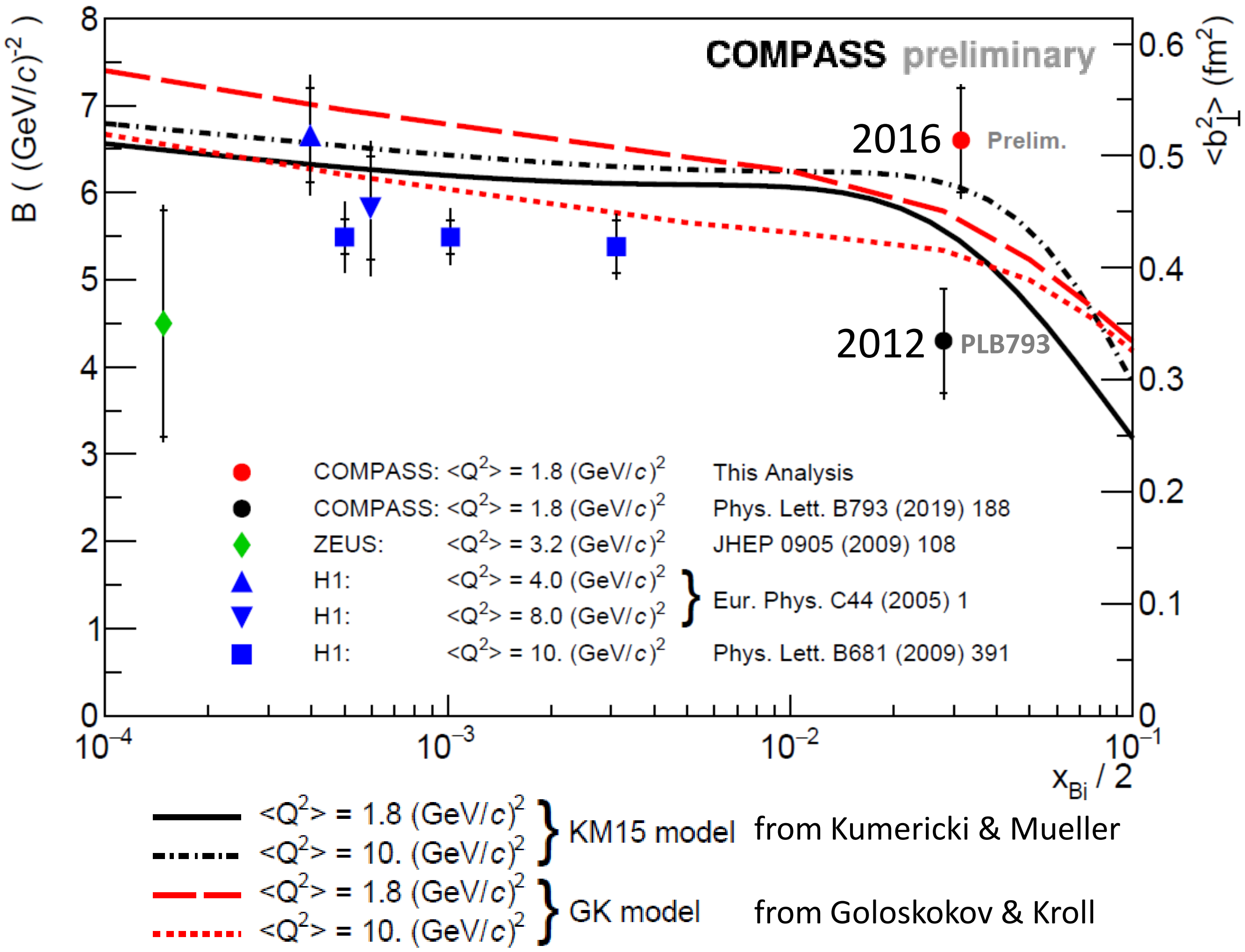




2012 statistics = Ref

2016 analysed statistics = 2.3 × Ref

2016+2017 expected statistics = 10 × Ref



Improvements in 2016 analysis compared to 2012

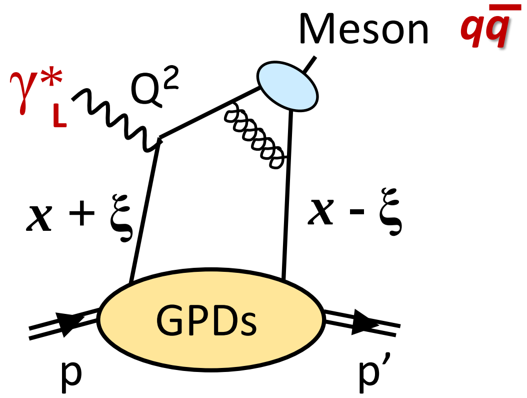
- same intensity with mu+ and mu- beam in 2016
- more advanced analysis with 2016 data, still ongoing
- π^0 contamination with different thresholds
- better MC description of the evolution in ν
- binning with 3 variables (t, Q^2, ν) or 4 variables (t, ϕ, Q^2, ν)
- different binning in t

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 an unpolarized nucleon

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 2012 - 16 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 $\langle x_B \rangle = 0.10$

ε close to 1

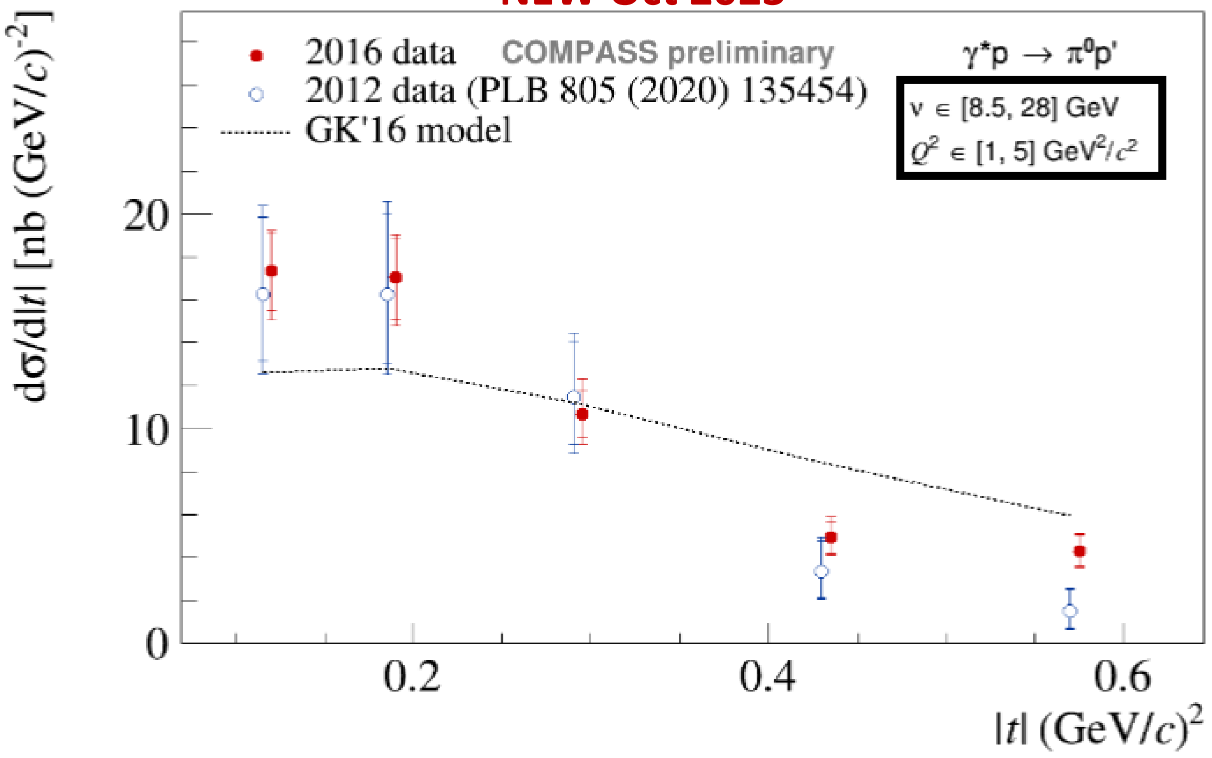
$$\frac{d\sigma_L}{dt} \propto \left|\langle\tilde{H}\rangle\right|^2 - \frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

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

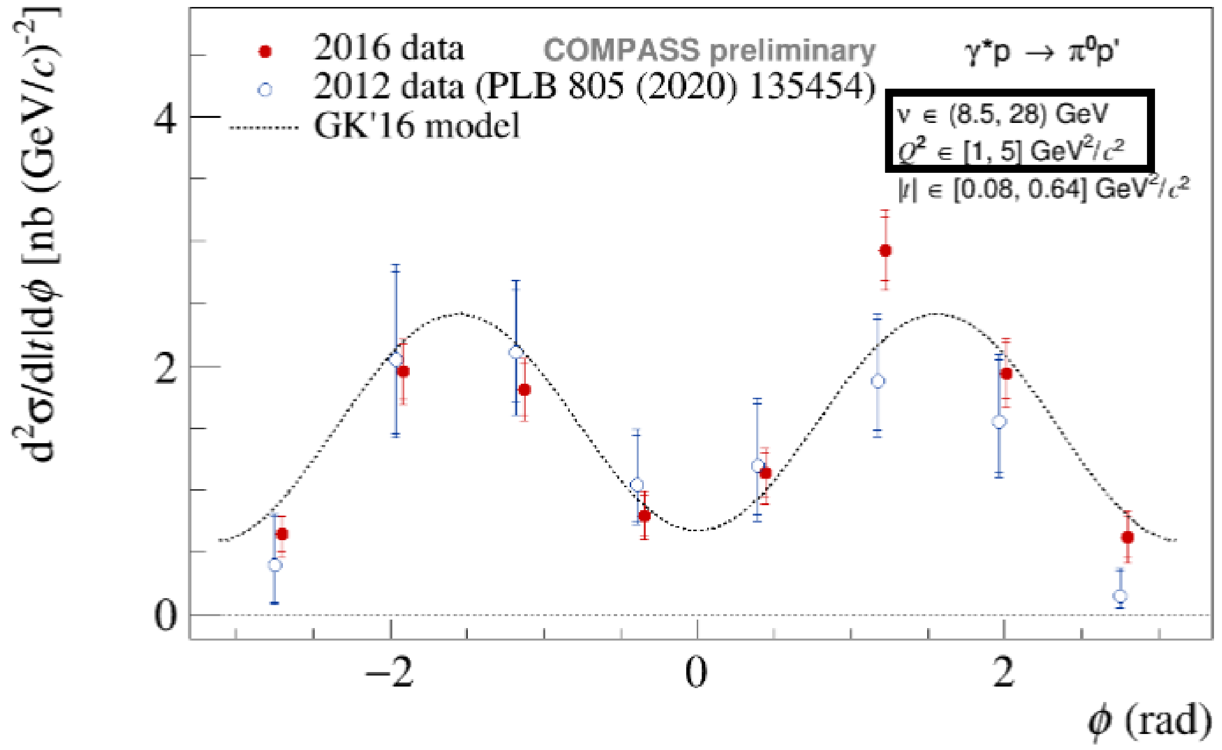
$$\frac{\sigma_{TT}}{dt} \propto \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

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

NEW Oct 2023



NEW Oct 2023



Models: **GK** Kroll Goloskokov EPJC47 (2011) Also **GGL**: Golstein Gonzalez Liuti PRD91 (2015)

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

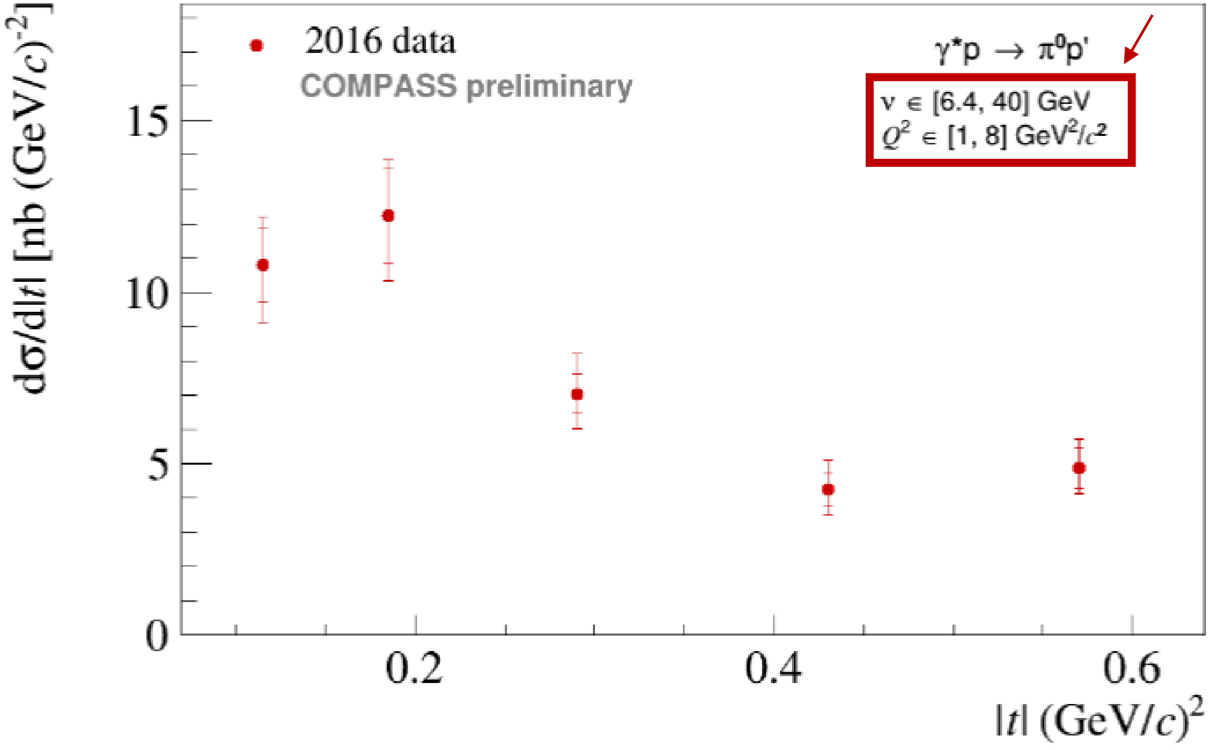
$$\frac{d\sigma_L}{dt} \propto \left|\langle\tilde{H}\rangle\right|^2 - \frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

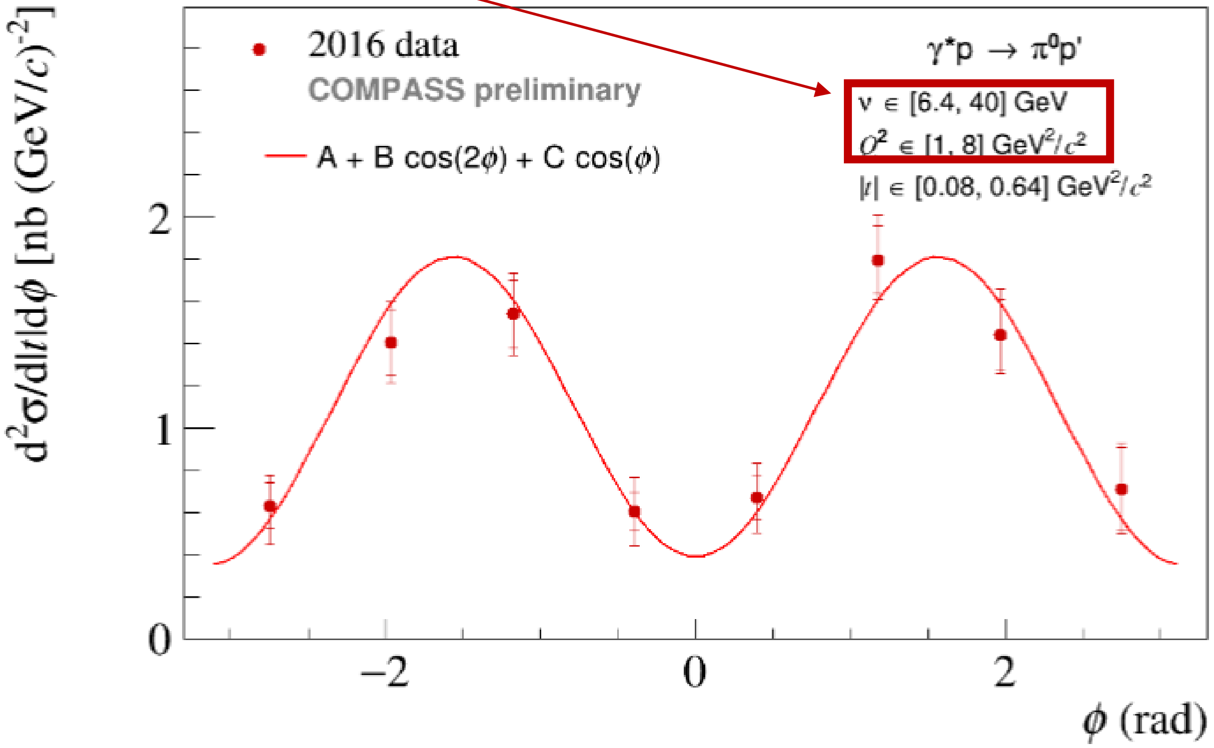
$$\frac{d\sigma_T}{dt} \propto |\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle\bar{E}_T\rangle|^2$$

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

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

NEW Oct 2023 **In a larger (υ, Q²) domain** **NEW Oct 2023**





COMPASS 2016 Exclusive π^0 production on unpolarized proton

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

$F\pi^0 = 2/3 F^u + 1/3 F^d$

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

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

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

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

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

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

NEW Oct 2023 COMPASS preliminary $\nu \in [6.4, 40]$ GeV $Q^2 \in [1, 8]$ GeV$^2/c^2$ $|t| \in [0.08, 0.64]$ GeV$^2/c^2$

The main systematic error is the error on the evaluation of the π° background contribution from SIDIS (LEPTO)

$$\left\langle \frac{\sigma_T}{|t|} + \epsilon\frac{\sigma_L}{|t|} \right\rangle = (6.9 \pm 0.3_{\text{stat}} \pm 0.8_{\text{syst}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

$$\left\langle \frac{\sigma_{TT}}{|t|} \right\rangle = (-4.5 \pm 0.5_{\text{stat}} \pm 0.2_{\text{syst}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

$$\left\langle \frac{\sigma_{LT}}{|t|} \right\rangle = (0.06 \pm 0.2_{\text{stat}} \pm 0.1_{\text{syst}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

σ_{TT} is negative and large comparatively to $\sigma_T + \varepsilon\,\sigma_L$

➔ impact of $\bar{E}_T$

σ_{LT} rather small

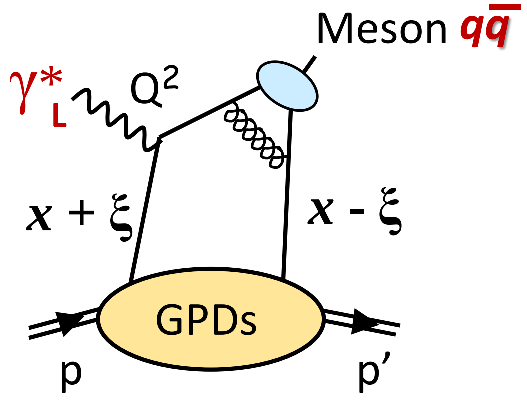
We will provide the evolution with 3 bins in υ and 4 bins in Q^2

GPDs and Hard Exclusive Meson Production

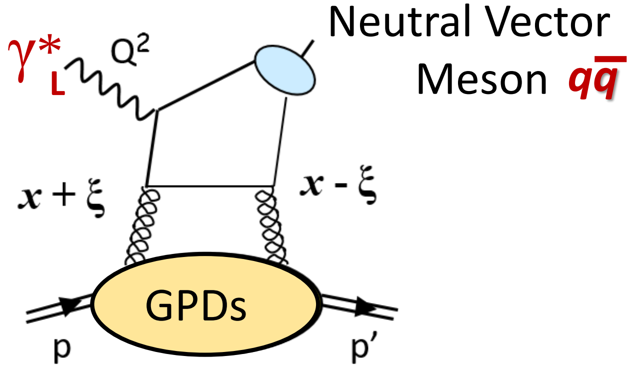
Factorisation proven only for σ_L

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

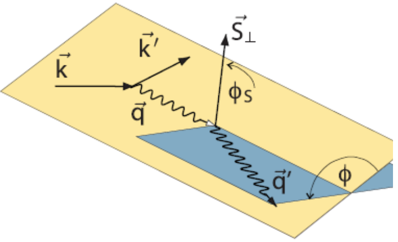
$H^q(x, \xi, t)$ $E^q(x, \xi, t)$

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

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

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

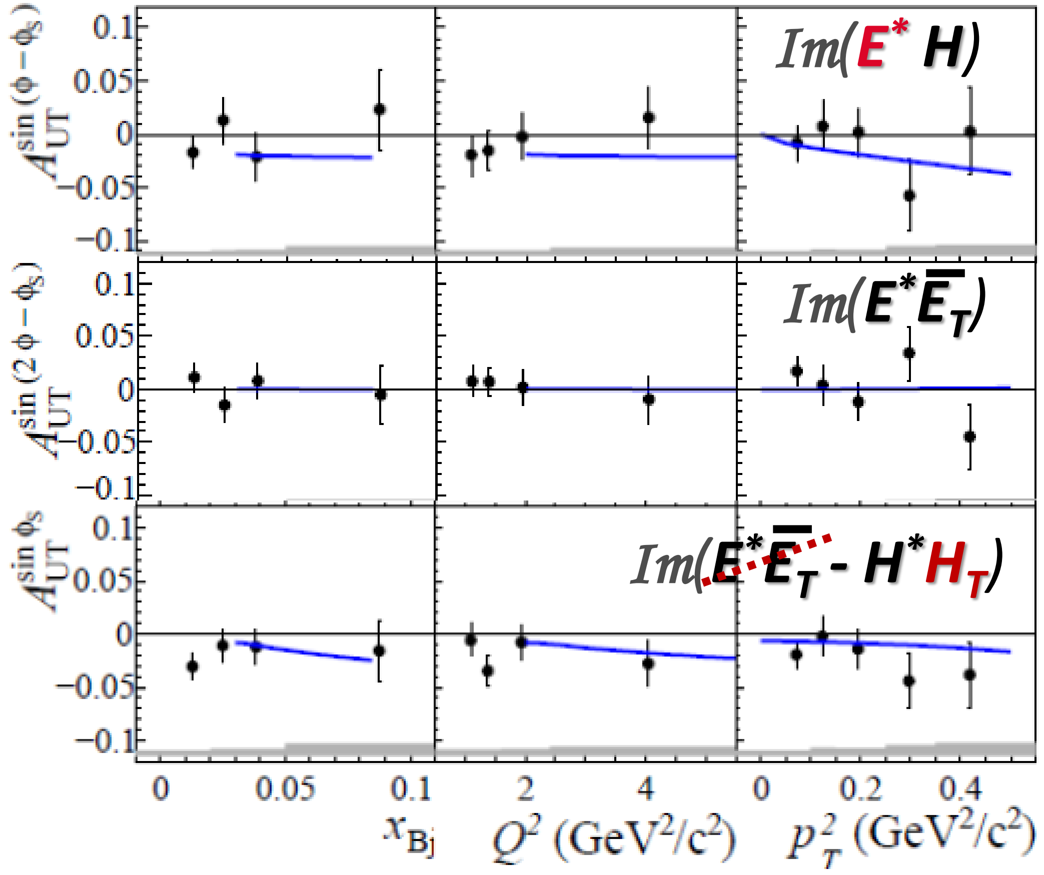
HEMP with Transversely Polarized Target without RPD



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

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

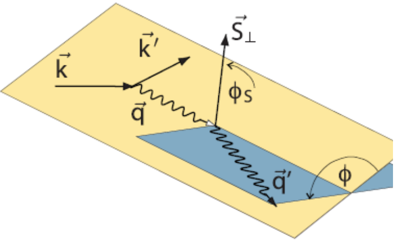
COMPASS, NPB 865 (2012) 1-20, PLB731 (2014) 19



Sensibility to E and H_T

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

COMPASS 2010 2007 HEMP with Transversely Polarized Target without RD



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

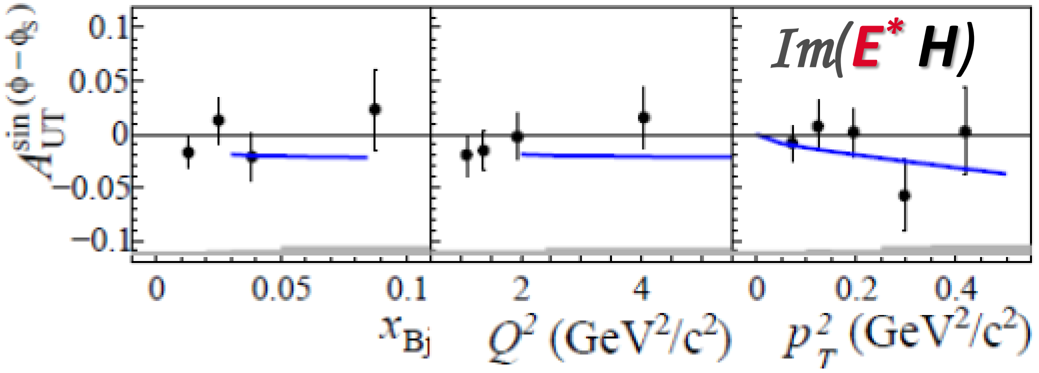
$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}\frac{E_g}{x}\right)$$

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

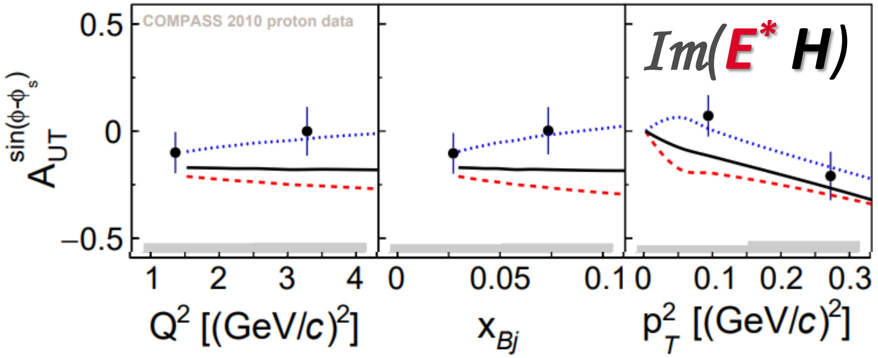
$$E_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}\frac{E_g}{x}\right)$$

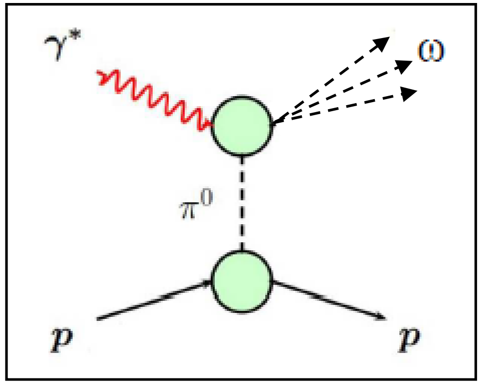
E^u and E^d of opposite sign

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 $\pi\omega$ FF but sign unknown

- positive $\pi\omega$ form factor
- no pion pole
- negative $\pi\omega$ form factor

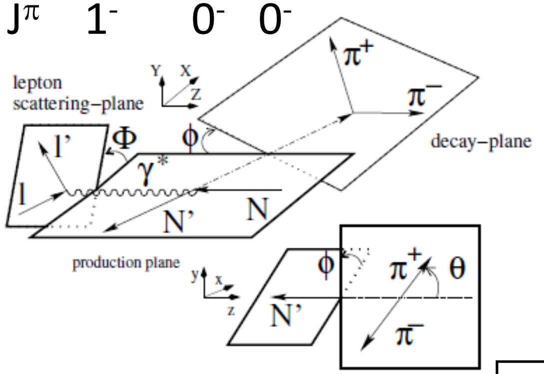
ω is more promising (see the larger scale)
but there is the inherent pion pole contribution

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:

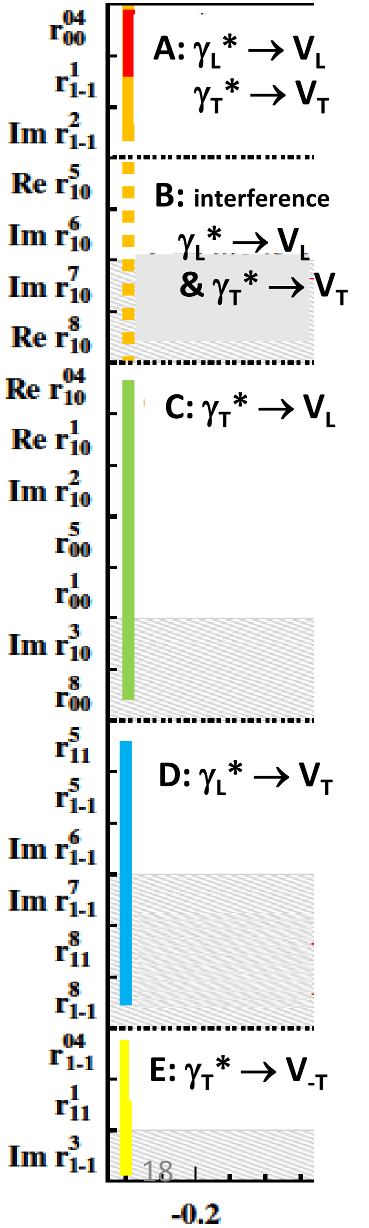
$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + P_b\mathcal{W}^{L}(\Phi,\phi,\cos\Theta)$$

15 'unpolarized' and 8 'polarized' SDMEs

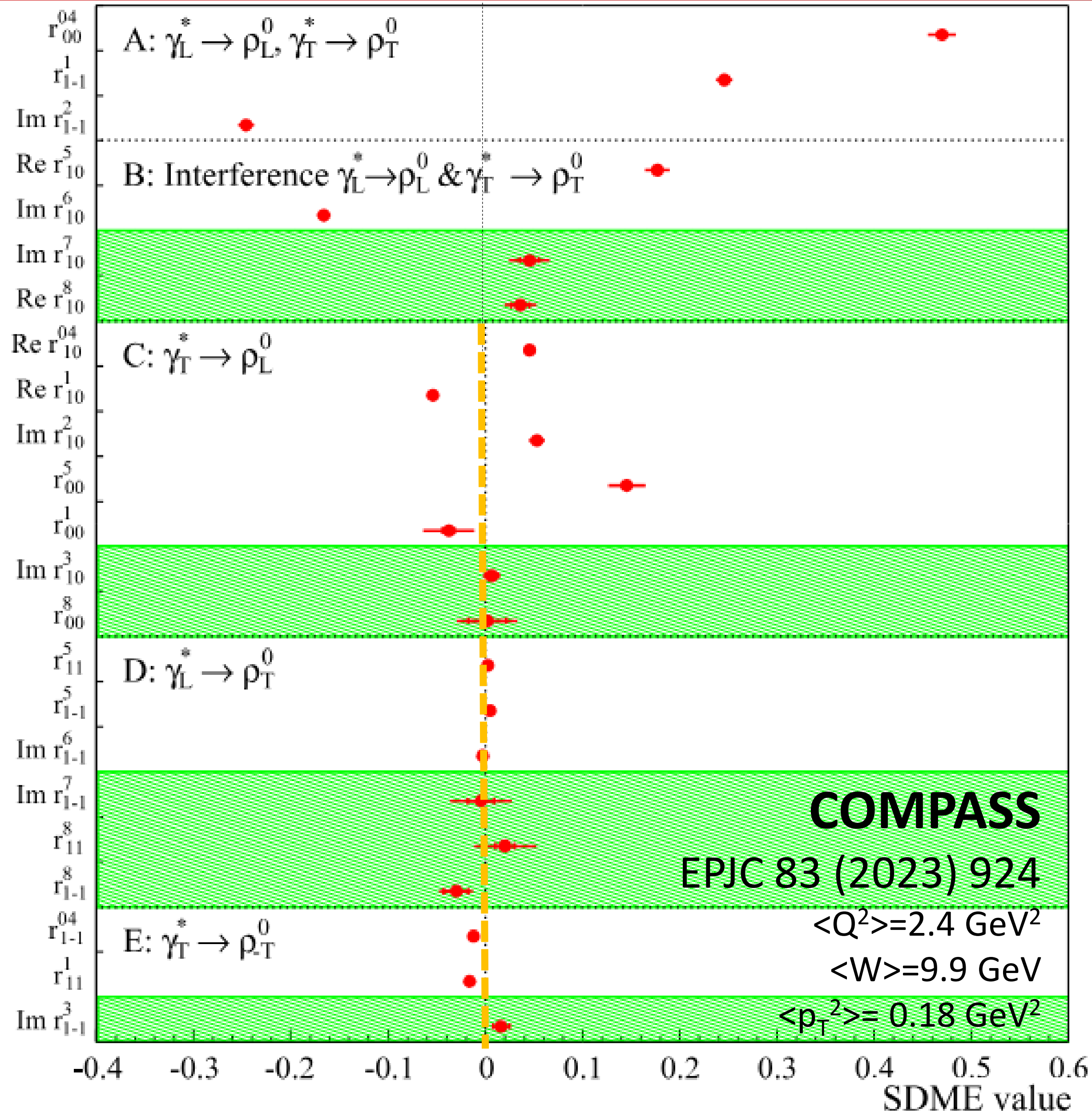
$$\begin{aligned}\mathcal{W}^{U}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[&\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi\\ &-\epsilon\cos 2\Phi\left(r^1_{11}\sin^2\Theta + r^1_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^1_{10}\}\sin 2\Theta\cos\phi - r^1_{1-1}\sin^2\Theta\cos 2\phi\right)\\ &-\epsilon\sin 2\Phi\left(\sqrt{2}\mathrm{Im}\{r^2_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^2_{1-1}\}\sin^2\Theta\sin 2\phi\right)\\ &+\sqrt{2\epsilon(1+\epsilon)}\cos\Phi\left(r^5_{11}\sin^2\Theta + r^5_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^5_{10}\}\sin 2\Theta\cos\phi - r^5_{1-1}\sin^2\Theta\cos 2\phi\right)\\ &+\sqrt{2\epsilon(1+\epsilon)}\sin\Phi\left(\sqrt{2}\mathrm{Im}\{r^6_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^6_{1-1}\}\sin^2\Theta\sin 2\phi\right)\Bigg],\end{aligned}$$

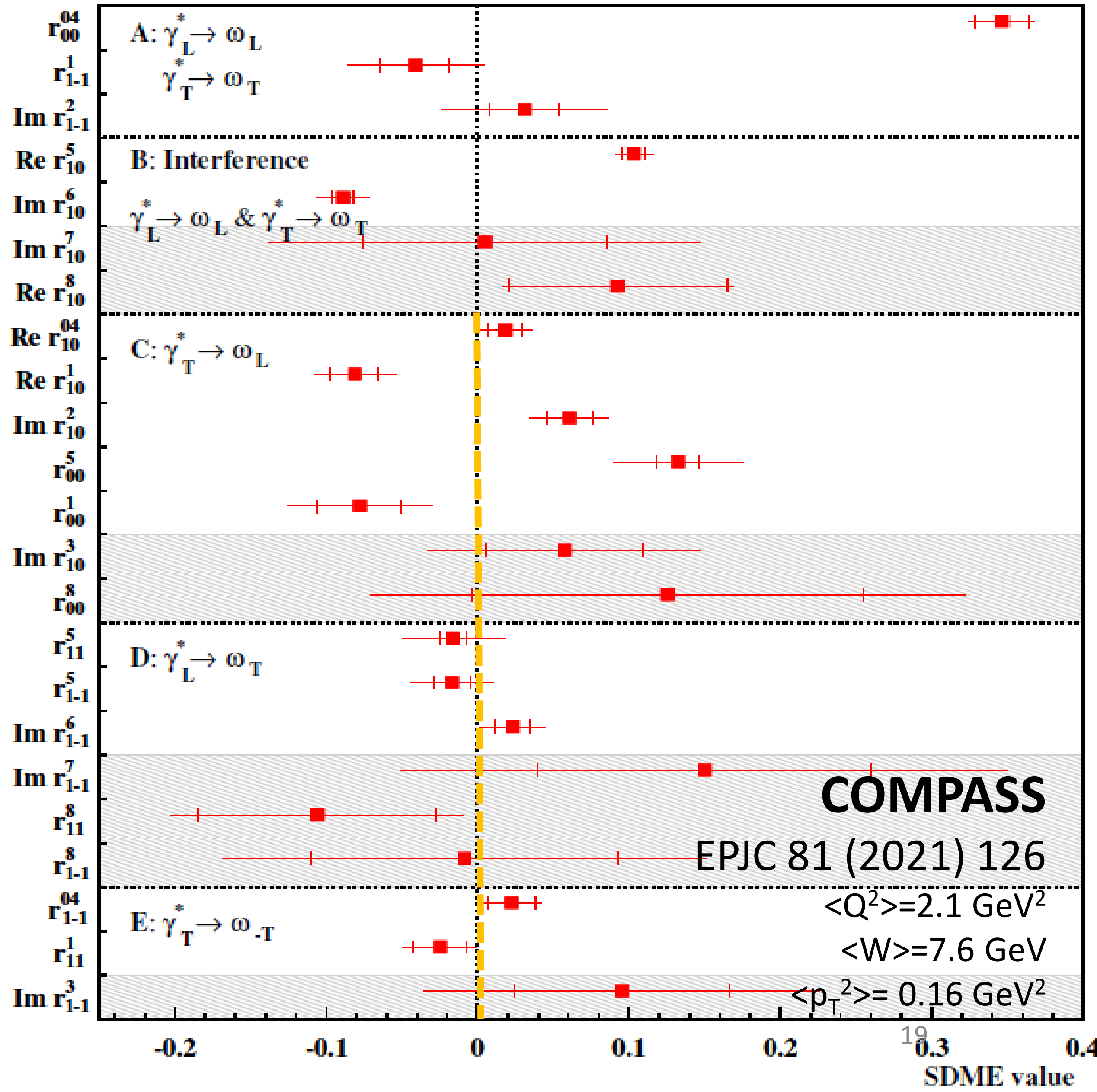
$$\begin{aligned}\mathcal{W}^{L}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[&\sqrt{1-\epsilon^2}\left(\sqrt{2}\mathrm{Im}\{r^3_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^3_{1-1}\}\sin^2\Theta\sin 2\phi\right)\\ &+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\left(\sqrt{2}\mathrm{Im}\{r^7_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^7_{1-1}\}\sin^2\Theta\sin 2\phi\right)\\ &+\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi - r^8_{1-1}\sin^2\Theta\cos 2\phi\right)\Bigg]\end{aligned}$$

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

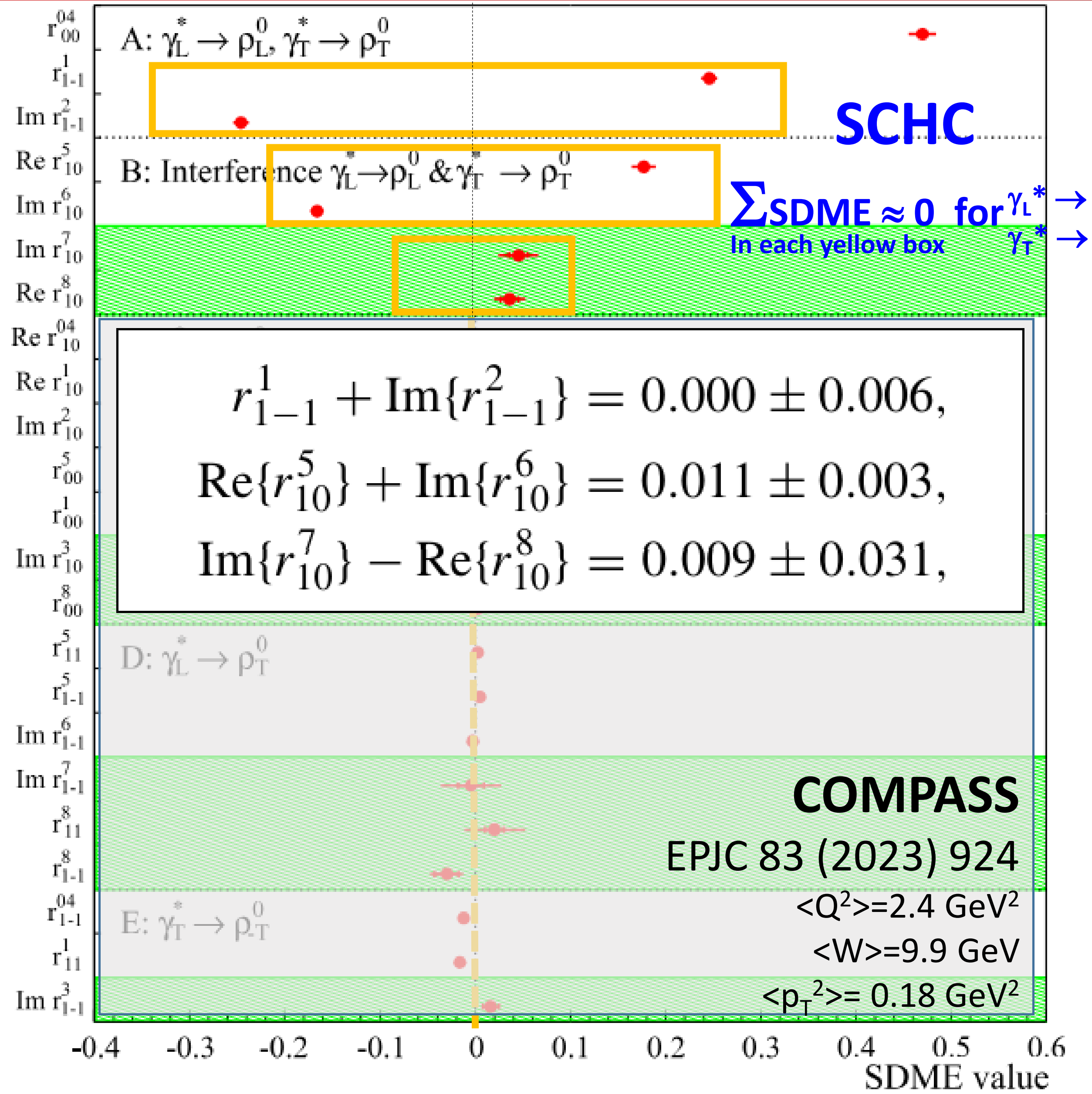


COMPASS 2012 Exclusive ρ^0 and ω production on unpolarized proton

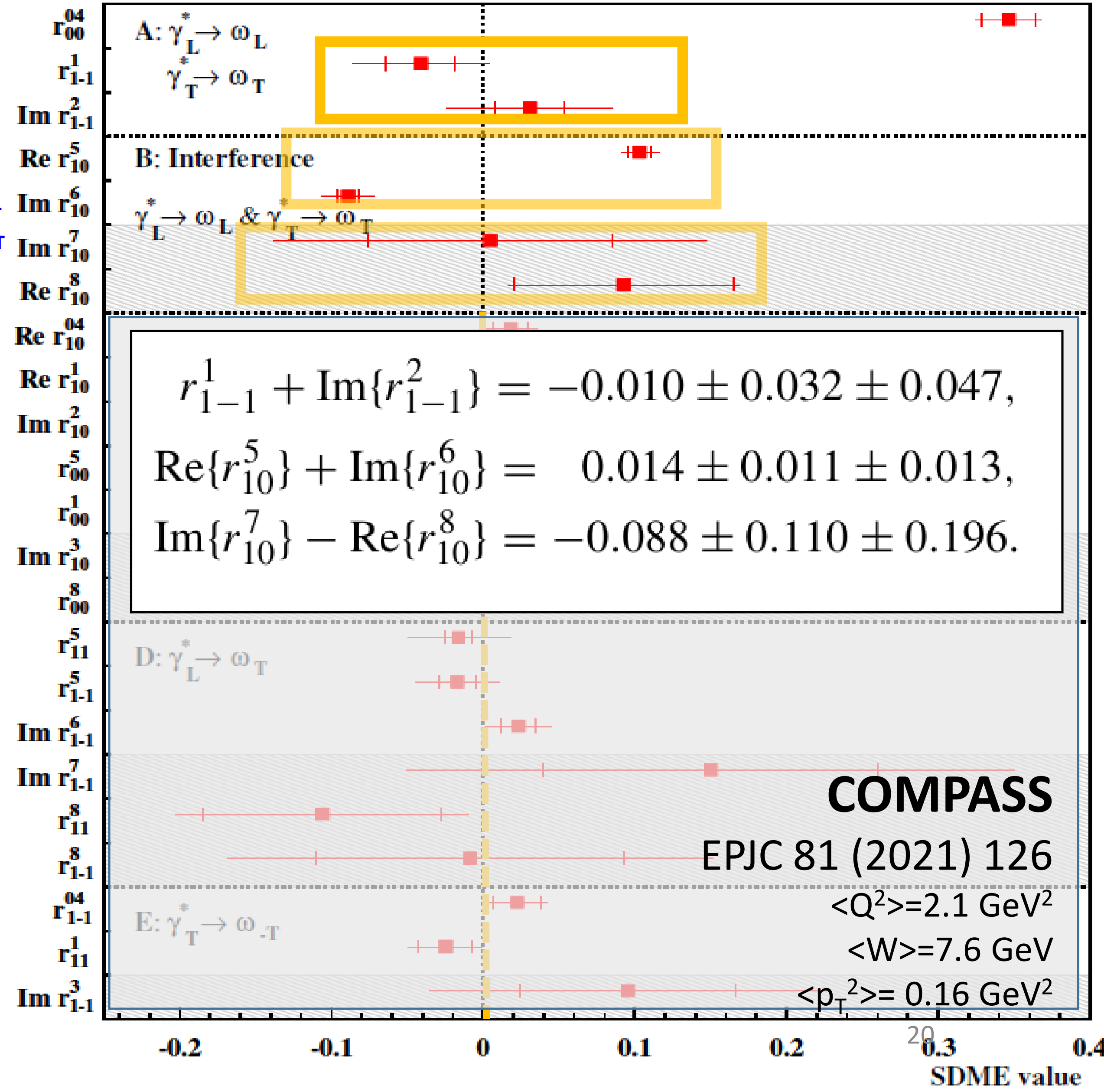




COMPASS 2012 Exclusive ρ^0 and ω production on unpolarized proton

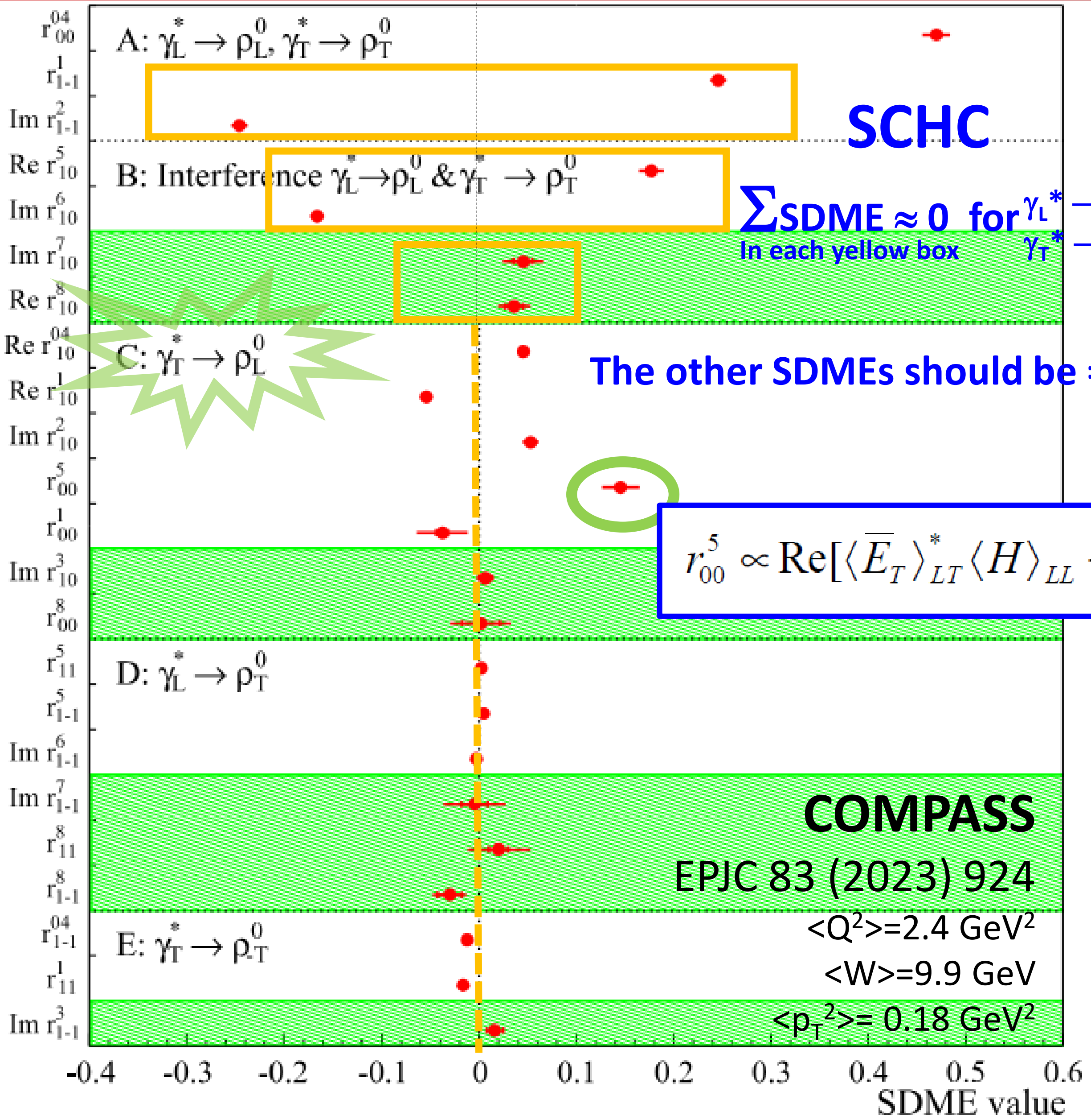


$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0.000 \pm 0.006,$$
$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0.011 \pm 0.003,$$
$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0.009 \pm 0.031,$$



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

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

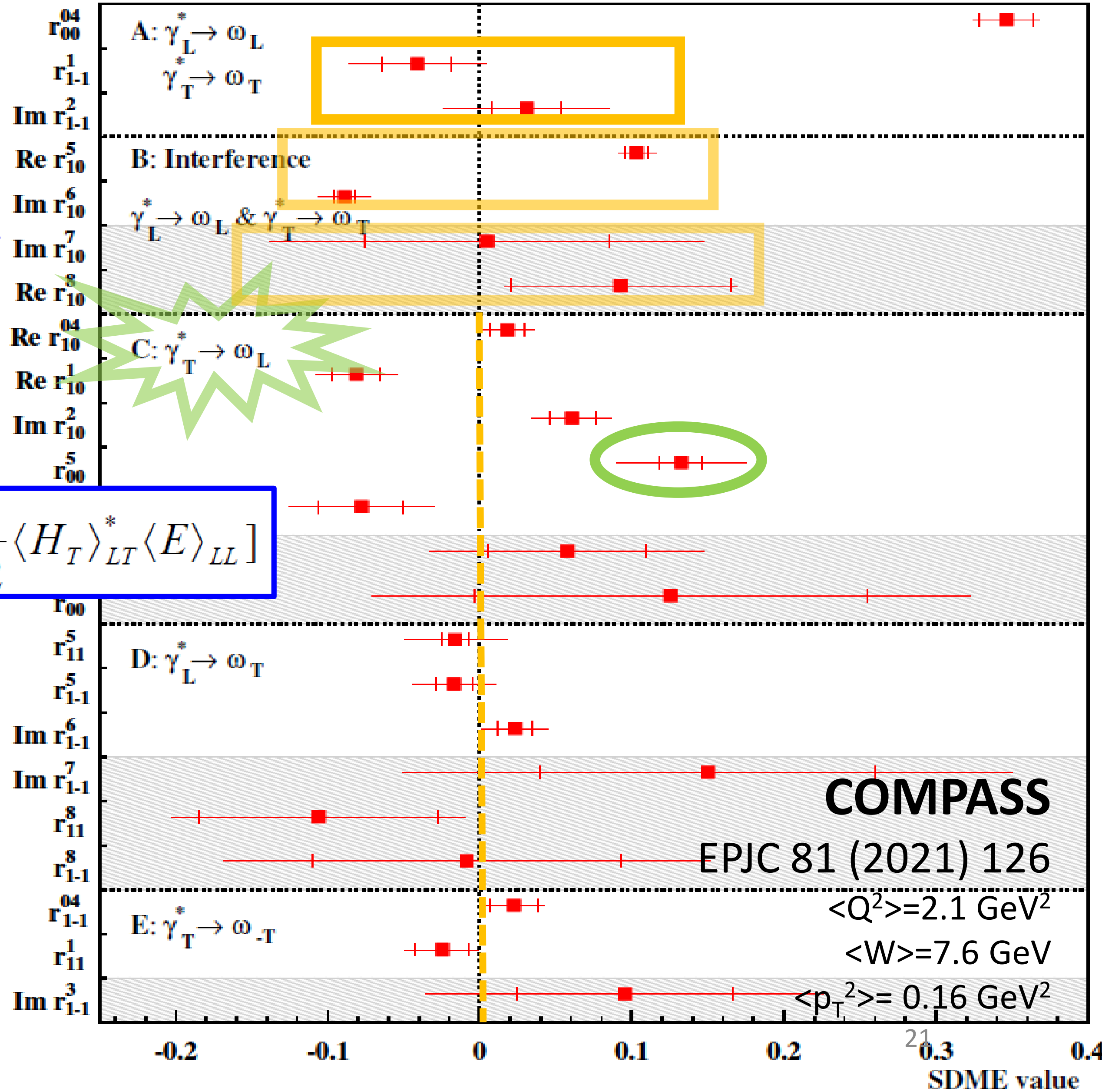


ΣSDME ≈ 0 for $\gamma_L^* \to V_L$, $\gamma_T^* \to V_T$

In each yellow box

The other SDMEs should be =0

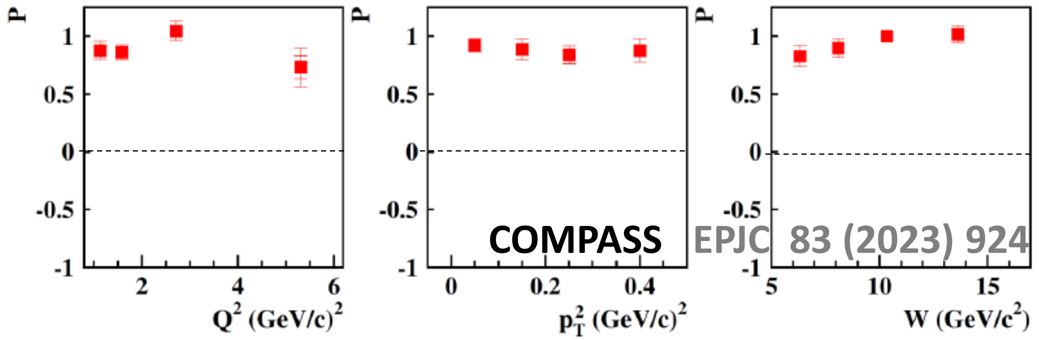
$$r^5_{00} \propto \mathrm{Re}[\langle \overline{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$$

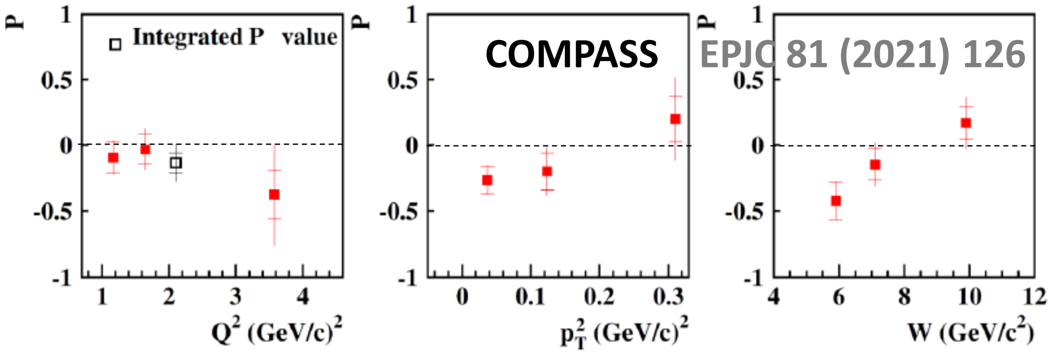


COMPASS 2012 Comparison ρ^0 and ω production

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

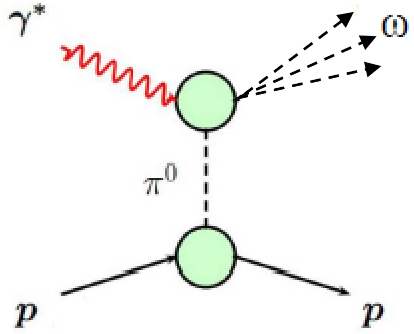
$$P = \frac{2r^1_{1-1}}{1 - r^{04}_{00} - 2r^{04}_{1-1}} \approx \frac{d\sigma^N_T(\gamma^*_T \to V_T) - d\sigma^U_T(\gamma^*_T \to V_T)}{d\sigma^N_T(\gamma^*_T \to V_T) + d\sigma^U_T(\gamma^*_T \to V_T)}$$



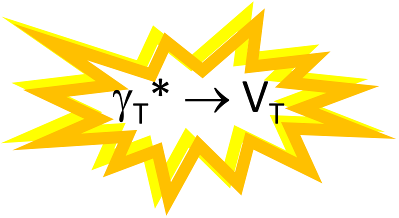


The pion pole exchange (UPE) is large for ω compared to ρ^0

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

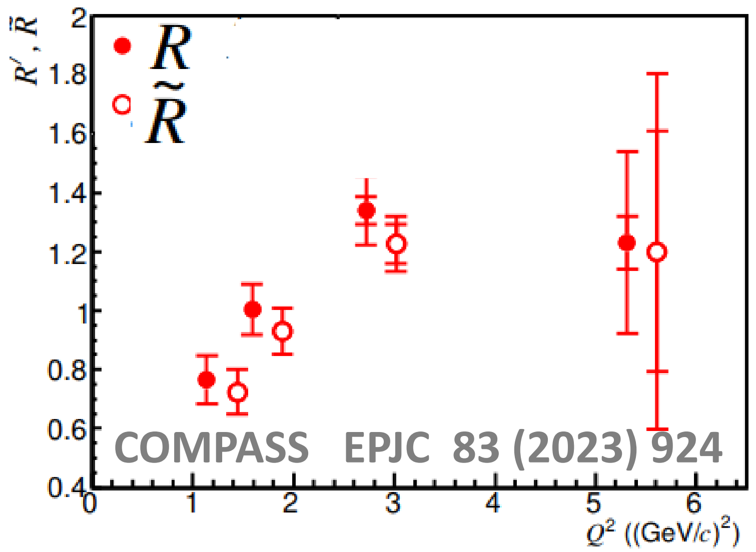
COMPASS 2012 $R = \sigma_L/\sigma_T$ for exclusive ρ^0 production

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

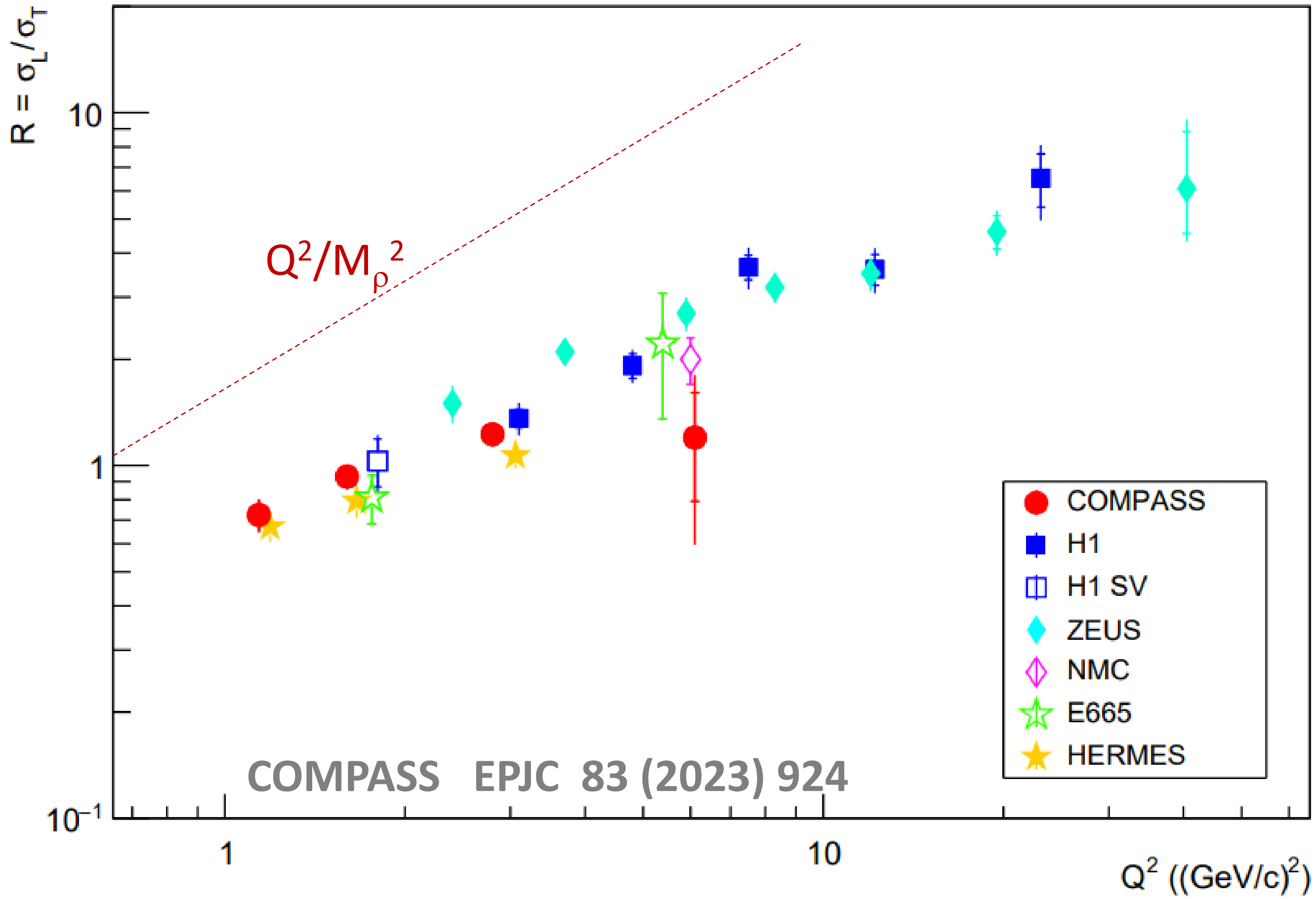
$$R = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$ **only if SCHC**

In COMPASS domain evaluation of **R** and

$\tilde{\mathbf{R}}$ considering violation of SCHC (and only NPE)



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



Deviations from the pQCD LO prediction in Q^2/M_ρ^2 due to QCD evolution and q_T

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

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

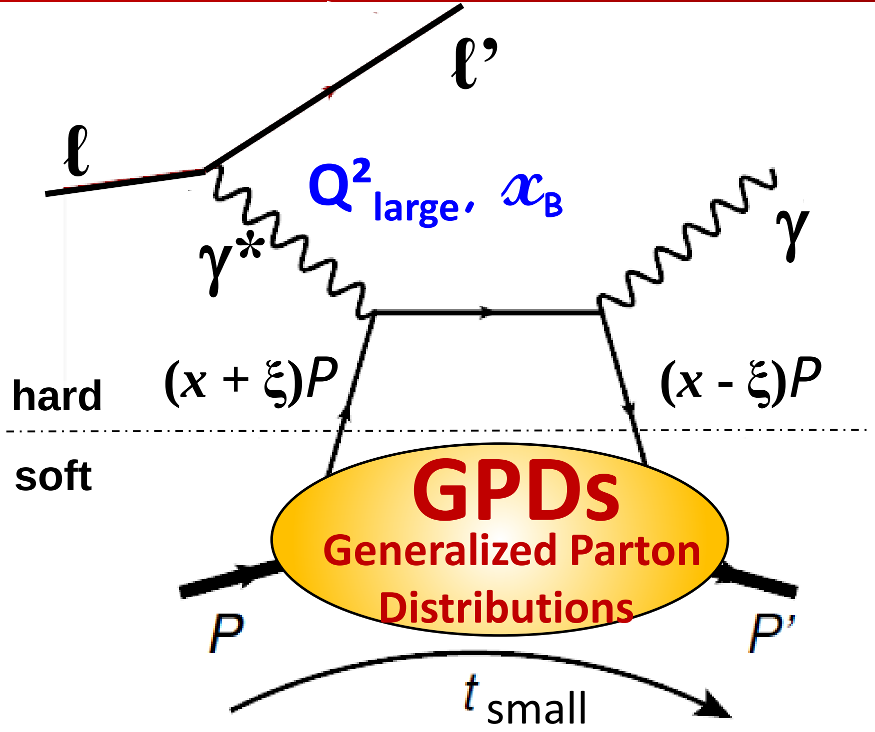
- ✓ **Cross section** or **SDME** for HEMP of π^0, ρ^0, ω, ϕ, J/ψ
  - ✓ Transversity GPDs
  - ✓ Gluon GPDs
  - ✓ Flavor decomposition

Thank You for Your Attention

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)

Factorization



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
ξ: transferred
} quark longitudinal momentum fraction

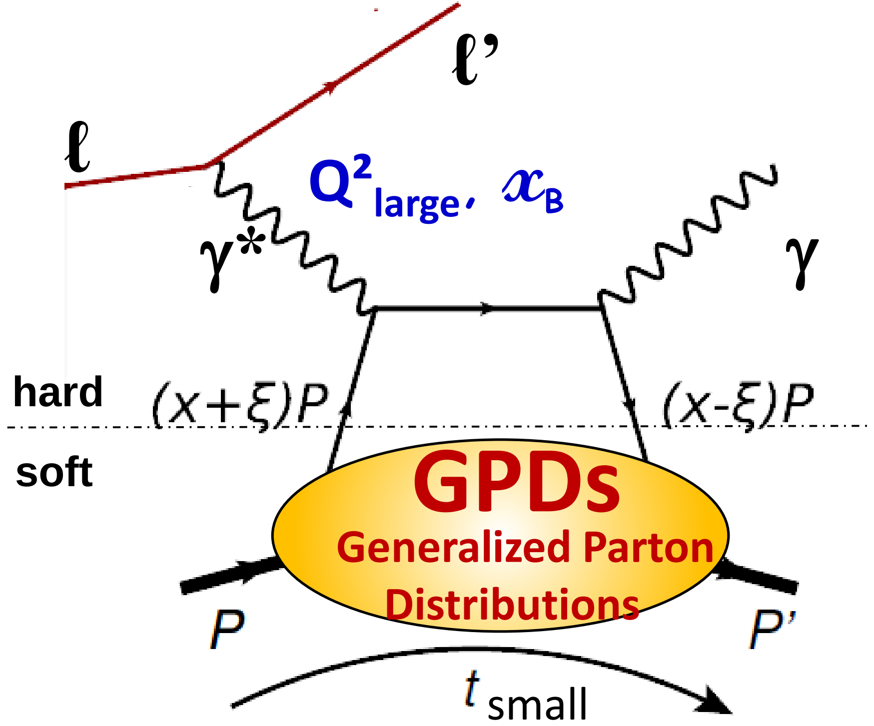
t: proton momentum transfer squared
related to $b_\perp$ via Fourier transform

Q²: virtuality of the virtual photon

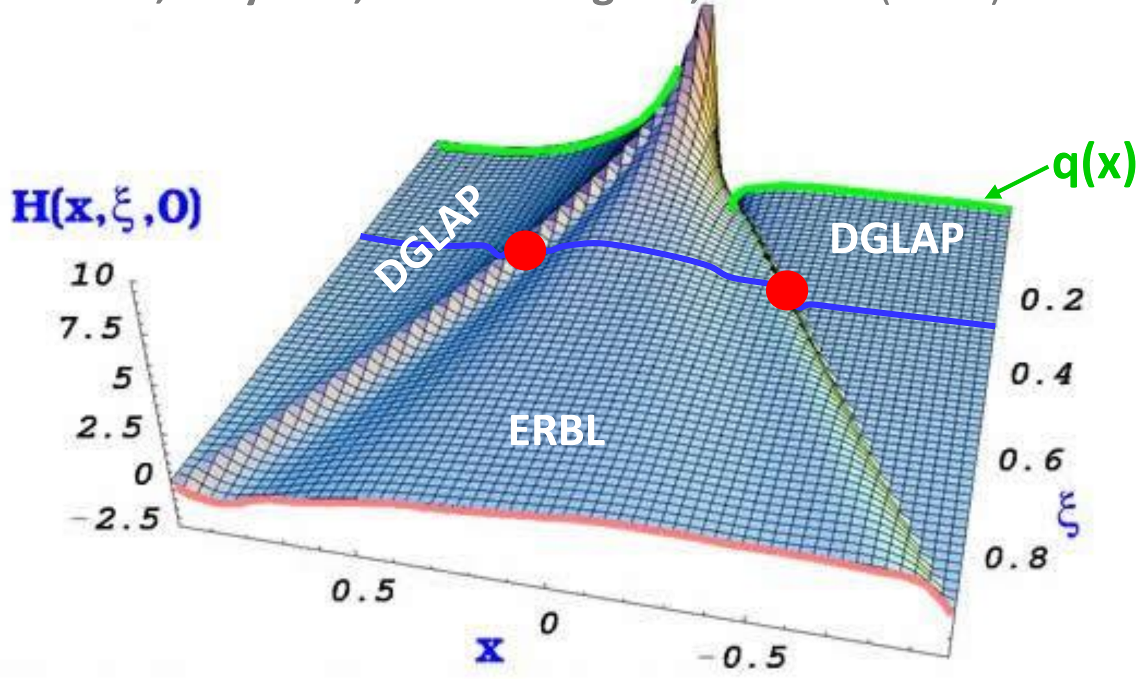
The variables measured in the experiment:

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)



Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



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 $\mathcal{H}$

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

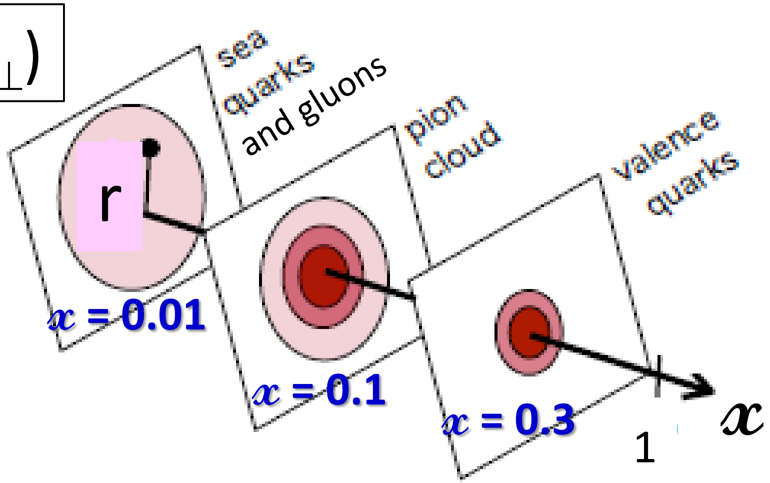
Deeply virtual Compton scattering (DVCS)

M. Burkardt, PRD66(2002)

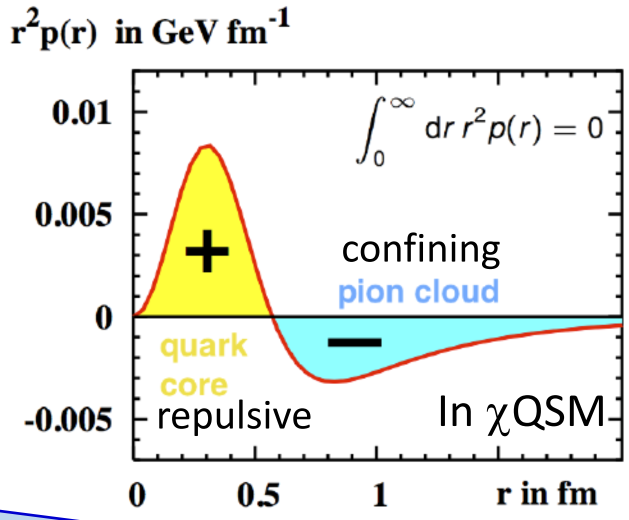
M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

Mapping in the transverse plane

$q(x, b_\perp)$



Pressure Distribution



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

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 $\mathcal{H}$

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

$d_1(t)$ D-term

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

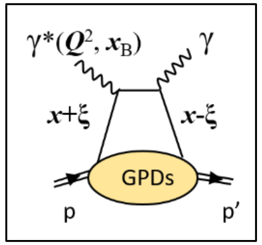
$$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS} \propto (Im\mathcal{H})^2$$

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

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

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

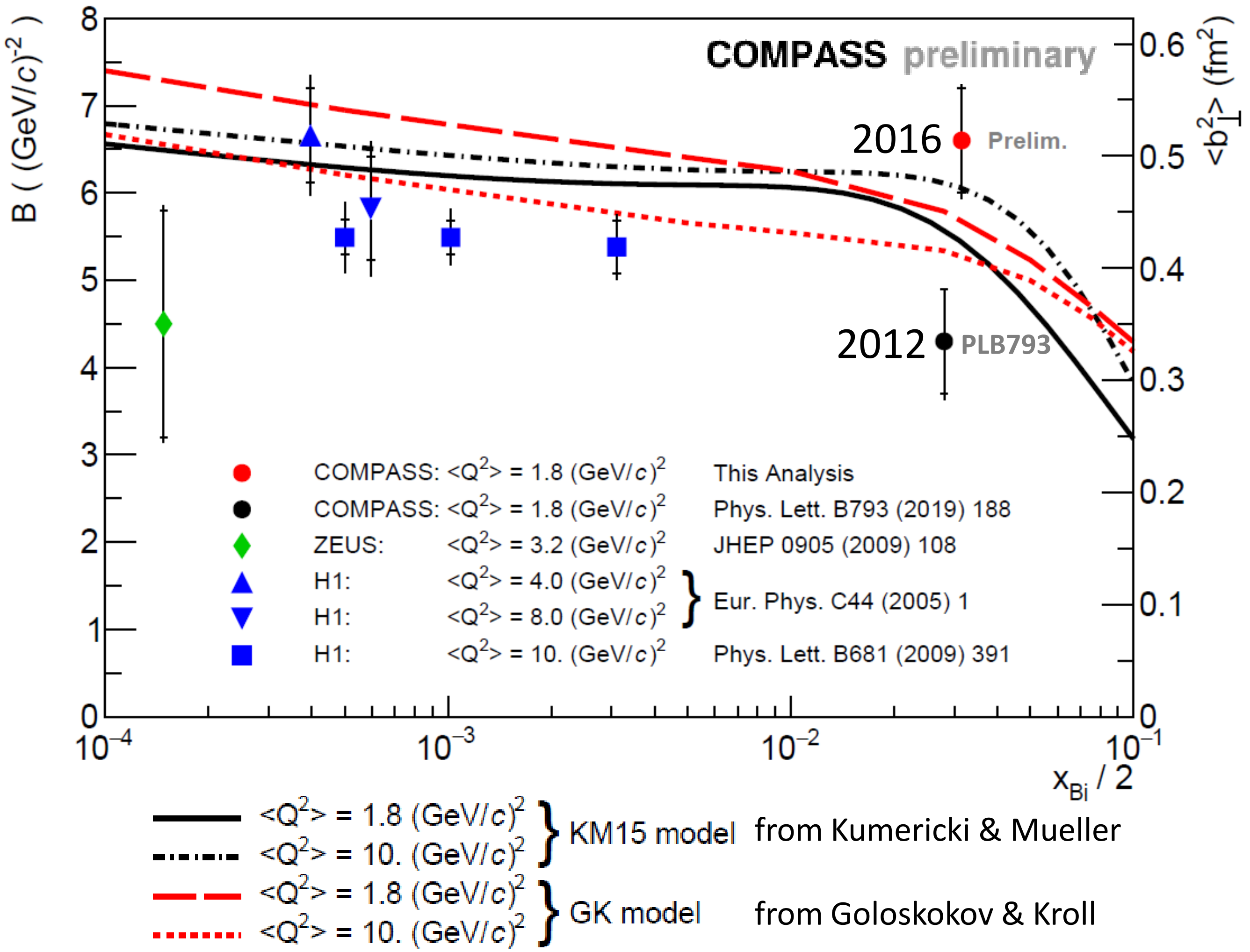
$x = \xi \approx x_B/2$ close to 0



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

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

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



COMPASS 2016 Exclusive π^0 production on unpolarized proton

$$\frac{\mathrm{d}^2\sigma_{\gamma^* p}^{\leftrightarrows}}{\mathrm{d}t\mathrm{d}\phi} = \frac{1}{2\pi}\left[\frac{\mathrm{d}\sigma_\mathrm{T}}{\mathrm{d}t} + \epsilon\frac{\mathrm{d}\sigma_\mathrm{L}}{\mathrm{d}t} + \epsilon\cos(2\phi)\frac{\mathrm{d}\sigma_\mathrm{TT}}{\mathrm{d}t} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\frac{\mathrm{d}\sigma_\mathrm{LT}}{\mathrm{d}t} \mp |P_l|\sqrt{2\epsilon(1-\epsilon)}\sin\phi\frac{\mathrm{d}\sigma'_\mathrm{LT}}{\mathrm{d}t}\right]$$

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

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

$$\frac{\mathrm{d}\sigma_\mathrm{TT}}{\mathrm{d}t} \propto t'|\langle\overline{E}_\mathrm{T}\rangle|^2,$$

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

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

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

Comparison ρ⁰ SDMEs at COMPASS and HERMES

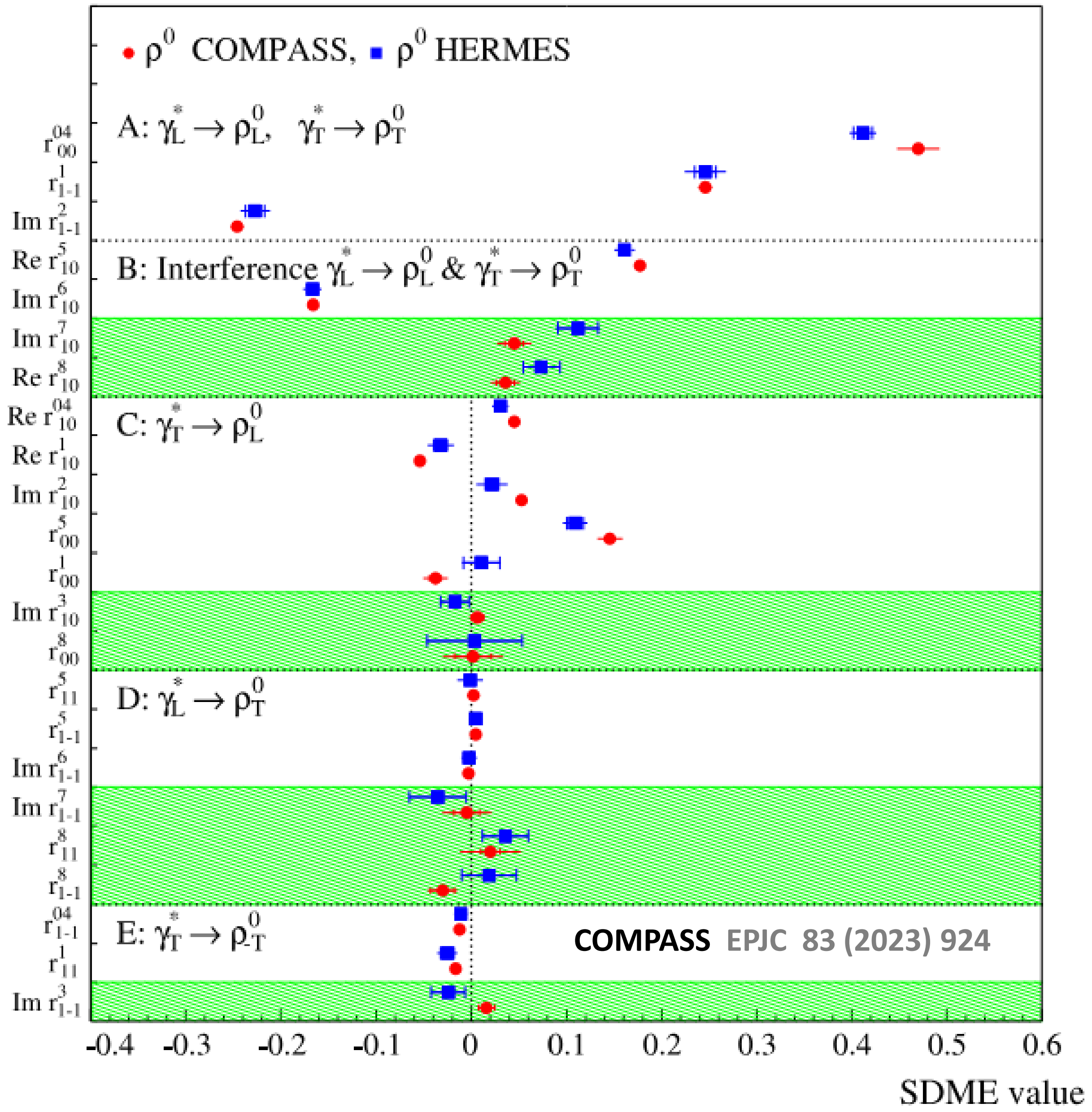


Fig. 12 Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle |t'|\rangle = 0.13$, 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

COMPASS 2012 R = σ_L/σ_T for exclusive ρ^0 production

$$\widetilde{R} = R' - \frac{\eta(1+\epsilon R')}{\epsilon(1+\eta)}, \tag{44}$$

where

$$\eta = \frac{(1+\epsilon R')}{N}\widetilde{\sum}\{|T_{01}|^2 + |U_{01}|^2 - 2\epsilon(|T_{10}|^2 + |U_{10}|^2)\}. \tag{45}$$

The quantity η can be approximately estimated as

$$\eta \approx (1+\epsilon R')(\tau_{01}^2 - 2\epsilon\tau_{10}^2). \tag{46}$$

For the amplitude T_{01} describing the transition $\gamma_T^* \to \rho_L^0$ the quantity τ_{01} is given by

$$\tau_{01} \approx \sqrt{\epsilon}\frac{\sqrt{(r_{00}^5)^2 + (r_{00}^8)^2}}{\sqrt{2r_{00}^{04}}}. \tag{31}$$

The quantity τ_{10}, which is related to the amplitude T_{10} describing the transition $\gamma_L^* \to \rho_T^0$, is approximated by

$$\tau_{10} \approx \frac{\sqrt{(r_{11}^5 + \mathrm{Im}\{r_{1-1}^6\})^2 + (\mathrm{Im}\{r_{1-1}^7\} - r_{11}^8)^2}}{\sqrt{2(r_{1-1}^1 - \mathrm{Im}\{r_{1-1}^2\})}}. \tag{32}$$