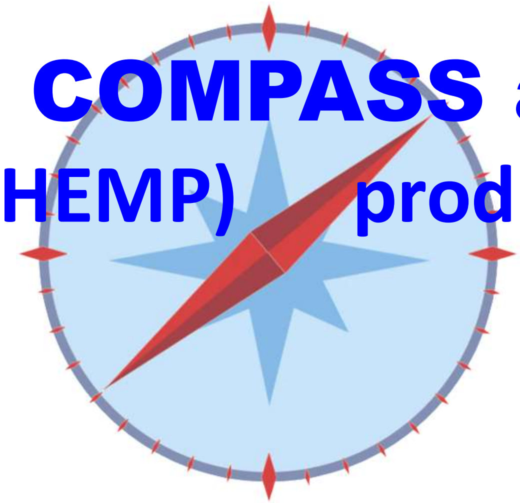
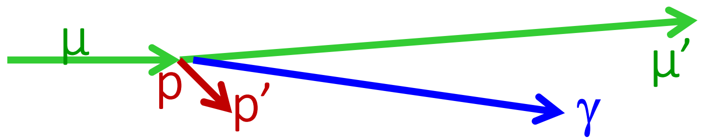
# Hard Exclusive Reactions at COMPASS at CERN

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



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 $\omega$ or …

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

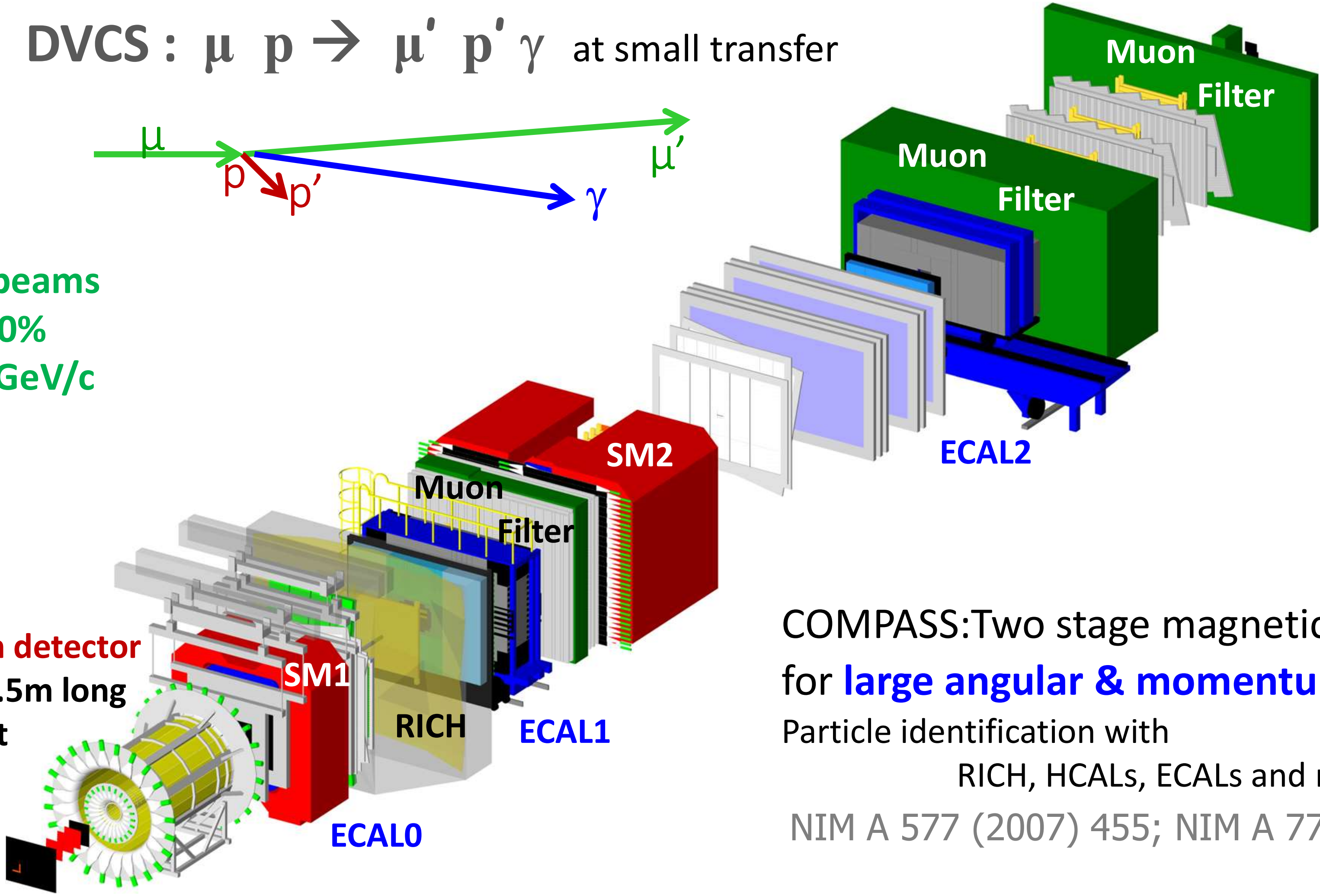
FONDAZIONE BRUNO KESSLER
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Opportunities with JLab Energy and Luminosity Upgrade

Trento, 26-30 September 2022

# Measurement of exclusive cross sections at COMPASS

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

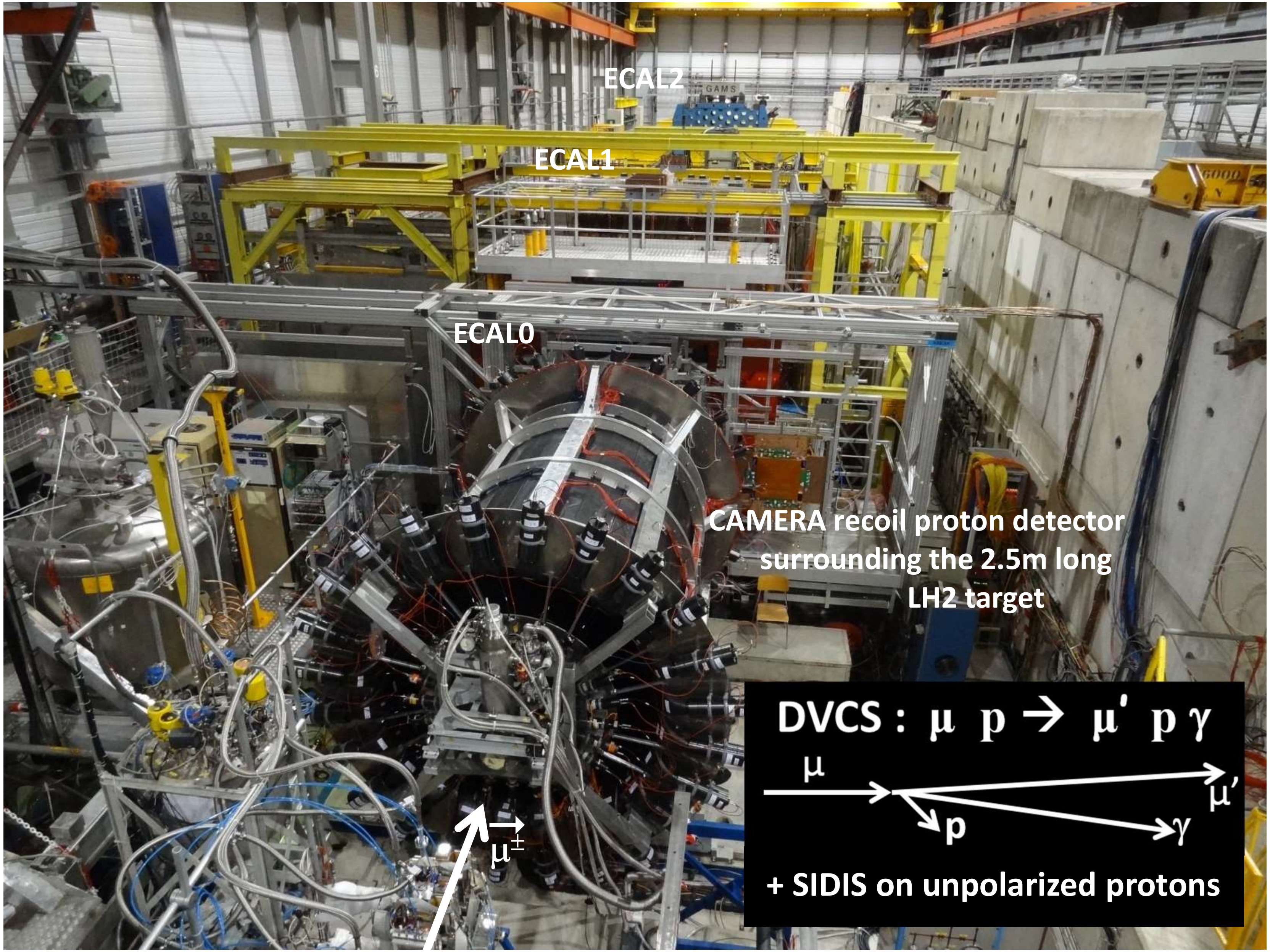



**Both $\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ beams**
**Polarisation ~ ±80%**
**Momentum 160 GeV/c**

**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

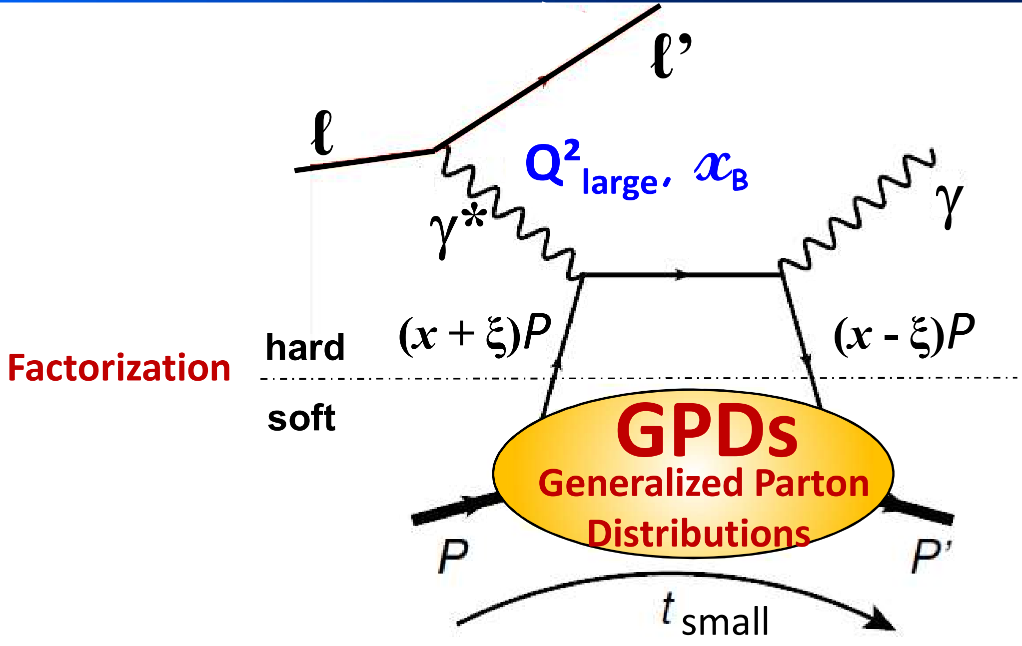
NIM A 577 (2007) 455; NIM A 779 (2015) 69




**2012:**
1 month pilot run

**2016 -17:**
2 x 6 month
data taking

# Deeply virtual Compton scattering (DVCS)




**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
ξ: transferred
} quark longitudinal momentum fraction

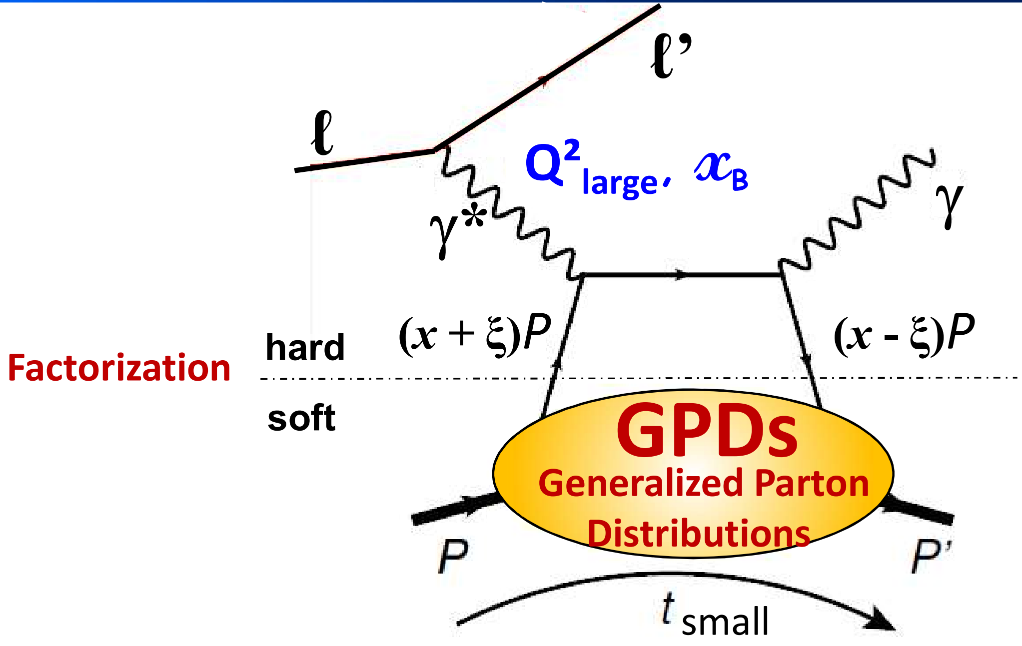
t: proton momentum transfer squared
related to $b_\perp$ via Fourier transform

$Q^2$: virtuality of the virtual photon

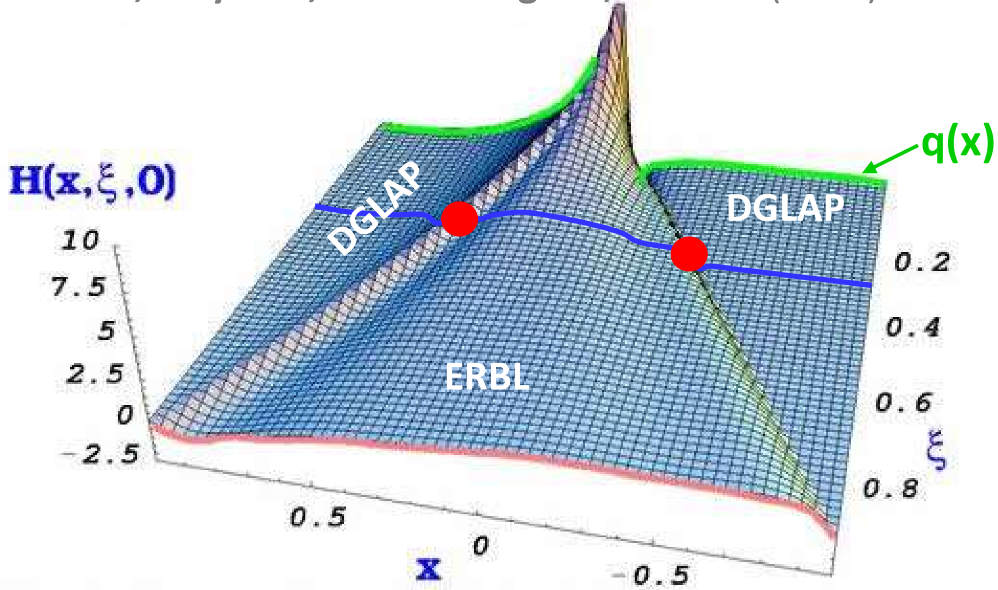
The variables measured in the experiment:

$E_\ell$, $Q^2$, $x_B \sim 2\xi/(1+\xi)$,
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 $\alpha_S$ (GPD **H**) :

Real part   Imaginary part

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

In an experiment we measure

Compton Form Factor $\mathcal{H}$

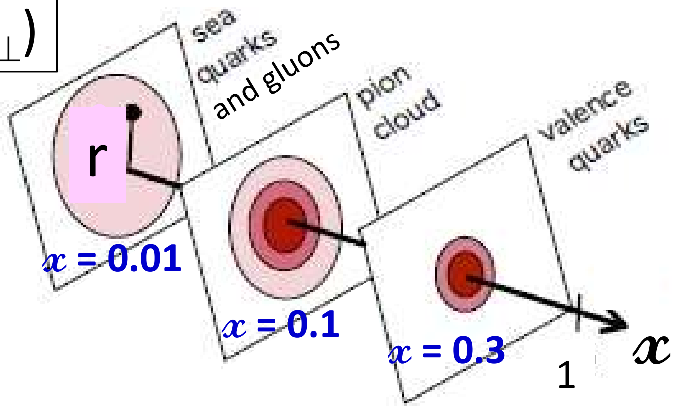
# Deeply virtual Compton scattering (DVCS)

**M. Burkardt**, PRD66(2002)

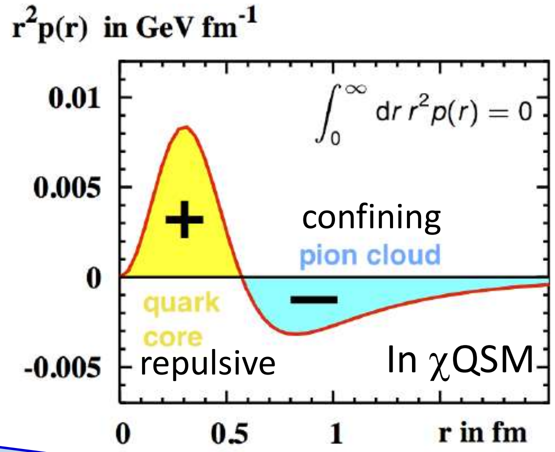
**M. Polyakov, P. Schweitzer**, Int.J.Mod.Phys. A33 (2018)

## Mapping in the transverse plane

$q(x, b_\perp)$




## Pressure Distribution




FT of H(x, ξ=0,t)

The amplitude DVCS at LT & LO in $\alpha_s$ (GPD **H**) :

**Real part** **Imaginary part**

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

In an experiment we measure

Compton Form Factor $\mathcal{H}$

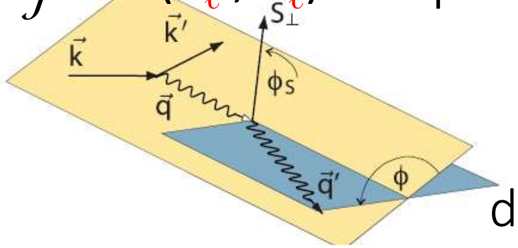
$$\mathcal{R}e\mathcal{H}(\xi,t) = \pi^{-1}\int_0^1 dx\, \frac{2x\; Im\mathcal{H}(x,t)}{x^2-\xi^2} + \Delta(t)$$

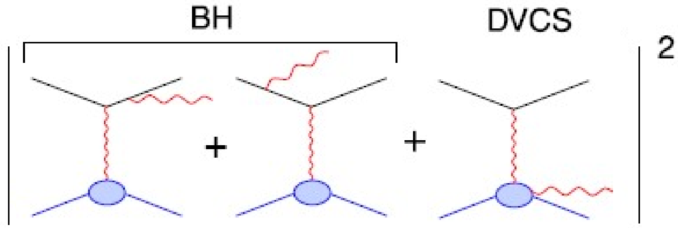
$d_1(t)$

D-term

# Deeply virtual Compton scattering (DVCS)

*lepton* ($P_\ell$ , $e_\ell$) and $\phi$



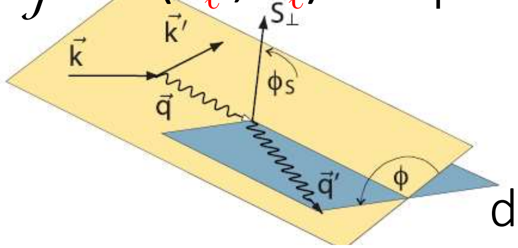

$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2$ + **Interference Term**

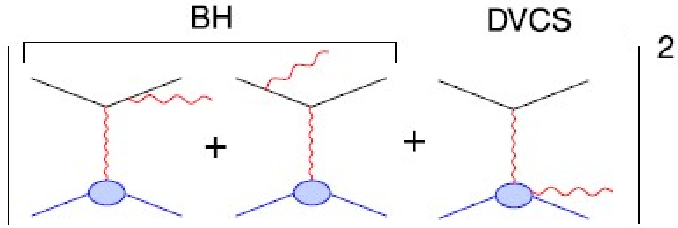
$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_\ell \, d\sigma^{DVCS}_{pol}\right) + \left(e_\ell \mathrm{Re}\, I + e_\ell P_\ell \,\mathrm{Im}\, I\right)$$

Well known

# Deeply virtual Compton scattering (DVCS)

*lepton* ($P_\ell$ , $e_\ell$) and $\phi$

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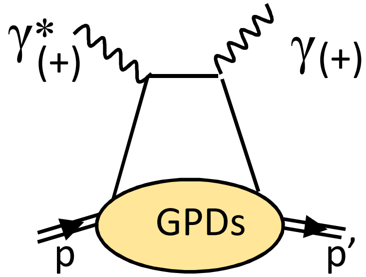
Well known

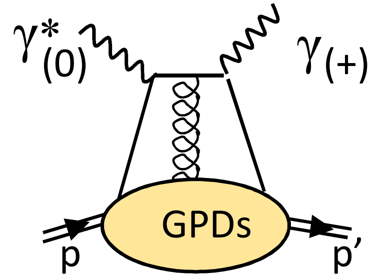
**With unpolarized target:**

**Belitsky, Müller, Kirner,** NPB629 (2002)

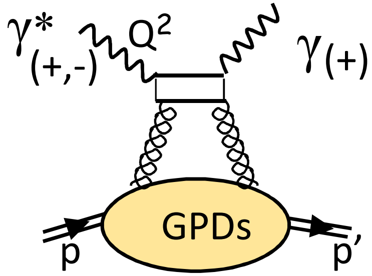
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$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




**LO,Twist-2**



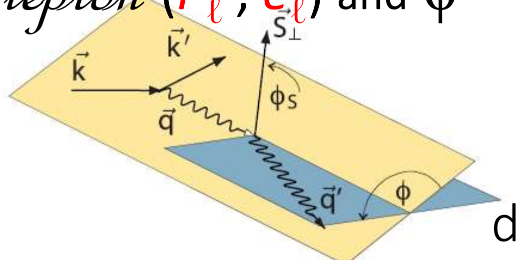

**HT,Twist-3**
suppressed by 1/Q

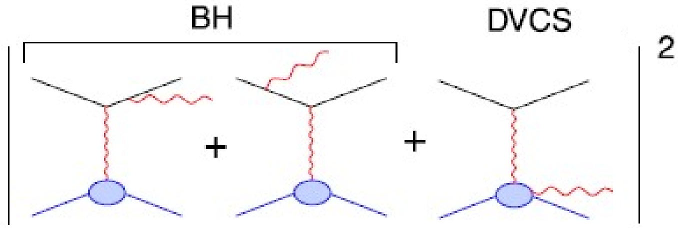



**NLO,Twist-2**
**double helicity flip**
suppressed by $\alpha_S$

# Deeply virtual Compton scattering (DVCS)

*lepton* ($P_\ell$ , $e_\ell$) and $\phi$




$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2 +$ 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 both $\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ beams we can build:**

**❶ beam charge-spin sum**

$$\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

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

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

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

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

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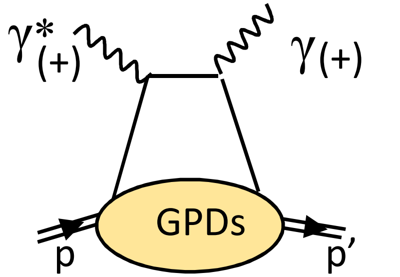
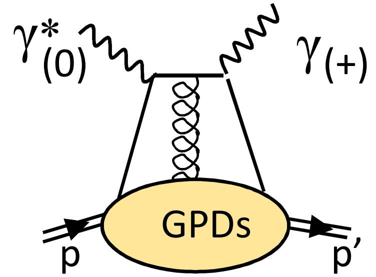
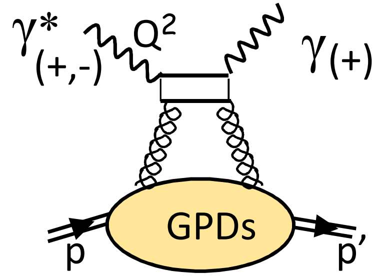



**LO,Twist-2**




**HT,Twist-3**

suppressed by 1/Q



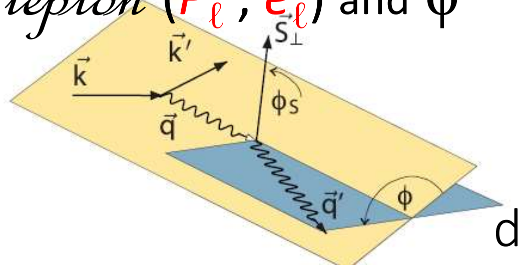

**NLO,Twist-2**

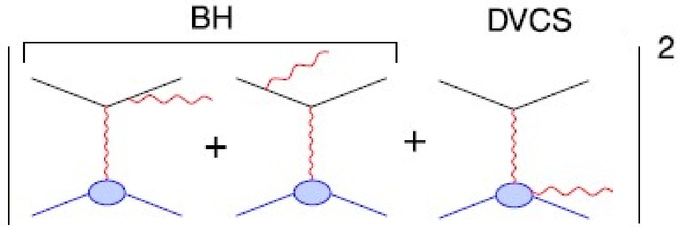
**double helicity flip**

suppressed by $\alpha_S$

# Deeply virtual Compton scattering (DVCS)

*lepton* ($P_\ell$ , $e_\ell$) and $\phi$

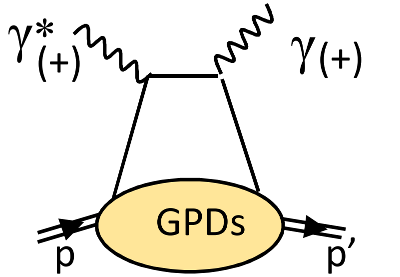


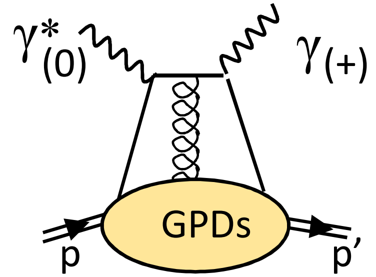



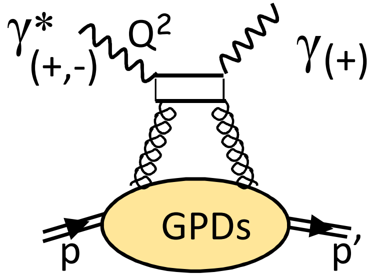

$$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2 + \text{Interference Term}$$

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

Well known




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

**❶ beam charge-spin sum**

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

**❷ difference**

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

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

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

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

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

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

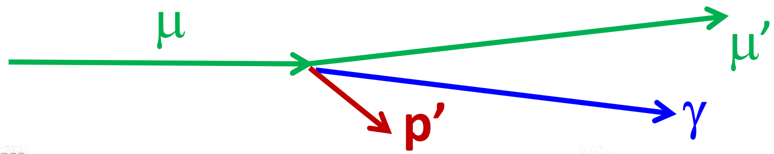
$s_1^I \propto \mathrm{Im}\,\mathcal{F}$

$c_1^I \propto \mathrm{Re}\,\mathcal{F}$

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

# COMPASS 2016 data Selection of exclusive single photon production

Comparison between the observables given by the spectro or by CAMERA



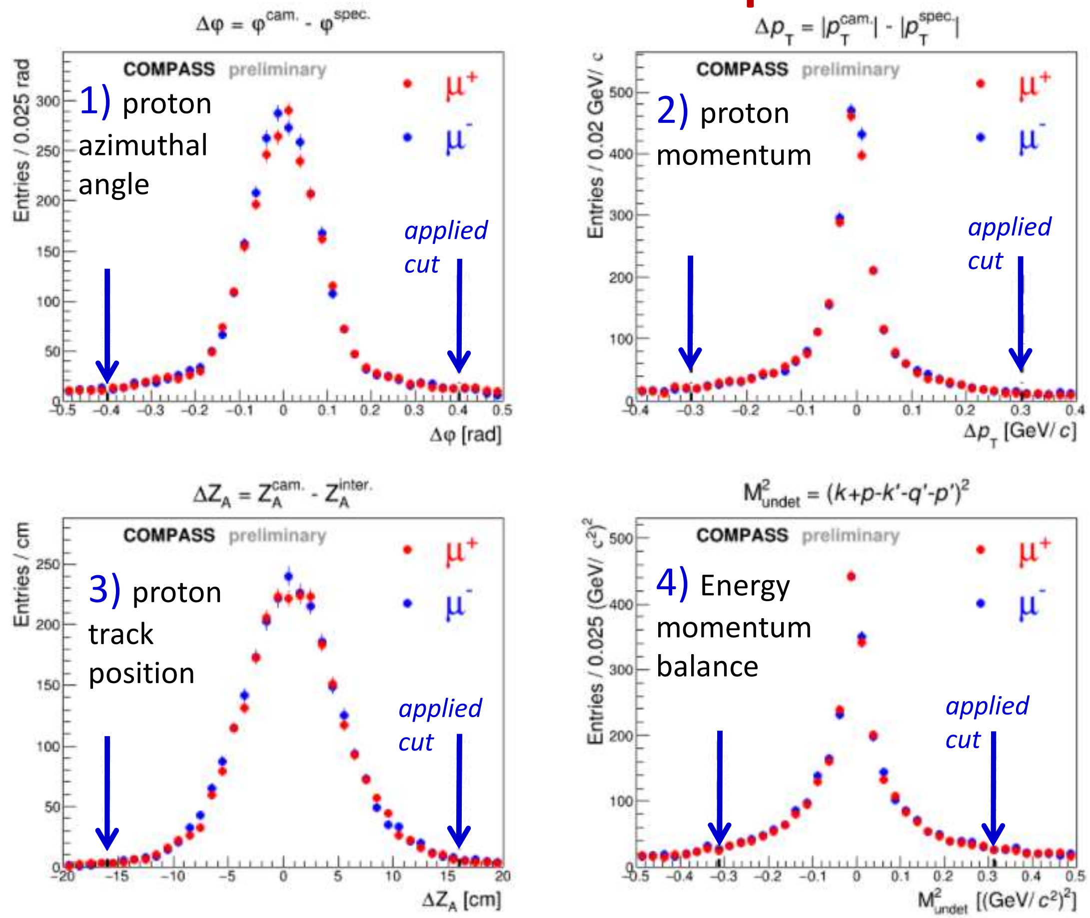

**DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$**

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



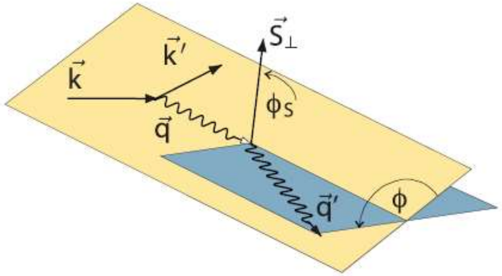

Good agreement between $\overleftarrow{\mu}^{+}$ **and** $\overrightarrow{\mu}^{-}$ yields

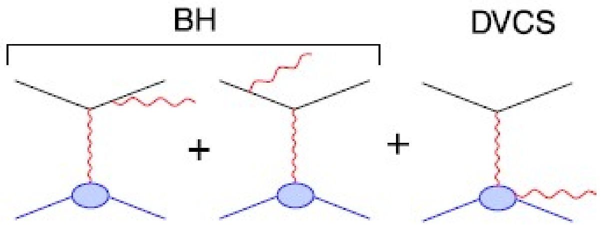
Important achievement for:

❶ $\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$ Easier, done first

❷ $\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$ Challenging, but promising

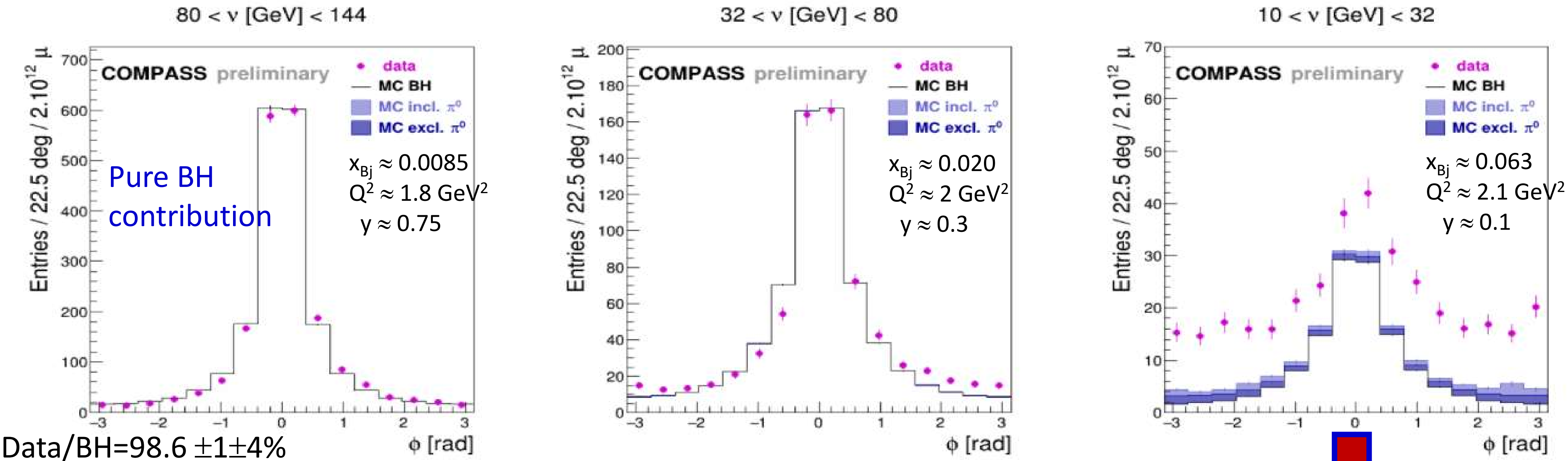
# COMPASS 2016 data DVCS+BH cross section at $E_\mu$=160 GeV




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

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




Data/BH=98.6 ±1±4%

MC: BH contribution evaluated for the integrated luminosity

$\pi^\circ$ 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:

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

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

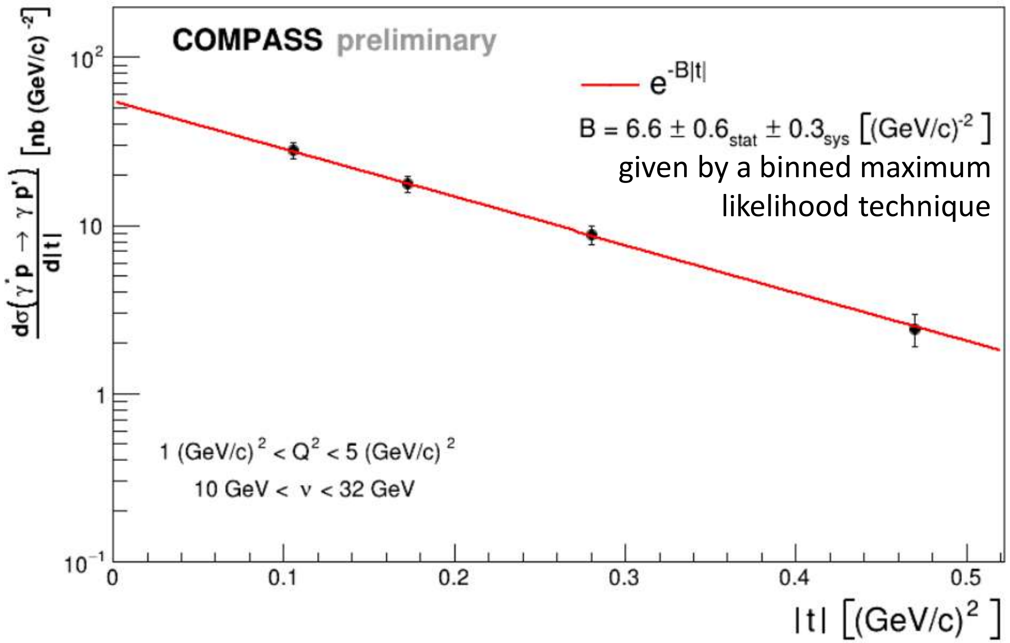
calculable
can be subtracted

All the other terms are cancelled in the integration over $\phi$

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

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

Flux for transverse
virtual photons



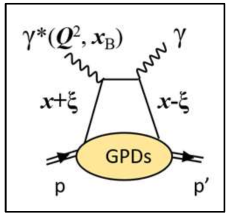
# COMPASS 12-16 Transverse extention of partons in the sea quark range

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

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

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

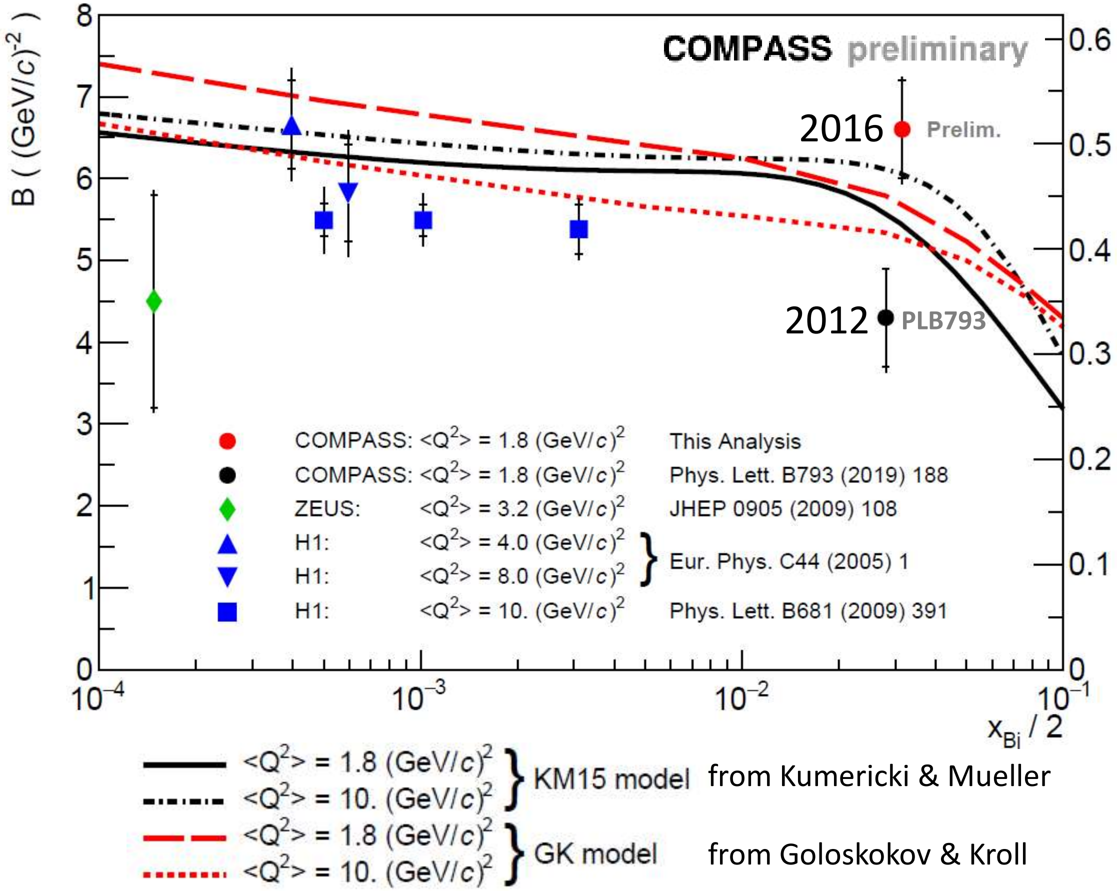
$Im\mathcal{H}$ = ***H*** $(x=\xi, \xi, t)$
$x = \xi \approx x_B/2$ close to 0




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

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

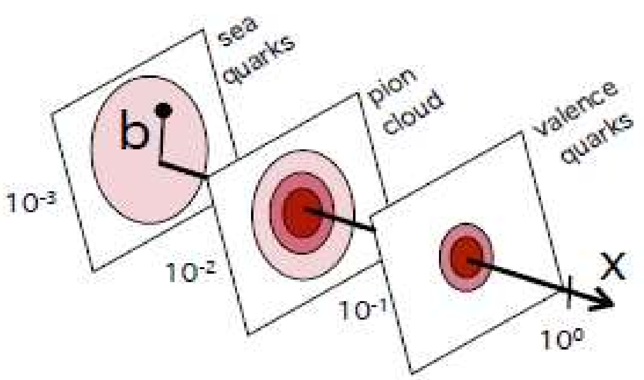
$$\langle b_\perp^2(x) \rangle \approx 2B(\xi)$$



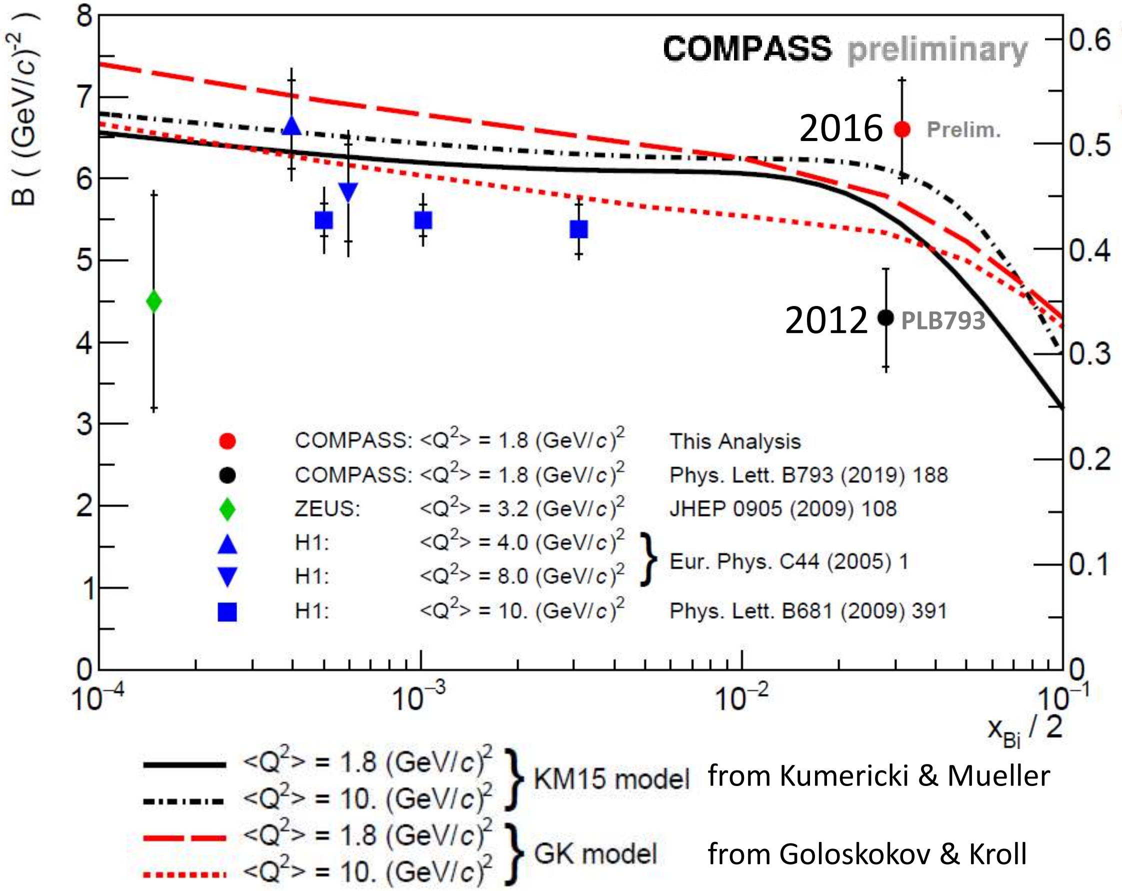
# COMPASS 12-16 Transverse extention of partons in the sea quark range

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

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




2012 statistics = Ref
2016 analysed statistics = 2.3 × Ref
2016+2017 expected statistics = 10 × Ref



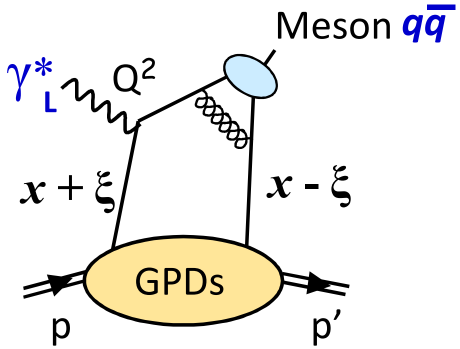

$3\sigma$ difference between 2012 and 2016 data

- more advanced analysis with 2016 data
- $\pi^0$ contamination with different thresholds
- binning with 3 variables $(t,Q^2,\nu)$ or 4 variables $(t,\phi,Q^2,\nu)$

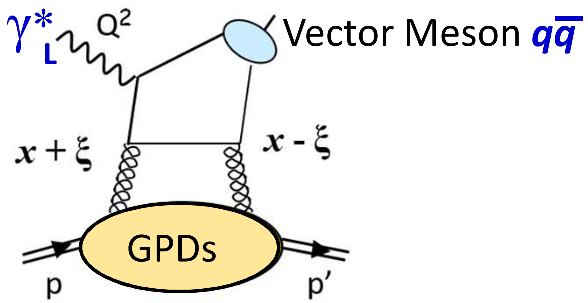
# GPDs and Hard Exclusive Meson Production

**Factorisation proven only for $\sigma_L$**

**Quark contribution**




**Gluon contribution at the same order in $\alpha_s$**




+ Non-perturbative Meson wave function

$$\rho^0 = \left[|u\bar{u}\rangle - |d\bar{d}\rangle\right]/\sqrt{2}$$
$$\omega = \left[|u\bar{u}\rangle + |d\bar{d}\rangle\right]/\sqrt{2}$$

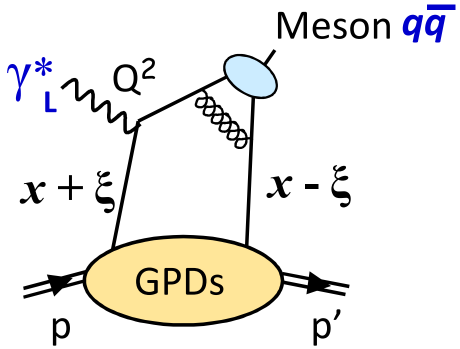
**4** chiral-even GPDs: helicity of parton unchanged

| | | |
|---|---|---|
| $\mathbf{H}^q(x, \xi, t)$ | $\mathbf{E}^q(x, \xi, t)$ (as Sivers with OAM) | **For Vector Meson** |
| $\tilde{\mathbf{H}}^q(x, \xi, t)$ | $\tilde{\mathbf{E}}^q(x, \xi, t)$ | **For Pseudo-Scalar Meson** |

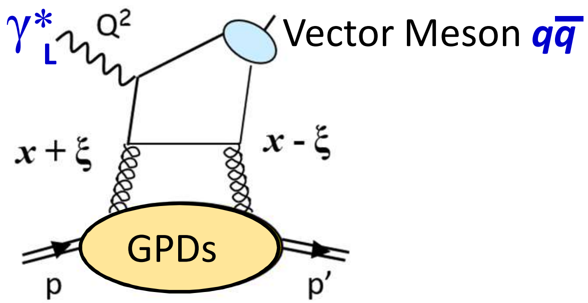
# GPDs and Hard Exclusive Meson Production

**Factorisation proven only for $\sigma_L$**

**Quark contribution**




**Gluon contribution at the same order in $\alpha_s$**




+ Non-perturbative Meson wave function

$$\rho^0 = \left[|u\bar{u}\rangle - |d\bar{d}\rangle\right]/\sqrt{2}$$
$$\omega = \left[|u\bar{u}\rangle + |d\bar{d}\rangle\right]/\sqrt{2}$$

**4** chiral-even GPDs: helicity of parton unchanged

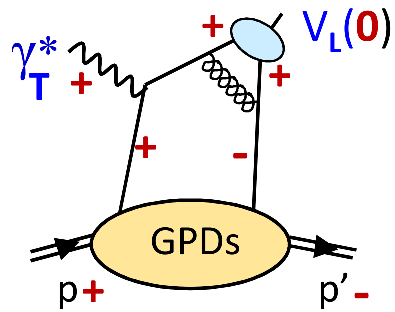
| | | |
|---|---|---|
| $H^q(x, \xi, t)$ | $E^q(x, \xi, t)$ (as Sivers with OAM) | **For Vector Meson** |
| $\tilde{H}^q(x, \xi, t)$ | $\tilde{E}^q(x, \xi, t)$ | **For Pseudo-Scalar Meson** |

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

| | | |
|---|---|---|
| $H^q_T(x, \xi, t)$ (as trans-versity) | $E^q_T(x, \xi, t)$ | $\bar{E}^q_T = 2\,\tilde{H}^q_T + E^q_T$ (as Boer-Mulders) |
| $\tilde{H}^q_T(x, \xi, t)$ | $\tilde{E}^q_T(x, \xi, t)$ | |

$\sigma_T$ is 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

$\mathcal{M}^{\gamma^*_T \to V_L}_{0-,++}$ sensitive to $H^q_T$
and to a twist-3 meson wave function



# COMPASS 2012 - 16 Exclusive $\pi^0$ production on unpolarized proton

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

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

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

COMPASS

$Q^2$=2.0 $GeV^2$

$x_B$=0.093

$|t|\sim$ 0.26 $GeV^2$

$\varepsilon$ close to 1

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

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

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

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

$$\left\langle\frac{\mathrm{d}\sigma_T}{\mathrm{d}|t|} + \epsilon\frac{\mathrm{d}\sigma_L}{\mathrm{d}|t|}\right\rangle = (8.2 \pm 0.9_{\mathrm{stat}}{}^{+\,1.2}_{-\,1.2}|_{\mathrm{sys}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}.$$

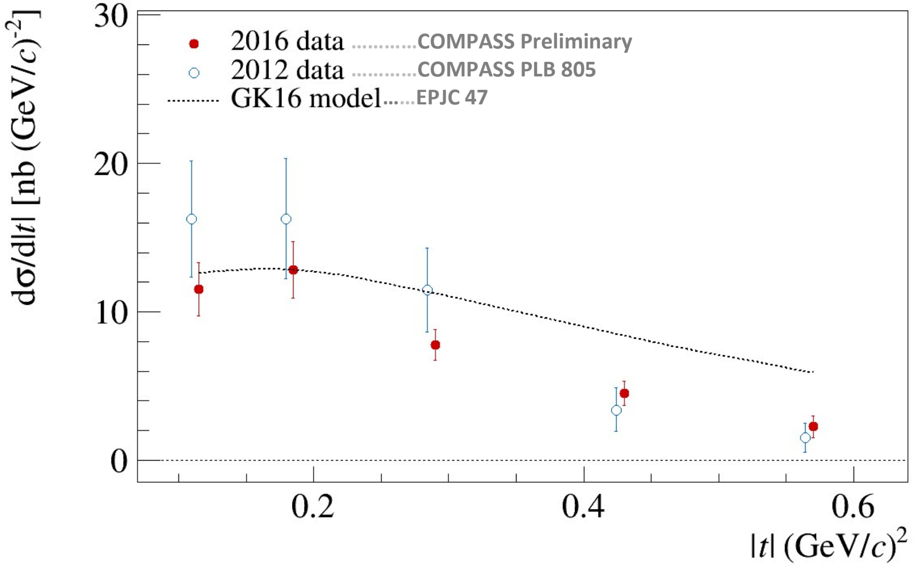
$$\left\langle\frac{\mathrm{d}\sigma_{TT}}{\mathrm{d}|t|}\right\rangle = (-6.1 \pm 1.3_{\mathrm{stat}}{}^{+\,0.7}_{-\,0.7}|_{\mathrm{sys}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

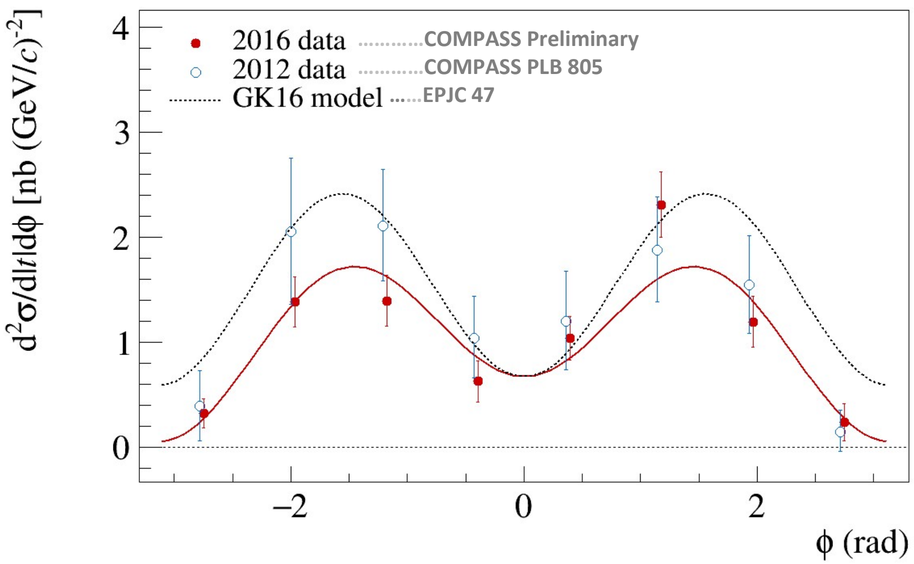
$$\left\langle\frac{\mathrm{d}\sigma_{LT}}{\mathrm{d}|t|}\right\rangle = (1.5 \pm 0.5_{\mathrm{stat}}{}^{+\,0.3}_{-\,0.2}|_{\mathrm{sys}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

PLB 805 (2020)

$\sigma_{TT}$ large - impact of $\bar{E}_T$

$\sigma_{LT}$ small but significantly positive as at CLAS




Data: **COMPASS,** PLB 805 (2020) Models: **GK** Kroll Goloskokov EPJC47 (2011) Also **GGL**: Golstein Gonzalez Liuti PRD91 (2015)

# COMPASS 2010 2007 HEMP with Transversely Polarized Target without RPD

Gparity: G(π)=-1; G(ρ)=+1; G(ω)=-1

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

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

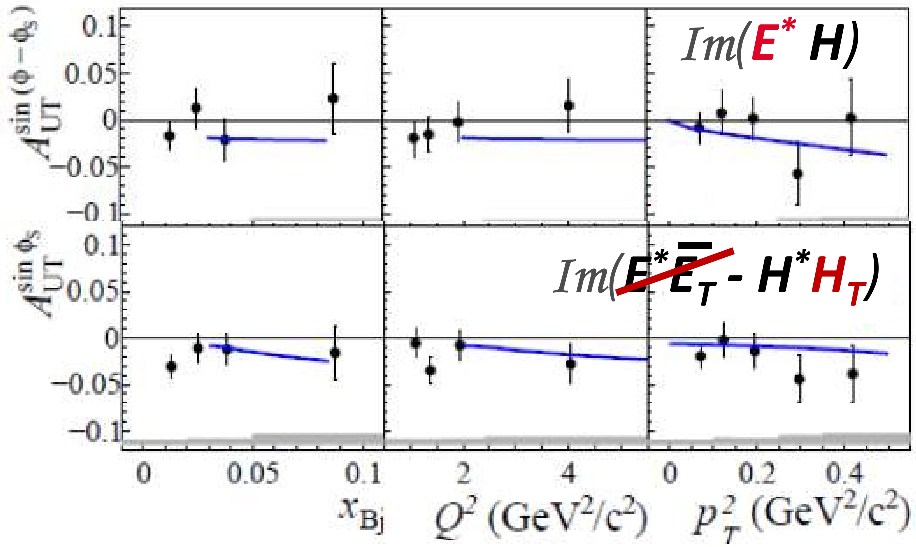
$\omega \to \pi^+\pi^-\pi^0$

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

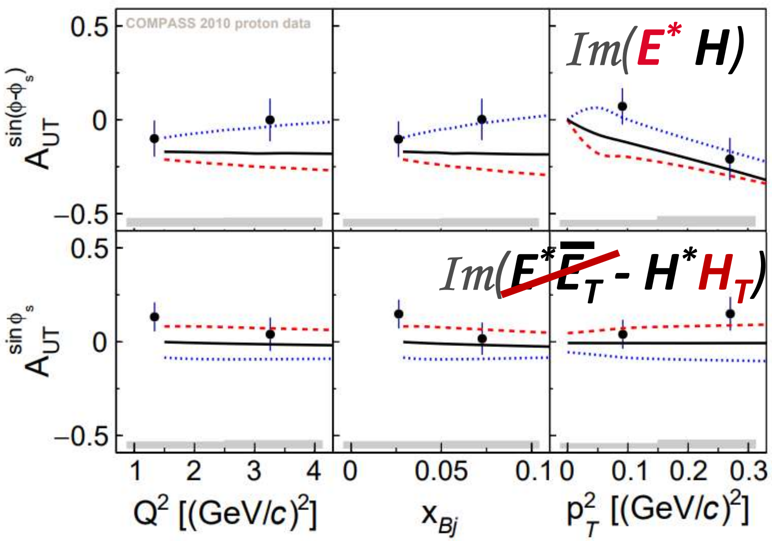
$E^u$ and $E^d$ of opposite sign

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

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

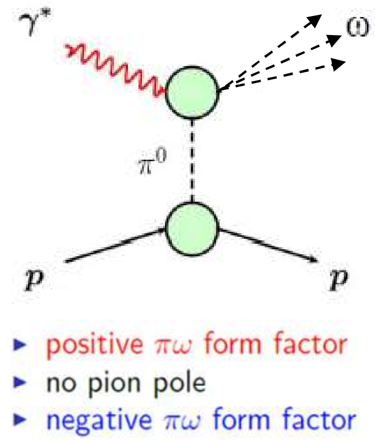


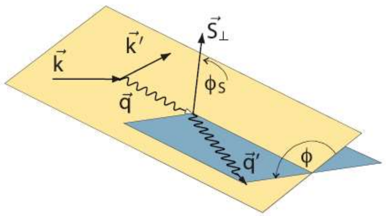

COMPASS, NPB 915 (**2017**)




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

Same for πω FF but sign unknown




**GK** Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small $x_B$

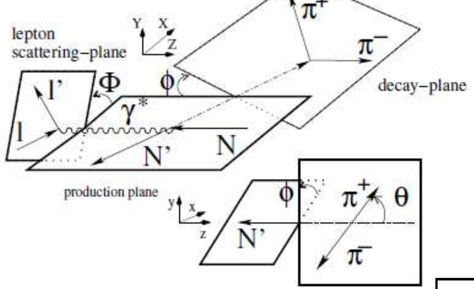
longitudinal $\gamma_L^* \, p \to M \, p$ and transv. polar. $\gamma_T^* \, p \to M \, p$

quark and gluon contributions (GPDs **H, E, $H_T$, $E_T$**) and beyond leading twist

# exclusive VM production with Unpolarised Target and SDME

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

$J^\pi \quad 1^- \quad 0^- \quad 0^-$




experimental angular distributions:

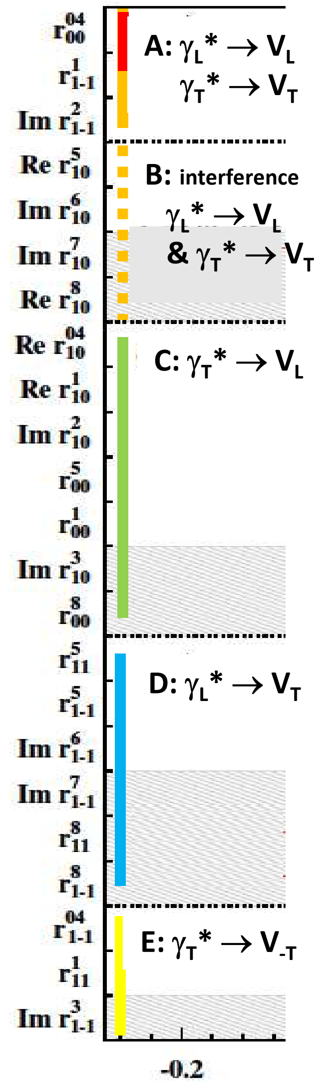
$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + P_b \mathcal{W}^{L}(\Phi,\phi,\cos\Theta)$$

15 'unpolarized' and 8 'polarized' SDMEs

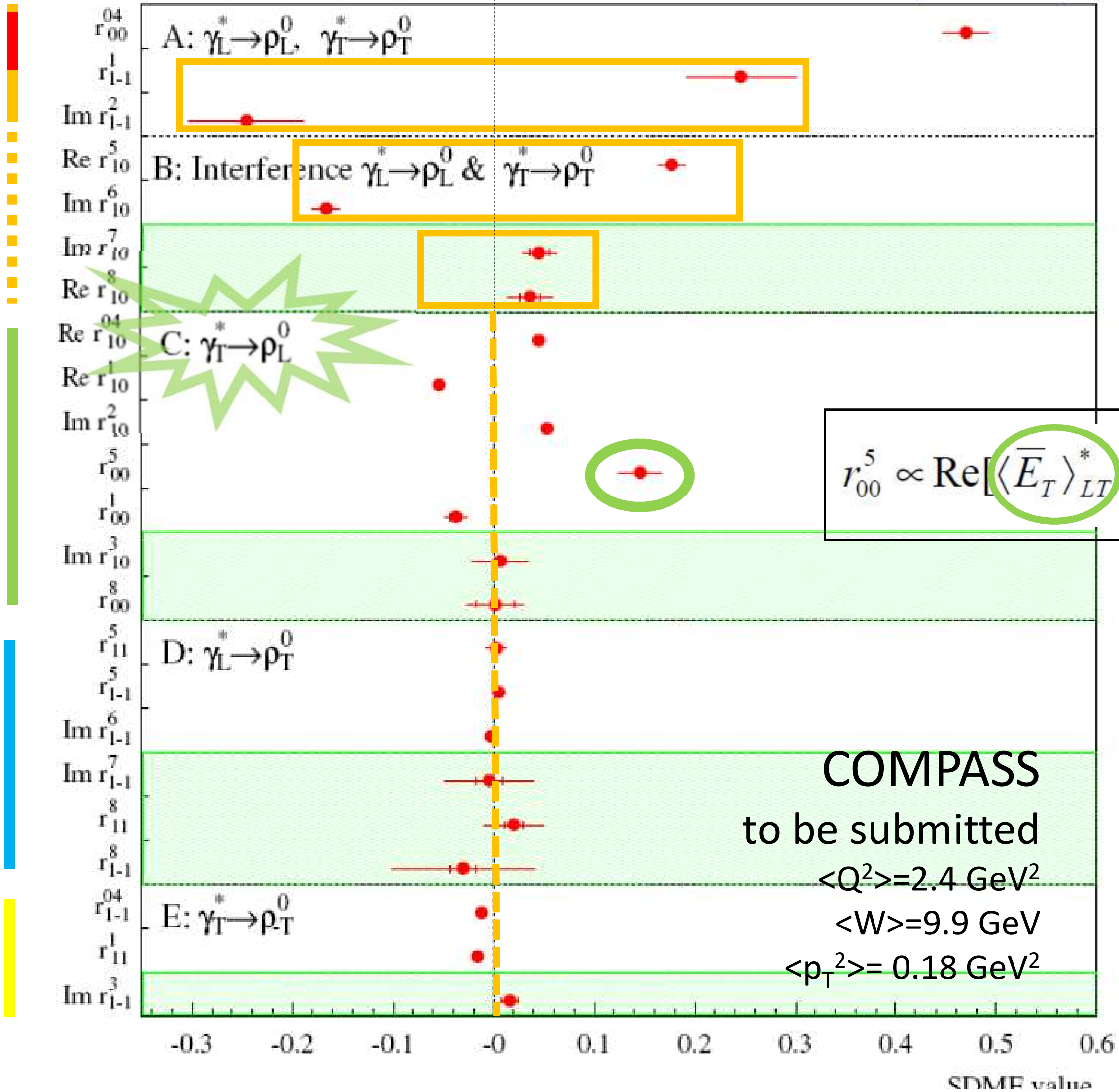
$$\mathcal{W}^{U}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta \quad \cos 2\phi$$
$$-\epsilon\cos 2\Phi\left(r^1_{11}\sin^2\Theta + r^1_{00}\cos^2\Theta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

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

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



# COMPASS 2012 Exclusive $\rho^0$ production on unpolarized proton




**If SCHC ($\lambda_\gamma = \lambda_V$)** — measurements:

$$r^1_{1-1} + \mathrm{Im}\{r^2_{1-1}\} = 0 \quad = 0.000 \pm 0.005 \pm 0.003$$

$$\mathrm{Re}\{r^5_{10}\} + \mathrm{Im}\{r^6_{10}\} = 0 \quad = 0.011 \pm 0.002 \pm 0.002$$

$$\mathrm{Im}\{r^7_{10}\} - \mathrm{Re}\{r^8_{10}\} = 0 \quad = 0.009 \pm 0.014 \pm 0.028$$

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

not observed for class C

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

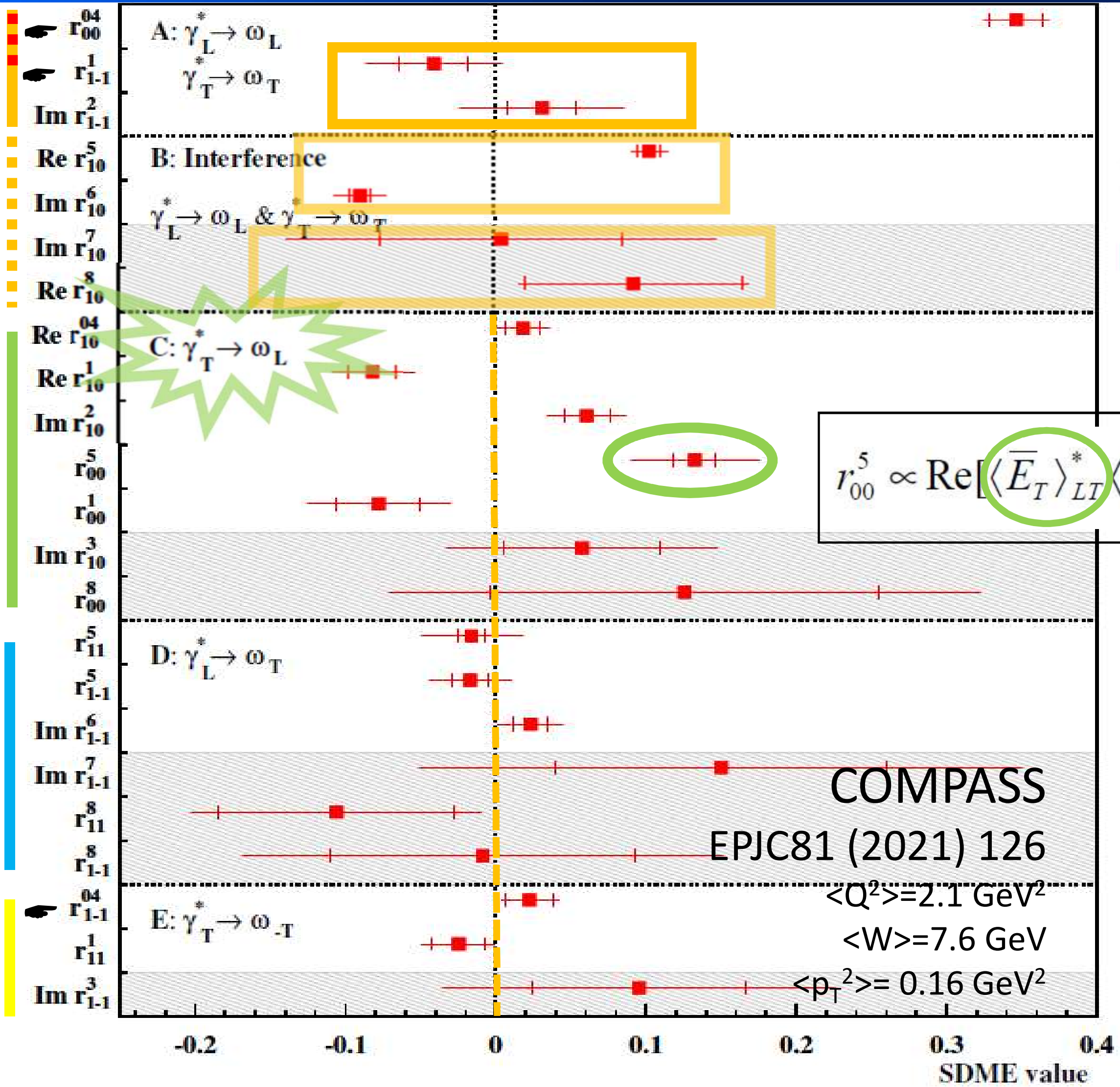
From Goloskokov and Kroll, EPJC74 (2014) 2725

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

➔ The first term dominates and $r^5_{00}$ probes $\overline{E}_T$

$(H^u, H^d)$ of same sign
$(\overline{E}^u_T, \overline{E}^d_T)$ of same sign
$(H^u_T, H^d_T)$ of opposite sign
$(E^u, E^d)$ of opposite sign

# 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

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

From Goloskokov and Kroll, EPJC74 (2014) 2725

$F\omega = 2/3 F^u - 1/3 F^d$

➔ Both 2 terms are important

($H^u$, $H^d$) of same sign

($\overline{E}^u_T$, $\overline{E}^d_T$) of same sign

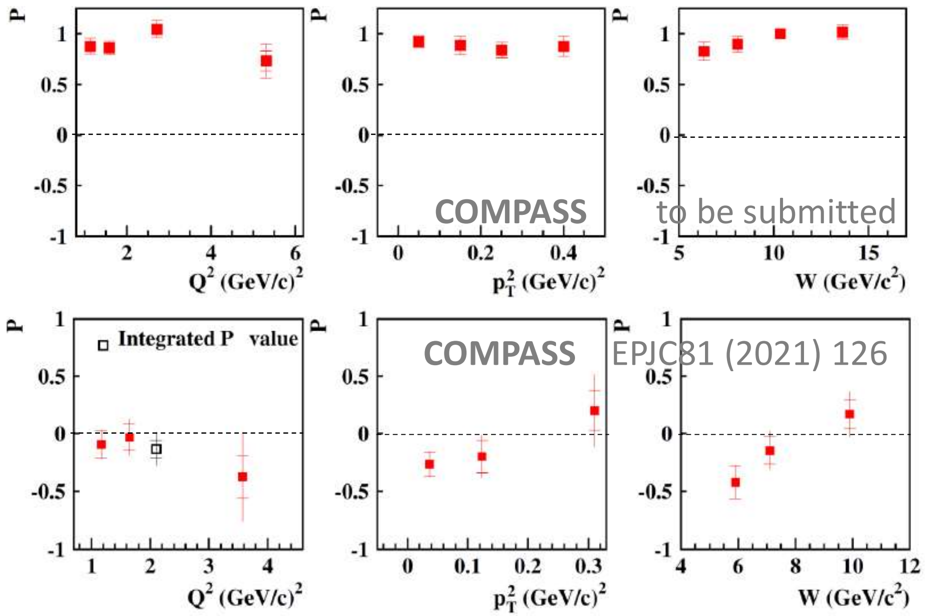
($H^u_T$, $H^d_T$) of opposite sign

($E^u$, $E^d$) of opposite sign

# COMPASS 2012 Comparison $\omega$ and $\rho^0$ production

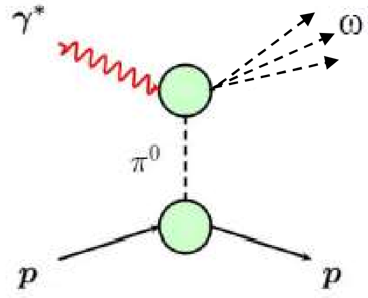
## Natural (N) to Unatural (U) Parity Exchange for $\gamma_T^* \to V_T$

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

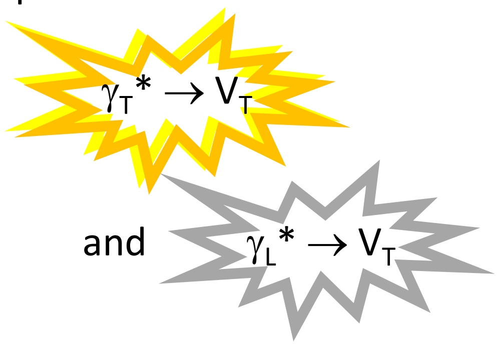



**The pion pole exchange (UPE)** is large for $\omega$ compared to $\rho^0$

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



It plays an important role in $\omega$ production for:




$\rho^0$: P~1 ➔ NPE dominance P~1

**NPE with GPDs $H$, $E$**

$\omega$: P~0 ➔ NPE ~ UPE

UPE dominance at small W and $p_T^2$

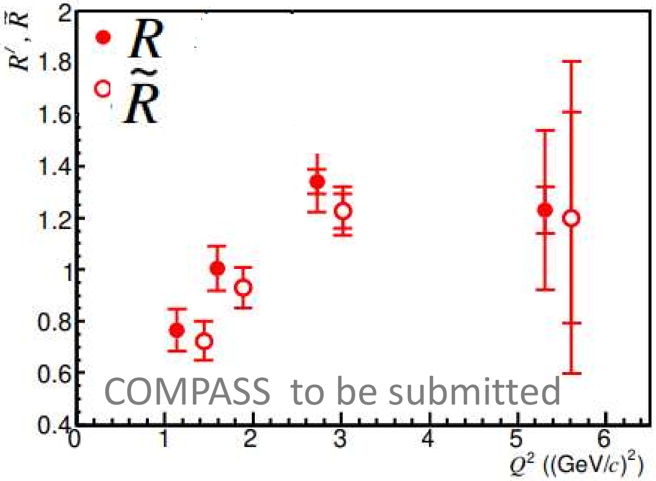
**UPE with GPDs $\tilde{H}$, $\tilde{E}$ and the dominant pion pole**

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

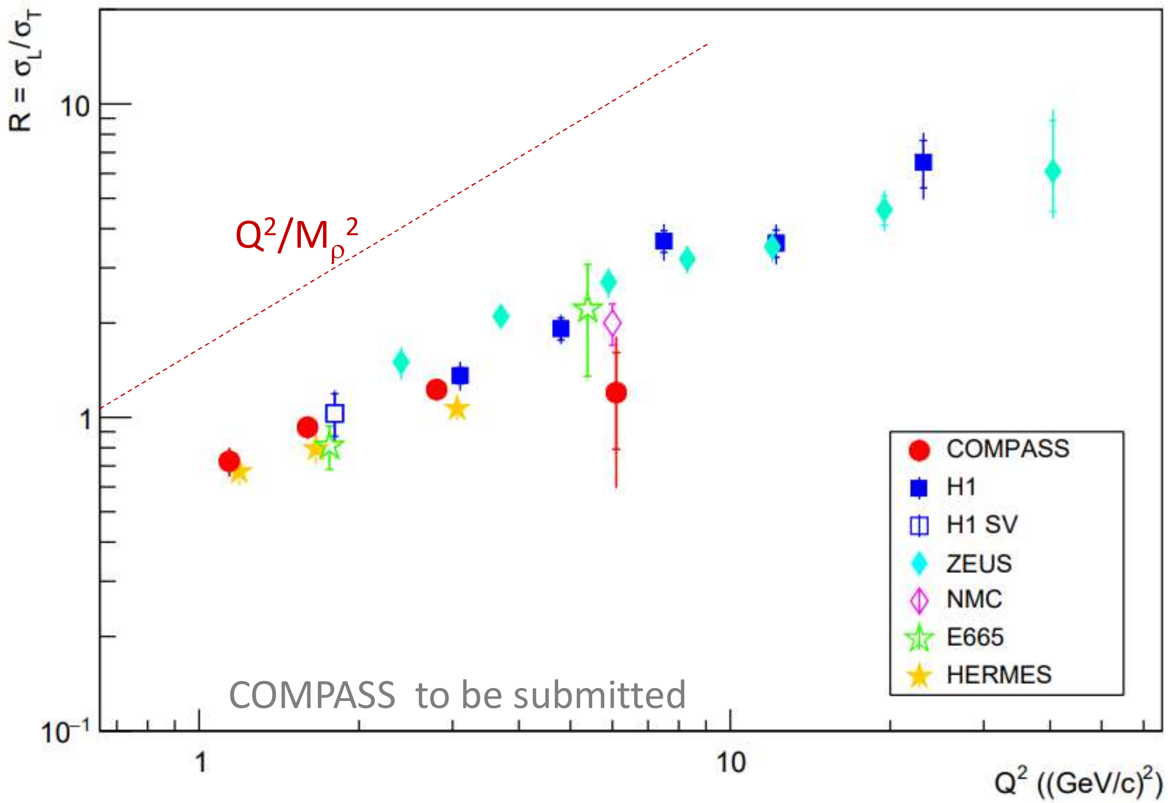
$$R = \frac{\sigma_L(\gamma_L^* \to V)}{\sigma_T(\gamma_T^* \to V)}$$

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

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




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




Deviation from the pQCD LO prediction in $Q^2/M_\rho^2$: QCD evolution and $q_T$

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

# COMPASS 2016+17 Outlook for DVCS and HEMP

✓ 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

✓ On-going analysis (Cross section, SDME) for HEMP of $\pi^0$, $\rho^0$, $\omega$, $\phi$, J/$\psi$

✓ Transversity GPDs

✓ Gluon GPDs

✓ Flavor decomposition

# COMPASS 2016+17 Outlook for DVCS and HEMP

- ✓ DVCS and the sum $\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$
  ➔ $c_0$ and $s_1$ and constrain on Im$\mathcal{H}$ and Transverse extension of partons

**For Jlab 20+ GeV**

- ✓ DVCS and the difference $\Delta \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$
  ➔ $c_1$ and constrain on Re$\mathcal{H}$ (>0 as H1 or <0 as HERMES)
  for D-term and pressure distribution

**Importance of $e^+$ beam**

- ✓ On-going analysis (Cross section, SDME) for HEMP of $\pi^0$, $\rho^0$, $\omega$, $\phi$, $J/\psi$
  - ✓ Transversity GPDs
  - ✓ Gluon GPDs
  - ✓ Flavor decomposition


**Importance of large luminosity**
**For DVCS, TCS, DDVCS, $J/\psi$ …**