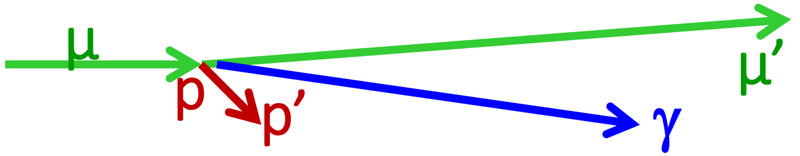
Hard Exclusive Reactions at COMPASS at CERN

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

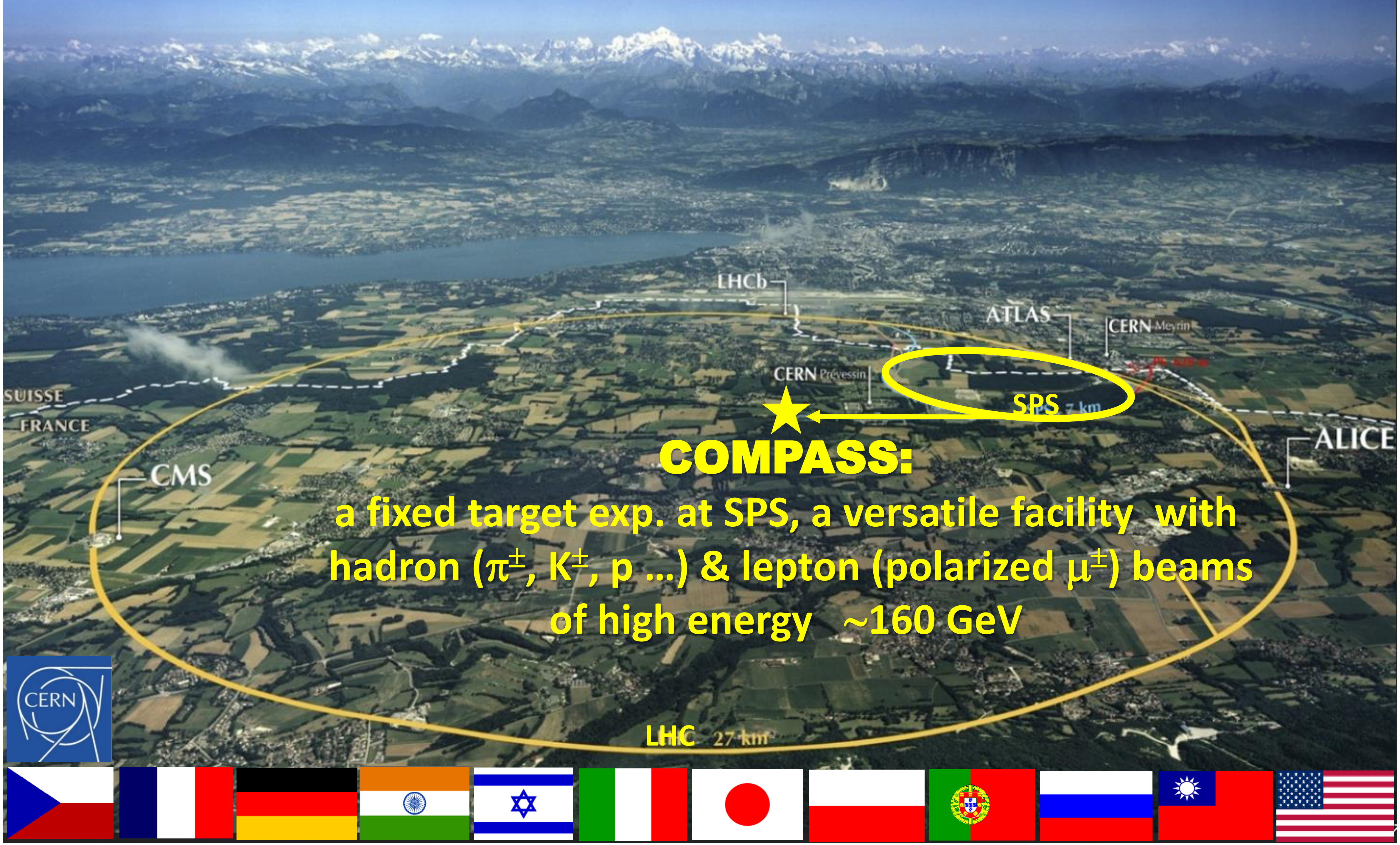
Nicole d'Hose – CEA – Université Paris-Saclay
for the COMPASS Collaboration

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



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

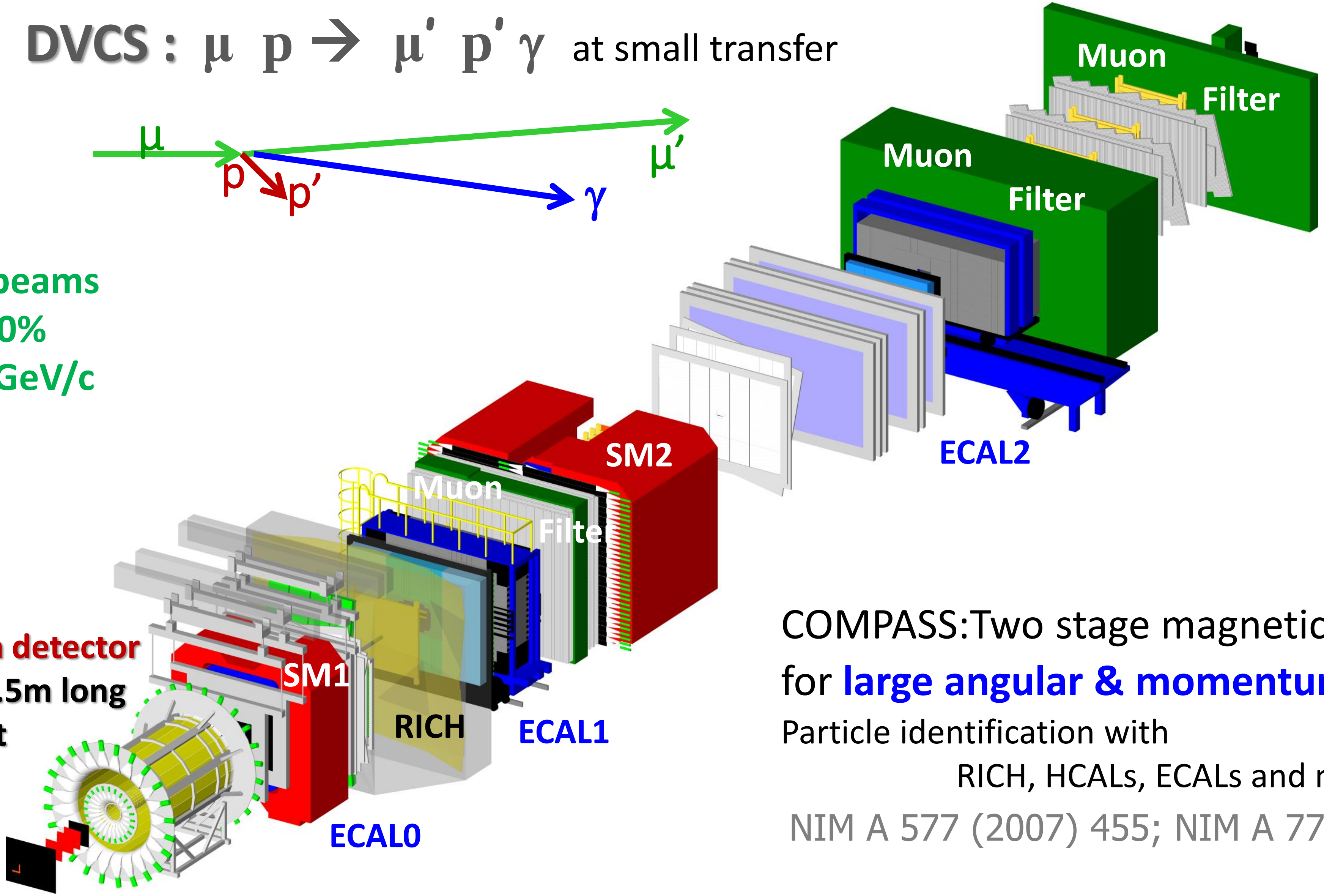
Vector Meson : $\mu \; p \rightarrow \mu' \; p' \, \rho$ or ω or …


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 ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams
of high energy ~160 GeV
CERN
LHC 27 km

The DVCS experiment 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

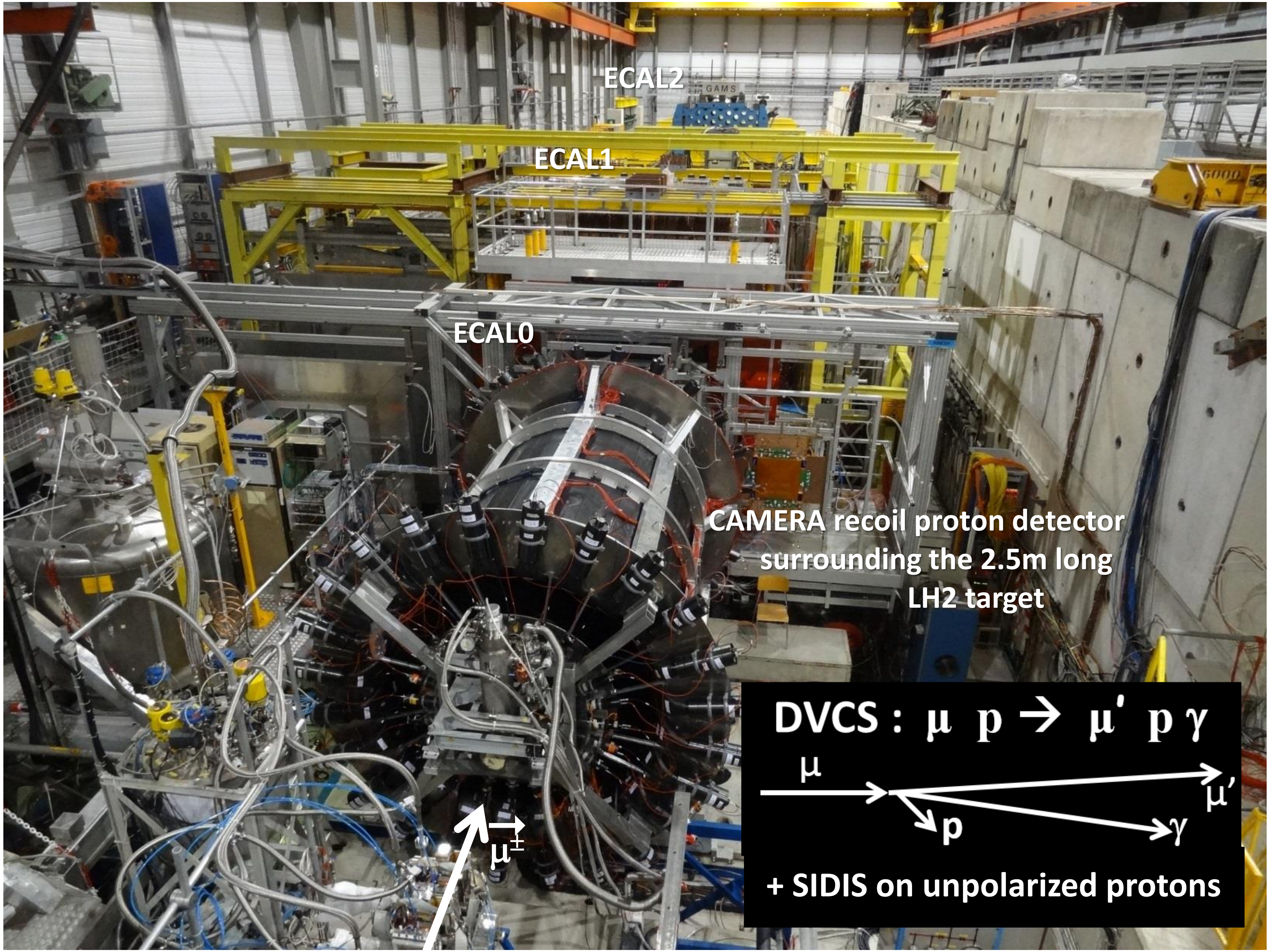


CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target

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

Particle identification with
RICH, HCALs, ECALs and muon filters

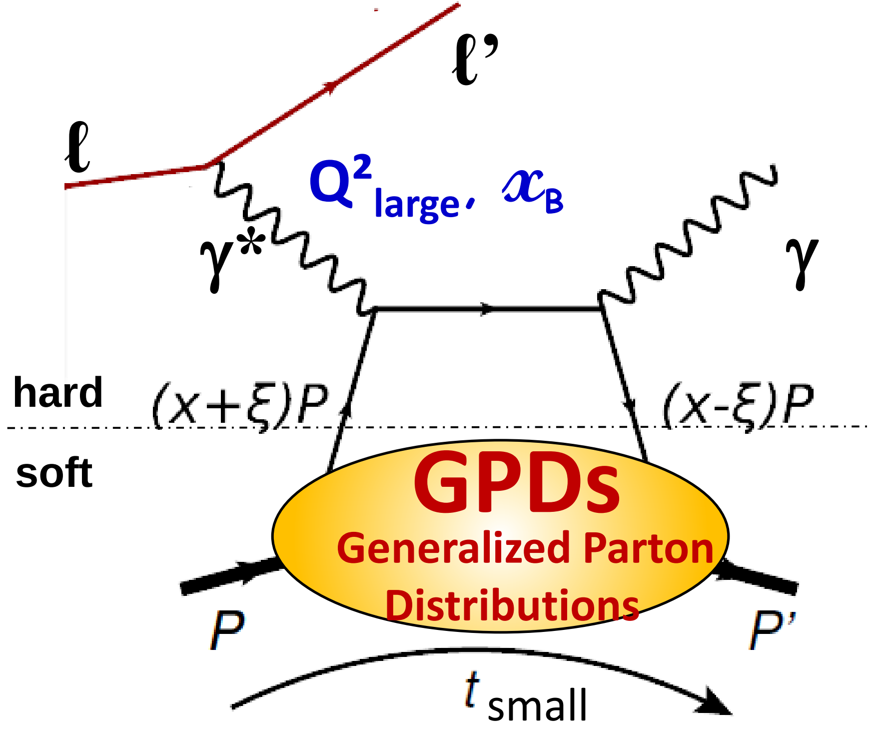
NIM A 577 (2007) 455; NIM A 779 (2015) 69



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 long. momentum

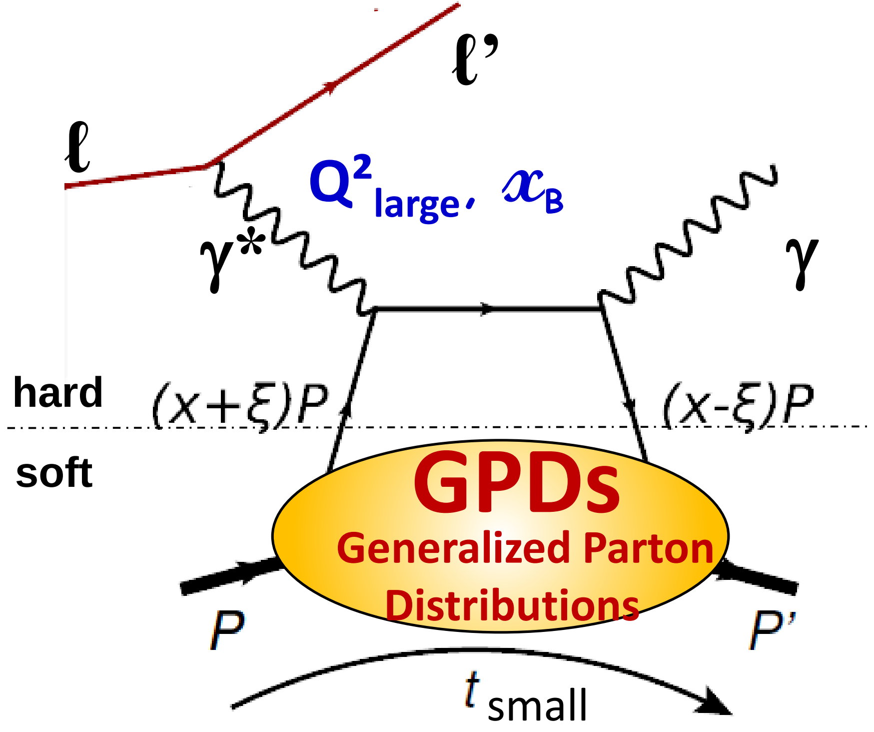
ξ: long. mom. difference

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

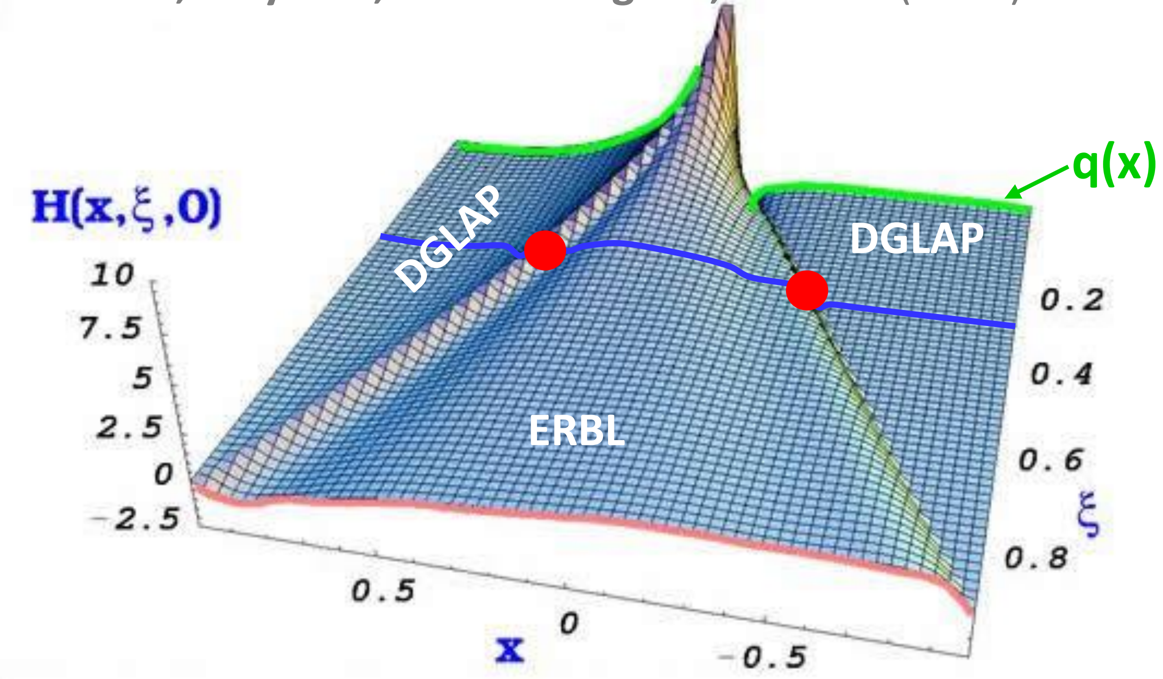
The variables measured in the experiment:

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

Deeply virtual Compton scattering (DVCS)



Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



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 $\mathcal{H}$

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

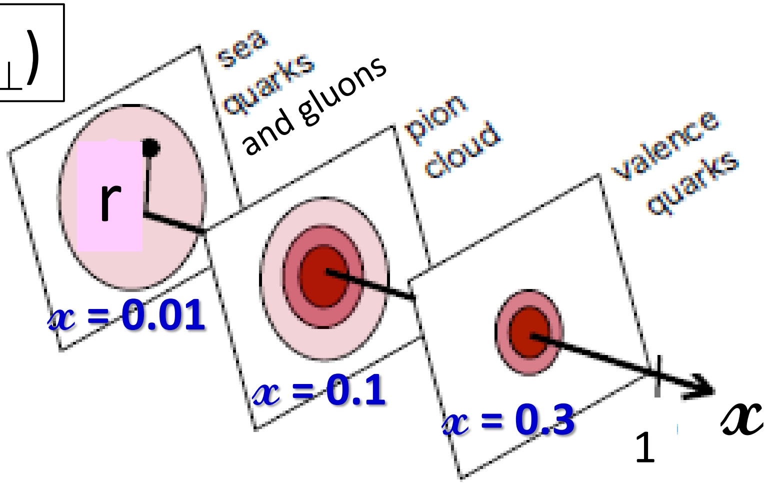
Deeply virtual Compton scattering (DVCS)

M. Burkardt, PRD66(2002)

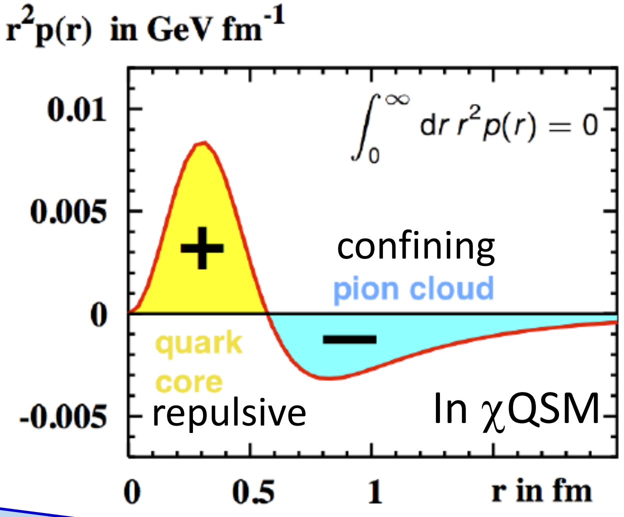
M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

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

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

t, ξ fixed

In an experiment we measure

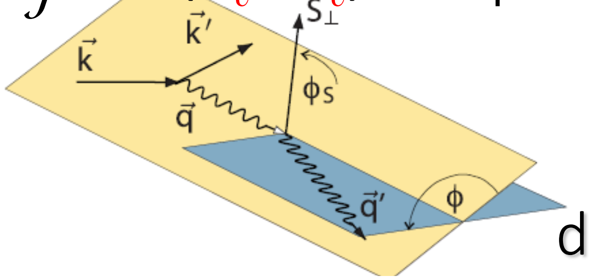
Compton Form Factor $\mathcal{H}$

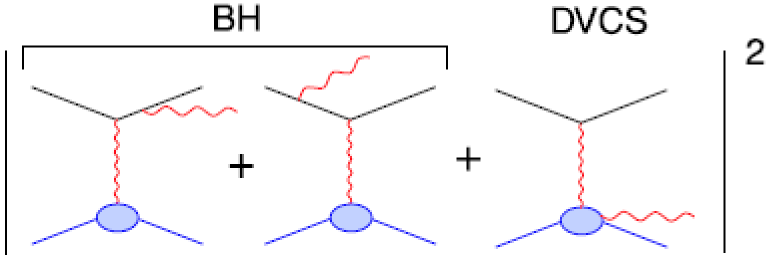
$$\mathcal{Re}\mathcal{H}(\xi,t) = \pi^{-1}\int dx \frac{Im\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

D-term $d_1(t)$

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





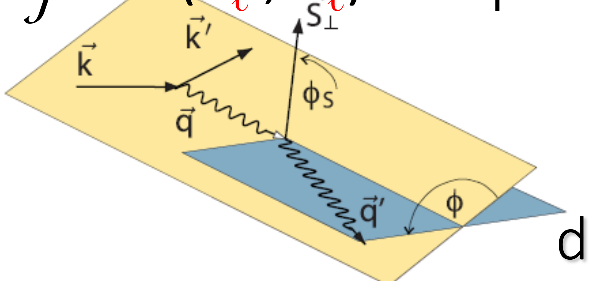
$$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2 + \text{Interference Term}$$

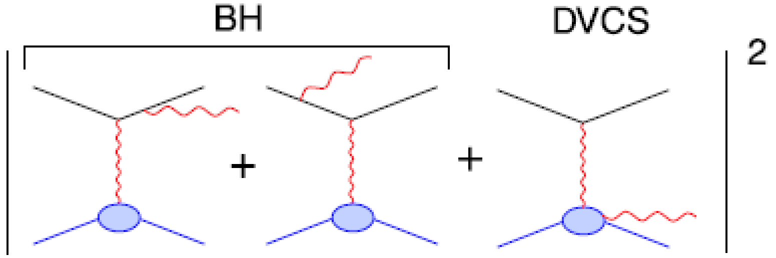
$$\frac{d^4\sigma(\ell p \to \ell p\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_\ell \, d\sigma^{DVCS}_{pol}\right) + (e_\ell \mathrm{Re}\, I + e_\ell P_\ell \,\mathrm{Im}\, I)$$

Well known

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ, e_ℓ) and ϕ

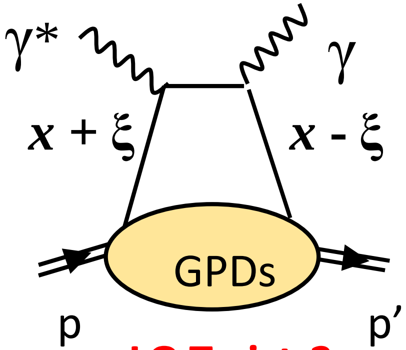




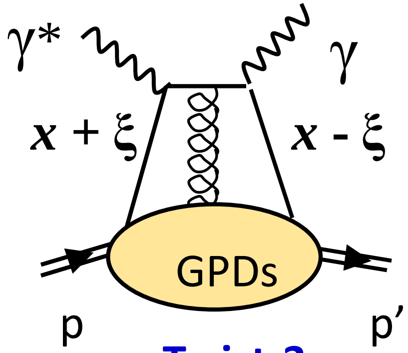
$$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2 + \text{Interference Term}$$

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

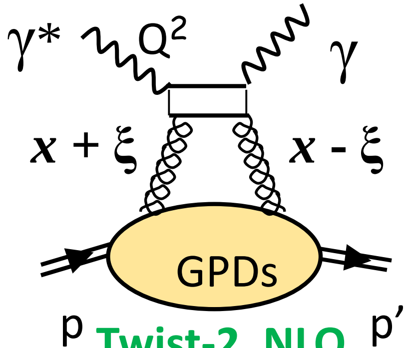
Well known



LO,Twist-2



Twist-3



Twist-2, NLO

double helicity flip

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

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

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

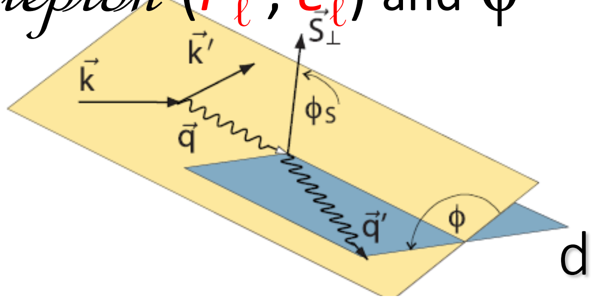
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

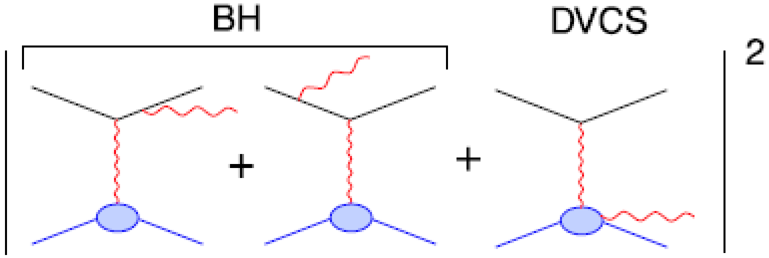
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

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

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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

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

Well known

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

❶ beam charge-spin sum

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

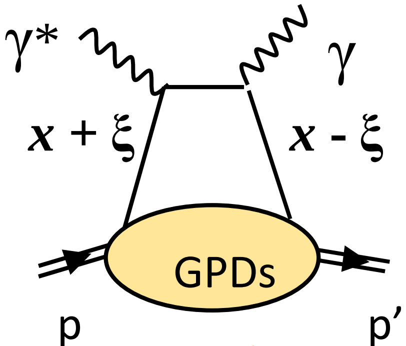
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH} \cos\phi + c_2^{BH} \cos 2\phi$$

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

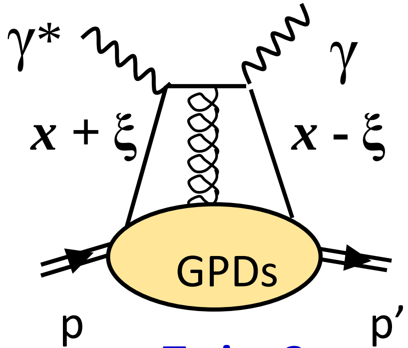
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS} \sin\phi$$

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

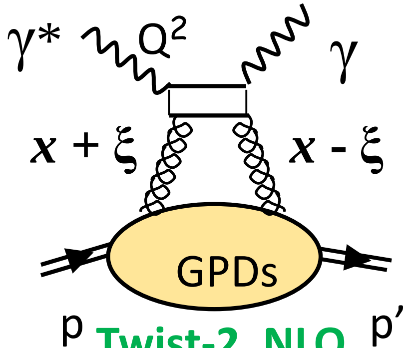
$$\text{Im}\, I \propto s_1^I \sin\phi + s_2^I \sin 2\phi$$



LO,Twist-2



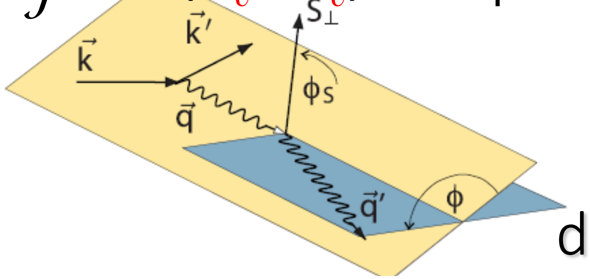
Twist-3

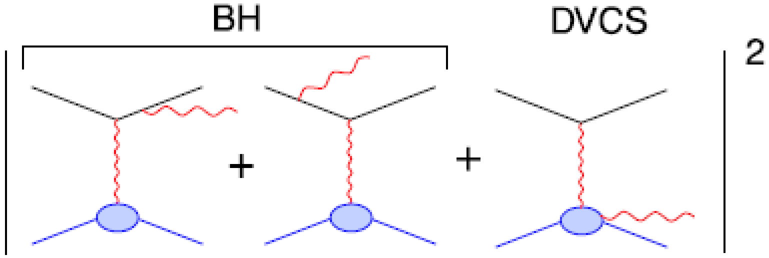


Twist-2, NLO
double helicity flip

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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

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

Well known

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

❶ beam charge-spin sum

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

❷ difference

$$\Delta \equiv d\overset{+}{\overleftarrow{\sigma}} - d\overset{-}{\overrightarrow{\sigma}}$$

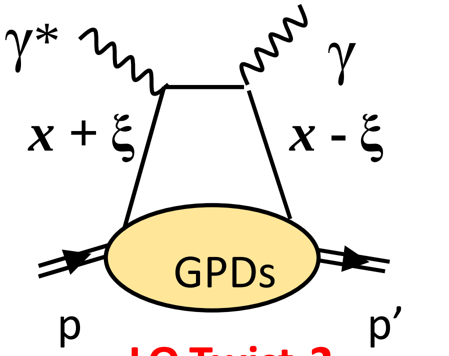
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

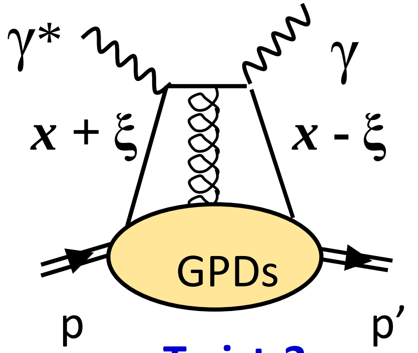
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

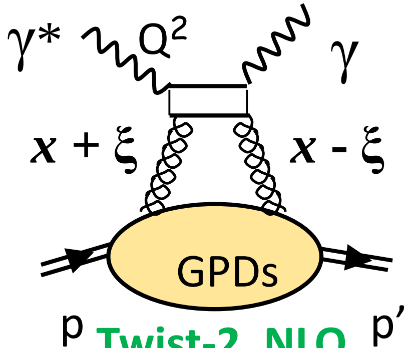
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



LO,Twist-2



Twist-3



Twist-2, NLO
double helicity flip

Deeply virtual Compton scattering (DVCS)

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

❶ beam charge-spin sum

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

❷ difference

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

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

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

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

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

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

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

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

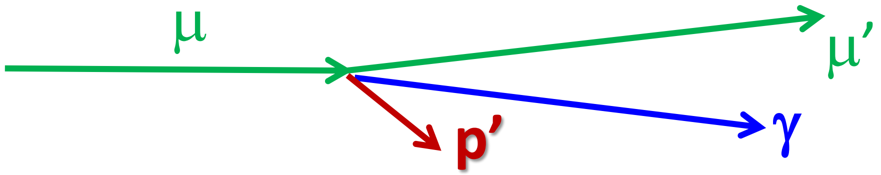
$$\Delta \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} \rightarrow c_1^I \propto \mathrm{Re}\,\mathcal{F}$$

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

at small x_B
COMPASS domain

COMPASS 2016 data — Exclusivity variables for DVCS

Comparison between the observables given by the spectro or by CAMERA



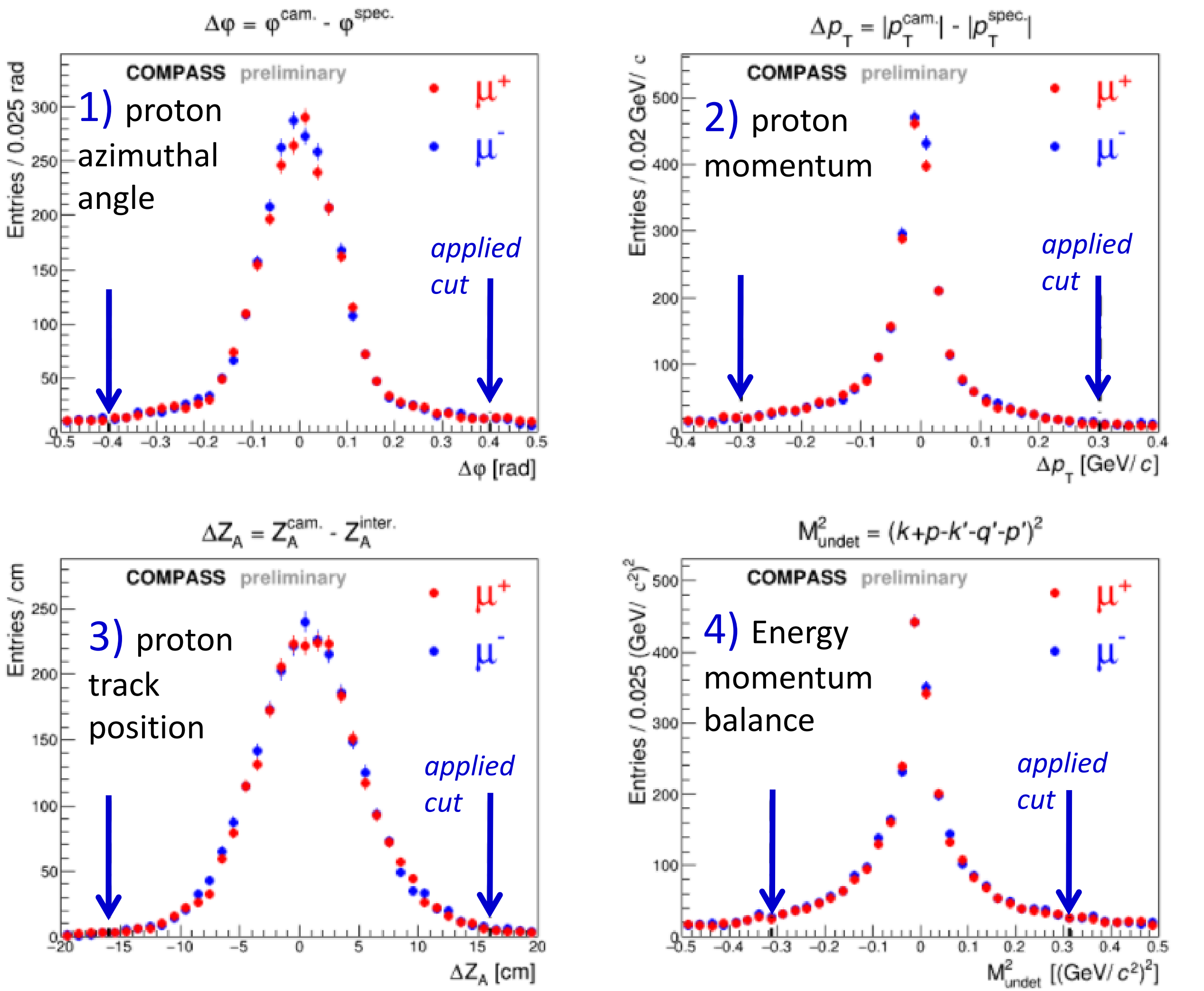
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

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



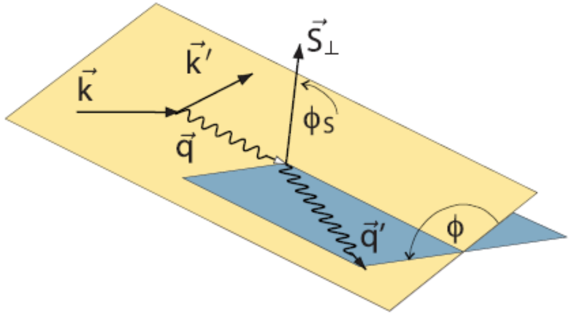
Good agreement between $\overleftarrow{\mu}^{+}$ **and** $\overrightarrow{\mu}^{-}$ yields

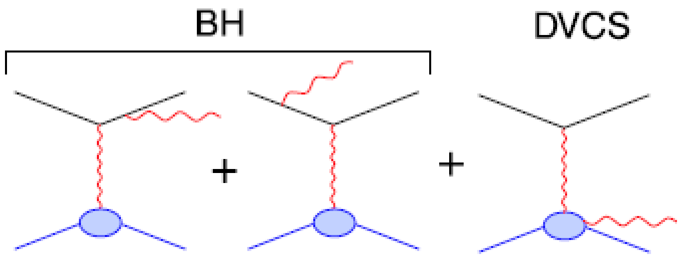
Important achievement for:

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**

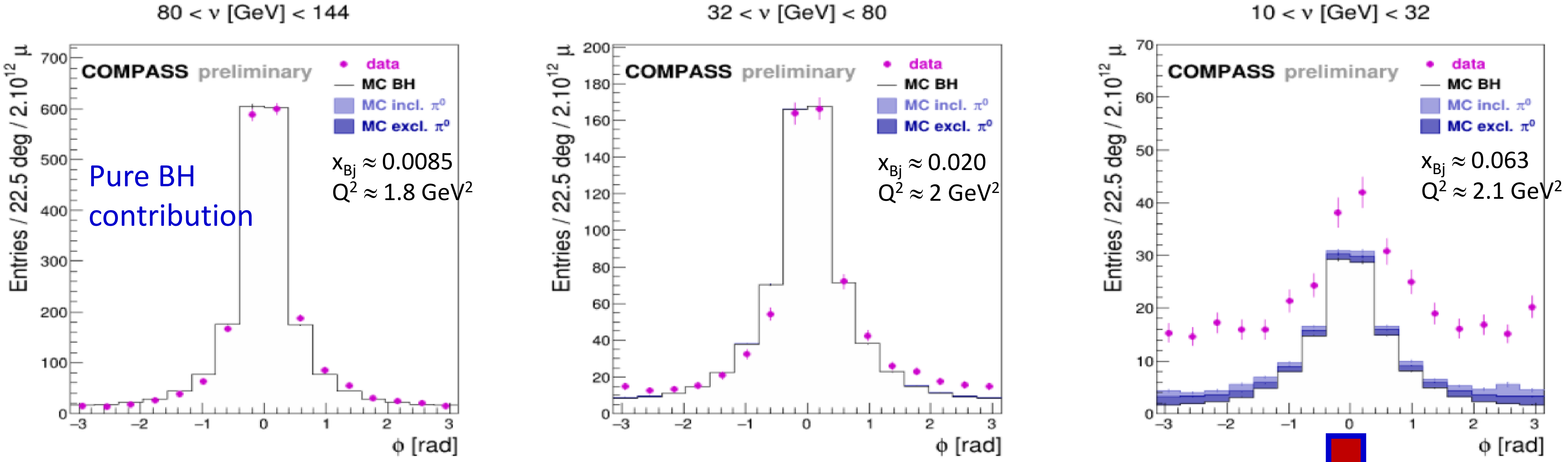
COMPASS 2016 data DVCS+BH cross section at Eμ=160 GeV





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

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



DVCS above the **BH** contrib.

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

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

At COMPASS using polarized positive and negative muon beams:

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

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

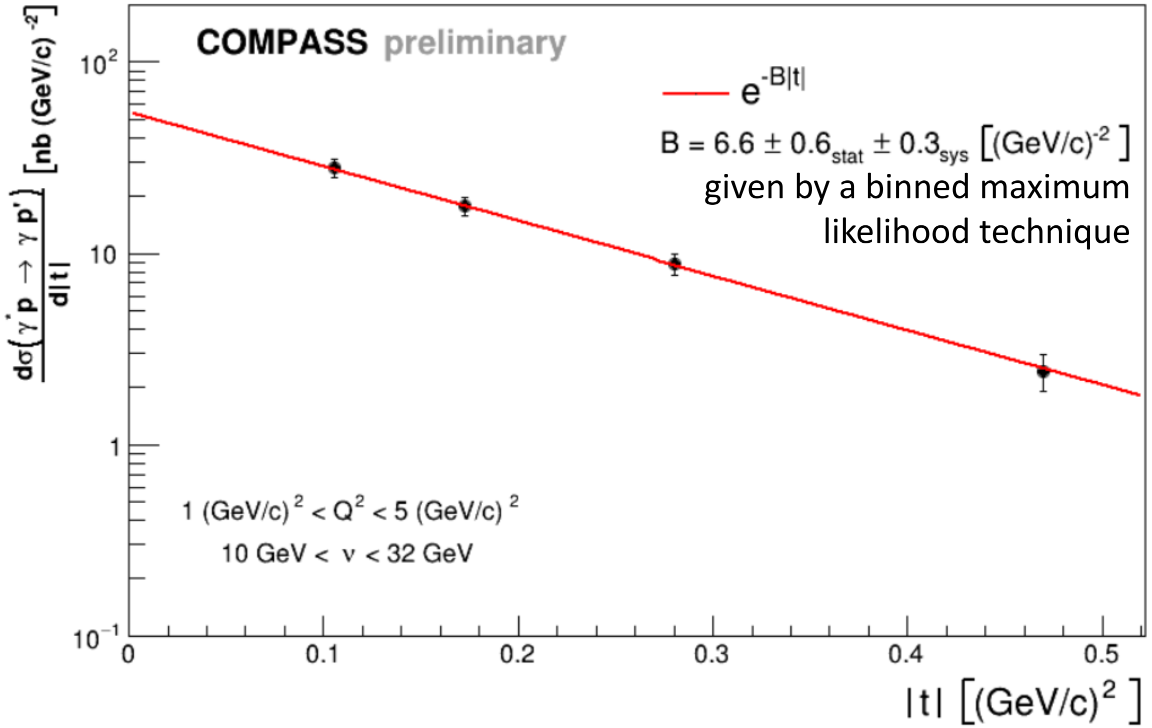
calculable
can be subtracted

All the other terms are cancelled in the integration over 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



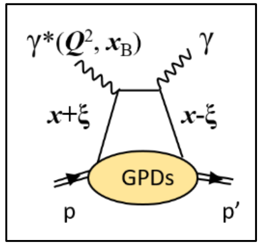
COMPASS 2016 Transverse extention of partons in the sea quark range

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

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

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

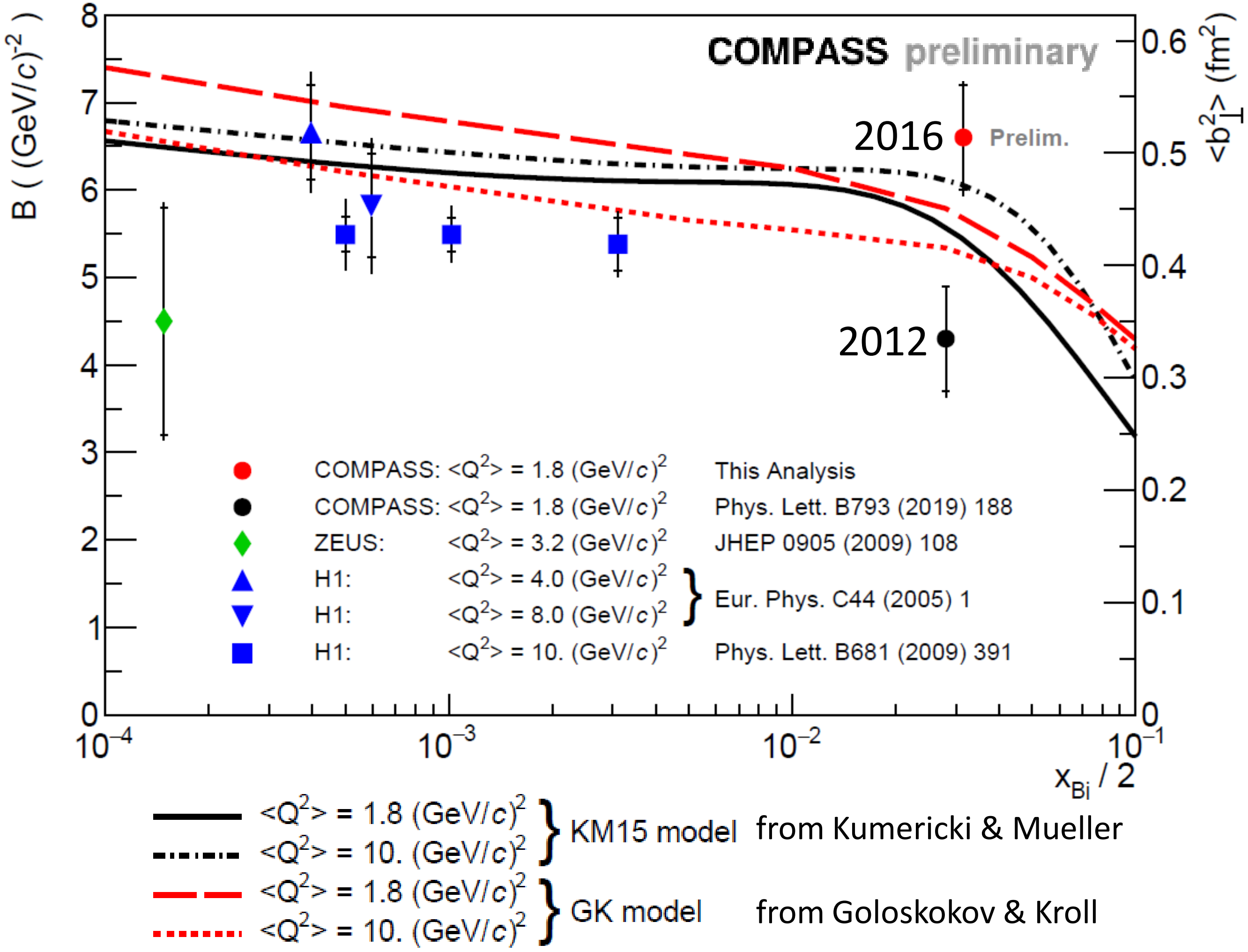
$Im\mathcal{H}$ = H (x=ξ, ξ, t)
$x = \xi \approx x_B/2$ close to 0



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

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

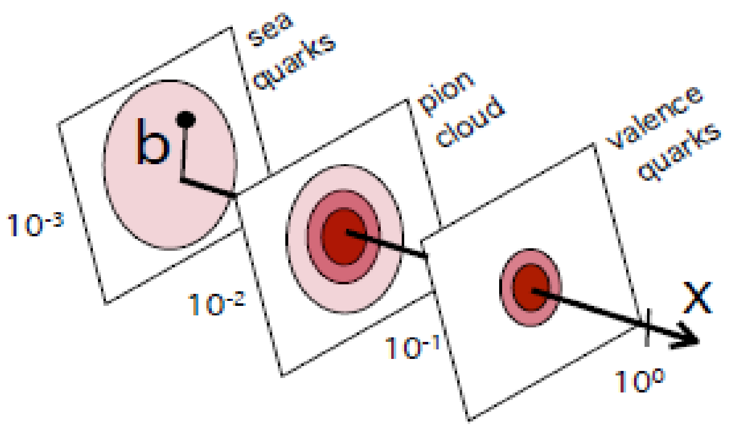
$$\langle b_\perp^2(x)\rangle \approx 2B(\xi)$$



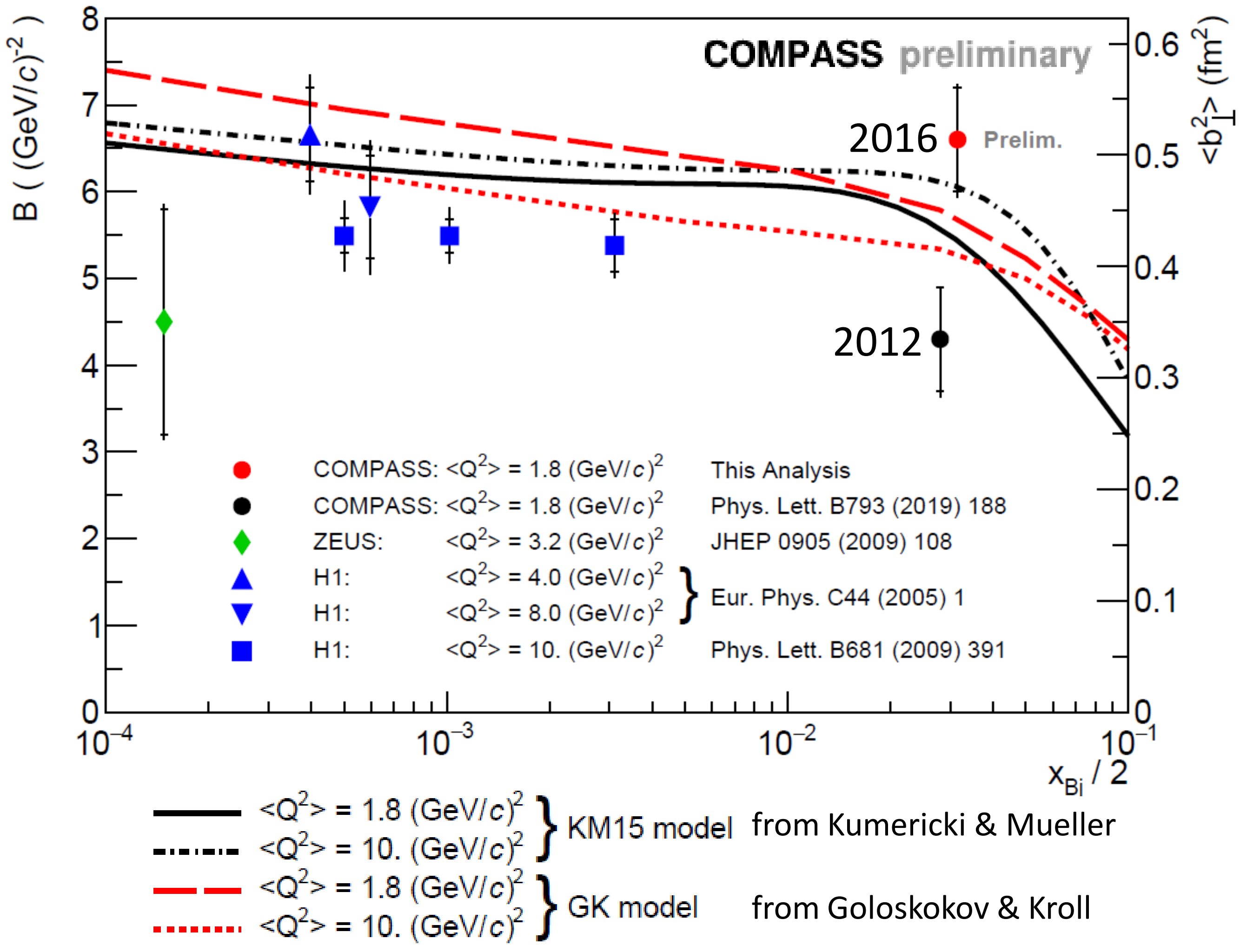
COMPASS 2016 Transverse extention of partons in the sea quark range

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

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



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



COMPASS 2016+17 in the next future

- ✓ Using the 3 domains in υ 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

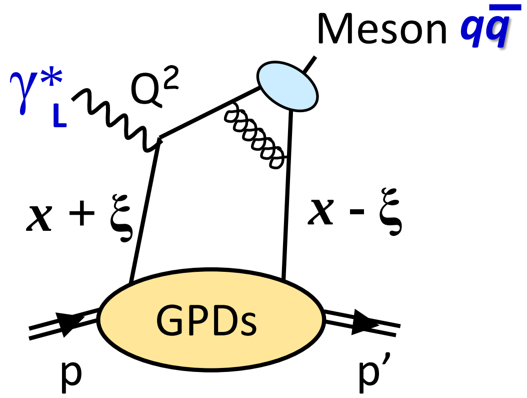
- ✓ Using the 3 domains in υ and the diff $\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$

  ➔ c_1 and constrain on Re$\mathcal{H}$ and D-term and pressure distribution

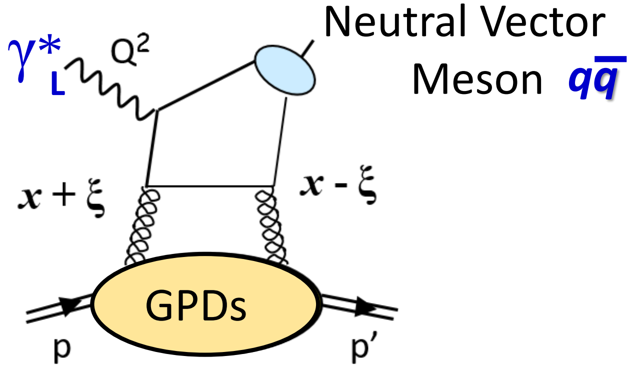
GPDs and Hard Exclusive Meson Production

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



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**

Flavor decomposition (val and sea quarks and gluons) **Diehl, Vinnikov** PLB 609 (2005)

$$F_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}F^u + \frac{1}{3}F^d + \frac{3}{4}\frac{F_g}{x}\right)$$
$$F_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}F^u - \frac{1}{3}F^d + \frac{1}{4}\frac{F_g}{x}\right)$$
$$F_{\phi} = -\frac{1}{3}F^s - \frac{1}{4}\frac{F_g}{x}.$$

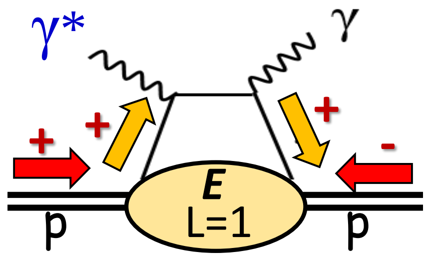
F for H, E …

✓H^u H^d of same sign
$\sigma_L(\rho^0) \sim 9 \times \sigma_L(\omega)$ with Unpol Target

✓E^u E^d of opposite sign
$A_{UT}^{\sin(\phi-\phi_s)} \sim \mathrm{Im}[\langle E\rangle^* \langle H\rangle]$
$A_{UT}^{\sin(\phi-\phi_s)}(\omega) > A_{UT}^{\sin(\phi-\phi_s)}(\rho^0)$ with Trans Pol Target

Access to the GPD E with transversely polarized target

(with DVCS on the proton or Vect Meson) or DVCS on the neutron



the Holy Grail with E: to reveal OAM

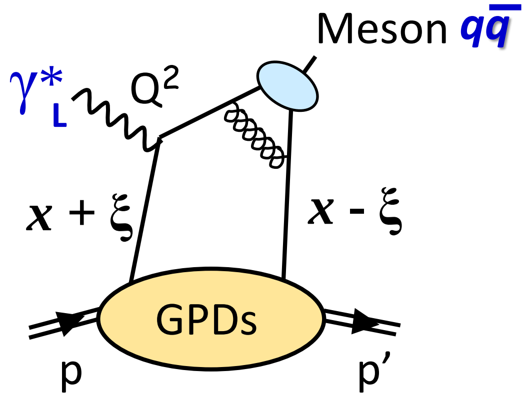
Ji: $2J^q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$

GPDs and Hard Exclusive Meson Production

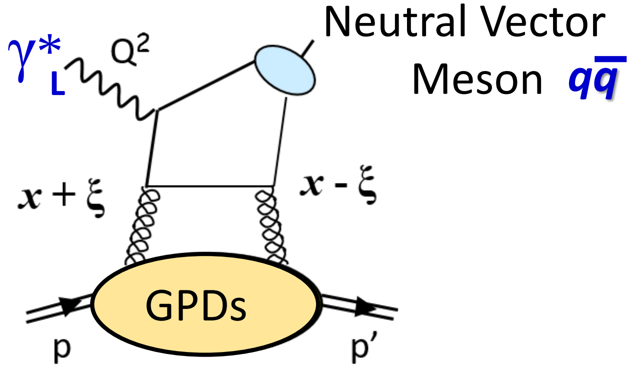
Factorisation proven only for σ_L

The meson wave function
Is an additional non-perturbative term

Quark contribution



Gluon contribution at the same order in α_s



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 transversity) $E^q_T(x, \xi, t)$

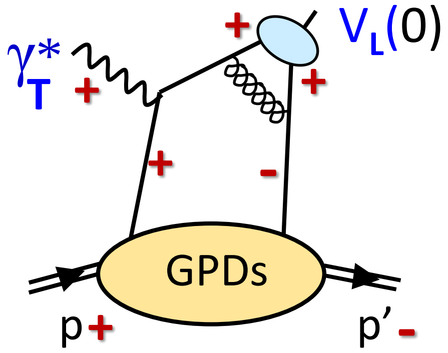
$\tilde{H}^q_T(x, \xi, t)$ $\tilde{E}^q_T(x, \xi, t)$

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

σ_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

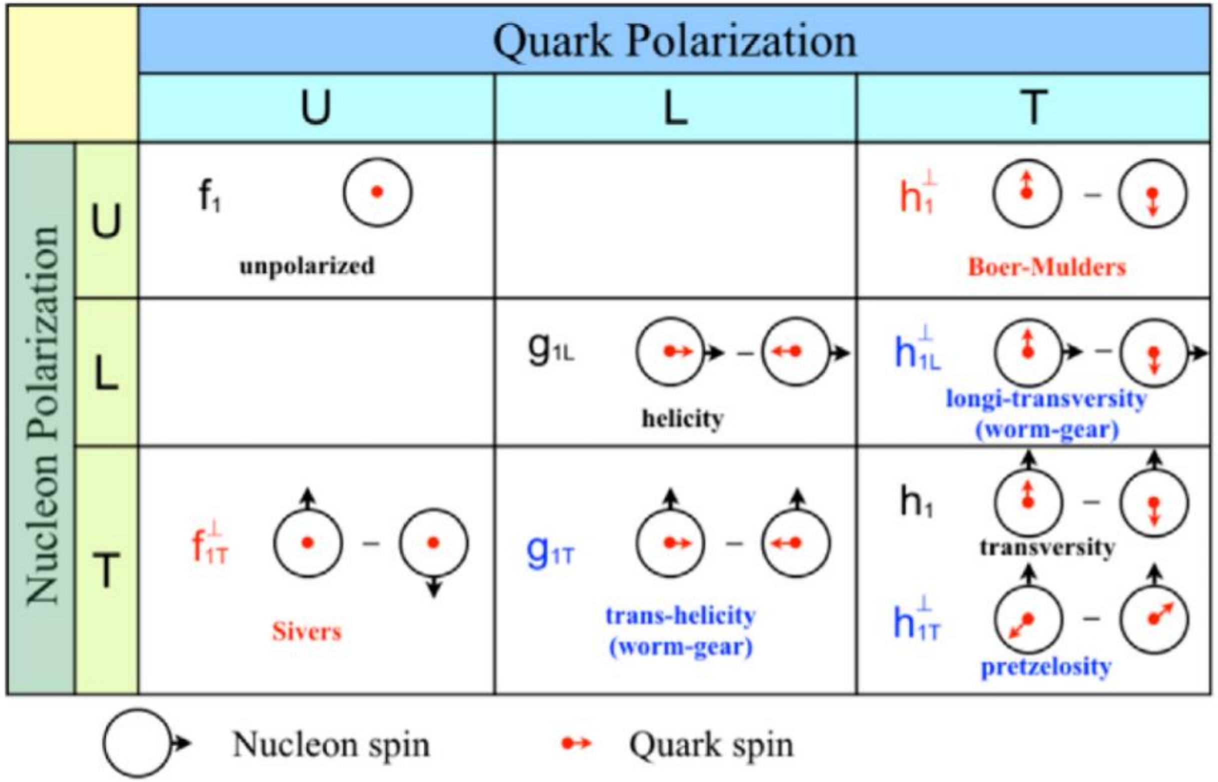
$\mathcal{M}^{\gamma^*_T \to V_L}_{0-,++}$ sensitive to H^q_T

and to a twist-3 meson wave function



8 GPDs in parallel of 8 TMDs

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



For valence contributions:

H^u H^d of same sign
$\tilde{H}^u$ $\tilde{H}^d$ of opposite sign
H_T^u H_T^d of opposite sign

E^u E^d of opposite sign
$\tilde{E}^u$ $\tilde{E}^d$ of same sign
$\bar{E}_T^u$ $\bar{E}_T^d$ of same sign

COMPASS 2012 Exclusive π^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
PLB 805 (2020)
Q^2=2.0 GeV^2
x_B=0.093
|t|~ 0.26 GeV^2
ε close to 1

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

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

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

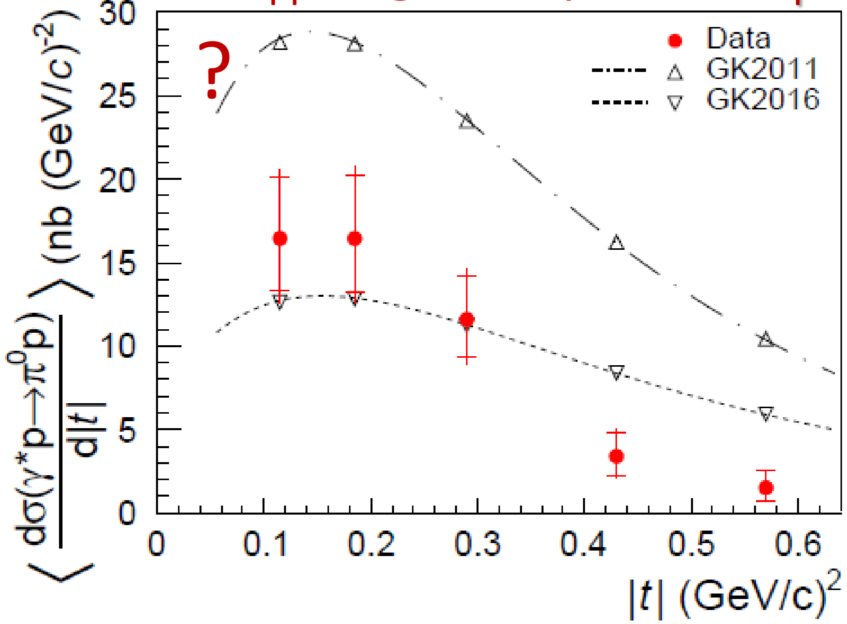
$$\frac{\sigma_{LT}}{dt} \propto \frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

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

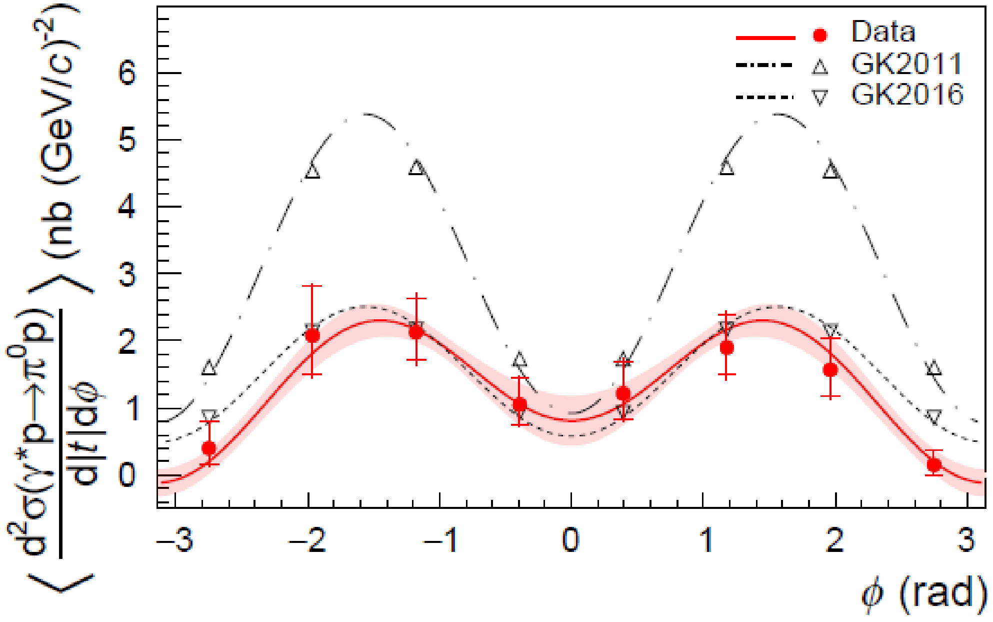
$$\left\langle\frac{d\sigma_{TT}}{d|t|}\right\rangle = (-6.1 \pm 1.3_{\mathrm{stat}}\,{}^{+\,0.7}_{-\,0.7}|_{\mathrm{sys}})\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$$

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

σ_{TT} large - impact of $\bar{E}_T$



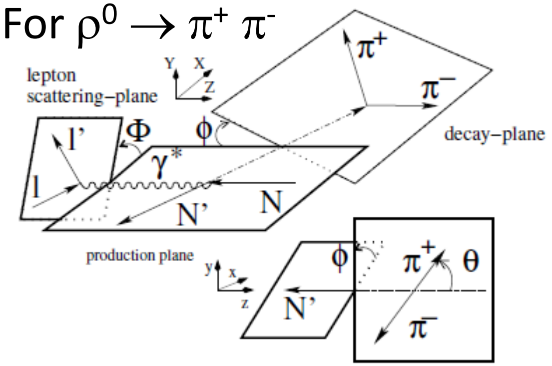
σ_{LT} small but significantly positive as at CLAS



Data: **COMPASS,** PLB 805 (2020) 135454 Models: **GK** Kroll Goloskokov EPJ47 (2011) Also **GGL**: Golstein Gonzalez Liuti PRD91 (2015)

exclusive VM production with Unpolarised Target and SDME

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



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

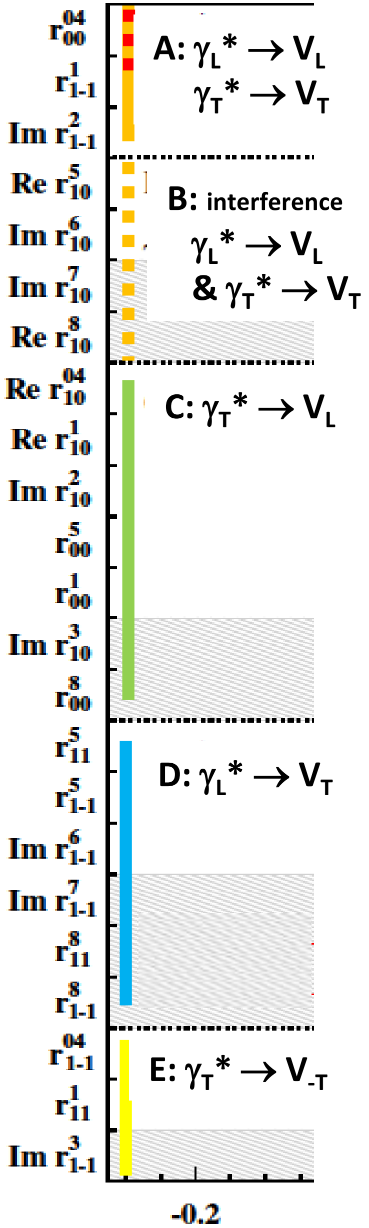
$$\mathcal{W}^{U}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta \cos 2\phi$$
$$-\epsilon\cos 2\Phi\left(r^1_{11}\sin^2\Theta + r^1_{00}\cos^2\Theta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

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

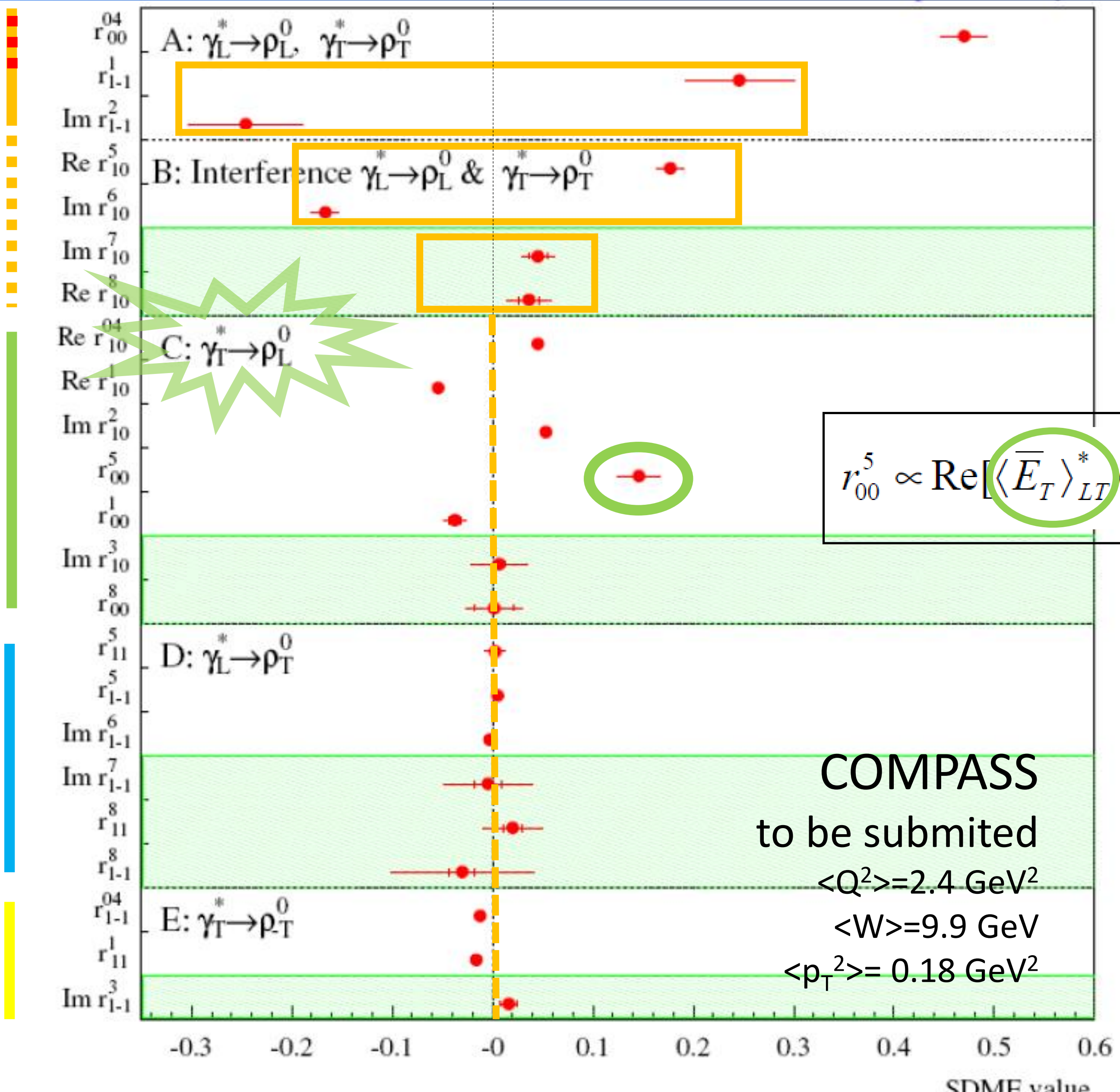
ε close to 1,
small $\mathcal{W}^L$
no L/T separation

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

related to $\frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$.



COMPASS 2012 Exclusive ρ^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

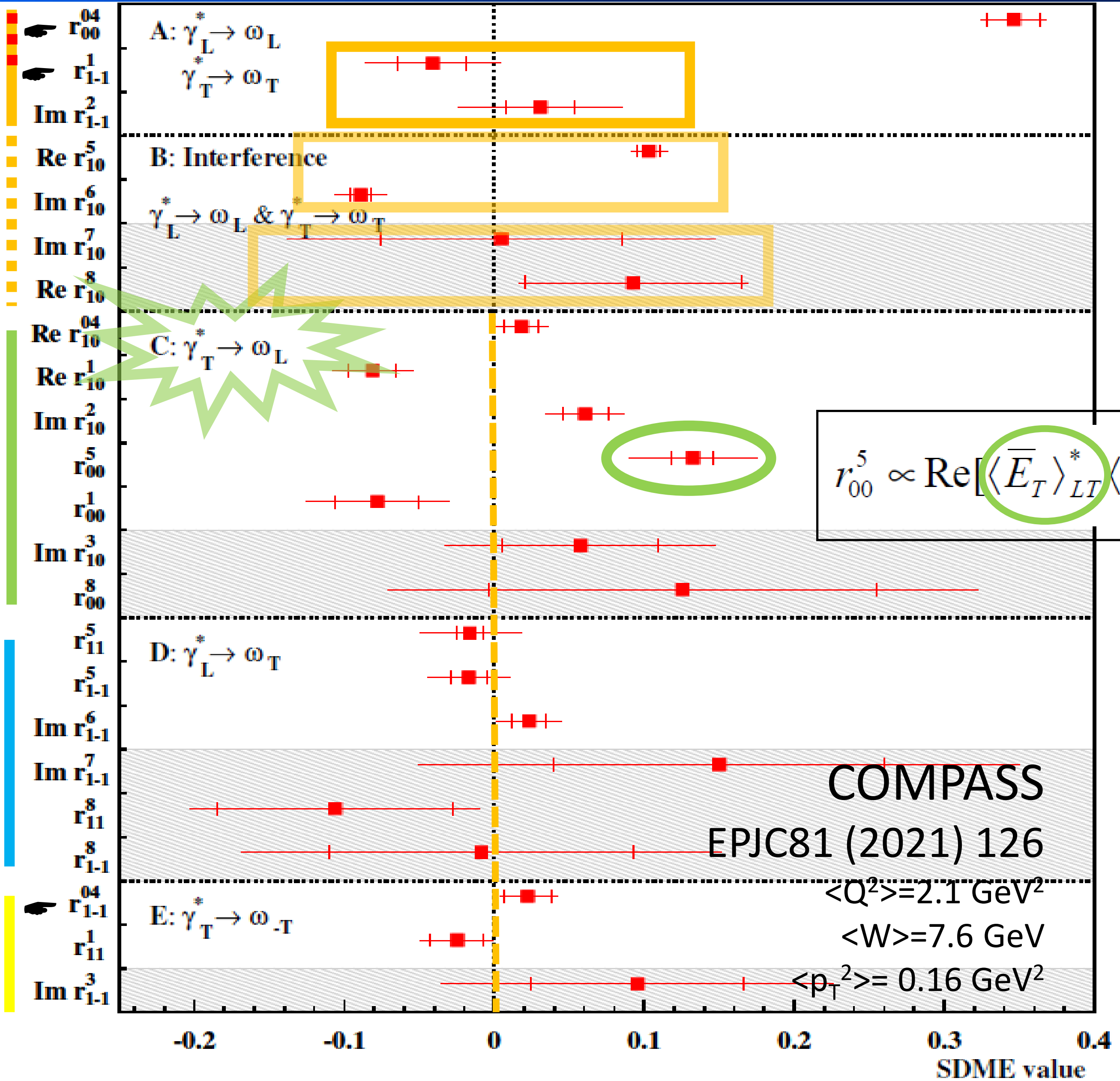
$$r^5_{00} \propto \mathrm{Re}[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$$

From Goloskokov and Kroll, EPJC74 (2014) 2725

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

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

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

E and H_T already studied in exclusive ρ^0, ω production with transvers. polar. Target COMPASS 2004-7-10 data

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

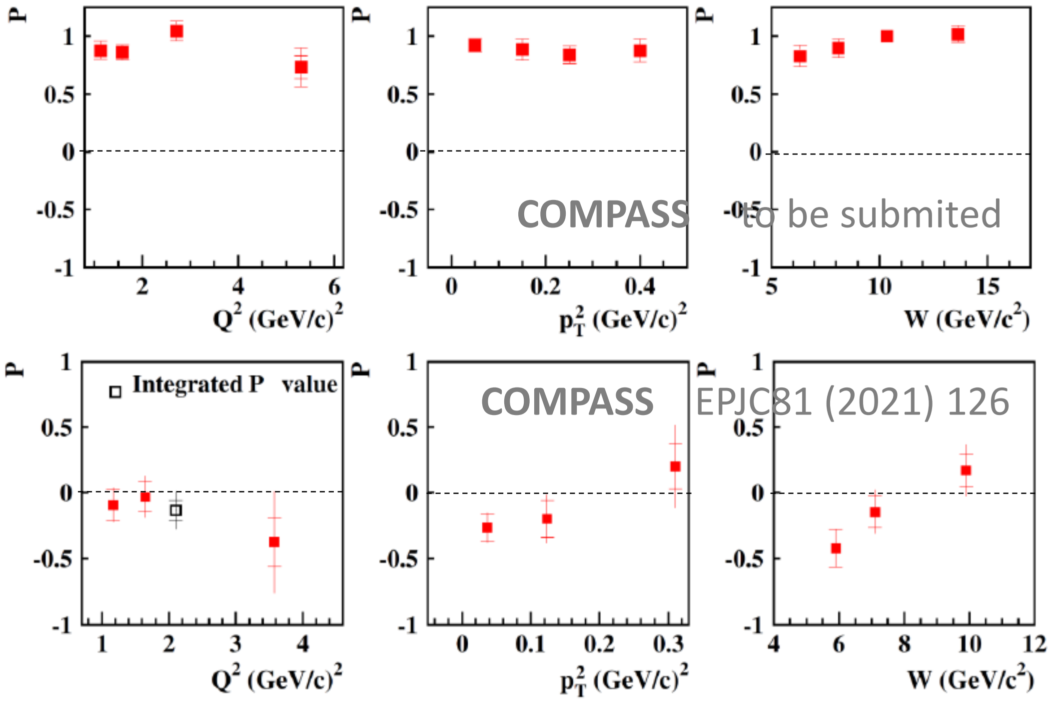
$$A^{\sin(\phi_s)}_{UT} \sim \mathrm{Im}\left[\langle H_T \rangle^*_{LT} \langle H \rangle_{LL}\right]$$

COMPASS 2012 Comparison ω and ρ^0 production

G-parity of ω is negative as for π ($\omega \to \pi^+ \pi^- \pi^0$ 89%)
G-parity of ρ^0 is positive ($\rho^0 \to \pi^+ \pi^-$ 100%)

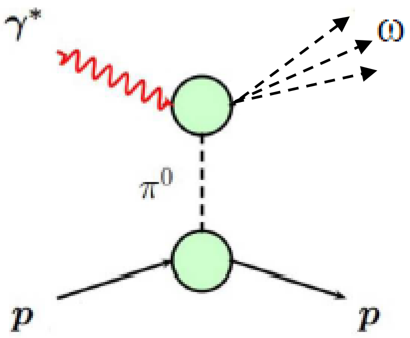
Natural (N) to Unatural (U) Parity Exchange for $\gamma_T^* \to V_T$

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



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

$\Gamma(\omega \to \pi^0 \gamma)$ = 9 $\times \Gamma(\rho^0 \to \pi^0 \gamma)$ as for the transition π^0V FF



It plays an important role in ω production for:

$\gamma_T^* \to V_T$

and

$\gamma_L^* \to V_T$

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 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$\mathcal{H}$ and 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