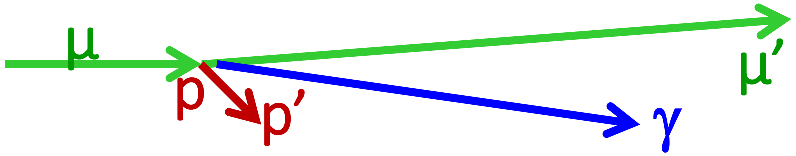
Hard Exclusive Reactions at COMPASS at CERN

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 : $\mu\ p \rightarrow \mu'\ p'\ \pi^0$

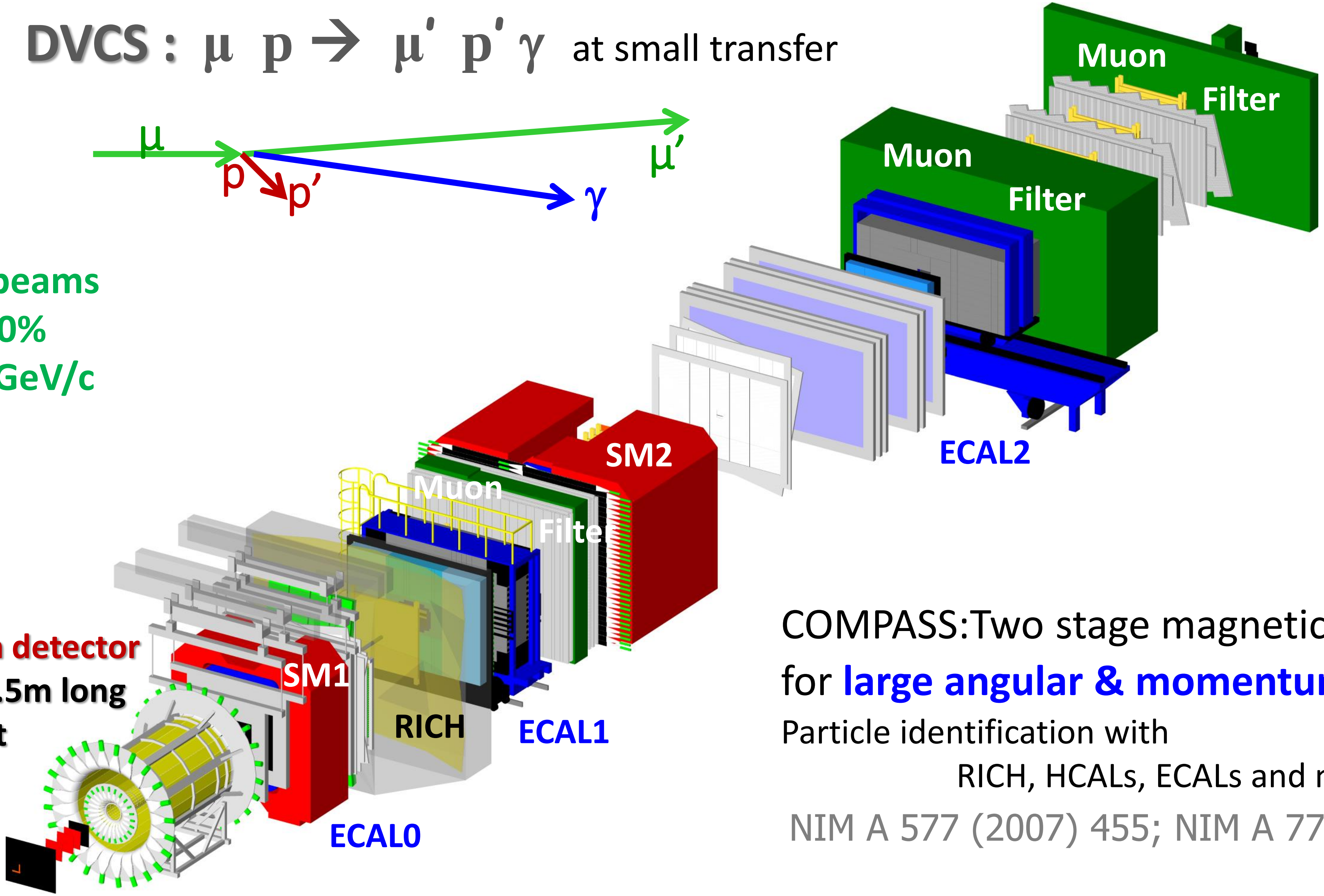
Markéta Pešková's talk today at 12:05

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

Measurement of exclusive cross sections at COMPASS

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

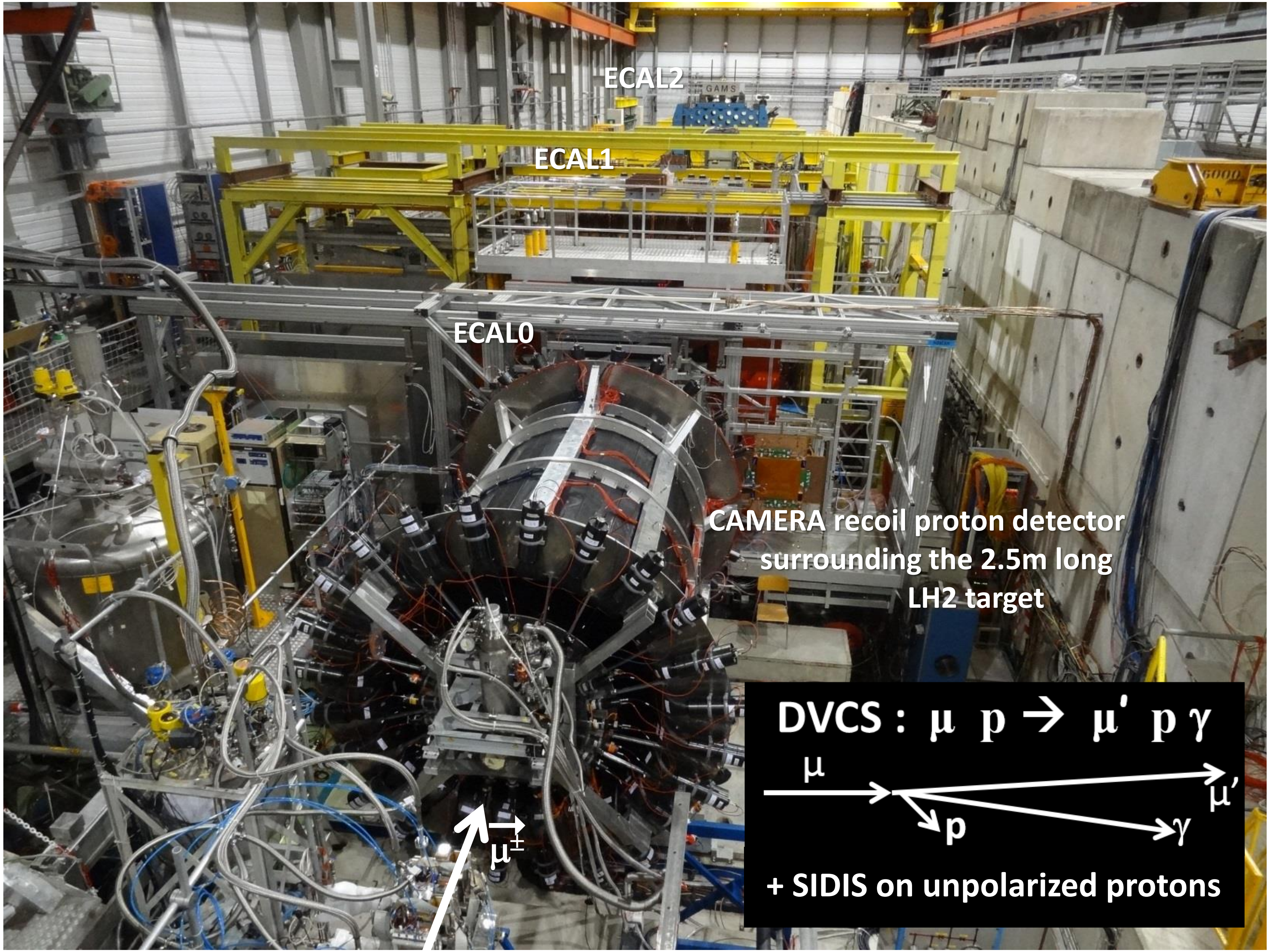
Both $\overleftarrow{\mu}^{+}$ and $\overrightarrow{\mu}^{-}$ beams
Polarisation ~ ±80%
Momentum 160 GeV/c



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



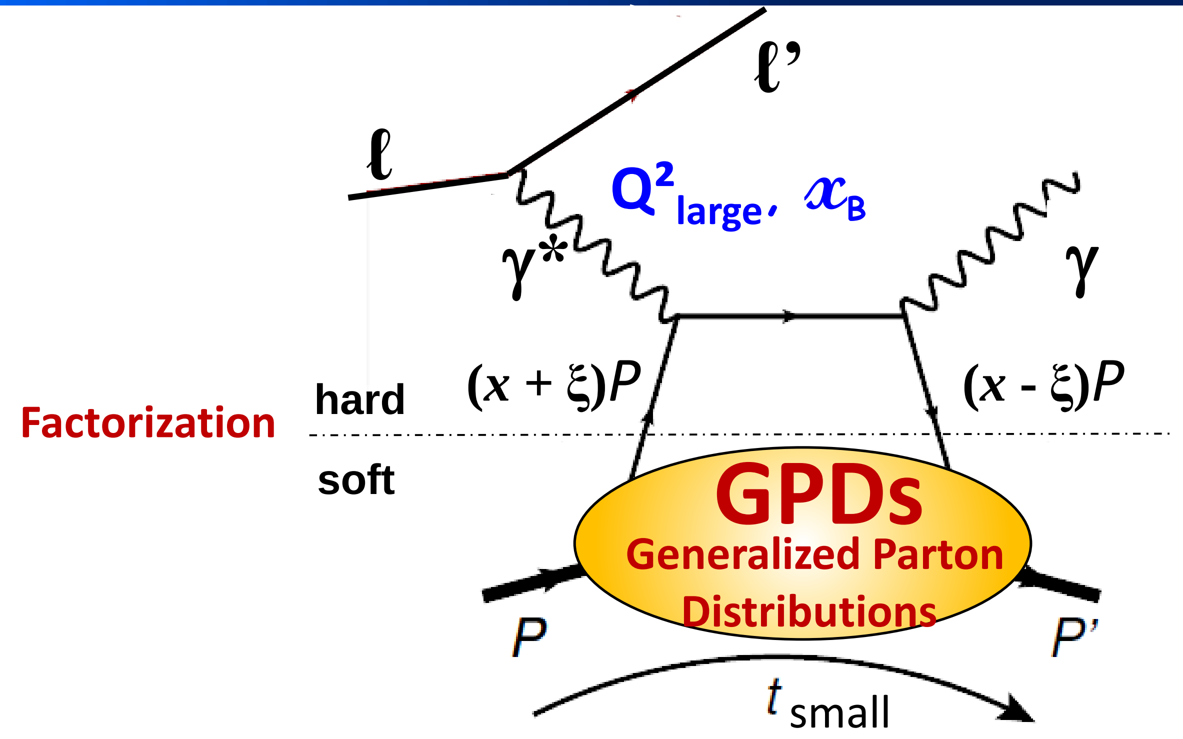
2012:

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: $\ell p \rightarrow \ell' p' \gamma$
the golden channel
because it interferes with
the Bethe-Heitler process

also meson production
$\ell p \rightarrow \ell' p' \pi, \rho, \omega$ or ϕ or J/ψ...

The GPDs depend on the following variables:

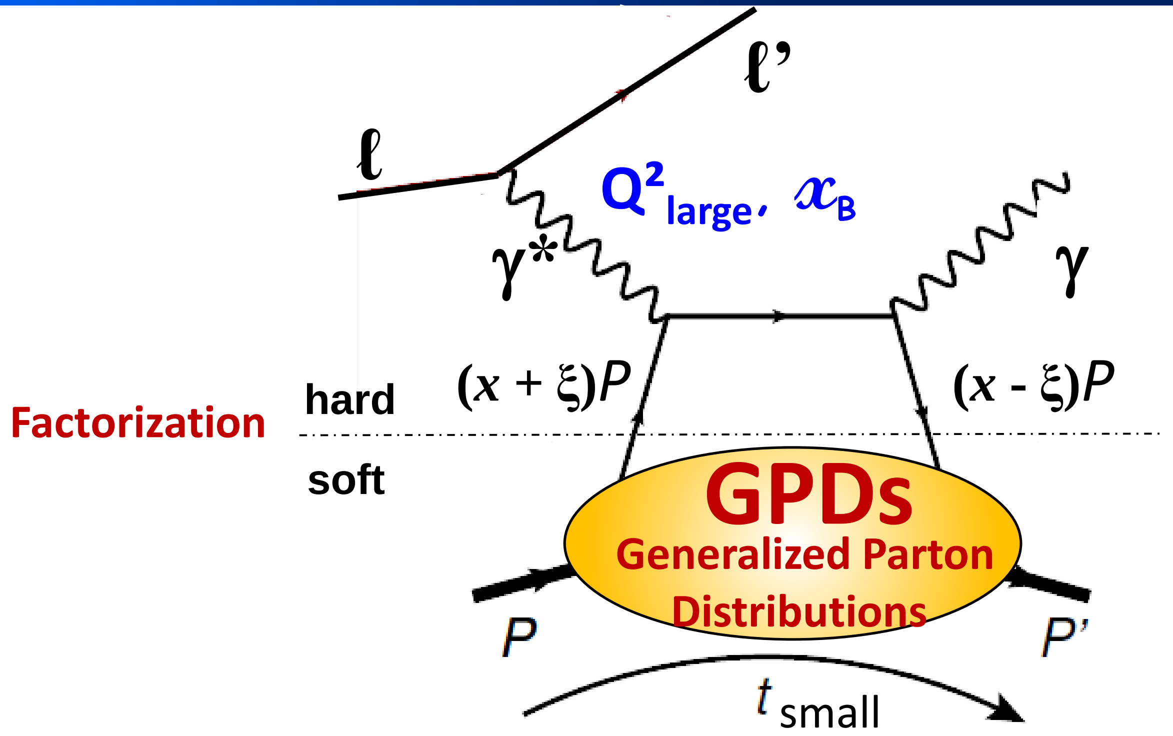
x: average
ξ: transferred
} quark longitudinal momentum fraction

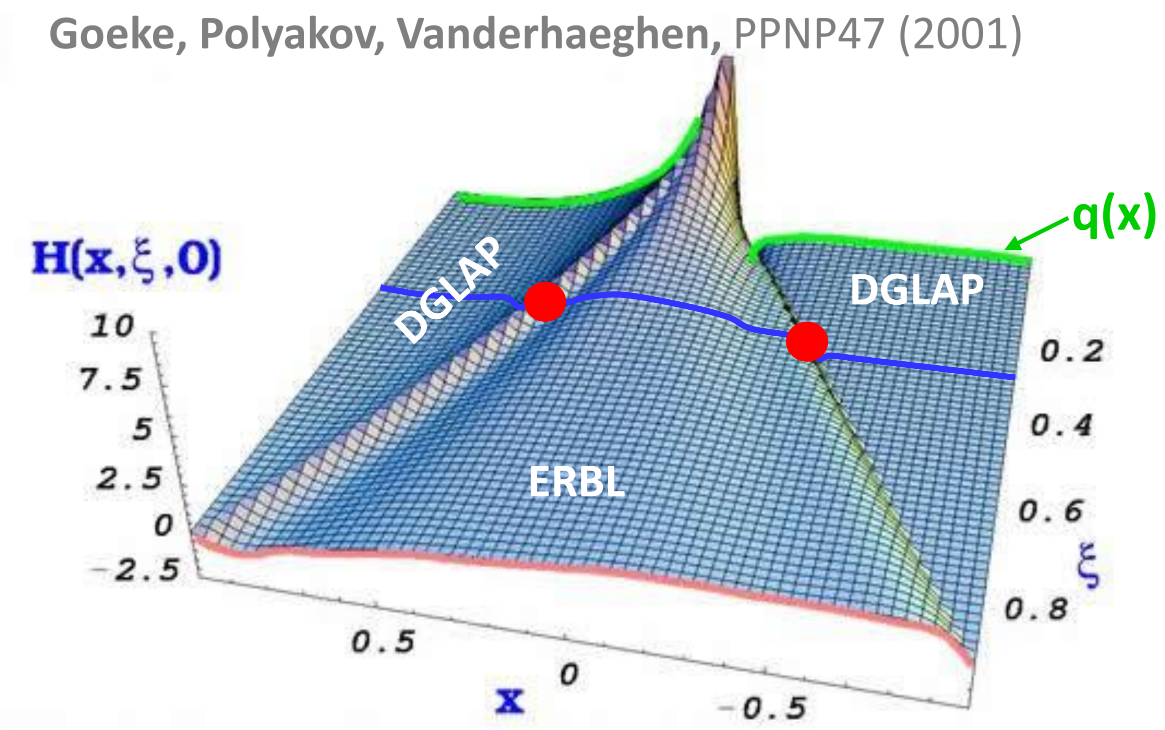
t: proton momentum transfer squared
related to $b_\perp$ via Fourier transform

The variables measured in the experiment:

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

Deeply virtual Compton scattering (DVCS)





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 $\mathcal{H}$

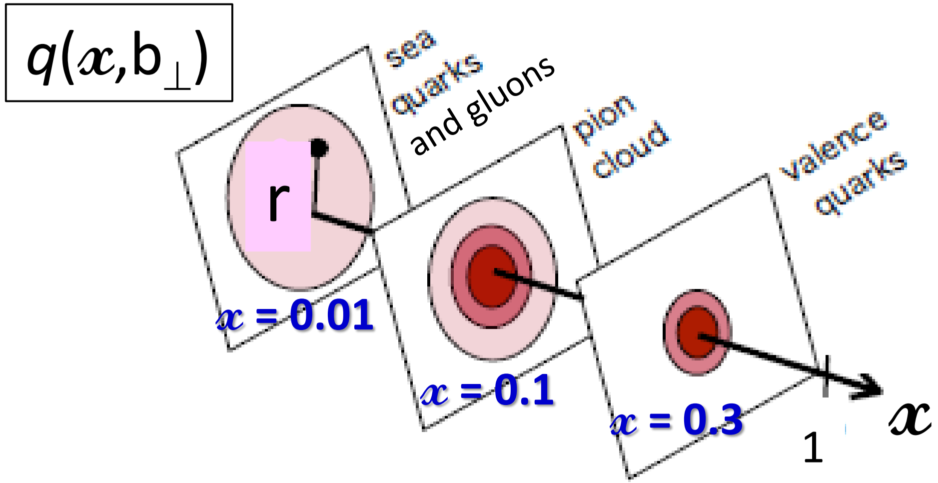
$$Re\mathcal{H}(\xi,t) = \pi^{-1}\int_0^1 dx \, \frac{2x \, Im\mathcal{H}(x,t)}{x^2-\xi^2} + \Delta(t)$$

Deeply virtual Compton scattering (DVCS)

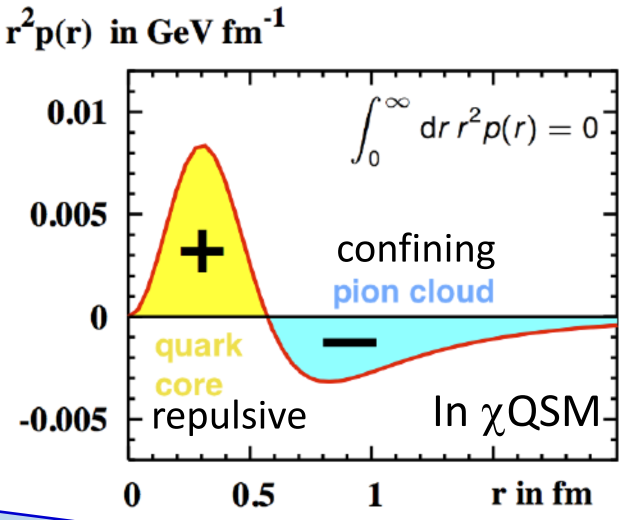
M. Burkardt, PRD66(2002)

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

Mapping in the transverse plane



Pressure Distribution



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

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

Real part **Imaginary part**

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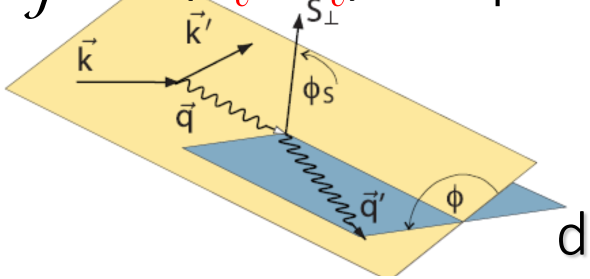
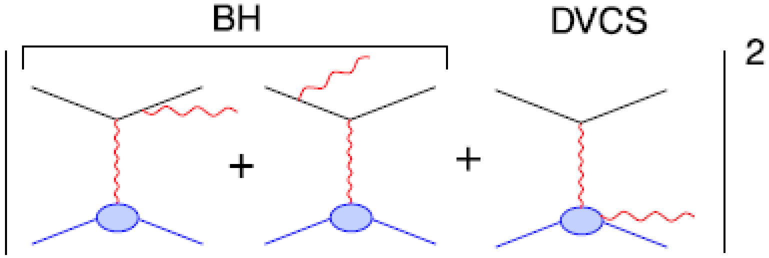
D-term $d_1(t)$

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





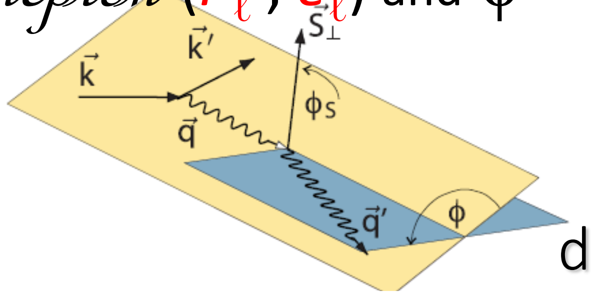
$$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2 + \text{Interference Term}$$

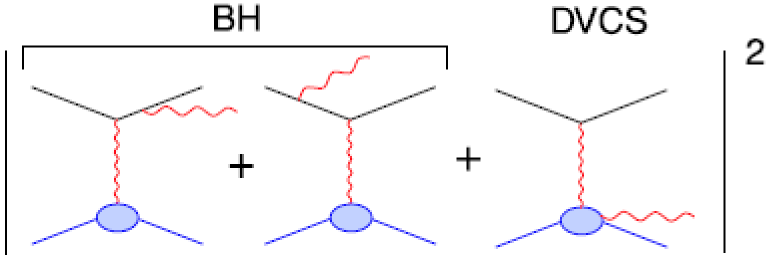
$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}\right) + (e_\ell \mathrm{Re}\, I + e_\ell P_\ell\, \mathrm{Im}\, I)$$

Well known

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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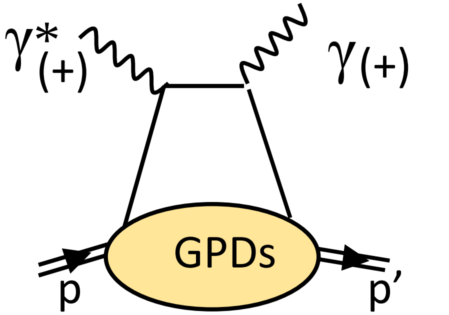
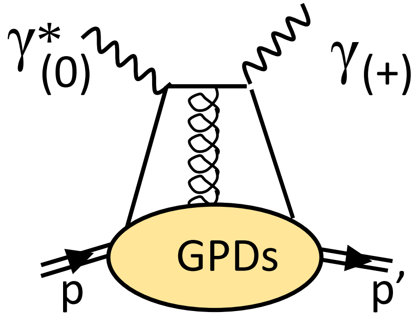
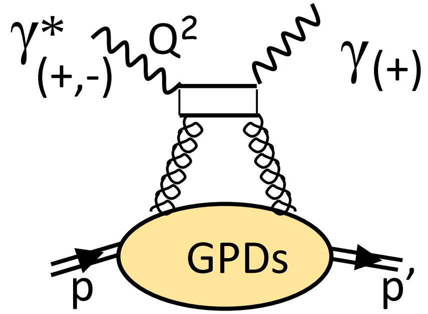


LO,Twist-2



Twist-3
suppressed by 1/Q



Twist-2, NLO
double helicity flip
suppressed by α_s

With unpolarized target:

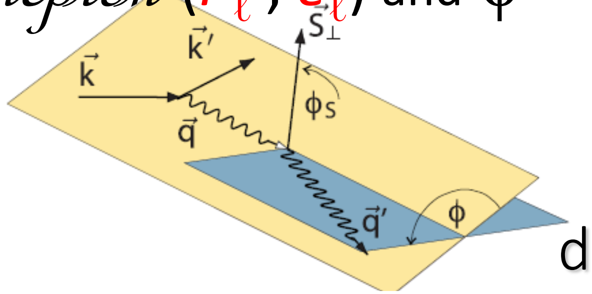
Belitsky, Müller, Kirner, NPB629 (2002)

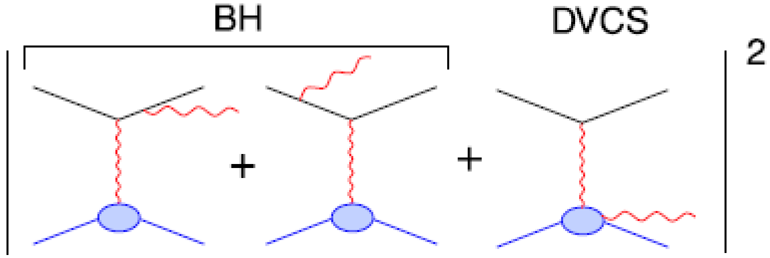
$$\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma^{DVCS}_{pol} &\propto s_1^{DVCS}\sin\phi \\
\mathrm{Re}\, I &\propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi +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

α_s suppressed

Deeply virtual Compton scattering (DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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

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

Well known

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

❶ beam charge-spin sum

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

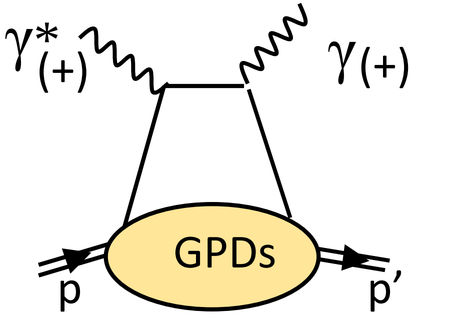
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

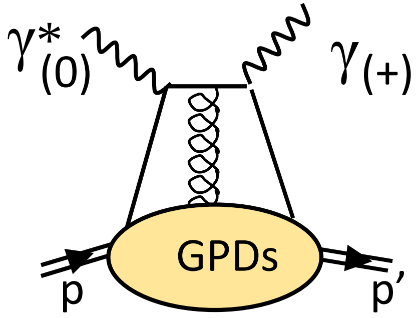
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

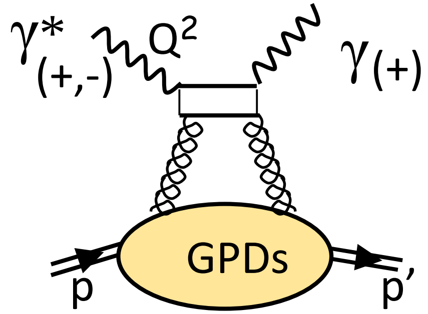
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



LO,Twist-2



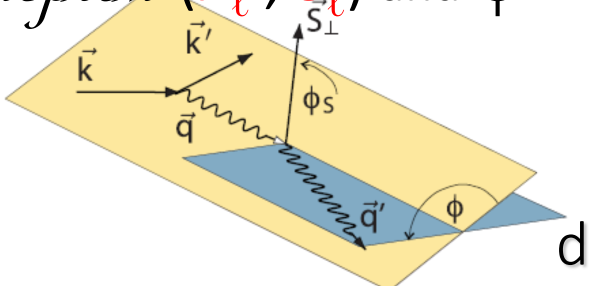
Twist-3
suppressed by 1/Q

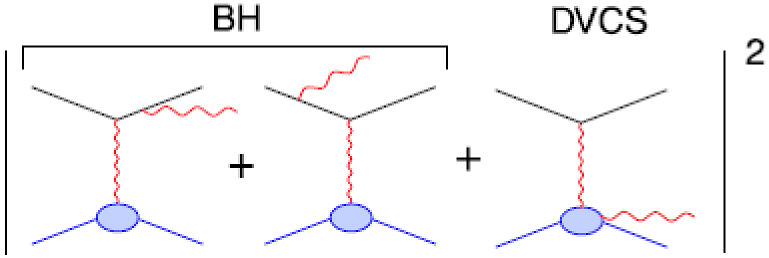


Twist-2, NLO
double helicity flip
suppressed by α_s

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 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

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

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

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

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

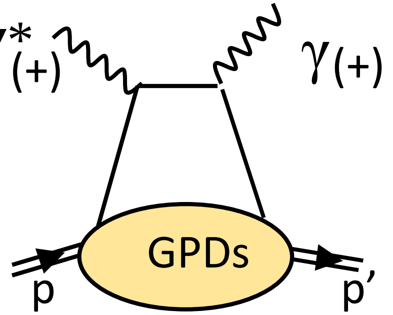
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

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

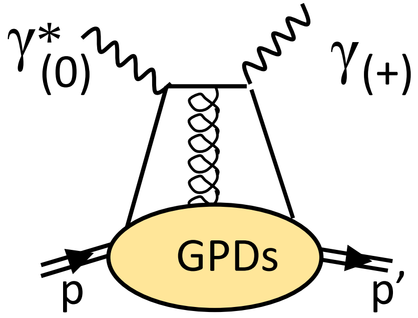
$s_1^I \propto \mathrm{Im}\,\mathcal{F}$

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

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

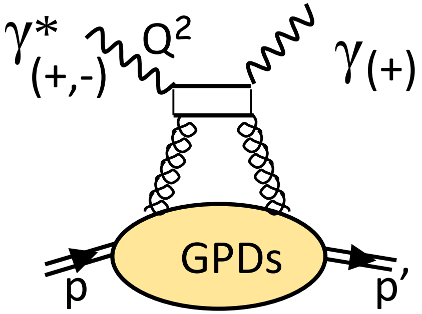


LO,Twist-2



Twist-3

suppressed by 1/Q



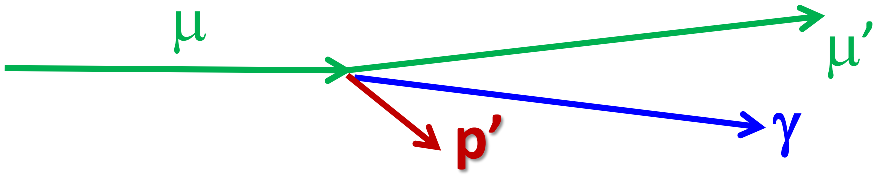
Twist-2, NLO

double helicity flip

suppressed by α_s

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

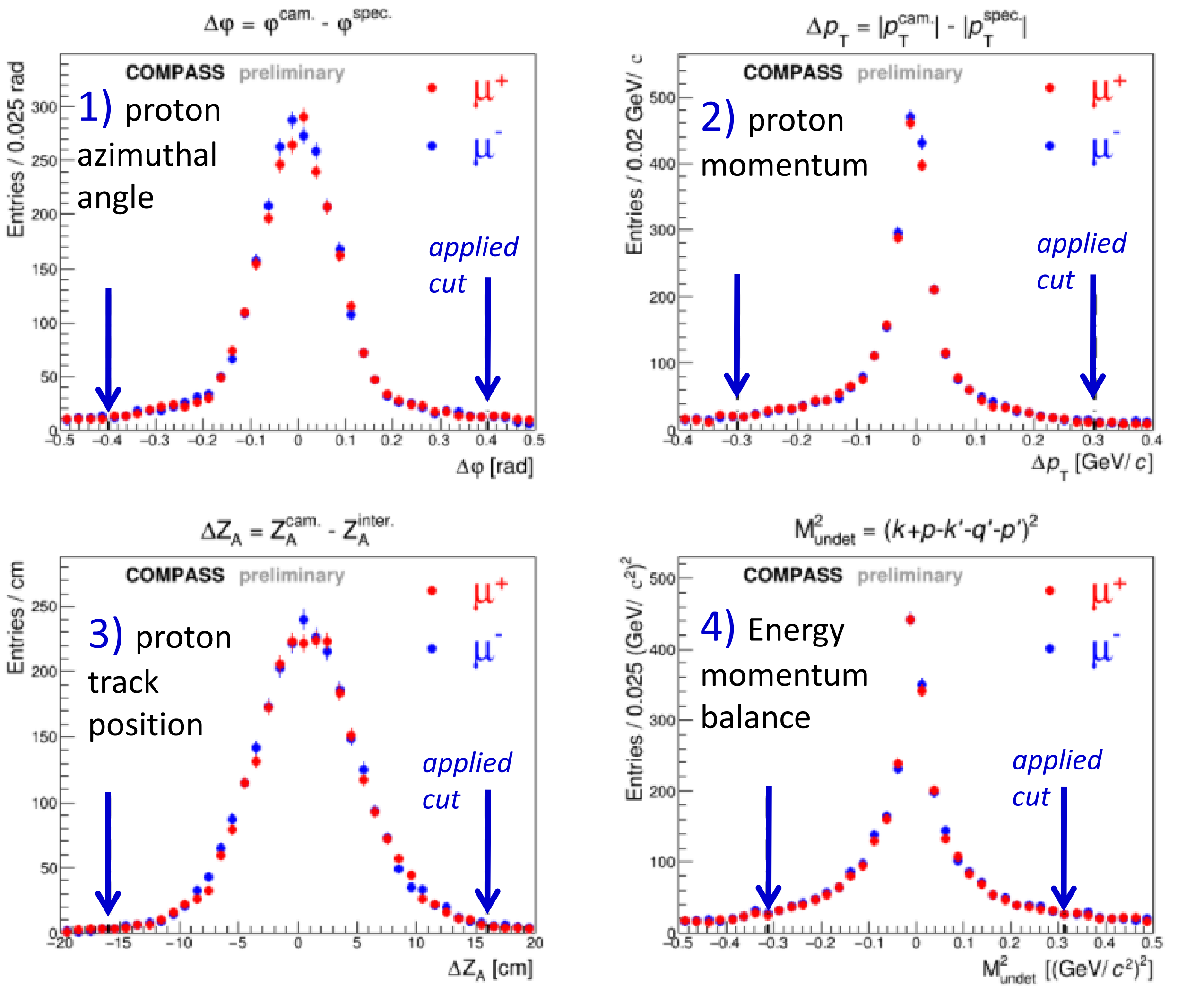
4) $M^2_{X=0} = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2$

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

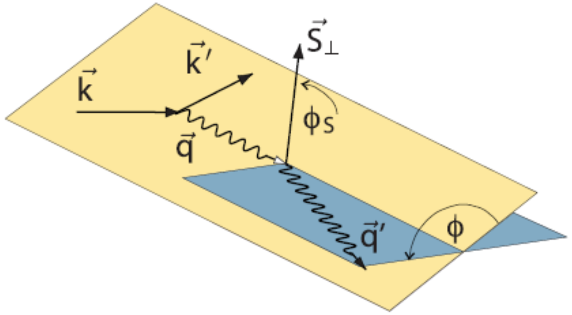
Important achievement for:

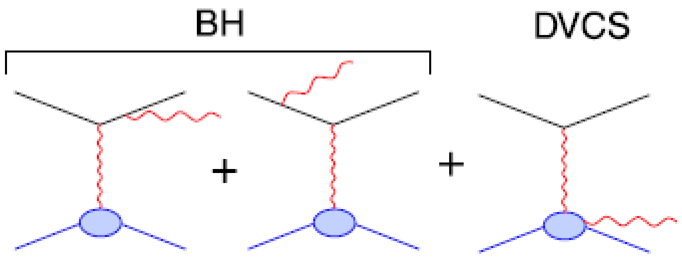
❶ $\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$ **Easier, done first**

❷ $\Delta \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$ **Challenging, but promising**



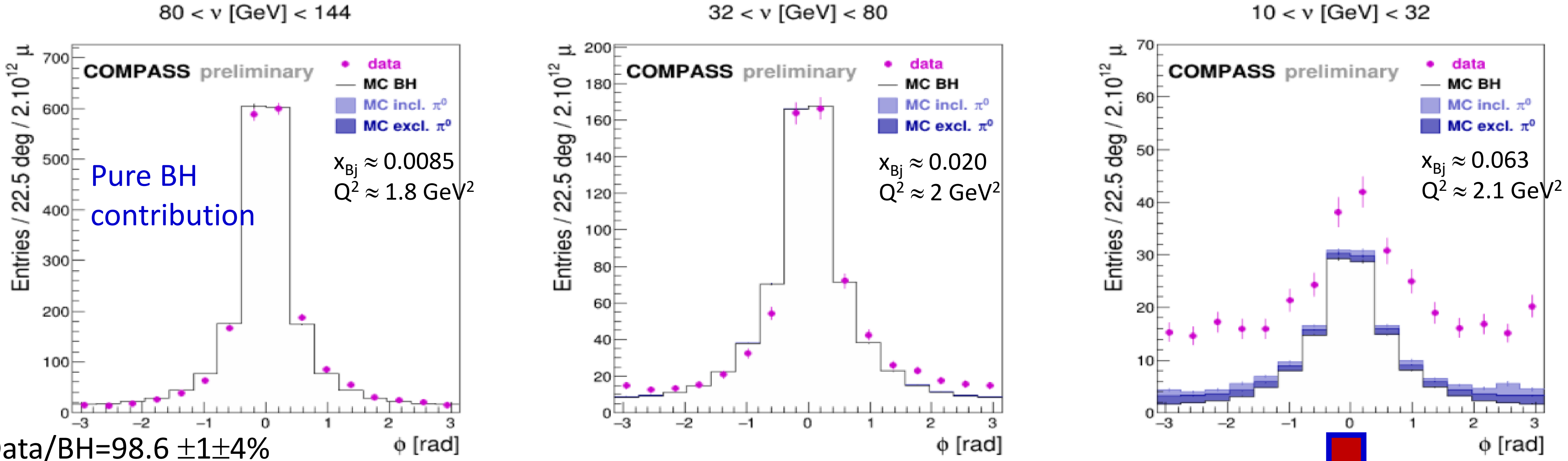
COMPASS 2016 data DVCS+BH cross section at Eμ=160 GeV





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

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



Data/BH=98.6 ±1±4%

DVCS above the BH contrib.

MC: BH contribution evaluated for the integrated luminosity
$\pi°$ 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:

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

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

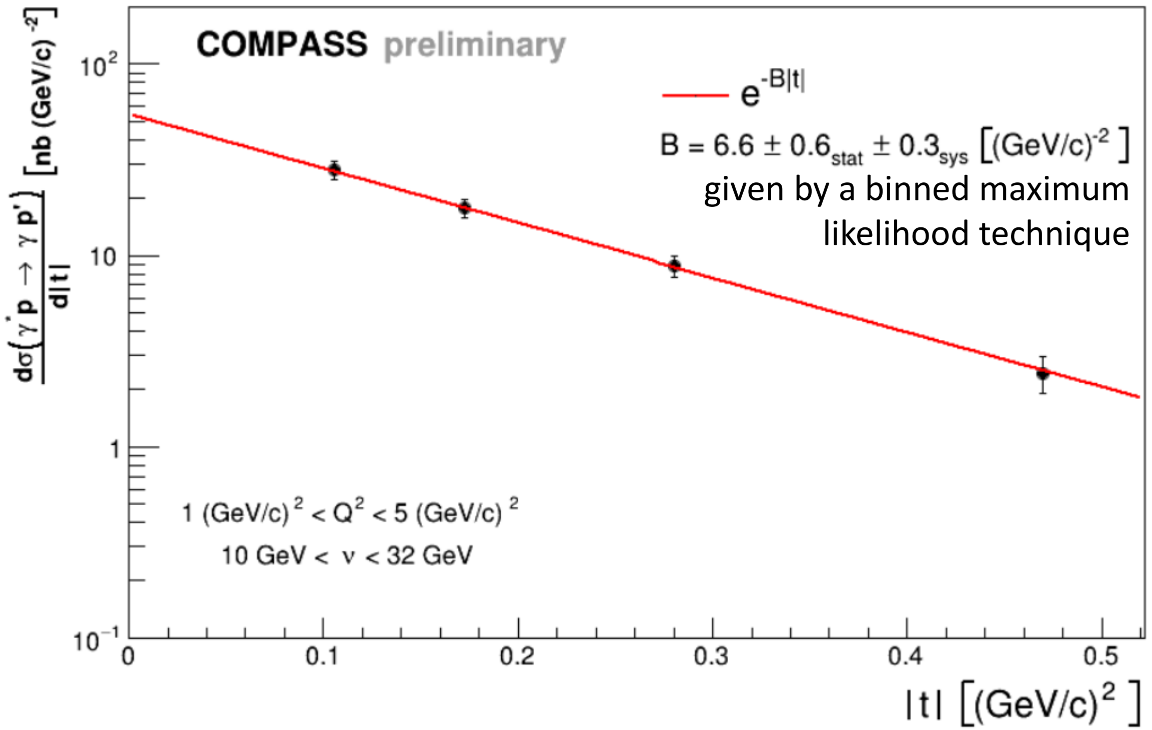
calculable
can be subtracted

All the other terms are cancelled in the integration over ϕ

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

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

Flux for transverse virtual photons



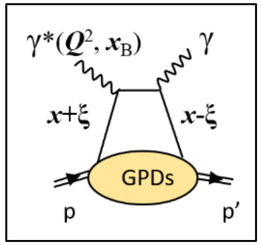
COMPASS 2016 Transverse extention of partons in the sea quark range

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

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

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

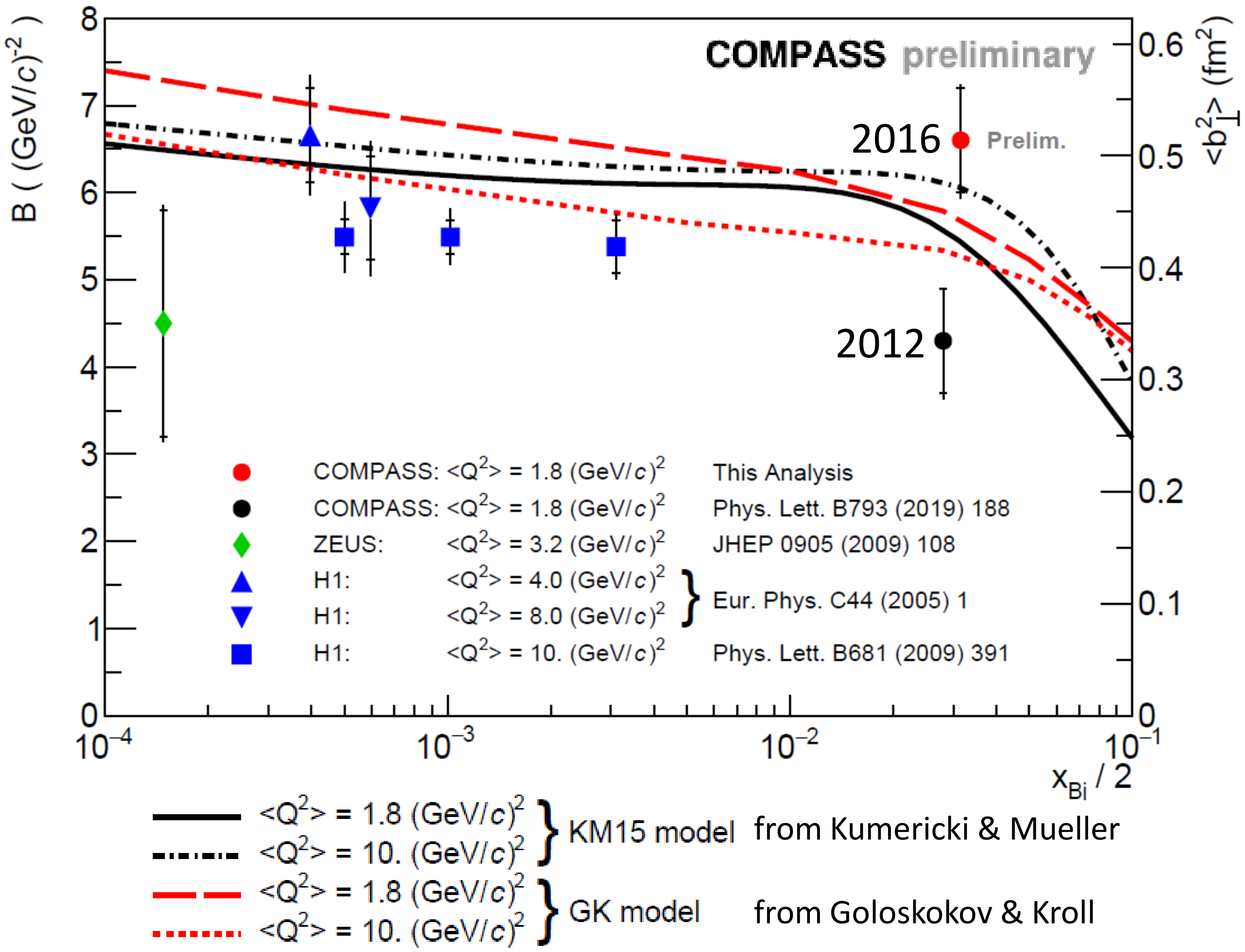
$Im\mathcal{H}$ = ***H*** (x=ξ, ξ, t)
$x = \xi \approx x_B/2$ close to 0



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

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

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



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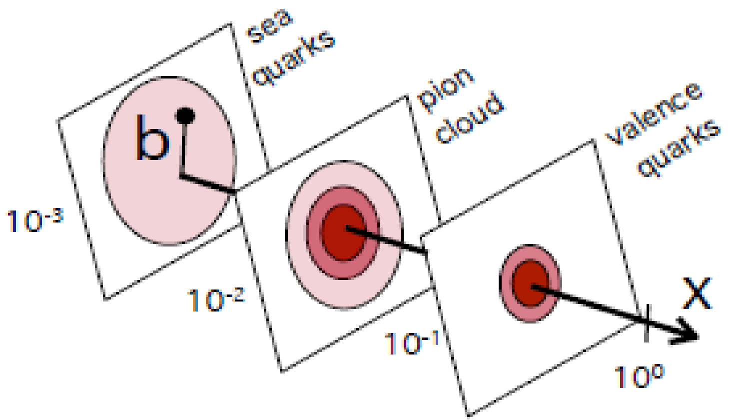
$$\langle b_\perp^2(x)\rangle \approx 2B(\xi)$$



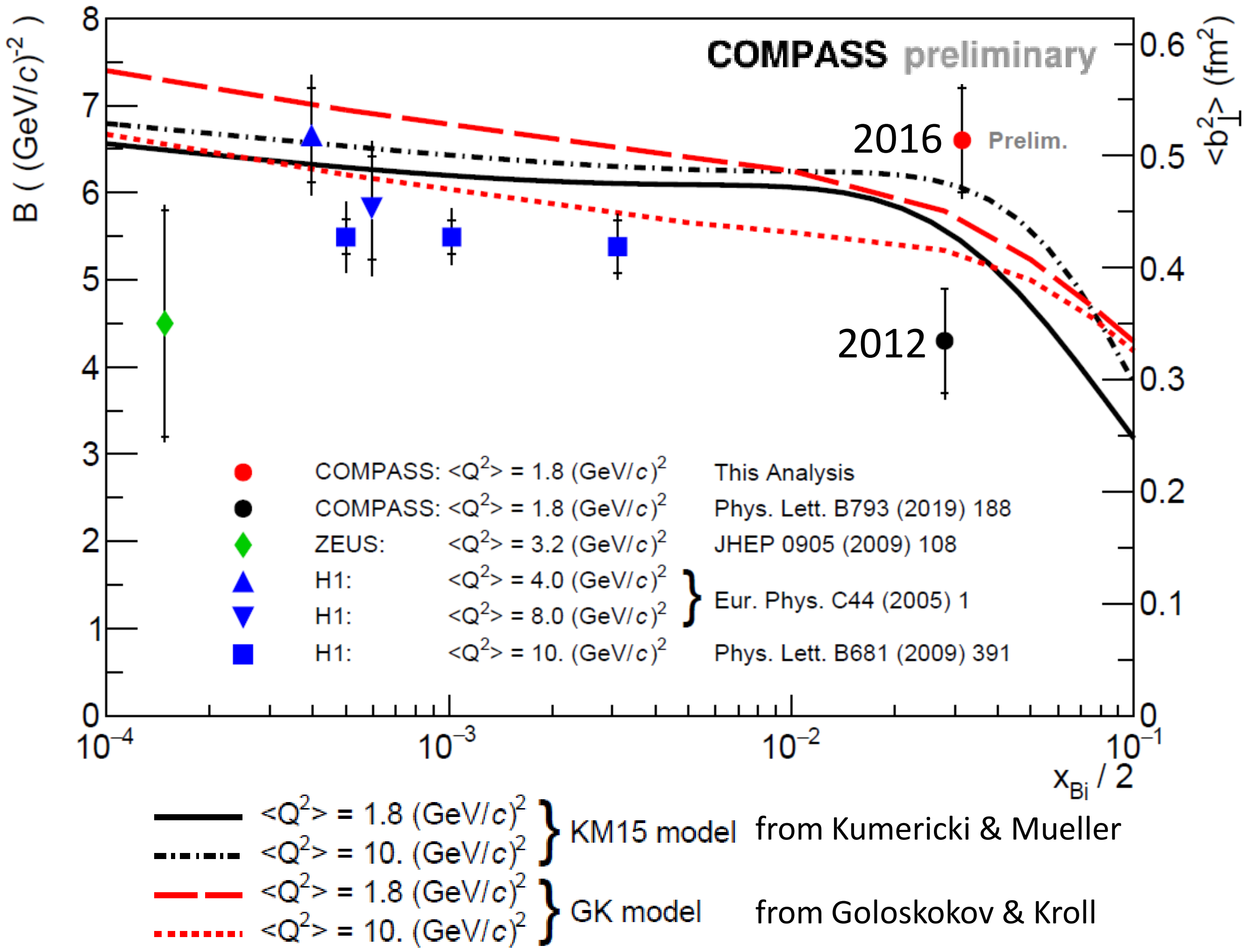
3σ difference between 2012 and 2016 data

- more advanced analysis with 2016 data
- π^0 contamination with different thresholds
- binning with 3 variables (t, Q^2, ν) or 4 variables (t, ϕ, Q^2, ν)

2012 statistics = Ref

2016 analysed statistics = 2.3 × Ref

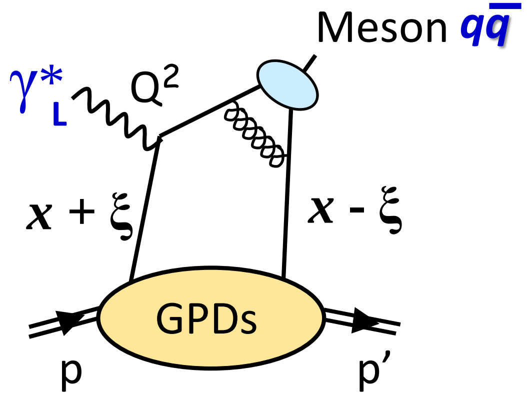
2016+2017 expected statistics = 10 × Ref



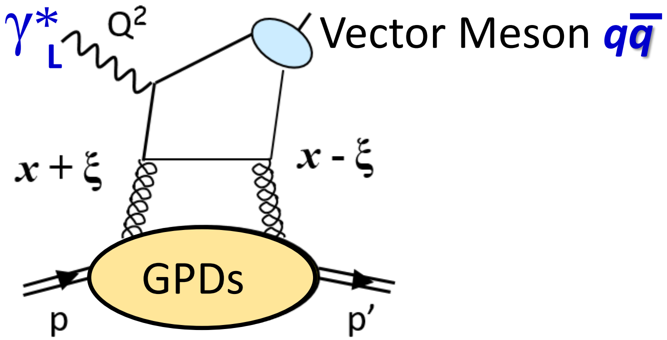
GPDs and Hard Exclusive Meson Production

Factorisation proven only for σ_L

Quark contribution



Gluon contribution at the same order in α_S



The meson wave function
Is an additional non-perturbative term

4 chiral-even GPDs: helicity of parton unchanged

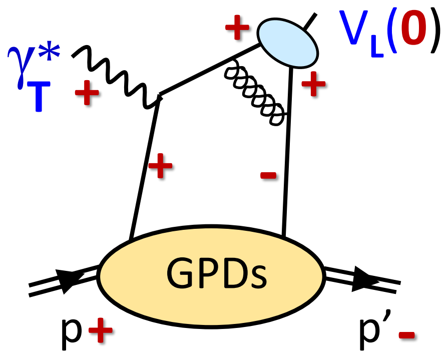
$\mathbf{H}^q(x, \xi, t)$	$\mathbf{E}^q(x, \xi, t)$ (as Sivers with OAM)	**For Vector Meson**
$\tilde{\mathbf{H}}^q(x, \xi, t)$	$\tilde{\mathbf{E}}^q(x, \xi, t)$	**For Pseudo-Scalar Meson**

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

$\mathbf{H}^q_T(x, \xi, t)$ (as transversity)	$\mathbf{E}^q_T(x, \xi, t)$	$\overline{\mathbf{E}}^q_T = 2\,\tilde{\mathbf{H}}^q_T + \mathbf{E}^q_T$ (as Boer-Mulders)
$\tilde{\mathbf{H}}^q_T(x, \xi, t)$	$\tilde{\mathbf{E}}^q_T(x, \xi, t)$	

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 $\mathbf{H}^q_T$
and to a twist-3 meson wave function



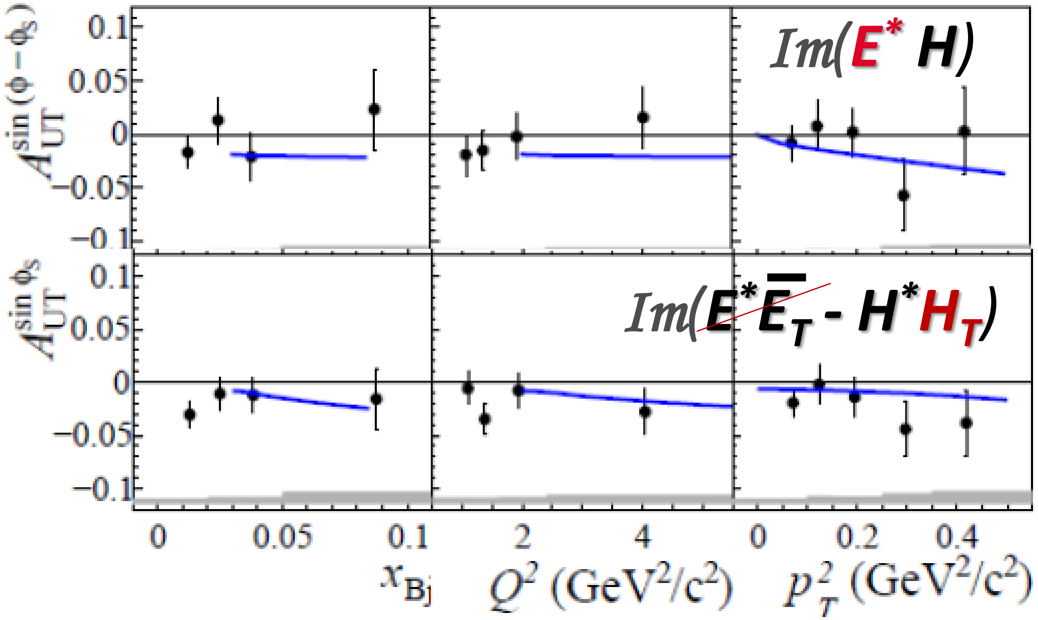
COMPASS 2010 2007 HEMP with Transversely Polarized Target without RPD

Gparity: G(π)=-1; G(ρ)=+1; G(ω)=-1

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

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

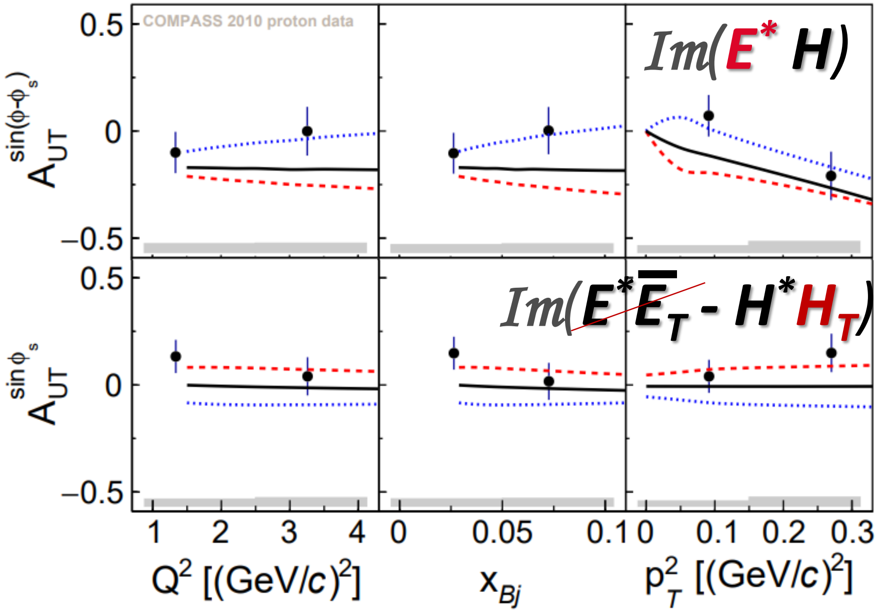
COMPASS, NPB 865 (**2012**) 1-20, PLB731 (**2014**) 19



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

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

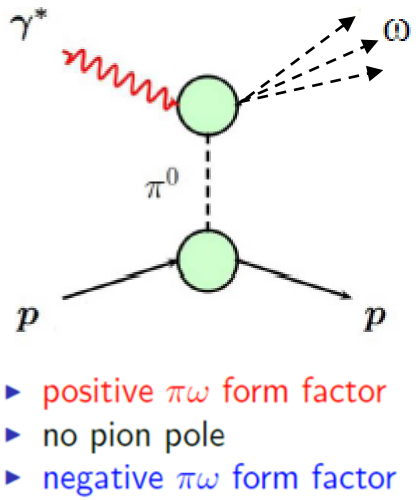
COMPASS, NPB 915 (**2017**)

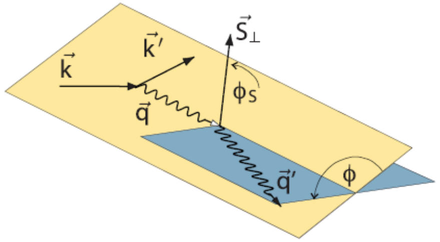


E^u and E^d of opposite sign

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

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



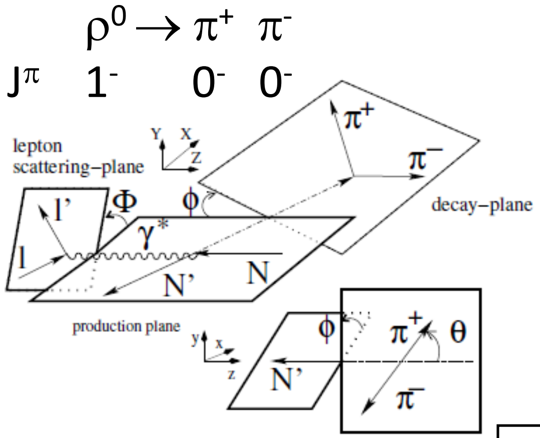


GK Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small x_B

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



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

$$\mathcal{W}^{U}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Big[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta \ \cos 2\phi$$

$$-\epsilon\cos 2\Phi\Big(r^{1}_{11}\sin^2\Theta + r^{1}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{1}_{10}\}\sin 2\Theta\cos\phi - r^{1}_{1-1}\sin^2\Theta\cos 2\phi\Big)$$

$$-\epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{2}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{2}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$

$$+\sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^{5}_{11}\sin^2\Theta + r^{5}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{5}_{10}\}\sin 2\Theta\cos\phi - r^{5}_{1-1}\sin^2\Theta\cos 2\phi\Big)$$

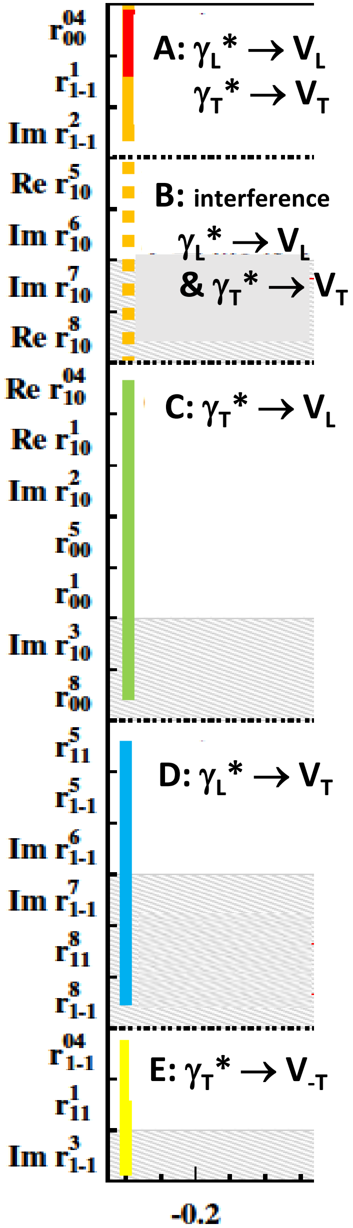
$$+\sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{6}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{6}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Big],$$

$$\mathcal{W}^{L}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Big[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r^{3}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{3}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$

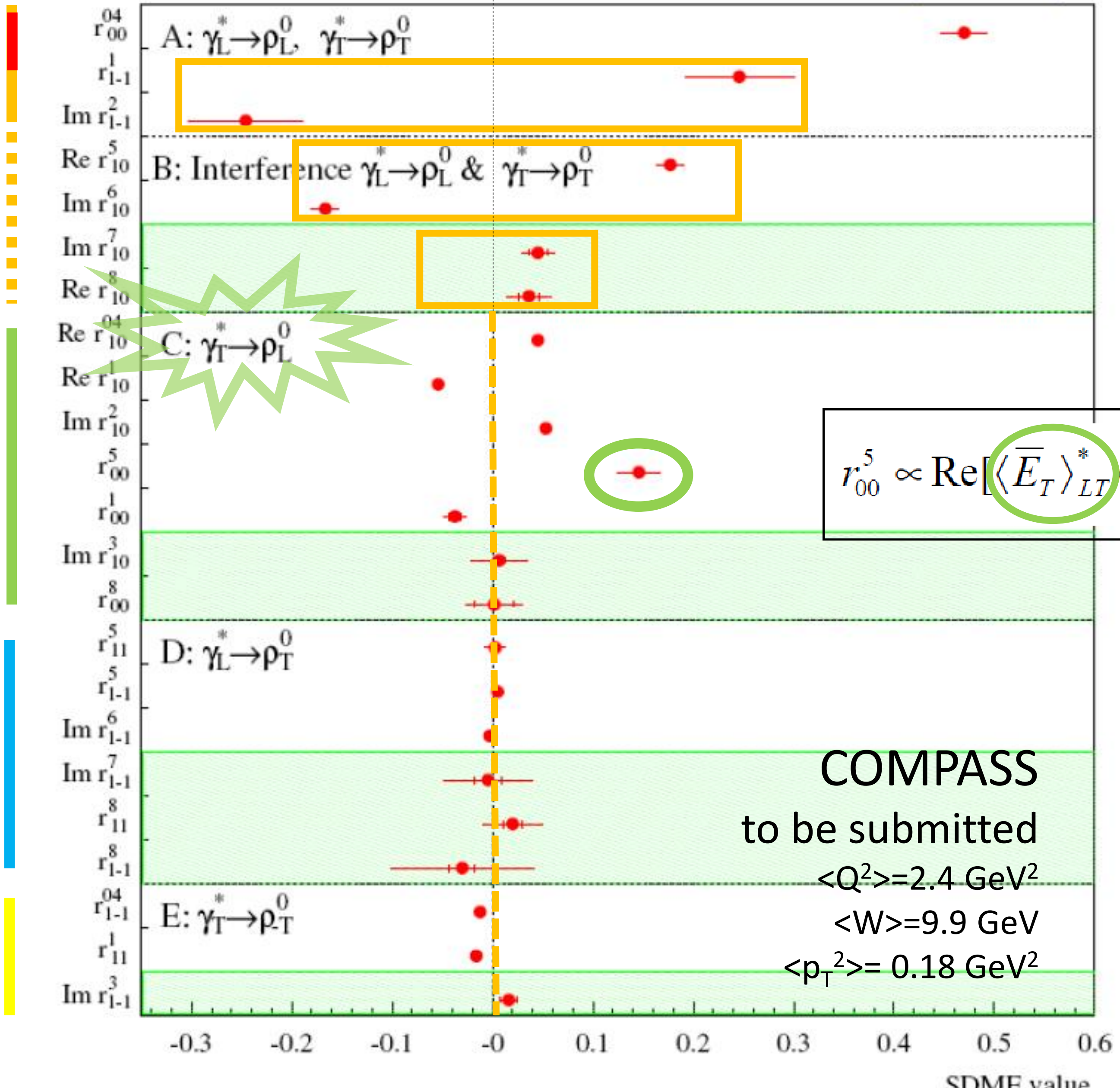
$$+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{7}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{7}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$

$$+\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^{8}_{11}\sin^2\Theta + r^{8}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{8}_{10}\}\sin 2\Theta\cos\phi - r^{8}_{1-1}\sin^2\Theta\cos 2\phi\Big)\Big]$$

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



COMPASS 2012 Exclusive ρ^0 production on unpolarized proton



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

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

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

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

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

not observed for class C

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

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 $\overline{E}_T$

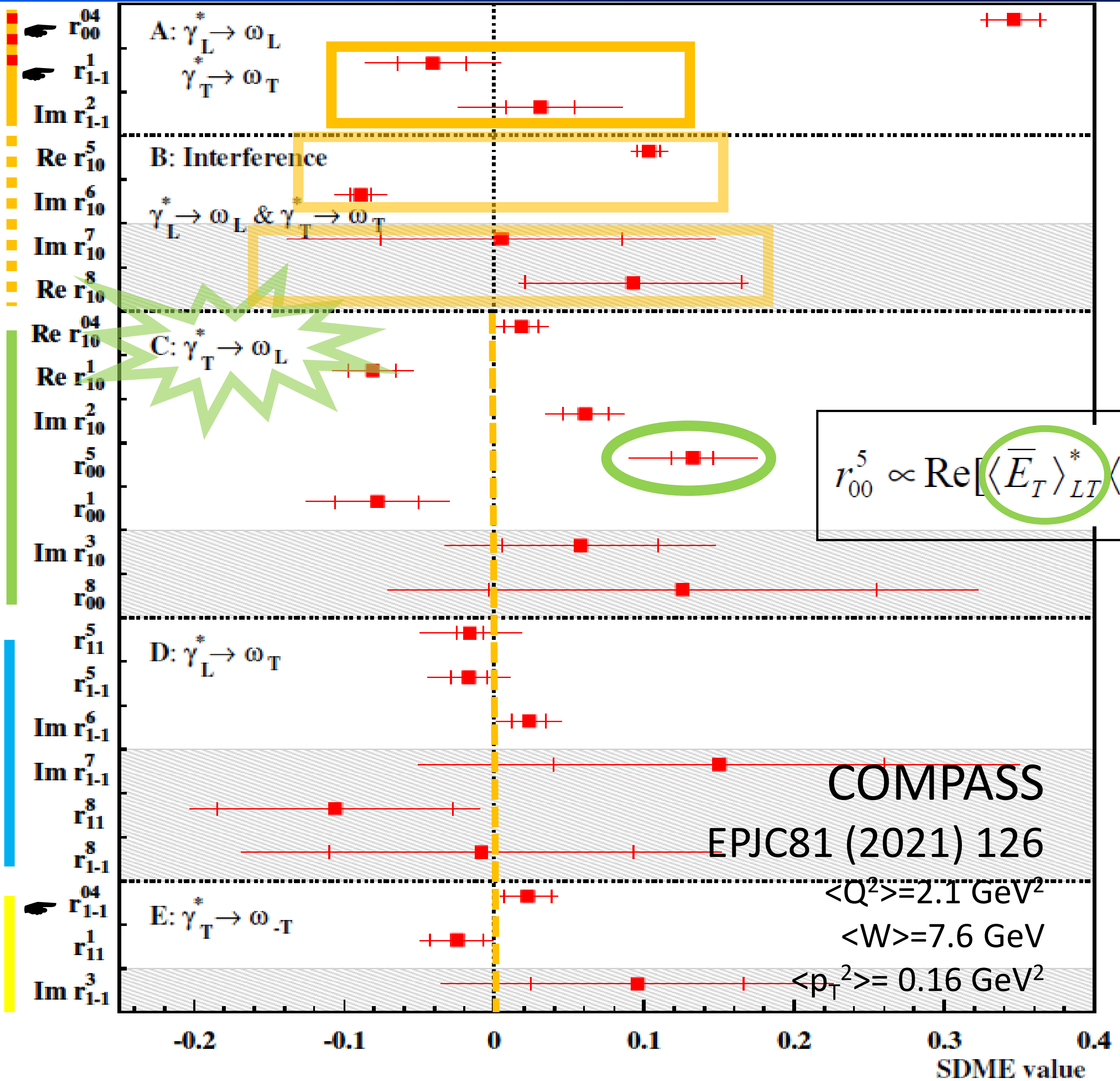
(H^u, H^d) of same sign

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

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

From Goloskokov and Kroll, EPJC74 (2014) 2725

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

➔ Both 2 terms are important

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

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

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

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

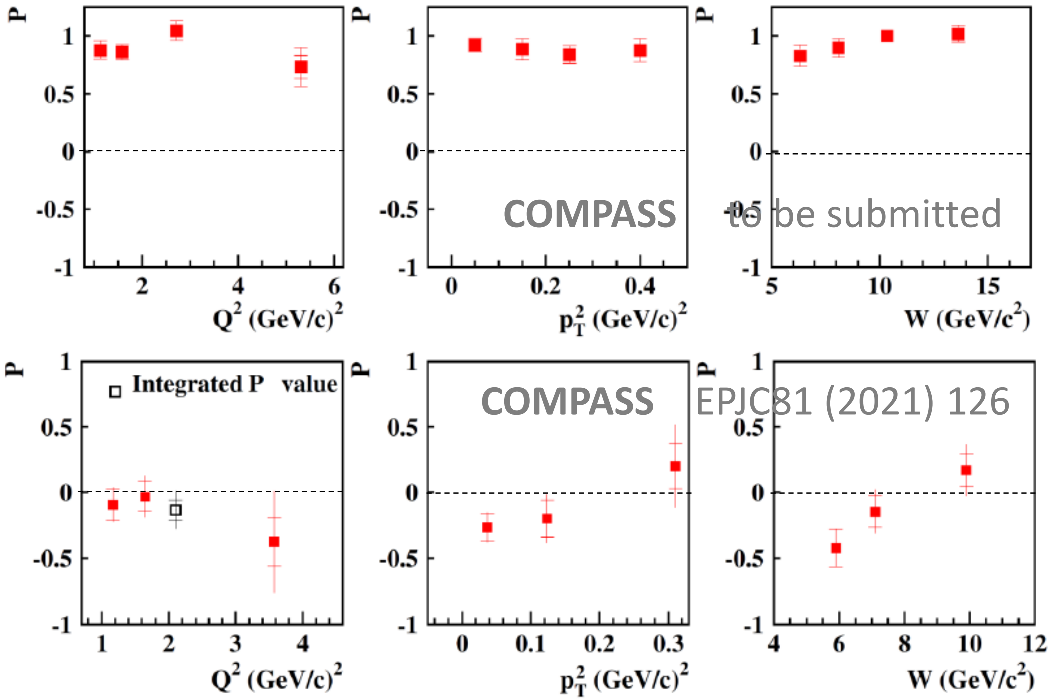
COMPASS 2012 Comparison ω and ρ^0 production

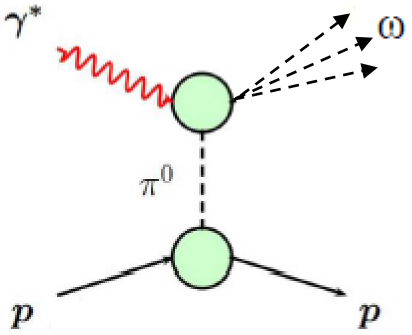
The pion pole exchange (UPE) is large for ω compared to ρ^0

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

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

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





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

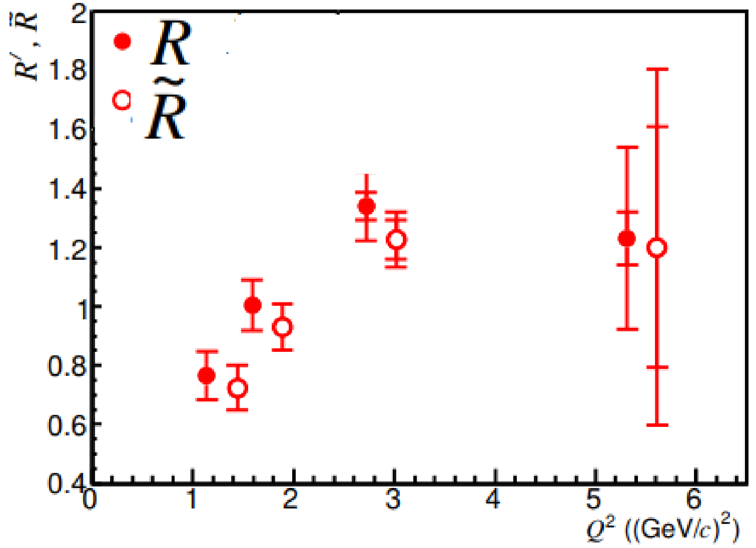
COMPASS 2012 $R = \sigma_L/\sigma_T$ for exclusive ρ^0 production

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

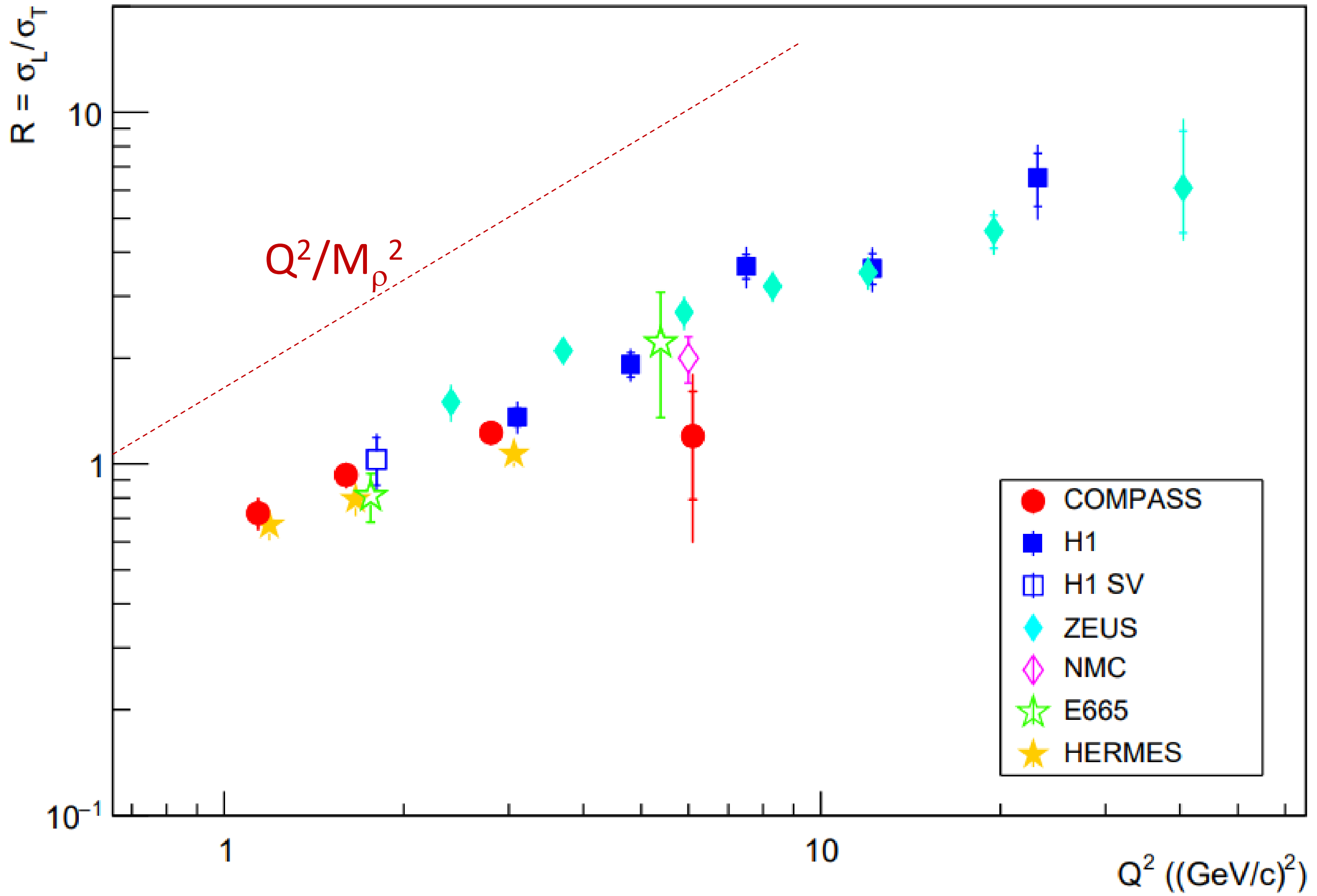
$$R = \frac{1}{\epsilon} \frac{r^{04}_{00}}{1 - r^{04}_{00}}$$ **only if SCHC**

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



COMPASS to be submitted

Deviation from the pQCD LO prediction in Q^2/M_ρ^2: QCD evolution and q_T

Transversize size effects of the meson smaller for σ_L than for σ_T

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

- ✓ DVCS and the difference $\Delta \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$

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

- ✓ On-going analysis (Cross section, SDME) for HEMP of π^0, ρ^0, ω, ϕ, J/ψ

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

Exclusive single photon events selection at high ν

μ^+ and μ^- yields renormalised to 10^{12} muons each

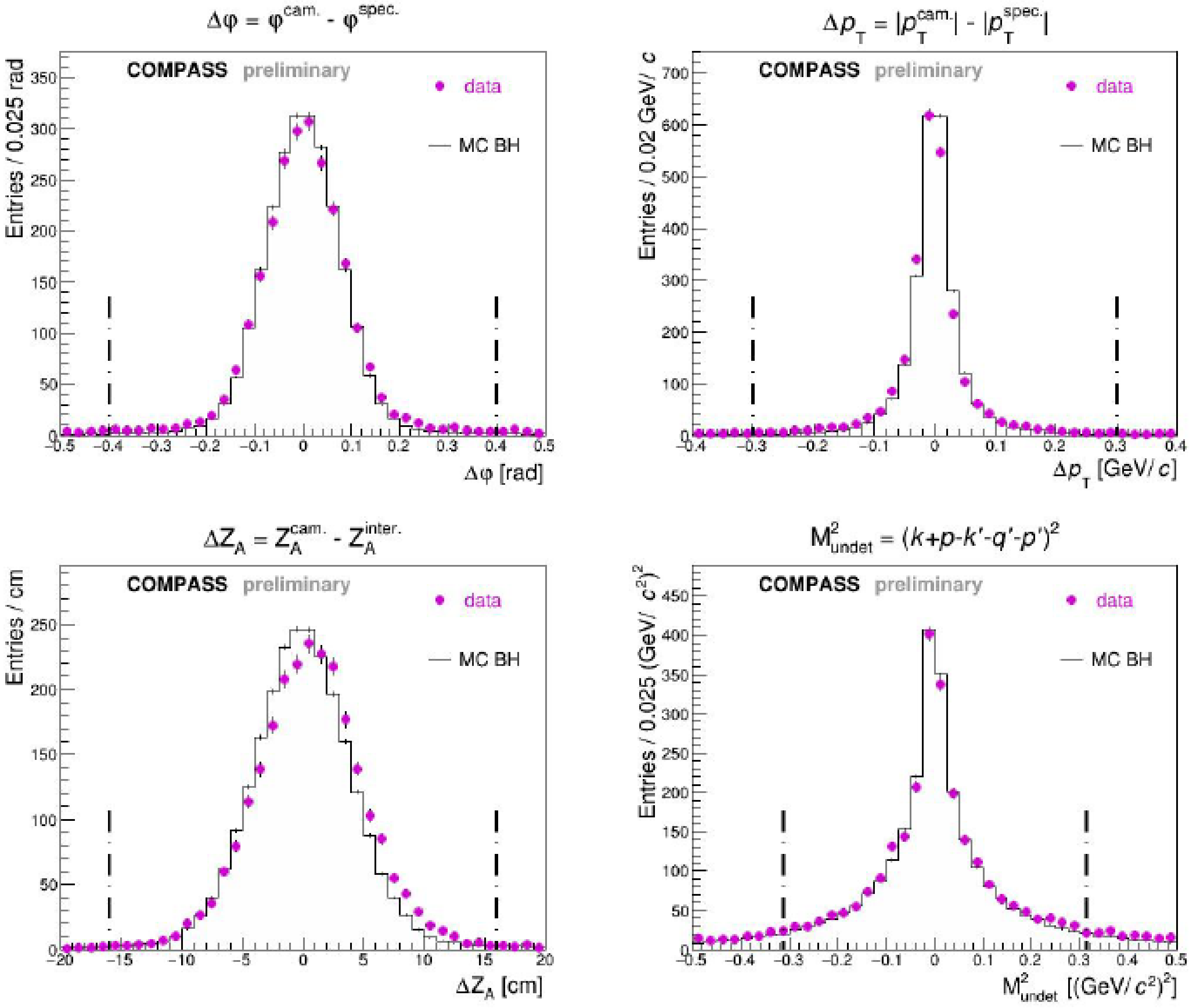
$80 < \nu$ [GeV] < 144

$\Delta\varphi = \varphi^{cam.} - \varphi^{spec.}$

$\Delta p_T = |p_T^{cam.}| - |p_T^{spec.}|$

$\Delta z_A = z_A^{cam.} - z_A^{spec.}$

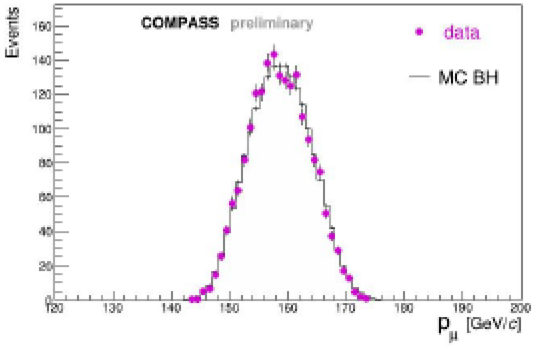
$M^2_{undet} = (k + p - k' - q' - p')^2$



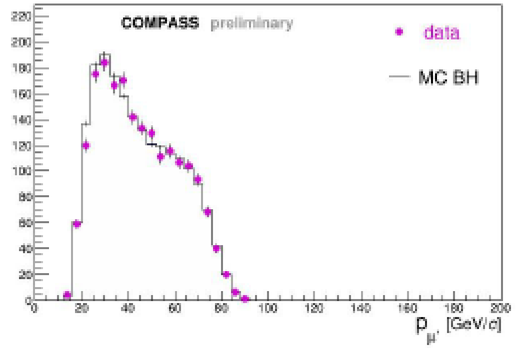
Each variable is plotted with the cuts on the 3 others applied

Muons

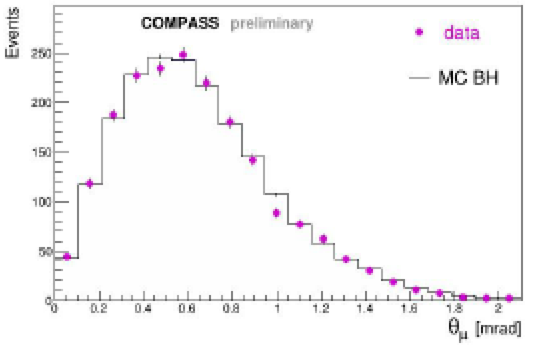
80 < ν [GeV] < 144

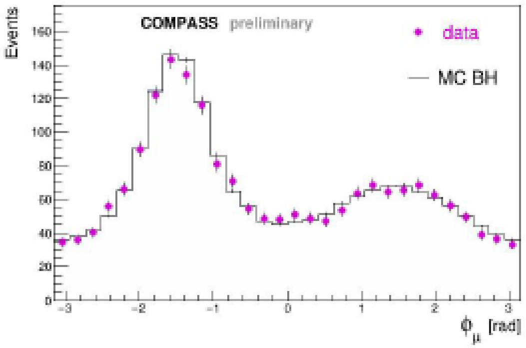


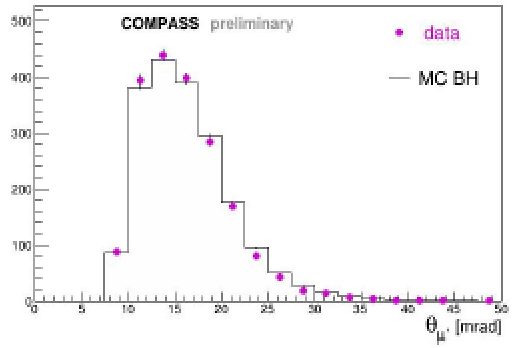
Beam muon

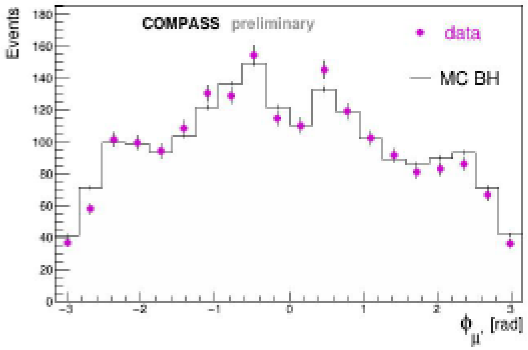


Scattered muon



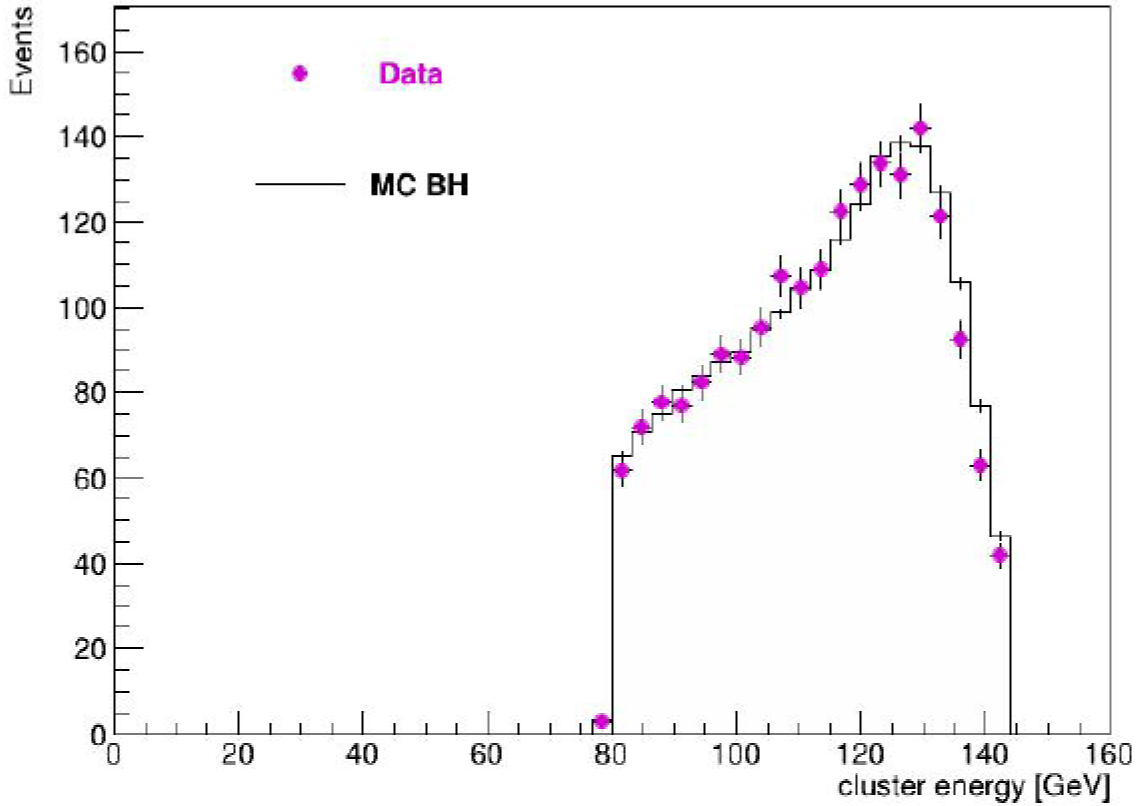


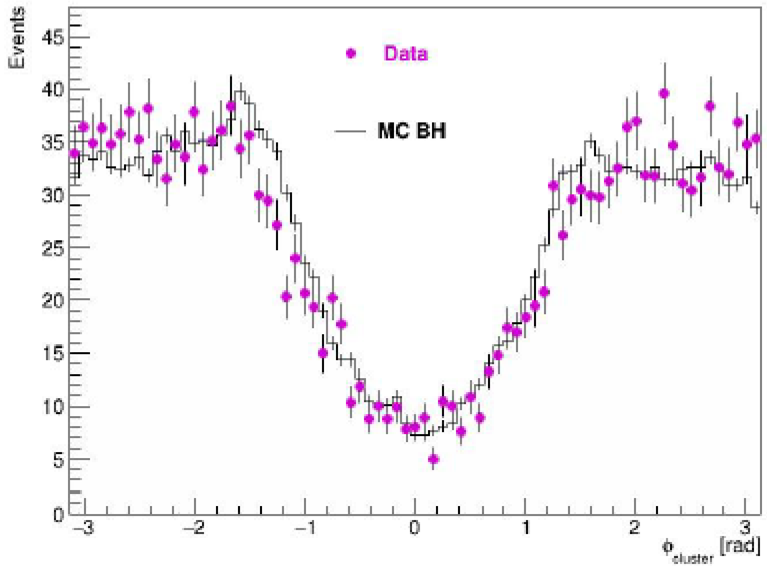


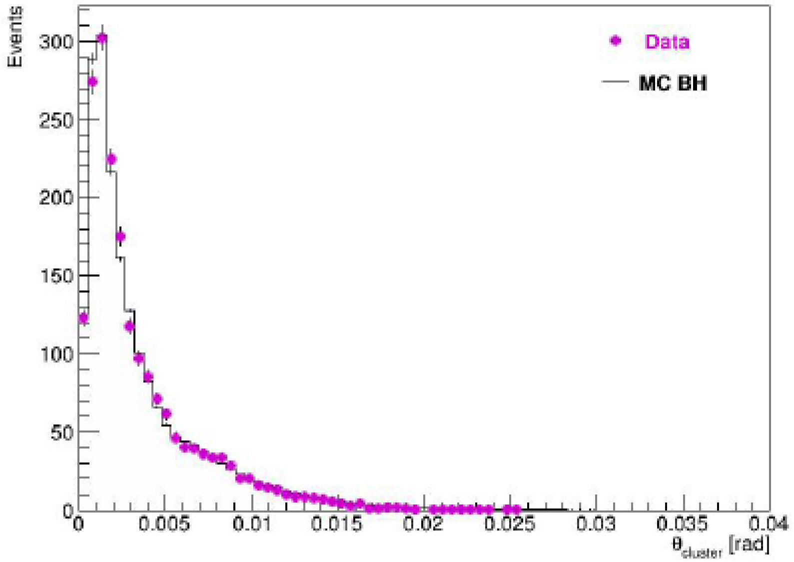


Photon - Ecal2 (Bethe-Heitler)

$80 < \nu$ [GeV] < 144







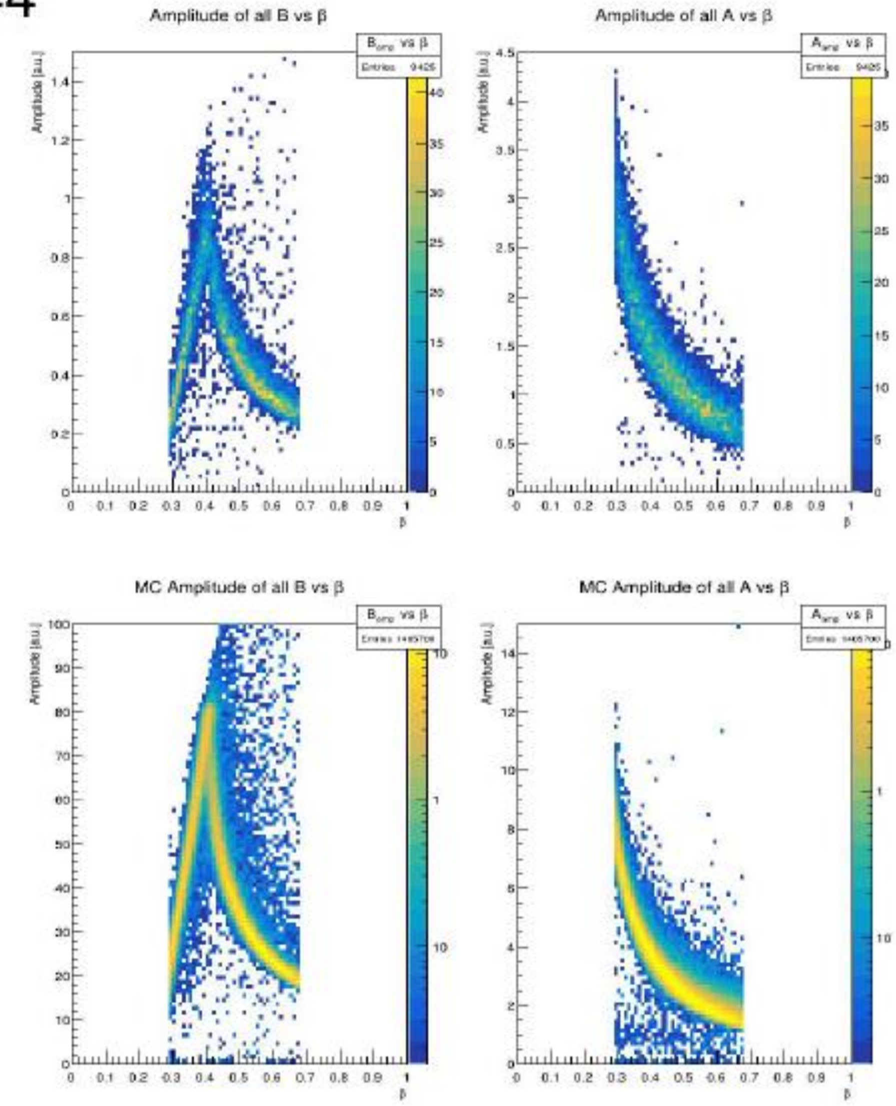
Proton

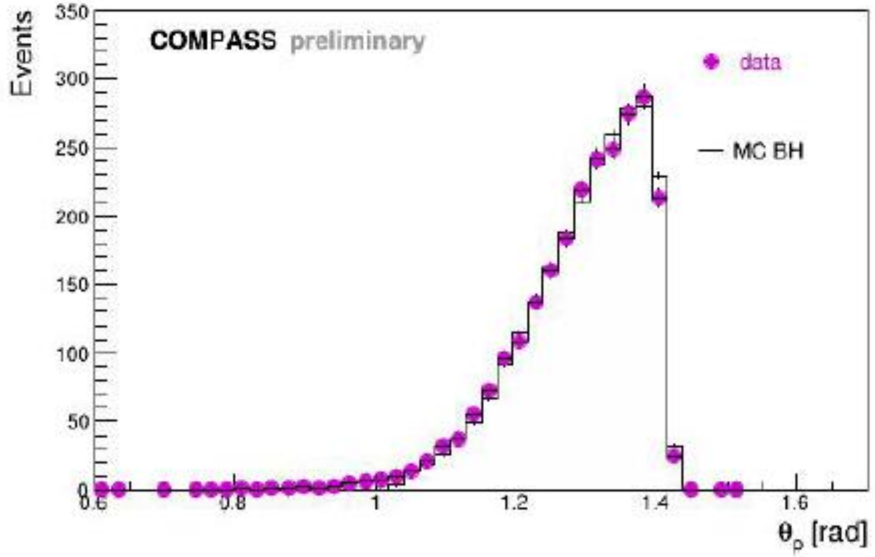
$80 < \nu$ [GeV] < 144

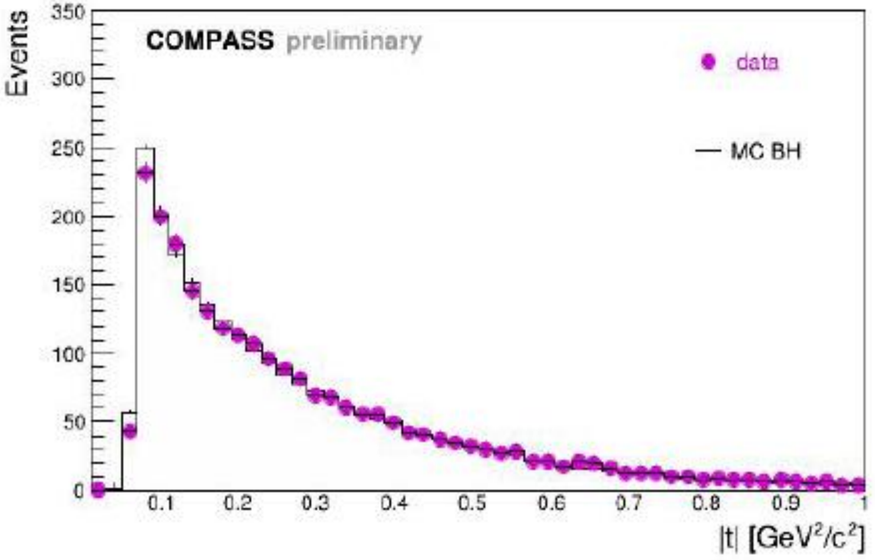
DATA

(t cut applied)

MC BH



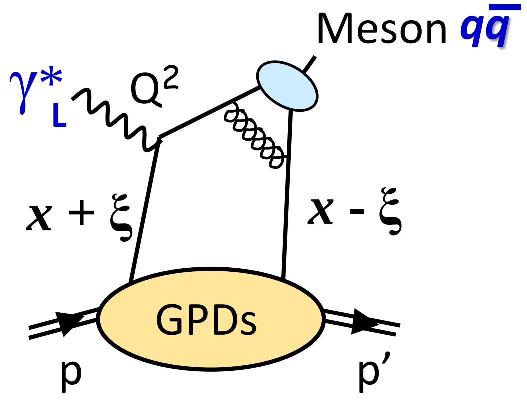




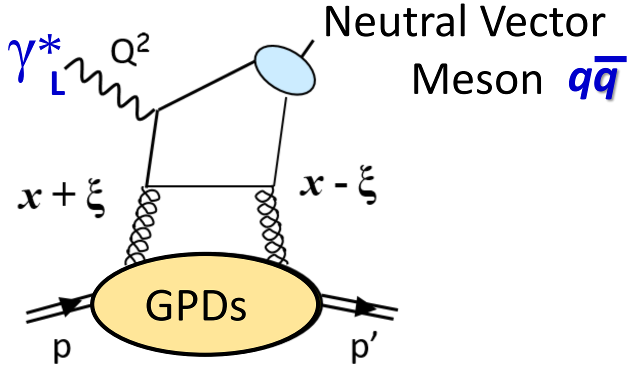
GPDs and Hard Exclusive Meson Production

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)

$$F_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}F^u + \frac{1}{3}F^d + \frac{3}{8}\frac{F_g}{x}\right)$$
$$F_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}F^u - \frac{1}{3}F^d + \frac{1}{8}\frac{F_g}{x}\right)$$
$$F_{\phi} = -\frac{1}{3}F^s - \frac{1}{8}\frac{F_g}{x}.$$

F for H, E …

✓H^u H^d of same sign

$\sigma_L(\rho^0) \sim 9 \times \sigma_L(\omega)$ with Unpol Target

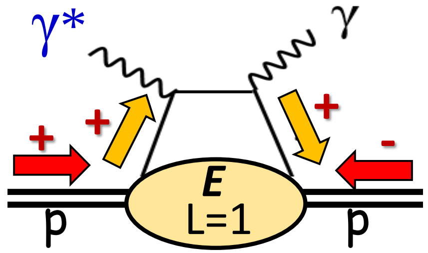
✓E^u E^d of opposite sign

$A_{UT}^{\sin(\phi-\phi_s)} \sim \mathrm{Im}[\langle E\rangle^* \langle H\rangle]$

$A_{UT}^{\sin(\phi-\phi_s)}(\omega) > A_{UT}^{\sin(\phi-\phi_s)}(\rho^0)$ with Trans Pol Target

Access to the GPD E with transversely polarized target

with DVCS on the proton or Vect Meson - OR - DVCS off the neutron

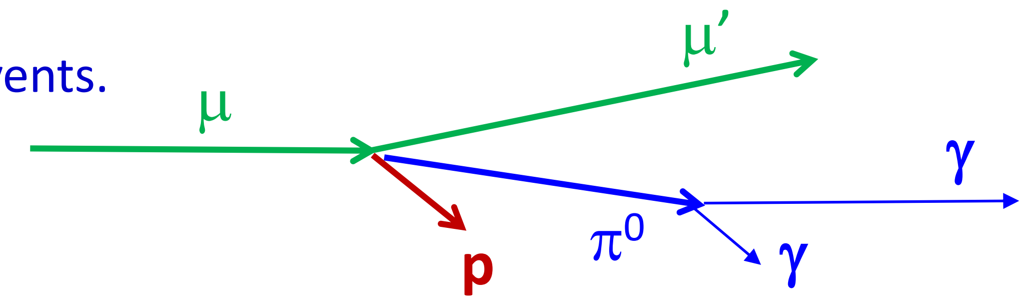


the Holy Grail with E: to reveal OAM

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

COMPASS 2016 data π^0 background estimation

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



Two possible case:

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

  the exclusive single photon candidate is combined with all detected photons below the DVCS threshold: 4,5 GeV in ECAL0, 1

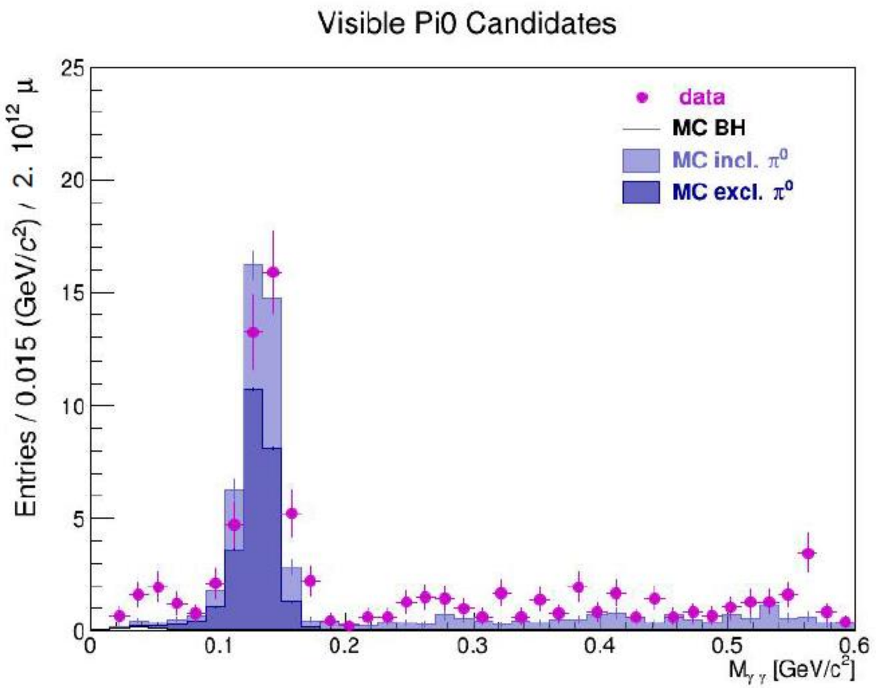
- **Invisible** (one γ lost ➔ estimated by MC)

  - Semi-inclusive LEPTO 6.1
  - Exclusive HEPGEN π^0
  - (Goloskokov-Kroll model)

Comparing the two components to the data allows the determination of their relative normalisation.

$$r_{LEPTO}=40\pm10\%$$

The sum of the 2 components is normalized to the visible π^0 contamination in the $M_{\gamma\gamma}$ peak



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

$$d\sigma^{\gamma^* p \to \gamma p'}_{\mathrm{DVCS}} / d|t|d\phi$$

$$10\ \mathrm{GeV} < \nu < 32\ \mathrm{GeV}$$
$$1\ (\mathrm{GeV}/c)^2 < Q^2 < 5\ (\mathrm{GeV}/c)^2$$
$$0.08\ (\mathrm{GeV}/c)^2 < |t| < 0.64\ (\mathrm{GeV}/c)^2$$

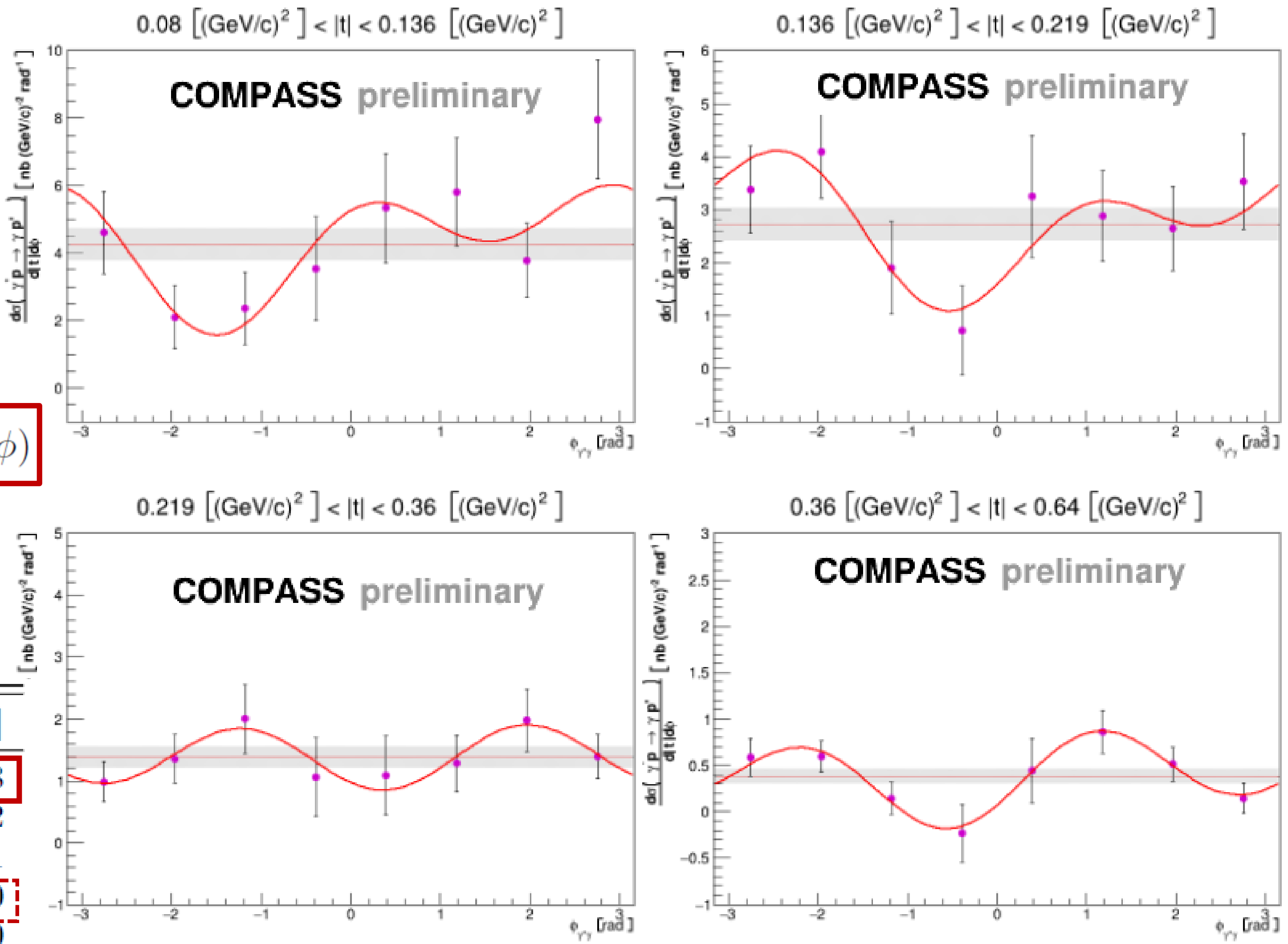
$$f(\phi) = c_0 + c_1 \cos(\phi) + c_2 \cos(2\phi) + s_1 \sin(\phi) + s_2 \sin(2\phi)$$

$c_0^{DVCS} \propto (Im\mathcal{H})^2$ $\quad s_1^I \propto (Im\mathcal{H})$

Results of the fit of $d\sigma^{\gamma^* p \to \gamma p'}_{\mathrm{DVCS}} / d|t|d\phi$ $\left[\mathrm{nb}\,(\mathrm{GeV}/c)^{-2}\,\mathrm{rad}^{-1}\right]$

$\lvert t\rvert$-bin	[0.08,0.136]	[0.136,0.219]	[0.219,0.36]	[0.36, 0.64]
c_0	4.26 ± 0.48	2.73 ± 0.31	1.38 ± 0.17	0.38 ± 0.08
c_1	-0.32 ± 0.73	-0.94 ± 0.45	-0.06 ± 0.25	-0.12 ± 0.12
c_2	1.30 ± 0.67	-0.20 ± 0.44	-0.35 ± 0.24	-0.20 ± 0.11
s_1	1.38 ± 0.61	1.09 ± 0.43	0.01 ± 0.24	0.17 ± 0.10
s_2	0.09 ± 0.78	0.44 ± 0.31	-0.33 ± 0.23	0.33 ± 0.10

In 4 |t| bins with similar statistics



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

At COMPASS using polarized positive and negative muon beams:

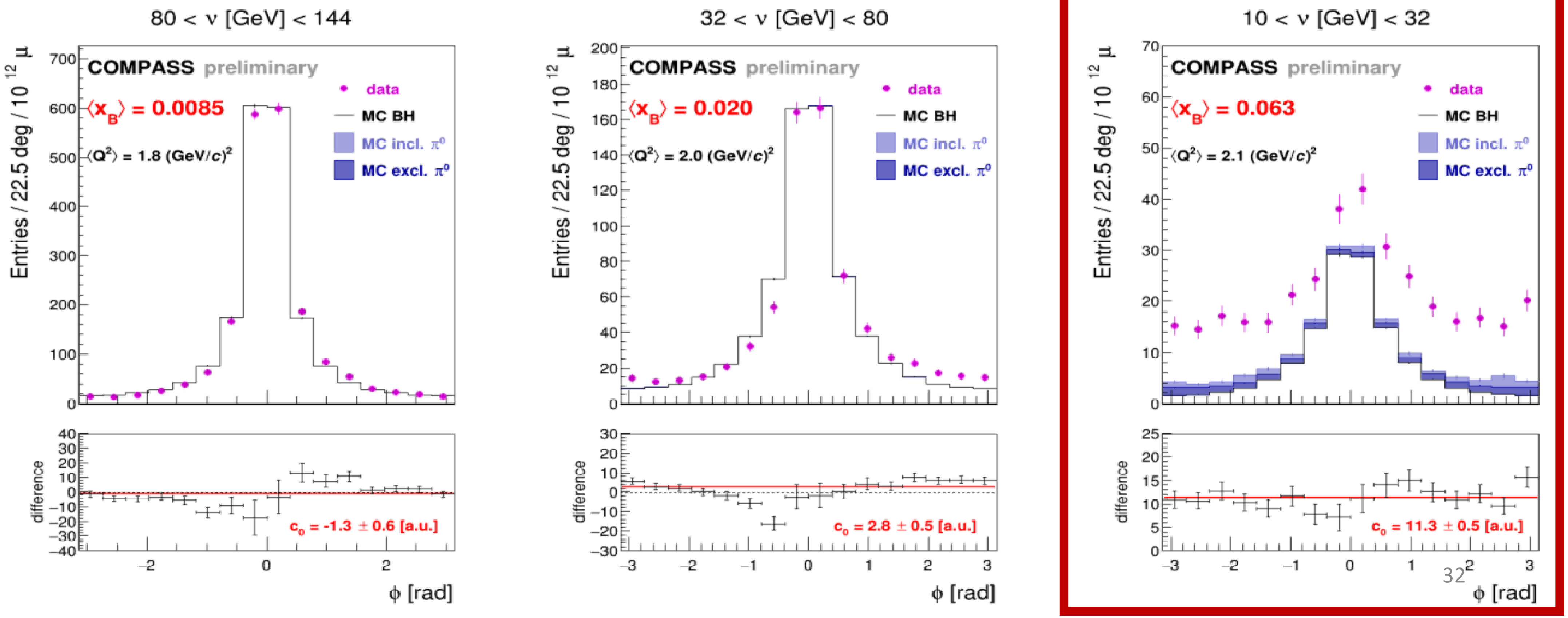
$$S_{CS,U} \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} = 2[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Im}\, I]$$

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

At small x_B

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

$s_1^I \propto (Im\mathcal{H})$



8 GPDs in parallel of 8 TMDs

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

		Quark Polarization		
		U	L	T
Nucleon Polarization	U	f_1 unpolarized		$h_1^{\perp}$ Boer-Mulders
	L		g_{1L} helicity	$h_{1L}^{\perp}$ longi-transversity (worm-gear)
	T	$f_{1T}^{\perp}$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity $h_{1T}^{\perp}$ pretzelosity

Nucleon spin   Quark spin

For valence contributions:

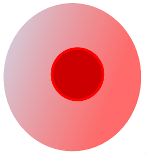
H^u H^d of **same** sign
$\tilde{H}^u$ $\tilde{H}^d$ of opposite sign
H_T^u H_T^d of opposite sign

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

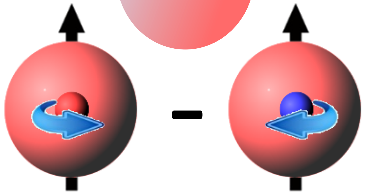
GPDs and TMDs

Chiral-even

$$H \longleftrightarrow q$$



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



Sivers: quark k_T
and nucleon transv. Spin

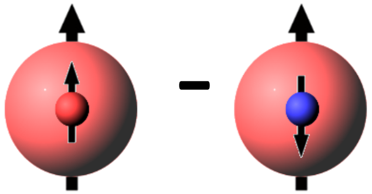
T-odd

the Holy Grail: to reveal OAM

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

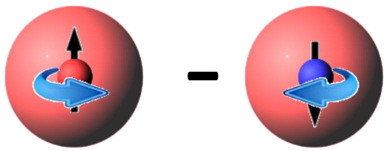
Chiral-odd

$$H_T \longleftrightarrow h_1$$



Transversity: quark spin
and nucleon transv. spin

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



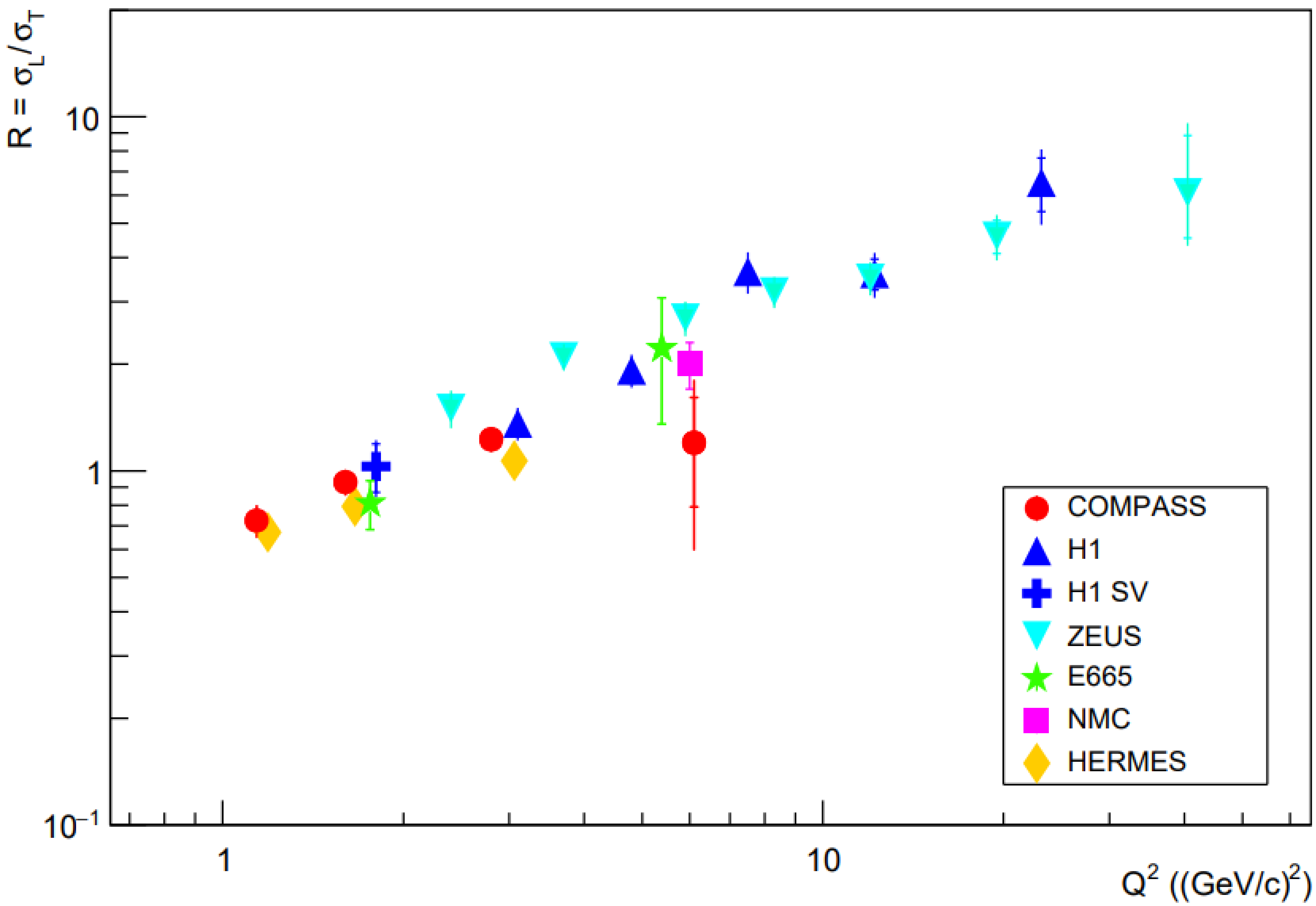
Boer-Mulders: quark k_T
and quark transverse spin

T-odd

$$F_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}F^u + \frac{1}{3}F^d + \frac{3}{8}\frac{F_g}{x}\right)$$

$$F_\omega = \frac{1}{\sqrt{2}}\left(\frac{2}{3}F^u - \frac{1}{3}F^d + \frac{1}{8}\frac{F_g}{x}\right)$$

$$F_\phi = -\frac{1}{3}F^s - \frac{1}{8}\frac{F_g}{x}.$$



$R = \sigma_L/\sigma_T$
10
1
10^{-1}
1
10
Q^2 ((GeV/c)^2)
COMPASS
H1
H1 SV
ZEUS
E665
NMC
HERMES

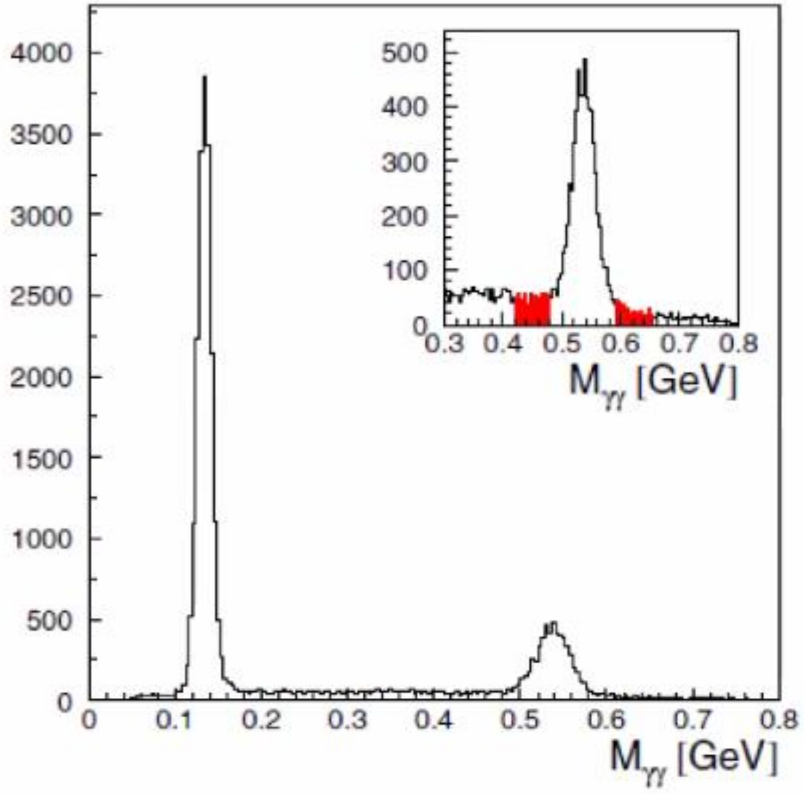
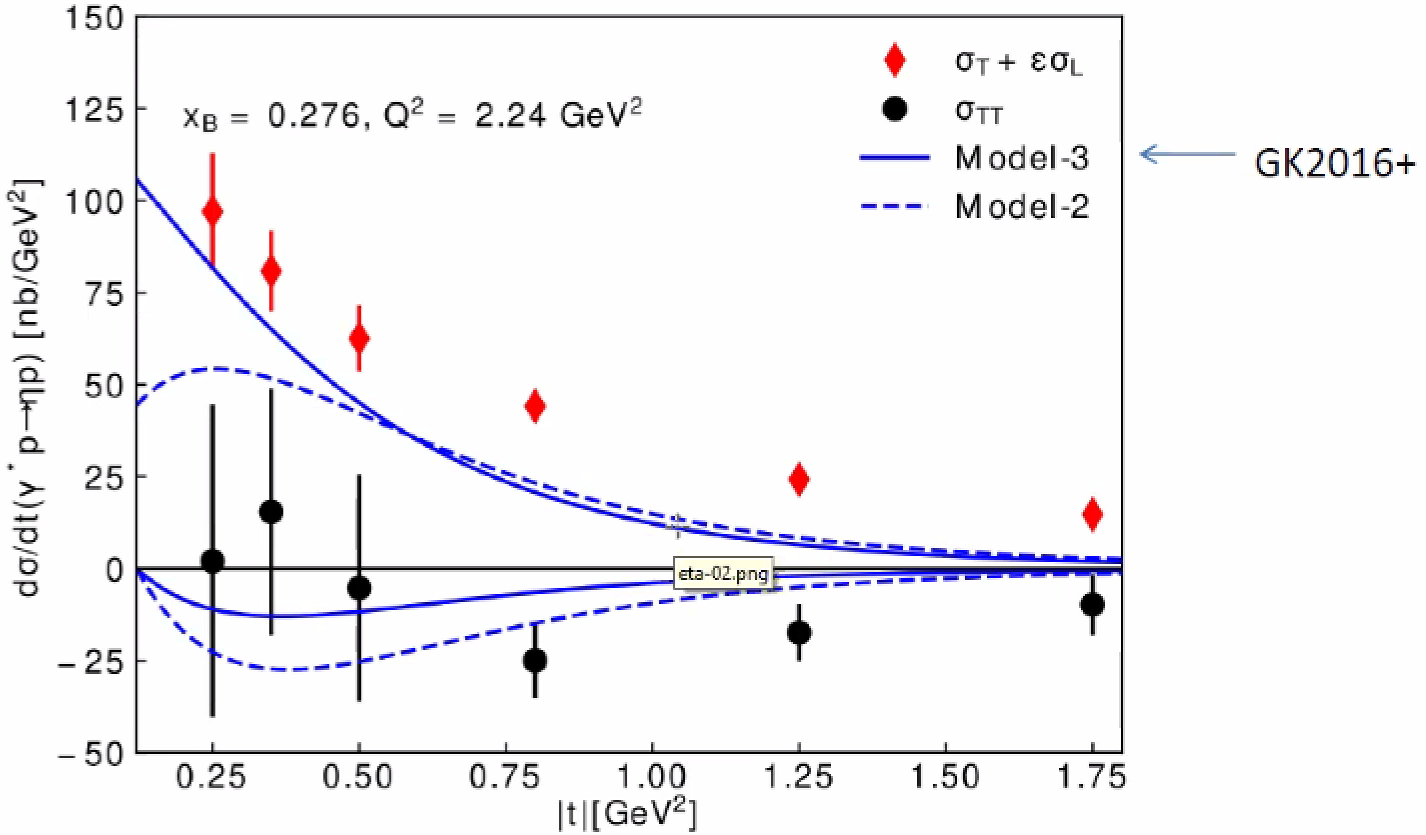


FIG. 8. The two-photon invariant-mass distribution $M_{\gamma\gamma}$ after all exclusivity cuts have been applied, for the case where the two photons are detected by the IC. The large peak at lower $M_{\gamma\gamma}$ is due to π^0 electroproduction and the smaller peak at higher $M_{\gamma\gamma}$ is due to η electroproduction. The inset magnifies the region around the η peak.

Eta and pi0
At JLab

CLAS η data & GK fits preliminary



π GK2016+ prediction η

For COMPASS