GPD Studies
at
the COMPASS Experiment

3D Structure of the Nucleon
Via Generalized Parton Distributions

Howard Johnson Incheon Airport Hotel
June 27, 2024

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Department of Physics, National Central University

Outline

- The COMPASS Experiment
- Deeply Virtual Compton Scattering (DVCS)
- Hard Exclusive Meson Production (HEMP)
- Summary

COMPASS Experiment

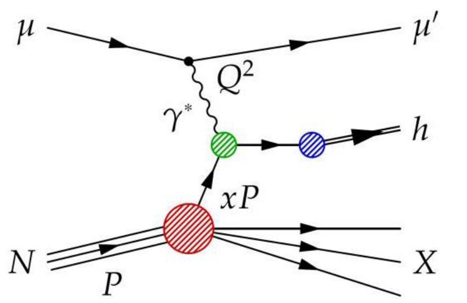
Versatile facility with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams of energy 100 to 200 GeV

~220 physicists from 25 Institutes of 13 Countries

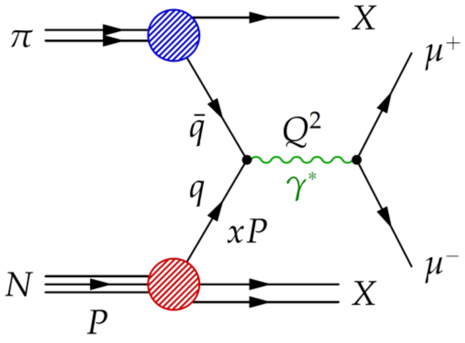
COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Multi-dimensional Partonic Structures

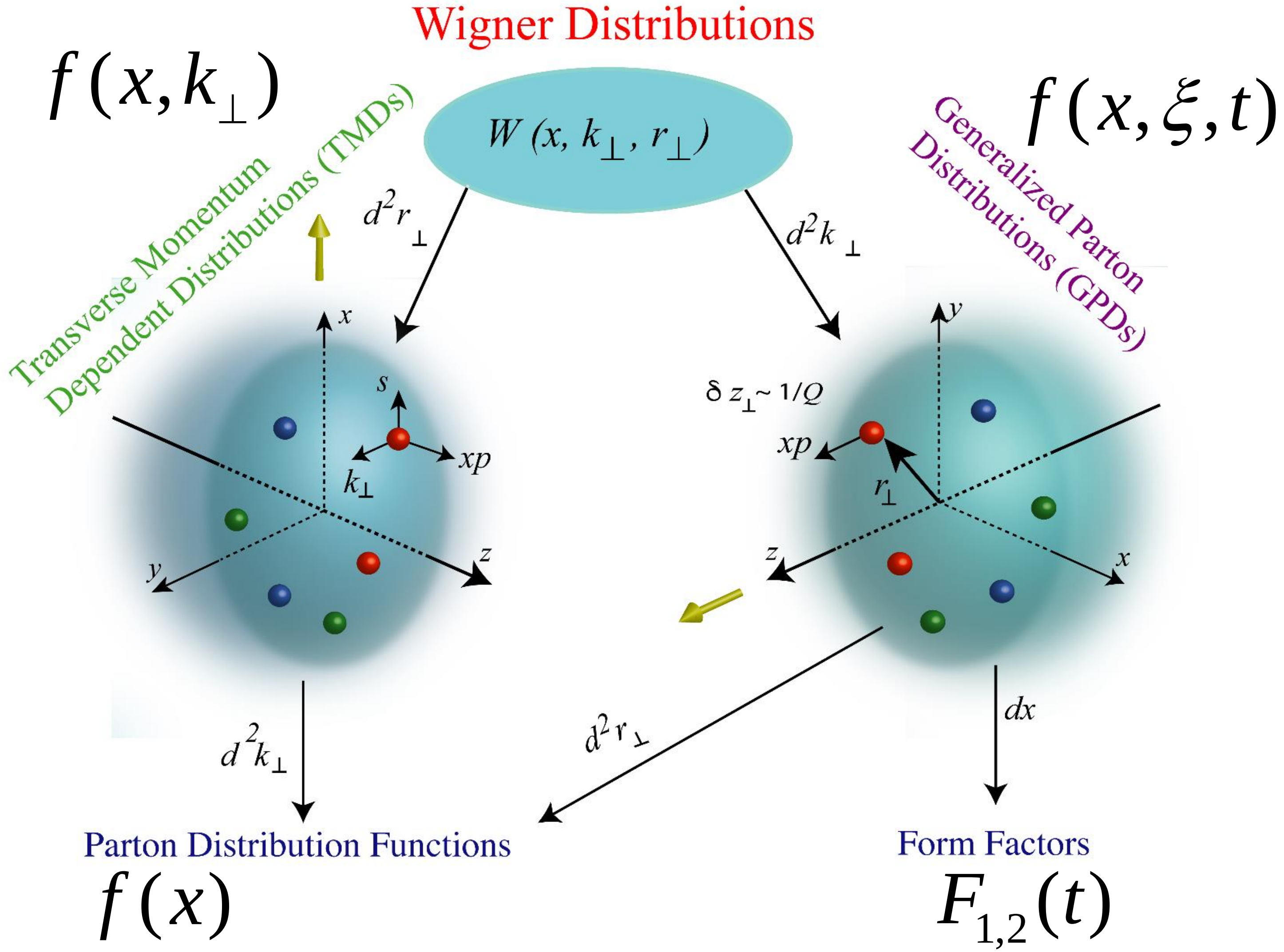
http://www.int.washington.edu/PROGRAMS/17-3/

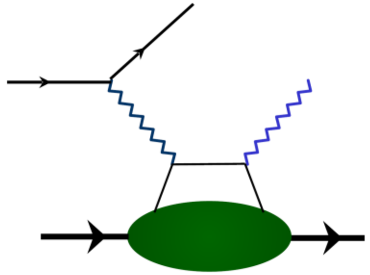


SIDIS

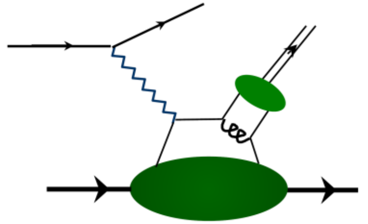


Drell-Yan





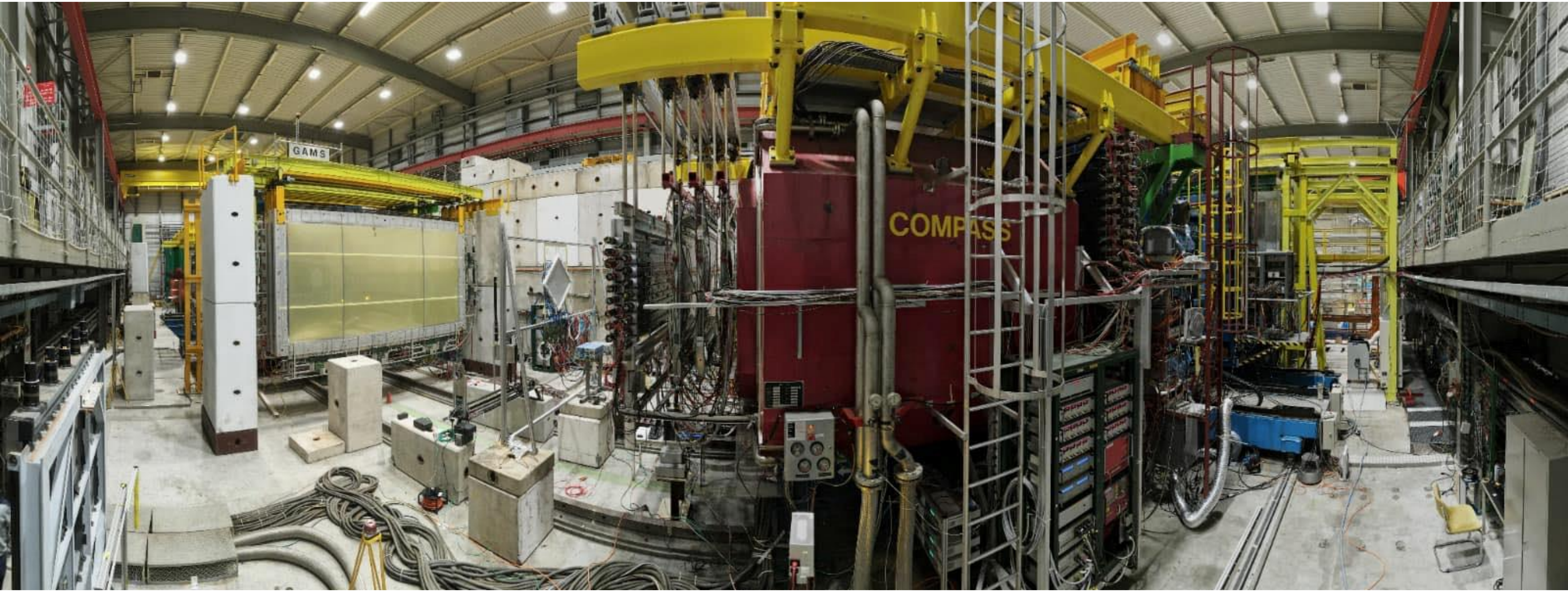
DVCS



HEMP

COMPASS investigates the multi-dimensional structure of nucleon via various processes

COMPASS Experimental Setup



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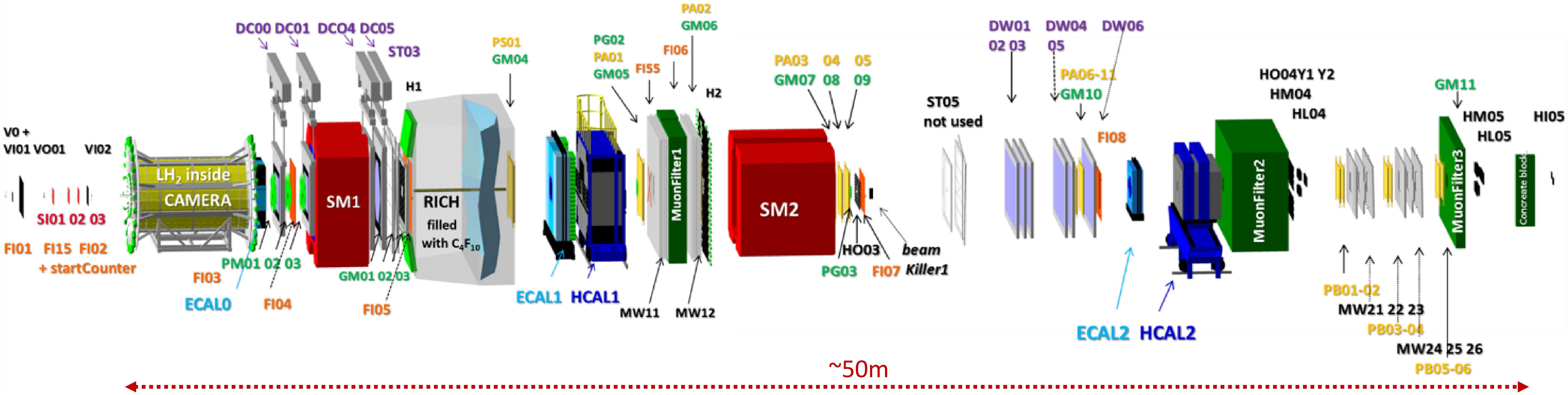


- Priamary beam – 400 GeV p from SPS
  - Impinging on Be production target
- 190 GeV secondary hadron beams
  - h^- beam: $97\% \, \pi^-, 2\% \, K^-, 1\% \, p$
  - h^+ beam: $75\% \, \pi^+, 24\% \, p, 1\% \, K^+$
- 160 GeV tertiary muon beams
  - $\mu^{\pm}$ longitudinally polarized

Large-acceptance forward spectrometer

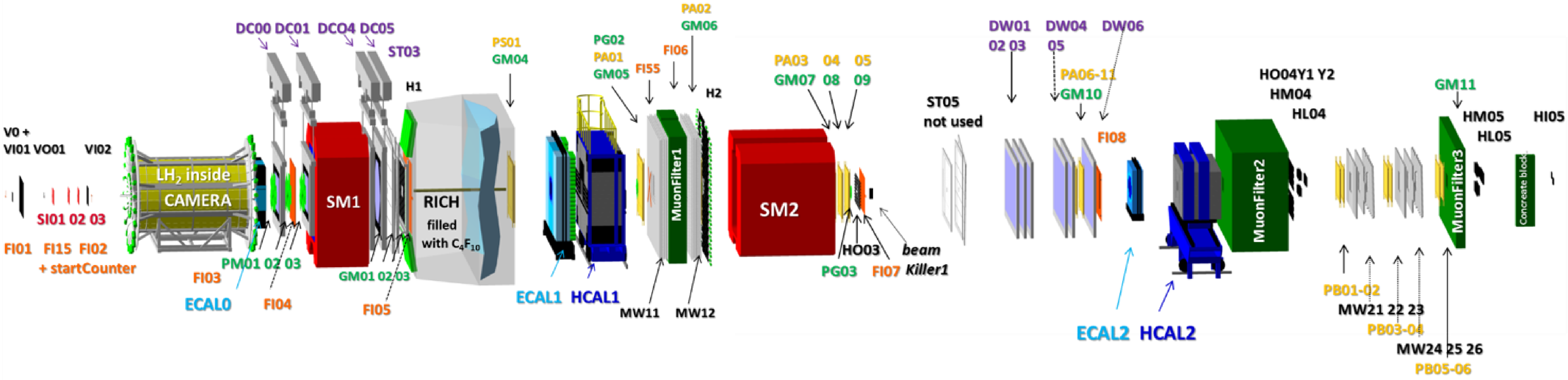
- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC, DC, straw
- PID – CEDARs, RICH, calorimeters, Muon Walls

Various targets:

- Polarized soild-state NH$_3$ or ^{6}LiD
- Liquid H$_2$
- Solid-state nuclear targets

❖ NIM A 577 (2007) & NIM A 779 (2015) 69

COMPASS Experimental Setup



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  - h^+ beam: 75% π^+, 24% p, 1% K^+
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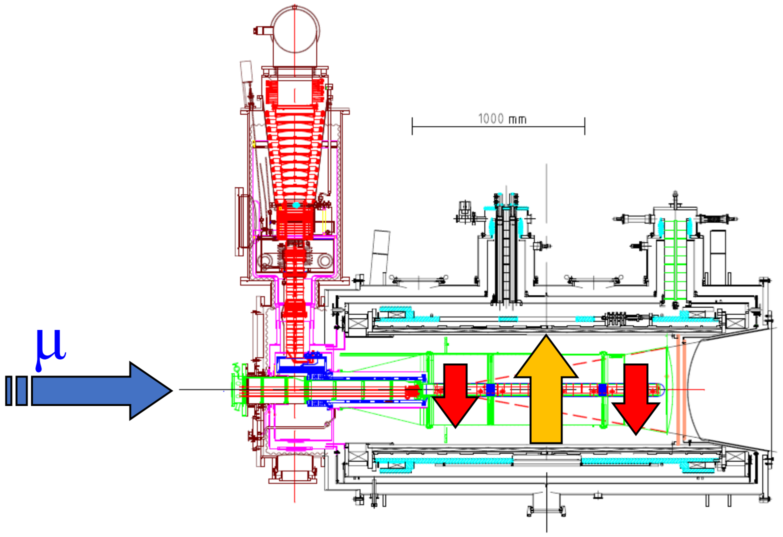
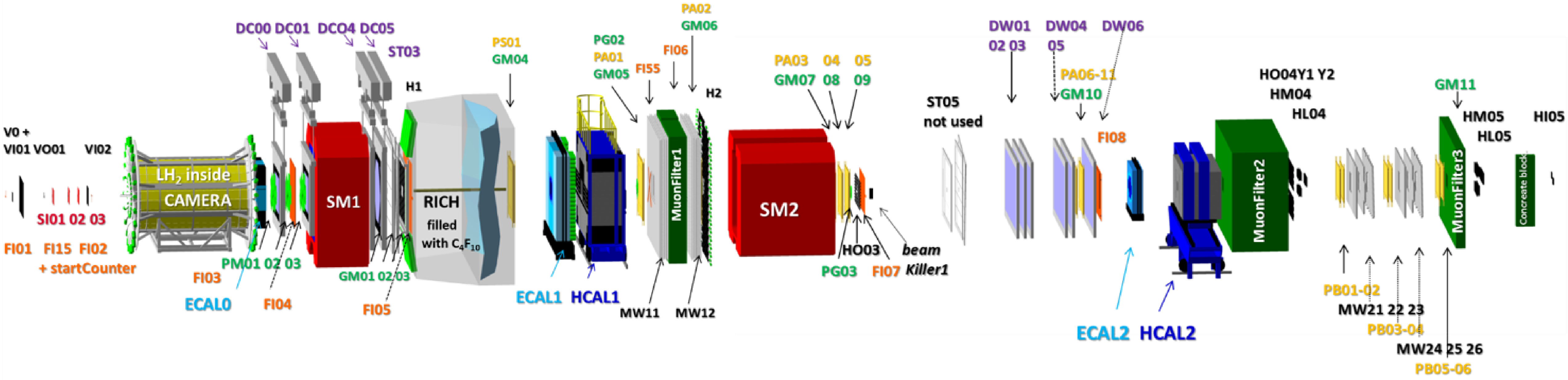
  - $\mu^\pm$ longitudinally polarized



- In early GPD studies, transversely polarized target was used.
- Polarization reversal by magnetic field rotation
- 2.5m unpolarized LH$_2$ target used in GPD dedicated runs

COMPASS Setup for Exclusive Processes



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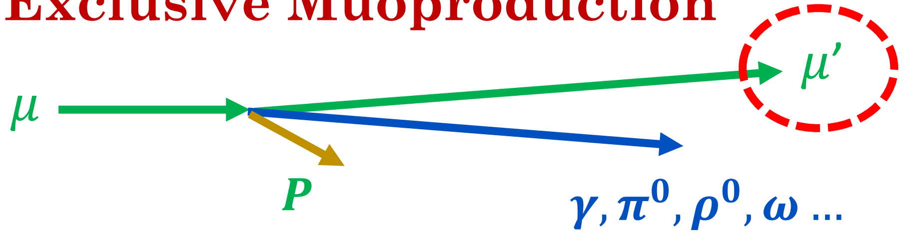
Exclusive Muoproduction



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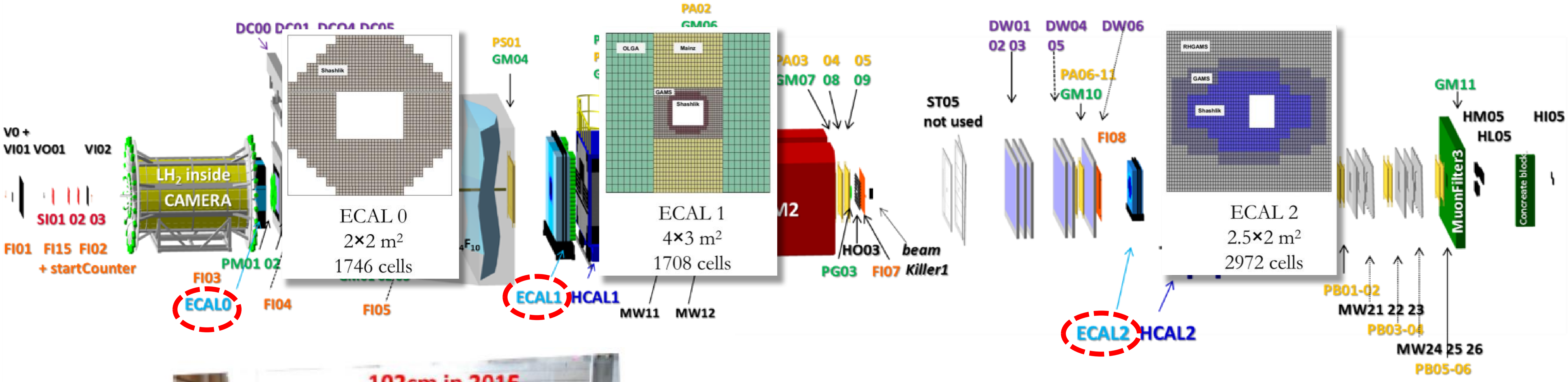

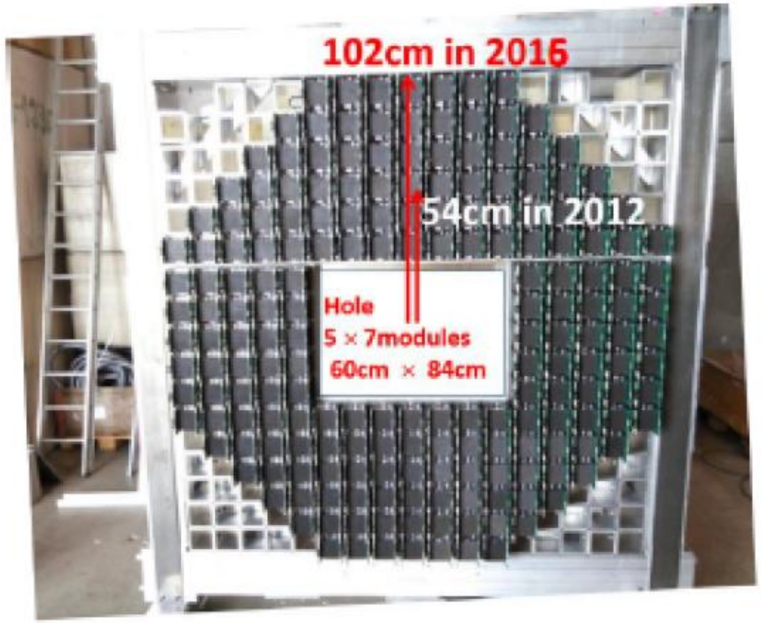

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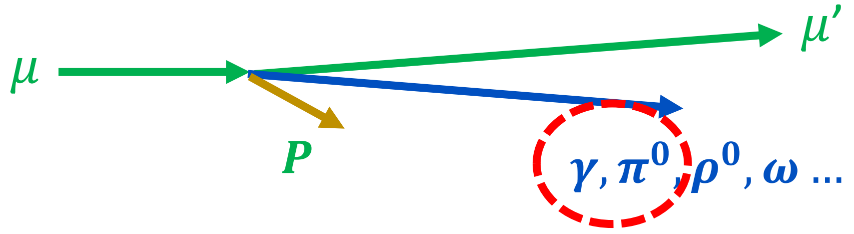

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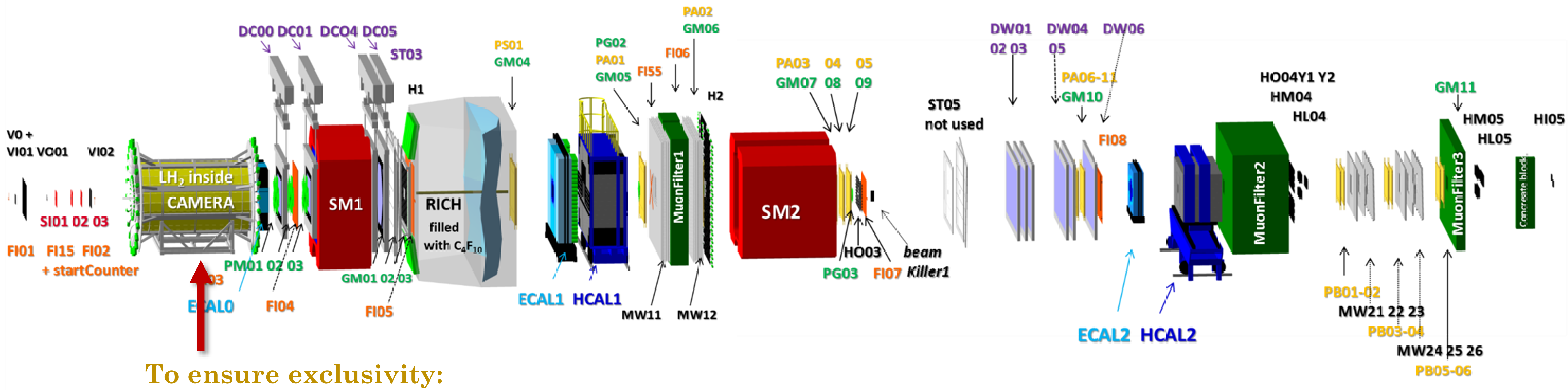
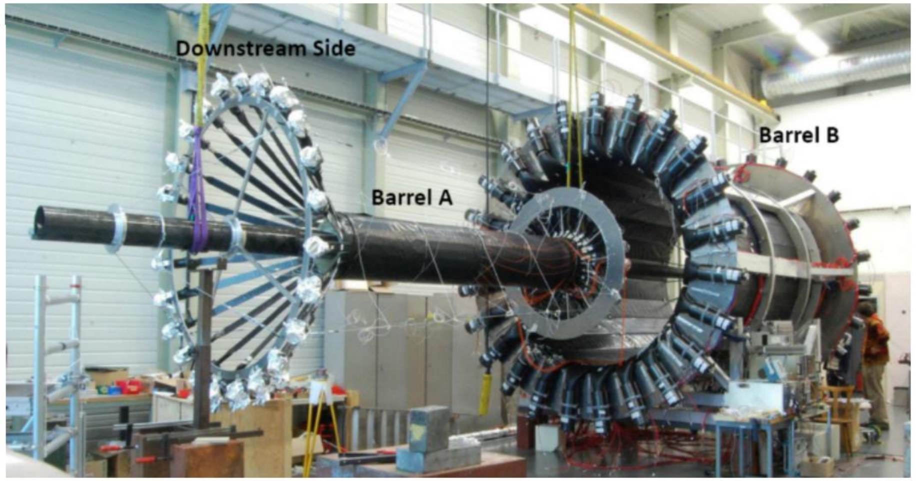
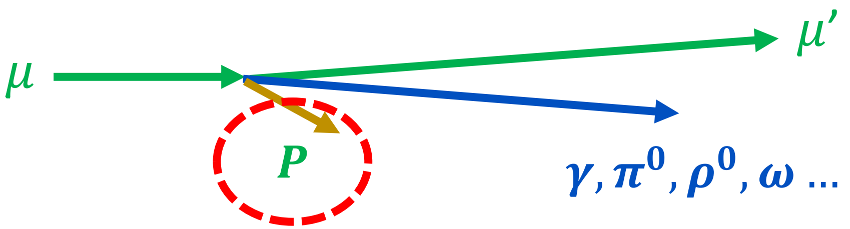


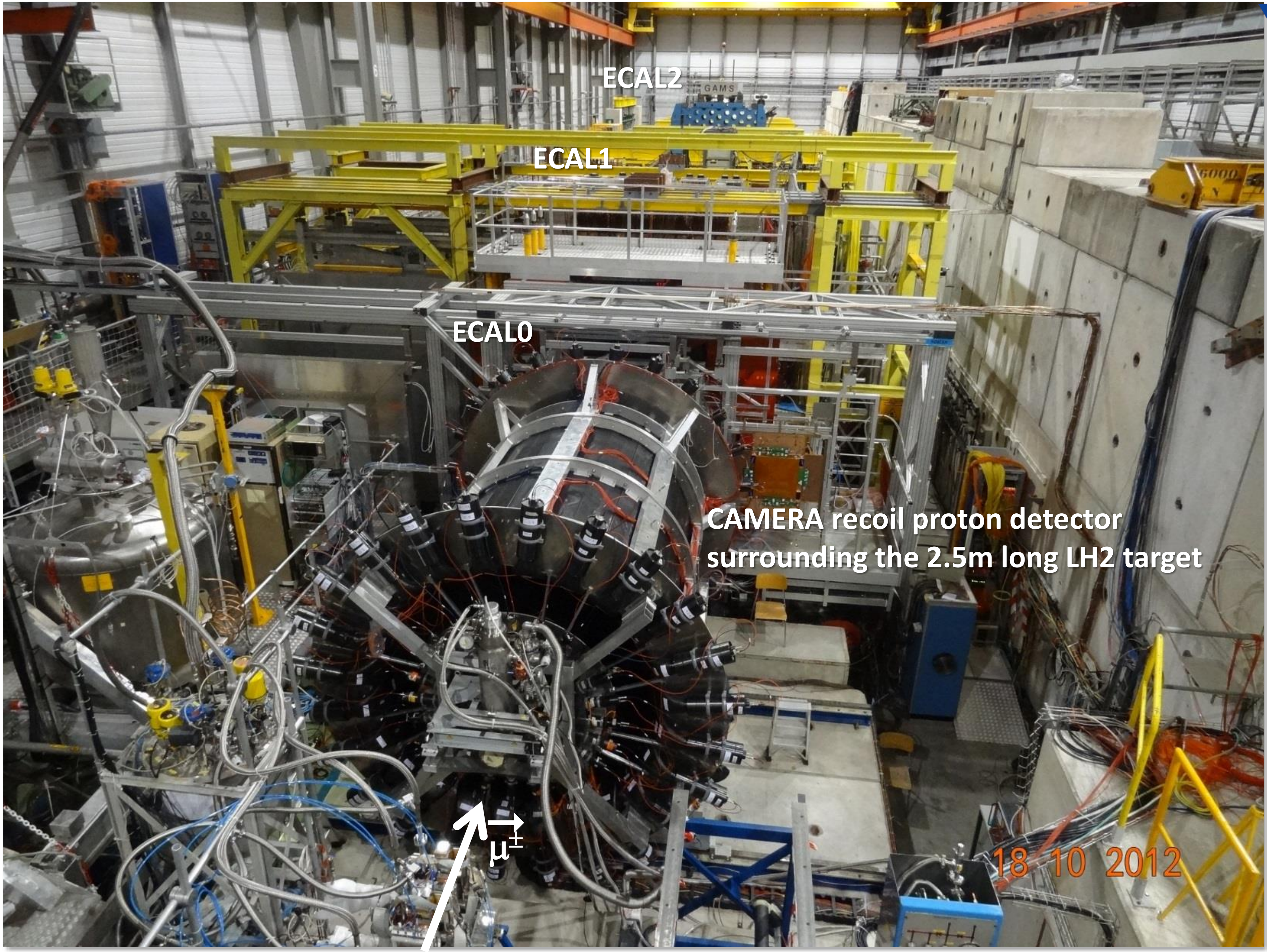
To ensure exclusivity:



CAMERA recoil proton detector

Exclusive Muoproduction





CAMERA recoil proton detector surrounding the 2.5m long LH2 target

COMPASS Experiment

2002-2022 COMPASS data taking

2002-2004	DIS & SIDIS, μ^+-**d**, 160 GeV, **L** & **T polarized target**
2005	*CERN accelerator shutdown, increase of COMPASS acceptance*
2006	DIS & SIDIS, μ^+-**d**, 160 GeV, **L polarized target**
2007	DIS & SIDIS, μ^+ -**p**, 160 GeV, **L** & **T polarized target**
2008-2009	Hadron spectroscopy & Primakoff reaction, **π/K/p** beam
2010	SIDIS, μ^+ -**p**, 160 GeV, **T polarized target**
2011	DIS & SIDIS, μ^+ -**p**, 200 GeV, **L polarized target**
2012	Primakoff reaction, **π/K/p** beam
2012 pilot run	DVCS/HEMP/SIDIS, μ^+ **&** μ^- -**p**, 160 GeV, **unpolarized target**
2013	*CERN accelerator shutdown, LS1*
2014-2015	Drell-Yan, **π-** -**p**, **T polarized target**
2016-2017	DVCS/HEMP/SIDIS, μ^+ **&** μ^- -**p**, 160 GeV, **unpolarized target**
2018	Drell-Yan, **π-** -**p**, **T polarized target**
2019-2020	*CERN accelerator shutdown, LS2*
2021-2022	SIDIS, μ^+-**d**, 160 GeV, **T polarized target**

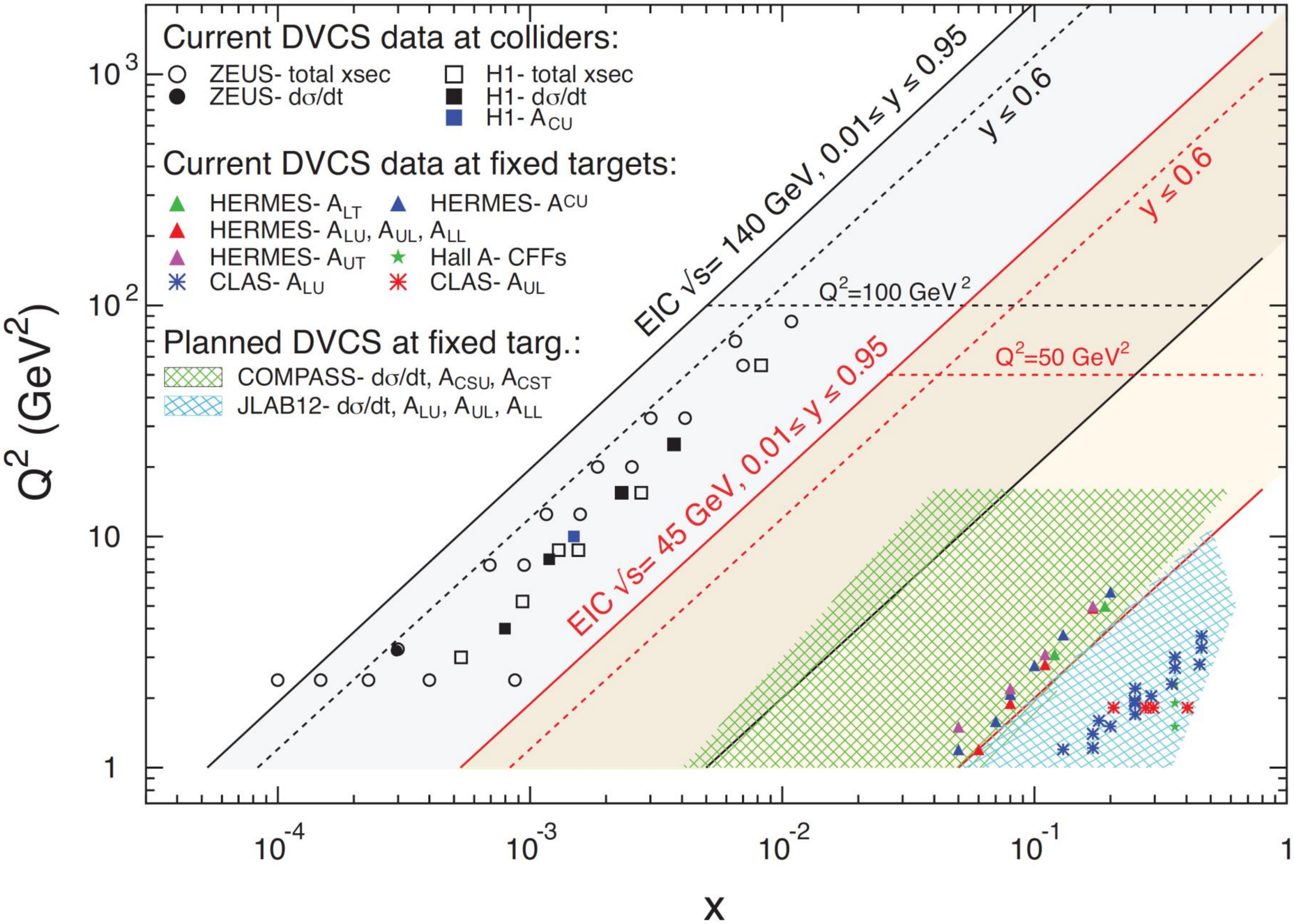
Study hadron structure with complmentary tools:

- **COMPASS holds the record for the longest-running CERN experiment**

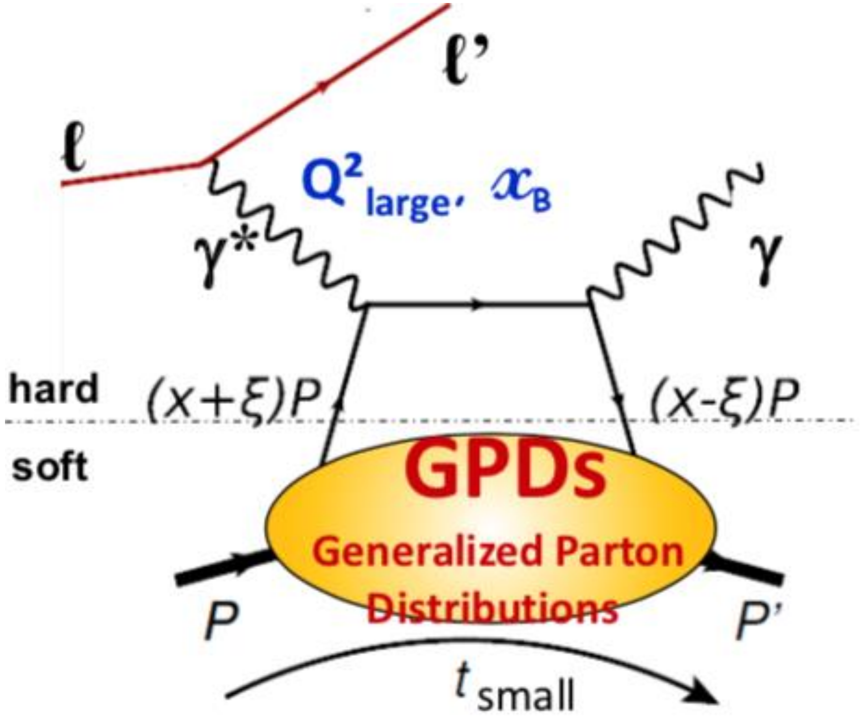
- 2012 pilot run with 4-week data taking
- 2016-17 dedicated run. 2 x 6 months.

Deeply Virtual Compton Scattering
@ COMPASS

Lanscape – Global Programs of DVCS



DVCS

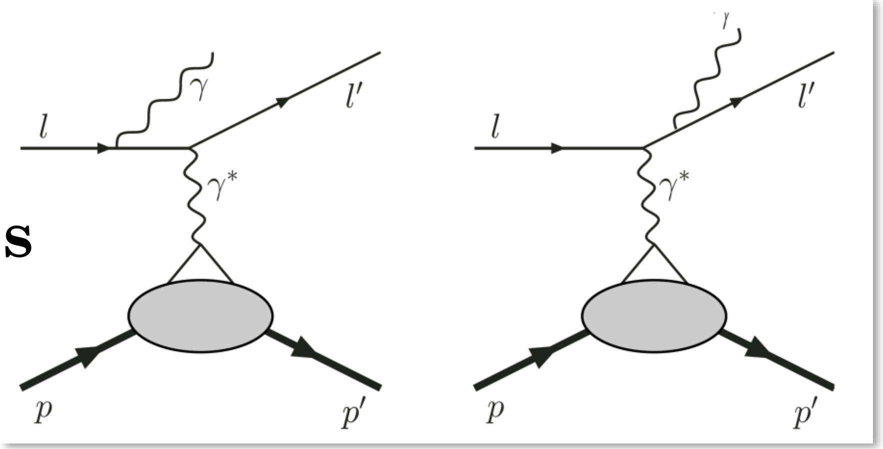


DVCS: $l + p \rightarrow l' + p' + \gamma$

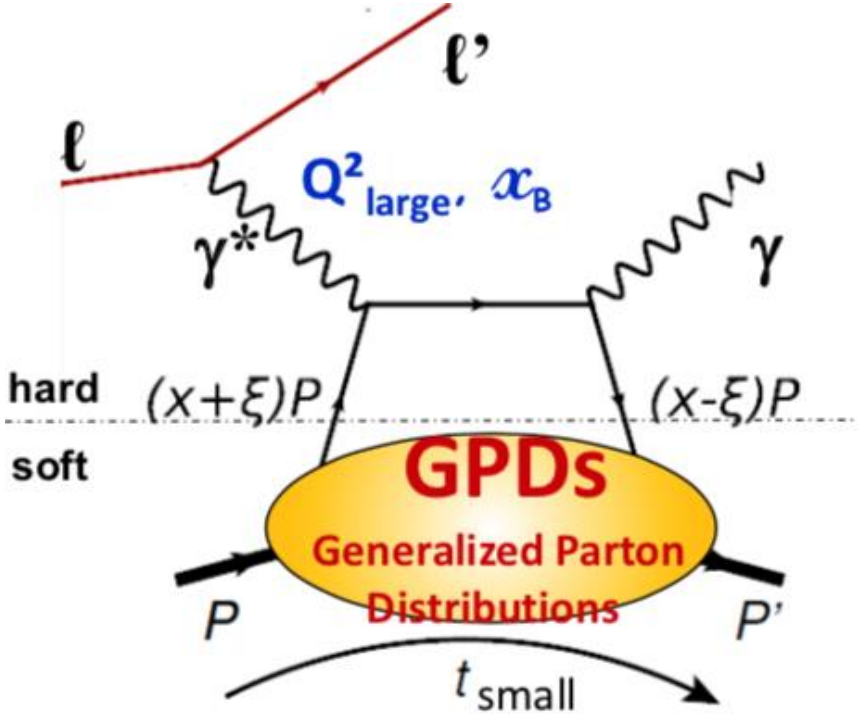
- ➢ As the golden channel to access GPDs, DVCS has been the workhorse for GPD Extraction.
- ➢ Its interference with the well-understood Bethe-Heitler process gives access to more info.

- ➢ The GPDs depend on the following variables:
  - x: average longitudinal momentum frac.
  - ξ: longitudinal momentum diff.
  - t: four momentum transfer (correlated to $b_\perp$ via Fourier transform)
  - Q^2: virtuality of γ^*

BH Process



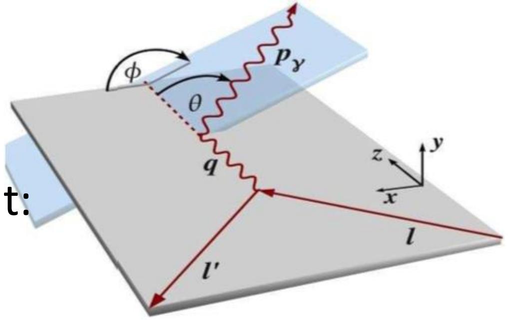
DVCS



DVCS: $l + p \to l' + p' + \gamma$

- With LH_2 target and small x_B coverage

→ focuses on **H** at COMPASS



- The variables measured in the experiment:

E_ℓ, Q^2, $x_{Bj} \sim 2\xi/(1+\xi)$,

t (or $\theta_{\gamma^*\gamma}$) and ϕ ($\ell\ell'$ plane/$\gamma\gamma^*$ plane)

CFF

GPD

REAL part

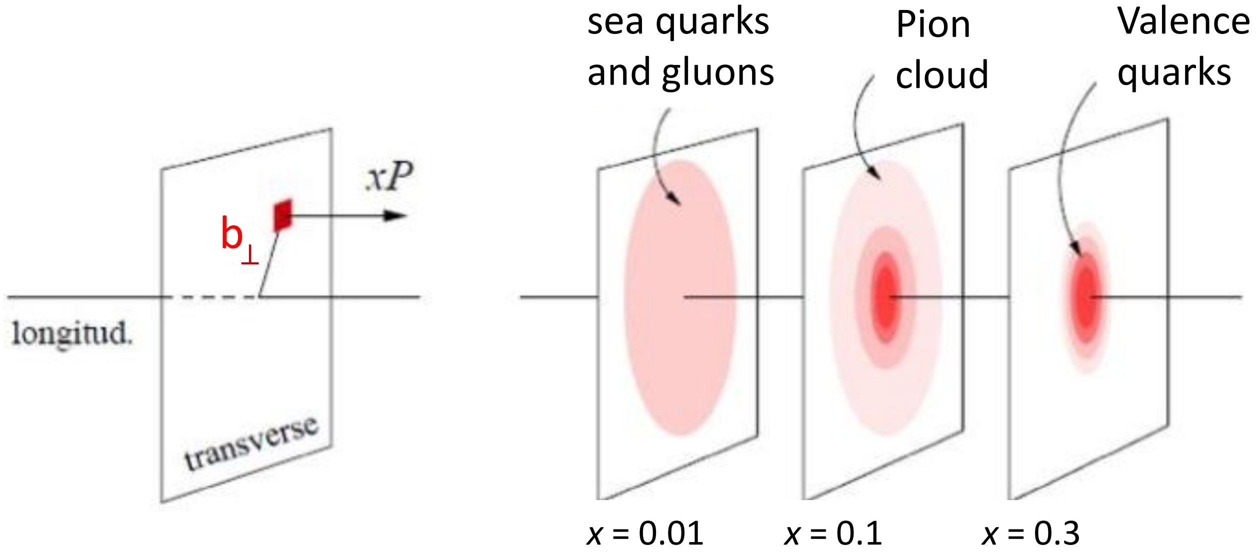
Imaginary part

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

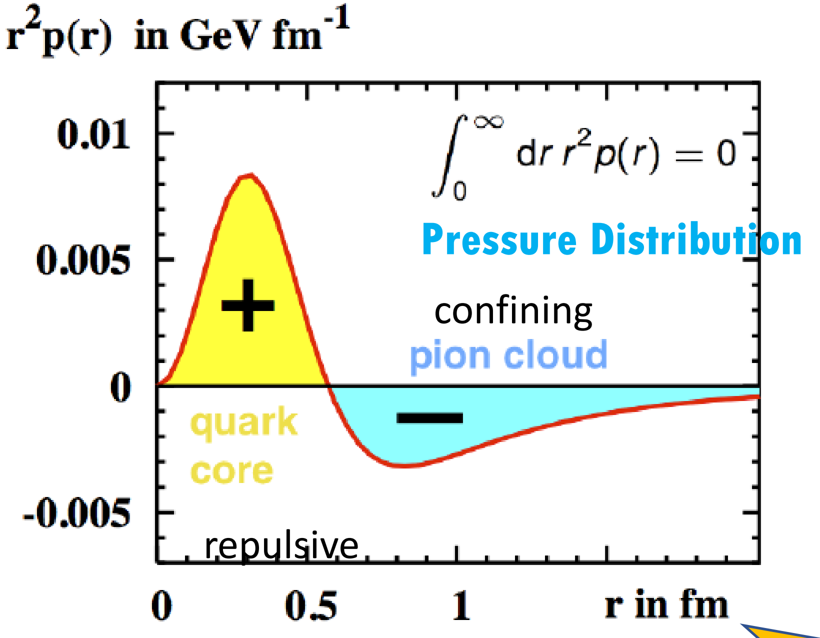
$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{\mathcal{I}m\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

Transverse Imaging and Pressure Distribution

Mapping in the transverse plane



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



FT of H(x, ξ=0,t)

CFF

GPD

REAL part

Imaginary part

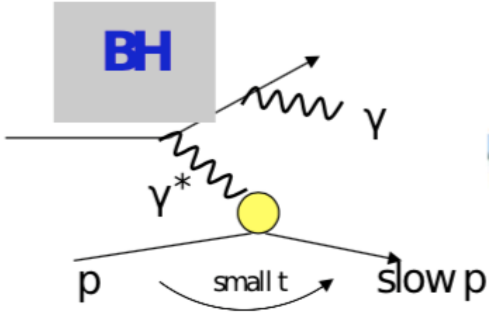
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx\, \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx\, \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

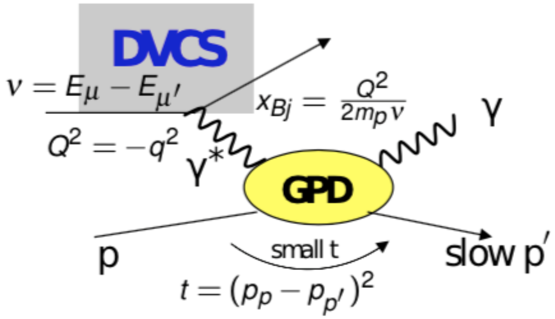
$$Re\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{Im\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

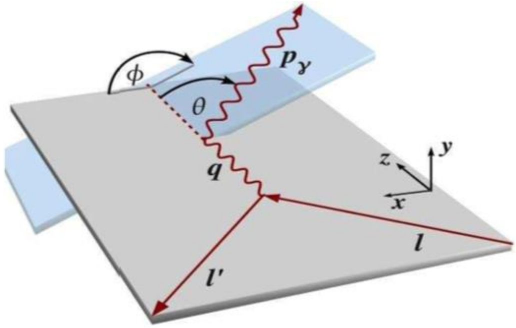
$d_1(t)$

D-term

Azimuthal Dependence of BH & DVCS







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

Beam Charge-spin difference & sum

$$\mathcal{D}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow})$$

$$S_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow})$$

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

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

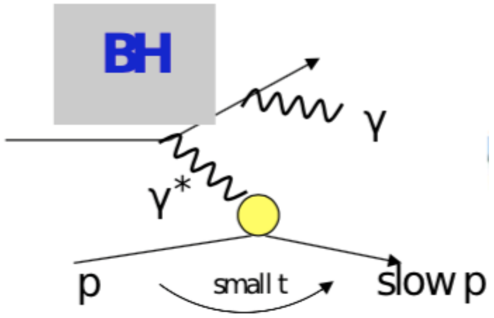
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

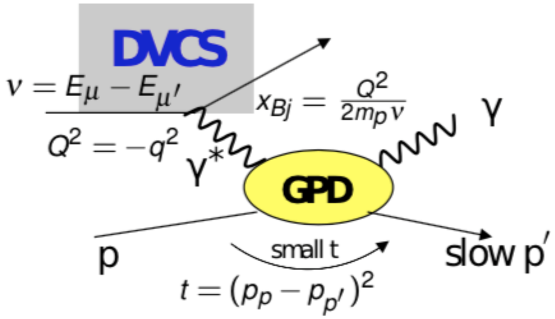
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

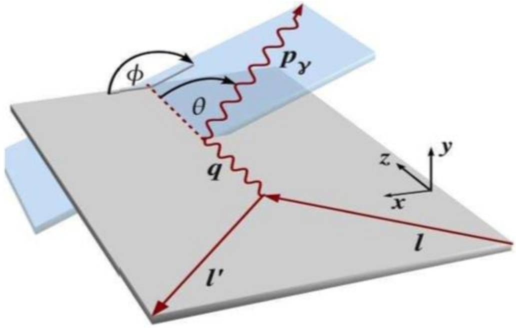
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$

Twist-2 >> 🟦 Twist-3, 🟩 Twist-2 - double helicity flip for gluons (NLO)

Azimuthal Dependence of BH & DVCS







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

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$\mathcal{D}_{CS,\,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow})$

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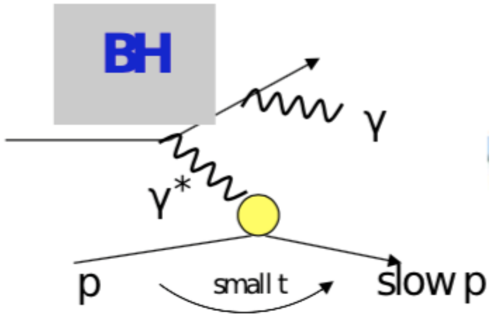
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

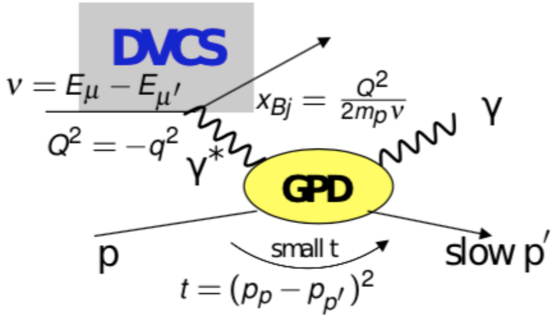
$\mathcal{D}_{CS,\,U}(\phi)$

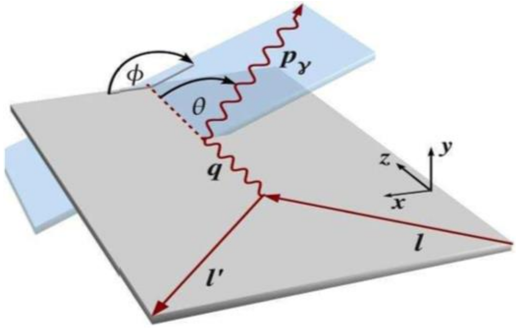
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$

Twist-2 >> ■ Twist-3, ■ Twist-2 - double helicity flip for gluons (NLO)

Azimuthal Dependence of BH & DVCS







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$$\begin{aligned} d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\ d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \end{aligned} \qquad \mathcal{S}_{\text{CS, U}}(\phi)$$

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

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

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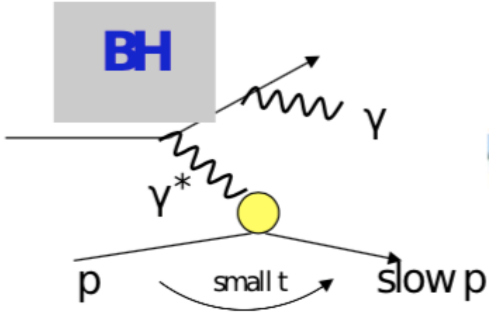
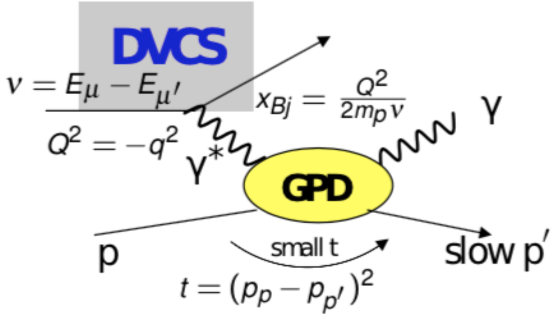
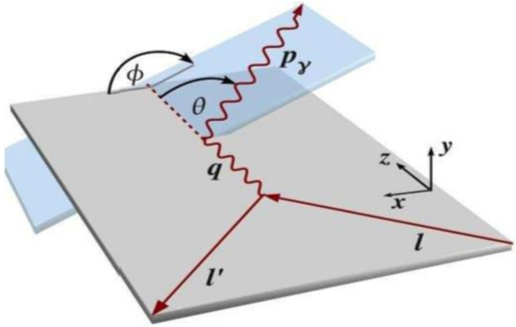
Azimuthal Dependence of BH & DVCS







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Beam Charge-spin difference & sum

$\mathcal{D}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow})$ → $C_1^I \propto Re\ \mathcal{F}$ More challenging

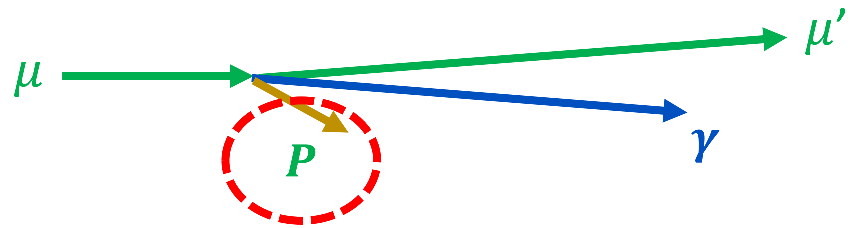
$\mathcal{S}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow})$ → $C_0^{DVCS} \propto (Im\mathcal{H})^2$ and $S_1^I \propto Im\ \mathcal{F}$ Easier to measure

$$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\mathcal{H} + t/4m^2\, F_2\, \mathcal{E} \xrightarrow[\text{Small } x_B \text{ at COMPASS}]{\text{Proton Target}} F_1\mathcal{H}$$

Compton Form factor linked to GPD **H**

Twist-2 >> 🟦 Twist-3, 🟩 Twist-2 - double helicity flip for gluons (NLO)

COMPASS 2016 Preliminary Results



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

Proton azimuthal angle

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

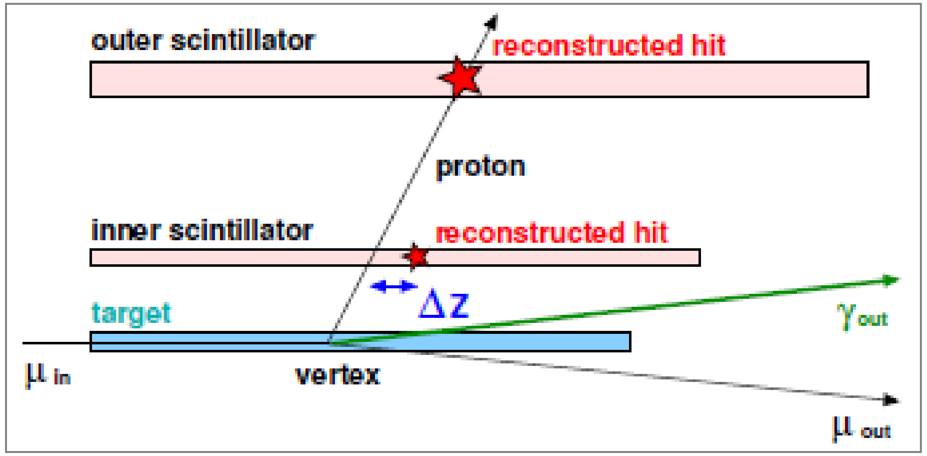
Proton momentum

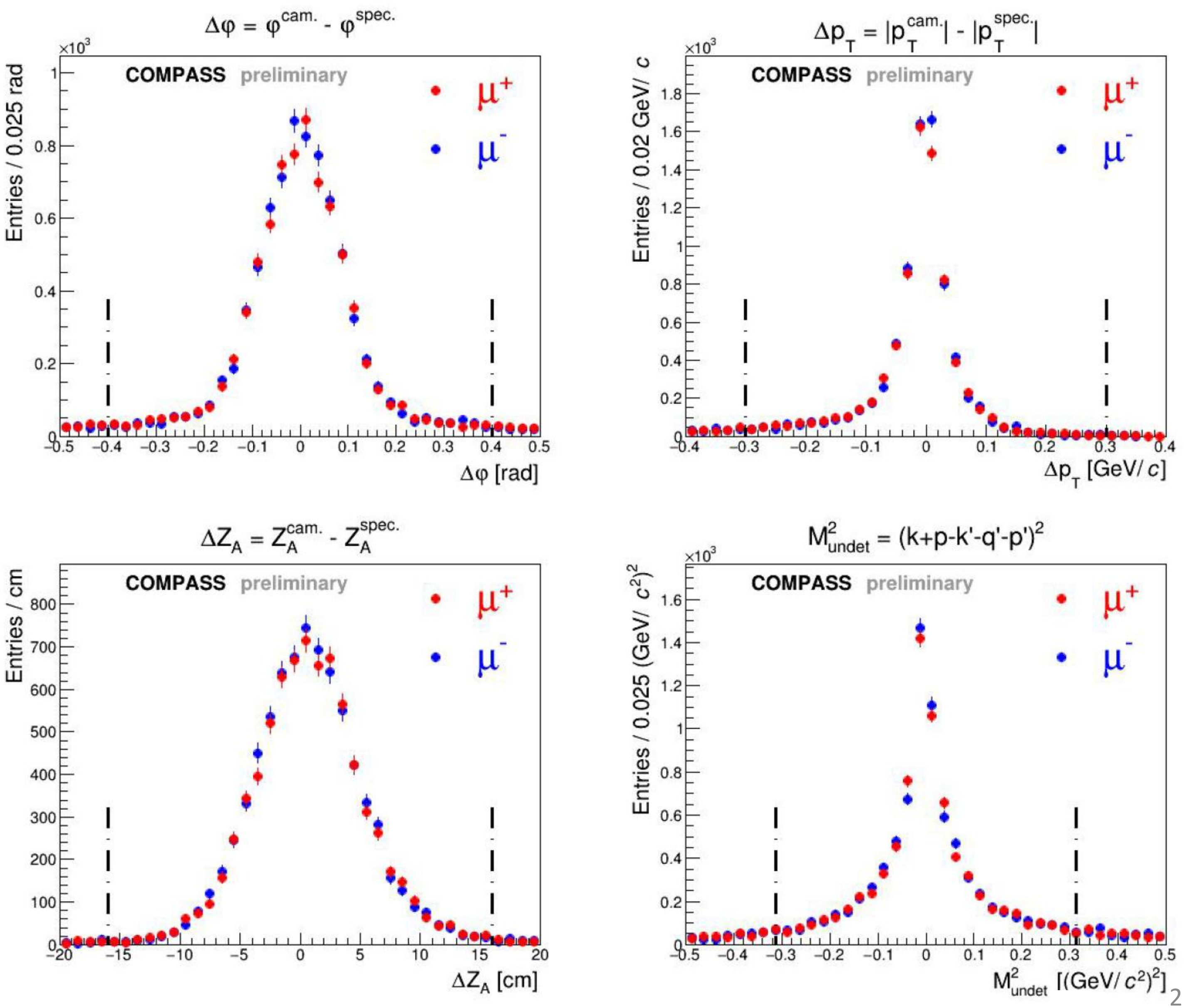
$\Delta z_A = z_A^{\text{cam.}} - z_A^{\text{spec.}}$

Proton track position

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

Energy momentum balance





COMPASS 2016 Preliminary Results

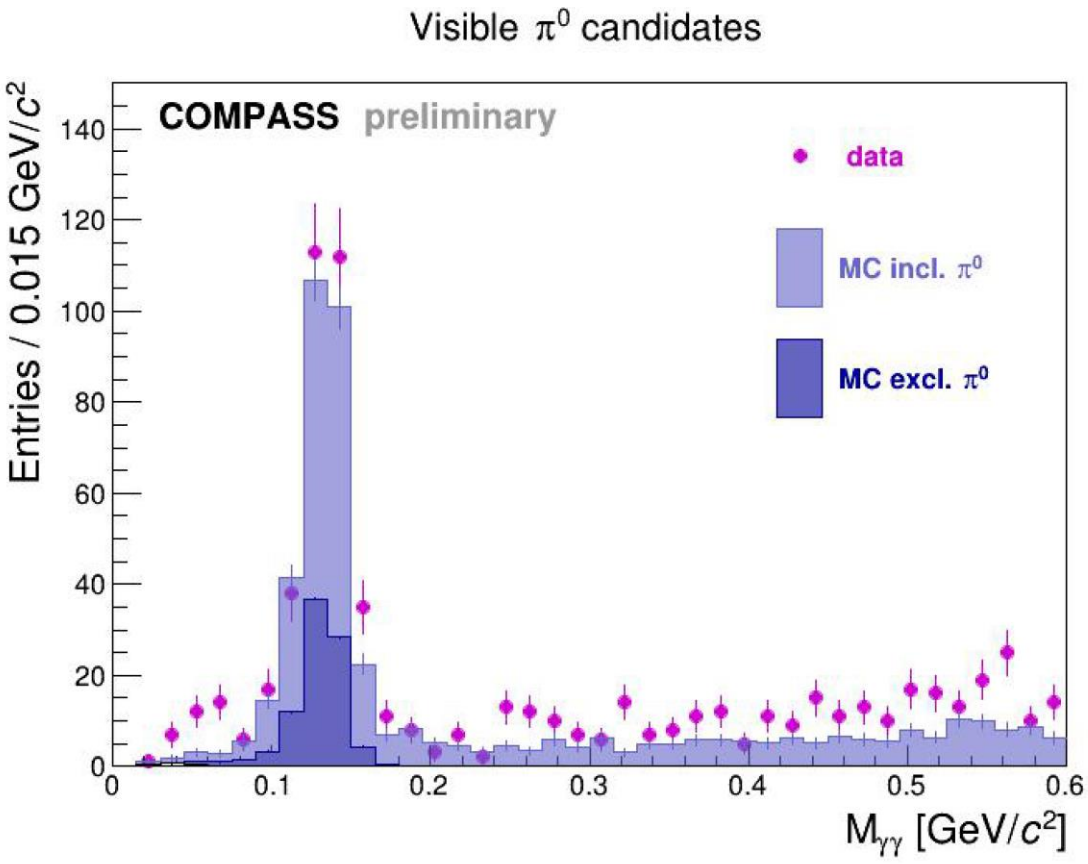
- **Main background of exclusive single photon events: π^0 decay**

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

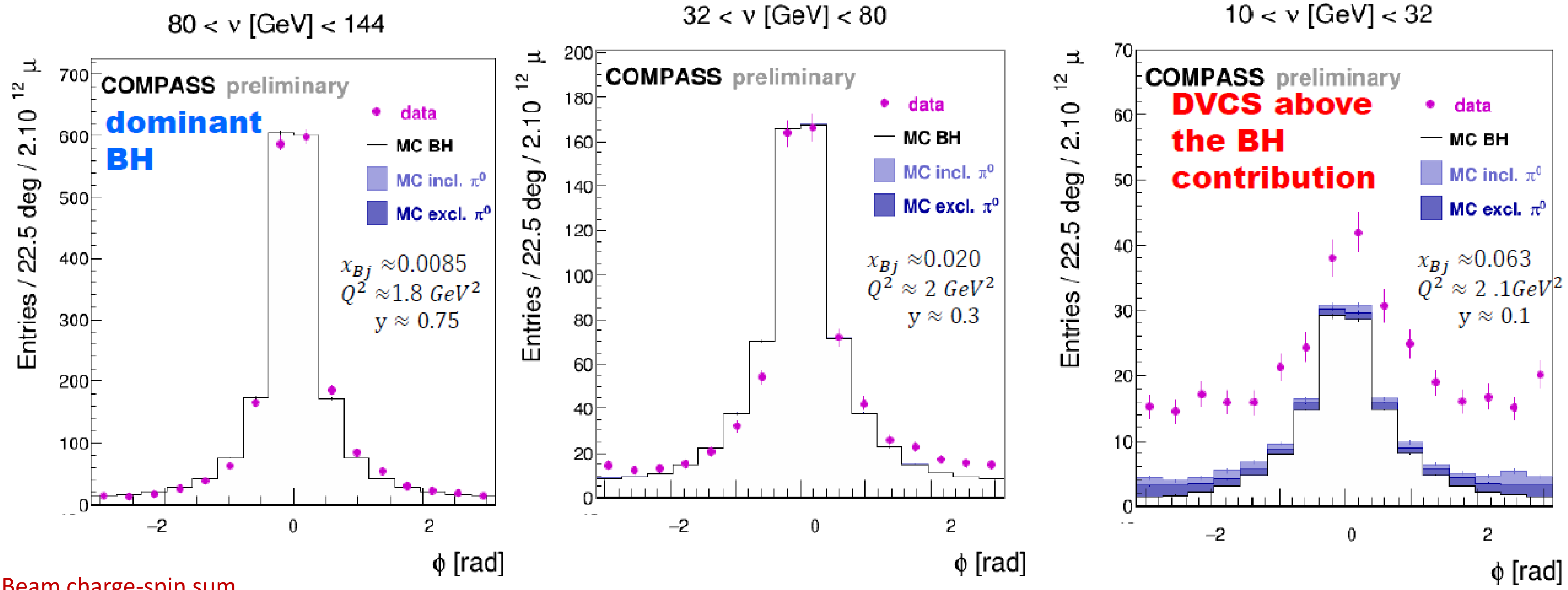
  A high-energy DVCS photon candidate is combined with all detected photons with energies lower than the DVCS threshold: (4,5) GeV in Ecal (0,1) respectively

- **Invisible** (one γ lost) – estimated by MC
  - **Semi-inclusive LEPTO 6.1**
  - **Exclusive HEPGEN π^0** (GK model)

The sum of LEPTO and HEPGEN contributions is normalized to the π^0 peak in $M_{\gamma\gamma}$ of the real data



COMPASS 2016 Preliminary Results



- Beam charge-spin sum

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

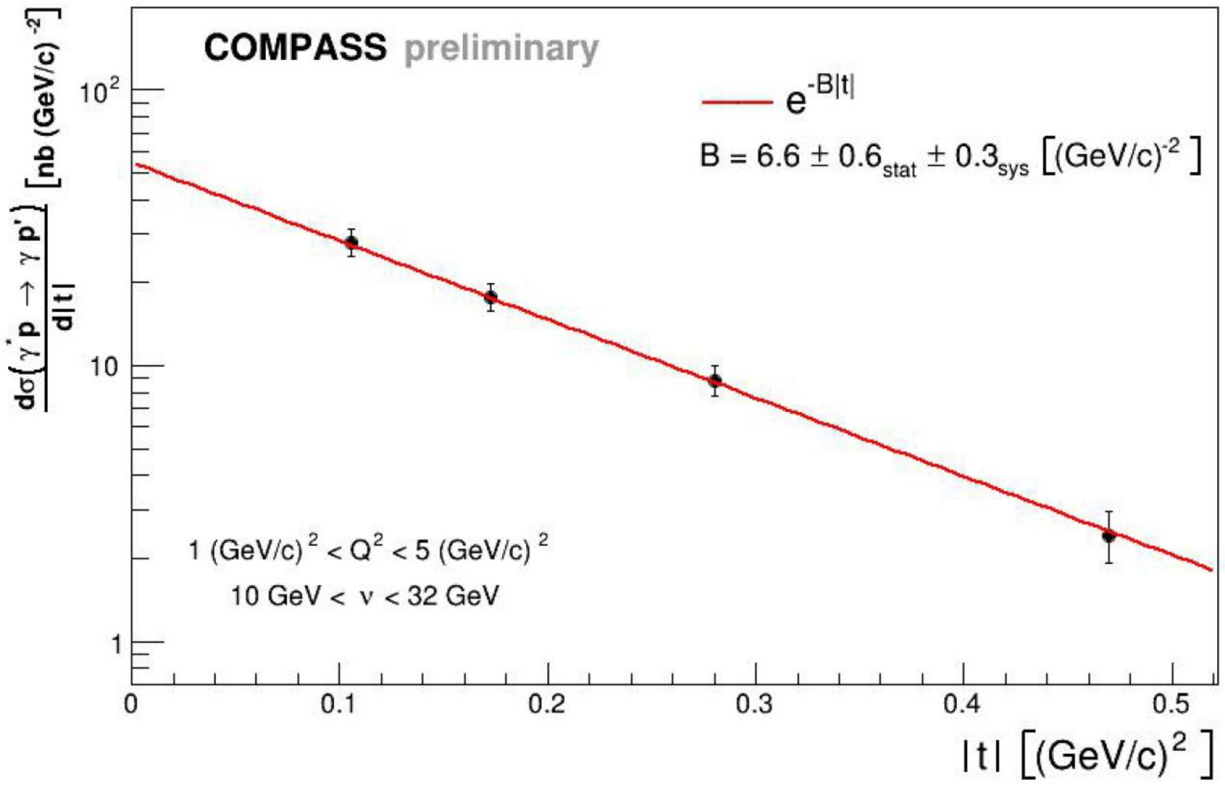
$$= 2[\, d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos\phi + c_2^{DVCS} \cos 2\phi + s_1^I \sin\phi + s_2^I \sin 2\phi \,]$$

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

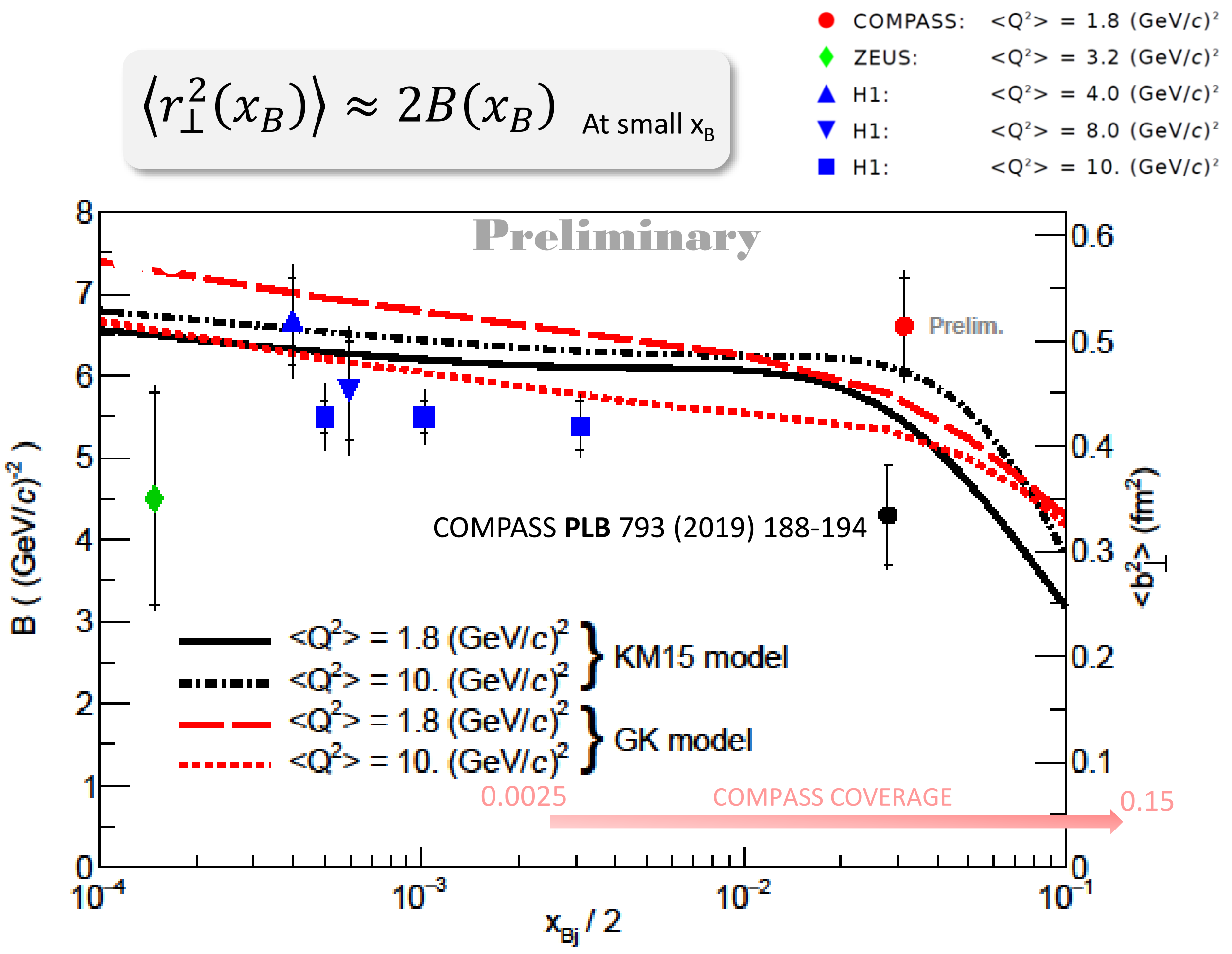
small x_{Bj} model dependent

Tranverse extension of partons – 2016 data

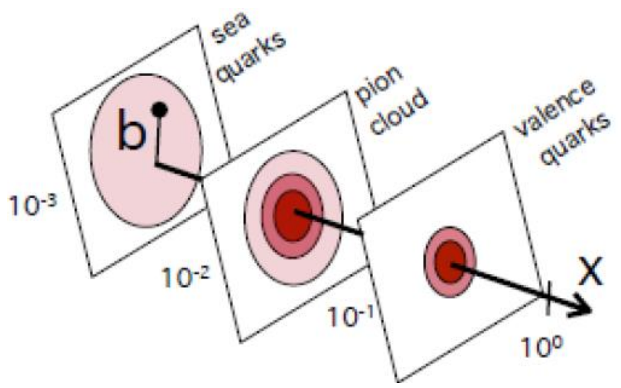
$d\sigma^{DVCS}/d|t| \propto e^{-B|t|}$



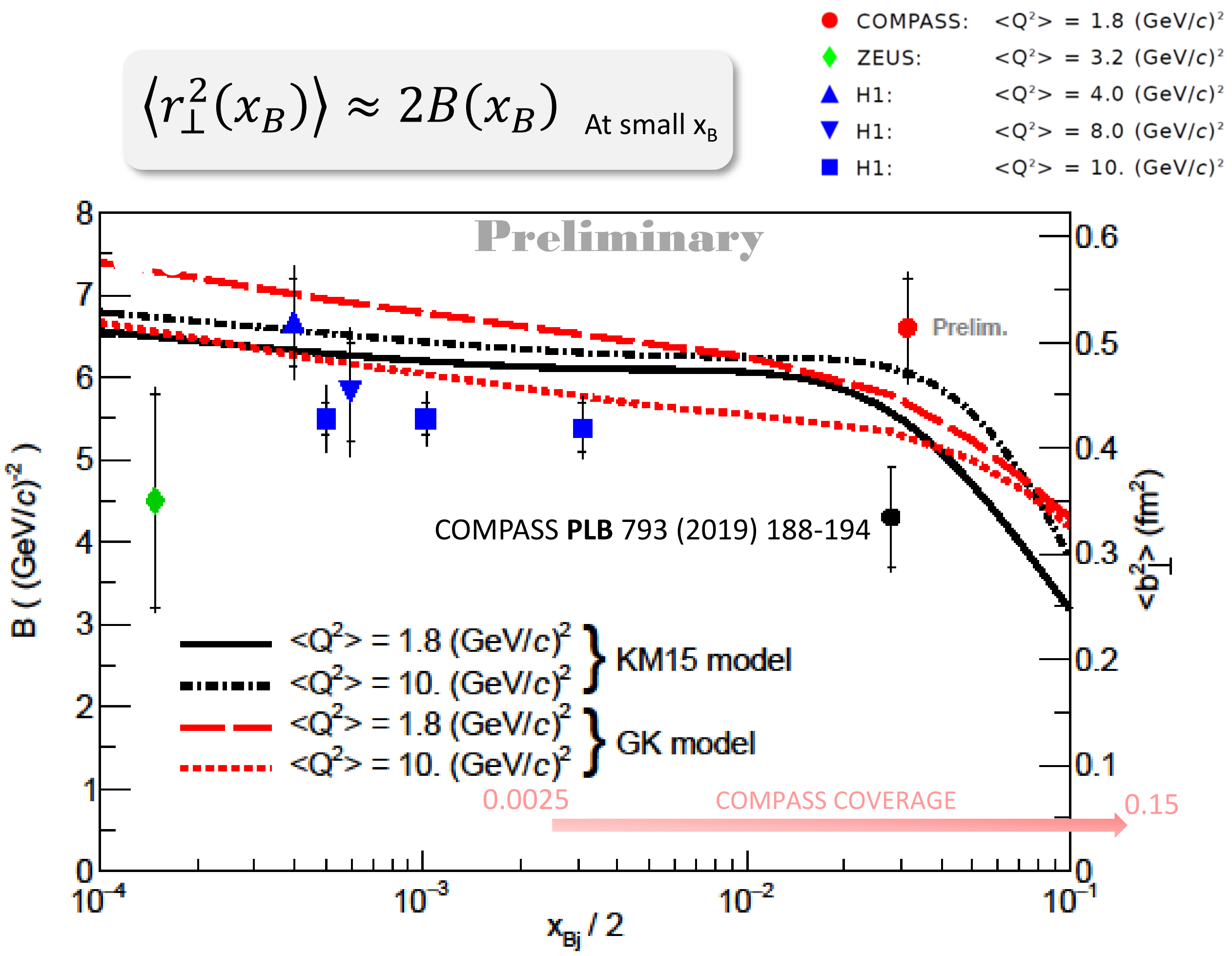
$\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$ At small x_B



Tranverse extension of partons – 2016 data



$\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$ At small x_B



- ➢ Improvements in the 2016 analysis, relative to 2012
  - μ^+ and μ^- beams at same intensity
  - More advanced analysis with 2016 data, ongoing
  - Improved π^0 contamination estimation
  - Better MC description in ν

- ➢ The transverse-size evolution as a function of x_{Bj} → Expect at least 3 x_{Bj} bins from 2016-17 data

Beam Charge-spin Difference

$\mathcal{D}_{CS,\,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow}) \rightarrow c_0^I + c_1^I \cos\phi$

BCSA = $\mathcal{D}_{CS,\,U}/\mathcal{S}_{CS,\,U} = A_0 + A_{CS,U}^{\cos\phi}\cos\phi + A_2\cos 2\phi$

$c_1^I \rightarrow \mathcal{R}e\, F_1 \mathcal{H}$

🟥 **VGG**

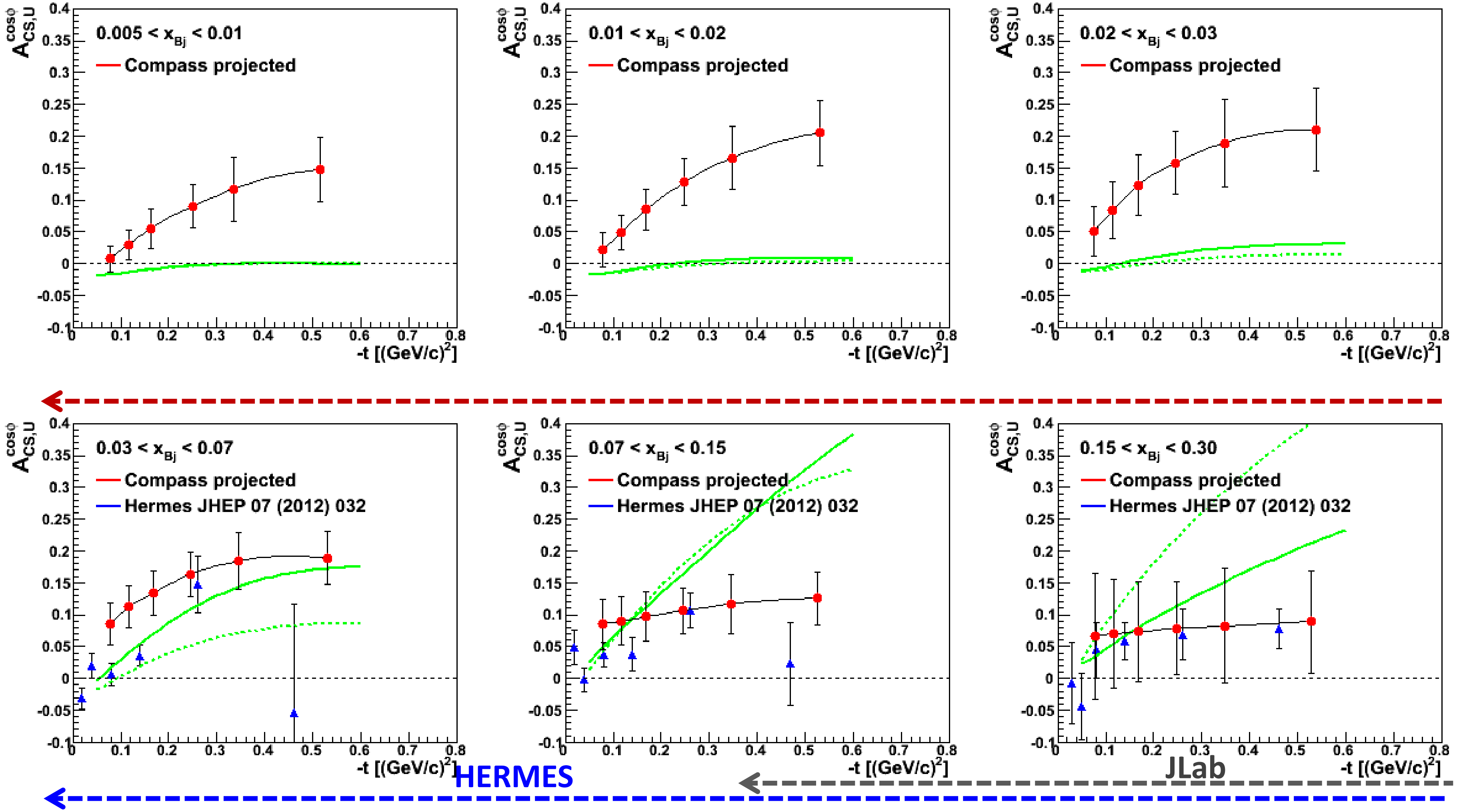
🟩 **KM10 – fit to data**

- With $\mathcal{R}e\, F_1 \mathcal{H}$ and $\mathcal{I}m\, F_1 \mathcal{H}$
  → Extraction of D-term

$\mathcal{R}e\,\mathcal{H}$ **> 0** at H1

< 0 at HERMES

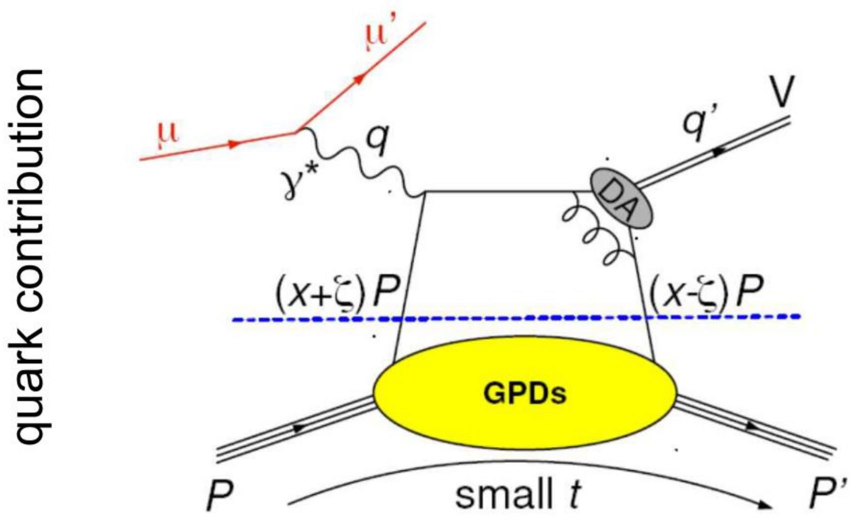
Value of x_{Bj} for the node?

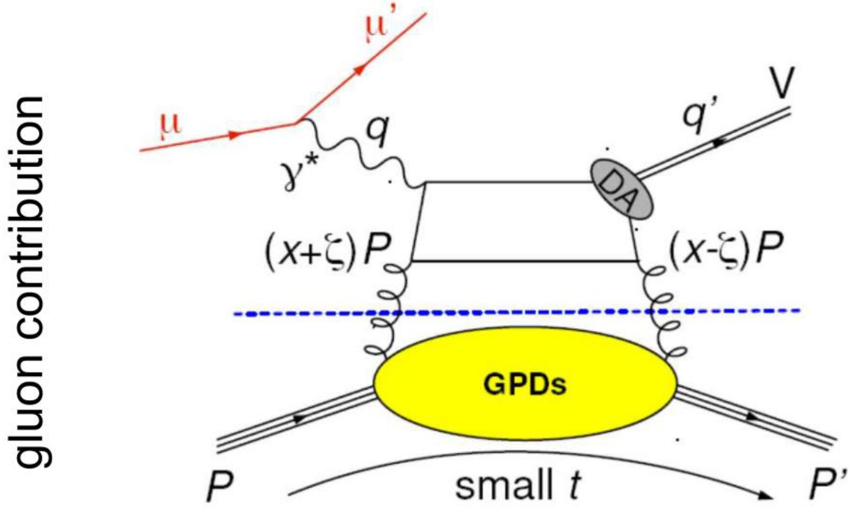


COMPASS 2 years of data Eμ= 160 GeV 1 < Q^2 < 8 GeV^2

Hard Exclusive Meson Production
@ COMPASS

GPDs in Hard Exclusive Meson Production





4 chiral-even GPDs: helicity of parton unchanged

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

$\tilde{H}^q(x, \xi, t)$ $\tilde{E}^q(x, \xi, t)$ → Pseudo-Scalar Meson

+ 4 chiral-odd (transversity) GPDs: helicity of parton changed

(not possible in DVCS)

$H_T^q(x, \xi, t)$ $E_T^q(x, \xi, t)$

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

$$\bar{E}_T^q = 2\,\tilde{H}_T^q + E_T^q$$

- Ability to probe the chiral-odd GPDs.
- Universality of GPDs, quark flavor filter
- In addition to nuclear structure, provide insights into reaction mechanism.
- Additional non-perturbative term from meson wave function.

Exclusive π^0 Production on Unpolarized Proton

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

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

ϵ : degree of longitudinal polarization

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

Leading twist expected be dominant

But measured as ≈ only a few % of $\frac{d\sigma_T}{dt}$

The other contributions arise from coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\boxed{|\langle H_T\rangle|}^2 - \frac{t'}{8m^2}\boxed{|\langle\bar{E}_T\rangle|}^2\right]$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\boxed{\langle H_T\rangle}^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\boxed{|\langle\bar{E}_T\rangle|}^2$$

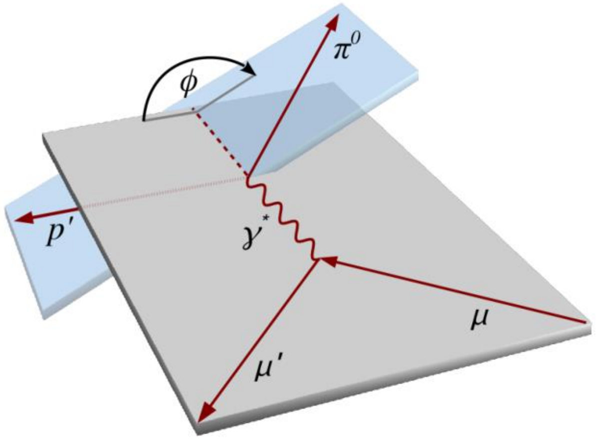
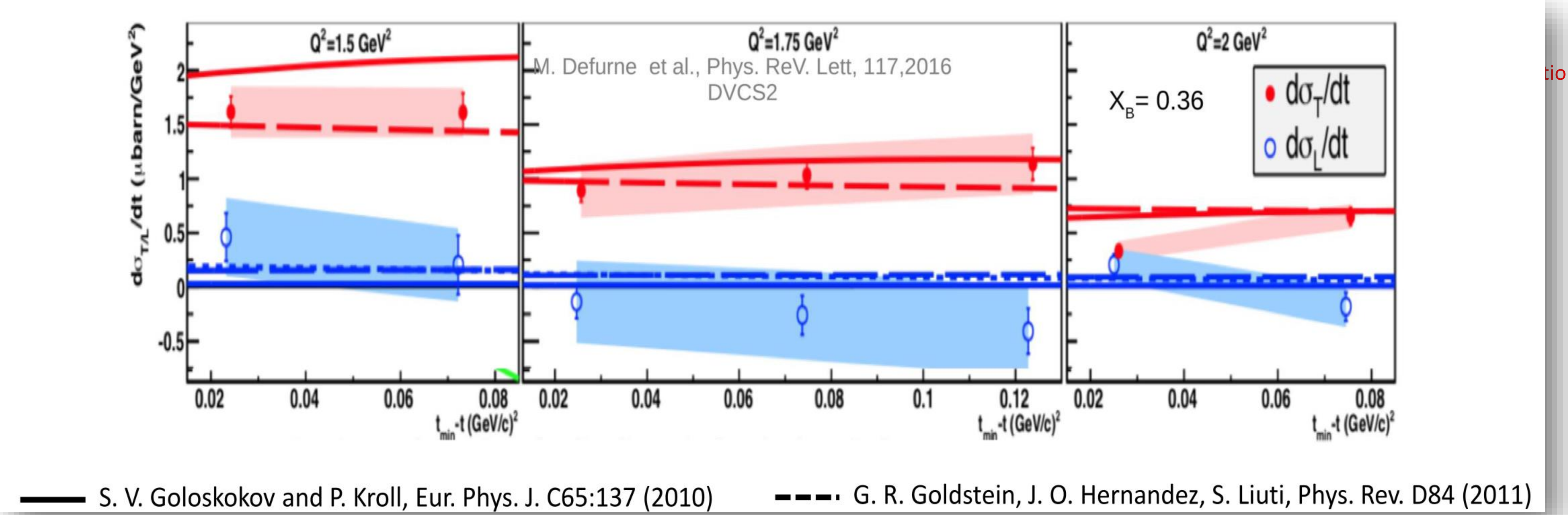


Fig: M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

Exclusive π^0 Production on Unpolarized Proton

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



M. Defurne et al., Phys. ReV. Lett, 117,2016
DVCS2

$X_B = 0.36$

S. V. Goloskokov and P. Kroll, Eur. Phys. J. C65:137 (2010)

G. R. Goldstein, J. O. Hernandez, S. Liuti, Phys. Rev. D84 (2011)

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

Exclusive π^0 Production on Unpolarized Proton

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

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

ϵ : degree of longitudinal polarization

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

Leading twist expected to be dominant

But measured as ≈ only a few % of $\frac{d\sigma_T}{dt}$

The other contributions arise from the coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

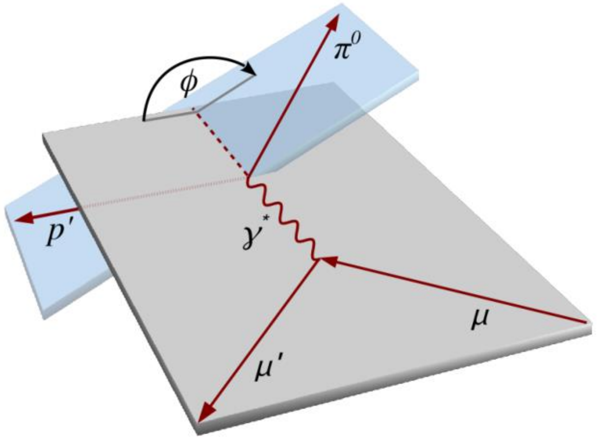
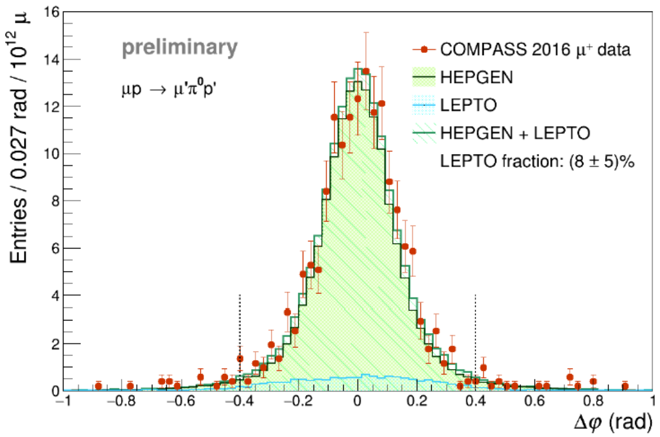
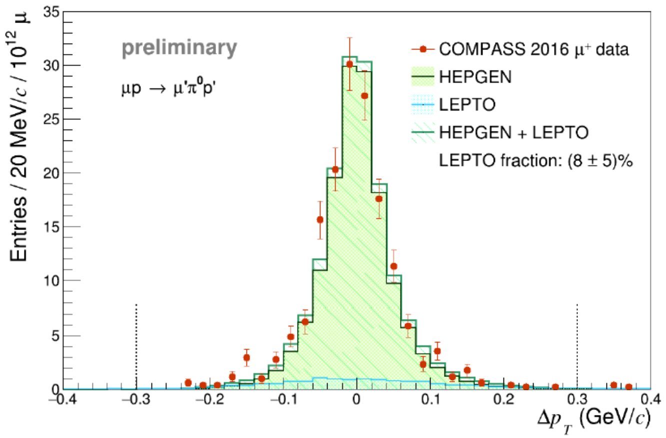


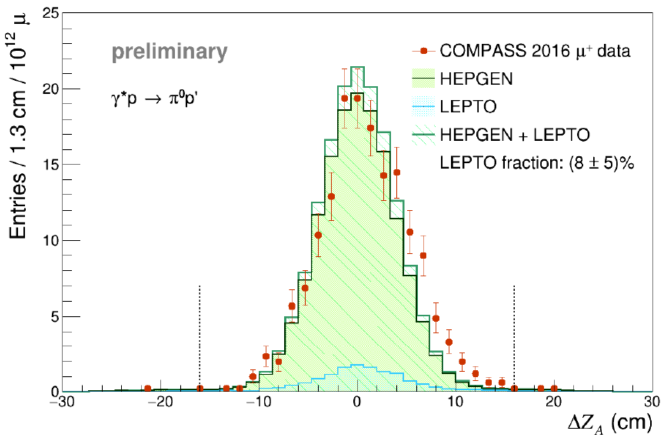
Fig: M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

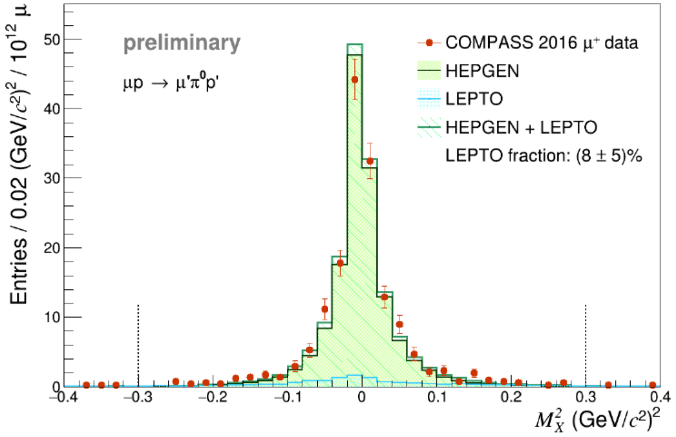
Exclusive π^0 Selection and Background Estimation

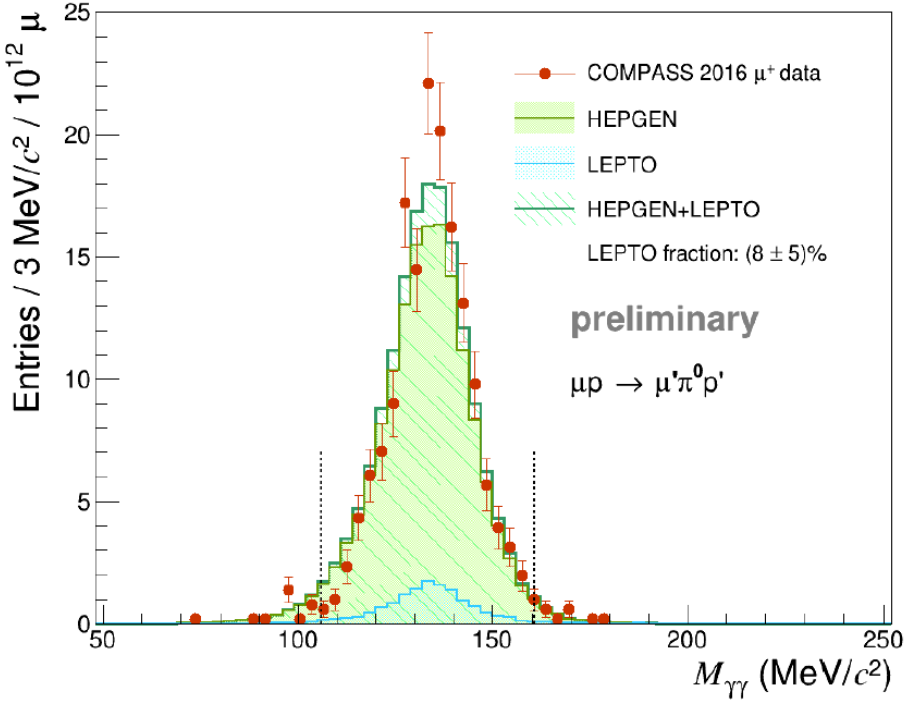
- Exclusivity ensured by cuts on *exclusivity variables, similar to DVCS.*
- Background fraction determined by fitting the exclusivity variables with Monte Carlo simulations.
  - *LEPTO* for non-exclusive background
  - *HEPGEN* of exclusive π^0 for signal











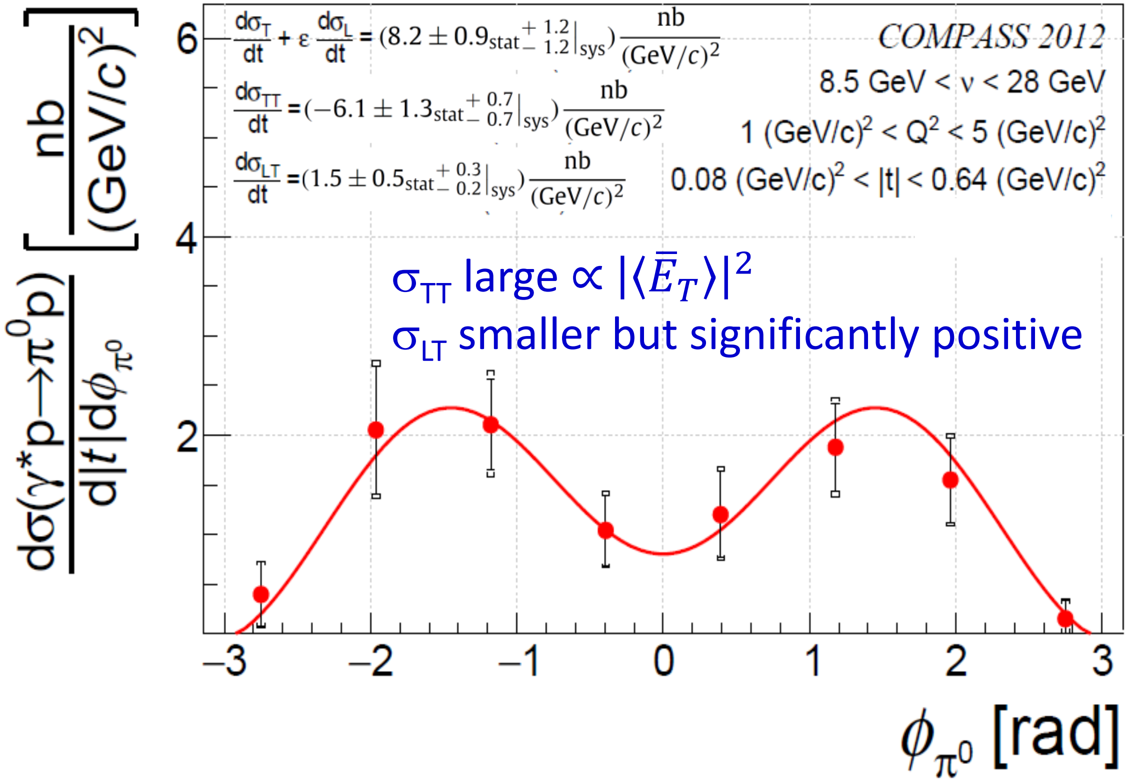
- In 2016 data, non-exclusive background fraction in data → 8 ± 5 %

2012 Exclusive π^0 Prod. on Unpolarized Proton

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

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

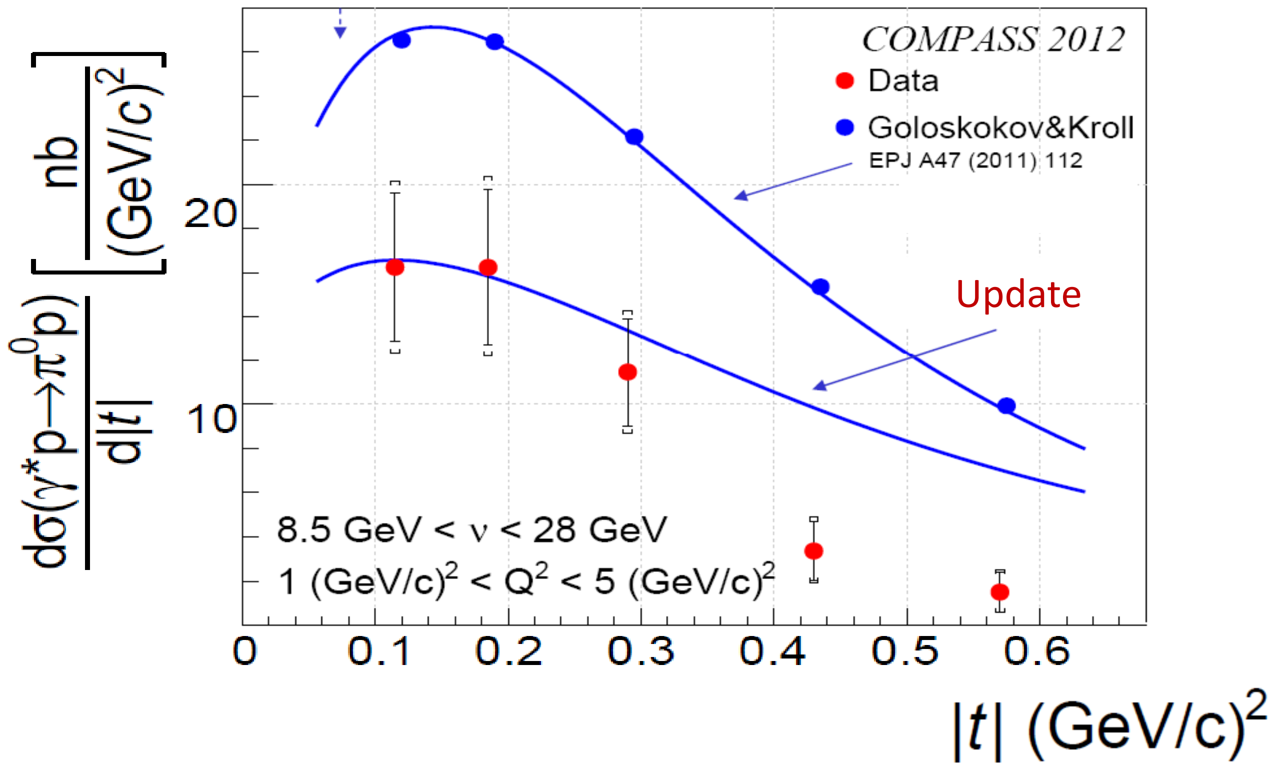
Chiral-odd GPDs



σ_{TT} large $\propto |\langle \bar{E}_T \rangle|^2$

σ_{LT} smaller but significantly positive

A dip at small t would indicate the significance of $\overline{E}_T$

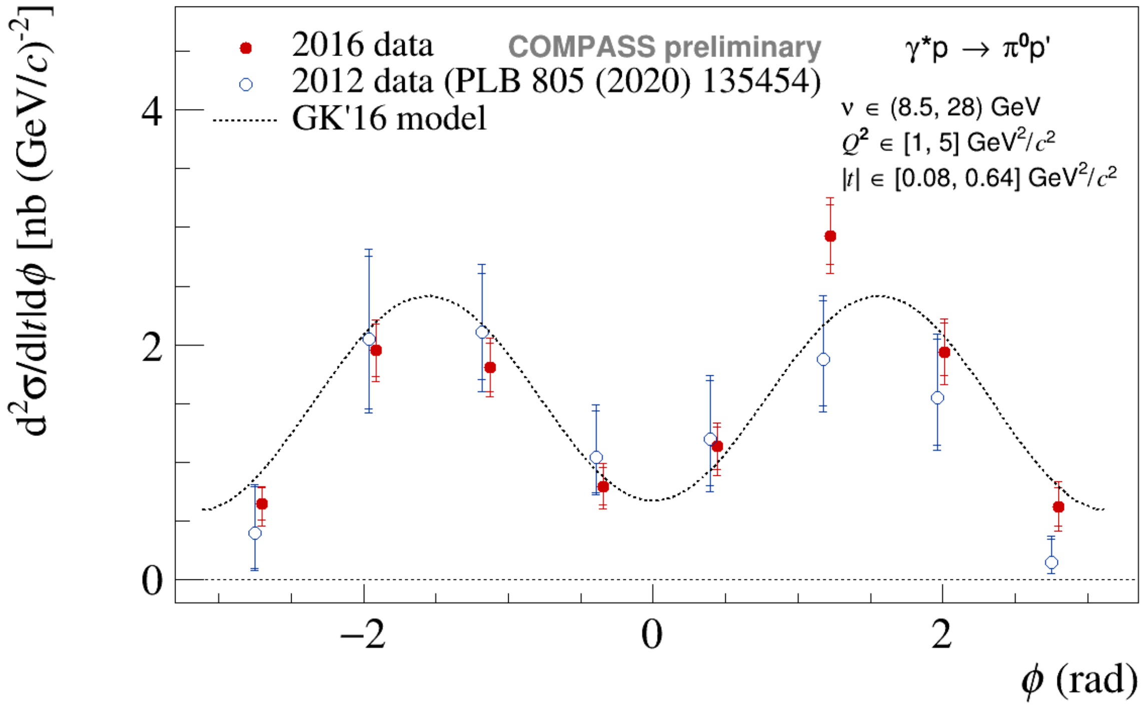


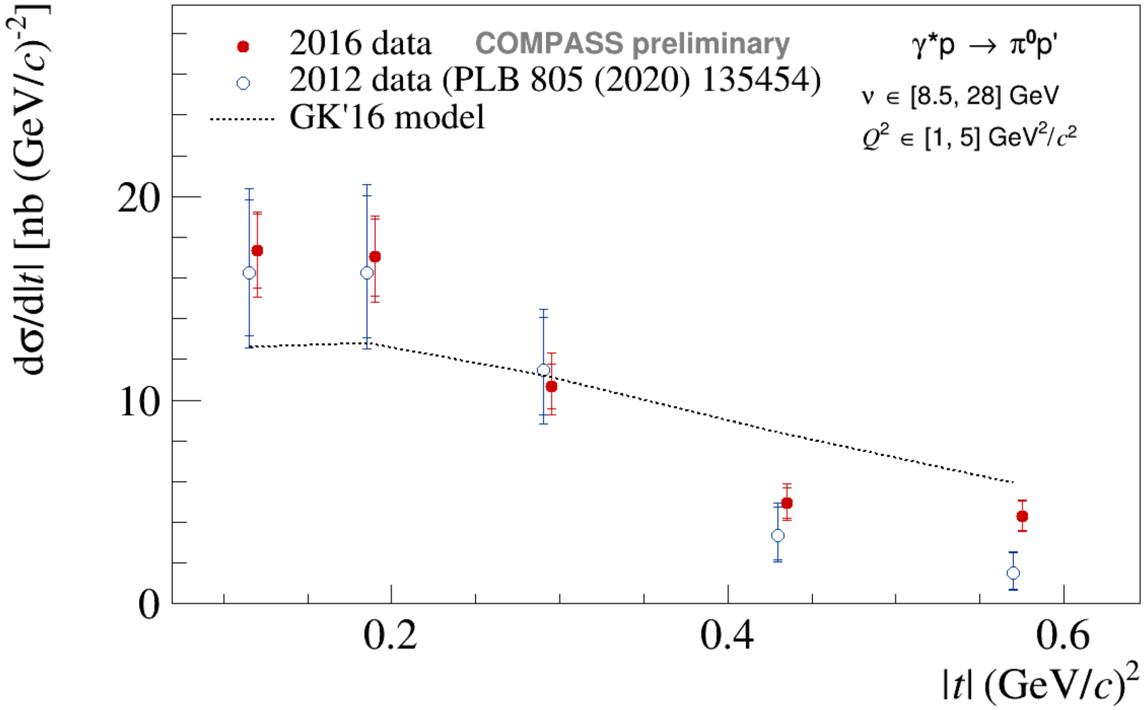
Update

COMPASS, **PLB** 805 (2020) 135454

2016 Exclusive π^0 Prod. on Unpolarized Proton

- **New 2016 data release:** statistics about 2.3 times larger than the published 2012 pilot run.

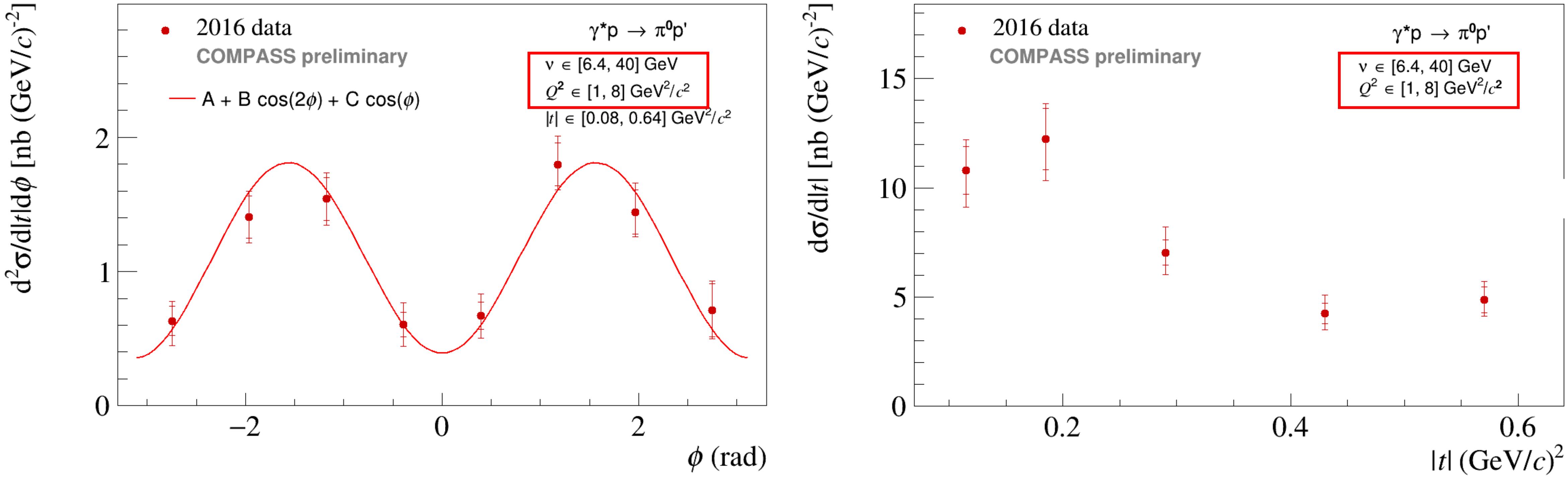




- Agree with previous measurements, with better uncertainty

2016 Exclusive π^0 Prod. on Unpolarized Proton

- **New 2016 data release:** statistics about 2.3 times larger than the published 2012 pilot run.

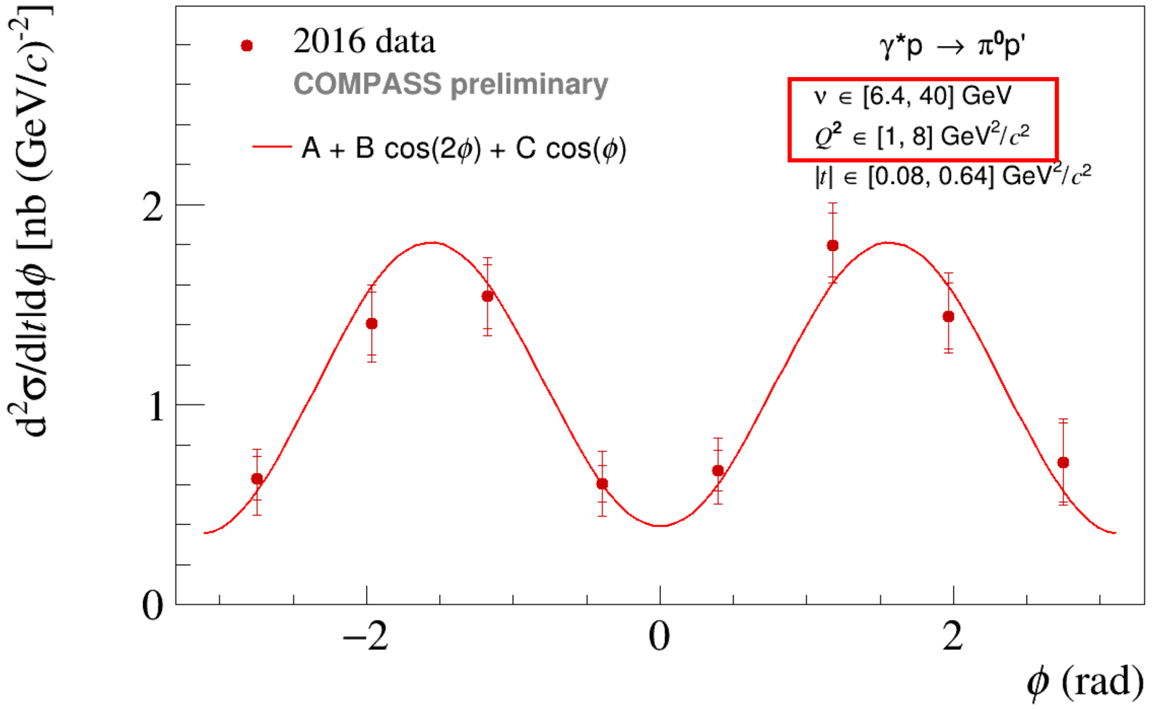


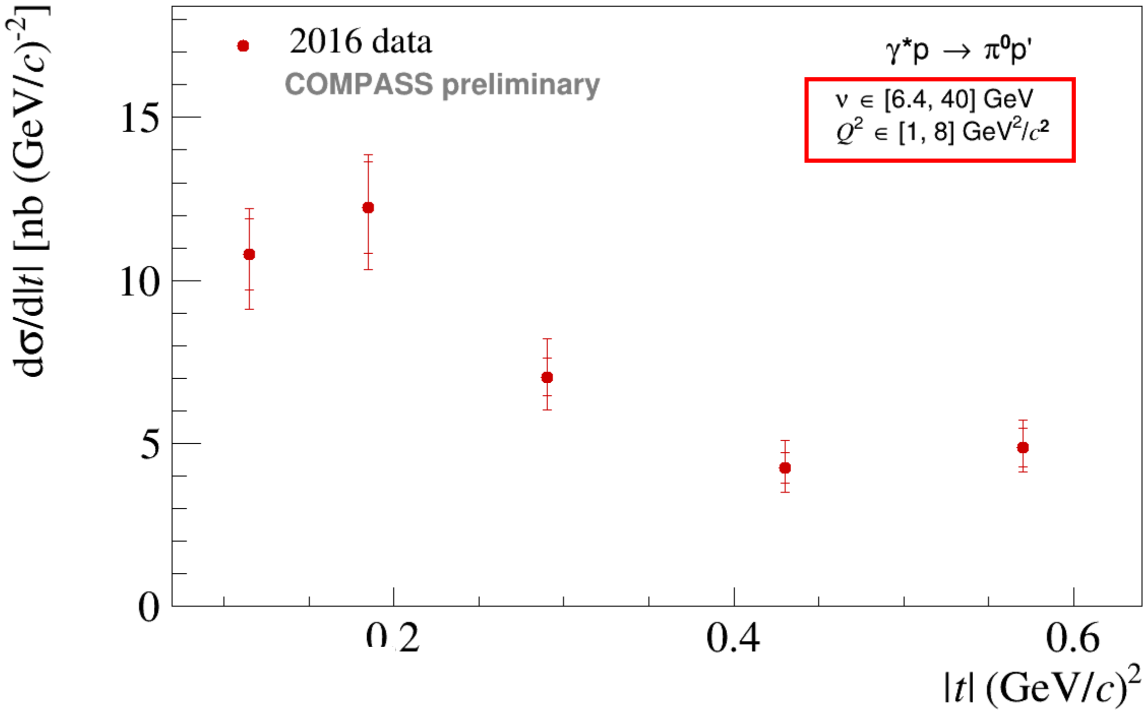
- Larger (ν, Q^2) domain achievable.

$\nu \in [8.5, 28] \rightarrow [6.4, 40]$ GeV
$Q^2 \in [1,5] \rightarrow [1,8]\ \mathrm{GeV}^2/c^2$
$|t| \in [0.08, 0.64]\ \mathrm{GeV}^2/c^2$

2016 Exclusive π^0 Prod. on Unpolarized Proton

- **New 2016 data release:** statistics about 2.3 times larger than the published 2012 pilot run.





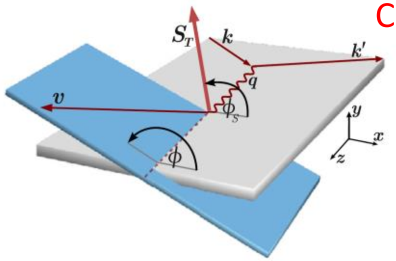
$$\left\langle \frac{\sigma_T}{|t|} + \epsilon \frac{\sigma_L}{|t|} \right\rangle = (6.9 \pm 0.3_{\text{stat}} \pm 0.8_{\text{syst}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$$

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

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

- Main systematic uncertainty comes from the evaluation of the π^0 background from SIDIS
- We will provide the evolution with 3 bins in ν and 4 bins in Q^2

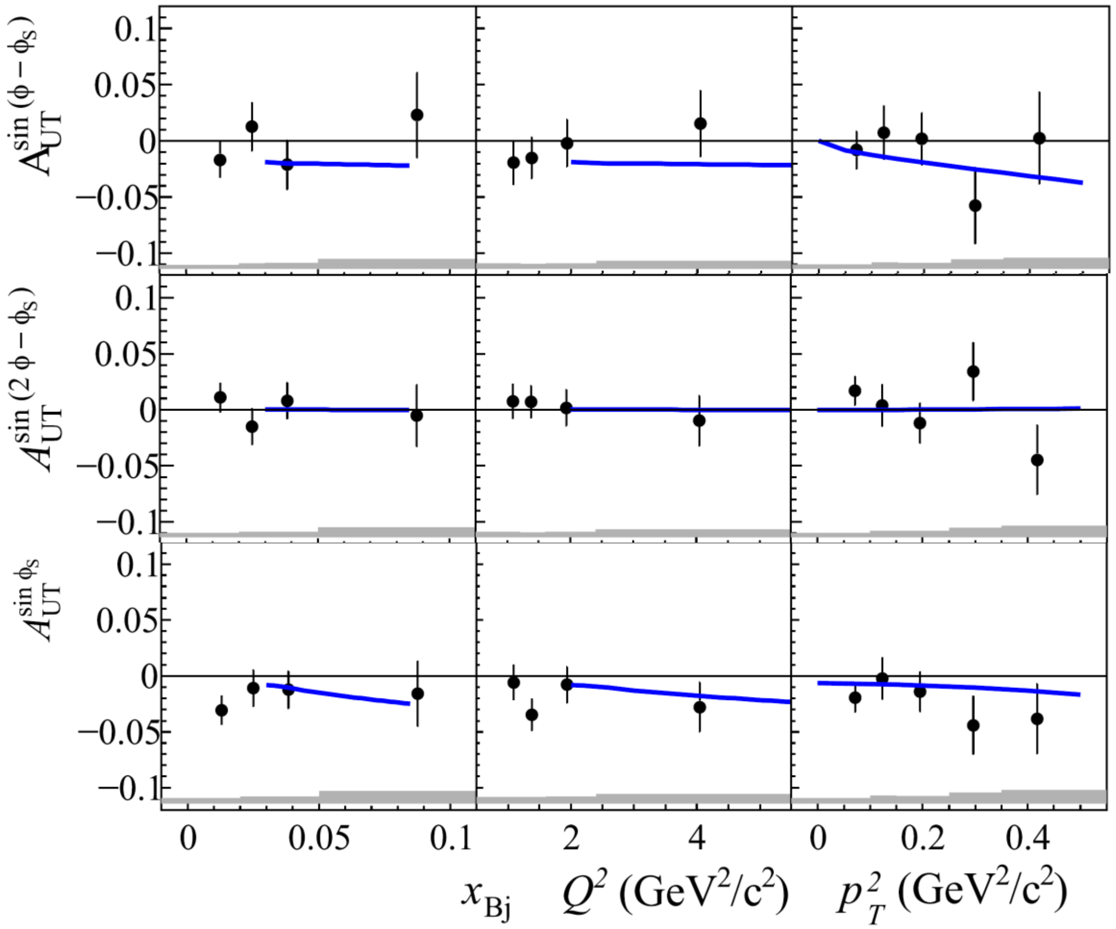
2007 & 2010 HEMP with Transversely Polarized Target



COMPASS, **NPB** 865 (2012) 1-20, **PLB** 731 (2014) 19

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

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

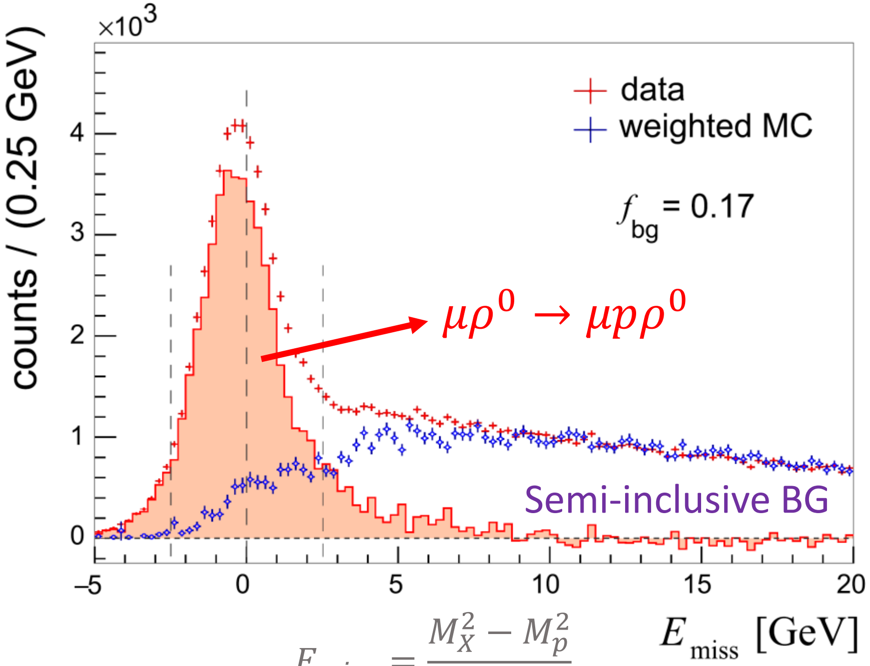


$\propto Im(E^*H)$

$\propto Im(E^*\bar{E}_T)$

$\propto Im(\cancel{E^*\bar{E}_T} - H^*H_T)$

- Exclusivity ensured by “missing mass technique”



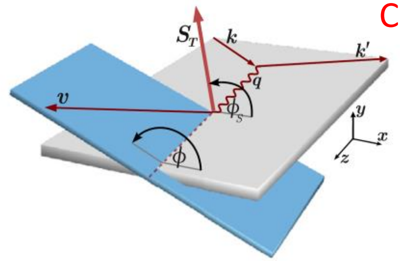
$$E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$$

- Sensibility to E and H_T

GK Model EPJC 42, 50, 53, 59, 65, 74

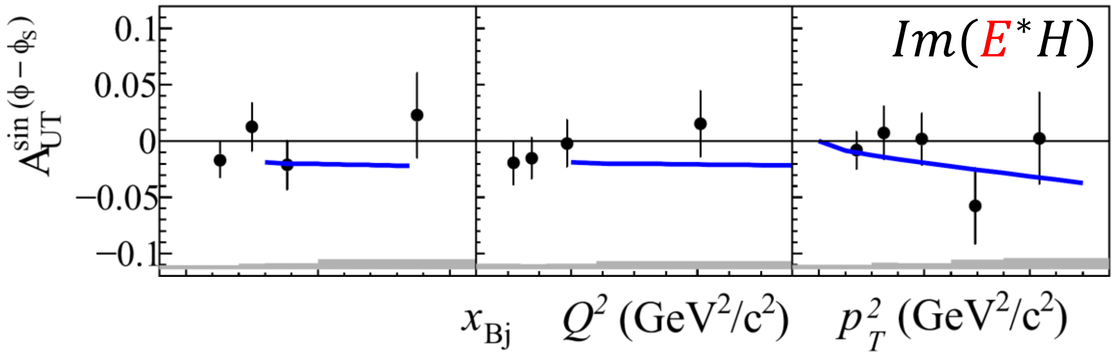
2007 & 2010 HEMP with Transversely Polarized Target

COMPASS, **NPB** 865 (2012) 1-20, **PLB** 731 (2014) 19



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

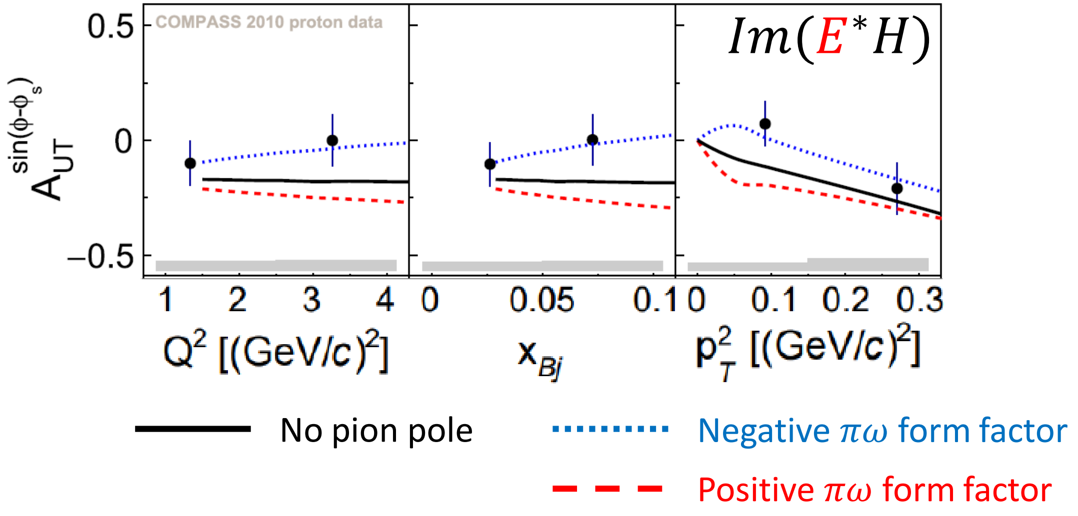
$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g/x\right)$$

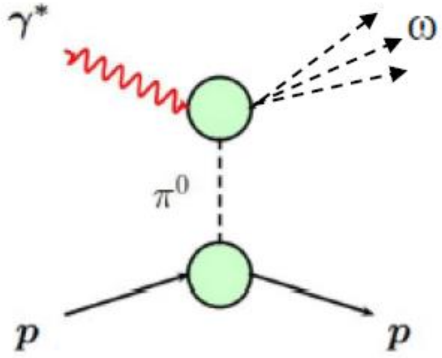


COMPASS, **NPB** 865 (2012) 1-20, **PLB** 731 (2014) 19

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

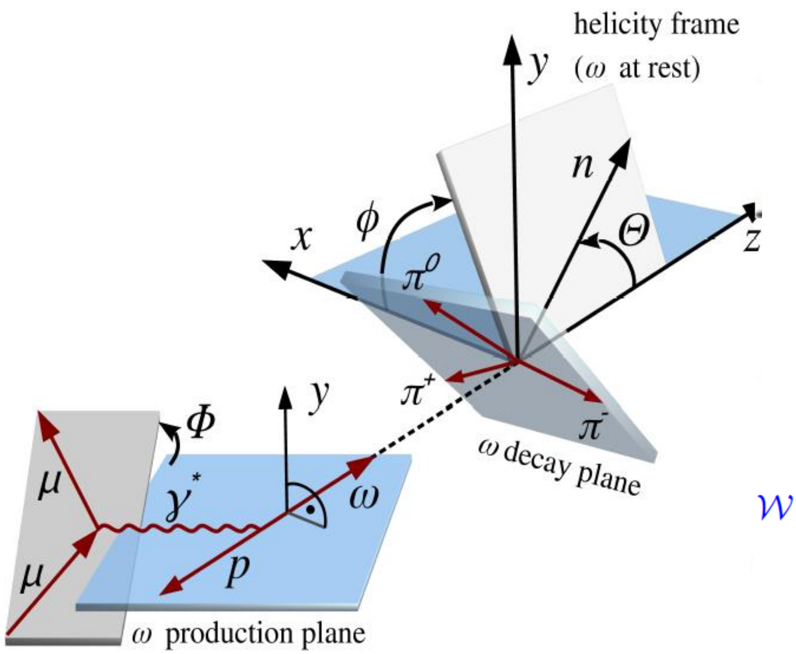
$$E_\omega = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}E^g/x\right)$$





- ➢ E^u and E^d are of opposite sign → ω is more promising for GPD study
- ➢ Nevertheless, obscured by the inherent pion pole contribution

Exclusive ω Production on Unpolarized Proton



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 SDMEs in $\mathcal{W}^U$ and 8 polarized in $\mathcal{W}^L$

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

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

- $\epsilon \to 1$, small $\mathcal{W}^L$

2012 Exclusive ω Prod. on Unpolarized Proton

SCHC ($\lambda_\gamma = \lambda_V$)

(S-Channel Helicity Conservation)

SCHC implies:

- $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$

= - 0.010 ± 0.032 ± 0.047 OK

- $\mathrm{Re}\, r^5_{10} + \mathrm{Im}^6_{10} = 0$

= 0.014 ± 0.011 ± 0.013 OK

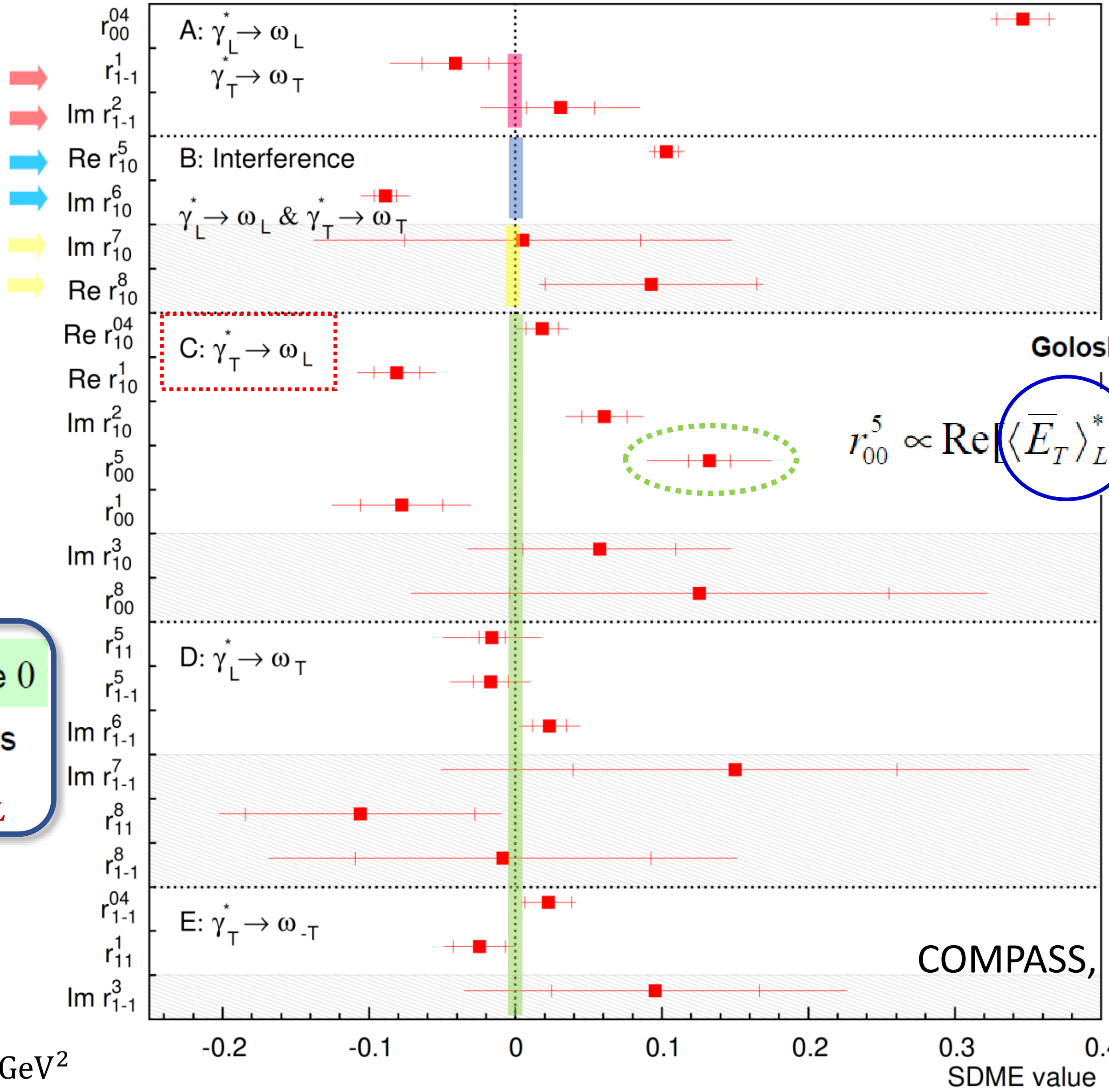
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

= - 0.088 ± 0.110 ± 0.196 OK

- all elements of classes C, D, E should be 0

for $\gamma^*_L \to \omega_T$ and $\gamma^*_T \to \omega_{-T}$ OK within errors

NOT OBSERVED for transitions $\gamma_T^* \to \omega_L$



■ SDMEs COMPASS

Goloskokov and Kroll, EPJC 74 (2014) 2725

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

Exclusive ρ⁰, ω production with trans. pol. target

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

COMPASS, **Eur.Phys.J.C** 81 (2021) 126

$\langle Q^2\rangle = 2.1\ \mathrm{GeV}^2, \langle W\rangle = 7.6\ \mathrm{GeV}, \langle P_T^2\rangle = 0.16\ \mathrm{GeV}^2$

2012 Exclusive ρ^0 Prod. on Unpolarized Proton

SCHC ($\lambda_\gamma = \lambda_V$)

(S-Channel Helicity Conservation)

SCHC implies:

- $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$

= -0.000 ± 0.006 OK

- $\mathrm{Re}\, r^5_{10} + \mathrm{Im}^6_{10} = 0$

= -0.011 ± 0.003 Violation

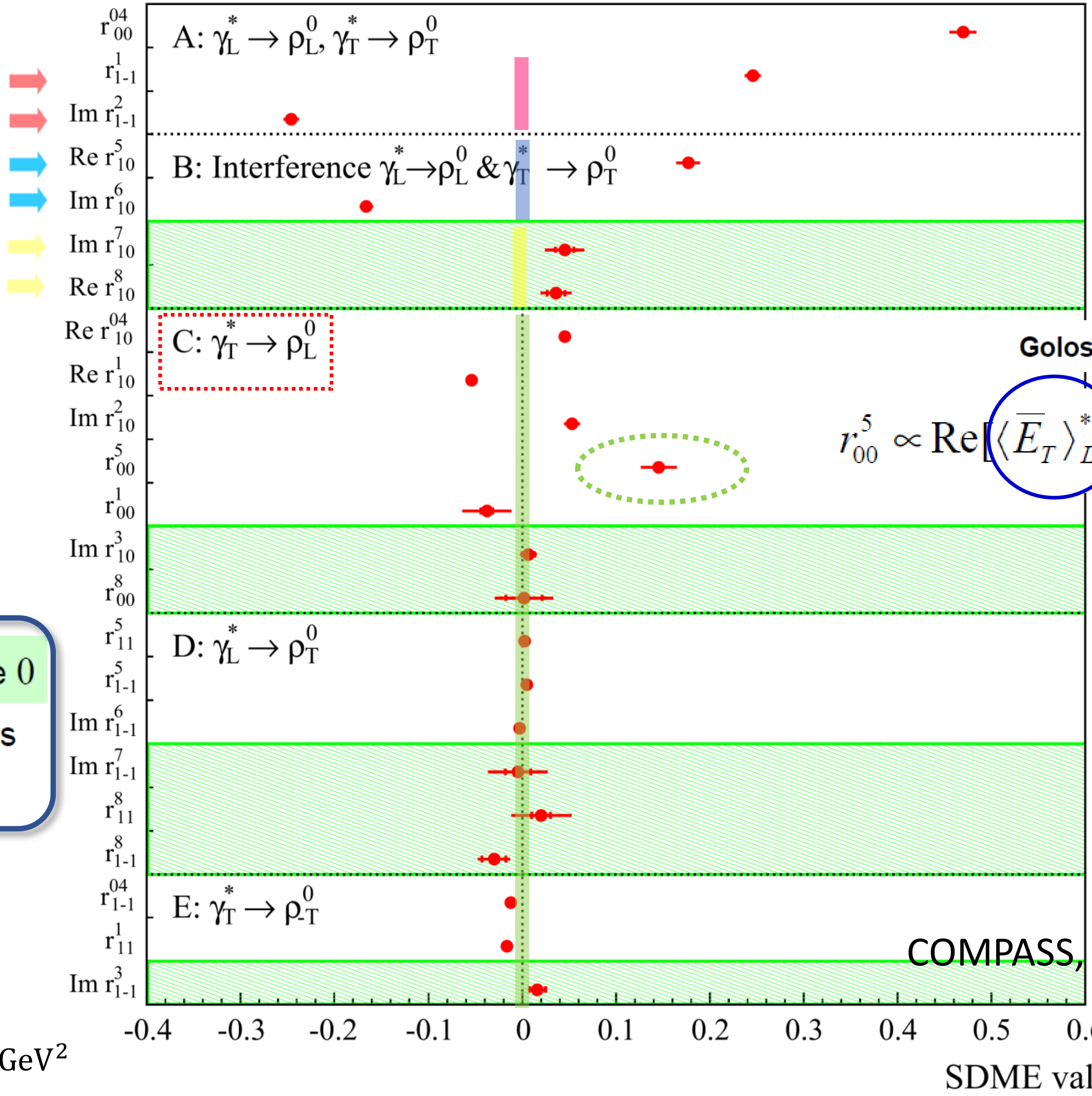
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

= -0.009 ± 0.031 OK

- all elements of classes C, D, E should be 0

for $\gamma^*_L \to \omega_T$ and $\gamma^*_T \to \omega_{-T}$ OK within errors

NOT OBSERVED for transitions $\gamma^*_T \to \rho^0_L$



Goloskokov and Kroll, EPJC 74 (2014) 2725

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

First term dominates

→ Probes $\bar{E}_T$

COMPASS, **Eur.Phys.J.C** 83 (2023) 924

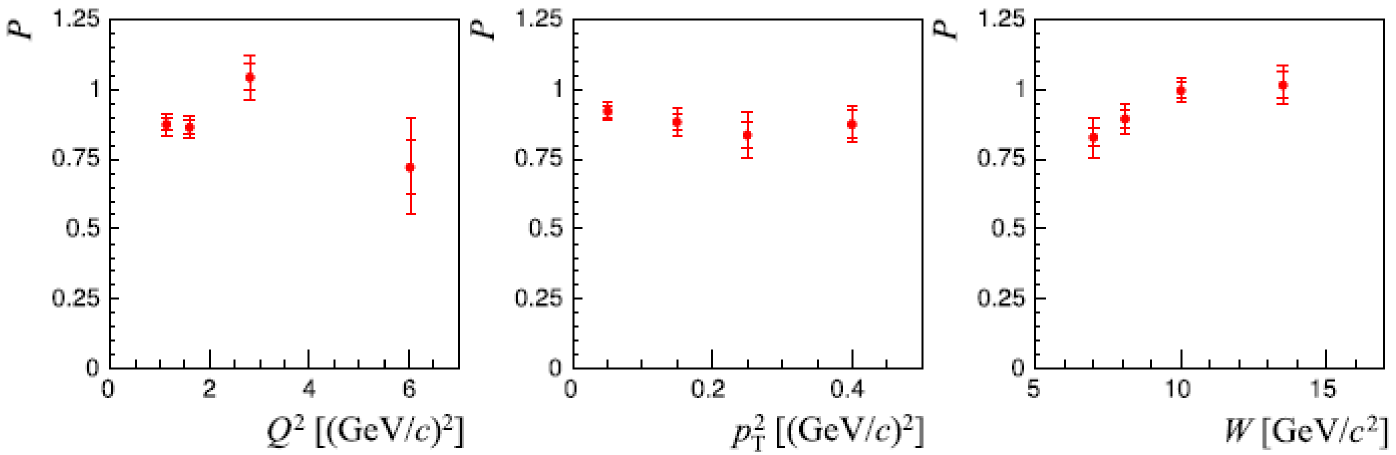
$\langle Q^2 \rangle = 2.4\ \mathrm{GeV}^2, \langle W \rangle = 9.9\ \mathrm{GeV}, \langle P_T^2 \rangle = 0.18\ \mathrm{GeV}^2$

2012 NPE-to-UPE Asymmetry

$$P = \frac{2r^{1}_{1-1}}{1 - r^{04}_{00} - 2r^{04}_{1-1}} \approx \frac{d\sigma^{N}_{T}(\gamma^{*}_{T} \to V_{T}) - d\sigma^{U}_{T}(\gamma^{*}_{T} \to V_{T})}{d\sigma^{N}_{T}(\gamma^{*}_{T} \to V_{T}) + d\sigma^{U}_{T}(\gamma^{*}_{T} \to V_{T})}$$

NPE-to-UPE asymmetry of cross sections for transitions $\gamma^{*}_{\mathrm{T}} \to V_{T}$

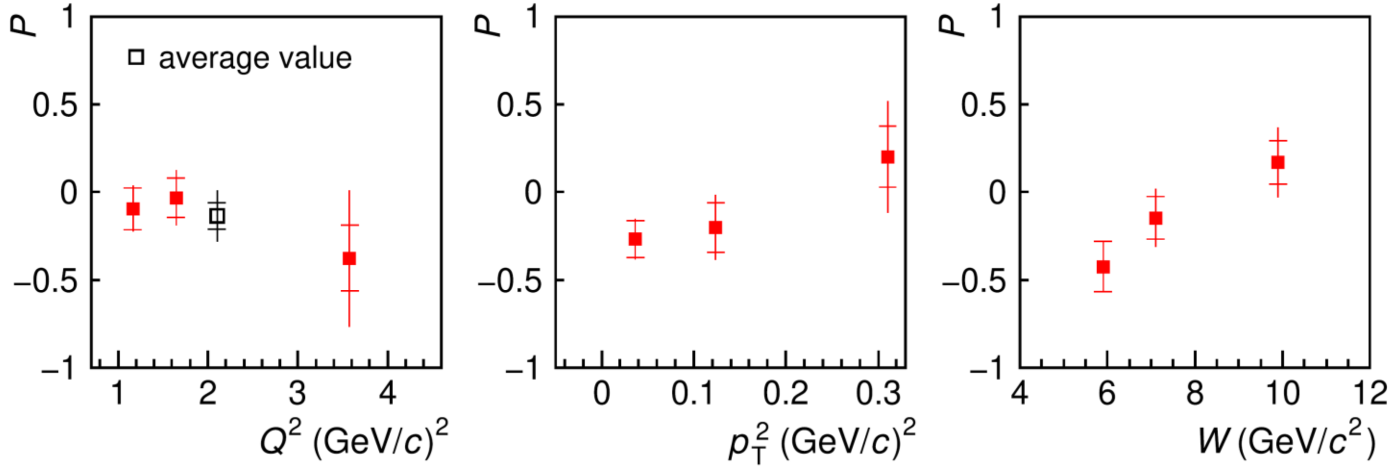
- ➢ NPE: Natural Parity Exchange
- ➢ UPE: Unnatural Parity Exchange



ρ^0

COMPASS, **Eur.Phys.J.C** 83 (2023) 924

- ➢ **NPE Dominance**
- ➢ **NPE → GPDs E, H**



ω

COMPASS, **Eur.Phys.J.C** 81 (2021) 126

- ➢ **NPE ≈ UPE on average**
- ➢ **UPE Dominance at small W and p_T^2**
- ➢ **UPE → GPDs $\widetilde{E}, \widetilde{H}$**

  + Pion pole (dominant)

2012 $R = \sigma_L/\sigma_T$ for Exclusive ρ^0 Production

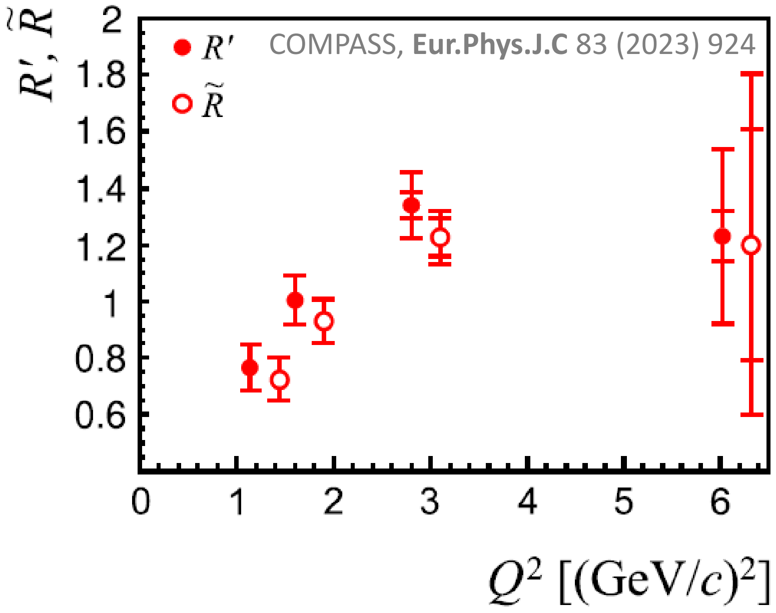
- Longitudinal-to-transverse γ^* cross section ratio:

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

  - Commonly used "effective" ratio ($R' = R$ only if SCHC):

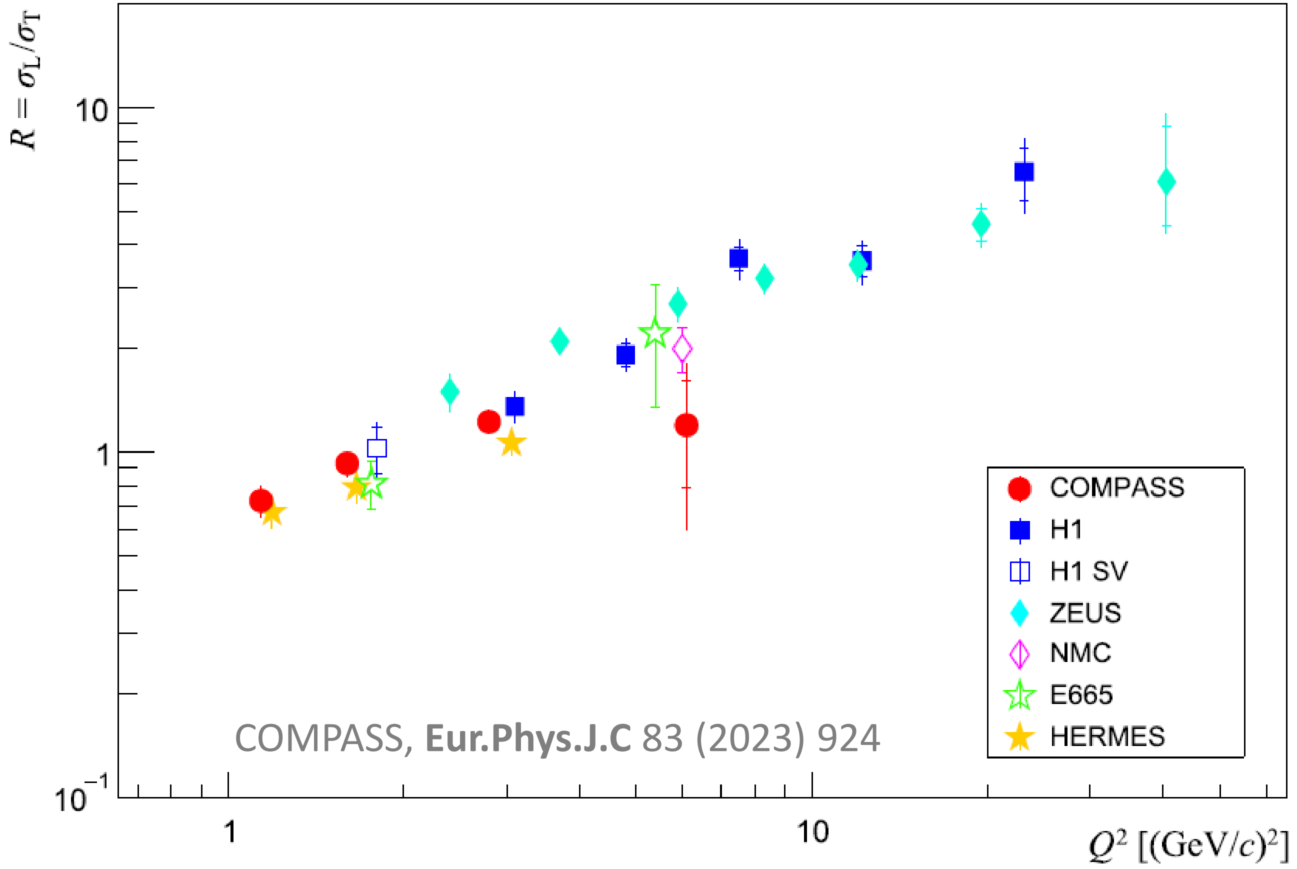
$$R' = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

  - Use of $\tilde{R}$, which takes SCHC violation into consideration, is preferred.



COMPASS, **Eur.Phys.J.C** 83 (2023) 924

Results of all experiments with $Q^2 > 1\ (\mathrm{GeV}/c)^2$



COMPASS, **Eur.Phys.J.C** 83 (2023) 924

- Leading-order pQCD predction: Q^2/M_ρ^2 → deviation due to effect of QCD evolution and q_T

Summary

DVCS cross sections with polarized μ+ and μ-

- Beam charge-spin sum → Im$\mathcal{H}(\xi,t)$ → Transverse extension of partons as a function of x_{Bj}
- Beam charge-spin difference → Re$\mathcal{H}(\xi,t)$ → D-term, pressure distribution

HEMP of π^0, ρ, ω, ϕ, J/ψ

- Cross setion of π^0, SDME of ρ & ω → Transversity GPDs & Flavor Decomposition
- ϕ, J/ψ → underway

- **COMPASS has entered its analysis phase, expect more results soon!**