
# Exclusive Reactions at COMPASS

**CIPANP 2025**

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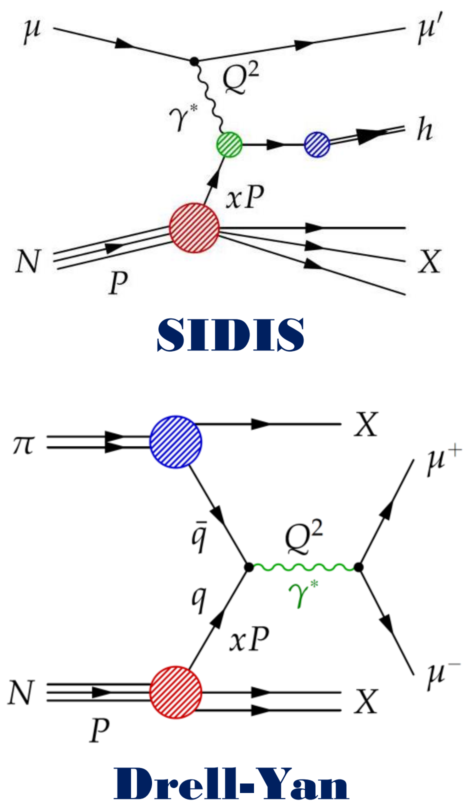
Po-Ju Lin

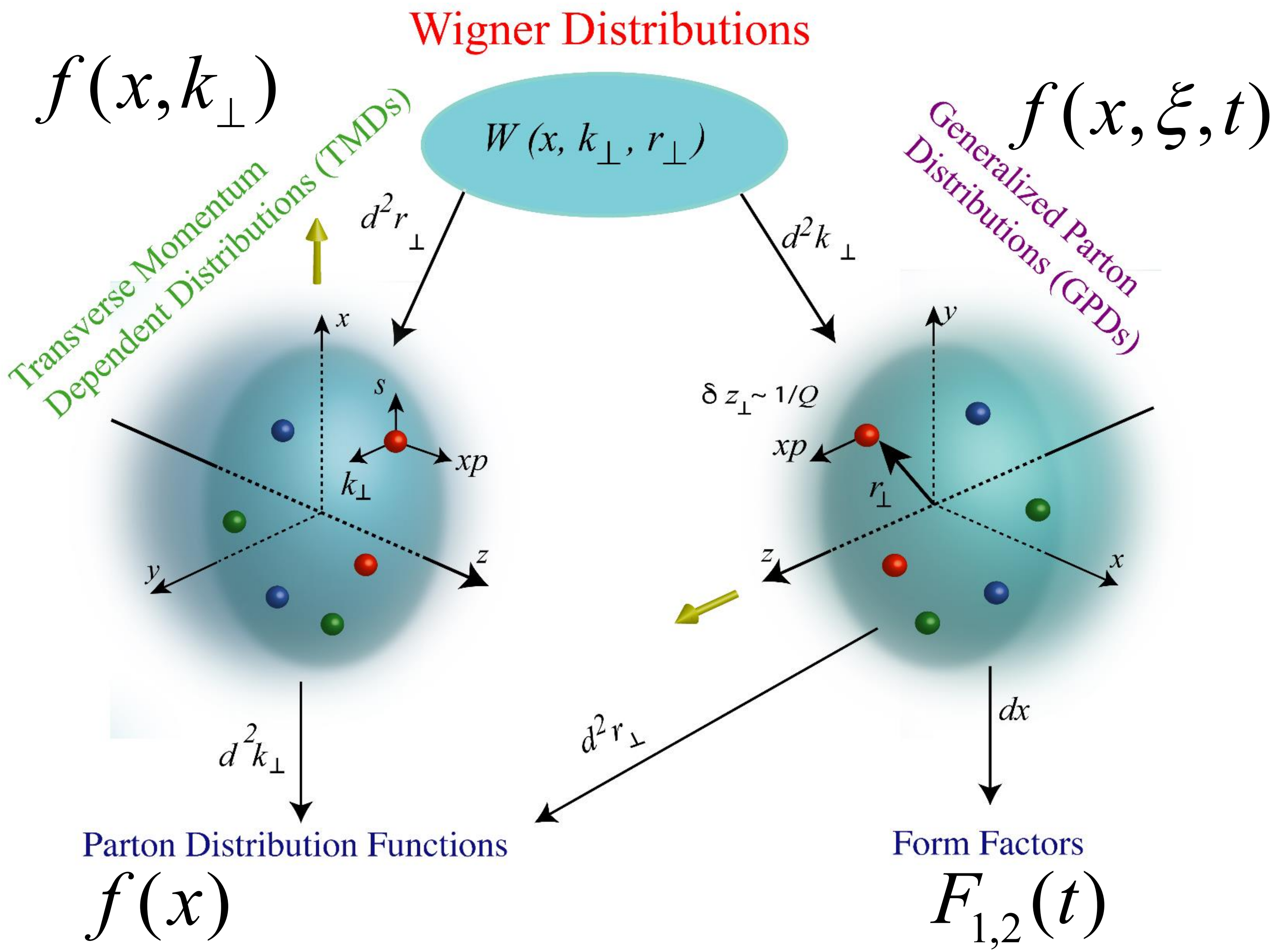
Department of Physics, National Central University

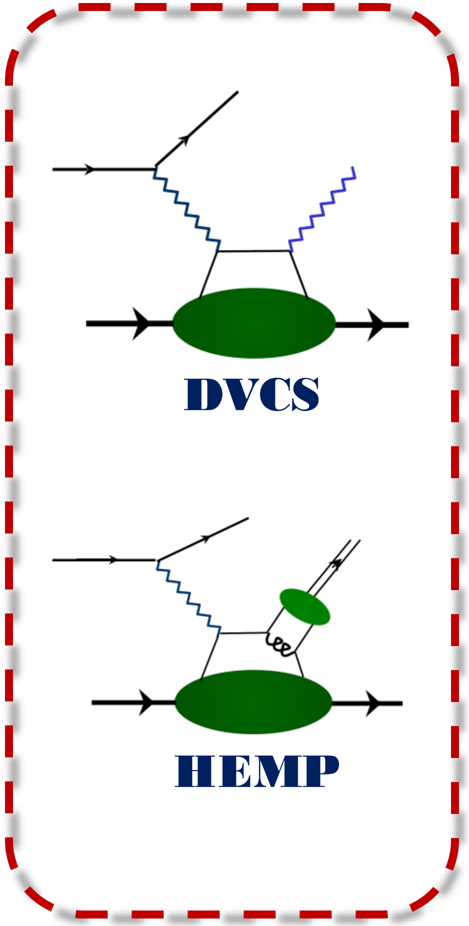
On behalf of the COMPASS Collaboration

# Multi-dimensional Partonic Structures

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



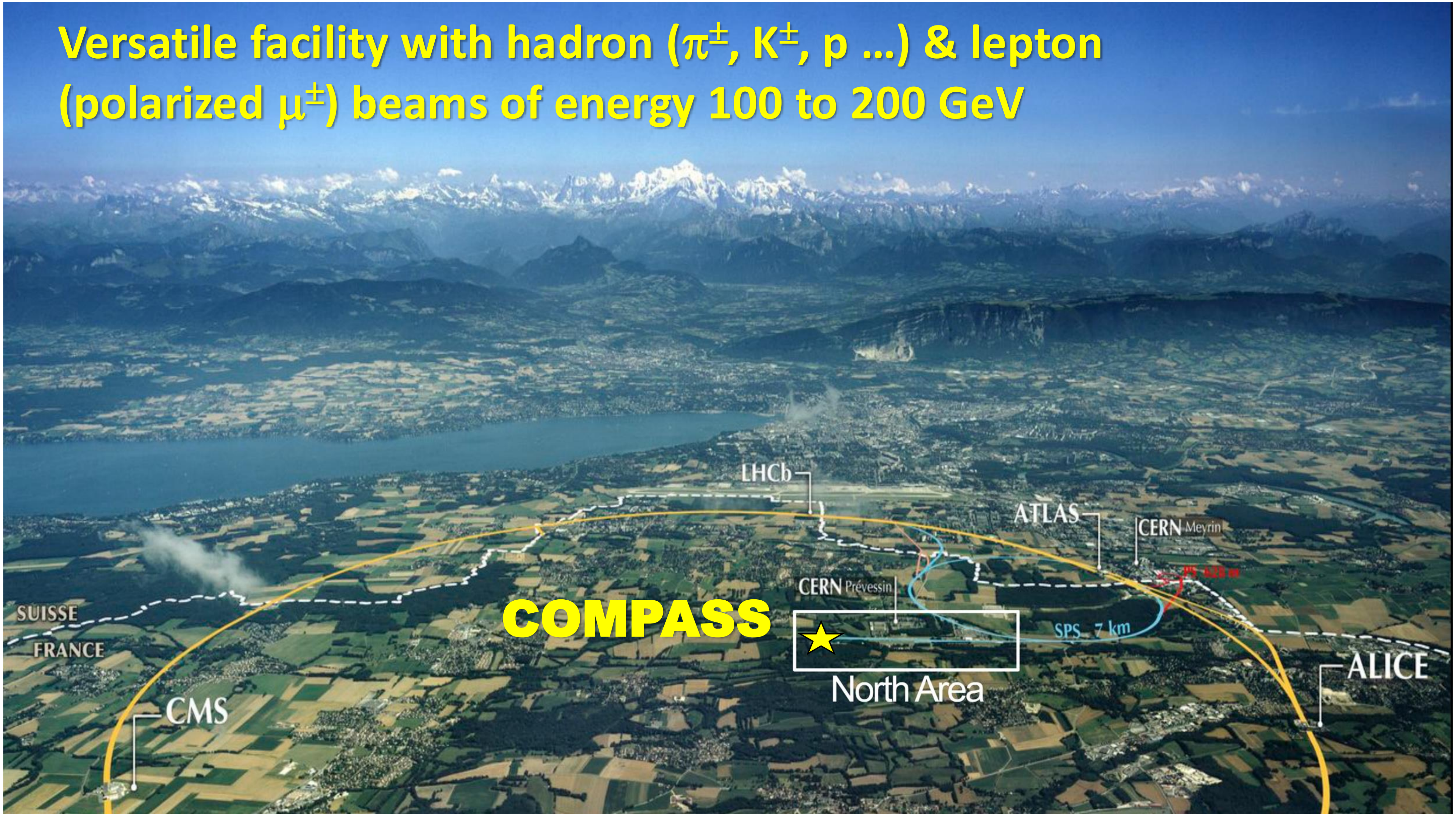




**COMPASS investigates the multi-dimensional structure of nucleon via various processes**

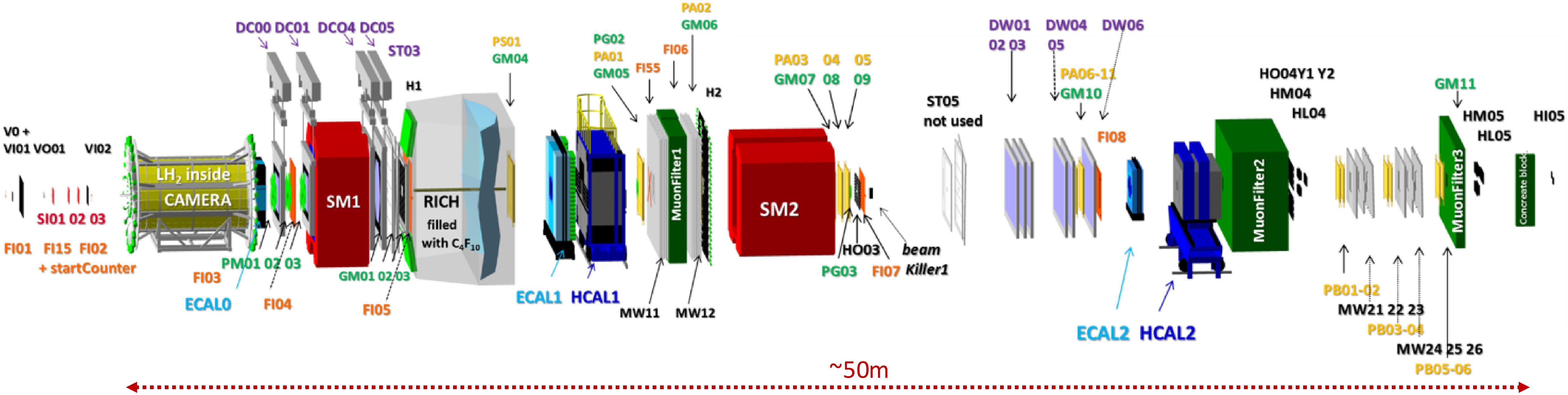
# COMPASS Experiment

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




**CO**mmon
**M**uon and
**P**roton
**A**pparatus for
**S**tructure and
**S**pectroscopy

# COMPASS Experimental Setup




- 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

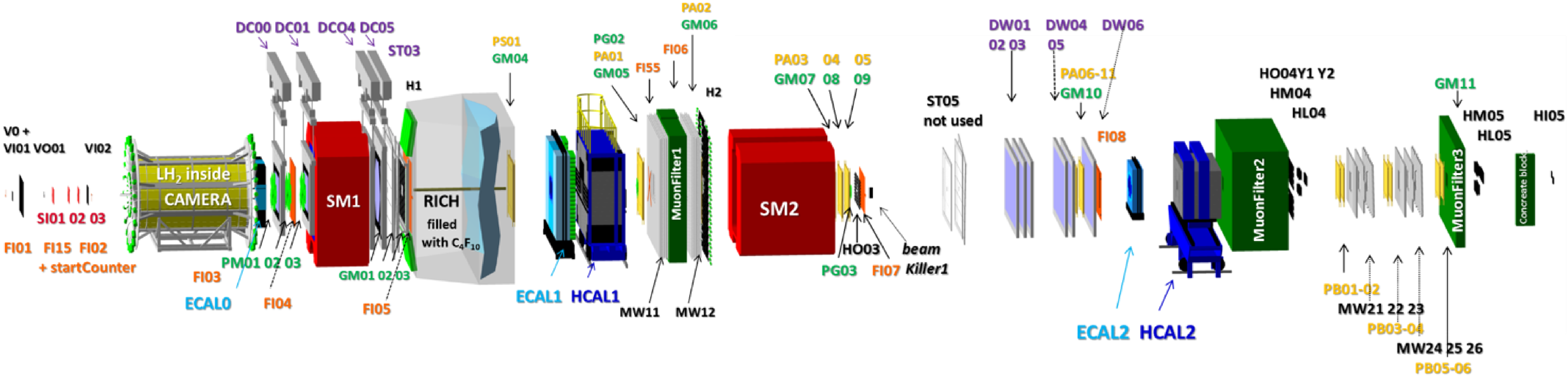
- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC, DC, straw
- PID – CEDARs, RICH, calorimeters, Muon Walls

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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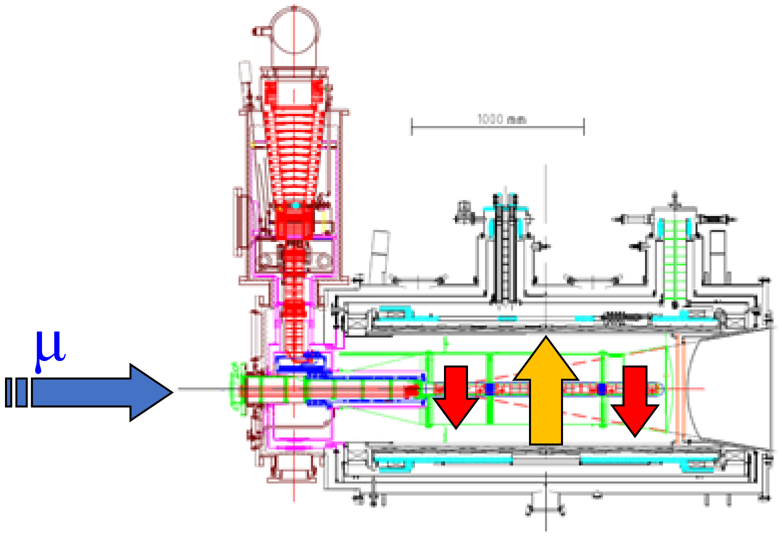
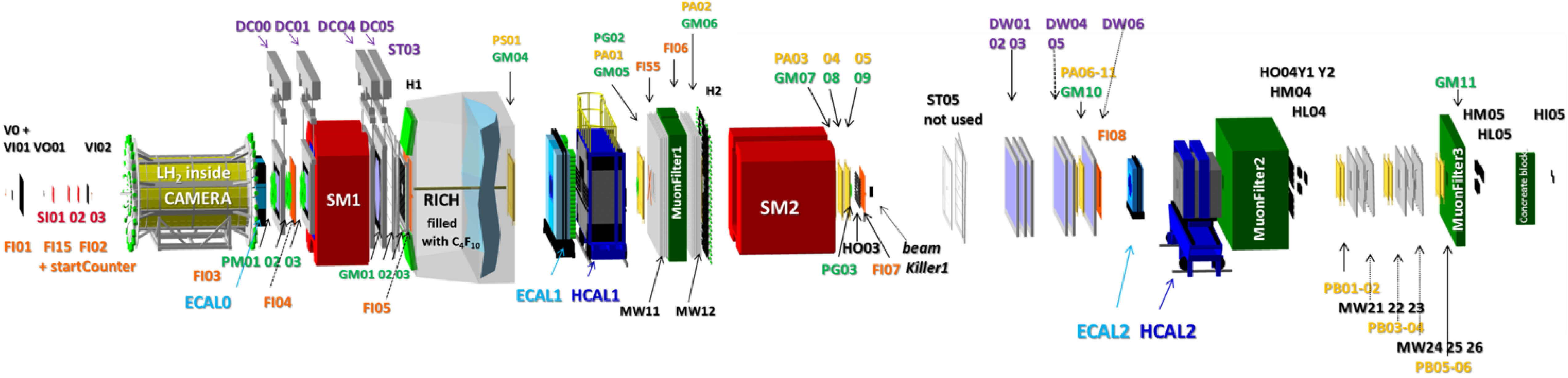



- In early GPD studies, transversely polarized target was used.
- Polarization reversal by magnetic field rotation
- 2.5m unpolarized $LH_2$ target used in GPD dedicated runs

# COMPASS Setup for Exclusive Processes

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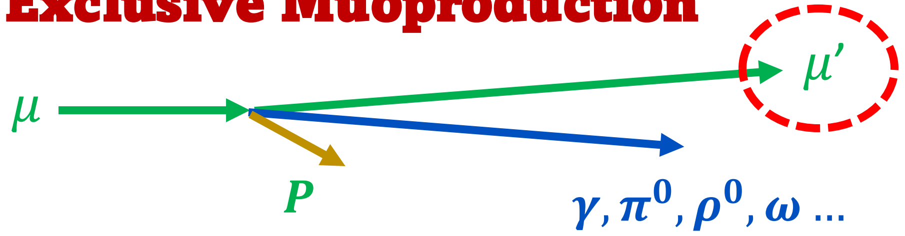
**Exclusive Muoproduction**



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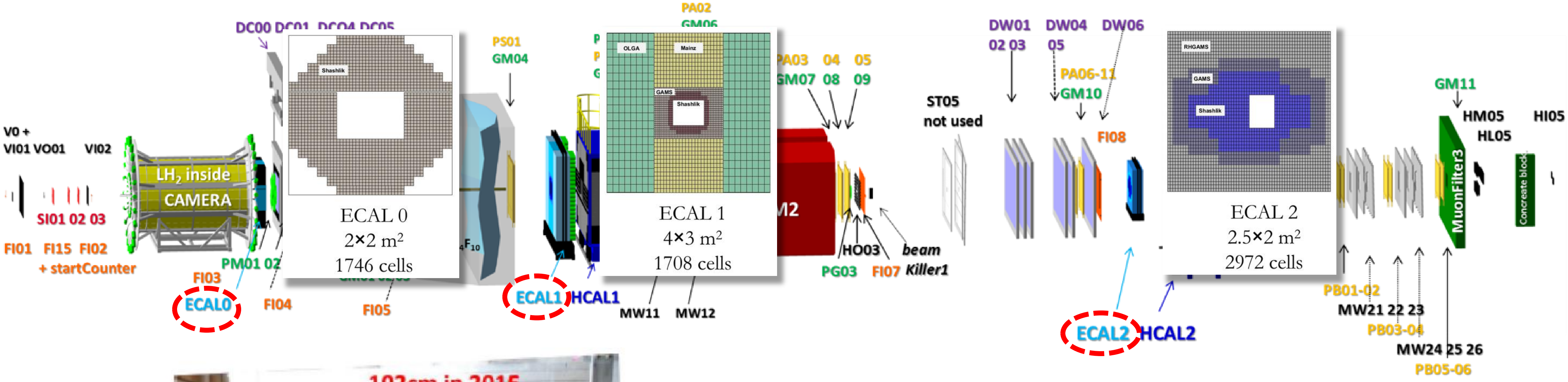
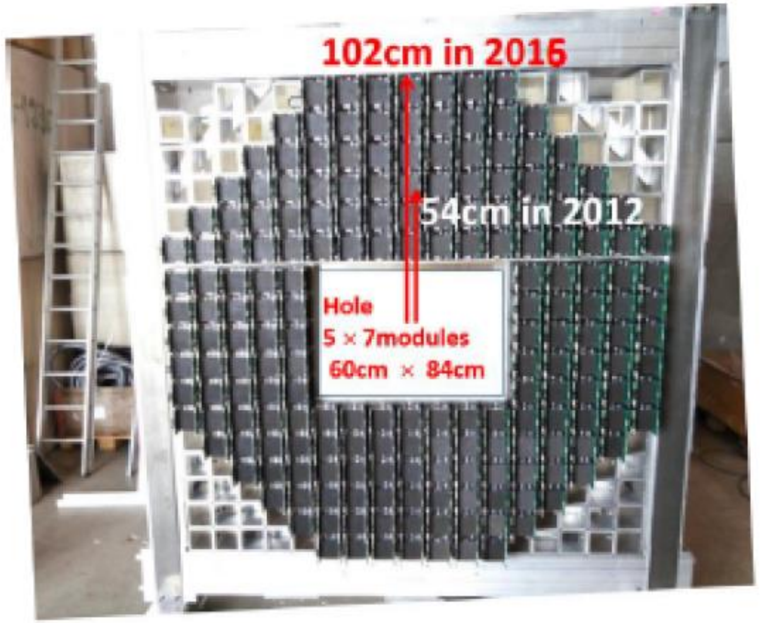
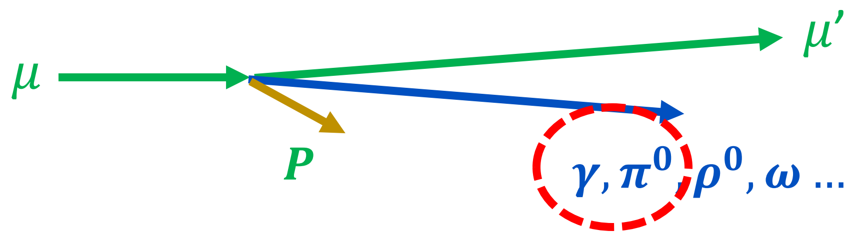



## Exclusive Muoproduction



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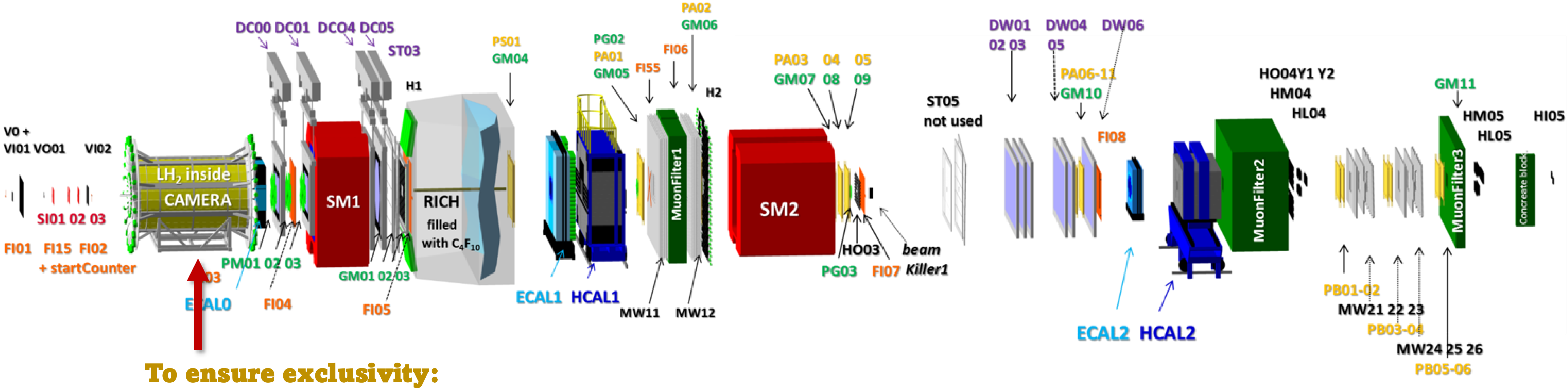
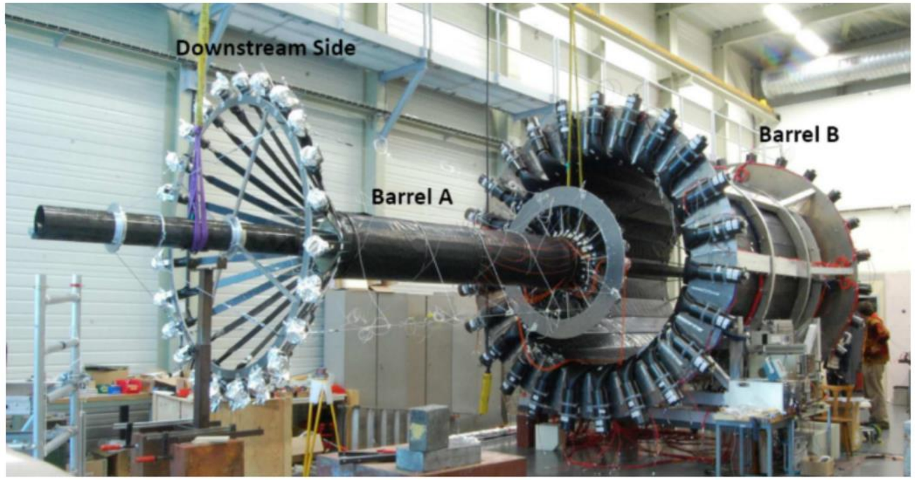
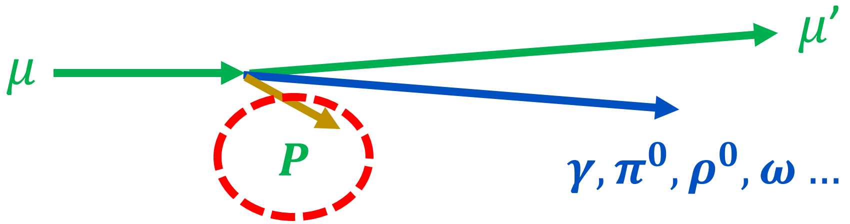



**To ensure exclusivity:**




CAMERA recoil proton detector

**Exclusive Muoproduction**



# COMPASS Experiment

2002-2022 COMPASS data taking

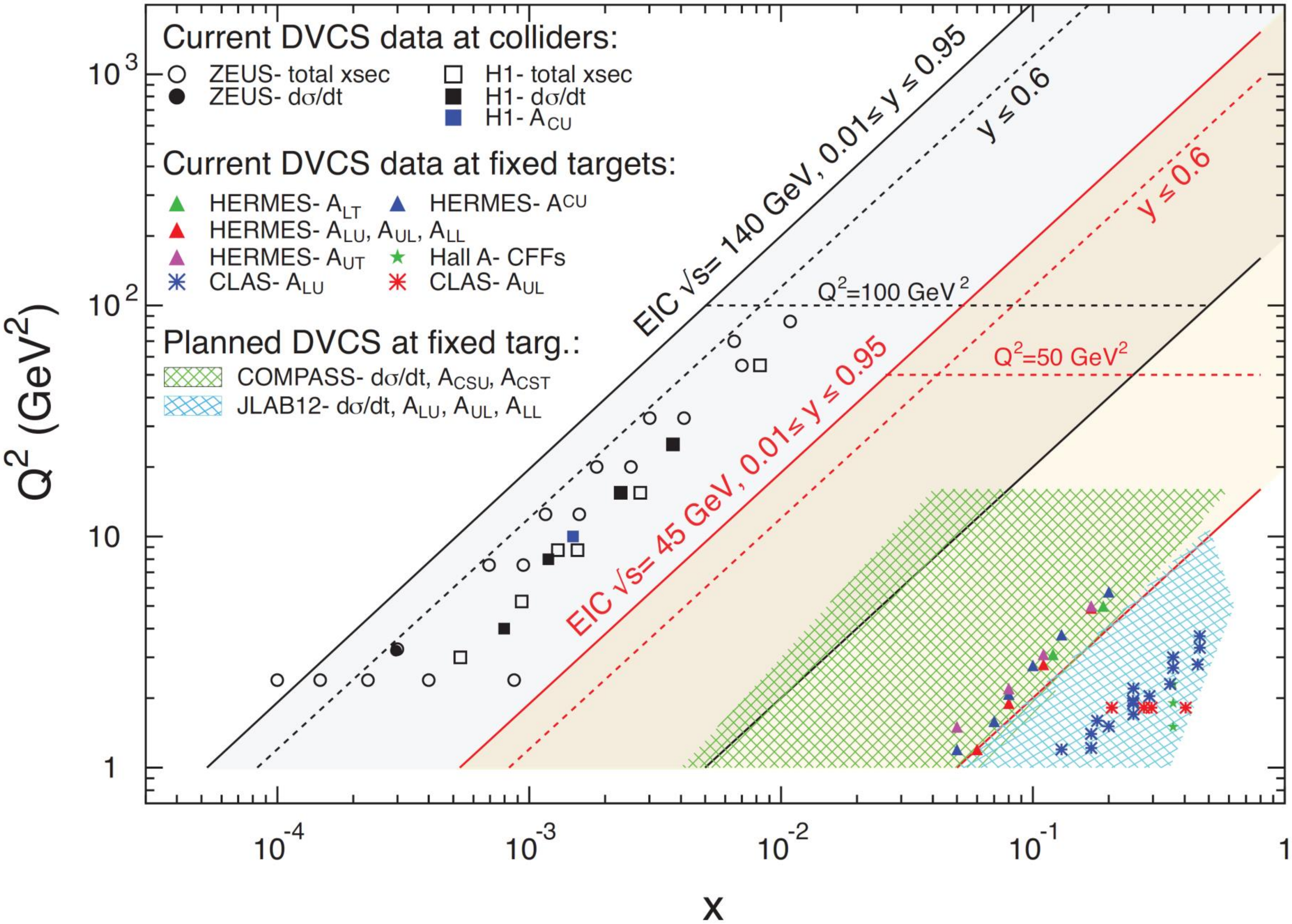
| | |
|---|---|
| 2002-2004 | DIS & SIDIS, $\mu^+$-d, 160 GeV, **L** & **T polarized target** |
| 2005 | *CERN accelerator shutdown, increase of COMPASS acceptance* |
| 2006<br>2007<br>2008-2009<br>2010<br>2011<br>2012<br>2012 pilot run | DIS & SIDIS, $\mu^+$-d, 160 GeV, **L polarized target**<br>DIS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

**Study hadron structure with complmentary tools:**

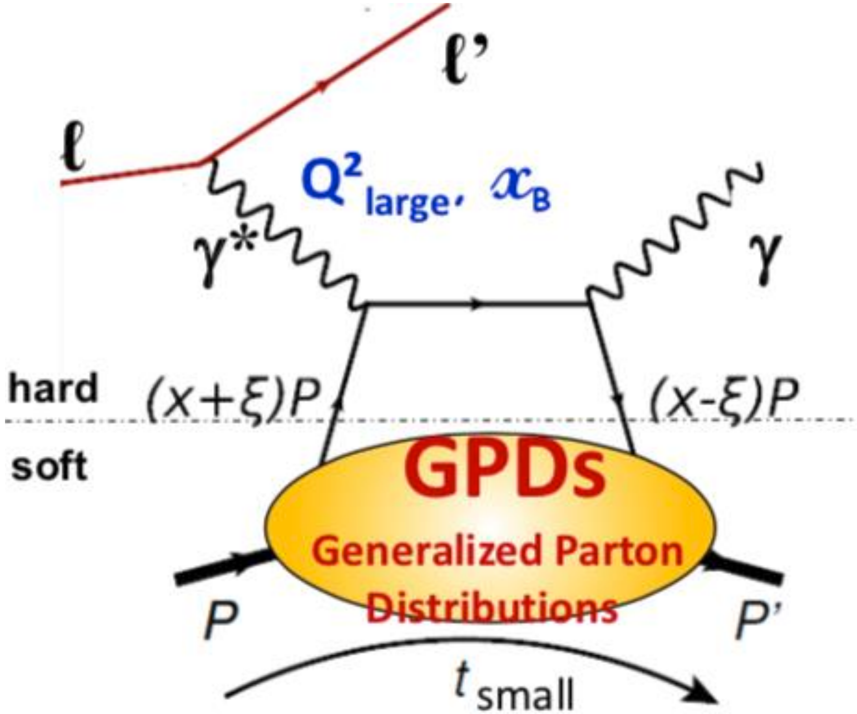
- **COMPASS holds the record for the longest-running CERN experiment**

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

# Lanscape – Global Programs of DVCS



# DVCS



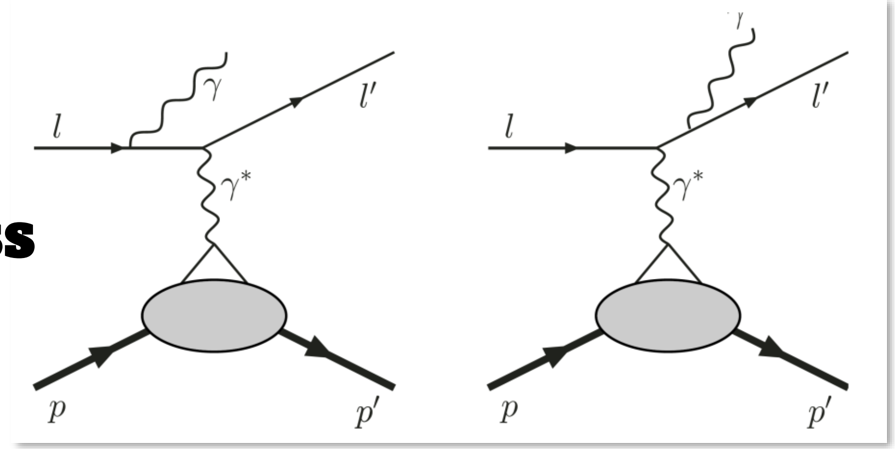

## DVCS: $l + p \rightarrow l' + p' + \gamma$

- 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.

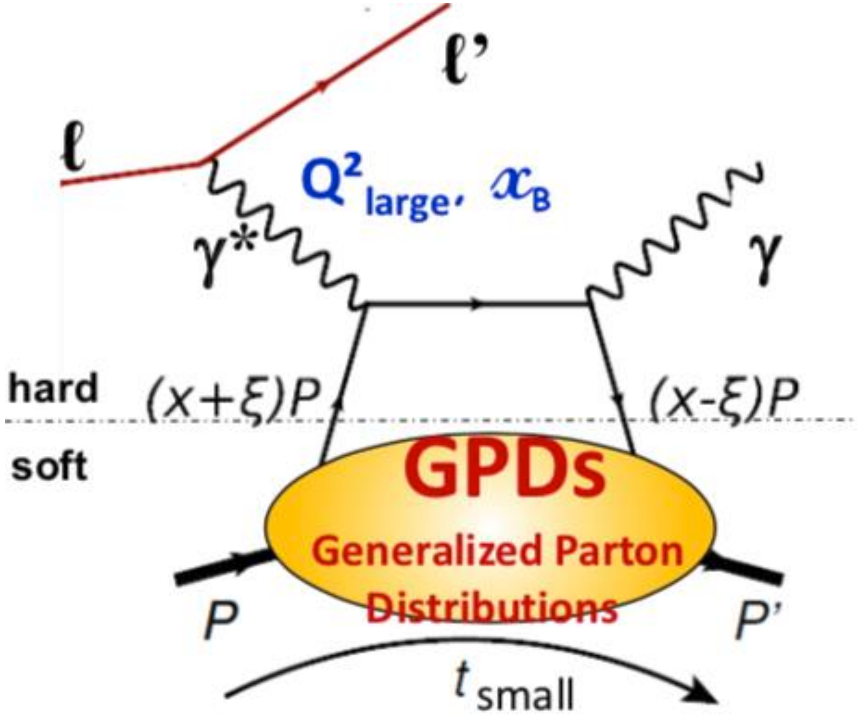
- The GPDs depend on the following variables:

  - $x$: average longitudinal momentum frac.
  - $\xi$: longitudinal momentum diff.
  - t: four momentum transfer
    (correlated to $b_\perp$ via Fourier transform)
  - $Q^2$: virtuality of $\gamma^*$

**BH Process**

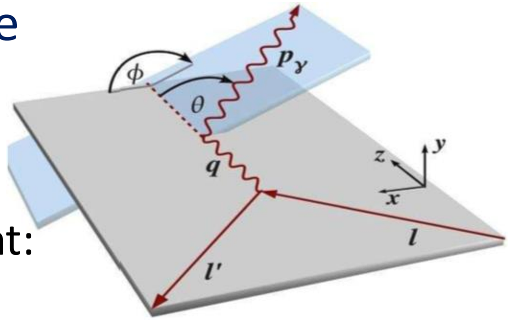


# DVCS




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

- With $LH_2$ target and small $x_B$ coverage
→ focuses on **H** at COMPASS




- The variables measured in the experiment:

$E_\ell$, $Q^2$, $x_{Bj} \sim 2\xi/(1+\xi)$,
t (or $\theta_{\gamma^*\gamma}$) and $\phi$ ($\ell\ell'$ plane/$\gamma\gamma^*$ plane)

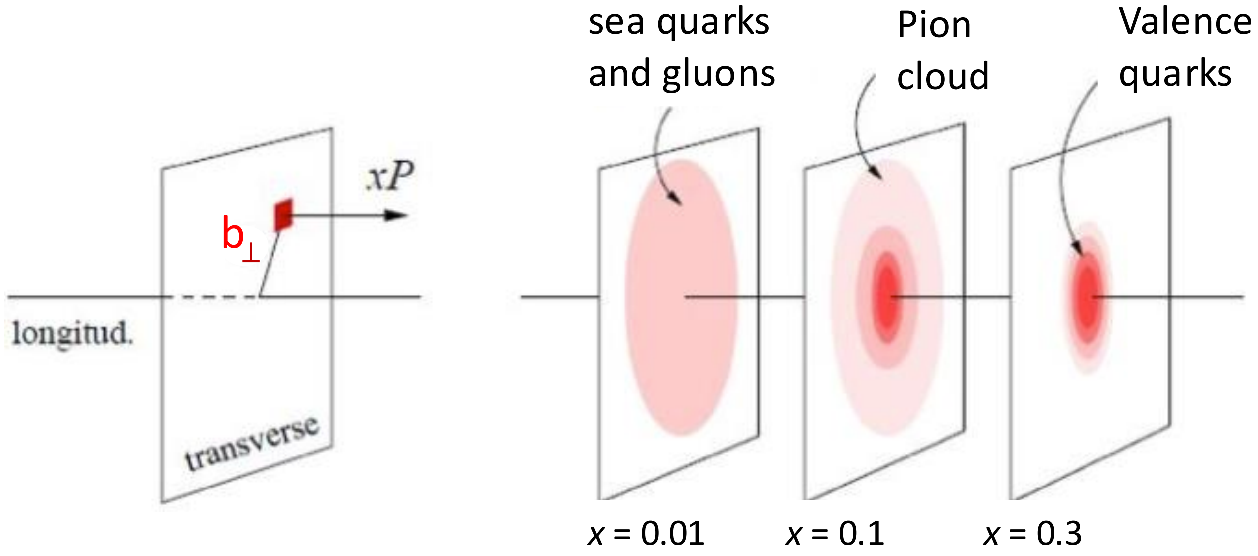
CFF GPD REAL part Imaginary part

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

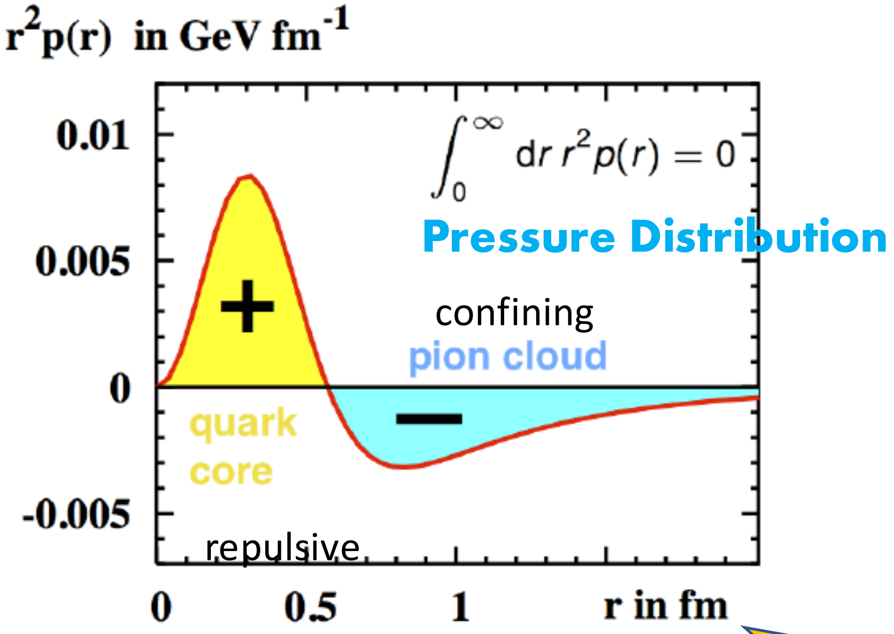
$$\mathcal{Re}\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{Im\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

# 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

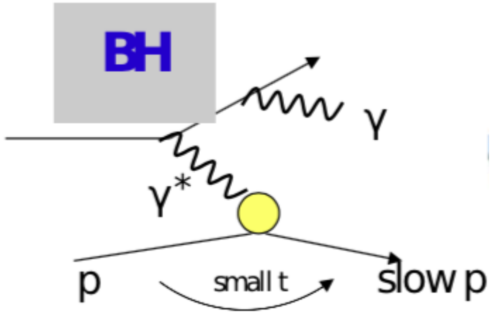
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

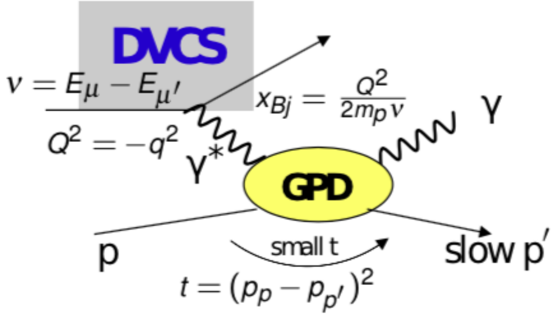
$$Re\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{Im\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

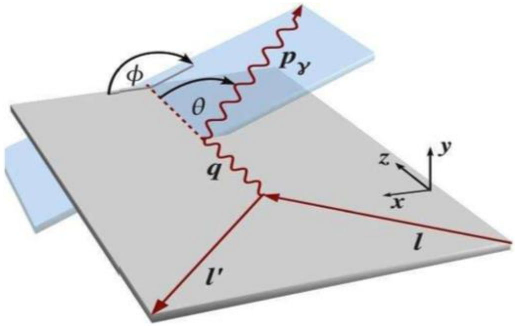
$d_1(t)$

D-term

# Azimuthal Dependence of BH & DVCS




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

Beam Charge-spin difference & sum

$$\boxed{\begin{aligned} \mathcal{D}_{\mathrm{CS,\,U}}(\phi) &\equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow}) \\ \mathcal{S}_{\mathrm{CS,\,U}}(\phi) &\equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \end{aligned}}$$

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

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

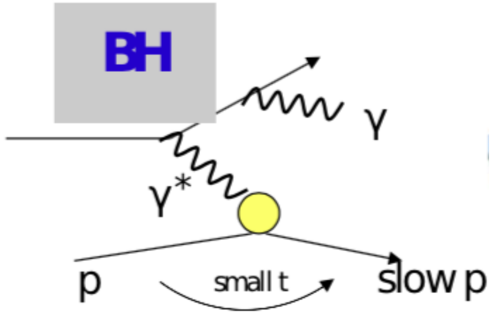
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

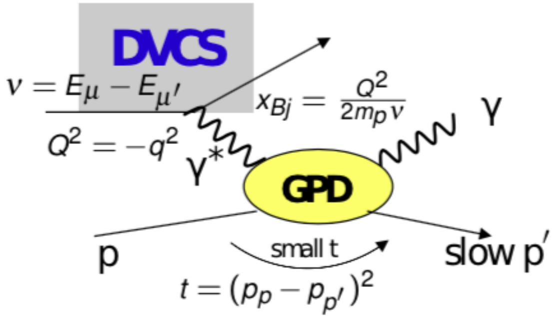
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

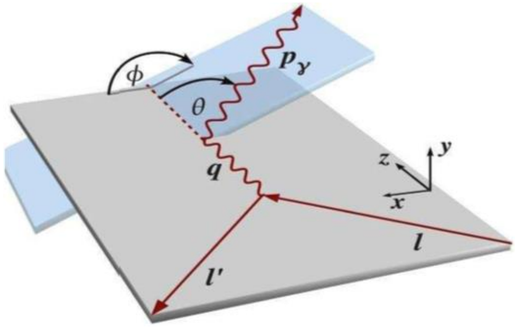
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$

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

# Azimuthal Dependence of BH & DVCS




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

Beam Charge-spin difference & sum

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

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

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

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

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

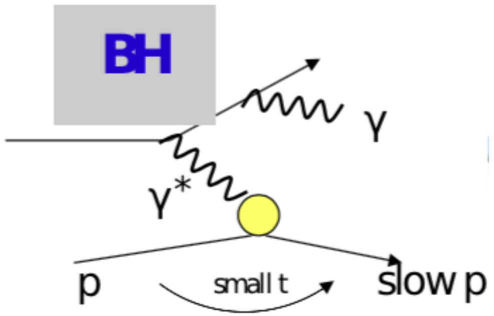
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

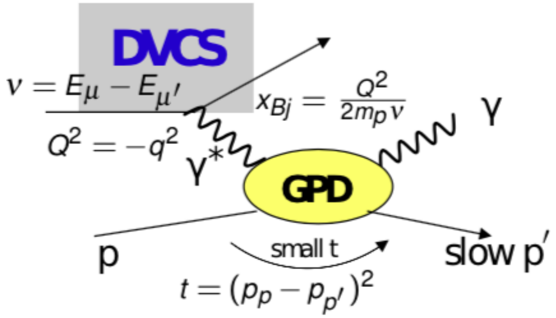
$\mathcal{D}_{CS,U}(\phi)$

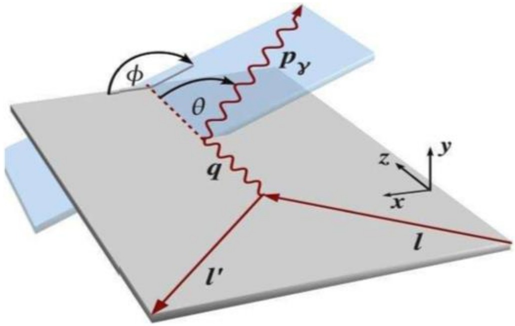
$$\mathrm{Im}\, I \propto s_1^I \sin\phi + s_2^I \sin 2\phi$$

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

# Azimuthal Dependence of BH & DVCS




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

Beam Charge-spin difference & sum

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

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

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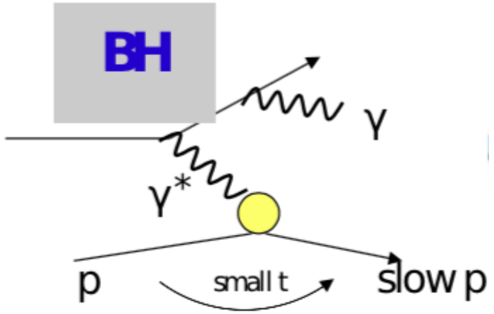


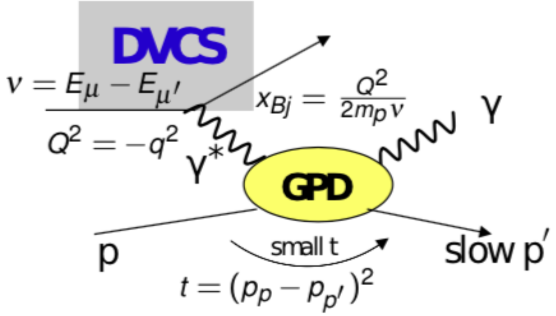


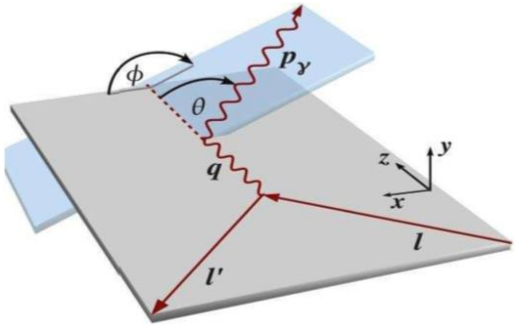


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Beam Charge-spin difference & sum

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

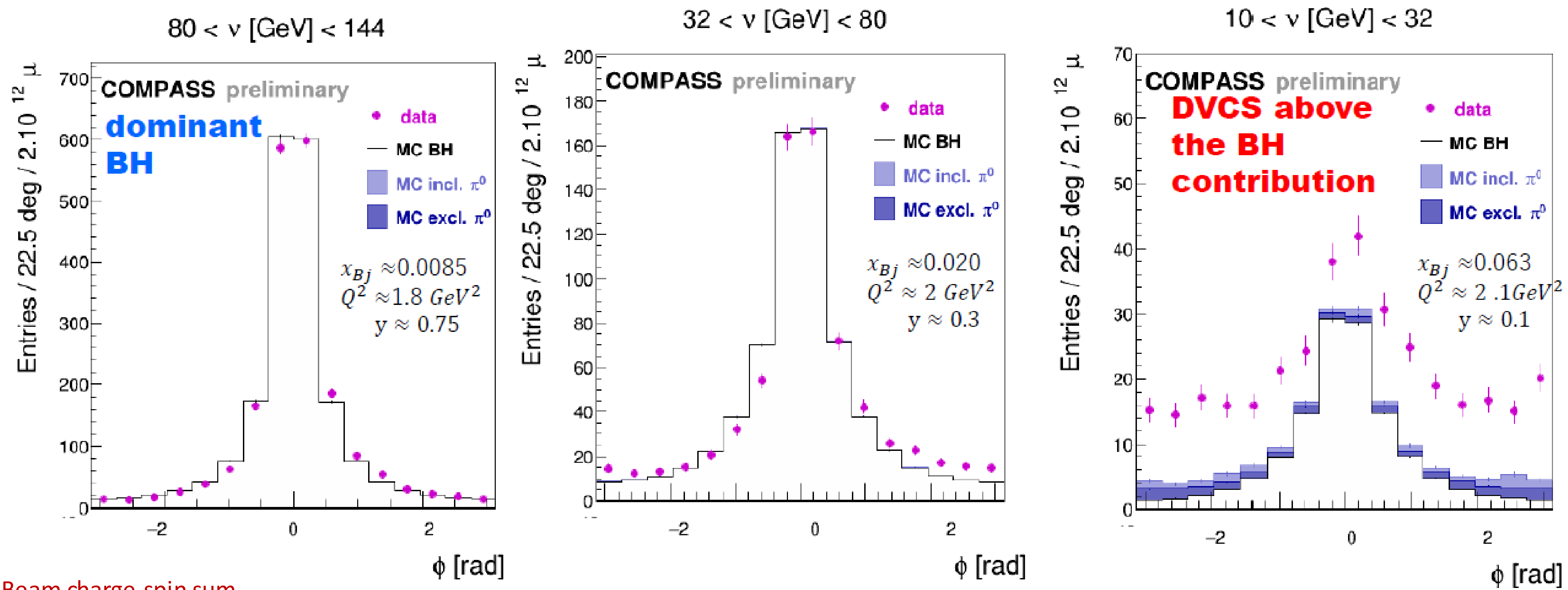
$\mathcal{S}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \Rightarrow C_0^{DVCS} \propto (Im\mathcal{H})^2$ and $S_1^I \propto Im\ \mathcal{F}$ Easier to measure

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

Compton Form factor linked to GPD **H**

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

# COMPASS 2016 Preliminary Results




- Beam charge-spin sum

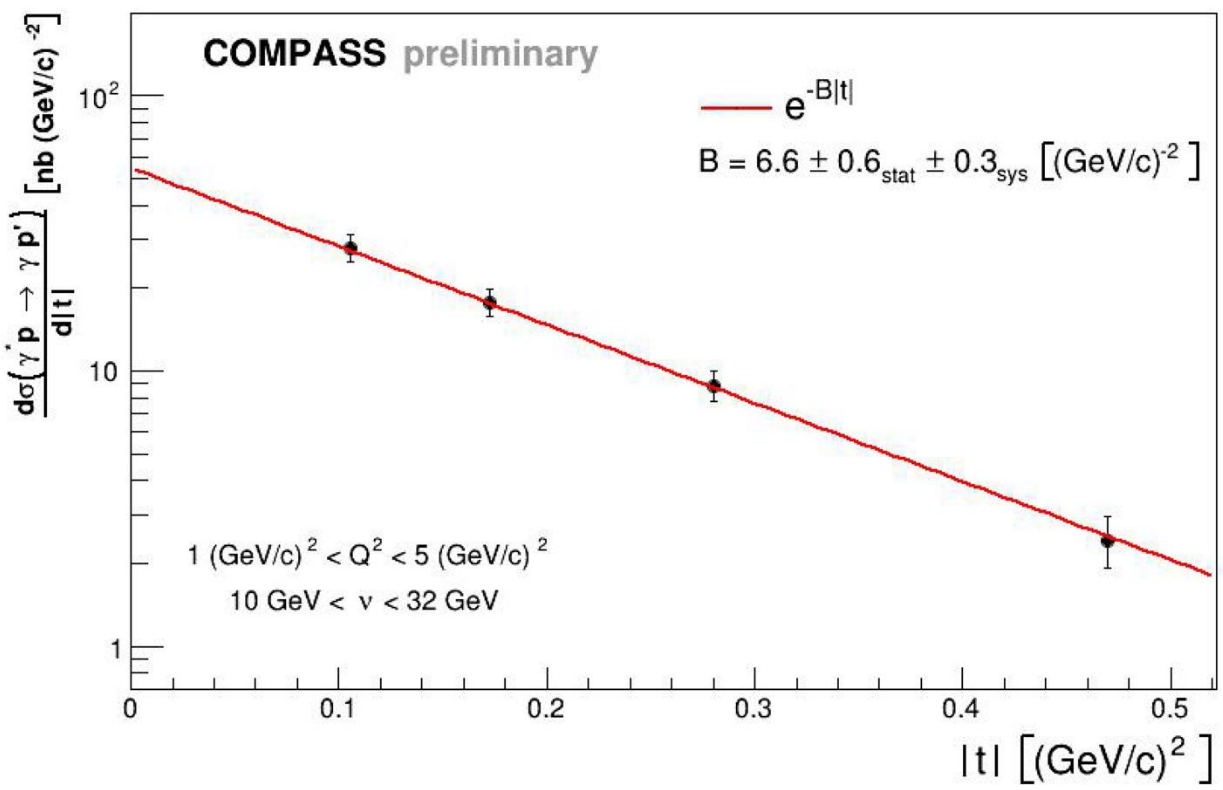
$$S_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) = 2[\, d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Im}\, I\,]$$

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

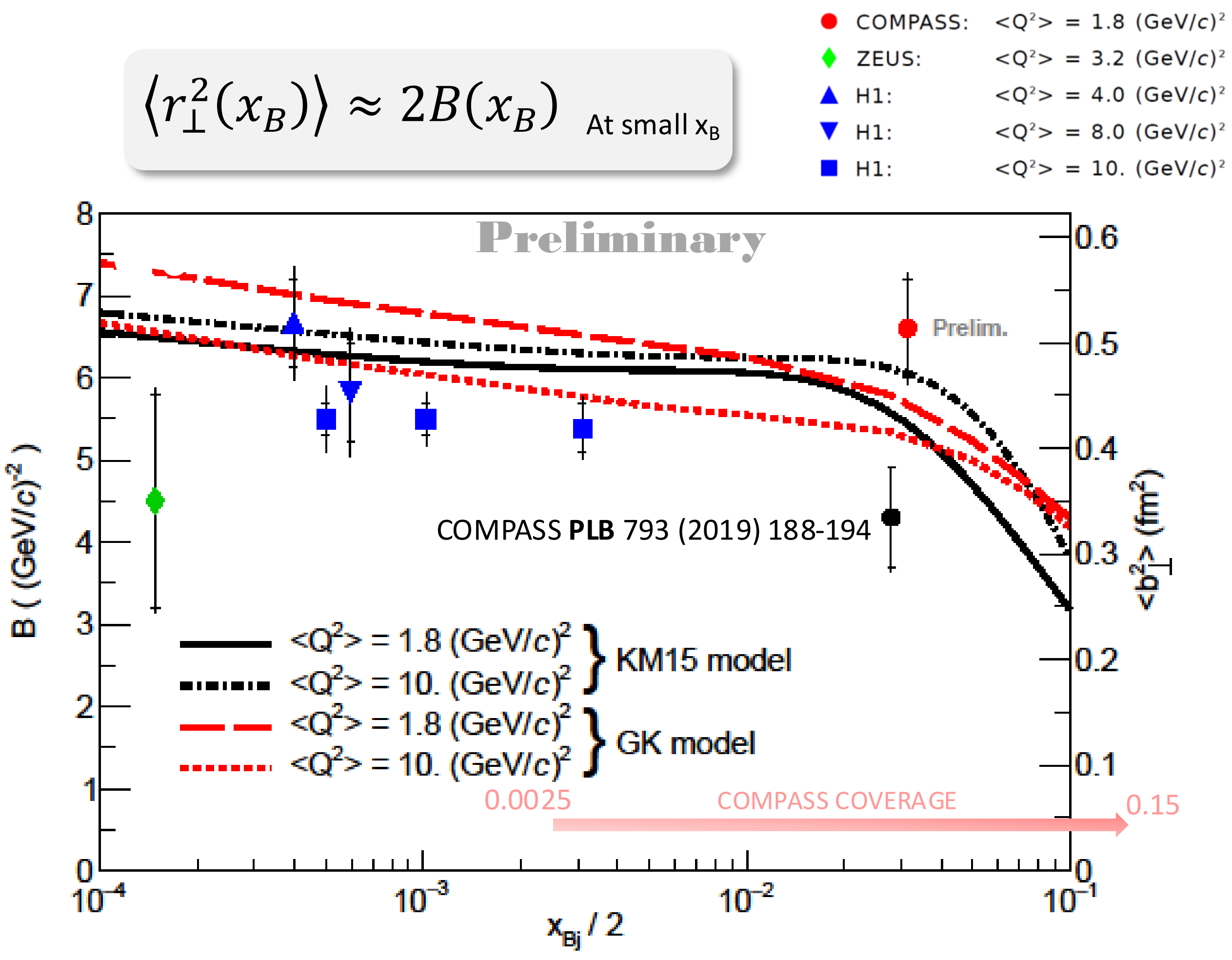
$$\boxed{c_0^{DVCS} \propto \underbrace{4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*)}_{\text{small } x_{Bj}} + \underbrace{\frac{t}{M^2}\mathcal{E}\mathcal{E}^*}_{\text{model dependent}} \rightarrow 4\,(\mathrm{Im}\,\mathcal{H})^2}$$

# Tranverse extension of partons – 2016 data

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



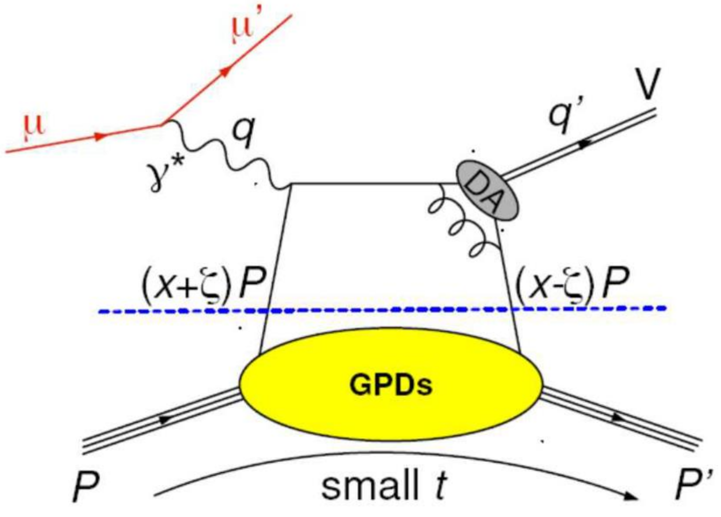

$$\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$$ At small $x_B$



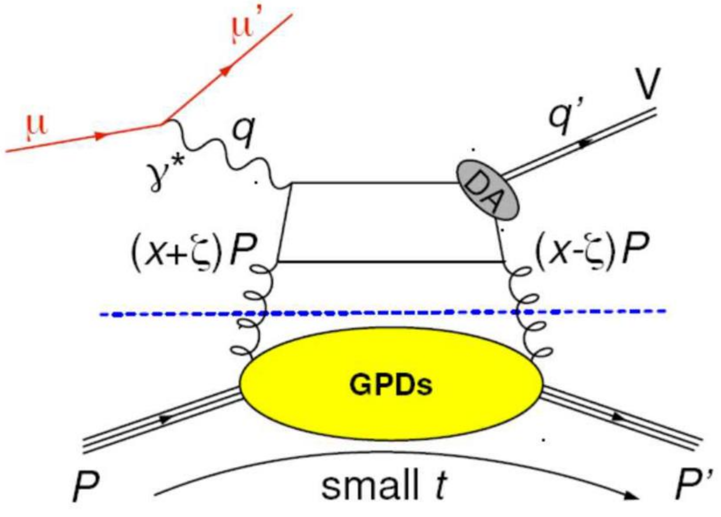

➢ The transverse-size evolution as a function of $x_{Bj}$ → Expect at least 3 $x_{Bj}$ bins from 2016-17 data

# GPDs in Hard Exclusive Meson Production

quark contribution




gluon contribution




4 chiral-even GPDs: helicity of parton unchanged

$\mathbf{H}^q(x, \xi, t)$ $\mathbf{E}^q(x, \xi, t)$ → **Vector Meson**

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

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

(not possible in DVCS)

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

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

$$\overline{\mathbf{E}}_T^q = 2\,\tilde{\mathbf{H}}_T^q + \mathbf{E}_T^q$$

- 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 $\pi^0$ Production on Unpolarized Proton

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

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

$\epsilon$ : 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

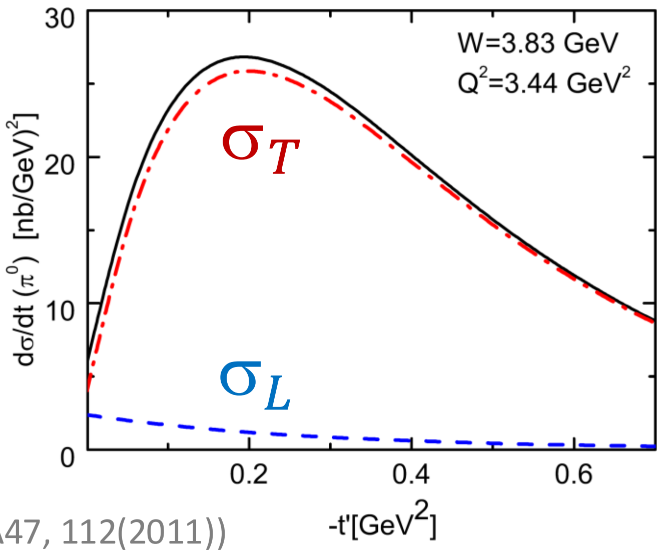
But measured as ≈ only a few % of $\frac{d\sigma_T}{dt}$

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

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

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

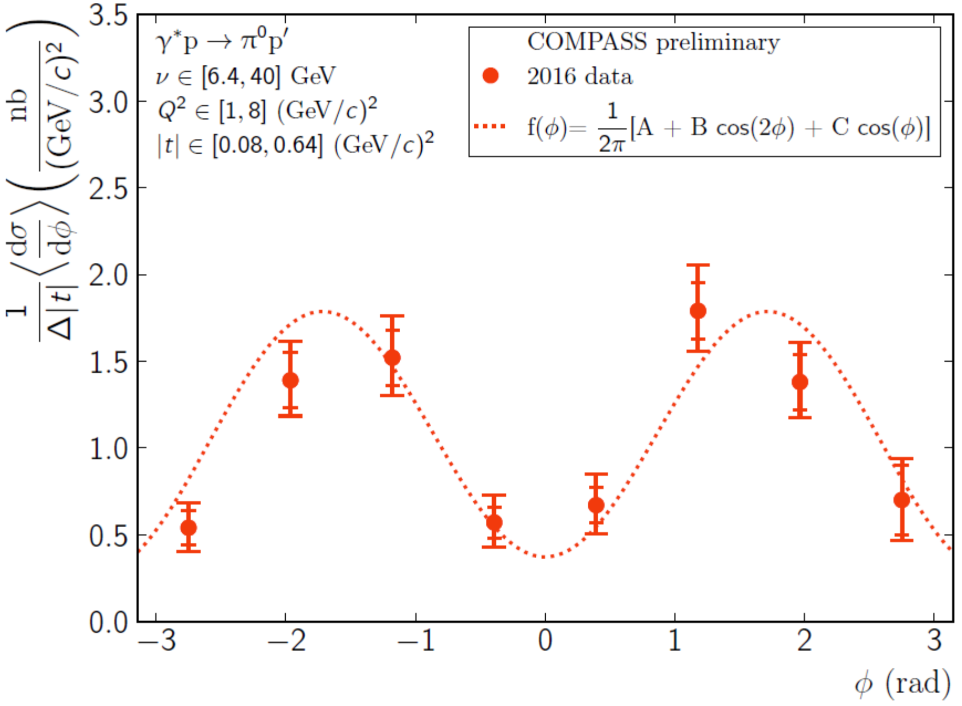
$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

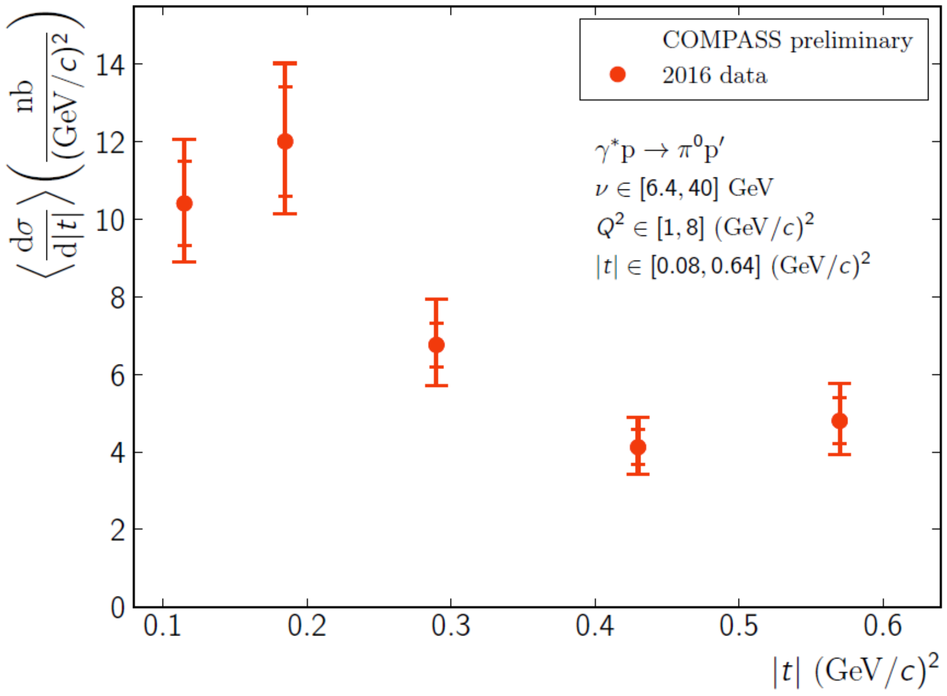



S. Goloskokov and P. Kroll (Eur.Phys.J A47, 112(2011))

# New 2016 Exclusive $\pi^0$ Prod. on Unpolarized Proton

➢ Kinematic domain: $\nu \in [6.4, 40]$ GeV and $Q^2 \in [1,8]$ GeV$^2/c^2$, $\langle x_B \rangle = 0.134$



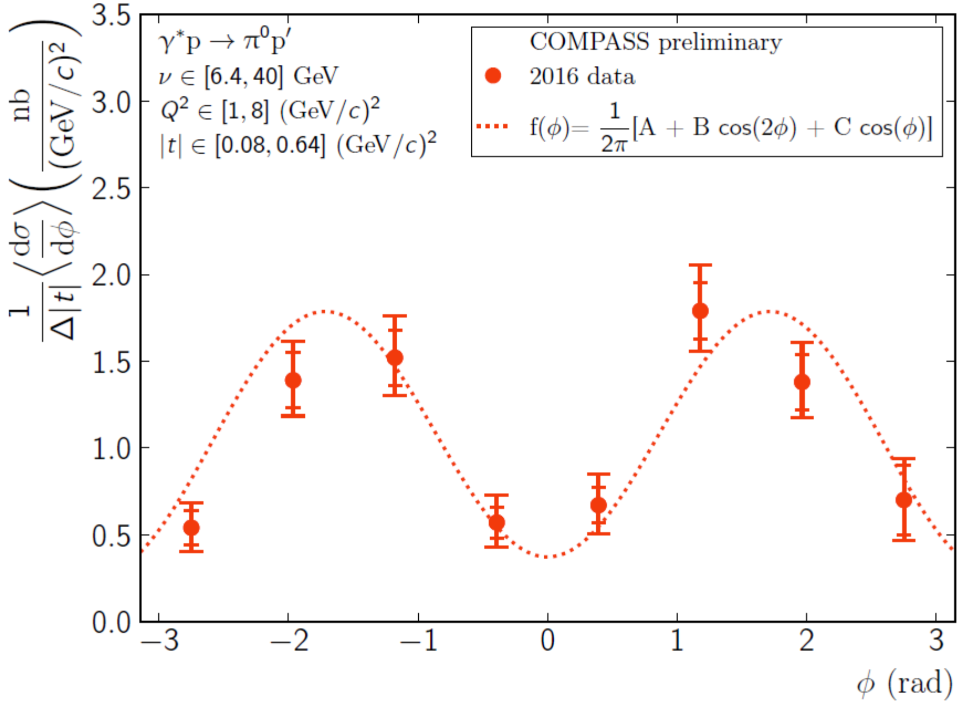

μ p → μ $\pi^0$ p

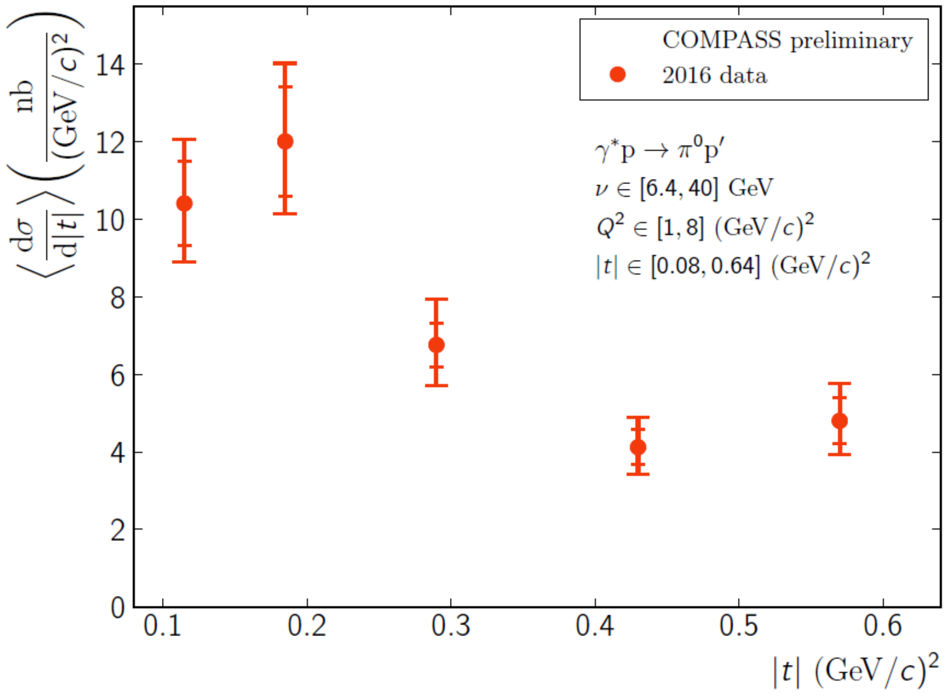
$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\boxed{\frac{d\sigma_T}{dt}} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \boxed{\frac{d\sigma_{TT}}{dt}} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \boxed{\frac{d\sigma_{LT}}{dt}}\right]$$

Chiral-odd GPDs

# New 2016 Exclusive $\pi^0$ Prod. on Unpolarized Proton

- Kinematic domain: $\nu \in [6.4, 40]$ GeV and $Q^2 \in [1,8]$ GeV$^2/c^2$, $\langle x_B \rangle = 0.134$




$$\left\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right\rangle = \left( 6.6 \pm 0.3_{stat} {}^{+0.9}_{-0.8} \Big|_{sys} \right) \frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{TT}}{dt} \right\rangle = \left( -4.6 \pm 0.5_{stat} {}^{+0.3}_{-0.3} \Big|_{sys} \right) \frac{nb}{(GeV/c)^2}$$

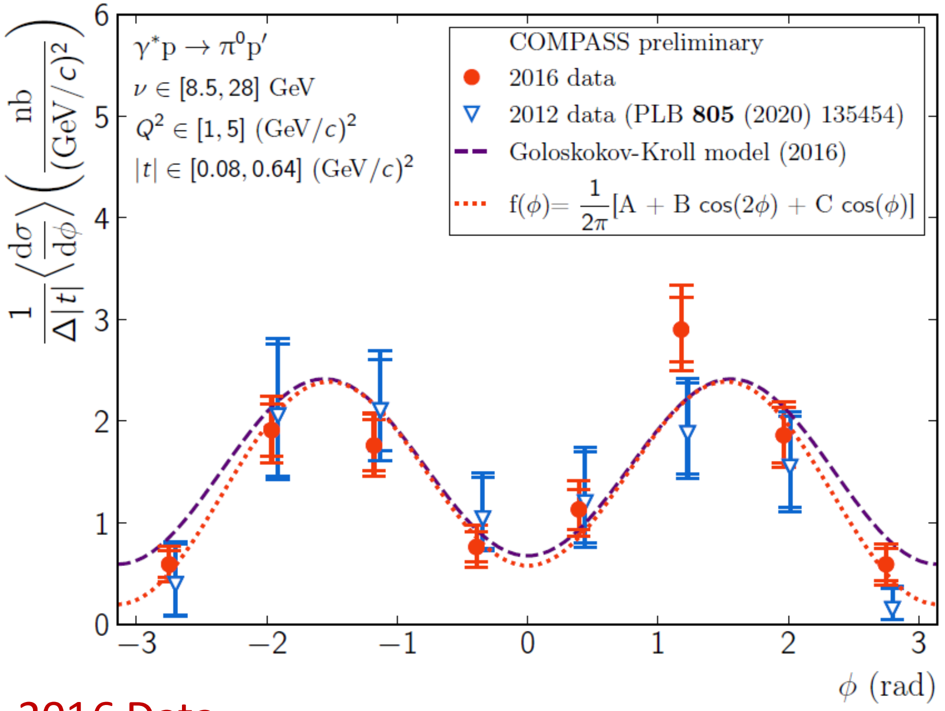
$$\left\langle \frac{d\sigma_{LT}}{dt} \right\rangle = \left( 0.2 \pm 0.2_{stat} {}^{+0.2}_{-0.2} \Big|_{sys} \right) \frac{nb}{(GeV/c)^2}$$

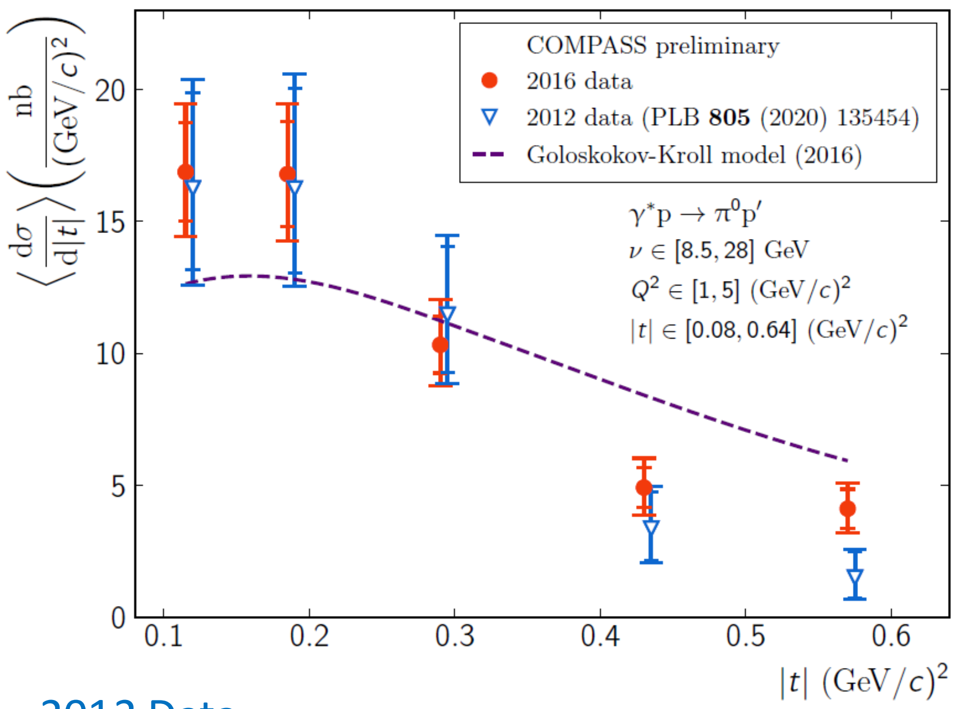
$\langle \epsilon \rangle = 0.997$

- Cross section extracted in a larger $(\nu, Q^2)$ domain, compared with the 2012 result. (COMPASS, **PLB** 805 (2020) 135454)
- Comparable $|\sigma_{TT}|$ and $\sigma_T + \epsilon\sigma_L$

# 2012-16 Exclusive $\pi^0$ Prod. Comparison

➢ Kinematic domain: $\nu \in [8.5, 28]$ GeV and $Q^2 \in [1,5]$ $GeV^2/c^2$, $\langle x_B \rangle = 0.10$




**2016 Data:**

$$\left\langle\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right\rangle = \left(8.7 \pm 0.5_{stat}{}^{+1.0}_{-1.0}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

$$\left\langle\frac{d\sigma_{TT}}{dt}\right\rangle = \left(-6.3 \pm 0.8_{stat}{}^{+0.4}_{-0.5}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

$$\left\langle\frac{d\sigma_{LT}}{dt}\right\rangle = \left(0.6 \pm 0.3_{stat}{}^{+0.3}_{-0.3}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

$\langle\epsilon\rangle = 0.996$

**2012 Data:**

$$\left\langle\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right\rangle = \left(8.1 \pm 0.9_{stat}{}^{+1.1}_{-1.0}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

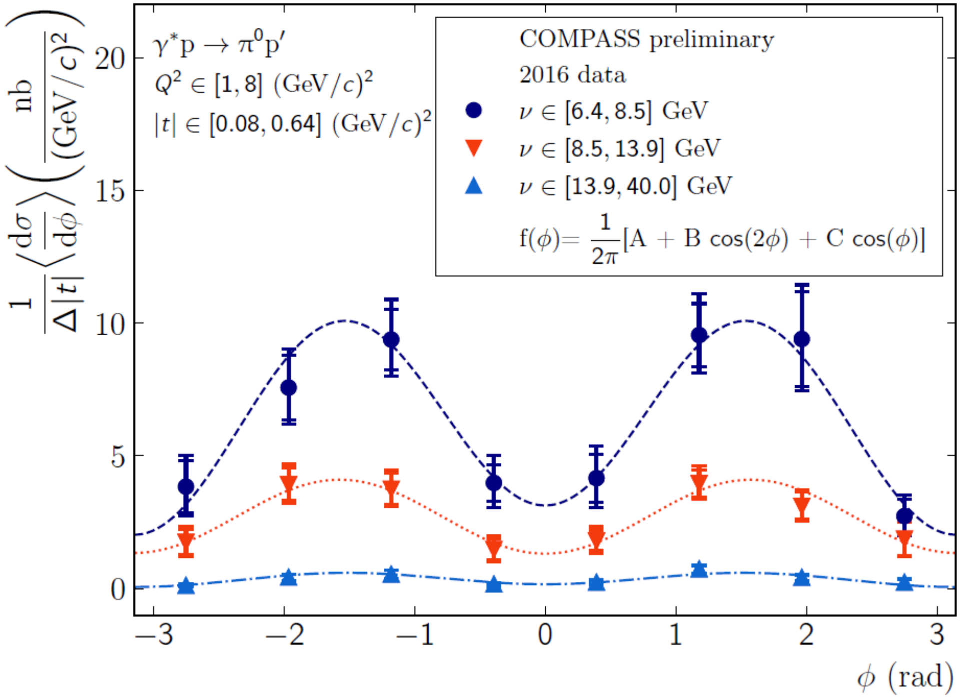
$$\left\langle\frac{d\sigma_{TT}}{dt}\right\rangle = \left(-6.0 \pm 1.3_{stat}{}^{+0.7}_{-0.7}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

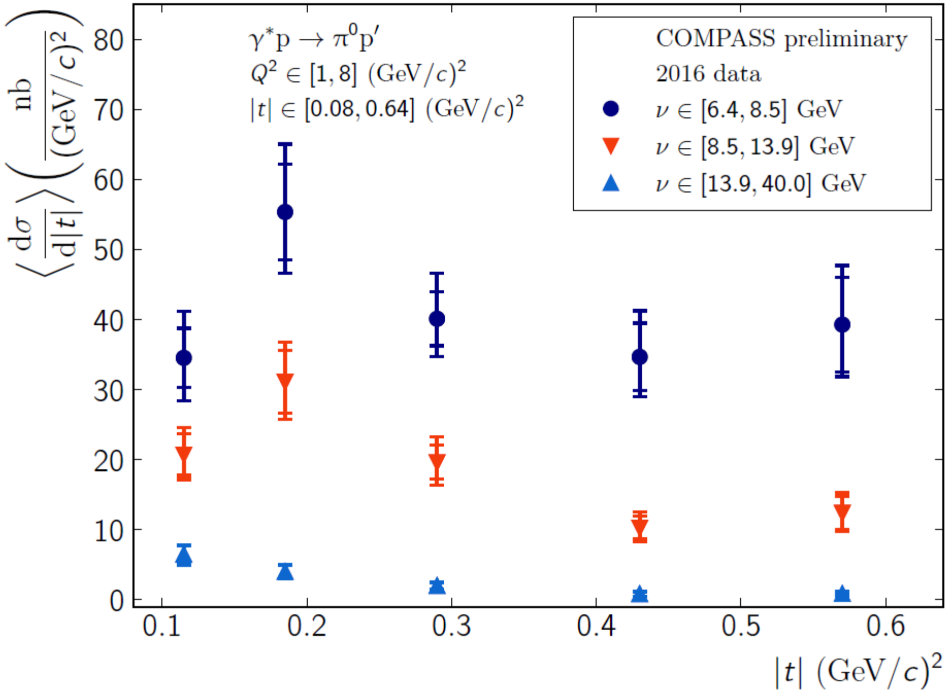
$$\left\langle\frac{d\sigma_{LT}}{dt}\right\rangle = \left(1.4 \pm 0.5_{stat}{}^{+0.3}_{-0.2}\Big|_{sys}\right)\frac{nb}{(GeV/c)^2}$$

$\langle\epsilon\rangle = 0.996$

# New 2016 Exclusive $\pi^0$ Cross-section Evolution with $\nu$

- Cross section decreases with increasing $\nu$

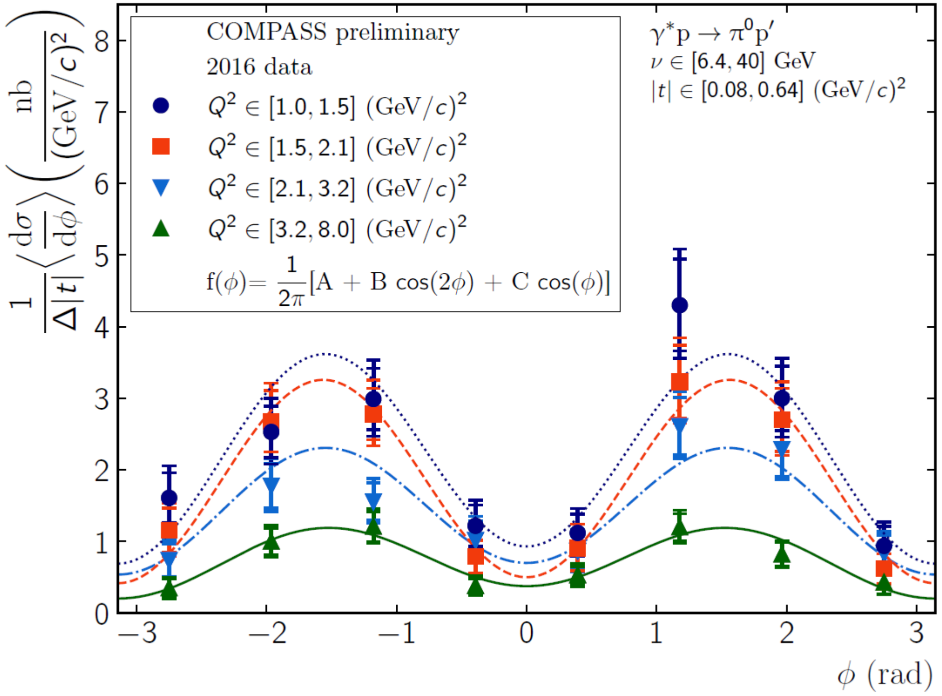


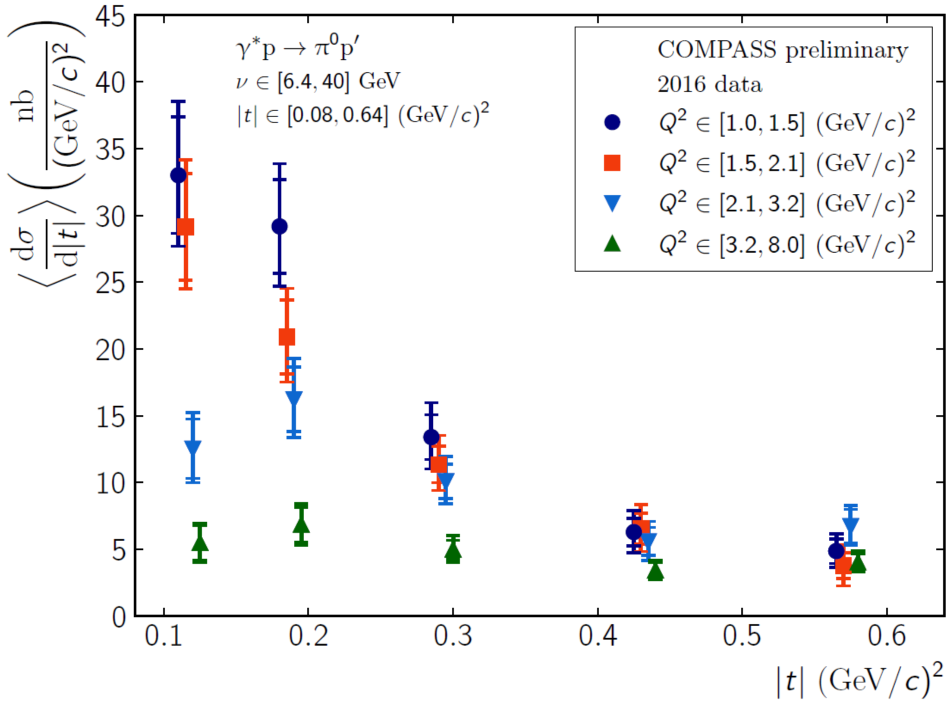




| | $\langle\nu\rangle$ [GeV] | $\langle Q^2\rangle$ [GeV$^2$/$c^2$] | $\langle x_B\rangle$ | $\langle\epsilon\rangle$ |
|---|---|---|---|---|
| $\nu \in [6.4, 8.5]$ | 7.35 | 2.15 | 0.156 | 0.999 |
| $\nu \in [8.5, 13.9]$ | 10.32 | 2.50 | 0.131 | 0.998 |
| $\nu \in [13.9, 40.0]$ | 21.08 | 2.09 | 0.057 | 0.989 |

# New 2016 Exclusive $\pi^0$ Cross-section Evolution with $Q^2$

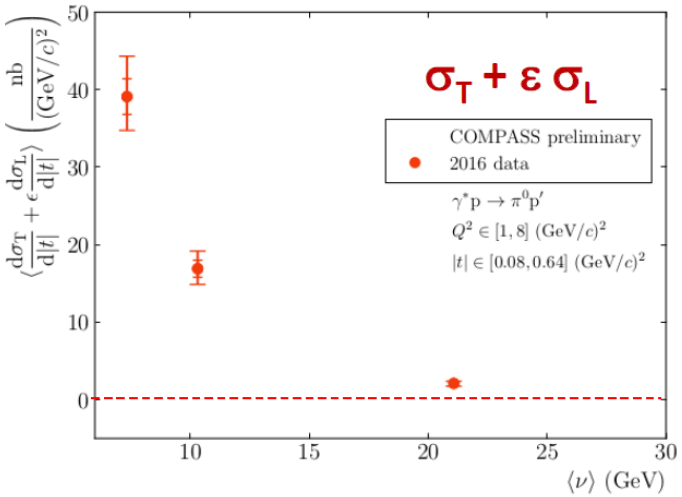
- Cross section decreases with increasing $Q^2$

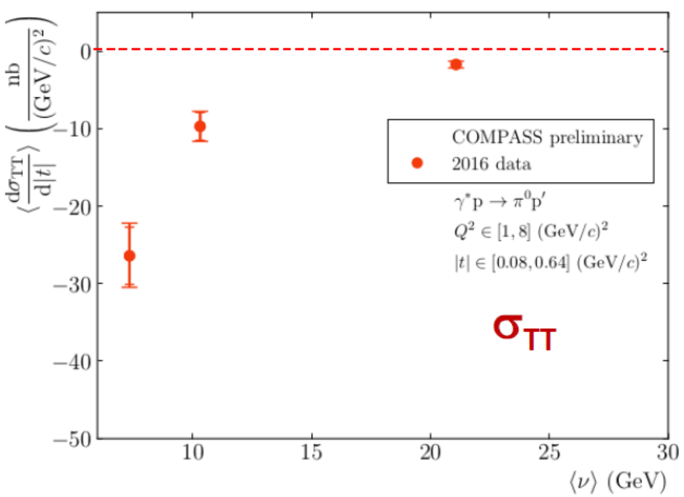


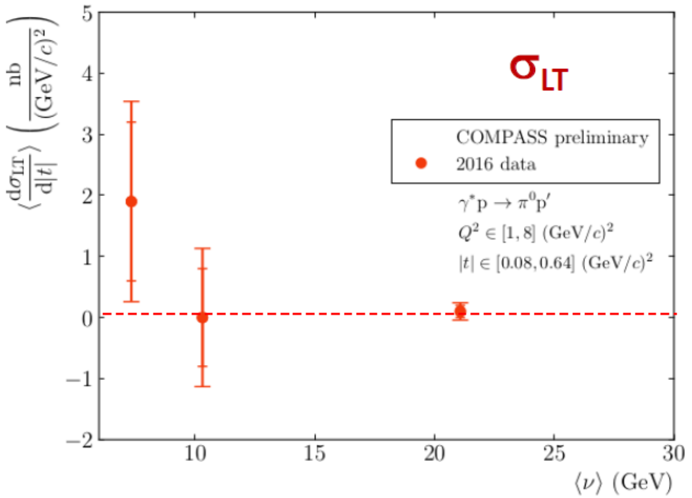



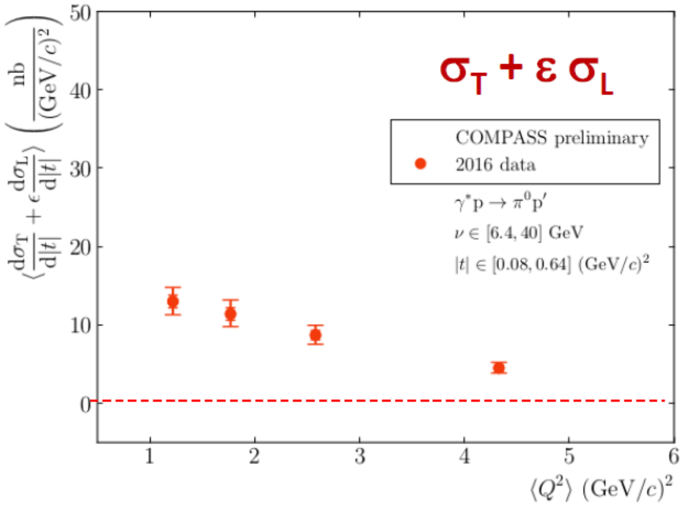

| | $\langle Q^2\rangle$ [GeV$^2/c^2$] | $\langle\nu\rangle$ [GeV] | $\langle x_B\rangle$ | $\langle\epsilon\rangle$ |
|---|---|---|---|---|
| $Q^2 \in [1.0, 1.5]$ | 1.22 | 10.54 | 0.072 | 0.997 |
| $Q^2 \in [1.5, 2.1]$ | 1.77 | 9.81 | 0.109 | 0.997 |
| $Q^2 \in [2.1, 3.2]$ | 2.58 | 9.82 | 0.157 | 0.997 |
| $Q^2 \in [3.2, 8.0]$ | 4.33 | 10.39 | 0.247 | 0.997 |

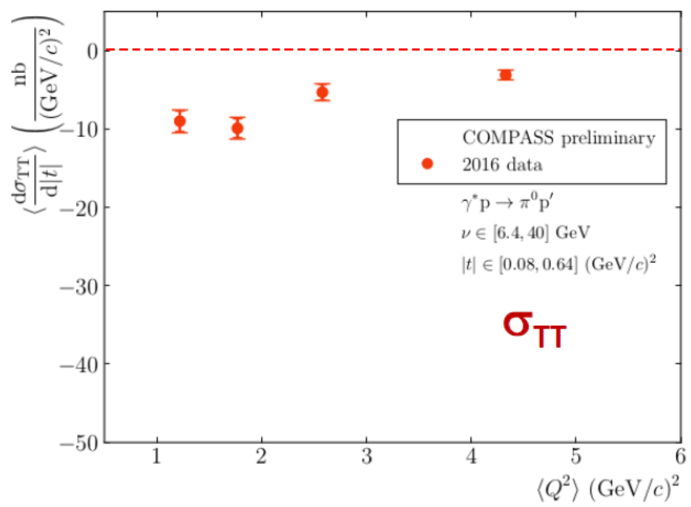
# New 2016 Evolution of the Structure Functions

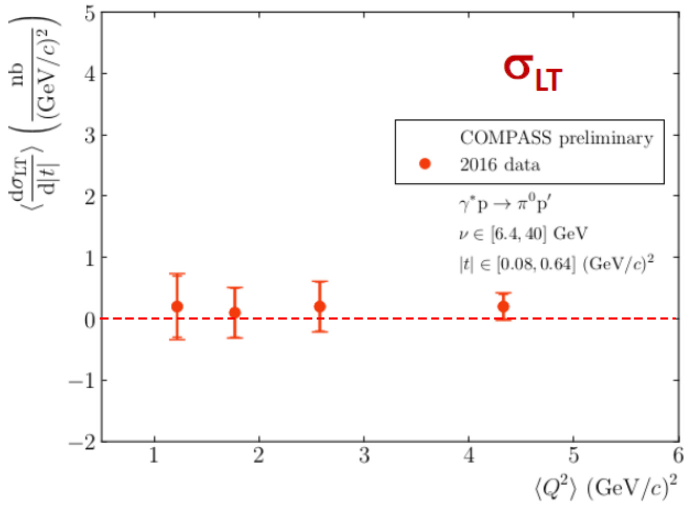


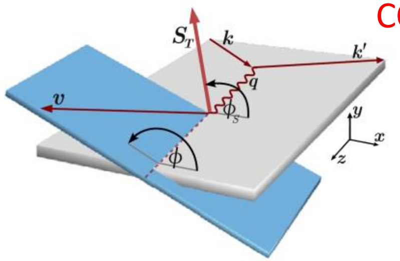




For both $\sigma_T + \epsilon\sigma_L$ and $\sigma_{TT}$
→ Relatively larger evolution in $\nu$, smaller in $Q^2$

$\sigma_{LT}$ consistent with 0

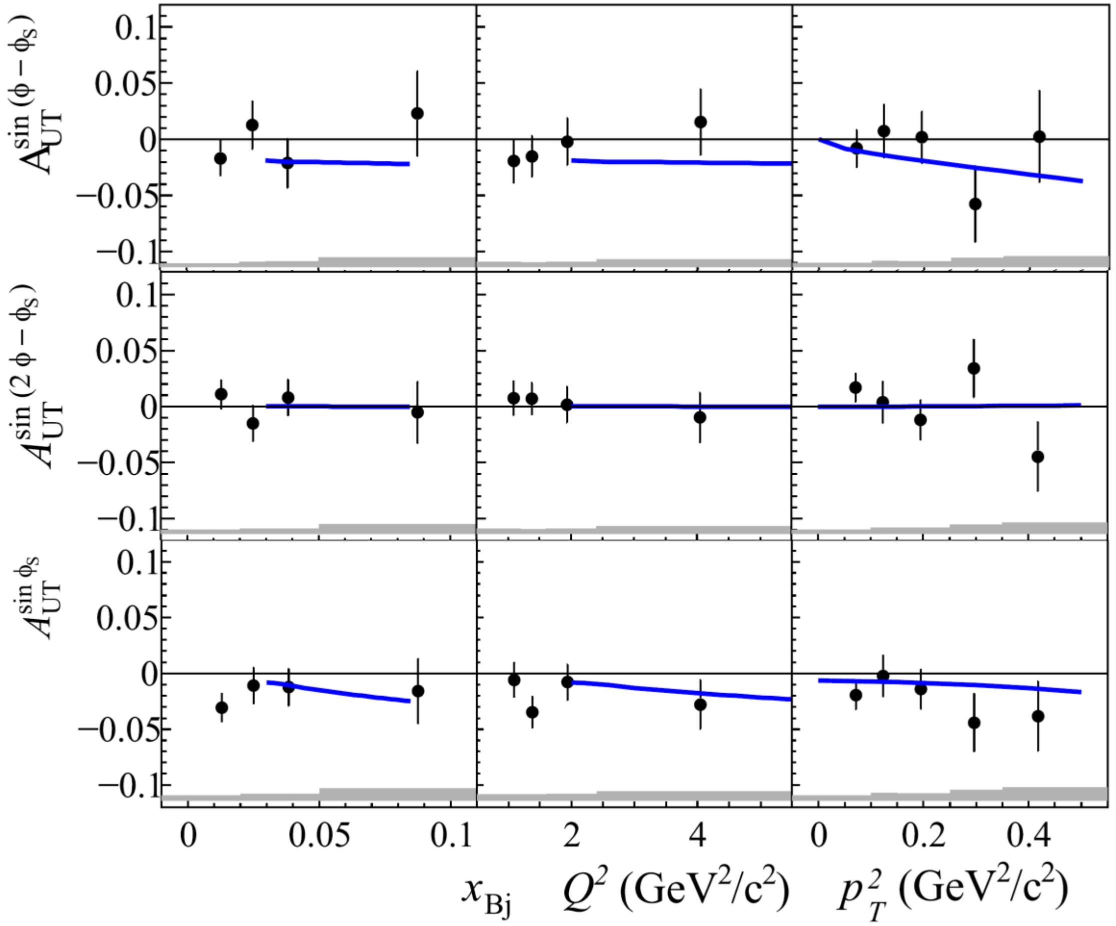
# 2007 & 2010 HEMP with Transversely Polarized Target

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




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

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

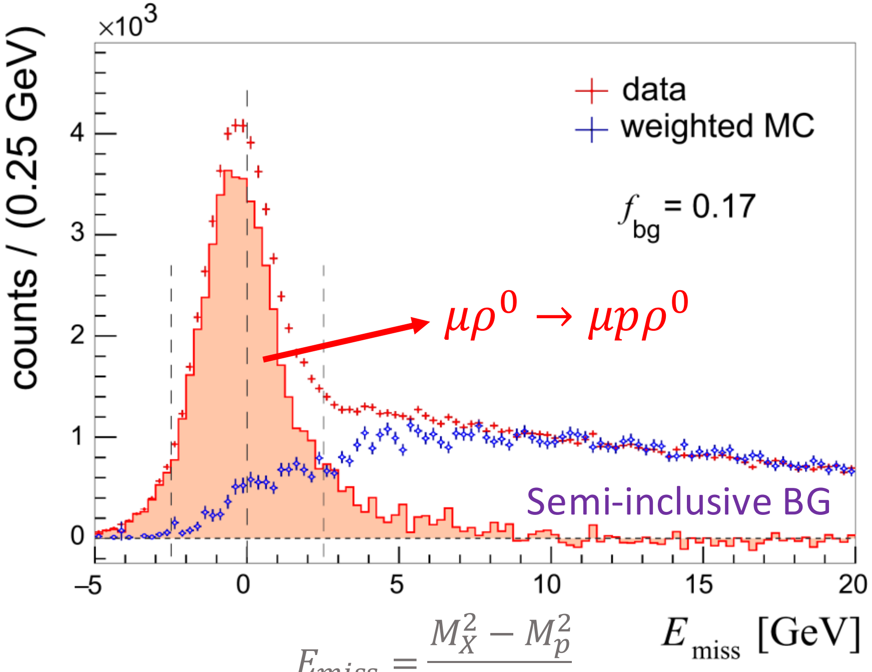



$\propto Im(E^*H)$

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

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

➢ Exclusivity ensured by “missing mass technique”

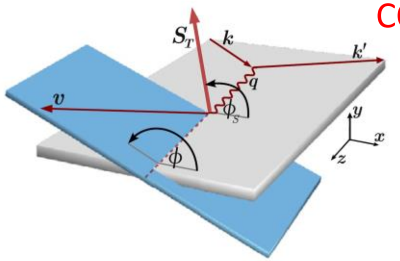



$$E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$$

➢ Sensibility to $E$ and $H_T$

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

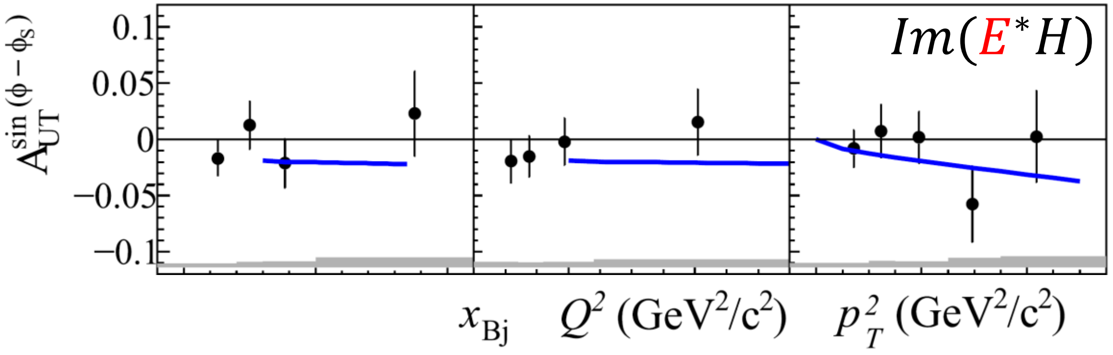
# 2007 & 2010 HEMP with Transversely Polarized Target




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

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

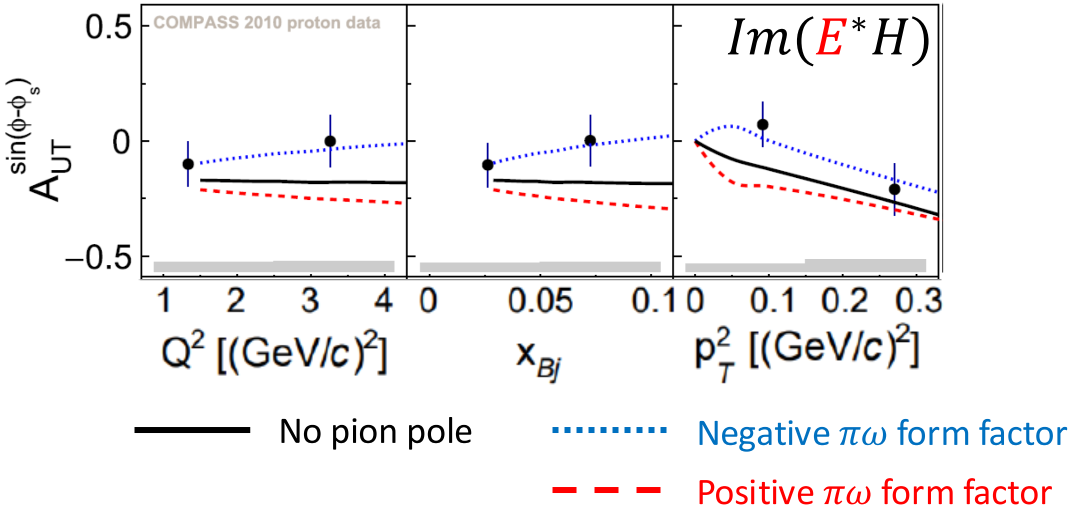
$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g/x\right)$$

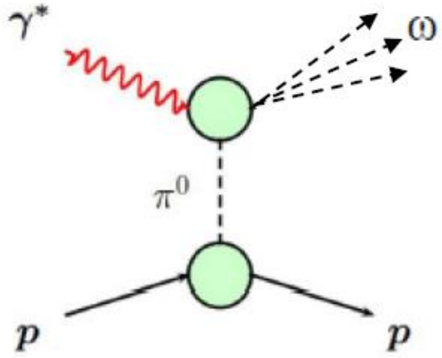



COMPASS, **NPB** 865 (2012) 1-20, **PLB** 731 (2014) 19

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

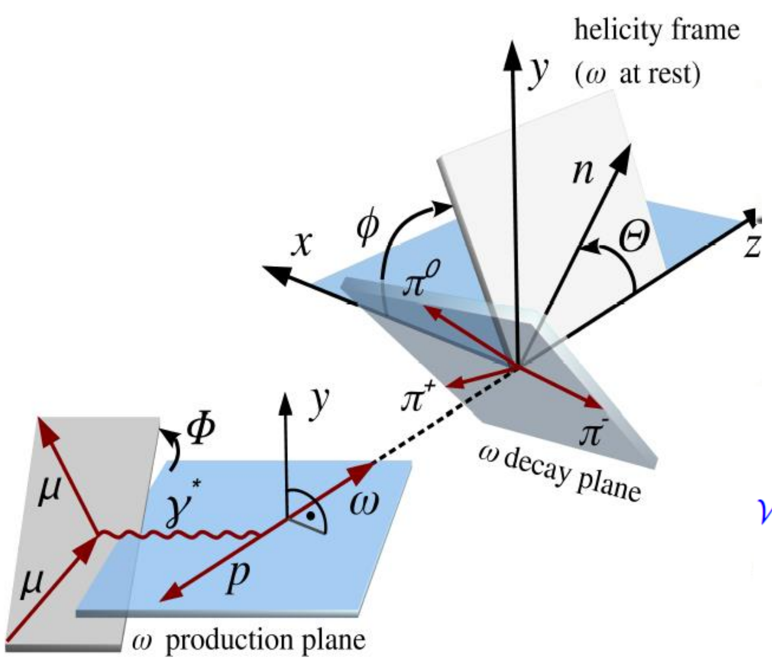
$$E_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}E^g/x\right)$$




- $E^u$ and $E^d$ are of opposite sign → $\omega$ 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 $\mathcal{W}^L$

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

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

- $\epsilon \to 1$, 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

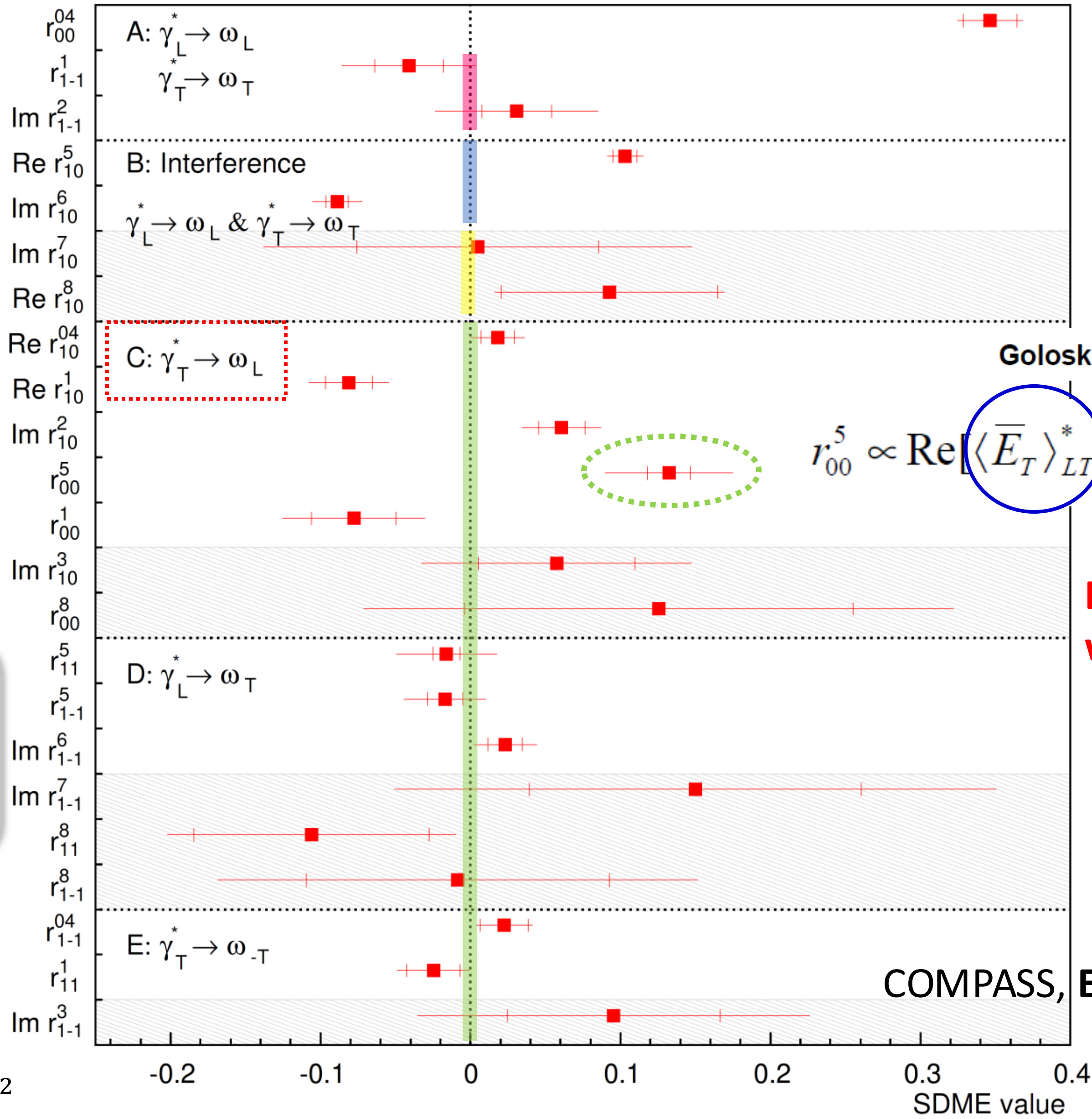
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

  = - 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 $\rho^0$, 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 $\rho^0$ Prod. on Unpolarized Proton

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

(S-Channel Helicity Conservation)

SCHC implies:

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

= $-0.000 \pm 0.006$ OK

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

= $-0.011 \pm 0.003$ Violation

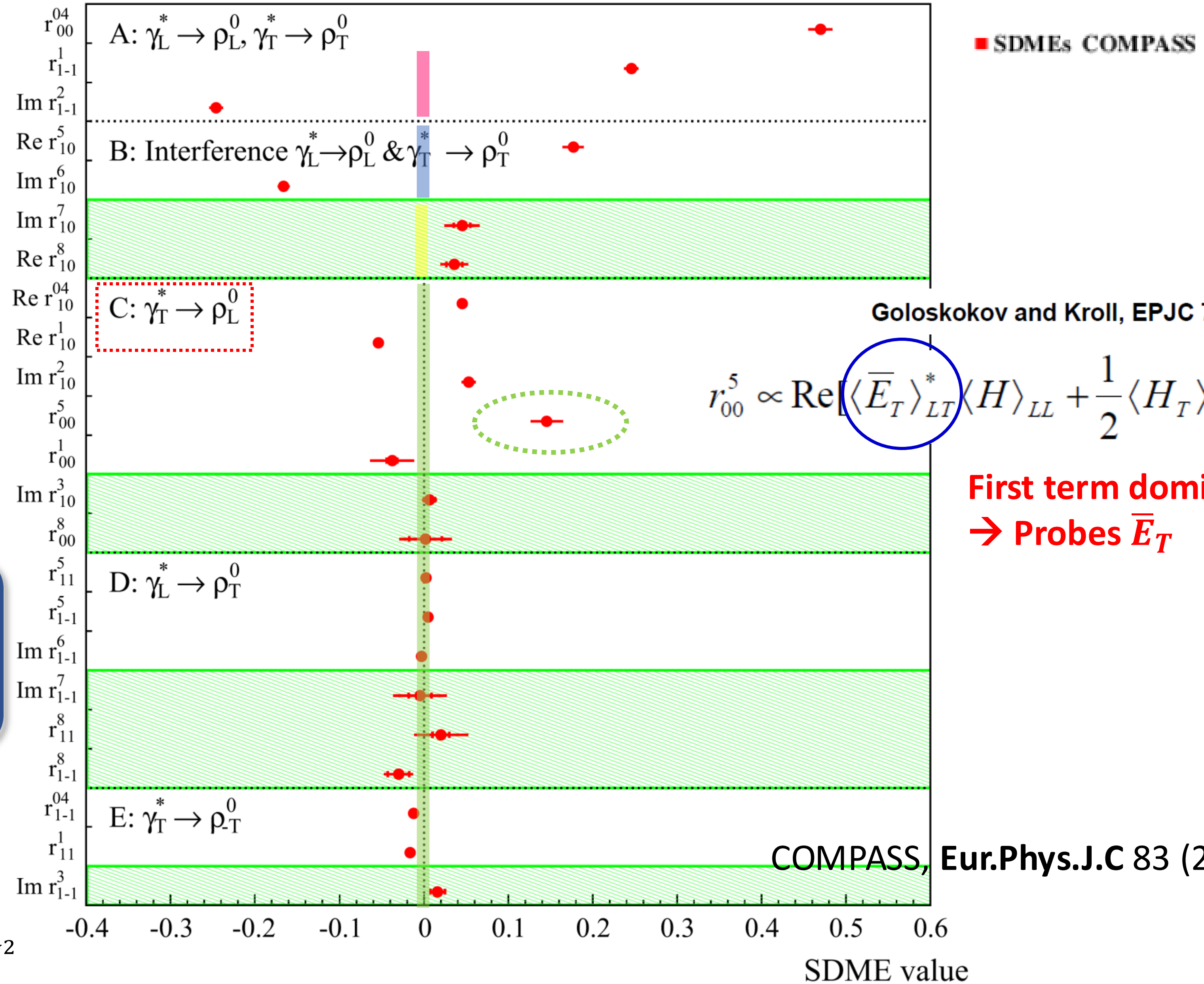
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

= $-0.009 \pm 0.031$ 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

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

# Summary

## DVCS cross sections with polarized $\mu+$ and $\mu-$

- 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

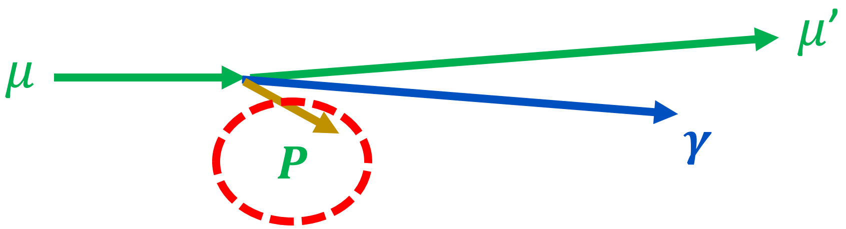
## **HEMP** of $\pi^0$, $\rho$, $\omega$, $\phi$, $J/\psi$

- Cross setion of $\pi^0$ → Submitted to Physics Letters B
- SDME of $\rho$ & $\omega$ → Transversity GPDs & Flavor Decomposition
- $\phi$, $J/\psi$ → underway


➢ **More results are coming!**

# Backup Slides

# COMPASS 2016 Preliminary Results




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

Proton azimuthal angle

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

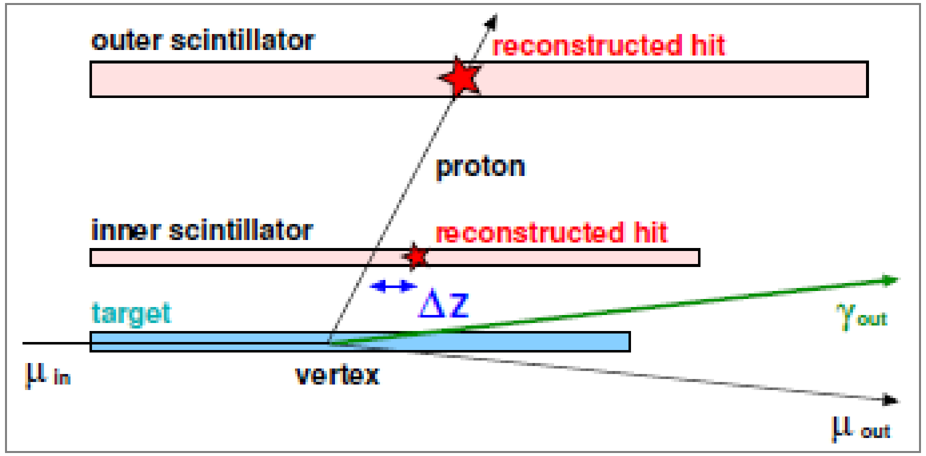
Proton momentum

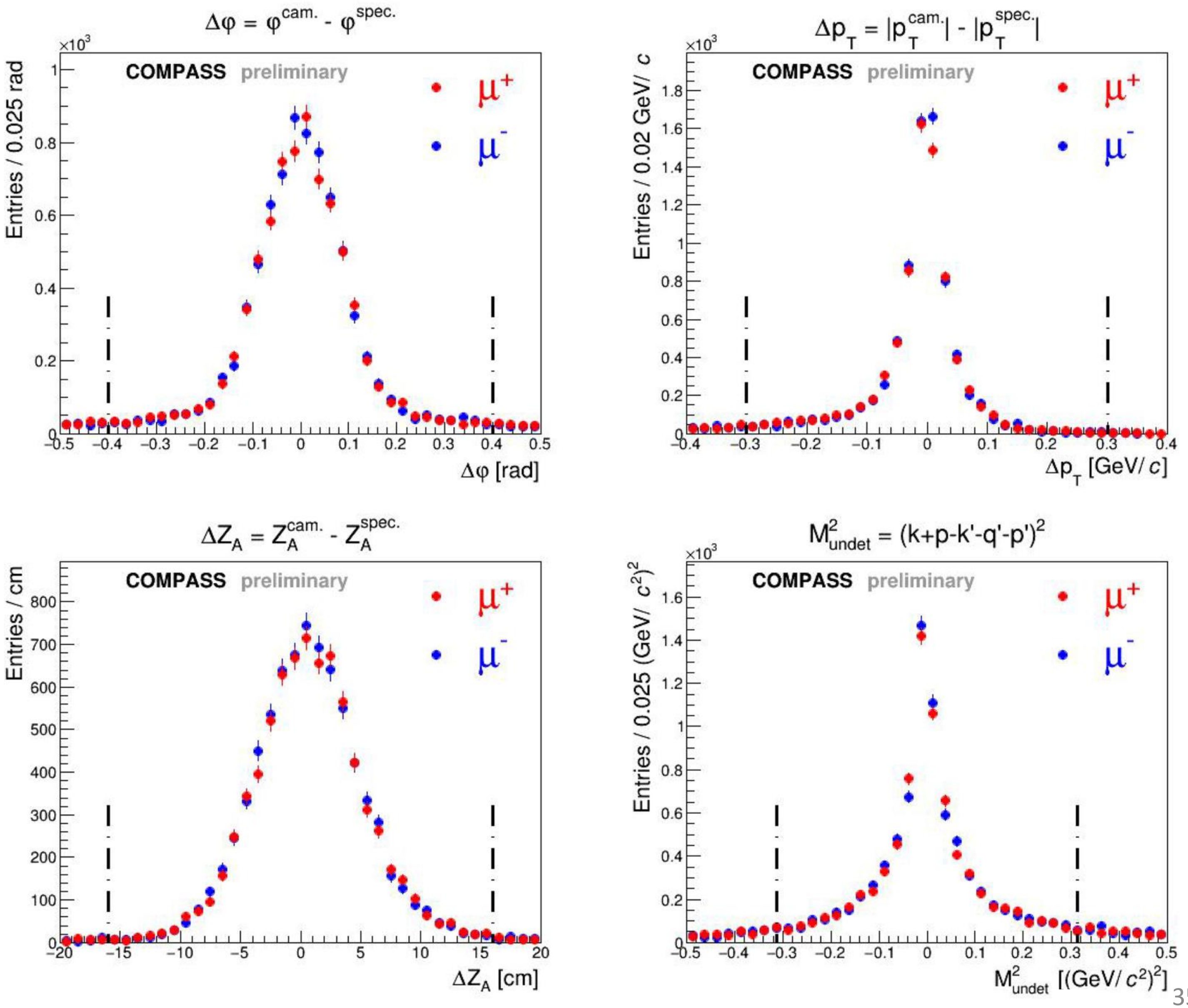
$\Delta Z_A = Z_A^{cam.} - Z_A^{spec.}$

Proton track position

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

Energy momentum balance



# COMPASS 2016 Preliminary Results

➢ **Main background of exclusive single photon events: $\pi^0$ decay**

➢ **Visible** (both $\gamma$ detected) – subtracted

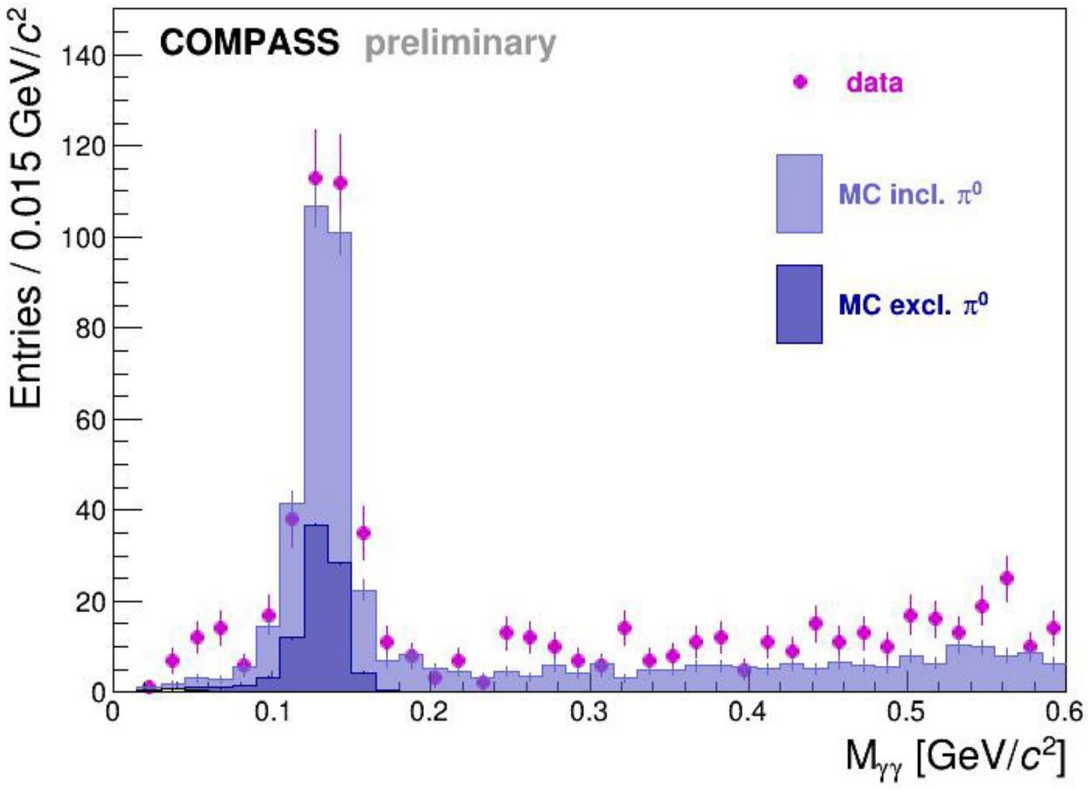
A high-energy DVCS photon candidate is combined with all detected photons with energies lower than the DVCS threshold: (4,5) GeV in Ecal (0,1) respectively

➢ **Invisible** (one $\gamma$ lost) – estimated by MC

- **Semi-inclusive LEPTO 6.1**
- **Exclusive HEPGEN $\pi^0$** (GK model)

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

Visible $\pi^0$ candidates



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

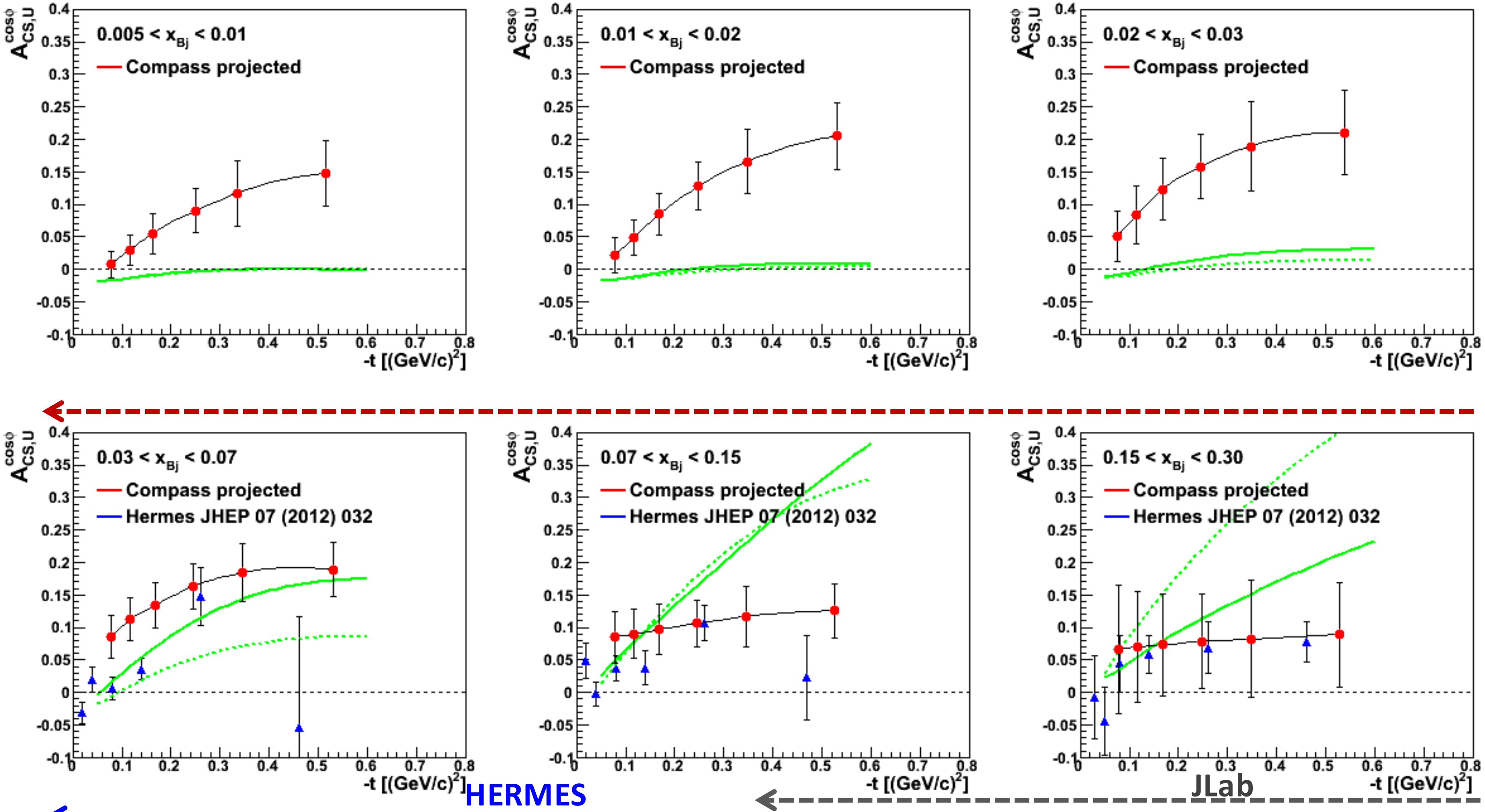
$c_1^I \rightarrow \mathcal{R}e\, F_1 \mathcal{H}$

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

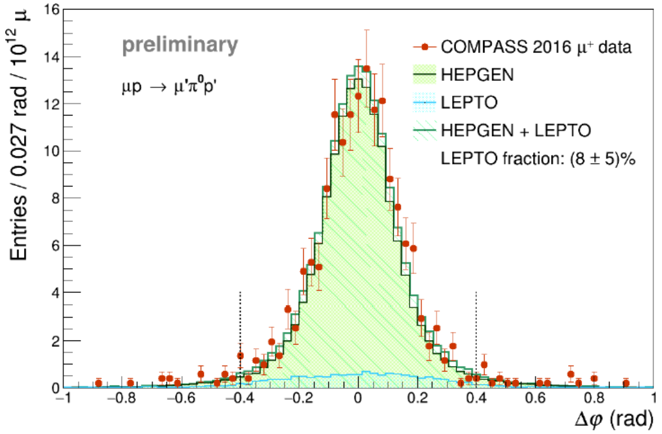
$\mathcal{R}e\, \mathcal{H}$ > 0 at H1
< 0 at HERMES
Value of $x_{Bj}$ for the node?

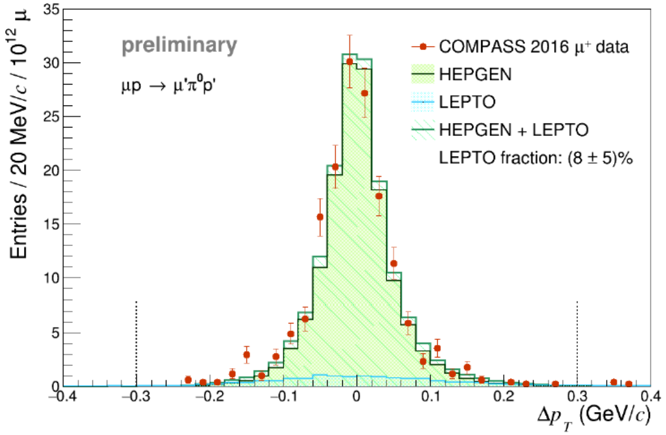


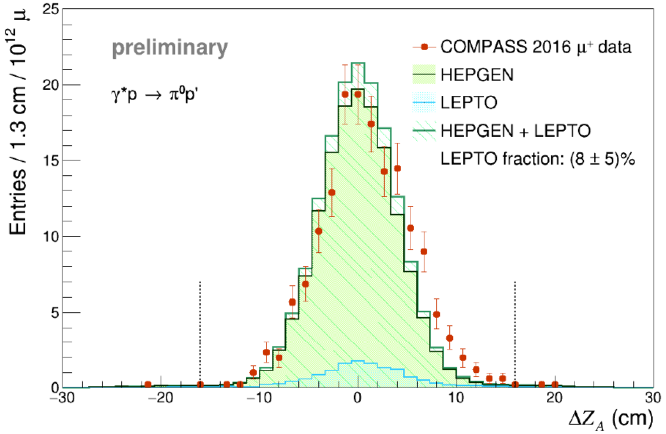

COMPASS 2 years of data Eμ= 160 GeV 1 < $Q^2$ < 8 $GeV^2$

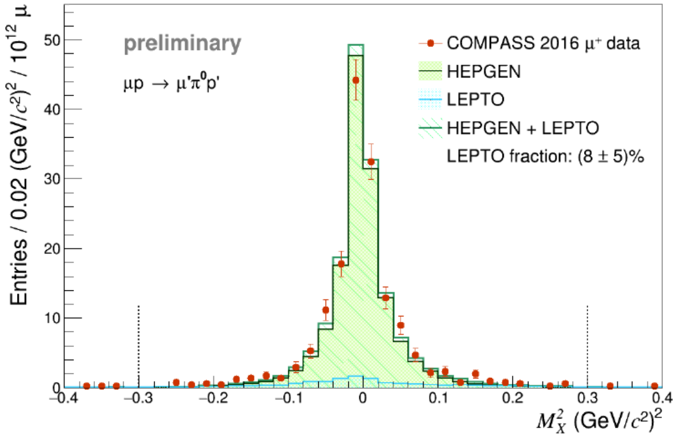
# Exclusive $\pi^0$ Selection and Background Estimation

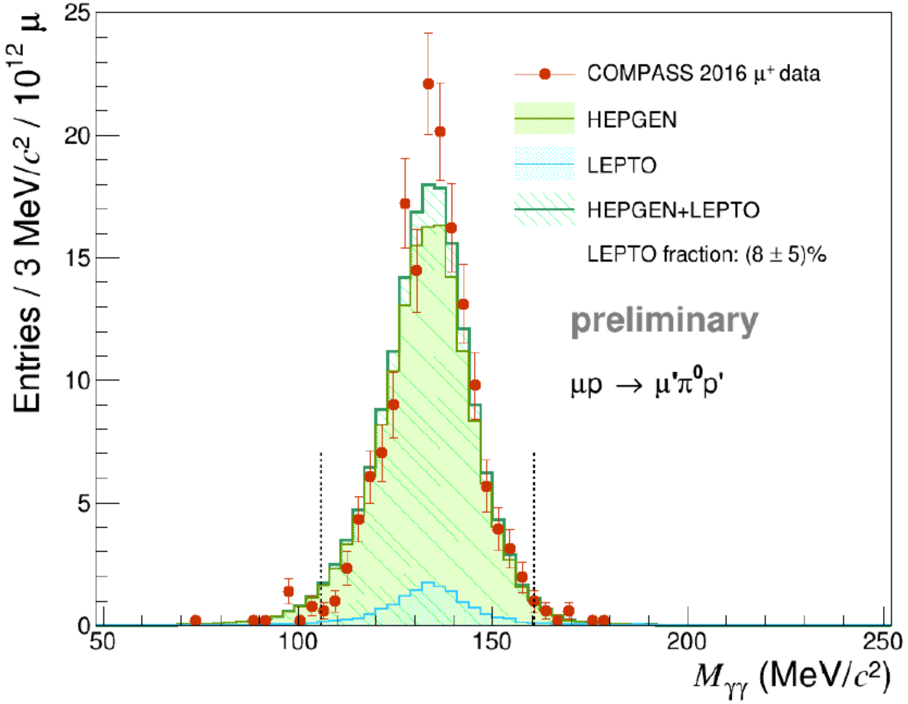
- Exclusivity ensured by cuts on *exclusivity variables, similar to DVCS.*
- Background fraction determined by fitting the exclusivity variables with Monte Carlo simulations.
  - *LEPTO* for non-exclusive background
  - *HEPGEN* of exclusive $\pi^0$ for signal



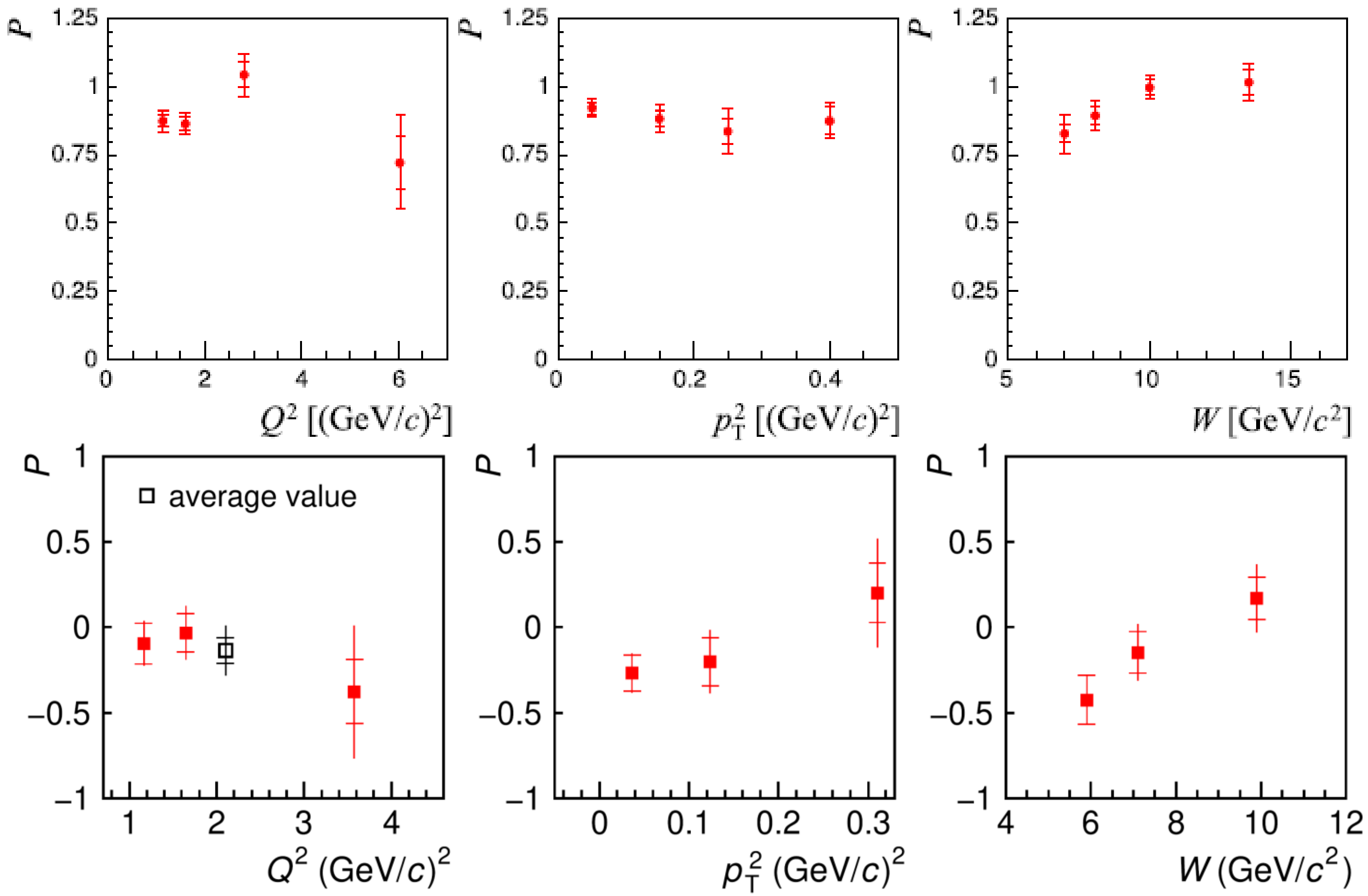

- In 2016 data, non-exclusive background fraction in data → $8 \pm 5$ %

# 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




$\rho^0$ COMPASS, **Eur.Phys.J.C** 83 (2023) 924

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

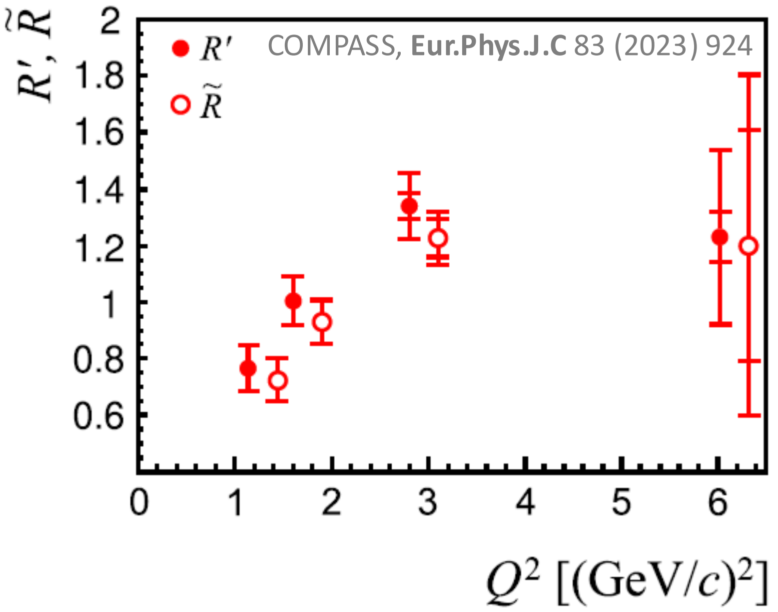
$\omega$ COMPASS, **Eur.Phys.J.C** 81 (2021) 126

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

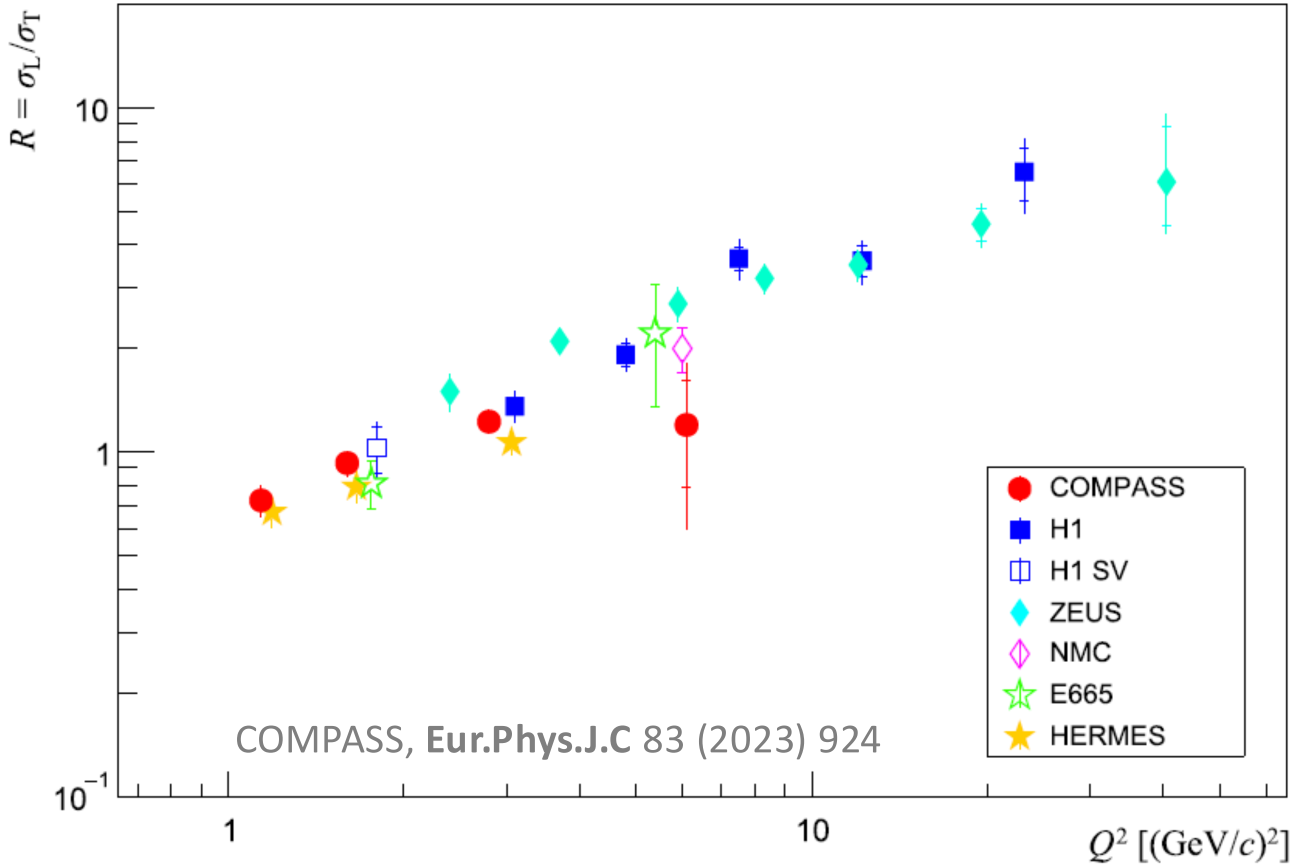
  **+ Pion pole (dominant)**

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

- Longitudinal-to-transverse $\gamma^*$ cross section ratio: $R = \dfrac{\sigma_L(\gamma_L^* \to V)}{\sigma_T(\gamma_T^* \to V)}$
  - Commonly used "effective" ratio ($R' = R$ only if SCHC): $R' = \dfrac{1}{\epsilon}\dfrac{r_{00}^{04}}{1 - r_{00}^{04}}$
  - Use of $\tilde{R}$, which takes SCHC violation into consideration, is preferred.



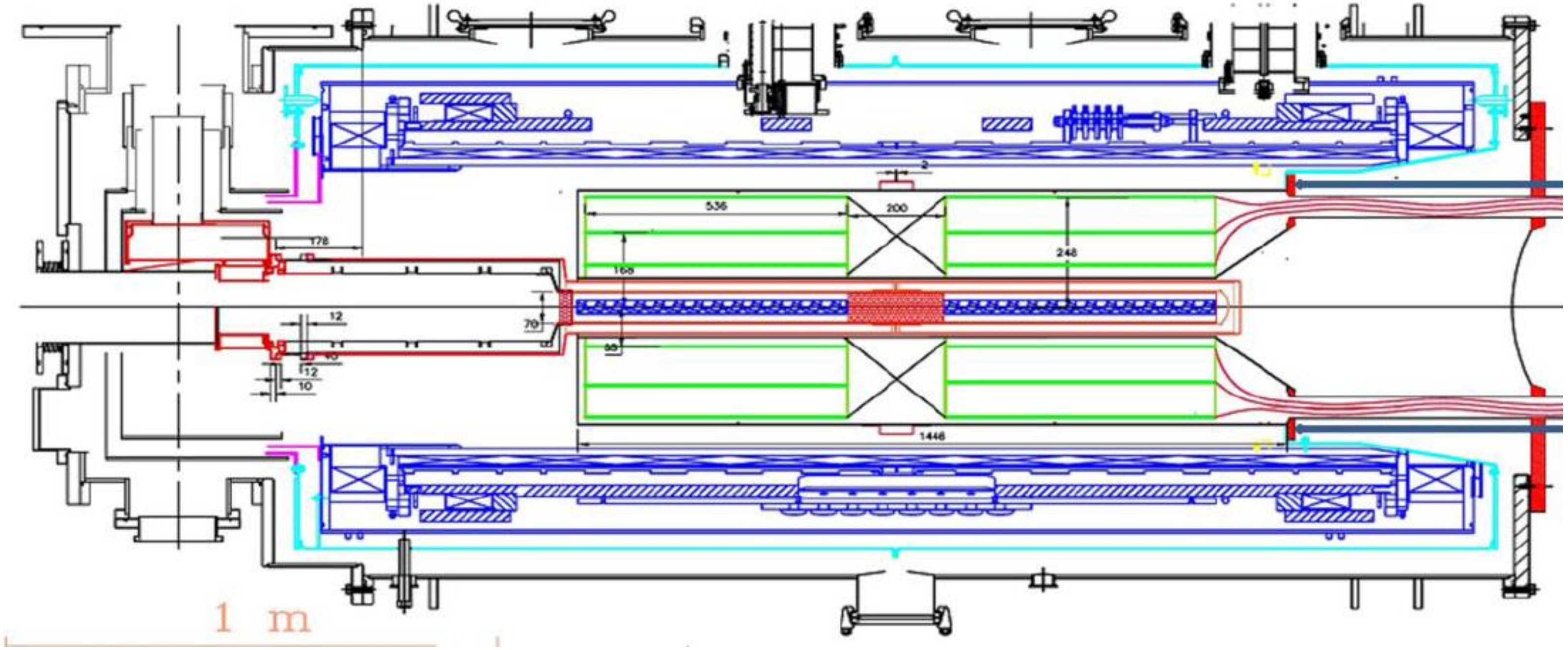

Results of all experiments with $Q^2 > 1\ (\mathrm{GeV}/c)^2$

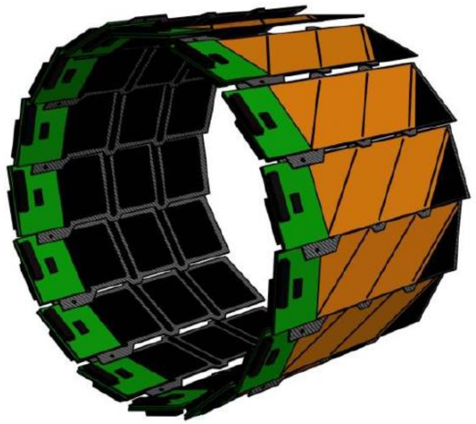



- Leading-order pQCD predction: $Q^2/M_\rho^2$ → deviation due to effect of QCD evolution and $q_T$

# Possible RPD for COMPASS$^{++}$/AMBER

A recoil proton detector (RPD) is mandatory to ensure the exclusivity. A Silicon detector is included *between* the target surrounded by the modified MW cavity *and* the polarizing magnet



A technology developed at JINR for NICA for the BM@N experiment

No possibility for ToF ➔ PID of p/$\pi$ with dE/dx
Momentum and trajectory measurments
$|t|_{min} \sim 0.1$ GeV