Exclusive Measurements at COMPASS

TQCD Meeting, Academia Sinica
September 16, 2022

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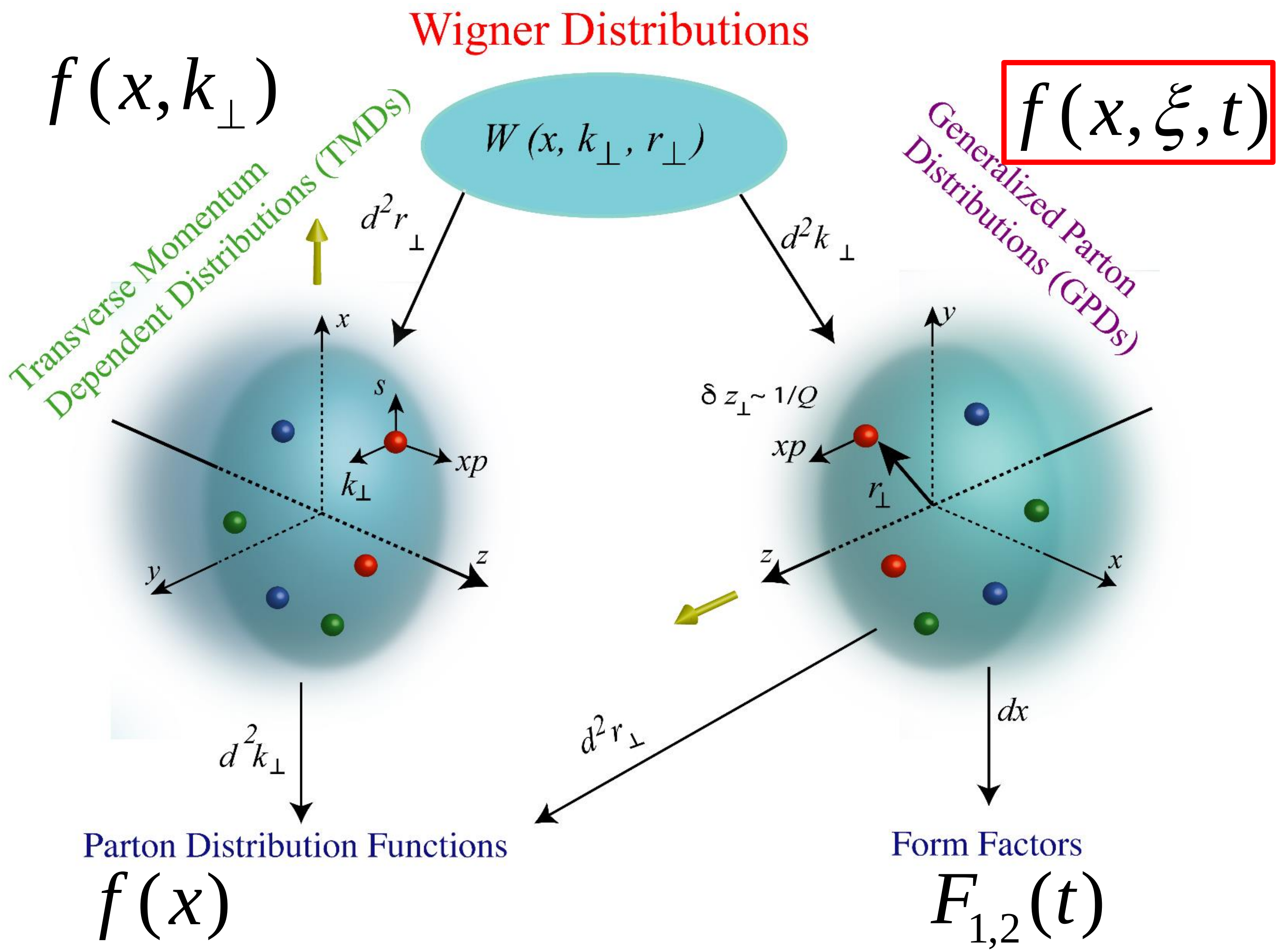
Institute of Physics, Academia Sinica

Multi-dimensional Partonic Structures



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

Outline

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

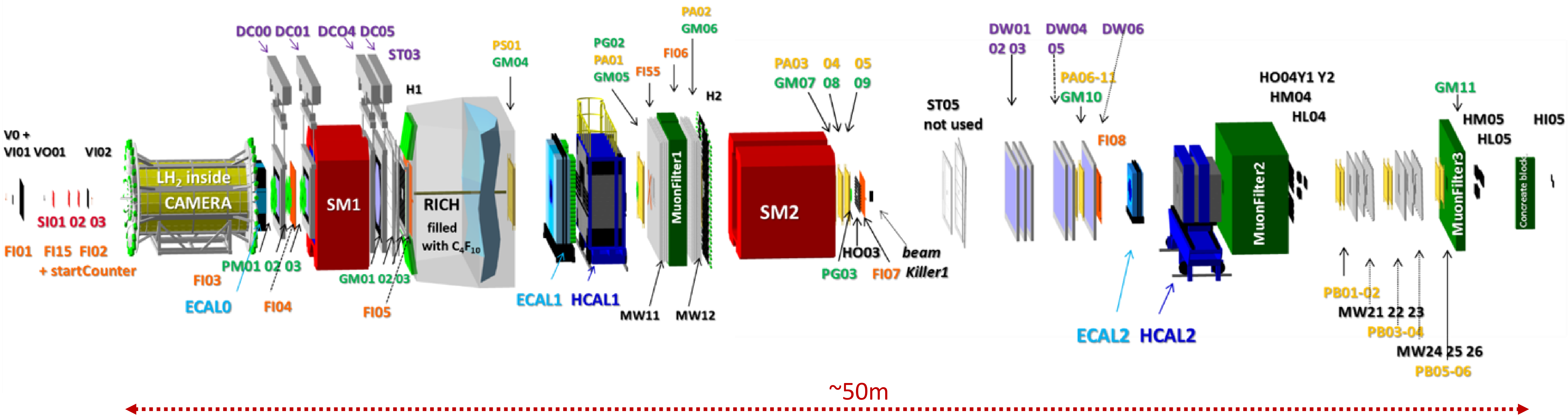
COMPASS Experiment

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

COMPASS Setup for Hard Exclusive Measurements



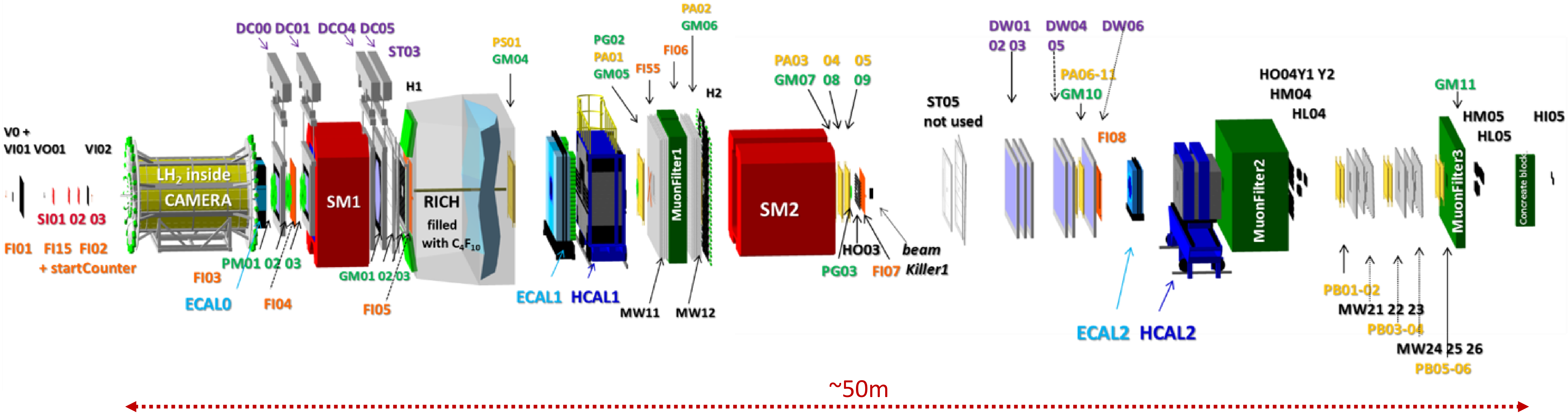
Muon Beams

- μ^+ & μ^- with opposite polarisation
- $About\ \pm 80\%$ polarisation
- Momentum: 160 GeV/c

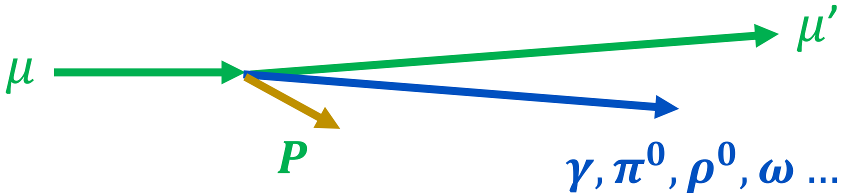
Two-stage, large angle, and wide momentum range spectrometer. PID including hadron absorbers, RICH, HCALs, ECALs, and muon filters.

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

COMPASS Setup for Hard Exclusive Measurements



Exclusive Muoproduction



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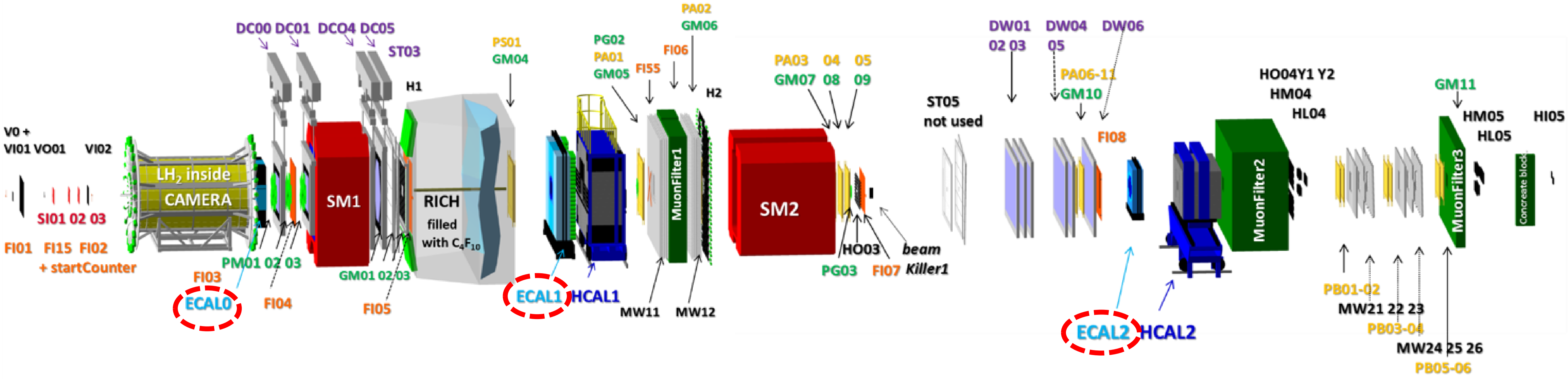

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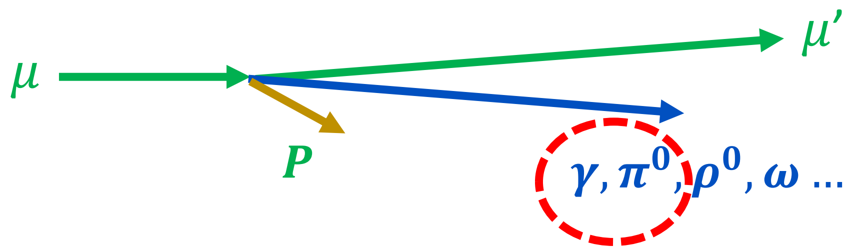

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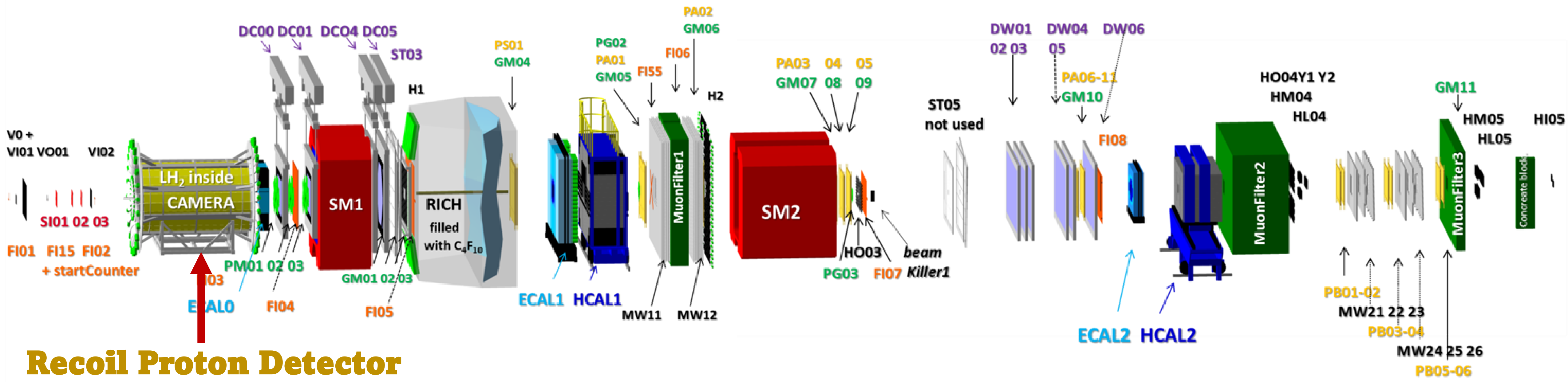

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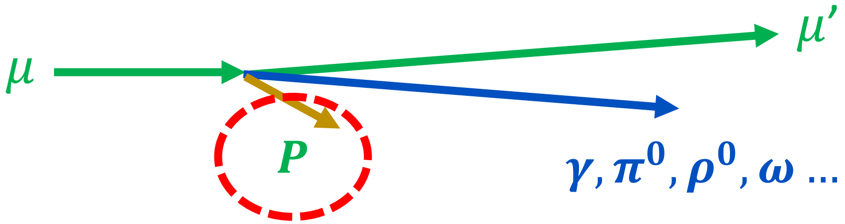

Two-stage, large angle, and wide momentum range spectrometer. PID including hadron absorbers, RICH, HCALs, ECALs, and muon filters.

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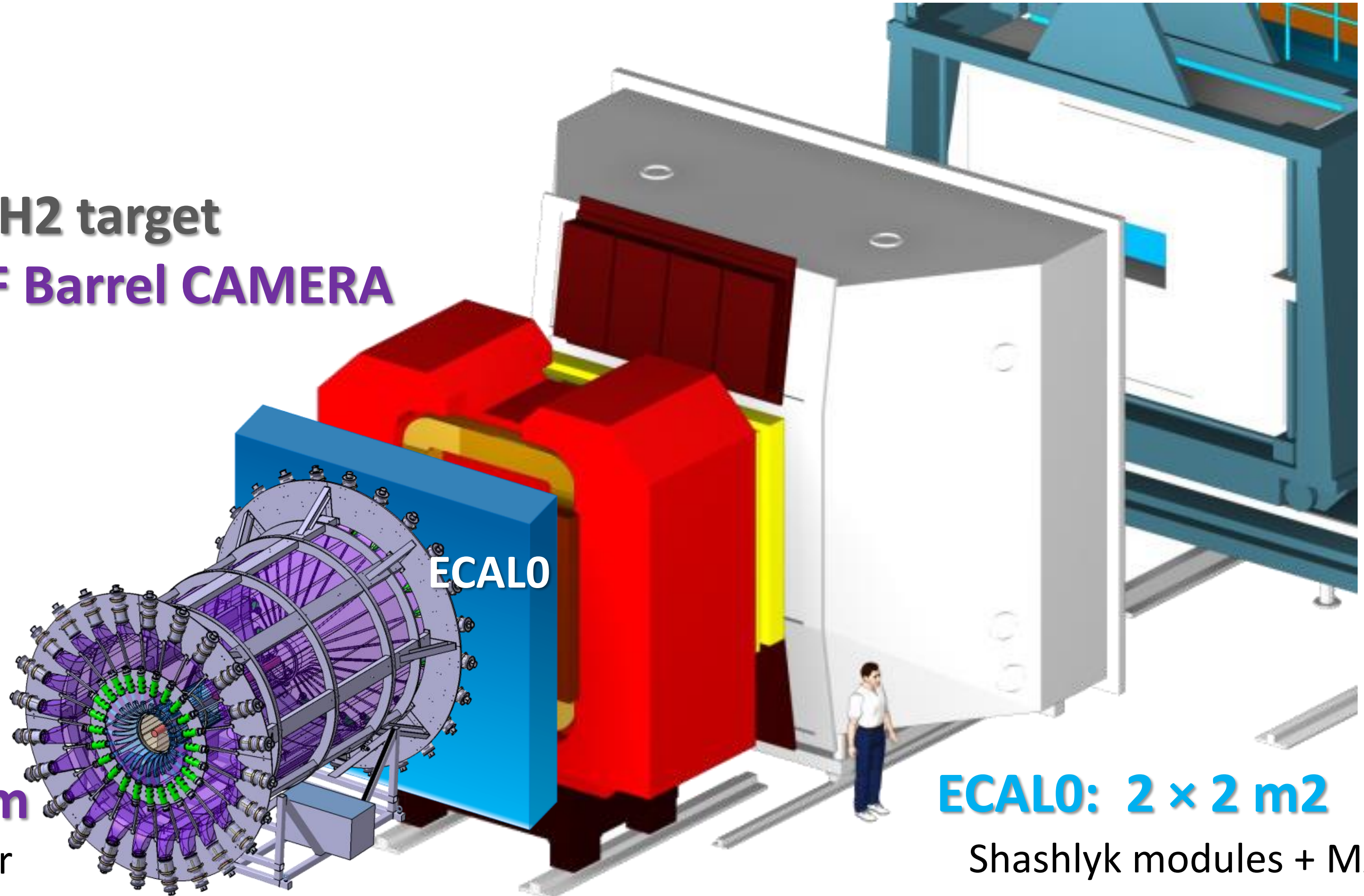
COMPASS Setup for Hard Exclusive Measurements

- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0



CAMERA

L=4m ∅=2m

24 inner & outer scintillators separated by about 1m

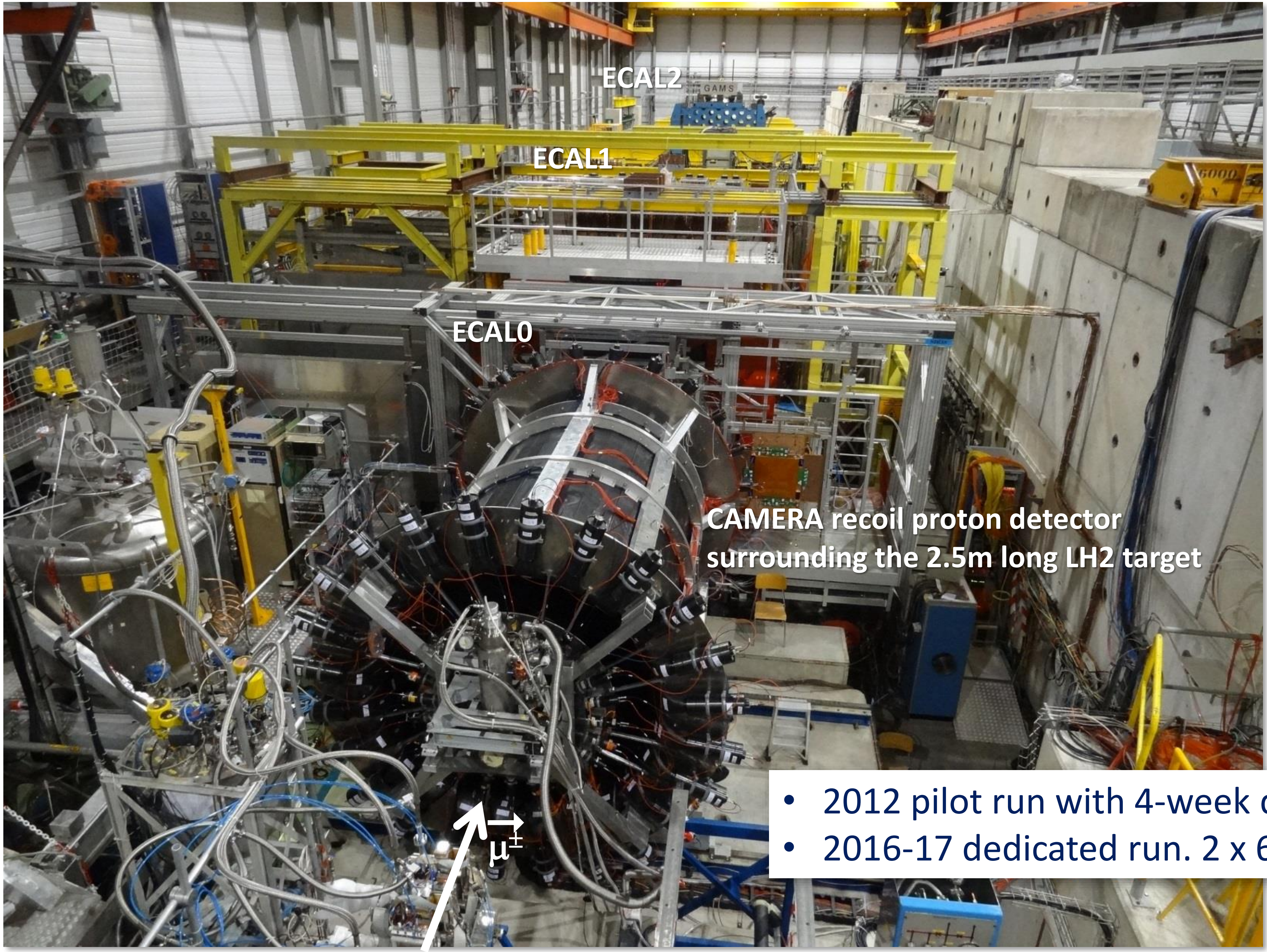
1 GHz SADC readout, 330ps ToF resolution

ECAL0: 2 × 2 m2

Shashlyk modules + MAPD readout

one module is made of 9 cells (4×4 cm^2)

= 194 modules or 1746 cells

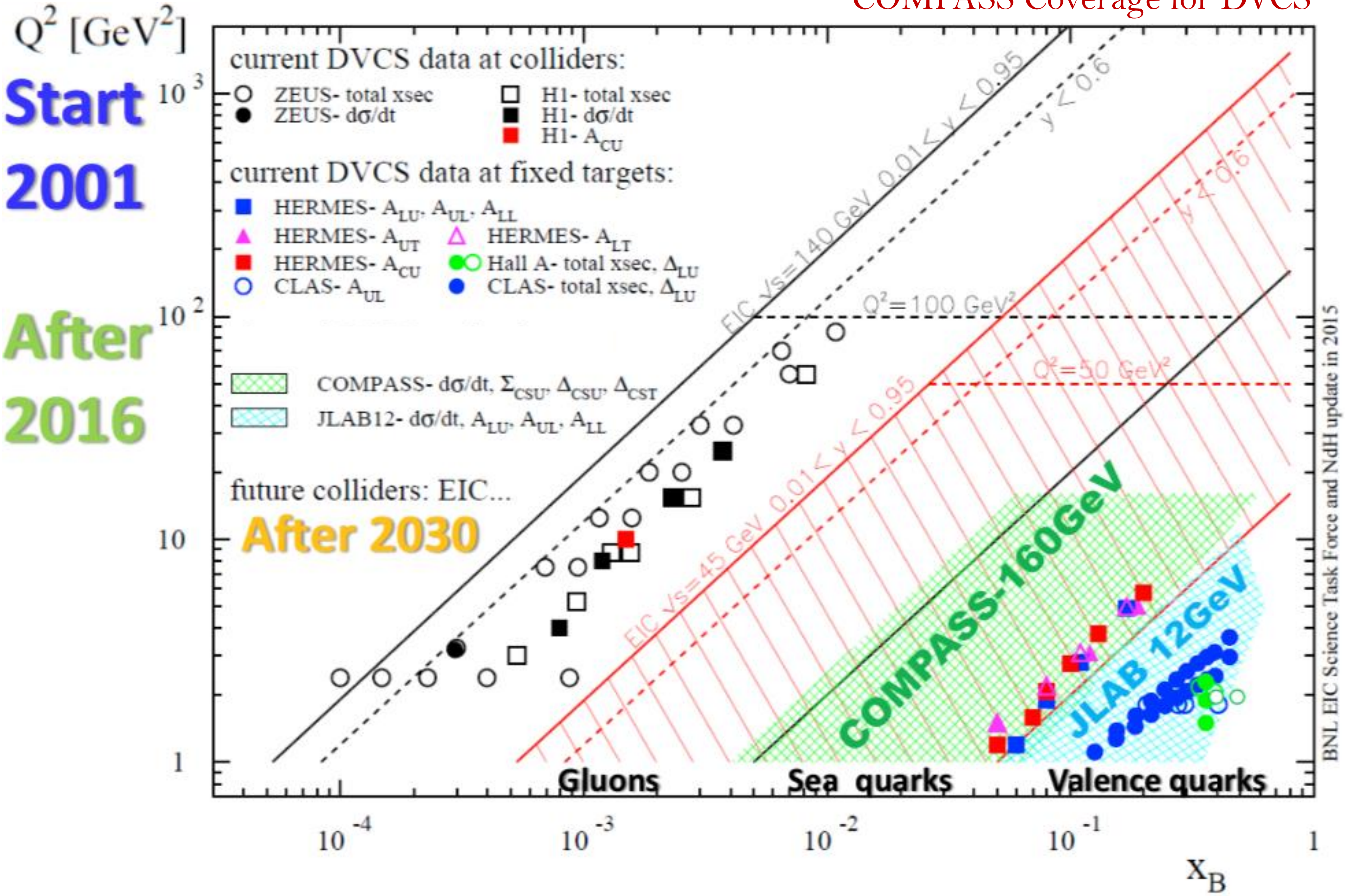


- 2012 pilot run with 4-week data taking
- 2016-17 dedicated run. 2 x 6 months.

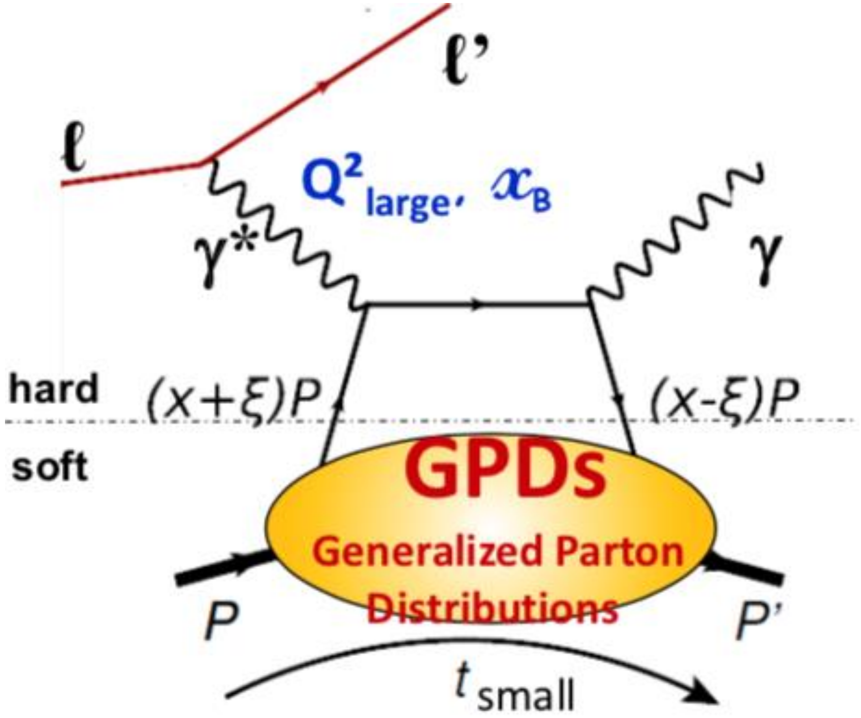
Deeply Virtual Compton Scattering @ COMPASS

DVCS at COMPASS

COMPASS Coverage for DVCS



DVCS



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

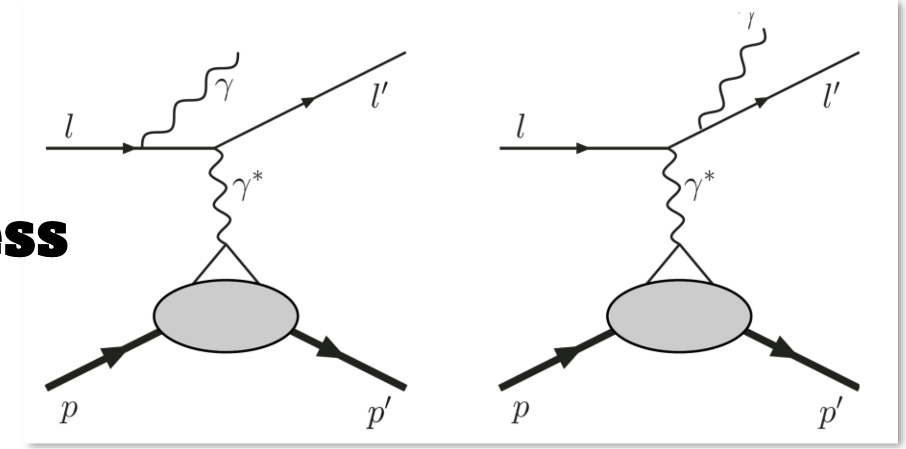
To experimentally access the information about Generalized Parton Distributions (GPDs), DVCS is regarded as the golden channel and its interference with the well-understood Bethe-Heitler process gives access to more info.

The variables measured in the experiment:

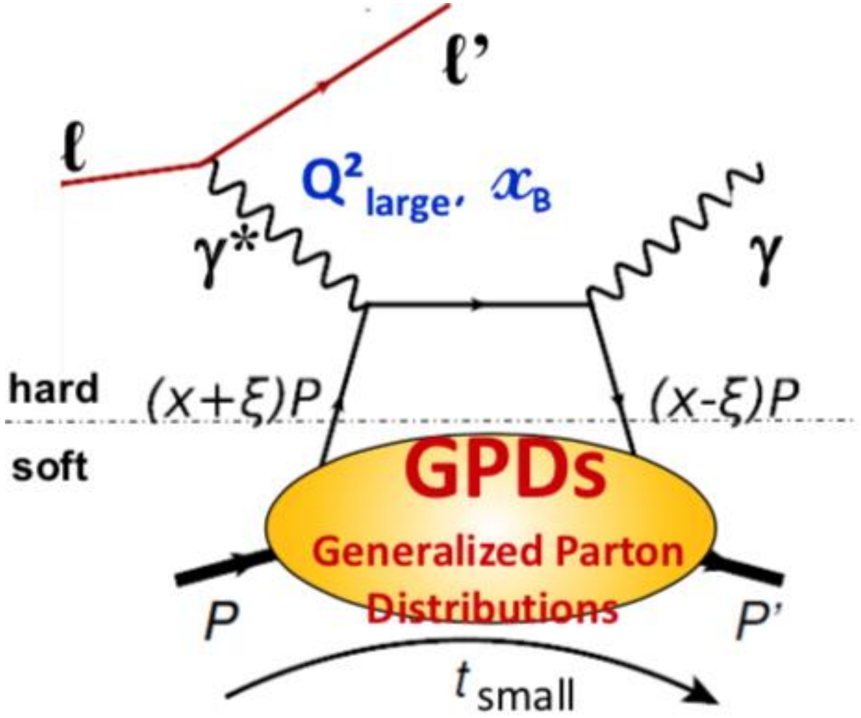
E_ℓ, Q^2, $x_{Bj} \sim 2\xi/(1+\xi)$,

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

BH Process



DVCS



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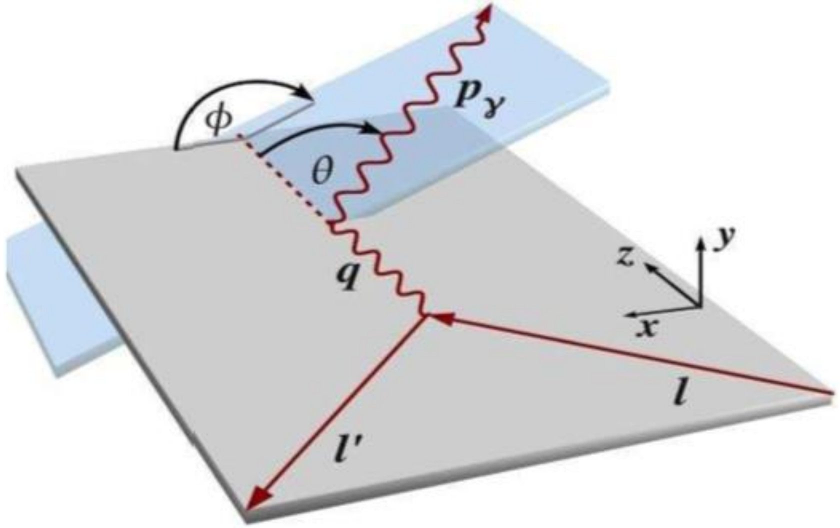
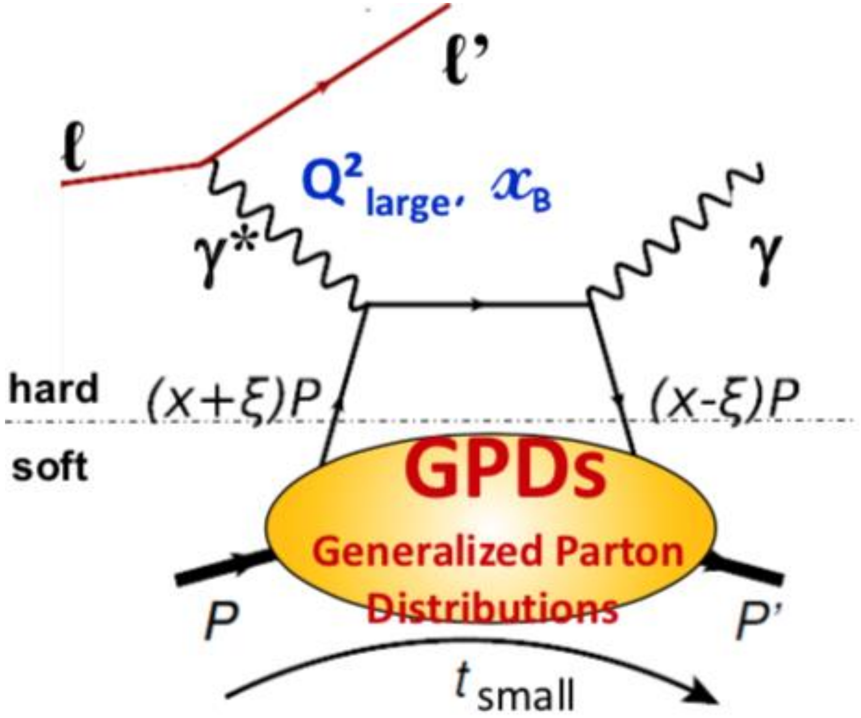


The variables measured in the experiment:

E_ℓ, Q^2, $x_{Bj} \sim 2\xi/(1+\xi)$,

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

DVCS



- 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^*

Sensible to 4 GPDs, with LH_2 target and small x_B coverage
→ focuses on **H** at COMPASS

CFF GPD

REAL part **Imaginary part**

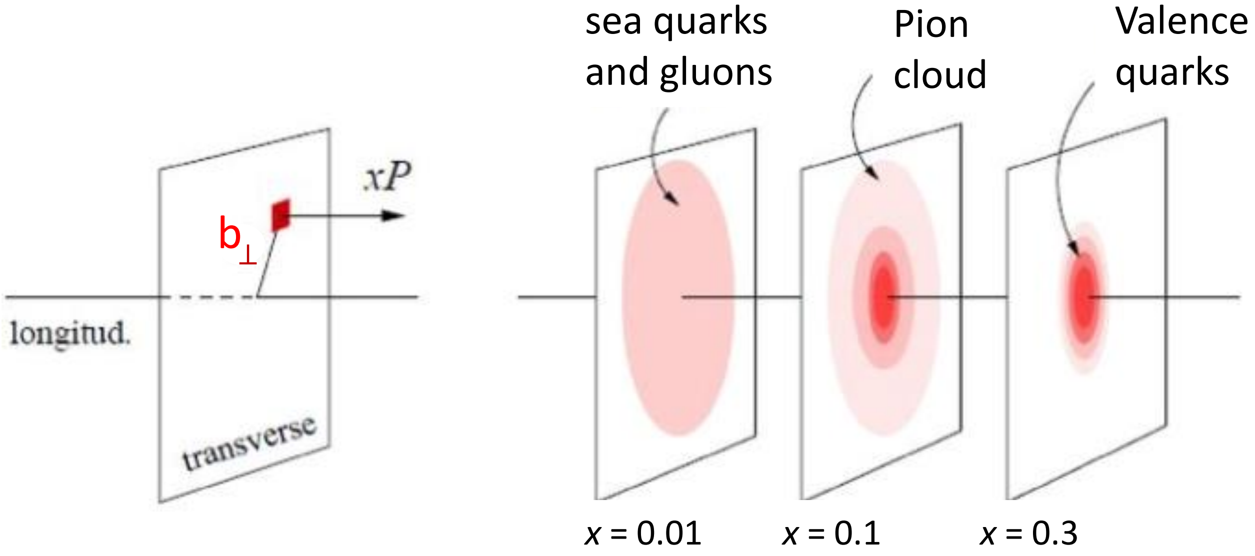
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\,\mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

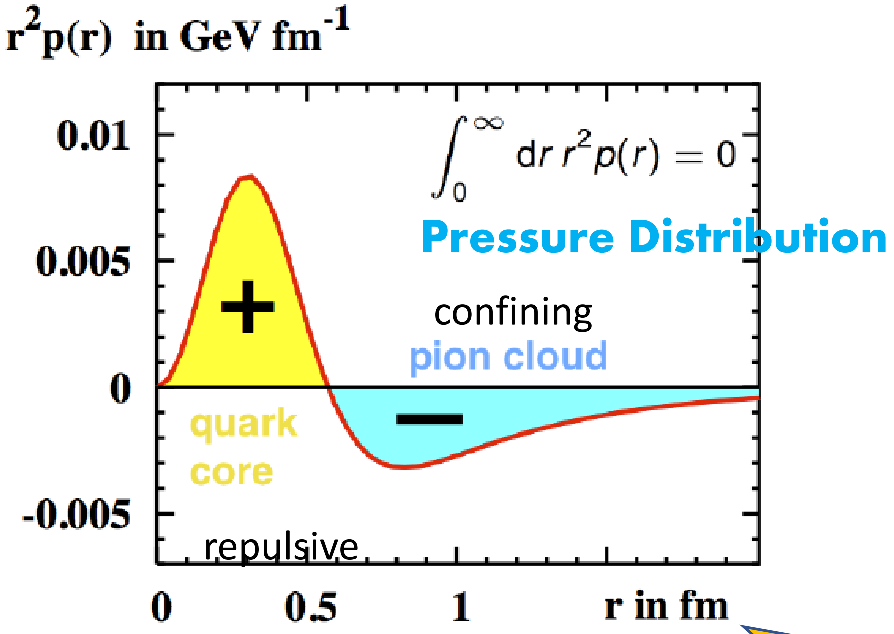
$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{\mathcal{I}m\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

Transverse Imaging and Pressure Distribution

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

Mapping in the transverse plane





FT of H(x, ξ=0,t)

CFF

GPD

REAL part

Imaginary part

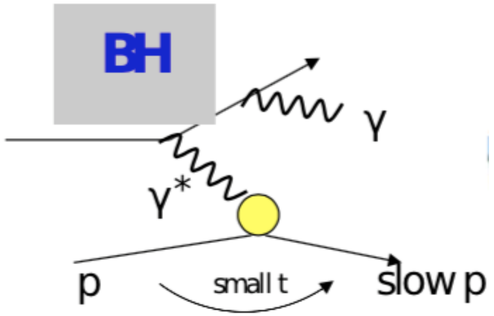
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx\, \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx\, \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

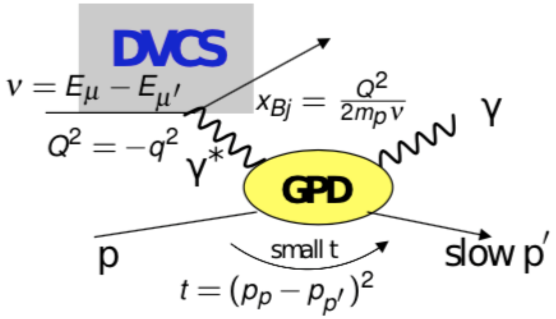
$$\mathcal{Re}\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{\mathcal{Im}\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

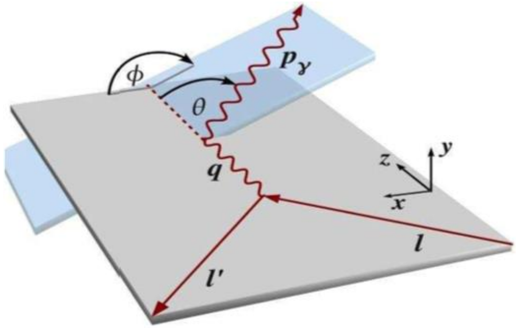
$d_1(t)$

D-term

Azimuthal Dependence of BH & DVCS







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

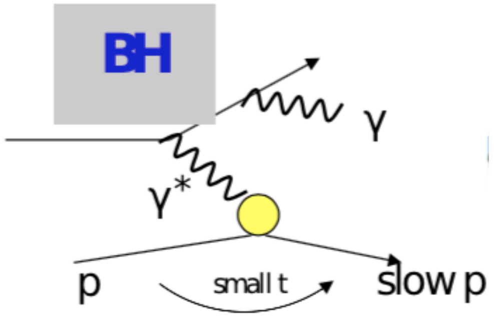
Beam Charge-spin difference & sum

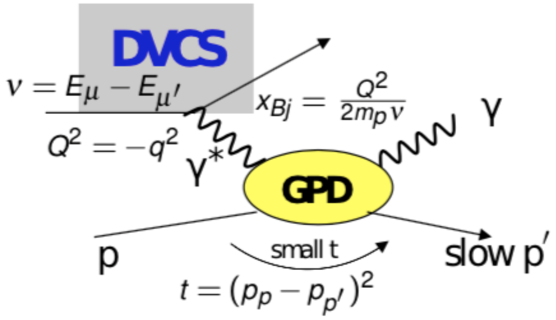
$$\mathcal{D}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow})$$
$$\mathcal{S}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow})$$

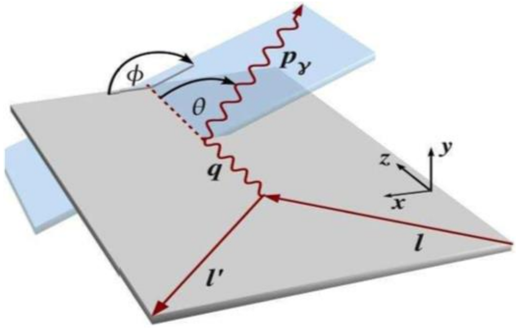
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$
$$\operatorname{Re} I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$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

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

Azimuthal Dependence of BH & DVCS







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

Well known

Beam Charge-spin difference & sum

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

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

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

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

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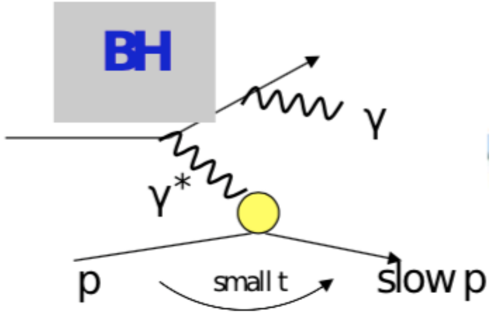
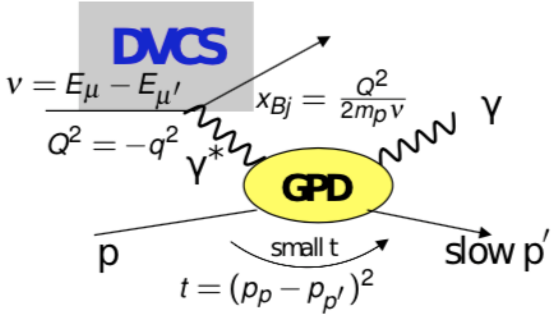
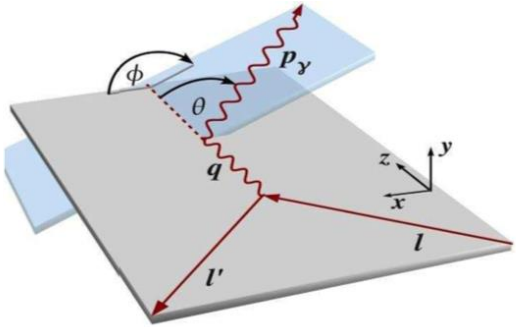
$\mathcal{D}_{\text{CS, U}}(\phi)$

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

Azimuthal Dependence of BH & DVCS







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

Well known

Beam Charge-spin difference & sum

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

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

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

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

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

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

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

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

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

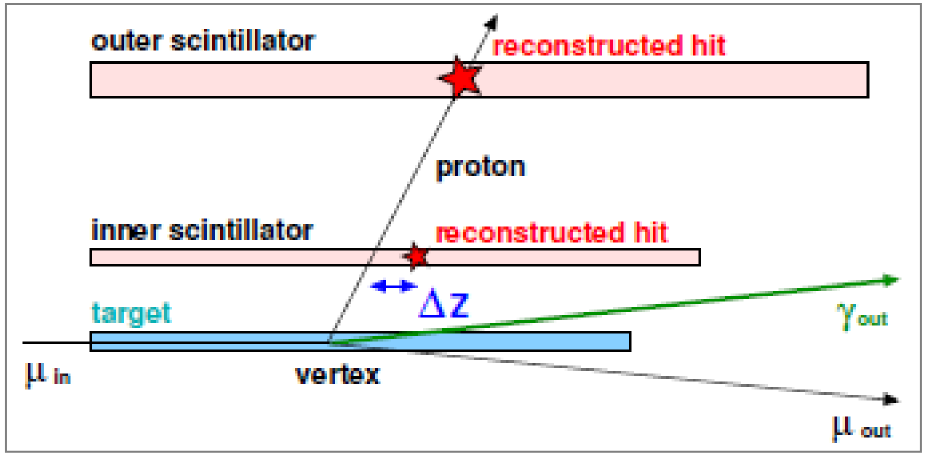
COMPASS 2016 Preliminary Results

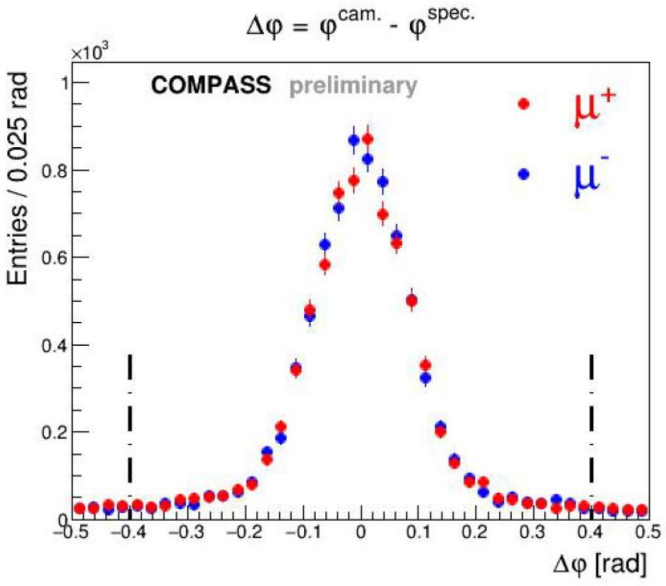
$\Delta\varphi = \varphi^{cam.} - \varphi^{spec.}$

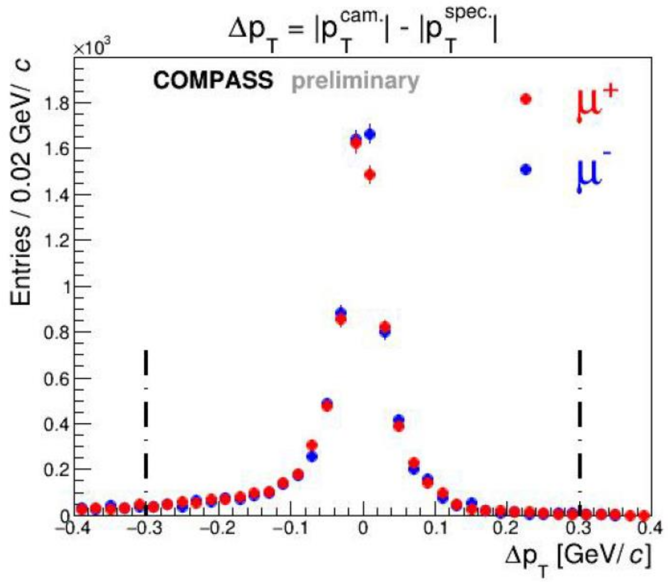
$\Delta p_T = |p_T^{cam.}| - |p_T^{spec.}|$

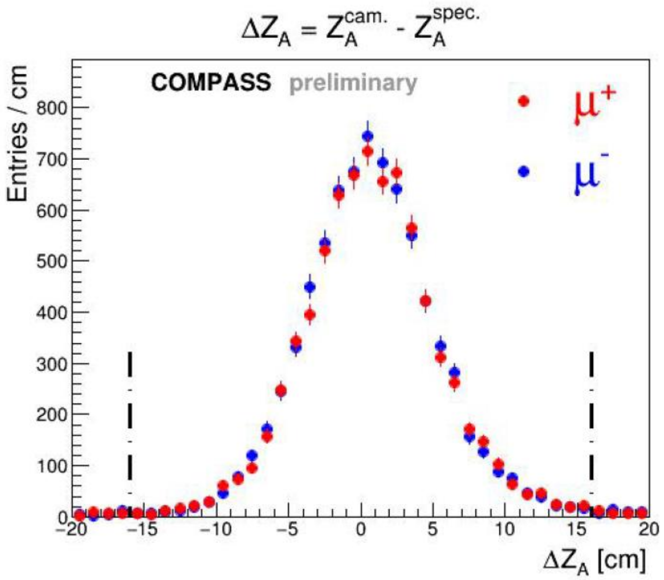
$\Delta z_A = z_A^{cam.} - z_A^{spec.}$

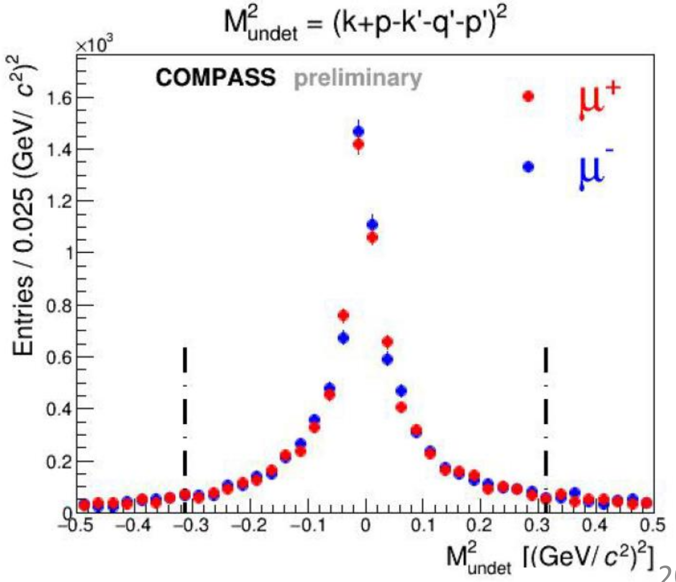
$M^2_{undet} = (k + p - k' - q' - p')^2$











COMPASS 2016 Preliminary Results

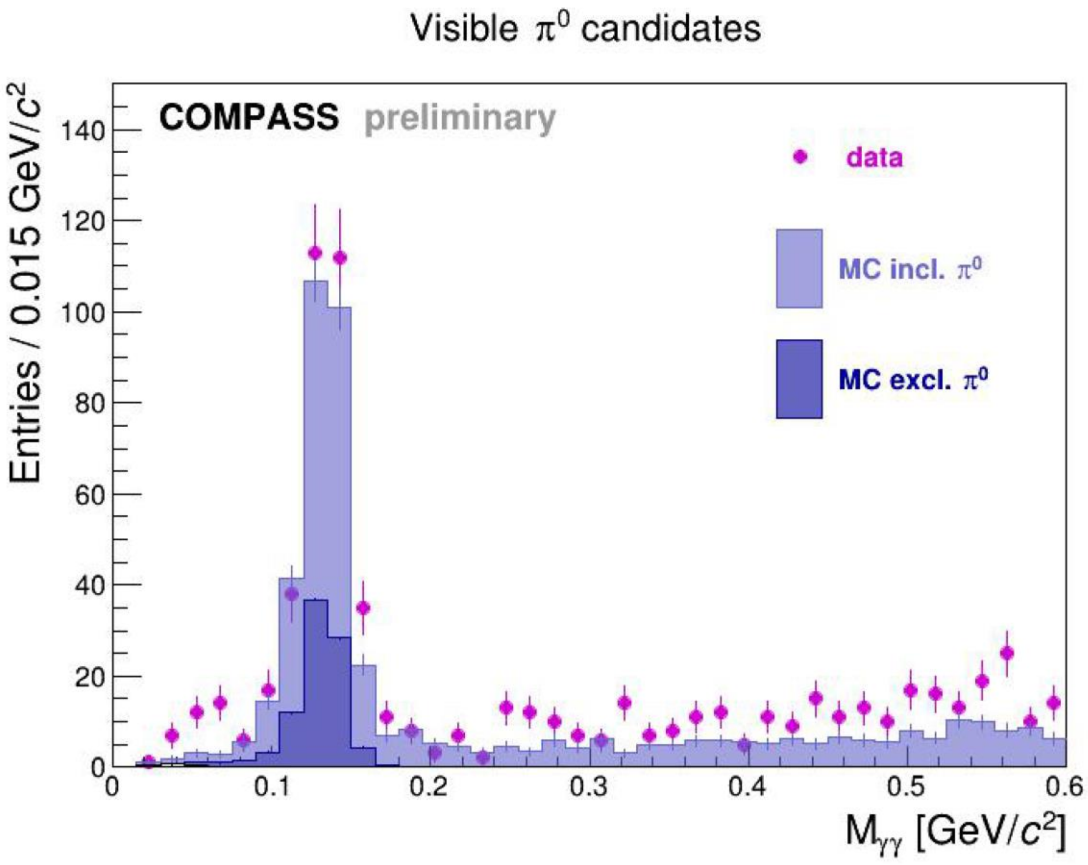
➢ **Main background of exclusive single photon events: π^0 decay**

➢ **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

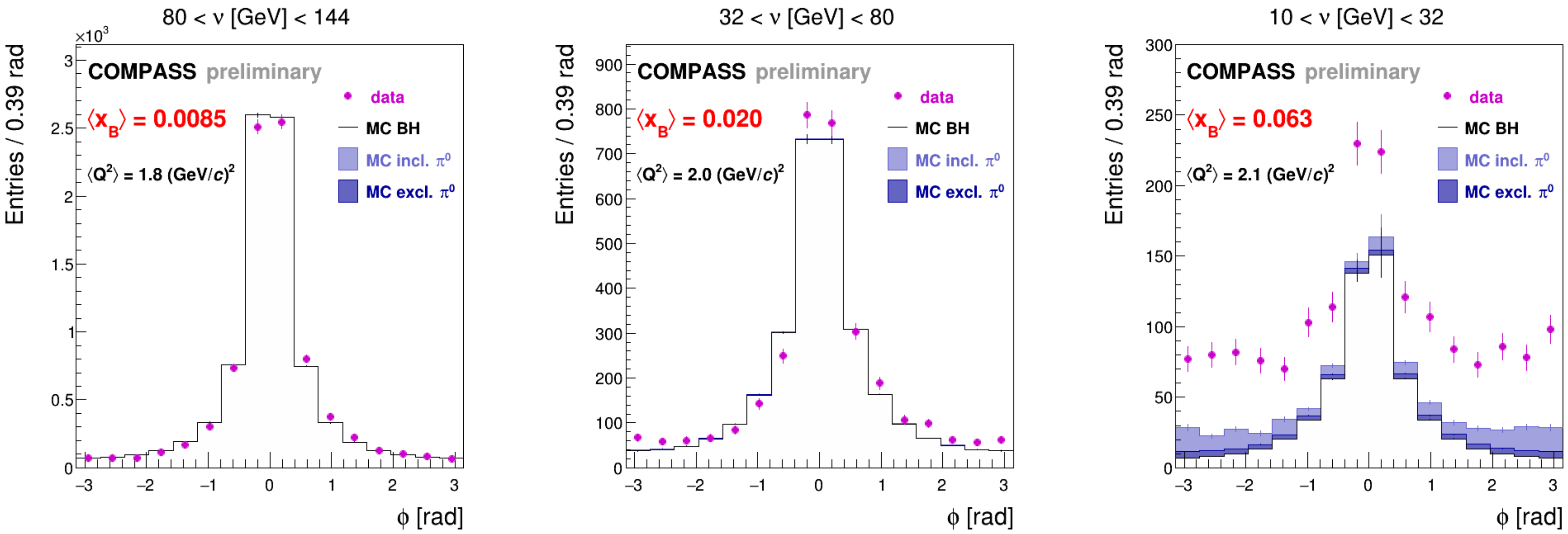
➢ **Invisible** (one γ lost) – estimated by MC

- **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

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

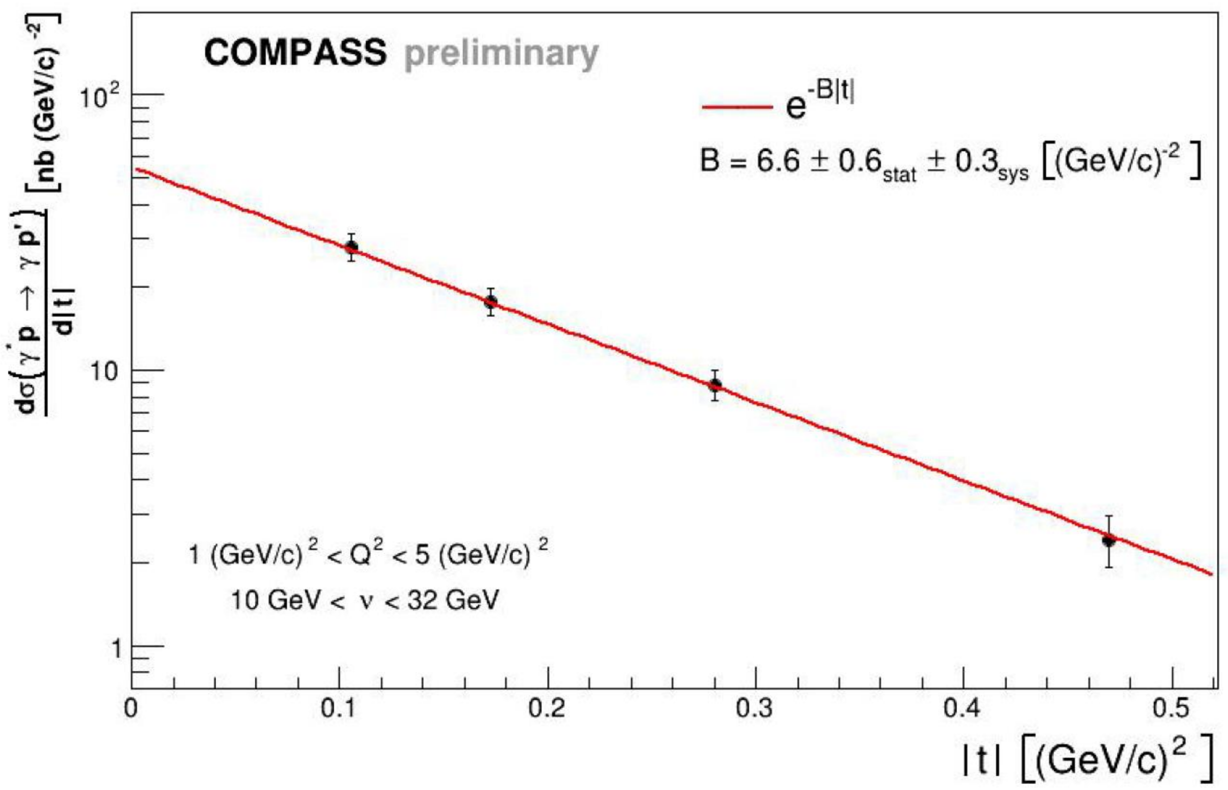
$$= 2[\, d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos\phi + c_2^{DVCS} \cos 2\phi + s_1^I \sin\phi + s_2^I \sin 2\phi \,]$$

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

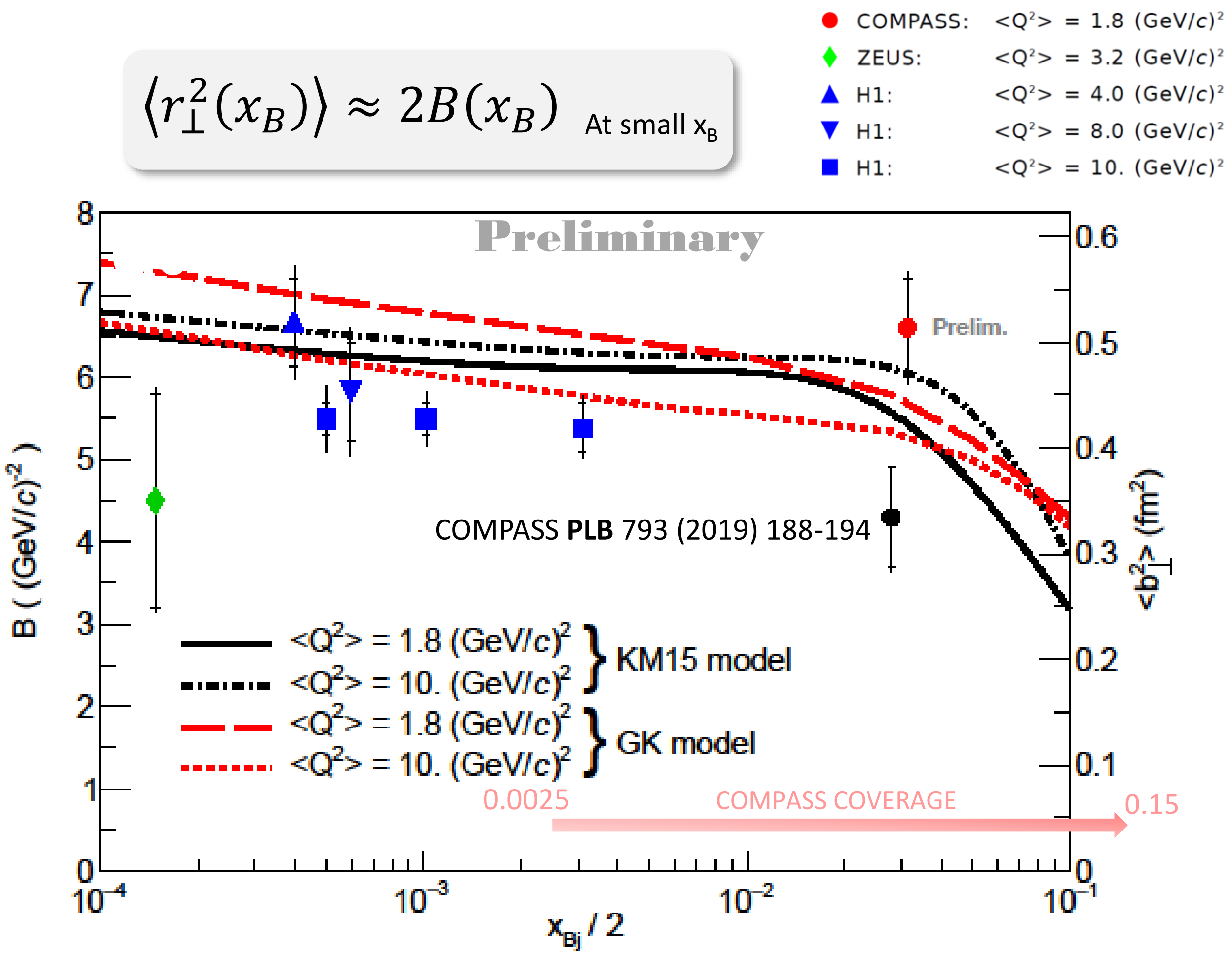
small x_{Bj} model dependent

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



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

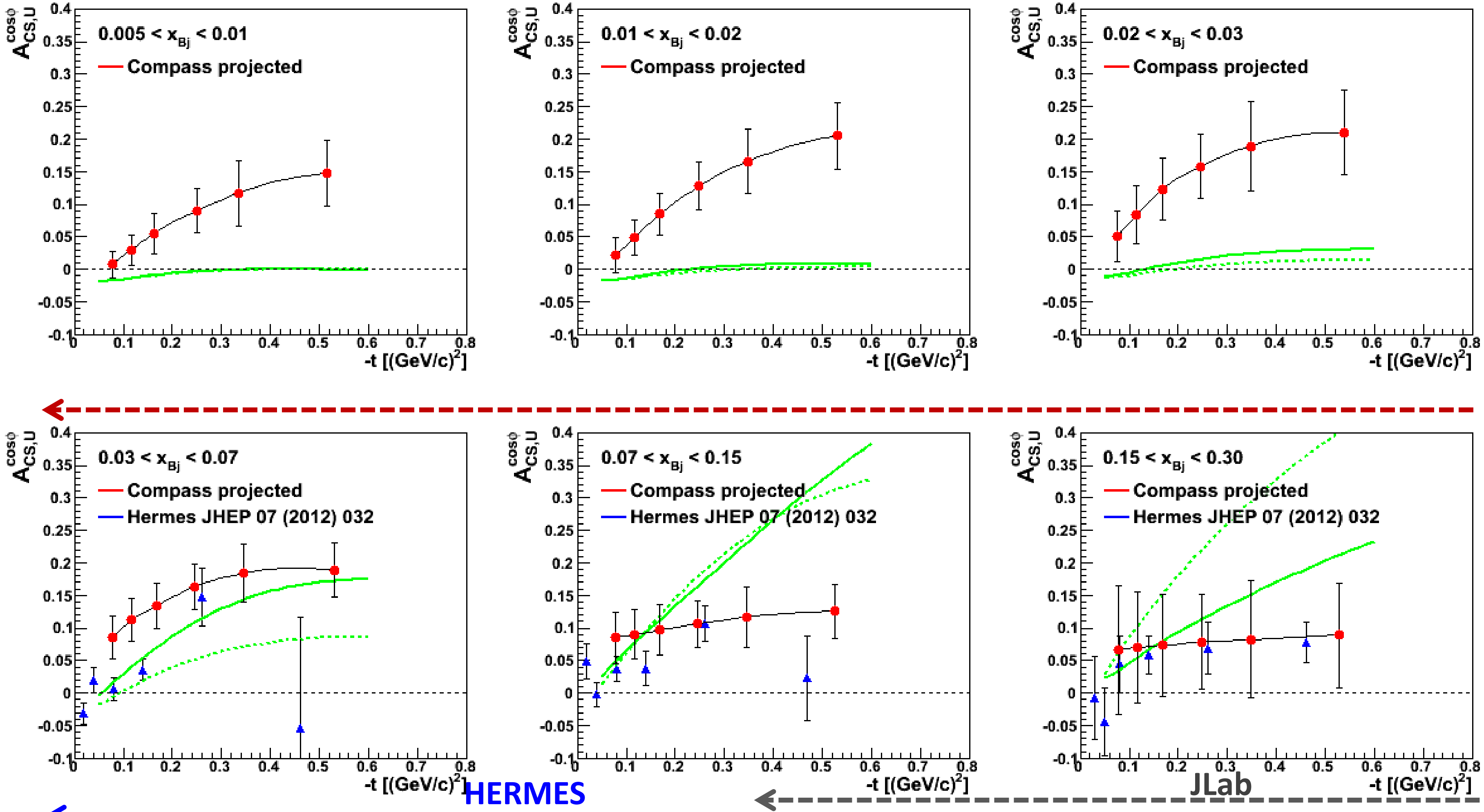
$c_1^I = \mathcal{R}e\, F_1 \mathcal{H}$

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

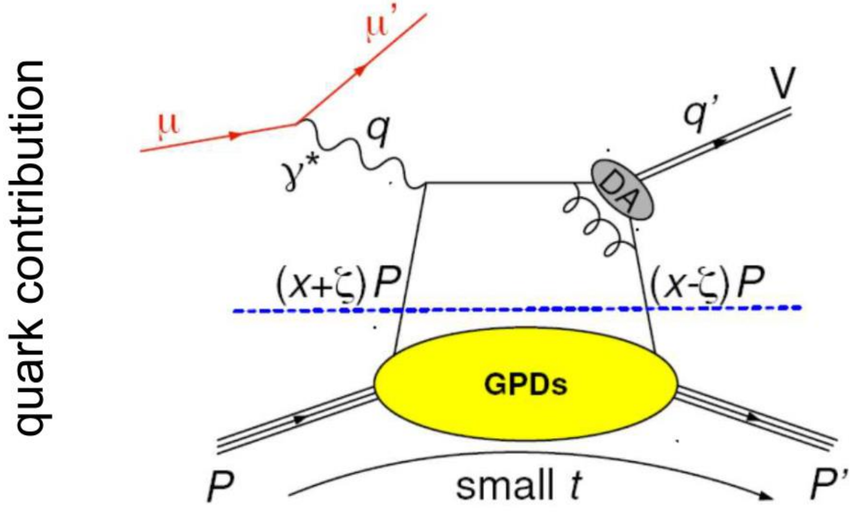
$\mathcal{R}e\,\mathcal{H}$ > 0 at H1
< 0 at HERMES
Value of x_{Bj} for the node?

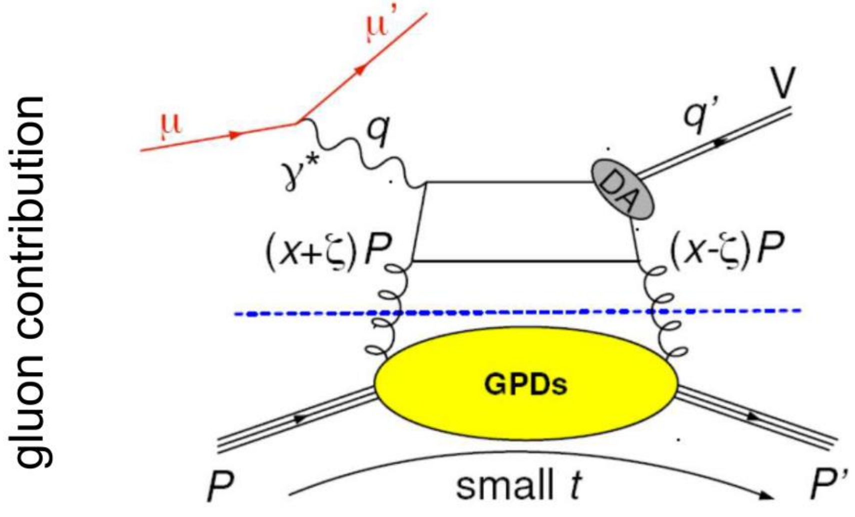


COMPASS 2 years of data Eμ= 160 GeV 1 < Q^2 < 8 GeV^2

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 or transversity GPDs: helicity of parton changed

(not possible in DVCS)

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

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

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

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

Exclusive π^0 Production on Unpolarized Proton

μ p → μ π^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

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

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

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

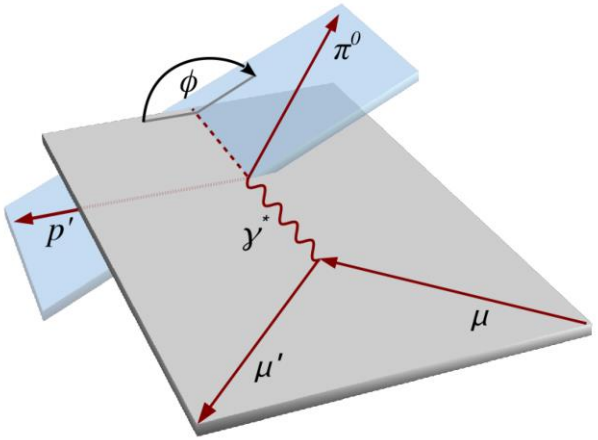
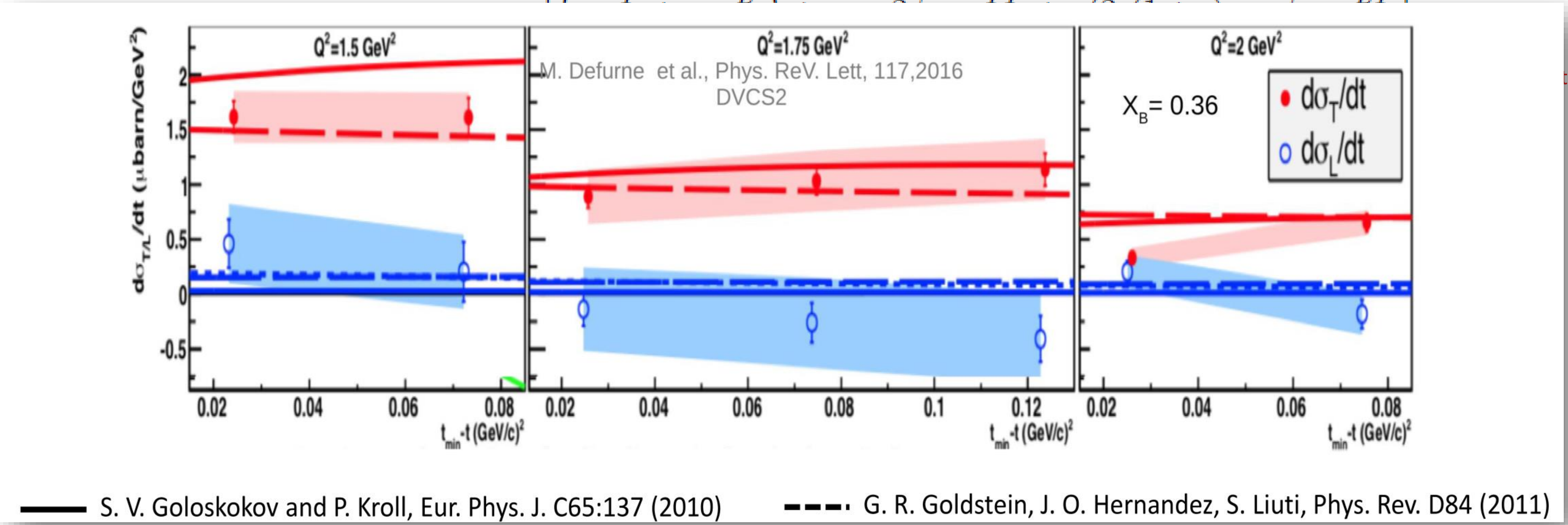


Fig: M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

Exclusive π^0 Production on Unpolarized Proton

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



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

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

Exclusive π^0 Production on Unpolarized Proton

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

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

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

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

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

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

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

A large contribution of $\bar{E}_T$ can be identified:
- **σ_{TT} measurement**
- **The dip at small |t| of σ_T**

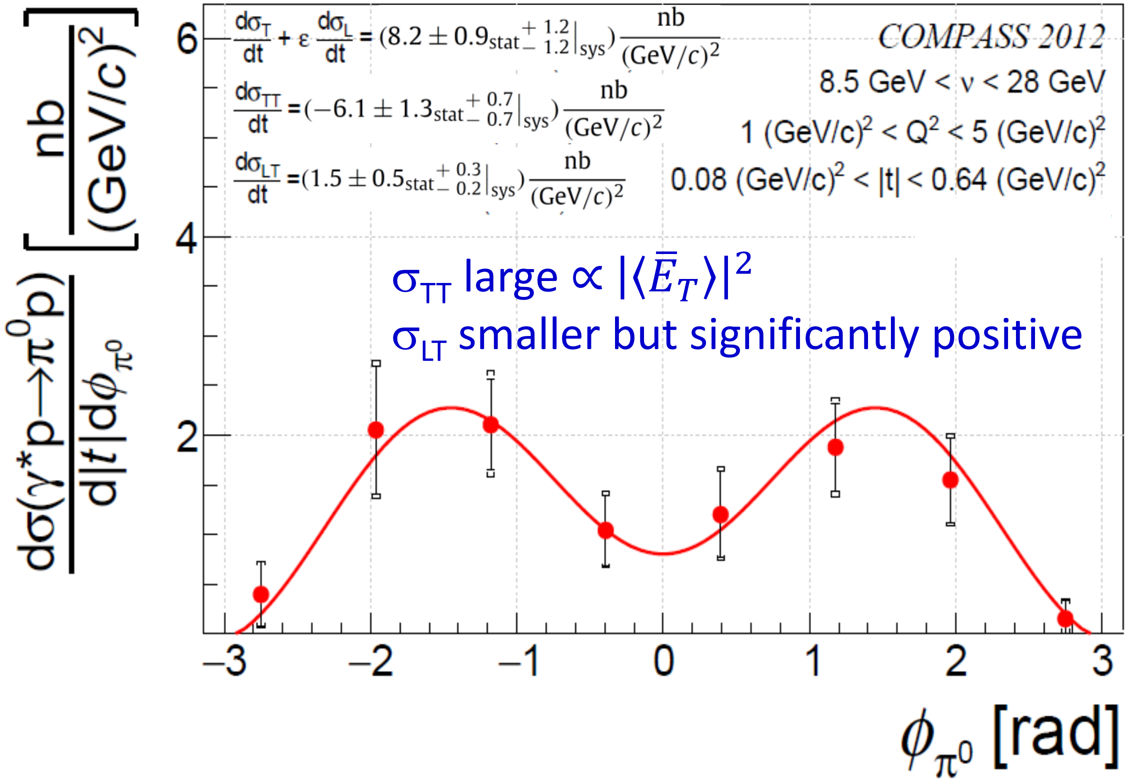
2012 Exclusive π^0 Prod. on Unpolarized Proton

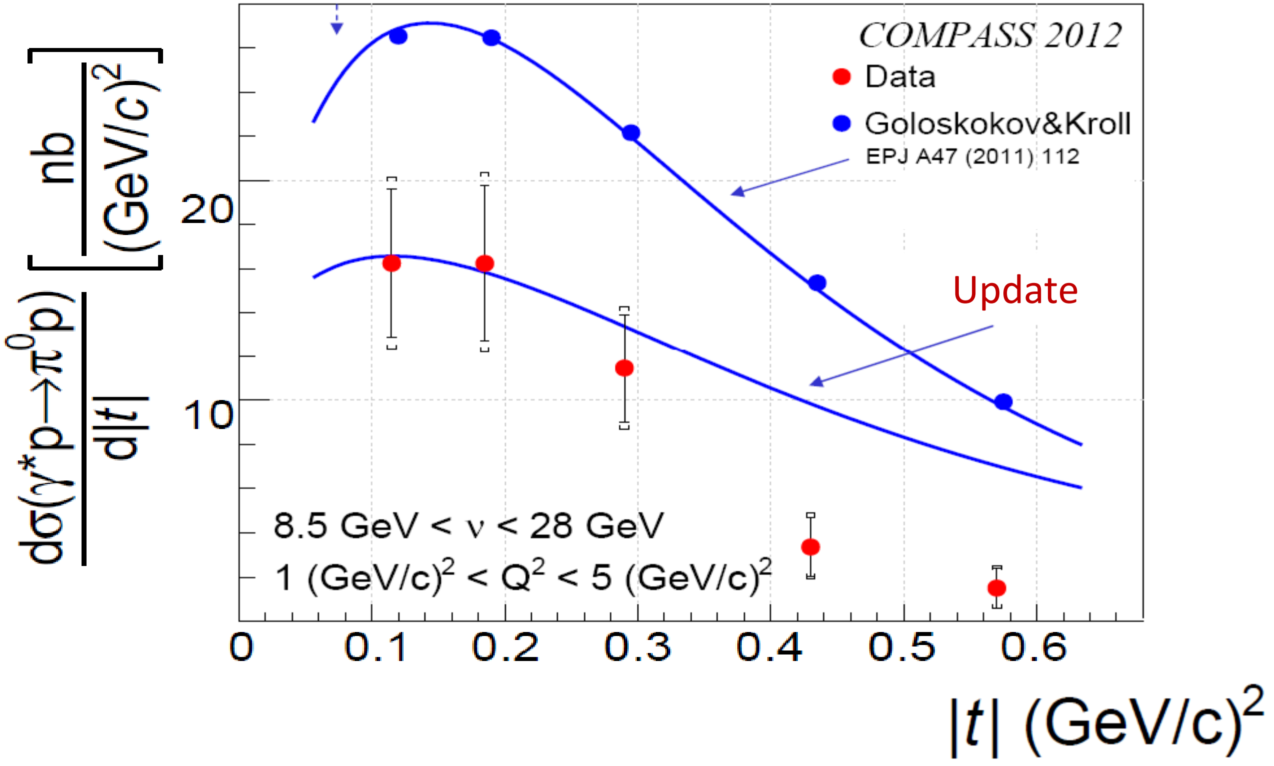
$\mu\, p \rightarrow \mu\, \pi^0\, p$

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

Chiral-odd GPDs

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

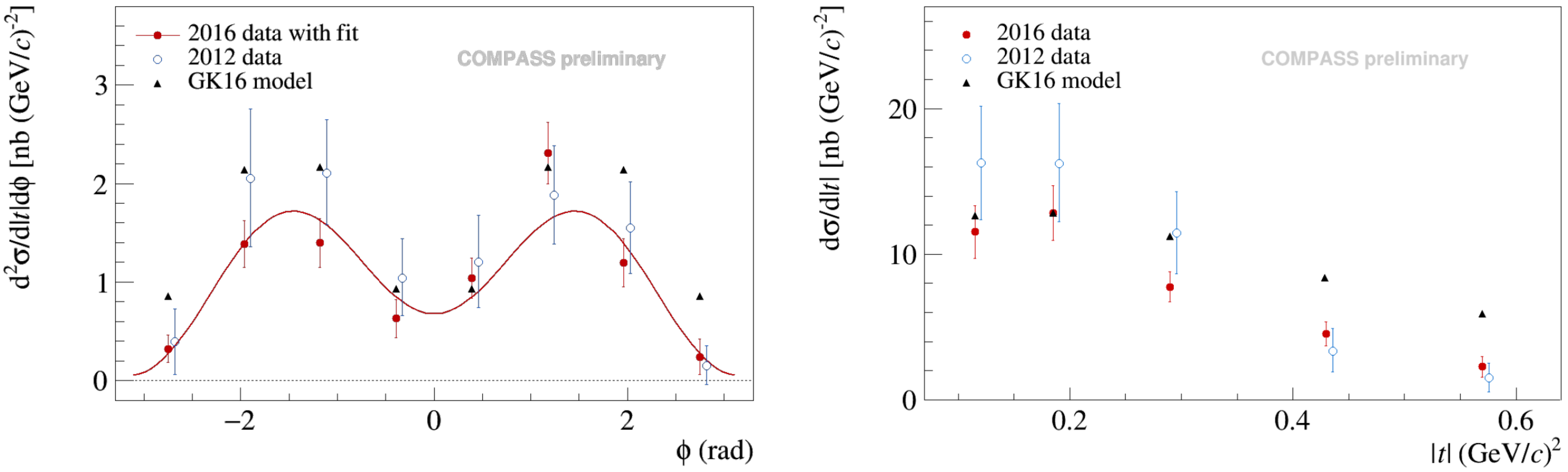




COMPASS, **PLB** 805 (2020) 135454

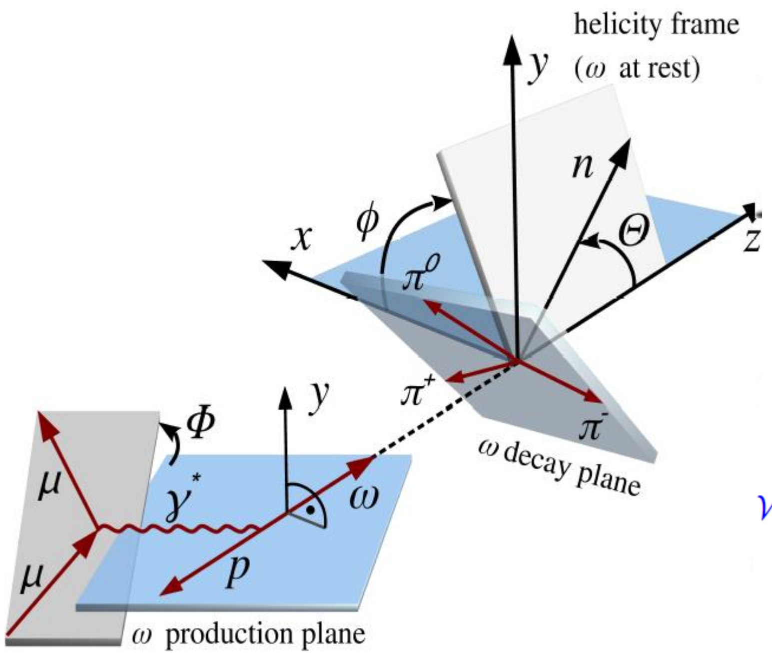
2016 Exclusive π^0 Prod. on Unpolarized Proton

- Preliminary results from 2016 data at low ξ ($\langle x_B \rangle = 0.0096$), with statistics about 2.3 times larger than the published 2012 pilot run.
- New inputs for phenomenological models.



- The whole collected 2016/2017 statistics ~ 9 times larger than the 2012 data → heading towards publication using the whole dataset.

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 $\mathcal{W}^L$

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

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

- $\epsilon \to 1$, 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

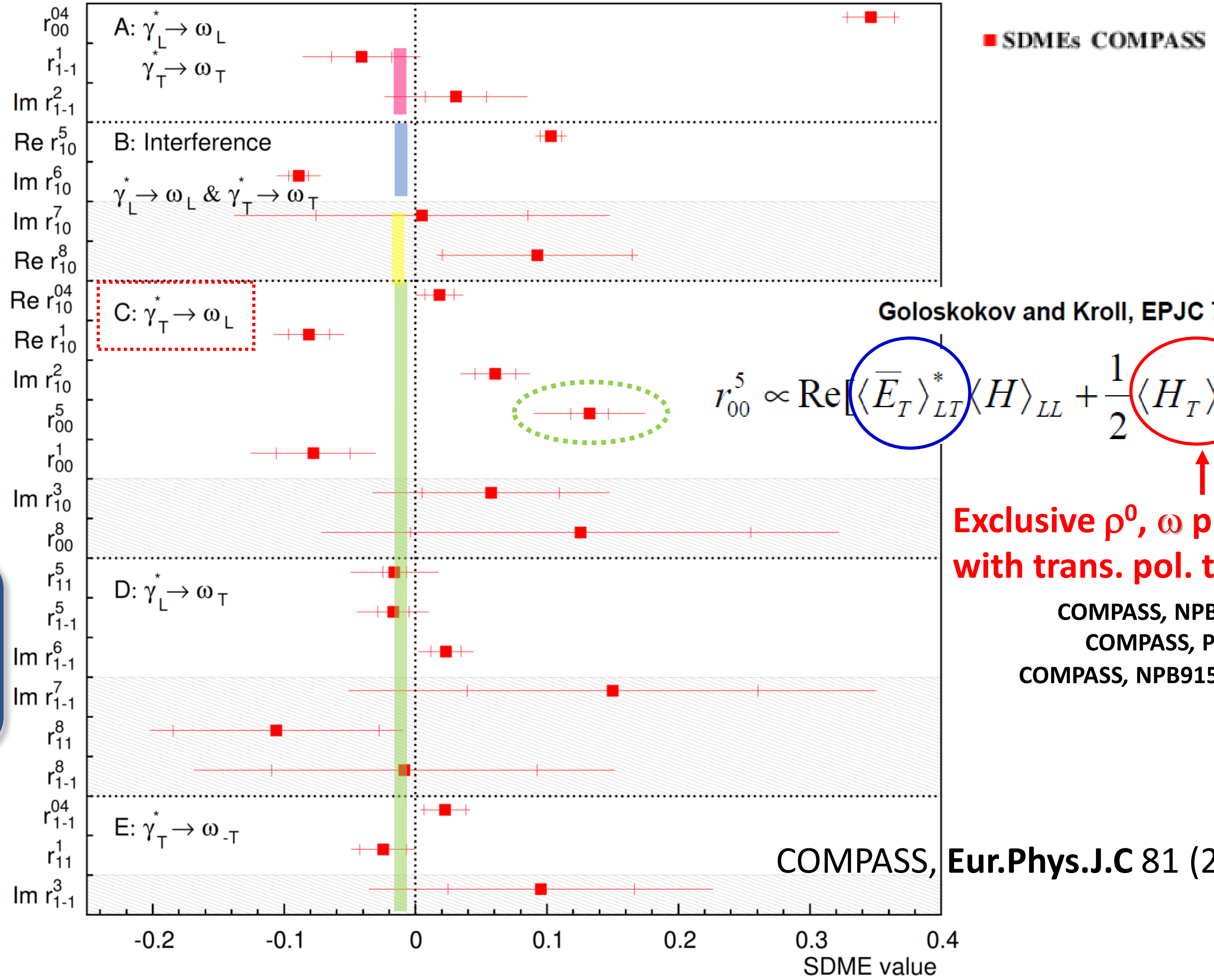
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

= - 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 $\gamma^*_T \to \omega_L$



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 ρ^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

2012 Exclusive ρ^0 Prod. on Unpolarized Proton

SCHC ($\lambda_\gamma = \lambda_V$)
(S-Channel Helicity Conservation)

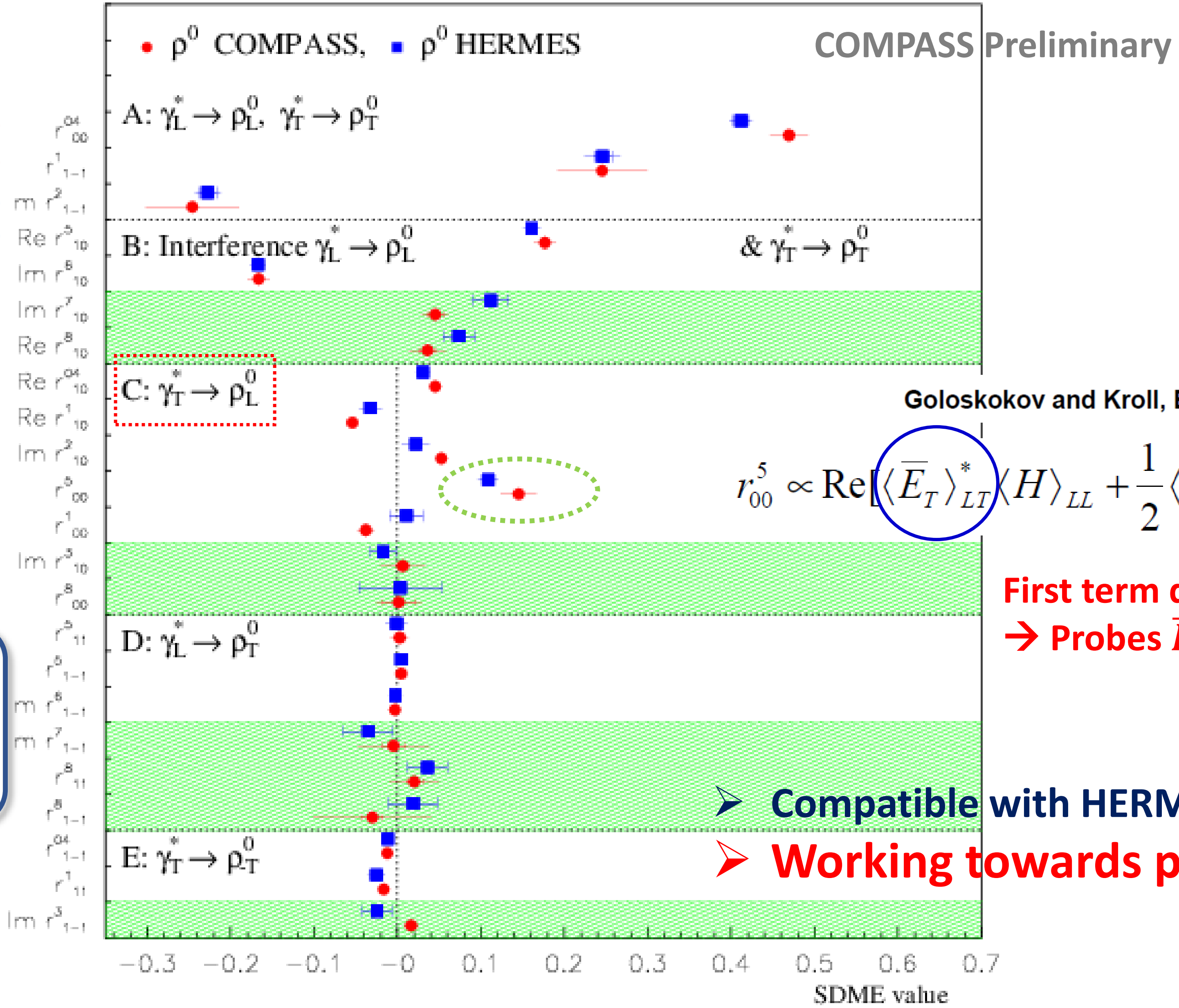
SCHC implies:

- $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$ **OK**
- $\mathrm{Re}\, r^5_{10} + \mathrm{Im}^6_{10} = 0$ **OK**
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$ ✓**OK**

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

for $\gamma^*_L \to \rho^0_T$ and $\gamma^*_T \to \rho^0_{-T}$ 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 $\bar{E}_T$

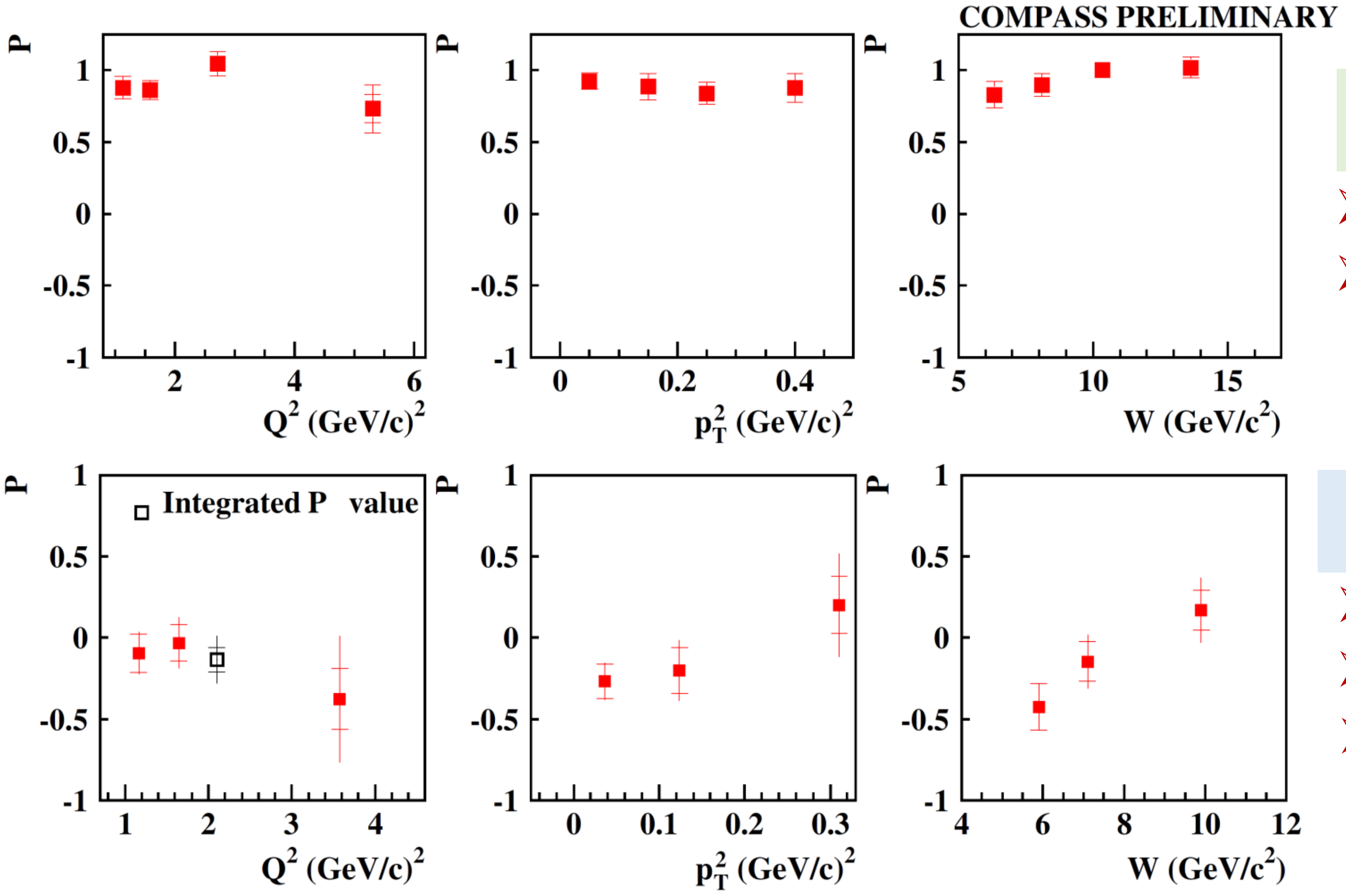
- Compatible with HERMES
- **Working towards publication!**

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 $\gamma^{*}_{T} \to V_{T}$

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



ρ^0

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

ω

- **NPE $\approx$ UPE on average**
- **UPE Dominance at small W and p_T^2**
- **UPE → GPDs $\tilde{E}, \tilde{H}$**
  + Pion pole (dominant)

Summary and Outlook

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

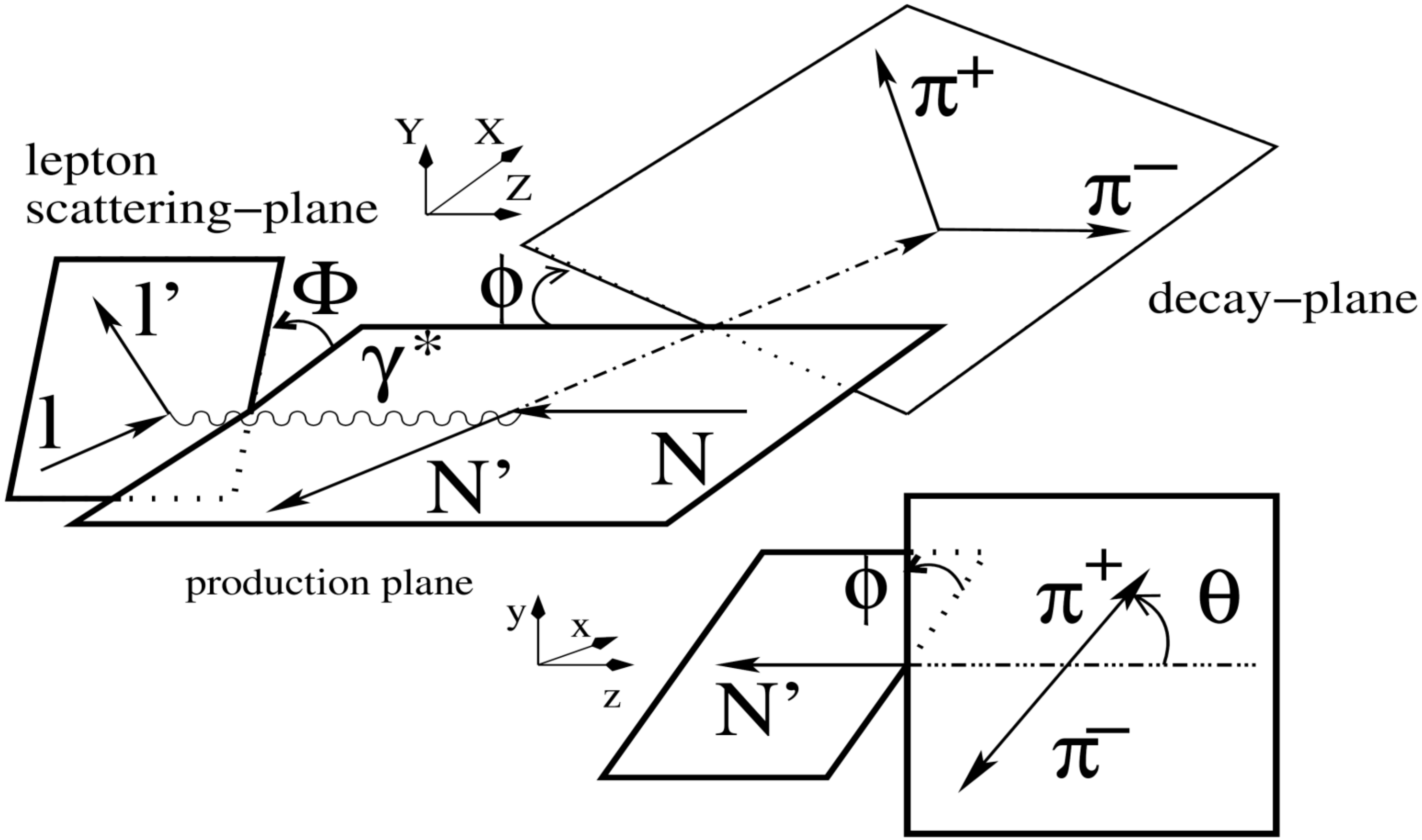
HEMP of π^0, ρ, ω, ϕ, J/ψ

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

On-going analysis on 2016-17 data.

Backup Slides

Exclusive ρ^0 Production on Unpolarized Proton



COMPASS^{++}/AMBER

A new QCD facility
at the M2 beam line of the CERN SPS

- Unique beam line with polarised $\mu^{\pm}$ and high-intensity **Pion** beam
- Possible high-intensity **antiproton** and **Kaon** beams, provided by RF-separation technique
- With upgraded apparatus

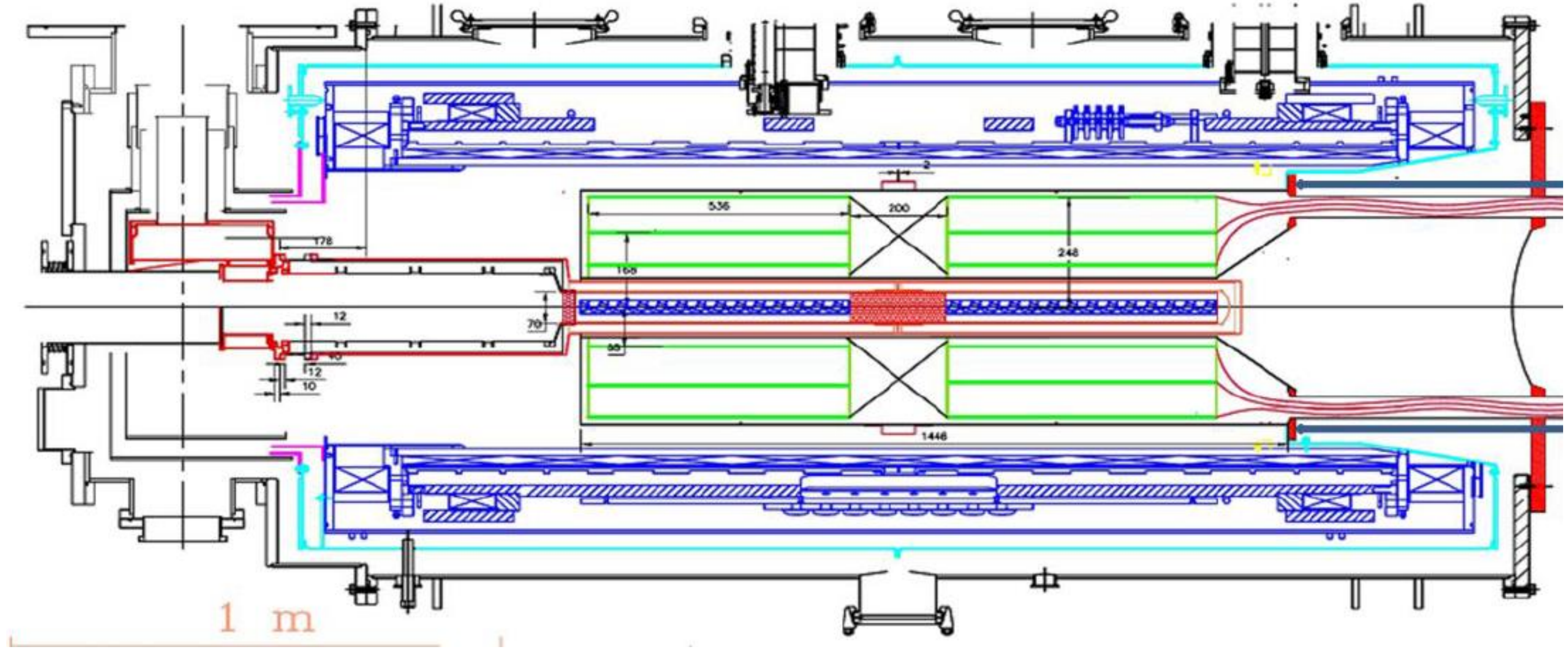
Proposed physics goals

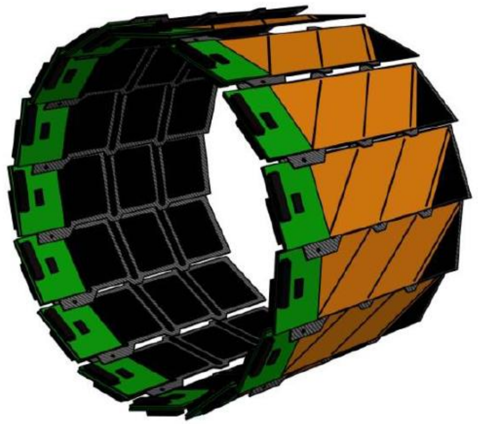
Proton Radius
Meson PDF – gluon PDF
Proton spin structure
3D imaging (TMDs and GPDs)
Hadron spectroscopy
Anti-matter cross section

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware Additions
μp elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^{\pm}$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^{\pm}$	$NH_3^{\uparrow}$	2022 2 years	recoil silicon, modified PT magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
$\overline{p}$-induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^{\pm}$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^{\pm}, \overline{p}$	$NH_3^{\uparrow}$, C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisability & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^{\pm}$ $\pi^{\pm}$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^{\pm}, \pi^{\pm}$	from H to Pb	2026 1 year	

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

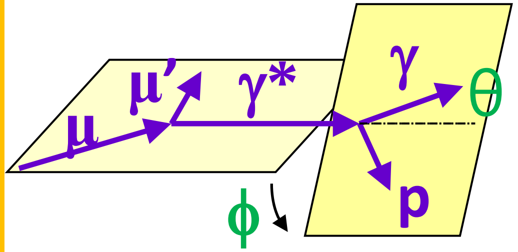
No possibility for ToF ➔ PID of p/π with dE/dx
Momentum and trajectory measurments
$|t|_{min} \sim 0.1$ GeV

ϕ Dep. of BH+DVCS with Unpol Target

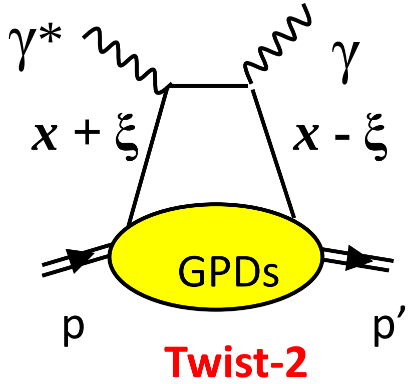
$$\frac{d^4\sigma(\ell p \to \ell p \gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + \left(d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}\right) + \left(e_\ell \mathrm{Re}\, I + e_\ell P_\ell\, \mathrm{Im}\, I\right)$$

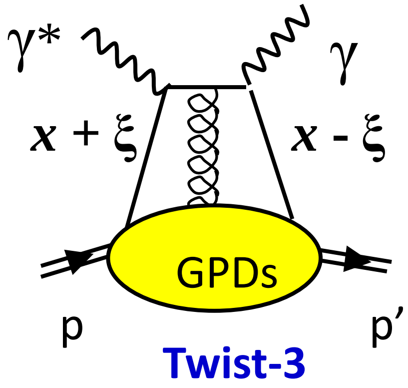
Well known

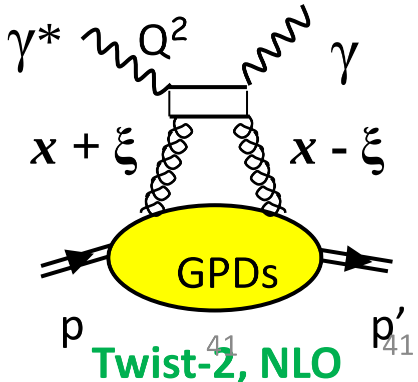
e-	μ±			
Σ	Σ	$d\sigma^{BH}$	$\propto$	$c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$
Σ	Σ	$d\sigma^{DVCS}_{unpol}$	$\propto$	$c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$
Δ	Δ	$d\sigma^{DVCS}_{pol}$	$\propto$	$s_1^{DVCS}\sin\phi$
Σ	Δ	$\mathrm{Re}\, I$	$\propto$	$c_0^I + c_1^I\cos\phi + c_2^I\cos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



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







$s_1^I = Im\ \mathcal{F}$

$c_1^I = Re\ \mathcal{F}$

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

$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2}\mathcal{E}\mathcal{E}^* \xrightarrow{\text{at small } x_B} 4\ (Im\ \mathcal{H})^2$$