DVCS and HEMP at COMPASS experiment for GPD studies

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On behalf of COMPASS Collaboration

Outline

- Physics motivations
- GPD, DVCS, HEMP
- COMPASS at CERN
- DVCS measurements at COMPASS
- 2016 data for exclusive photon production
- 2012-16 data Transverse extension of partons
- GPD and HEMP
- Transverse-target spin asymmetries in HEMP of ρ and ω
- SDMEs in HEMP of ρ and ω
- Exclusive π^0 production cross section
- Summary

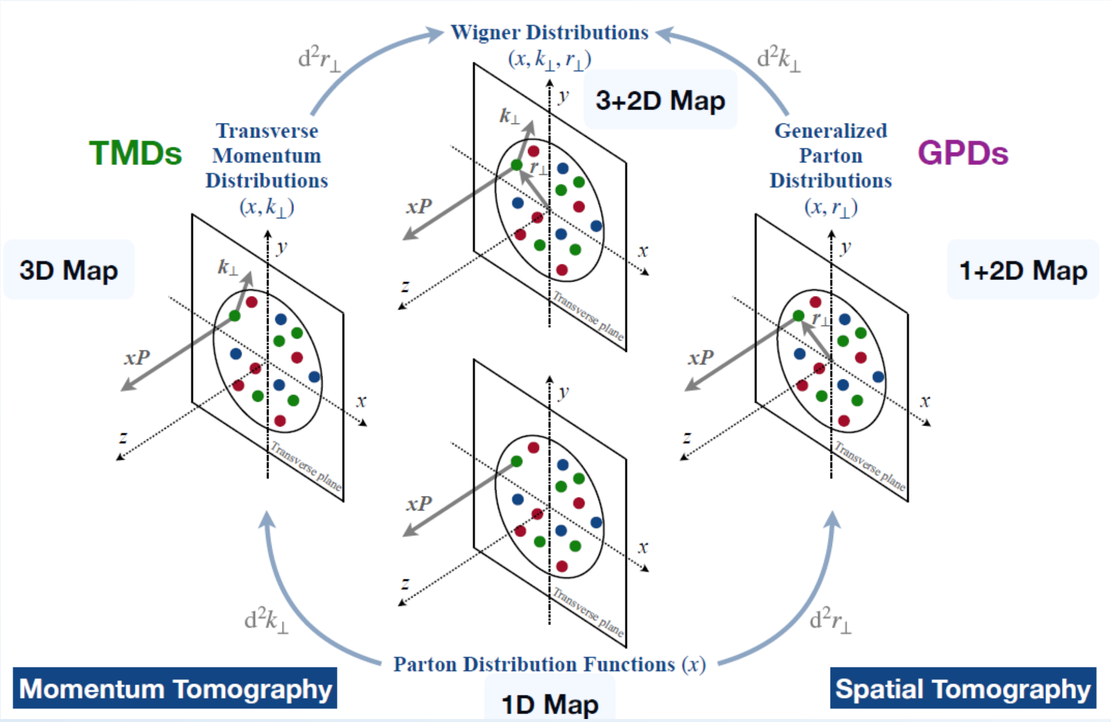
Physics motivations

We are interested in ;

- How are hadrons made up with the partons?
- What is the origin of nucleon spin?
- How is the nucleon spin made up with parton's spin and OAMs? (Spin puzzle)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- How is the nucleon spin correlated with the motion of partons?
- What is the relation between Bjorken-x and the transverse position of the partons?
- How does the spin influence the position distribution?



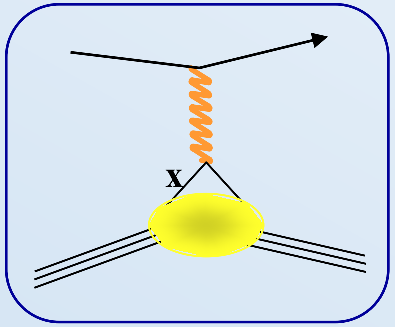
courtesy of Yu-Hsiang Lien, COMPASS (DIS2021)

One of the key concepts to solve the problems is the Generalized Parton Distributions (GPDs)

Generalized Parton Distributions

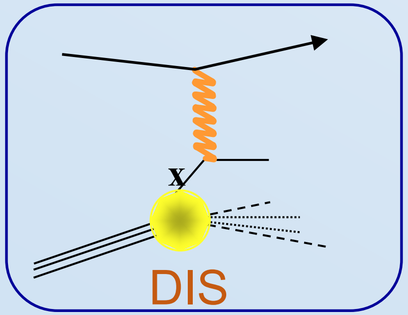
GPD is important concept merging the Form Factor (FF) and the PDF

- Form Factor probes transverse position of partons



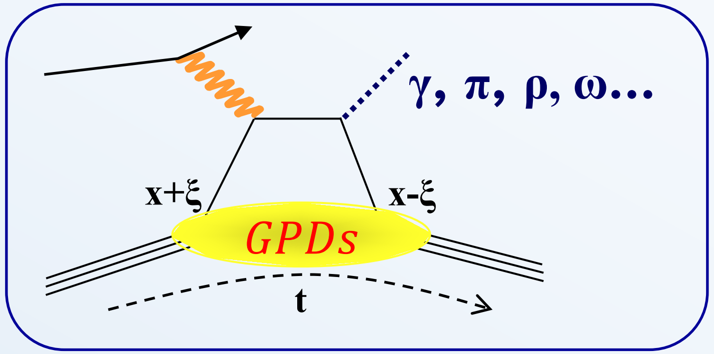
elastic scattering

- PDF probes longitudinal parton momentum (x)



DIS

- GPD provides correlation between x and the position of the partons



hard exclusive productions

- forward limit gives PDF,

$$H(x,0,0) = q(x)$$

- moments of GPDs are form factors, e.g.

$$\int dx\, H(x,\xi,t) = F_1(t)$$

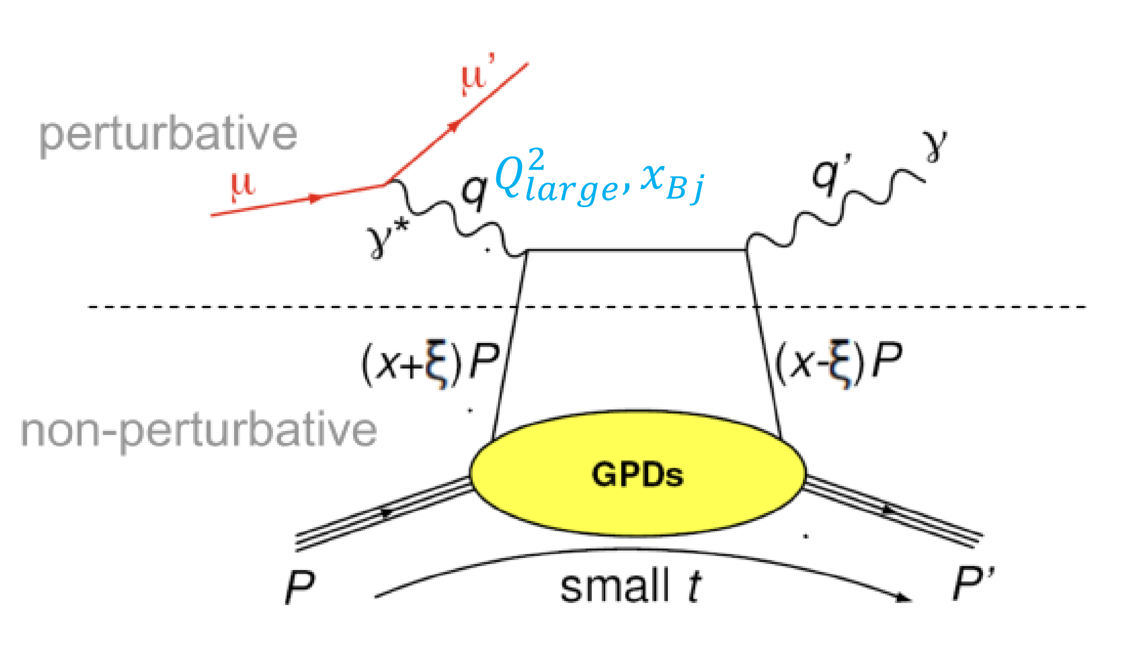
- impact-parameter representation:

$$q_f(x,b_\perp) = \frac{1}{(2\pi)^2}\int d^2\Delta_\perp e^{-ib_\perp\cdot\Delta_\perp} H^f(x,0,-\Delta_\perp)$$

- Ji's sum rule :

$$J_f = \frac{1}{2}\int_{-1}^{1} dxx\left[H^f(x,0,t\to 0) + E^f(x,,t\to 0)\right]$$

Deeply Virtual Compton Scattering (DVCS)



- $q = (p_\mu - p_{\mu'})$: 4-momentum of virtual photon
- $Q^2 = -q^2$: virtual photon virtuality
- $t = (p_P - p_{P'})^2$: 4-momentum transfer to nucleon squared
- x: average longitudinal momentum fraction
- ξ: half of longitudinal momentum fraction transfer

DVCS: most simple reaction in order to study GPDs

4 (chiral-even) GPDs for each quark flavor in LO and leading twist

No Nucleon spin flip	With Nucleon spin flip
$H^q(x,\xi,t)$	$E^q(x,\xi,t)$
$\tilde{H}^q(x,\xi,t)$	$\tilde{E}^q(x,\xi,t)$

- **skewness** $\xi \simeq x_B/(2-x_B)$ in Bjorken limit (Q^2 large & x_B, t fixed)

Transverse imaging and Pressure distribution with GPD

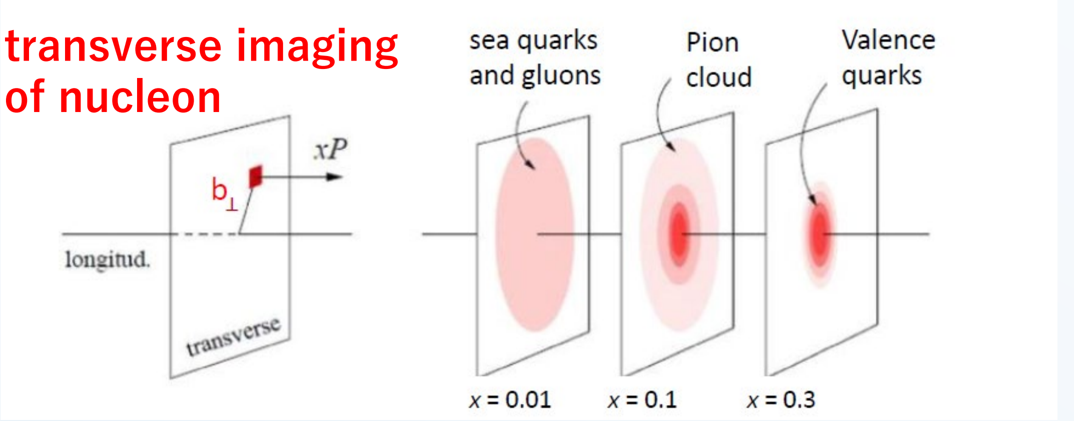
In experiments, GPD is accessed through
Compton Form Factor (CFF):

CFF convolution hard process ⊗ GPD

GPD

$$\mathcal{H}(\xi,t)=\sum_f e_f^2 \int_{-1}^{+1} dx \left\{\frac{1}{\xi-x-i\varepsilon}-\frac{1}{\xi+x-i\varepsilon}\right\} H^f(x,\xi,t)$$

t, ξ *fixed*



with complex integration

Imaginary part

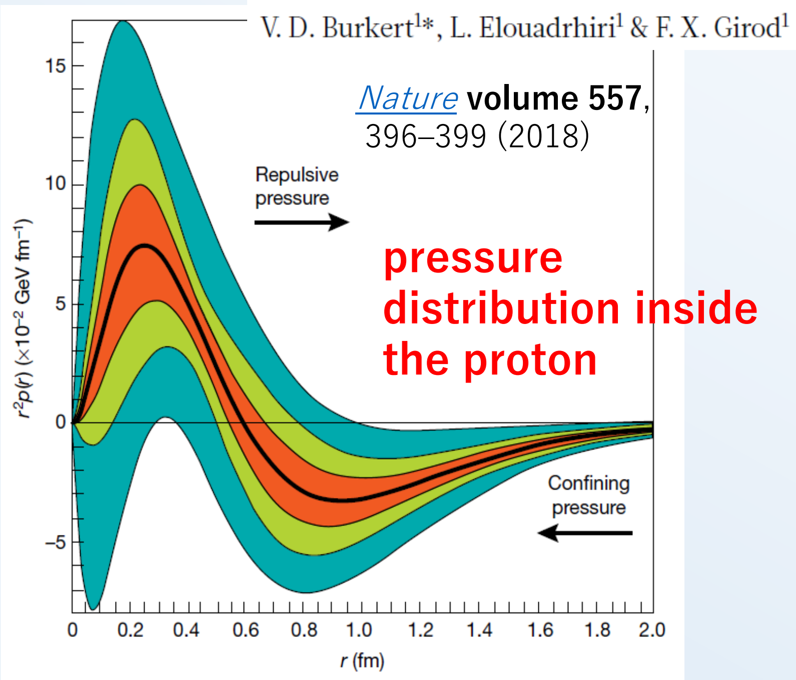
$$\mathcal{Jm}\mathcal{H}(\xi,t) = \sum_f e_f^2\, \pi[H^f(x=+\xi,\xi,t) - H^f(x=-\xi,\xi,t)]$$

Real part

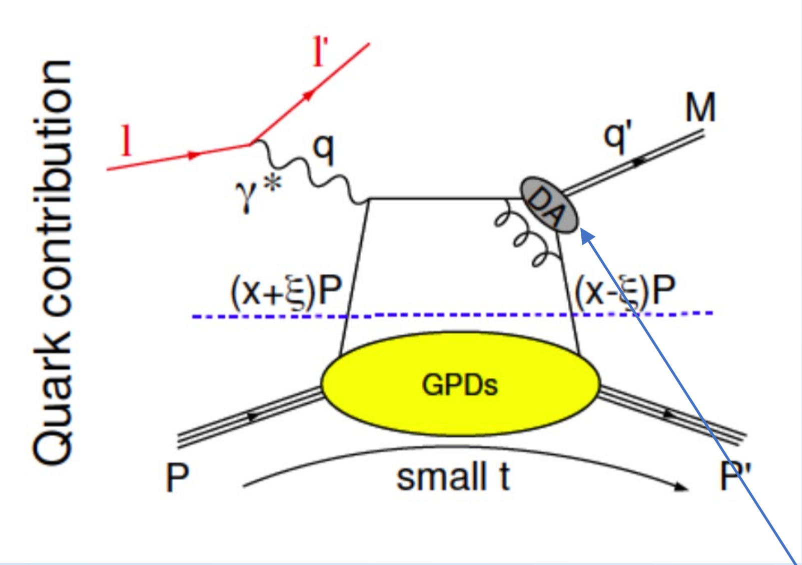
$$\mathcal{Re}\mathcal{H}(\xi,t) = \sum_f e_f^2\, \mathcal{P} \int_{-1}^{+1} dx \left[\frac{1}{x-\xi} - \frac{1}{x+\xi}\right] H^f(x,\xi,t)$$

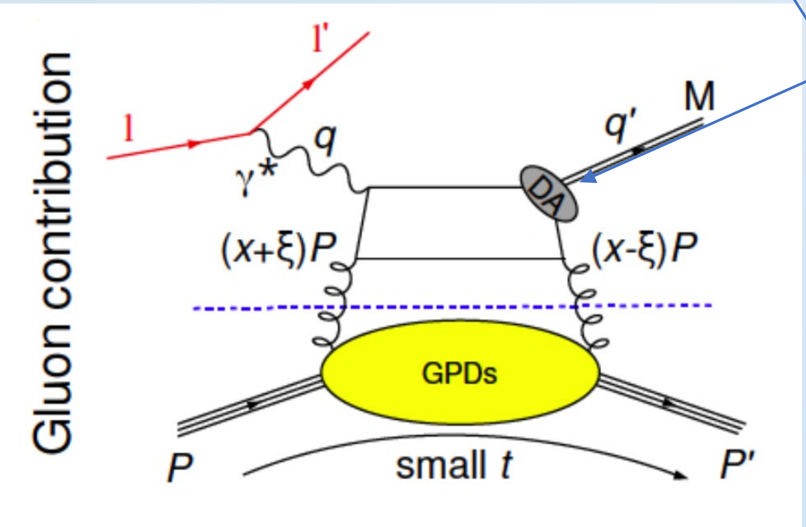
dispersion relation

$$\mathcal{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{+1} dx \left\{\frac{1}{\xi-x}-\frac{1}{\xi+x}\right\} \mathcal{Jm}\mathcal{H}(\xi,t) + D(t)$$



Hard Exclusive Meson Production （HEMP)





- HEMP is alternatively important in GPD studies
- take account of the meson structure
- HEMP allows to give chiral-odd GPDs

$$H_T\ ,\ E_T\ ,\ \tilde{E}_T \text{ and } \bar{E}_T \equiv 2\tilde{H}_T + E_T$$

- Sensitive to gluon GPDs (same order in α_s)

Diehl, Vinnikov, Phys. Lett. B 609 (2005) 286

- Provide different flavor combinations for different mesons

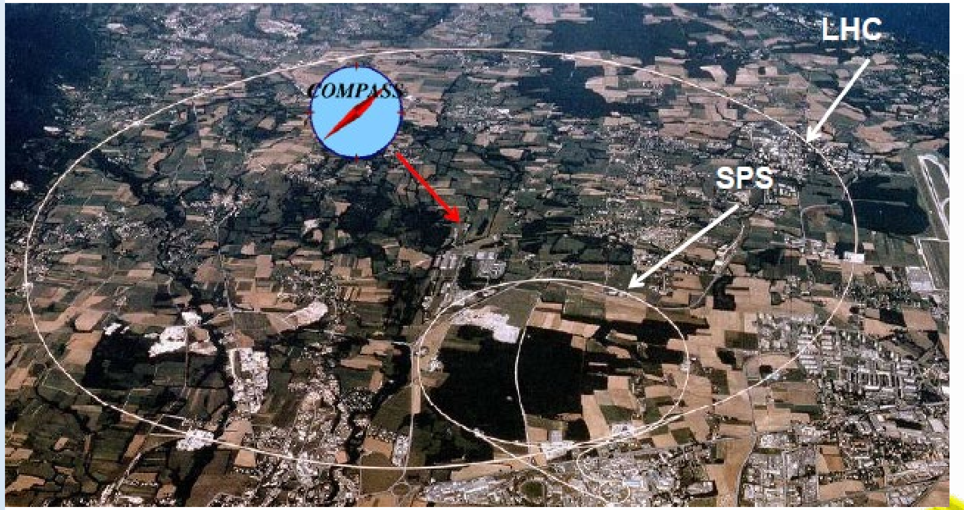
Distribution Amplitude:

structure of the meson

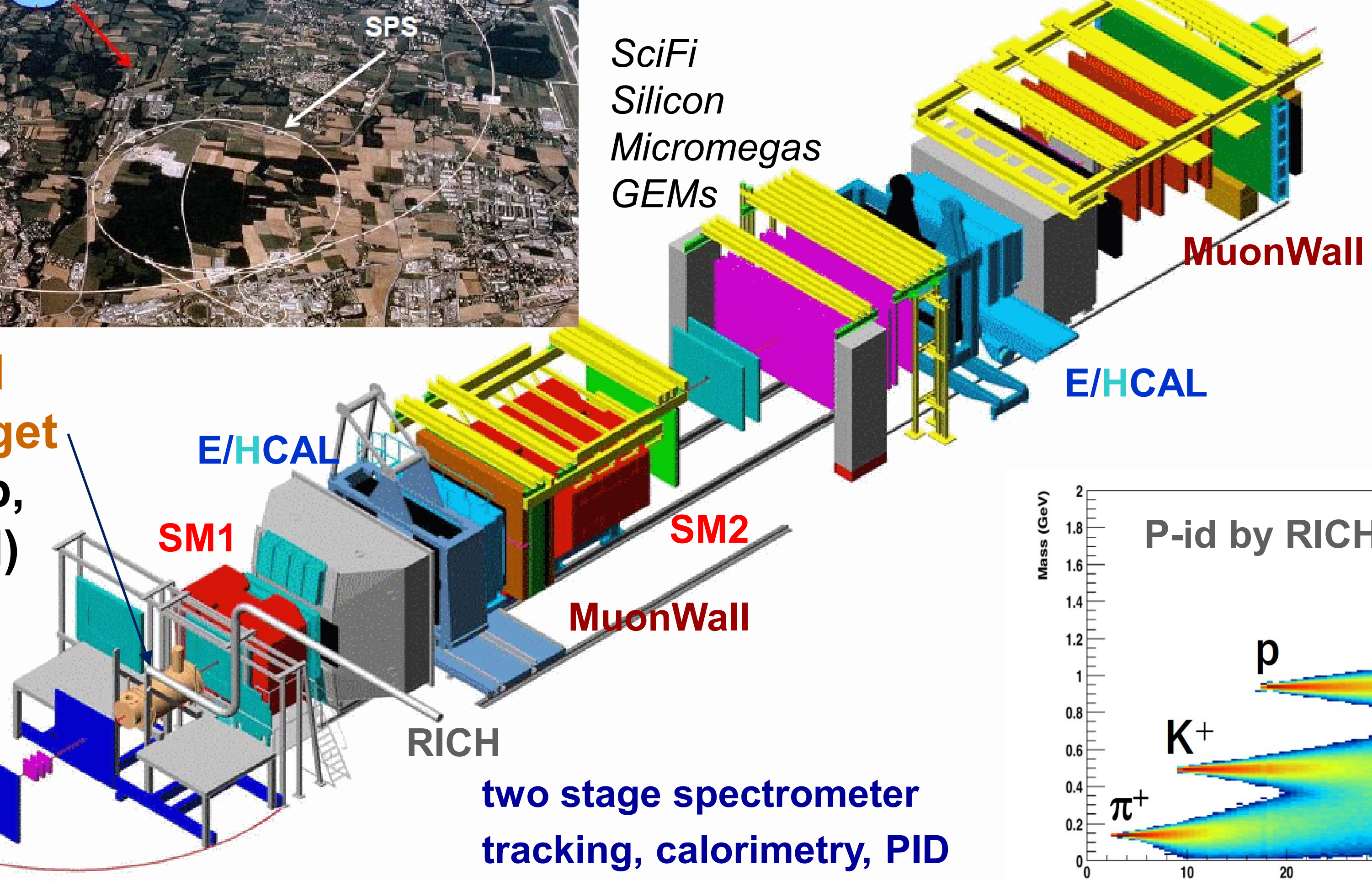
- We look at transverse-spin asymmetries, spin-density matrix elements for exclusive vector meson production, and cross section for exclusive π^0 production

COMPASS

COMPASS at CERN



data taking: 2002-2022

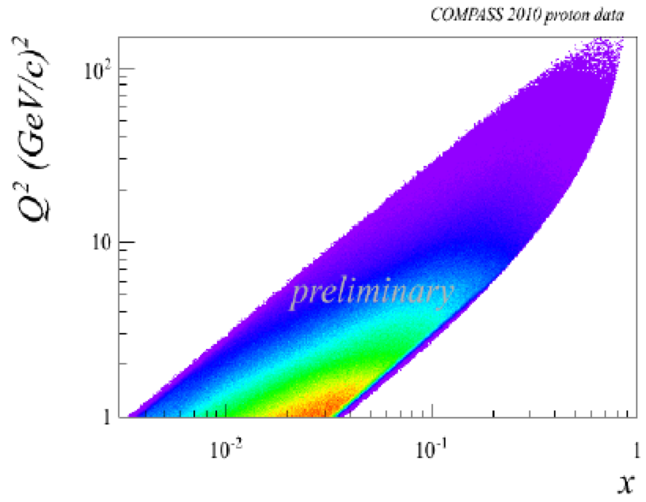


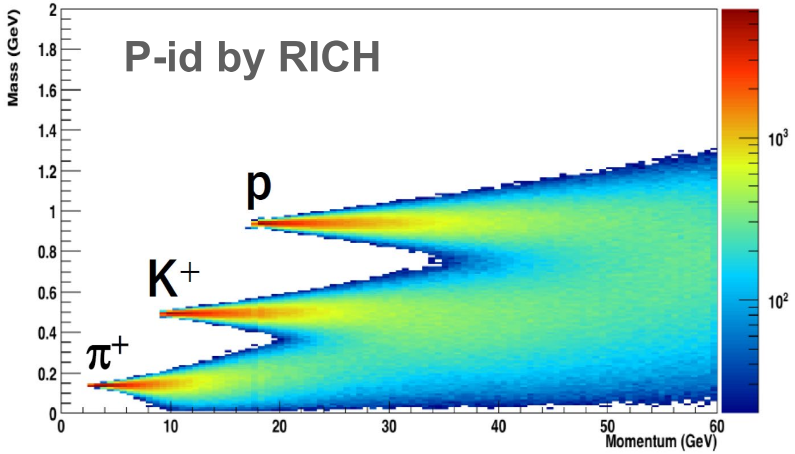
Polarised solid Target (NH_3 for p, ^{6}LiD for d)

Pol. μ beam fom SPS 160-200 GeV, pol. = 80%

two stage spectrometer

tracking, calorimetry, PID





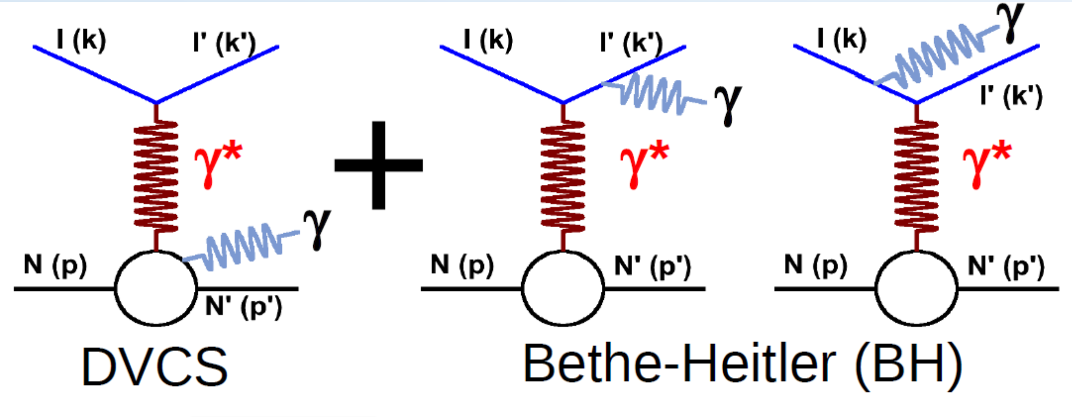
DVCS

DVCS measurements @ COMPASS

- study exclusive photon production for DVCS

$$\mu + p \to \mu' + p' + \gamma$$

- Bethe-Heitler(BH) process also gives the same final state



$$\sigma(\mu p \to \mu' p' \gamma) = \sigma_{DVCS} + \sigma_{BH} + \sigma_{Int.}$$

Dedicated data taking for DVCS (and HEMP)

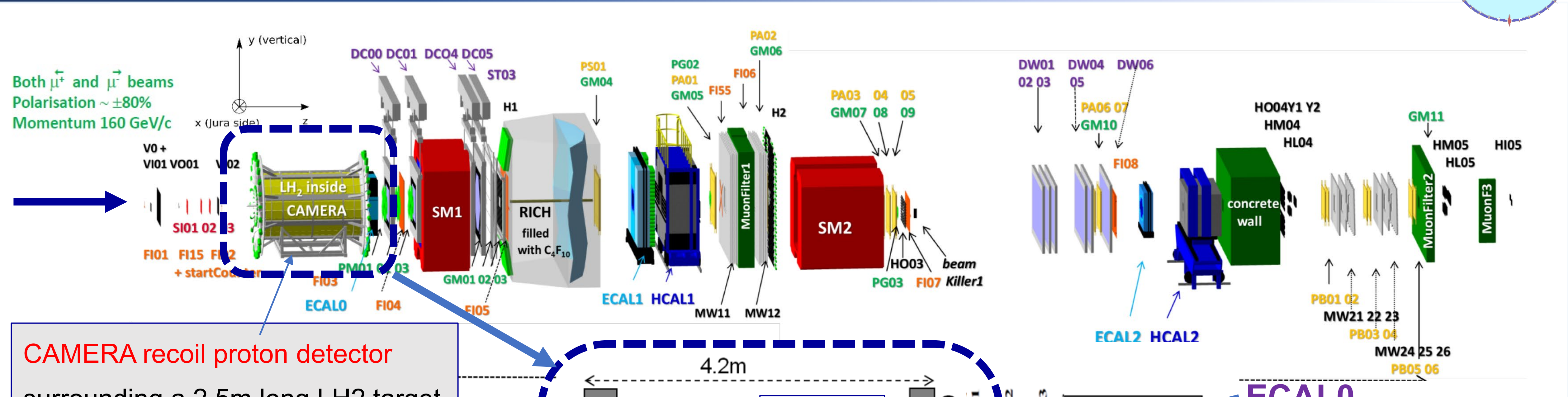
- 2012 pilot run for 4 weeks

  → Analysis finished and published

- Long runs in 2016/17
  - 2x6 months

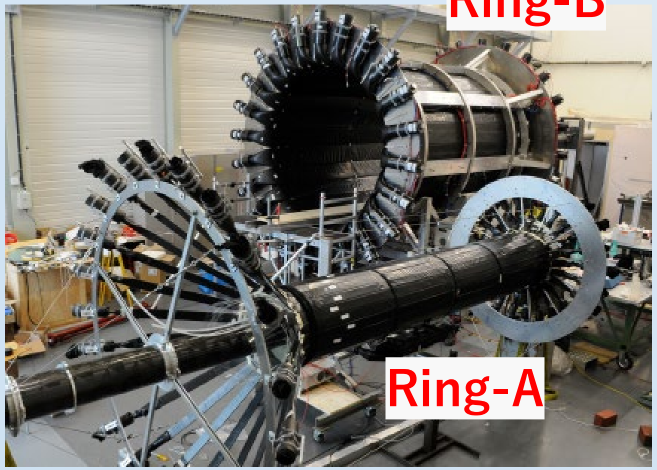
    2016+2017 statistics: 9x 2012
  - Analysis on going → preliminary results
- 2016 data will be presented in this talk

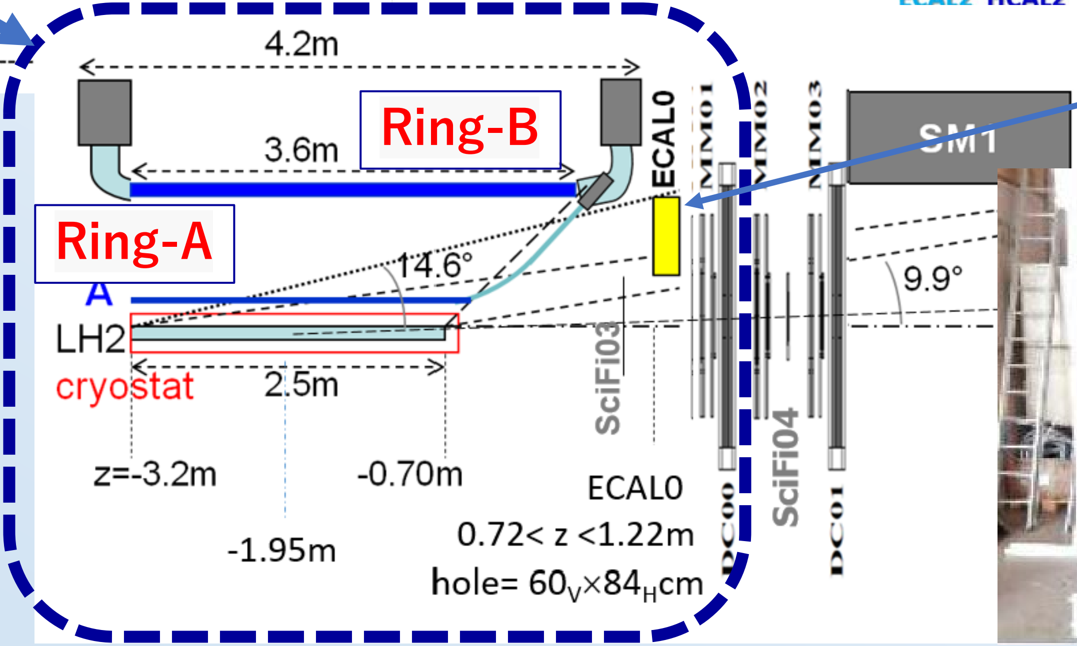
Dedicated Setup for DVCS & HEMP @ COMPASS



CAMERA recoil proton detector

surrounding a 2.5m long LH2 target





ECAL0
Shashalyk, 2200 ch.

Access to CFFs @ COMPASS

opposite charge and spin states for μ-beam

160GeV $\mu^{+\leftarrow}$ & $\mu^{-\rightarrow}$

spin charge

$$d\sigma = d\sigma_{UU}^{BH} + \left(d\sigma_{UU}^{DVCS} + P_\mu d\sigma_{LU}^{DVCS}\right) + e_\mu \left(d\sigma_{UU}^{\mathcal{I}} + P_\mu d\sigma_{LU}^{\mathcal{I}}\right)$$

[1] beam charge & spin sum

$$\mathcal{S}_{CS,U} = d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2\left(d\sigma_{UU}^{BH} + d\sigma_{UU}^{DVCS} - |P_\mu| d\sigma_{LU}^{\mathcal{I}}\right)$$

easier, to be done first

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

$$s_1^{\mathcal{I}} \propto \mathrm{Im}\,(F_1\mathcal{H})$$

in the COMPASS kinematics

small x_B and $|t|$, for proton target ($F_1 > F_2$)

[2] beam charge & spin difference

$$\mathcal{D}_{CS,U} = d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}} = 2\left(-|P_\mu| d\sigma_{LU}^{DVCS} + |e_\mu| d\sigma_{LU}^{\mathcal{I}}\right)$$

BH cancels

challenging, but promising

$$c_0^{\mathcal{I}}, c_1^{\mathcal{I}} \propto \mathrm{Re}\,(F_1\mathcal{H})$$

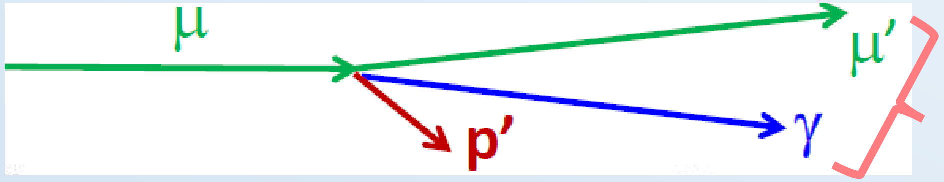
$$s_k^i = \sin(k\phi_{\gamma\gamma^\star})$$

$$c_k^i = \cos(k\phi_{\gamma\gamma^\star})$$

i: DVCS/BH/I

2016 data Exclusive photon production

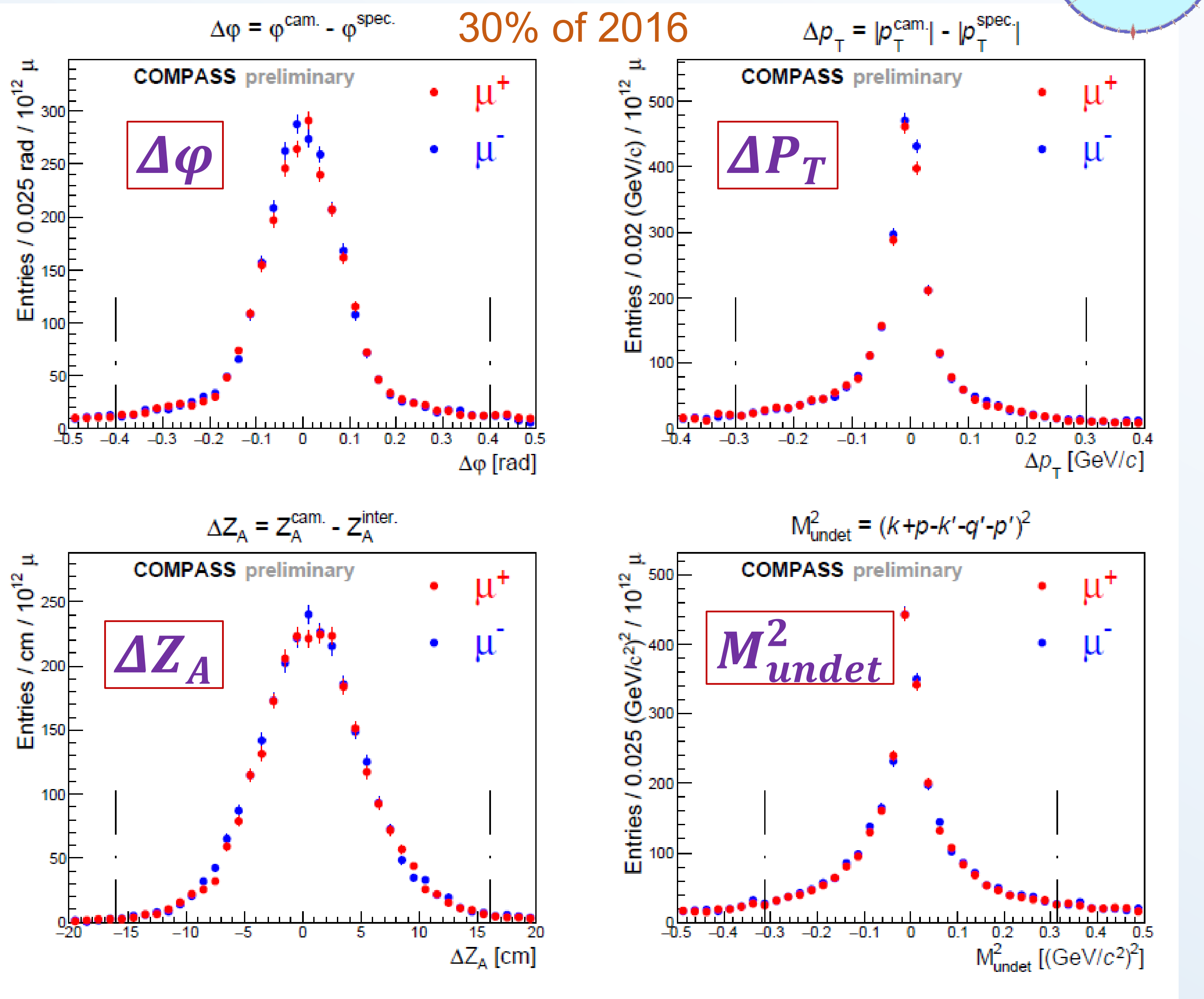
information given by the spectrometer
and also CAMERA



CAMERA spectrometer

$$\Delta\varphi = \varphi^{CAM} - \varphi^{SPEC}$$
$$\Delta P_T = P_T^{CAM} - P_T^{SPEC}$$
$$\Delta Z_A = Z_A^{CAM} - Z_A^{Inter.}$$
$$M_{undet}^2 = (k + p - k' - q' - p')^2$$

exclusive events surely selected

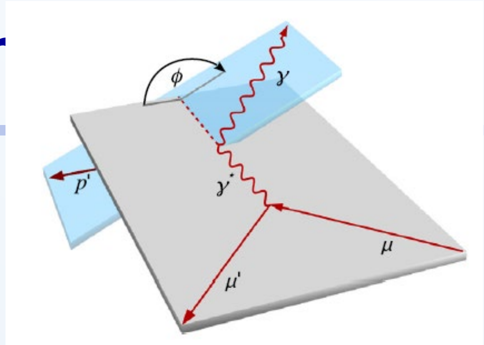


2016 data Charge Spin sum ; ϕ disturibution

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

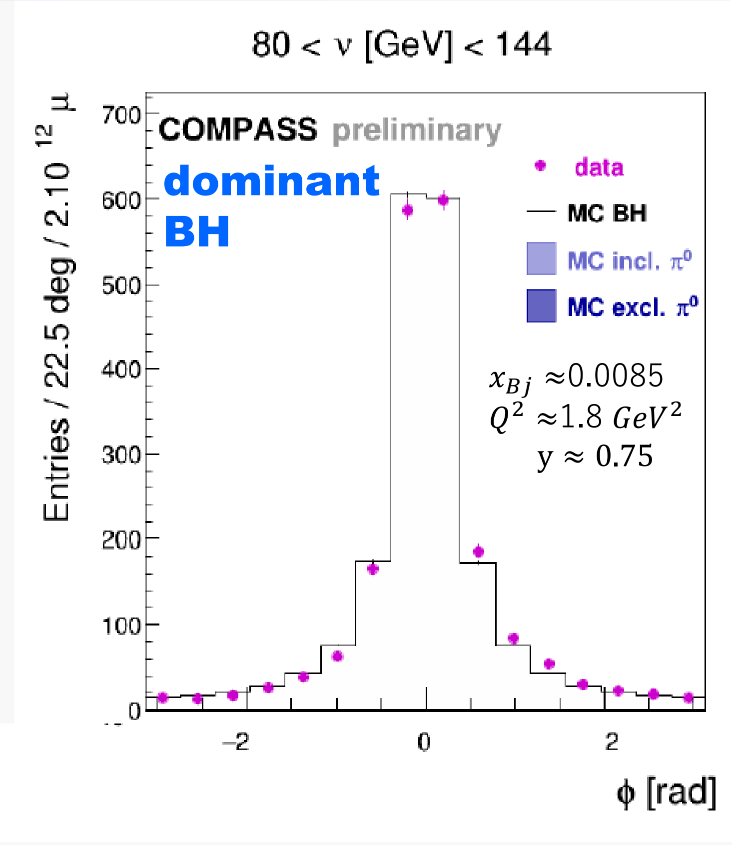
30% of 2016 data analyzed

ν: virtual photon energy

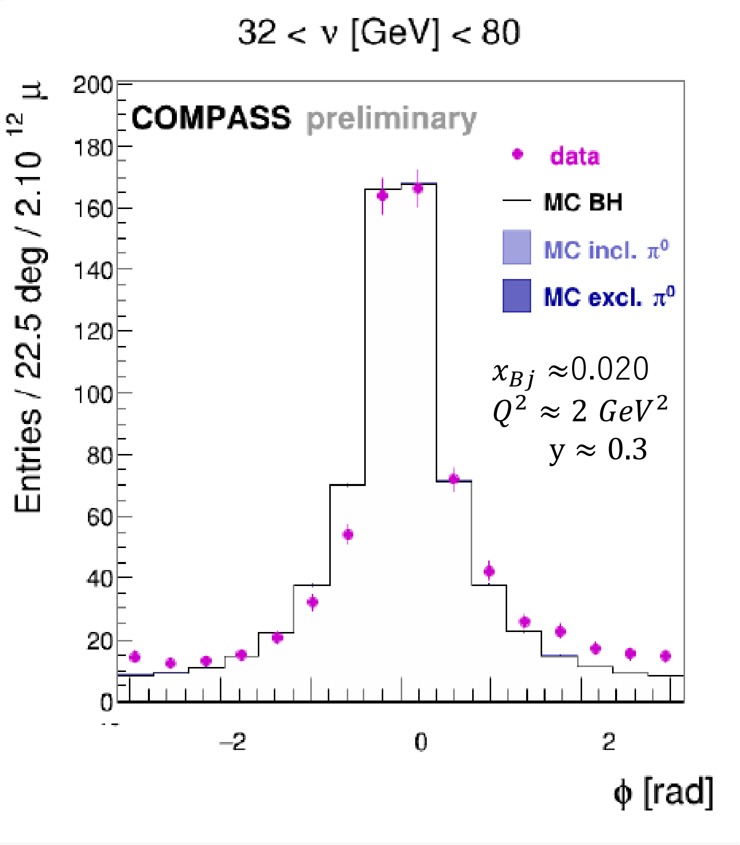


$\phi = \phi_{\gamma^*\gamma}$

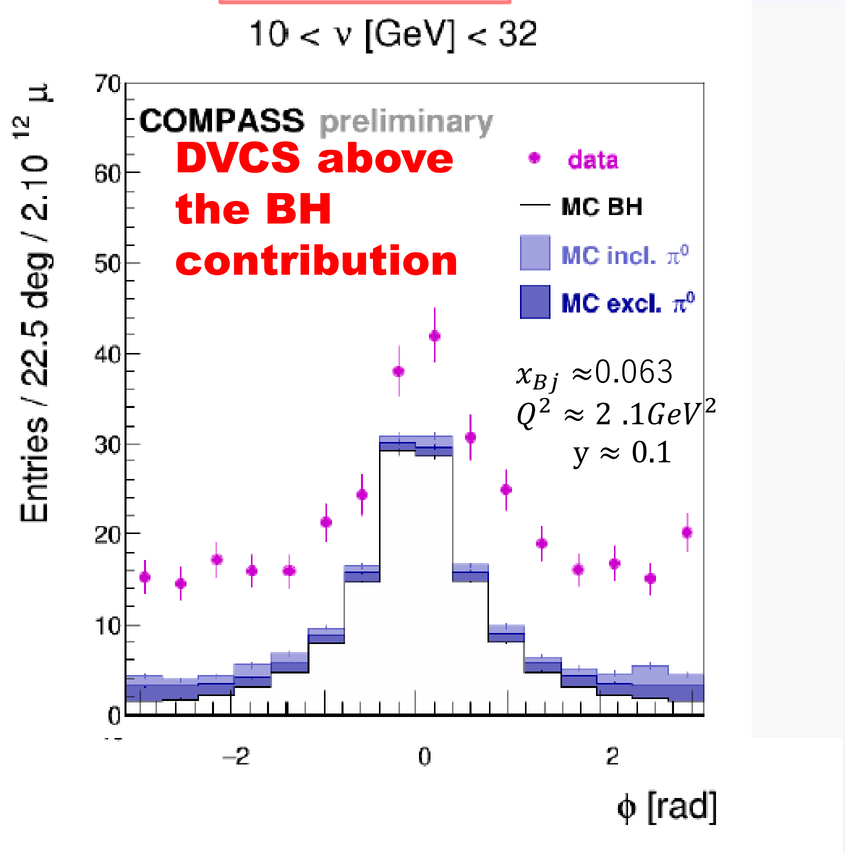
high ν



middle ν



low ν



2016 data DVCS cross section

DVCS cross section evaluated from 10 < ν < 32 GeV data

$$d\sigma^{I} \propto \left(s_1^I \sin\phi_{\gamma^*\gamma} + s_2^I \sin 2\phi_{\gamma^*\gamma}\right)$$

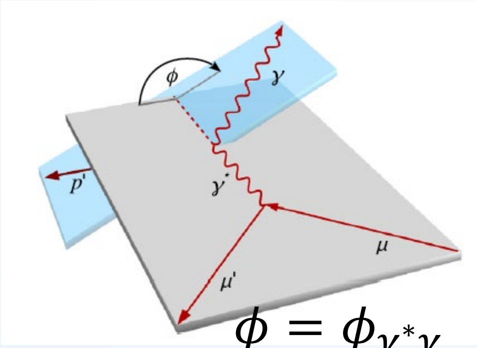
cancellation

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} - |P_\mu| d\sigma^{I})$$

calculable
(well known)

$$d\sigma^{DVCS}_{unpol} \propto \left(c_0^{DVCS} + c_1^{DVCS}\cos\phi_{\gamma^*\gamma} + c_2^{DVCS}\cos 2\phi_{\gamma^*\gamma}\right)$$

cancellation



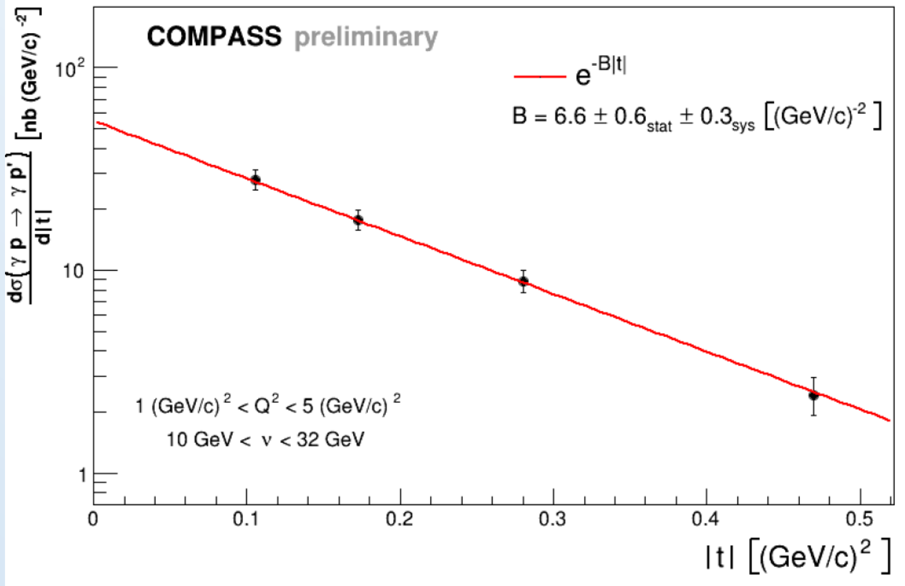
- subtract BH contribution and integrating over ϕ

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

- cross section for virtual photon

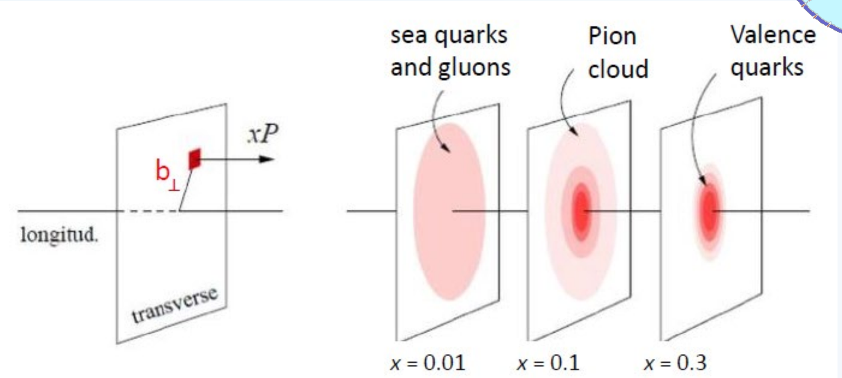
$$\frac{d\sigma^{\gamma^* p}}{d|t|} = \frac{1}{\Gamma(Q^2,\nu,E_\mu)} \frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt}$$

flux



2012-16 data Transverse extension of partons

$c_0^{DVCS} \approx (\mathcal{I}m\mathcal{H})^2$ in COMPASS with $x_{Bj} = 0.06$



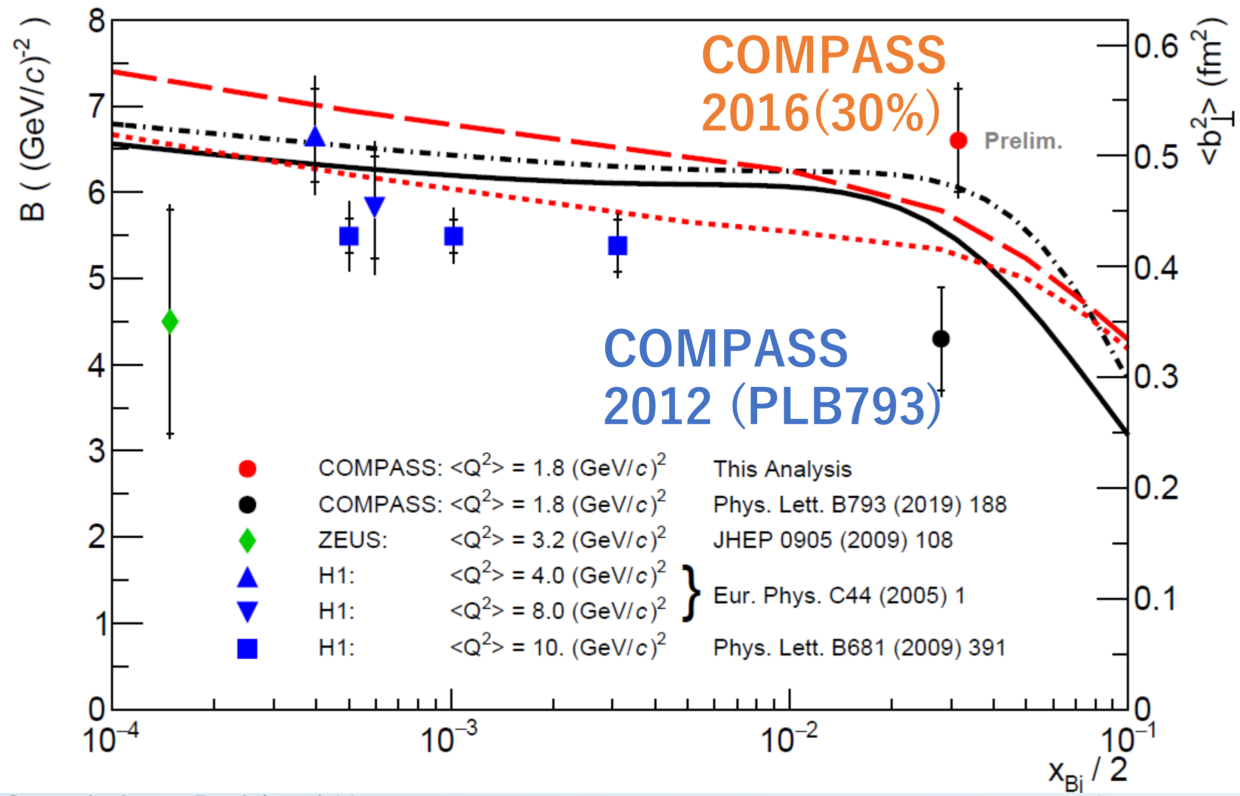
Impact-parameter representation [Burkardt, Int. J. Mod. Phys. A18 (2003) 173]

$$q(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ib_\perp \cdot \Delta_\perp} H(x, 0, -\Delta_\perp^2)$$

The DVCS cross section allows to probe the transverse extension of partons

$$\frac{d\sigma^{DVCS}}{dt} \propto e^{-B|t|} = e^{-\frac{1}{2}\langle b_\perp^2 \rangle |t|}$$

$$\langle b_\perp^2 \rangle = \frac{\int d^2 b_\perp b_\perp^2 q(x, b_\perp)}{\int d^2 b_\perp q(x, b_\perp)} = -4 \frac{\partial}{\partial t} \ln H(x, 0, t)|_{t=0}$$



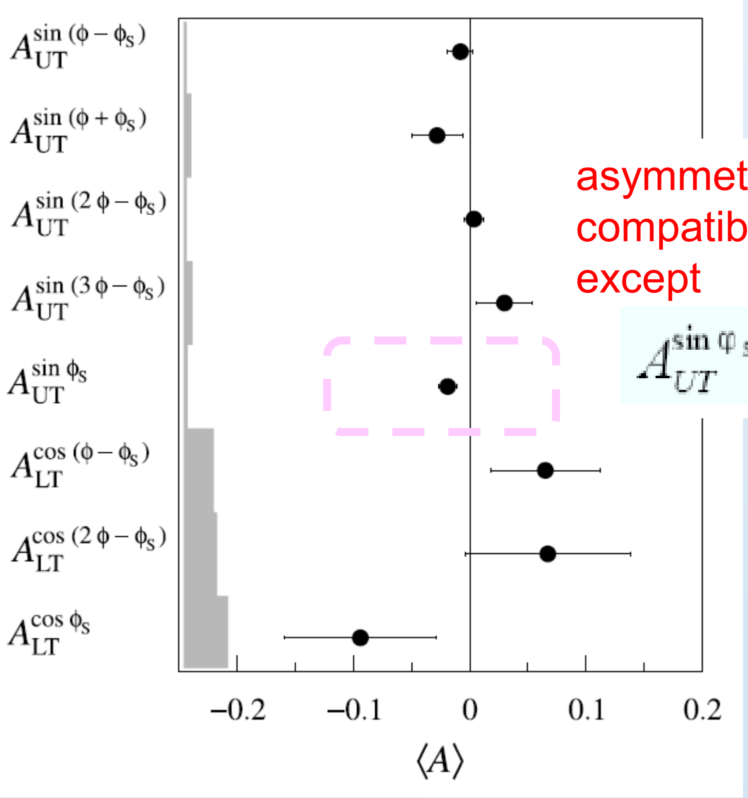
HE vector meson P

Transverse-target spin asymmetries for HEMP of ρ and ω

$\mu^+ p^\uparrow \longrightarrow \mu\, p\, \rho^0/\omega$ 160 GeV/c μ^+ with $P_\mu \approx -80\%$

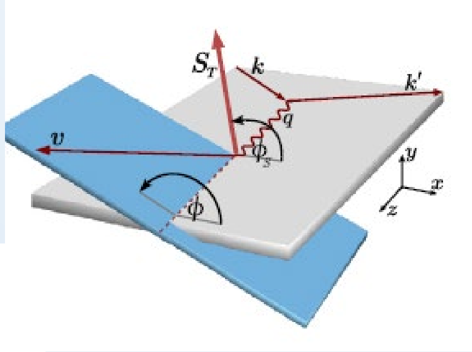
data collected with the standard setup with the polarized target

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



asymmetries small, compatible with 0, except

$$A_{UT}^{\sin\phi_S} = -0.019 \pm 0.008 \pm 0.003$$



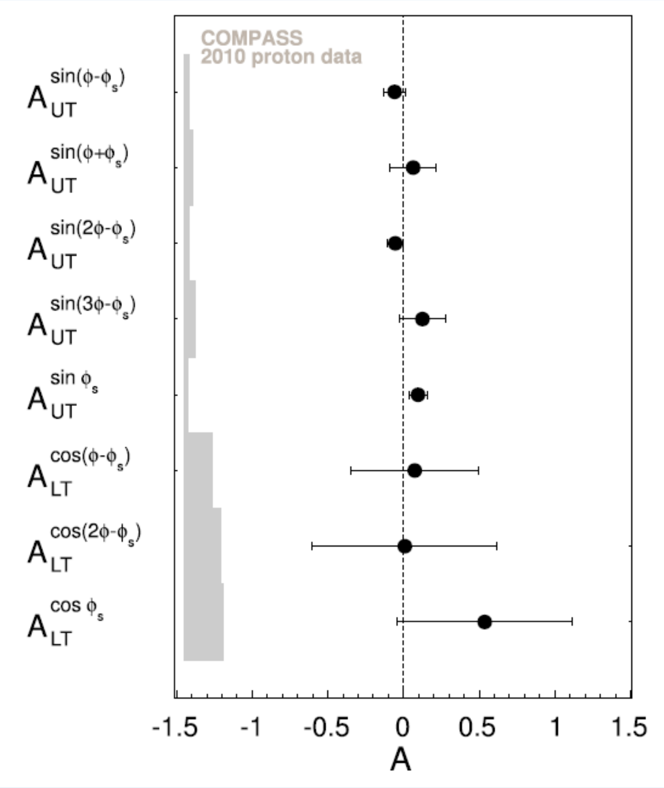
indication of GPD H_T contribution

reasonable agreement with GPD-GK model

COMPASS NPB 865 (2012)1, PLB731 (2014) 19

2007&10 data for NH3 target

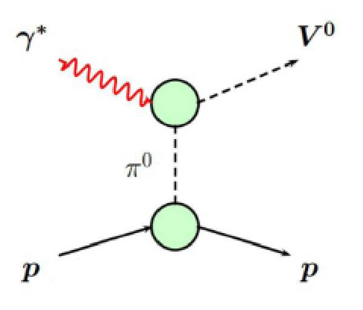
$\omega \rightarrow \pi^+ \pi^- \pi^0$



COMPASS NPB915 (2017)

2010 data for NH3 target

promising agreement with GPD-GK model with pion pole

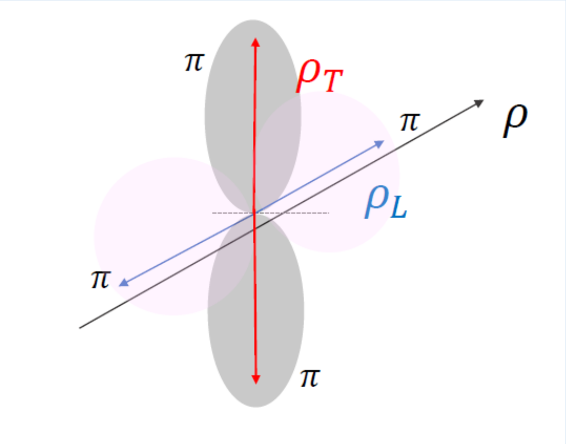


EPJ A50 (2014) 146

Spin density matrix elements for HEMP of ρ and ω

$\mu^{\pm} p \longrightarrow \mu \; p \; \rho^0/\omega$ 160 GeV/c $\mu^{\pm}$ with $P_\mu \approx \mp 80\%$

- Spin density matrix elements (**SDMEs**) describe how the spin components of the virtual photon are transferred to the created vector meson
- provide test of s-channel helicity conservation (SCHC)
- Further constraints on GPD parameterization
- Sensitive to chiral-odd GPDs H_T and $\tilde{E}_T$



spin state of the vector meson is given by the decay angular distribution

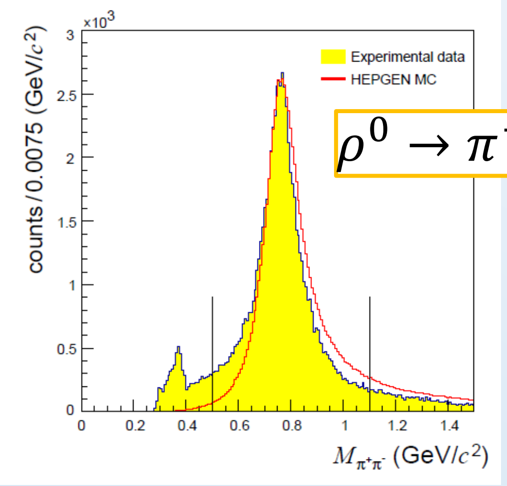
a set of the SDMEs

$$d\sigma \propto \mathcal{W}(\Re, \Phi, \phi, cos\theta)$$

23 SDMEs in total:

15 unpolarized and 8 polarized

Spin density matrix elements for HEMP of ρ

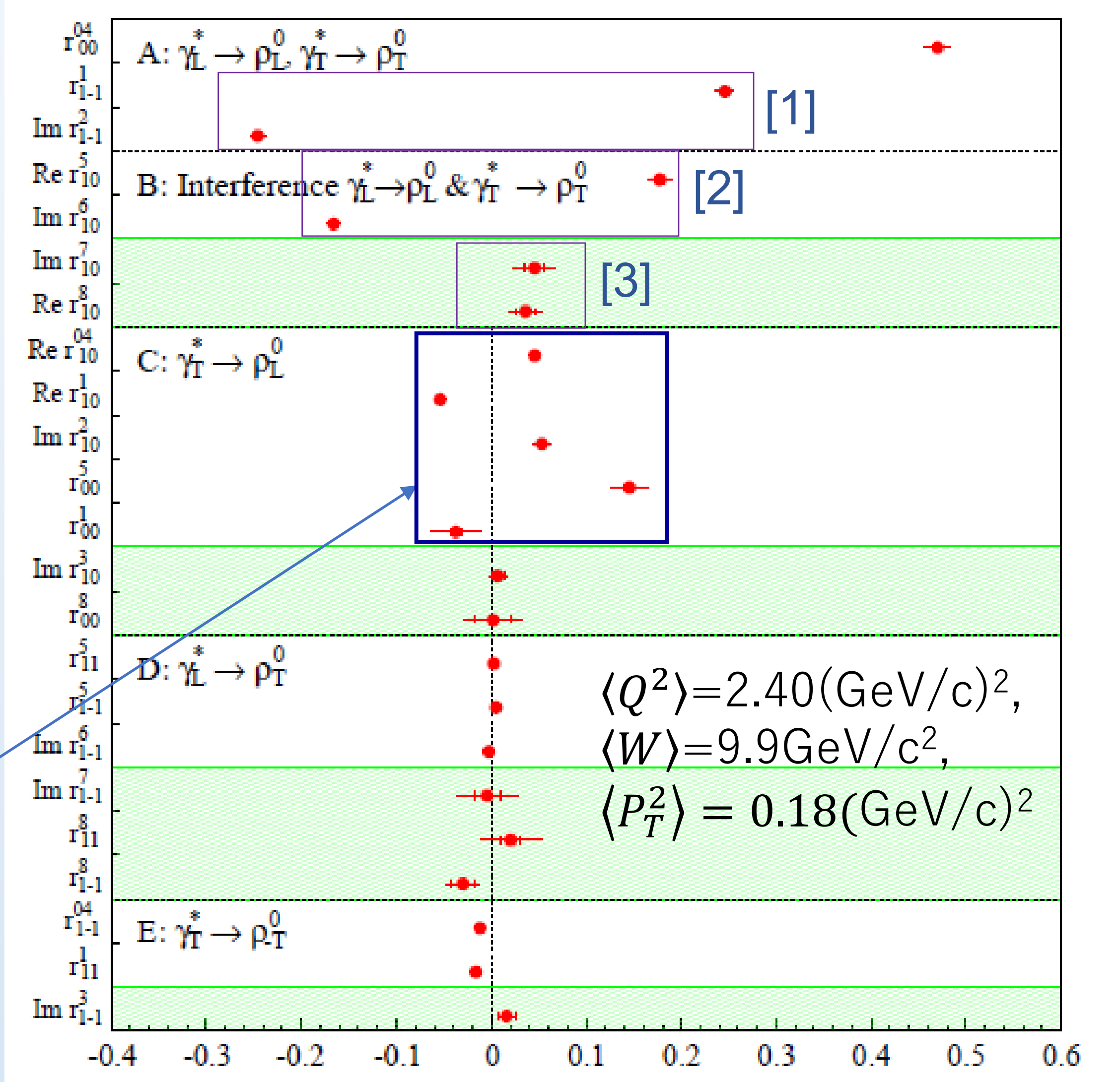


data collected with the dedicated setup with the H2 target

misidentified KK peak < 0.4 GeV

interference between resonant and non-resonant $\pi\pi$ seen (B.G.3%)

COMPASS 2012 data



EPJC (2023) 83 924

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

measurements

[1] $r^1_{1-1} + \mathcal{Im}(r^2_{1-1}) = 0$ ← $0.000 \pm 0.005 \pm 0.003$

[2] $\mathcal{Re}(r^5_{10}) + \mathcal{Im}(r^6_{10}) = 0$ ← $0.011 \pm 0.002 \pm 0.002$

[3] $\mathcal{Im}(r^7_{10}) - \mathcal{Re}(r^8_{10}) = 0$ ← $0.009 \pm 0.014 \pm 0.028$

All other elements should be 0

Clear deviation of SCHC

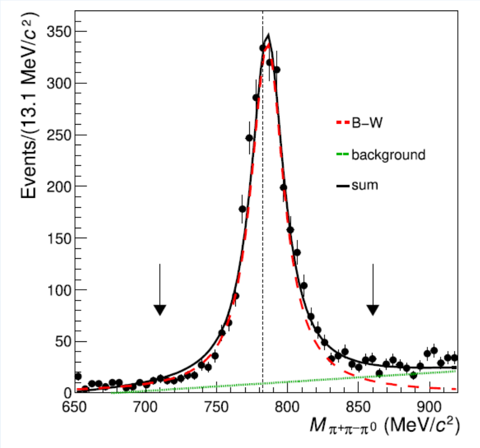
possible Interpretation with chiral-odd GPDs:

H_T and $\bar{E}_T \equiv 2\widetilde{H}_T + E_T$

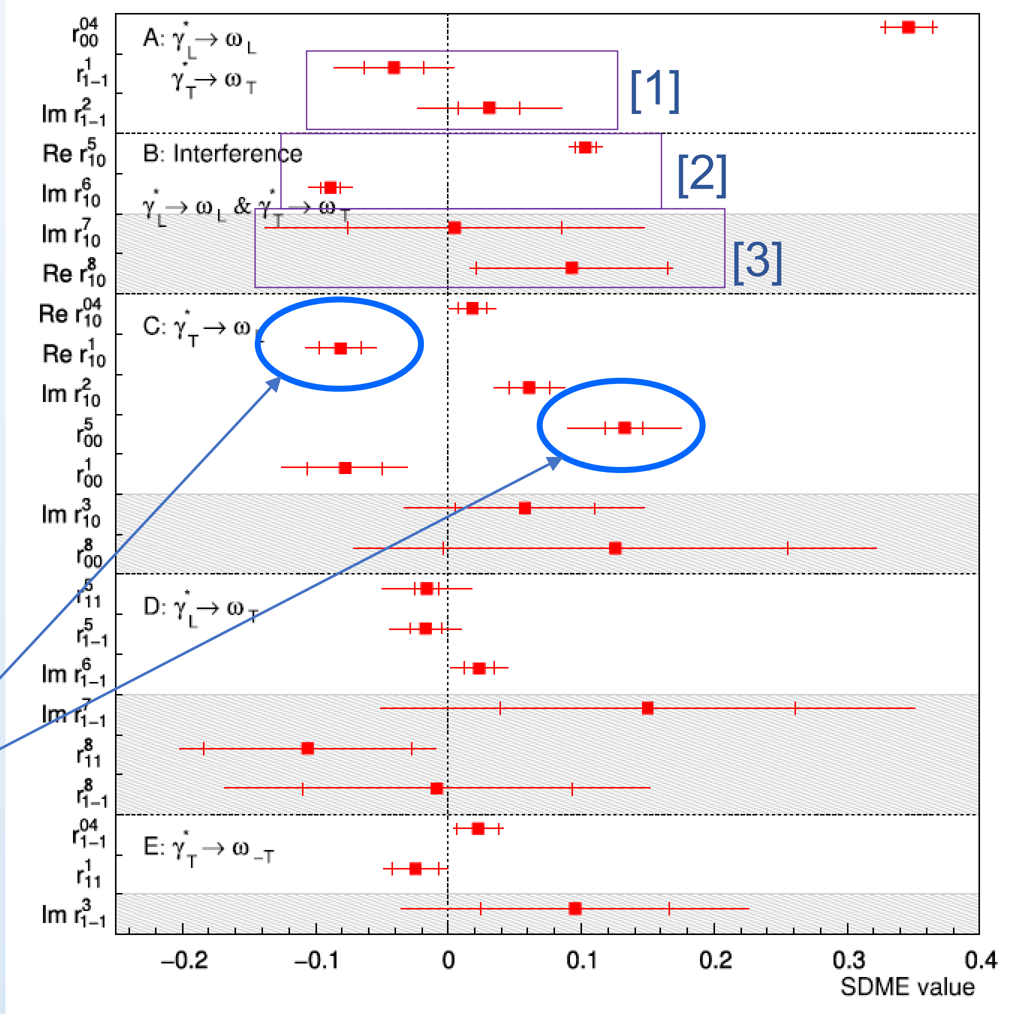
Goloskokov, Kroll, EPJC 74 (2014) 2725

Spin density matrix elements for HEMP of ω

$$\omega \to \pi^+ \pi^- \pi^0$$
$(Br \approx 89\%)$



COMPASS 2012 data



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

measurements

[1] $r^1_{1-1} + \mathcal{Im}(r^2_{1-1}) = 0$ ← $-0.010 \pm 0.032 \pm 0.047$

[2] $\mathcal{Re}(r^5_{10}) + \mathcal{Im}(r^6_{10}) = 0$ ← $0.014 \pm 0.011 \pm 0.013$

[3] $\mathcal{Im}(r^7_{10}) - \mathcal{Re}(r^8_{10}) = 0$ ← $0.088 \pm 0.110 \pm 0.196$

All other elements should be 0

Clear violation of SCHC
for $\mathcal{R}e r^{04}_{10}$ and r^5_{00}

related to the chiral-odd GPDs
H_T and $\bar{E}_T \equiv 2\widetilde{H}_T + E_T$ in the GPD GK model

COMPASS EPJC (2021) 81126

Spin density matrix elements for HEMP of ω

ω data in comparison with the GPD model

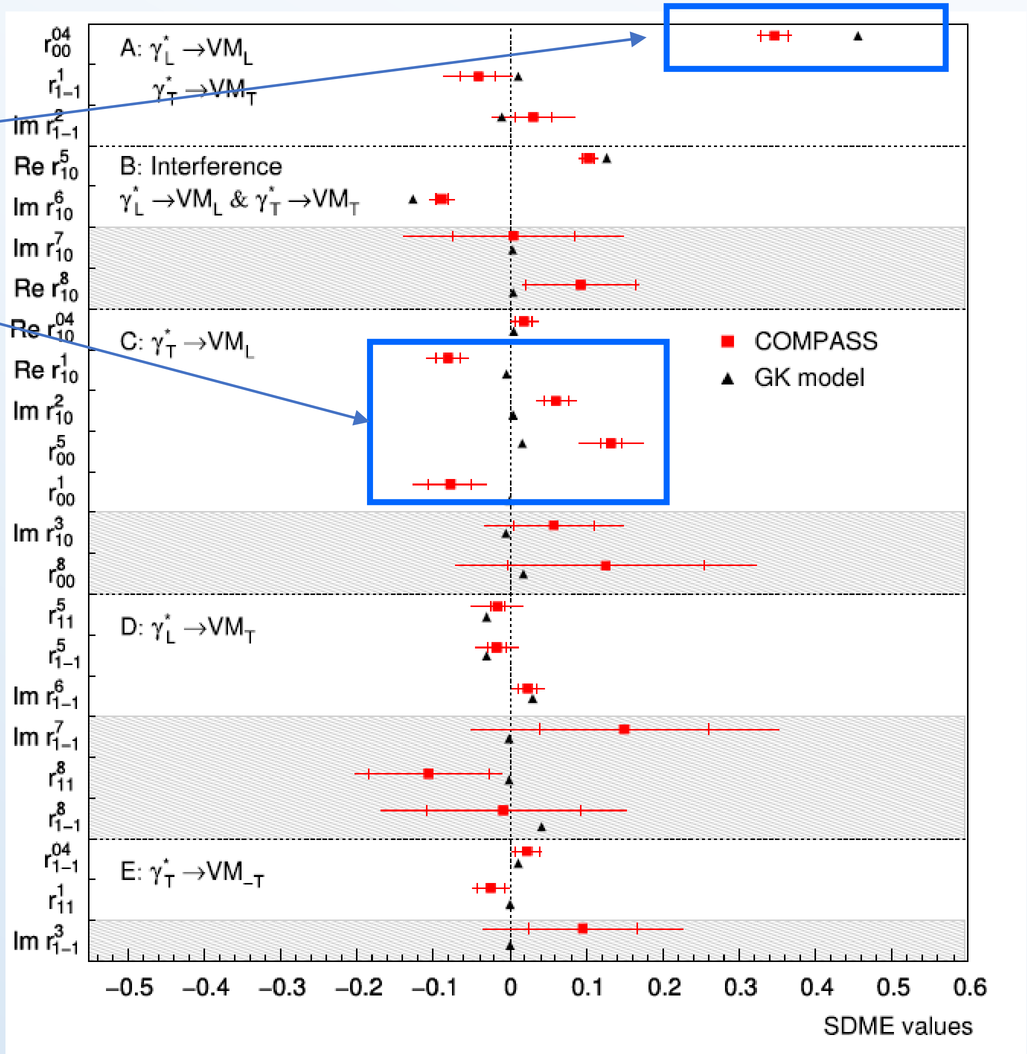
- r_{00}^{04} is significantly different from the model
- Clear deviation for $\gamma_T^* \rightarrow \omega_L$ elements

GPD GK model

[Eur. Phys. J. C **74**, 2725 (2014), Eur. Phys. J. A **50**, 146 (2014)]

- chiral-odd GPDs included
- pion-pole exchange included
- tuned to HERMES results on SDMEs and spin asymmetries for ρ and ω production

COMPASS 2012 data



COMPASS EPJC (2021) 81126

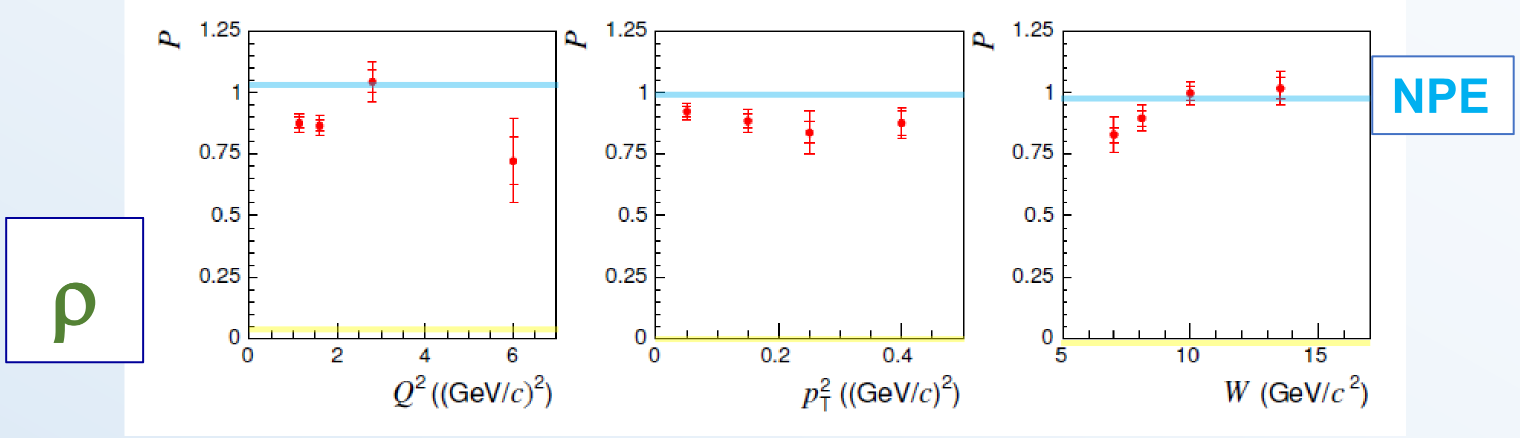
ρ and ω comparison ; Parity exchange property

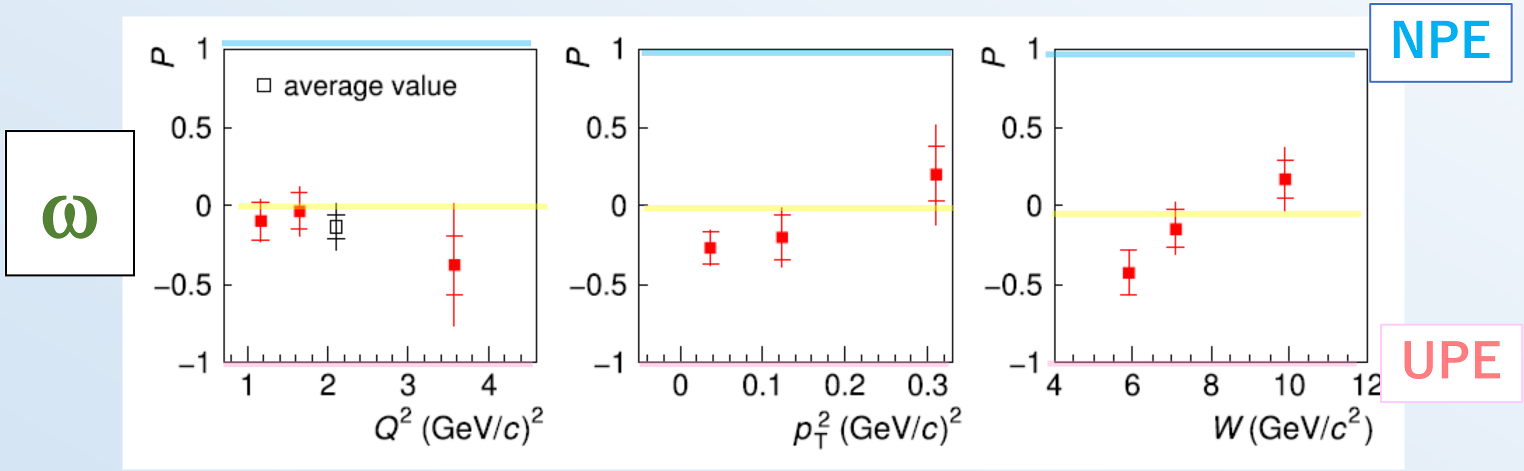
Parity exchange property

NPE/UPE asymmetry for $\gamma_T^* \to V_L$

$$P \equiv \frac{d\sigma_T^{NPE} - d\sigma_T^{UPE}}{d\sigma_T^{NPE} + d\sigma_T^{UPE}} \approx \frac{2r_{1-1}^{1}}{1 - r_{00}^{04} - r_{1-1}^{04}}$$

- ρ production
  - NPE dominant
  - Sensitive to GPDs *E*, *H*
- ω production
  - NPE~UPE on average
  - Sensitive also to GPDs $\tilde{E}$, $\tilde{H}$ and pion pole





$HE\ \pi^0 P$

Exclusive π^0 production cross section

$$\mu^{\pm}\, p \longrightarrow \mu\;\; p\;\; \pi^0$$

160 GeV/c $\mu^{\pm}$ with $P_\mu \approx \mp 80\%$

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

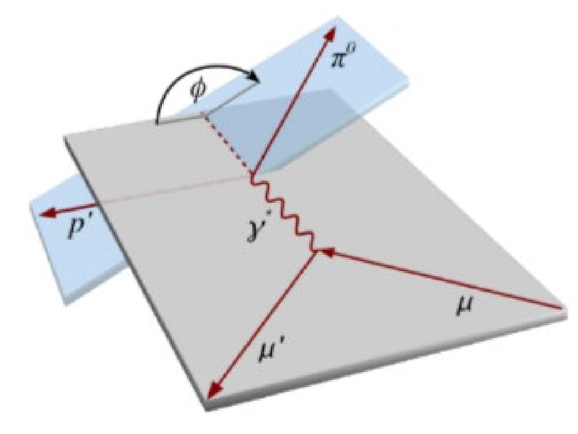
$$\frac{d\sigma_T}{dt} \sim |\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2$$

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

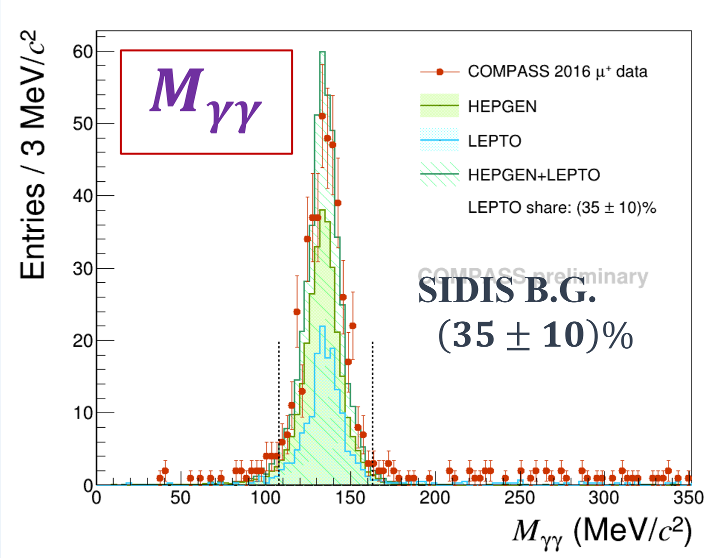
$$\frac{d\sigma_{TT}}{dt} \sim \frac{t'}{16m^2}|\langle \bar{E}_T\rangle|^2$$

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

COMPASS
$\langle x_B \rangle = 0.10$
ε close to 1



2016 data collected with the dedicated setup with the H2 target



$$\frac{d\sigma}{dt\,d\phi} \sim A + B\cos(2\phi) + C\cos(\phi)$$

$\langle GPD\rangle$: denotes convolution of GPD and DA of the meson

$t' = t - t_{min}$, where $|t_{min}|$ is minimum value of $|t|$

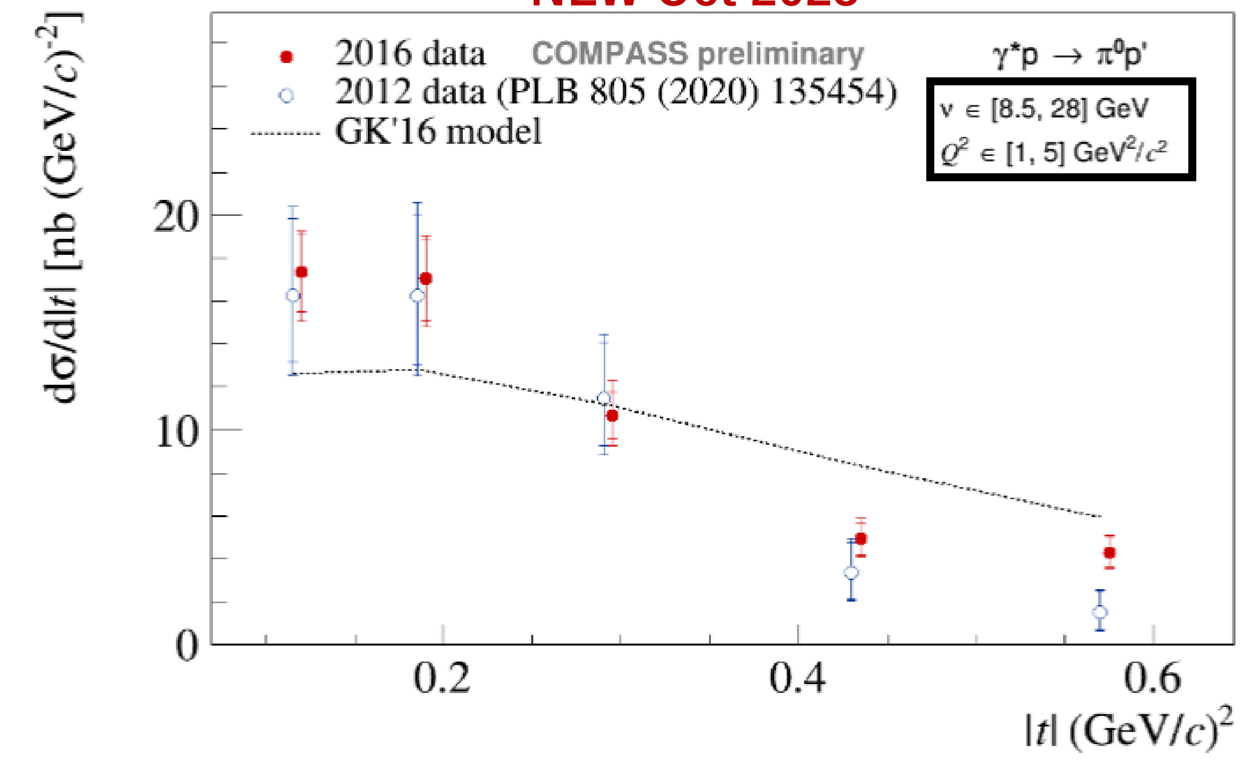
L, T indices indicate polarization of virtual photon. Double index –interference

Exclusive π^0 production cross section

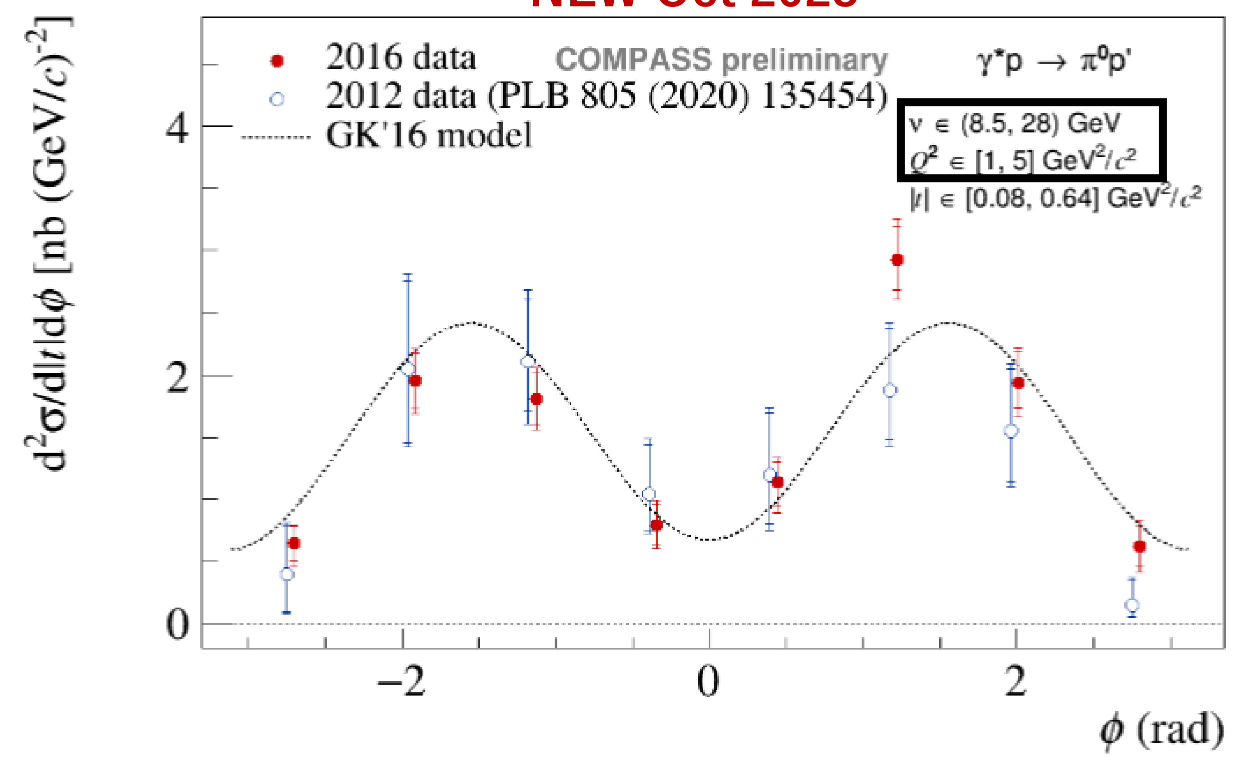
$$\mu^{\pm} p \longrightarrow \mu \;\; p \;\; \pi^0$$

160 GeV/c $\mu^{\pm}$ with $P_\mu \approx \mp 80\%$

NEW Oct 2023



NEW Oct 2023



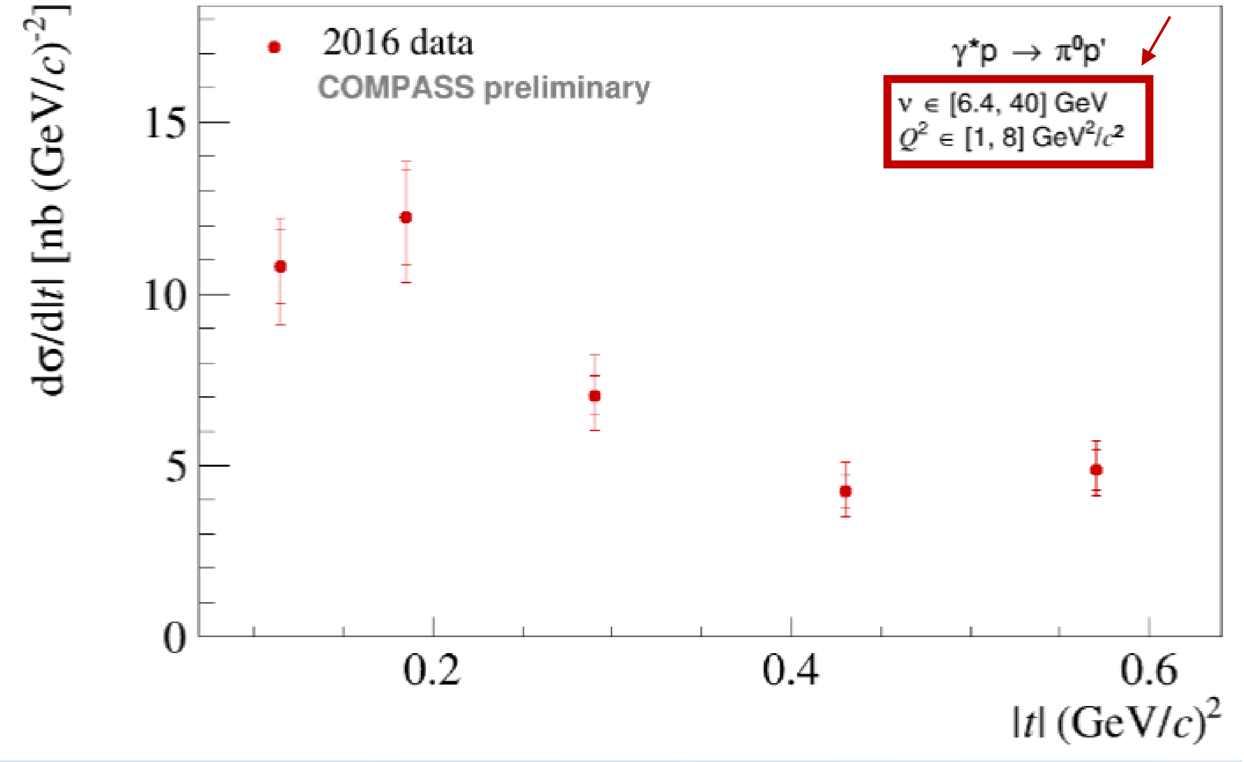
Models: **GK** Kroll Goloskokov EPJC47 (2011)   Also **GGL**: Golstein Gonzalez Liuti PRD91 (2015)

Exclusive π^0 production cross section

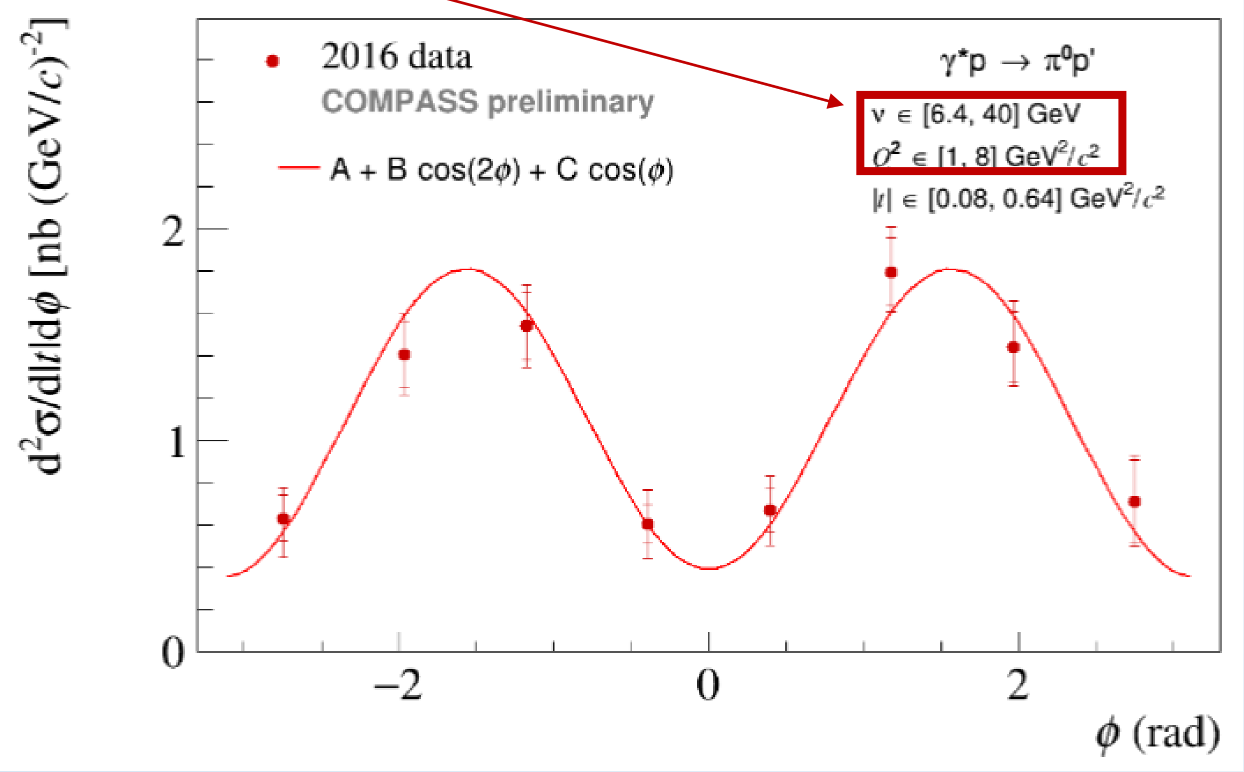
ECAL0 (2016/17) to enlarge the kinematic domain

2016 data in larger υ and Q^2 domain

NEW Oct 2023



In a larger (υ, Q^2) domain **NEW Oct 2023**



Exclusive π^0 production cross section

$\mu^{\pm} p \longrightarrow \mu \; p \; \pi^0$ 160 GeV/c $\mu^{\pm}$ with $P_\mu \approx \mp 80\%$

@COMPASS <x_B>= 0.13

$\nu \in [6.4, 40]$ GeV

$Q^2 \in [1, 8]$ GeV^2/c^2

$|t| \in [0.08, 0.64]$ GeV^2/c^2

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

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

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

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

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

from the fit

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

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

negative → role of $\bar{E}_T$

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

rather small

We will determine the evolution with υ and Q^2

The 2017 data set will still increase the statistics (by a factor 3)

$\langle GPD \rangle$: denotes convolution of GPD and DA of the meson

$t' = t - t_{min}$, where $|t_{min}|$ is minimum value of $|t|$

L, T indices indicate polarization of virtual photon. Double index –interference

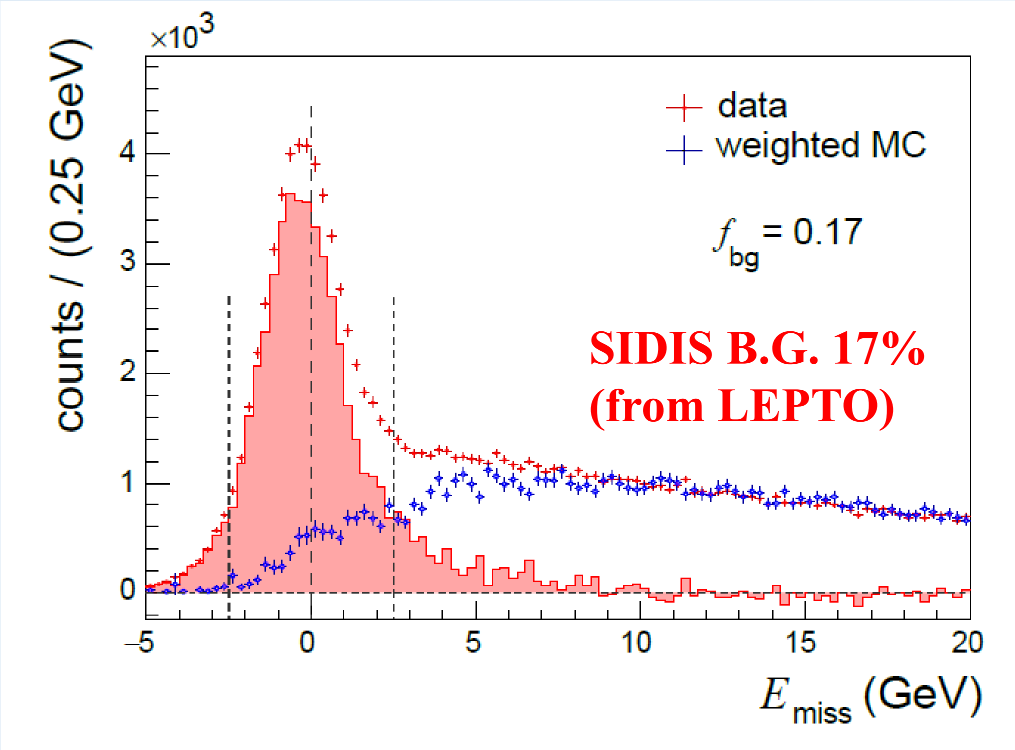
Summary and outlook

- GPD is one of the key concepts to solve the problems of the nucleon structure
- COMPASS measurements related to the GPD have been reported.
- The new data for DVCS have been presented(30% of 2016).
- Results of ρ and ω production have been given:
  Transverse-target spin asymmetries and SDMEs
- The new data for the cross section for π^0 exclusive production have been shown (full of 2016)
- These results are useful to give constraints to GPDs
- More data are being analyzed (in particular 2017 data)
- HEMP for ϕ (σ and SDMEs); work in progress on 2016 data
- HEMP for J/ψ ; feasibility study on going

Backup Slides

Background for excl.-ρ production

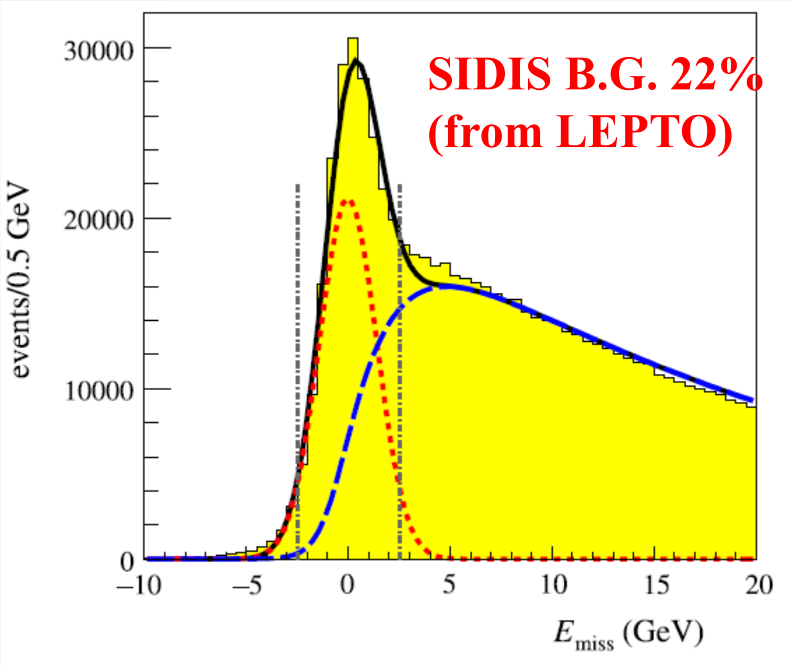
SDME



COMPASS arXiv:2210.16932v1 acc. EPJC

angular distribution corrected by SIDIS MC

Target spin asymmetry

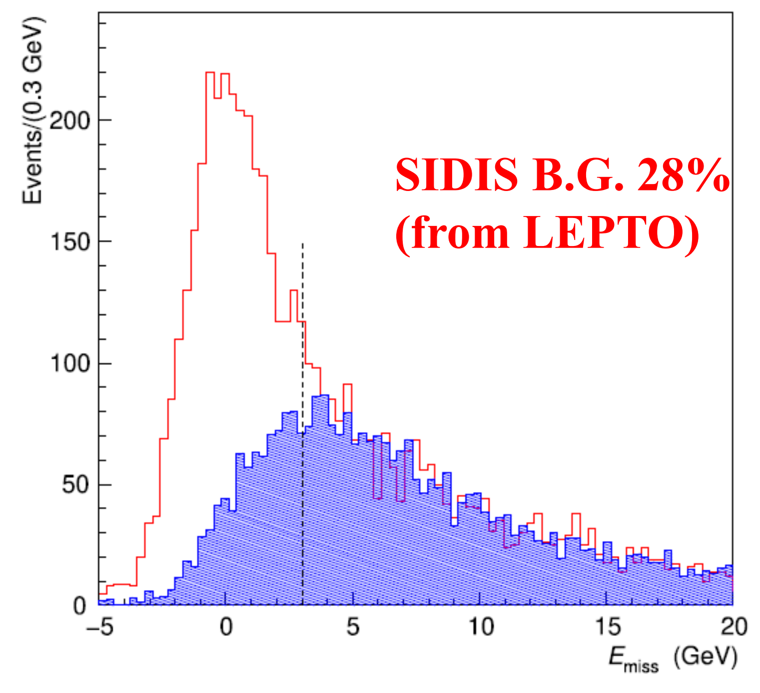


COMPASS PLB731 (2014) 19

angular distribution corrected by SIDIS MC

Background for excl.-ω production

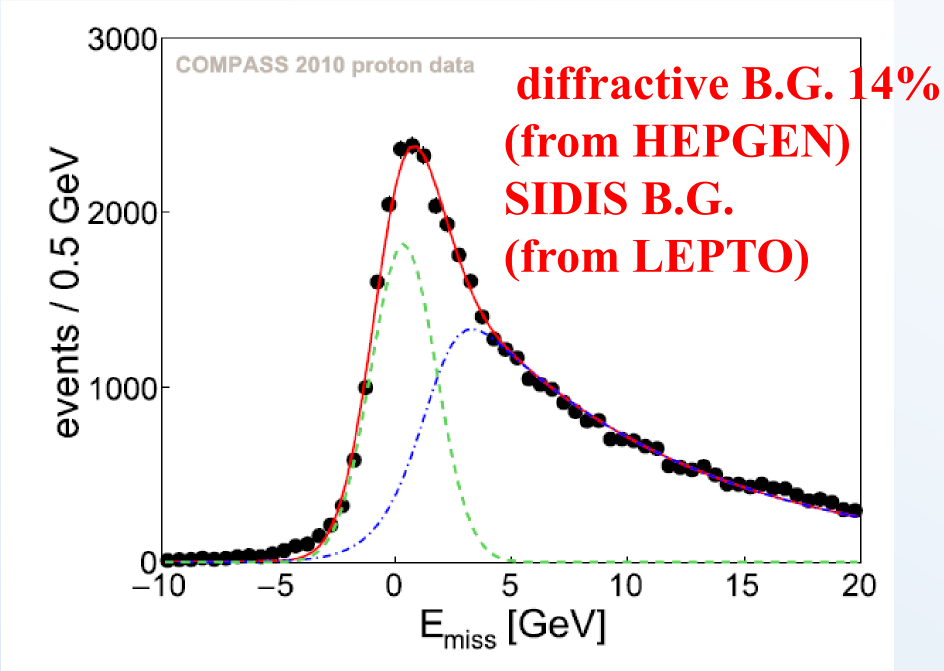
SDME



COMPASS EPJC (2021) 81126

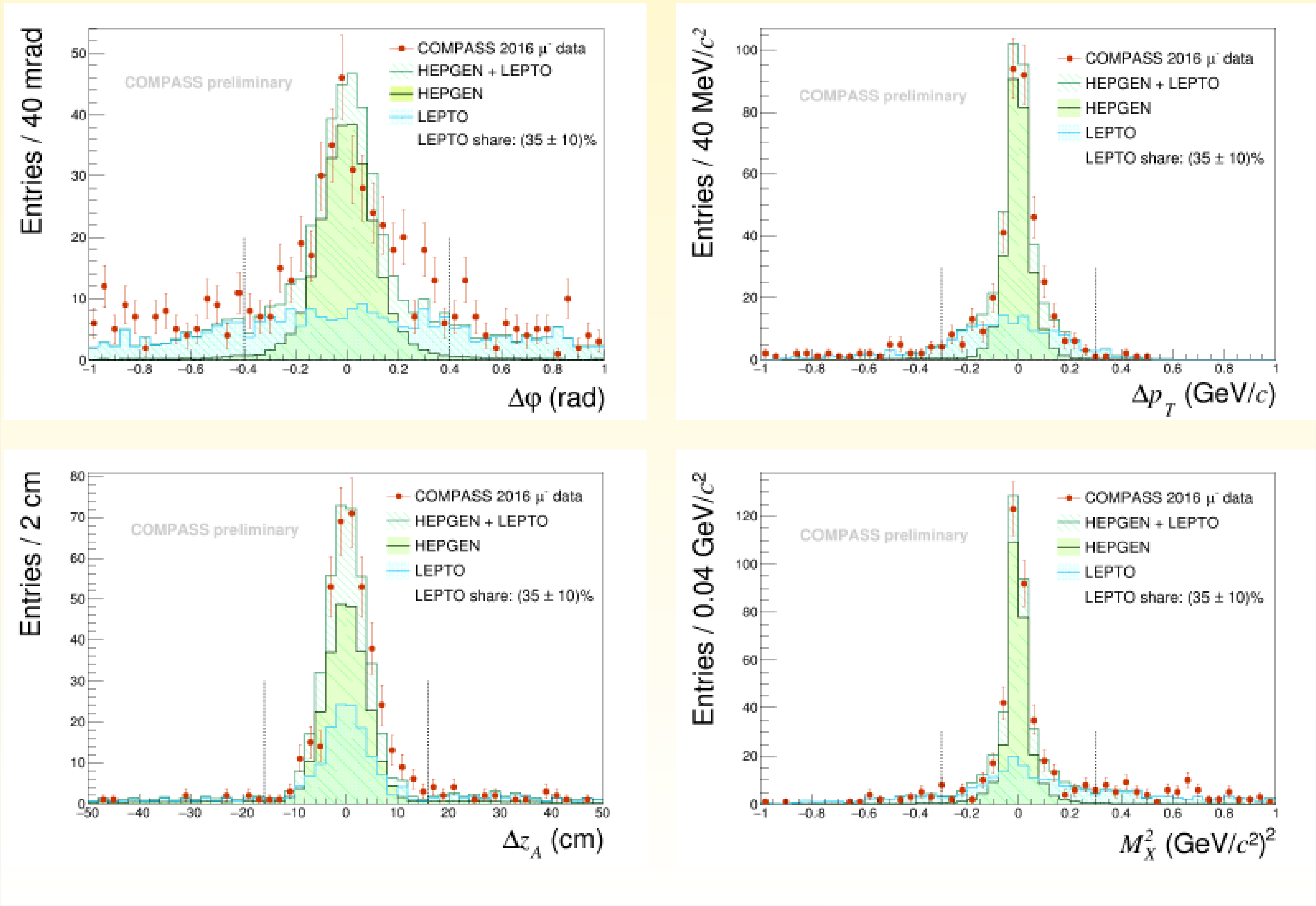
angular distribution corrected by MC

Target spin asymmetry



angular distribution corrected by MC

Background for excl.-π^0 production



exclusive π^0
(from HEPGEN++)
SIDIS B.G.
(from LEPTO)

B.G. $(35 \pm 10)\%$

Summary table for GPDs

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

- 4 chiral-even, 4 chiral-odd (subscript T).
- 2 T-odd ($E, \bar{E}_T$).