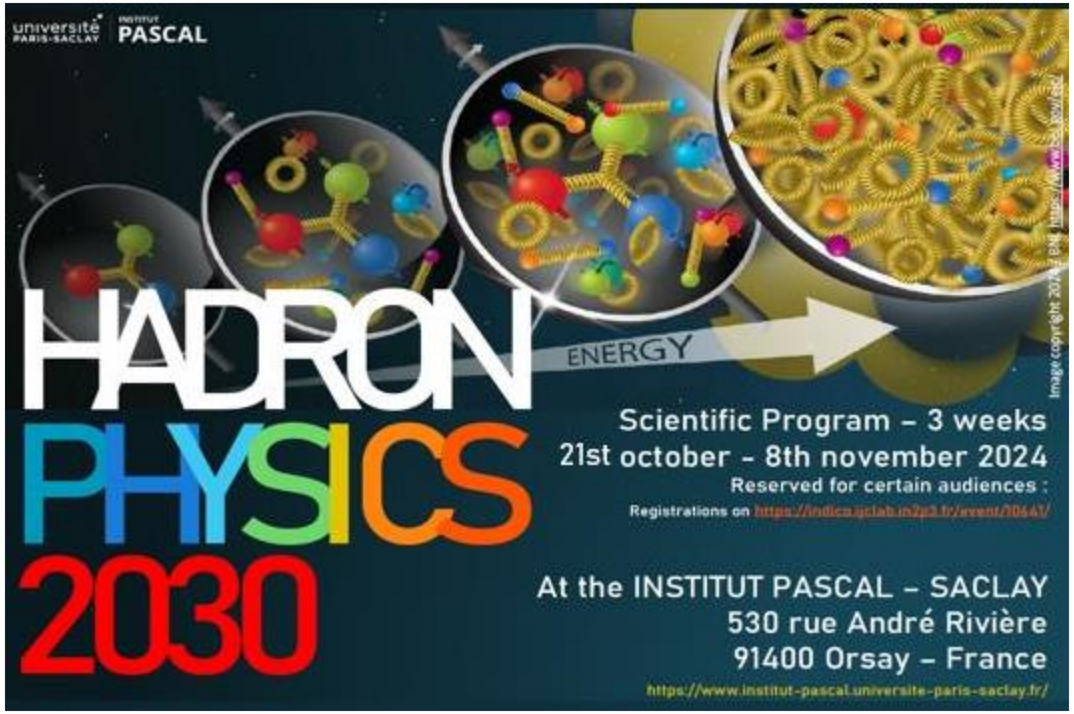
Use of positive and negative polarized muon beams to study exclusive reactions at COMPASS at CERN

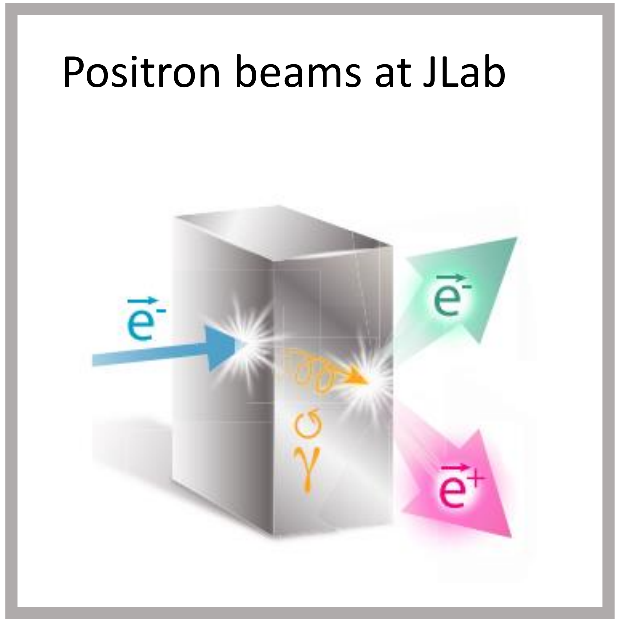


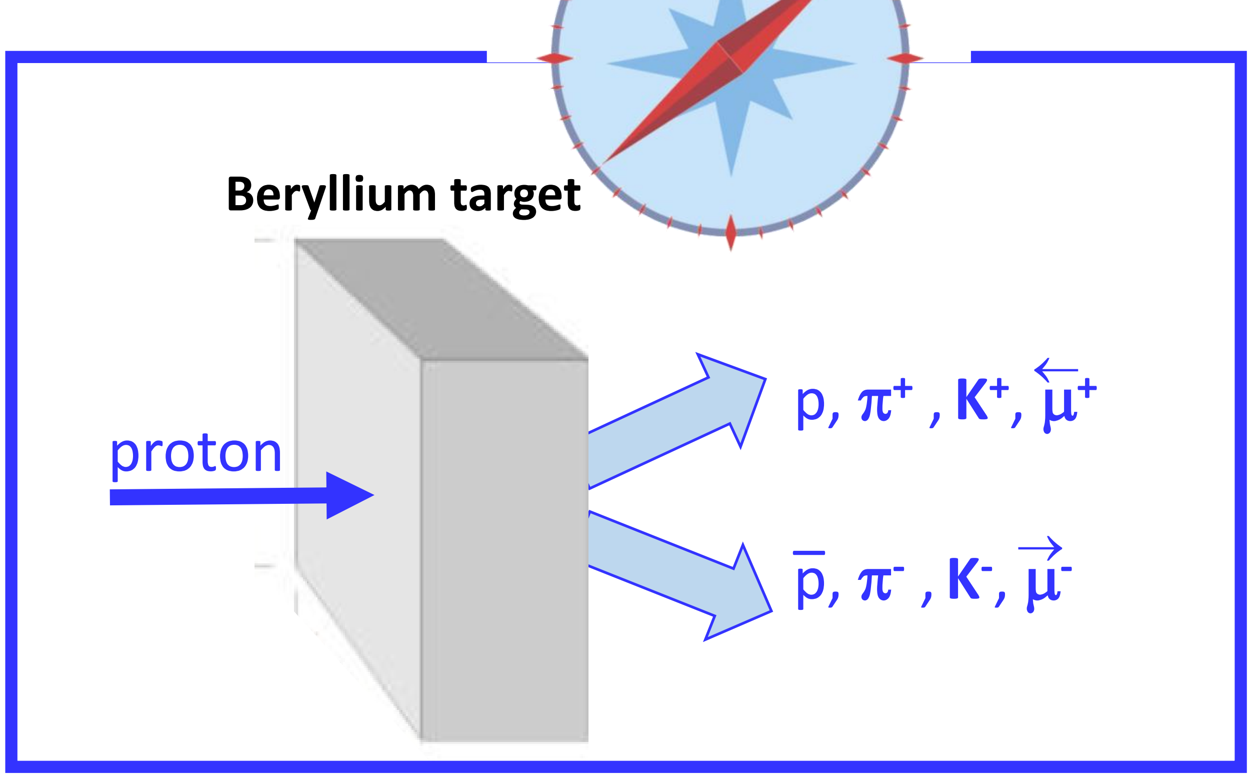
Hadron Physics 2030, 21/10/2024

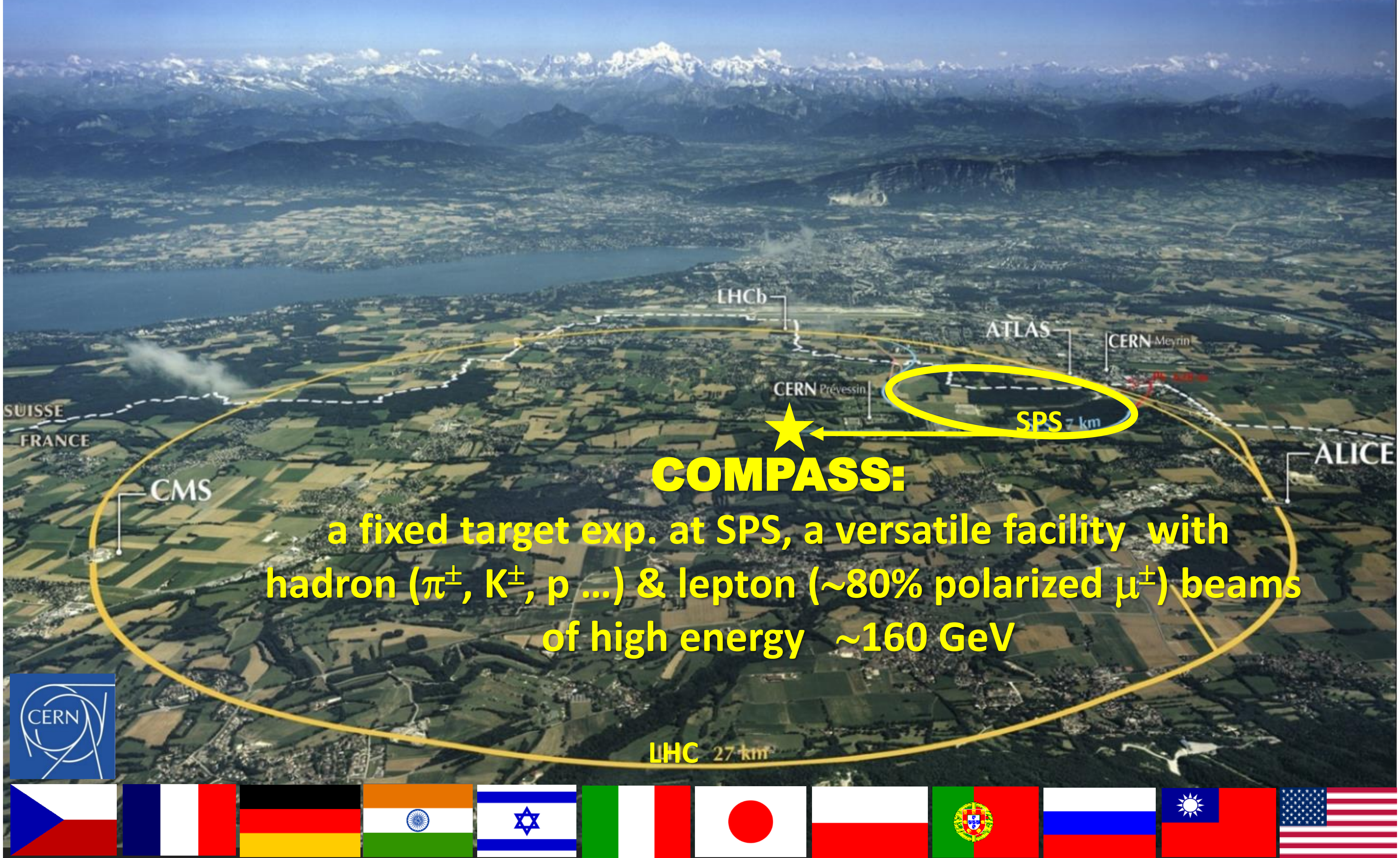
Nicole d’Hose, CEA, UniversitéParis-Saclay

Use of positive and negative polarized muon beams to study exclusive reactions

at COMPASS at CERN



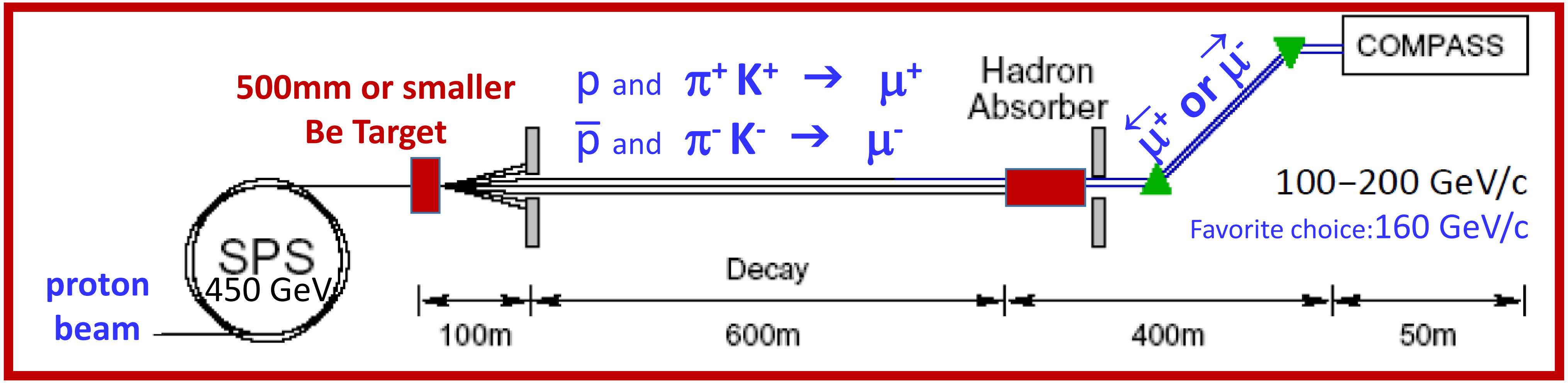




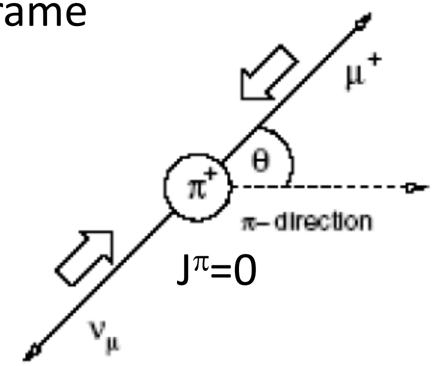
COMPASS:

a fixed target exp. at SPS, a versatile facility with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (~80% polarized $\mu^{\pm}$) beams of high energy ~160 GeV

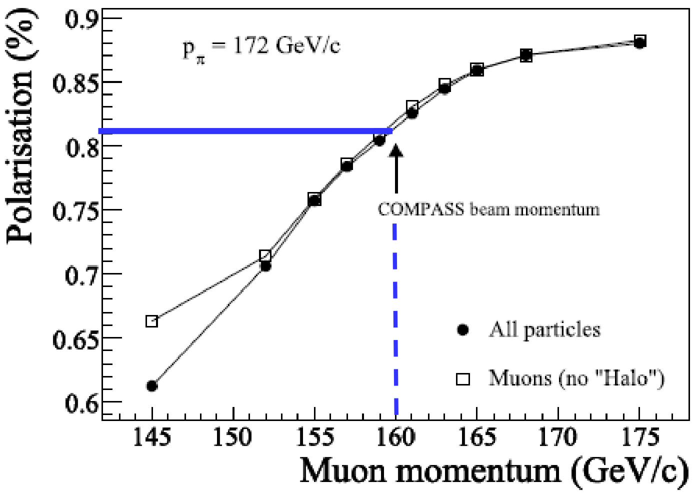
Positive and Negative Polarized Muon Beam at COMPASS

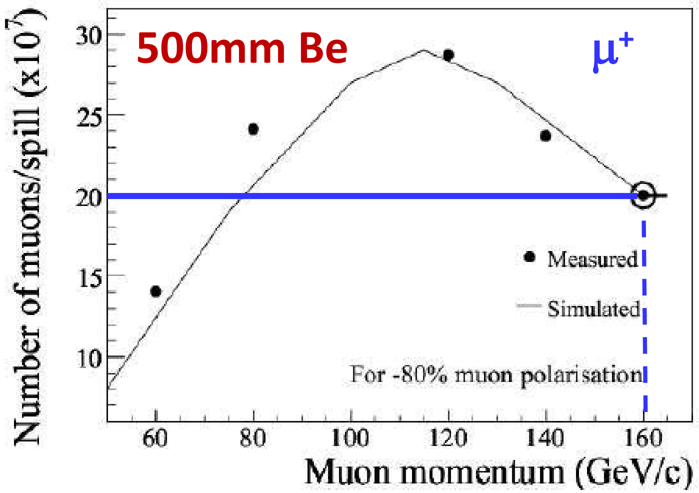


Weak decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$
Parity violation and helicity conservation
the muons are 100% polarized in the pion rest frame



Left-handed ν_μ and μ^+
Right-handed $\bar{\nu}_\mu$ and μ^-





In the lab the muon polarization depends on momenta of both meson and muon

Optimisation of both polarization & muon fluxes: 160 GeV/c ~80% polarization

500mm Be	**20 $10^7 \mu^+$/spill but only 7.4 $10^7 \mu^-$/spill**
100mm Be	**to get about 7.4 $10^7 \mu^+$/spill**

Discussed in this talk:

Advantage of positive and negative polarized muon beams for:

1. Deeply Virtual Compton Scattering (DVCS)

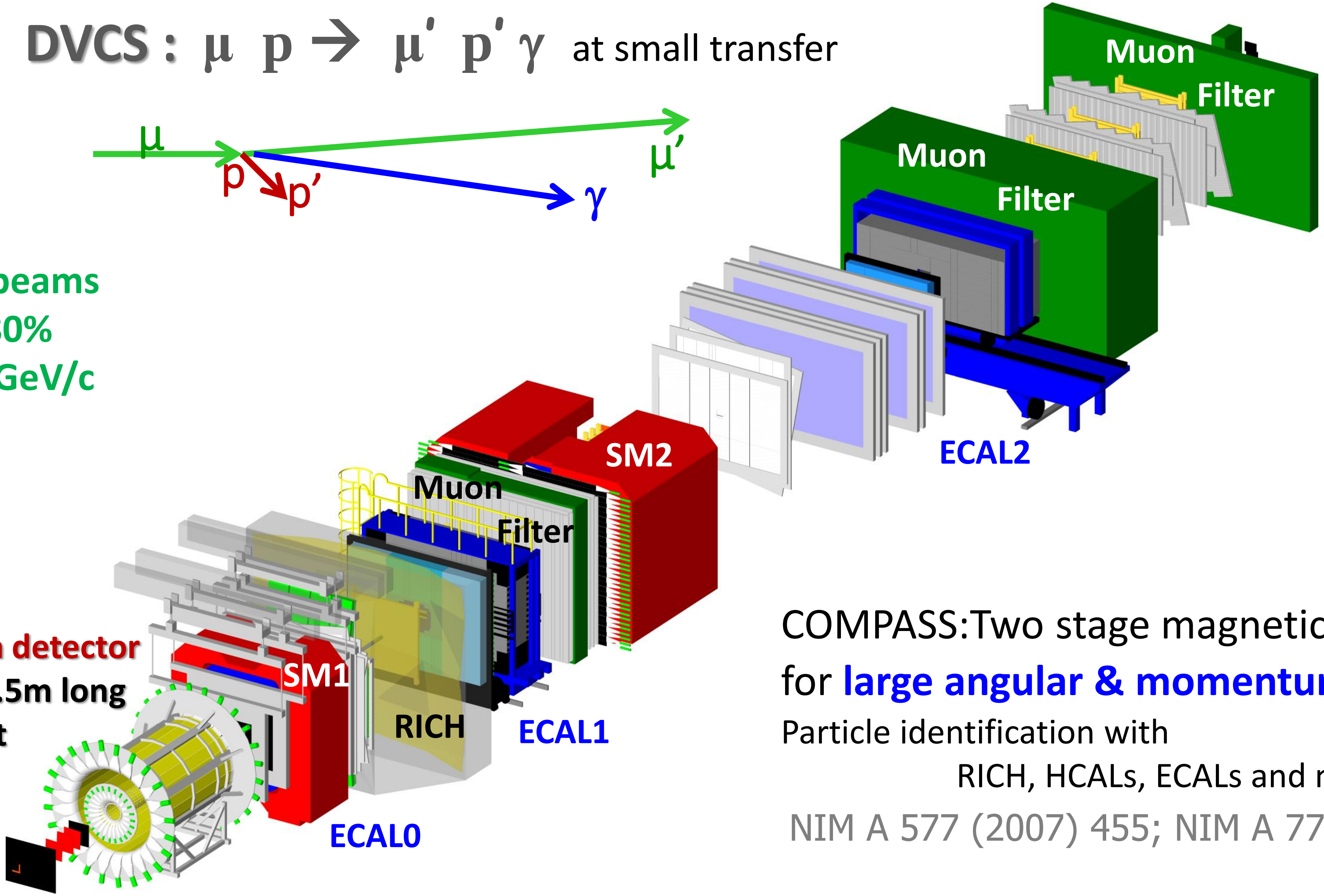
2. Exclusive π^0 production **with new results**

Measurement of exclusive cross sections at COMPASS

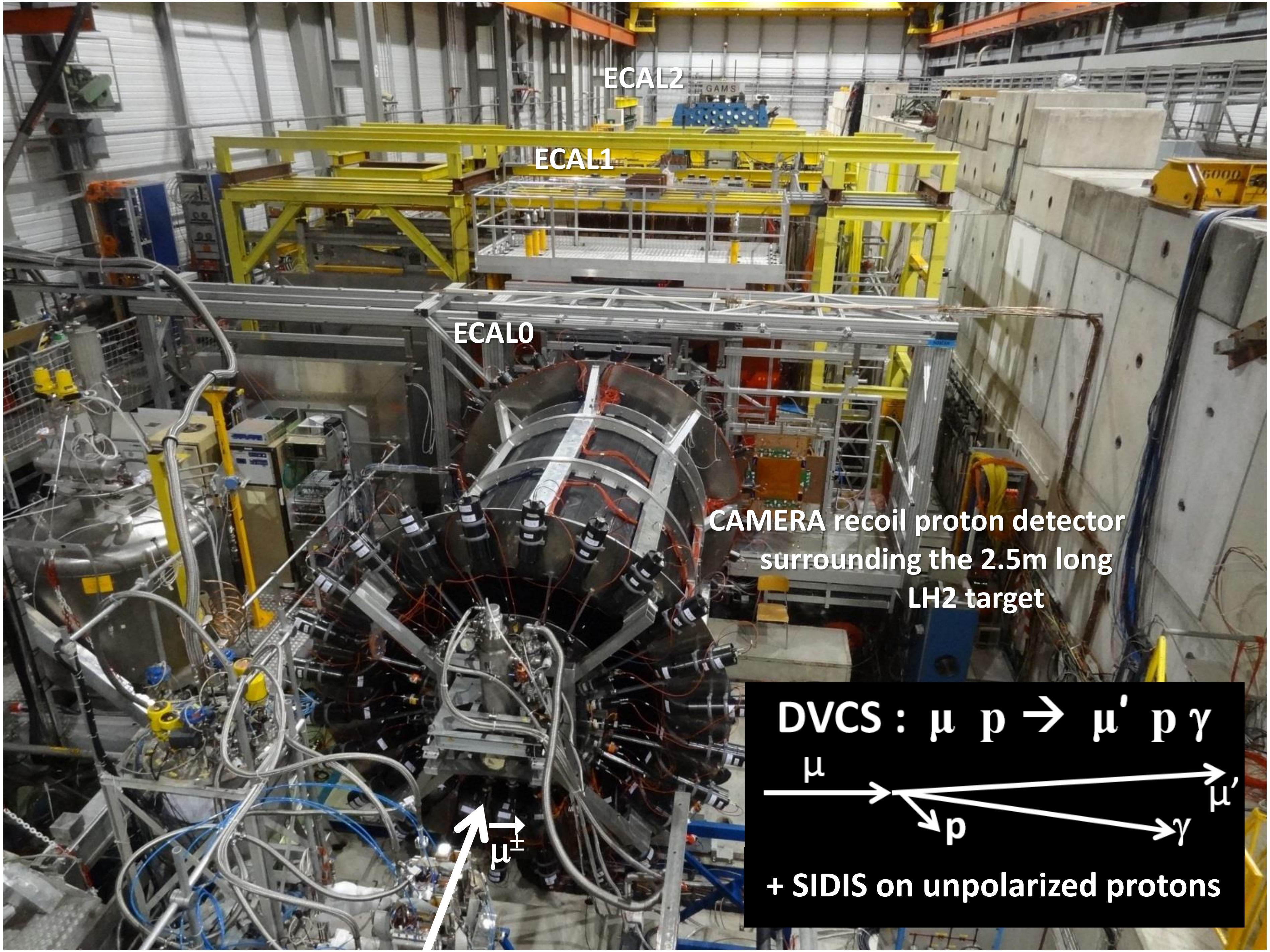
DVCS : $\mu \; p \rightarrow \mu' \; p' \gamma$ at small transfer

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

CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target



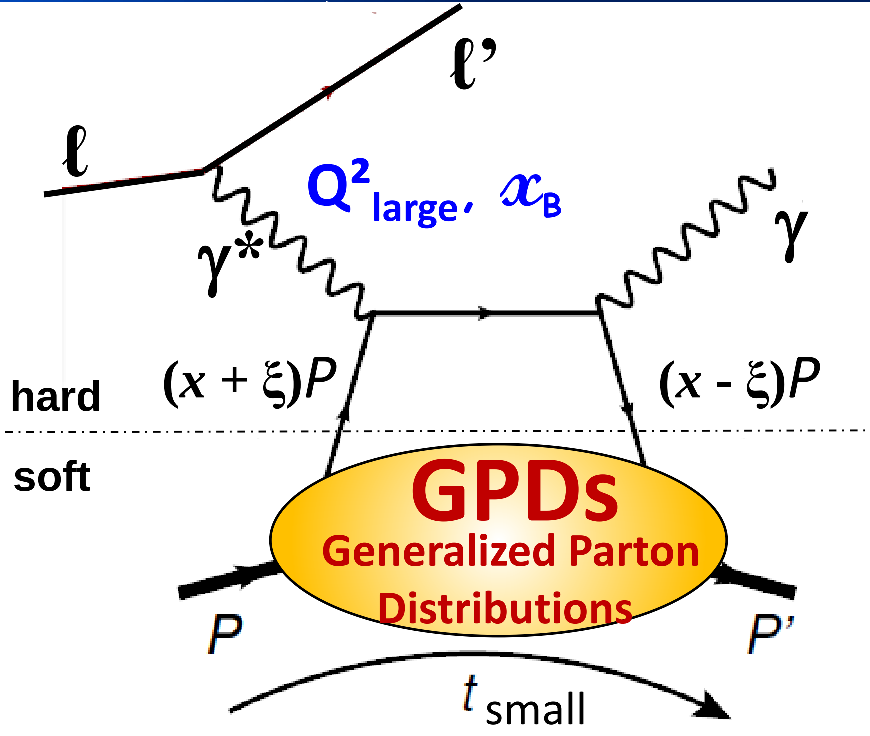
COMPASS:Two stage magnetic spectrometer
for **large angular & momentum acceptance**
Particle identification with
RICH, HCALs, ECALs and muon filters
NIM A 577 (2007) 455; NIM A 779 (2015) 69



2012:
1 month pilot run

2016 -17:
2 x 6 month
data taking

Deeply virtual Compton scattering (DVCS)



D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

DVCS: **ℓp→ ℓ' p' γ**
the golden channel
because it interferes with
the Bethe-Heitler process

also meson production
ℓp→ ℓ' p' π^0, ρ, ω or **ϕ** or **J/ψ…**

The GPDs depend on the following variables:

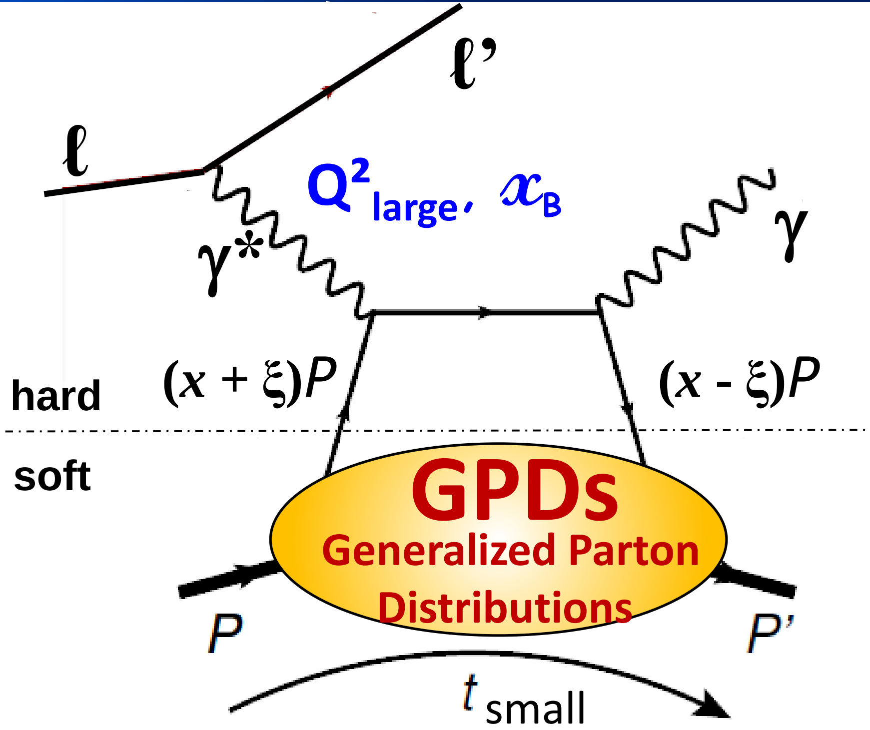
x: average
ξ: transferred
} quark longitudinal momentum fraction

t: proton momentum transfer squared
related to $b_\perp$ via Fourier transform
Q^2: virtuality of the virtual photon

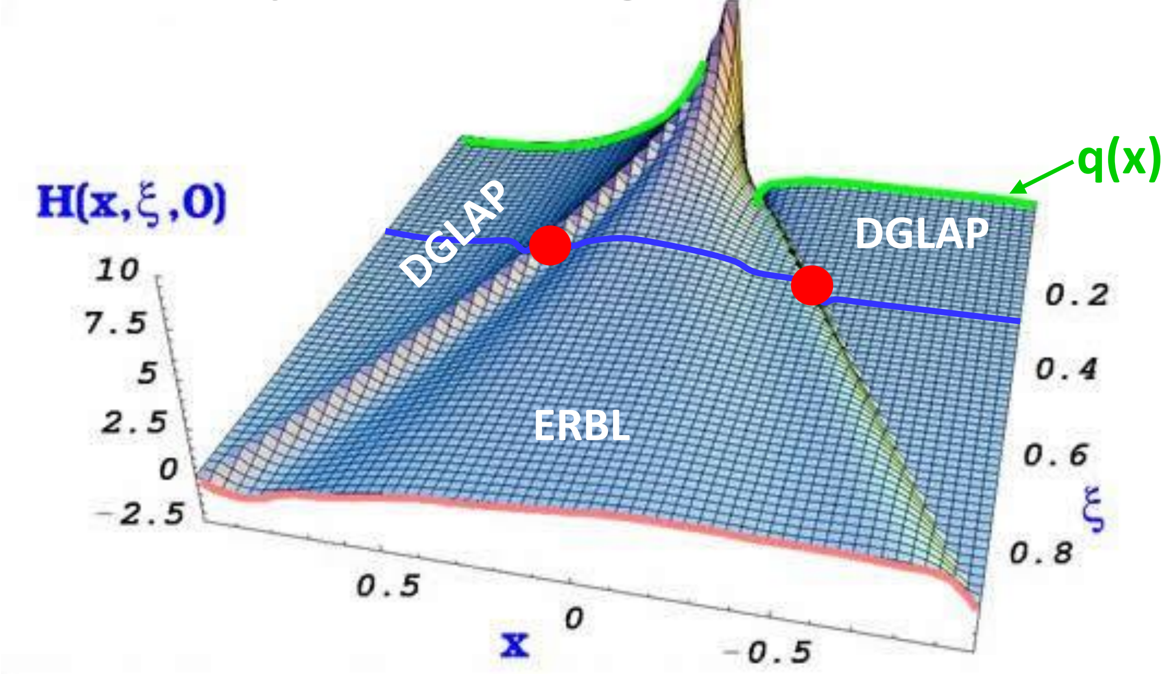
The variables measured in the experiment:

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

Deeply virtual Compton scattering (DVCS)



Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



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

Real part Imaginary part

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

In an experiment we measure Compton Form Factor $\mathcal{H}$

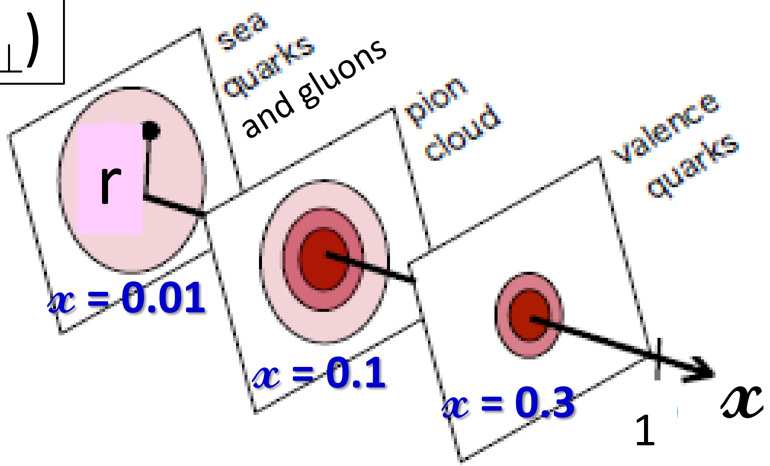
Deeply virtual Compton scattering (DVCS)

M. Burkardt, PRD66(2002)

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

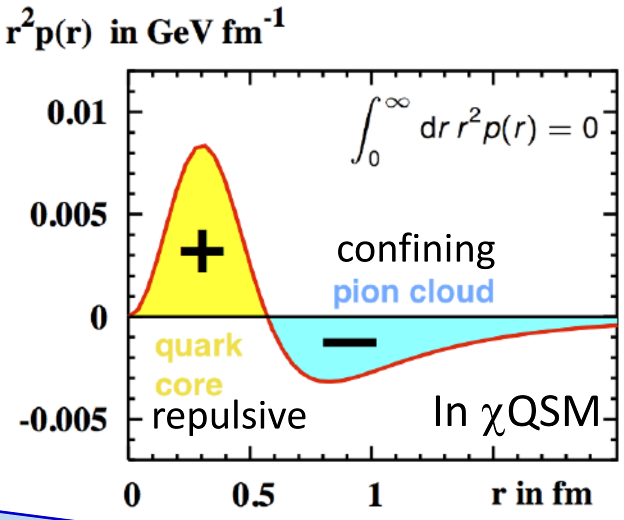
Mapping in the transverse plane

$q(x, b_\perp)$



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

Pressure Distribution



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

Real part **Imaginary part**

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

In an experiment we measure

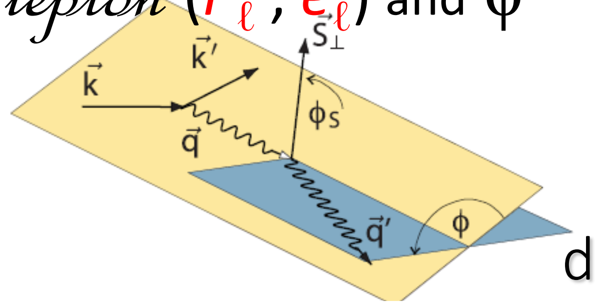
Compton Form Factor $\mathcal{H}$

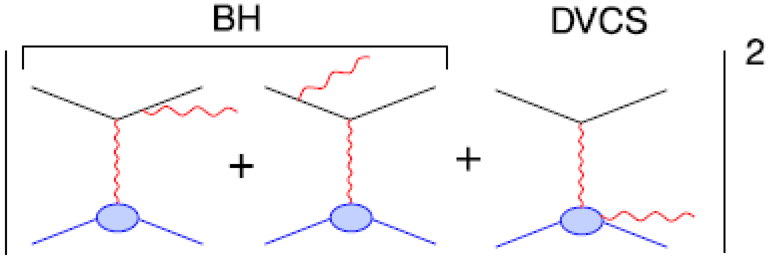
$$\mathcal{R}e\mathcal{H}(\xi,t) = \pi^{-1}\int_0^1 dx \frac{2x\ Im\mathcal{H}(x,t)}{x^2-\xi^2} + \Delta(t)$$

D-term $d_1(t)$

Exclusive single photon production (BH + DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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

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

Well known

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

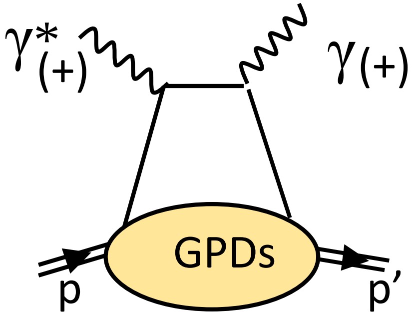
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

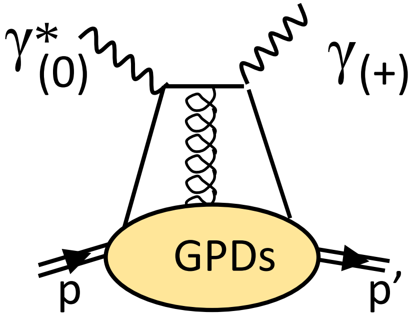
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

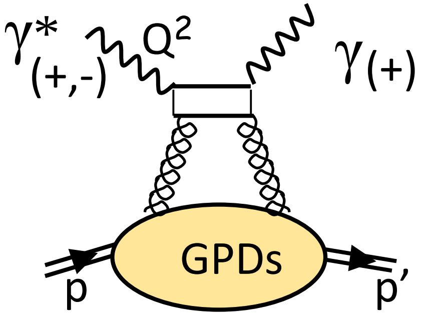
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



LO,Twist-2



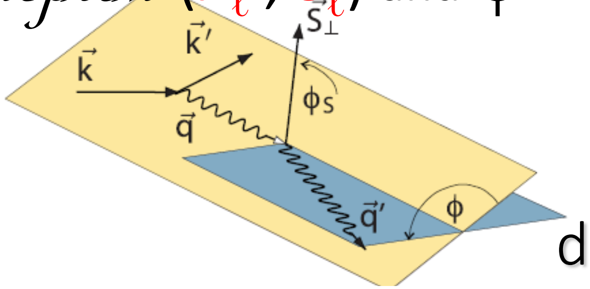
HT,Twist-3
suppressed by 1/Q

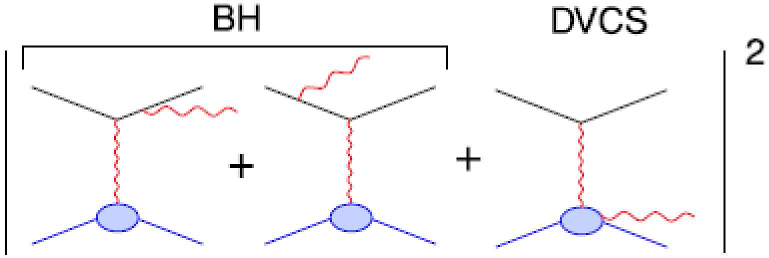


NLO,Twist-2
double helicity flip
suppressed by α_S

Exclusive single photon production (BH + DVCS)

lepton (P_ℓ , e_ℓ) and ϕ





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

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

Well known

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

With polarized electrons

$d\sigma^{\leftarrow} - d\sigma^{\rightarrow}$

With electrons and positrons

$d\sigma^{+} - d\sigma^{-}$

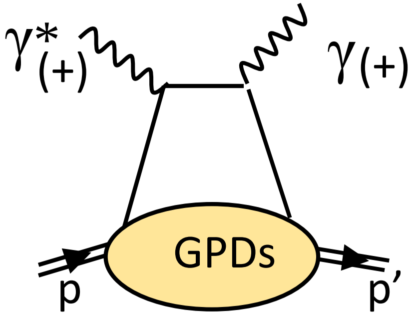
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

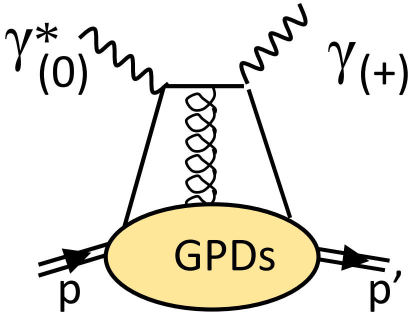
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

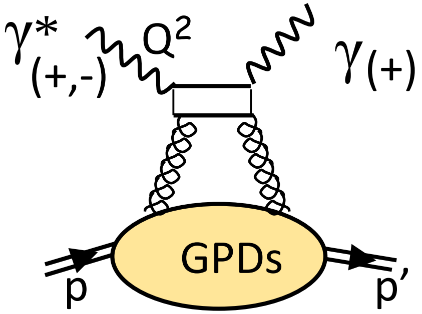
$$\mathrm{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



LO,Twist-2



HT,Twist-3
suppressed by 1/Q



NLO,Twist-2
double helicity flip
suppressed by α_S

Exclusive single photon production (BH + DVCS)

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

❶ **beam charge-spin sum**

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

❷ **difference**

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

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

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

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

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

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

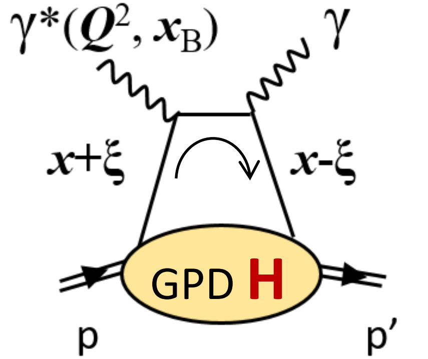
$\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$ ➔ $s_1^I \propto Im\,\mathcal{F}$

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

$\Delta \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$ ➔ $c_1^I \propto Re\,\mathcal{F}$

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

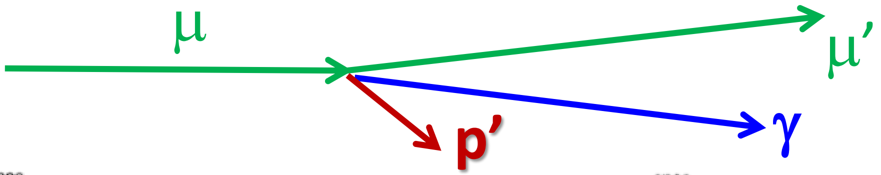
at small x_B
COMPASS domain



LO,Twist-2
$\xi \approx x_B/2$
x in the loop

COMPASS 2016 data Selection of exclusive single photon production

Comparison between the observables given by the spectro or by CAMERA



DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

1) $\Delta\varphi = \varphi^{cam} - \varphi^{spec}$

2) $\Delta p_T = p_T^{cam} - p_T^{spec}$

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

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

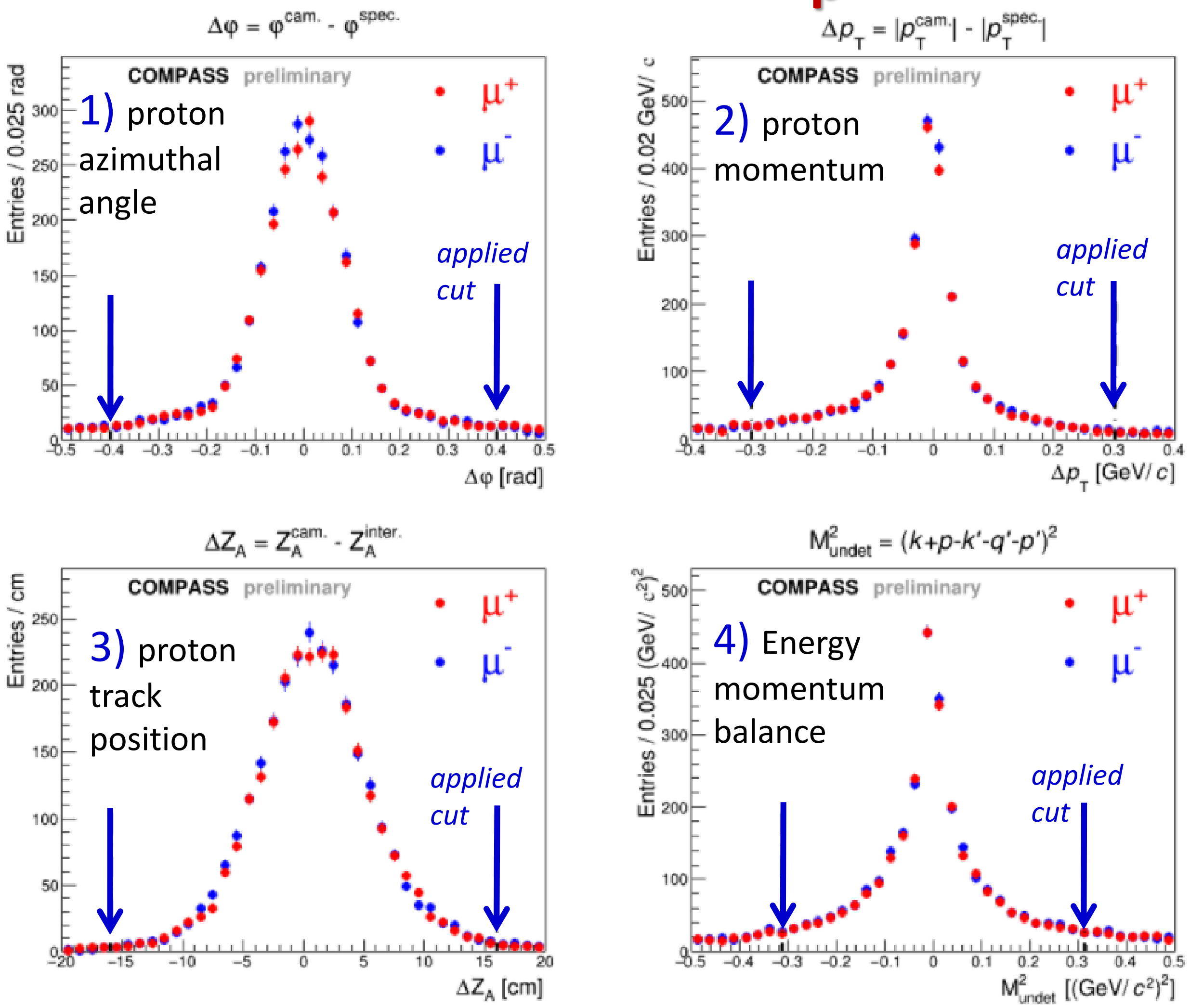
Good agreement between $\overleftarrow{\mu}^{+}$ **and** $\overrightarrow{\mu}^{-}$ yields

Important achievement for:

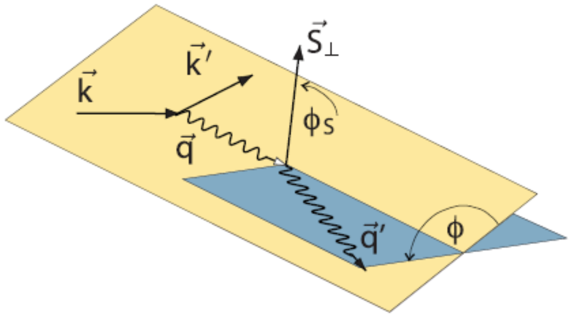
❶ $\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$ **Easier, done first**

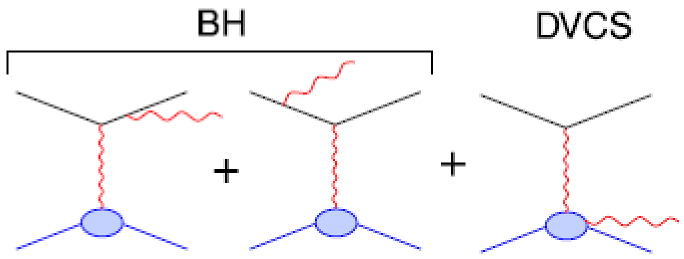
❷ $\Delta \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$ **Challenging, but promising**

Necessity to use the same μ^+ and μ^- flux



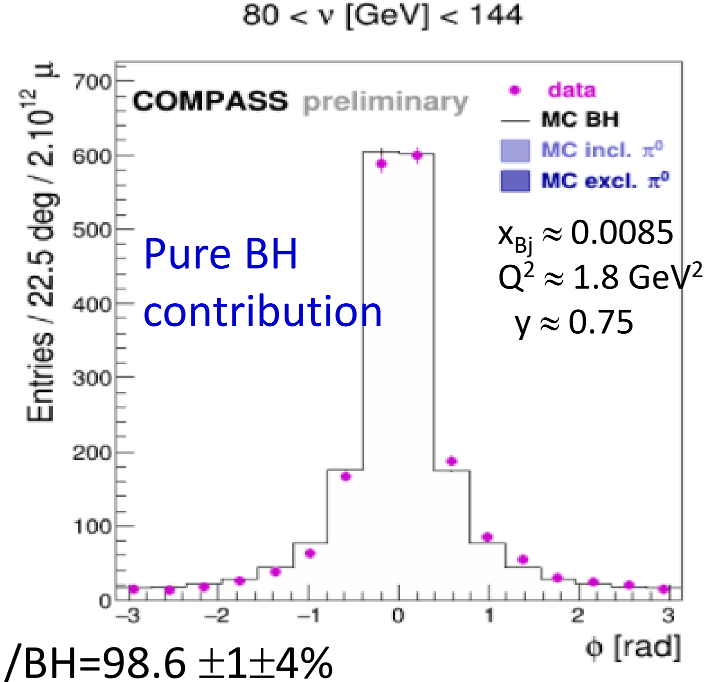
COMPASS 2016 data DVCS+BH cross section at E_μ=160 GeV

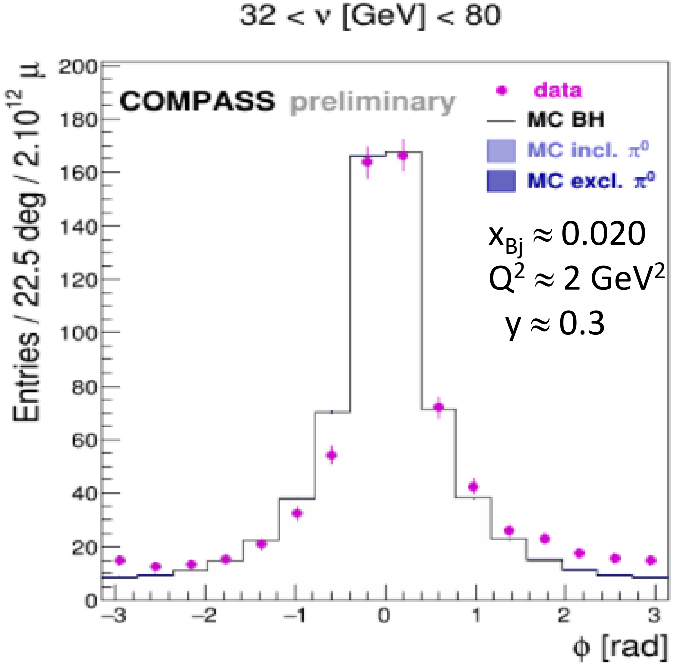


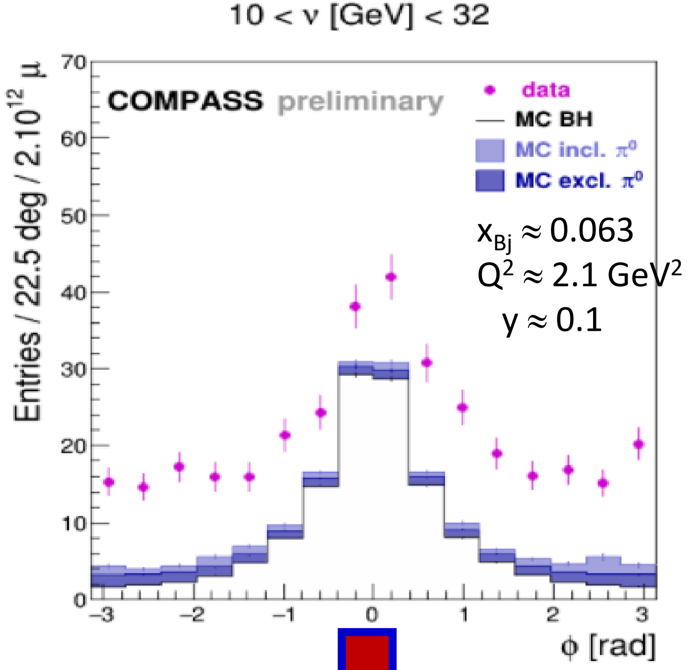


$$\Sigma = d\sigma\,(\overleftarrow{\mu^{+}}) + d\sigma\,(\overrightarrow{\mu^{-}})$$

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







Data/BH=98.6 ±1±4%

MC: BH contribution evaluated for the integrated luminosity
π° background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

DVCS above the BH contrib.

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

At COMPASS using polarized positive and negative muon beams:

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

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

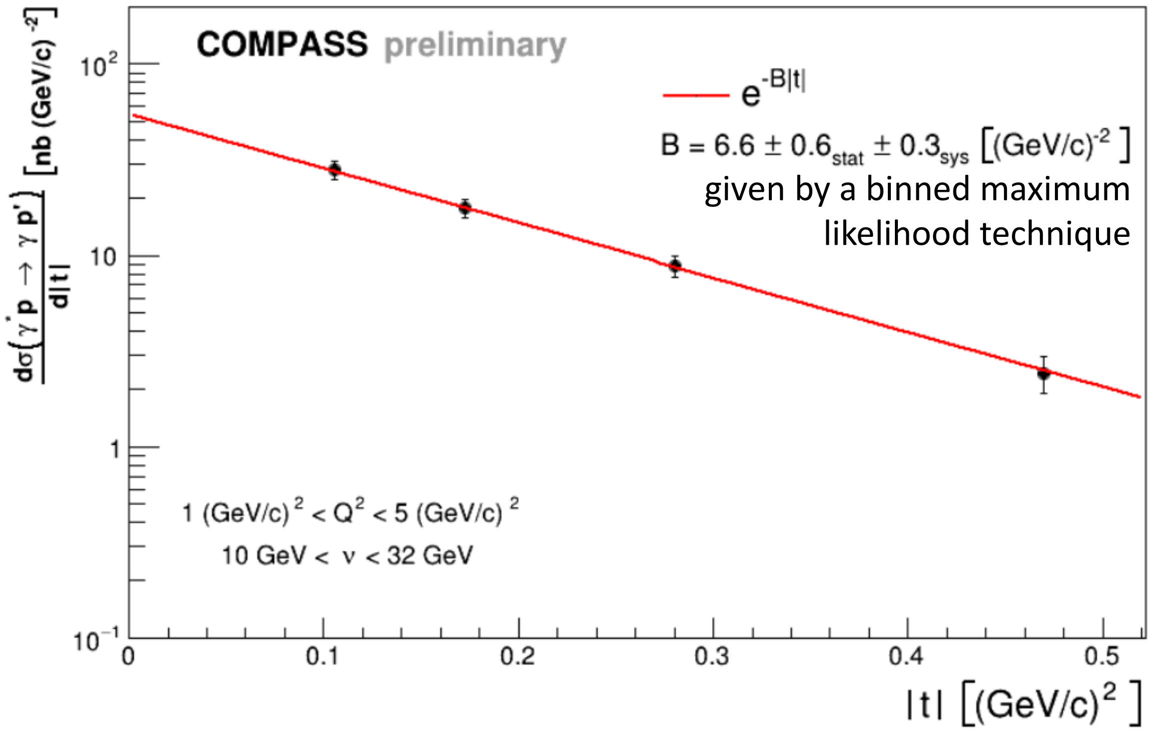
calculable
can be subtracted

All the other terms are cancelled in the integration over ϕ

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

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

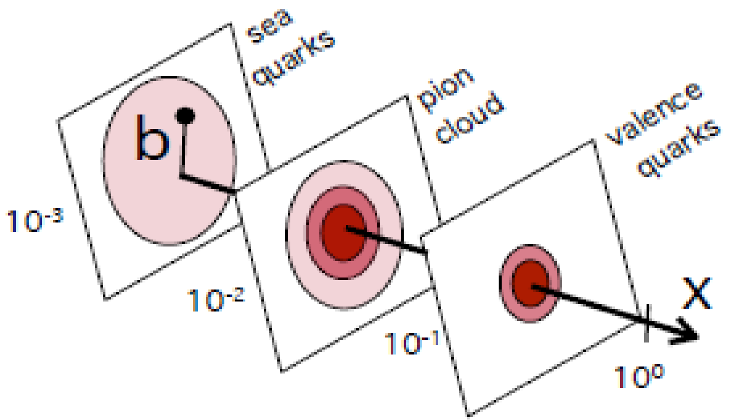
Flux for transverse
virtual photons



COMPASS 12-16 Transverse extention of partons in the sea quark range

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

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



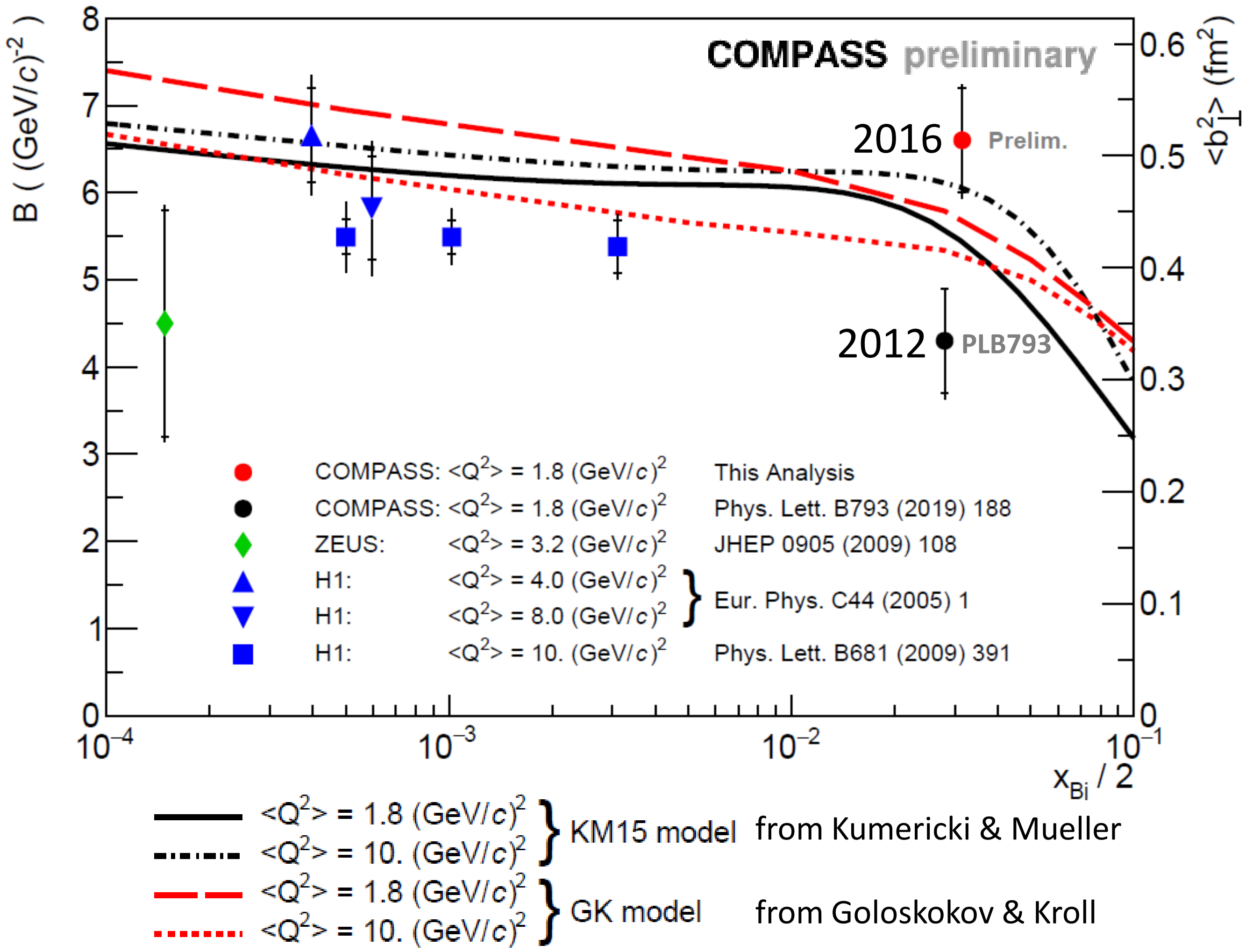
Improvements in 2016 analysis compared to 2012:

- same intensity with μ^+ and μ^- beam in 2016
- more advanced analysis with 2016 data
- π^0 contamination with different thresholds
- binning with 3 variables (t, Q^2, ν) or 4 variables (t, ϕ, Q^2, ν)
- Different bining in t

2012 statistics = Ref

2016 analysed statistics = 2.3 × Ref

2016+2017 expected statistics = 10 × Ref



Possible next steps for DVCS

✓ DVCS and the sum $\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$

➔ $c_0 \sim (\mathrm{Im}\mathcal{H})^2$ final conclusion using all the data sets 2012, 2016, 2017

➔ $s_1 \sim \mathrm{Im}\mathcal{H}$

constrain on $\mathrm{Im}\mathcal{H}$ and Transverse extension of partons

✓ DVCS and the difference $\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$

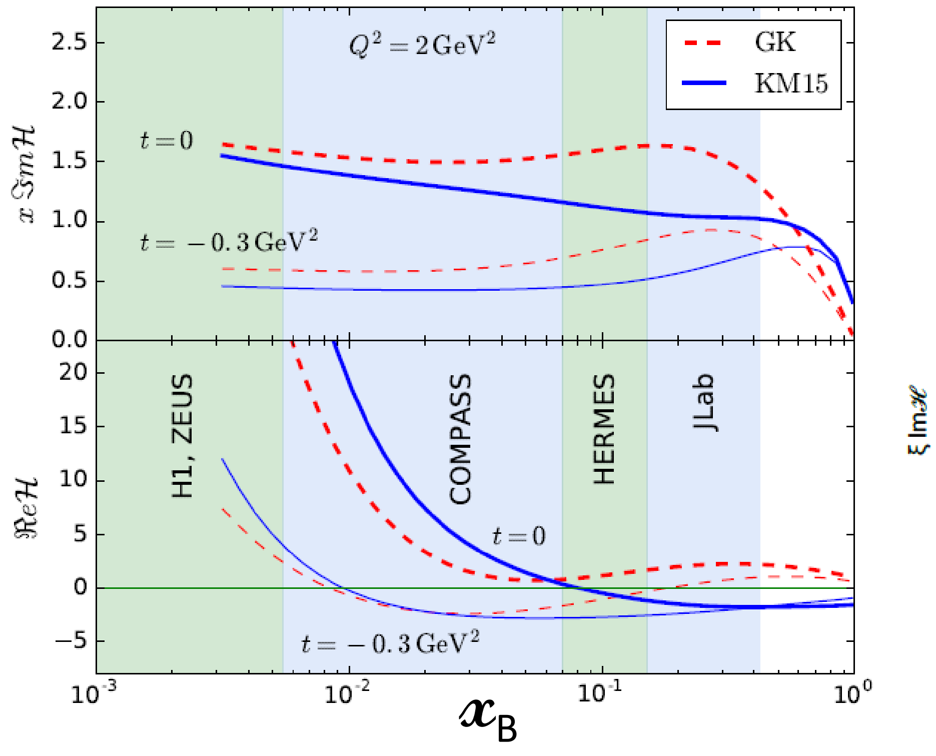
➔ c_1 and constrain on $\mathrm{Re}\mathcal{H}$ (>0 as H1 or <0 as HERMES)

for D-term and pressure distribution

ImH and ReH using global fits of the world data

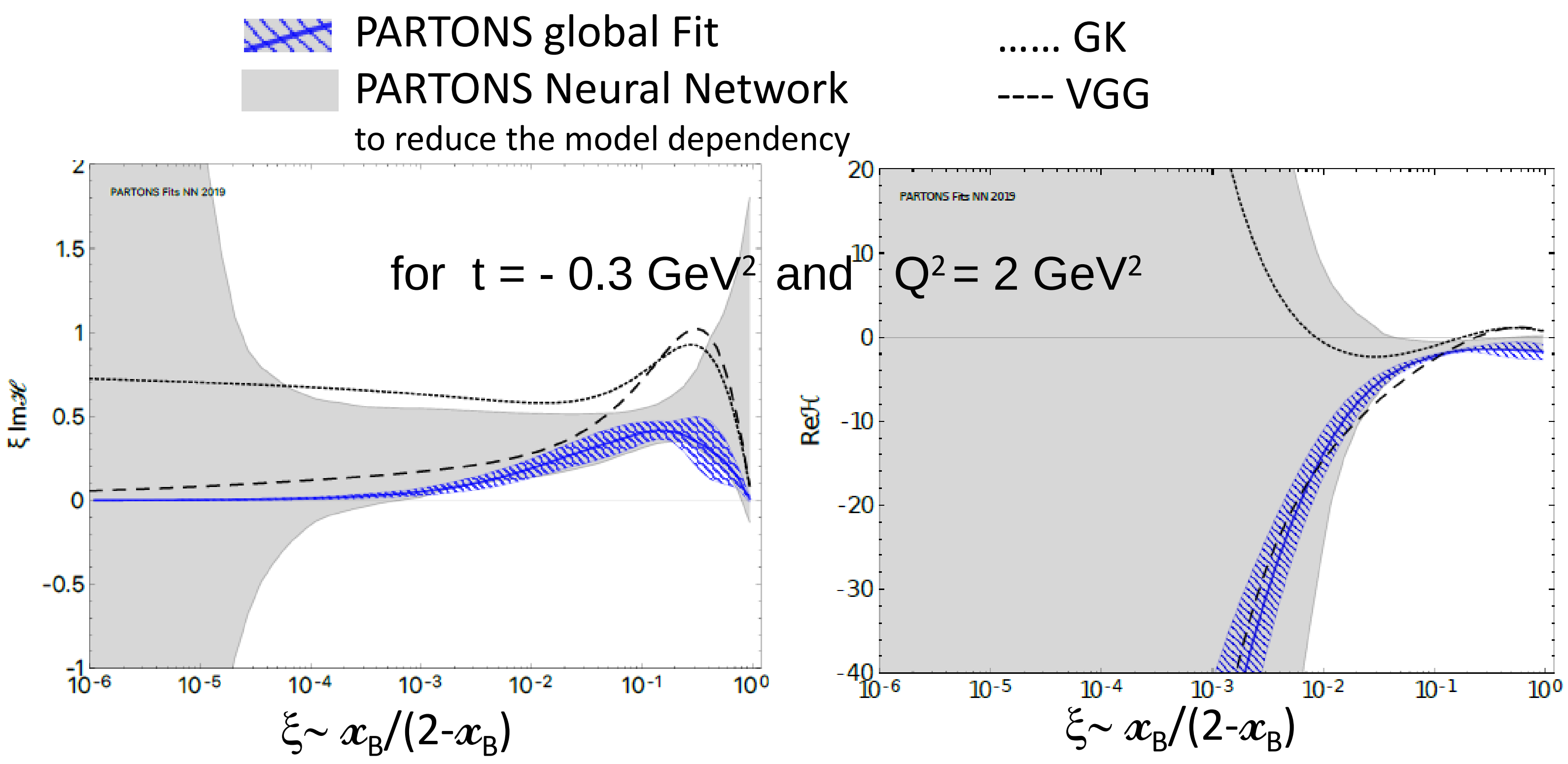
Global Fit KM15
Compared to GK Model GK

Kumericki, Mueller, NPB (2010) 841, private com.



Global Fits using PARTONS framework
Compared to GK and VGG Models

Moutarde, Sznajder, Wagner, Eur. Phys. J. C 79 (2019) 7, 614



Reminder with BCA: **ReH < 0 at HERMES**
> 0 at H1 (but not used in PARTONS?)

ReH is still poorly known (importance of **DVCS** with $\mu^\pm$ at COMPASS, $e^\pm$ at JLab or **TCS** at JLab and EIC)

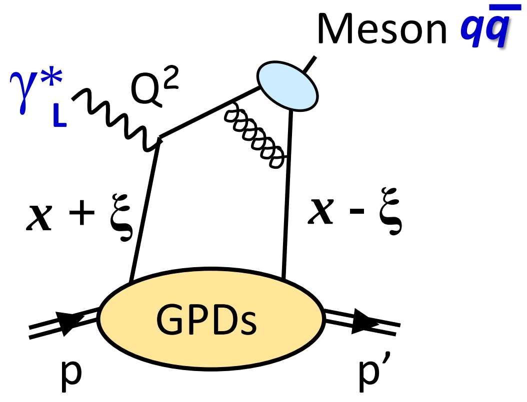
GPDs and Hard Exclusive Meson Production

Factorisation proven only for σ_L

The meson wave function

Is an additional non-perturbative term

Quark contribution



For Pseudo-Scalar Meson, as π^0

chiral-even GPDs: helicity of parton unchanged

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

+ chiral-odd or transversity GPDs: helicity of parton changed

$H_T^q(x, \xi, t)$ (as the transversity TMD)

related in the forward limit to transversity and the tensor charge

$\bar{E}_T^q = 2\,\tilde{H}_T^q + E_T^q$ (as the Boer-Mulders TMD)

related to the distortion of the transversely polarized quark distribution in the unpolarized proton and to its transverse anomalous magnetic moment

σ_T is asymptotically suppressed by $1/Q^2$ but large contribution observed

GK model: k_T of q and $\bar{q}$ and Sudakov suppression factor are considered

Chiral-odd GPDs with a twist-3 meson wave function

GPDs and Hard Exclusive π^0 Production

$$\frac{d^4\sigma_{\mu p}^{\leftrightarrows}}{dQ^2 d\nu d|t| d\phi} = \Gamma(Q^2,\nu,E_\mu)\,\frac{d^2\sigma_{\gamma^* p}^{\leftrightarrows}}{d|t| d\phi}$$

$$\frac{d^2\sigma_{\gamma^* p}^{\leftrightarrows}}{d|t| d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\frac{d\sigma_{LT}}{dt} \mp |P_l|\sqrt{2\epsilon(1-\epsilon)}\sin\phi\frac{d\sigma_{LT'}}{dt}\right]$$

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

At COMPASS $\langle\epsilon\rangle = 0.997$ $\quad |P_l|\sqrt{2\epsilon(1-\epsilon)} \simeq 0.06$

❶ **the beam charge-spin sum, or spin-independent cross section**

$$\Sigma \equiv \frac{d^2\sigma_{\gamma^* p}}{dt d\phi} = \frac{1}{2}\left(\frac{d^2\sigma_{\gamma^* p}^{\leftarrow}}{dt d\phi} + \frac{d^2\sigma_{\gamma^* p}^{\rightarrow}}{dt d\phi}\right)$$

❷ **the difference**

$$\Delta \equiv \left(\frac{d^2\sigma_{\gamma^* p}^{\leftarrow}}{dt d\phi} - \frac{d^2\sigma_{\gamma^* p}^{\rightarrow}}{dt d\phi}\right)$$

$$\frac{d\sigma_L}{dt} \propto \left[(1-\xi^2)|\langle\widetilde{H}\rangle|^2 - 2\xi^2\,\mathrm{Re}\left[\langle\widetilde{H}\rangle^*\langle\widetilde{E}\rangle\right] - \frac{t'}{4M^2}\xi^2|\langle\widetilde{E}\rangle|^2\right],$$

$$\frac{d\sigma_T}{dt} \propto \left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle\overline{E}_T\rangle|^2\right],$$

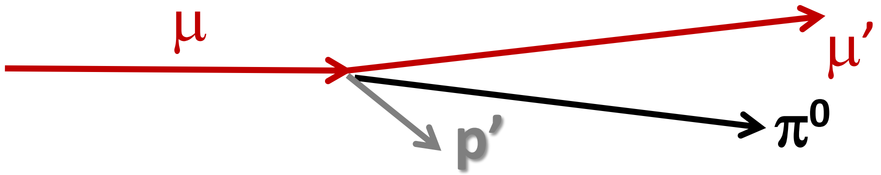
$$\frac{d\sigma_{TT}}{dt} \propto \frac{t'}{16M^2}|\langle\overline{E}_T\rangle|^2,$$

$$\frac{d\sigma_{LT}}{dt} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\;\mathrm{Re}\left[\langle H_T\rangle^*\langle\widetilde{E}\rangle + \langle\overline{E}_T\rangle^*\langle\widetilde{H}\rangle\right],$$

$$\frac{d\sigma_{LT'}}{dt} \propto \xi\sqrt{1-\xi^2}\sqrt{-t'}\;\mathrm{Im}\left[\langle H_T\rangle^*\langle\widetilde{E}\rangle + \langle\overline{E}_T\rangle^*\langle\widetilde{H}\rangle\right].$$

COMPASS 2016 Exclusive π^0 production on unpolarized proton

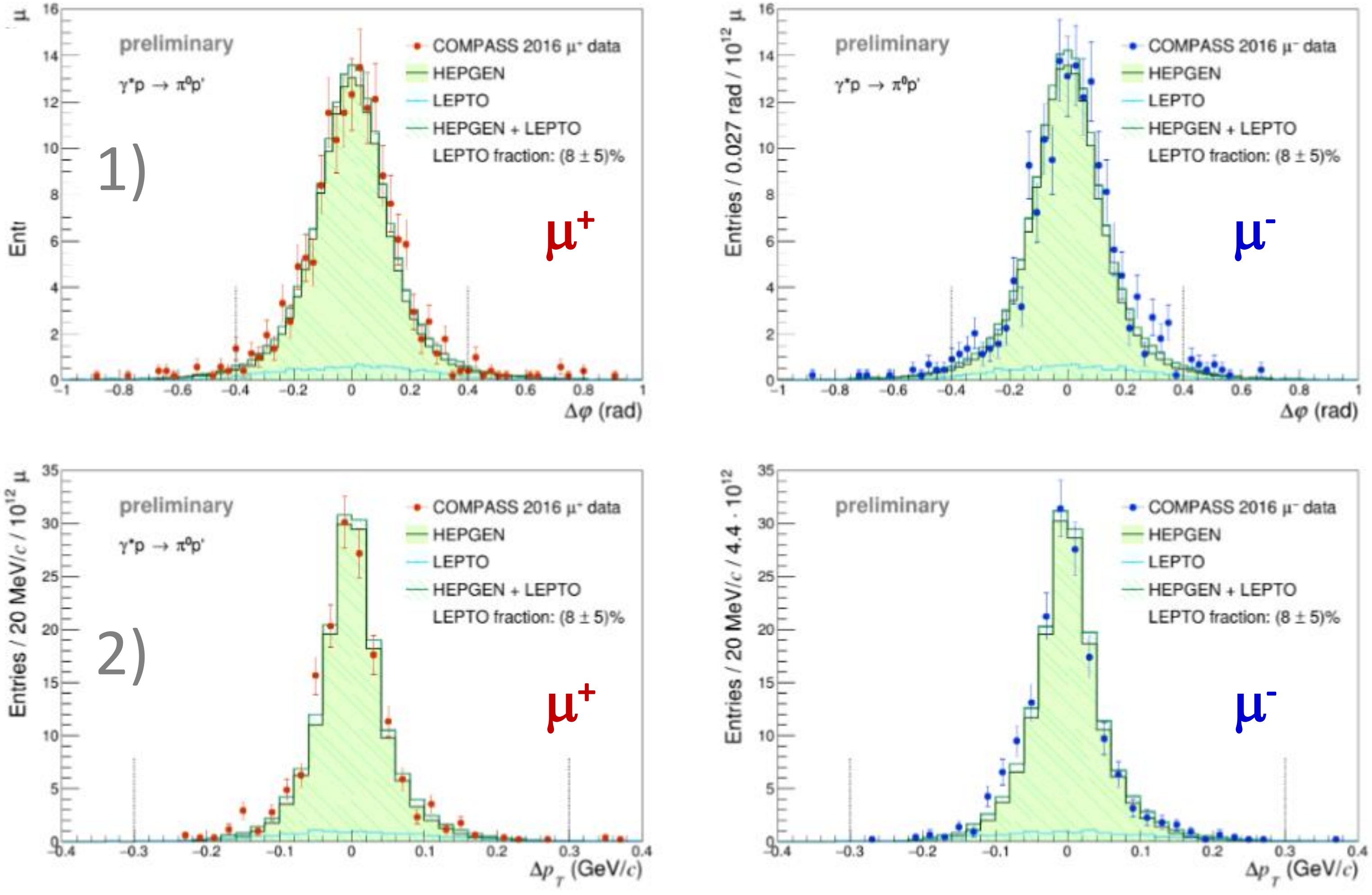
Comparison between the observables given by the spectro or by CAMERA



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

1) $\Delta\varphi = \varphi^{cam} - \varphi^{spec}$

2) $\Delta p_T = p_T^{cam} - p_T^{spec}$



Good description of the data with MC including

Exclusive π^0 production (HEPGEN)

+ Semi-inclusive π^0 production (LEPTO)

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

COMPASS 2016 Exclusive π^0 production on unpolarized proton

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

$\mu^\pm$ beams with opposite polarization

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

COMPASS
$\langle x_B\rangle = 0.13$
ε close to 1

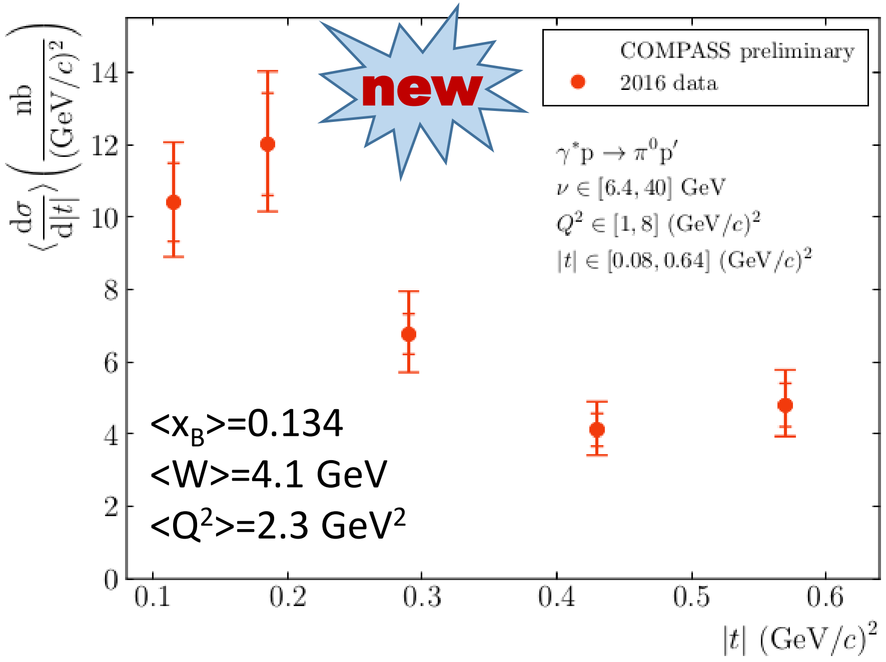
$$\frac{d\sigma_L}{dt}\propto\left|\langle\tilde{H}\rangle\right|^2-\frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

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

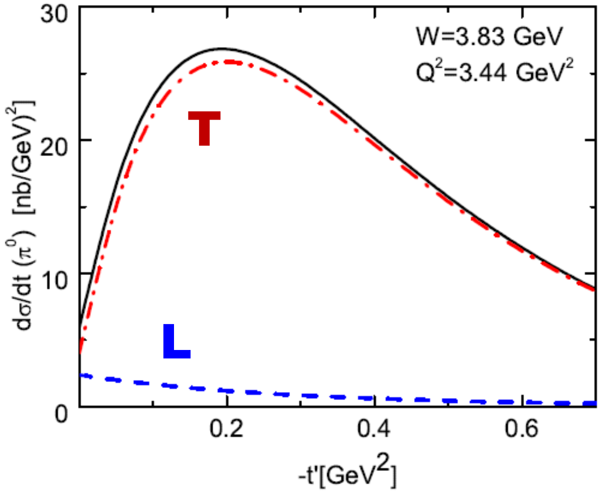
$$\frac{\sigma_{TT}}{dt}\propto\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\frac{\sigma_{LT}}{dt}\propto\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle+\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle\right]$$

$F_{\pi^0}=2/3F^u+1/3\,F^d$ $(\tilde{H}^u\ \tilde{H}^d)$ $(\tilde{E}^u\ \tilde{E}^d)$ $(H^u_T\ H^d_T)$ of opposite sign $(\bar{E}^u_T\ \bar{E}^d_T)$ of **same** sign ➔ **clearly enhanced contribution**



S. Goloskokov, P. Kroll, EPJC47 (2011)



Typical dip of the cross section as a function of $-t' = -(t-t_0) \approx |t|$

$|t_0| \approx 10^{-2}$ GeV^2

COMPASS 2016 Exclusive π^0 production on unpolarized proton

$\mu^{\pm}$ p → $\mu^{\pm}$ π^0 p

$\mu^{\pm}$ beams with opposite polarization

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

COMPASS
$\langle x_B\rangle$= 0.13
ε close to 1

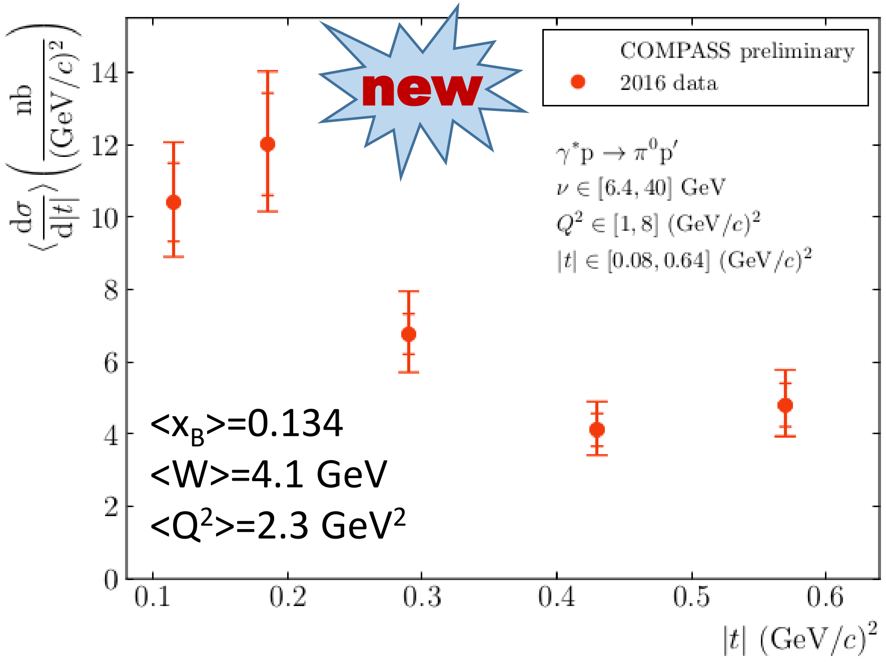
$$\frac{d\sigma_L}{dt}\propto\left|\langle\tilde{H}\rangle\right|^2-\frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

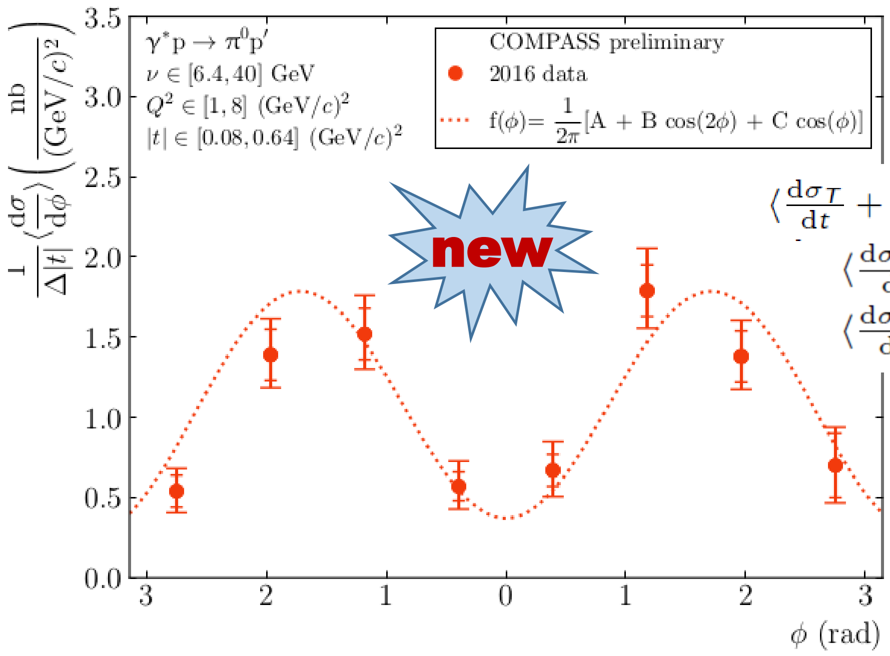
$$\frac{d\sigma_T}{dt}\propto|\langle H_T\rangle|^2-\frac{t'}{8m^2}|\langle\bar{E}_T\rangle|^2$$

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

$$\frac{\sigma_{LT}}{dt}\propto\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle+\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle\right]$$

$F\pi^0=2/3F^u+1/3\,F^d$ $(\tilde{H}^u\ \tilde{H}^d)$ $(\tilde{E}^u\ \tilde{E}^d)$ $(H^u_T\ H^d_T)$ of opposite sign $(\bar{E}^u_T\ \bar{E}^d_T)$ of **same** sign → **clearly enhanced contribution**





$$\left\langle\frac{d\sigma_T}{dt}+\epsilon\frac{d\sigma_L}{dt}\right\rangle=\left(6.6\pm0.3_{stat}{}^{+\,0.9}_{-\,0.8}\Big|_{sys}\right)\ \frac{nb}{(GeV/c)^2}$$

$$\left\langle\frac{d\sigma_{TT}}{dt}\right\rangle=\left(-4.6\pm0.5_{stat}{}^{+\,0.3}_{-\,0.3}\Big|_{sys}\right)\ \frac{nb}{(GeV/c)^2}$$

$$\left\langle\frac{d\sigma_{LT}}{dt}\right\rangle=\left(0.2\pm0.2_{stat}{}^{+\,0.2}_{-\,0.2}\Big|_{sys}\right)\ \frac{nb}{(GeV/c)^2}$$

$\langle\epsilon\rangle$= 0.997

$|\sigma_{TT}|$ almost as large as $\sigma_T+\varepsilon\,\sigma_L$

→ impact of $\bar{E}_T$

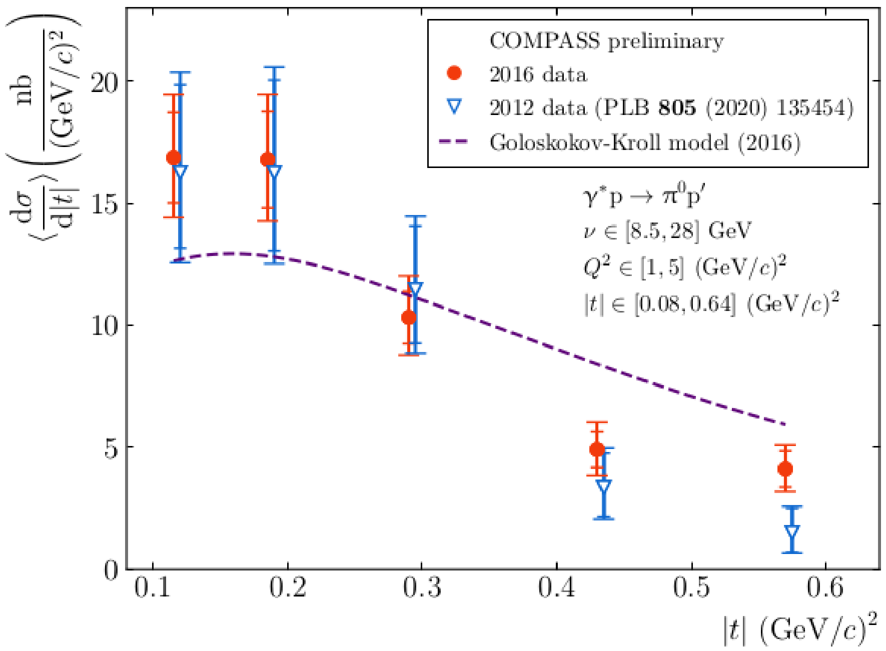
σ_{LT} rather small

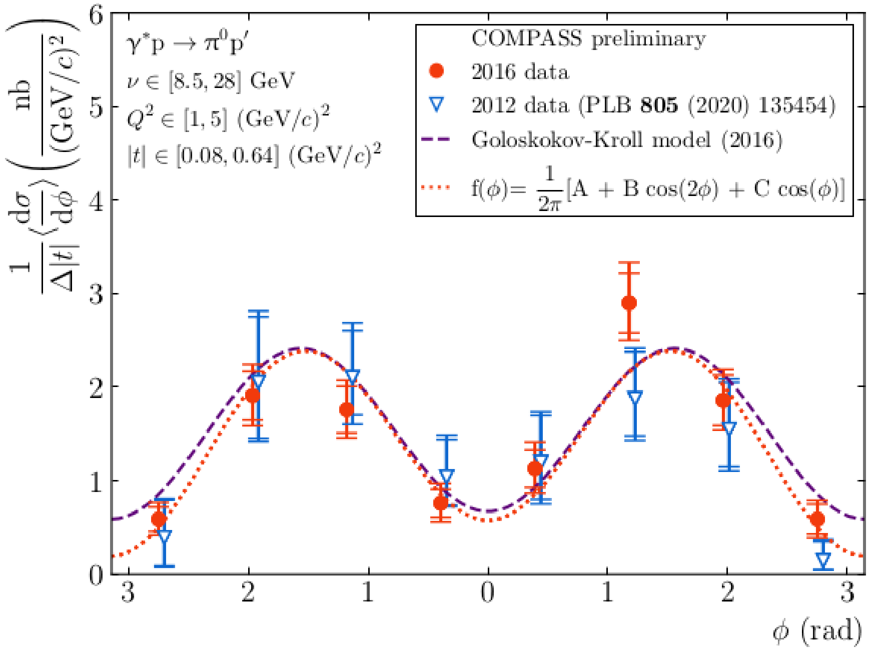
Cross section for $\upsilon\in[6.4, 40]$ GeV and $Q^2\in[1, 8]$ GeV^2 $\langle x_B\rangle$ = 0.13

COMPASS 2012-16 Exclusive π^0 production on unpolarized proton

2016 kinematic domain: Cross section for $\upsilon \in [6.4, 40]$ GeV and $Q^2 \in [1, 8]$ GeV^2 $\langle x_B \rangle = 0.13$

2012 kinematic domain for comparison: $\upsilon \in [8.5, 28]$ GeV and $Q^2 \in [1, 5]$ GeV^2 $\langle x_B \rangle = 0.10$





new

2012 data:

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

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

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

$\langle \epsilon \rangle = 0.996$

2016 data:

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

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

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

$\langle \epsilon \rangle = 0.996$

$|\sigma_{TT}|$ almost as large as $\sigma_T + \varepsilon\,\sigma_L$

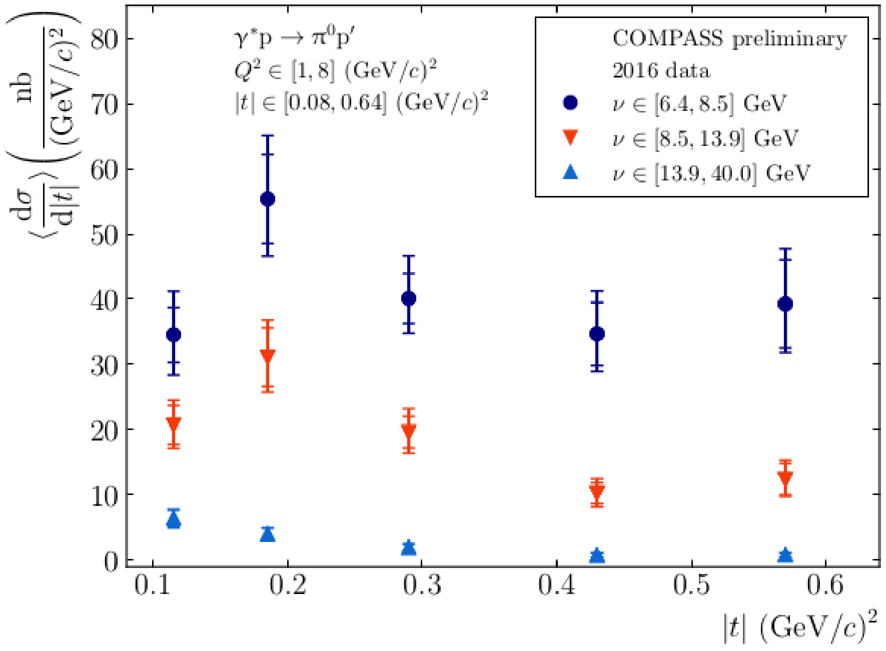
➔ impact of $\bar{E}_T$

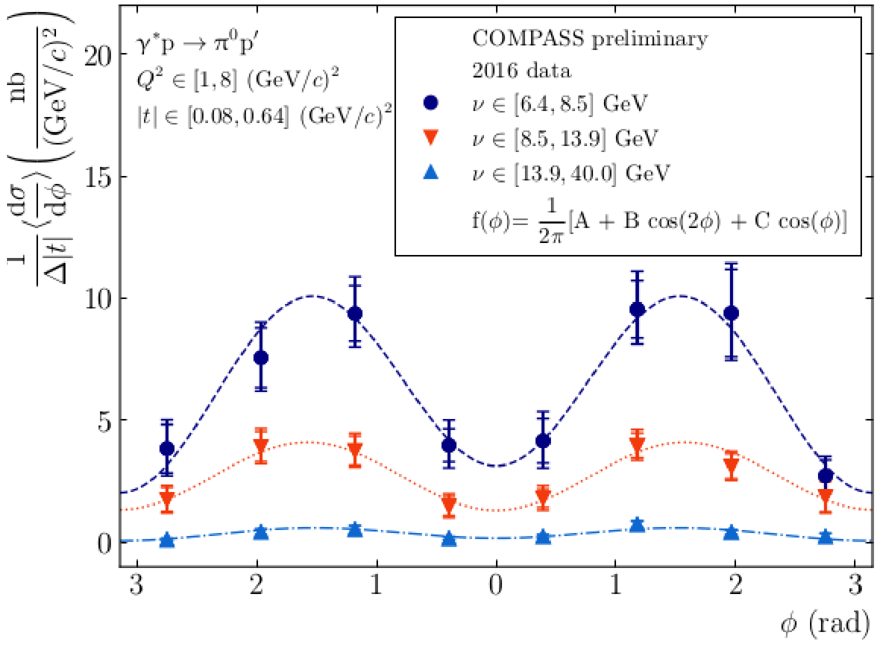
σ_{LT} rather small

Exclusive π^0 production on unpolarized proton

Evolution of the cross section with υ: σ ↘ when υ ↗

new





➔ Extraction of

$\sigma_T + \varepsilon \sigma_L$

σ_{TT}

σ_{LT}

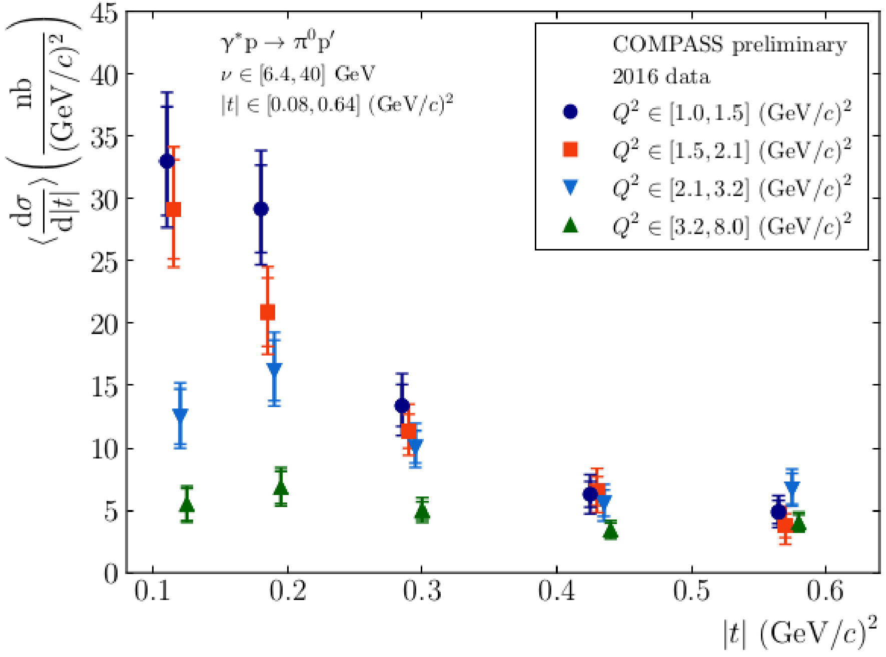
in 3 υ bins

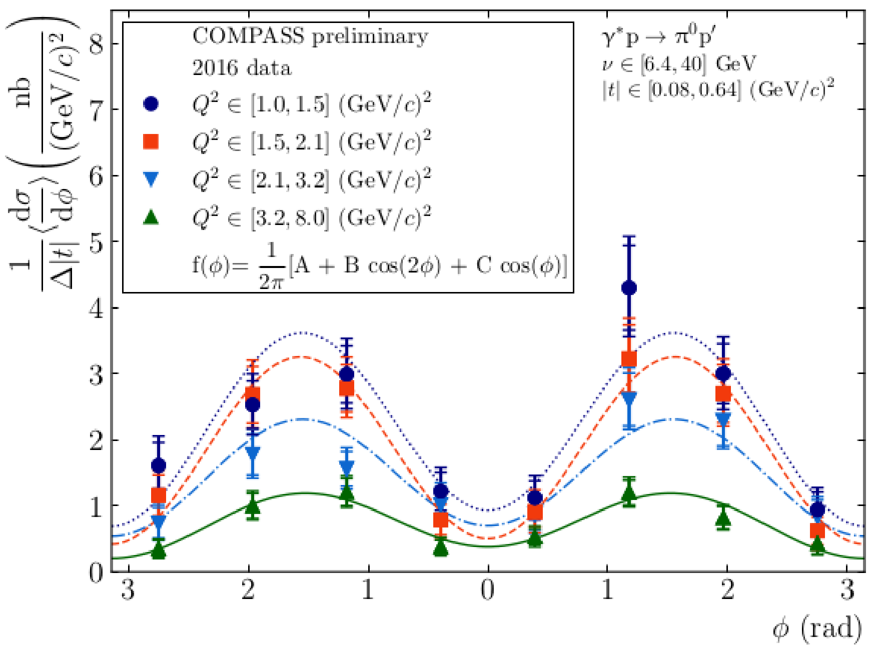
	$\langle \nu \rangle$ [GeV]	$\langle Q^2 \rangle$ [GeV^2/c^2]	$\langle x_B \rangle$	$\langle \epsilon \rangle$
$\nu \in [6.4, 8.5]$	7.35	2.15	0.156	0.999
$\nu \in [8.5, 13.9]$	10.32	2.50	0.131	0.998
$\nu \in [13.9, 40.0]$	21.08	2.09	0.057	0.989

COMPASS 2016 Exclusive π^0 production on unpolarized proton

Evolution of the cross section with Q^2 : σ ↘ when Q^2 ↗

new





➔ Extraction of

$\sigma_T + \varepsilon \sigma_L$

σ_{TT}

σ_{LT}

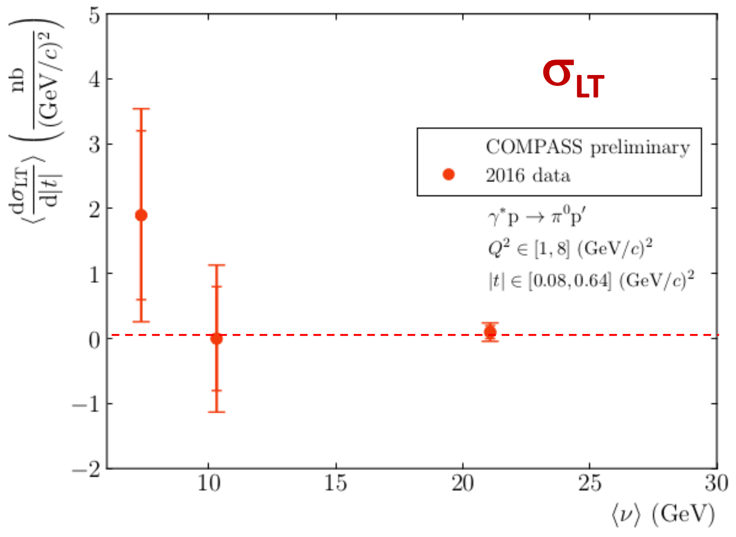
in 4 Q^2 bins

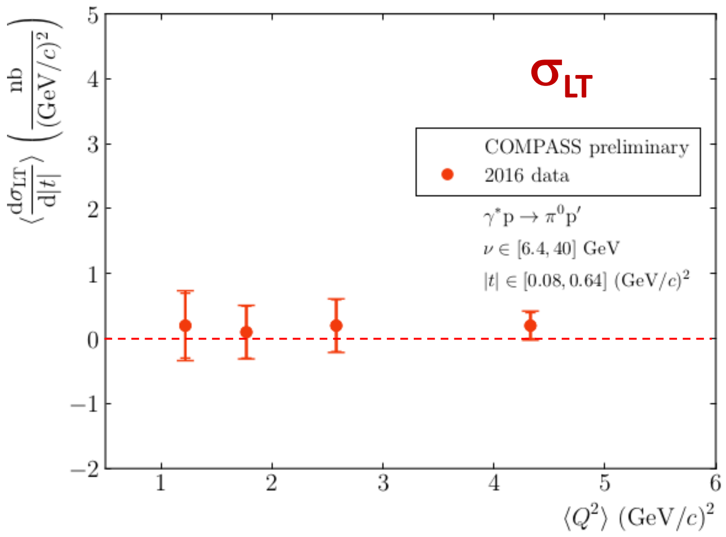
	$\langle Q^2 \rangle$ [GeV^2/c^2]	$\langle \nu \rangle$ [GeV]	$\langle x_B \rangle$	$\langle \epsilon \rangle$
$Q^2 \in [1.0, 1.5]$	1.22	10.54	0.072	0.997
$Q^2 \in [1.5, 2.1]$	1.77	9.81	0.109	0.997
$Q^2 \in [2.1, 3.2]$	2.58	9.82	0.157	0.997
$Q^2 \in [3.2, 8.0]$	4.33	10.39	0.247	0.997

COMPASS 2016 Exclusive π^0 production on unpolarized proton

Evolution of the structure functions with υ and Q^2

new



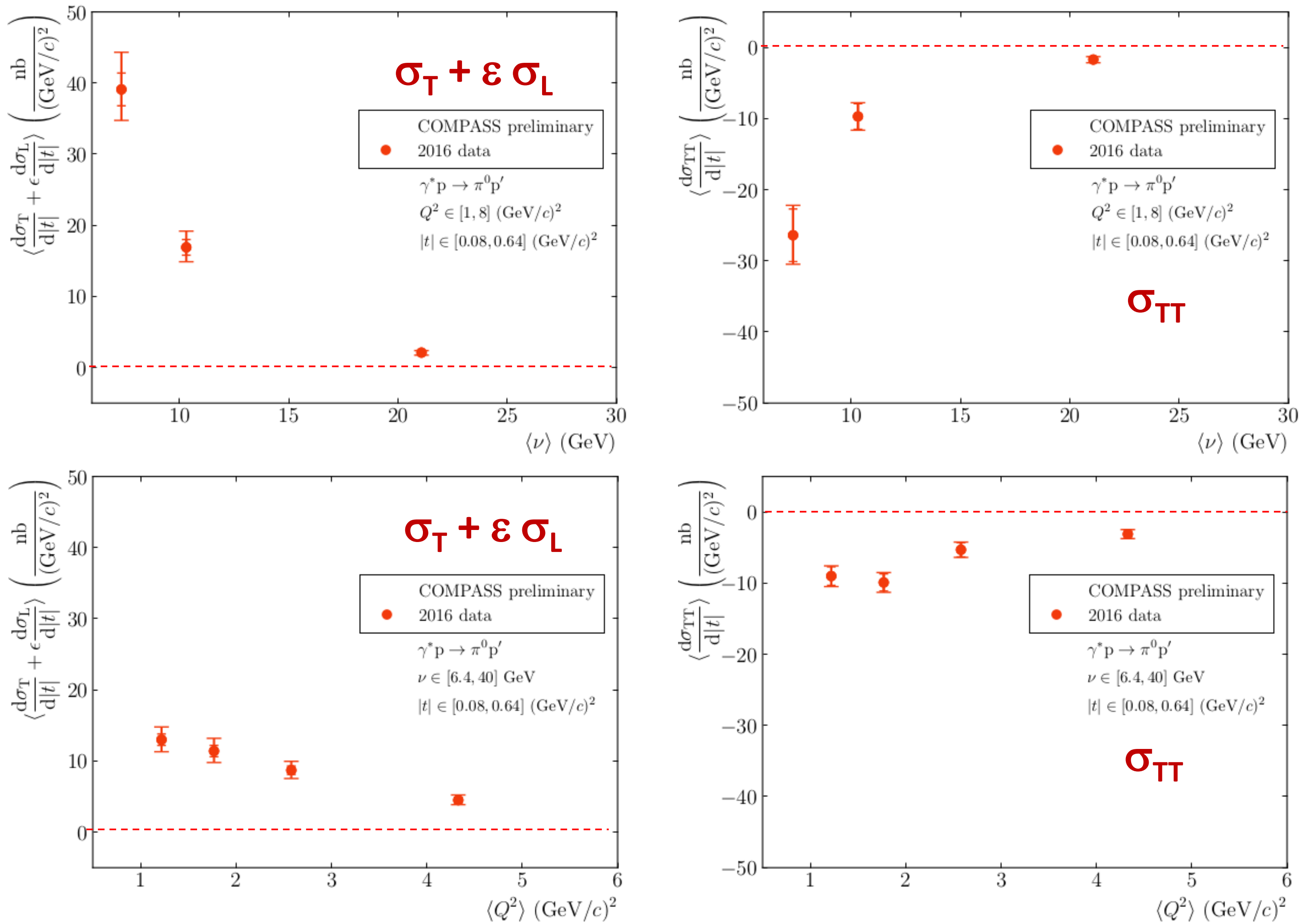


σ_{LT} close to 0

COMPASS 2016 Exclusive π^0 production on unpolarized proton

Evolution of the structure functions with υ and Q^2

new



Both $\sigma_T + \varepsilon\,\sigma_L$ and σ_{TT}
large evolution with υ
small evolution with Q^2

Impact of these data for modeling $\bar{E}_T$ (and other GPDs) contributions at twist-3 and NLO

Recent work on twist-3 contribution
G. Duplančić, P. Kroll and K. Passek-Kumerički, PRD109 (2024)

Also S. Golosgokov et al.
S. Liuti et al.

Lessons on experiments with data collected with ℓ+ and ℓ- beams

For ex: $\sigma^{\pm} = (\varepsilon\, \sigma_L + \sigma_T) + a \cos2\phi\, \sigma_{TT} + b \cos\phi\, \sigma_{LT} + c \sin\phi\, \sigma_{LT'}$

With polarized electron beams we change continously from one to the other polarization to build directly only 1 observable:
asymmetry = (N+ - N-) / (N+ + N-) gives the sinϕ term with small systematic errors

Richness but complexity dealing with runs with ℓ+ and ℓ- beams ➔ we build 4 correlated observables or cross sections:

σ^+	➔ Constant, cos ϕ, cos 2 ϕ and sin ϕ	terms
σ^-	➔ Constant, cos ϕ, cos 2 ϕ and sin ϕ	terms
$\sigma^+ + \sigma^-$	➔ Constant, cos ϕ, cos 2 ϕ	terms
$\sigma^+ - \sigma^-$	➔ sin ϕ	term

- ✓ Necessity of accurate acceptance and efficiency determination
- ✓ Requirement of detector stability for ℓ+ and ℓ- runs not taken at the same time
- ✓ Background depending on the lepton flux (recommendation to use the same lepton flux)
- ✓ Relative positions of background (mainly electrons) and signal are not located at the same place in the detectors with ℓ+ and ℓ- beams ➔ precise MC description
- ✓ Radiative corrections of opposite sign for ℓ+ and ℓ- for the 2 photon exchange (to be discussed with A. Afanasev....)