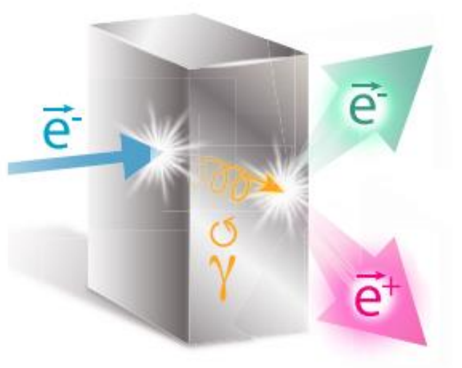
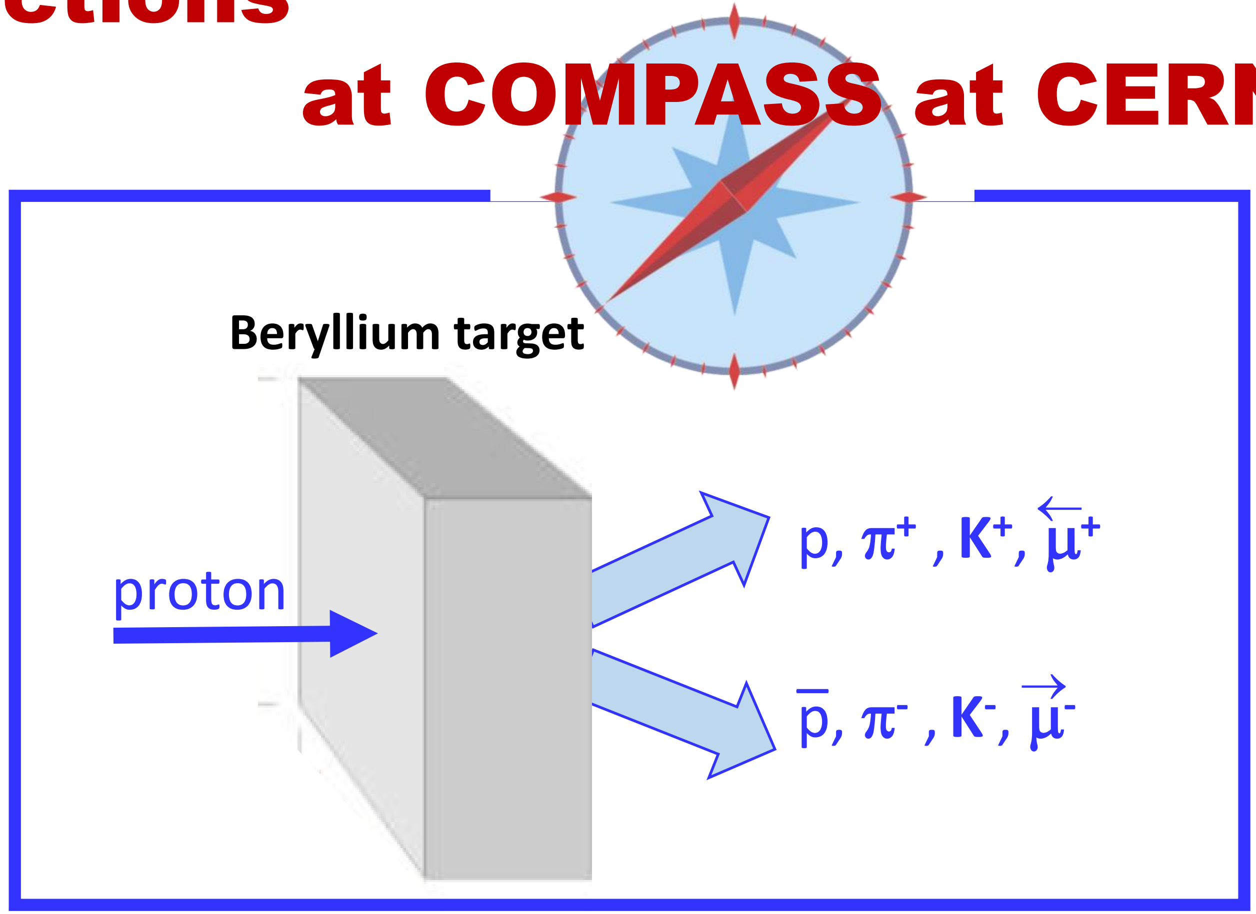
Use of positive and negative polarized muon beams to study exclusive reactions at COMPASS at CERN

Positron beams at JLab

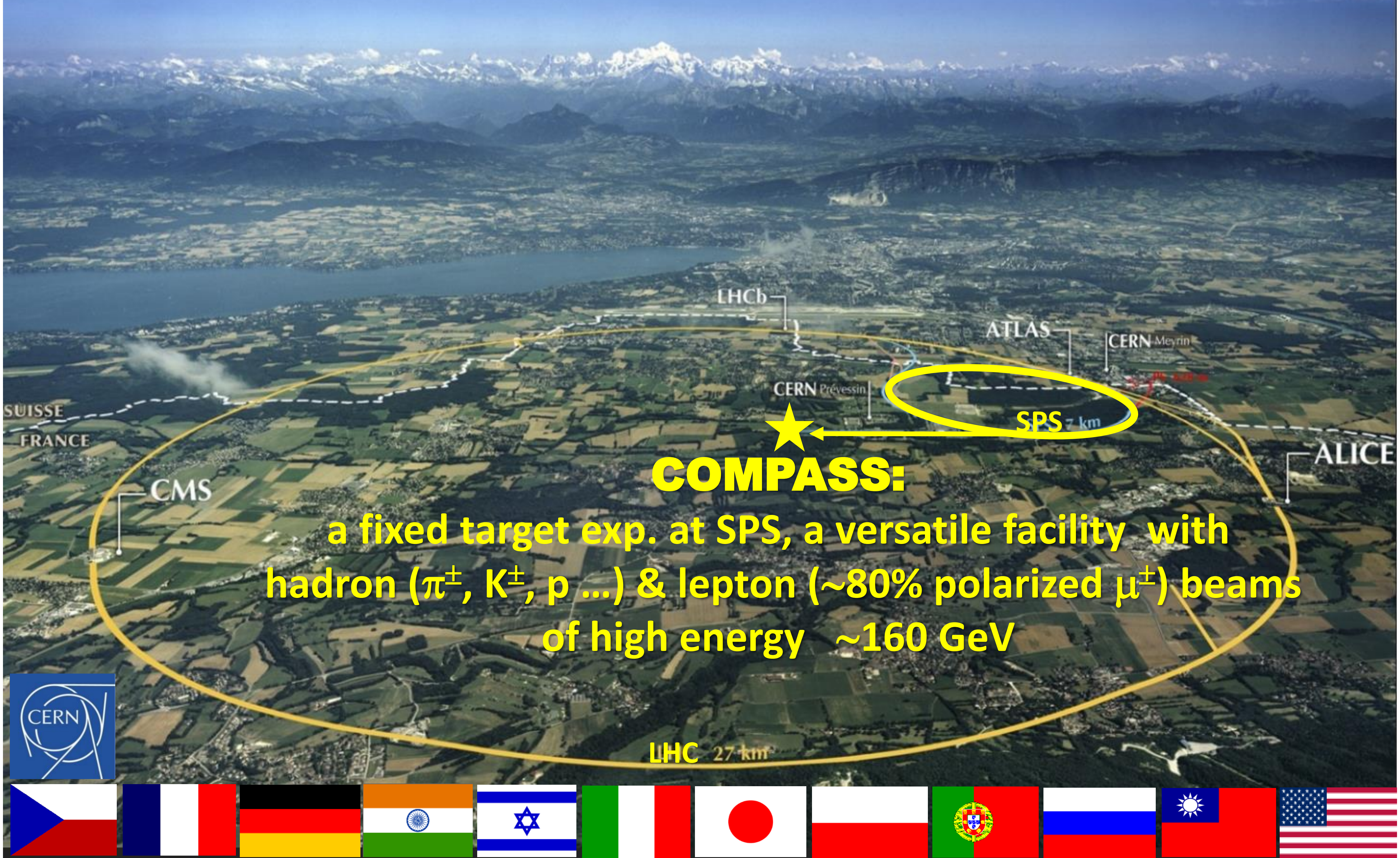




Positron Working Group Workshop, Washington

Nicole d'Hose, CEA, Université Paris-Saclay

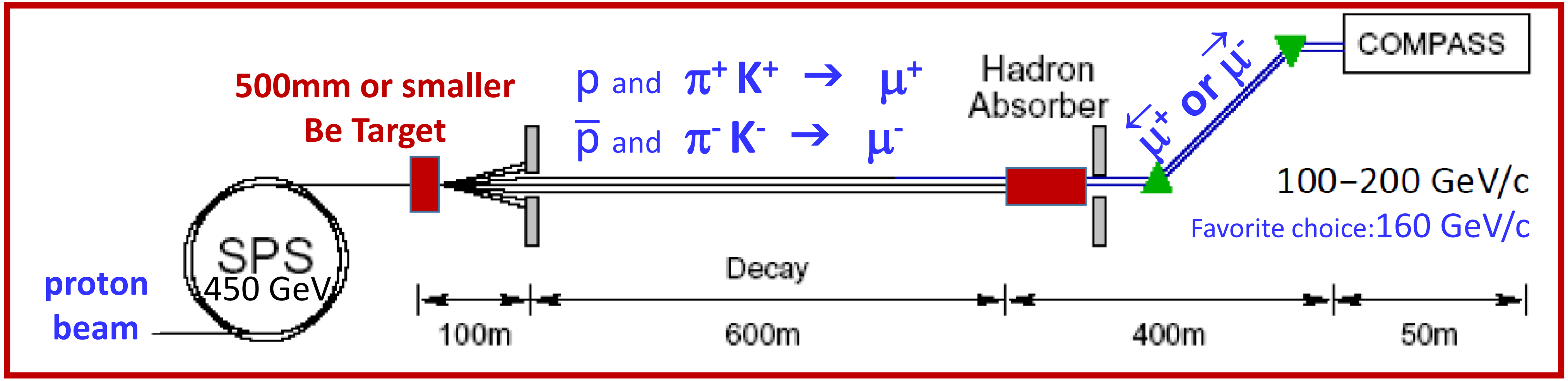
20 March 2024



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

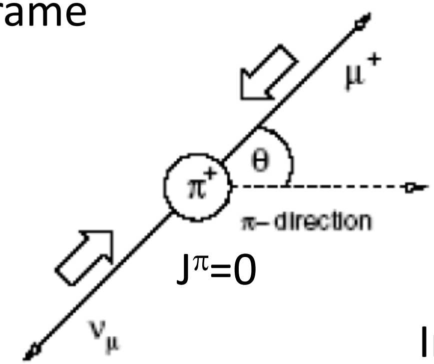
Positive and Negative Polarized Muon Beam at COMPASS

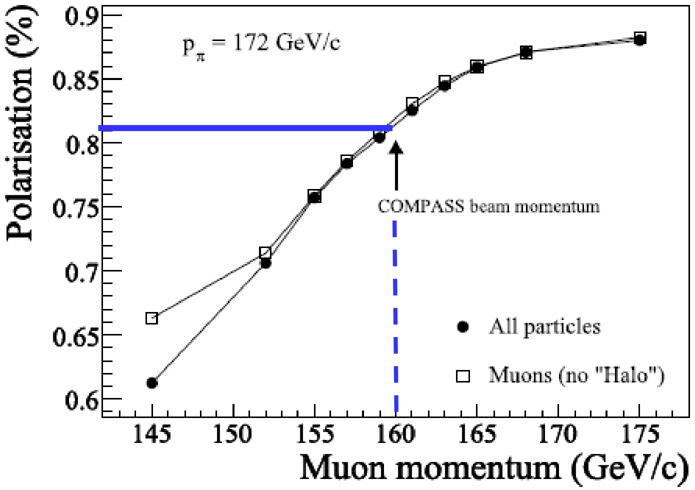


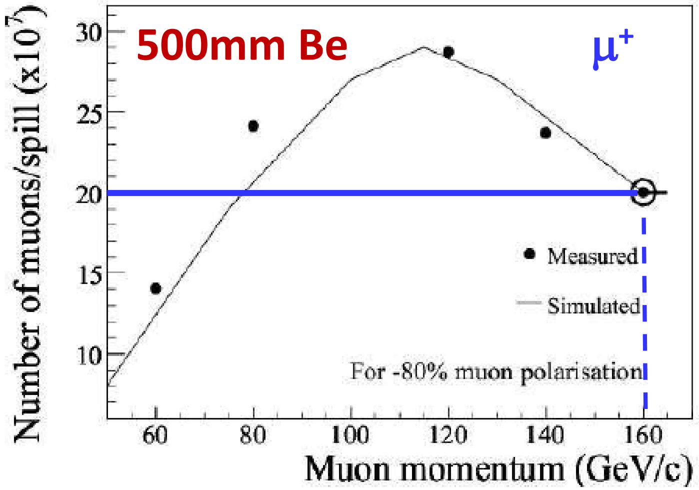
Weak decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$

Parity violation and helicity conservation

the muons are 100% polarized in the pion rest frame







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

Left-handed ν_μ and μ^+

Right-handed $\bar{\nu}_\mu$ and μ^-

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:

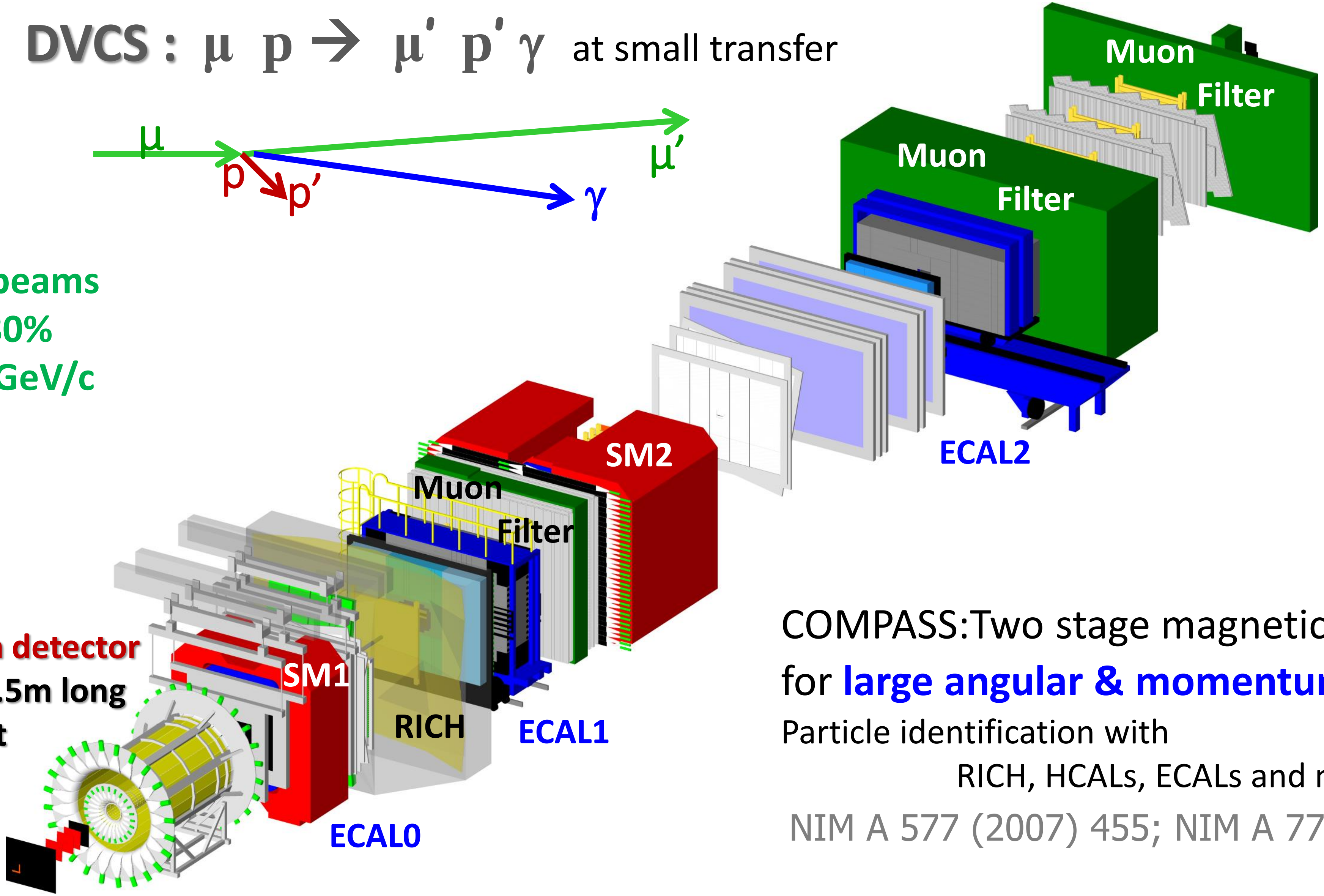
Advantage of positive and negative polarized muon beams for:

1. Deeply Virtual Compton Scattering (DVCS)

2. Exclusive π^0 production

Measurement of exclusive cross sections at COMPASS

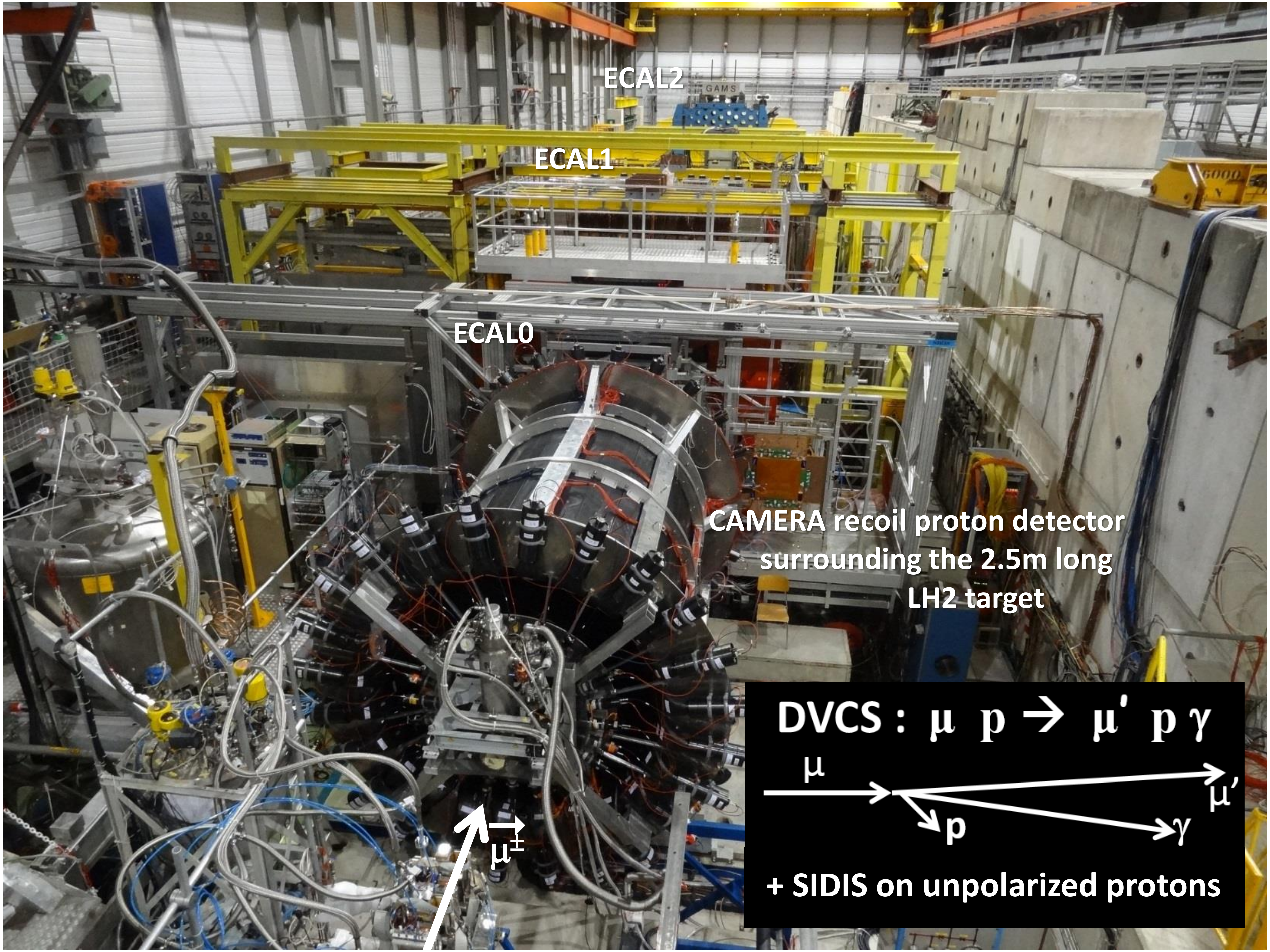
DVCS : $\mu\ p \rightarrow \mu'\ p'\ \gamma$ at small transfer



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

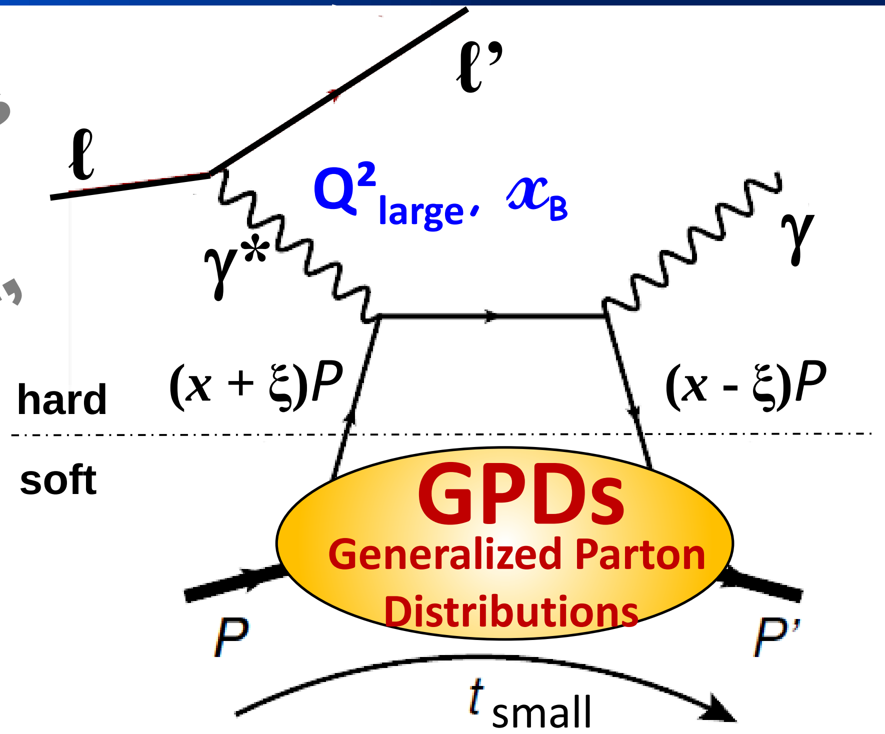


2012:
1 month pilot run

2016 -17:
2 x 6 month
data taking

Deeply virtual Compton scattering (DVCS)

after talks given by Sebastian, Hervé, Pierre…



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

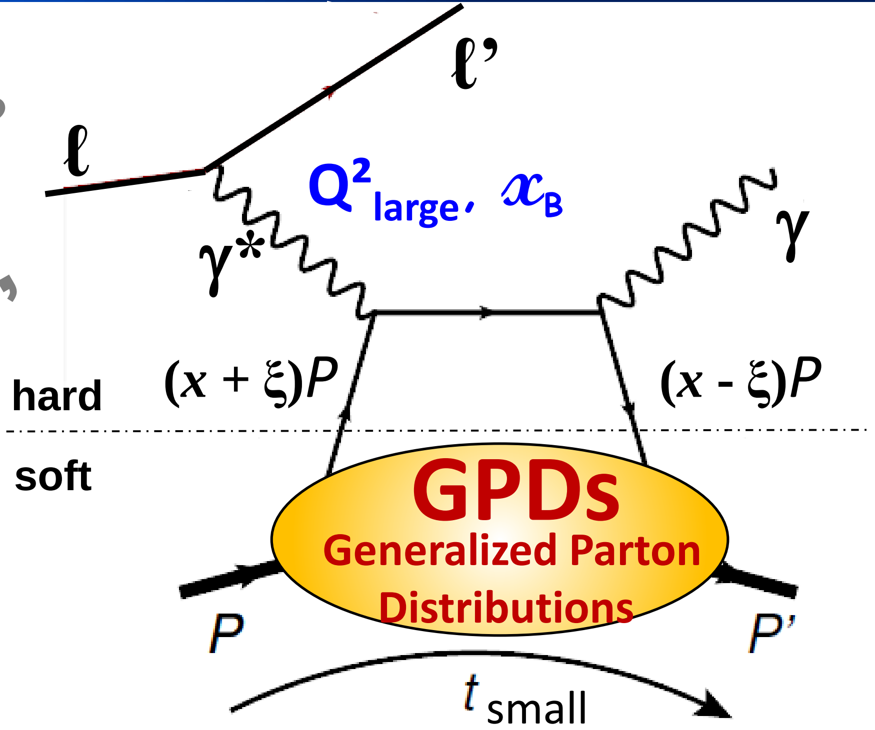
Q^2: virtuality of the virtual photon

The variables measured in the experiment:

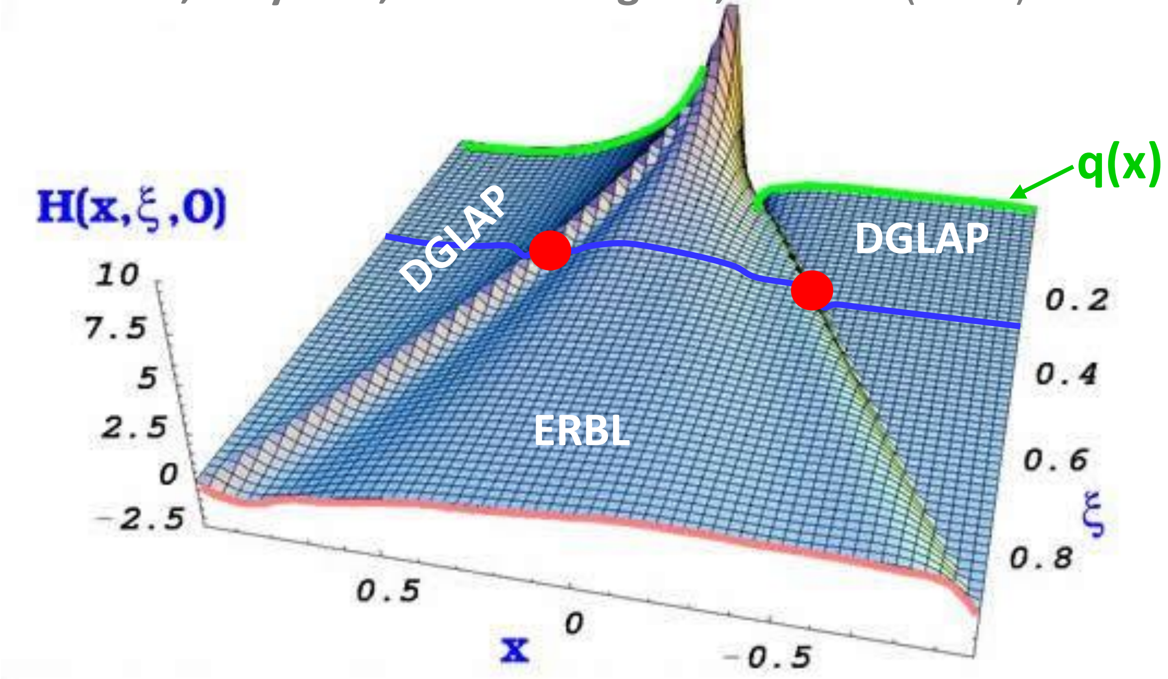
E_ℓ, Q^2, $x_B \sim 2\xi/(1+\xi)$,
t (or $\theta_{\gamma^*\gamma}$) and ϕ (ℓℓ' plane/γγ* plane)

Deeply virtual Compton scattering (DVCS)

after talks given by Sebastian, Hervé, Pierre...



Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



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

Real part Imaginary part

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

t, ξ fixed

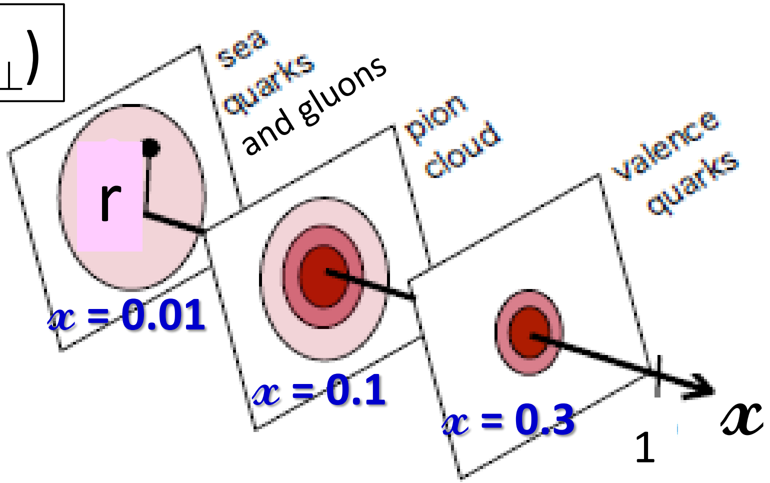
In an experiment we measure Compton Form Factor $\mathcal{H}$

Deeply virtual Compton scattering (DVCS)

M. Burkardt, PRD66(2002)

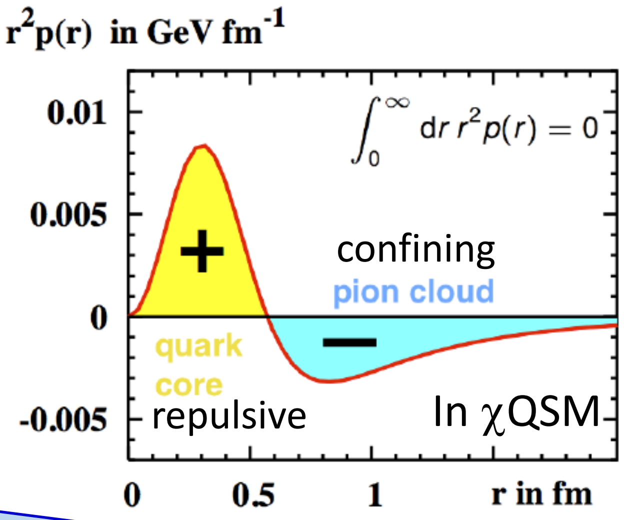
M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

Mapping in the transverse plane



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

Pressure Distribution



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

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

t, ξ fixed

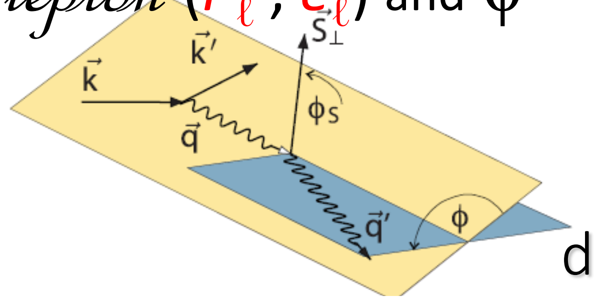
In an experiment we measure Compton Form Factor $\mathcal{H}$

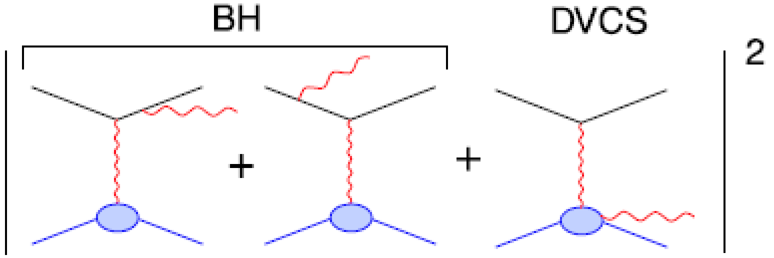
$$\mathcal{R}e\mathcal{H}(\xi,t) = \pi^{-1}\int_0^1 dx \frac{2x\, Im\mathcal{H}(x,t)}{x^2-\xi^2} + \Delta(t)$$

D-term $d_1(t)$

Deeply virtual Compton scattering (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)

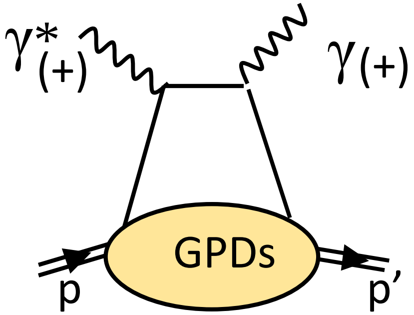
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

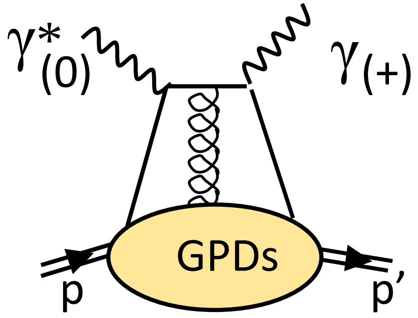
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

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

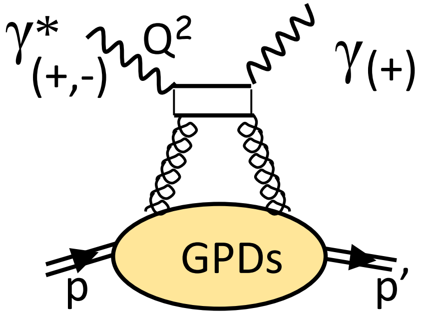


LO,Twist-2



HT,Twist-3

suppressed by 1/Q

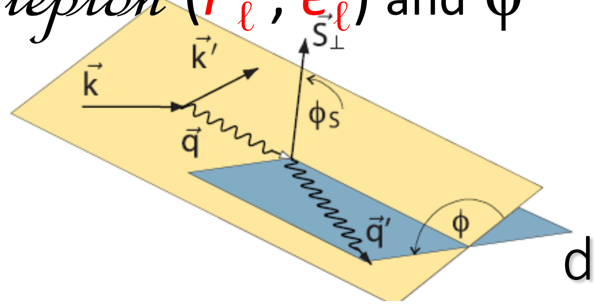


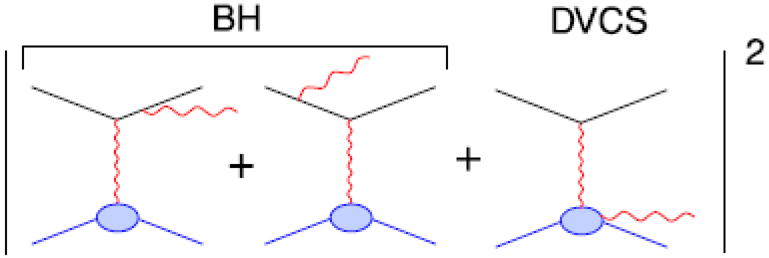
NLO,Twist-2
double helicity flip

suppressed by α_s

Deeply virtual Compton scattering (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)

With polarized electrons

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

With electrons and positrons

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

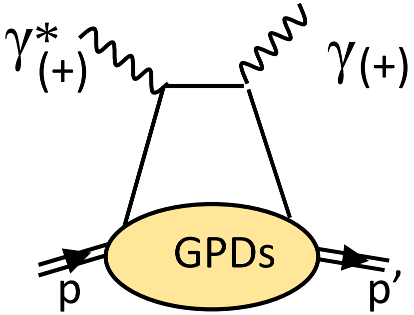
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

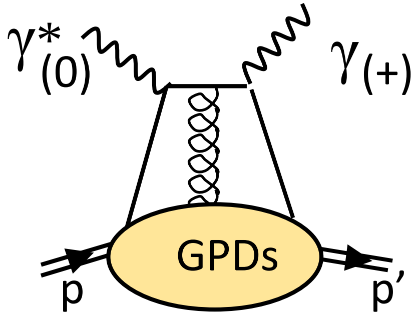
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

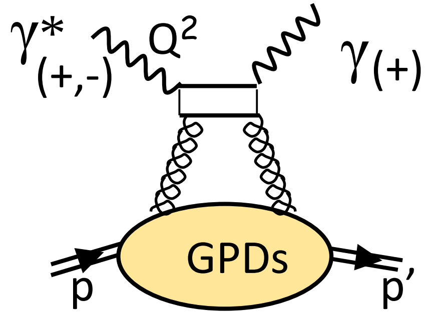
$$\mathrm{Im}\, I \propto s_1^{I}\sin\phi + s_2^{I}\sin 2\phi$$



LO,Twist-2



HT,Twist-3
suppressed by 1/Q



NLO,Twist-2
double helicity flip
suppressed by α_s

Deeply virtual Compton scattering (DVCS)

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

❶ beam charge-spin sum

$$\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$$

❷ difference

$$\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$$

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

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

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

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

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

$$\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} \rightarrow s_1^I \propto Im\ \mathcal{F}$$

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

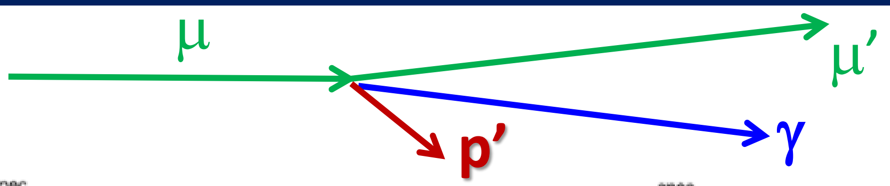
$$\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}} \rightarrow c_1^I \propto Re\ \mathcal{F}$$

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

at small x_B
COMPASS domain

COMPASS 2016 data Selection of exclusive single photon production

Comparison between the observables given by the spectro or by CAMERA



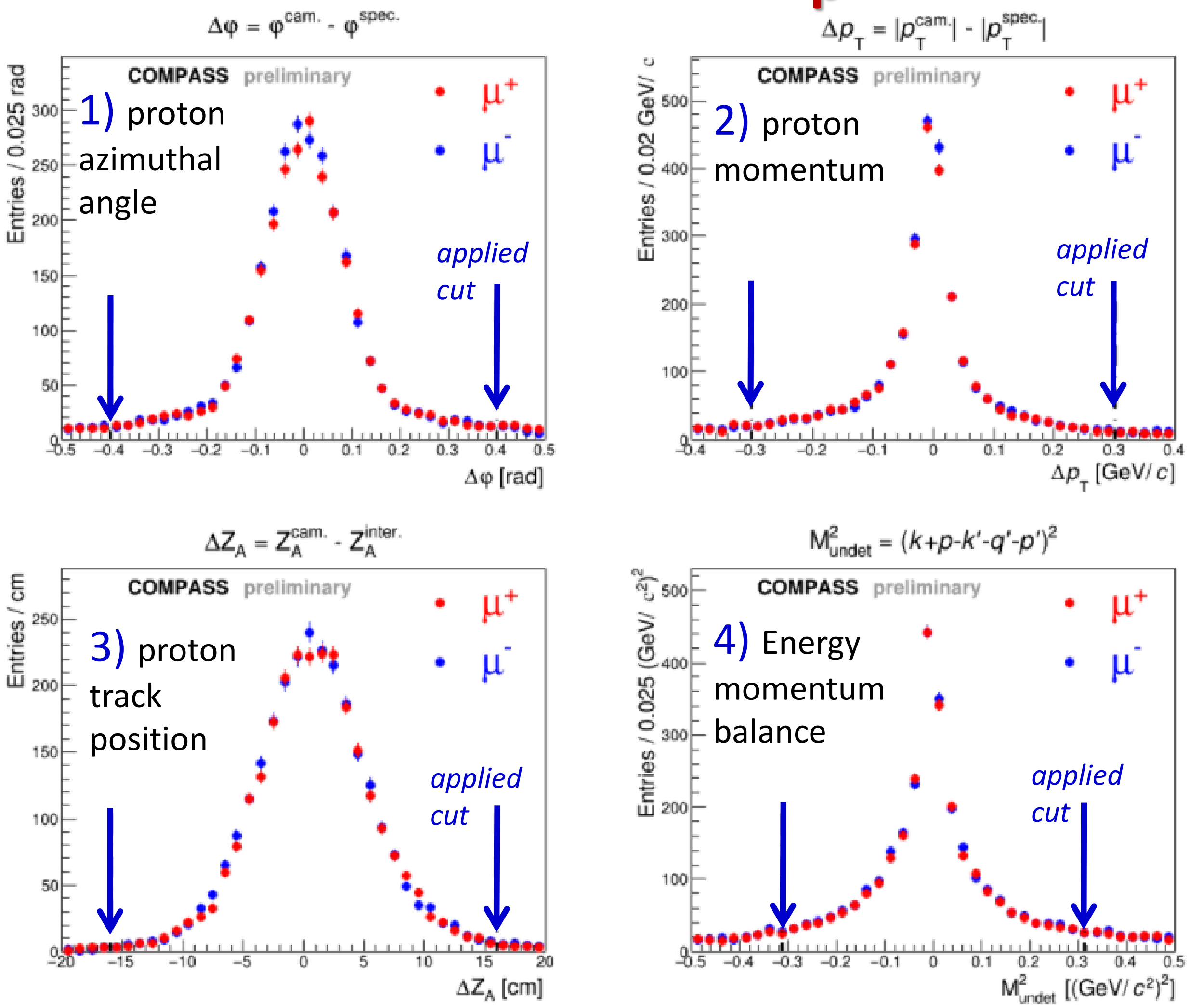
DVCS : μ p → μ' p γ

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

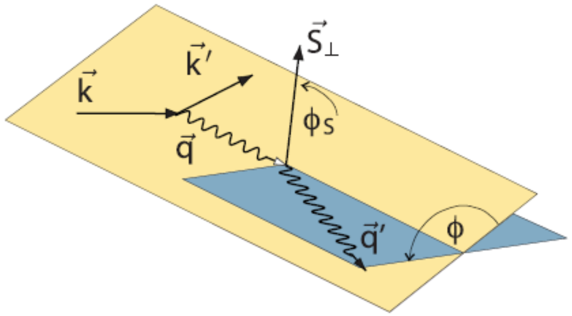
Important achievement for:

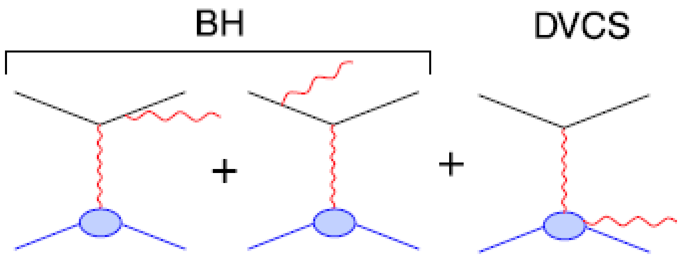
❶ $\Sigma \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}$ **Easier, done first**

❷ $\Delta \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}$ **Challenging, but promising**

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

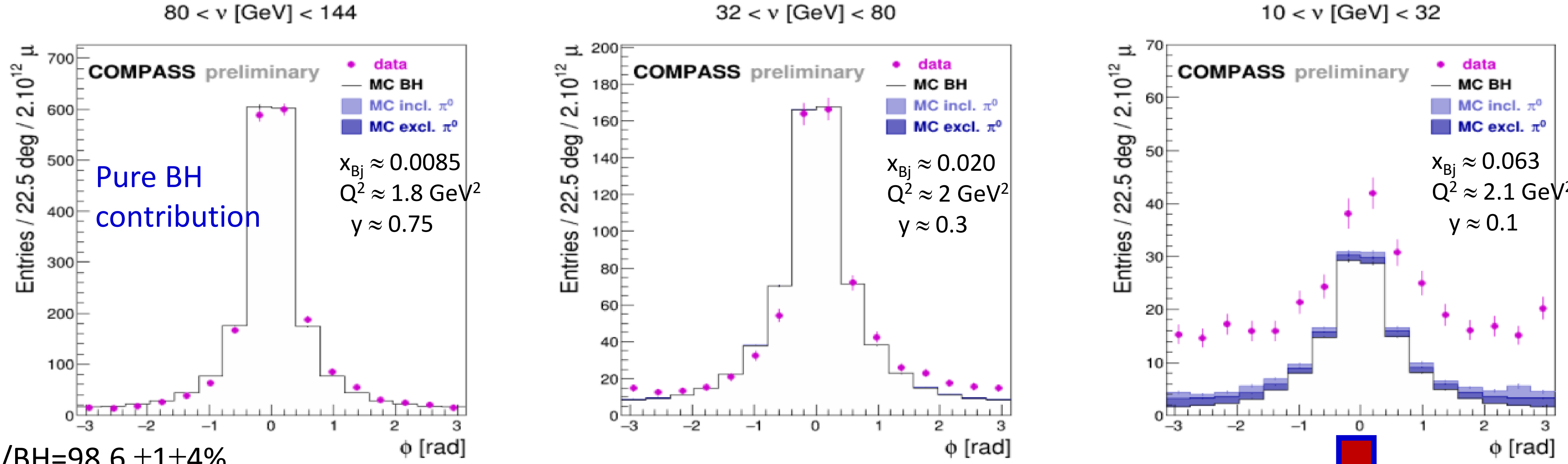
COMPASS 2016 data — DVCS+BH cross section at Eμ=160 GeV





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

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



Data/BH=98.6 ±1±4%

MC: BH contribution evaluated for the integrated luminosity
$\pi°$ 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:

$$\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Im}\, I]$$

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

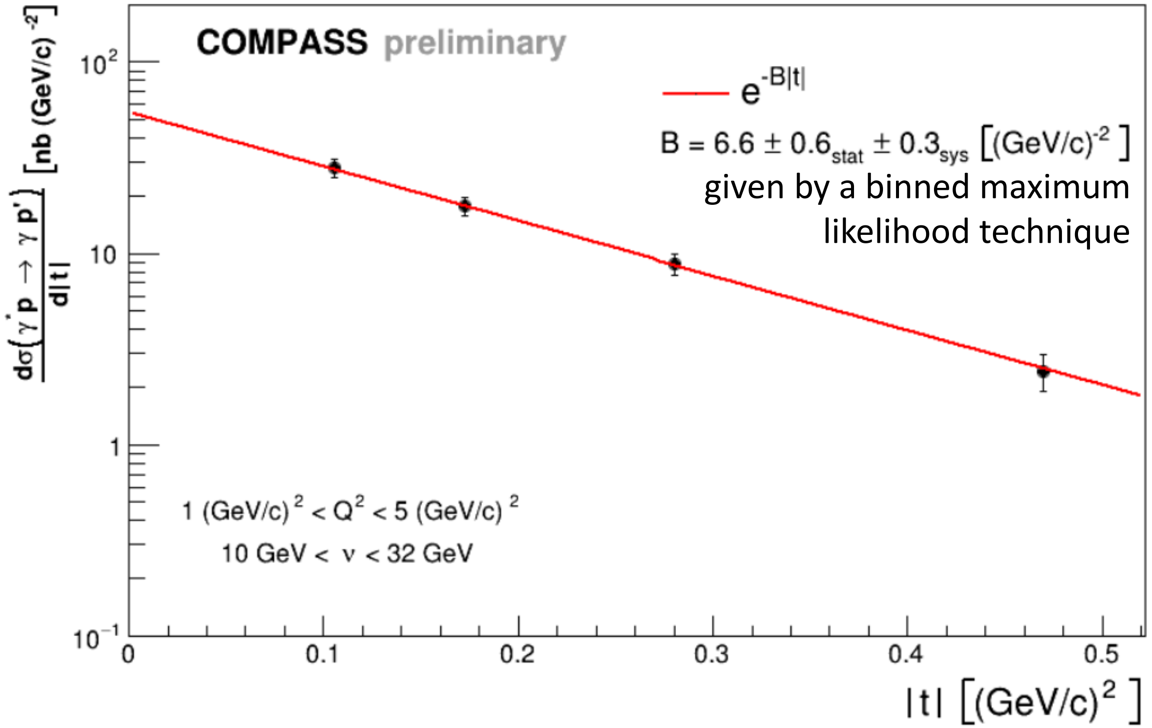
calculable
can be subtracted

All the other terms are cancelled in the integration over ϕ

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

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

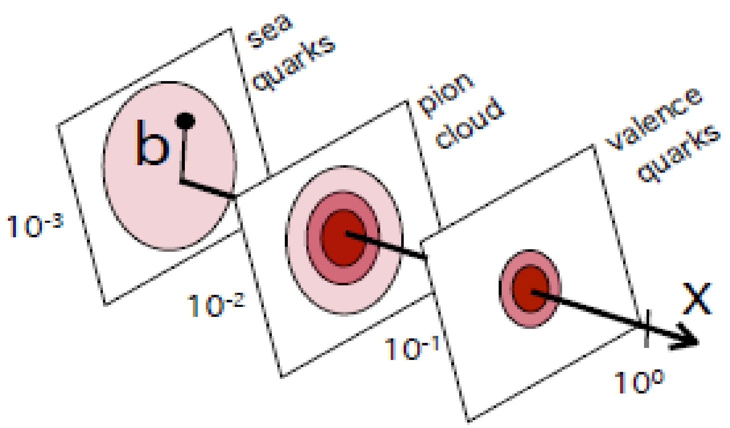
Flux for transverse
virtual photons



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

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

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



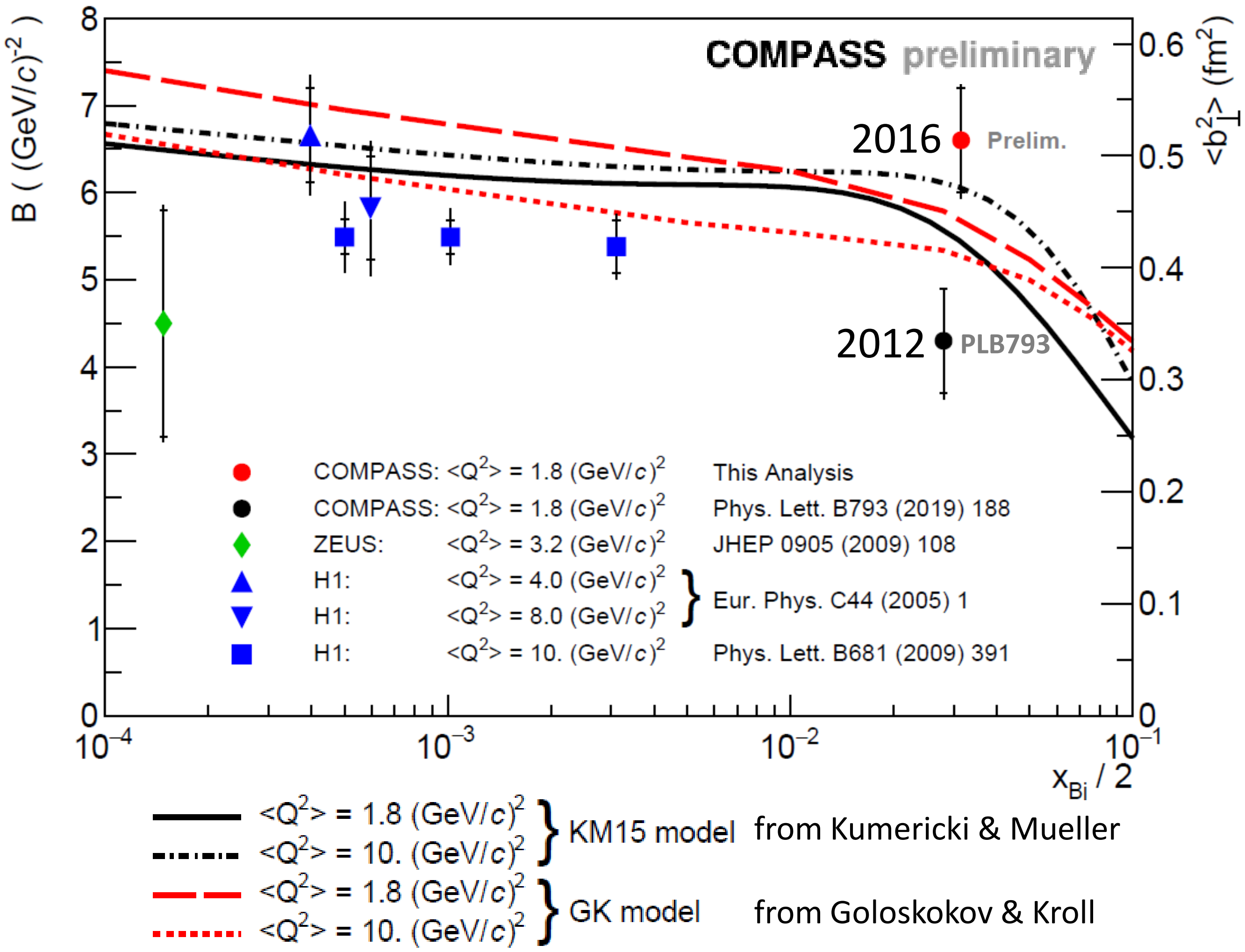
3σ difference between 2012 and 2016 data

- 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)

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)

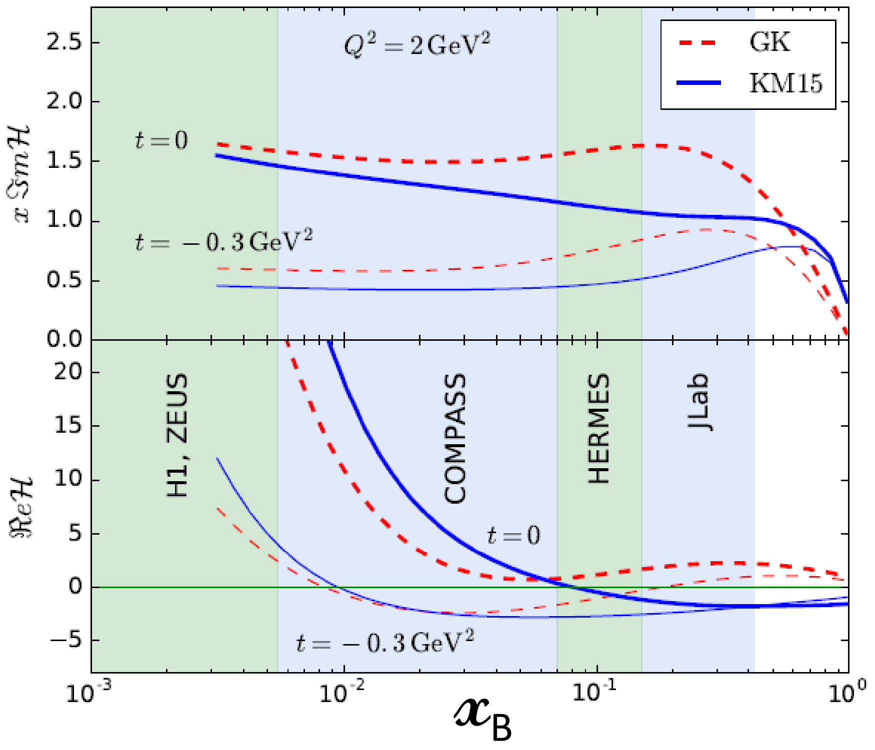
for D-term and pressure distribution

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

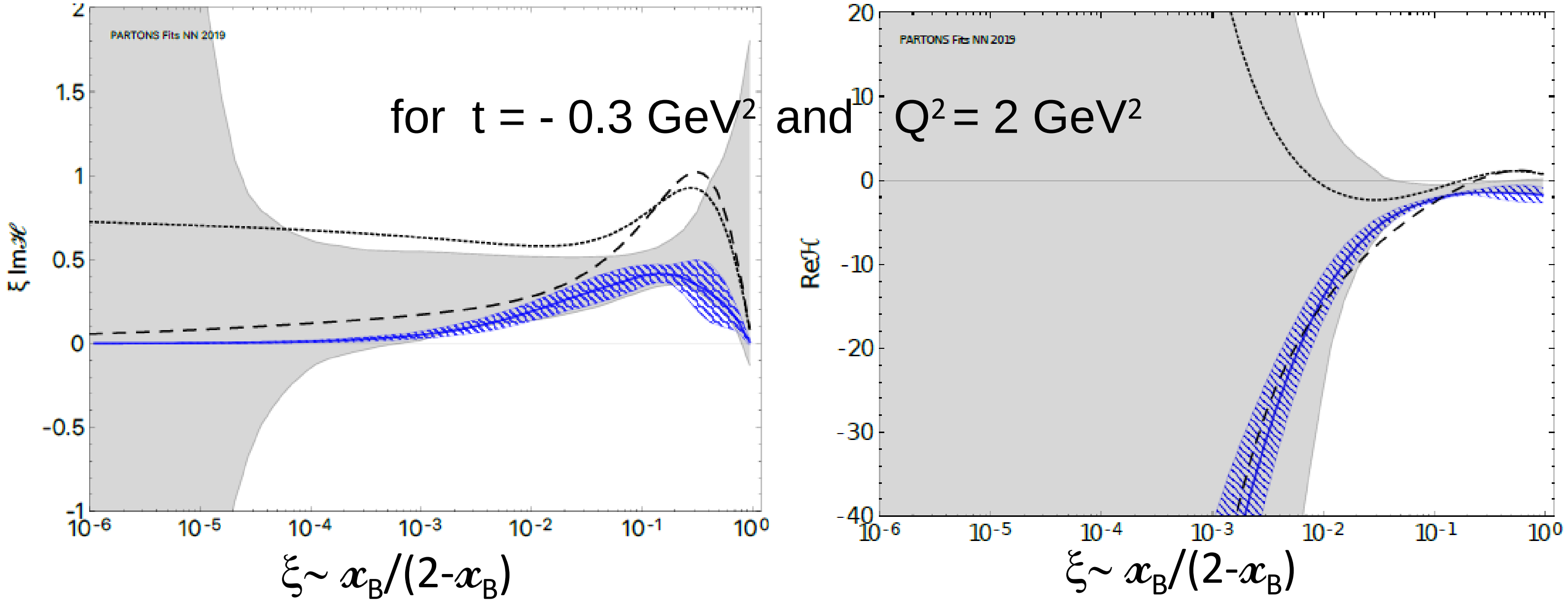
PARTONS global Fit

PARTONS Neural Network to reduce the model dependency

…… GK

---- VGG

for $t = -0.3$ GeV^2 and $Q^2 = 2$ GeV^2



Reminder with BCA: **ReH < 0** at HERMES

> 0 at H1 (but not used in PARTONS?)

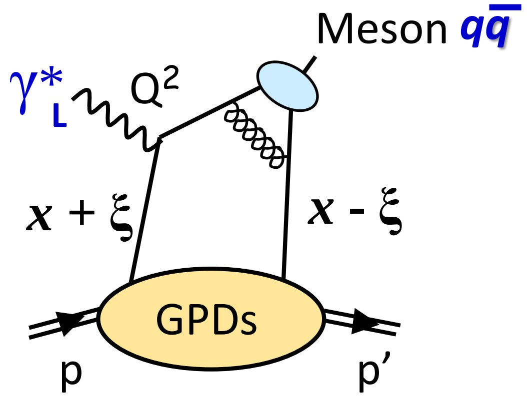
ReH is still poorly known (importance of DVCS with $\mu^\pm$ at COMPASS, $e^\pm$ at JLab or TCS at JLab and EIC)

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

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

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

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

related to the transverse spin structure and to 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 polarized quark distribution
in the transverse plane for an unpolarized nucleon

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:

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

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

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

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

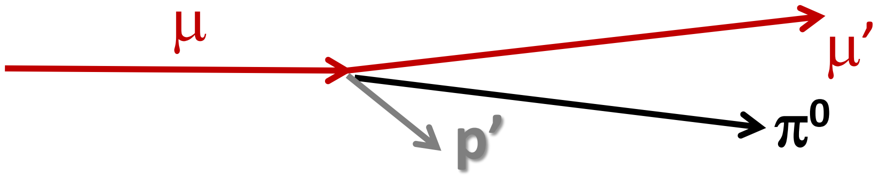
$$\frac{d\sigma_{TT}}{dt} \propto t' |\langle\bar{E}_T\rangle|^2,$$

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

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

COMPASS 2016 Exclusive π^0 production on unpolarized proton

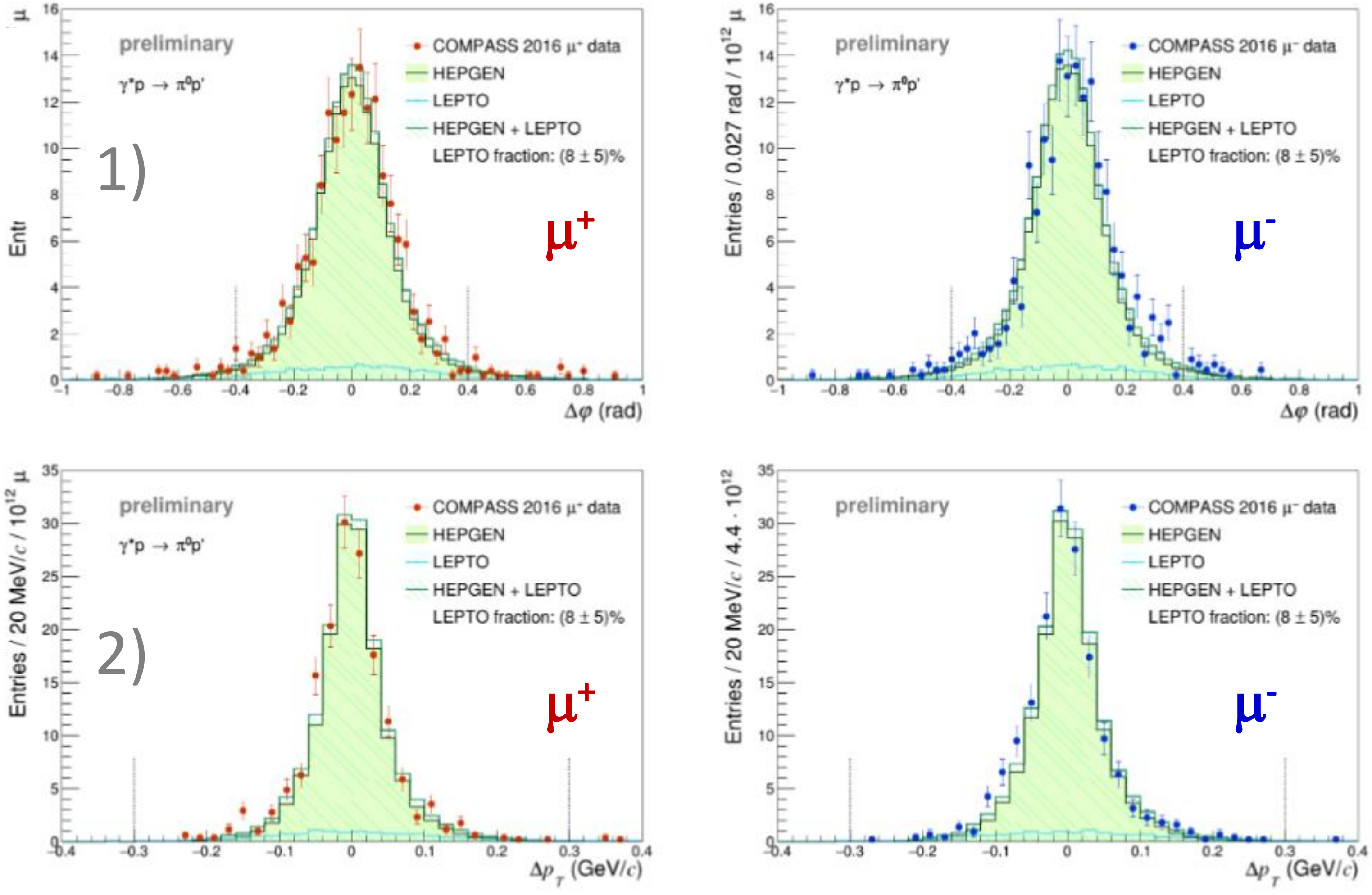
Comparison between the observables given by the spectro or by CAMERA



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

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 2012 - 16 spin-independent cross section for exclusive π^0

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

$\mu^{\pm}$ 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

$\langle x_B \rangle = 0.10$

ε close to 1

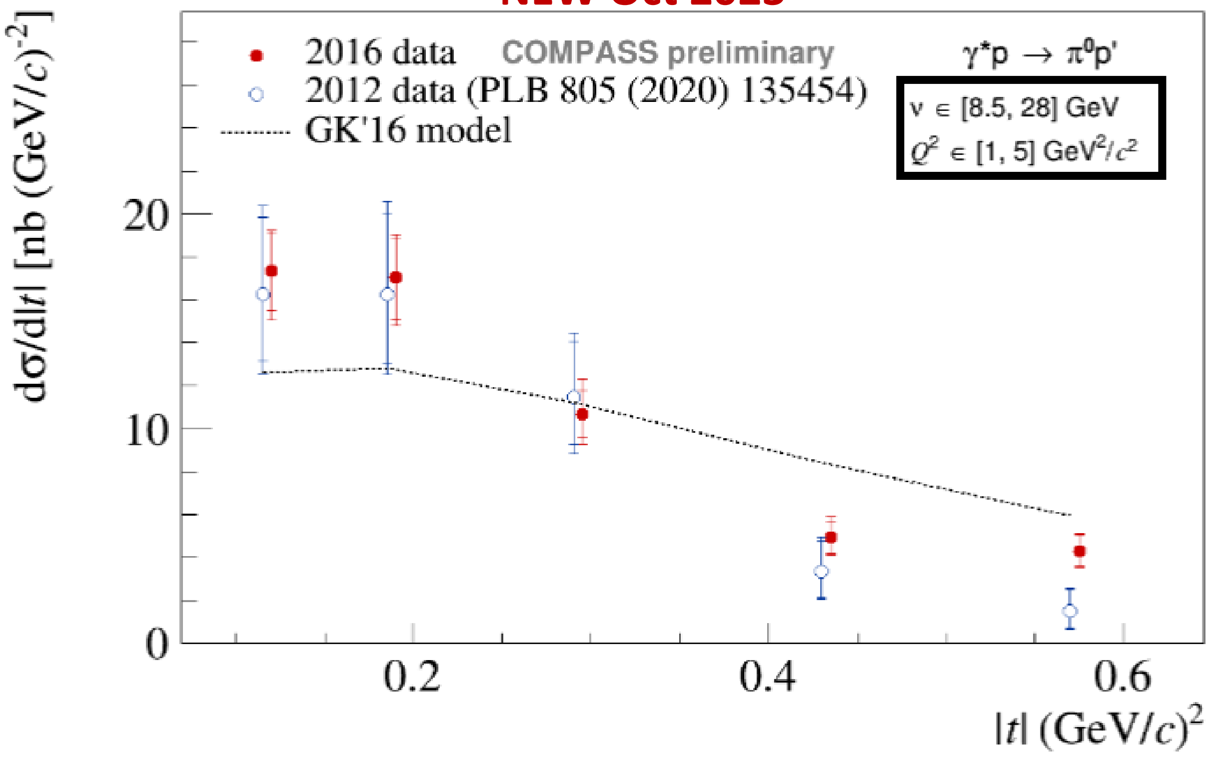
$$\frac{d\sigma_L}{dt} \propto \left|\langle\tilde{H}\rangle\right|^2 - \frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

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

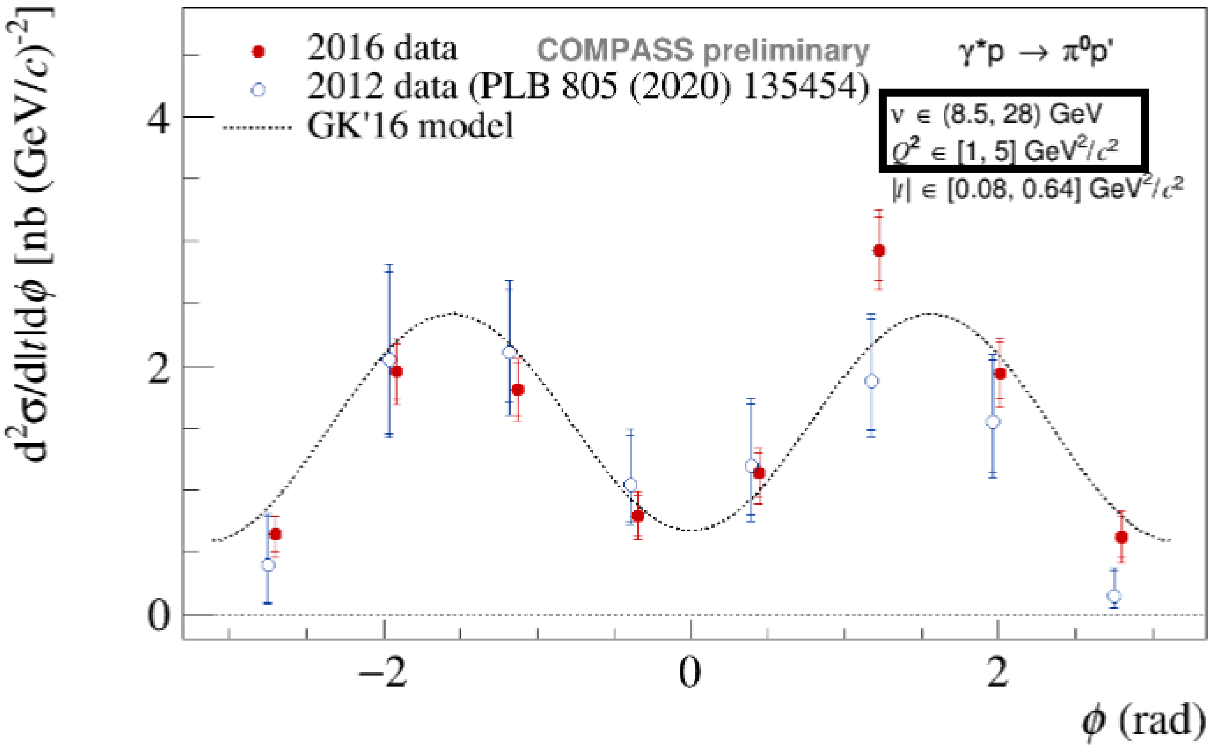
$$\frac{\sigma_{TT}}{dt} \propto \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

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

NEW Oct 2023



NEW Oct 2023



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

COMPASS 2016 spin-independent cross section for exclusive π^0

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

$\mu^\pm$ 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

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

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

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

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

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In a larger (υ, Q^2) domain

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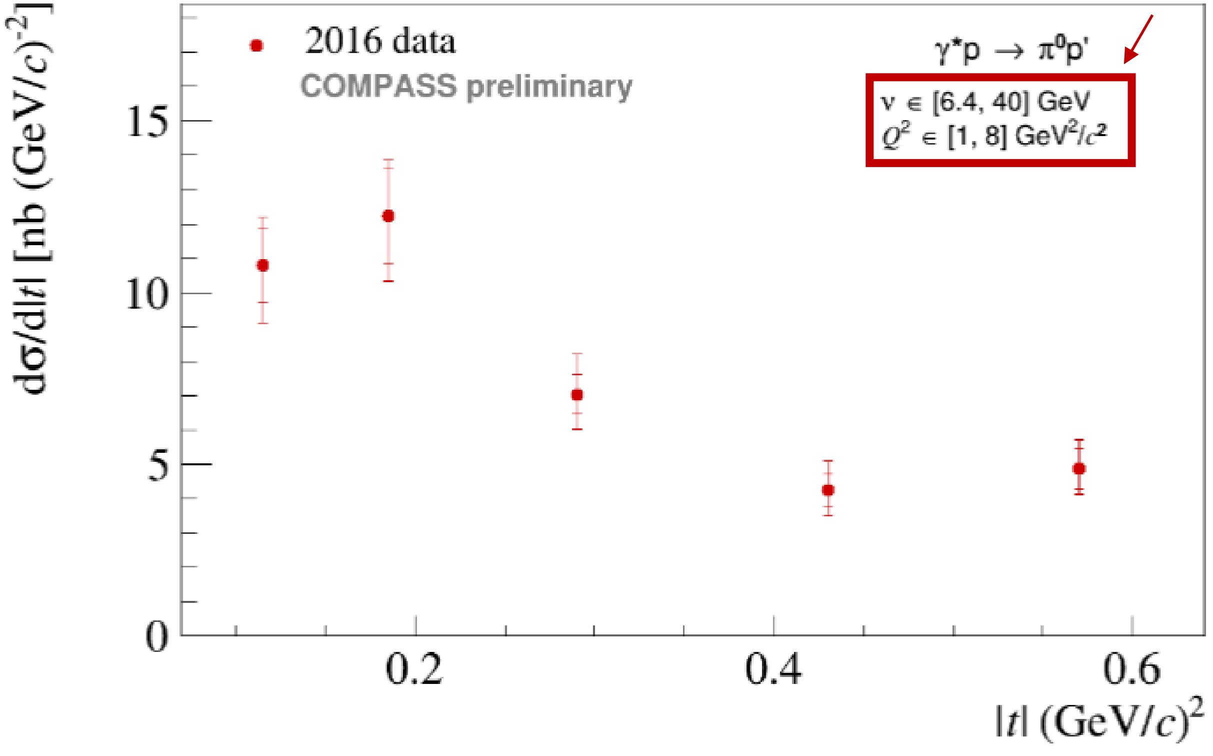
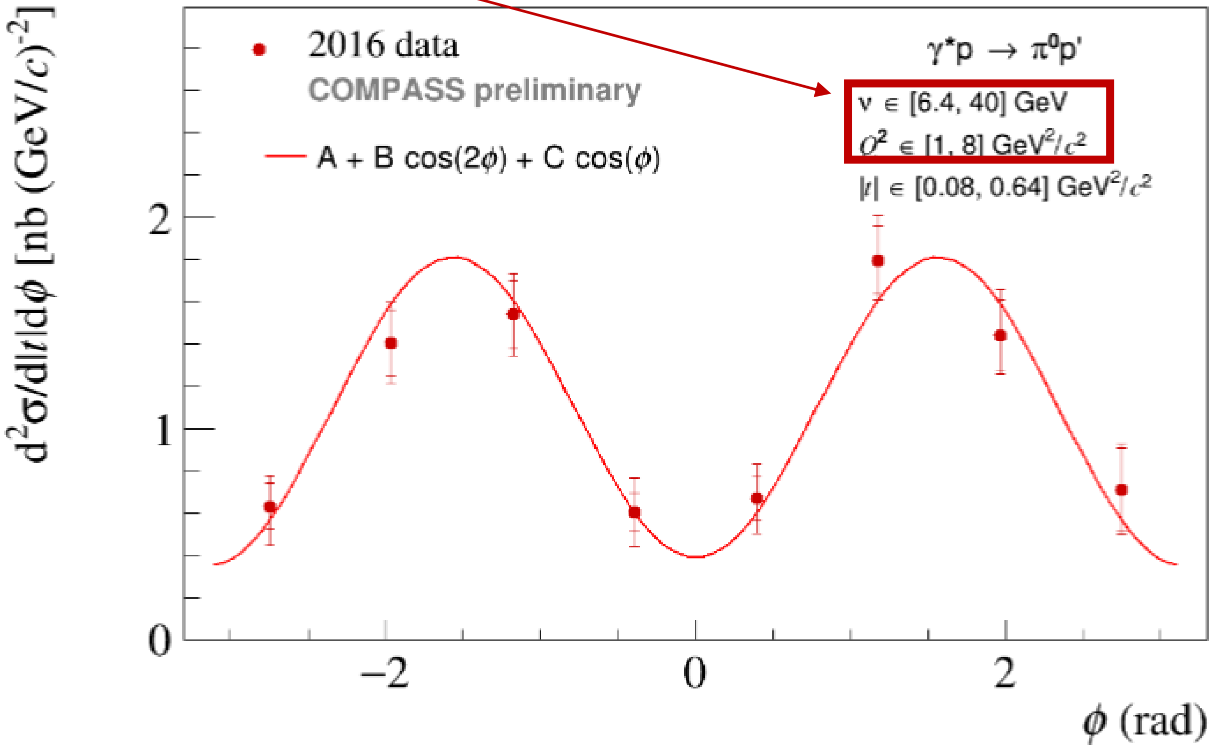




COMPASS 2016 spin-independent cross section for exclusive π^0

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

$\mu^\pm$ 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

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

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

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

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

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

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

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

NEW Oct 2023

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

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

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

σ_{TT} is negative and large comparatively to $\sigma_T + \varepsilon\,\sigma_L$

➔ impact of $\bar{E}_T$

σ_{LT} rather small

We will present soon the evolution in 3 bins in υ and 4 bins in Q^2

The 2017 data set will still increase the statistics

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

For ex: $\sigma^{\pm} = (\varepsilon\, \sigma_L + \sigma_T) + a \cos 2\phi\, \sigma_{TT} + b \cos\phi\, \sigma_{LT} + c \sin\phi\, \sigma_{LT'}$

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

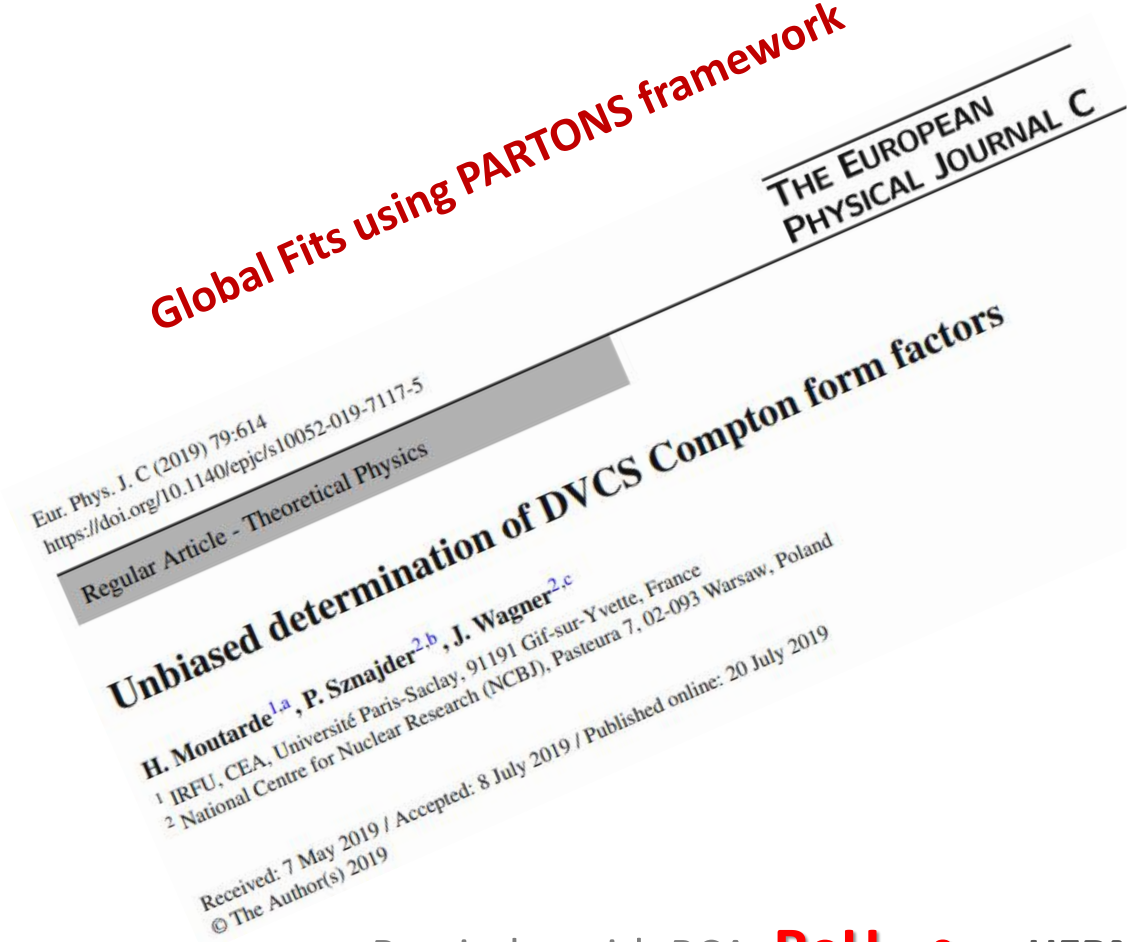
Richness but complexity dealing with runs with ℓ+ and ℓ- beams ➔ we build 4 correlated observables or 4 cross sections:

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 (see Andrei Afanasev....)

ImH and ReH using global fits of the world data

Global Fits using PARTONS framework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Regular Article - Theoretical Physics

Unbiased determination of DVCS Compton form factors

H. Moutarde[1,a], P. Sznajder[2,b], J. Wagner[2,c]
[1] IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[2] National Centre for Nuclear Research (NCBJ), Pasteura 7, 02-093 Warsaw, Poland

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Table 2: DVCS data used in this analysis.

No.	Collab.	Year	Ref.	Observable		Kinematic dependence	No. of points used / all
1	HERMES	2001	[40]	A_{LU}^{+}		ϕ	10 / 10
2		2006	[41]	$A_{C}^{\cos i\phi}$	$i=1$	t	4 / 4
3		2008	[42]	$A_{C}^{\cos i\phi}$	$i=0,1$	x_{Bj}	18 / 24
				$A_{UT,DVCS}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0$		
				$A_{UT,I}^{\sin(\phi-\phi_S)\cos i\phi}$	$i=0,1$		
				$A_{UT,I}^{\cos(\phi-\phi_S)\sin i\phi}$	$i=1$		
4		2009	[43]	$A_{LU,I}^{\sin i\phi}$	$i=1,2$	x_{Bj}	35 / 42
				$A_{LU,DVCS}^{\sin i\phi}$	$i=1$		
				$A_{C}^{\cos i\phi}$	$i=0,1,2,3$		
5		2010	[44]	$A_{UL}^{+,\sin i\phi}$	$i=1,2,3$	x_{Bj}	18 / 24
				$A_{LL}^{+,\cos i\phi}$	$i=0,1,2$		
6		2011	[45]	$A_{LT,DVCS}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1$	x_{Bj}	24 / 32
				$A_{LT,DVCS}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1$		
				$A_{LT,I}^{\cos(\phi-\phi_S)\cos i\phi}$	$i=0,1,2$		
				$A_{LT,I}^{\sin(\phi-\phi_S)\sin i\phi}$	$i=1,2$		
7		2012	[46]	$A_{LU,I}^{\sin i\phi}$	$i=1,2$	x_{Bj}	35 / 42
				$A_{LU,DVCS}^{\sin i\phi}$	$i=1$		
				$A_{C}^{\cos i\phi}$	$i=0,1,2,3$		
8	CLAS	2001	[47]	$A_{LU}^{-,\sin i\phi}$	$i=1,2$	—	0 / 2
9		2006	[48]	$A_{UL}^{-,\sin i\phi}$	$i=1,2$	—	2 / 2
10		2008	[49]	A_{LU}^{-}		ϕ	283 / 737
11		2009	[50]	A_{LU}^{-}		ϕ	22 / 33
12		2015	[51]	A_{LU}^{-}, A_{UL}^{-}, A_{LL}^{-}		ϕ	311 / 497
13		2015	[52]	$d^4\sigma_{UU}^{-}$		ϕ	1333 / 1933
14	Hall A	2015	[34]	$\Delta d^4\sigma_{LU}^{-}$		ϕ	228 / 228
15		2017	[35]	$\Delta d^4\sigma_{LU}^{-}$		ϕ	276 / 358
16	COMPASS	2018	[36]	$d^3\sigma_{UU}^{\pm}$		t	2 / 4
17	ZEUS	2009	[37]	$d^3\sigma_{UU}^{+}$		t	4 / 4
18	H1	2005	[38]	$d^3\sigma_{UU}^{+}$		t	7 / 8
19		2009	[39]	$d^3\sigma_{UU}^{\pm}$		t	12 / 12
						SUM:	2624 / 3996

Reminder with BCA: **ReH** < 0 at HERMES

> 0 at H1 not used?