Hotel Zora, Primosten
17-22 September 2018

GPD at COMPASS

1- DVCS

2- HEMP

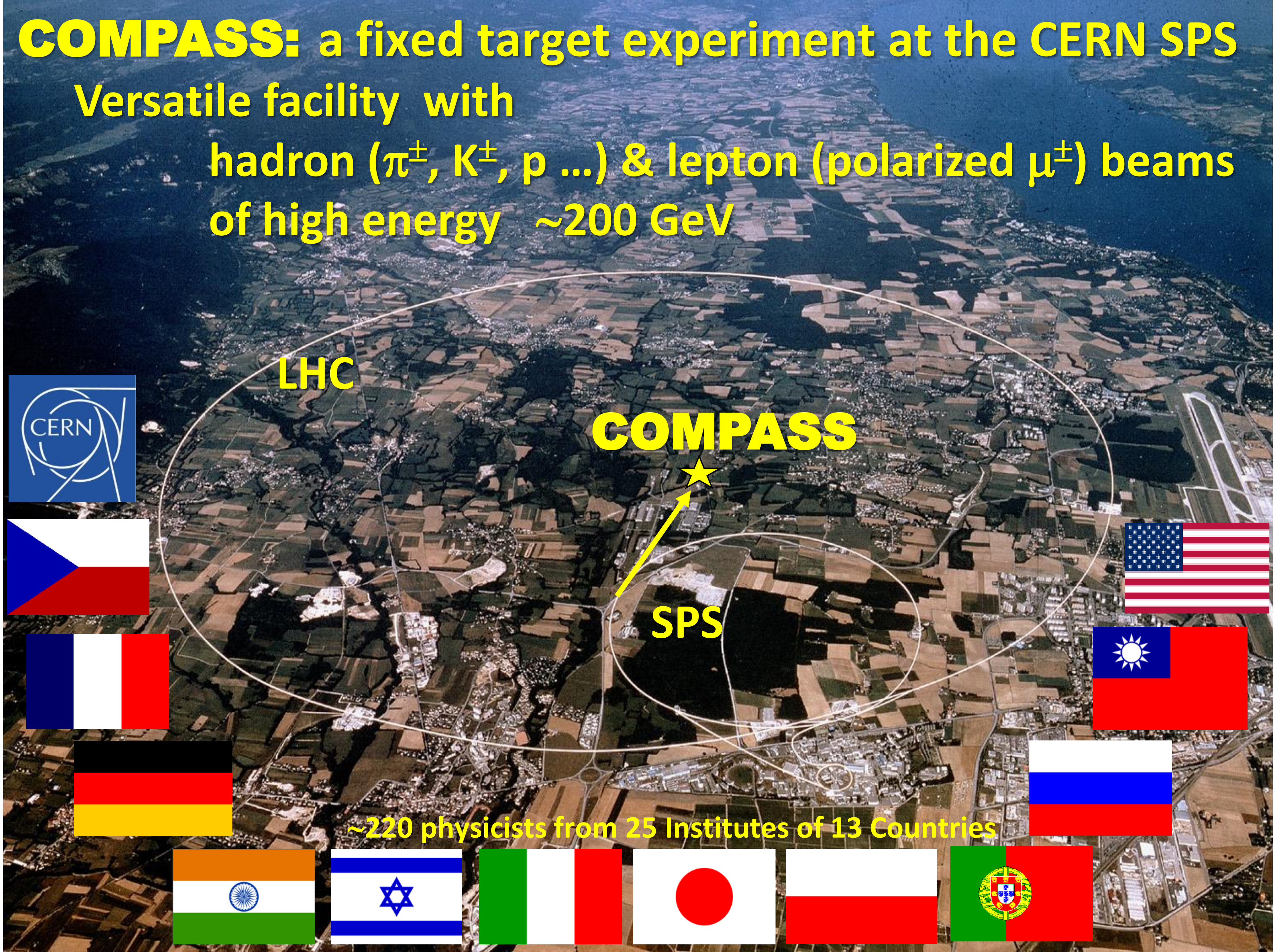
Nicole d’Hose – CEA – Université Paris-Saclay

COMPASS: a fixed target experiment at the CERN SPS

Versatile facility with

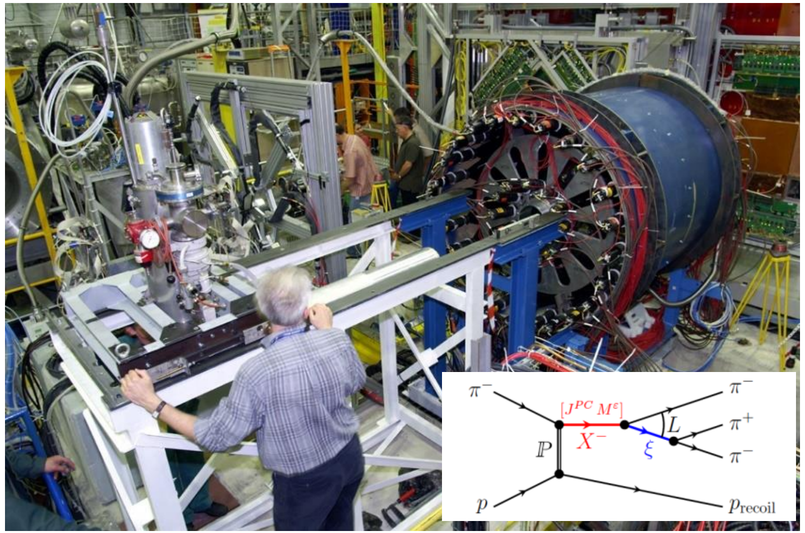
hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams

of high energy ~200 GeV



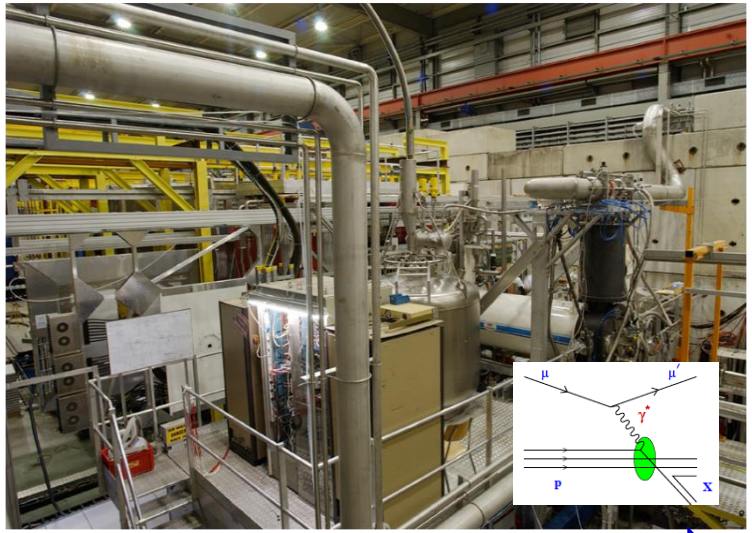
~220 physicists from 25 Institutes of 13 Countries

COMPASS: a Facility to study QCD



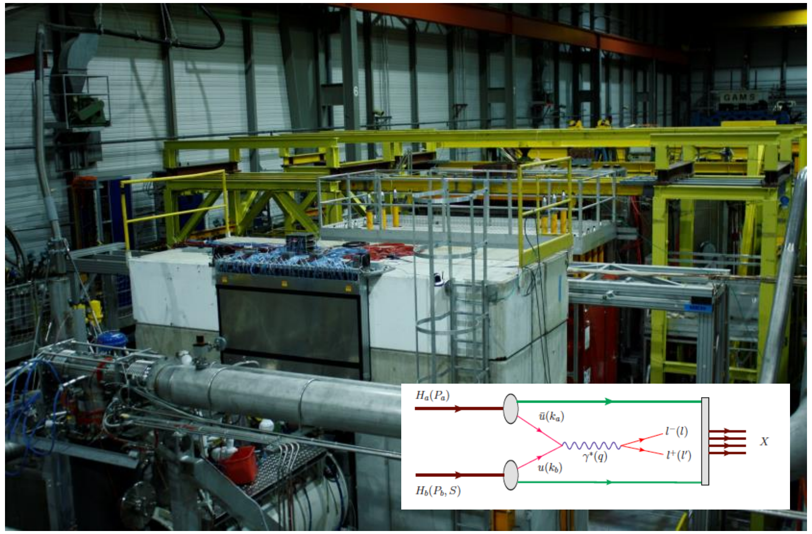
Hadron Spectroscopy with π beams
Test of ChPT & π polarizabilities

COMPASS-I
1997-2011



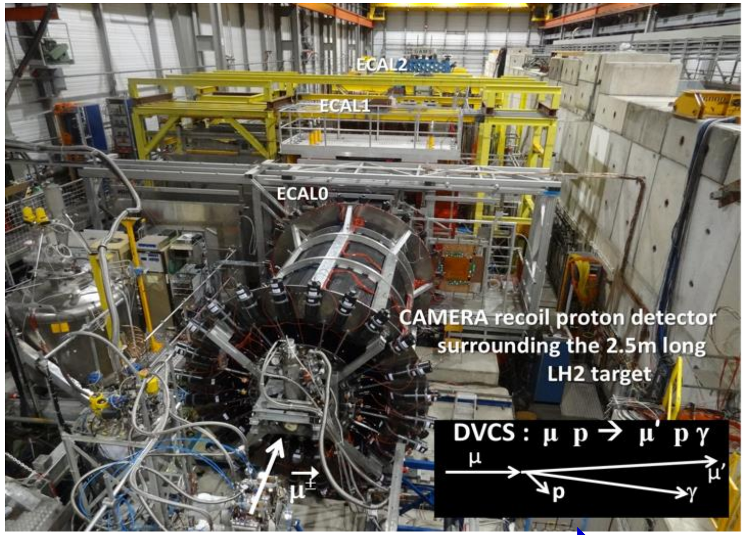
polarized SIDIS (and HEMP) with $\vec{\mu}$ beams
with Long or Trans. Polarized Targets

COMPASS-II
2012-2021



Polarised Drell-Yan with π beams

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

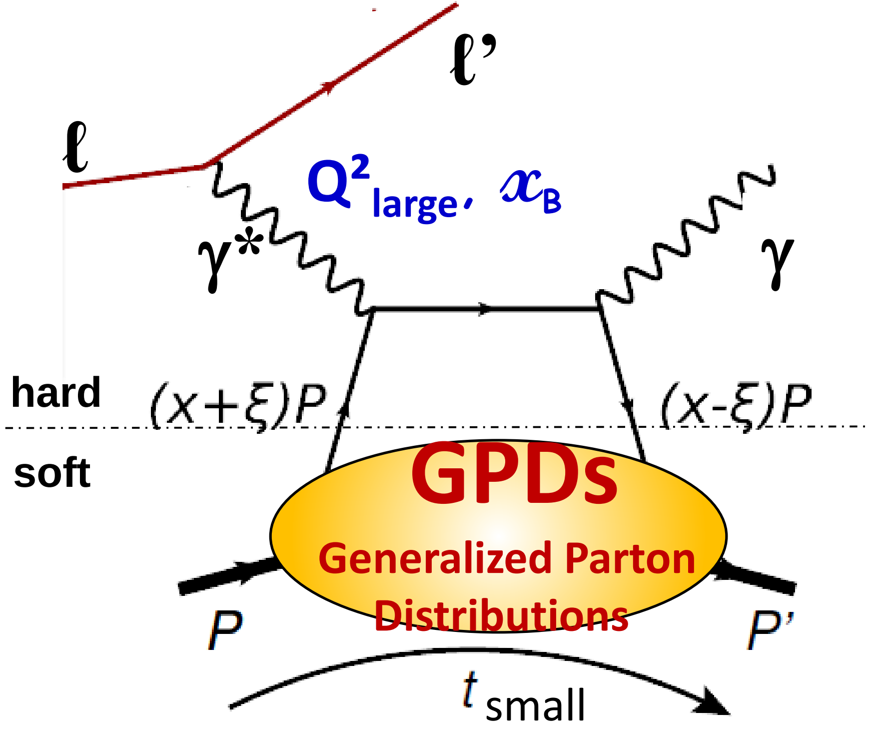


1 month in 2012
6 months in 2016
6 months in 2017

DVCS-HEMP (GPDs) & unp. SIDIS with with $\vec{\mu}$ beams with LH2 target

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: $\ell p \rightarrow \ell' p' \gamma$
the golden channel
because it interferes with
the Bethe-Heitler process

also meson production
$\ell p \rightarrow \ell' p' \pi, \rho, \omega$ or ϕ or J/ψ…

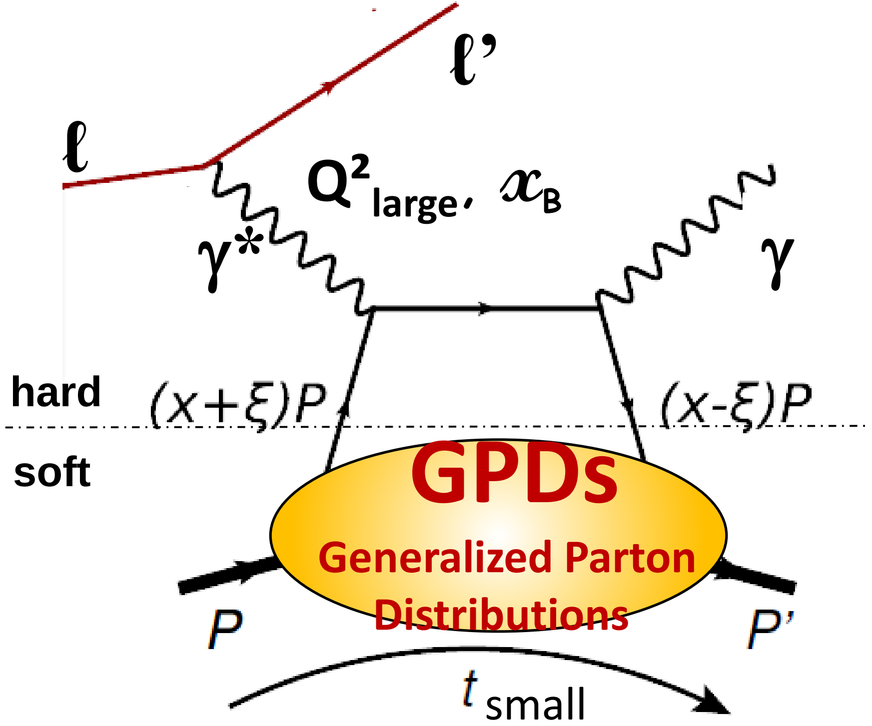
The GPDs depend on the following variables:

- x: average long. momentum
- ξ: long. mom. difference
- t: four-momentum transfer
  related to $b_\perp$ via Fourier transform

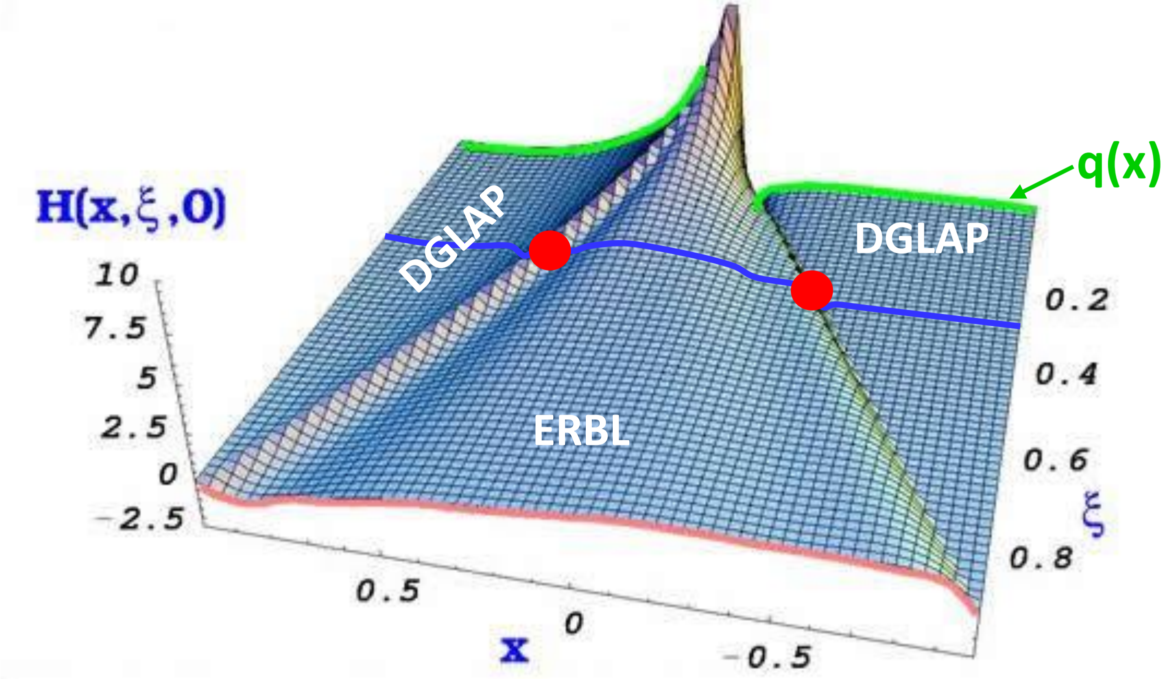
The variables measured in the experiment:

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)



From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)



The amplitude DVCS at LT & LO in α_S:

Real part Imaginary part

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

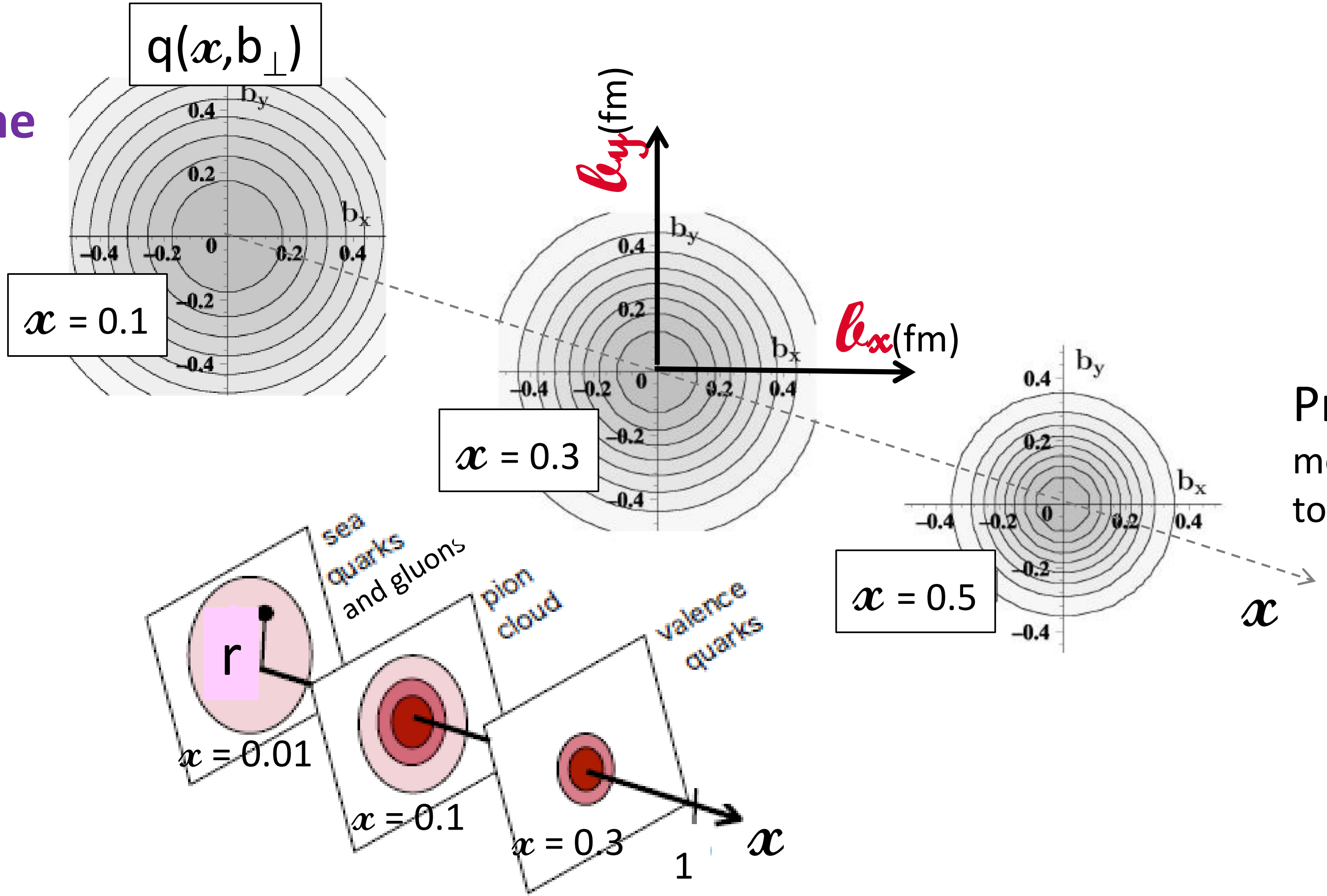
GPD **H**, Compton Form Factor $\mathcal{H}$

$$\mathcal{R}e\mathcal{H}(x,t) = \int_{-1}^{1} dx\, \frac{Im\mathcal{H}(x,t)}{x-\xi} + d(t)$$

GPDs and 3D imaging

M. Burkardt, PRD66(2002)

mapping in the transverse plane
Impact parameter distribution



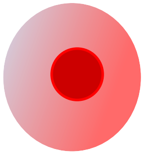
Proton
moving
towards us

Correlation between the spatial distribution of partons
and the longitudinal momentum fraction

GPDs and Energy-Momentum Tensor and Confinement

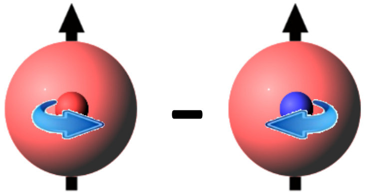
GPDs can provide an experimental answer by exploiting their equivalence to the gravitational form factors of the nucleon energy-momentum-tensor (fundamental nucleon properties)

$$\mathbf{H}^q(x, \xi, t) \xrightarrow{t\to 0} q(x) \text{ or } f_1(x)$$



"Elusive"

$$\mathbf{E}^q(x, \xi, t) \longleftrightarrow f_{1T}(x, k_T)$$



Sivers: quark k_T & nucleon transv. spin

mass & energy distribution

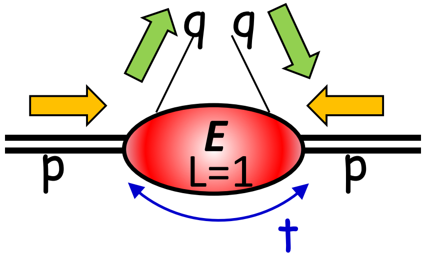
$$\int dx\, x\, H^q(x,\xi,t) = A^q(t) + \frac{4}{5}\xi^2 d_1^q(t)$$
$$\int dx\, x\, E^q(x,\xi,t) = B^q(t) - \frac{4}{5}\xi^2 d_1^q(t)$$

Angular momentum distribution

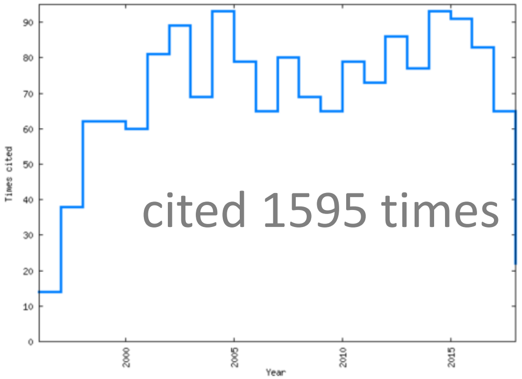
Force & Pressure distribution

$$2J^q = \lim_{t\to 0} \int x\, (\mathbf{H}^q(x, \xi, t) + \mathbf{E}^q(x, \xi, t))\, dx$$

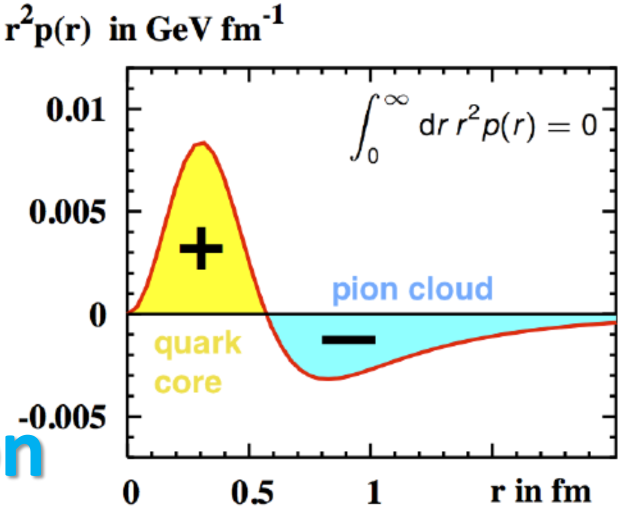
Ji sum rule: PRL78 (1997)



Relation to OAM



M. Polyakov, P. Schweitzer

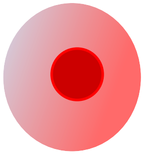


Pressure Distribution

The GPD E is the grail for OAM quest

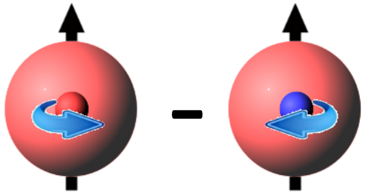
GPDs can provide an experimental answer by exploiting their equivalence to the gravitational form factors of the nucleon energy-momentum-tensor (fundamental nucleon properties)

$\mathbf{H}^q(x, \xi, t) \xrightarrow{t\to 0} q(x)$ or $f_1(x)$



''Elusive''

$\mathbf{E}^q(x, \xi, t) \longleftrightarrow f_{1T}(x, k_T)$



Sivers: quark k_T & nucleon transv. spin

$$\boxed{2\mathbf{J}^q = \lim_{t\to 0} \int x \left(\mathbf{H}^q(x, \xi, t) + \mathbf{E}^q(x, \xi, t)\right) dx}$$

$\frac{1}{2} = \mathbf{J}^q + \mathbf{J}^g = \frac{1}{2}\Delta\Sigma + \mathbf{L}^q + \mathbf{J}^g$ **Ji** PRL78 (1997)

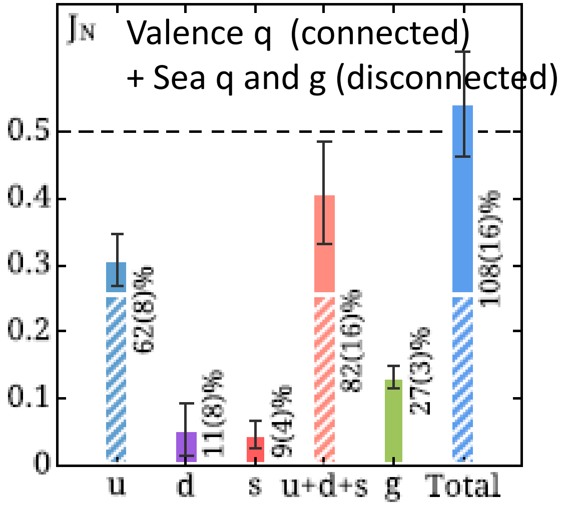
$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathscr{L}^q + \Delta G + \mathscr{L}^g$ Jaffe and Manohar NPB337 (1990)

$\frac{1}{2}\Delta\Sigma \sim 0.15$ well know from DIS/SIDIS

$\Delta G \sim 0.2$ known from SIDIS/pp

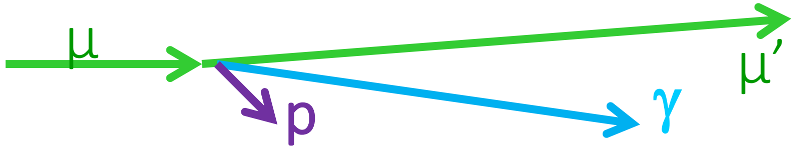
L and $\mathscr{L}$ unknown

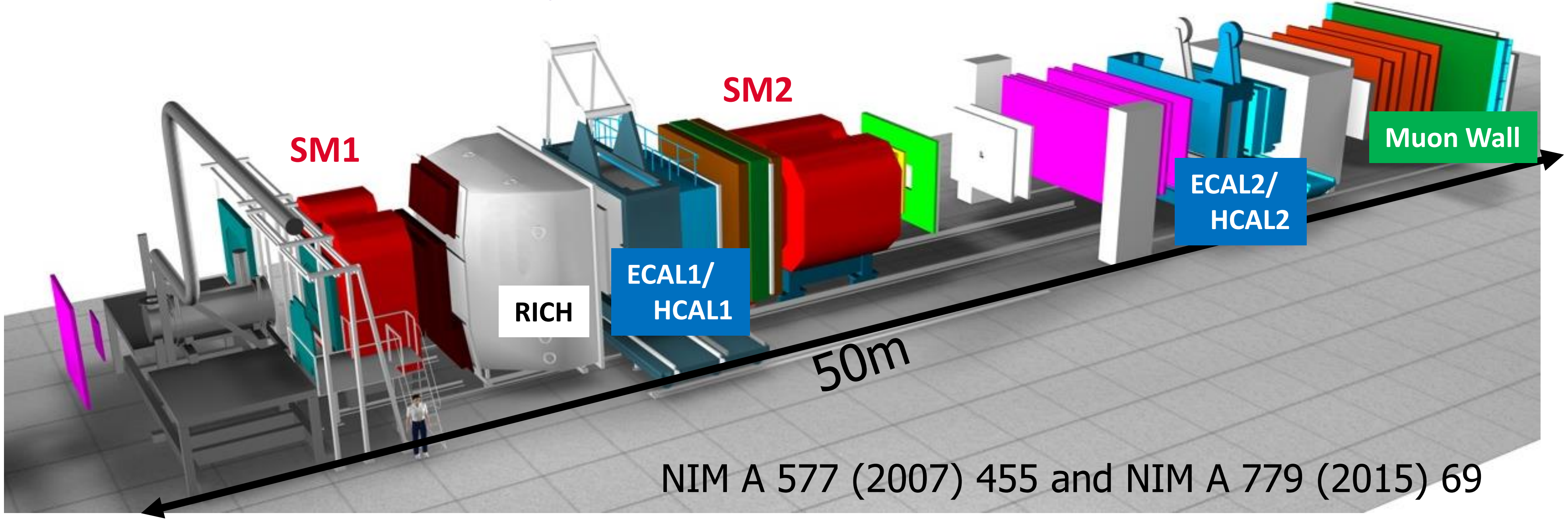
Lattice: Alexandrou et al.
PRL119(2017)142002
$J^u=0.31$ $J^d=0.05$ $J^s=0.05$
$\frac{1}{2}\Delta\Sigma=0.20$ **$L^q=0.21$**
$J^g=0.13$



The DVCS experiment at COMPASS

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





NIM A 577 (2007) 455 and NIM A 779 (2015) 69

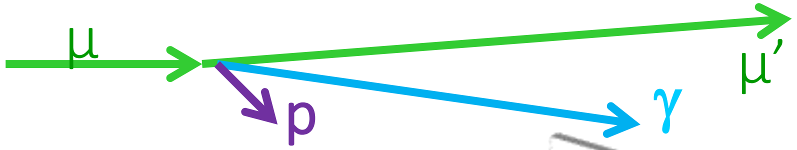
Two stage magnetic spectrometer for **large angular & momentum acceptance**

Particle identification with:

- Ring Imaging Cerenkov Counter
- Electromagnetic calorimeters (**ECAL1** and **ECAL2**)
- Hadronic calorimeters
- Hadron absorbers

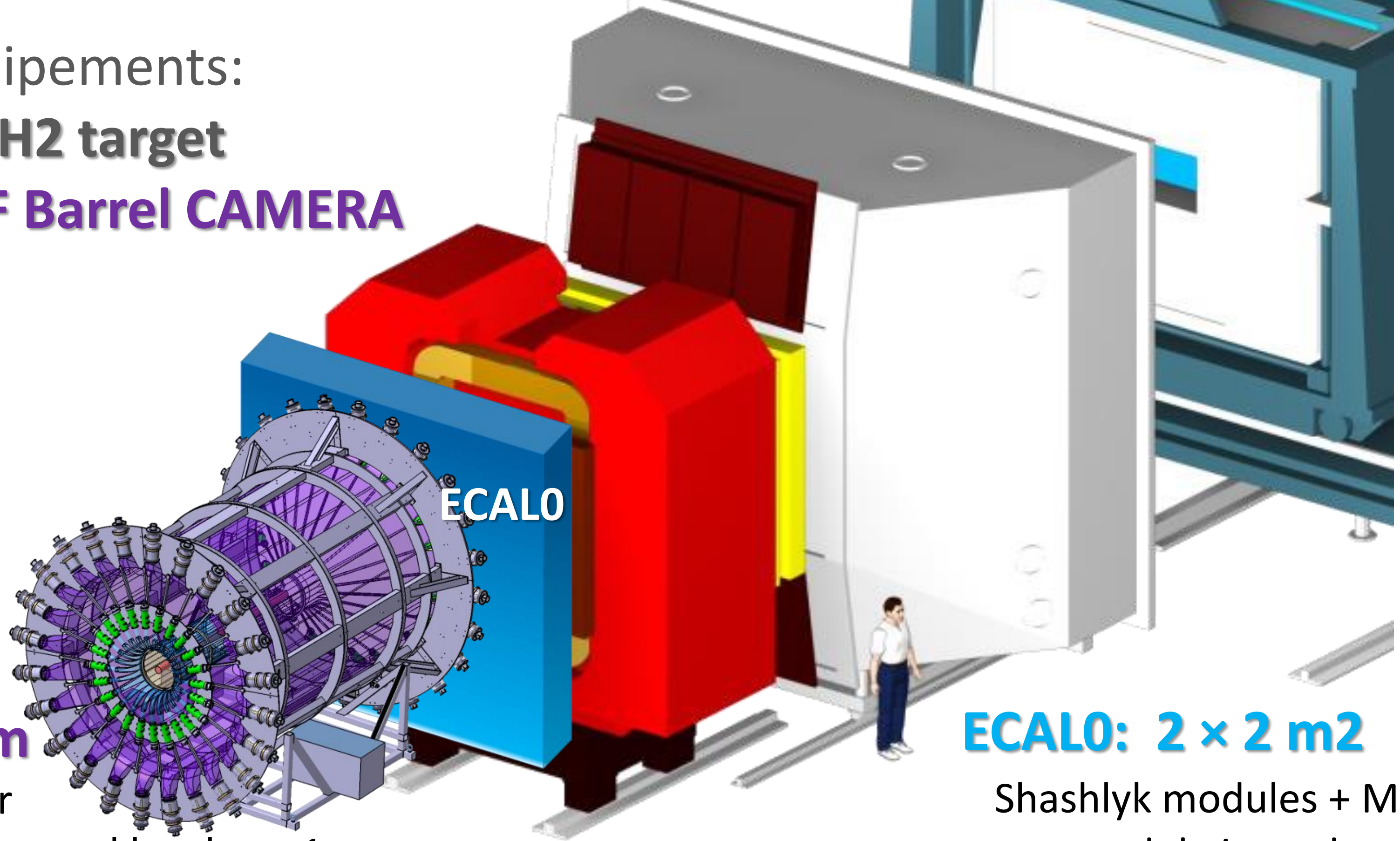
The DVCS experiment at COMPASS

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



New equipements:

- **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

Selection of exclusive evts with recoil detection
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

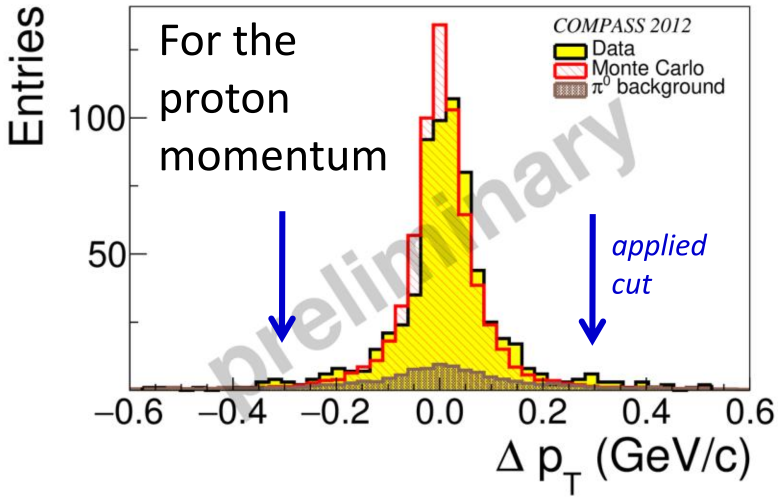
Reconstructed vertex in the target volume

1 single photon with energy above DVCS threshold: $E\gamma$ in $\mathrm{Ecal}_{0,1,2} > 4,5,10$ GeV

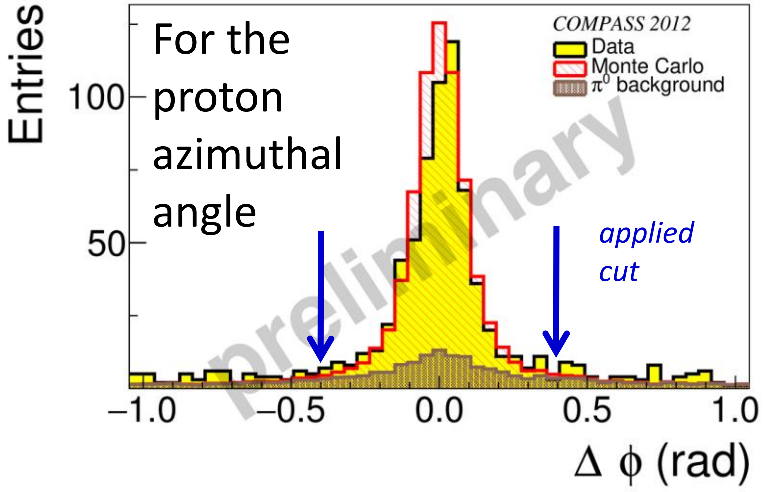
1 proton candidate $0.08\ \mathrm{GeV}^2 < |t| < 0.64\ \mathrm{GeV}^2$

Comparison between the proton observables measured by CAMERA or reconstructed by the spectro

$$\Delta p_\perp = p_{\perp,meas}^{prot} - p_{\perp,recon}^{prot}$$

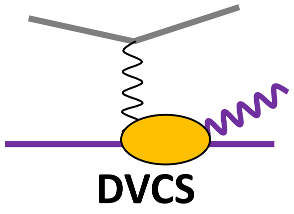


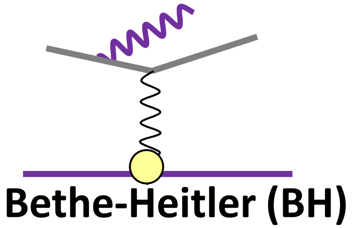
$$\Delta\varphi = \varphi_{meas}^{prot} - \varphi_{recon}^{prot}$$



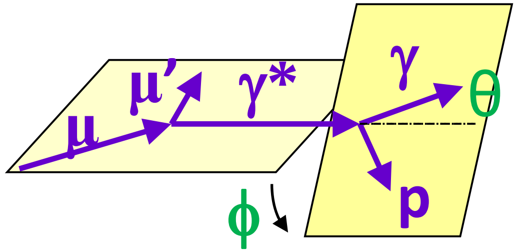
In this bin $x_B > 0.03$ or $10 < \upsilon < 32$GeV there is a sizeable π^0 contamination

Impact of the 160 GeV beam energy on DVCS+BH





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



E_ℓ =160 GeV

MC: — BH normalisation based on integrated luminosity

▨ π° background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

BH dominates

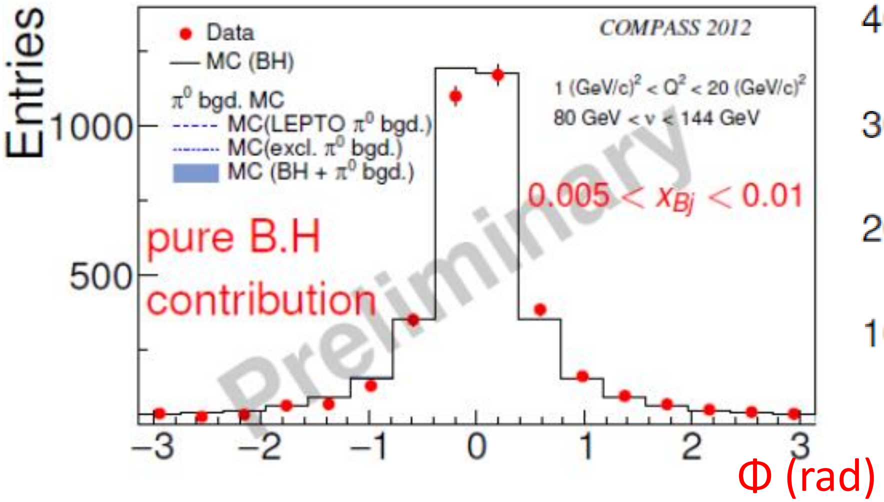
Reference yield

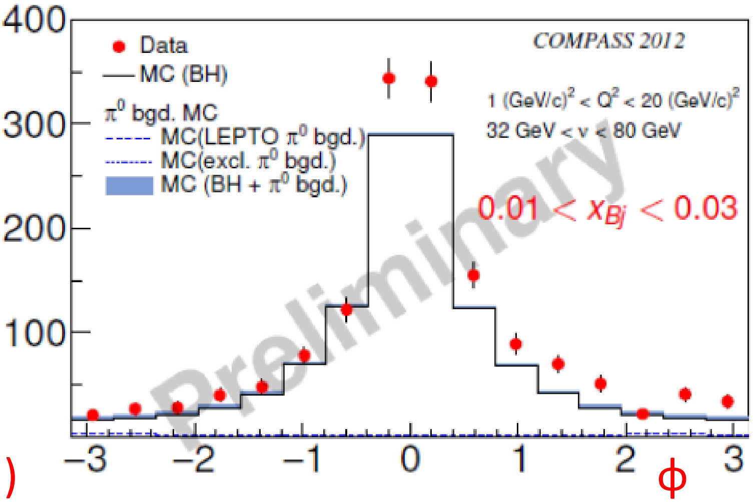
DVCS amplitude studied

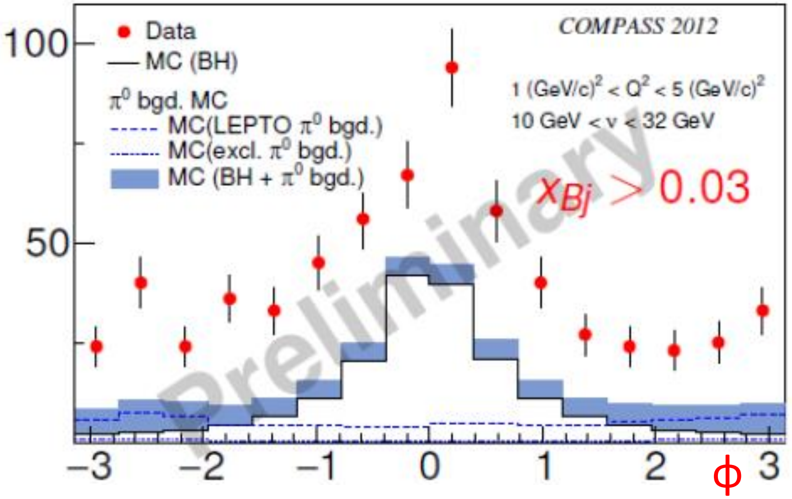
via the Interference

DVCS dominates

Study of $d\sigma^{DVCS}/dt$







Azimuthal dependence of BH+DVCS with Unpol Target

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

Σ	Σ
Σ	Σ
Δ	Δ
Σ	Δ
Δ	Σ
⇆ e-	⇆ μ±

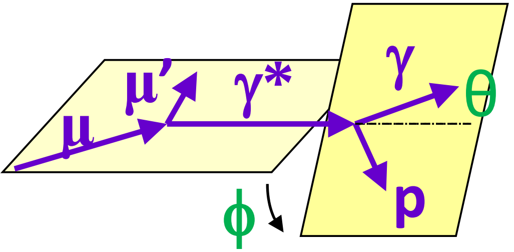
$$\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma^{DVCS}_{pol} &\propto s_1^{DVCS}\sin\phi \\
\mathrm{Re}\, I &\propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi +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

$s_1^I = Im\ \mathcal{F}$ $c_1^I = Re\ \mathcal{F}$

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

NB: to extract $\mathcal{E}$ use a neutron (deuteron) target or a transversely pol. target

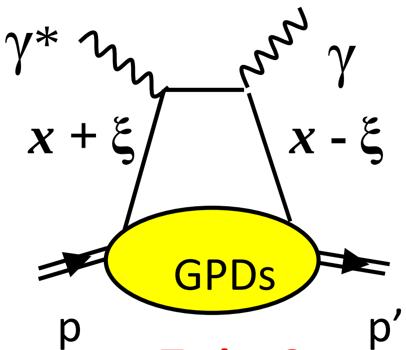
to extract $\tilde{\mathcal{H}}$ use a longitudinally polarized target



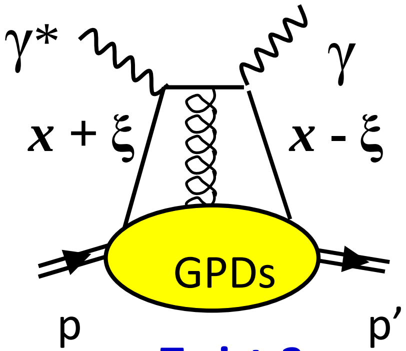
Twist-2 >>

🟦 Twist-3,

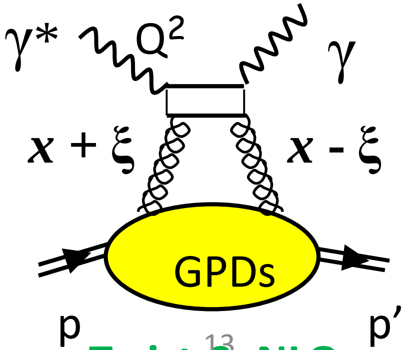
🟩 Twist-2
double helicity flip
for gluons (NLO)



Twist-2



Twist-3



Twist-2, NLO

integrated DVCS cross section

At COMPASS with polarized positive and negative muon beams:

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

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

calculable
can be subtracted

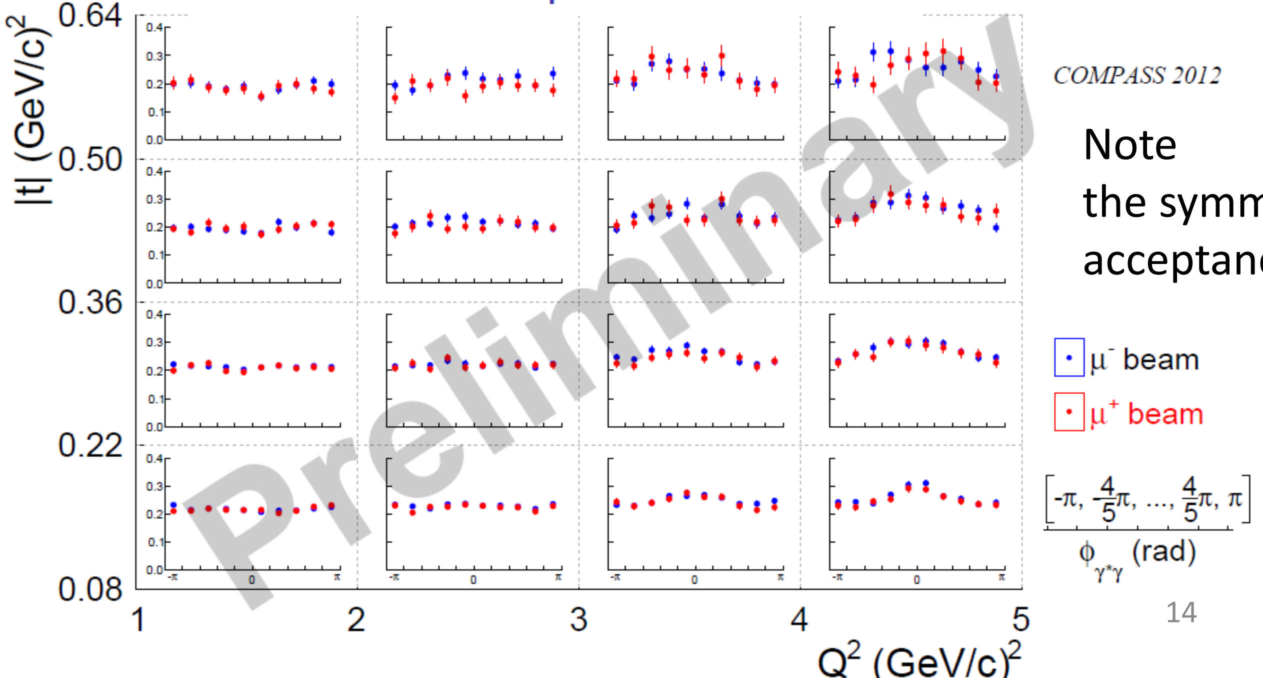
All the other terms are cancelled in the integration over phi

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

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

Flux for transverse
virtual photons

COMPASS acceptance for DVCS

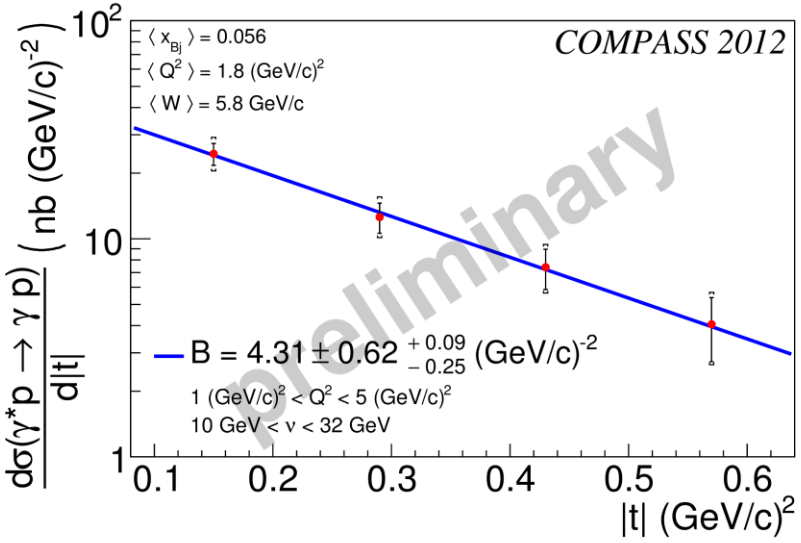


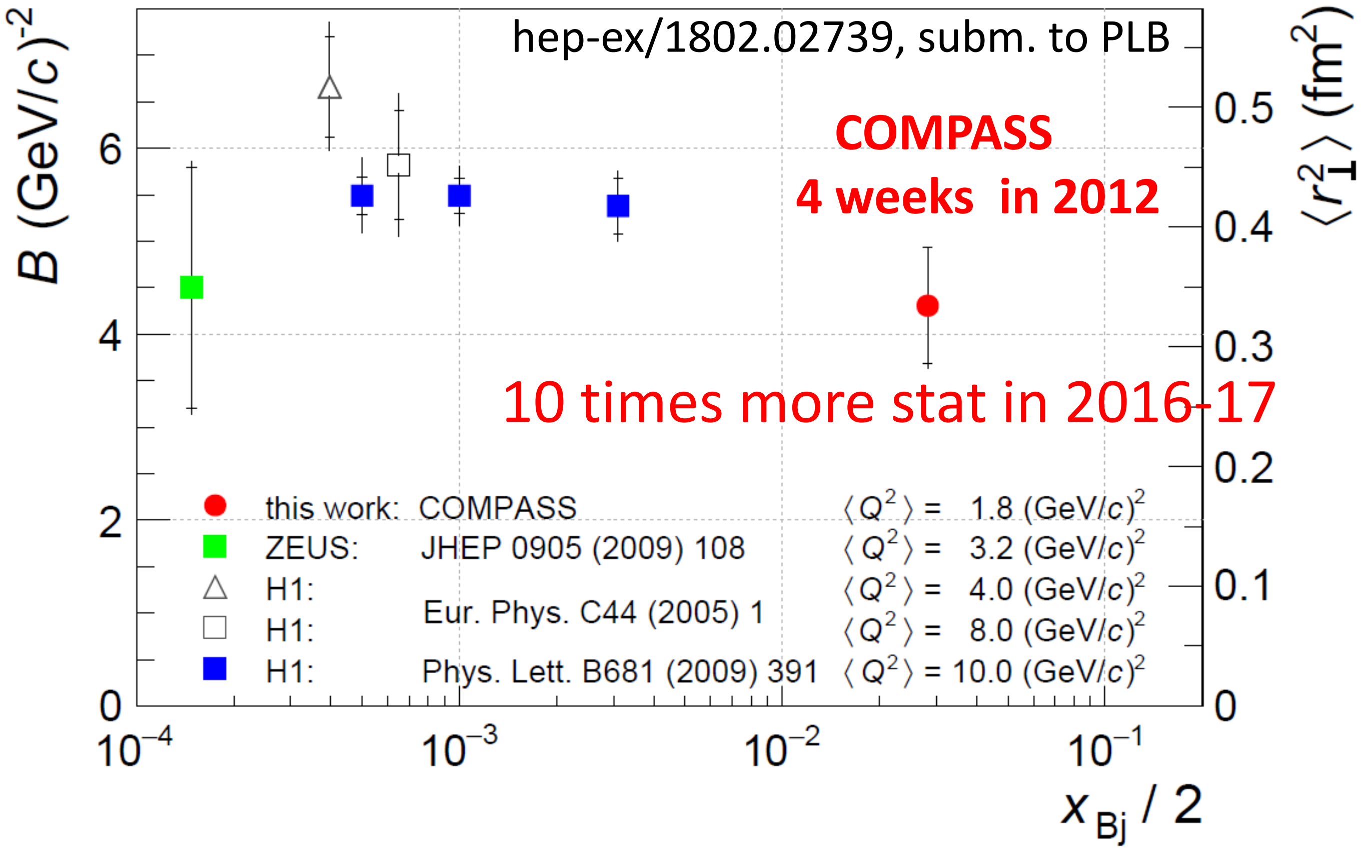
Note
the symmetric
acceptance

Sea quark imaging @ COMPASS

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

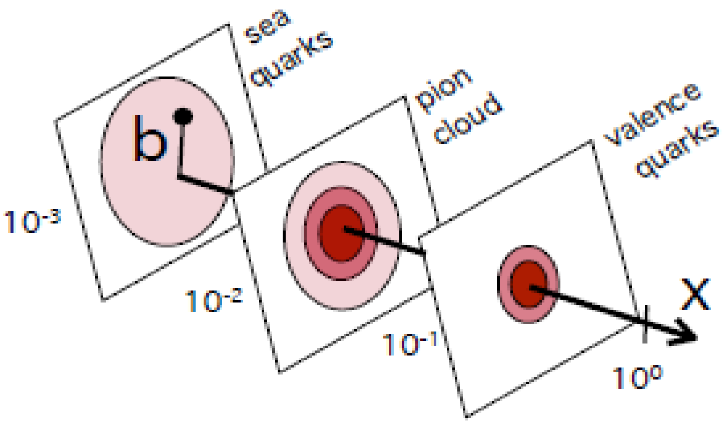
$$\langle r_\perp^2(x_B) \rangle \approx 2B(x_B)$$




hep-ex/1802.02739, subm. to PLB

COMPASS
4 weeks in 2012

10 times more stat in 2016-17



$$B = (4.31 \pm 0.62_{\rm stat} \; {}^{+\,0.09}_{-\,0.25}\big|_{\rm sys})\ ({\rm GeV}/c)^{-2}$$

$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\rm stat} \; {}^{+\,0.01}_{-\,0.02}\big|_{\rm sys})\ {\rm fm}$$

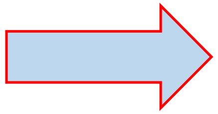
Transverse extension of partons in the proton

Comparison to GPD models

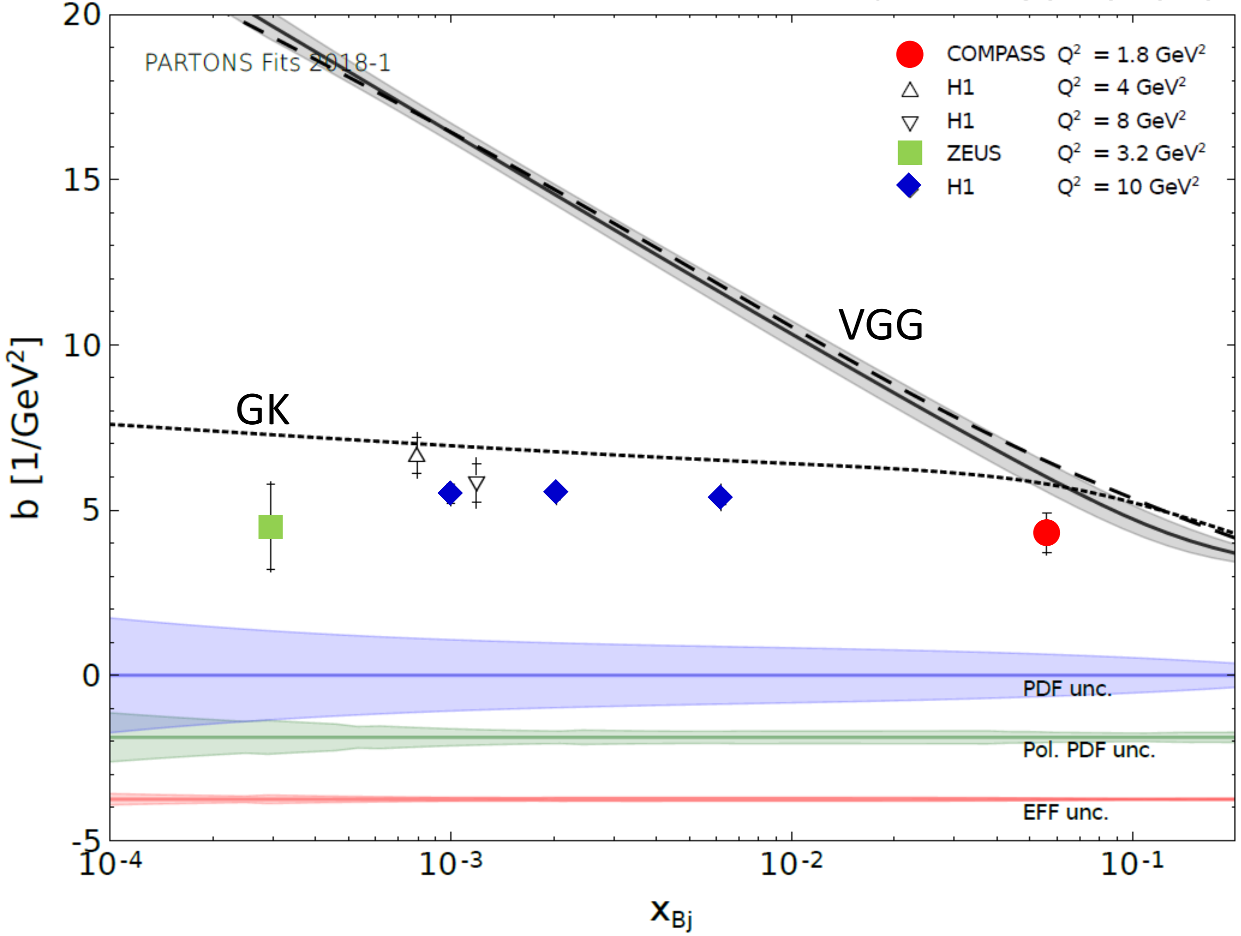
Figure from Moutarde, Sznajder, Wagner
arXiv: 1807.07620

The grey band is a global fit of CFF
in the PARTON framework
at LO and LT using a GPD parametrization
(only valence and sea quarks)

GK includes gluons (at next order in α_S)



Manifestation of gluons or NLO



What will come next?

4 weeks in 2012

2 years of data in 2016-17 ➔ 10 times more stat

At COMPASS with polarized positive and negative muon beams:

$$\boxed{\mathcal{S}_{CS,U} \equiv \ d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}}$$

The sum of DVCS x-sections at small x_B
mostly sensitive to $\mathrm{Im}\mathcal{H}(\xi,t)$
➔ transverse extension of partons

$$\boxed{\mathcal{D}_{CS,U} \equiv \ d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}}$$

The difference of DVCS x-section at small x_B
mostly sensitive to $\mathrm{Re}\mathcal{H}(\xi,t)$

$\mathrm{Im}\mathcal{H}(\xi,t) + \mathrm{Re}\mathcal{H}(\xi,t)$ ➔ D-term and pressure distribution

Beam Charge and Spin Diff. @ COMPASS

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}} = 2[d\sigma^{DVCS}_{pol} + \mathrm{Re}\, I] \xrightarrow{L.T.} c_0^I + c_1^I \cos\phi$$

$\mathcal{R}e\,\mathcal{H}$ **> 0** at H1

< 0 at HERMES

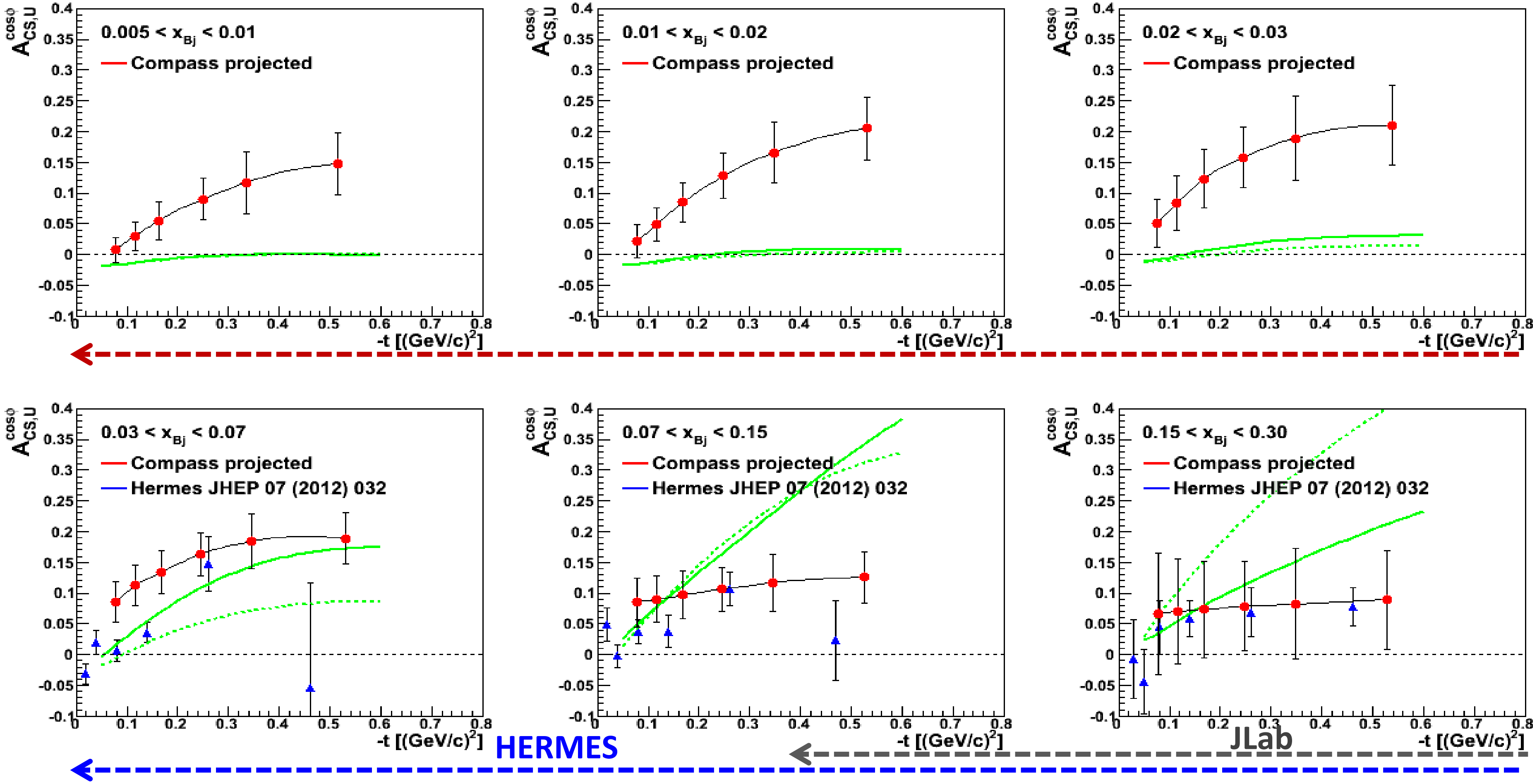
Value of x_B for the node?

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

Predictions with

VGG

KM10



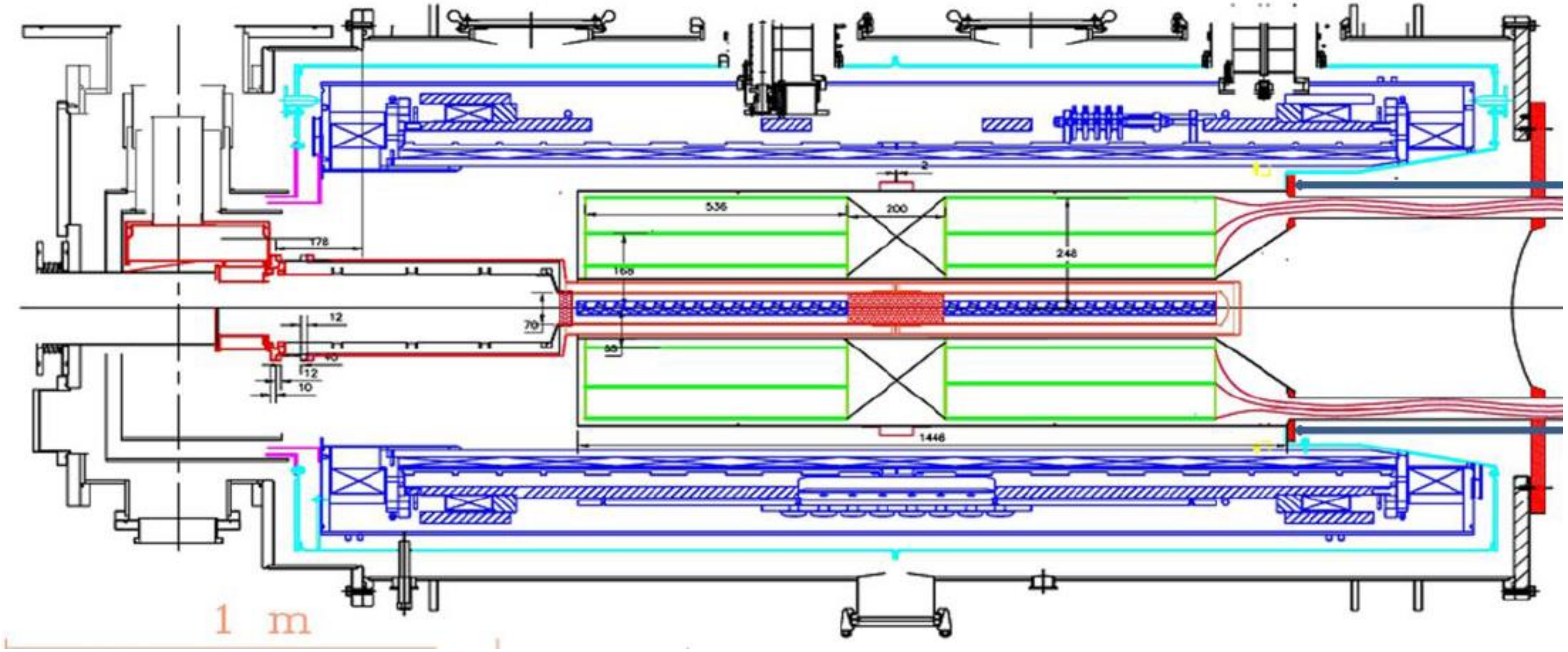
COMPASS 2 years of data Eμ= 160 GeV 1 < Q^2 < 8 GeV^2

And for the GPD E, the holy grail for Orbital Angular Momentum?

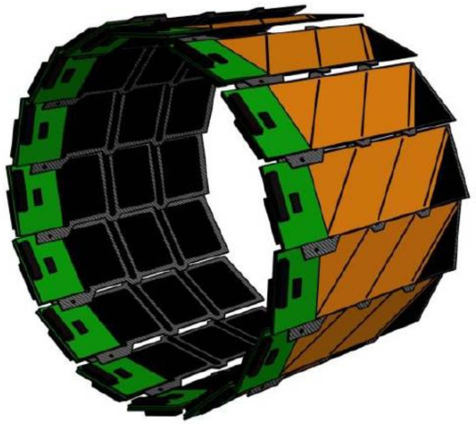
LoI for the future after 2022

Possible recoil detection with the COMPASS polarized target

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



3 cylindrical layers of Silicon det. are included in ~18cm



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

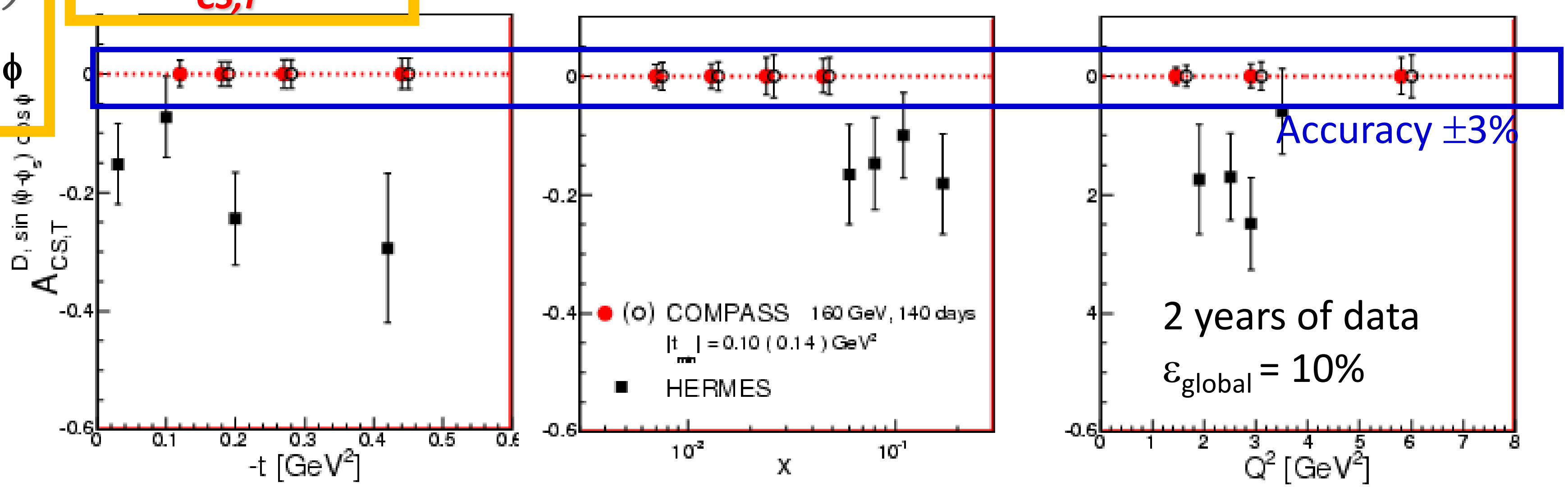
DVCS with 160 GeV pol. μ^+ & μ^- beams and Transv Pol target

$$\mathcal{D}_{CS,T} \equiv \Delta\sigma_T(\mu^{+\downarrow}) - \Delta\sigma_T(\mu^{-\uparrow})$$

$$\rightarrow Im(F_2\mathcal{H} - F_1\mathcal{E})\,\sin(\phi-\phi_s)\cos\phi$$

$$\mathcal{A}^{\sin(\phi-\phi_s)\cos\phi}_{\mathcal{D}_{CS,T}}$$

1.2m long transv. polarized NH_3 target



Accuracy ±3%

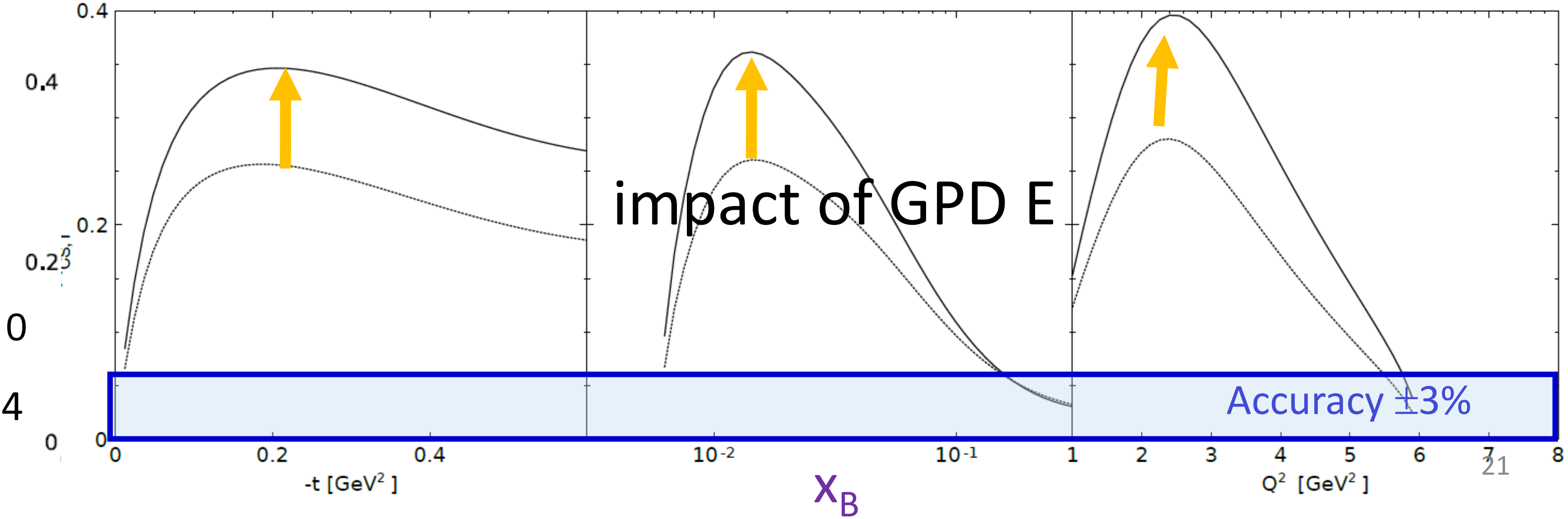
2 years of data

ε_{global} = 10%

From Pawel Sznajder
Using the PARTONS code
Formalism at LO

————	GK and CFFs@LO
- - - - - -	Idem with GPDs E = 0

$J^u \sim 0.23$; $|J^d| < 0.05$; $|J^s| < 0.04$



impact of GPD E

Accuracy ±3%

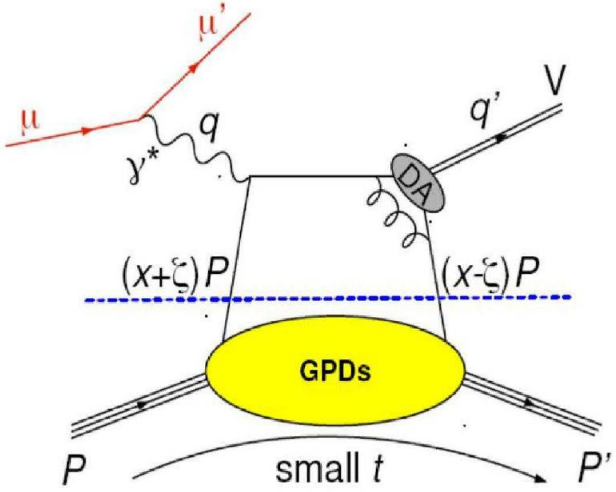
Now HEMP,

pseudo-scalar meson π^0

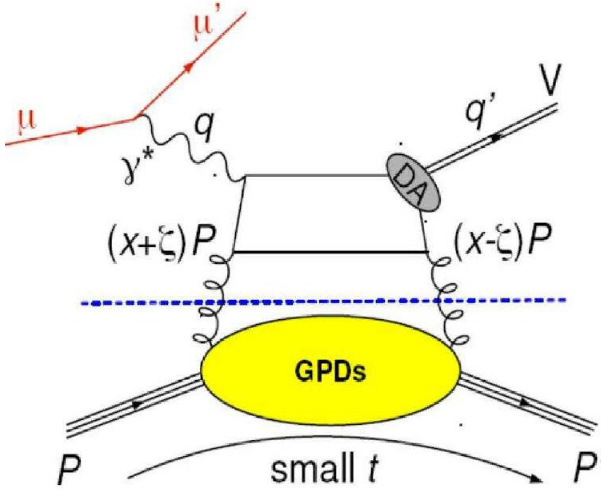
vector mesons ρ and ω

GPDs and Hard Exclusive Meson Production

Quark contribution



Gluon contribution at the same order in α_S



The Meson Distribution Amplitude
Is an additional non-perturbative term

4 chiral-even GPDs: helicity of parton unchanged

$H^q(x, \xi, t)$ $E^q(x, \xi, t)$ **For Vector Meson**

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

+ 4 chiral-odd or transversity GPDs: helicity of parton changed
(not possible in DVCS)

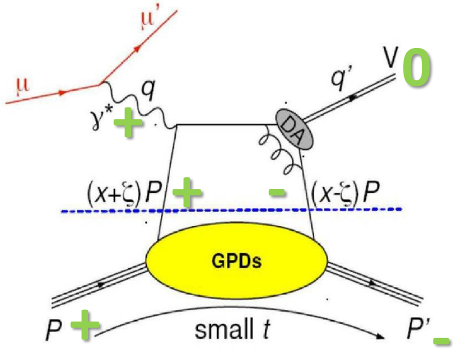
$H_T^q(x, \xi, t)$ $E_T^q(x, \xi, t)$

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

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

Factorisation proven only for σ_L (σ_T suppressed by $1/Q^2$) but the diagram with these **helicities** is possible and is expressed with transversity GPDs

$\mathfrak{M}_{0-,++}$



Exclusive π^0 production on unpolarized proton

e p → e π^0 p

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

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

Leading twist should be dominant

but ≈ 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

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

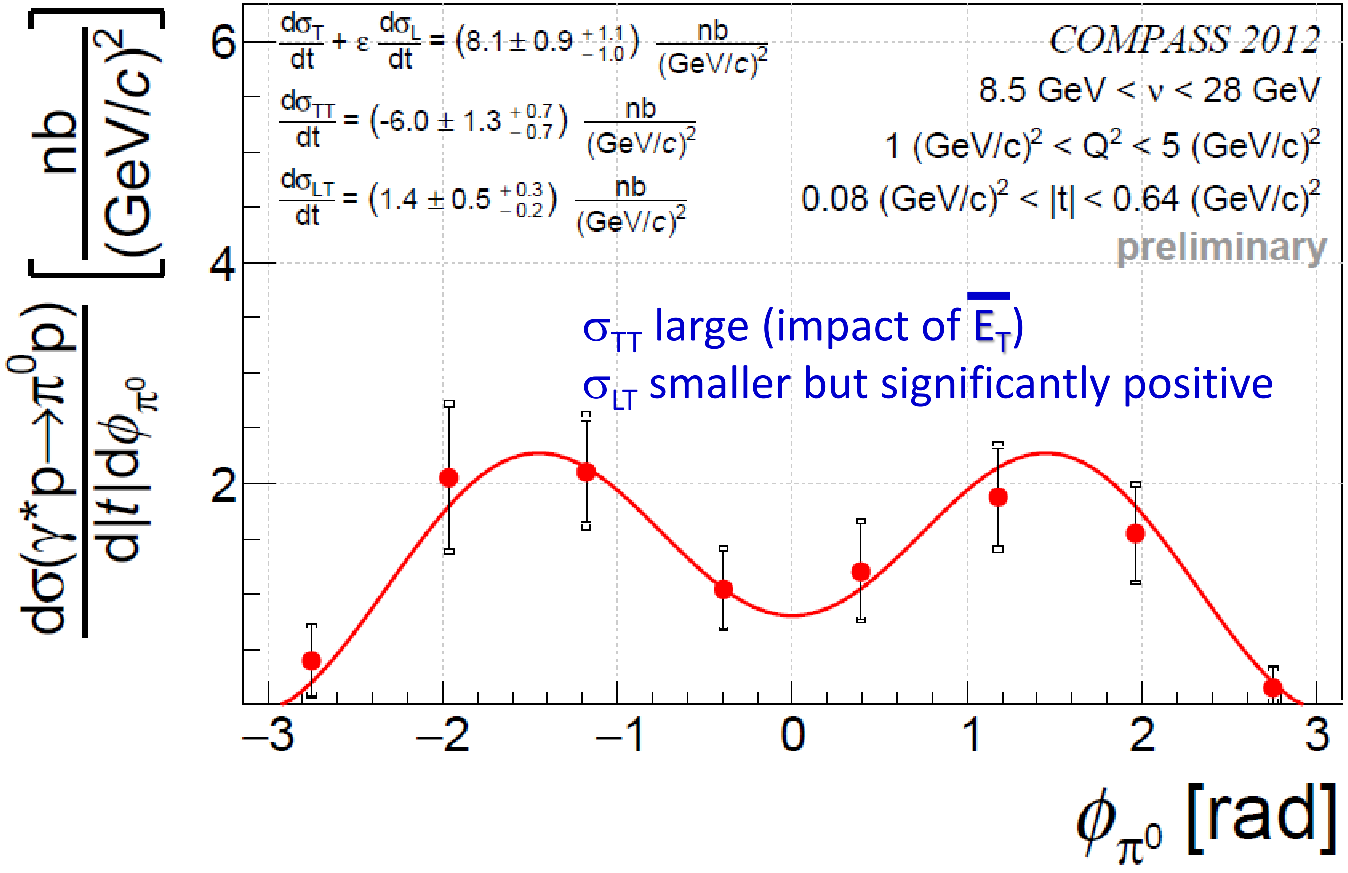
$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

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

A large impact of $\bar{E}_T$
should be clearly visible in σ_{TT}
and in the dip at small |t| of σ_T

Exclusive π^0 production on unpolarized proton

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

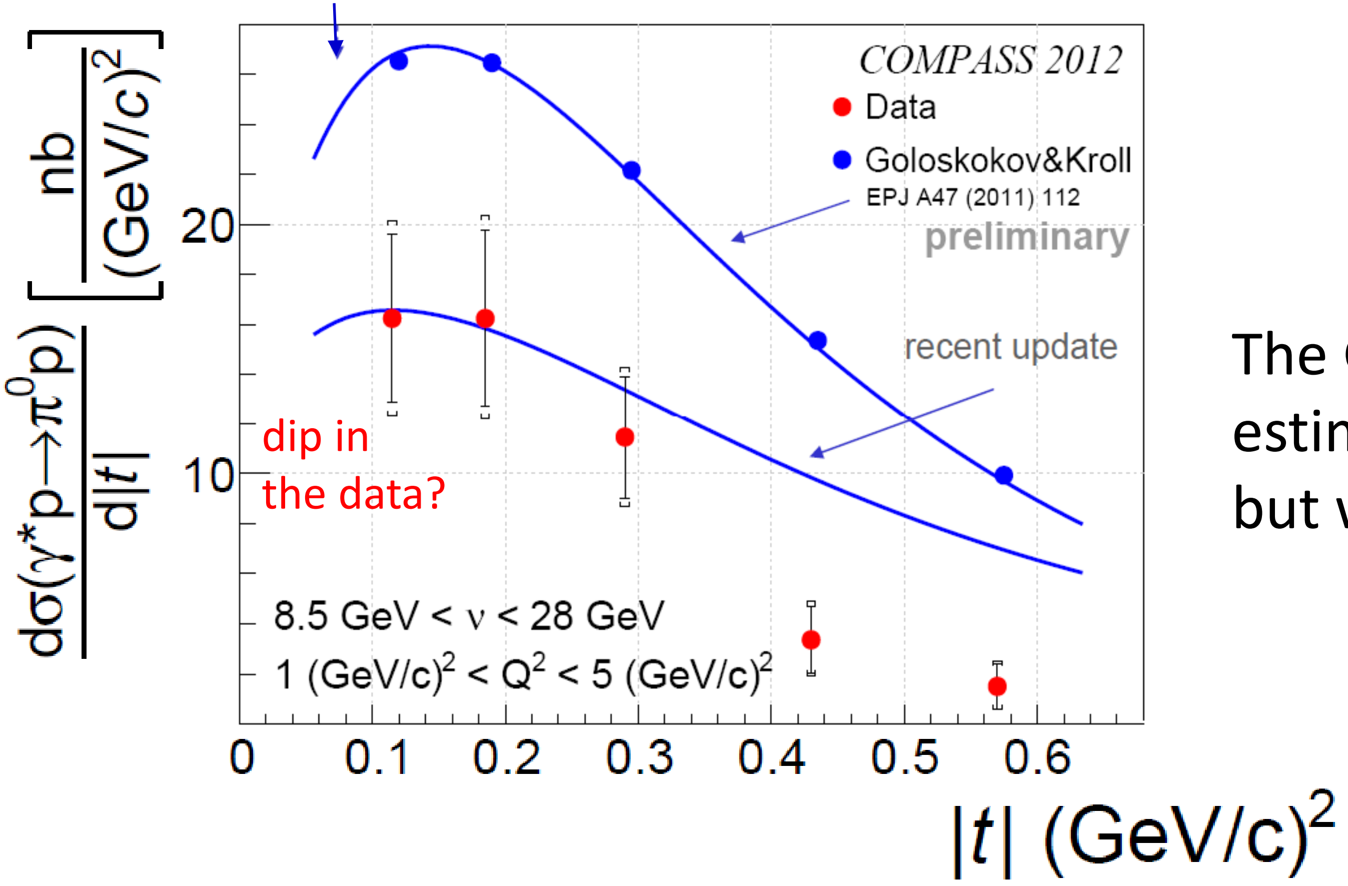


σ_{TT} large (impact of $\bar{E}_T$)

σ_{LT} smaller but significantly positive

Exclusive π^0 production on unpolarized proton

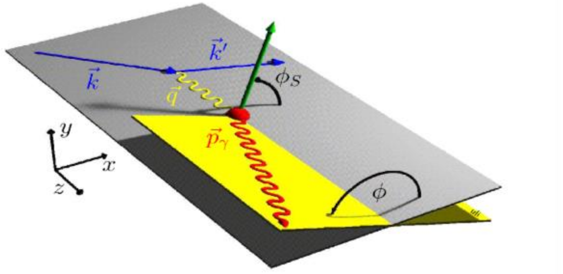
The dip at small t
indicates the large impact of $\bar{E}_T$



dip in
the data?

The GK model
estimates better the data
but with a different shape

Exclusive ρ^0 production with transversely polarized target



$$\left[\frac{\alpha_{\rm em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_B}{x_B}\,\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_{Bj}\,dQ^2\,dt\,d\phi\,d\phi_s}$$

$$= \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++}-\varepsilon\cos(2\phi)\,\mathrm{Re}\,\sigma_{+-}^{++}-\sqrt{\varepsilon(1+\varepsilon)}\cos\phi\,\mathrm{Re}\left(\sigma_{+0}^{++}+\sigma_{+0}^{--}\right)$$

$$-P_\ell\sqrt{\varepsilon(1-\varepsilon)}\sin\phi\,\mathrm{Im}\left(\sigma_{+0}^{++}+\sigma_{+0}^{--}\right)$$

$$-S_T\Big[\underline{\sin(\phi-\phi_S)}\,\mathrm{Im}\left(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-}\right)+\frac{\varepsilon}{2}\underline{\sin(\phi+\phi_S)}\,\mathrm{Im}\,\sigma_{+-}^{+-}+\frac{\varepsilon}{2}\underline{\sin(3\phi-\phi_S)}\,\mathrm{Im}\,\sigma_{+-}^{-+}$$

transv. polar. target

$$+\sqrt{\varepsilon(1+\varepsilon)}\,\underline{\sin\phi_S}\,\mathrm{Im}\,\sigma_{+0}^{+-}+\sqrt{\varepsilon(1+\varepsilon)}\,\underline{\sin(2\phi-\phi_S)}\,\mathrm{Im}\,\sigma_{+0}^{-+}\Big]$$

$$+S_T P_\ell\Big[\sqrt{1-\varepsilon^2}\,\underline{\cos(\phi-\phi_S)}\,\mathrm{Re}\,\sigma_{++}^{+-}$$

transv. polar. target + long. polar. beam

$$-\sqrt{\varepsilon(1-\varepsilon)}\,\underline{\cos\phi_S}\,\mathrm{Re}\,\sigma_{+0}^{+-}-\sqrt{\varepsilon(1-\varepsilon)}\,\underline{\cos(2\phi-\phi_S)}\,\mathrm{Re}\,\sigma_{+0}^{-+}\Big]$$

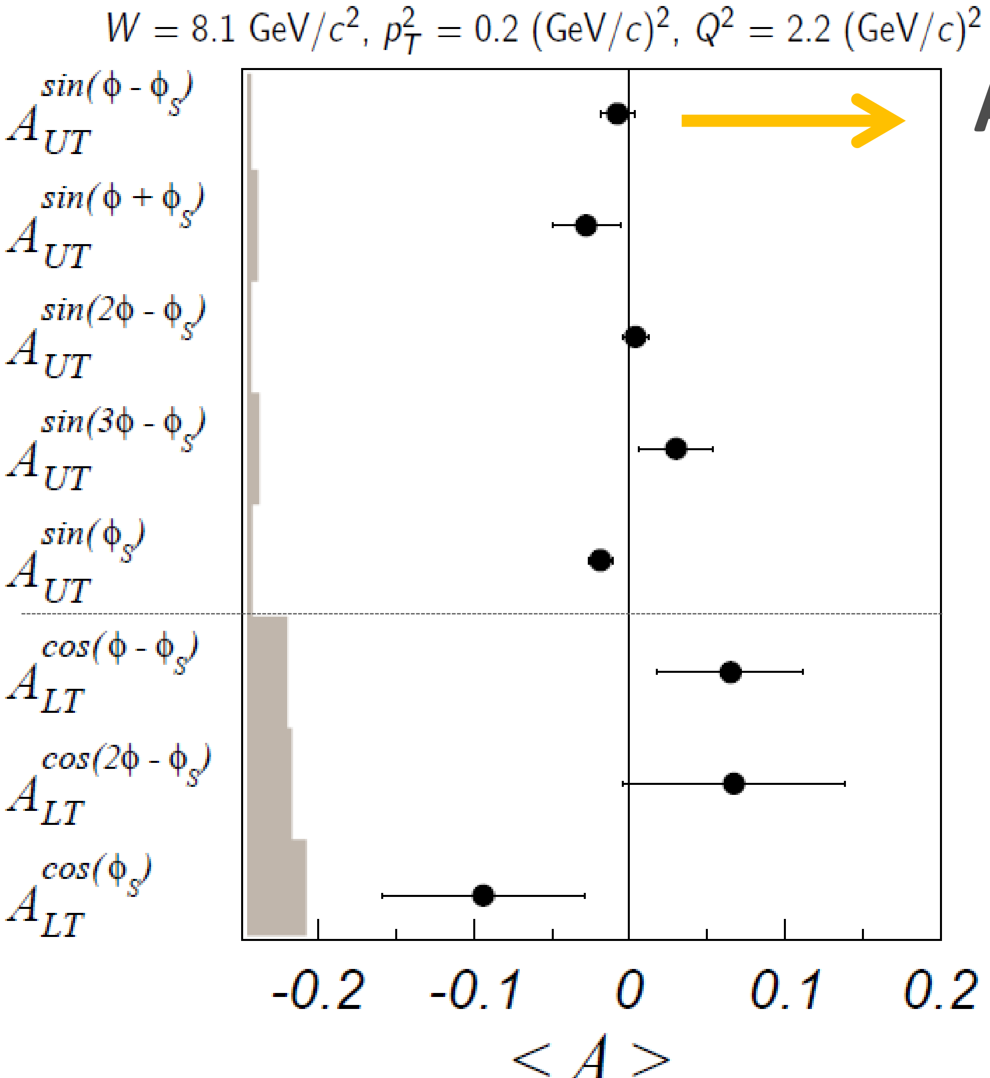
σ ij for nucleon helicity
mn for photon helicity

Dominant interference terms:
LL $\gamma^*_L \rightarrow \rho^0_L$
then LT $\gamma^*_T \rightarrow \rho^0_L$

exclusive ρ^0 production with Transv. Polar. Target

$$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non detected}}$$
$$\hookrightarrow \pi^+\pi^-$$

COMPASS 2007-2010,without recoil detector



$$A_{UT}^{\sin(\phi-\phi_S)} \propto Im(\mathcal{E}^{*}\mathcal{H})$$

$E\rho^0 \propto 2/3\ E^u + 1/3\ E^d + 3/4\ E^g$

- ✓ Cancellation between gluon and sea contributions
- ✓ $E^{u\ val} \sim -E^{d\ val}$

COMPASS, NPB 865 (2012) 1-20

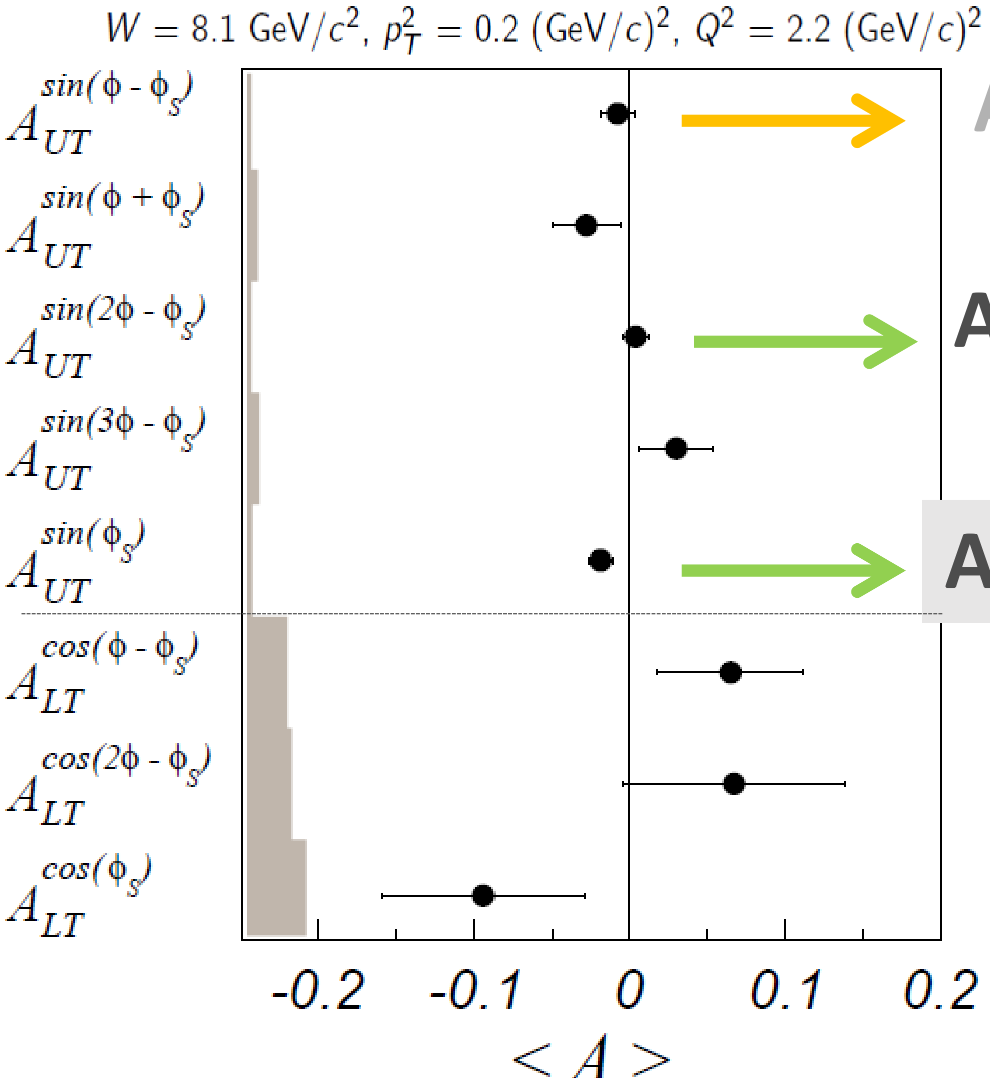
ω production should be more powerful

$E\omega \propto 2/3\ E^u - 1/3\ E^d + 1/4\ E^g$

exclusive ρ^0 production with Transv. Polar. Target

$$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non detected}}$$
$$\hookrightarrow \pi^+\pi^-$$

COMPASS 2007-2010,without recoil detector



$$A_{UT}^{\sin(\phi-\phi_S)} \propto Im(\mathcal{E}^* \mathcal{H})$$

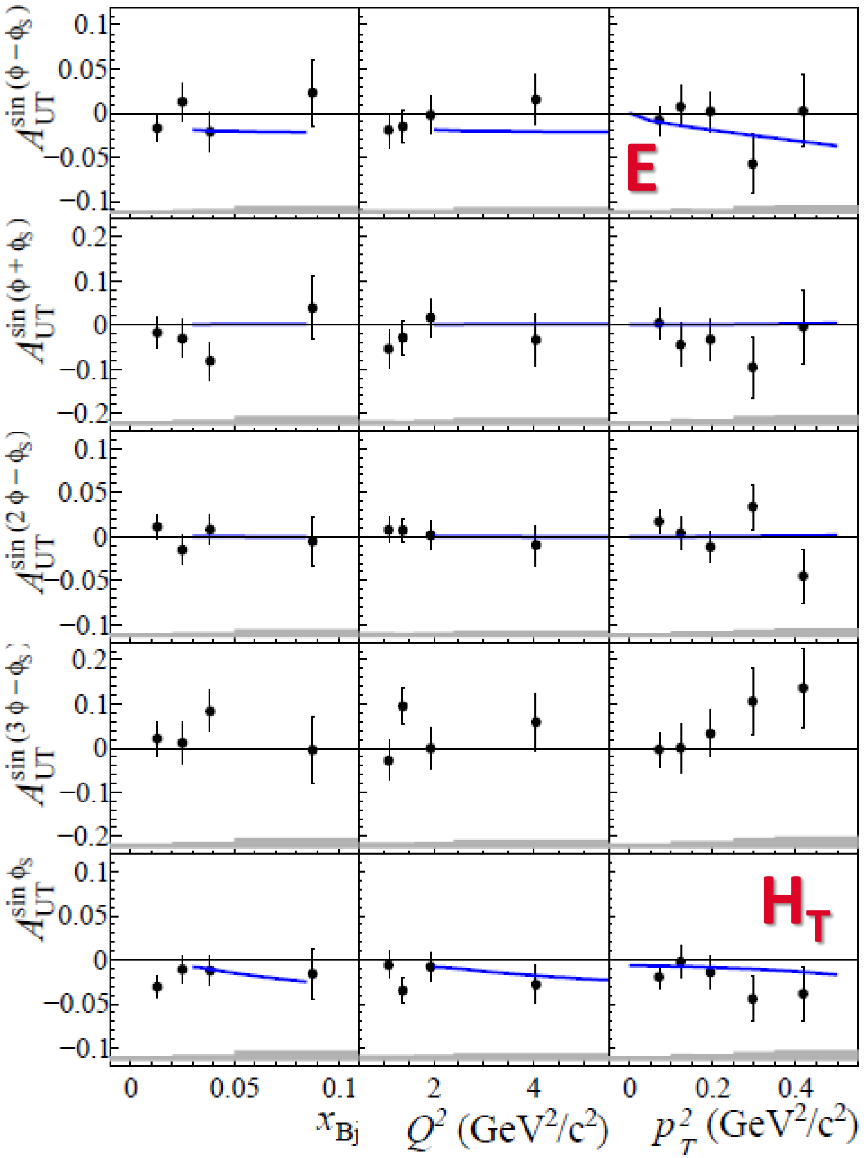
$$A_{UT}^{\sin(2\phi-\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T)$$

$$A_{UT}^{\sin(\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$$

➔ H_T should not be small

COMPASS, PLB731 (2014) 19

exclusive ρ^0 production with Transv. Polar. Target



$\langle x_{Bj} \rangle \approx 0.039$, $\langle Q^2 \rangle \approx 2.0$ GeV^2, $\langle p_T^2 \rangle \approx 0.18$ GeV^2

$$\mu\ p \rightarrow \mu' + \underset{\hookrightarrow \pi^+\pi^-}{\rho^0} + p_{\text{non detected}}$$

Comparison with a phenomenological GPD-based model

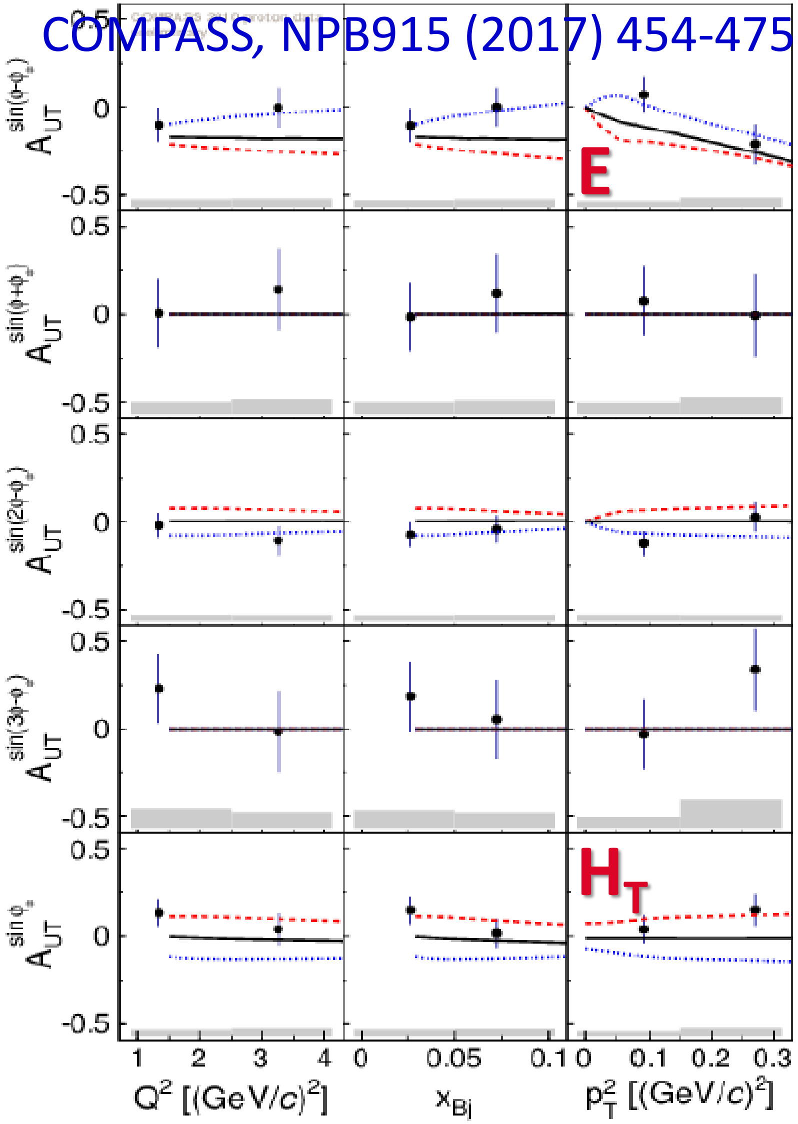
Goloskokov and Kroll (EPJ C74 (2014))

- Phenomenological 'handbag' approach
- Includes twist-3 ρ^0 meson wave functions
- Includes contributions from γ^*_L and γ^*_T

Large contribution of the GPDs E and H_T

COMPASS, PLB731 (2014) 19

exclusive ω production with Transv. Polar. Target



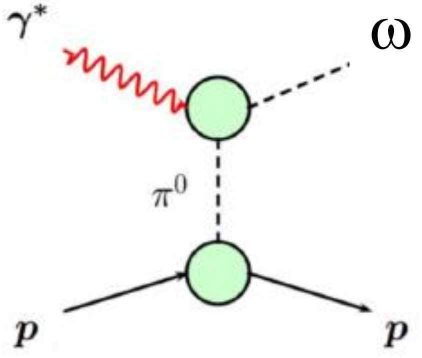
COMPASS, NPB915 (2017) 454-475

$\langle x_{Bj} \rangle \approx 0.049$, $\langle Q^2 \rangle \approx 2.2$ GeV^2
$\langle p_T^2 \rangle \approx 0.17$ GeV^2, $\langle W \rangle \approx 7.1$ GeV^2

$\mu \; p \rightarrow \mu' + \omega + p_{\text{non détecté}}$
$\hookrightarrow \pi^+\pi^-\pi^0$

GK model predictions (EPJ A50 (2014))
including all the GPDs and transverse GPDs

+ the pion pole exchange which is large for ω production



- positive $\pi\omega$ form factor
- no pion pole
- negative $\pi\omega$ form factor

no unambigous
determination of the sign

exclusive ω production with Unpolarised Target and SDME

Spin density matrix elements are bilinear combinations of the helicity amplitudes $\boxed{F(\gamma^*(\lambda_\gamma) \to V(\lambda_V))}$

$\boxed{\lambda_\gamma = \pm 1, 0}$ $\boxed{\lambda_V = \pm 1, 0}$

$$\boxed{\rho^{\alpha}_{\lambda_V \lambda'_V}} = \frac{1}{2\mathcal{N}} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} \boxed{F_{\lambda_V \lambda'_N;\lambda_\gamma \lambda_N}} \boxed{\varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma}} \boxed{F^*_{\lambda'_V \lambda'_N;\lambda'_\gamma \lambda_N}}$$

9 cases for the photon: transversely (unpol, lin in 2 ⊥ dir, circ) $\alpha = 0 \div 3$

longitudinally $\alpha = 4$

interferences $\alpha = 5 \div 8$

$$r^{\alpha}_{\lambda_V \lambda'_V} \propto \rho^{\alpha}_{\lambda_V \lambda'_V} \;/\; (1 + \varepsilon R)$$

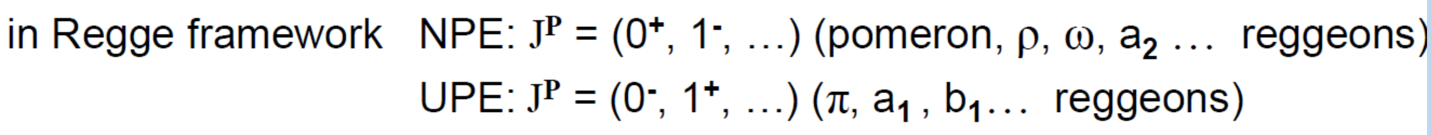
$$r^{04}_{\lambda_V \lambda'_V} \propto (\rho^{0}_{\lambda_V \lambda'_V} + \varepsilon R \; \rho^{4}_{\lambda_V \lambda'_V}) \;/\; (1 + \varepsilon R)$$

If transverse and longitudinal photons are not separated $R = \sigma_L / \sigma_T$

GOAL: test of s-channel helicity conservation ($\lambda_\gamma = \lambda_V$)

in GPD models: SCHC-violation $\gamma_T \to V_L$ implies quark helicity flip or transverse GPDs

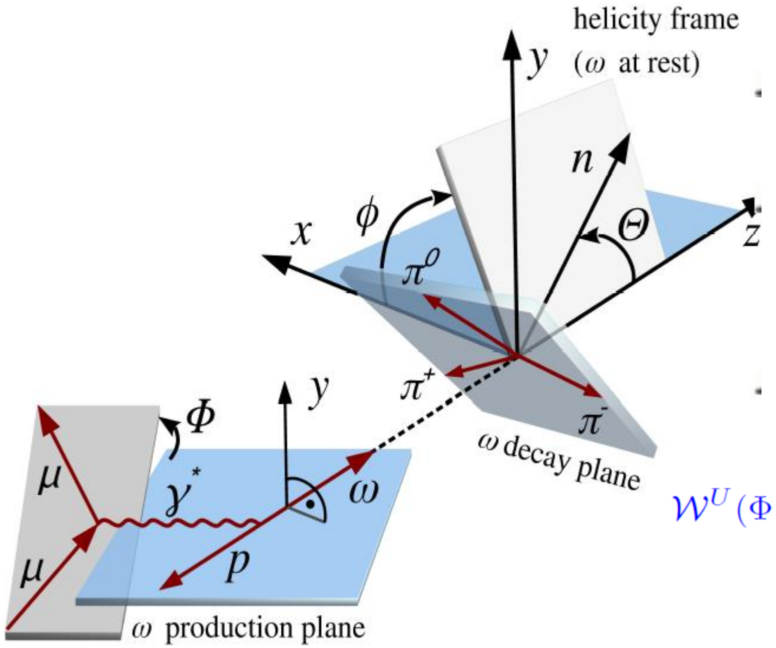
decomposition of F into Natural (N) Parity and Unnatural (U) Parity exchange amplitude



in Regge framework NPE: $J^P = (0^+, 1^-, \ldots)$ (pomeron, ρ, ω, a_2 … reggeons)

UPE: $J^P = (0^-, 1^+, \ldots)$ (π, a_1, b_1… reggeons)

exclusive ω production with Unpolarised Target and SDME



experimental angular distributions

$$\mathcal{W}^{U+L}(\Phi,\phi,\cos\Theta) = \mathcal{W}^{U}(\Phi,\phi,\cos\Theta) + \boxed{P_b}\,\mathcal{W}^{L}(\Phi,\phi,\cos\Theta)$$

15 'unpolarized' and 8 'polarized' SDMEs

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

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

exclusive ω production with Unpolarised Target and SDME

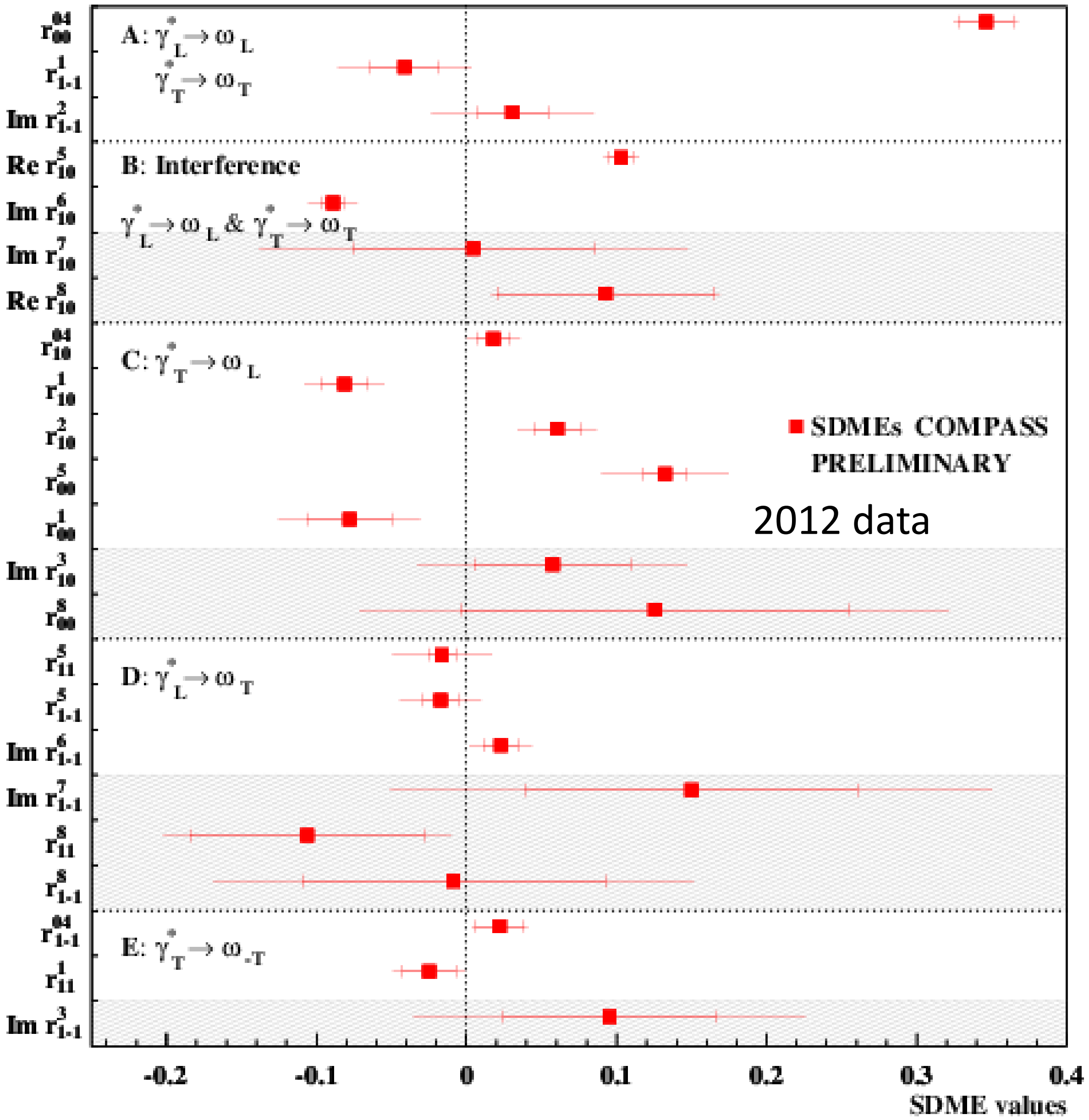
$1 < Q^2 < 10$ GeV^2	$\langle Q^2 \rangle = 2.13$ GeV^2
$5 < W < 20$ GeV	$\langle W \rangle = 7.6$ GeV
$0.01 < p_T^2 < 0.5$ GeV^2	$\langle p_T^2 \rangle = 0.16$ GeV^2

CAMERA not used in this analysis

Unbinned ML fit to experimental angular distributions taking into account acceptance and fraction of background

23 SDMEs in 5 classes A, B, C, D, E depending on helicity transitions

SDMEs dependent on beam polarisation Shown within shaded areas



Test of s-channel helicity conservation

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

SCHC implies:

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

  $= -0.010 \pm 0.032 \pm 0.047$ OK

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

  $= 0.014 \pm 0.011 \pm 0.013$ OK

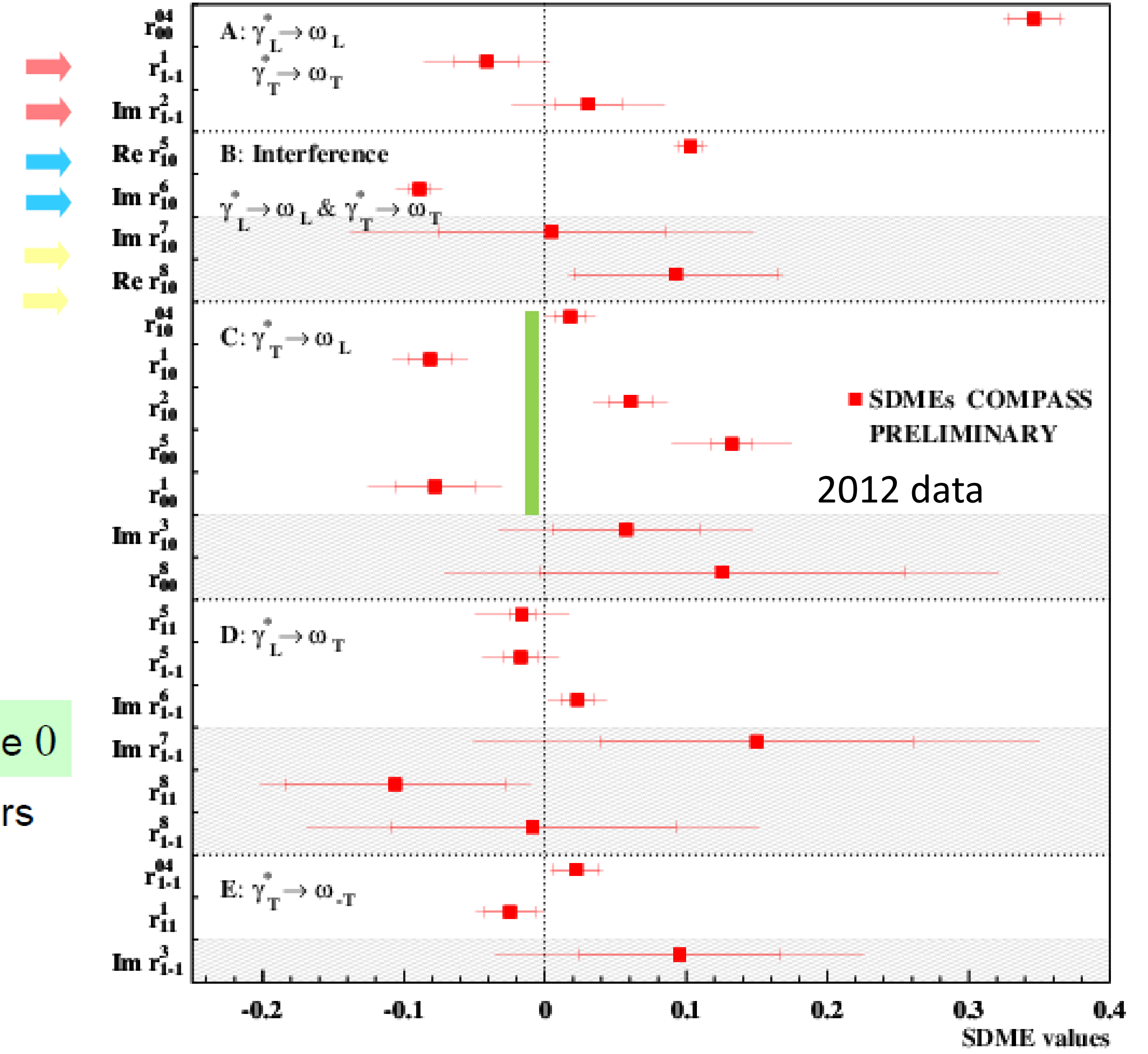
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

  $= -0.088 \pm 0.110 \pm 0.196$ OK

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

for $\gamma^*_L \rightarrow \omega_T$ and $\gamma^*_T \rightarrow \omega_{-T}$ OK within errors

not obeyed for transitions $\gamma^*_T \rightarrow \omega_L$

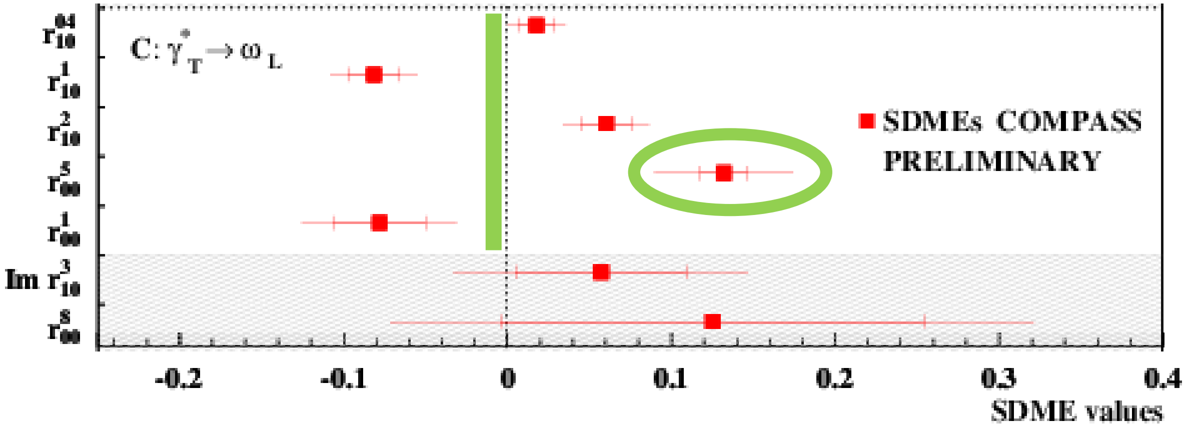


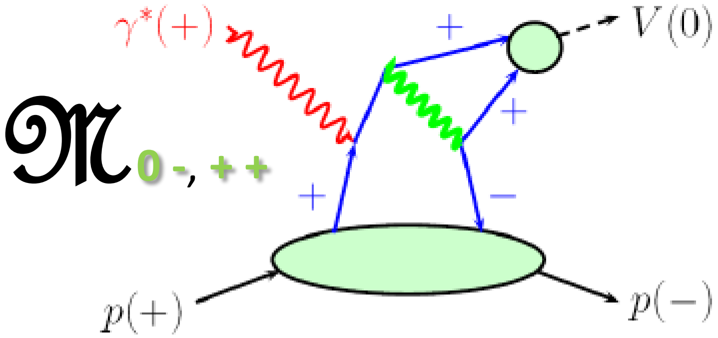
Transition $\gamma^*_T \rightarrow \omega_L$

possible GPD interpretation

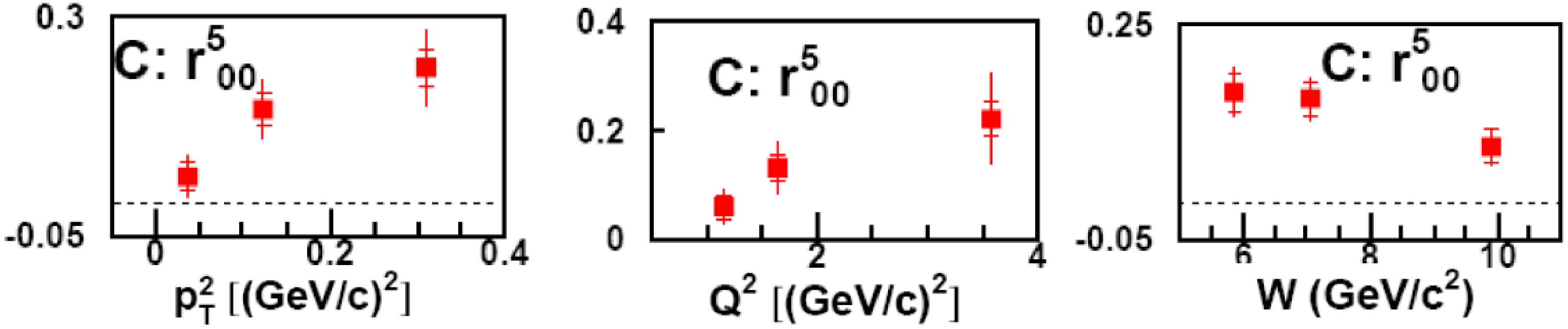
Goloskokov and Kroll, EPJC 74 (2014) 2725

$$r^5_{00} \propto \mathrm{Re}[\langle \overline{E}_T\rangle^*_{LT}\langle H\rangle_{LL} + \frac{1}{2}\langle H_T\rangle^*_{LT}\langle E\rangle_{LL}]$$





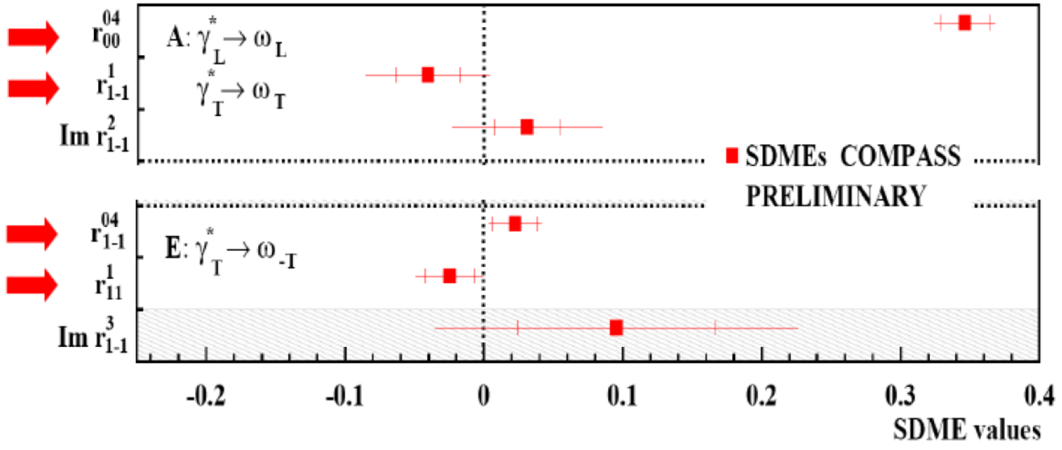
COMPASS preliminary



Unnatural parity exchange contribution

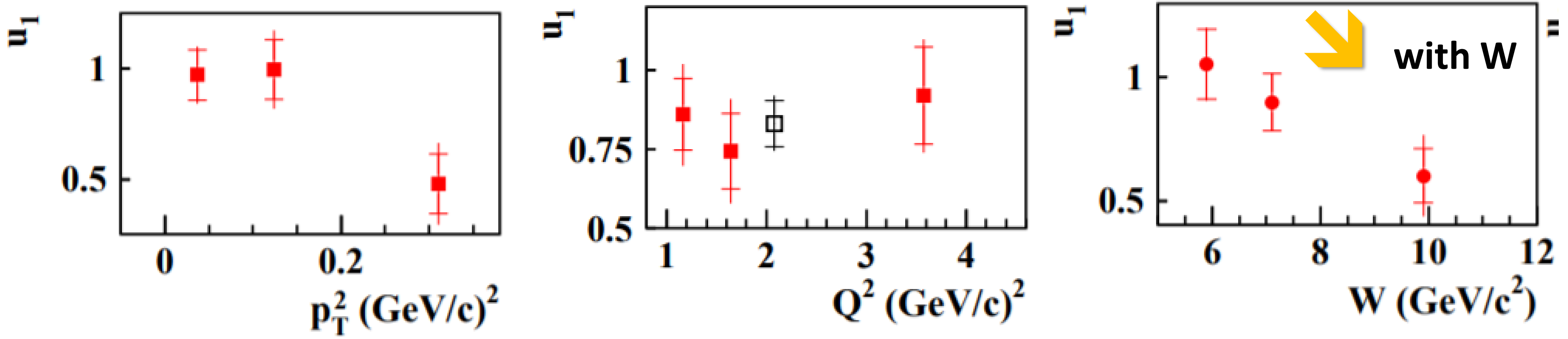
$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1}$$

$$= \sum_{\lambda_N \lambda'_N} \frac{4\epsilon |U_{1\lambda'_N 0\lambda_N}|^2 + 2|U_{1\lambda'_N 1\lambda_N} + U_{-1\lambda'_N 1\lambda_N}|^2}{N}$$



$u1 > 0 \implies$ UPE contribution

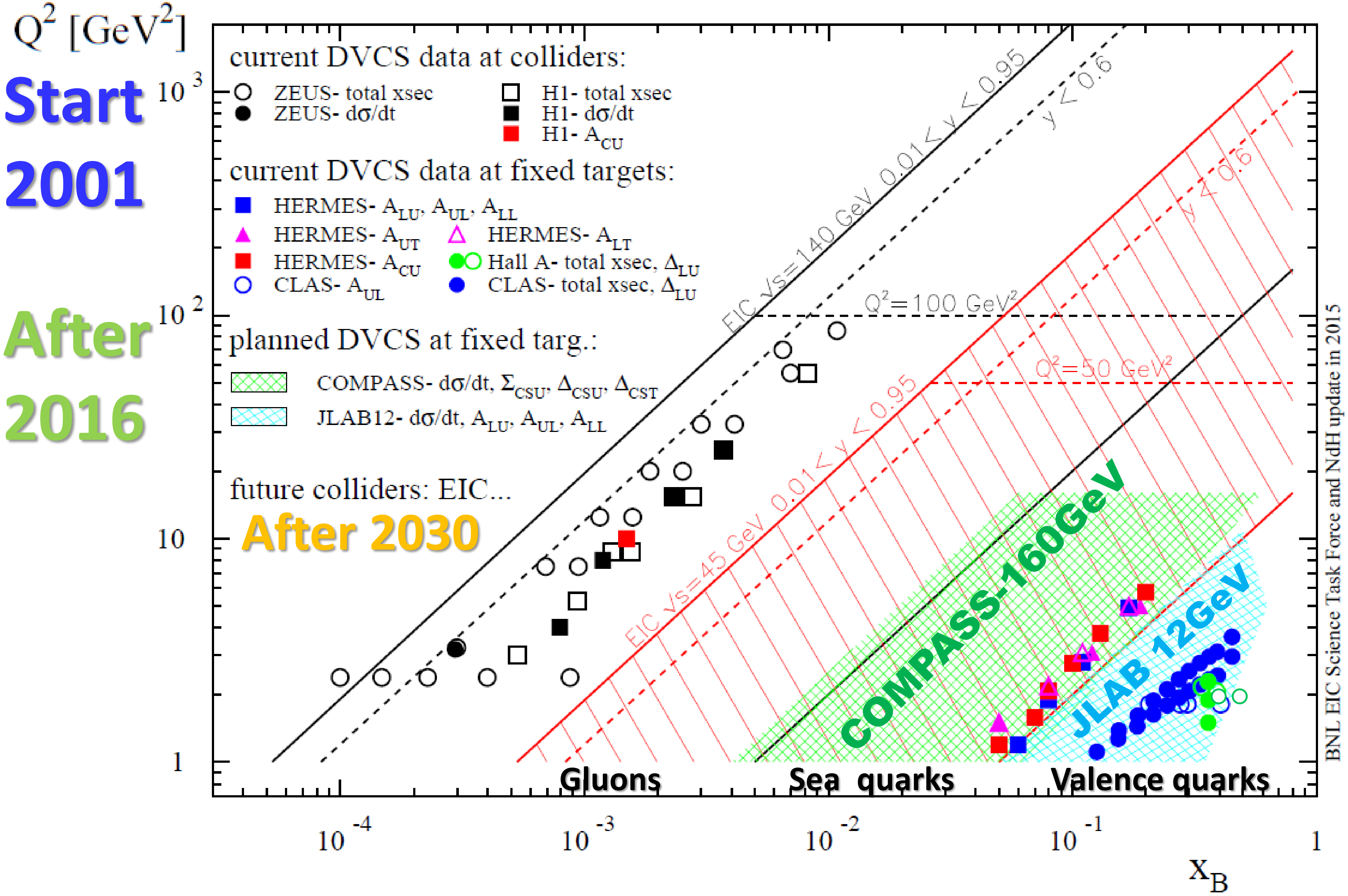
COMPASS preliminary



possible GPD interpretation **Goloskokov and Kroll, EPJA 50 (2014) 146**

contribution of amplitudes depending on helicity GPDs $\widetilde{E}, \widetilde{H}$ the former parameterised predominantly by **pion-pole exchange**

The past and future DVCS experiments



Start 2001

After 2016

After 2030

Conclusions

From 2016-17 data

sum and difference of DVCS x-sections with polarized μ+ and μ-

- ➔ transverse extension of partons as a function of x_B
- ➔ Im$\mathcal{H}(\xi,t)$ and Re$\mathcal{H}(\xi,t)$ for D-term and pressure distribution

HEMP $\pi^0, \rho, \omega, \phi,$ J/ψ ➔ transverse GPDs - universality of GPDs - flavor decomposition

Program starting in 2022

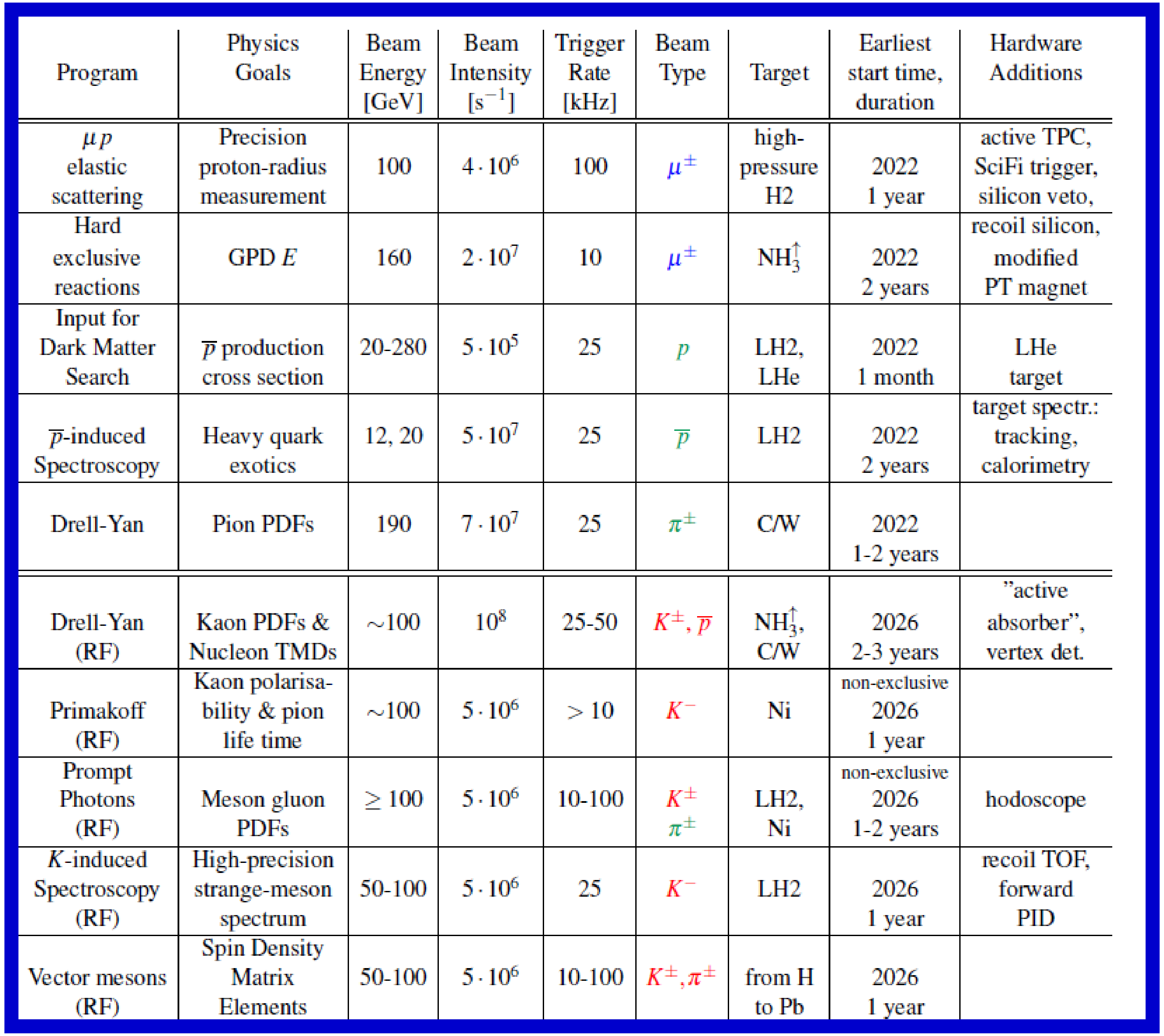
Letter of Intent Draft 1.0: https://arXiv.org/abs/1808.00848

New collaborators are welcome, sign up here:
https://nqf-m2.web.cern.ch

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

Letter of Intent - Draft 1.0: https://arXiv.org/abs/1808.00848

Program starting in 2022



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	~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 polarisa-bility & pion life time	~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	

Beam line unique with polarised μ+ and μ- and high intensity pion beam

**Possible RF separated beam
for high intensity antiproton and K beams**

Versatile apparatus (Upgrade ++)

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

SPARES

Valence quark imaging at Jlab and HERMES

Fit of 8 CFFs at L.O and L.T.

Dupré, Guidal, Vanderhaeghen, PRD95, 011501(R)(2017)

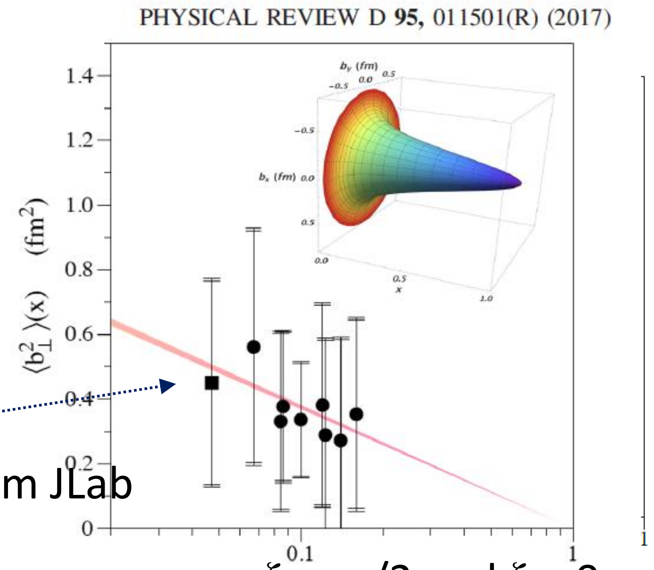
Dupré, Guidal, Nicolai, Vanderhaeghen, arXiv: 1704.07330

$$s_1^I = Im\, F_1 \mathcal{H}$$

- ☐ CLAS σ and Δσ
- ▲ HallA σ and Δσ
- ● CLAS A_{UL} and A_{LL}
- ★ VGG model

— Fit $A\, e^{-B|t|}$

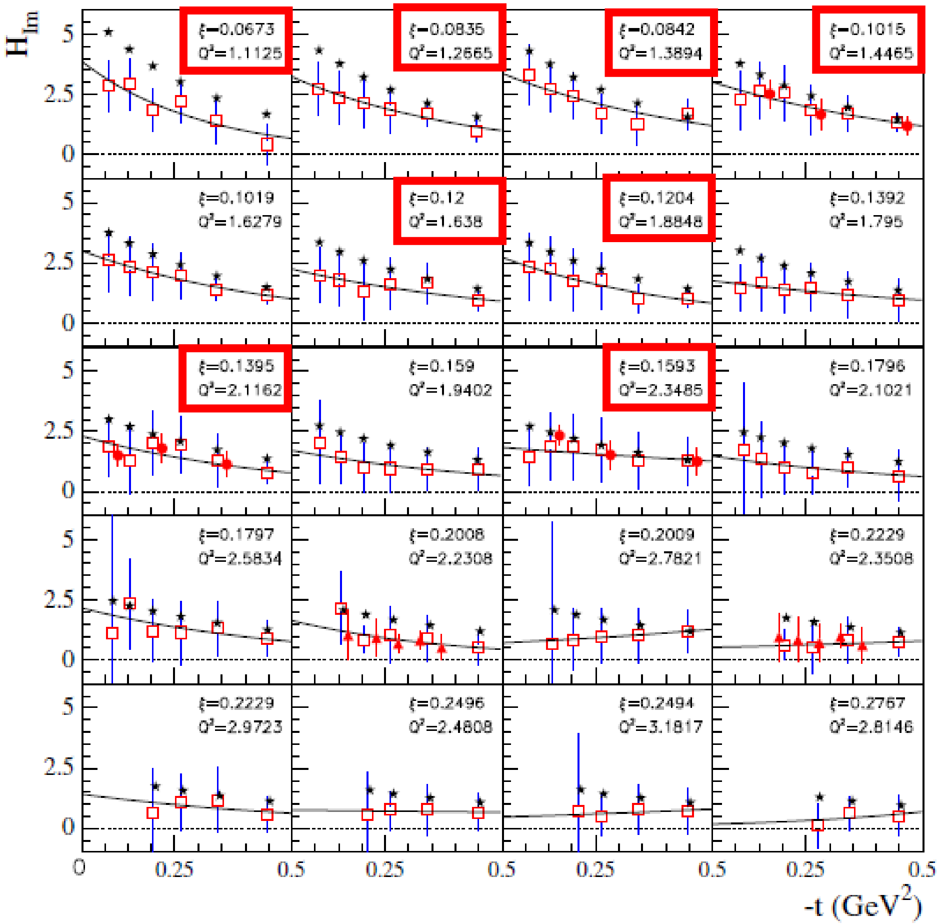
$$< b_\perp^2 > \approx 4\,B$$



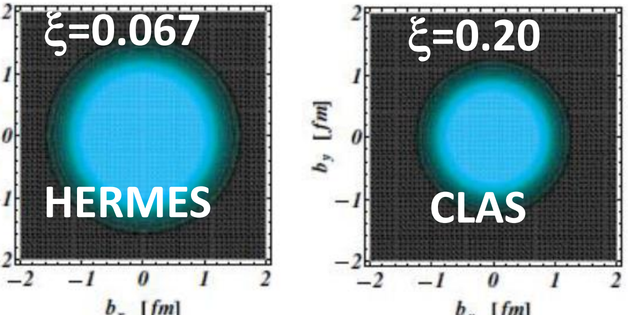
HERMES

+ 8 points from JLab

$x = \xi \sim x_{Bj}/2$ and $\xi \rightarrow 0$



Guidal,
Moutarde,
Vanderhaeghen,
Rept. Prog. Phys. 76 (2013)



proton tomography or parton distributions in tranv plane

Unpol. DVCS x-section at small x_B mostly sensitive to
Im$\mathcal{H}(\xi,t)$ α $H(\xi,\xi,t)$ and $\xi \sim x_B/2$

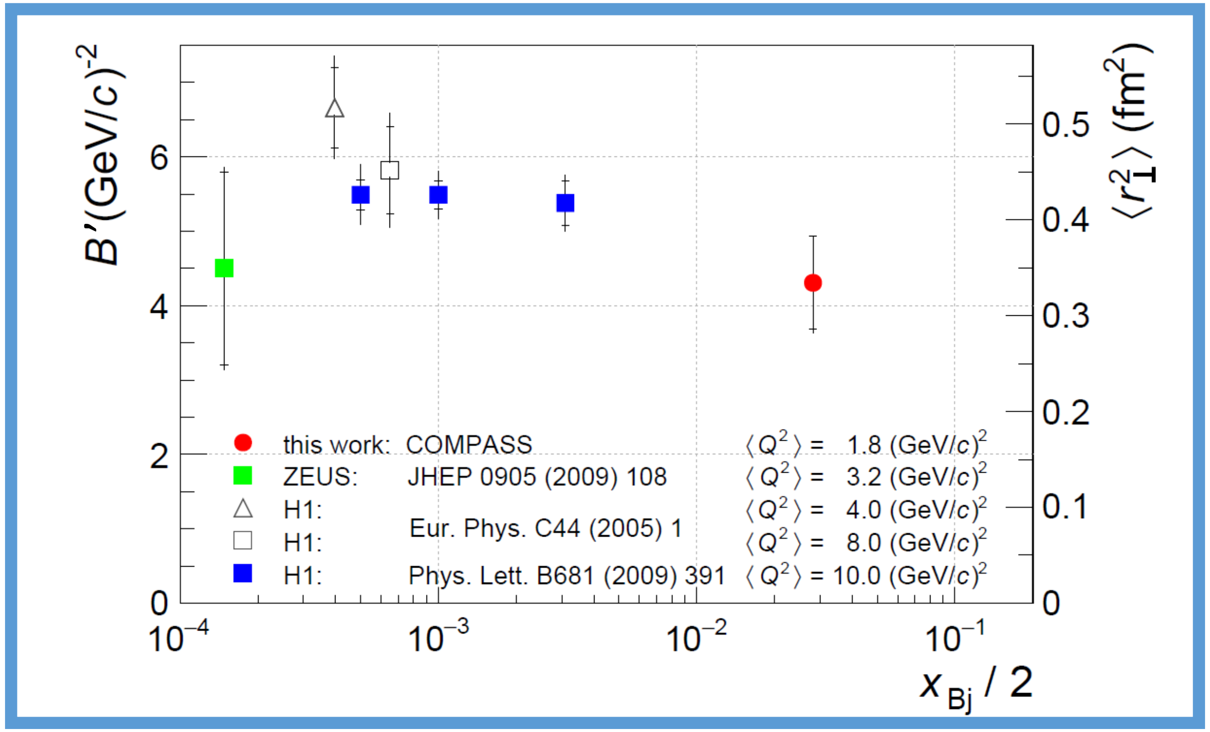
$$\langle b_\perp^2(x)\rangle^f = -4\frac{\partial}{\partial t}\ln H^f(x,0,t)\Big|_{t=0}$$

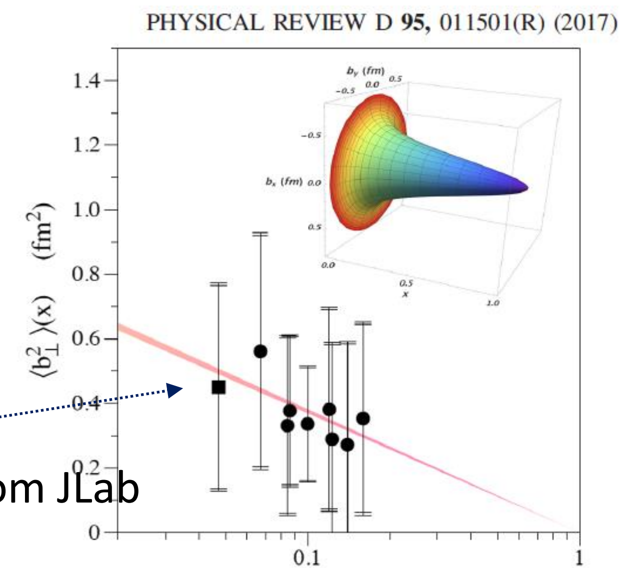
$d\sigma_{DVCS}/dt$ α $e^{-B'|t|}$ ➔ $< r_\perp^{\,2}(x_B)> \approx 2B'(x_B)$

$H(x,0,t)$ α $e^{-B_0(x)|t|}$ $<b_\perp^{\,2}(x)>=4B_0(x)$

$H(x=\xi,\xi,t)$ α $e^{-B(\xi)|t|}$ $<r_\perp^{\,2}(\xi)>= 4B(\xi)$

Model dependent



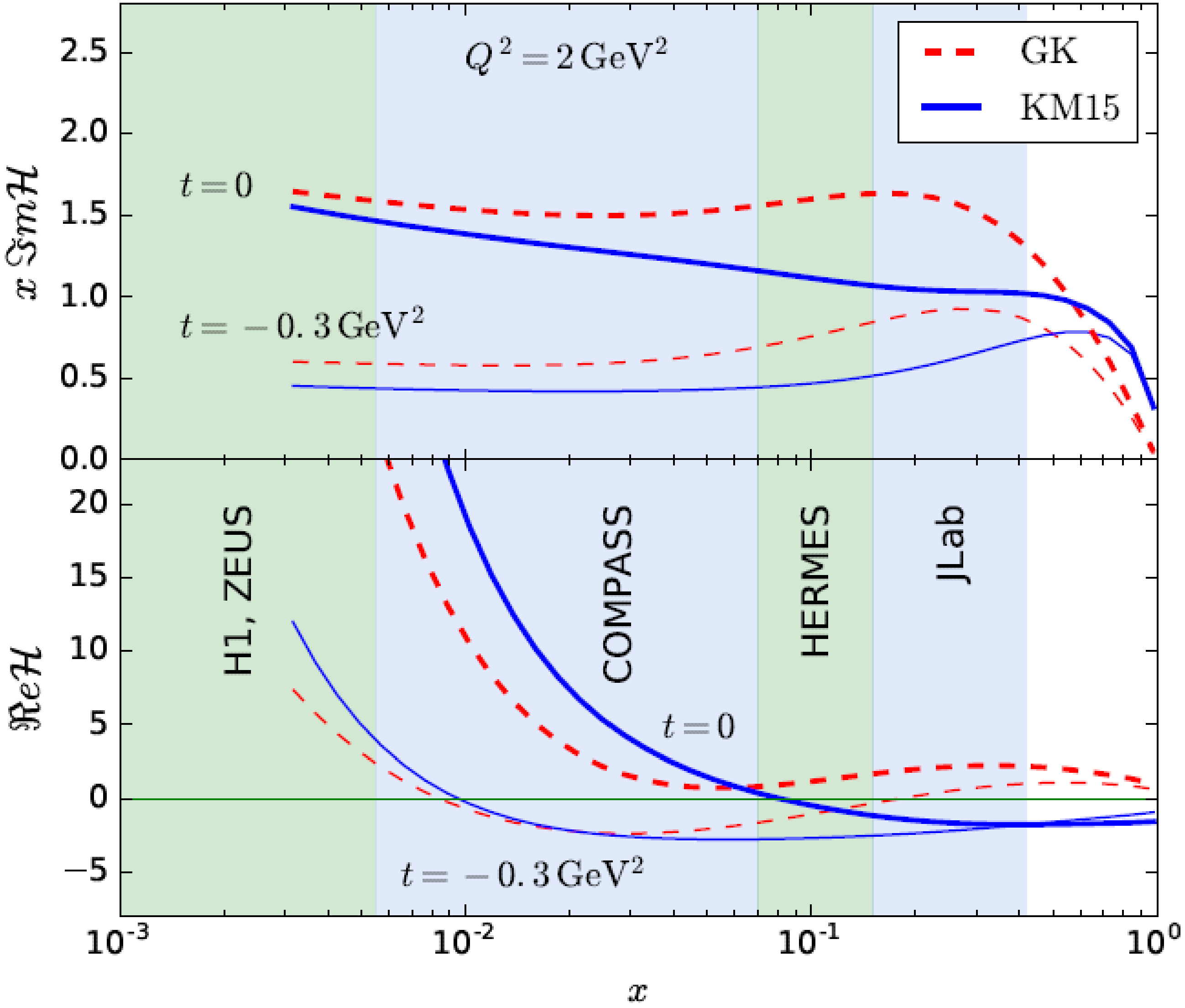


HERMES

+ 8 points from JLab

$x = \xi \sim x_{Bj}/2$ and $\xi \rightarrow 0$

Present knowledge of the GPD H in global analysis



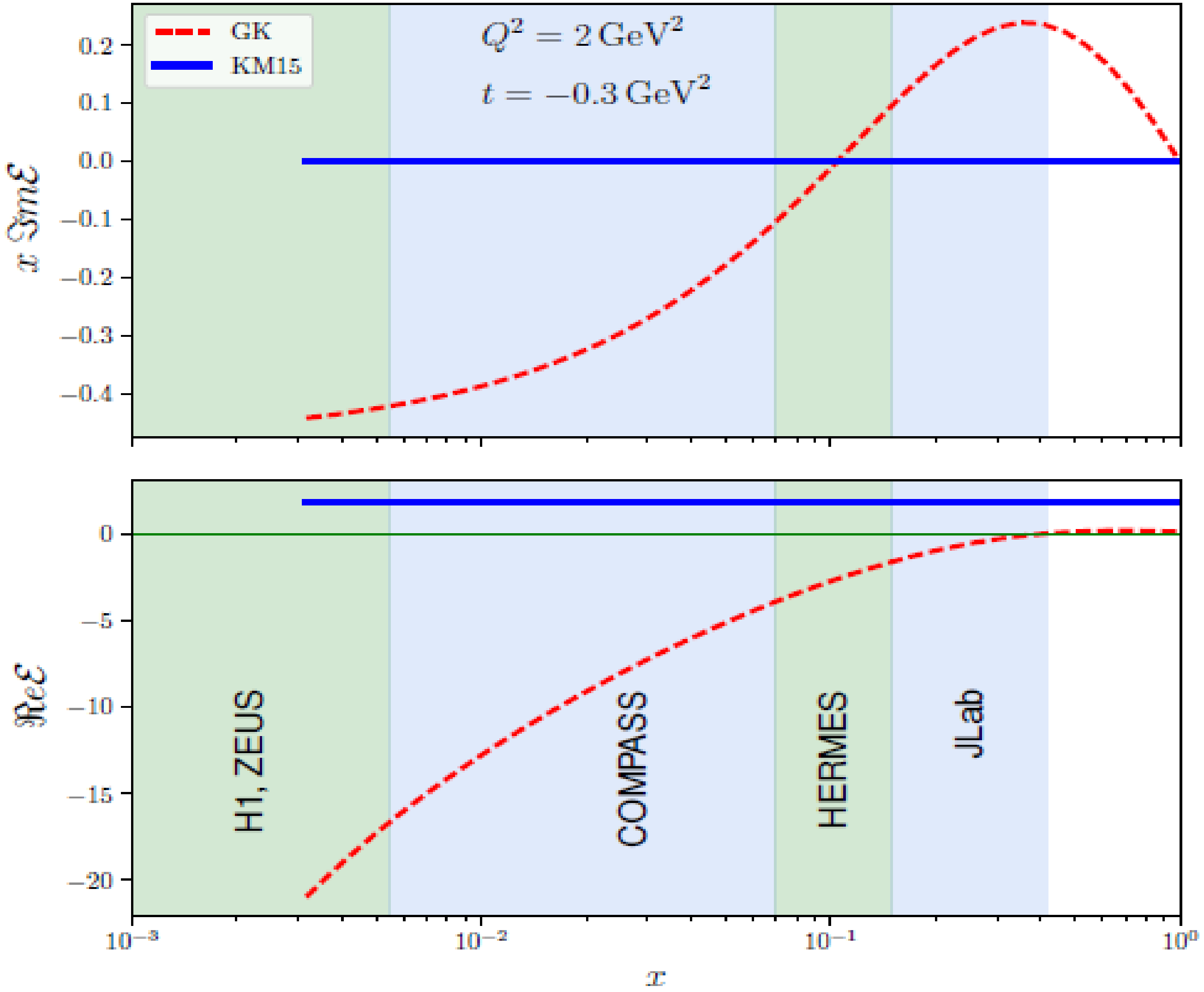
Im H
is rather
well known

Re H linked
to the ***d term***
is still poorly
constrained

KM15 K Kumericki and D Mueller arXiv:1512.09014v1
GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)

Present knowledge of the GPD E in global analysis

Figure made by D. Mueller and K. Kumericki



Im E
is rather unknown

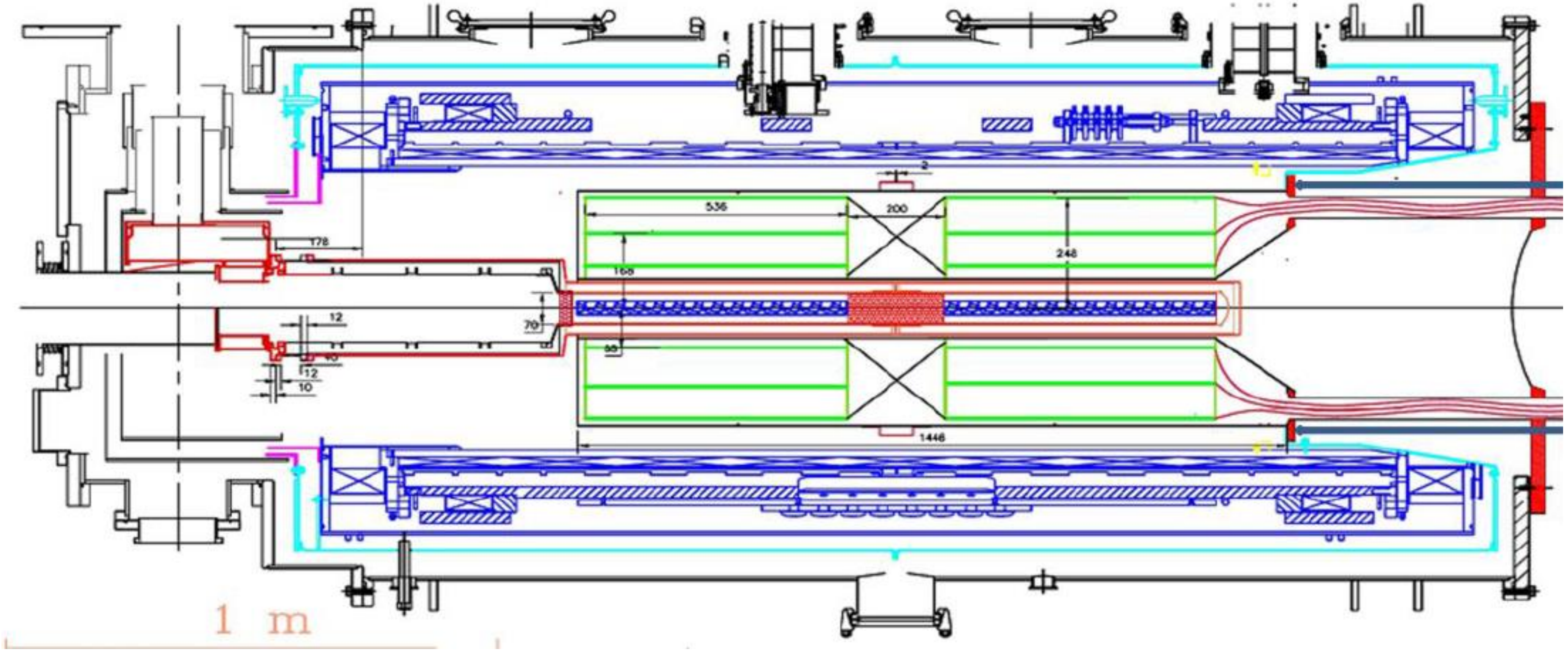
Re E
is rather unknown

KM15 K Kumericki and D Mueller arXiv:1512.09014v1

GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011)

Possible recoil detection with the COMPASS polarized target

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



3 cylindrical layers of Silicon det. are included in ~18cm

No possibility for ToF
➔PID of p/π with dE/dx
momentum (as low as possible)
and trajectory measurments

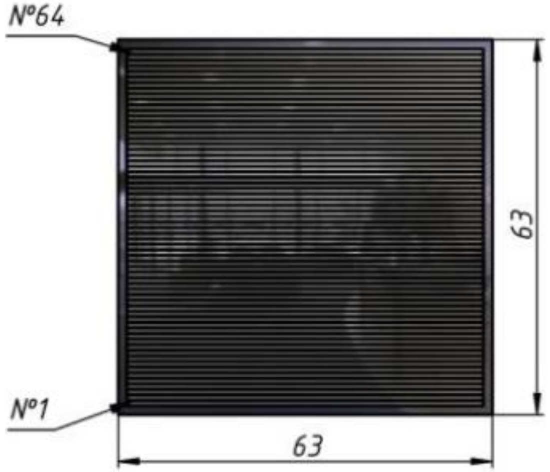
Environment:

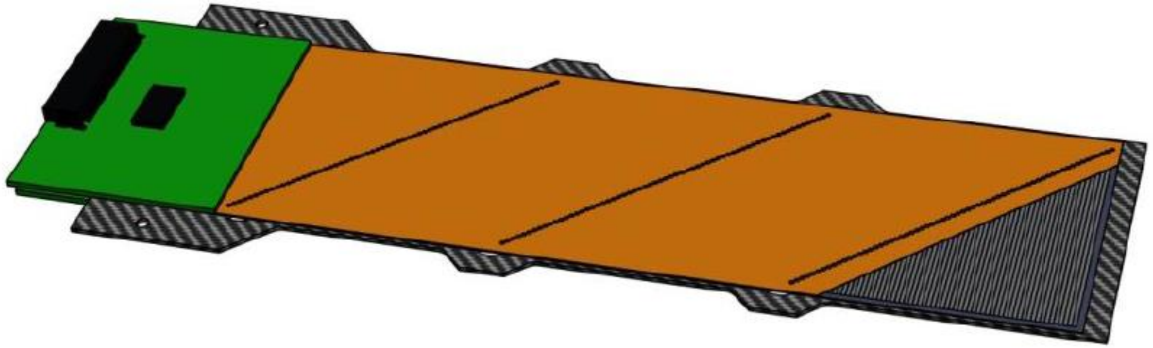
- Magnetic field (long and transv) 0.5-2T
- Presence of MW field temporary
- A low temperature 5-10K
- A vacuum of about 10^{-6} mm Hg

Modified MW as thin as possible 0.2-0.6mm thick copper foil

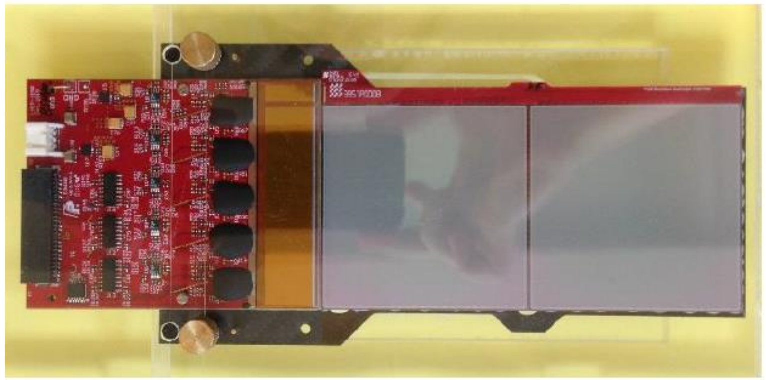
Operation of SI and evacuation of the heat of the read out electronics:
SI detectors in a separate block warmed at ~70K and ‘’warm’’ chips fixed on the flange at the room temp
(use of 1.25m long flat aluminium-polyimide multilayer flexible buses)

A technology developed at LHEP at JINR for NICA

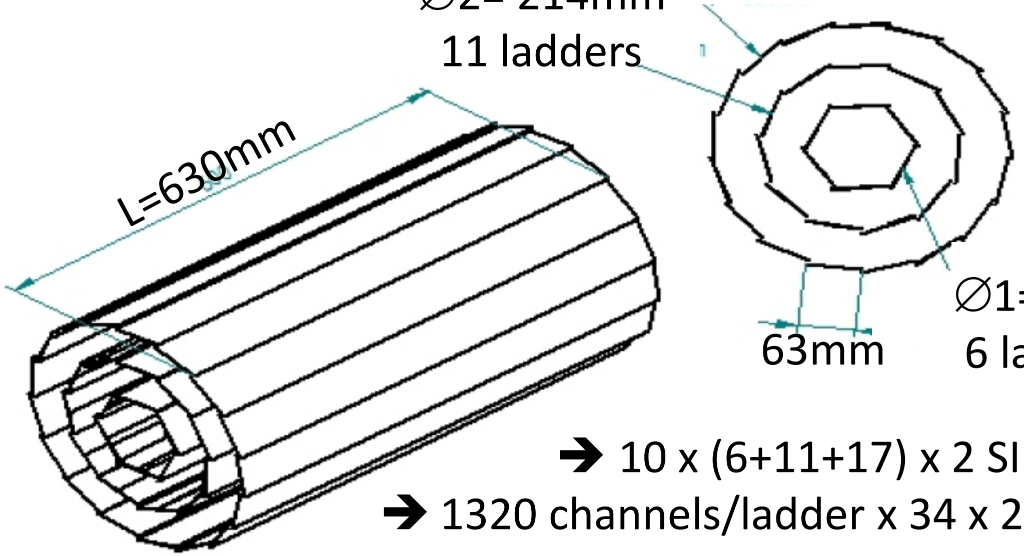




The ladder supporting the double-sided SI strip detector, 63x63 mm each, with a strip pitch of **500 µm**



Silicon detector unit with electronics developed for BM@N experiment.



∅3= 336mm
17 ladders

Thickness det1,2,3
=100, 100, 300µm

∅2= 214mm
11 ladders

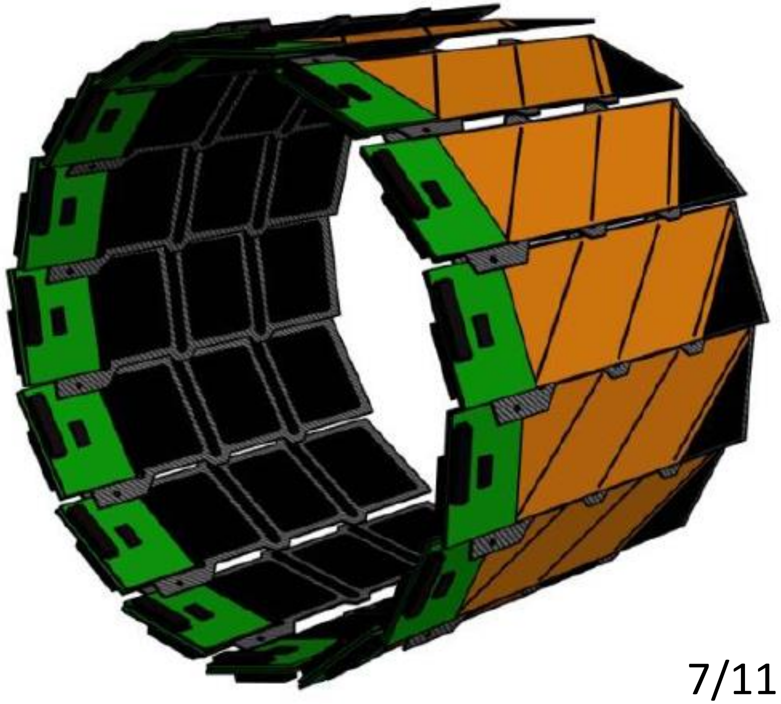
L=630mm

63mm

∅1= 110mm
6 ladders

→ 10 x (6+11+17) x 2 SI detectors = 680 detectors

→ 1320 channels/ladder x 34 x 2 ladders= 90 000 channels



Performances studied in MC

New Silicon detector with NH3 target

tmin

NH3 target	radius 20mm	
MW Cavity	thickness	0.6 mm
1^{st} SI det	thickness	300 μm
2^{nd} SI det	thickness	1000μm

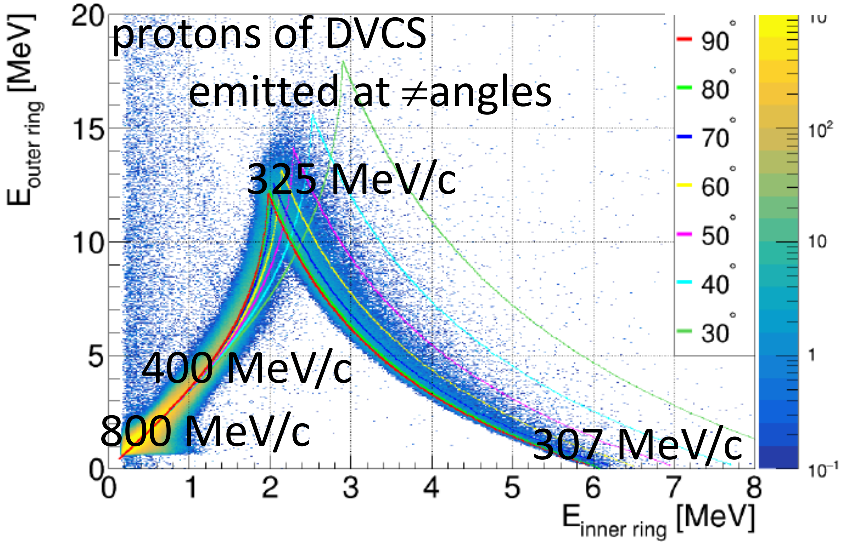
-tmin= 0.092 GeV^2 Pp=306.7 MeV/c Combined eff ($\mu p \gamma$) = 40%

CAMERA with LH2 target

-tmin= 0.066 GeV^2 Pp=258.5 MeV/c Combined eff ($\mu p \gamma$) = 56%

Particle Identification

TGEANT



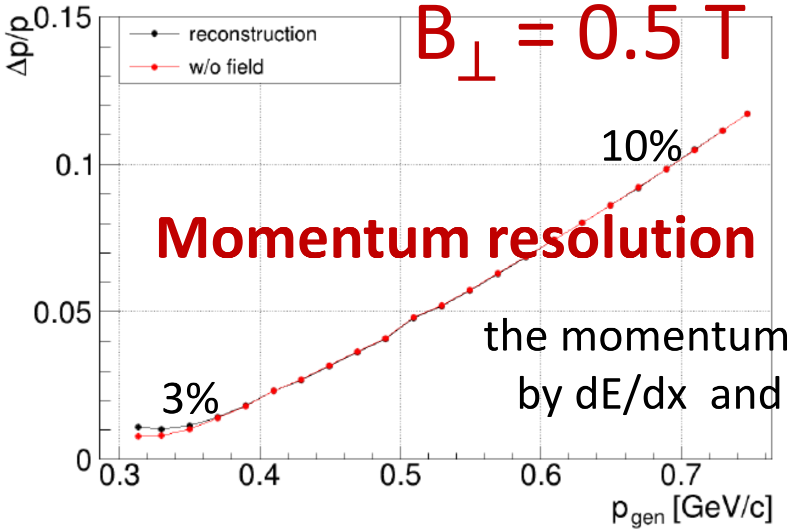
protons of DVCS emitted at ≠angles

325 MeV/c

400 MeV/c

800 MeV/c

307 MeV/c



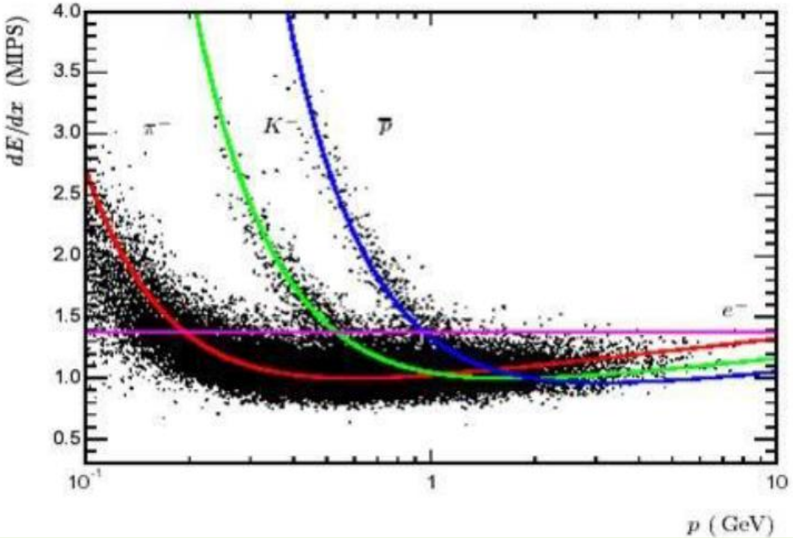
$B_{\perp}$ = 0.5 T

10%

Momentum resolution

3%

the momentum determined by dE/dx and θ angle



DVCS with 160 GeV pol. μ^+ & μ^- beams and Transv Pol target

$$\mathcal{S}_{CS,T} \equiv \Delta\sigma_T(\mu^{+\downarrow}) + \Delta\sigma_T(\mu^{-\uparrow})$$

→ (- Re$\mathcal{E}$ Im$\mathcal{H}$ + Im$\mathcal{E}$ Re$\mathcal{H}$)sin(ϕ- ϕs)

$$\mathcal{A}_{\mathcal{S}}^{\sin(\phi-\phi_s)}$$

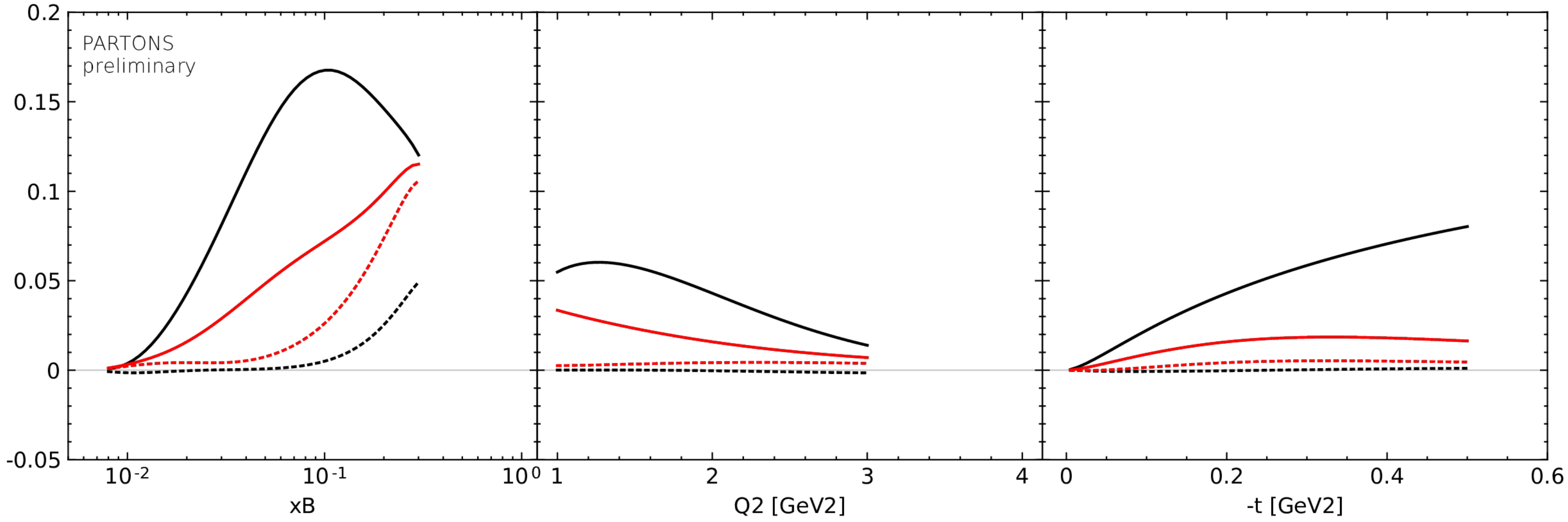
From Pawel Sznajder
Using the PARTONS code
Formalism at LO

——————

- - - - - - - - - Idem with GPDs E = 0

——————

- - - - - - - - - Idem with GPDs E = 0



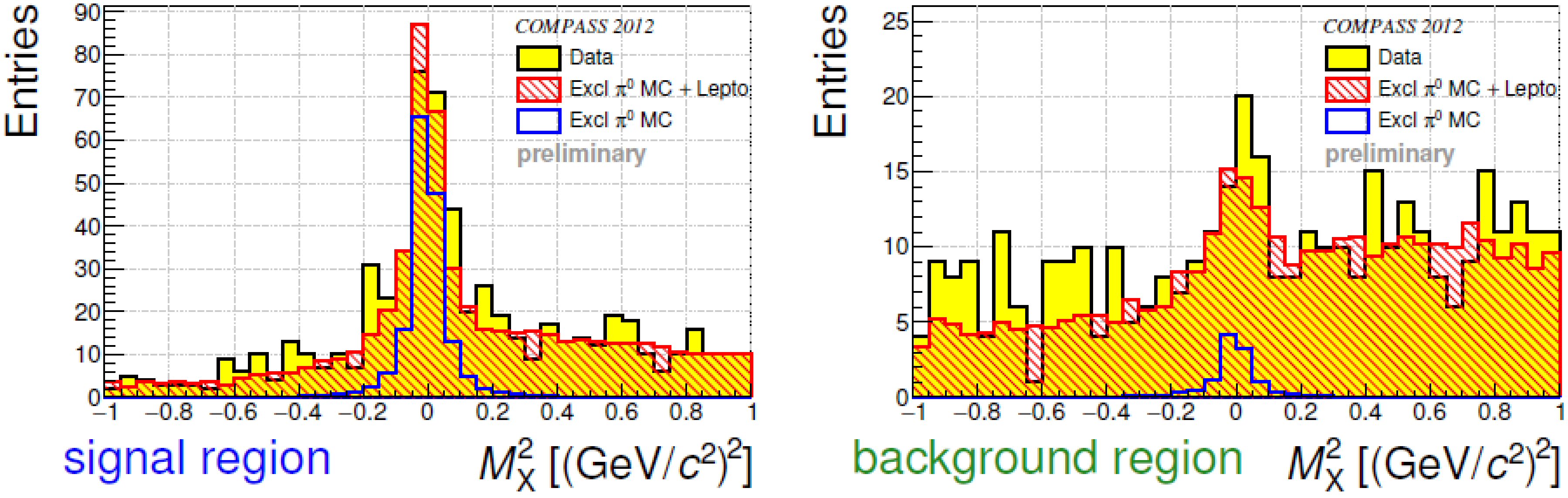
Exclusive π^0 production on unpolarized proton

SIDIS background estimation

- use LEPTO MC to describe non exclusive background
- use exclusive π^0 MC to describe signal contribution
- find best description of data
  - in signal region (only two photon clusters)
  - in background region (more photon clusters)

Four-momentum balance:

$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\pi^0})^2$$



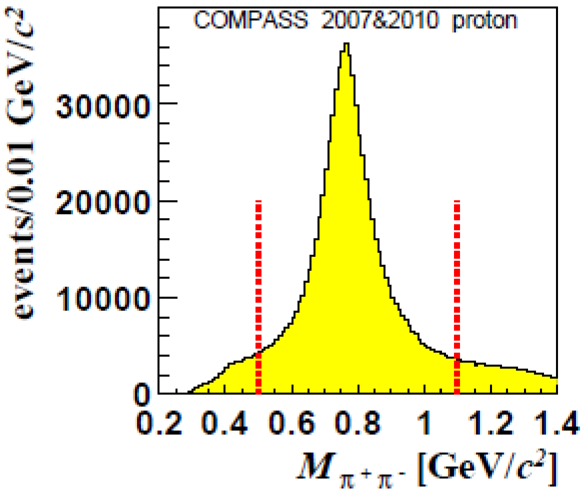
signal region

background region

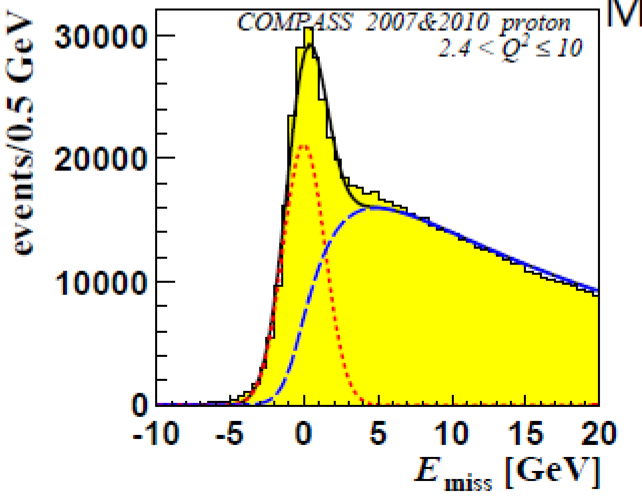
Selection of exclusive evts without recoil detection

$\mu \; p_{\text{in NH3}} \rightarrow \mu' \; V \; p_{\text{non detected}}$

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



$E_{miss} = (M^2_X - M_p^2)/2M_p$



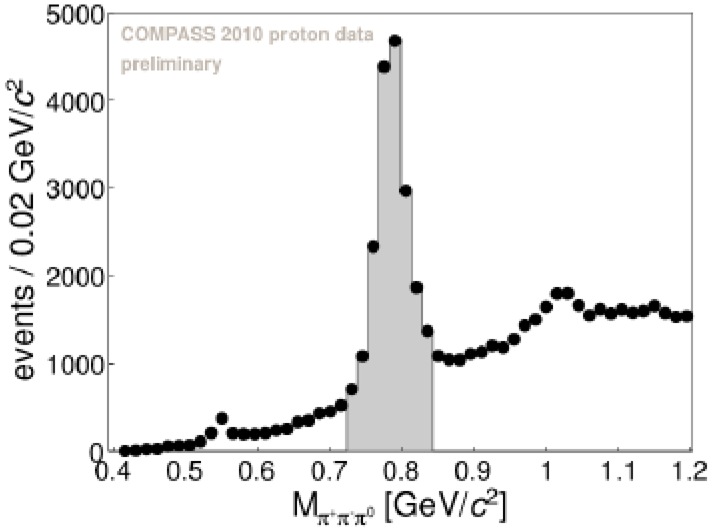
$$M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_V)^2$$

$-2.5 < E_{miss} < 2.5$ GeV

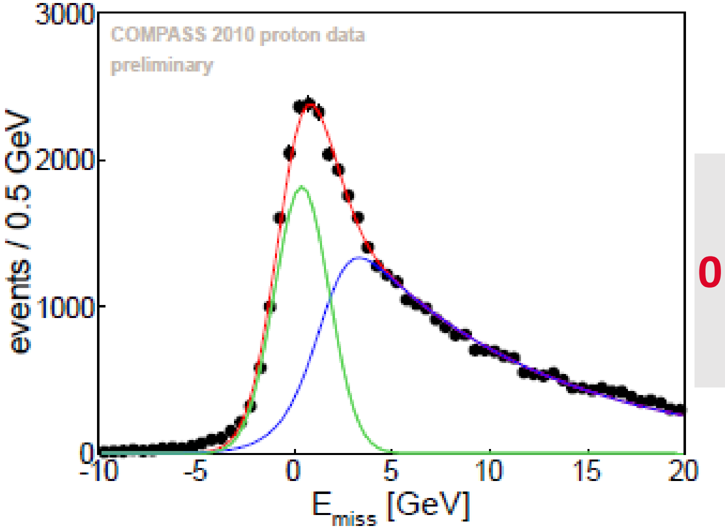
$0.1 < p_T^2 < 0.5$ GeV²

Background ~22%

$V = \omega \rightarrow \pi^+\pi^-\pi^0$ BR=89%



$E_{miss} = (M^2_X - M_p^2)/2M_p$



$-3 < E_{miss} < 3$ GeV

$0.05 < p_T^2 < 0.5$ GeV²

Background ~34%