DVCS and Exclusive Meson Production Measurements at the COMPASS Experiment

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on behalf of the COMPASS collaboration

ICHEP 2020
July 30, 2020

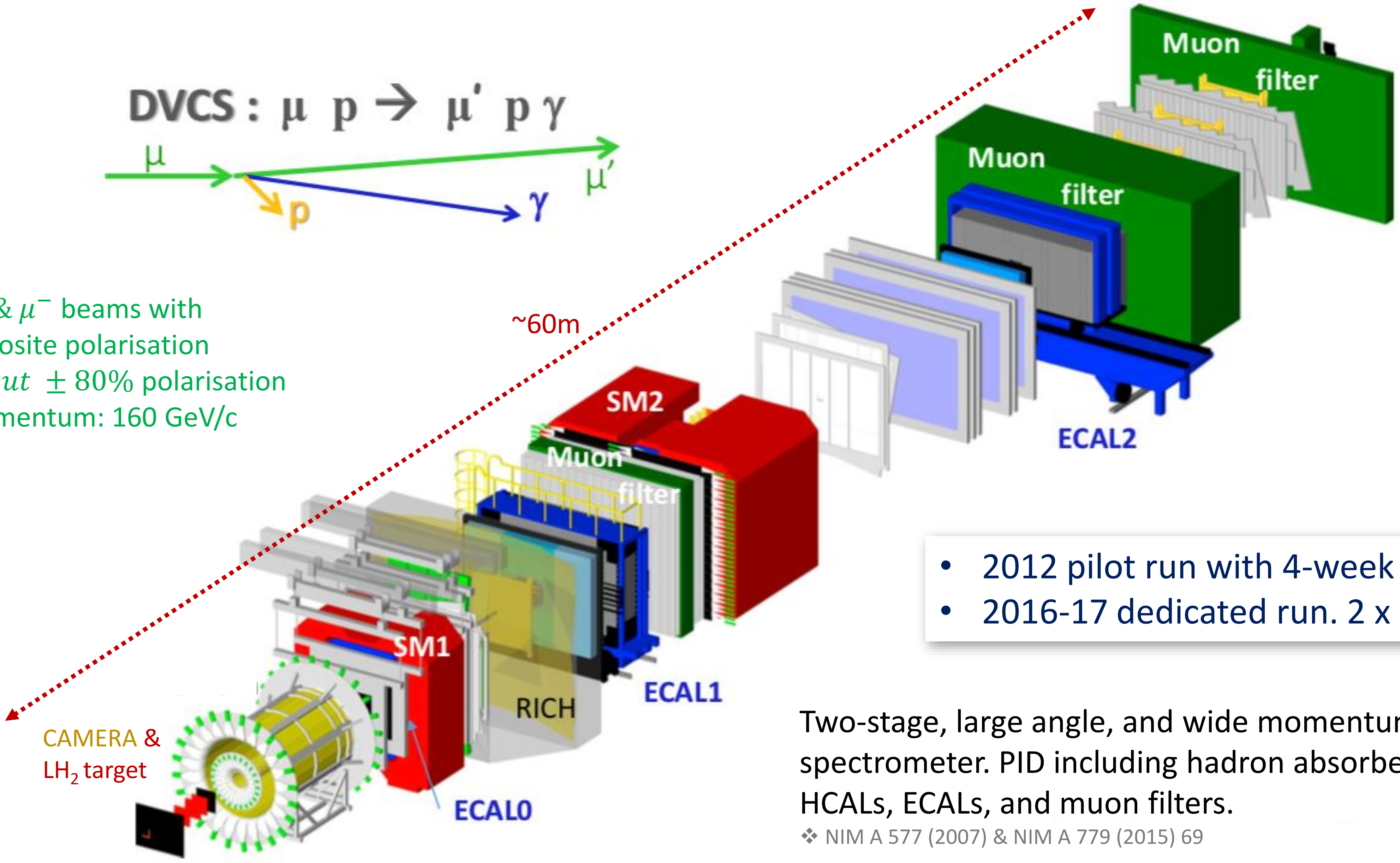
Outline

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

COMPASS Experiment

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

COMPASS Setup for Hard Exclusive Measurements



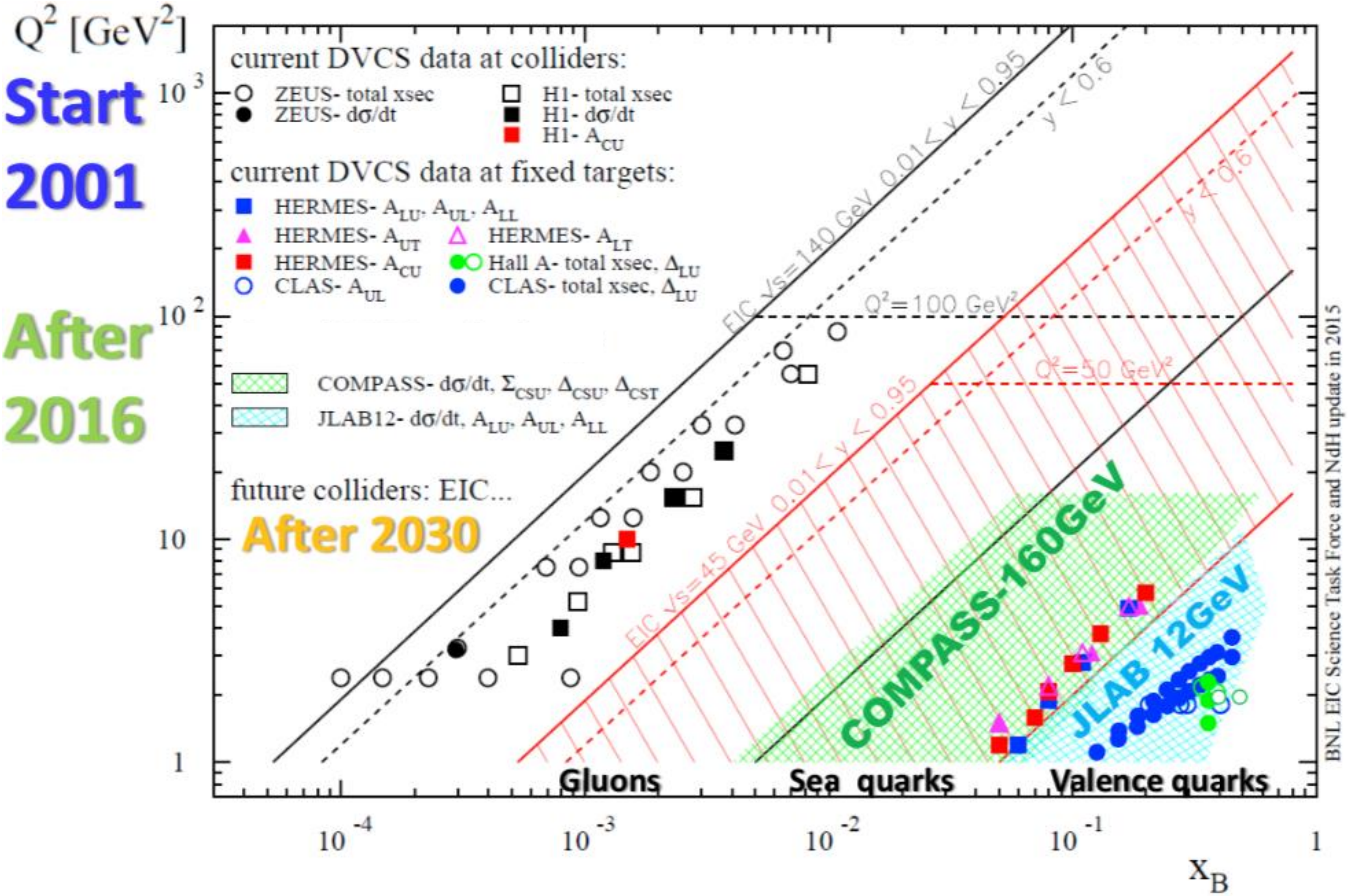
- μ^+ & μ^- beams with opposite polarisation
- $About\ \pm 80\%$ polarisation
- Momentum: 160 GeV/c

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

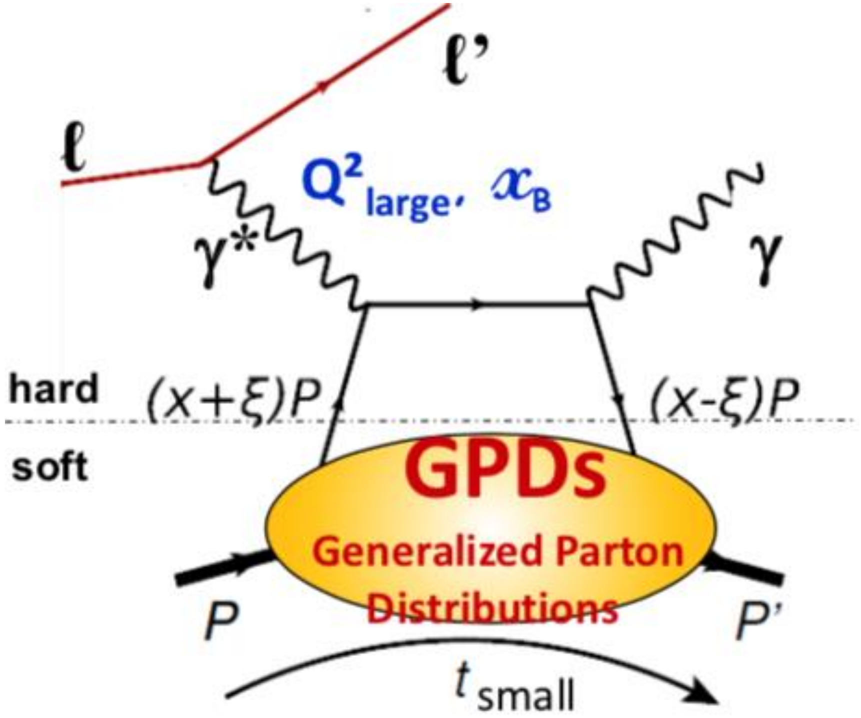
Two-stage, large angle, and wide momentum range spectrometer. PID including hadron absorbers, RICH, HCALs, ECALs, and muon filters.

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

COMPASS Coverage for DVCS

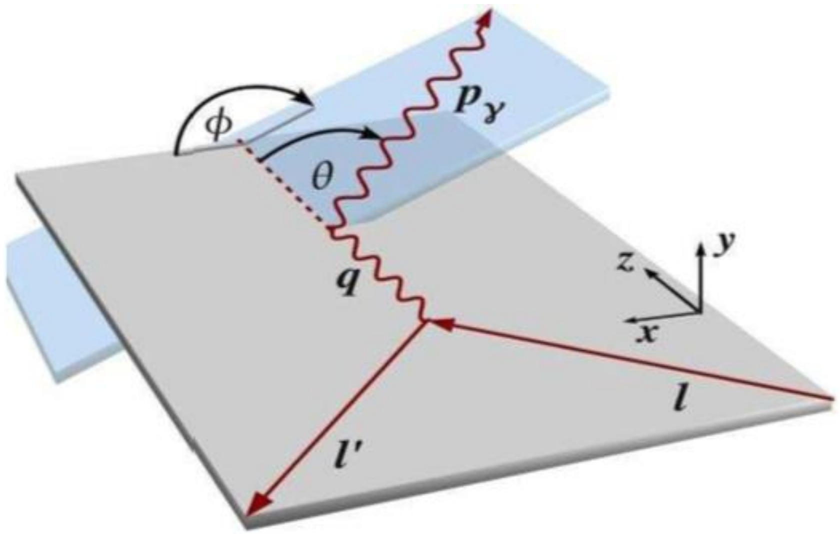


DVCS



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

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

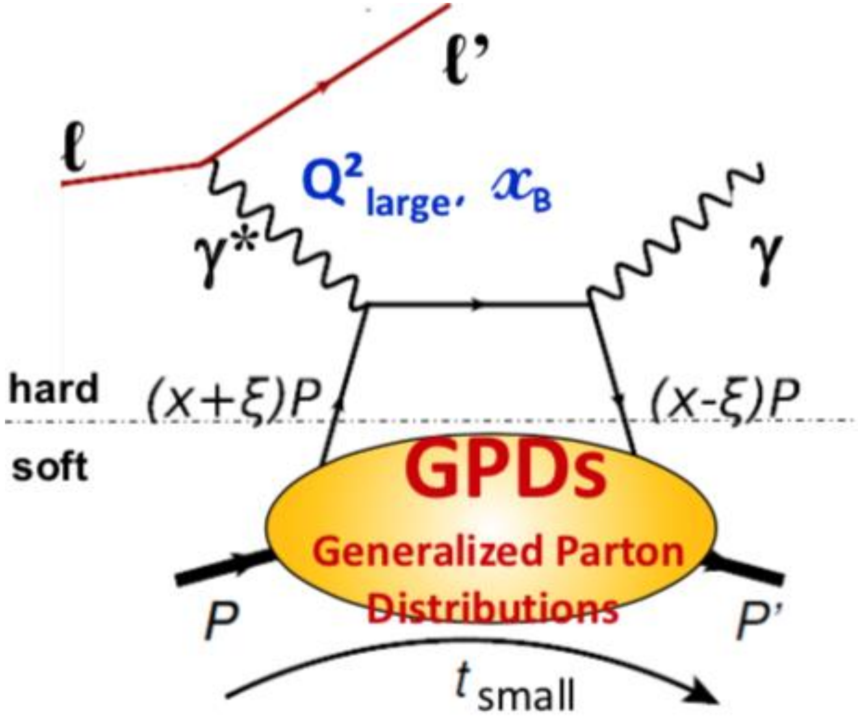


The variables measured in the experiment:

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

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

DVCS



- The GPDs depend on the following variables:

  x: average longitudinal momentum frac.

  ξ: longitudinal momentum diff.

  t: four momentum transfer
  (correlated to $b_\perp$ via Fourier transform)

  Q^2: virtuality of γ^*

Sensible to 4 GPDs, at COMPASS with small x_B
→ focuses on **H**

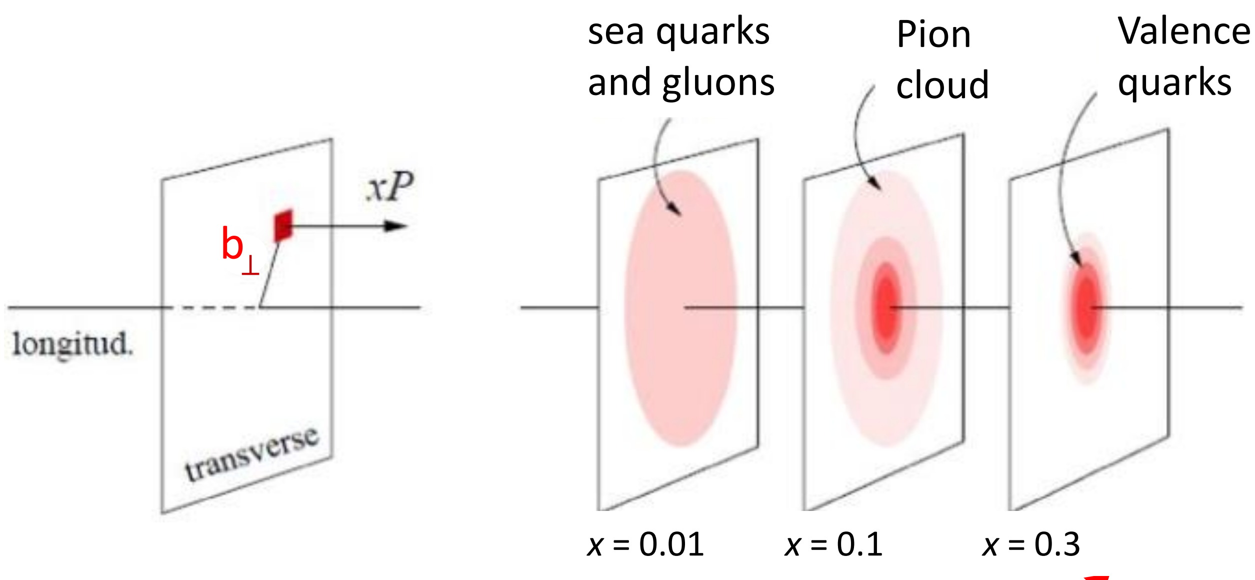
CFF — GPD — REAL part — Imaginary part

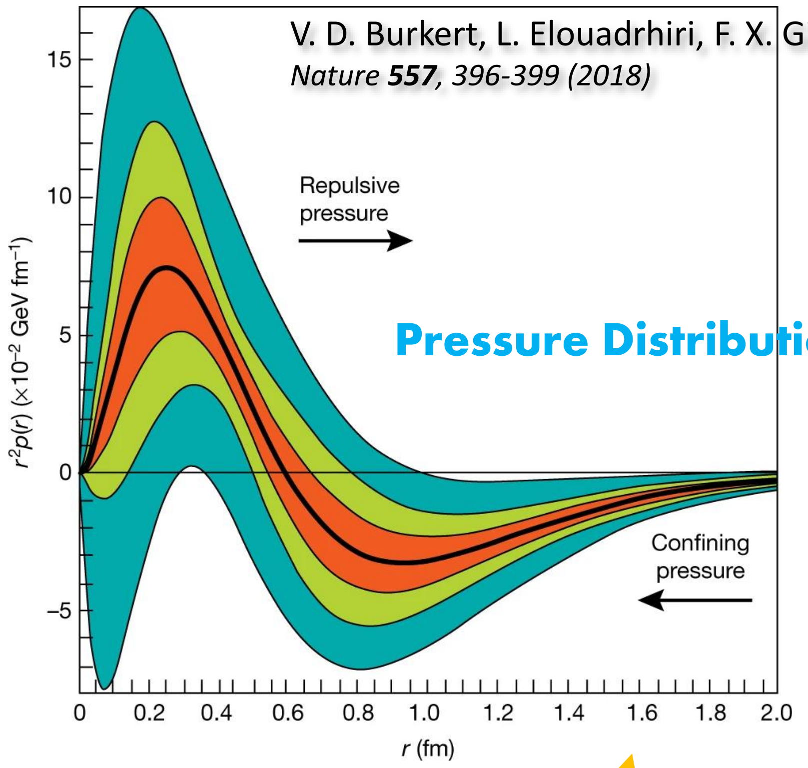
$$\mathcal{H} = \int_{-1}^{+1} dx \, \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \, \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi \, \mathbf{H}(x=\pm\xi,\xi,t)$$

t, ξ fixed

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

Transverse Imaging and Pressure Dist.





CFF

GPD

REAL part

Imaginary part

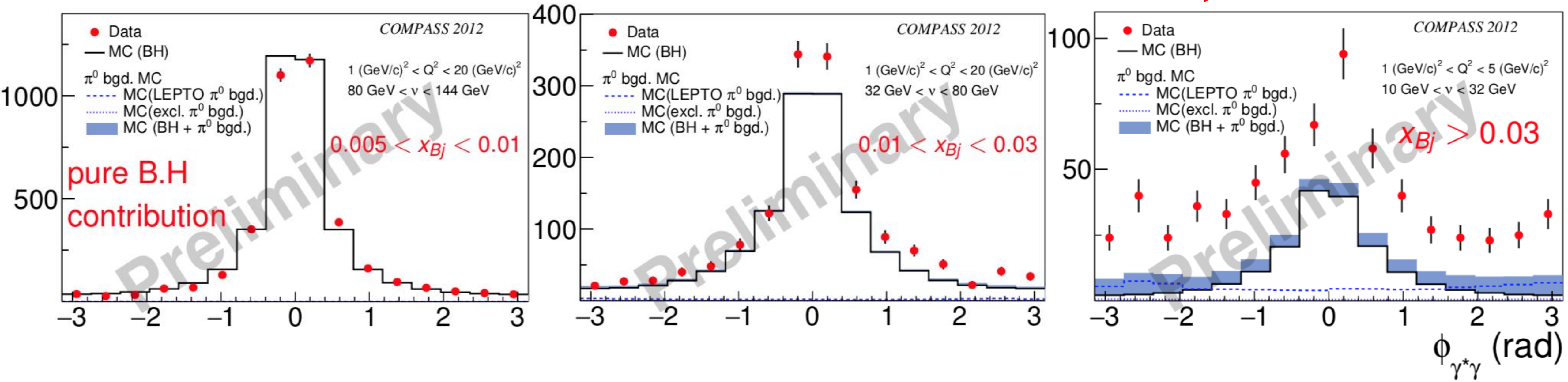
$$\mathcal{H} = \int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t)$$

t, ξ fixed

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

Extraction of DVCS Events - 2012 data

Increasing x_{Bj}



- Beam charge-spin sum

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

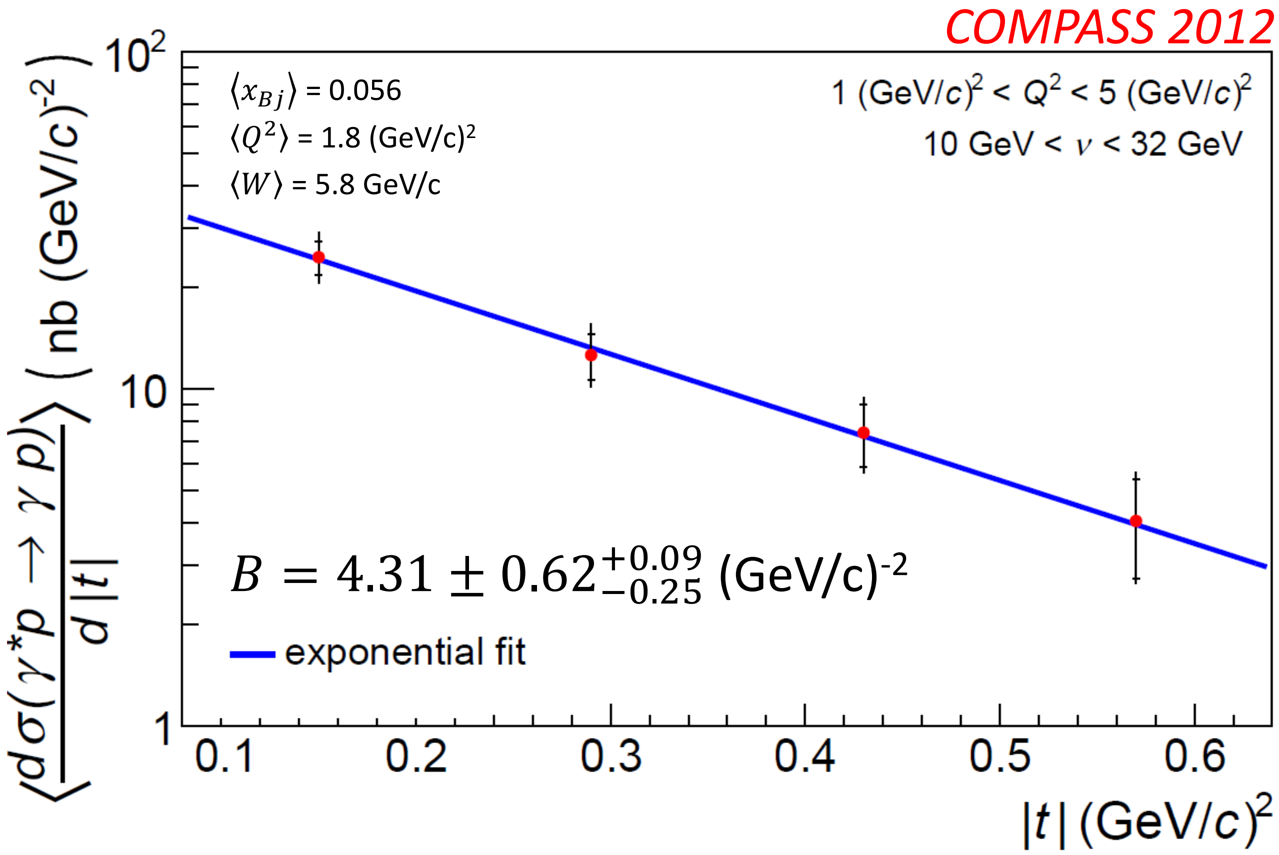
$$= 2[\, d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos\phi + s_1^I \sin\phi + s_2^I \sin 2\phi \,]$$

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

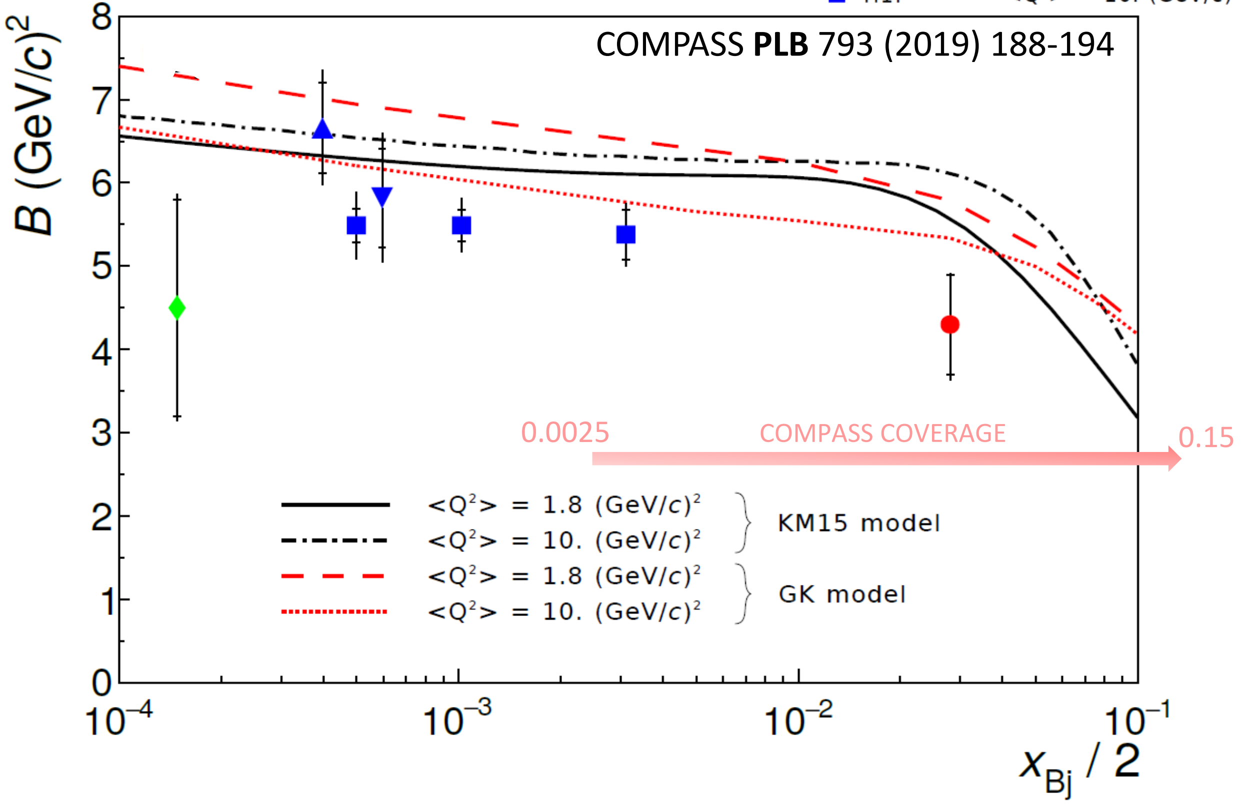
small x_{Bj} model dependent

Tranverse extension of partons – 2012 data

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



$\langle r_\perp^2(x_{Bj}) \rangle \approx 2B(x_{Bj})$ At small x_{Bj}

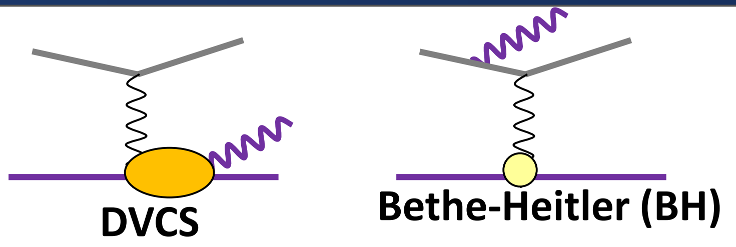


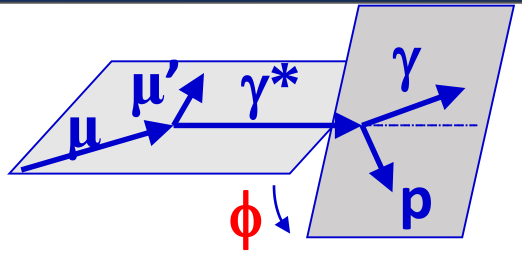
- The transverse-size evolution as a function of x_{Bj}
  - → Expect at least 3 x_{Bj} bins from 2016-17 data

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

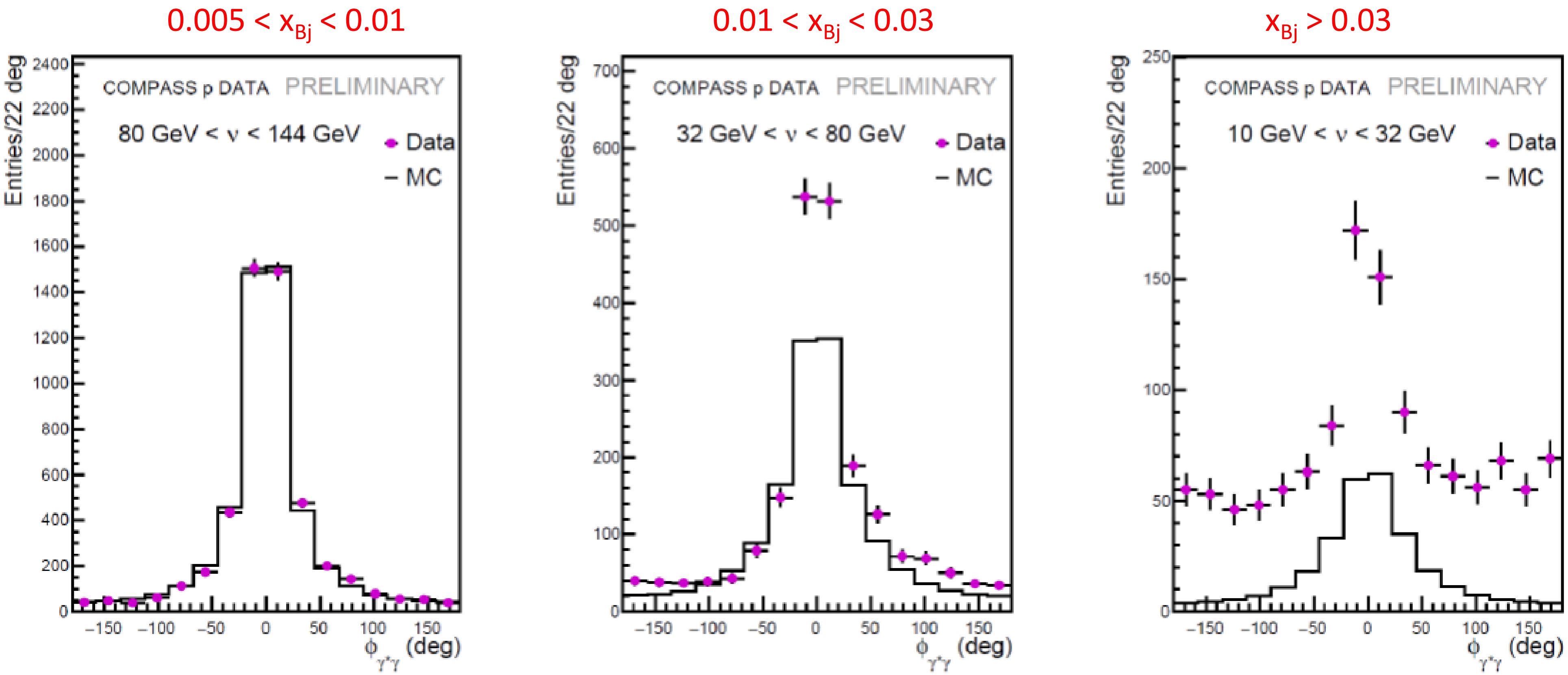
With $\langle x_{Bj} \rangle$ = 0.056

2016 – 2017 Data First Insight





Only 13% of 2016-17 data



No π^0 subtraction.

DVCS contribution at high x_{Bj} will allow to perform re-analysis $d\sigma^{DVCS}/dt \propto e^{-B'|t|}$

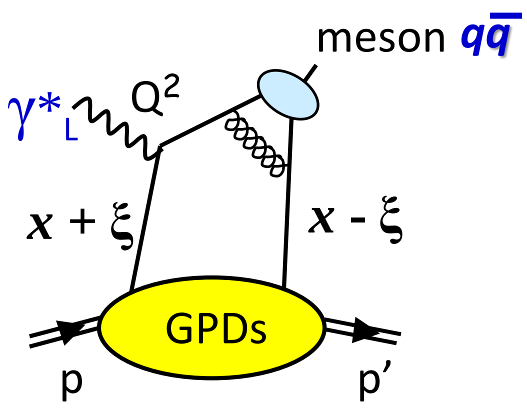
$= c_0^{DVCS}$

BLUE WATERS

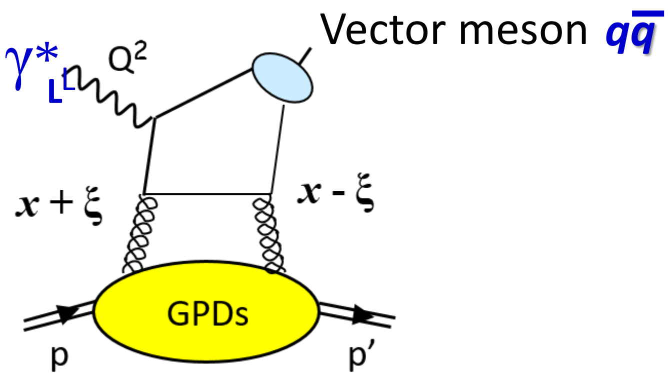
This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications. This work is also part of the "Mapping Proton Quark Structure using Petabytes of COMPASS Data" PRAC allocation supported by the National Science Foundation (award number OCI 1713684).

GPDs in Hard Exclusive Meson Production

Quark contribution



Gluon contribution at the same order in α_s



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)

$H_T^q(x, \xi, t)$	$E_T^q(x, \xi, t)$	$\bar{E}_T^q = 2\,\tilde{H}_T^q + E_T^q$
$\tilde{H}_T^q(x, \xi, t)$	$\tilde{E}_T^q(x, \xi, t)$	

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

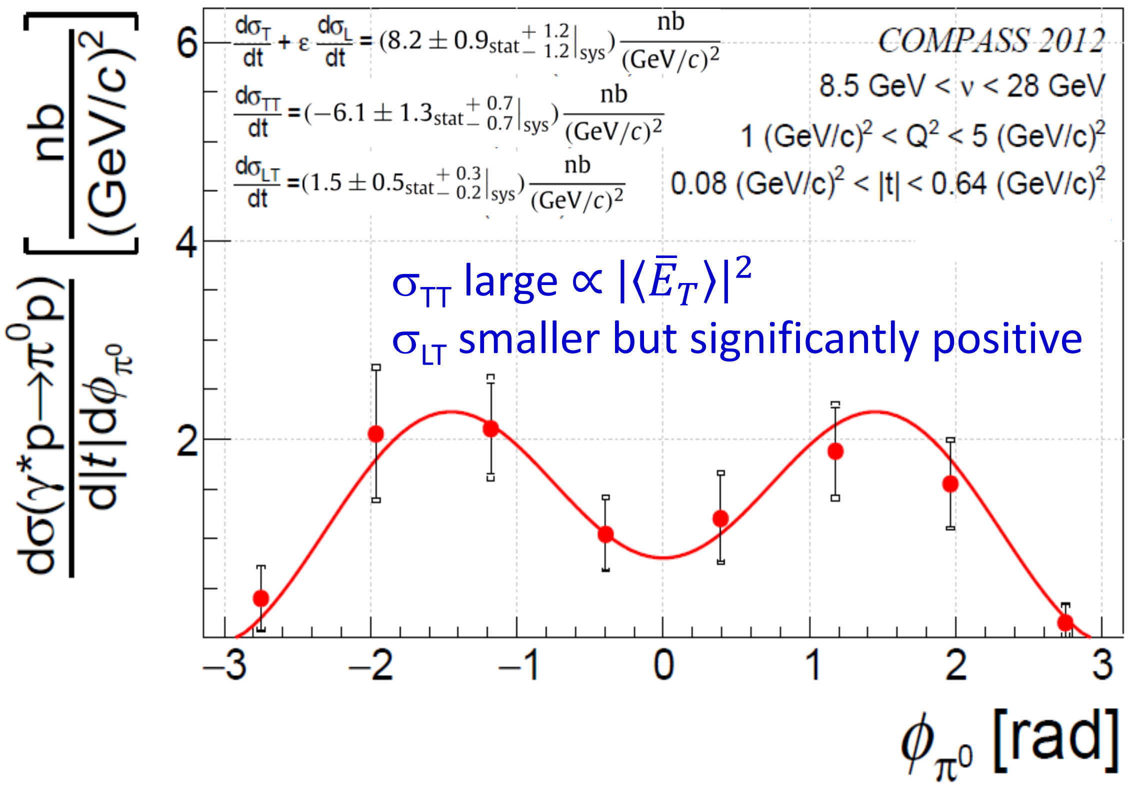
2012 Exclusive π^0 Prod. on Unpolarized Proton

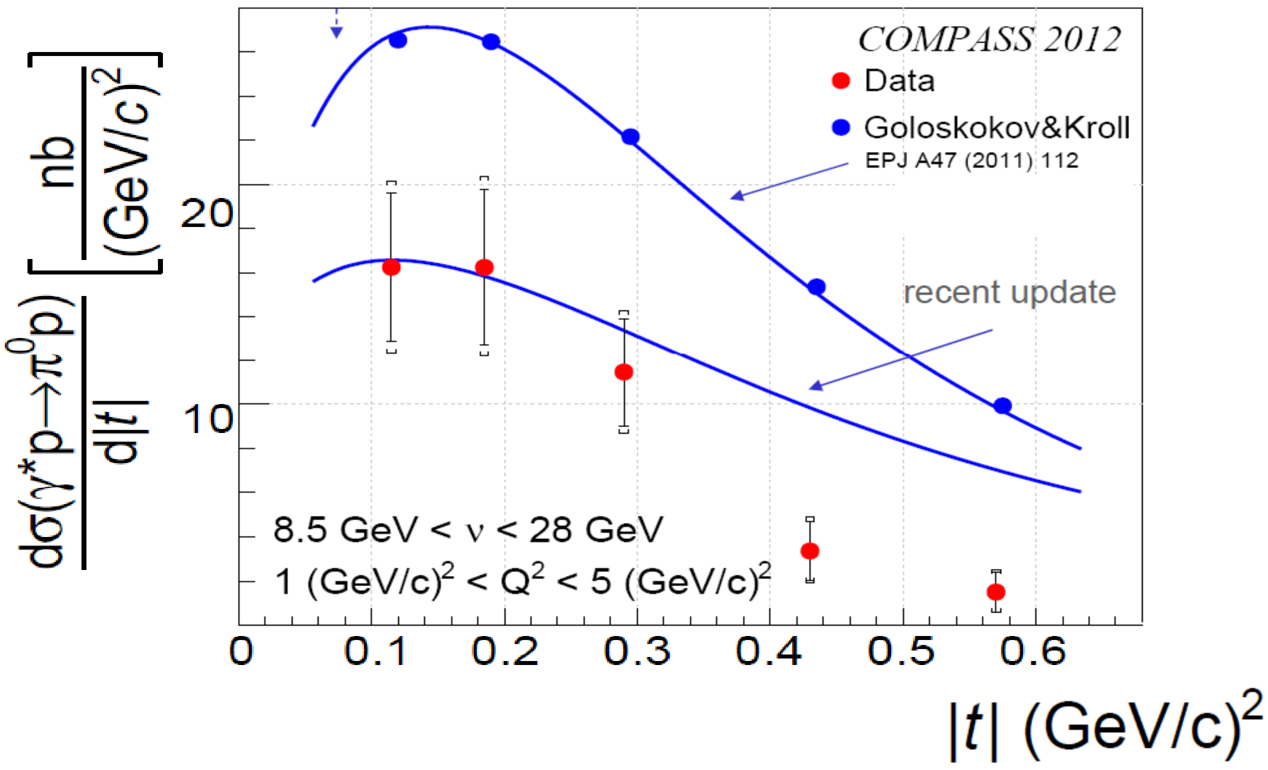
$\mu\, p \rightarrow \mu\, \pi^0\, p$

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

Chiral-odd GPDs

A dip at small t would indicate a large impact of $\bar{E}_T$





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

2012 Exclusive ω Prod. on Unpolarized Proton

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

(S-Channel Helicity Conservation)

SCHC implies:

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

  = - 0.010 ± 0.032 ± 0.047 OK

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

  = 0.014 ± 0.011 ± 0.013 OK

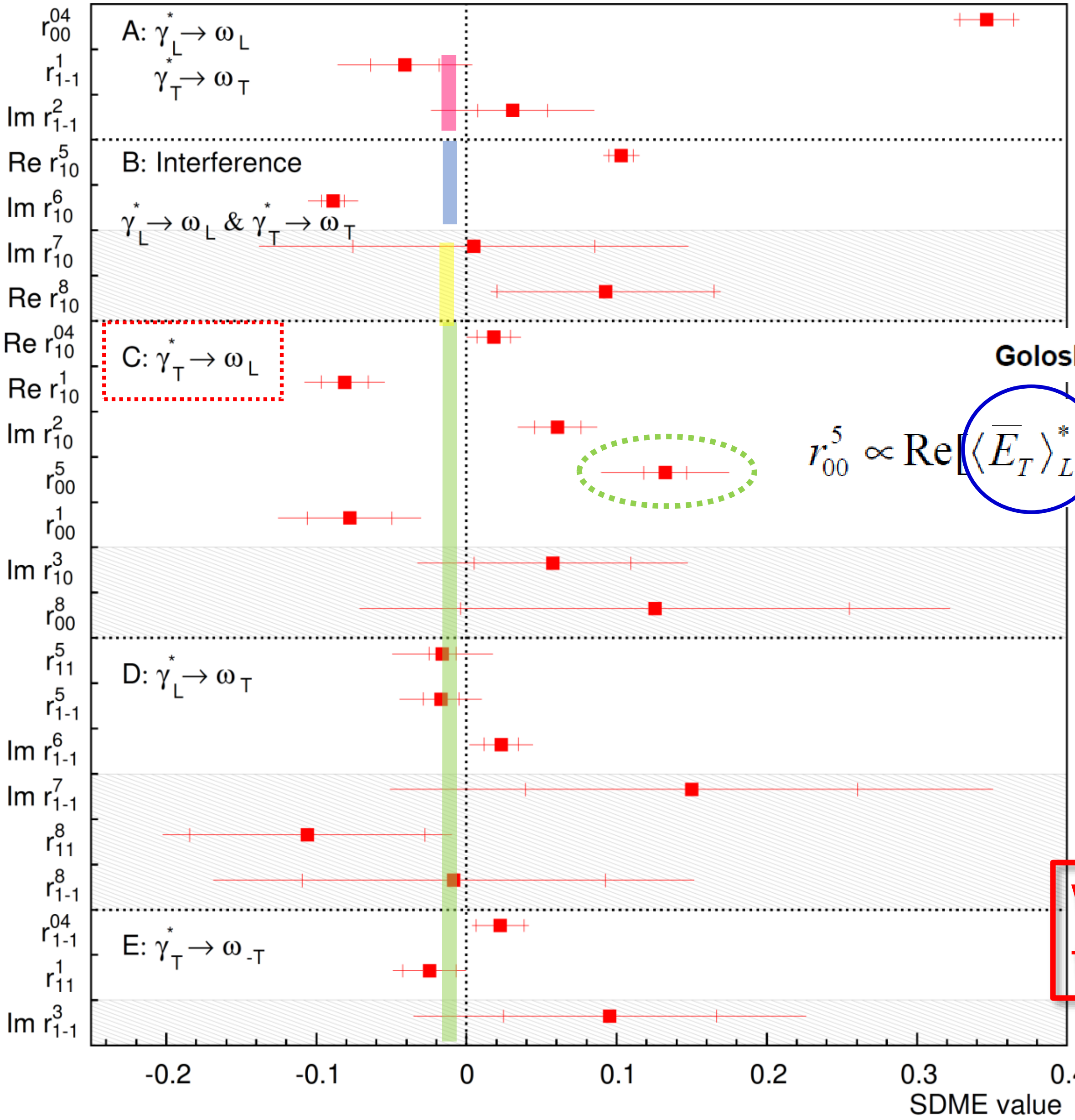
- $\text{Im}\, r^7_{10} - \text{Re}\, r^8_{10} = 0$

  = - 0.088 ± 0.110 ± 0.196 OK

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

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

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



Goloskokov and Kroll, EPJC 74 (2014) 2725

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

Exclusive ρ^0, ω production with trans. pol. target

COMPASS, NPB865 (2012) 1-20
COMPASS, PLB731 (2014) 19
COMPASS, NPB915 (2017) 454-475

Will be submitted to arXiv very soon!

Summary and Outlook

- GPD by DVCS and HEMP in COMPASS

DVCS x-sections with polarized μ+ and μ-

→ Transverse extension of partons as a function of x_{Bj}

→ Im$\mathcal{H}$(ξ,t) and Re$\mathcal{H}$(ξ,t) for D-term and pressure distribution

HEMP of π^0, ρ, ω, ϕ, J/ψ

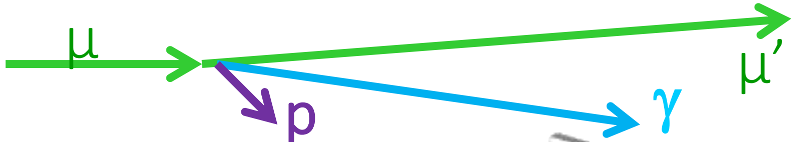
→ Universality of GPDs - Transverse GPDs - Flavor Decomposition

On-going analysis on 2016-17 data.

Backup Slides

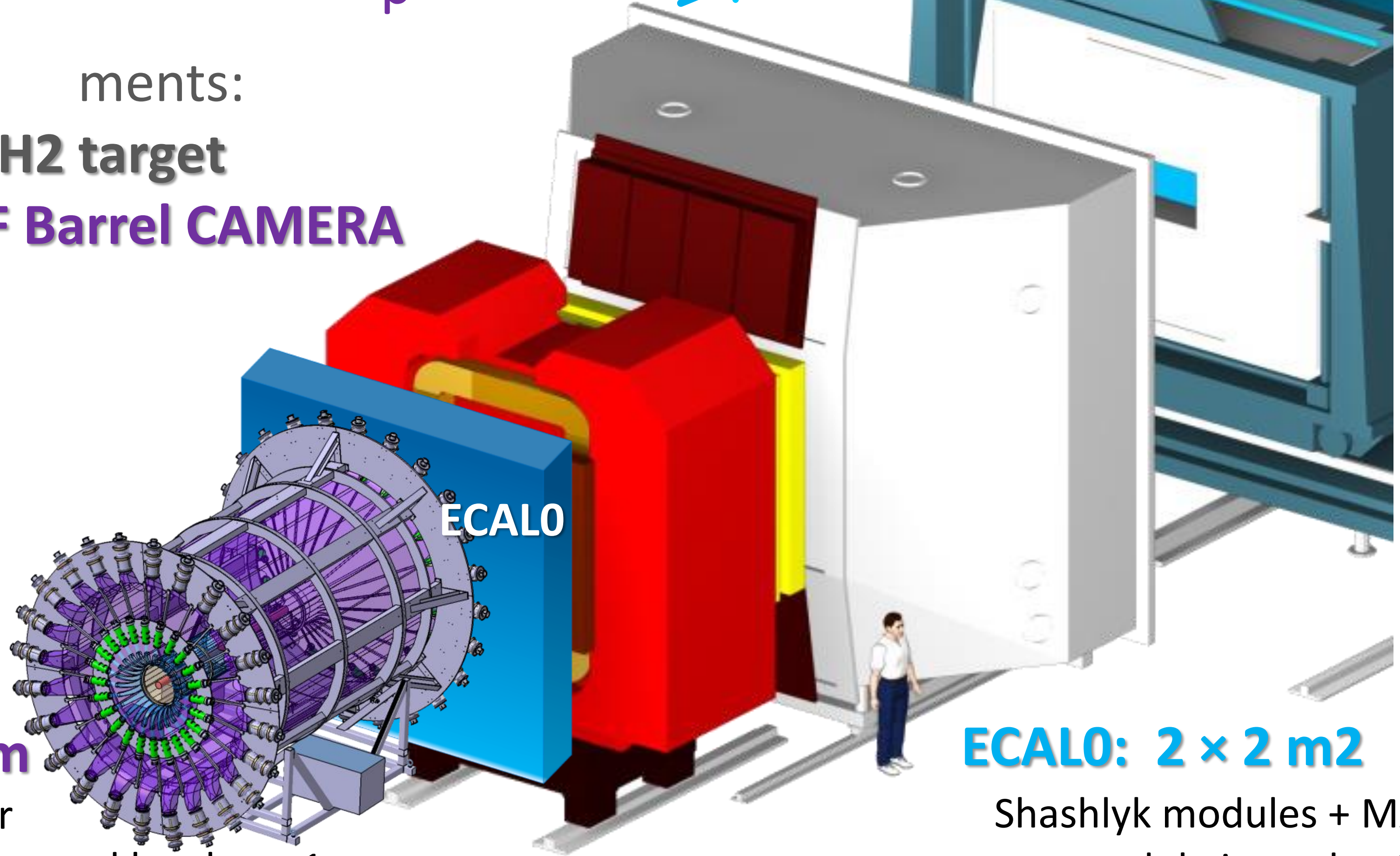
COMPASS Setup for GPD Measurement

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



ments:

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



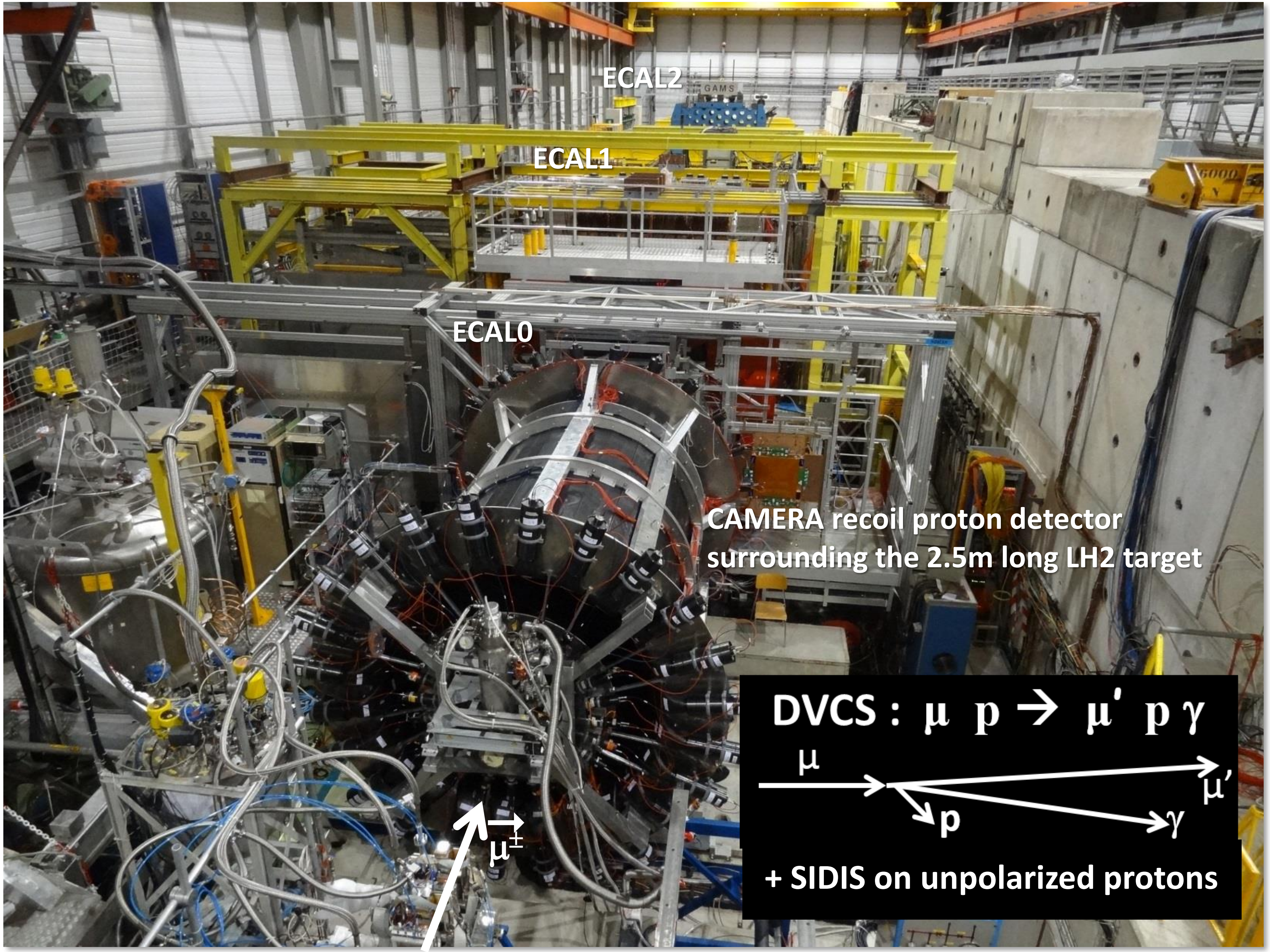
CAMERA

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


ECAL2
GAMS
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long LH2 target
$\vec{\mu}^{\pm}$
DVCS : μ p → μ' p γ
μ
μ'
p
γ
+ SIDIS on unpolarized protons

COMPASS

COMPASS^{++}/AMBER

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

Letter of Intent - Draft 1.0: https://arXiv.org/abs/1808.0084

Expected to start at 2022

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

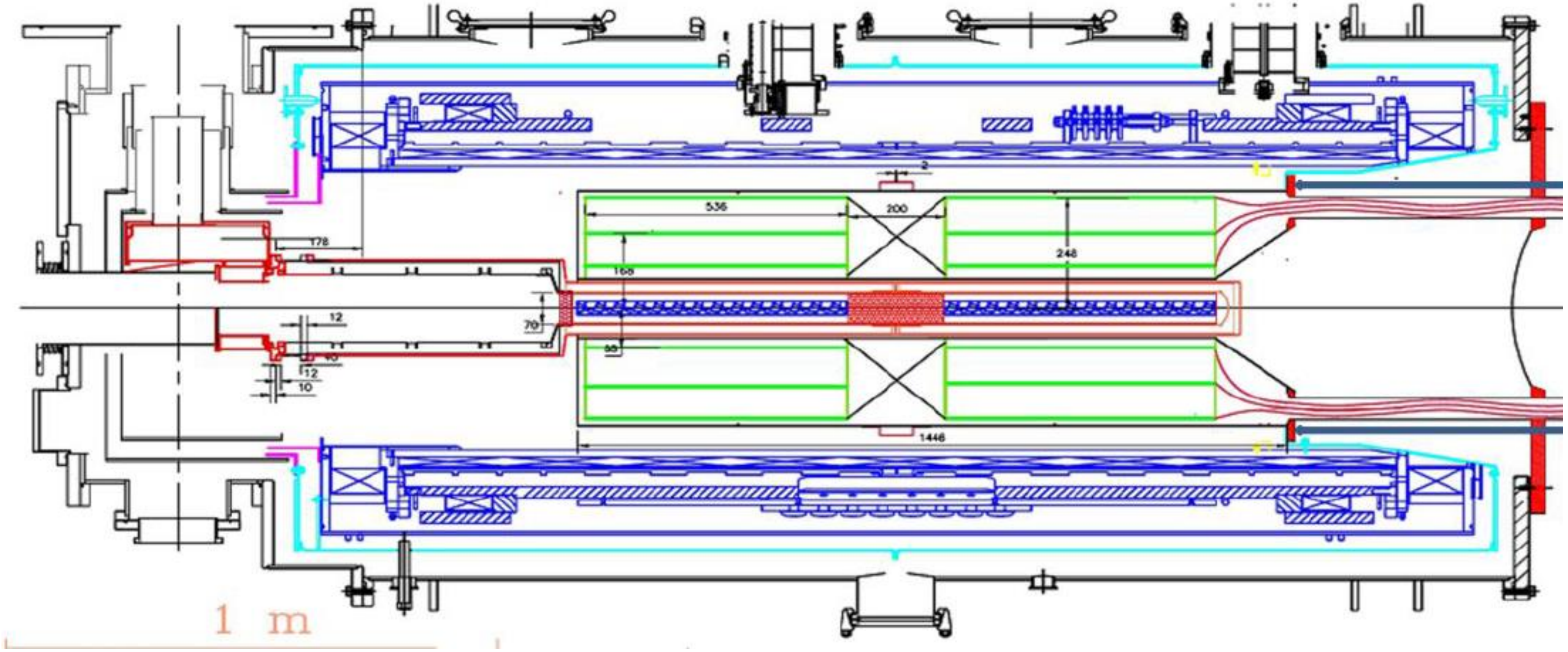
Proposed physics goals

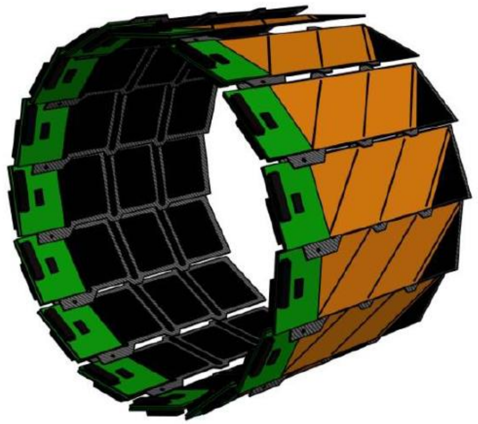
Proton Radius
Meson PDF – gluon PDF
Proton spin structure
3D imaging (TMDs and GPDs)
Hadron spectroscopy
Anti-matter cross section

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware Additions
μp elastic scattering	Precision proton-radius measurement	100	$4\cdot10^6$	100	$\mu^{\pm}$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2\cdot10^7$	10	$\mu^{\pm}$	$NH_3^{\uparrow}$	2022 2 years	recoil silicon, modified PT magnet
Input for Dark Matter Search	$\bar{p}$ production cross section	20-280	$5\cdot10^5$	25	p	LH2, LHe	2022 1 month	LHe target
$\bar{p}$-induced Spectroscopy	Heavy quark exotics	12, 20	$5\cdot10^7$	25	$\bar{p}$	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7\cdot10^7$	25	$\pi^{\pm}$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^{\pm}, \bar{p}$	$NH_3^{\uparrow}$, C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5\cdot10^6$	>10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥100	$5\cdot10^6$	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	$5\cdot10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5\cdot10^6$	10-100	$K^{\pm}, \pi^{\pm}$	from H to Pb	2026 1 year	

Possible RPD for COMPASS^{++}/AMBER

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





A technology developed at JINR for NICA for the BM@N experiment

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

ϕ Dep. of BH+DVCS with Unpol Target

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

Well known

Σ	Σ
Σ	Σ
Δ	Δ
Σ	Δ
Δ	Σ
⇆ e-	⇆ μ±

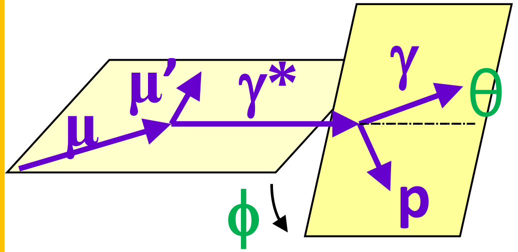
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

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

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

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

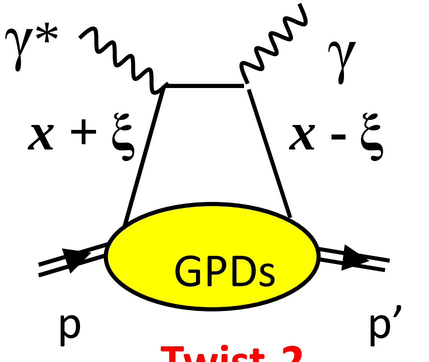


Twist-2 >>

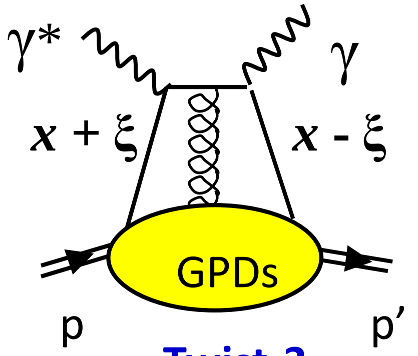
■ Twist-3,

■ Twist-2

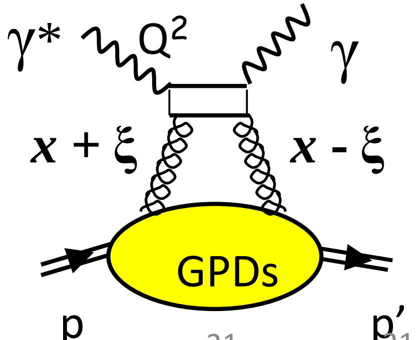
double helicity flip for gluons (NLO)



Twist-2



Twist-3



Twist-2, NLO

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

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

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

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

Beam Charge-spin Difference

$\mathcal{D}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow}) \rightarrow c_0^I + c_1^I \cos\phi$

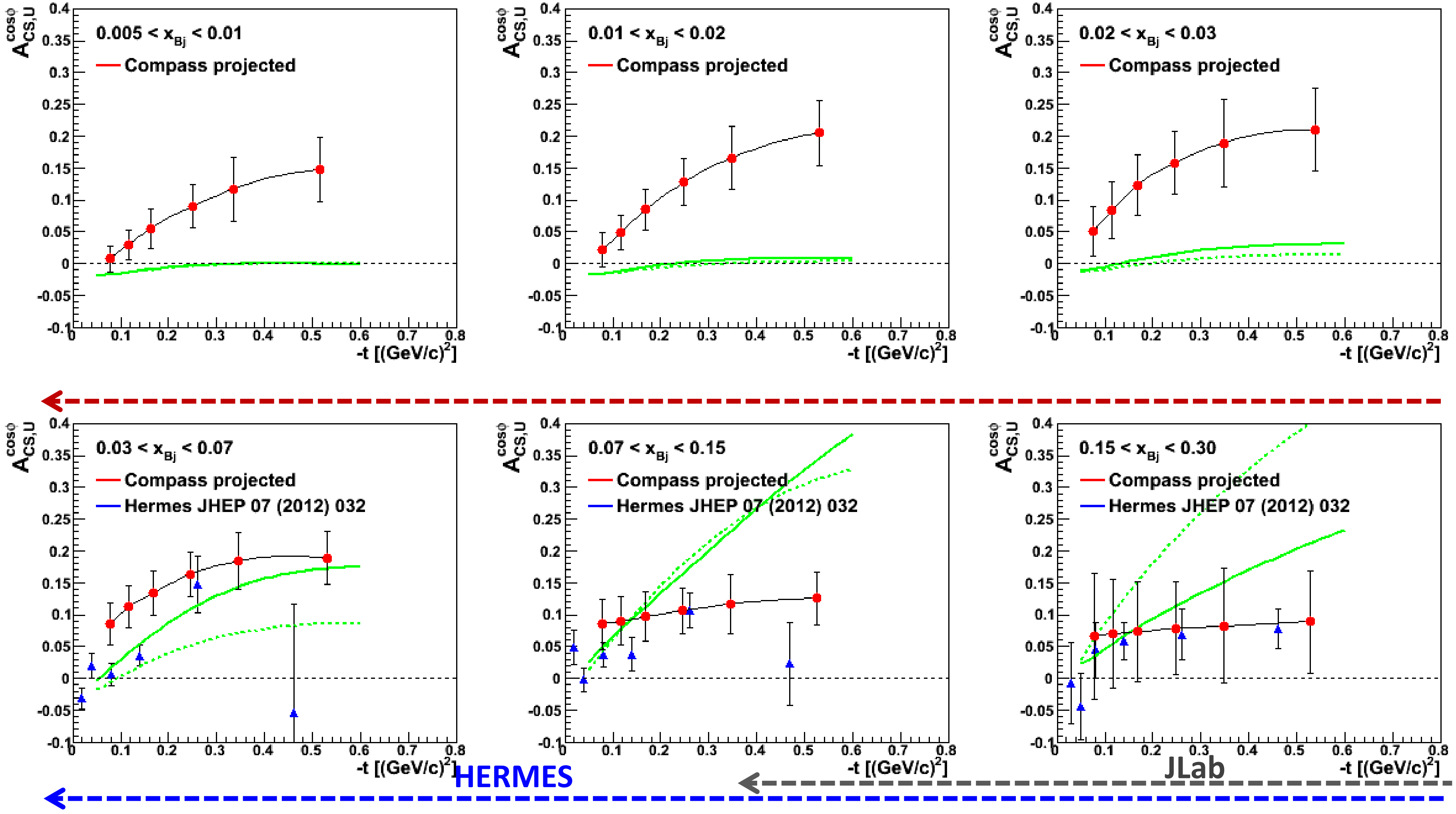
$c_1^I = \mathcal{R}e\, F_1 \mathcal{H}$

KM10

VGG

- With $\mathcal{R}e\, F_1 \mathcal{H}$ and $\mathcal{I}m\, F_1 \mathcal{H}$
  → Extraction of D-term

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

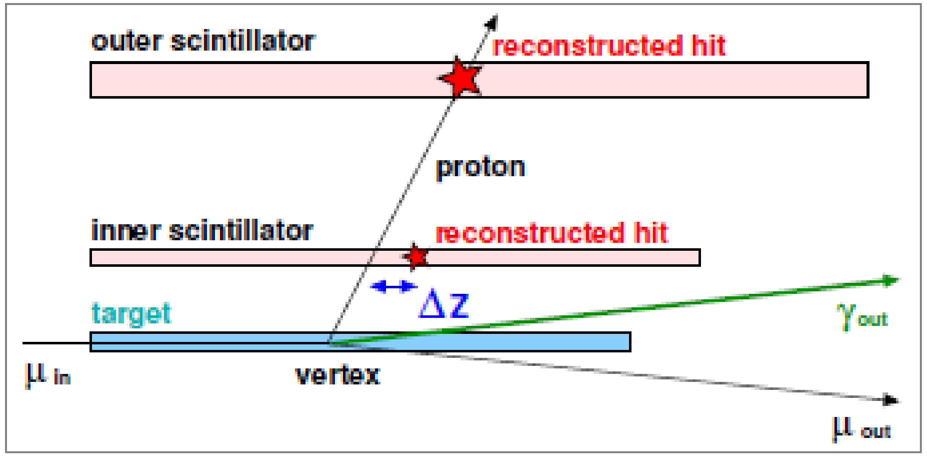


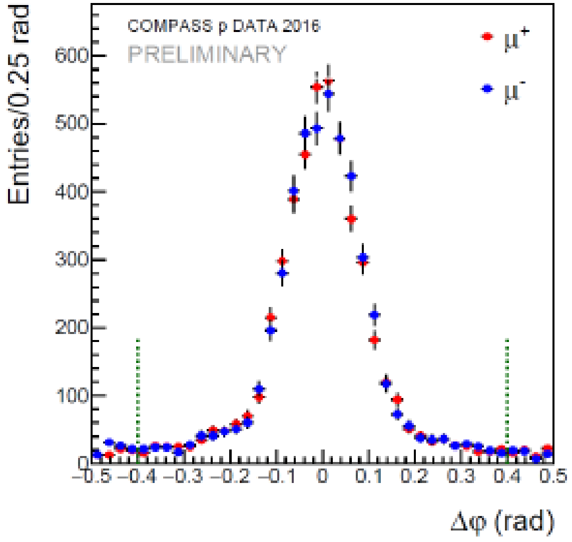
COMPASS 2 years of data Eμ= 160 GeV 1 < Q^2 < 8 GeV^2

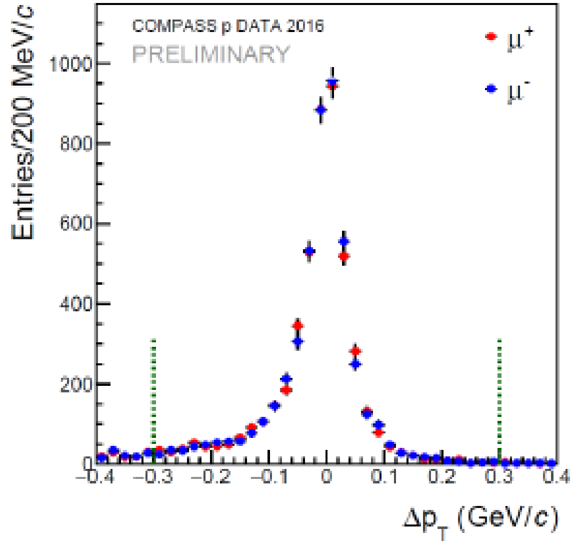
2016 – 2017 Data First Insight

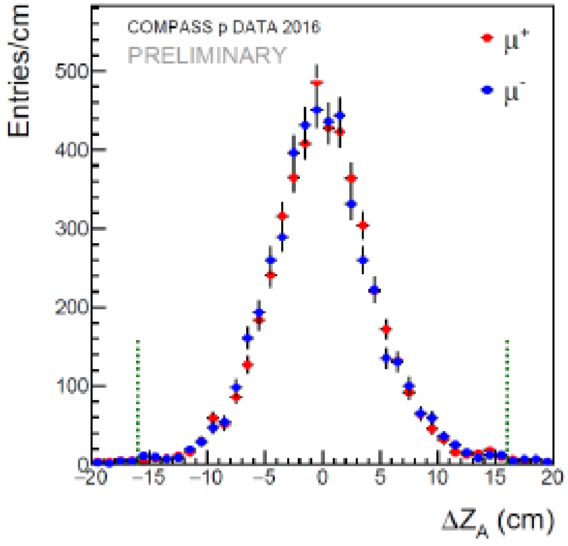
DVCS : μ p → μ' p γ

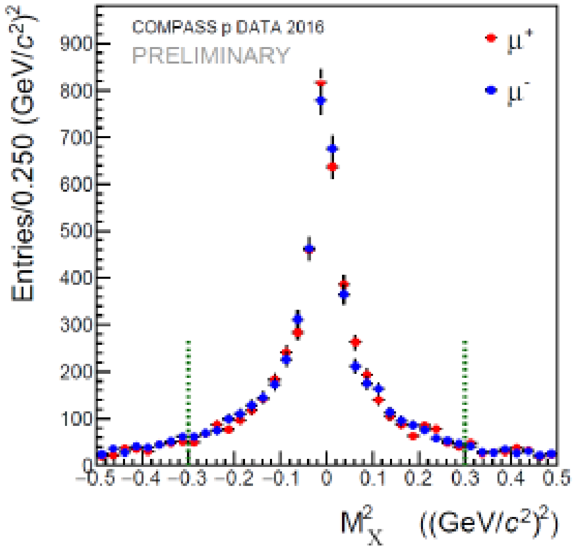
1) $\Delta p_T = p_T^{cam} - p_T^{spec}$
2) $\Delta\varphi = \varphi^{cam} - \varphi^{spec}$
3) $\Delta z_A = z_A^{cam} - z_A^{Z_B \text{ and vertex}}$
4) $M^2_{X=0} = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2$











Exclusive π^0 Production on Unpolarized Proton

e p → e π^0 p

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

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

Leading twist expected be dominant

But measured as ≈ only a few % of $\frac{d\sigma_T}{dt}$

The other contributions arise from coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

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

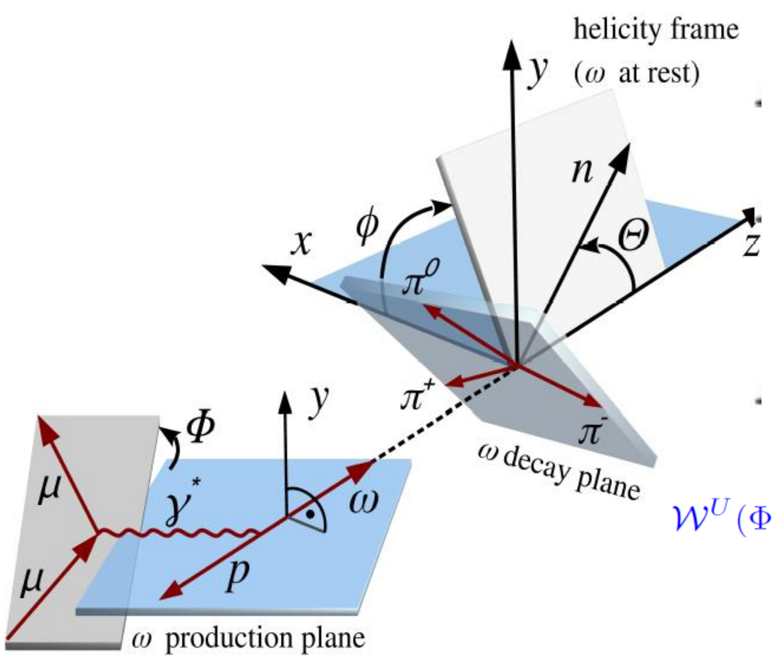
$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

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

A large impact of $\bar{E}_T$ can be identified:

- σ_{TT} contribution
- The dip at small |t| of σ_T

Exclusive ω Production on Unpolarized Proton



experimental angular distributions

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

Self analysis… with phi and cosTheta

15 'unpolarized' and 8 'polarized' SDMEs

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

cos2ϕ

$$-\epsilon\cos 2\Phi\Big(r^{1}_{11}\sin^2\Theta + r^{1}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{1}_{10}\}\sin 2\Theta\cos\phi - r^{1}_{1-1}\sin^2\Theta\cos 2\phi\Big)$$

$$-\epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{2}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{2}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$

$$+\sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^{5}_{11}\sin^2\Theta + r^{5}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{5}_{10}\}\sin 2\Theta\cos\phi - r^{5}_{1-1}\sin^2\Theta\cos 2\phi\Big)$$

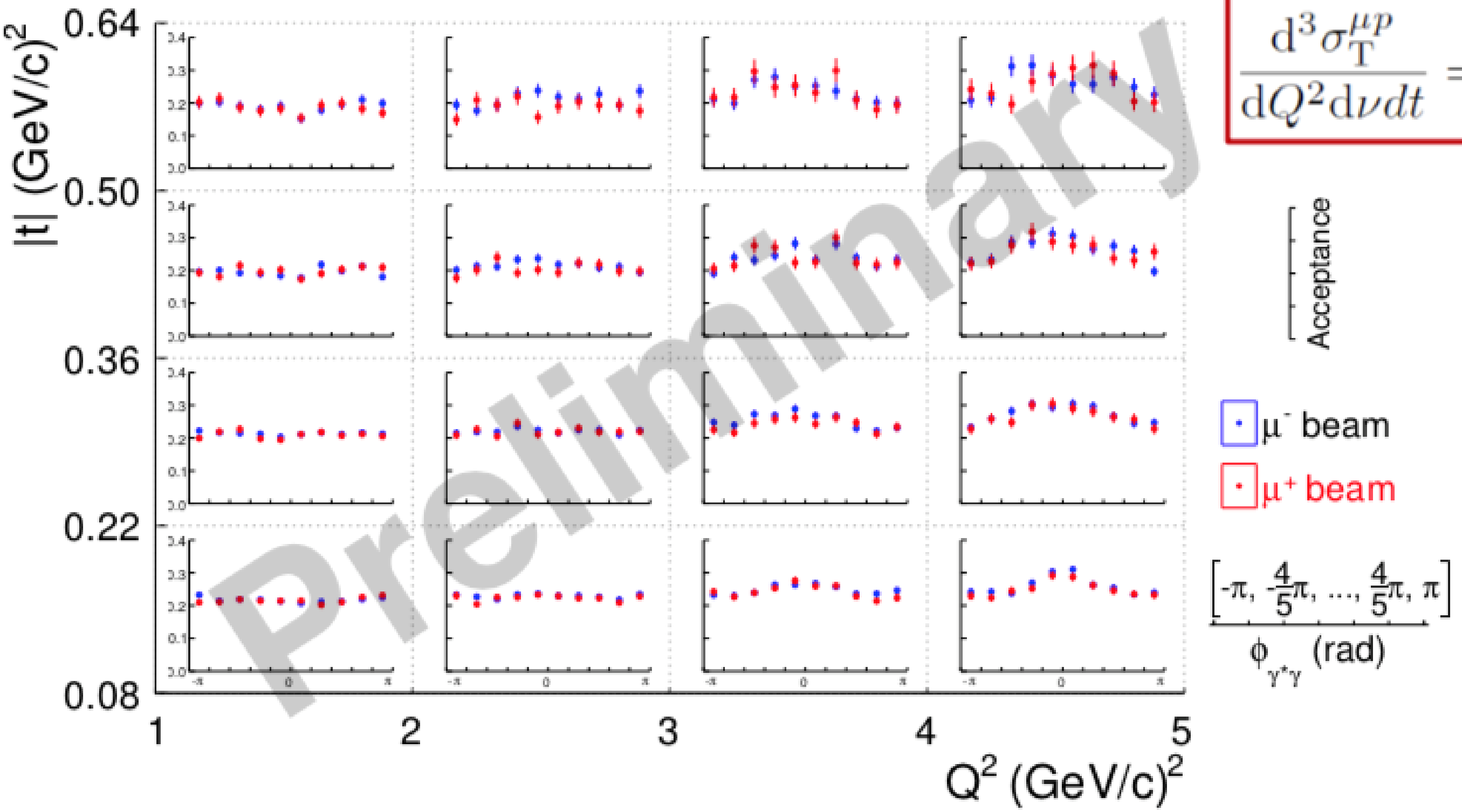
$$+\sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{6}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{6}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Bigg],$$

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

$$+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{7}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{7}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$

$$+\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^{8}_{11}\sin^2\Theta + r^{8}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{8}_{10}\}\sin 2\Theta\cos\phi - r^{8}_{1-1}\sin^2\Theta\cos 2\phi\Big)\Bigg]$$

COMPASS Acceptance of ϕ for DVCS

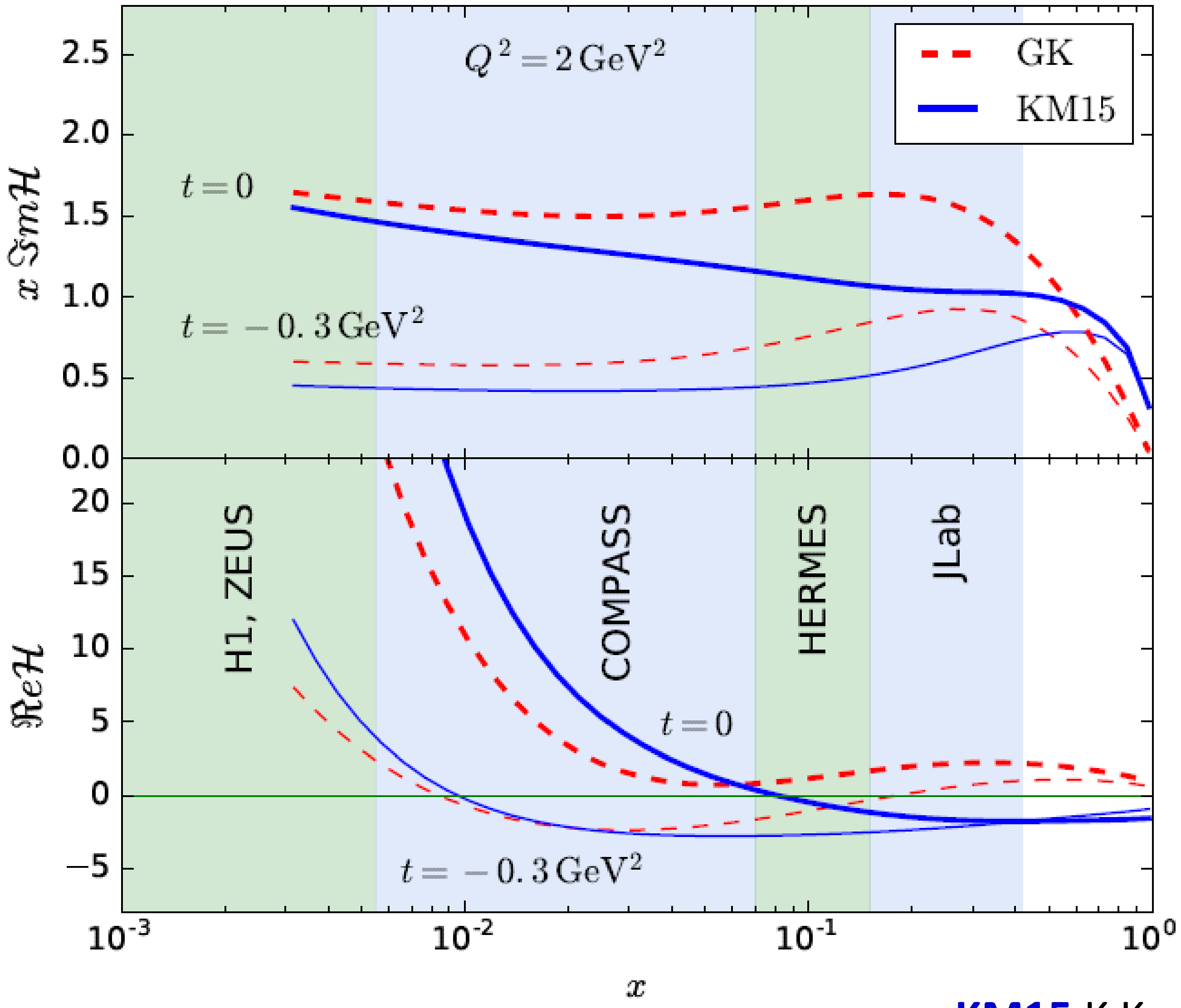


$$\frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt} = \int_{-\pi}^{\pi} d\phi\, (d\sigma - d\sigma^{BH}) \propto c_0^{DVCS}$$

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

Flux of transverse virtual photons

GPD H Global Analysis



Im ℋ
is better understood

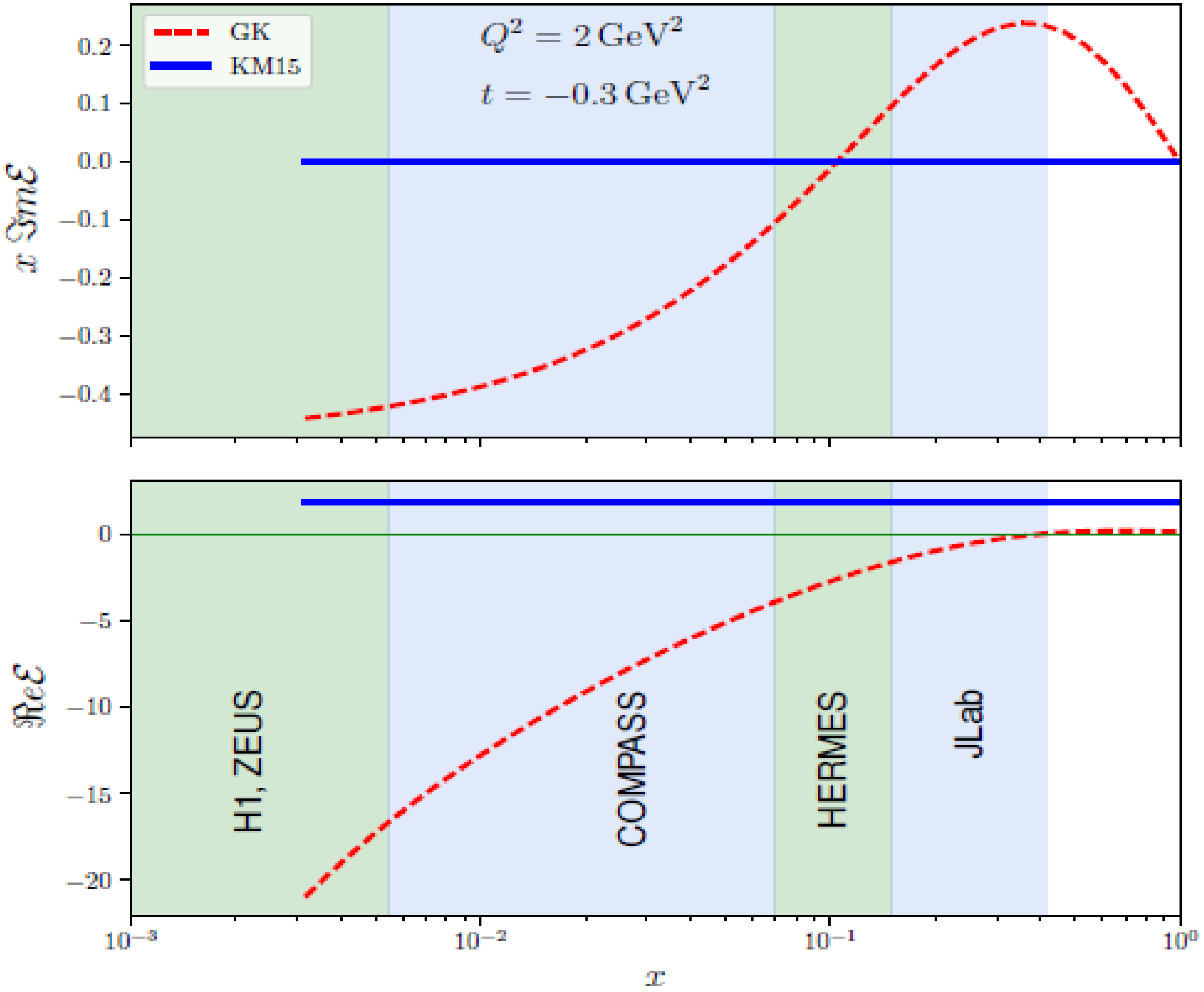
Re ℋ linked to the ***d term***
is still poorly constrained

KM15 K Kumericki and D Mueller [arXiv:1512.09014v1]

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

GPD E 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)