



Exclusive Reactions Studied in the COMPASS Experiment at CERN

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on behalf of the COMPASS collaboration

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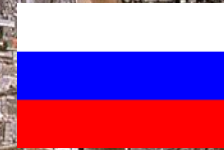
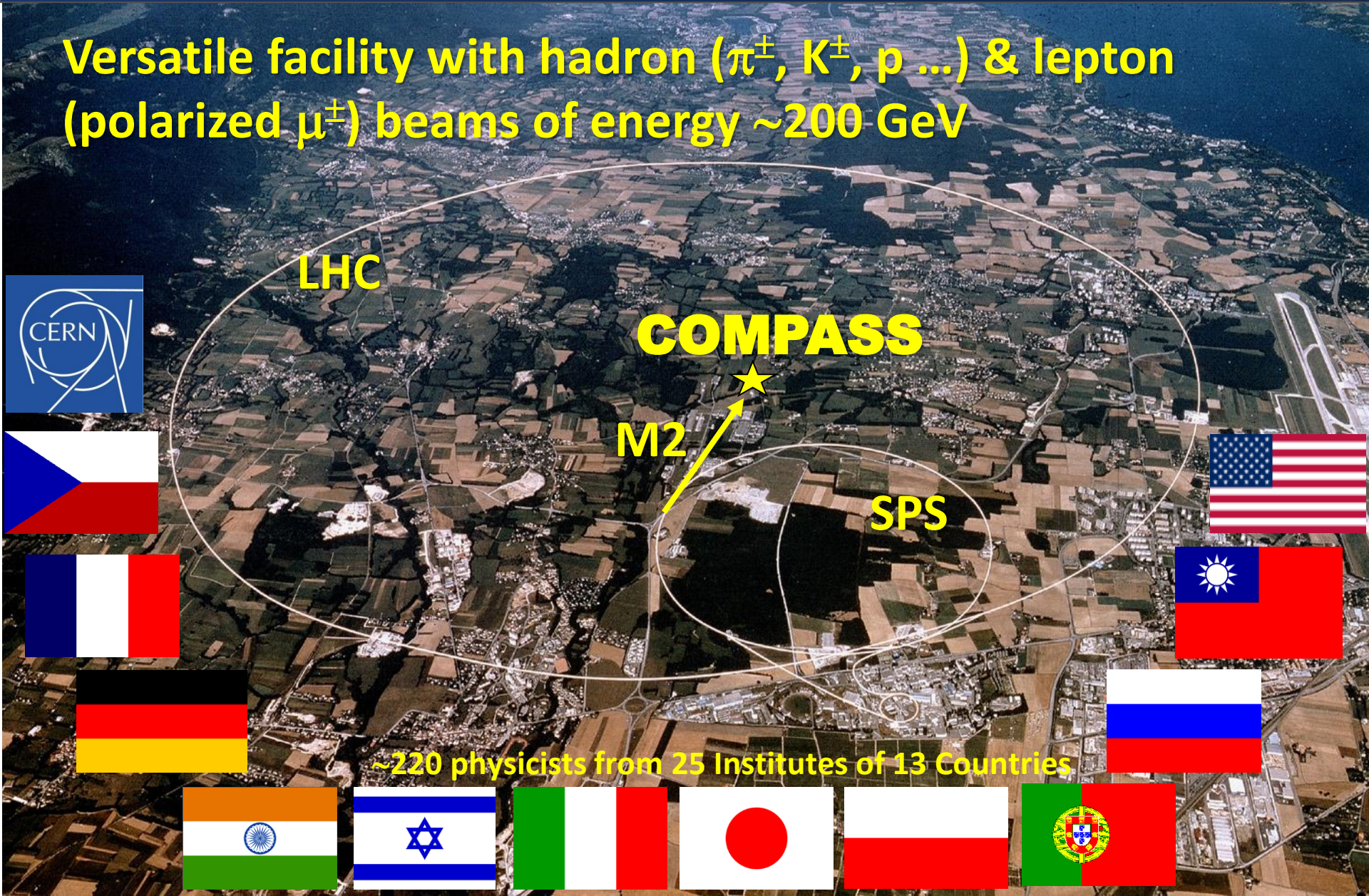


- The COMPASS Experiment
- Deeply Virtual Compton Scattering (DVCS)
- Hard Exclusive Meson Production (HEMP)
- Summary and Outlook

COMPASS Experiment



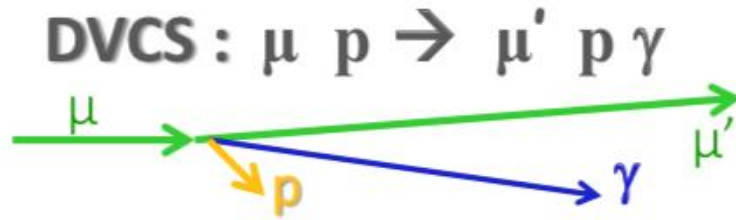
Versatile facility with hadron (π^\pm , K^\pm , p ...) & lepton (polarized μ^\pm) beams of energy ~ 200 GeV



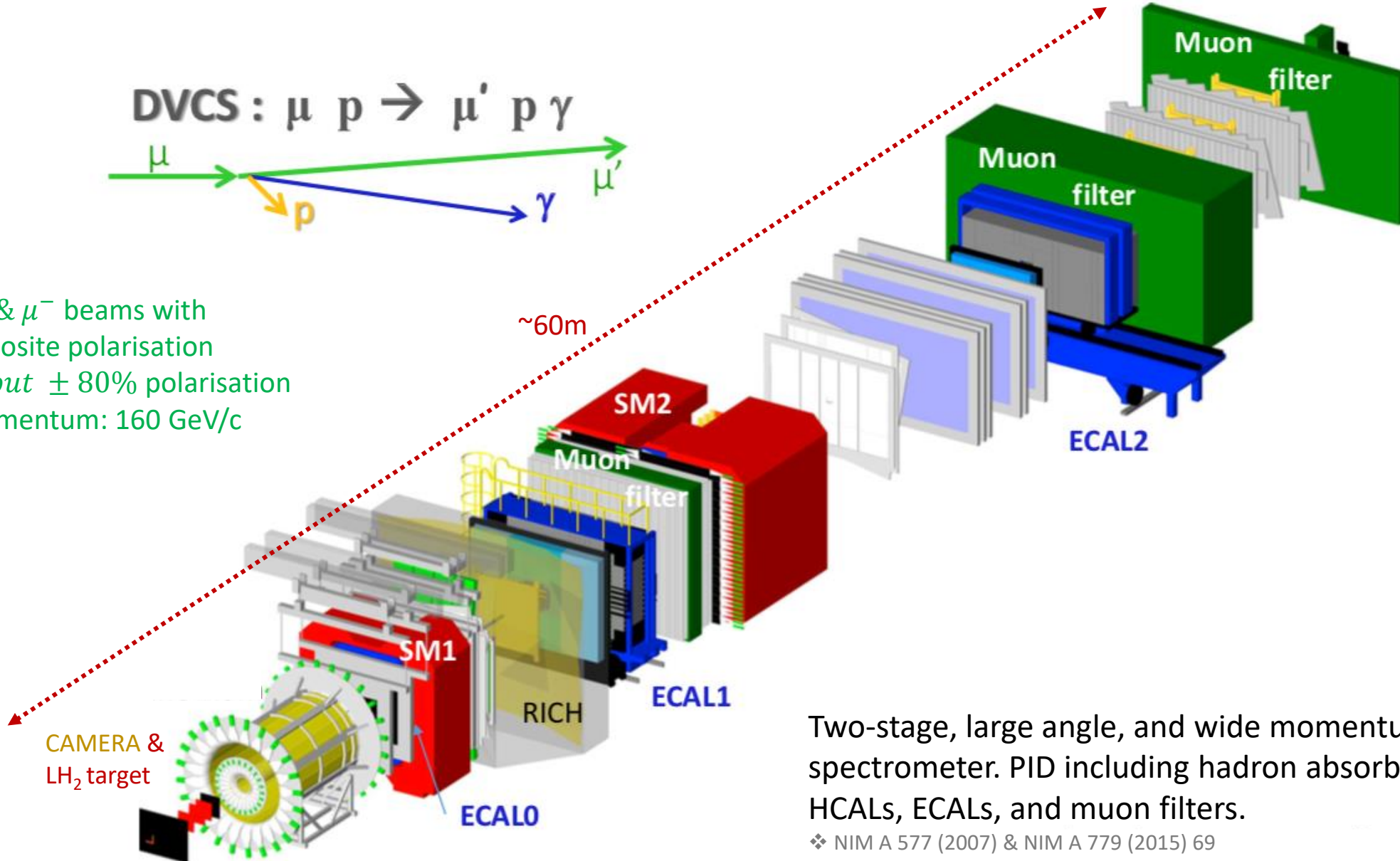
COmmun
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

~ 220 physicists from 25 Institutes of 13 Countries

COMPASS Setup for Hard Exclusive Measurements



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



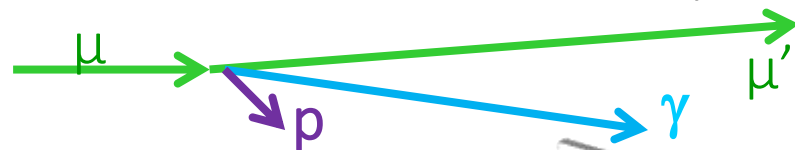
Two-stage, large angle, and wide momentum range spectrometer. PID including hadron absorbers, RICH, HCALs, ECALs, and muon filters.

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

COMPASS Setup for GPD Measurement



$$\text{DVCS} : \mu p \rightarrow \mu' p \gamma$$

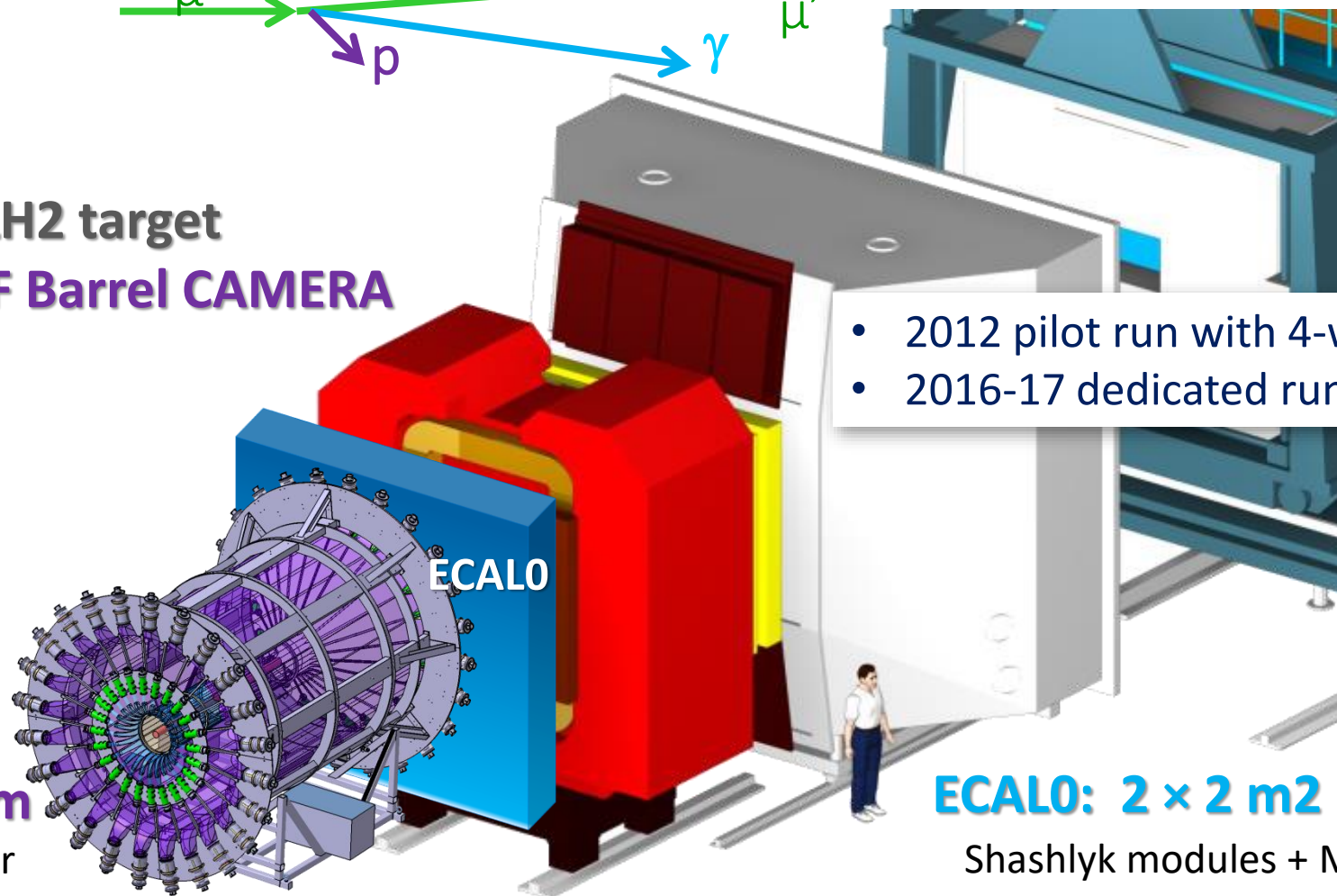


- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECALO

CAMERA

L=4m \varnothing =2m

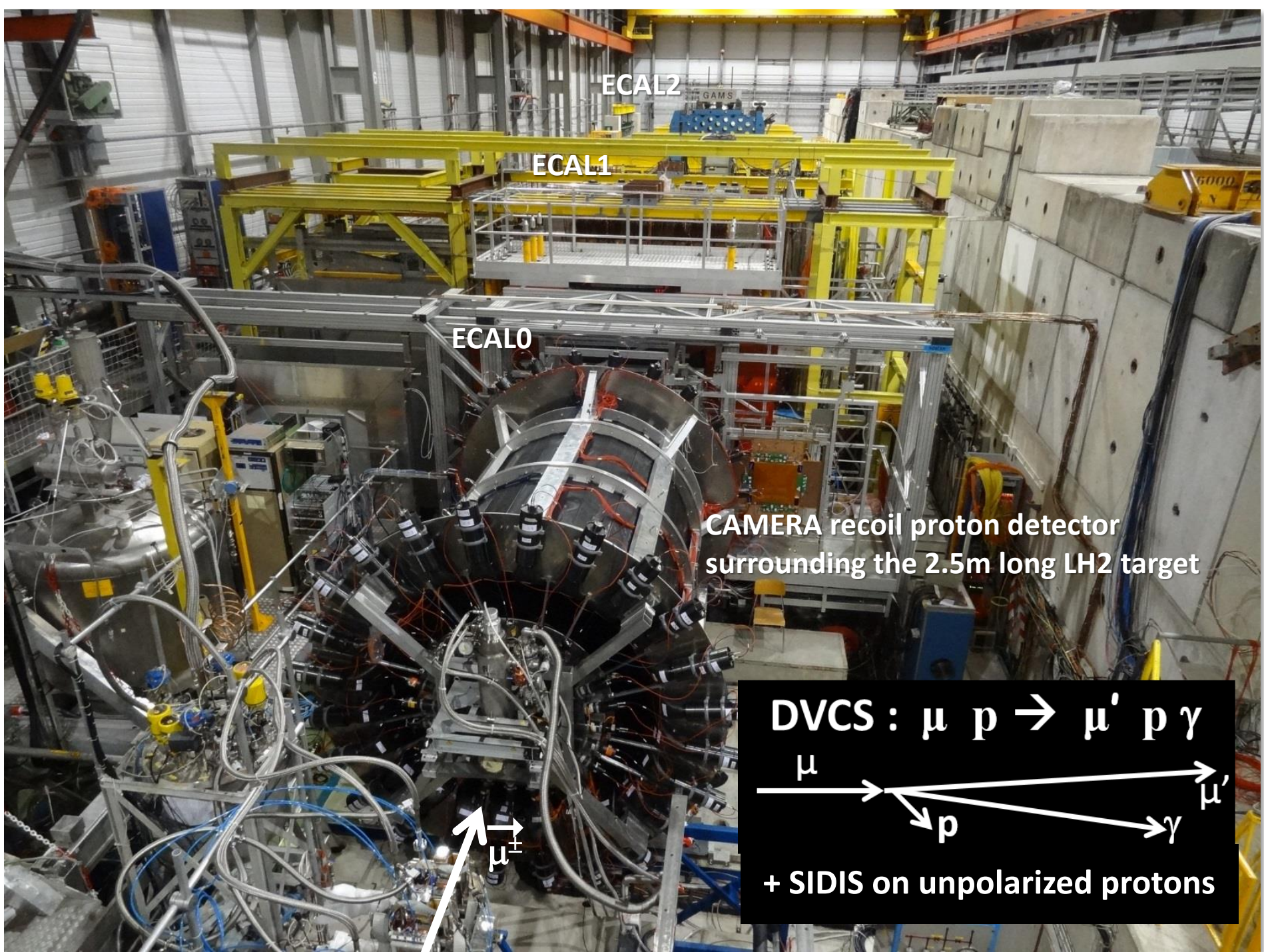
24 inner & outer scintillators separated by about 1m
1 GHz SADC readout, 330ps ToF resolution



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

ECALO: 2 x 2 m²

Shashlyk modules + MAPD readout
one module is made of 9 cells (4x4 cm²)
= 194 modules or 1746 cells



ECAL2

ECAL1

ECAL0

CAMERA recoil proton detector
surrounding the 2.5m long LH2 target

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

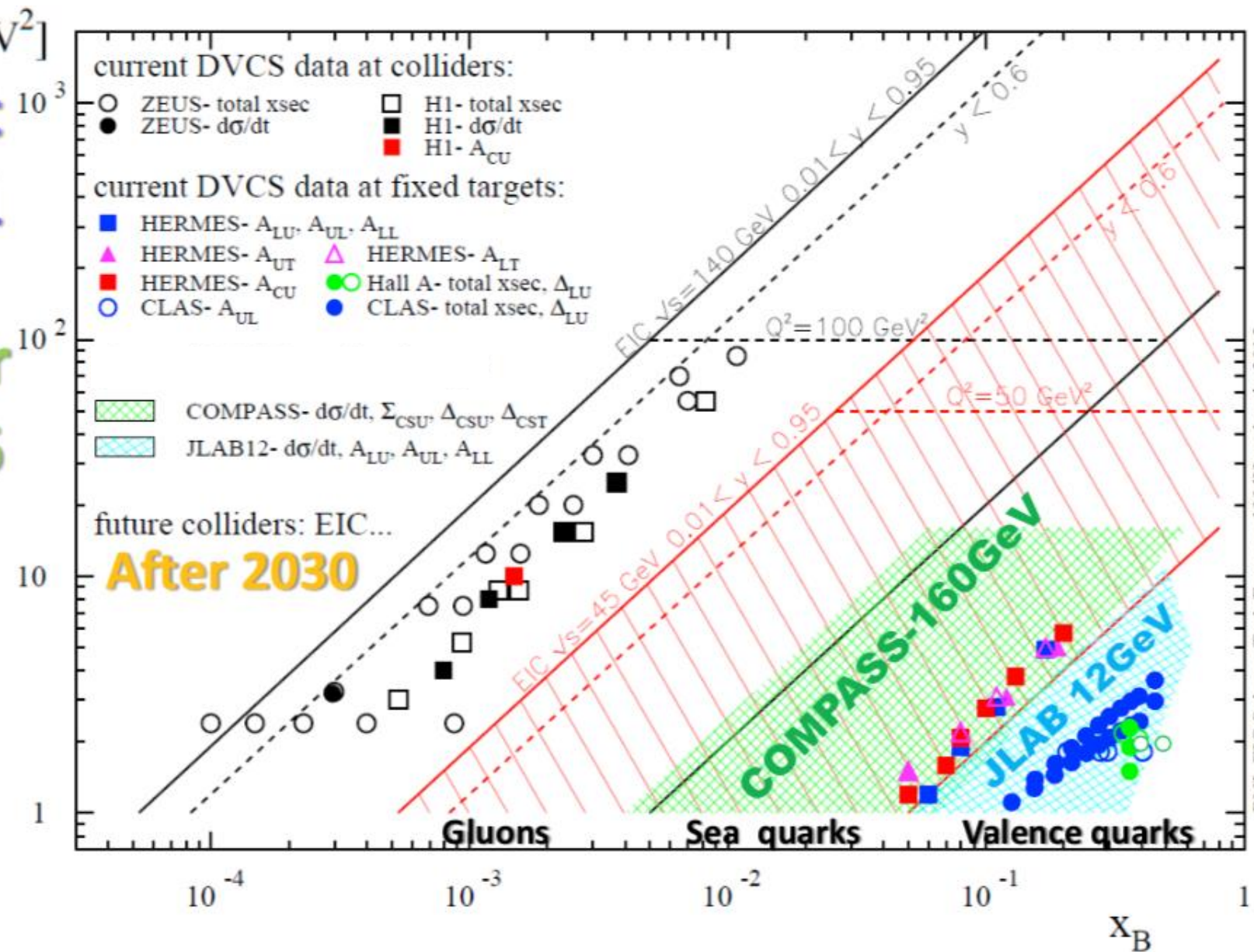
+ SIDIS on unpolarized protons

COMPASS Coverage for DVCS

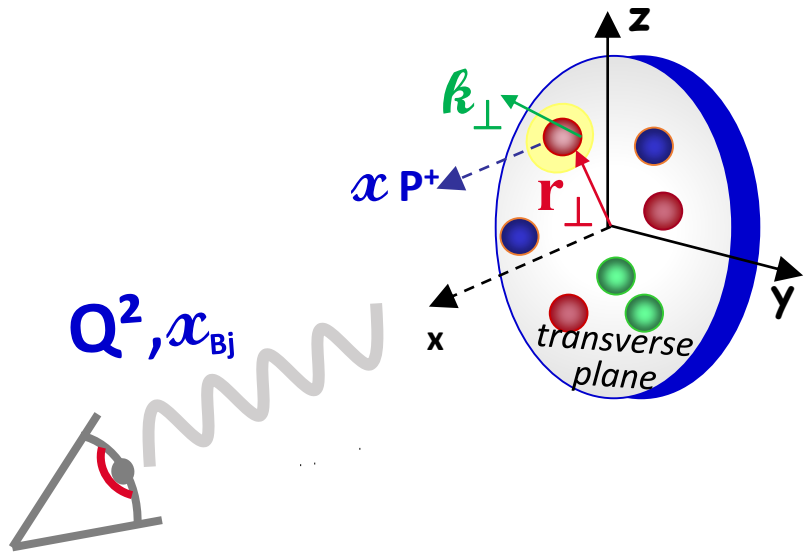


Start
2001

After
2016



Proton Picture

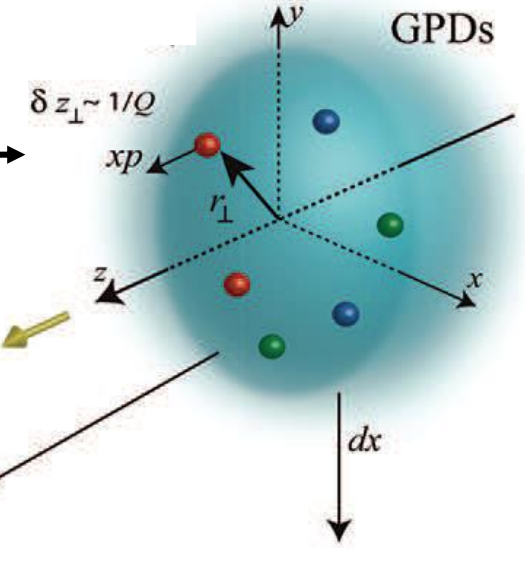


Wigner distributions

$$\mathcal{W}(x, \mathbf{k}_\perp, \mathbf{r}_\perp)$$

- The complete partonic description of the nucleon

$$\int d\mathbf{k}_\perp$$



$$\delta z_\perp \sim 1/Q$$

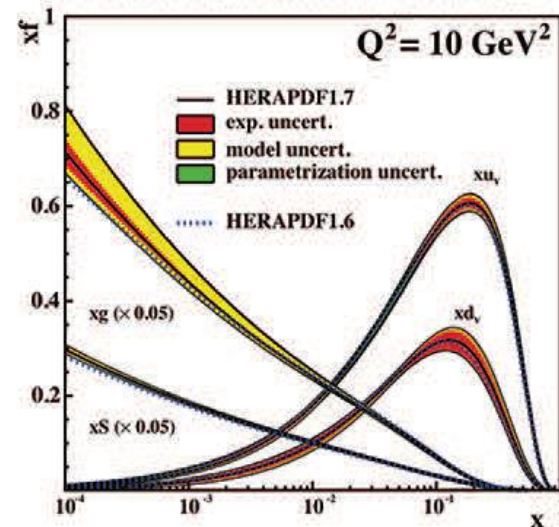
$$d^2 r_\perp$$

$$dx$$

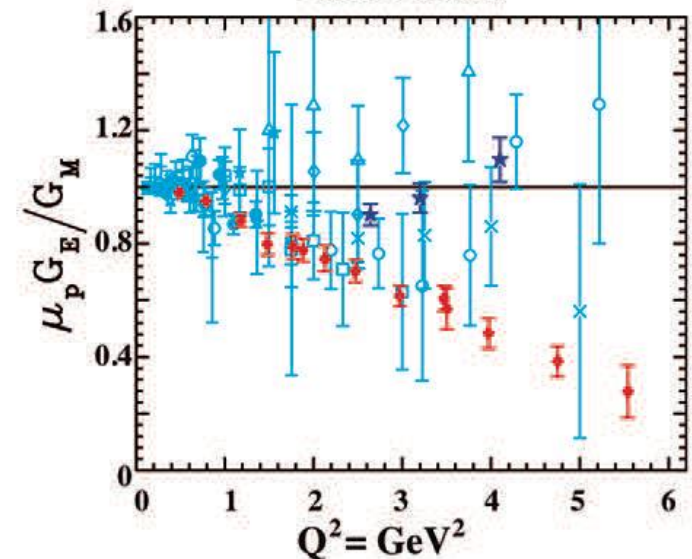
Generalized Parton Distributions

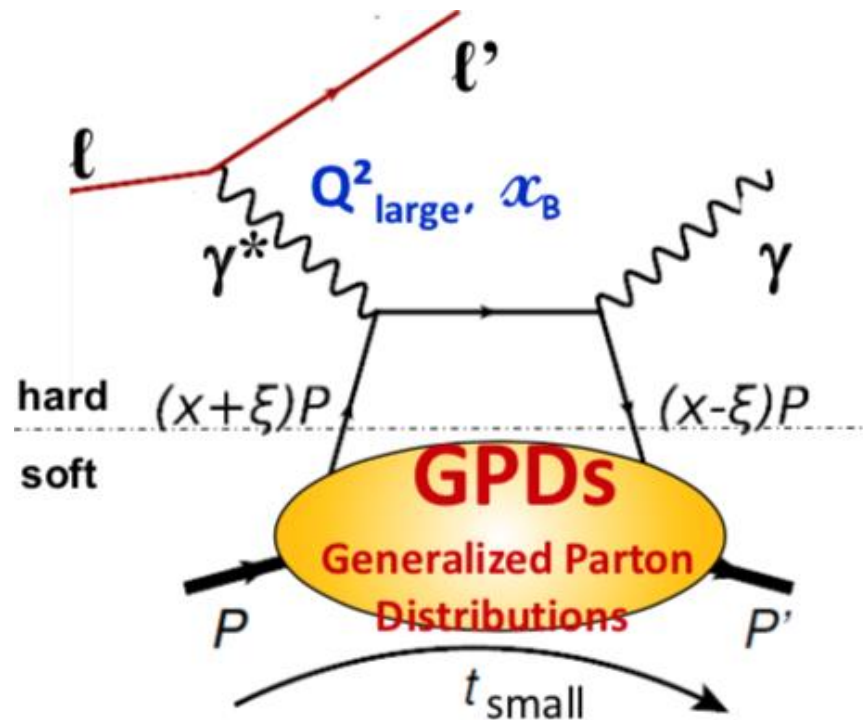
- 8 in total
- Info. on transverse position
- Embody both PDFs and Form factors
- Accessible in exclusive processes

Parton Distribution Functions



Form Factors





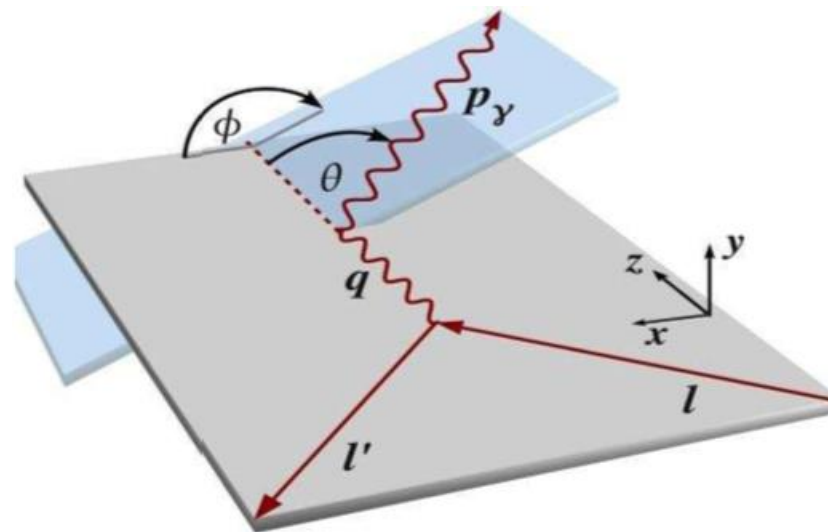
$$\text{DVCS: } l + p \rightarrow l' + p' + \gamma$$

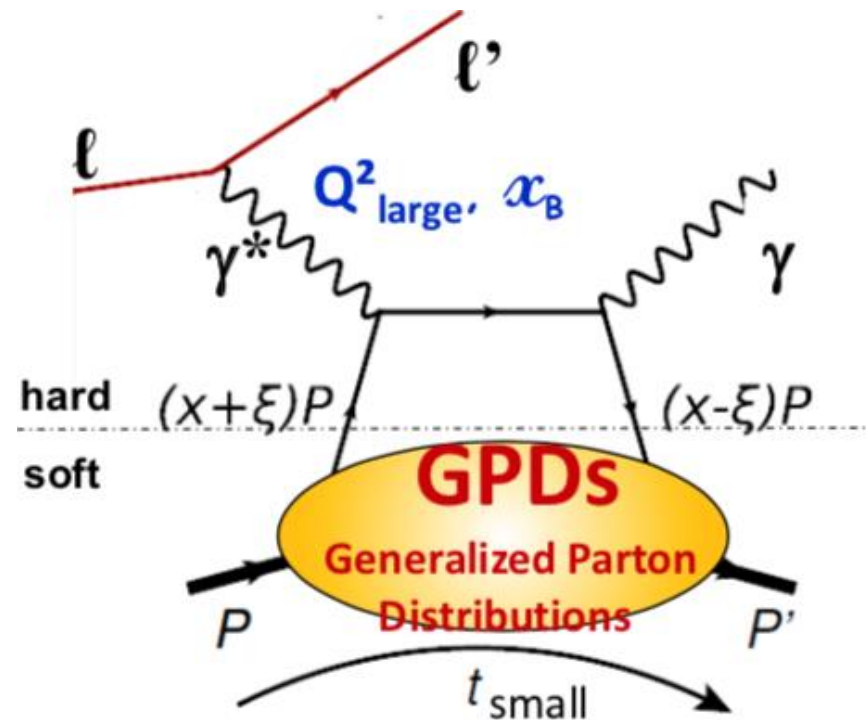
To experimentally access the information about Generalized Parton Distributions (GPDs), DVCS is regarded as the golden channel and its interference with the well-known BH process gives access to more info.

The variables measured in the experiment:

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

$$t \text{ (or } \theta_{\gamma^*\gamma}) \text{ and } \phi \text{ (} l l' \text{ plane}/\gamma\gamma^* \text{ plane)}$$





➤ 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

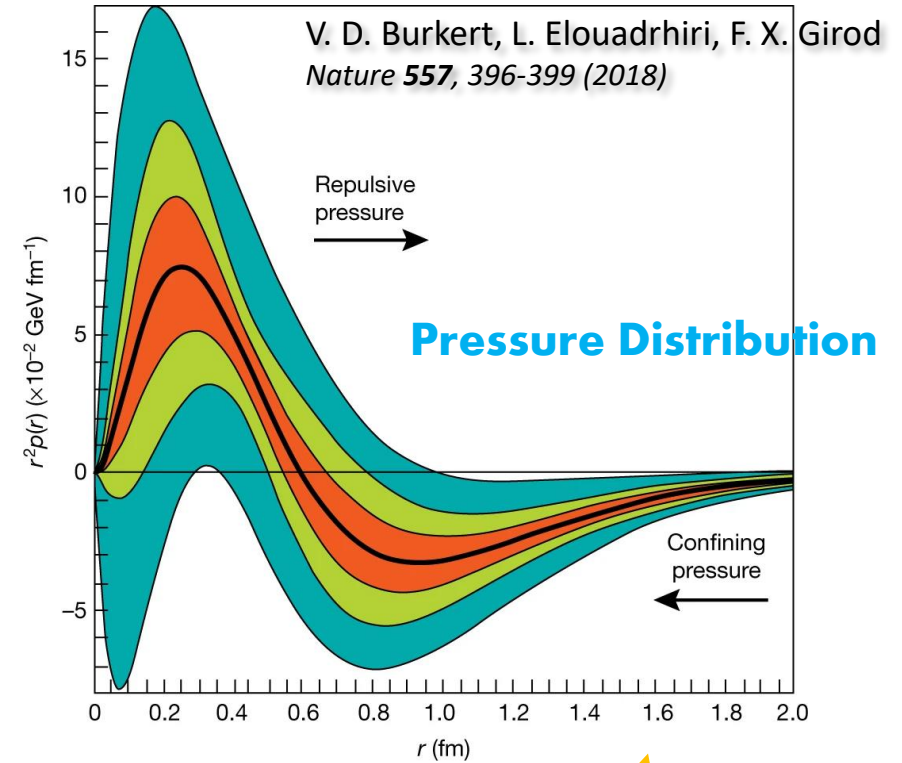
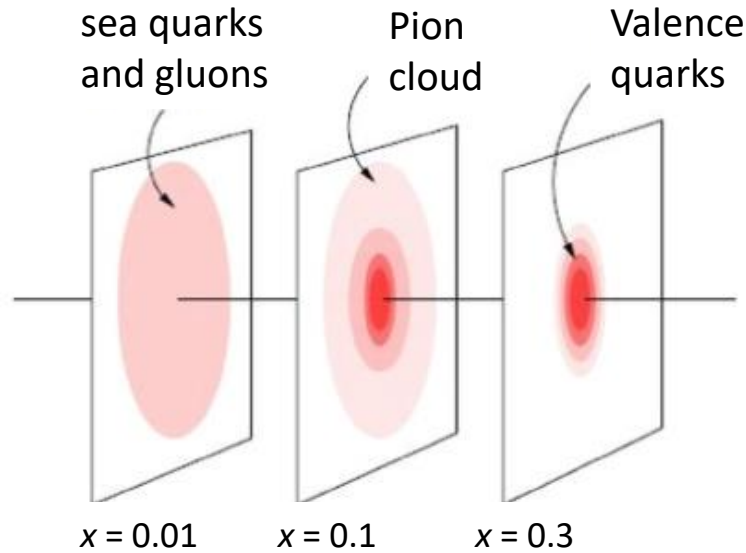
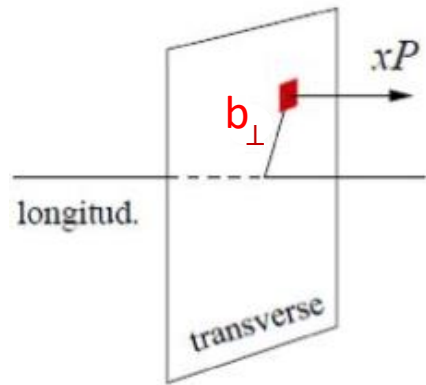
CFE \dashrightarrow $\mathcal{H} = \int_{-1}^{+1} dx \frac{\mathbf{H}(x, \xi, t)}{x - \xi + i\epsilon}$ \dashrightarrow GPD

t, ξ fixed

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

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

Transverse Imaging and Pressure Dist.



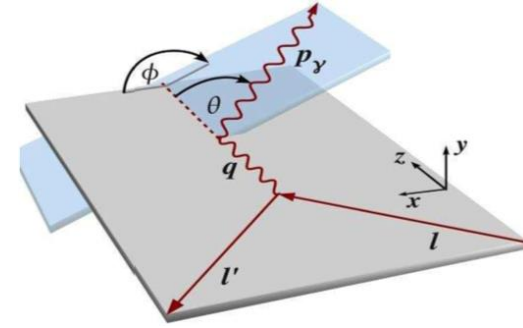
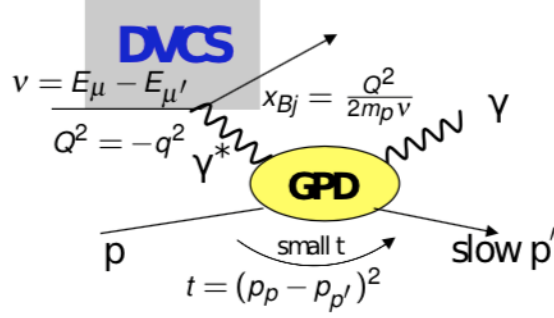
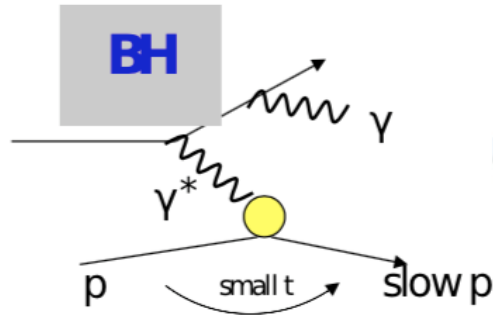
CFP → $\mathcal{H} = \int_{-1}^{+1} dx \frac{\mathbf{H}(x, \xi, t)}{x - \xi + i\epsilon}$ (t, ξ fixed)

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

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

Imaginary part → $d(t)$ (circled in yellow)

Azimuthal Dependence



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

Well known

Beam Charge-spin difference & sum

$$\mathcal{D}_{CS,u}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow})$$

$$\mathcal{S}_{CS,u}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow})$$

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

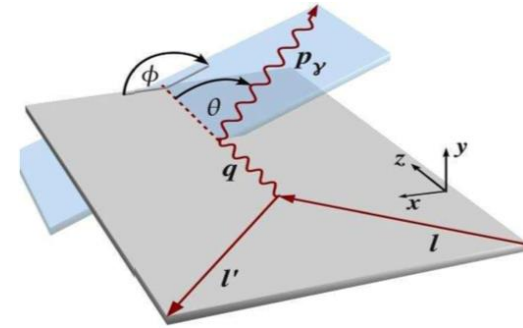
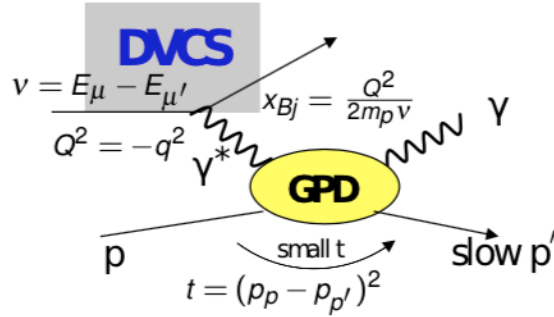
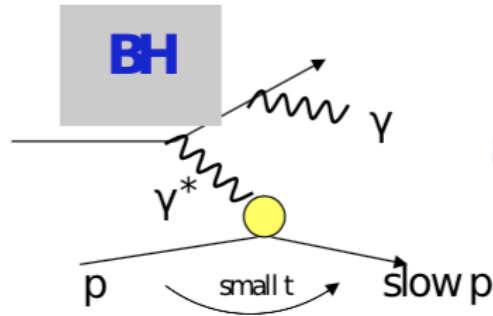
$$d\sigma_{unpol}^{DVCS} \propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi$$

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

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

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

Azimuthal Dependence



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

Well known

Beam Charge-spin difference & sum

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

$$\mathcal{S}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow})$$

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

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

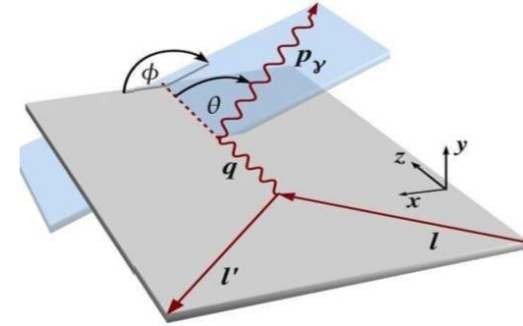
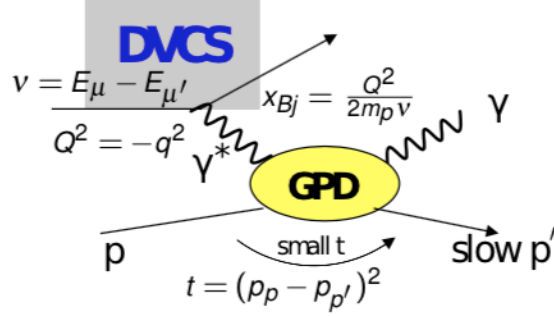
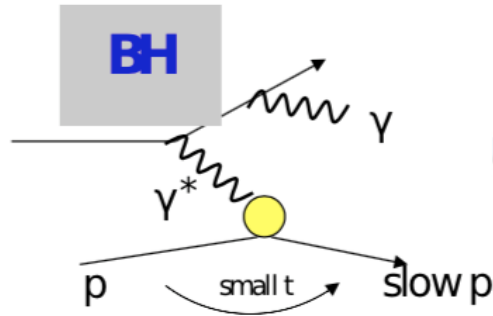
$$d\sigma_{pol}^{DVCS} \propto s_1^{DVCS} \sin \phi$$

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

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

$\mathcal{D}_{CS,U}(\phi)$

Azimuthal Dependence



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

Well known

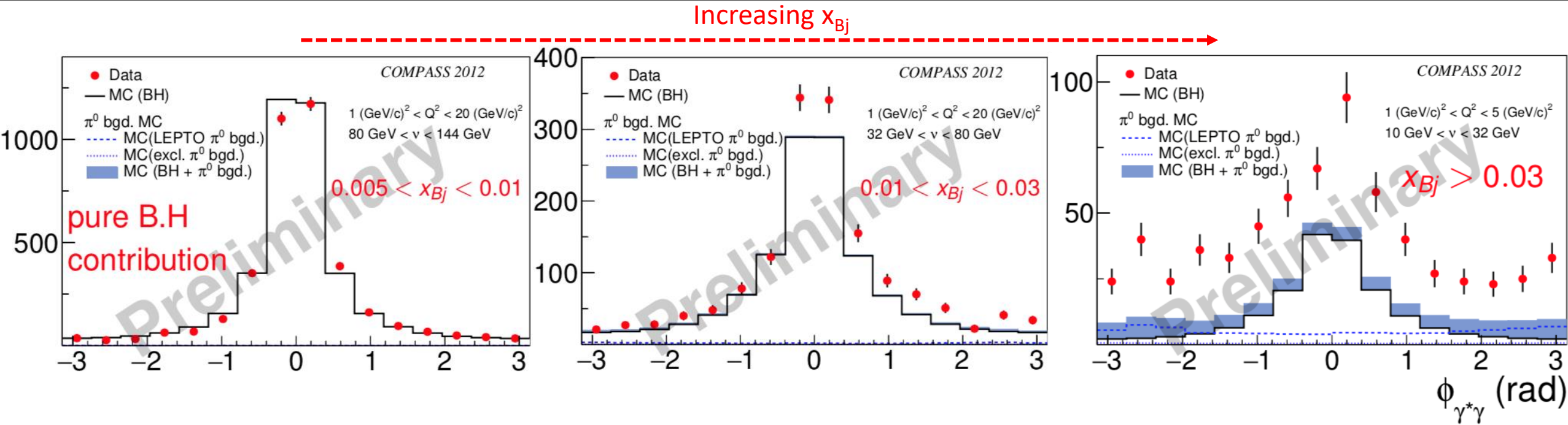
Beam Charge-spin difference & sum

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

$$\mathcal{S}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow})$$

$d\sigma^{BH}$	$\propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi$	$\mathcal{S}_{CS,U}(\phi)$
$d\sigma_{unpol}^{DVCS}$	$\propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi$	
$d\sigma_{pol}^{DVCS}$	$\propto s_1^{DVCS} \sin \phi$	
$\text{Re } I$	$\propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi$	
$\text{Im } I$	$\propto s_1^I \sin \phi + s_2^I \sin 2\phi$	$\mathcal{S}_{CS,U}(\phi)$

Extraction of DVCS Events - 2012 data

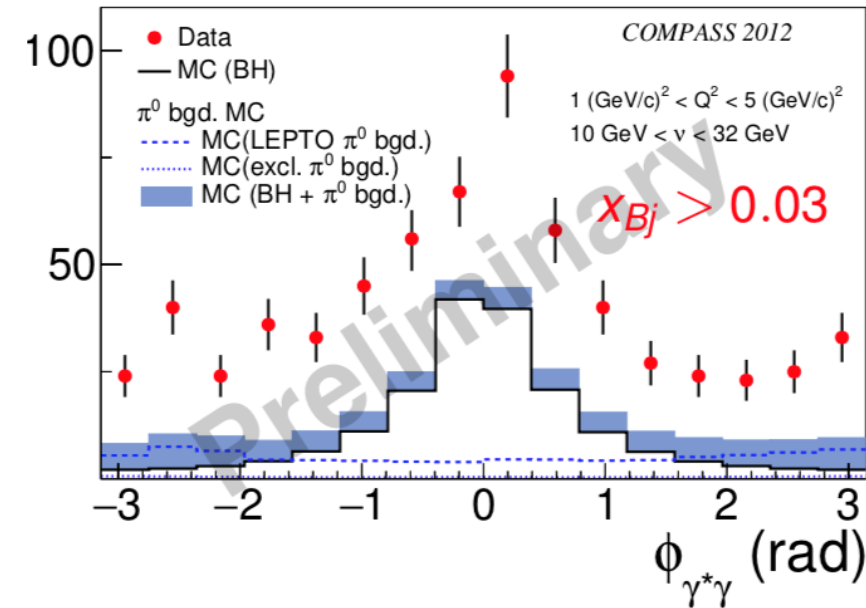
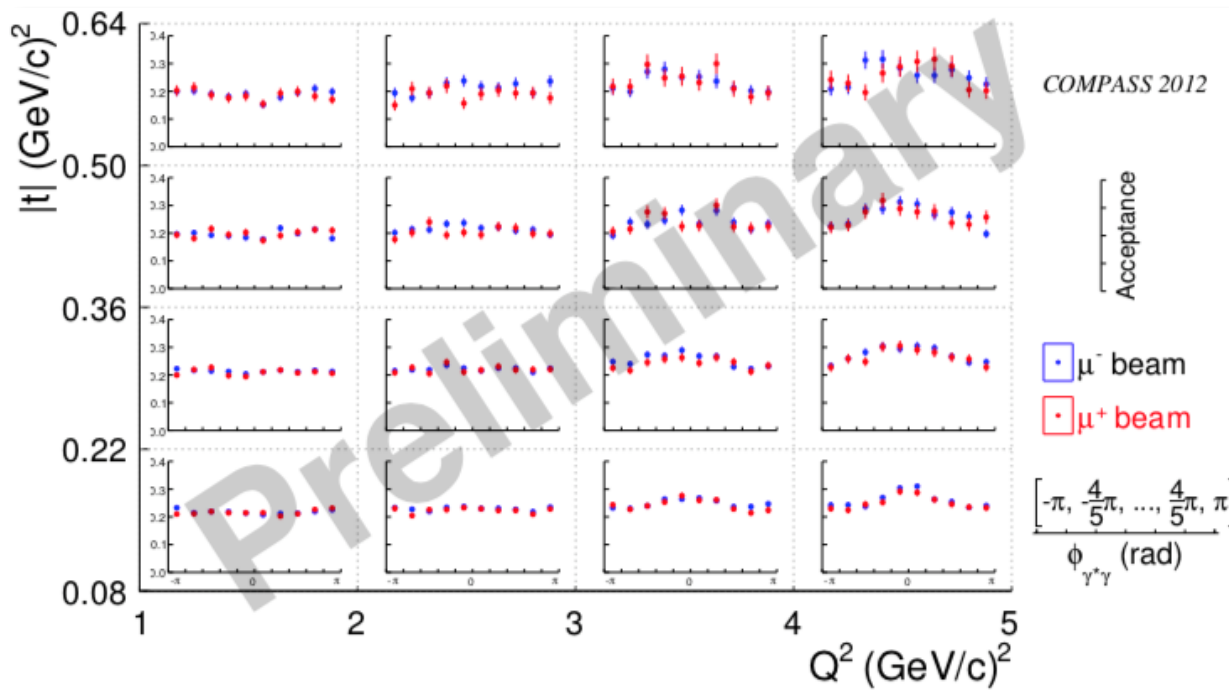


➤ Beam charge-spin sum

$$\begin{aligned}
 S_{CS,u}(\phi) &\equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) = 2[d\sigma^{BH} + d\sigma_{unpol}^{DVCS} + \text{Im } I] \\
 &= 2[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos \phi + s_1^I \sin \phi + s_2^I \sin 2\phi]
 \end{aligned}$$

$$c_0^{DVCS} \underset{\text{small } x_{Bj}}{\propto} 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2} \mathcal{E}\mathcal{E}^* \rightarrow 4 (\text{Im } \mathcal{H})^2 \underset{\text{model dependent}}{}$$

Extraction of DVCS Events - 2012 data



➤ Beam charge-spin sum

$$\begin{aligned}
 S_{CS, U}(\phi) &\equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) = 2[d\sigma^{BH} + d\sigma_{unpol}^{DVCS} + \text{Im } I] \\
 &= 2[\cancel{d\sigma^{BH}} + \underbrace{c_0^{DVCS}}_{\text{red circle}} + \cancel{c_1^{DVCS} \cos \phi} + \cancel{c_2^{DVCS} \cos \phi} + \cancel{s_1^I \sin \phi} + \cancel{s_2^I \sin 2\phi}]
 \end{aligned}$$

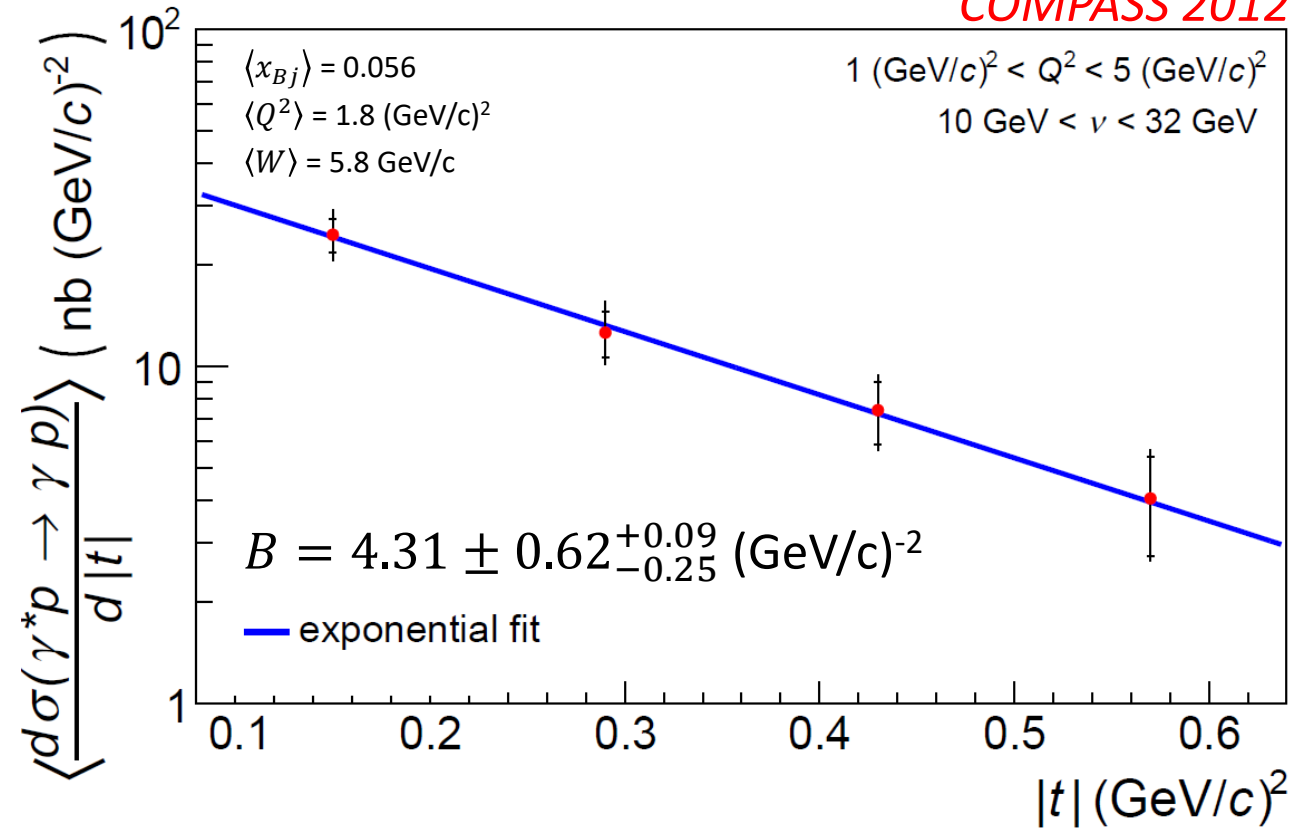
$$\underbrace{c_0^{DVCS}}_{\text{small } x_{Bj}} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2} \mathcal{E}\mathcal{E}^* \rightarrow 4 (\text{Im } \mathcal{H})^2 \quad \text{model dependent}$$

Transverse extension of partons – 2012 data



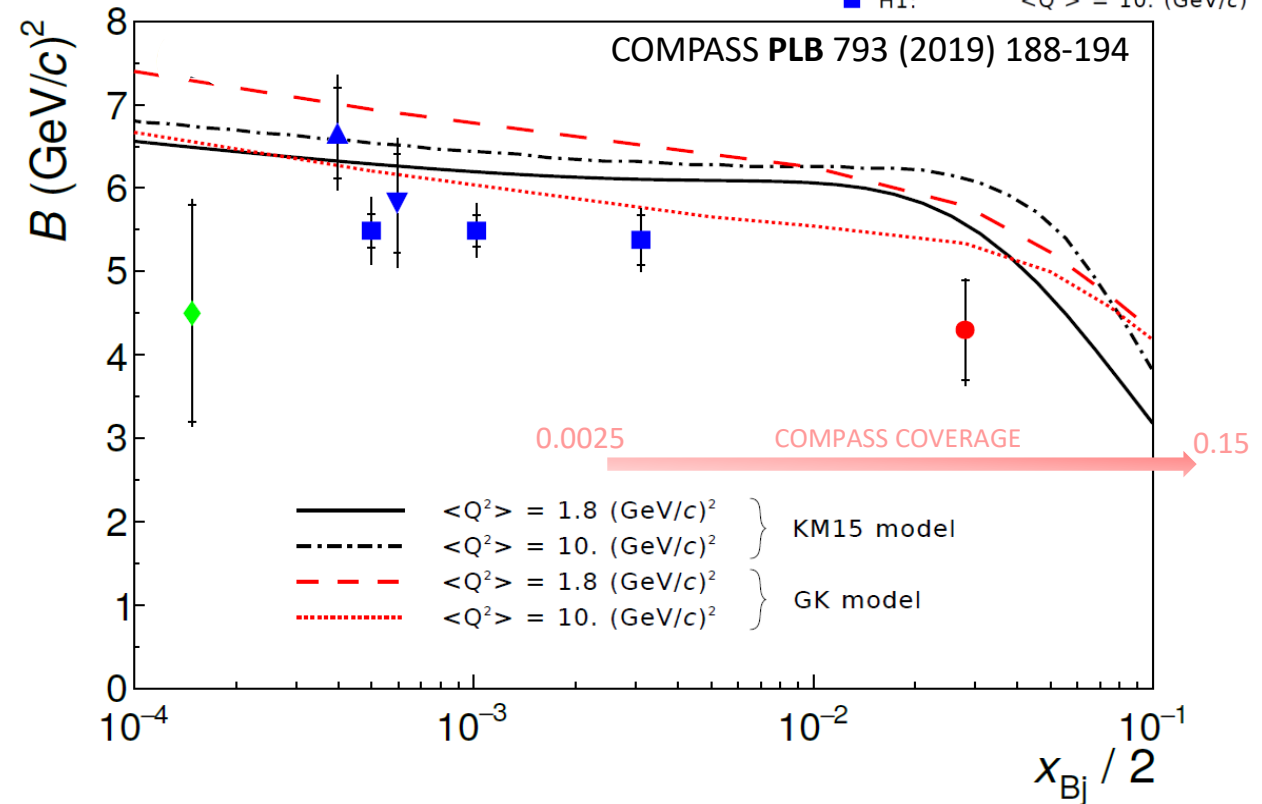
$$d\sigma^{DVCS}/d|t| \propto e^{-B|t|}$$

COMPASS 2012



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

- COMPASS: $\langle Q^2 \rangle = 1.8 \text{ (GeV/c)}^2$
- ◆ ZEUS: $\langle Q^2 \rangle = 3.2 \text{ (GeV/c)}^2$
- ▲ H1: $\langle Q^2 \rangle = 4.0 \text{ (GeV/c)}^2$
- ▼ H1: $\langle Q^2 \rangle = 8.0 \text{ (GeV/c)}^2$
- H1: $\langle Q^2 \rangle = 10. \text{ (GeV/c)}^2$

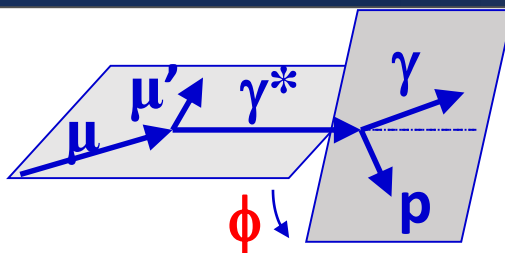
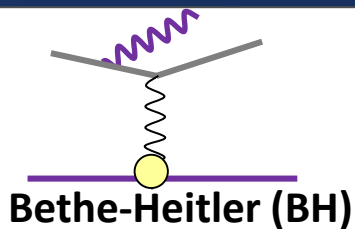
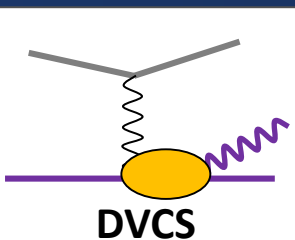


- The transverse-size evolution as a function of x_{Bj}
 - Expect at least 3 x_{Bj} bins from 2016-17 data

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

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

2016 – 2017 Data First Insight

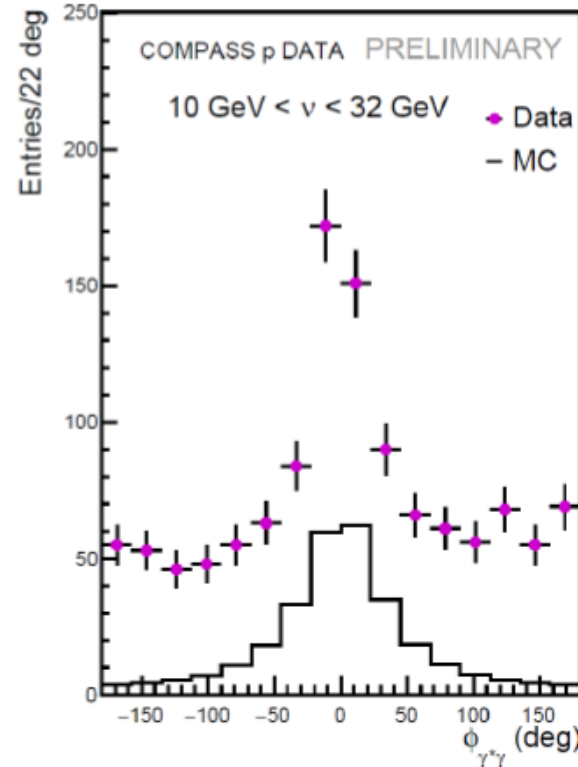
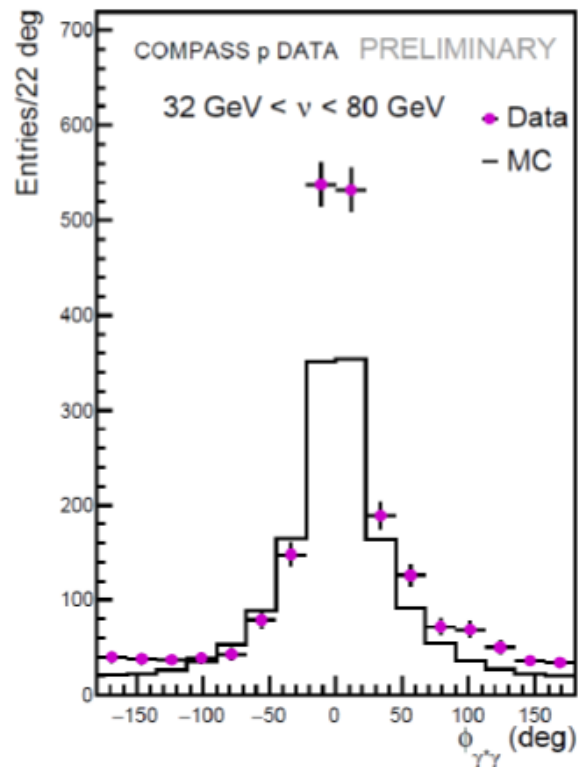
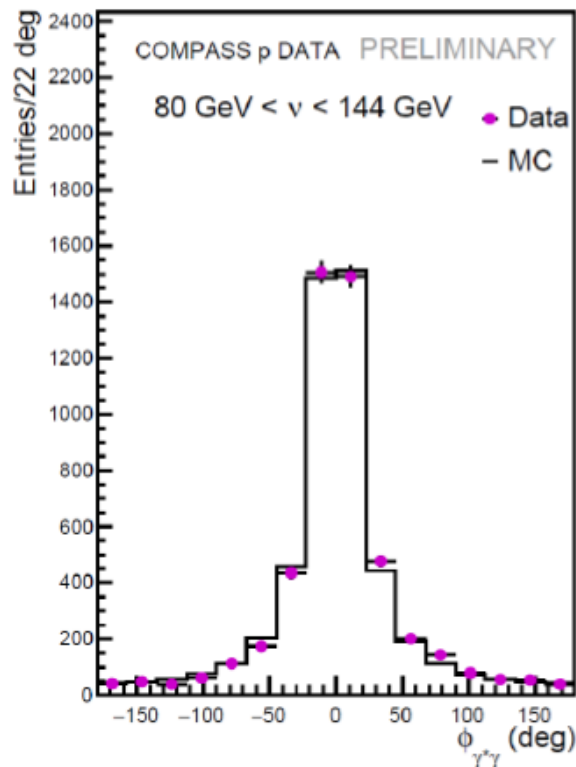


Only 13% of 2016-17 data

$0.005 < x_{Bj} < 0.01$

$0.01 < x_{Bj} < 0.03$

$x_{Bj} > 0.03$



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).

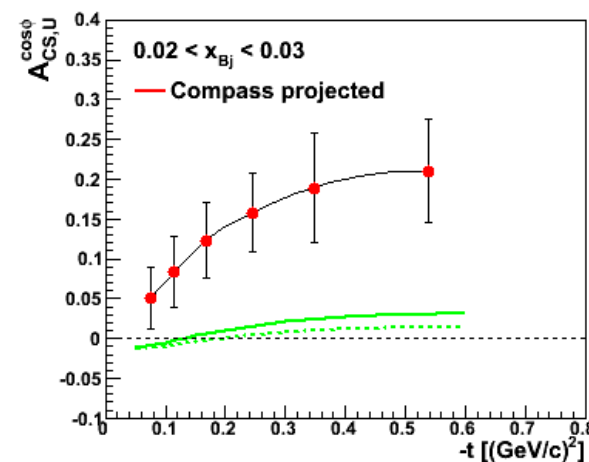
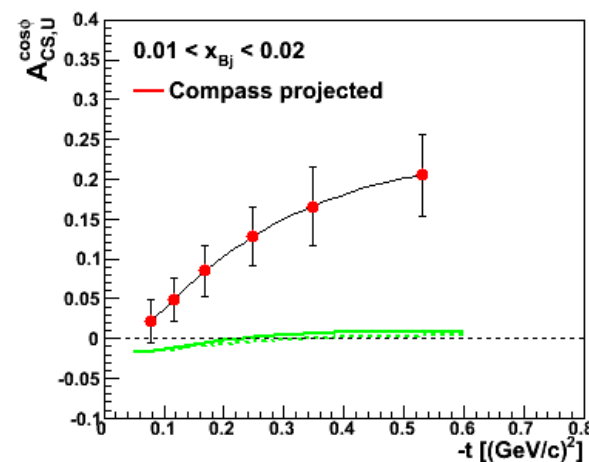
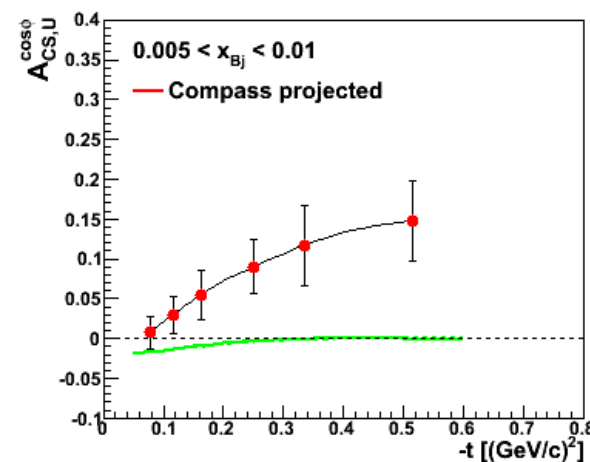
Beam Charge-spin Difference



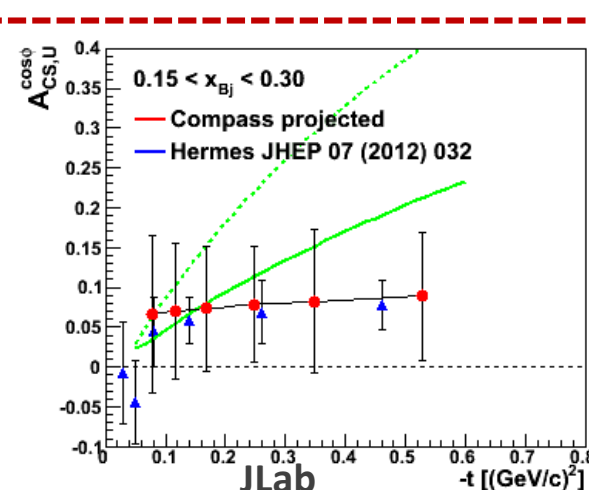
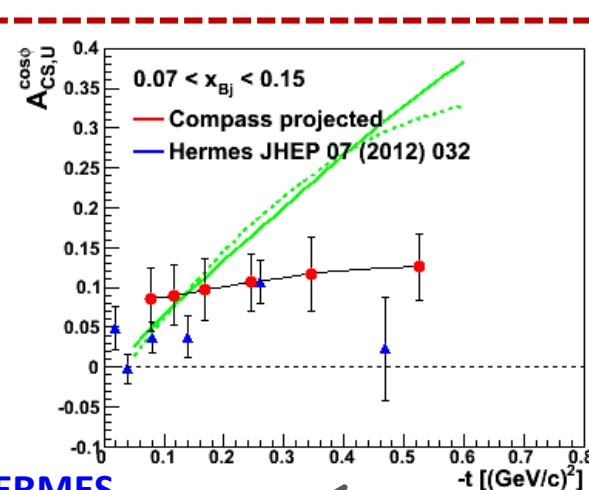
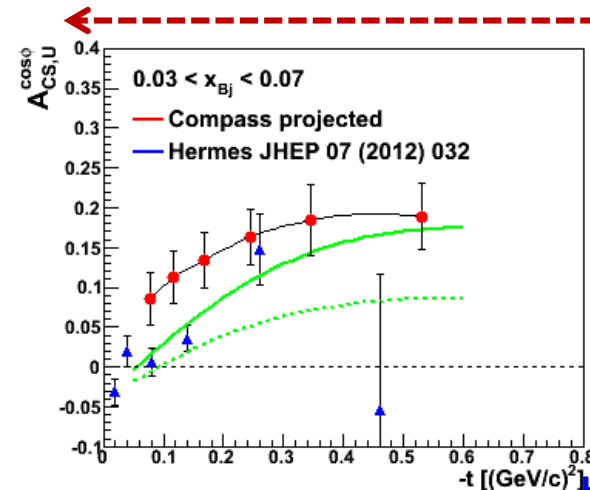
$$D_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow}) \rightarrow c_0^I + c_1^I \cos \phi$$

$$c_1^I = \text{Re } F_1 \mathcal{H}$$

— KM10
— VGG



➤ With $\text{Re } F_1 \mathcal{H}$ and $\text{Im } F_1 \mathcal{H}$
 → Extraction of **D-term**



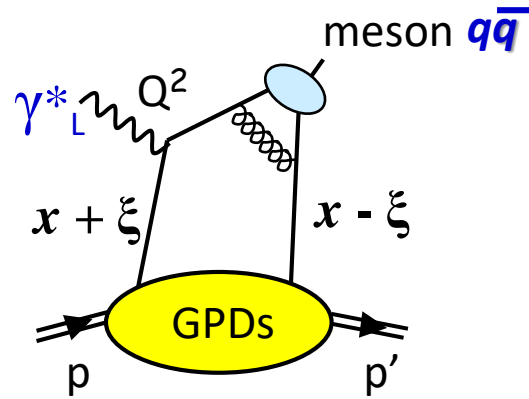
$\text{Re } \mathcal{H} > 0$ at H1
 < 0 at HERMES
 Value of x_{Bj} for the node?

← HERMES ← JLab
← COMPASS 2 years of data $E_\mu = 160 \text{ GeV}$ $1 < Q^2 < 8 \text{ GeV}^2$

GPDs in Hard Exclusive Meson Production



Quark contribution



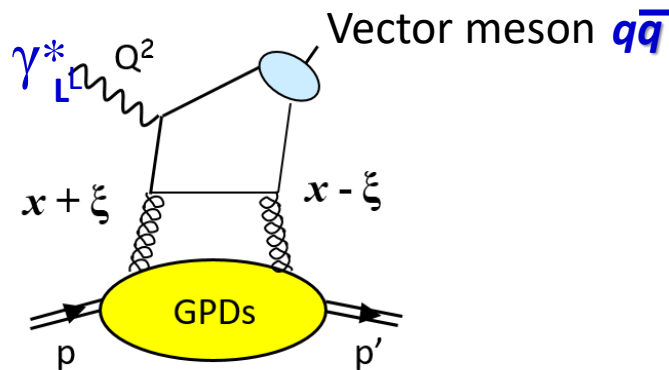
4 chiral-even GPDs: helicity of parton unchanged

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

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

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

Gluon contribution at the same order in α_s



- 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

Exclusive π^0 Production on Unpolarized Proton



$$\mu p \rightarrow \mu \pi^0 p \quad \frac{d^2\sigma}{dt d\phi_\pi} = \frac{1}{2\pi} \left[\left(\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right) + \epsilon \cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_\pi \frac{d\sigma_{LT}}{dt} \right]$$

↪ Chiral-odd GPDs ←

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

Leading twist expected be dominant
 But measured as \approx 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

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

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

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

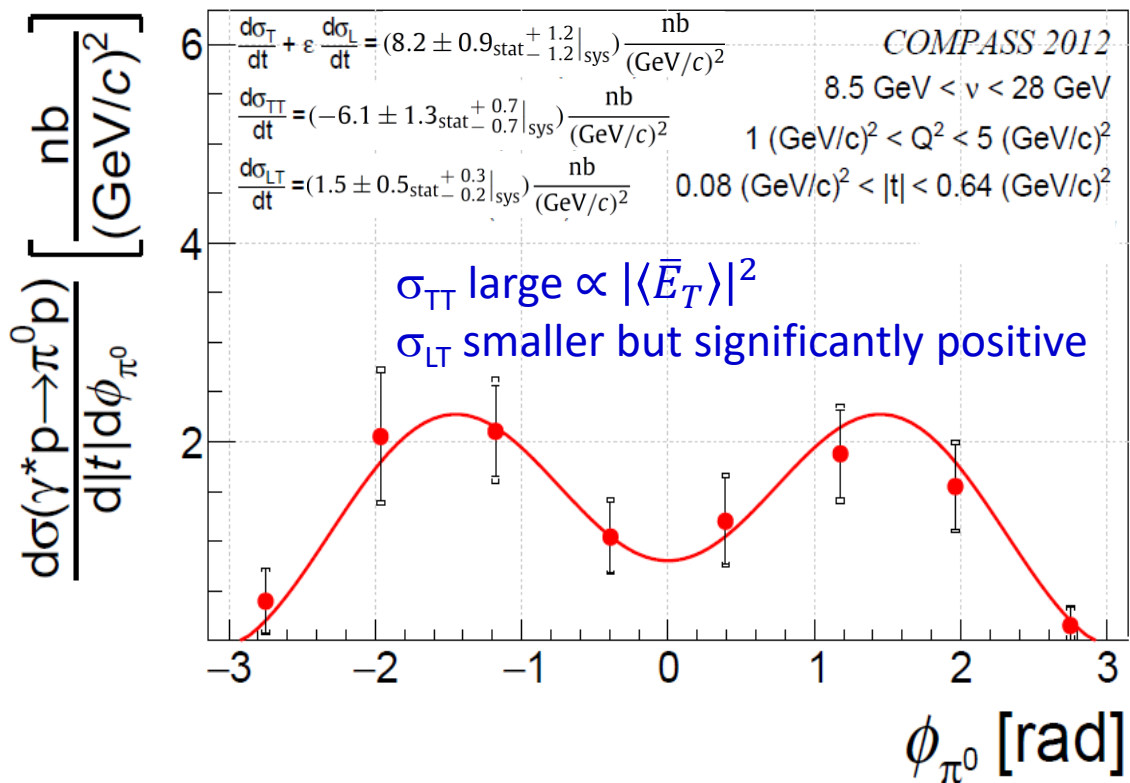
The presence of \bar{E}_T can be identified:

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

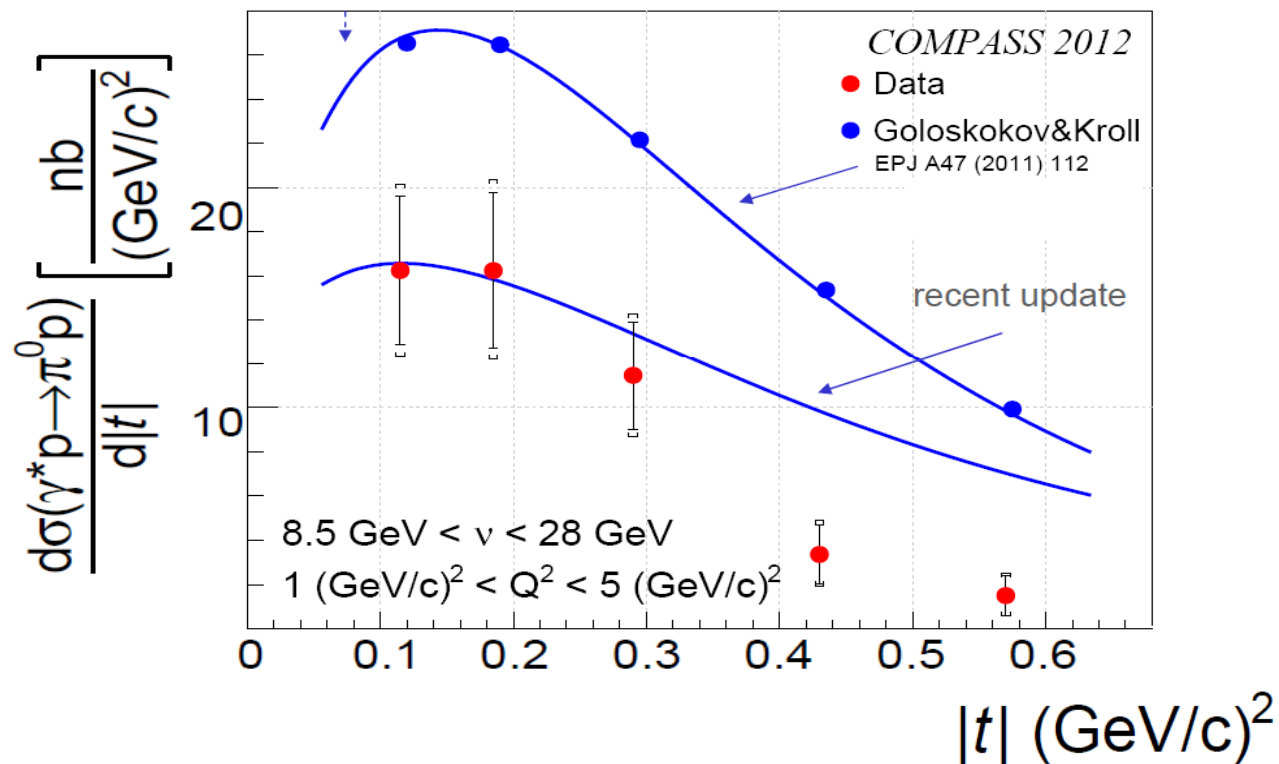
2012 Exclusive π^0 Prod. on Unpolarized Proton



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



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



2012 Exclusive ω Prod. on Unpolarized Proton



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

(S-Channel Helicity Conservation)

SCHC implies:

• $r_{1-1}^1 + \text{Im} r_{1-1}^2 = 0$

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

• $\text{Re} r_{10}^5 + \text{Im} r_{10}^6 = 0$

= $0.014 \pm 0.011 \pm 0.013$ OK

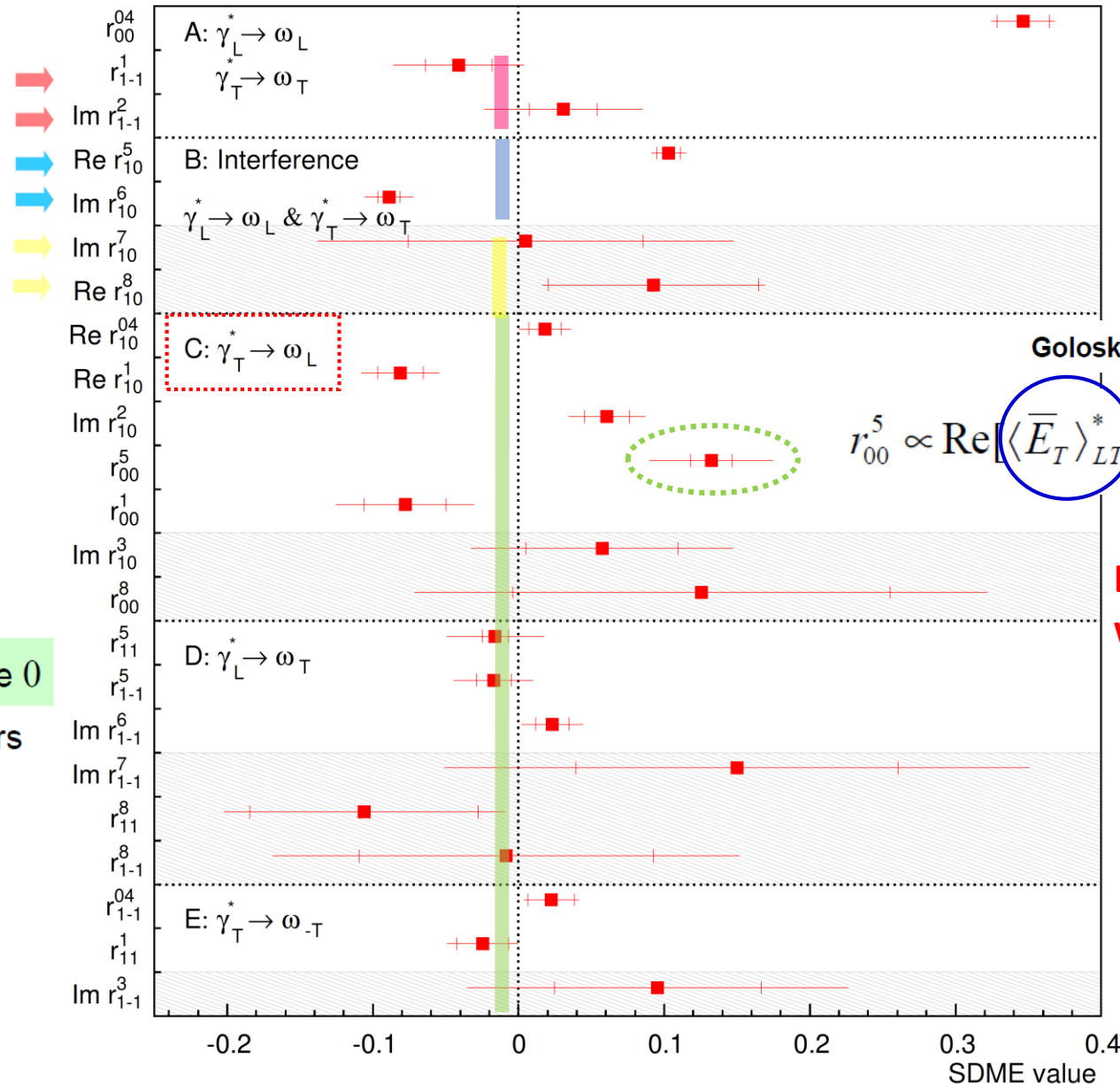
• $\text{Im} r_{10}^7 - \text{Re} r_{10}^8 = 0$

= $-0.088 \pm 0.110 \pm 0.196$ 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 $\gamma_T^* \rightarrow \omega_L$



■ SDMEs COMPASS
PRELIMINARY

Goloskokov and Kroll, EPJC 74 (2014) 2725

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

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

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

arXiv:2009.03271

➤ 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}
- $\text{Im}\mathcal{H}(\xi,t)$ and $\text{Re}\mathcal{H}(\xi,t)$ for D-term and pressure distribution

HEMP of π^0 , ρ , ω , ϕ , J/ψ

- Universality of GPDs - Transversity GPDs - Flavor Decomposition



On-going analysis on 2016-17 data.



Backup Slides

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

Expected to start at 2022

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

Proposed physics goals

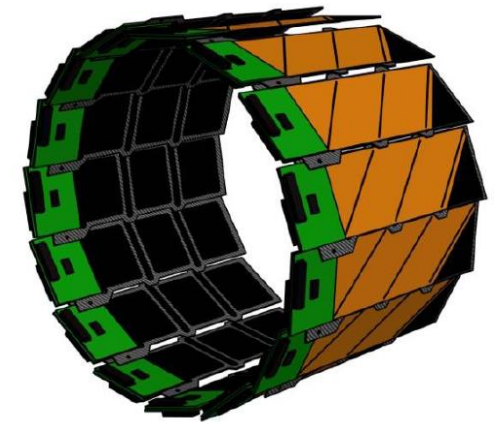
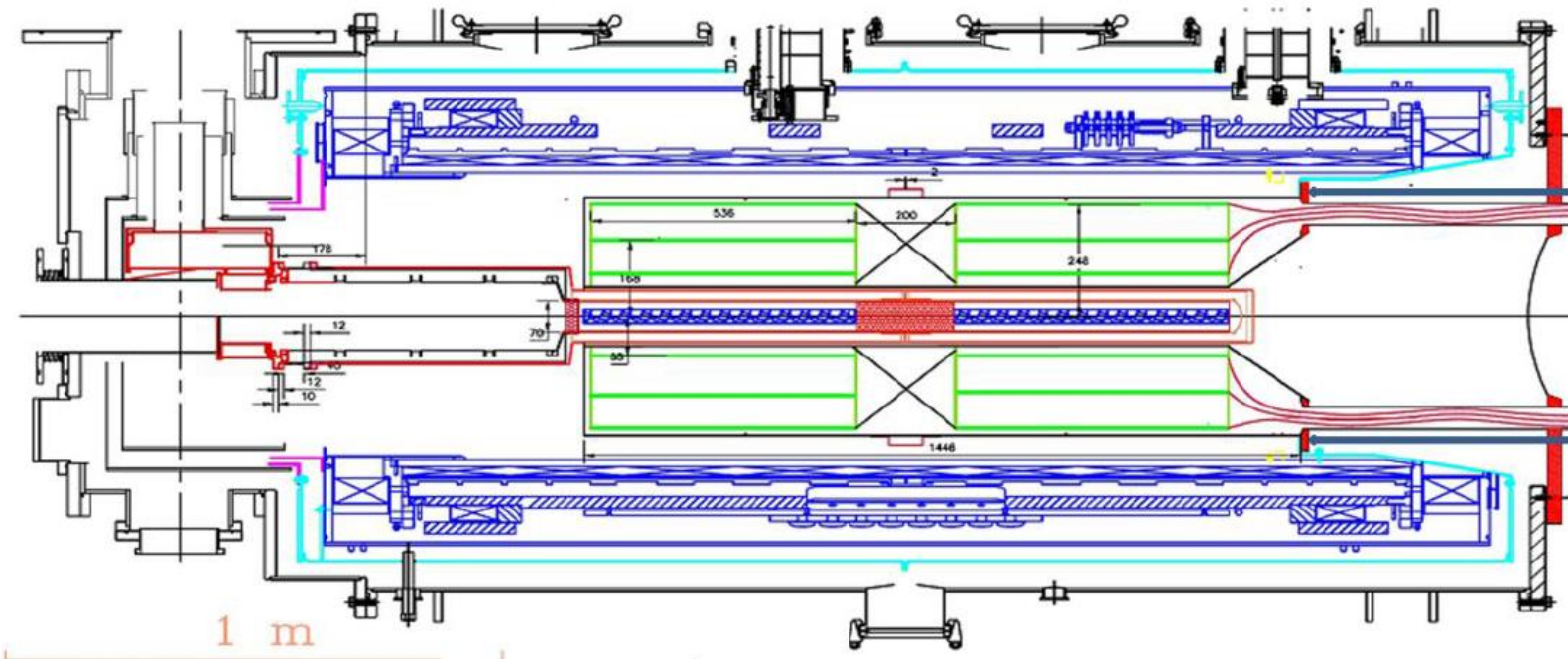
Proton Radius
Meson PDF – gluon PDF
Proton spin structure
3D imaging (TMDs and GPDs)
Hadron spectroscopy
Anti-matter cross section

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	$4 \cdot 10^6$	100	μ^\pm	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	μ^\pm	NH_3^\dagger	2022 2 years	recoil silicon, modified PT magnet
Input for Dark Matter Search	\bar{p} production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
\bar{p} -induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	\bar{p}	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	π^\pm	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	~ 100	10^8	25-50	K^\pm, \bar{p}	NH_3^\dagger , C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisability & 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 π^\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, π^\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 measurements
 $|t|_{\min} \sim 0.1 \text{ GeV}$

ϕ Dep. of BH+DVCS with Unpol Target



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

Σ	Σ
Σ	Σ
Δ	Δ
Σ	Δ
Δ	Σ
$\uparrow\downarrow$	$\uparrow\downarrow$
e^-	μ^\pm

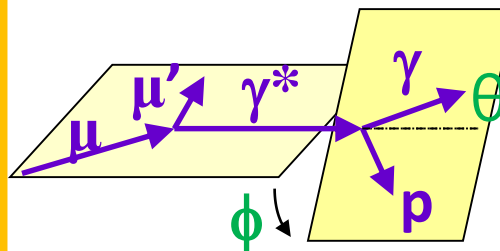
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi$$

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

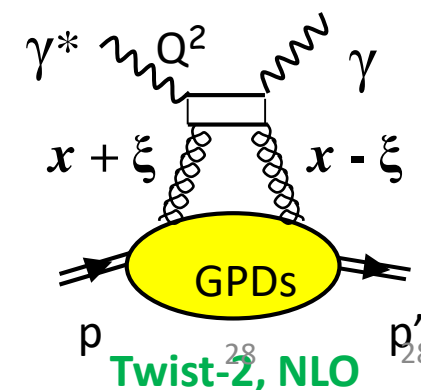
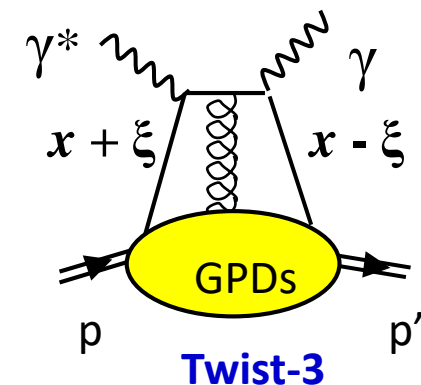
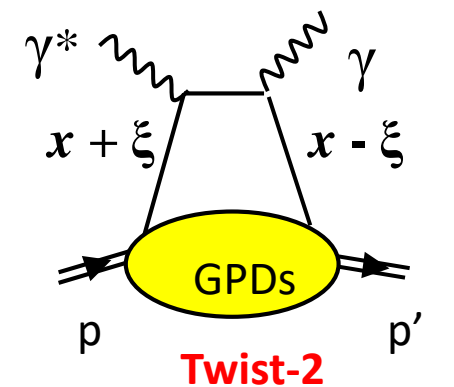
$$d\sigma_{pol}^{DVCS} \propto s_1^{DVCS} \sin \phi$$

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

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



Twist-2 >>
 ■ Twist-3,
 ■ Twist-2
 double helicity flip
 for gluons (NLO)



$$s_1^I = \text{Im } \mathcal{F} \quad c_1^I = \text{Re } \mathcal{F} \quad \mathcal{F} = F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - t/4m^2 F_2 \mathcal{E} \xrightarrow{\text{at small } x_B} F_1 \mathcal{H}$$

for proton

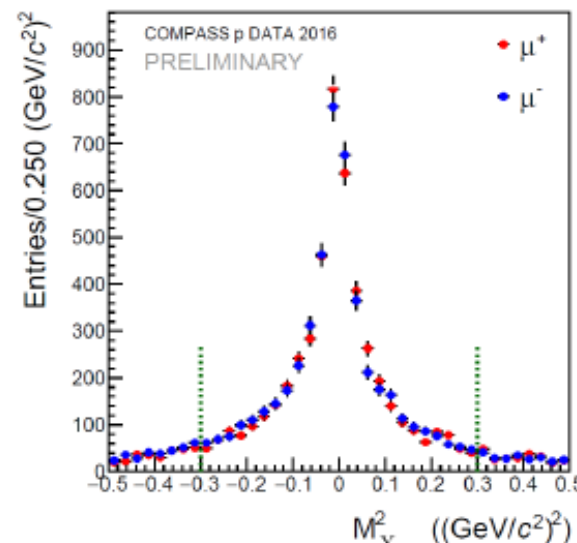
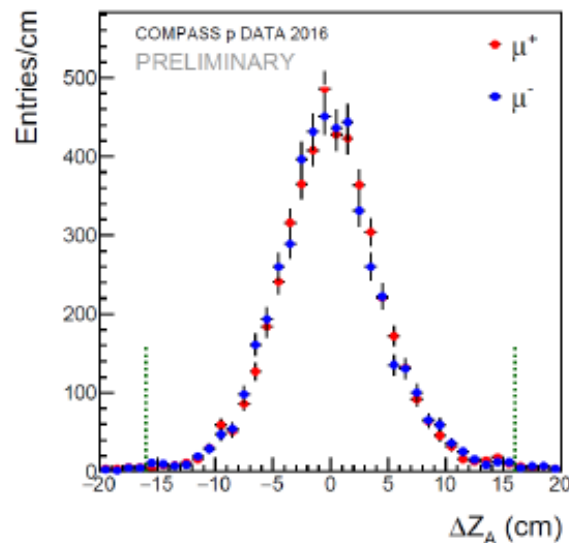
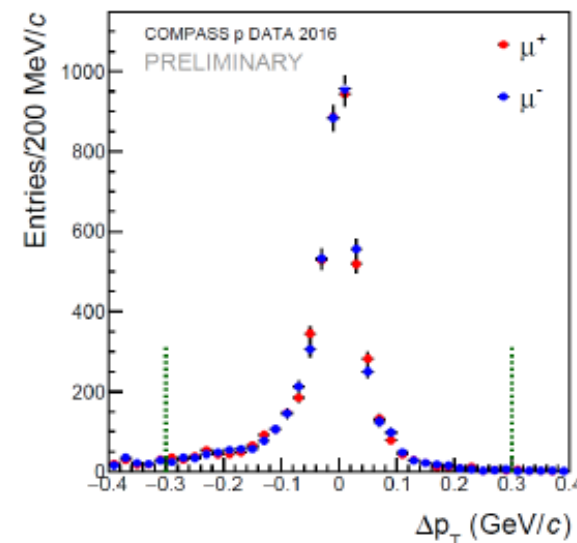
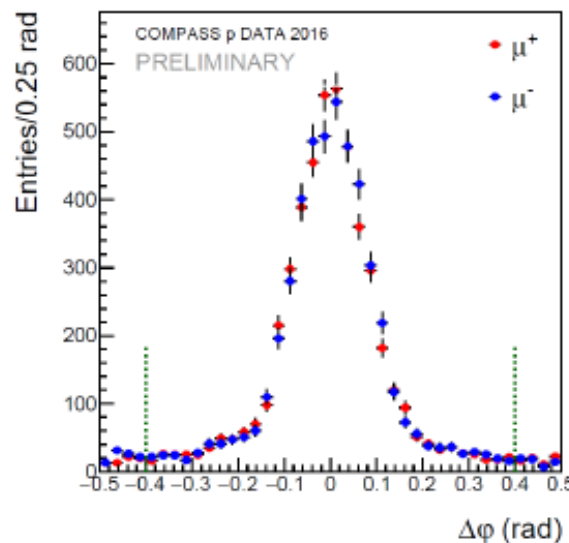
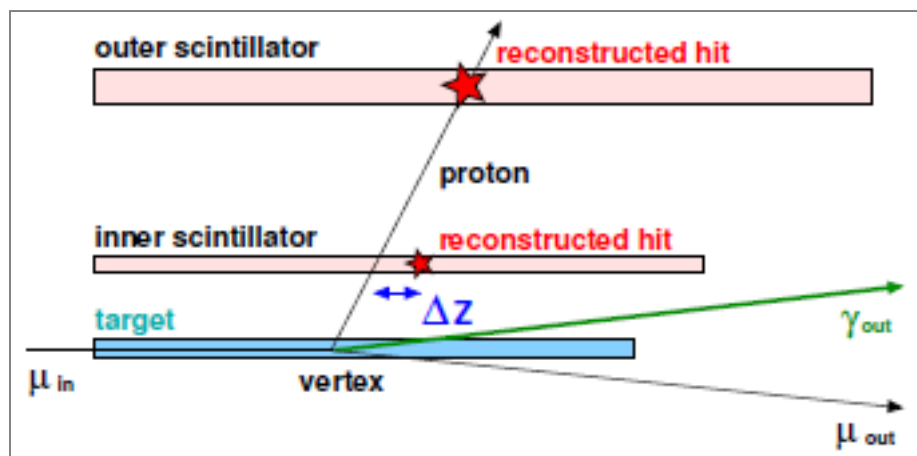
$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2} \mathcal{E}\mathcal{E}^* \xrightarrow{\text{at small } x_B} 4 (\text{Im } \mathcal{H})^2$$

2016 – 2017 Data First Insight



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

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



Exclusive ω Production on Unpolarized Proton



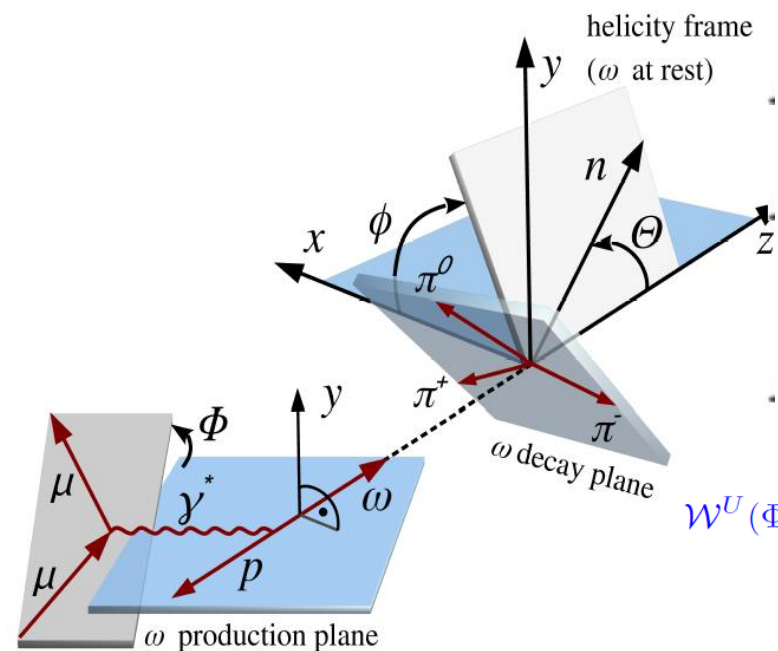
experimental angular distributions

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

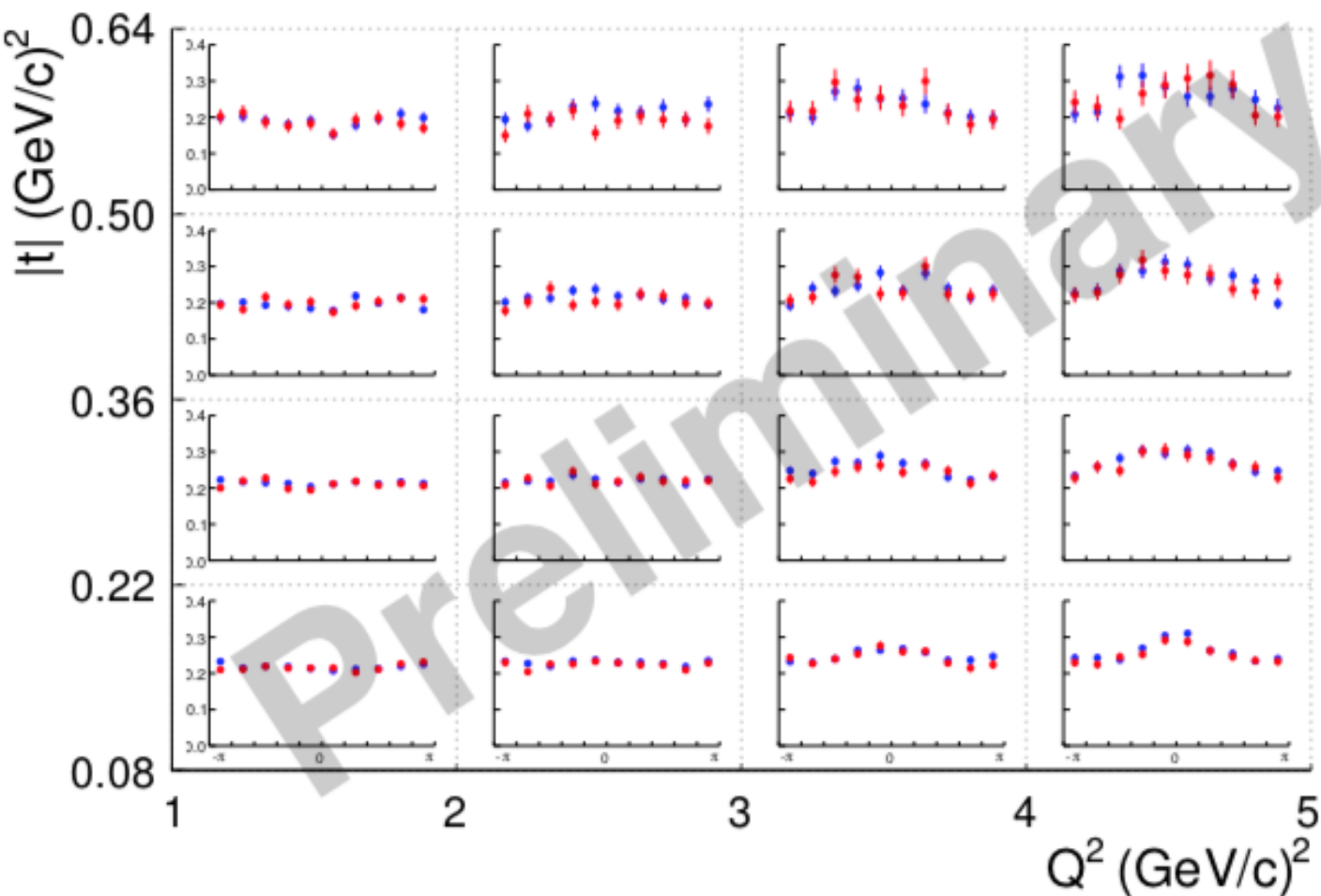
Self analysis... with phi and cosTheta

15 'unpolarized' and 8 'polarized' SDMEs

$$\begin{aligned} \mathcal{W}^U(\Phi, \phi, \cos \Theta) = & \frac{3}{8\pi^2} \left[\frac{1}{2}(1 - r_{00}^{04}) + \frac{1}{2}(3r_{00}^{04} - 1) \cos^2 \Theta - \sqrt{2}\text{Re}\{r_{10}^{04}\} \sin 2\Theta \cos \phi - r_{1-1}^{04} \sin^2 \Theta \cos 2\phi \right. \\ & - \epsilon \cos 2\Phi (r_{11}^1 \sin^2 \Theta + r_{00}^1 \cos^2 \Theta - \sqrt{2}\text{Re}\{r_{10}^1\} \sin 2\Theta \cos \phi - r_{1-1}^1 \sin^2 \Theta \cos 2\phi) \\ & - \epsilon \sin 2\Phi (\sqrt{2}\text{Im}\{r_{10}^2\} \sin 2\Theta \sin \phi + \text{Im}\{r_{1-1}^2\} \sin^2 \Theta \sin 2\phi) \\ & + \sqrt{2\epsilon(1+\epsilon)} \cos \Phi (r_{11}^5 \sin^2 \Theta + r_{00}^5 \cos^2 \Theta - \sqrt{2}\text{Re}\{r_{10}^5\} \sin 2\Theta \cos \phi - r_{1-1}^5 \sin^2 \Theta \cos 2\phi) \\ & \left. + \sqrt{2\epsilon(1+\epsilon)} \sin \Phi (\sqrt{2}\text{Im}\{r_{10}^6\} \sin 2\Theta \sin \phi + \text{Im}\{r_{1-1}^6\} \sin^2 \Theta \sin 2\phi) \right], \\ \mathcal{W}^L(\Phi, \phi, \cos \Theta) = & \frac{3}{8\pi^2} \left[\sqrt{1-\epsilon^2} (\sqrt{2}\text{Im}\{r_{10}^3\} \sin 2\Theta \sin \phi + \text{Im}\{r_{1-1}^3\} \sin^2 \Theta \sin 2\phi) \right. \\ & + \sqrt{2\epsilon(1-\epsilon)} \cos \Phi (\sqrt{2}\text{Im}\{r_{10}^7\} \sin 2\Theta \sin \phi + \text{Im}\{r_{1-1}^7\} \sin^2 \Theta \sin 2\phi) \\ & \left. + \sqrt{2\epsilon(1-\epsilon)} \sin \Phi (r_{11}^8 \sin^2 \Theta + r_{00}^8 \cos^2 \Theta - \sqrt{2}\text{Re}\{r_{10}^8\} \sin 2\Theta \cos \phi - r_{1-1}^8 \sin^2 \Theta \cos 2\phi) \right] \end{aligned}$$



COMPASS Acceptance of ϕ for DVCS



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

Acceptance

- μ^- beam
- μ^+ beam

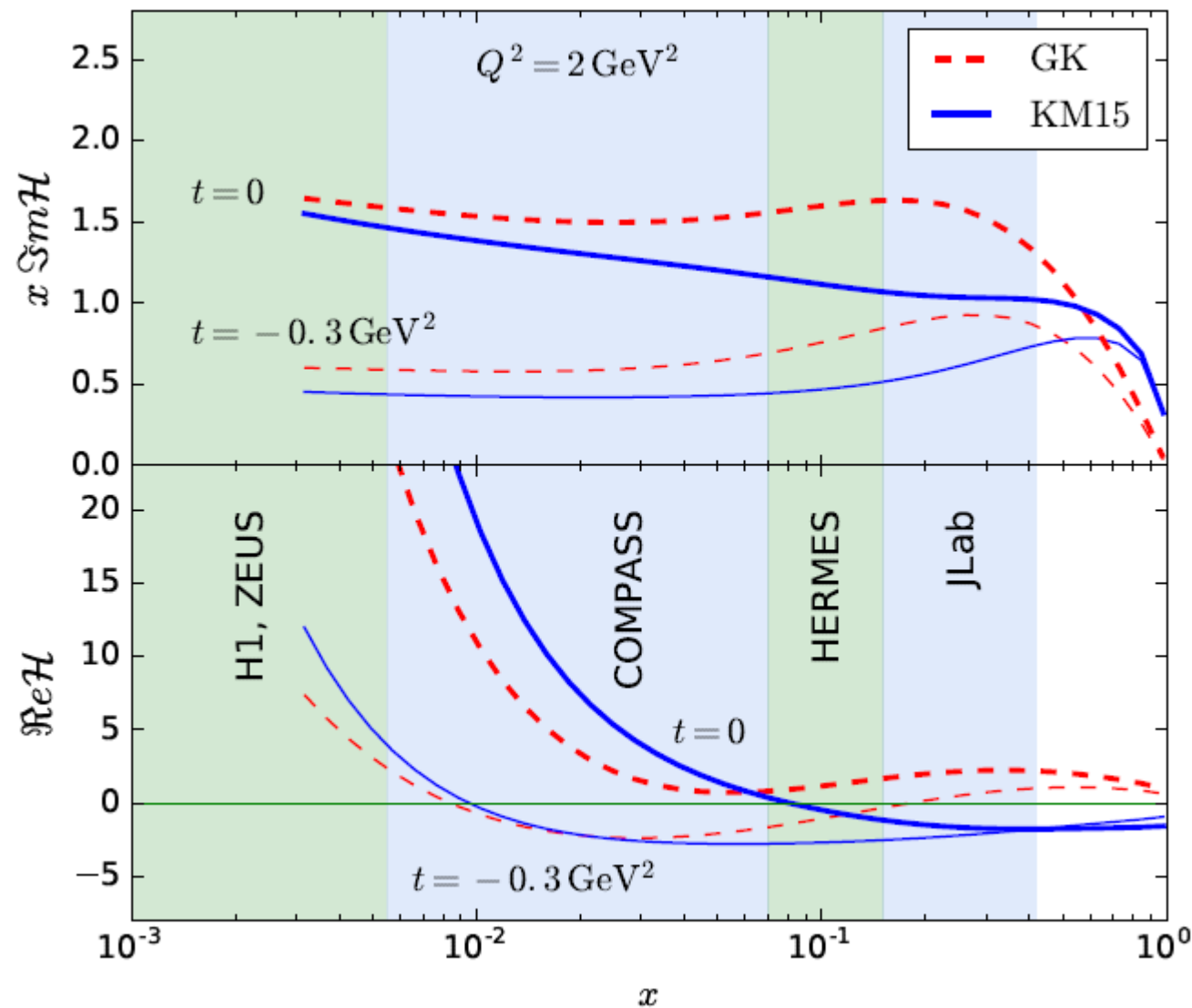
$$\left[-\pi, -\frac{4}{5}\pi, \dots, \frac{4}{5}\pi, \pi\right]$$

$\phi_{\gamma^* \gamma}$ (rad)

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

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

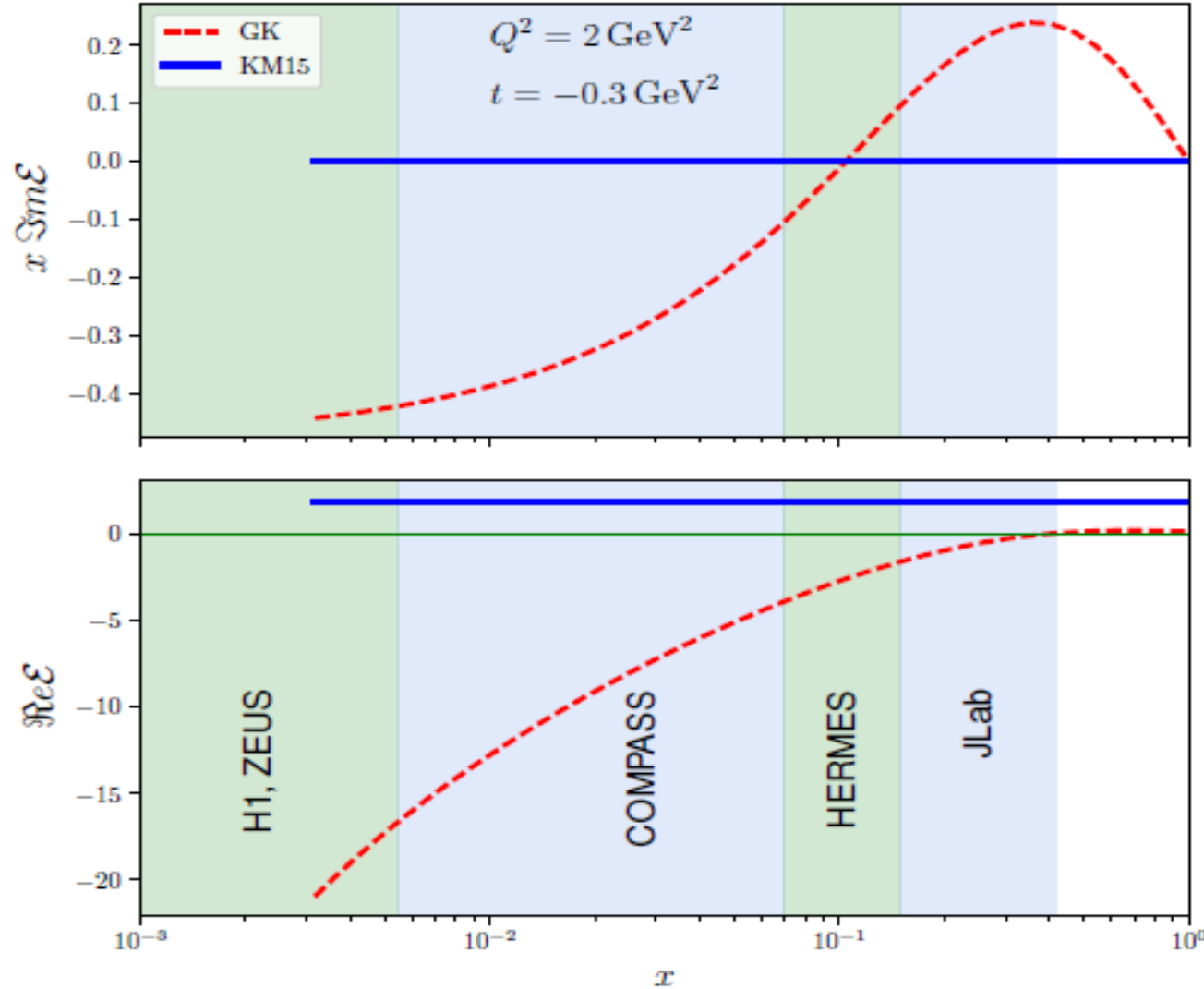
KM15 K Kumericki and D Mueller [arXiv:1512.09014v1](https://arxiv.org/abs/1512.09014v1)

GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011) ³²

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](https://arxiv.org/abs/1512.09014v1)

GK S.V. Goloskokov, P. Kroll, EPJC53 (2008), EPJA47 (2011) 33