Recent Results of GPD Measurements at COMPASS and JLab Hall A

NCU workshop on EIC physics and detectors
November 09, 2022

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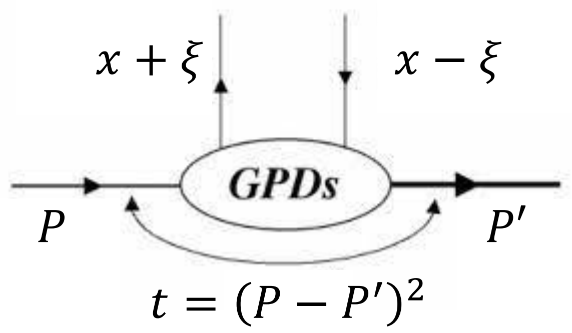
Generalized Parton Distributions (GPDs)



- At fixed Q^2 , the GPDs depend on the following variables:

  x: average longitudinal momentum fraction

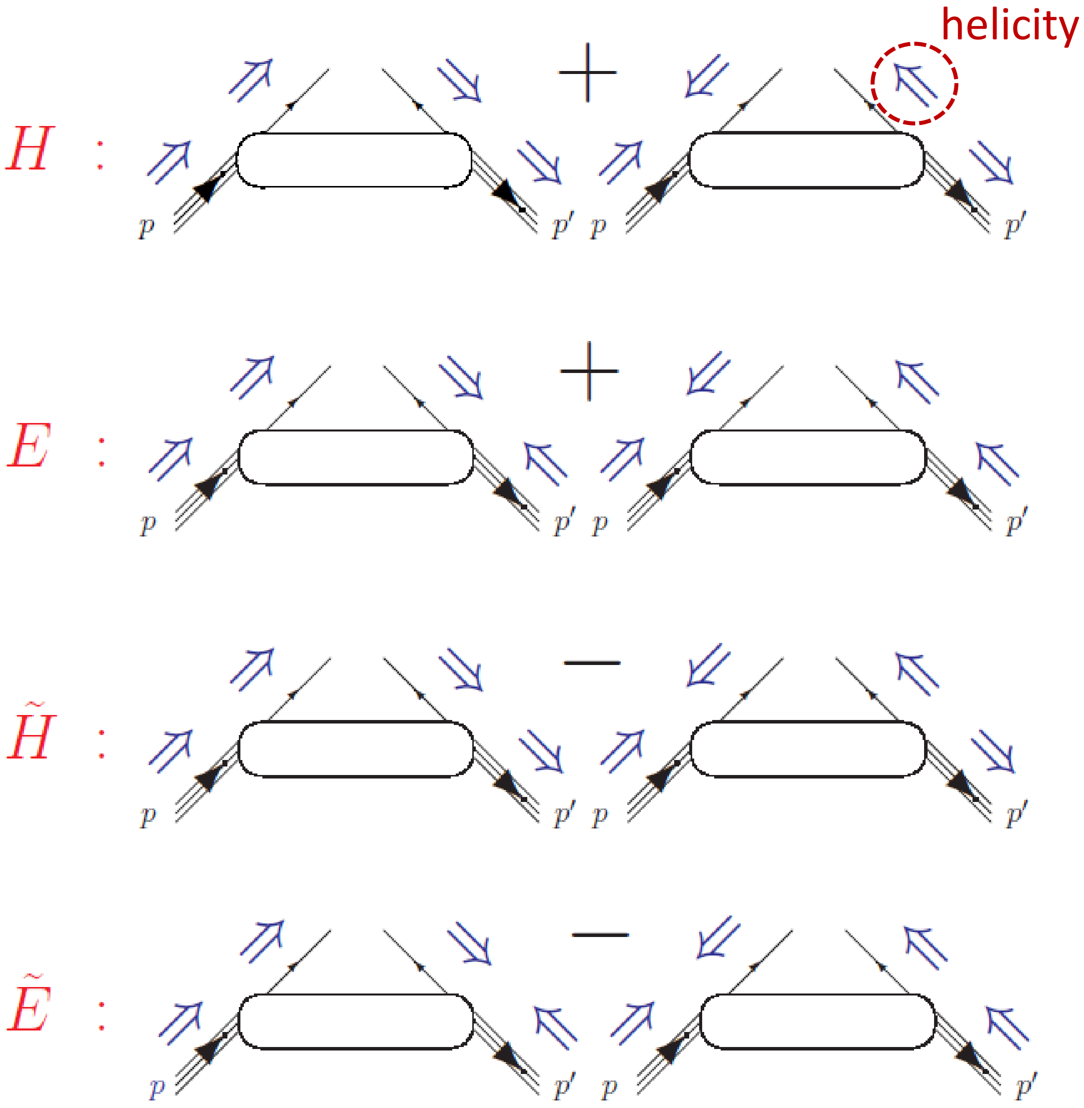
  ξ: longitudinal momentum difference

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

- A total of 8 GPDs for a specific parton

4 Chiral-even (parton helicity unchanged): $H, E, \tilde{H}, \tilde{E}$

4 Chiral-odd (parton helicity changed): $H_T, E_T, \tilde{H}_T, \tilde{E}_T$



Generalized Parton Distributions (GPDs)

Dirac FF

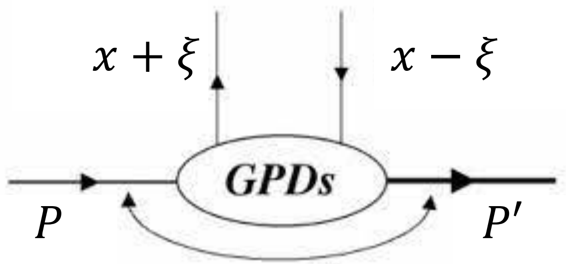
$$\int H_f(x,\xi,t)dx = F_1^f(t)$$

$$\int E_f(x,\xi,t)dx = F_2^f(t)$$

Pauli FF

First Moment

Form Factors



$t = (P-P')^2$

$\xi = t = 0$

PDFs

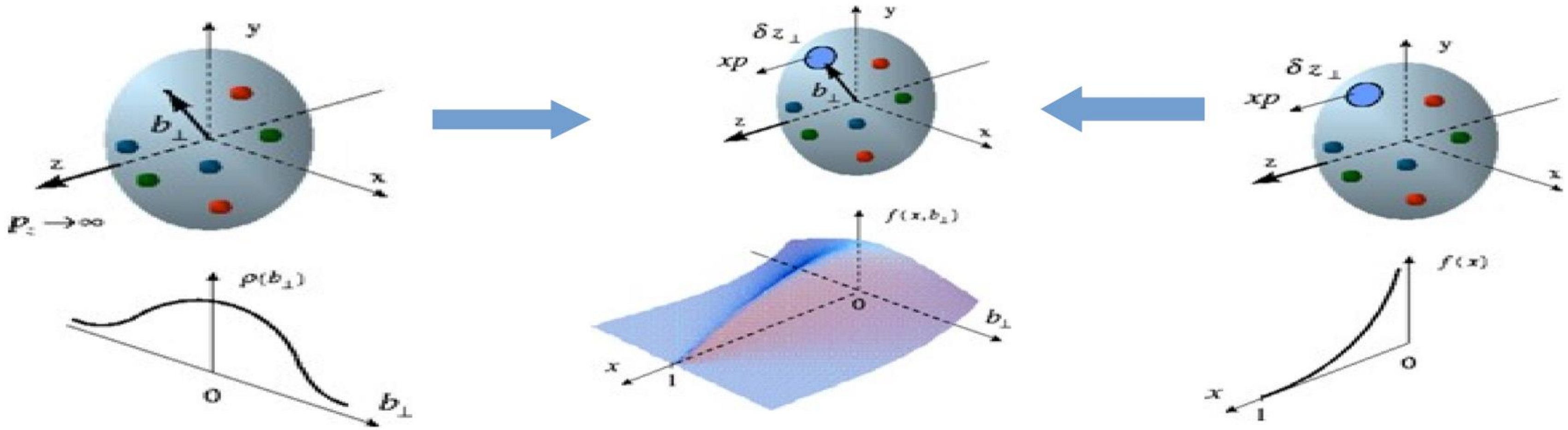
Unpolarized

$$H_f(x,0,0) = q_f(x)$$

$$\widetilde{H}_f(x,0,0) = \Delta q_f(x)$$

Polarized

➢ **GPDs embody both PDFs and FFs**



- **Form Factors (FFs)**
  - ✔ Spatial distribution
  - ✗ Momentum distribution
- **Generalized Parton Distributions (GPDs)**
  - ✔ Spatial distribution
  - ✔ Longitudinal momentum distribution
- **Parton Distribution Functions (PDFs)**
  - ✔ Longitudinal momentum distribution
  - ✗ Spatial distribution

Generalized Parton Distributions (GPDs)

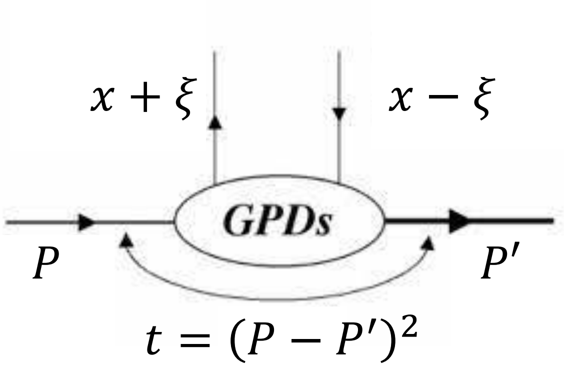
Dirac FF

$$\int H_f(x,\xi,t)dx = F_1^f(t)$$

$$\int E_f(x,\xi,t)dx = F_2^f(t)$$

Pauli FF

First Moment ← Form Factors



$\xi = t = 0$ → PDFs

Unpolarized

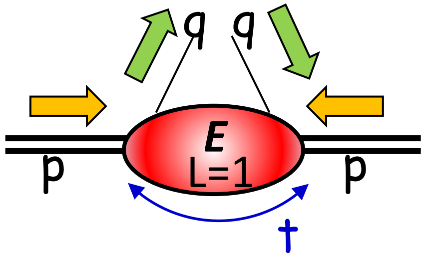
$$H_f(x,0,0) = q_f(x)$$

$$\tilde{H}_f(x,0,0) = \Delta q_f(x)$$

Polarized

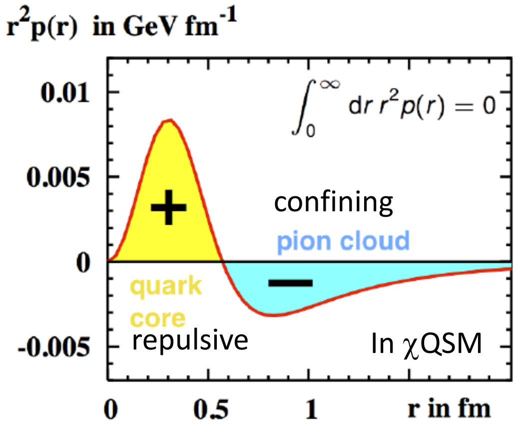
Provides information on the interesting properties of the nucleon.

- **Mapping the transverse plane distribution of parton**
- **Pressure distribution inside nucleon**
- **Angular momentum of parton**



$$J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

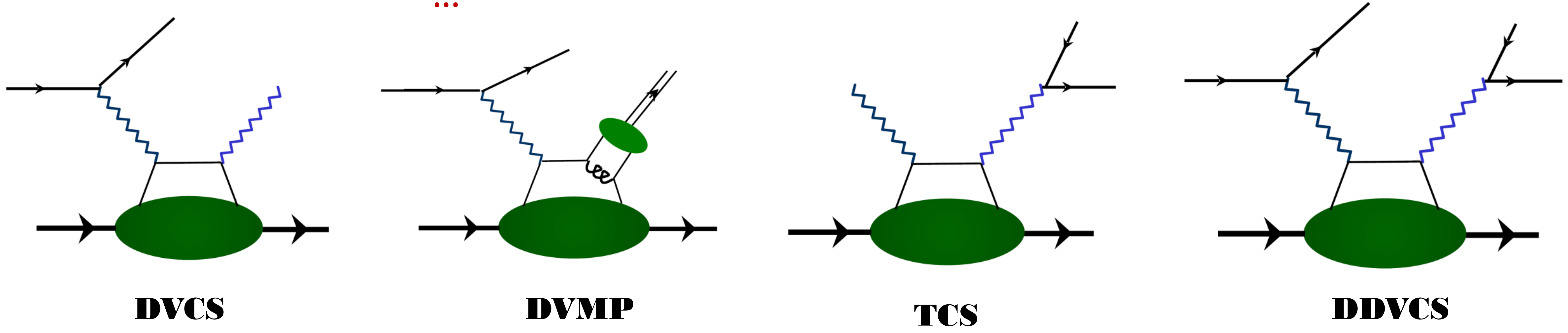
Ji's Sum Rule



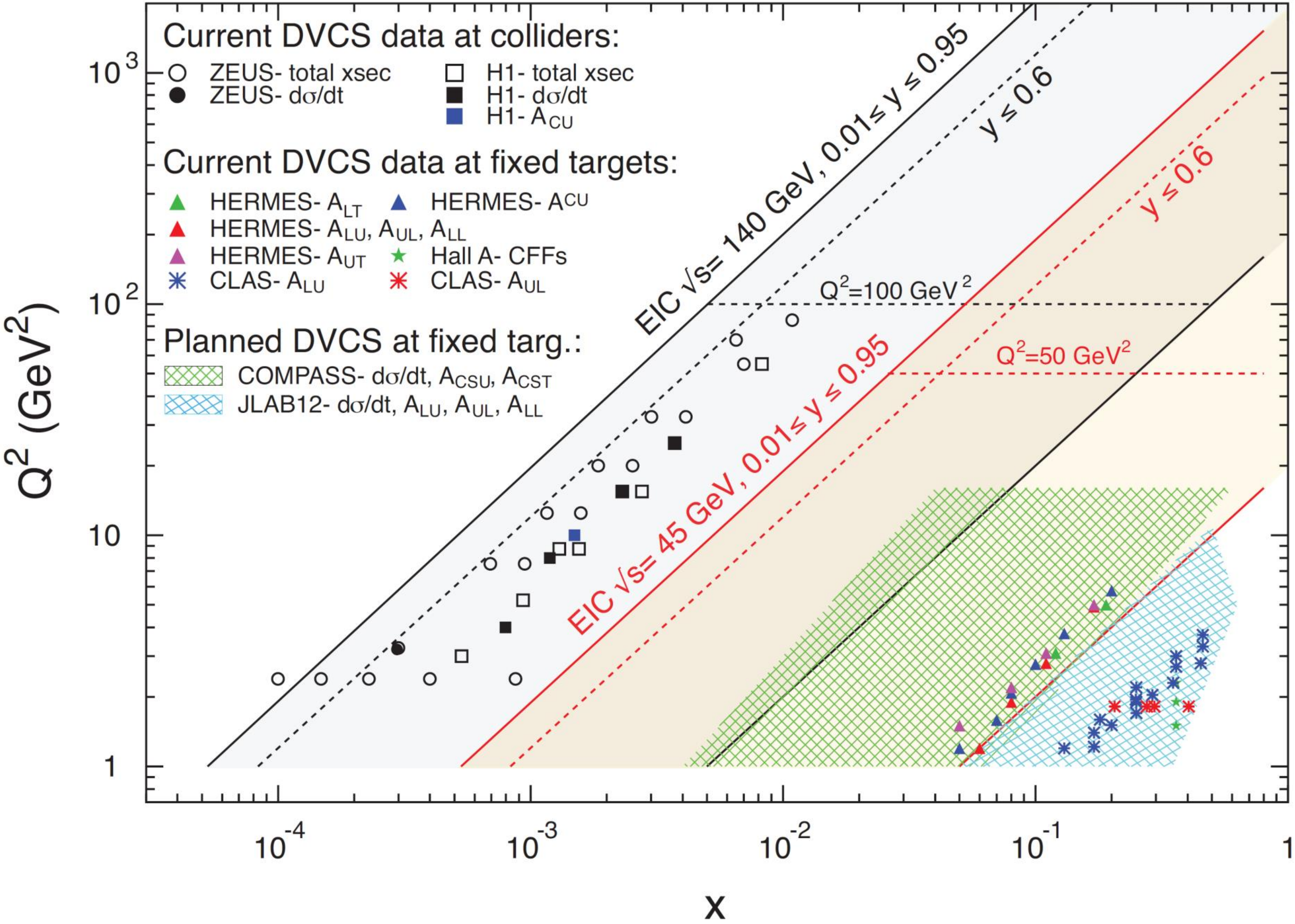
M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

Exclusive Process

- Use exclusive processes, where all final state particles are “identifieded”, to access the muliti-variable dependence of GPDs, and constrain the GPD parameterization with measurements in various phase space.
- Processes:
  - Deeply Virtual Compton Scattering (DVCS)
  - Deeply Virtual Meson Production (DVMP)
  - Time-like Compton Scattering (TCS)
  - Double DVCS (DDVCS)
  - …

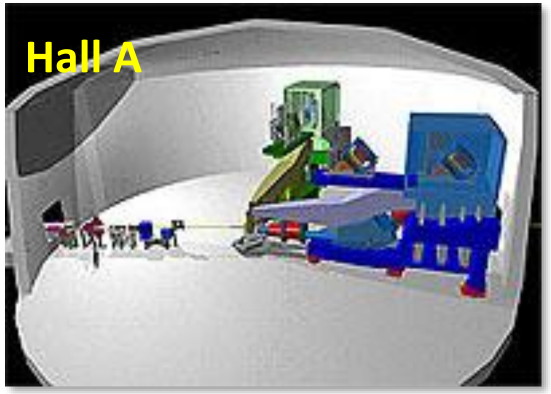


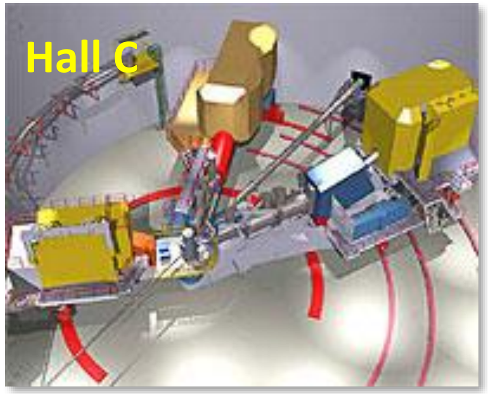
Landscape – Global Programs of DVCS



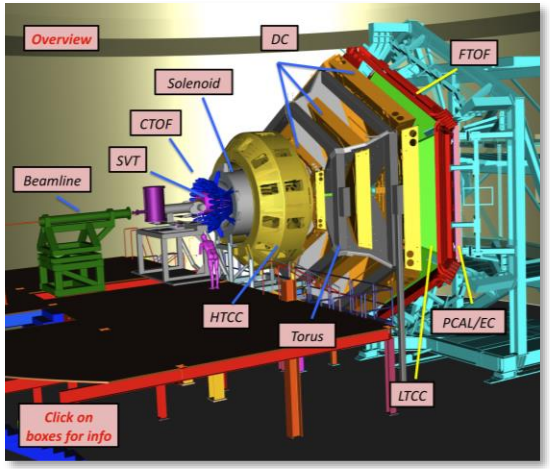
JLab & COMPASS

- **Jlab: Hall A, C, CLAS** High Luminosity Polar. **6** & **12 GeV e-**
Long., (Trans.) polarised p & nuclear target
Missing mass technique (A,C) and complete detection (CLAS)



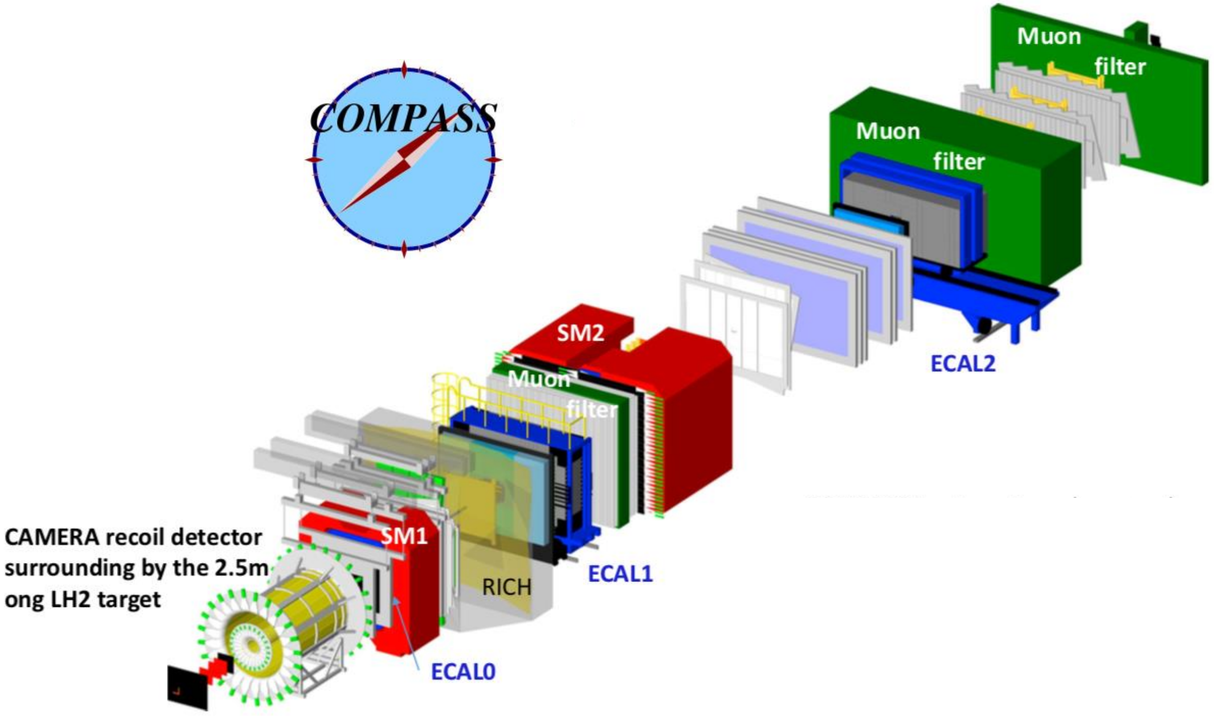


- High luminosity, limited kinematic coverage
  → Test the validity of theoretical formalism

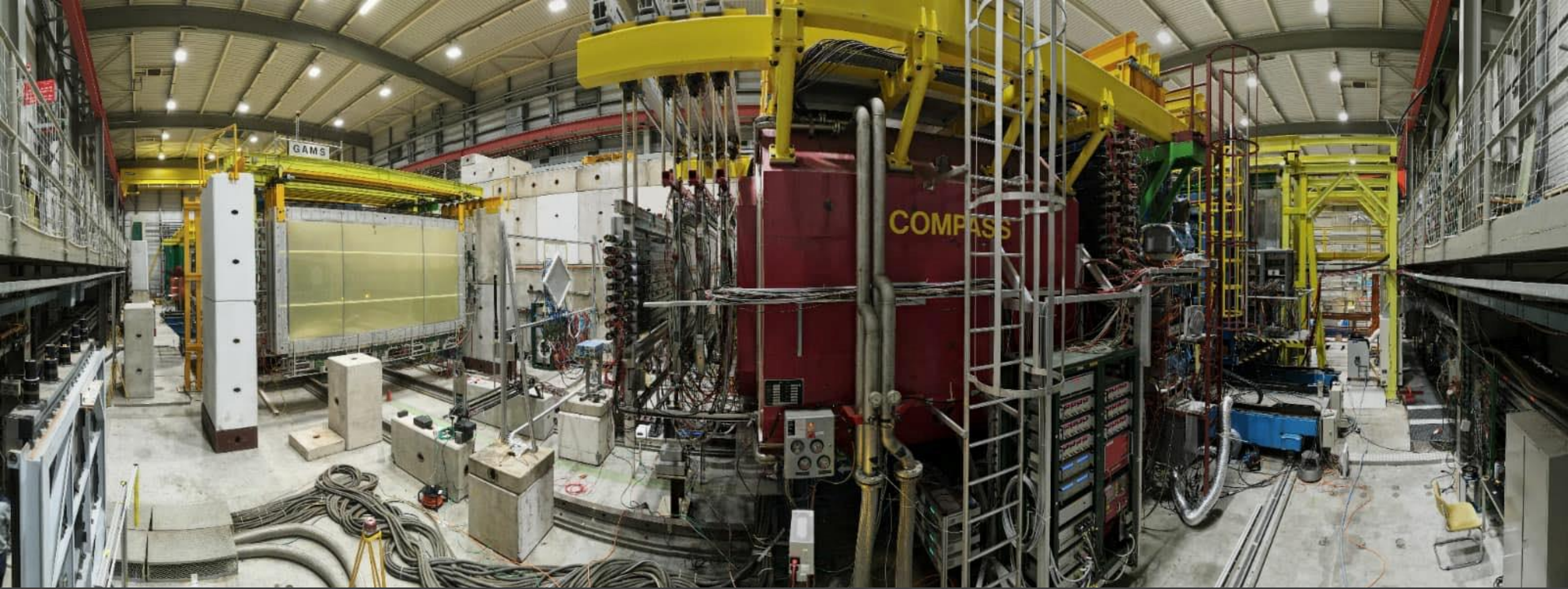


Hall B – CLAS 12

- Lower luminosity, wide kinematic coverage
  → Map the GPDs



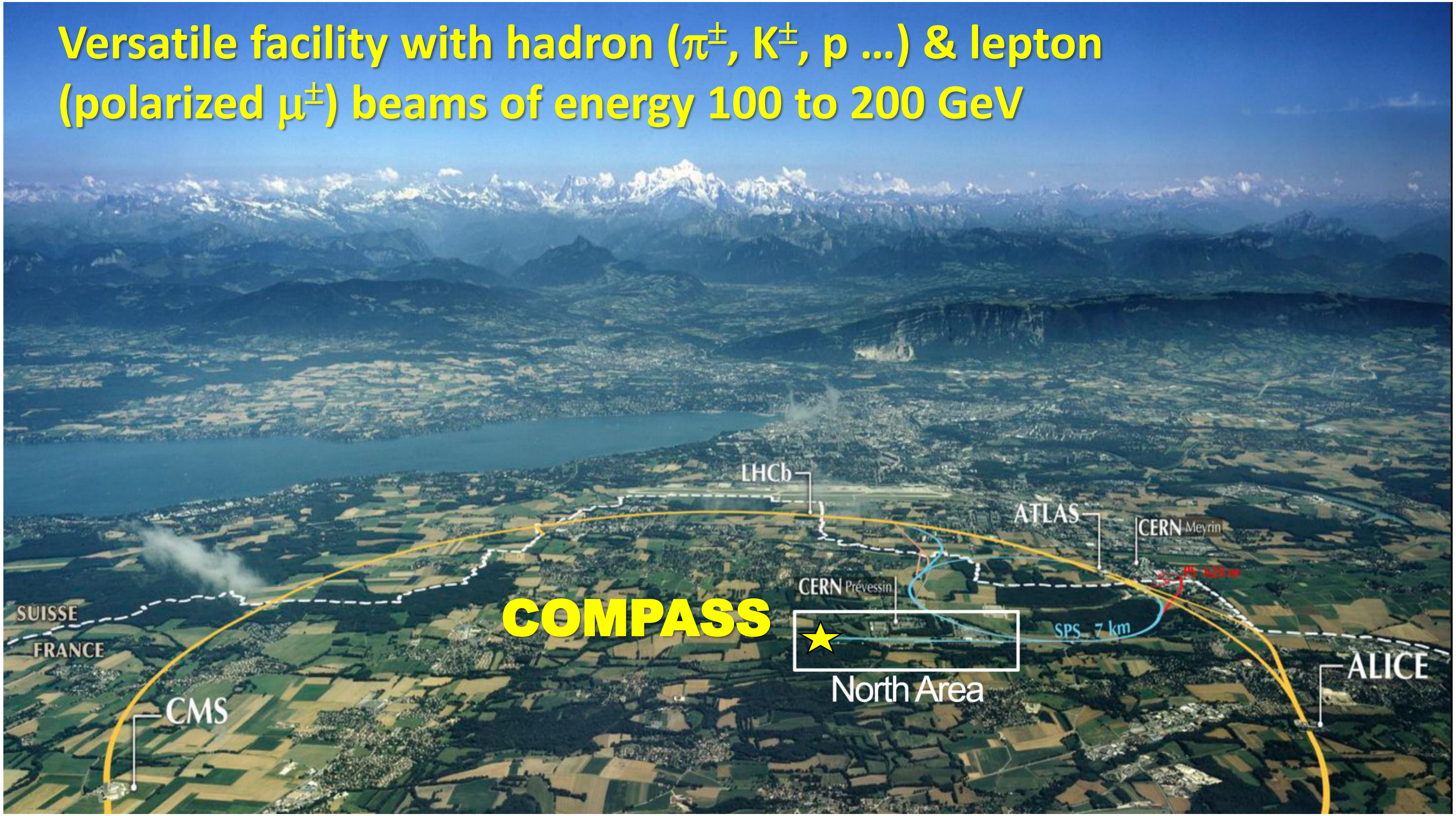
- **COMPASS @ CERN:** Polarised **160 GeV μ+/μ-**
p target, (Trans.) polarised ***target with recoil p detection***



Deeply Virtual Compton Scattering @ COMPASS

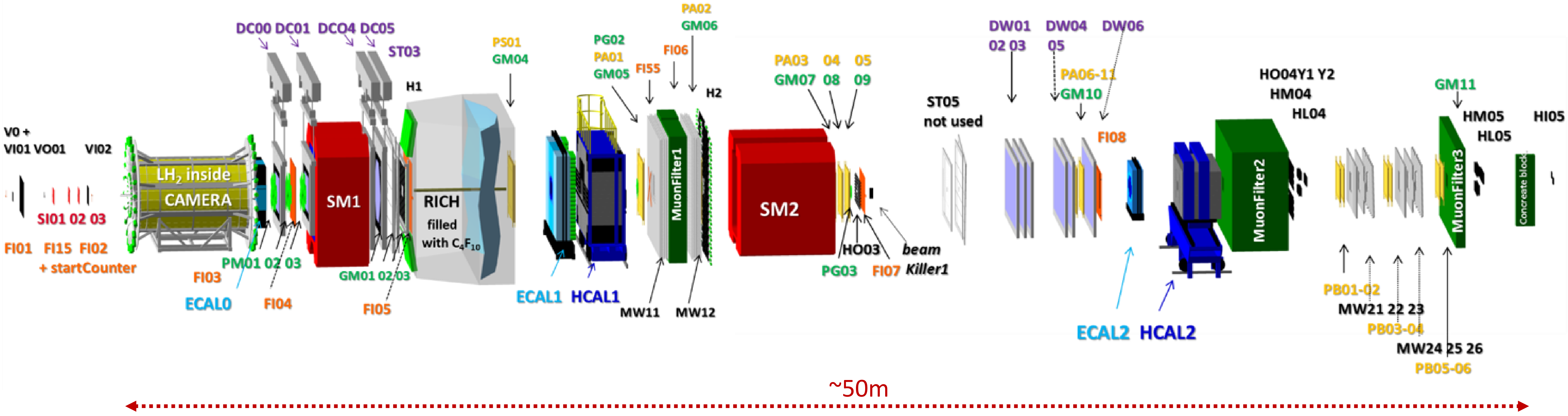
COMPASS Experiment

Versatile facility with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams of energy 100 to 200 GeV



COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

COMPASS Setup for Hard Exclusive Measurements



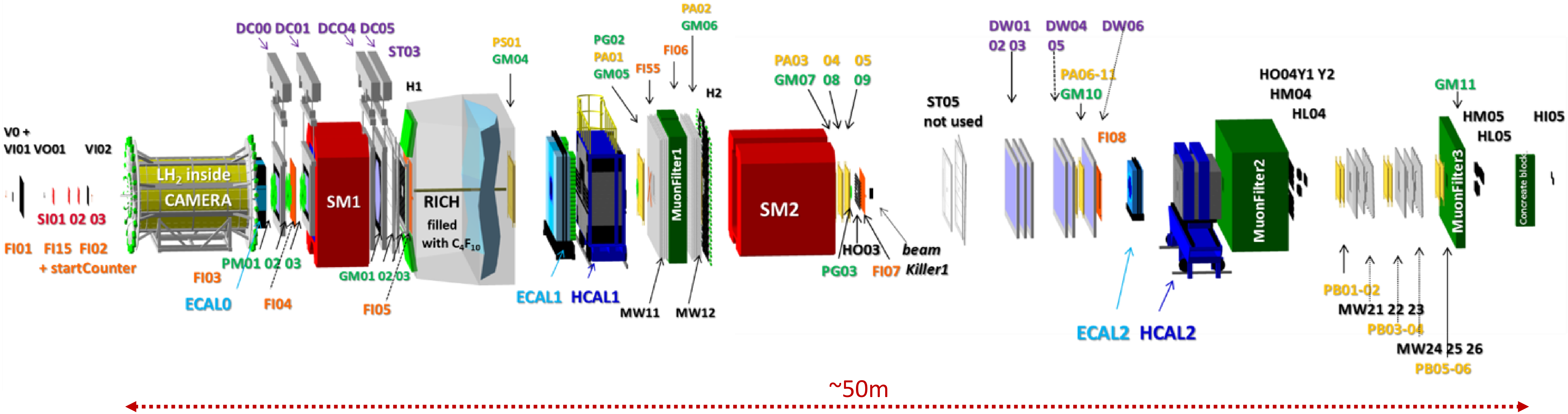
Muon Beams

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

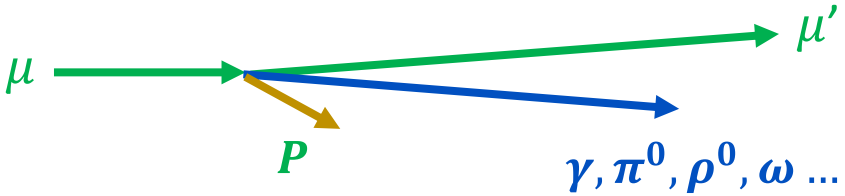
Two-stage, large angle, and wide momentum range spectrometer. PID including hadron absorbers, RICH, HCALs, ECALs, and muon filters.

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

COMPASS Setup for Hard Exclusive Measurements



Exclusive Muoproduction



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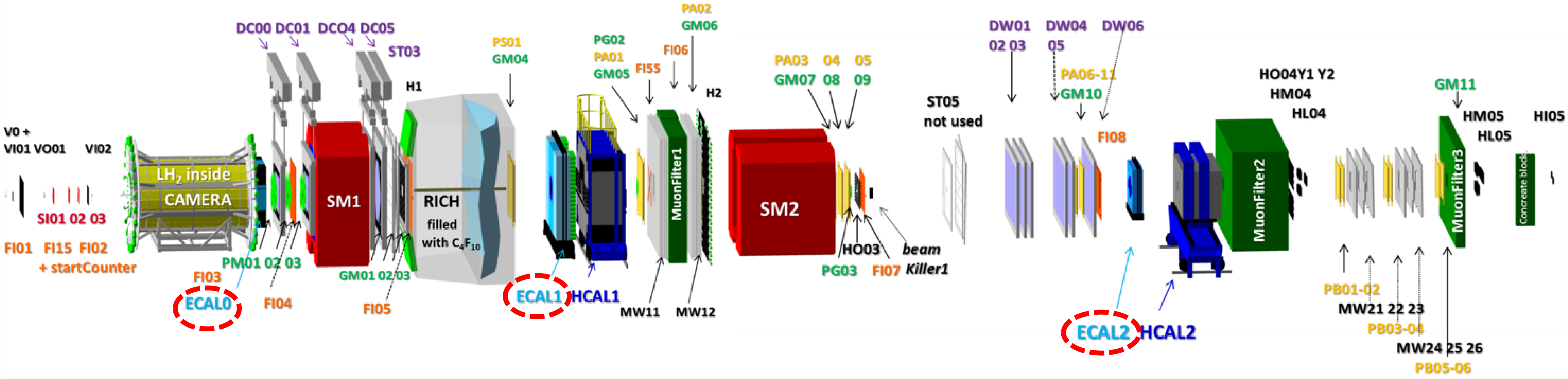

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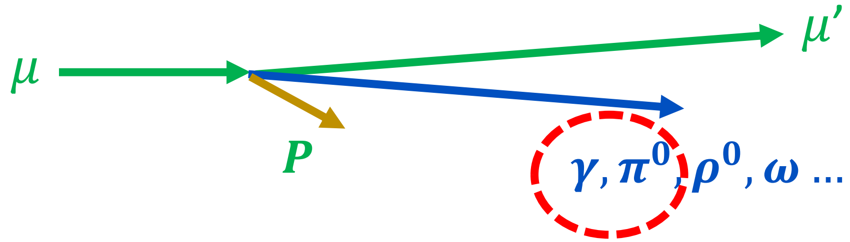
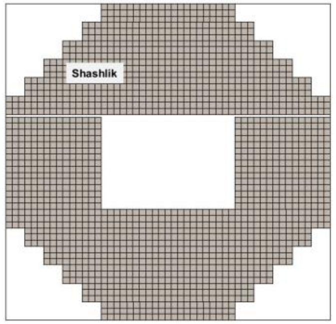
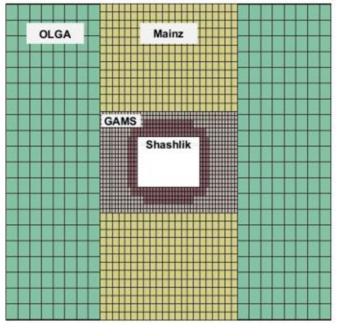
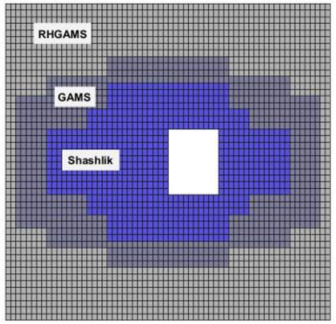




ECAL 0
2×2 m²
1746 cells

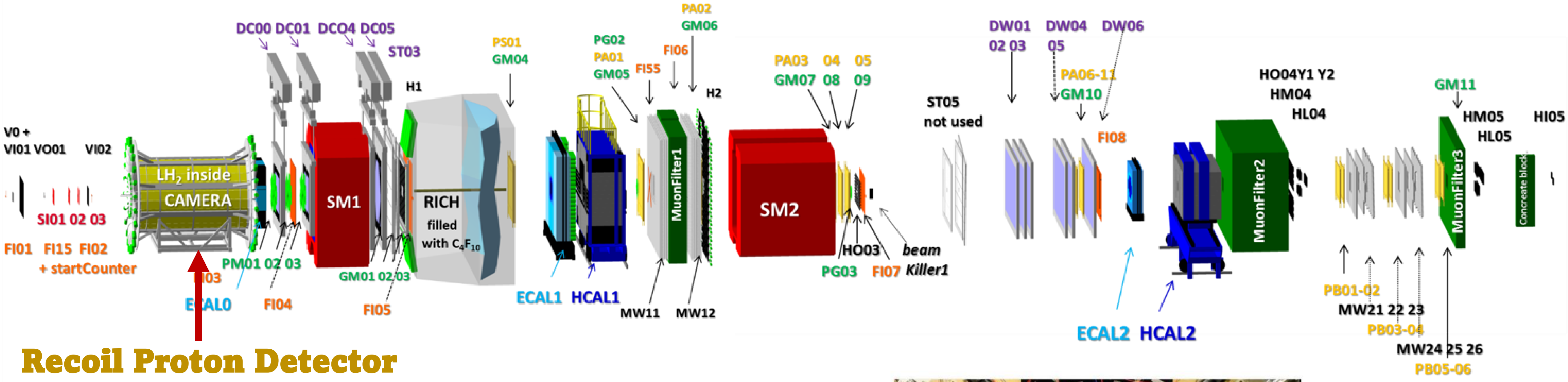


ECAL 1
4×3 m²
1708 cells



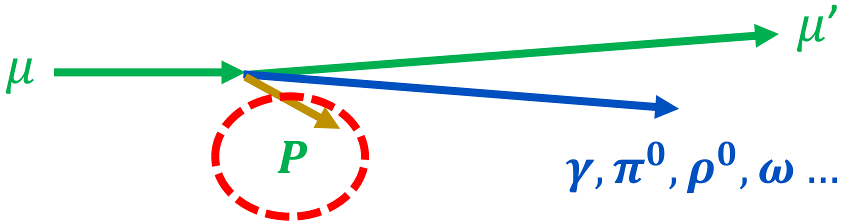
ECAL 2
2.5×2 m²
2972 cells

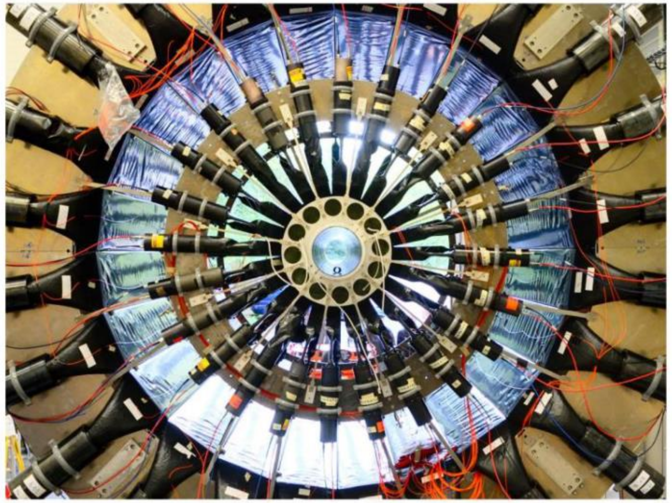
COMPASS Setup for Hard Exclusive Measurements



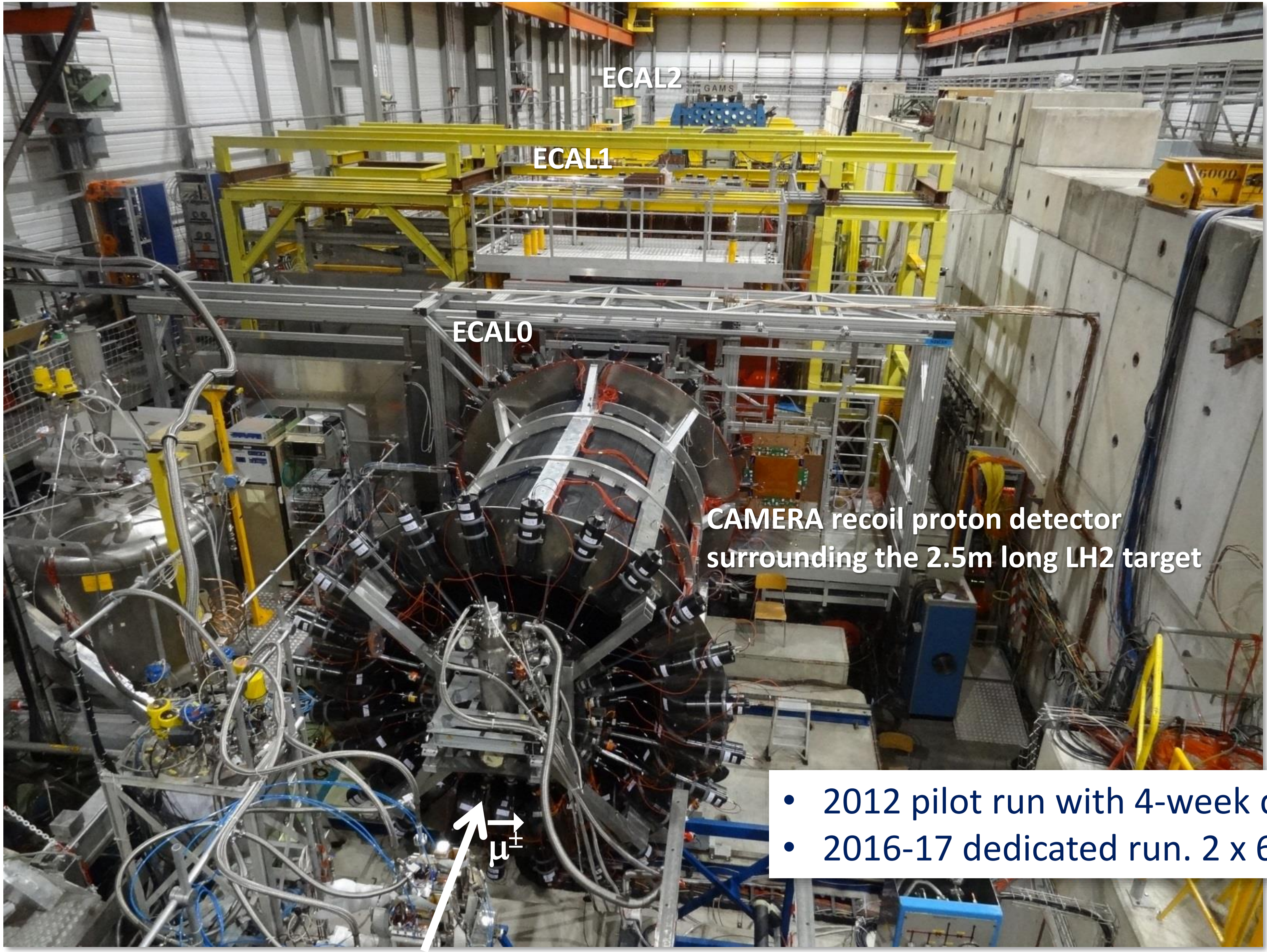
Recoil Proton Detector (CAMERA)

Exclusive Muoproduction



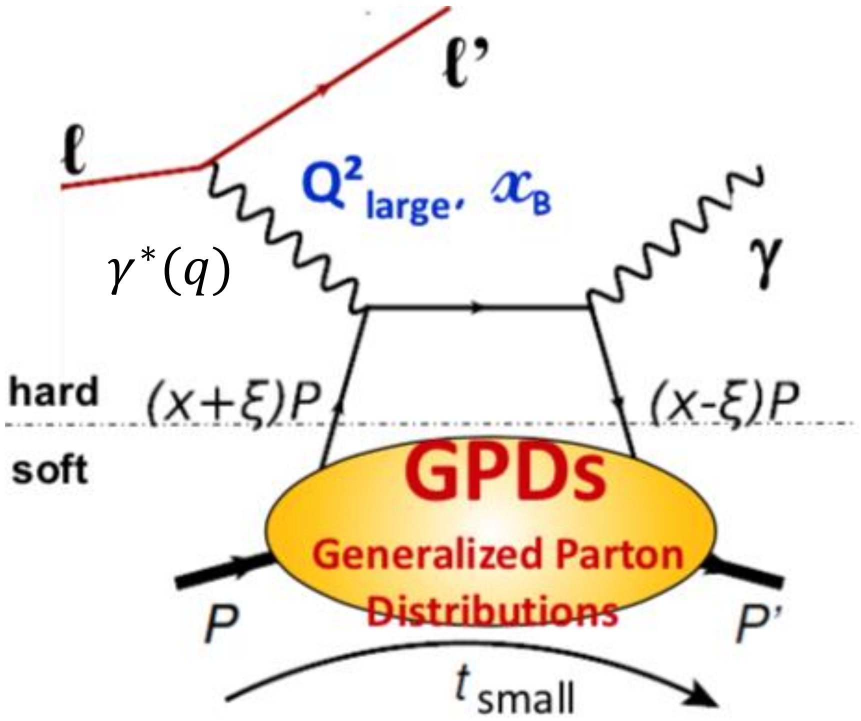


transverse picture of CAMERA



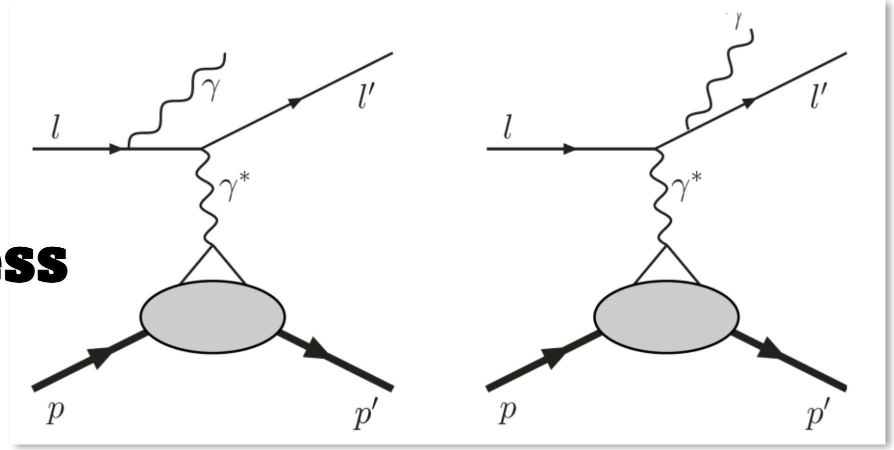
- 2012 pilot run with 4-week data taking
- 2016-17 dedicated run. 2 x 6 months.

Deeply Virtual Compton Scattering



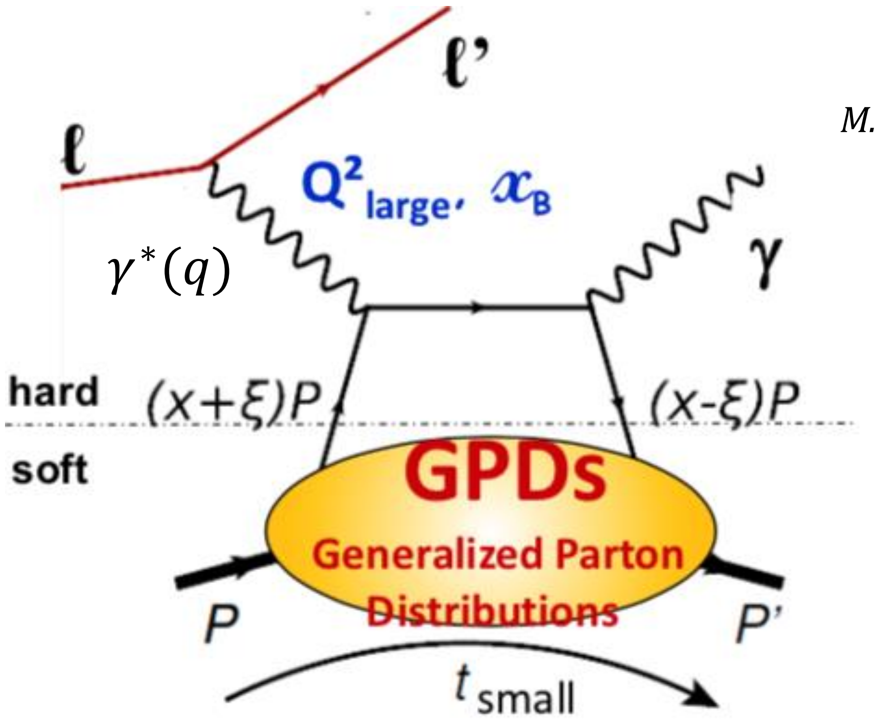
DVCS: $l + p \to l' + p' + \gamma$

BH Process



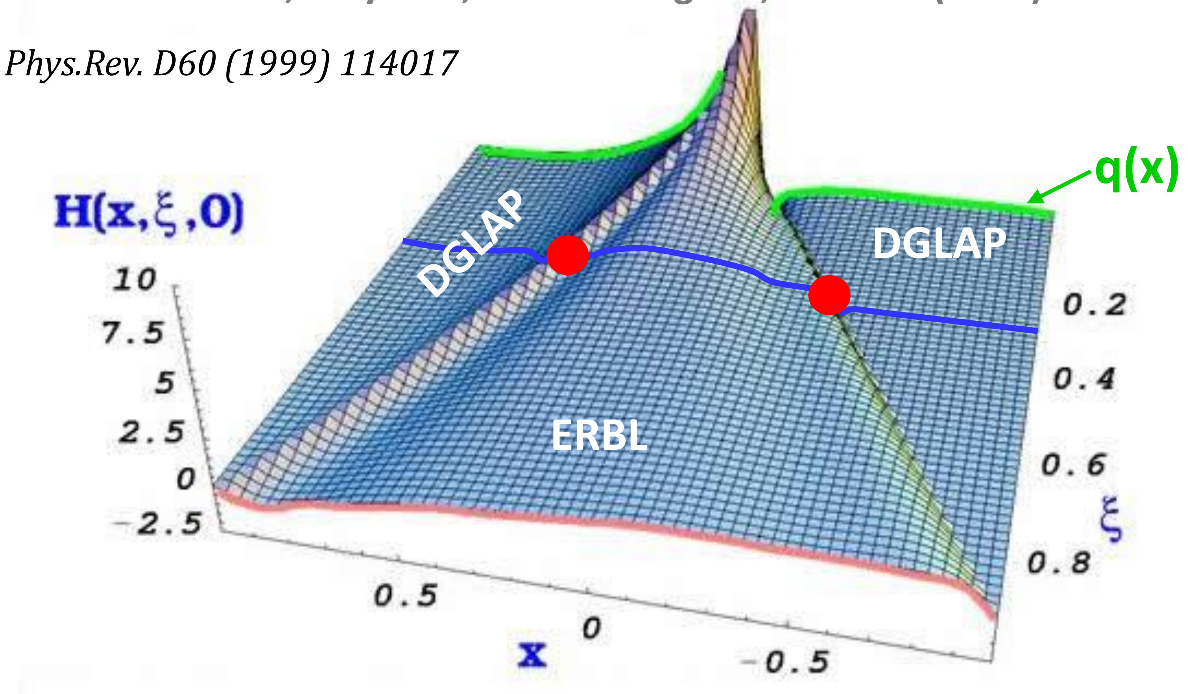
- DVCS is regarded as the golden channel and gives access to four chiral-even GPDs $H, \tilde{H}, E, \tilde{E}(x, \xi, t)$. Its interference with the well-understood Bethe-Heitler process gives access to more info.
- With LH_2 target and small x_B coverage → focuses on **H** at COMPASS

Compton Form Factors (CFFs)



From Goeke, Polyakov, Vanderhaeghen, PNPP47 (2001)

M. Polyakov , C. Weiss, Phys.Rev. D60 (1999) 114017



CFF GPD

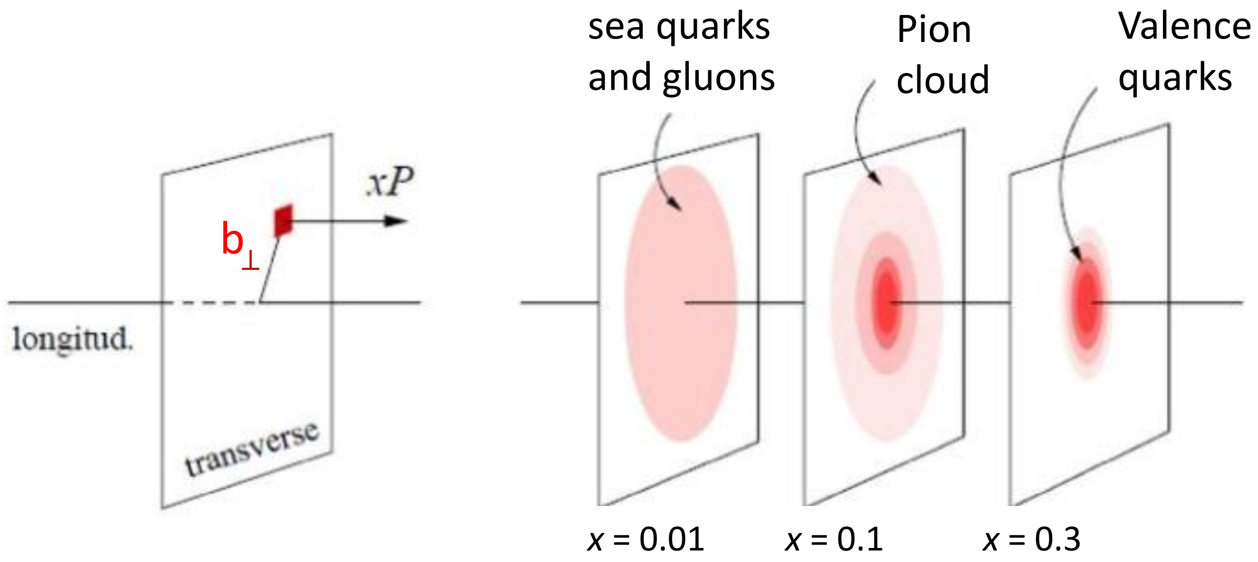
REAL part Imaginary part

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

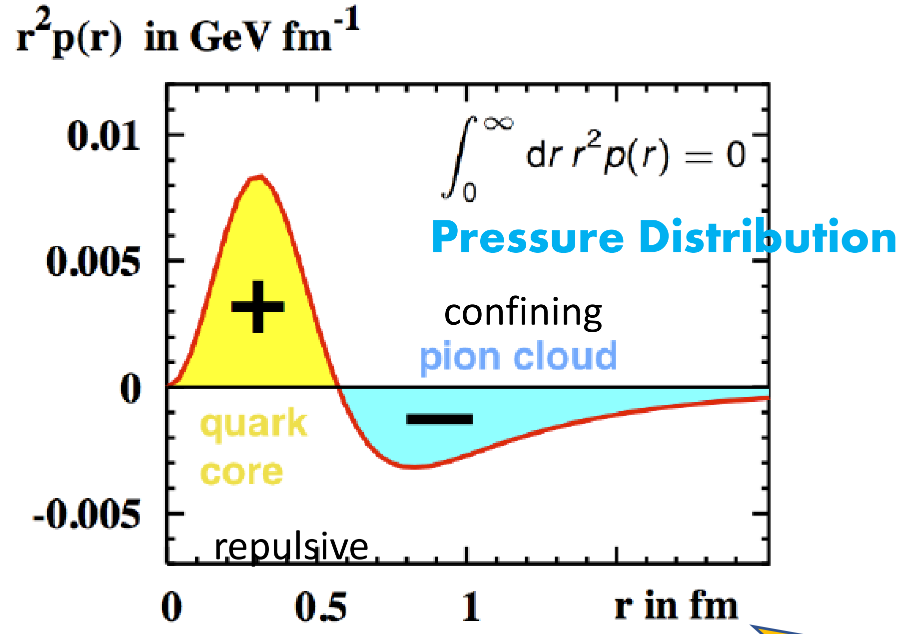
$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \, \frac{Im\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

Transverse Imaging and Pressure Distribution

Mapping in the transverse plane



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



FT of H(x, ξ=0,t)

CFF

GPD

REAL part

Imaginary part

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

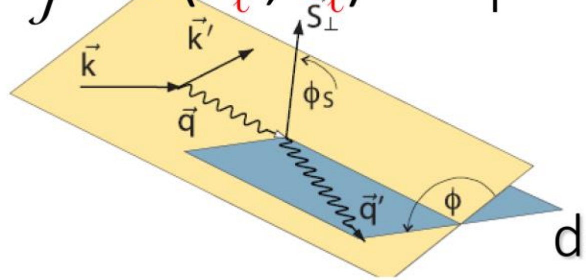
$$Re\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{Im\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

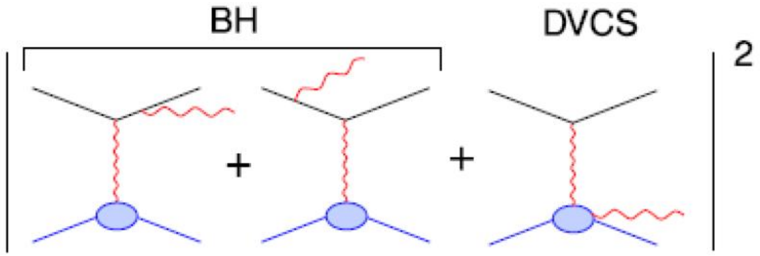
$d_1(t)$

D-term

Azimuthal Dependence of BH & DVCS

lepton (P_ℓ , e_ℓ) and ϕ





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

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

Well known

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

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

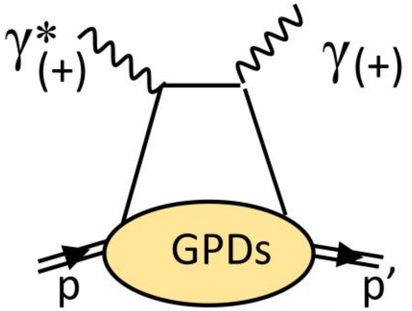
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

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

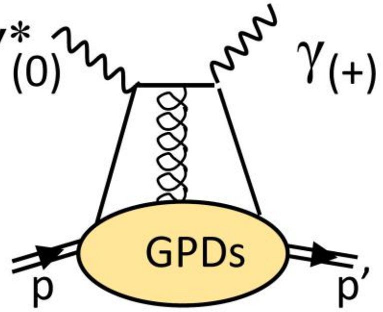
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

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

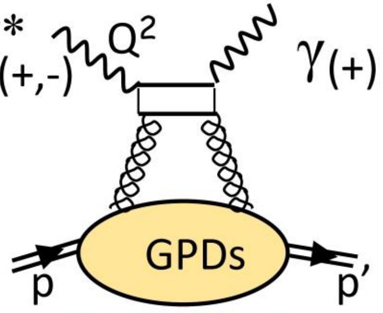
- **Each term involves different form factors.**



LO,Twist-2



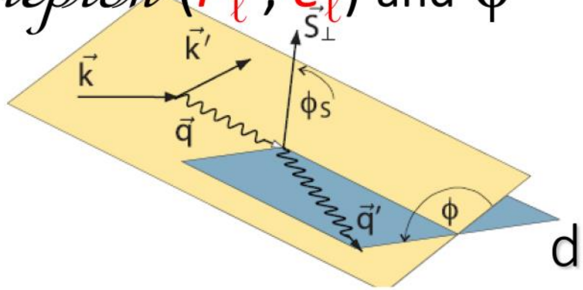
HT,Twist-3
suppressed by 1/Q

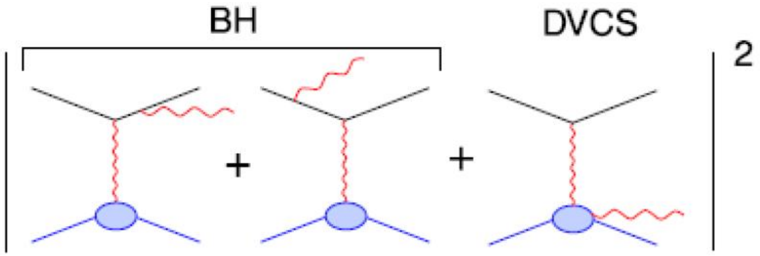


NLO,Twist-2
double helicity flip
suppressed by α_S

Azimuthal Dependence of BH & DVCS

lepton (P_ℓ, e_ℓ) and ϕ





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With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

❶ beam spin diff

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

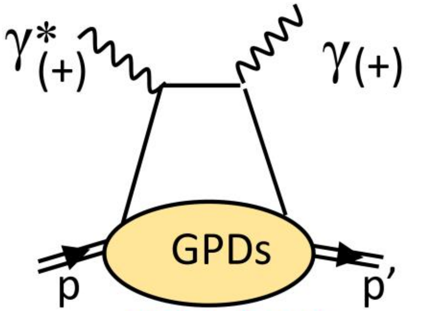
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

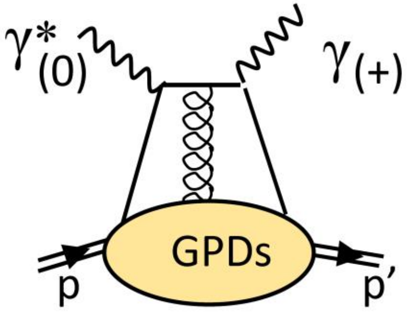
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

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

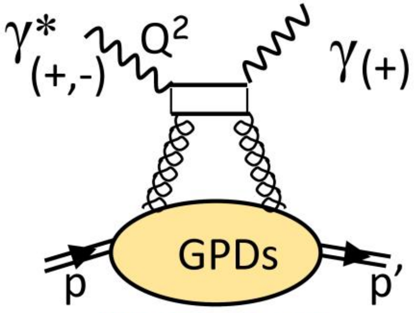
$$\text{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi$$



LO,Twist-2



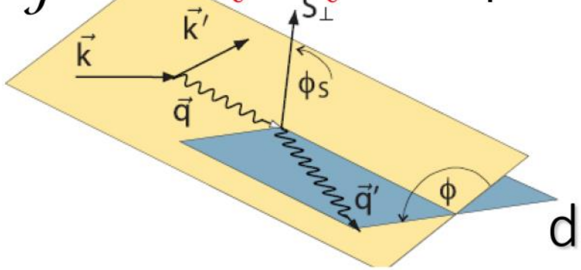
HT,Twist-3
suppressed by 1/Q

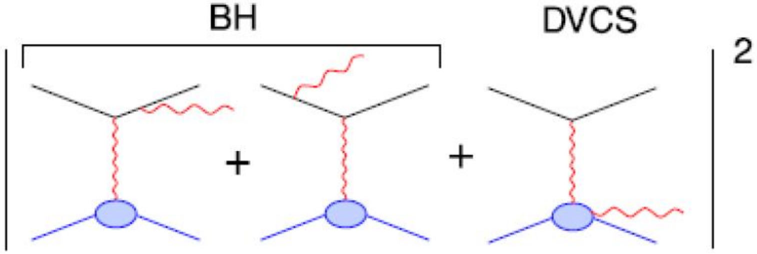


NLO,Twist-2
double helicity flip
suppressed by α_S

Azimuthal Dependence of BH & DVCS

lepton (P_ℓ , e_ℓ) and ϕ





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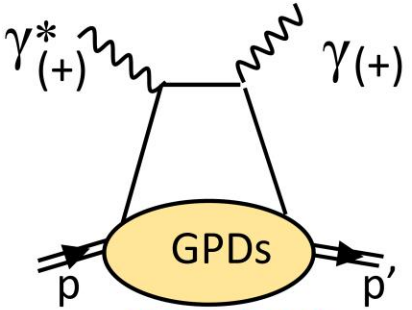
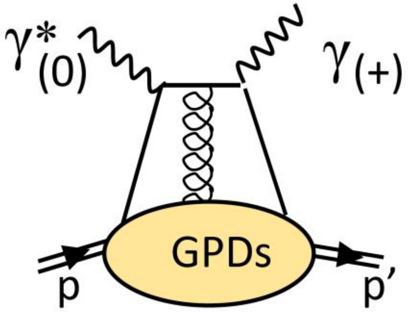
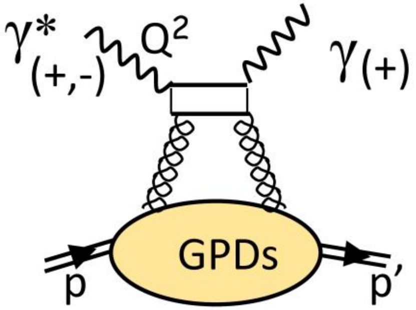


LO,Twist-2



HT,Twist-3
suppressed by 1/Q



NLO,Twist-2
double helicity flip
suppressed by α_S

With unpolarized target:

❶ **beam spin diff**

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

❷ **beam spin sum**

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

Belitsky, Müller, Kirner, NPB629 (2002)

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

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

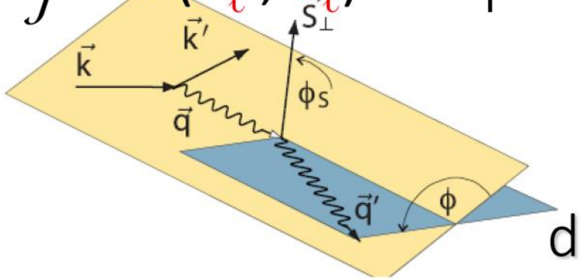
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

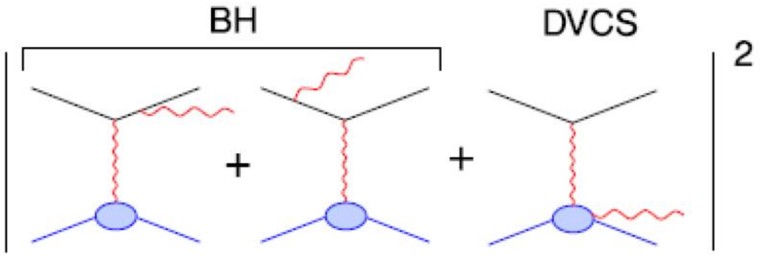
$$\mathrm{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

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

Azimuthal Dependence of BH & DVCS

lepton (P_ℓ, e_ℓ) and ϕ

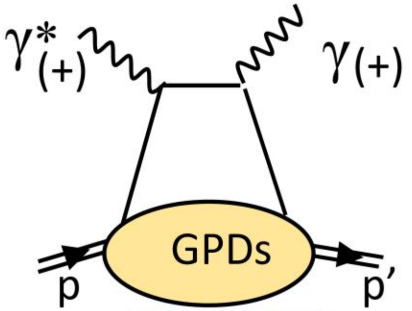




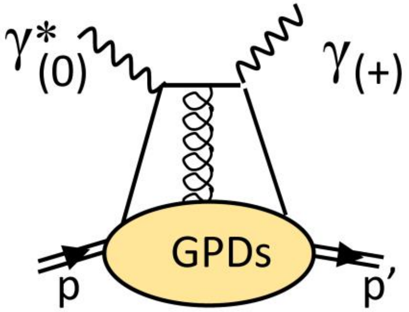
$$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2 + \text{Interference Term}$$

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

Well known

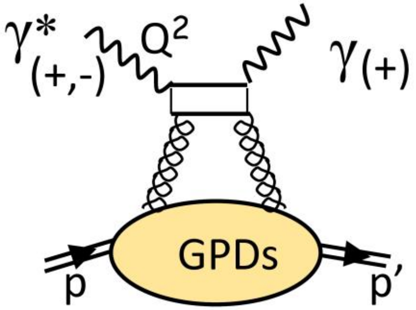


LO,Twist-2



HT,Twist-3

suppressed by 1/Q



NLO,Twist-2

double helicity flip

suppressed by α_S

With unpolarized target:

❶ beam charge-spin sum

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

Belitsky, Müller, Kirner, NPB629 (2002)

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

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

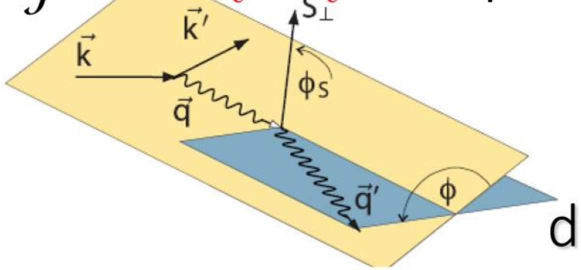
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$

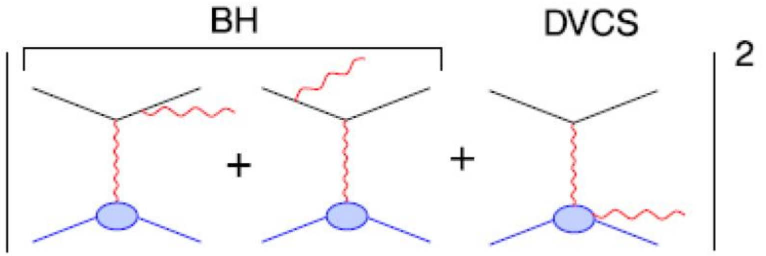
$$\text{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi$$

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

Azimuthal Dependence of BH & DVCS

lepton (P_ℓ , e_ℓ) and ϕ

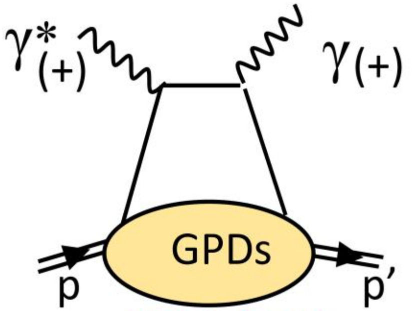




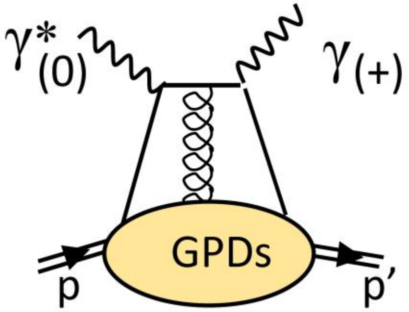
$d\sigma = |T^{BH}|^2 + |T^{DVCS}|^2$ + Interference Term

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

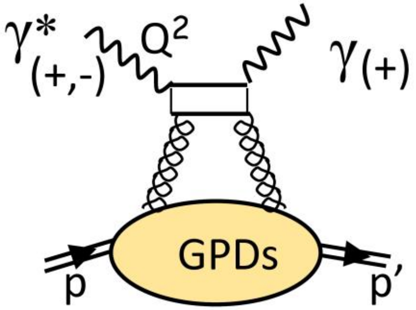
Well known



LO,Twist-2



HT,Twist-3
suppressed by 1/Q



NLO,Twist-2
double helicity flip
suppressed by α_s

With unpolarized target:

❶ **beam charge-spin sum**

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

❷ **difference**

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

Belitsky, Müller, Kirner, NPB629 (2002)

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

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

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

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

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

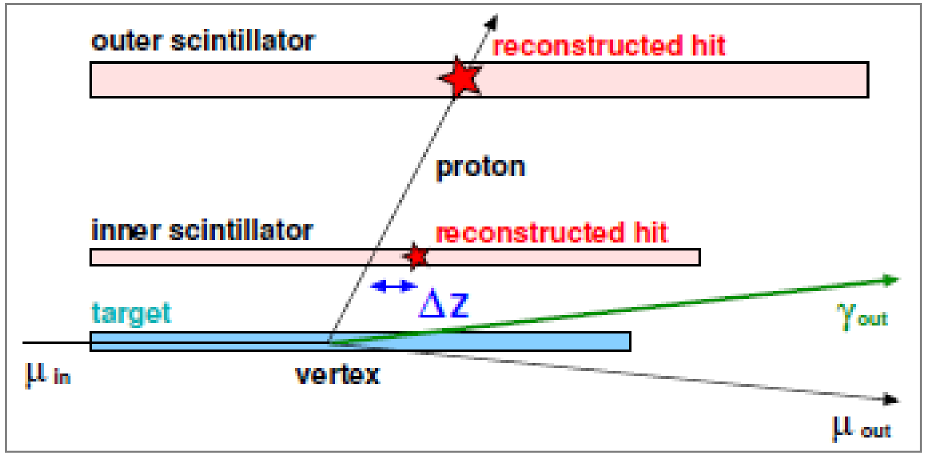
COMPASS 2016 Preliminary Results

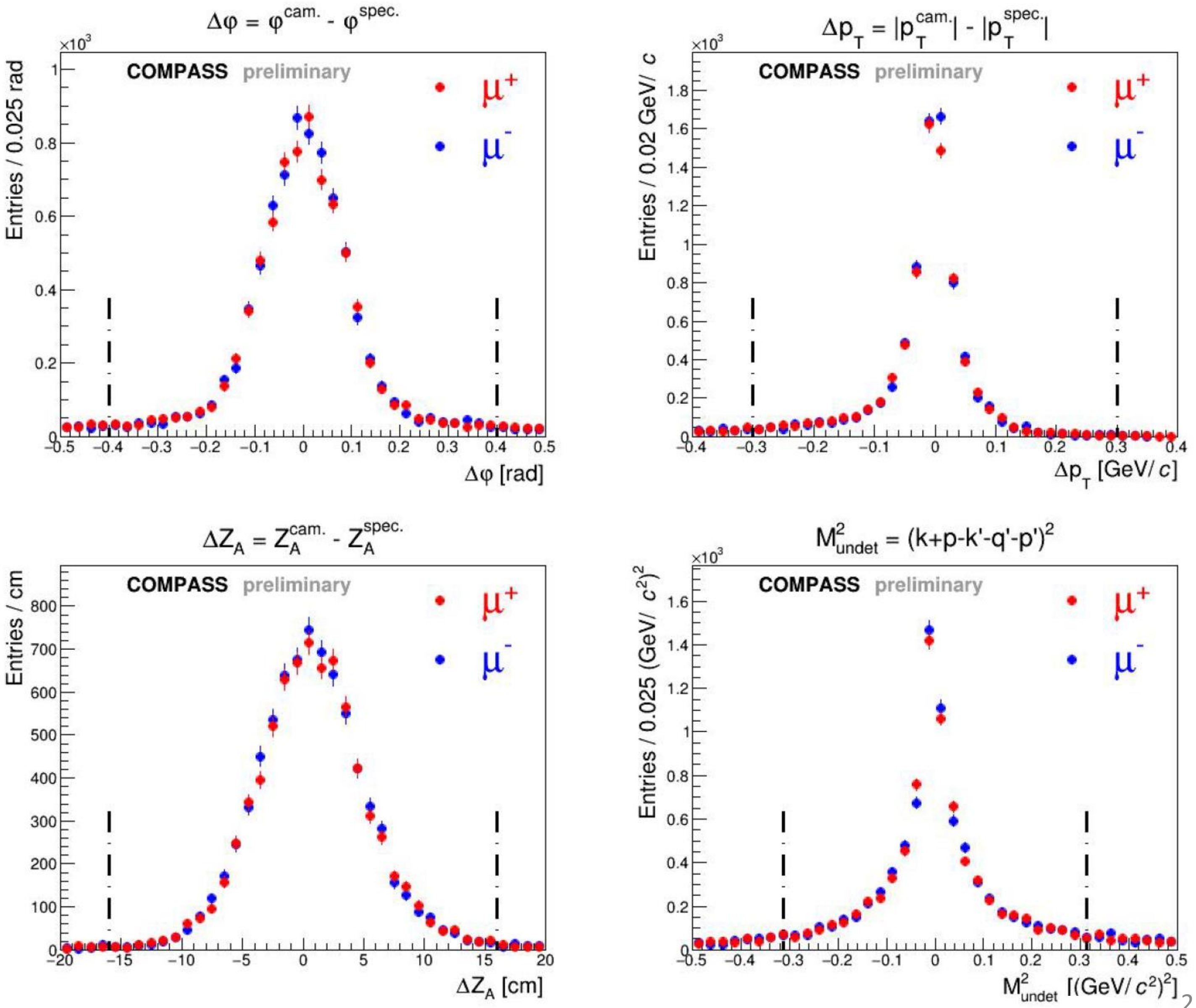
$$\Delta\varphi = \varphi^{cam.} - \varphi^{spec.}$$

$$\Delta p_T = |p_T^{cam.}| - |p_T^{spec.}|$$

$$\Delta z_A = z_A^{cam.} - z_A^{spec.}$$

$$M^2_{undet} = (k + p - k' - q' - p')^2$$





COMPASS 2016 Preliminary Results

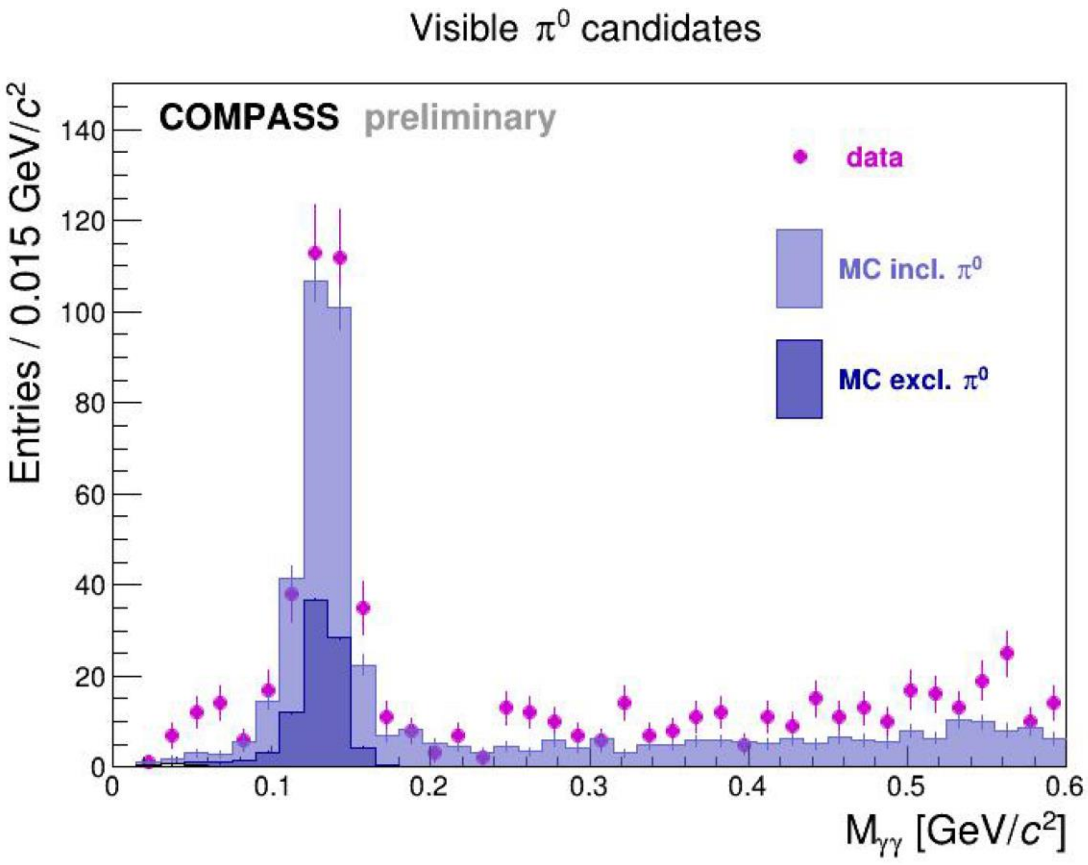
➢ **Main background of exclusive single photon events: π^0 decay**

➢ **Visible** (both γ detected) – subtracted

A high-energy DVCS photon candidate is combined with all detected photons with energies lower than the DVCS threshold: (4,5) GeV in Ecal (0,1) respectively

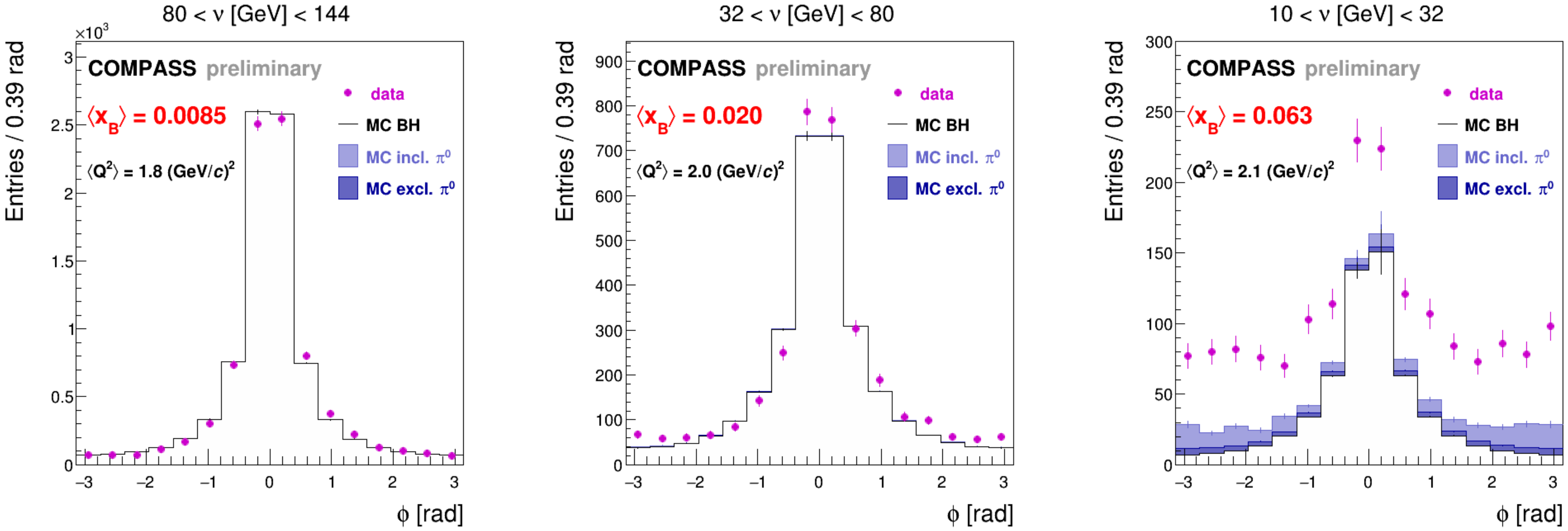
➢ **Invisible** (one γ lost) – estimated by MC

- **Semi-inclusive LEPTO 6.1**
- **Exclusive HEPGEN π^0** (GK model)



The sum of LEPTO and HEPGEN contributions is normalized to the π^0 peak in $M_{\gamma\gamma}$ of the real data

COMPASS 2016 Preliminary Results



- Beam charge-spin sum

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

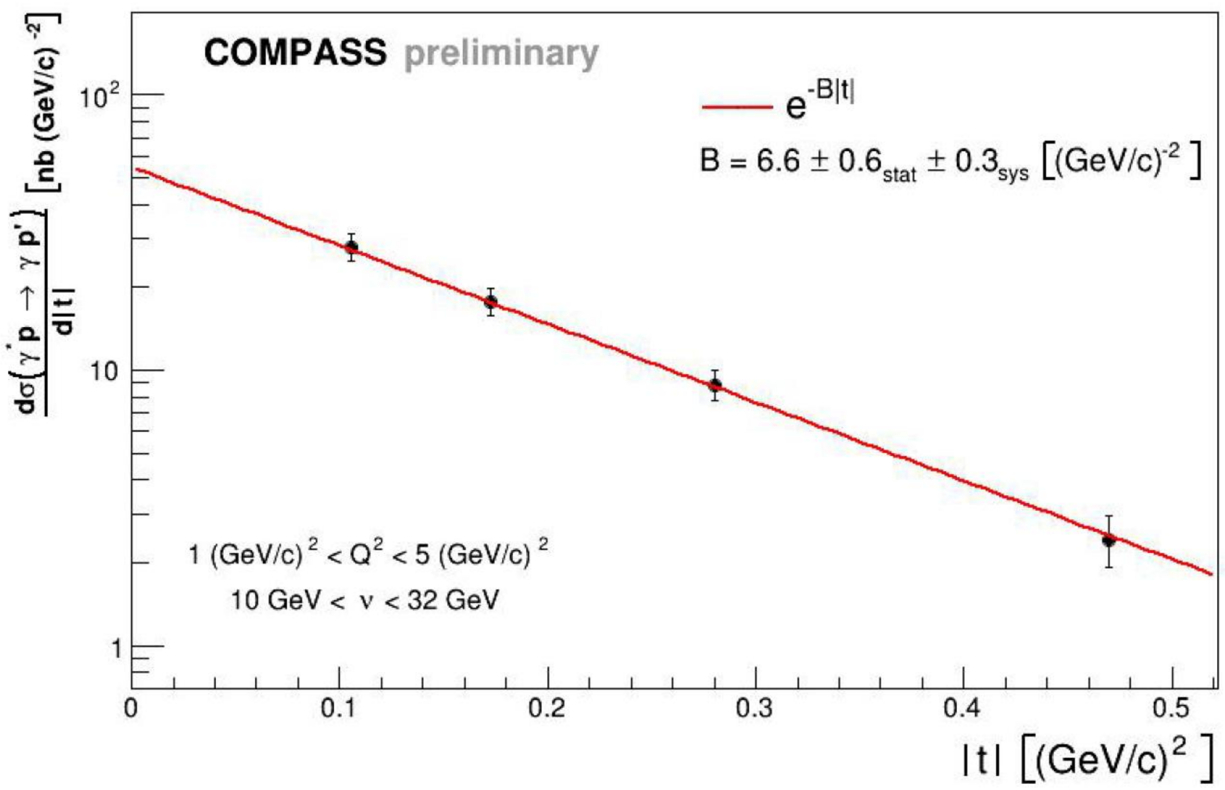
$$= 2[\, d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi + s_1^I \sin\phi + s_2^I \sin 2\phi \,]$$

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

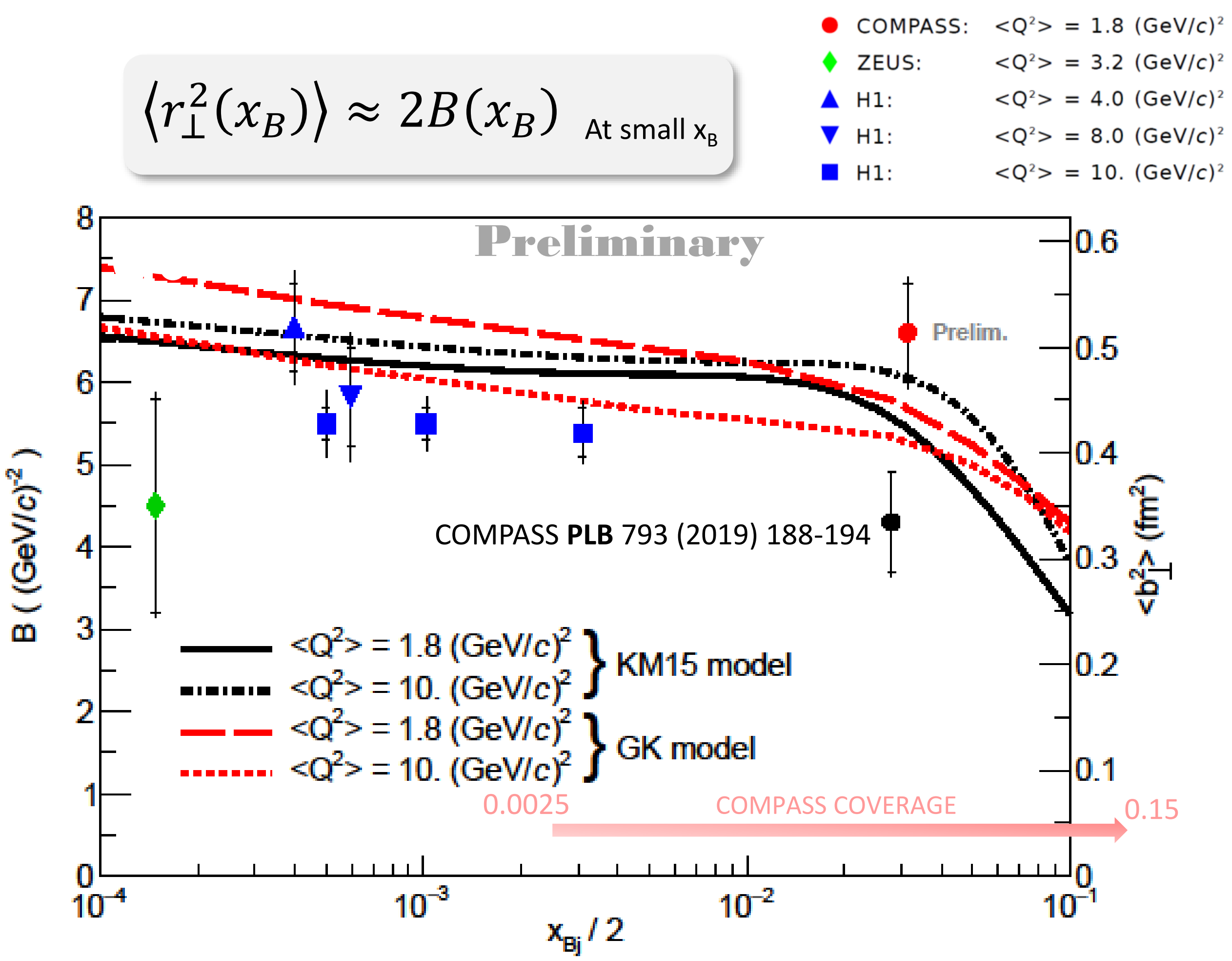
small x_{Bj} model dependent

Tranverse extension of partons – 2016 data

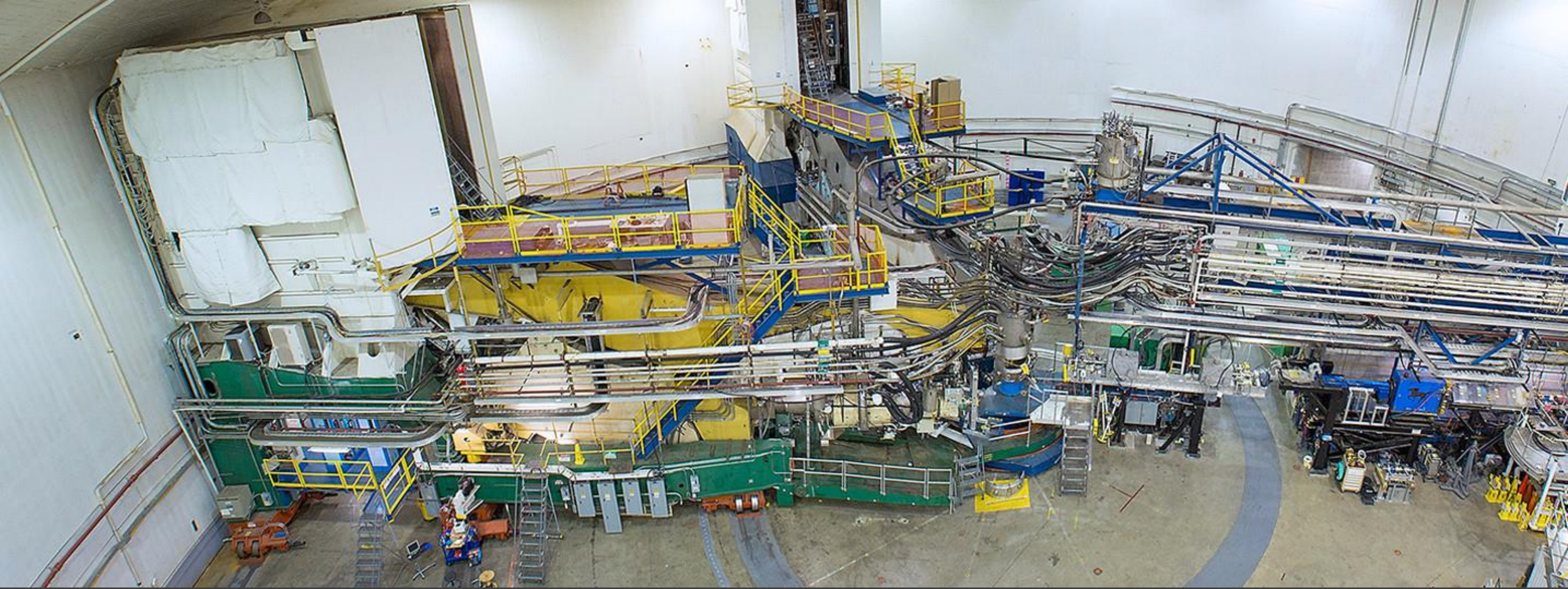
$$d\sigma^{DVCS}/d|t| \propto e^{-B|t|}$$



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

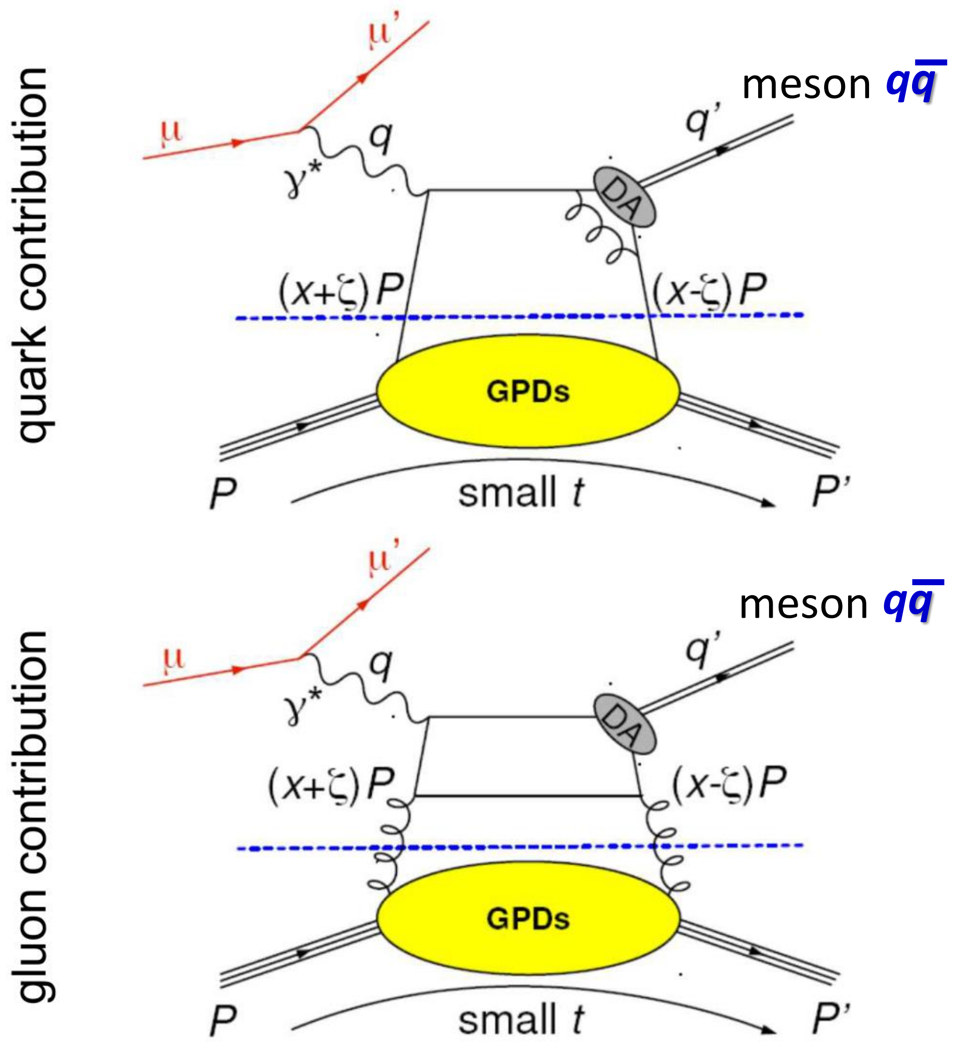


➢ The transverse-size evolution as a function of x_{Bj} → Expect at least 3 x_{Bj} bins from 2016-17 data



Hard Exclusive $\boldsymbol{\pi^0}$ Production @ Jlab Hall A

Deeply Virtual Meson Production (DVMP)



4 chiral-even GPDs: helicity of parton unchanged

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

+ 4 chiral-odd or transversity GPDs: helicity of parton changed

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

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

- Ability to probe the chiral-odd GPDs.
- Additional non-perturbative term from meson wave function → more difficult for GPD extraction
- In addition to nuclear structure, provide insights into reaction mechanism

Exclusive π^0 Production

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

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma_\gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{TL'}}{dt}\sin(\phi)\right]$$

ϵ: degree of longitudinal polarization
h: helicity of the initial lepton

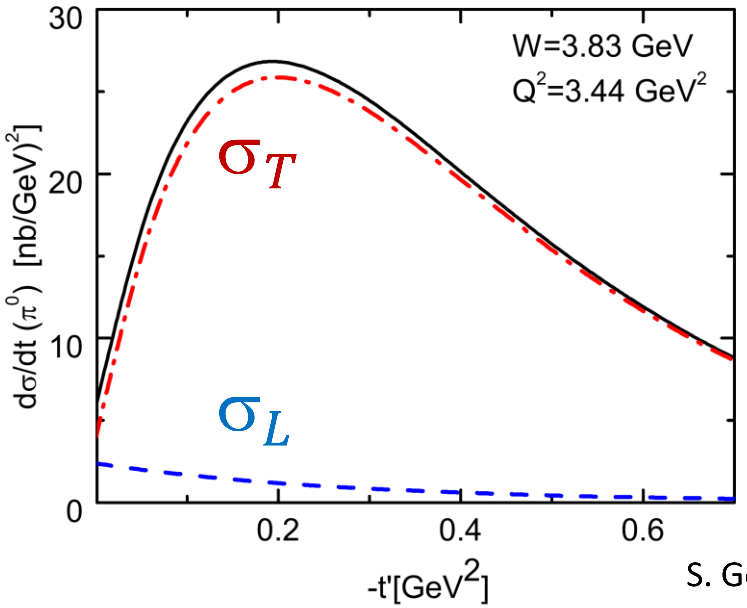
- Factorization proven only for σ_L, which depends on chiral-even GPDs only
- At sufficiently high Q^2, expect $\sigma_L \propto Q^{-6}$ while σ_T asymptotically suppressed and $\propto Q^{-8}$ → σ_L dominance
- Previous experiments with limited reach in Q^2 suggest the dominance of σ_T

Exclusive π^0 Production

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

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma_\gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{TL'}}{dt}\sin(\phi)\right]$$

ϵ: degree of longitudinal polarization
h: helicity of the initial lepton



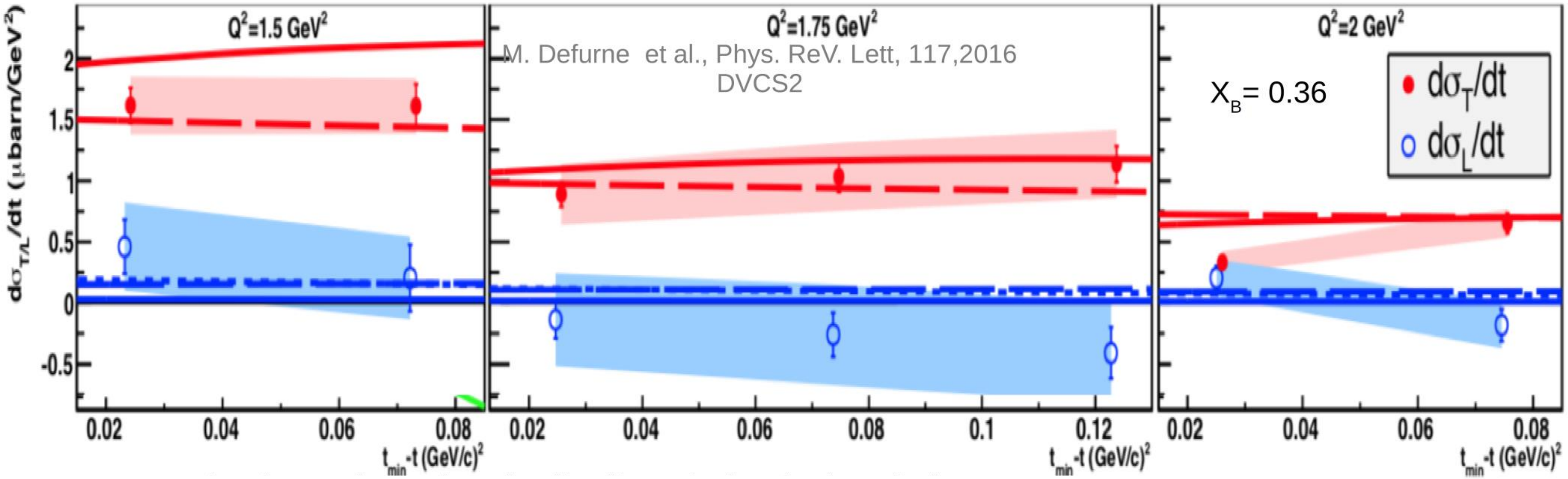
- Modeling of σ_T → coupling between transversity GPDs and twist-3 pion amplitude

S. Goloskokov and P. Kroll (Eur.Phys.J A47, 112(2011))

Exclusive π^0 Production

e p → e π^0 p

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma_\gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{TL'}}{dt}\sin(\phi)\right]$$



—— S. V. Goloskokov and P. Kroll, Eur. Phys. J. C65:137 (2010)

- - - - G. R. Goldstein, J. O. Hernandez, S. Liuti, Phys. Rev. D84 (2011)

Exclusive π^0 Production

e p → e π^0 p

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma_\gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{TL'}}{dt}\sin(\phi)\right]$$

ϵ: degree of longitudinal polarization

h: helicity of the initial lepton

- $\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2 \mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$
- $\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$
- $\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$
- $\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$

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

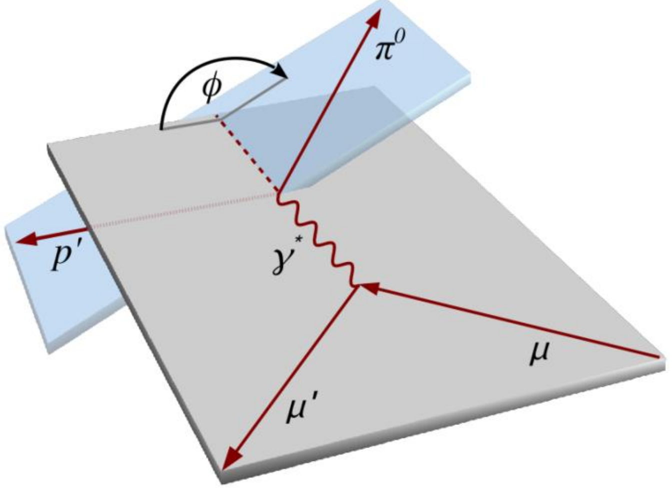


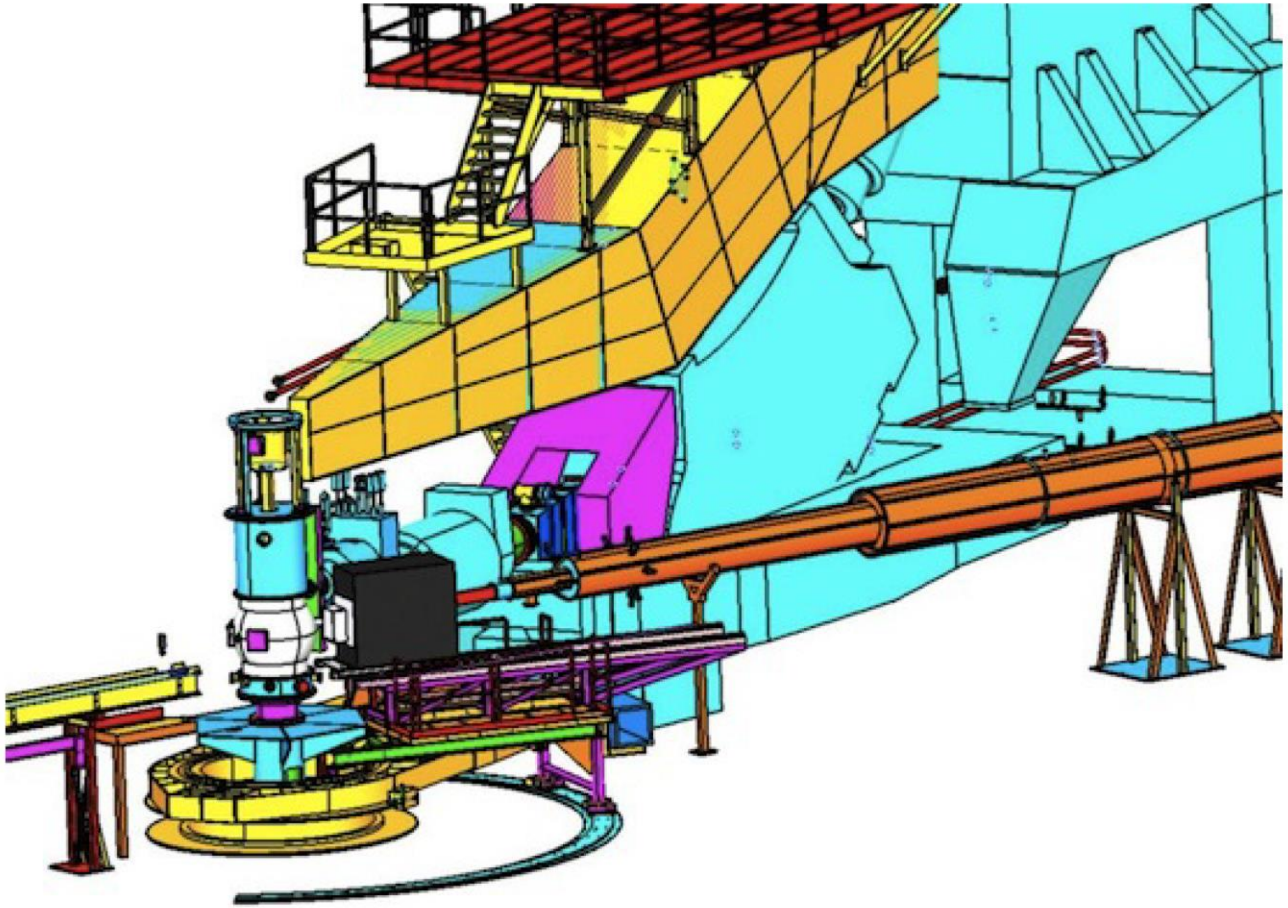
Fig: M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

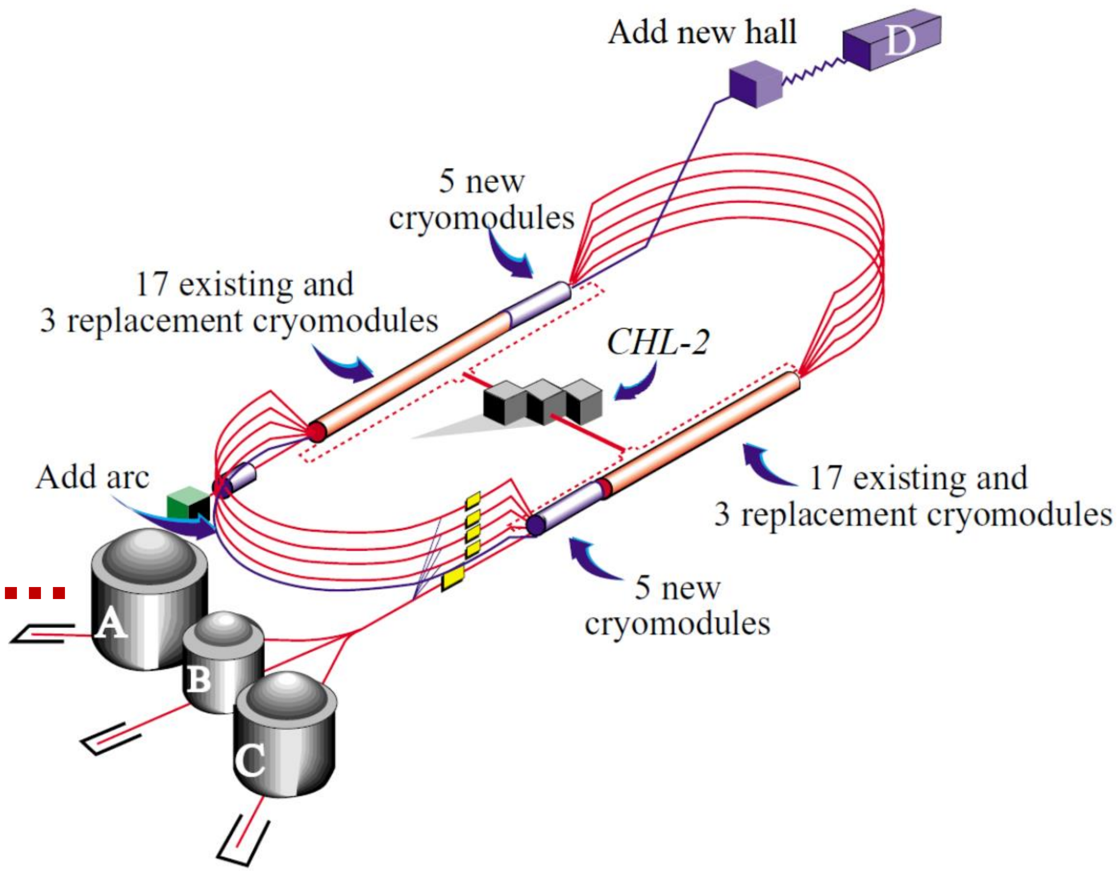
S. V. Goloskokov and P. Kroll, Eur. Phys. J. A 47 (2011) 112

I. Bedlinskiy, et al. (CLAS Collaboration), Phys. Rev. C 90 (2014) 025205

Jefferson Lab Hall A experiment E12-06-114

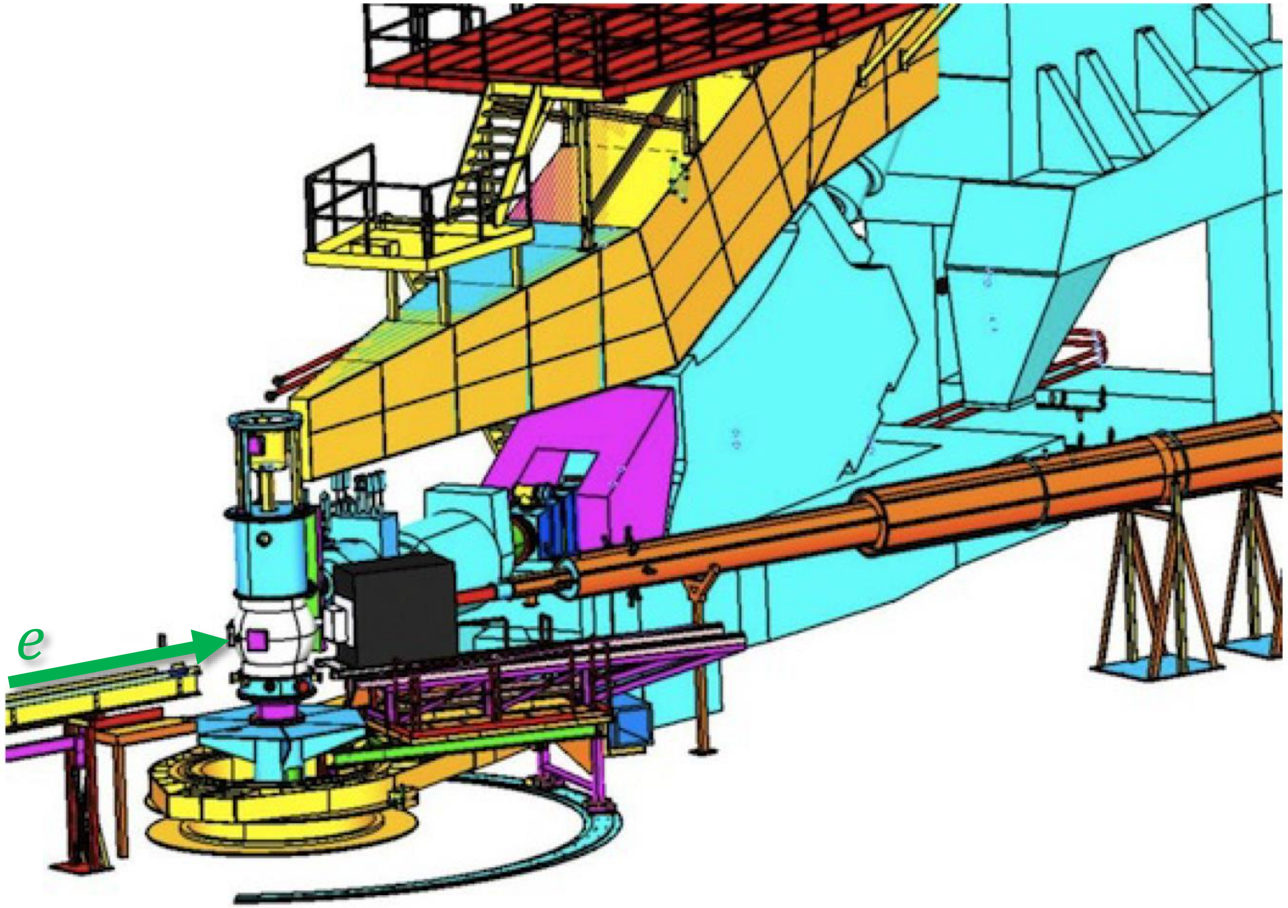
https://www.jlab.org/div_dept/physics_division/GeV/whitepaperv11/index.html



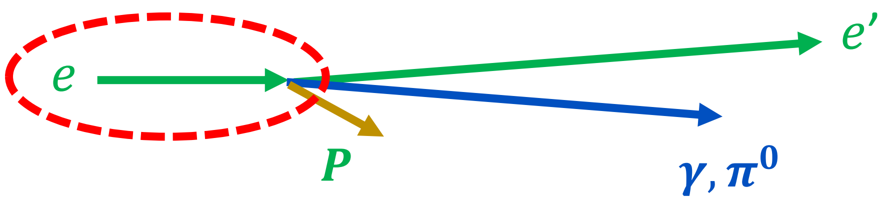


- 3rd Generation DVCS project @ Hall A→ CEBAF12 grants the ability to explore high x_B with extended Q^2.

E12-06-114 Experimental Setup

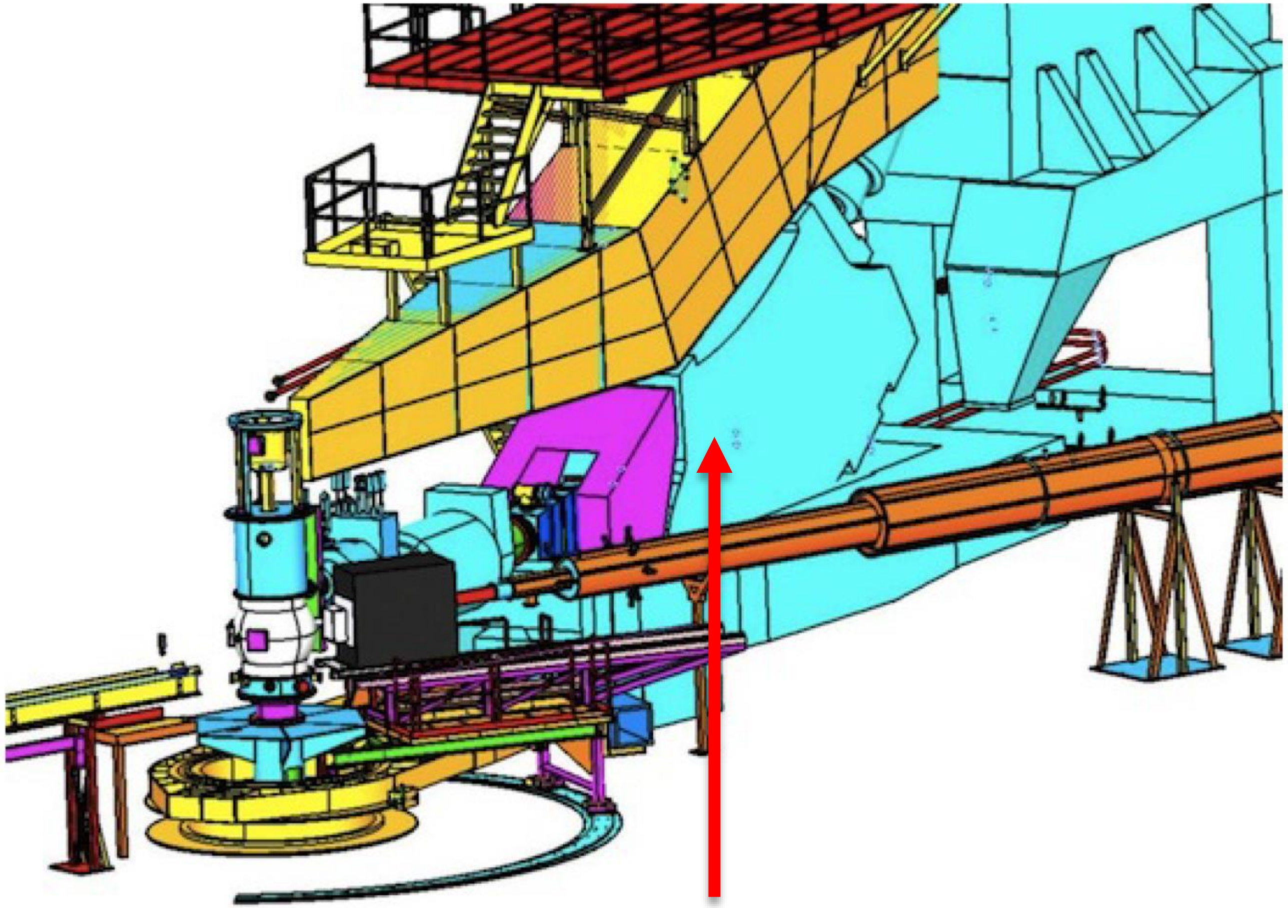


DVCS & Exclusive π^0 Production



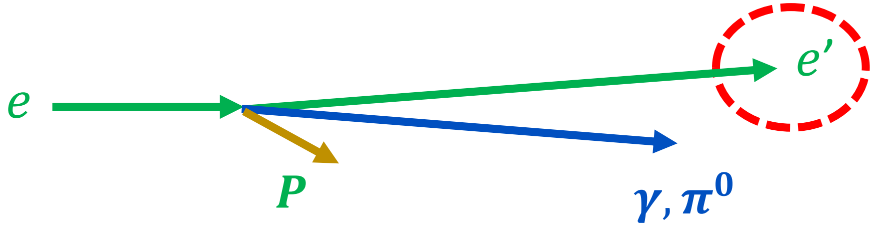
- **Electron beam**
  - **polarisation ~ 85%**
  - **helicity flipped at 30 Hz**
  - **luminosity: ~ 10^{38} Hz/cm^2**
- **LH_2 target**
  - **6.35 cm diameter, 15 cm long**

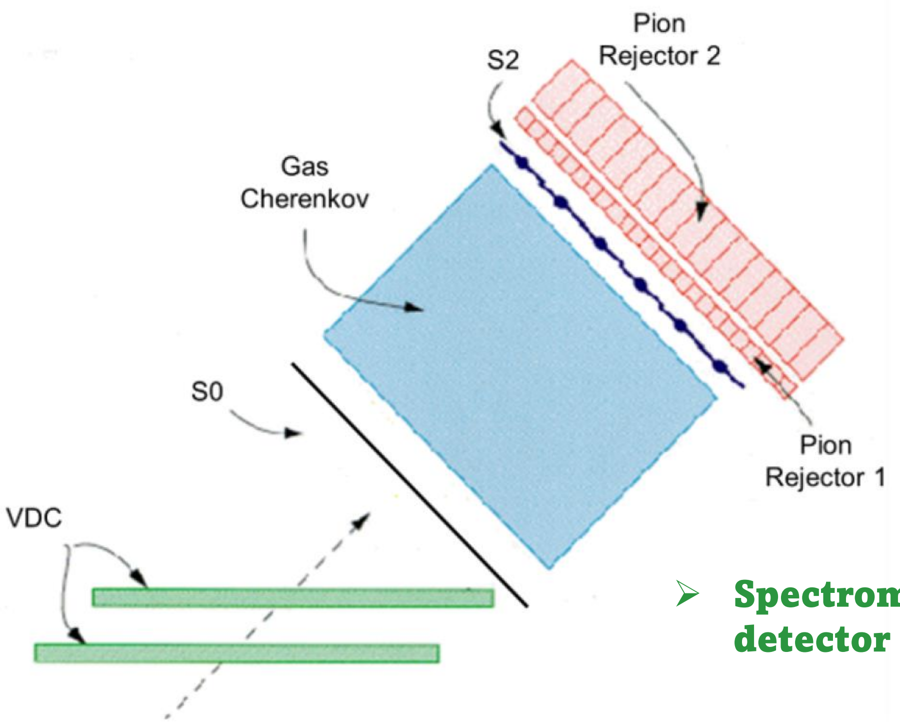
E12-06-114 Experimental Setup



Left High Resolution Spectrometer (LHRS)

DVCS & Exclusive π^0 Production

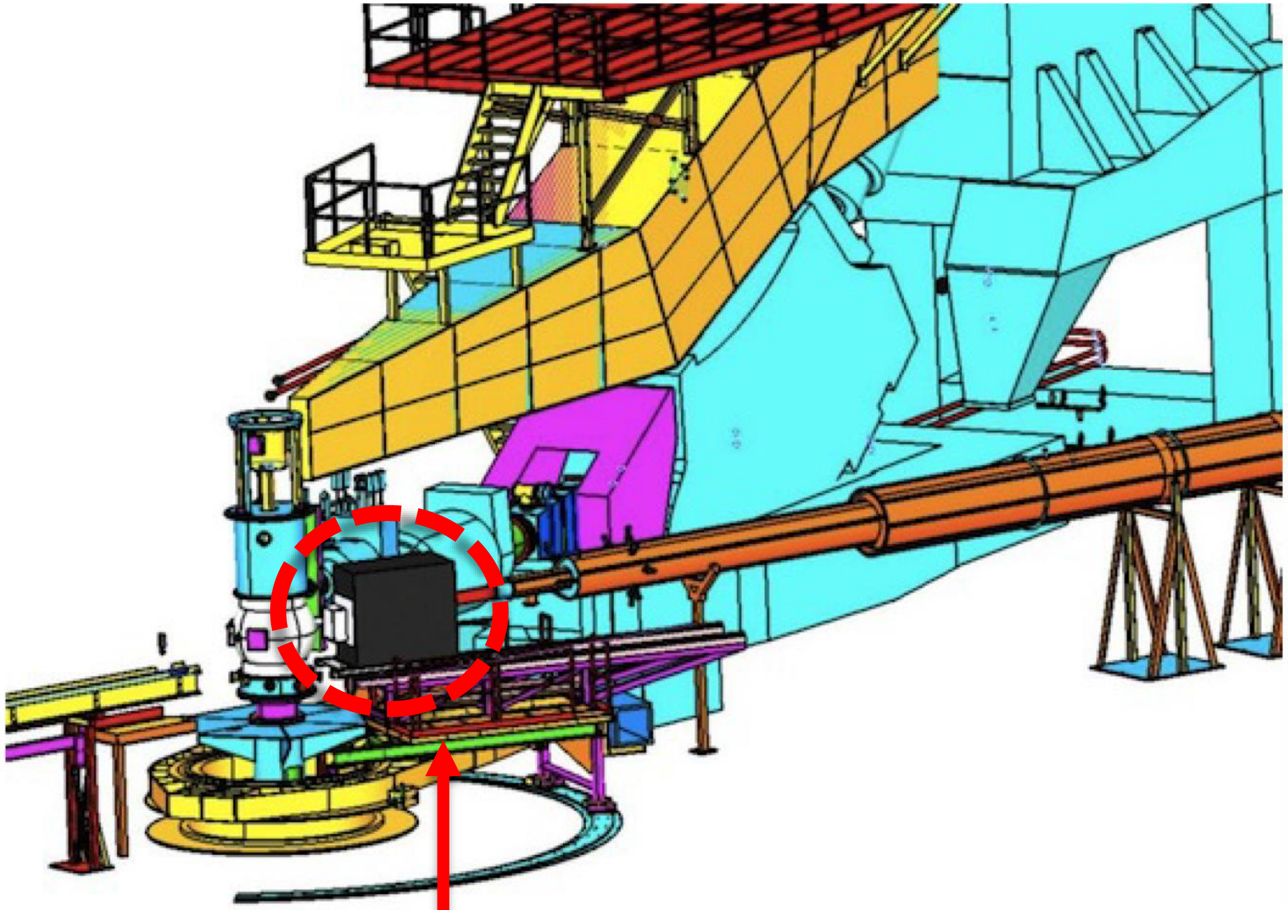




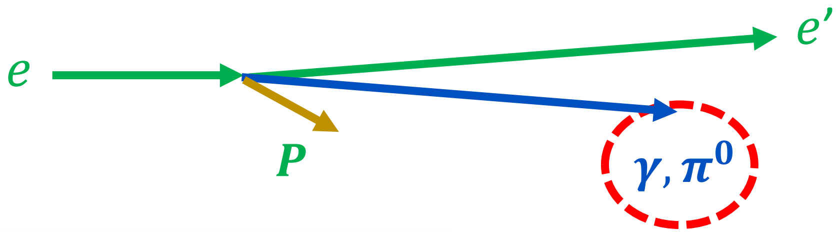
- **Spectrometer detector package**

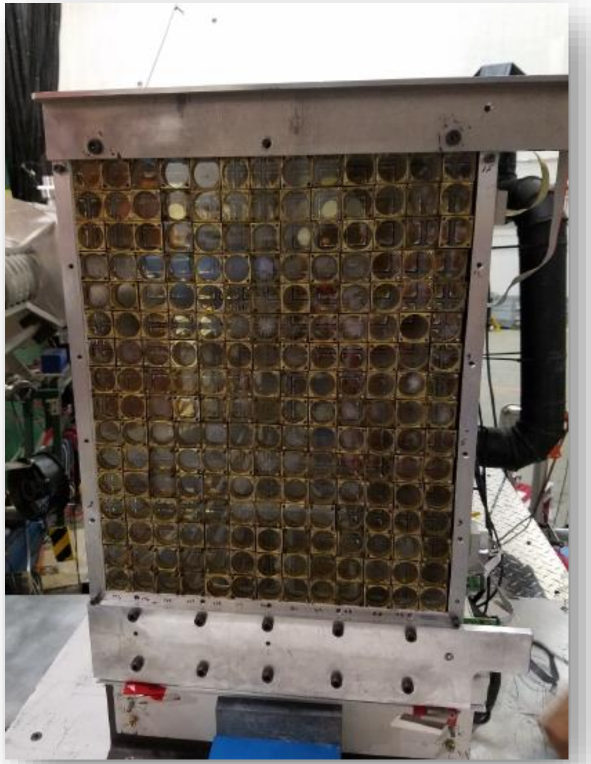
- **δP/P resolution ~ 10^{-4} @ 4.3 GeV**

E12-06-114 Experimental Setup



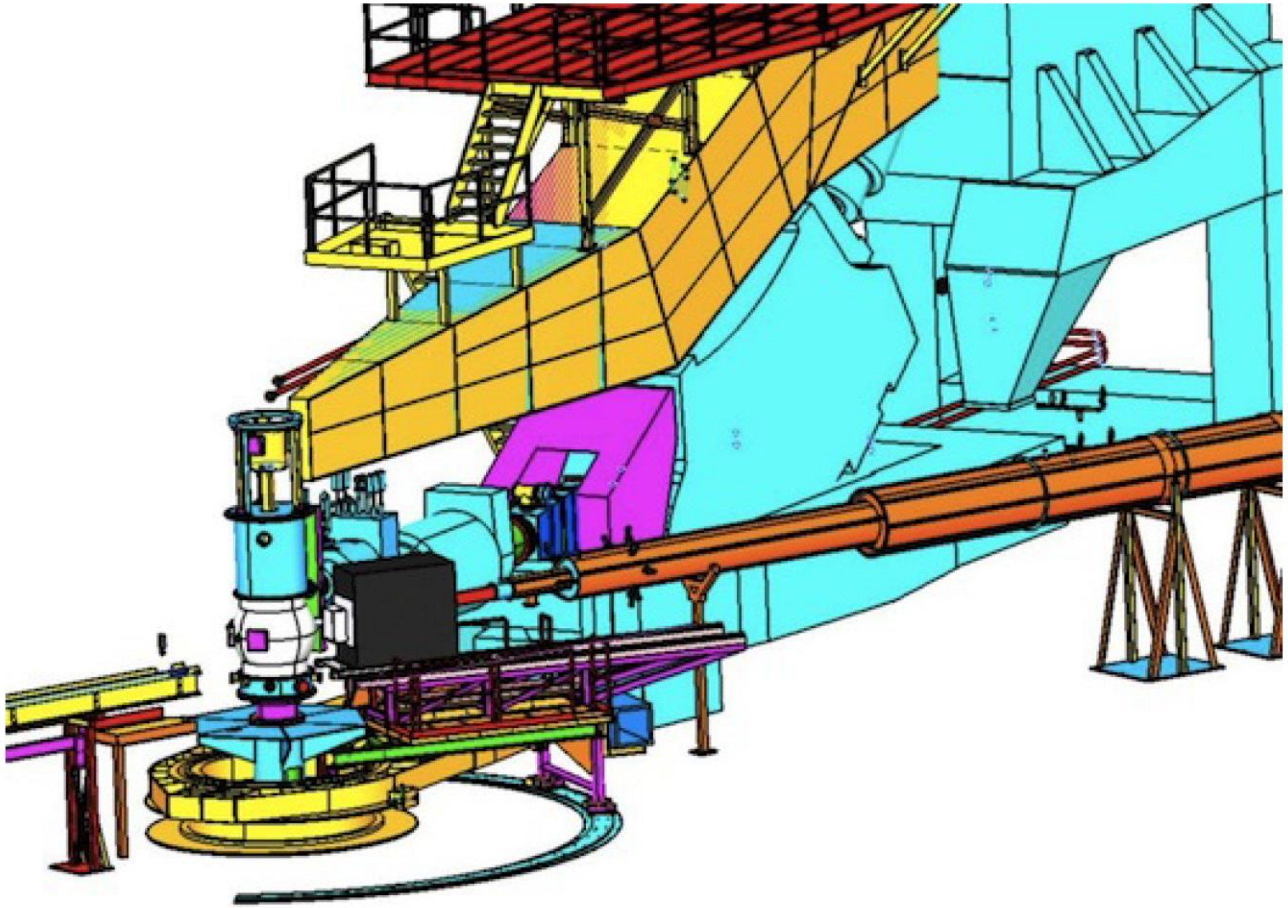
DVCS & Exclusive π^0 Production



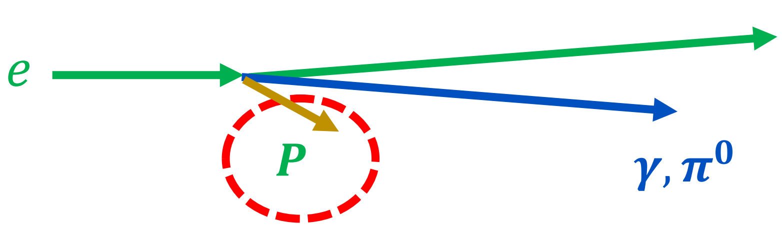


- **ECAL**
  - **208 blocks of PF_2**
  - **$3 \times 3 \times 18.6$ cm^3 each**
  - **~ 20 radiation lengths**
  - **Moliere radius 2.2cm**
  - **E resolution ~ 3% @ 4.2 GeV**

E12-06-114 Experimental Setup



DVCS & Exclusive π^0 Production

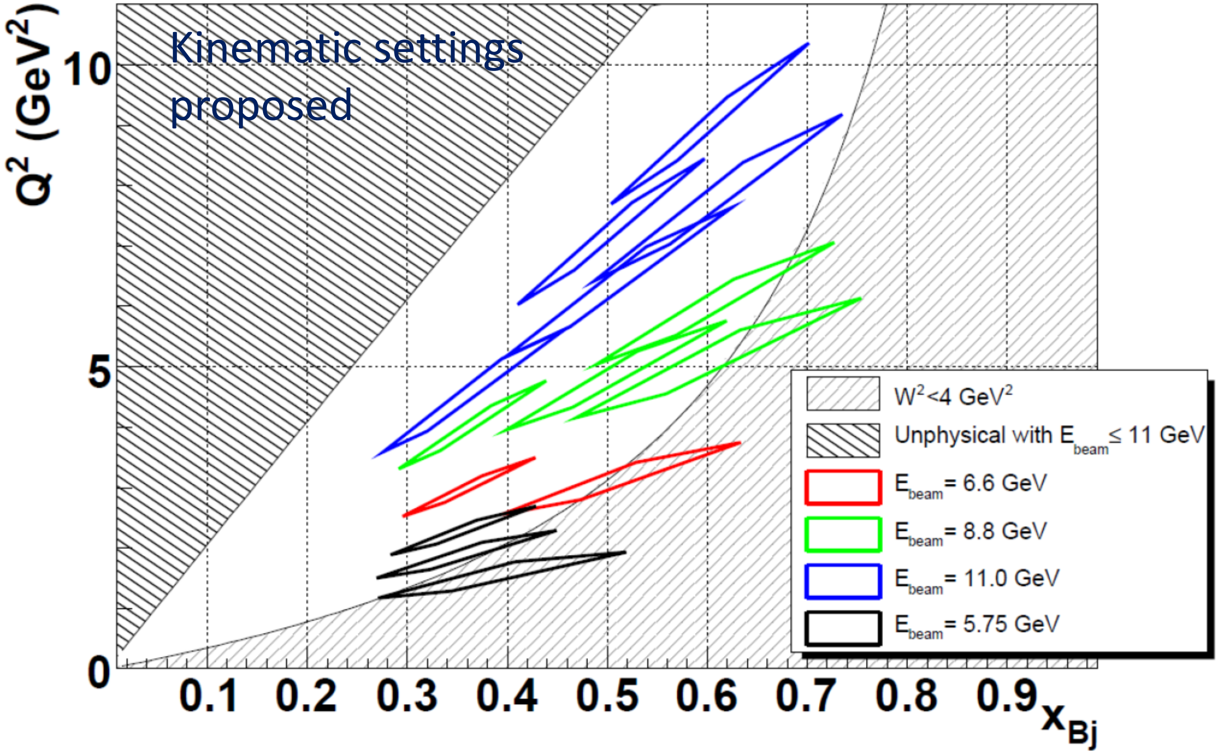


Recoil Proton

- **Not detected**
- **Exclusivity of events ensured using missing mass, M_X^2**

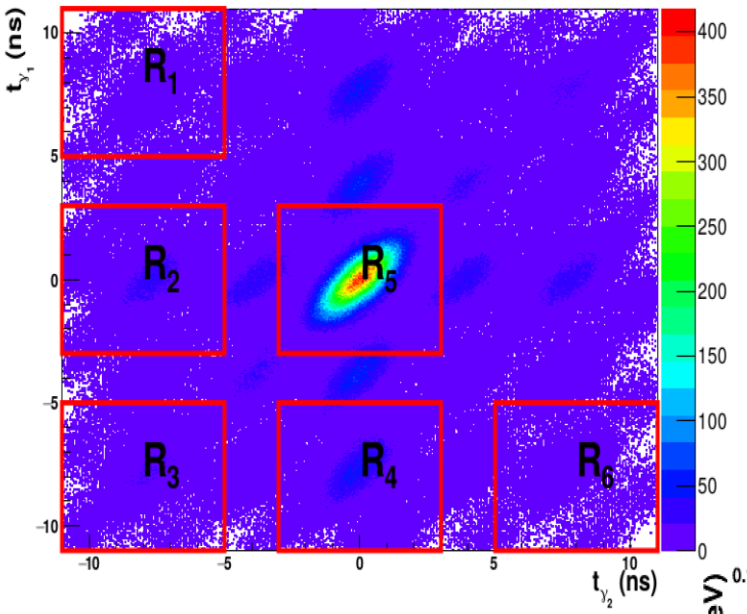
E12-06-114 Kienmatic Settings

x_B label	0.36			0.48				0.60	
$\langle x_B \rangle$	0.36	0.36	0.36	0.48	0.45	0.46	0.46	0.59	0.60
E (GeV)	7.38	8.52	10.59	4.49	8.85	8.85	10.99	8.52	10.59
Q^2 (GeV^2)	3.11	3.57	4.44	2.67	4.06	5.16	6.56	5.49	8.31
W^2 (GeV^2)	6.51	7.29	8.79	3.81	5.62	6.67	8.32	4.58	6.46
$-t_{\min}$ (GeV^2)	0.16	0.17	0.17	0.33	0.35	0.35	0.36	0.67	0.71
ϵ	0.61	0.62	0.63	0.51	0.71	0.55	0.52	0.66	0.50

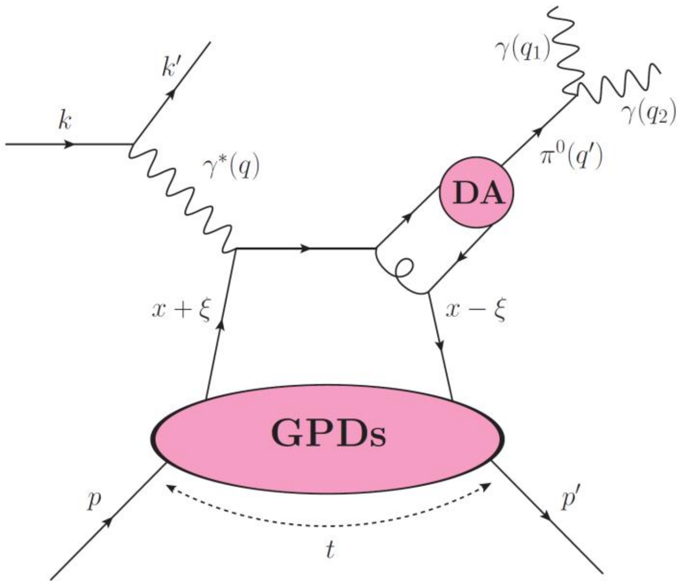


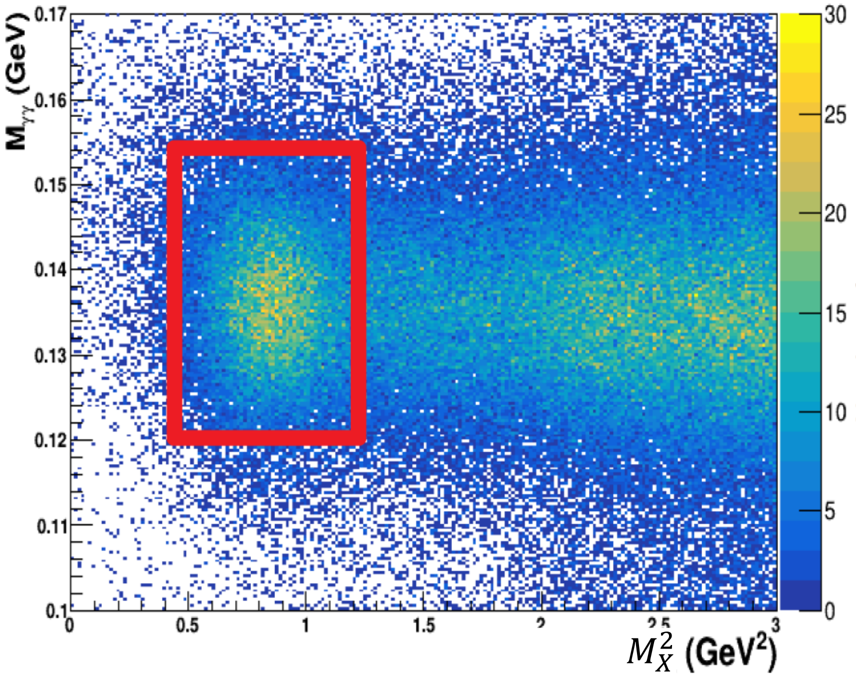
- Ran in 2014 & 2016
- 9 settings with x_B of 0.36, 0.48, and 0.6 and Q^2 ranging from about 3 to 8 GeV^2
- About 50% of allocated 100 PAC days
- Missing PAC days reallocated to the future experiment @ Hall C

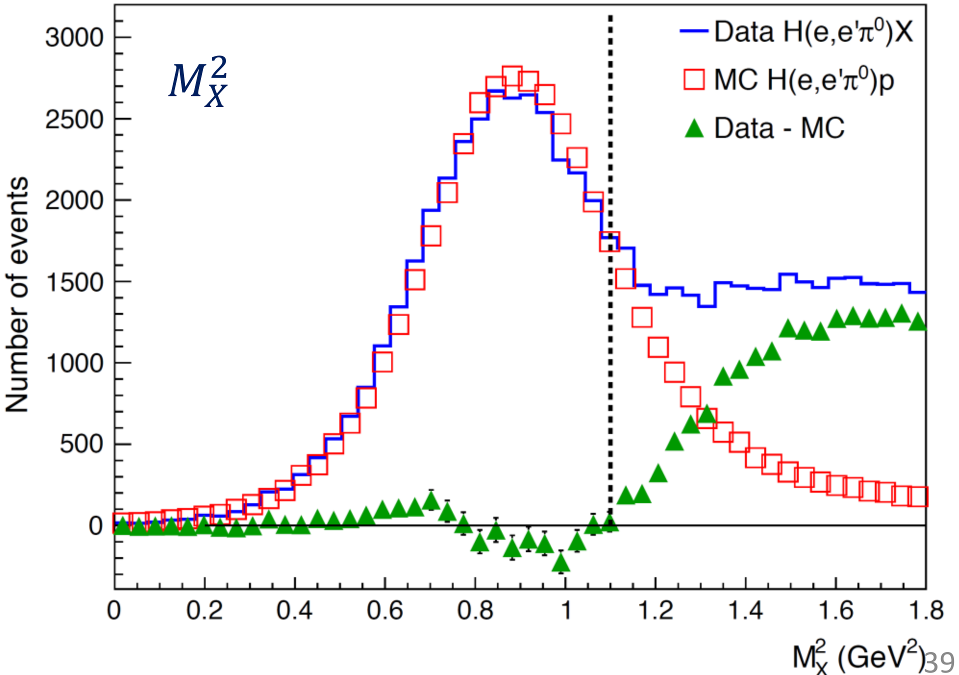
Exclusive π^0 Event Selection



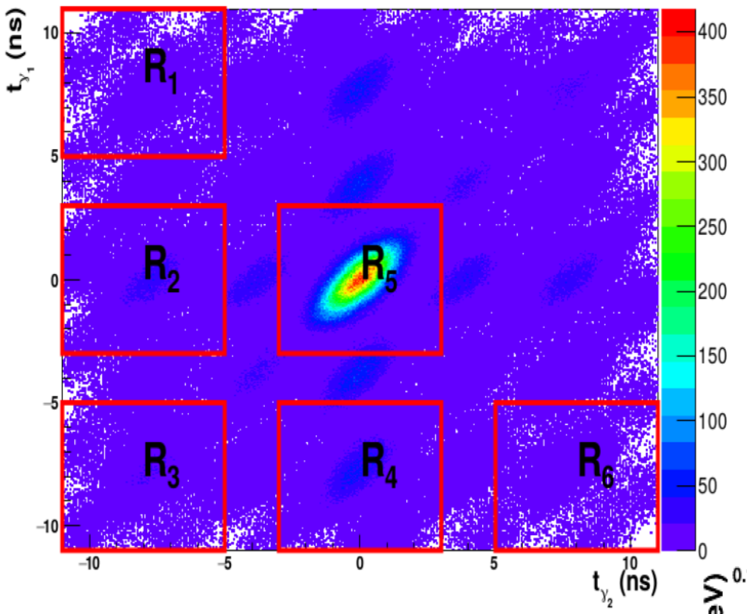
- Main background: accidentals. The backgound in the signal coincidence window, [-3,3] ns, is estimated via other time windows.
- Exclusivity → remove the $M_X^2 = (k + P - k' - q_1 - q_2)^2$ contribution from inclusive channels, threshold ≈ 1.15 GeV²
- π^0 events → select events with invariant mass $M_{\gamma\gamma} = \sqrt{(q_1 + q_2)^2}$ around the π^0 mass



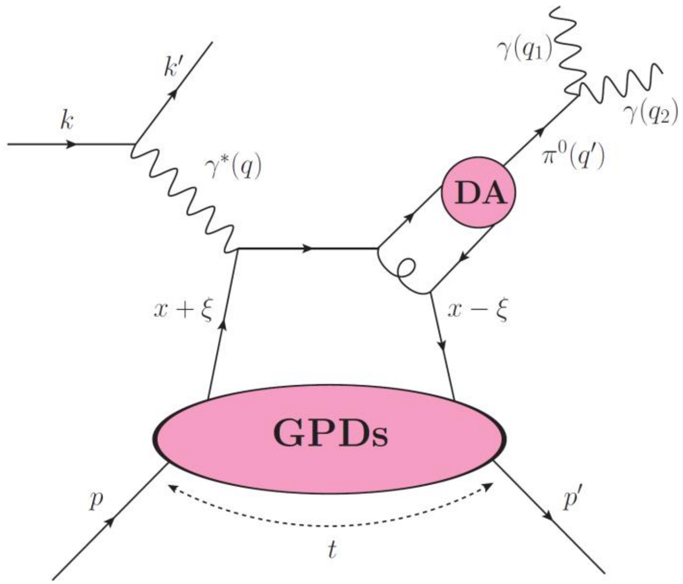


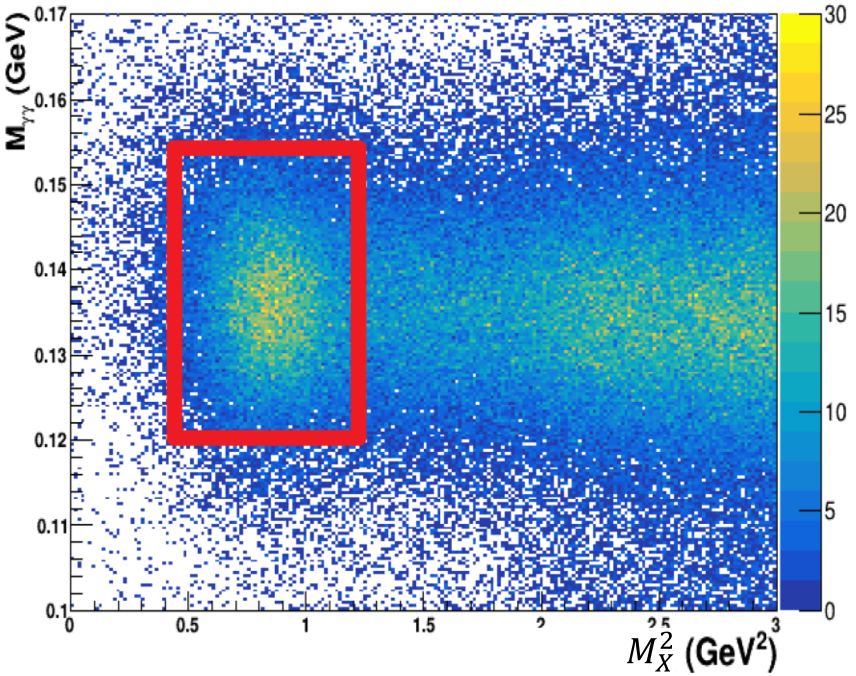


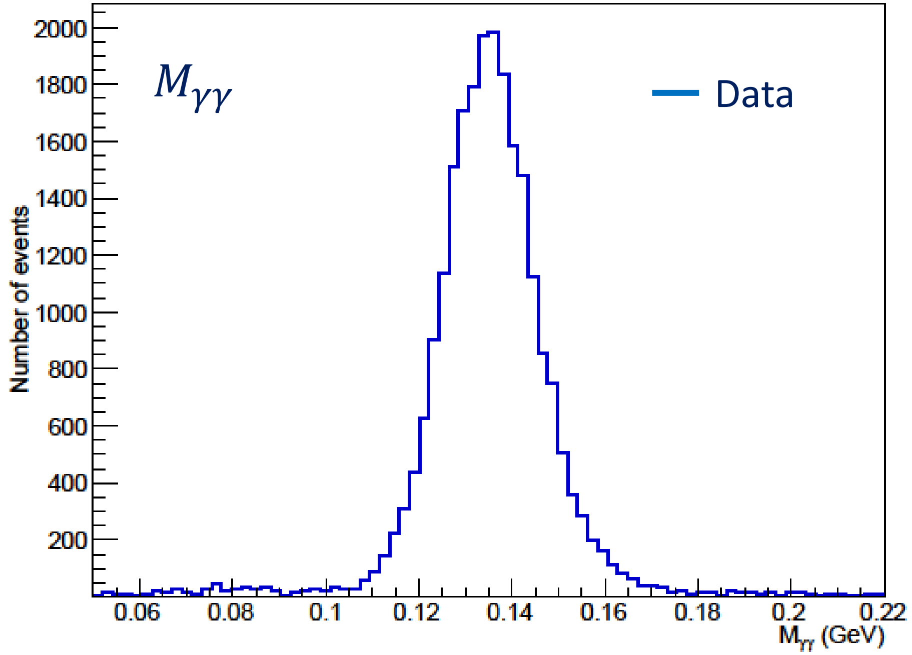
Exclusive π^0 Event Selection



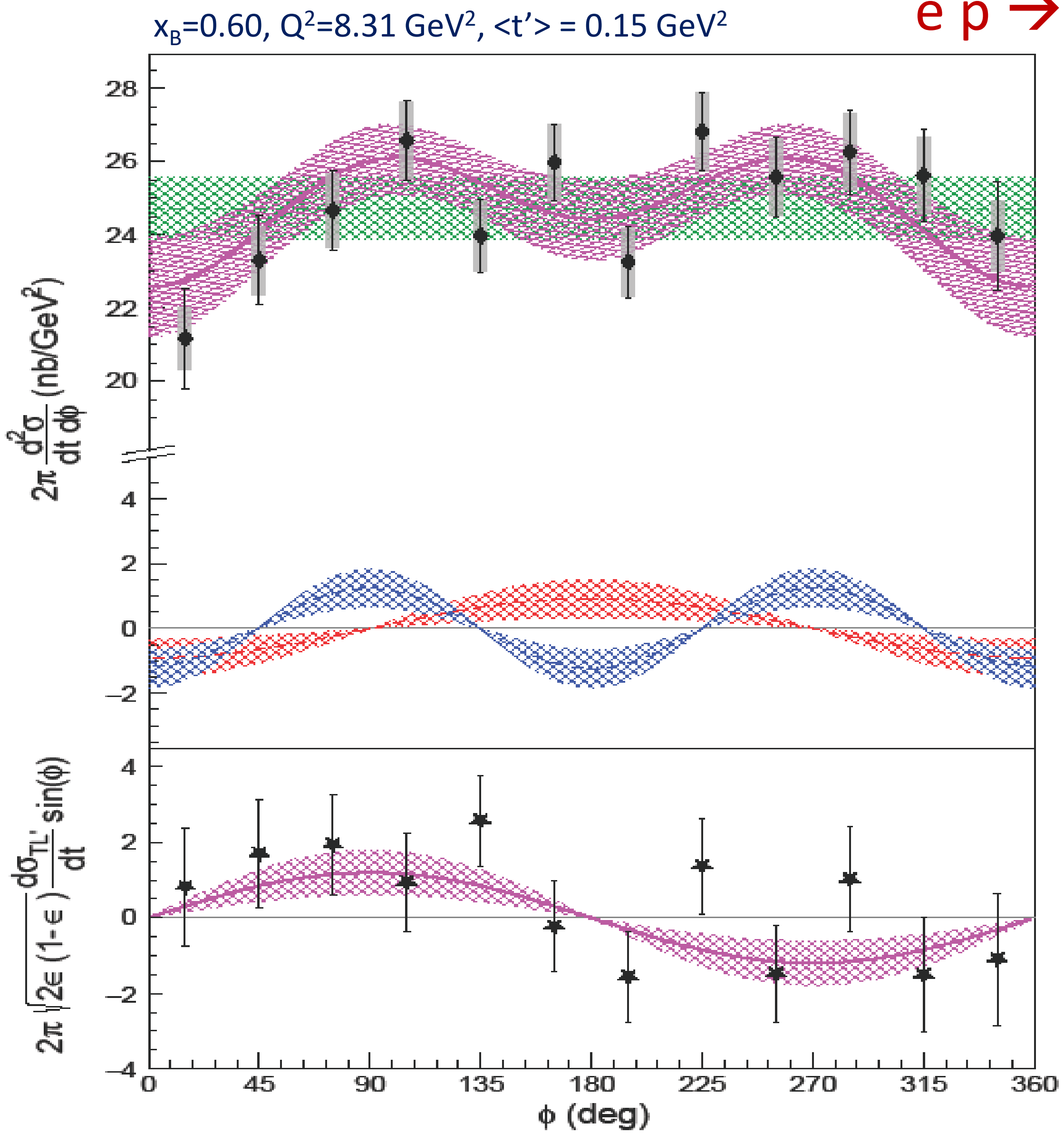
- Main background: accidentals. The backgound in the signal coincidence window, [-3,3] ns, is estimated via other time windows.
- Exclusivity → remove the $M_X^2 = (k + P - k' - q_1 - q_2)^2$ contribution from inclusive channels, threshold ≈ 1.15 GeV²
- π^0 events → select events with invariant mass $M_{\gamma\gamma} = \sqrt{(q_1 + q_2)^2}$ around the π^0 mass







Structure-function Extraction



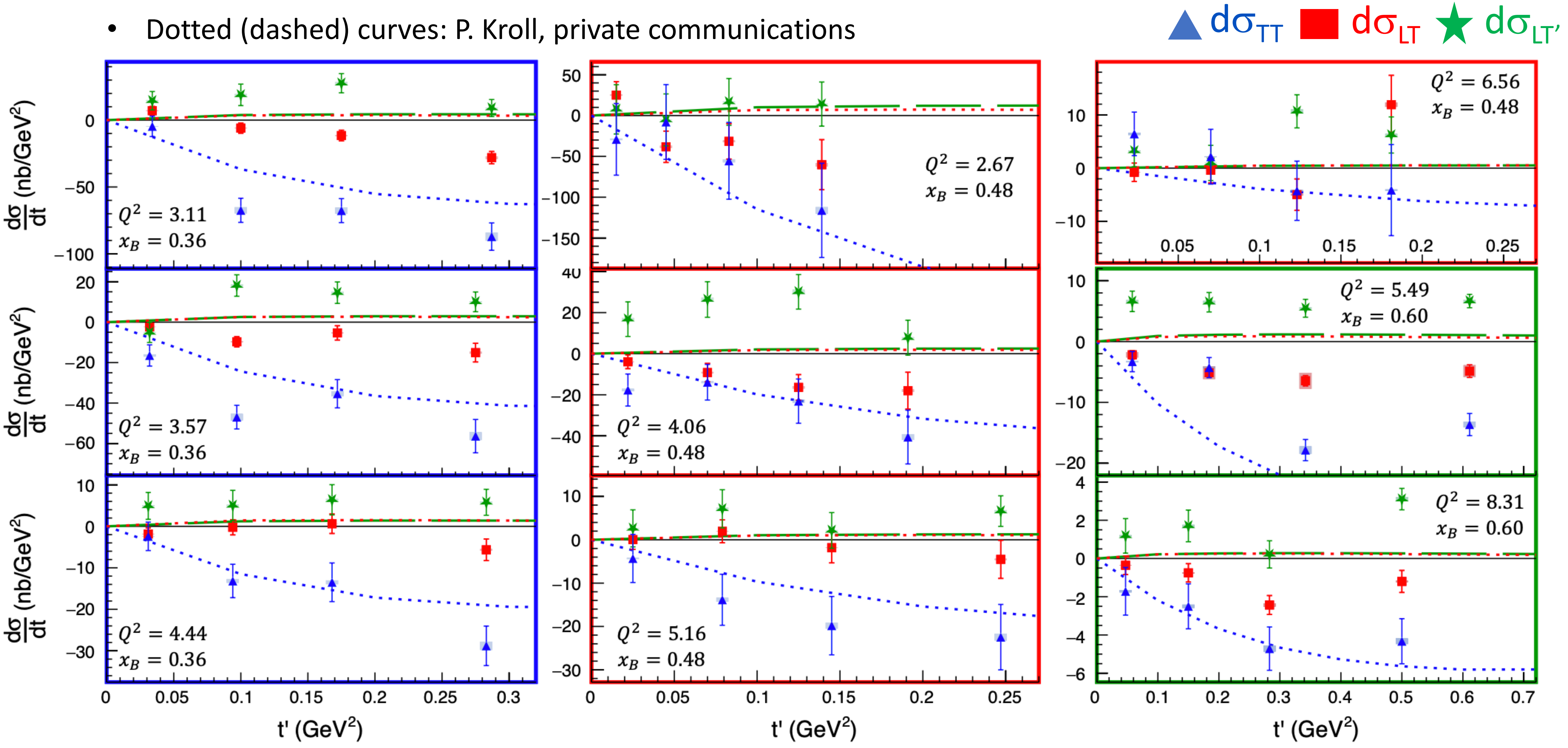
e p → e π^0 p

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\frac{d^2\,\Gamma_\gamma}{dQ^2 dx_B}(Q^2, x_B, E)$$
$$\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin(\phi)\right]$$

- Structure functions extracted for all 9 kinematic settings
- Extract different terms via their corresponding ϕ dependence
- $d\sigma_T$ and $d\sigma_L$ can't be seperated, extracted as $d\sigma_U = d\sigma_T + \varepsilon d\sigma_L$
- Main systematic errors come from deviation observed in DIS events and the exclusivity cuts

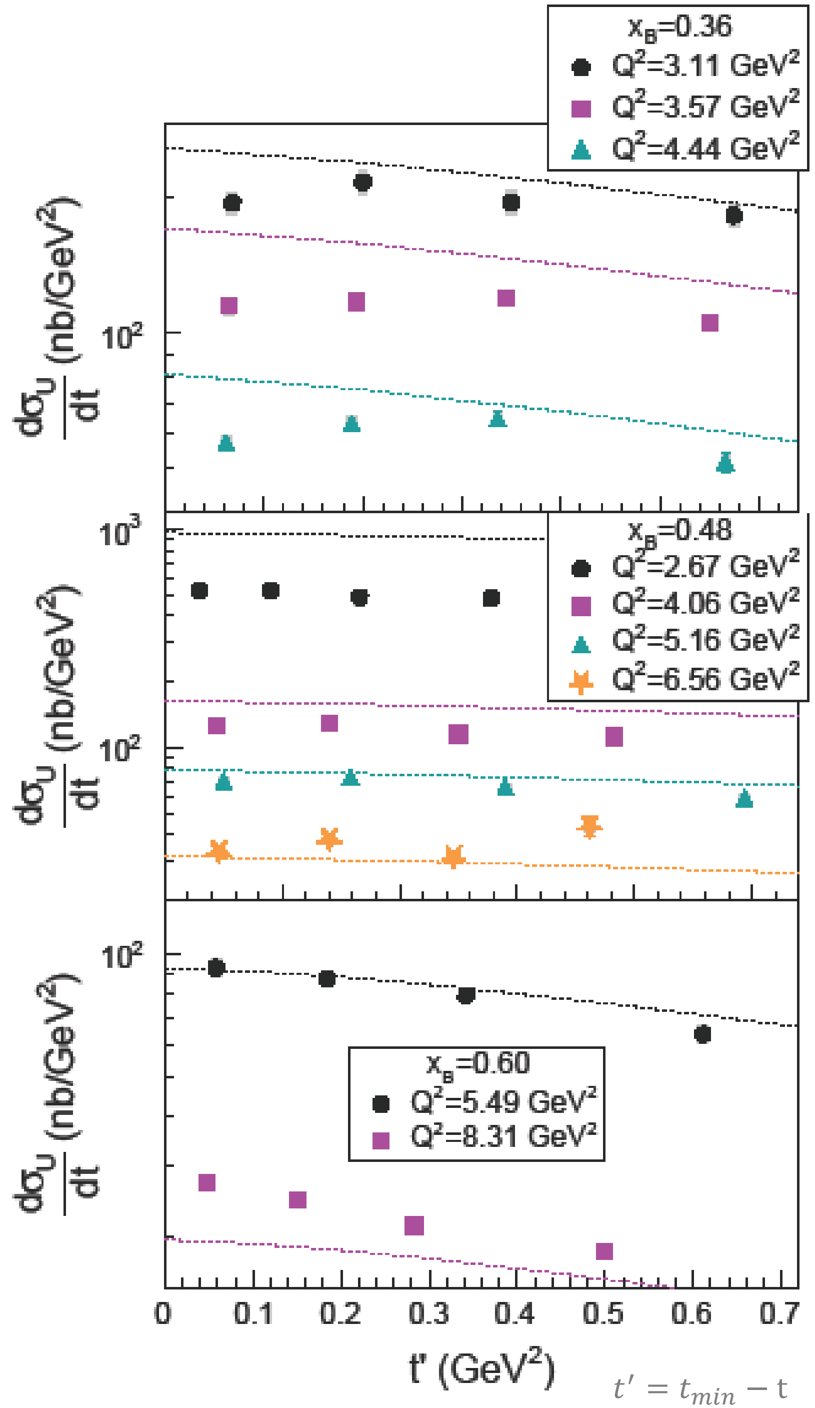
Structure Functions

- Dotted (dashed) curves: P. Kroll, private communications



$t' = t_{min} - t$

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301



$t' = t_{min} - t$

Structure Functions

- Solid Markers: Measured $d\sigma_U = d\sigma_T + \varepsilon d\sigma_L$
- Dotted curves: P. Kroll, private communications

➢ Reasonable agreement in $d\sigma_U$ and $d\sigma_{TT}$

➢ $d\sigma_{TT}$ larger than $d\sigma_{LT}$ & $d\sigma_{LT'}$ in general

- Hint the dominance of σ_T → as suggested by the GK model

➢ GK underestimates both σ_{LT}& $\sigma_{LT'}$

- Suggest a larger contribution of the logitudinal amplitude than the one expected by GK.

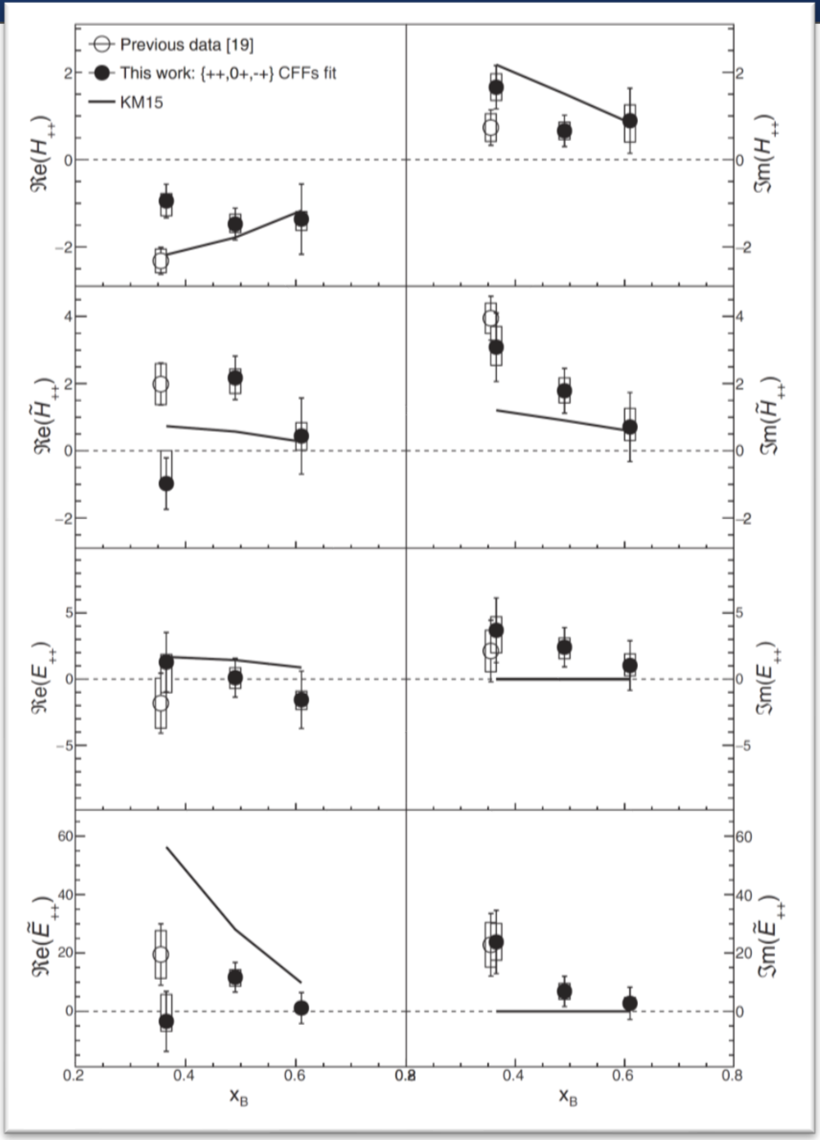
➢ Sign difference in σ_{LT}

- Different from Hall B or COMPASS results

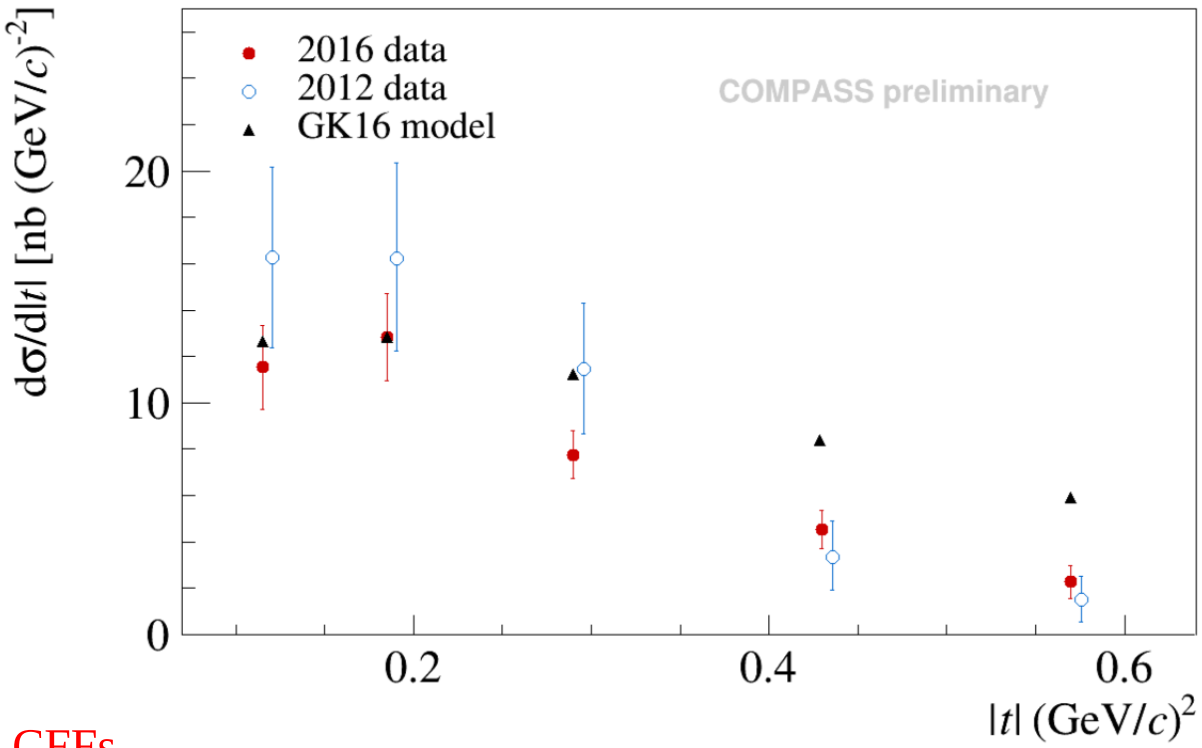
➢ Provide useful input for understanding the GPDs involved in the valence domain

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301

DVCS @ Hall A & Exclusive π^0 @ COMPASS



- ➤ Preliminary results from 2016 data at low ξ ($\langle x_B \rangle = 0.0096$), with statistics about 2.3 times larger than the published 2012 pilot run.
- ➤ New inputs for phenomenological models.

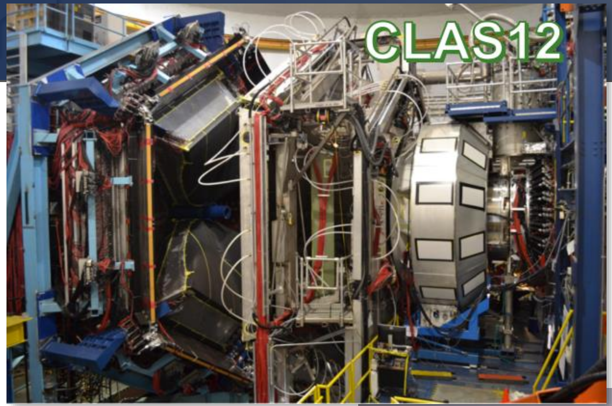


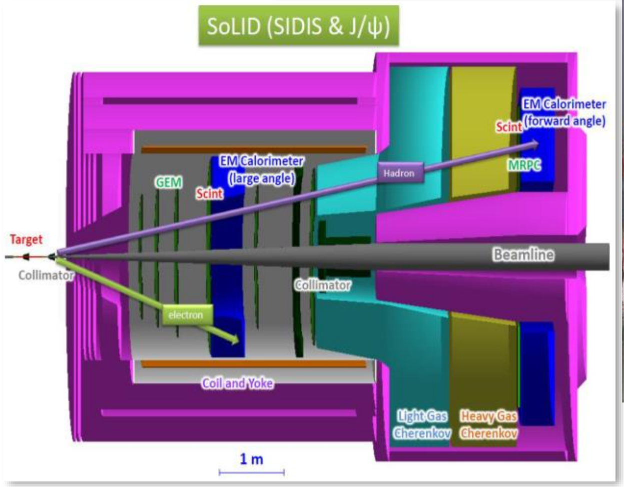
- ➤ First experimental extraction of all four helicity-conserving CFFs

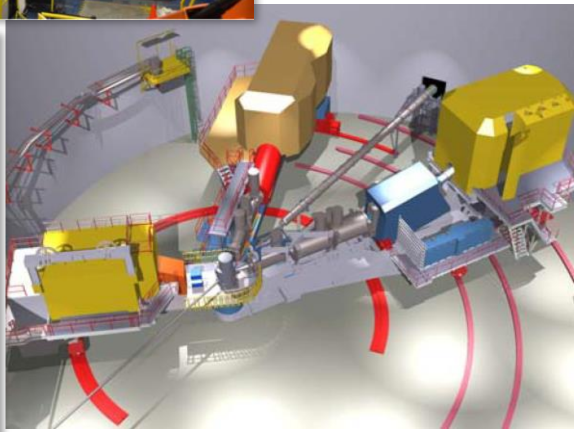
F. Georges et al. (JLab Hall A Collaboration), Phys. Rev. Lett. 128, 252002 (June 2022)

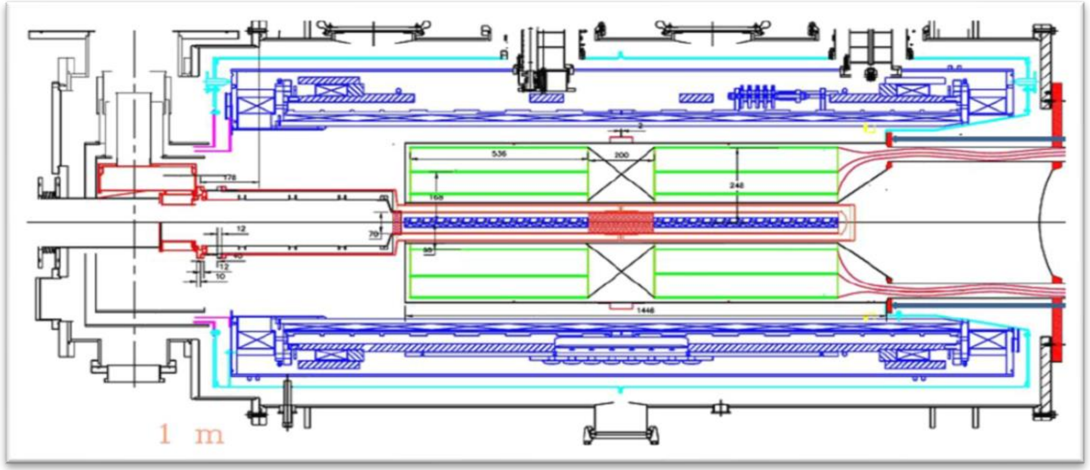
Near Future

- Expect fruitful measurements coming from JLab-12
  - Continuation of DVCS & π^0 at Hall C
  - DVCS, DVMP, TCS, even DDVCS









Silicone proton recoil detector between target & polarizing magnet

- COMPASS/AMBER
  - DVCS → $\mathrm{Re}H$ with charge-spin asymmetry
  - DVMP of $\pi^0, \omega, \rho, J/\psi$
  - Transversely polarized target in AMBER?

Summary & Outlook

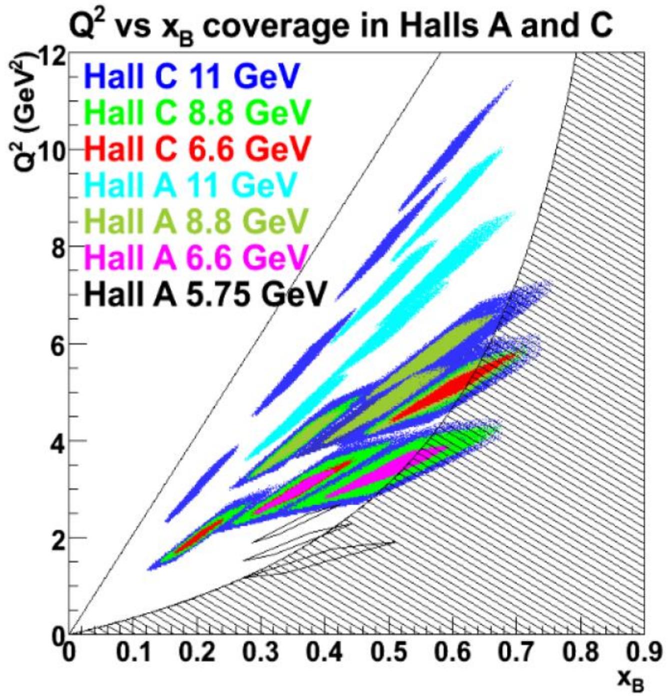
COMPASS: DVCS x-sections with polarized μ+ and μ-

- Beam charge-spin sum → Im$\mathcal{H}$(ξ,t) → Transverse extension of partons
- Beam charge-spin difference → Re$\mathcal{H}$(ξ,t) → D-term, pressure distribution
- Meson Production → Flavor decomposition, gluon GPD

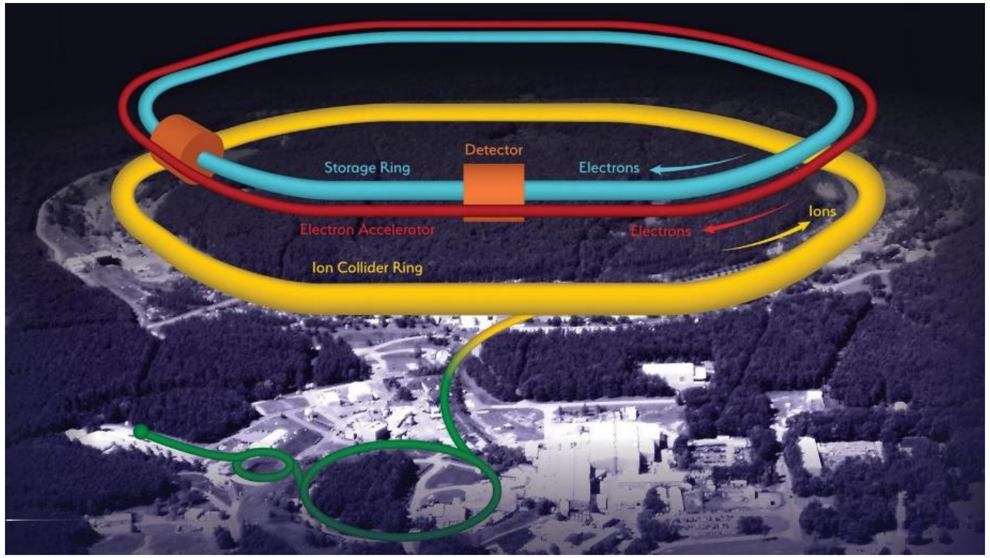
Jlab Hall A E12-06-114: Exclusive π^0 Production

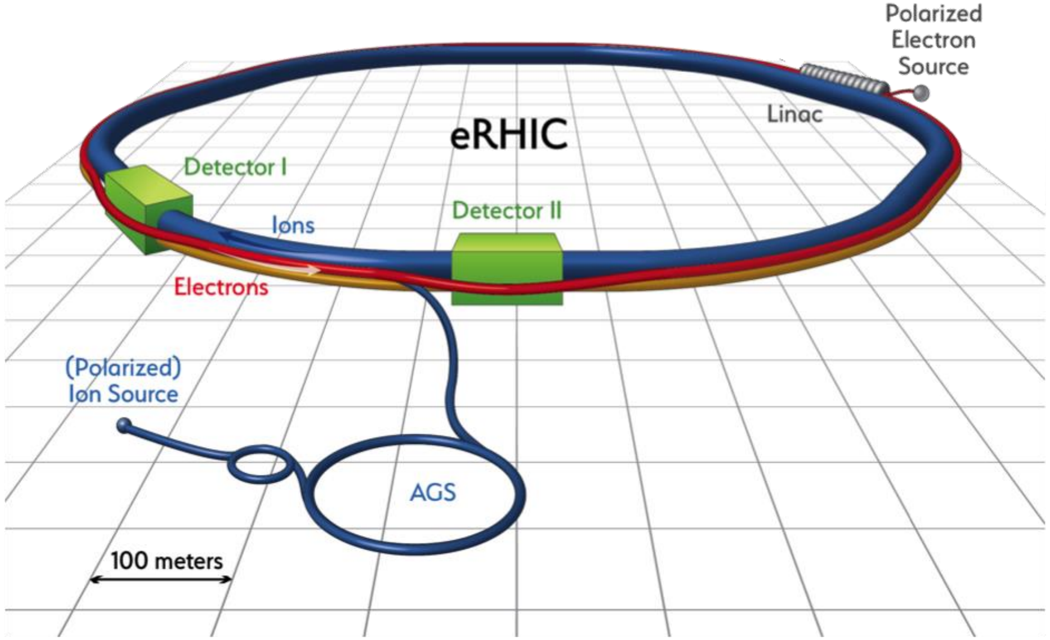
- Reasonable description of results by GK model, improvements required
- Provide inputs for transversity GPD parameterization
- Extension to higher Q^2 and lower x_B
- σ_T and σ_L separation of π^0 production

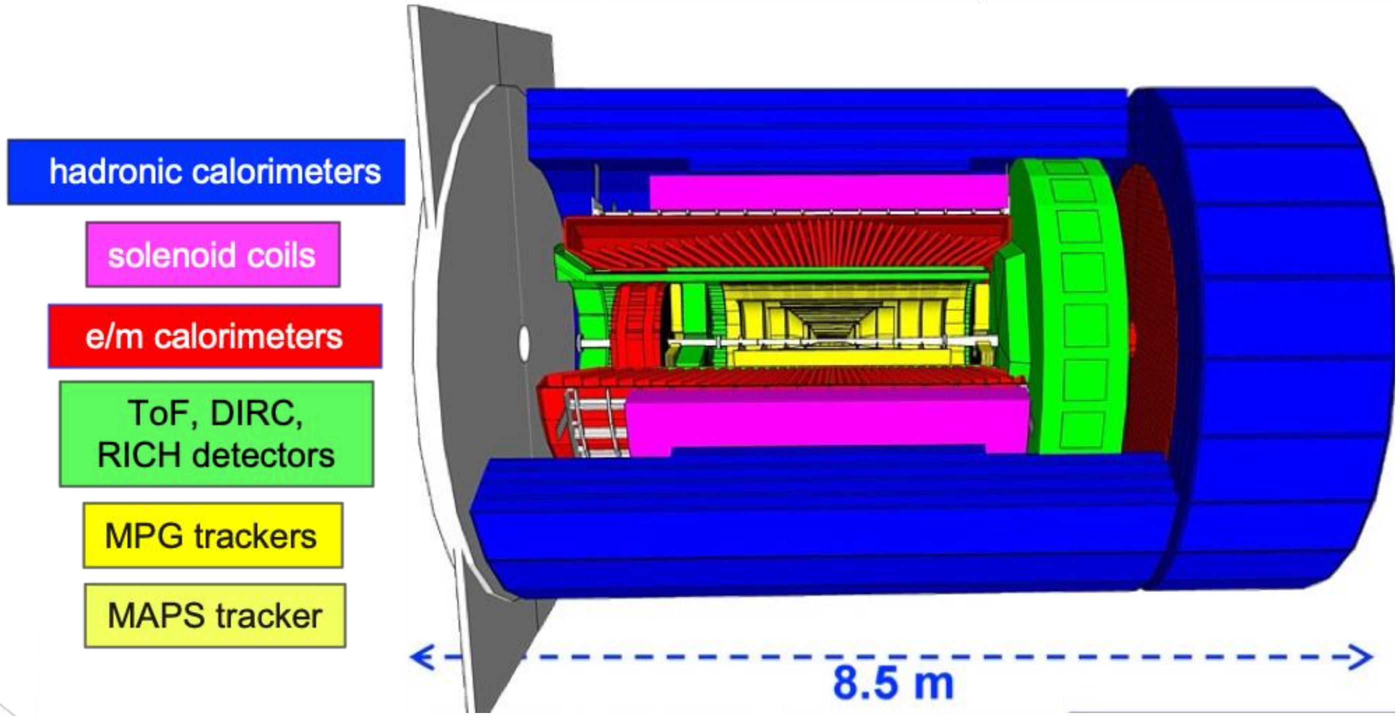
} Hall C E12-13-010 (applies to the last two items)



Looking forward to GPD Measurements at EIC







Thank you

Backup Slides

COMPASS^{++}/AMBER

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

- 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

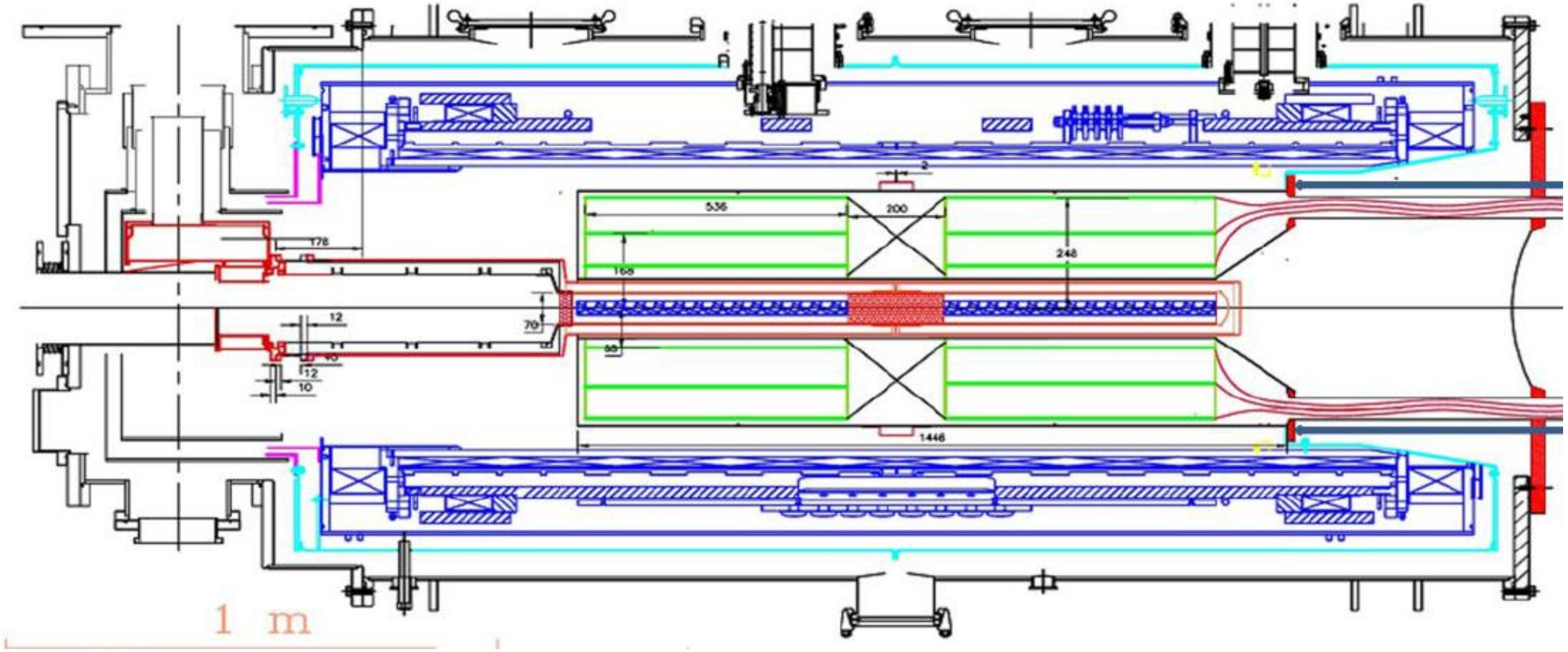
Proposed physics goals

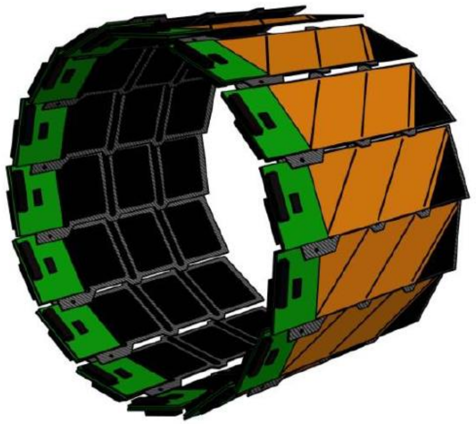
Proton Radius
Meson PDF – gluon PDF
Proton spin structure
3D imaging (TMDs and GPDs)
Hadron spectroscopy
Anti-matter cross section

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	$4 \cdot 10^6$	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	$\sim$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	$\sim$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	

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

Beam Charge-spin Difference

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

BCSA = $\mathcal{D}_{CS,\,U}/\mathcal{S}_{CS,\,U} = A_0 + A_{CS,U}^{\cos\phi}\cos\phi + A_2\cos 2\phi$

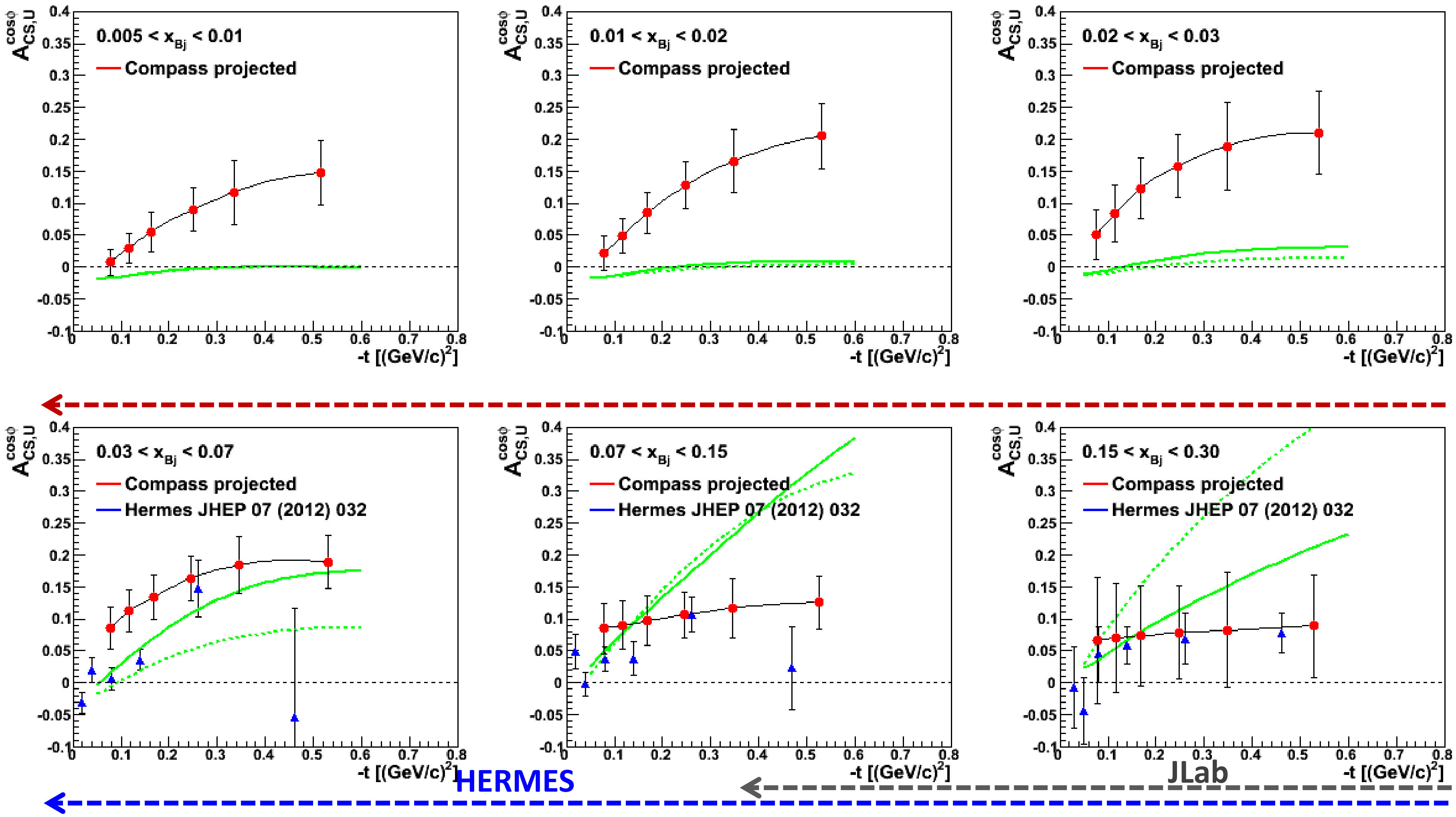
$c_1^I = \mathcal{R}e\, F_1 \mathcal{H}$

VGG

KM10 – fit to data

- 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?



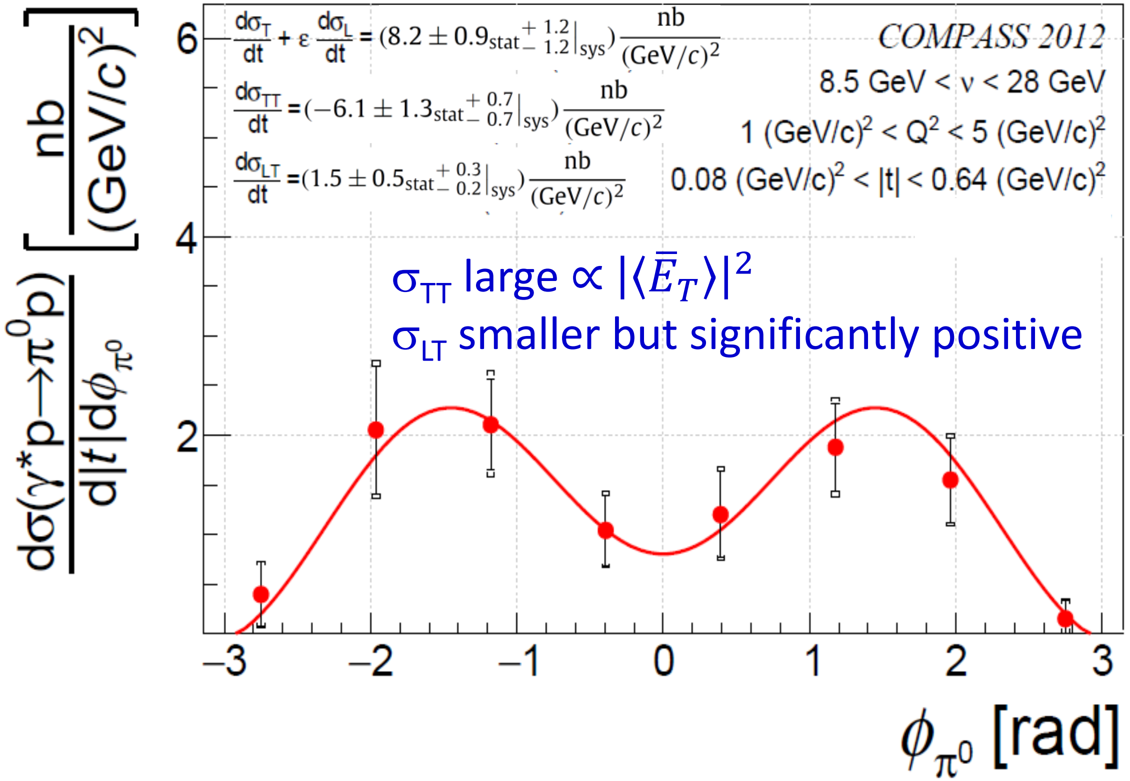
COMPASS 2 years of data Eμ= 160 GeV 1 < Q^2 < 8 GeV^2

2012 Exclusive π^0 Prod. on Unpolarized Proton

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

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

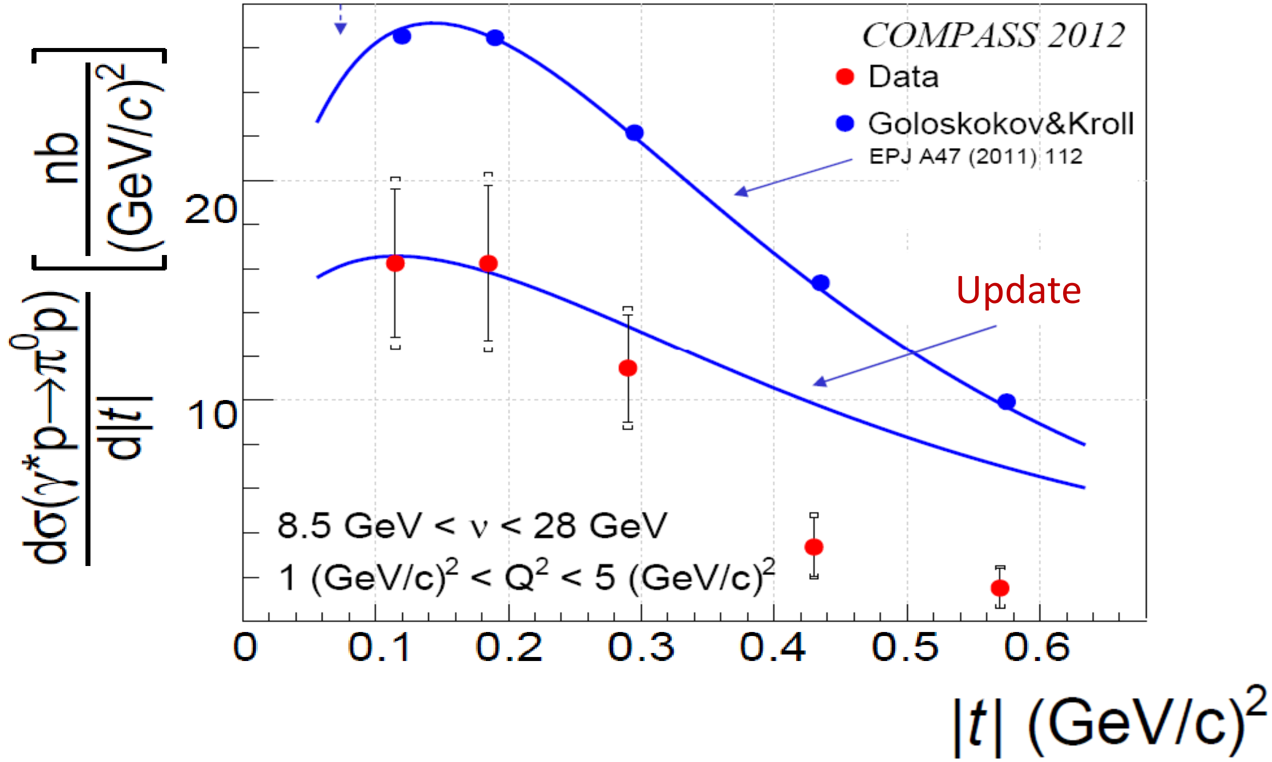
Chiral-odd GPDs



σ_{TT} large $\propto |\langle \bar{E}_T \rangle|^2$

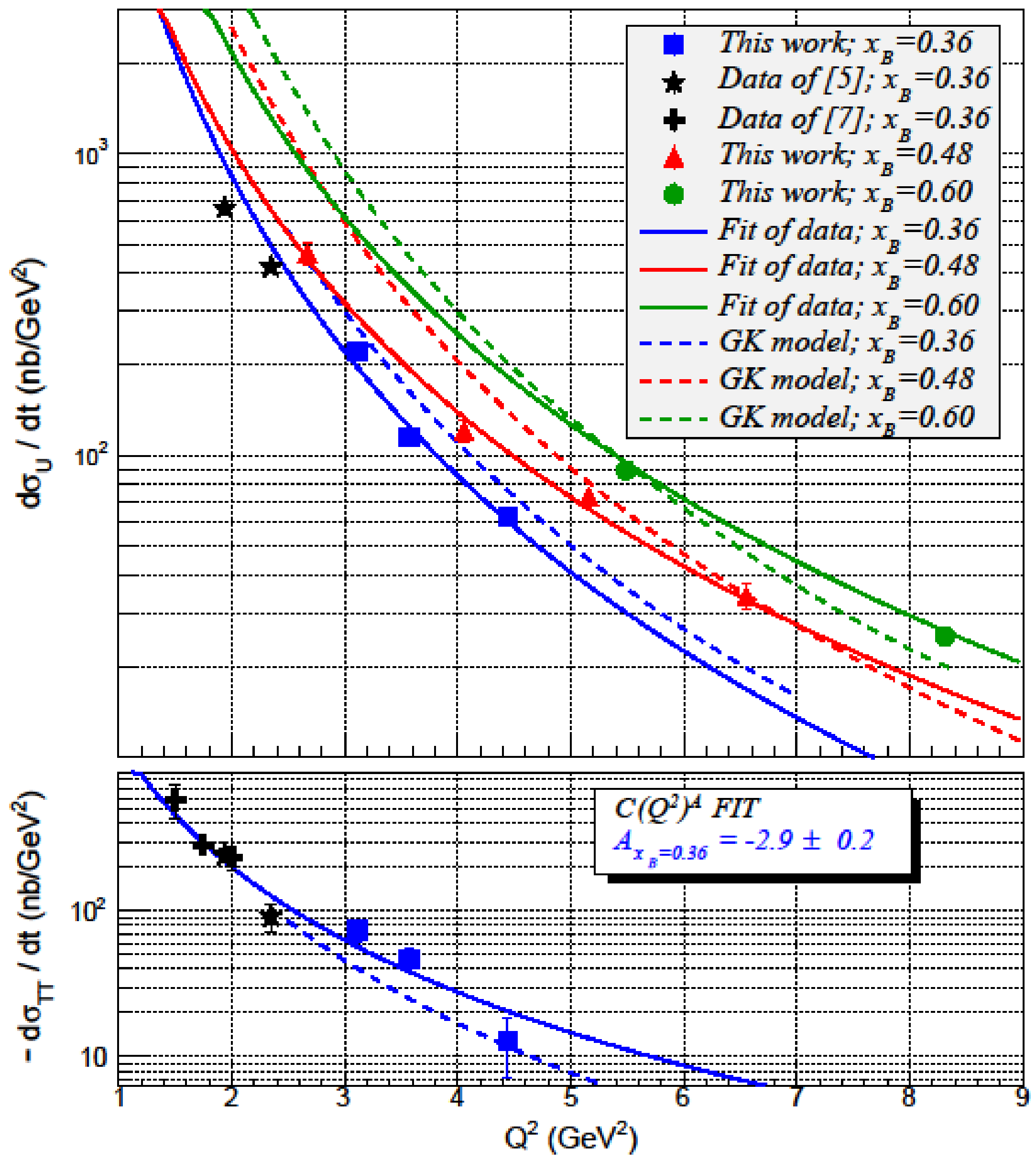
σ_{LT} smaller but significantly positive

A dip at small t would indicate the significance of $\bar{E}_T$



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

Q^2 Dependence



- Dashed curves: P. Kroll, private communications
- Solid Markers: Experimental measurements

<t'> = 0.1 GeV^2

- ■ This work, $x_B = 0.36$
- ▲ This work, $x_B = 0.48$
- ● This work, $x_B = 0.60$
- ★ E. Fuchey *et al*, Phys. Rev. C 83, 025201 (2011)
- ✚ M. Defurne *et al*, Phys. Rev. Lett. 117, 262001 (2016)

➢ $C(Q^2)^A$ exp(-Bt') fit to experimental results of $d\sigma_U$ in different x_B → solid curves

$x_B = 0.36 \rightarrow A = -3.3 \pm 0.1$

$x_B = 0.48 \rightarrow A = -2.9 \pm 0.1$

$x_B = 0.60 \rightarrow A = -3.1 \pm 0.1$

➢ Q^2 dependence closer to Q^{-6}, rather than Q^{-8} as expected for σ_T at high Q^2

M. Dlamini *et al*, Phys. Rev. Lett **127**, 152301

Hall A DVCS Cross Sections

x_B=0.36, Q^2=3.7GeV^2, t=–0.33GeV^2; x_B=0.48, Q^2=5.4 GeV^2, t=–0.33 GeV^2; x_B=0.6, Q^2=8.4 GeV^2, t=–0.91 GeV^2