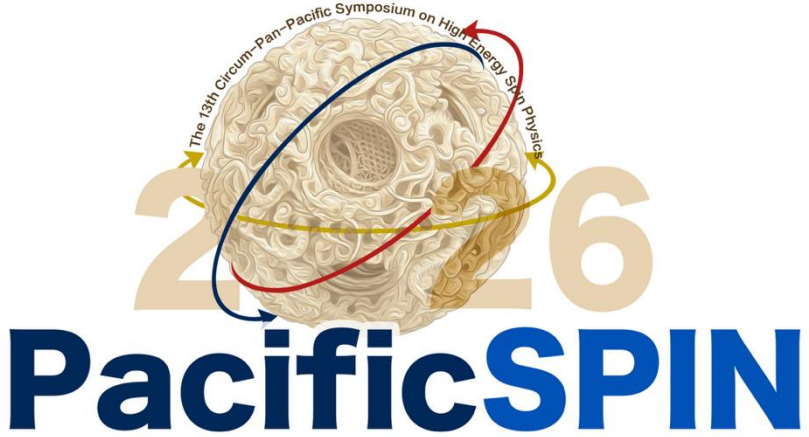
GPD Measurements from COMPASS and JLab Hall A/C



Taipei, Taiwan

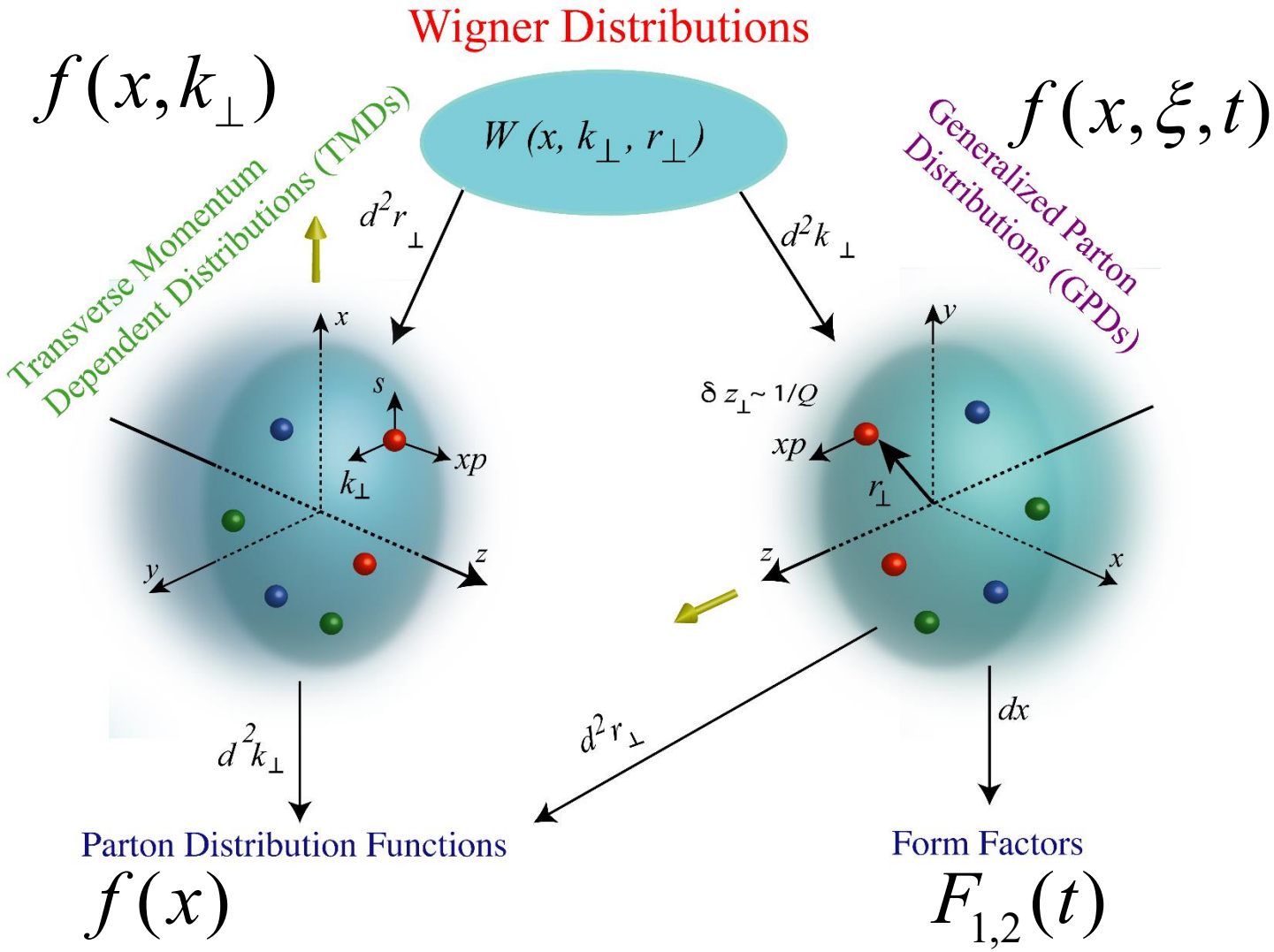
October 28th , 2026

Po-Ju Lin

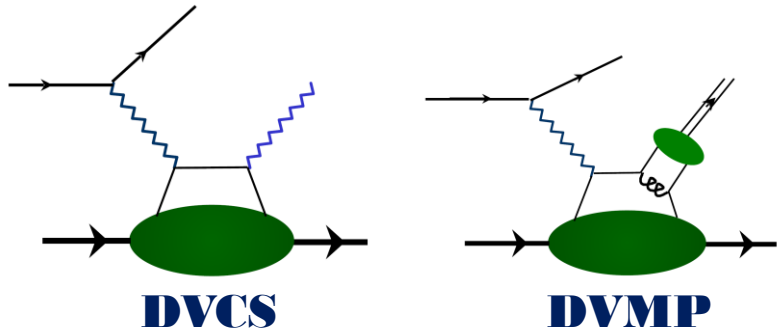
Department of Physics, National Central University

Multi-dimensional Partonic Structures

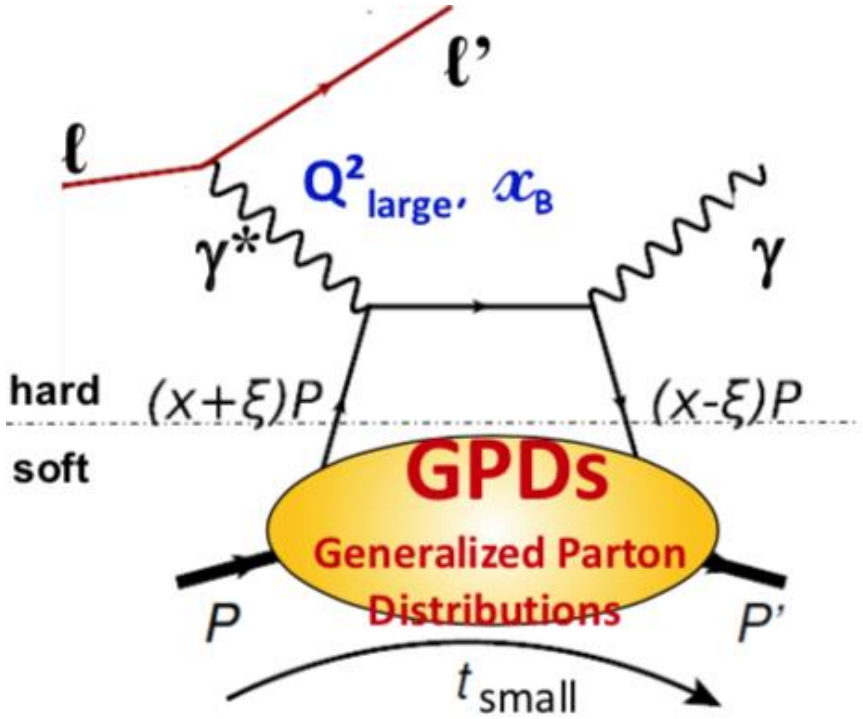
http://www.int.washington.edu/PROGRAMS/17-3/



- GPDs correlate the transverse position to the longitudinal momentum of partons. Provide interesting insights of hadron properties.
- GPDs can be accessed via exclusive processes



DVCS



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

- The golden channel. 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.

CFF $\mathcal{H}(\xi, t)$ — GPD $\mathbf{H}(x, \xi, t)$

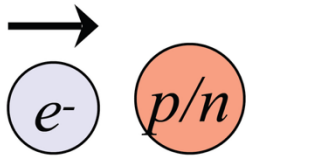
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

REAL part — Imaginary part

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

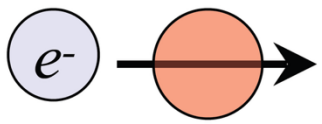
Sensitivity to CFFs

Beam, target polarisation



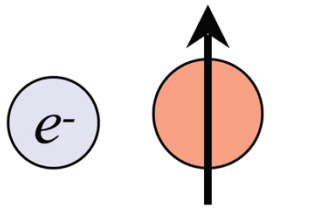
$$\Delta\sigma_{LU} \sim \sin\phi\, \Im(F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E)\, d\phi$$

→ Proton: $Im\{\boldsymbol{H_p}, \tilde{H}_p, E_p\}$; Neutron: $Im\{H_n, \tilde{H}_n, \boldsymbol{E_n}\}$



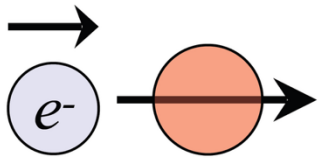
$$\Delta\sigma_{UL} \sim \sin\phi\, \Im(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \xi \frac{t}{4M^2} F_2 \tilde{E} + ...)\, d\phi$$

→ Proton: $Im\{\boldsymbol{H_p}, \tilde{\boldsymbol{H}}_p\}$; Neutron: $Im\{\boldsymbol{H_n}, E_n, \tilde{E}_n\}$



$$\Delta\sigma_{UT} \sim \cos\phi\, \Im(\frac{t}{4M^2}(F_2 H - F_1 E) + ...) d\phi$$

→ Proton: $Im\{\boldsymbol{H_p}, \boldsymbol{E_p}\}$; Neutron: $Im\{\boldsymbol{H_n}\}$

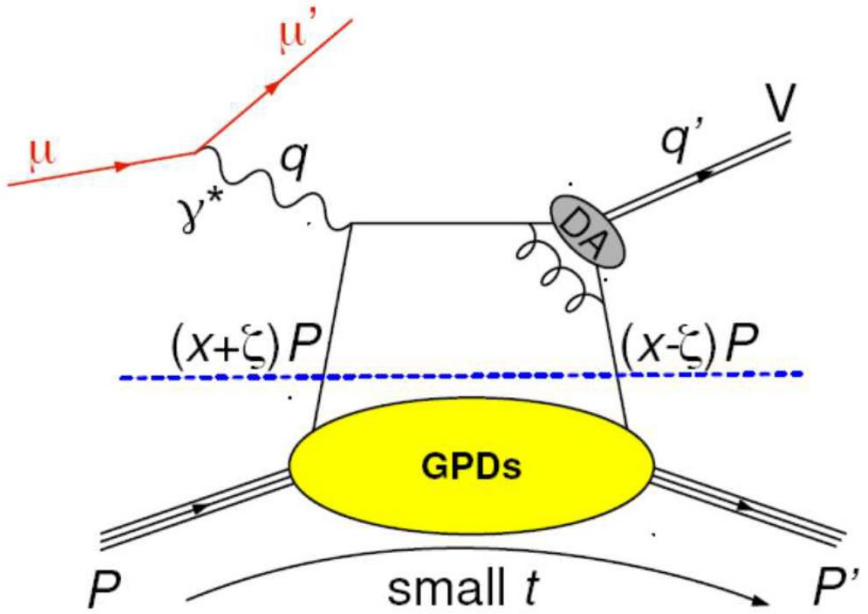


$$\Delta\sigma_{LL} \sim (A + B\cos\phi)\, \Re(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + ...) d\phi$$

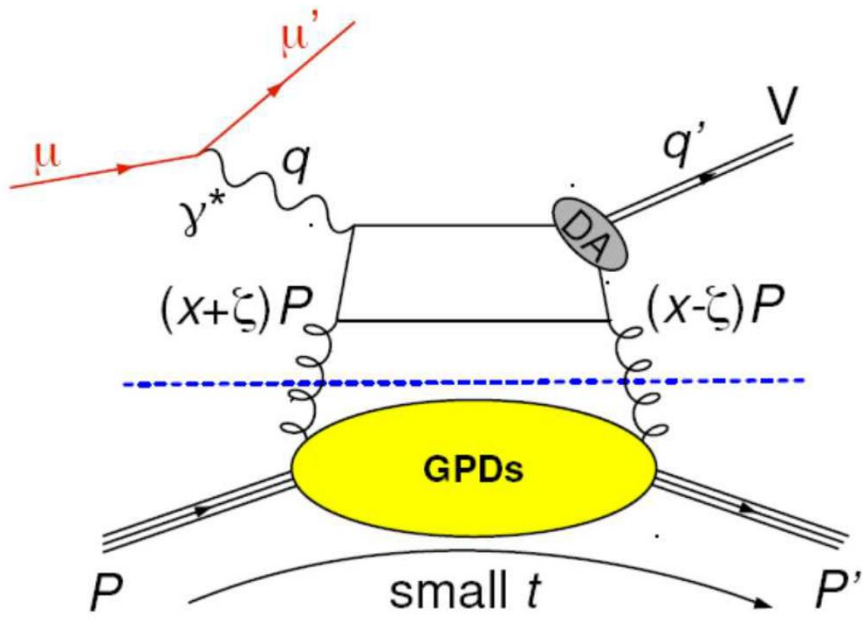
→ Proton: $Re\{\boldsymbol{H_p}, \tilde{\boldsymbol{H}}_p\}$; Neutron: $Re\{\boldsymbol{H_n}, E_n, \tilde{E}_n\}$

GPDs in Deeply Virtual Meson Production

quark contribution



gluon contribution



- Ability to probe the chiral-odd GPDs.
- Examine Universality of GPDs
- Flavor decomposition

Chiral-odd (transversity) GPDs:

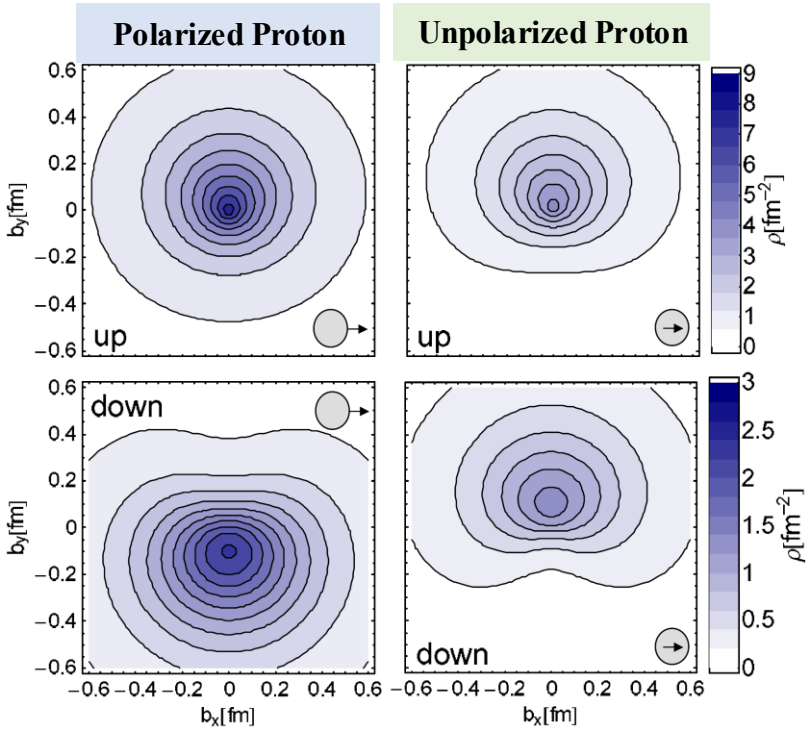
$H_T^q(x, \xi, t)$ $E_T^q(x, \xi, t)$

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

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

Chiral-odd GPDs

Nucleon polarization	Quark polarization: U	Quark polarization: L	Quark polarization: T
U	H		$\bar{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$



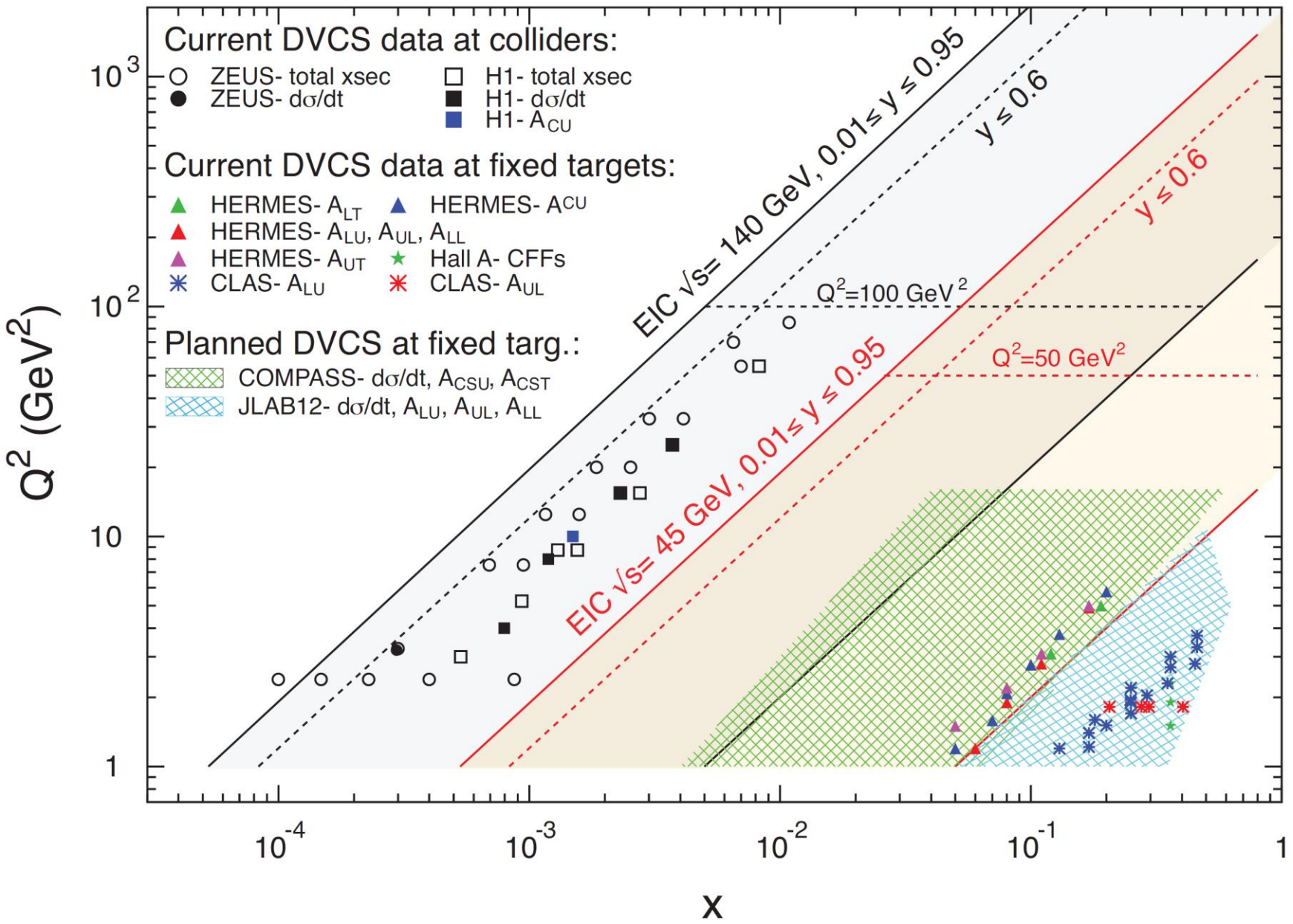
Described by E

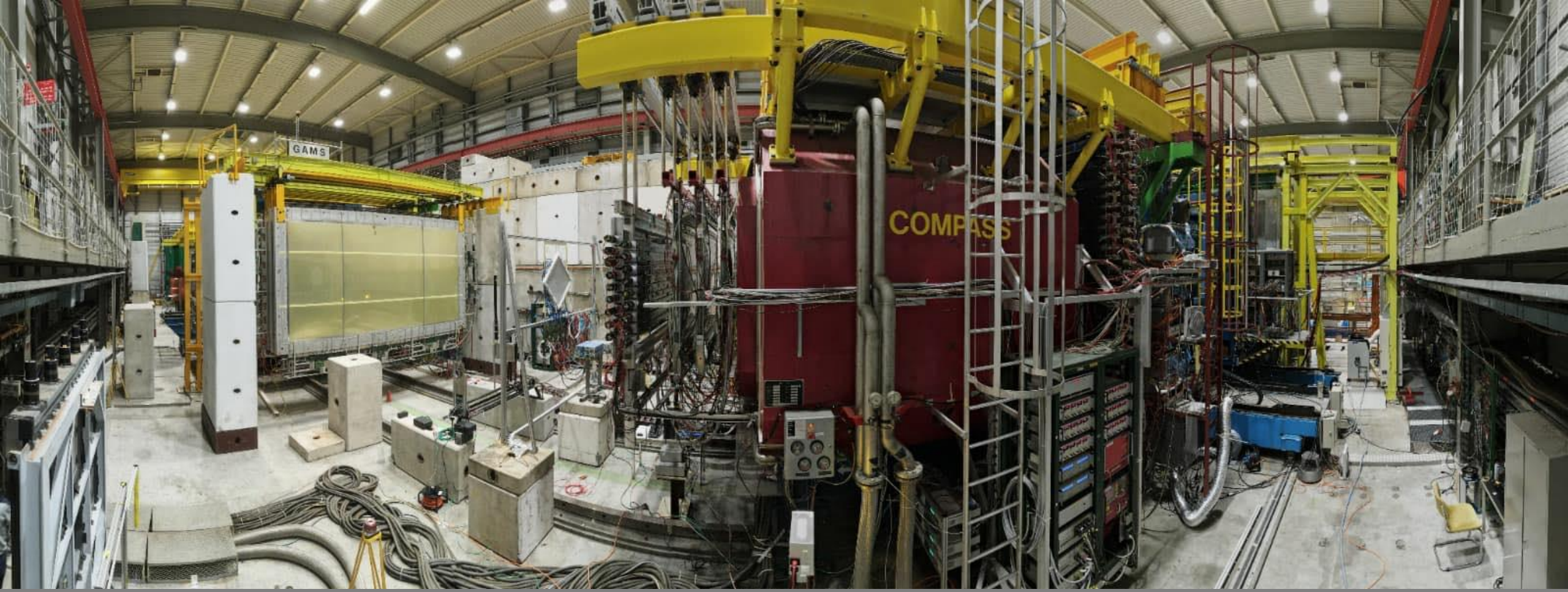
Described by $\bar{E}_T = 2\tilde{H}_T + E_T$

Lattice Calculation: Gockeler *PRL* 222001 (2007)

- $\bar{E}_T$ is related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon
- Chiral-odd GPDs H_T
  - Generalization of transversity distribution $h_1(x)$
    → related to the transverse spin structure
  - Tensor charge

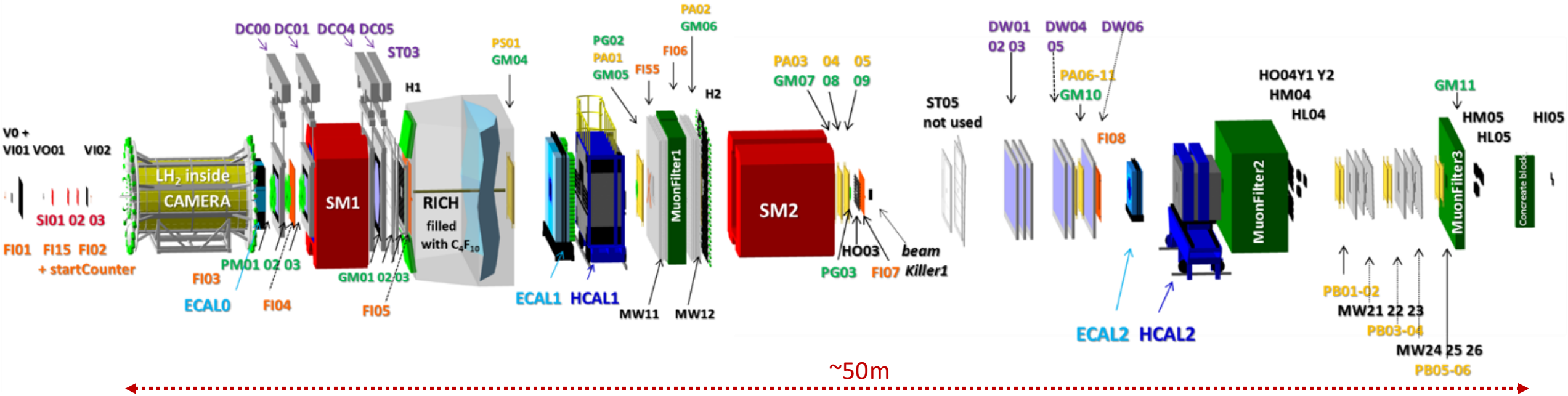
Landscape


Current DVCS data at colliders:
ZEUS- total xsec
ZEUS- dσ/dt
H1- total xsec
H1- dσ/dt
H1- A_CU
Current DVCS data at fixed targets:
HERMES- A_LT
HERMES- A^CU
HERMES- A_LU, A_UL, A_LL
HERMES- A_UT
Hall A- CFFs
CLAS- A_LU
CLAS- A_UL
Planned DVCS at fixed targ.:
COMPASS- dσ/dt, A_CSU, A_CST
JLAB12- dσ/dt, A_LU, A_UL, A_LL
EIC √s= 140 GeV, 0.01≤ y ≤ 0.95
y ≤ 0.6
Q²=100 GeV²
Q²=50 GeV²
y ≤ 0.6
EIC √s= 45 GeV, 0.01≤ y ≤ 0.95
Q² (GeV²)
10³
10²
10
1
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
x



GPD Measurements @ COMPASS

COMPASS Setup for Exclusive Processes



- Priamary beam – 400 GeV p from SPS
  - Impinging on Be production target
- 190 GeV secondary hadron beams
  - h^- beam: $97\%\ \pi^-, 2\%\ K^-, 1\%\ p$
  - h^+ beam: $75\%\ \pi^+, 24\%\ p, 1\%\ K^+$
- **160 GeV tertiary muon beams**
  - **$\mu^\pm$ longitudinally polarized**

Large-acceptance forward spectrometer

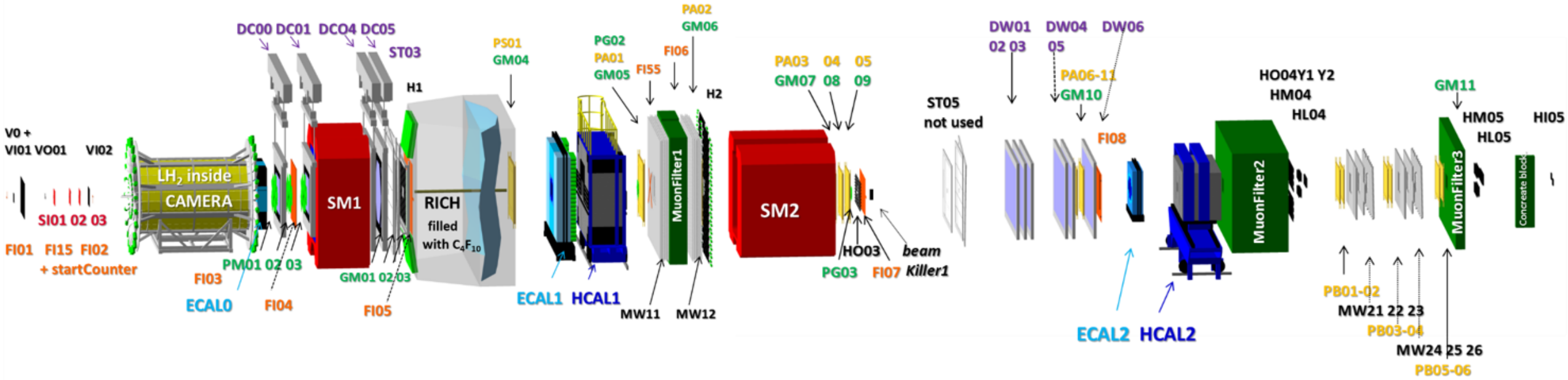
- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC, DC, straw
- PID – CEDARs, RICH, calorimeters, Muon Walls

Various targets:

- Polarized soild-state NH_3 or ^6LiD
- Liquid H_2
- Solid-state nuclear targets

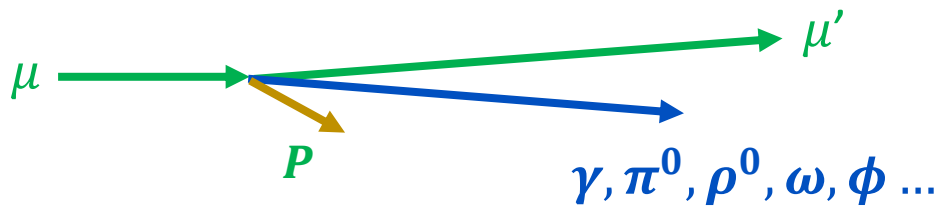
❖ NIM A 577 (2007) & NIM A 779 (2015) 69

COMPASS Setup for Exclusive Processes

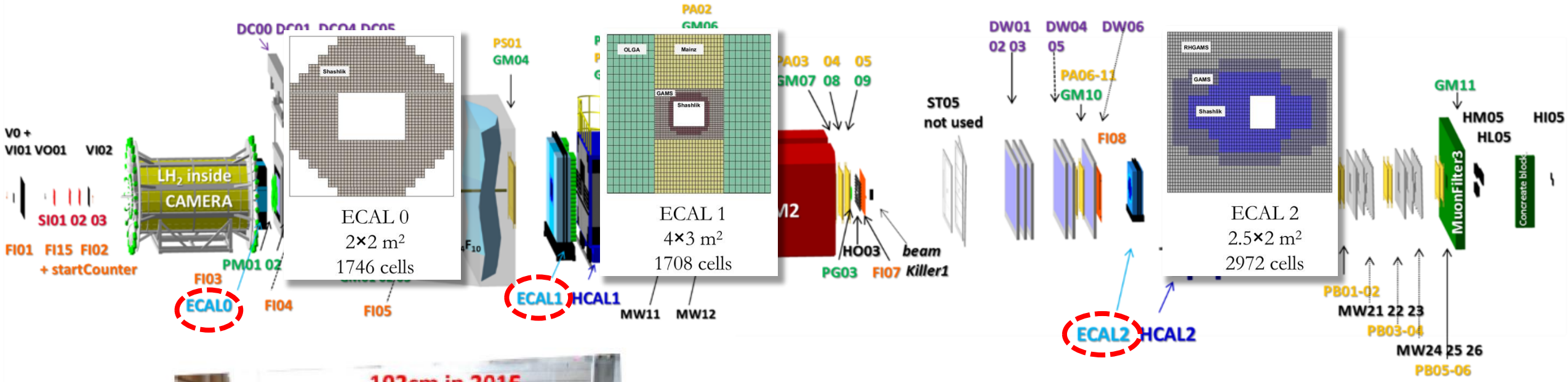


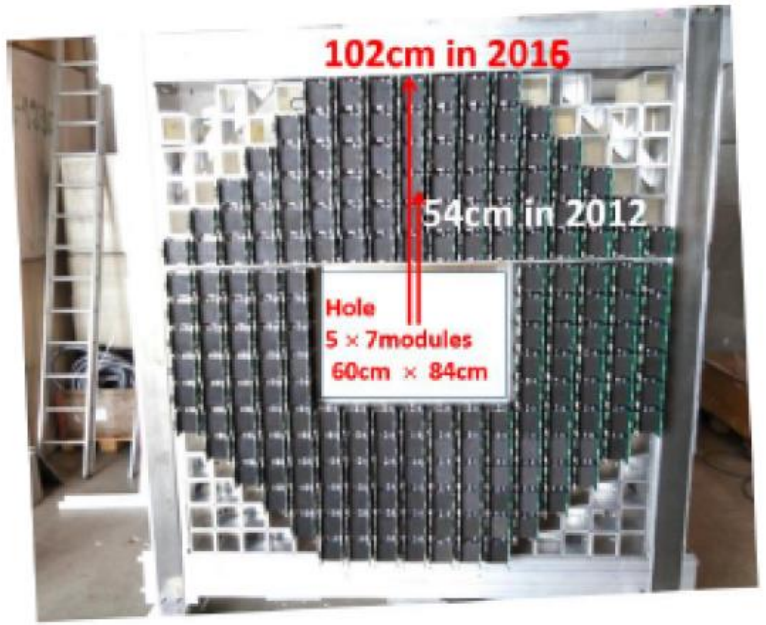
- Priamary beam – 400 GeV p from SPS
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  - h^- beam: $97\%\ \pi^-, 2\%\ K^-, 1\%\ p$
  - h^+ beam: $75\%\ \pi^+, 24\%\ p, 1\%\ K^+$
- **160 GeV tertiary muon beams**
  - **$\mu^\pm$ longitudinally polarized**

Exclusive Muoproduction

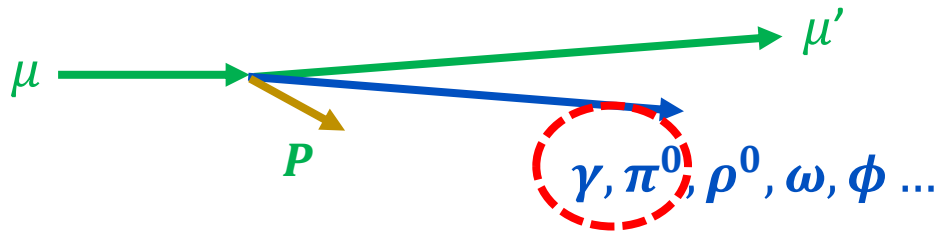


COMPASS Setup for Exclusive Processes

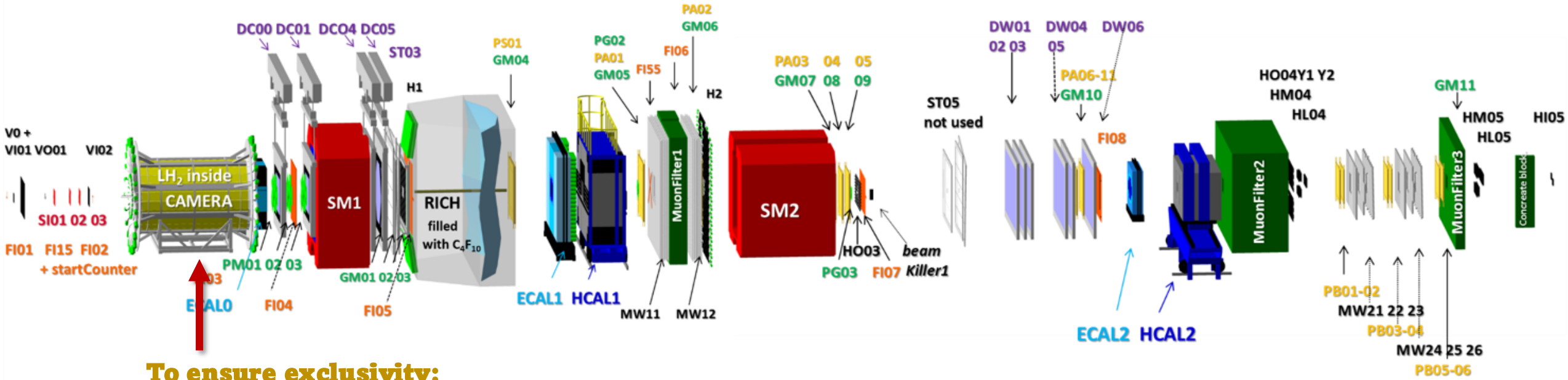




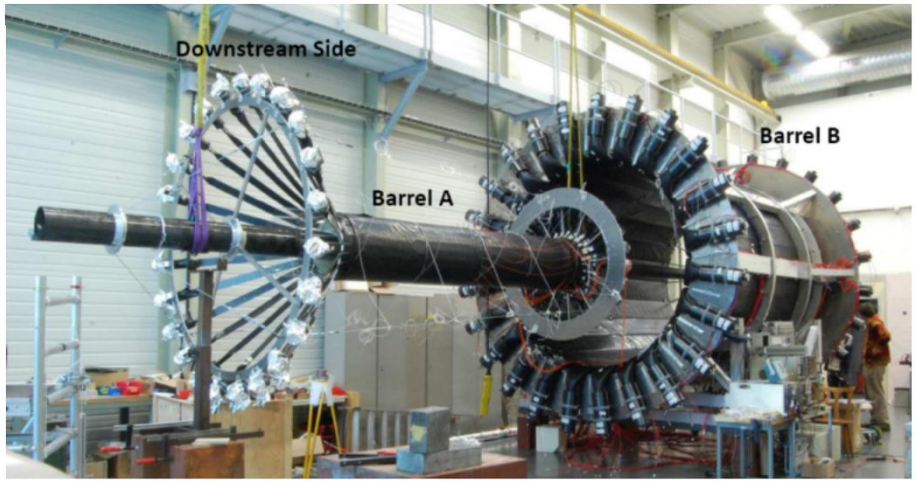
Exclusive Muoproduction



COMPASS Setup for Exclusive Processes

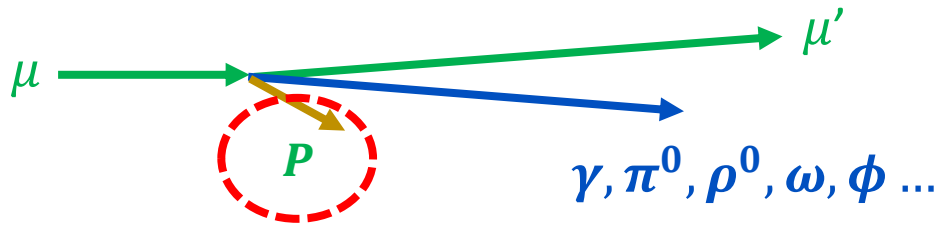


To ensure exclusivity:



CAMERA recoil proton detector

Exclusive Muoproduction



COMPASS Experiment

2002-2022 COMPASS data taking

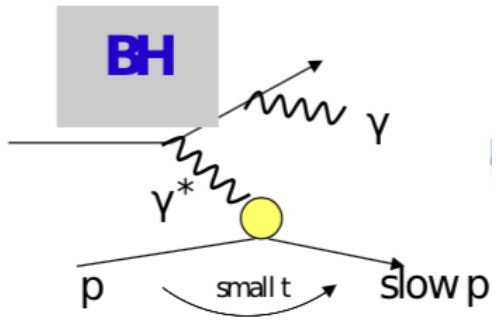
2002-2004	DIS & SIDIS, μ^+-**d**, 160 GeV, **L** & **T polarized target**
2005	*CERN accelerator shutdown, increase of COMPASS acceptance*
2006	DIS & SIDIS, μ^+-**d**, 160 GeV, **L polarized target**
2007	DIS & SIDIS, μ^+ -**p**, 160 GeV, **L** & **T polarized target**
2008-2009	Hadron spectroscopy & Primakoff reaction, **π/K/p** beam
2010	SIDIS, μ^+ -**p**, 160 GeV, **T polarized target**
2011	DIS & SIDIS, μ^+ -**p**, 200 GeV, **L polarized target**
2012	Primakoff reaction, **π/K/p** beam
2012 pilot run	DVCS/HEMP/SIDIS, μ^+ **&** μ^- -**p**, 160 GeV, **unpolarized target**
2013	*CERN accelerator shutdown, LS1*
2014-2015	Drell-Yan, π^- -**p**, **T polarized target**
2016-2017	DVCS/HEMP/SIDIS, μ^+ **&** μ^- -**p**, 160 GeV, **unpolarized target**
2018	Drell-Yan, π^- -**p**, **T polarized target**
2019-2020	*CERN accelerator shutdown, LS2*
2021-2022	SIDIS, μ^+-**d**, 160 GeV, **T polarized target**

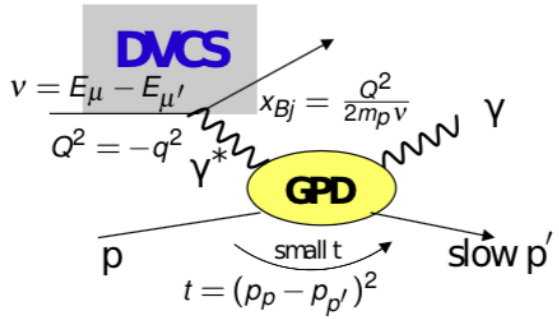
Study hadron structure with complmentary tools:

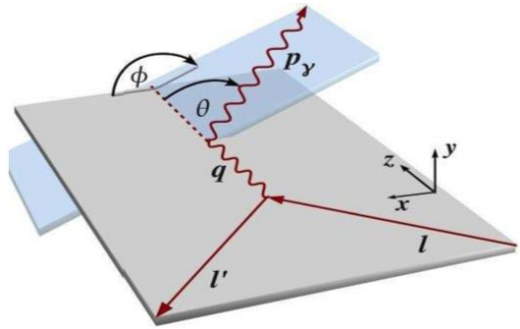
- **COMPASS holds the record for the longest-running CERN experiment**

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

Azimuthal Dependence of BH & DVCS







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

Beam Charge-spin difference & sum

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

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

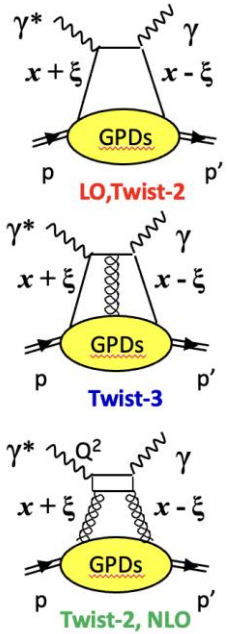
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

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

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

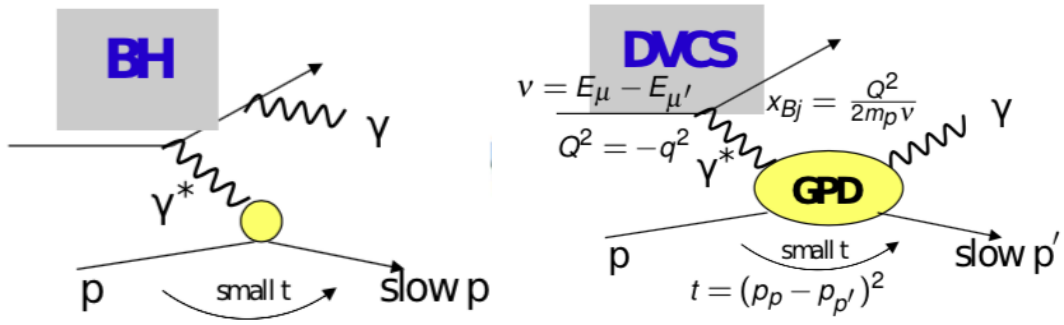
$$\mathrm{Re}\, I \propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi$$

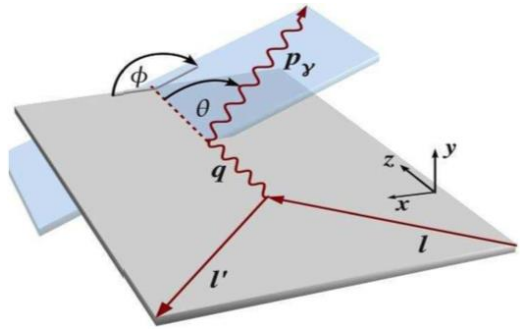
$$\mathrm{Im}\, I \propto s_1^{I}\sin\phi + s_2^{I}\sin 2\phi$$



Twist-2 >> Twist-3, Twist-2 - double helicity flip for gluons

Azimuthal Dependence of BH & DVCS





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

Beam Charge-spin difference & sum

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

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

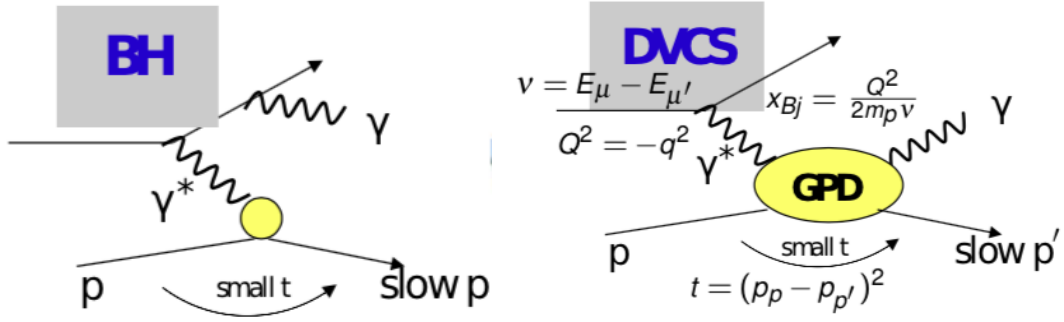
$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \quad \Big\} \mathcal{S}_{CS,U}(\phi)$$

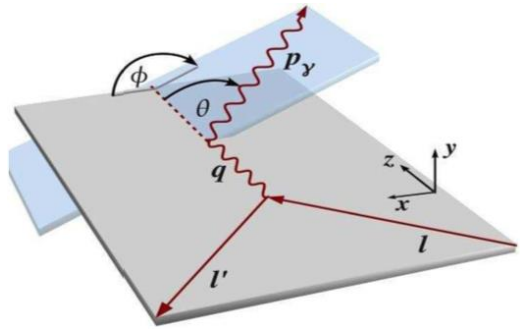
$$d\sigma^{DVCS}_{pol} \propto s_1^{DVCS}\sin\phi$$
$$\text{Re}\, I \propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \quad \Big\} \mathcal{D}_{CS,U}(\phi)$$

$$\text{Im}\, I \propto s_1^I\sin\phi + s_2^I\sin 2\phi \quad \Big\} \mathcal{S}_{CS,U}(\phi)$$

Twist-2 >> Twist-3, Twist-2 - double helicity flip for gluons

Azimuthal Dependence of BH & DVCS





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

Beam Charge-spin difference & sum

$\mathcal{D}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) - d\sigma(\mu^{-\rightarrow})$ ➡ $C_1^I \propto Re\ \mathcal{F}$ — More challenging

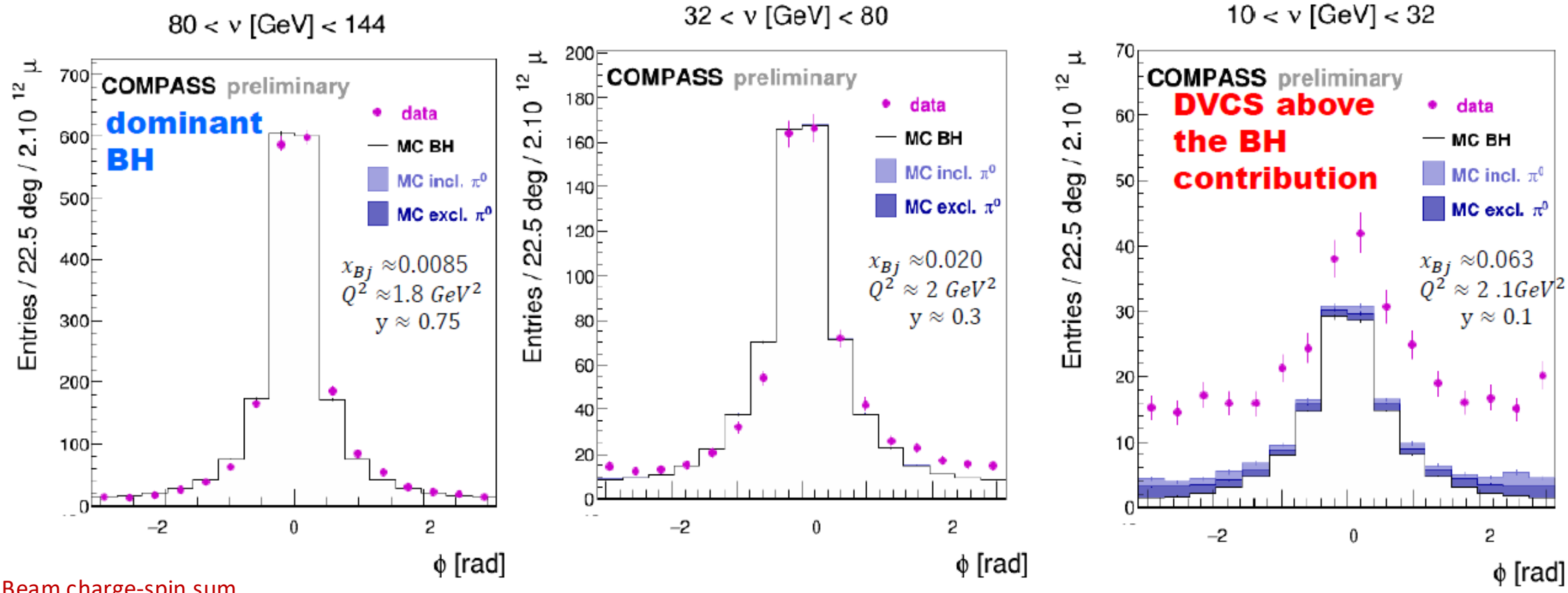
$\mathcal{S}_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow})$ ➡ $C_0^{DVCS} \propto (Im\mathcal{H})^2$ and $S_1^I \propto Im\ \mathcal{F}$ — Easier to measure

$$\mathcal{F} = F_1\mathcal{H} + \xi(F_1+F_2)\mathcal{H} + t/4m^2 F_2\,\mathcal{E} \xrightarrow[\text{Small } x_B \text{ at COMPASS}]{\text{Proton Target}} F_1\mathcal{H}$$

Compton Form factor linked to GPD **H**

Twist-2 >> Twist-3, Twist-2 - double helicity flip for gluons

COMPASS 2016 Preliminary Results



- Beam charge-spin sum

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

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

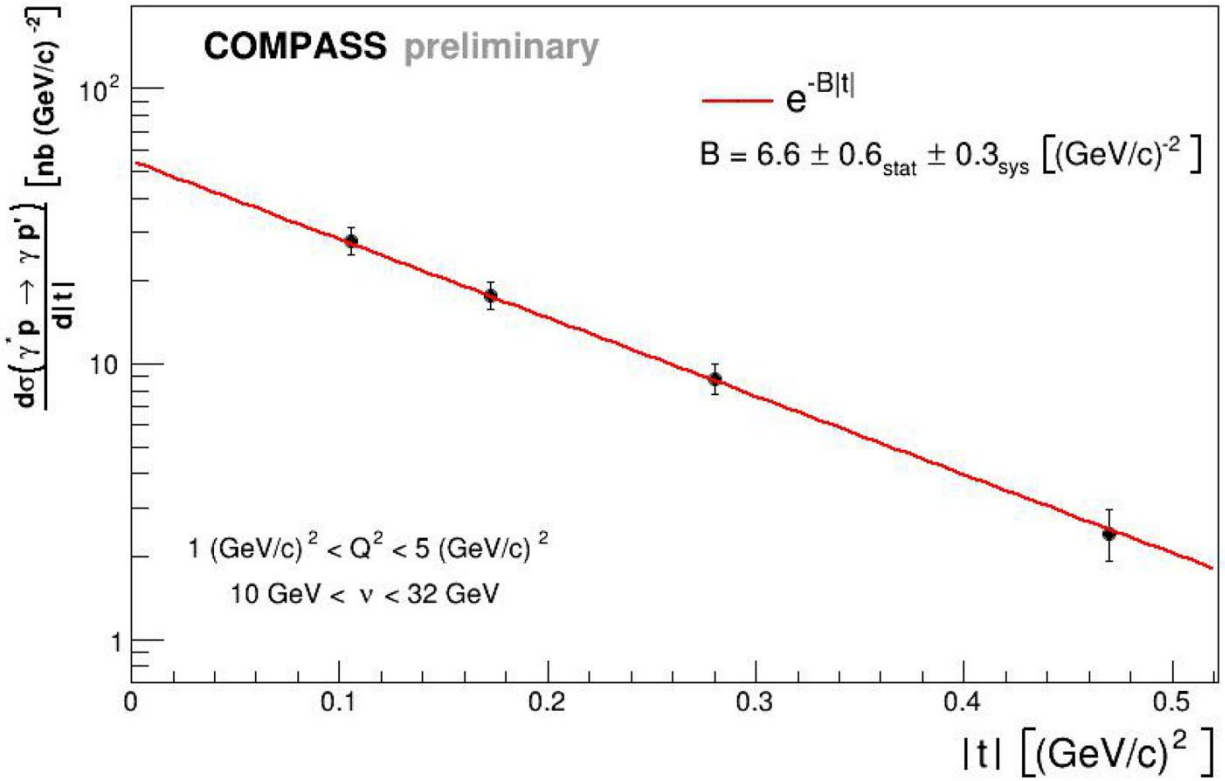
$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2}\mathcal{E}\mathcal{E}^* \rightarrow 4\,(Im\,\mathcal{H})^2$$

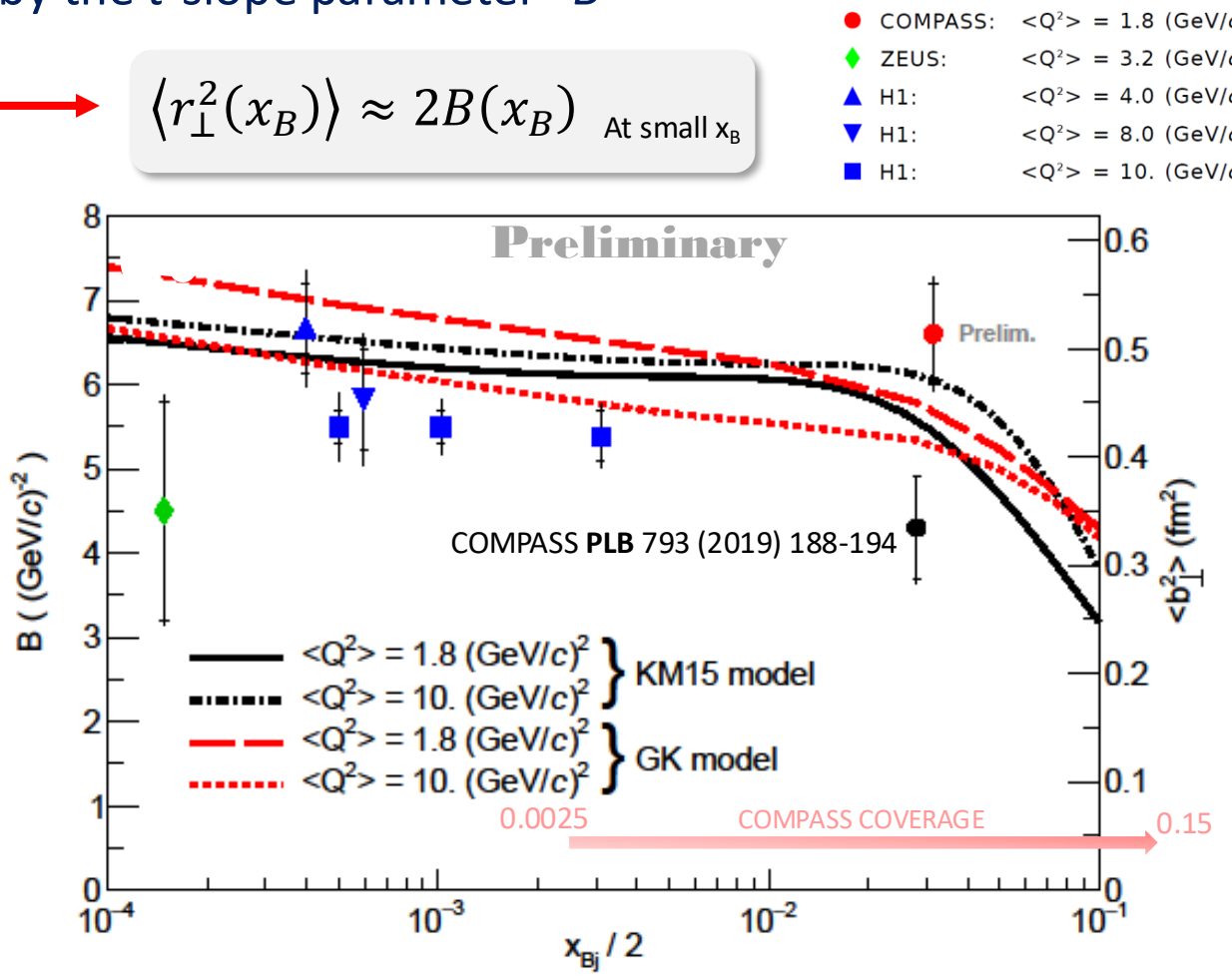
small x_{Bj} — model dependent

Transverse extension of partons – 2016 data

- The transverse extension can be deduced by the *t*-slope parameter "*B*"

$$d\sigma^{DVCS}/d|t| \propto e^{-B|t|} \quad \rightarrow \quad \langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$$ 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

Exclusive π^0 Production on Unpolarized Proton

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

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

ϵ : degree of longitudinal polarization

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

Leading twist expected be dominant

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

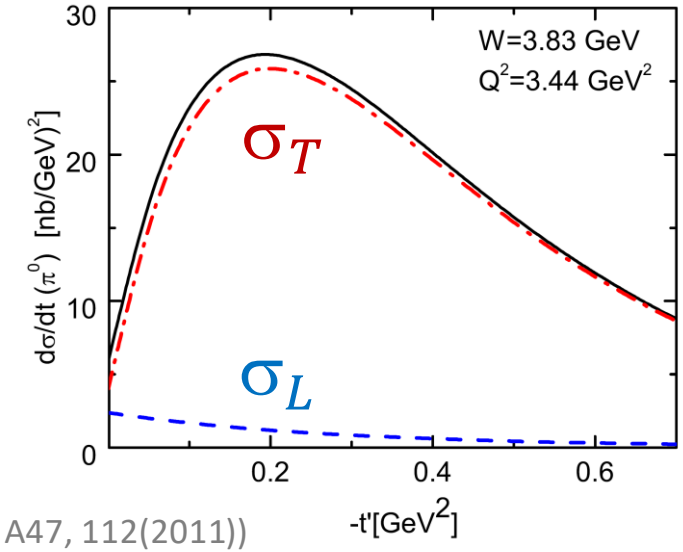
The other contributions arise from coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

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

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

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

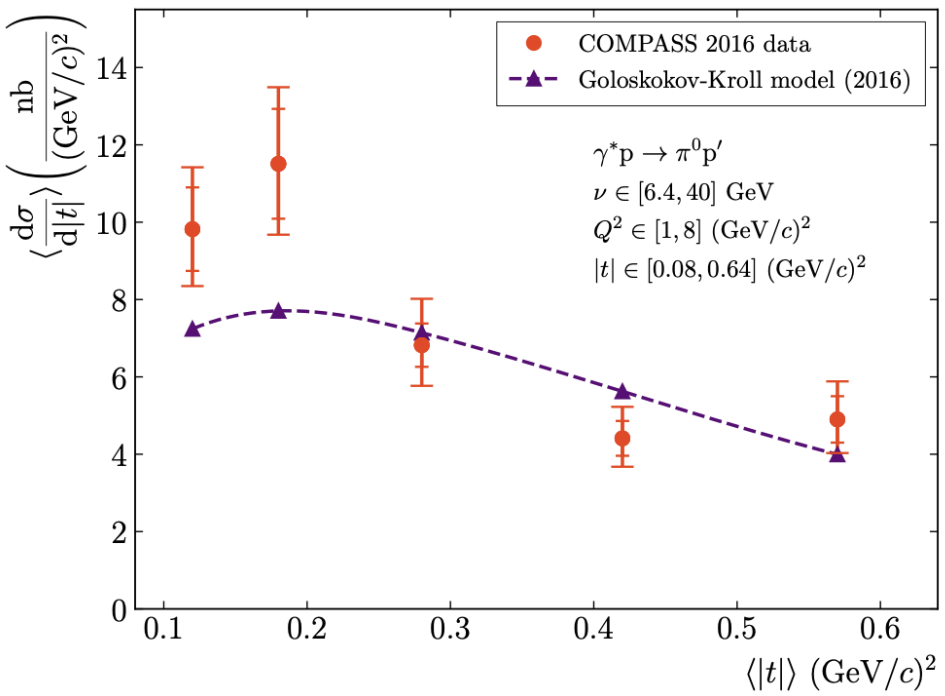
$$\bar{E}_T = 2\tilde{H}_T + E_T$$

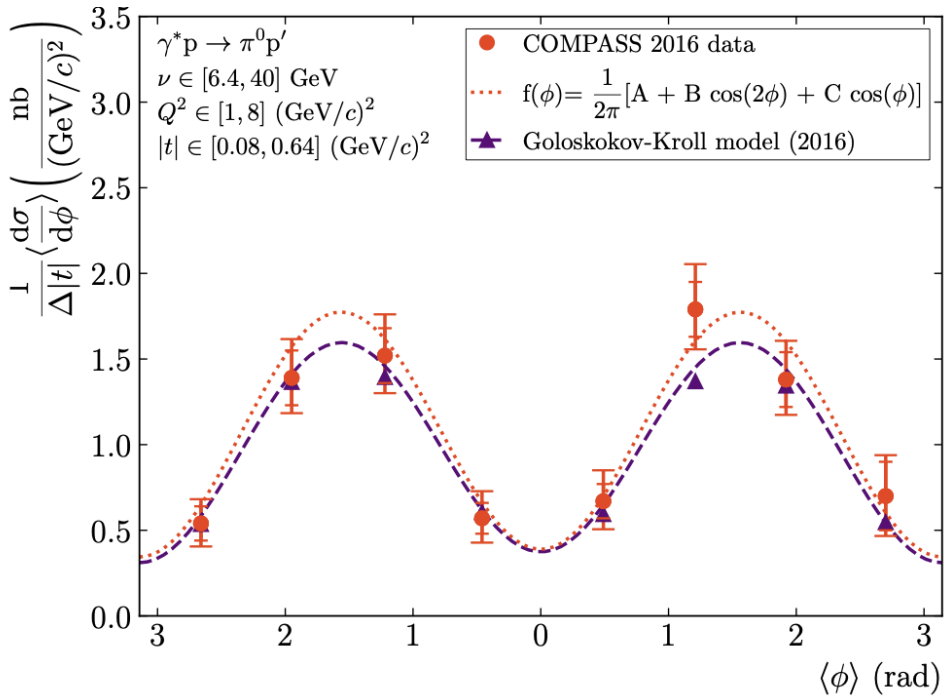


S. Goloskokov and P. Kroll (Eur.Phys.J A47, 112(2011))

New 2016 Exclusive π^0 Prod. on Unpolarized Proton

- Kinematic domain: $\nu \in [6.4, 40]$ GeV and $Q^2 \in [1,8]$ GeV$^2/c^2$, $\langle x_B \rangle = 0.134$





$$\left\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right\rangle = \left(6.7 \pm 0.3_{stat}{}^{+0.9}_{-0.8}\Big|_{sys} \right) \frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{TT}}{dt} \right\rangle = \left(-4.4 \pm 0.5_{stat}{}^{+0.3}_{-0.3}\Big|_{sys} \right) \frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{LT}}{dt} \right\rangle = \left(0.1 \pm 0.2_{stat}{}^{+0.2}_{-0.2}\Big|_{sys} \right) \frac{nb}{(GeV/c)^2}$$

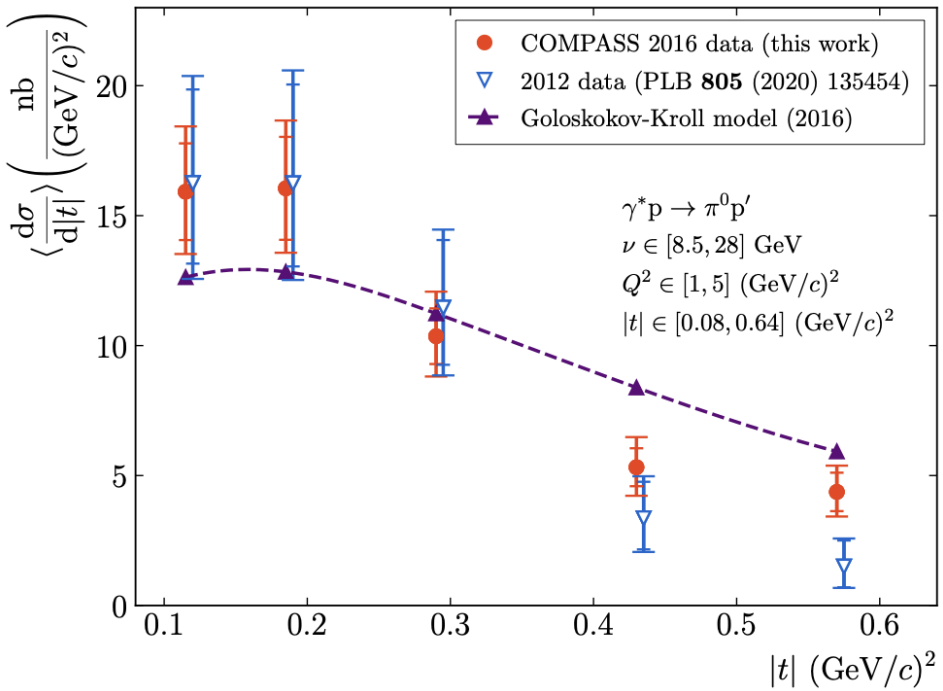
$\langle \epsilon \rangle = 0.997$

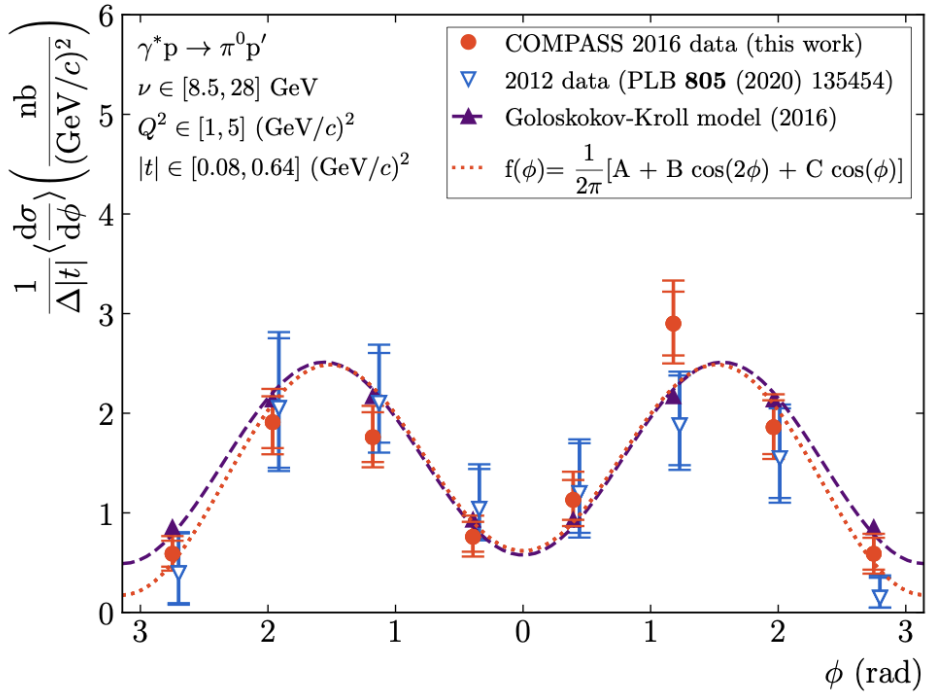
- Cross section extracted in a larger (ν, Q^2) domain, compared with the 2012 result. (COMPASS, **PLB** 805 (2020) 135454)
- Comparable $|\sigma_{TT}|$ and $\sigma_T + \epsilon\sigma_L$

Phys. Lett. B 870 (2025) 139832

2012-16 Exclusive π^0 Prod. Comparison

- Kinematic domain: $\nu \in [8.5, 28]$ GeV and $Q^2 \in [1,5]$ GeV$^2/c^2$, $\langle x_B \rangle = 0.103$





2016 Data:

$$\left\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right\rangle = \left(9.0 \pm 0.5_{stat}{}^{+1.0}_{-1.0}\Big|_{sys}\right) \frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{TT}}{dt} \right\rangle = \left(-6.6 \pm 0.8_{stat}{}^{+0.4}_{-0.5}\Big|_{sys}\right) \frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{LT}}{dt} \right\rangle = \left(0.7 \pm 0.3_{stat}{}^{+0.3}_{-0.3}\Big|_{sys}\right) \frac{nb}{(GeV/c)^2}$$

$\langle \epsilon \rangle = 0.996$

2012 Data:

$$\left\langle \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right\rangle = \left(8.1 \pm 0.9_{stat}{}^{+1.1}_{-1.0}\Big|_{sys}\right) \frac{nb}{(GeV/c)^2}$$

$$\left\langle \frac{d\sigma_{TT}}{dt} \right\rangle = \left(-6.0 \pm 1.3_{stat}{}^{+0.7}_{-0.7}\Big|_{sys}\right) \frac{nb}{(GeV/c)^2}$$

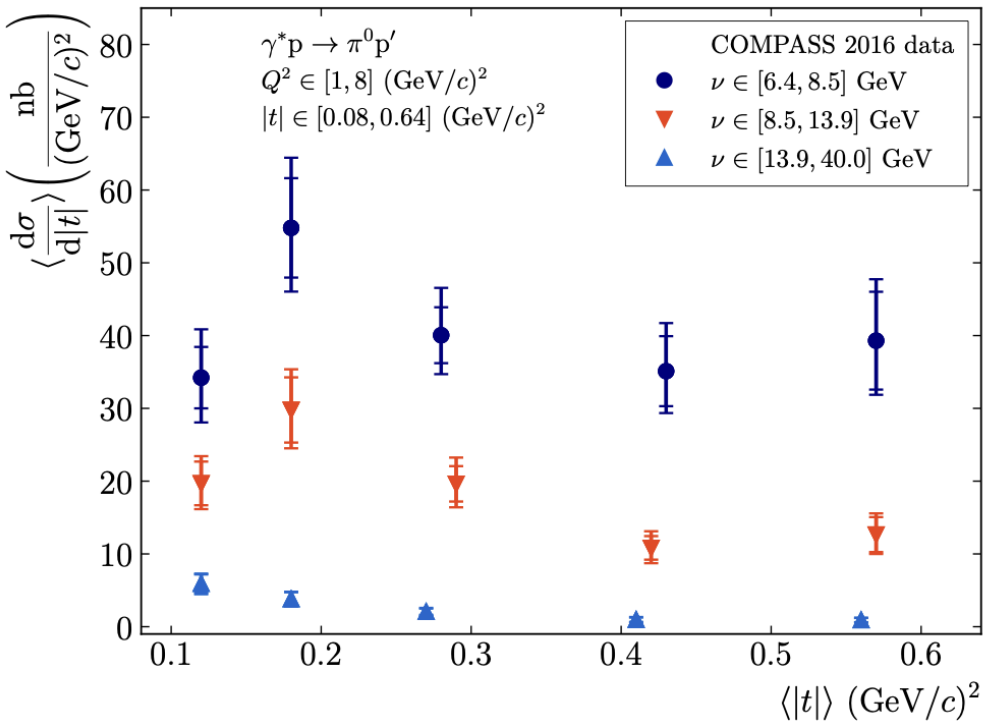
$$\left\langle \frac{d\sigma_{LT}}{dt} \right\rangle = \left(1.4 \pm 0.5_{stat}{}^{+0.3}_{-0.2}\Big|_{sys}\right) \frac{nb}{(GeV/c)^2}$$

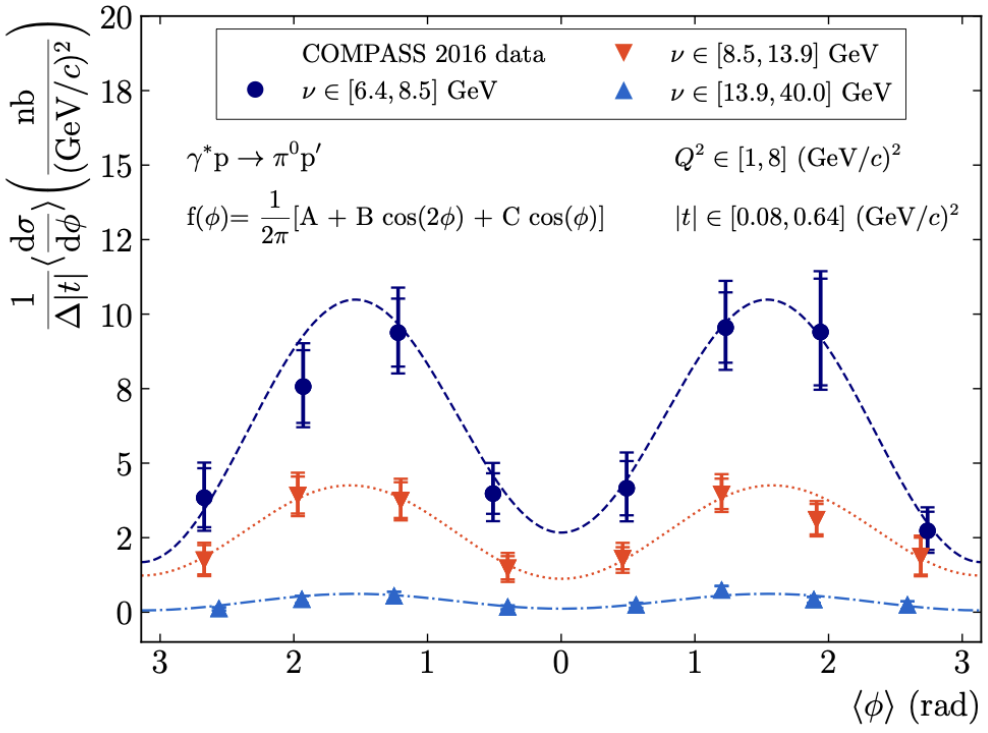
$\langle \epsilon \rangle = 0.996$

Phys. Lett. B 870 (2025) 139882

New 2016 Exclusive π^0 Cross-section Evolution with ν

- Cross section decreases with increasing ν



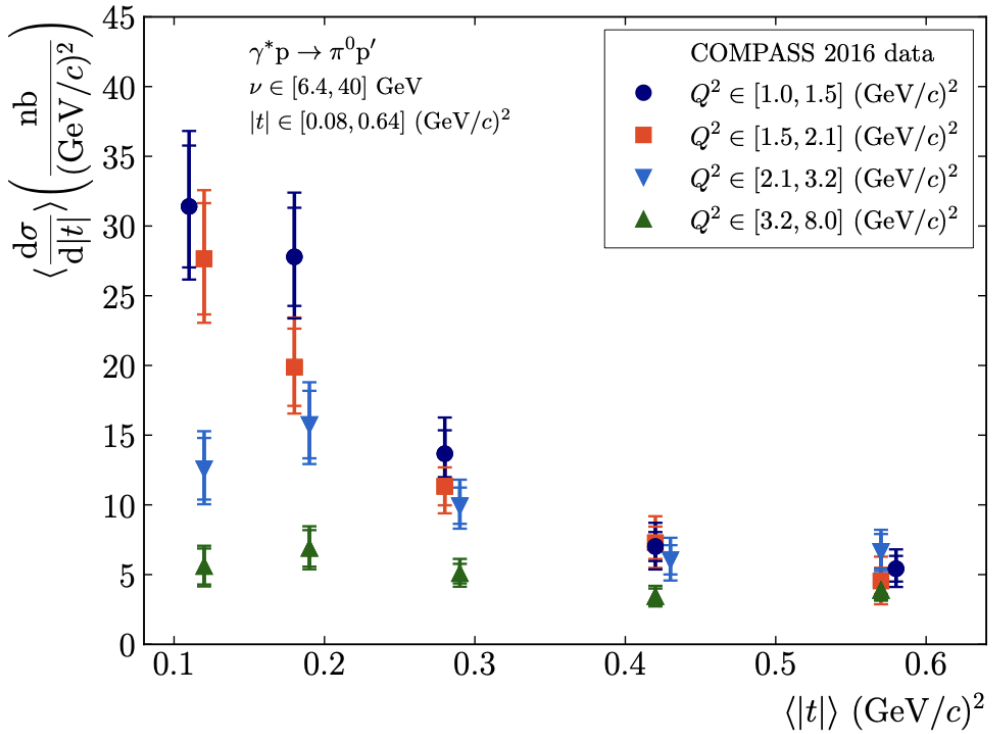


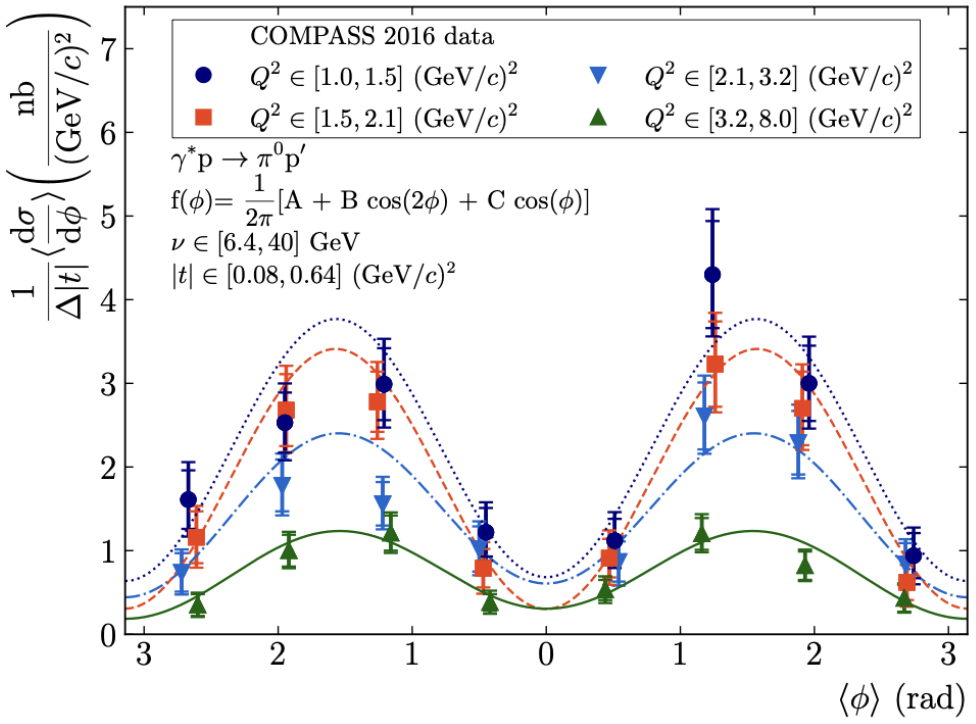
ν-range	$\langle Q^2 \rangle$ [(GeV/c)^2]	$\langle \nu \rangle$ [GeV]	$\langle \lvert t \rvert \rangle$ [(GeV/c)^2]	$\langle W \rangle$ [GeV/c^2]	$\langle x_{Bj} \rangle$	$\langle y \rangle$	$\langle \varepsilon \rangle$
6.4 – 8.5	2.15	7.35	0.31	3.53	0.156	0.046	0.999
8.5 – 13.9	2.50	10.32	0.29	4.20	0.131	0.065	0.998
13.9 – 40.0	2.09	21.08	0.24	6.12	0.057	0.133	0.989
	$Q^2 \in [1,8]$		$\lvert t \rvert \in [0.08, 0.64]$				

Phys. Lett. B 870 (2025) 139832

New 2016 Exclusive π^0 Cross-section Evolution with Q^2

- Cross section decreases with increasing Q^2

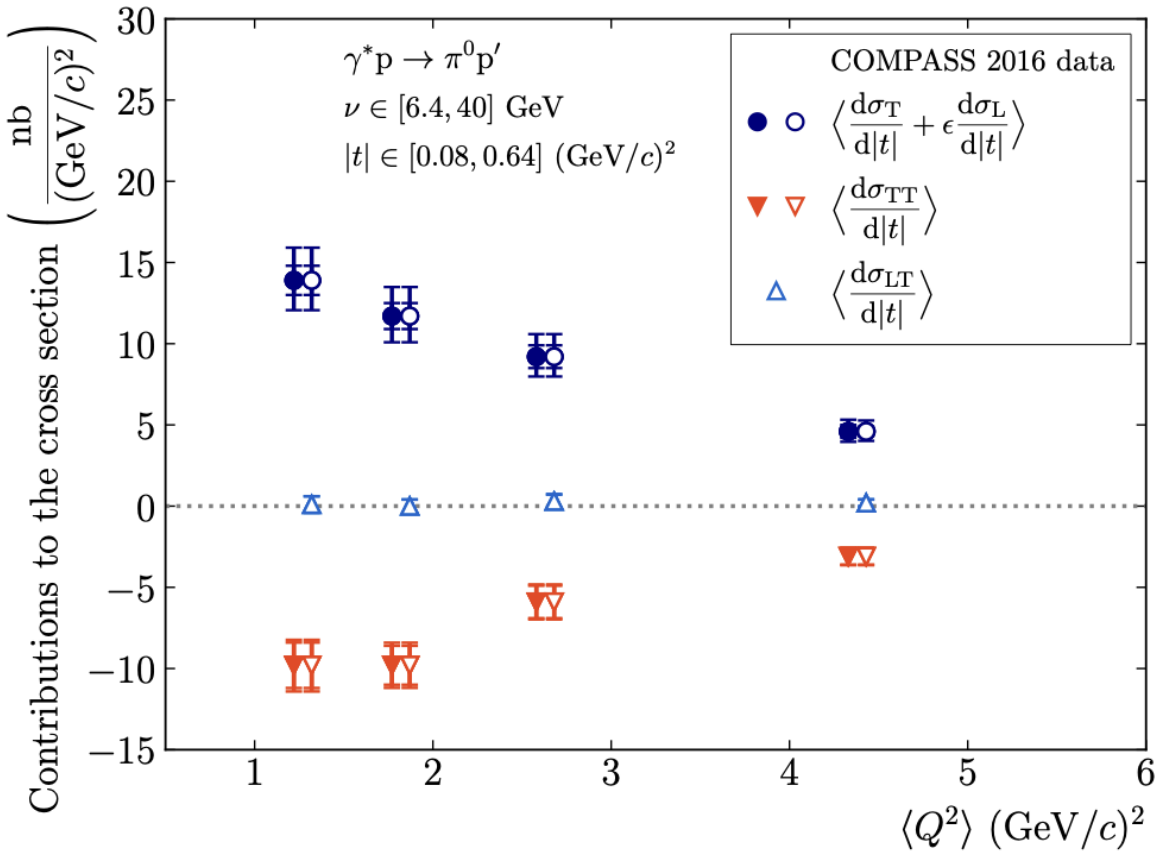


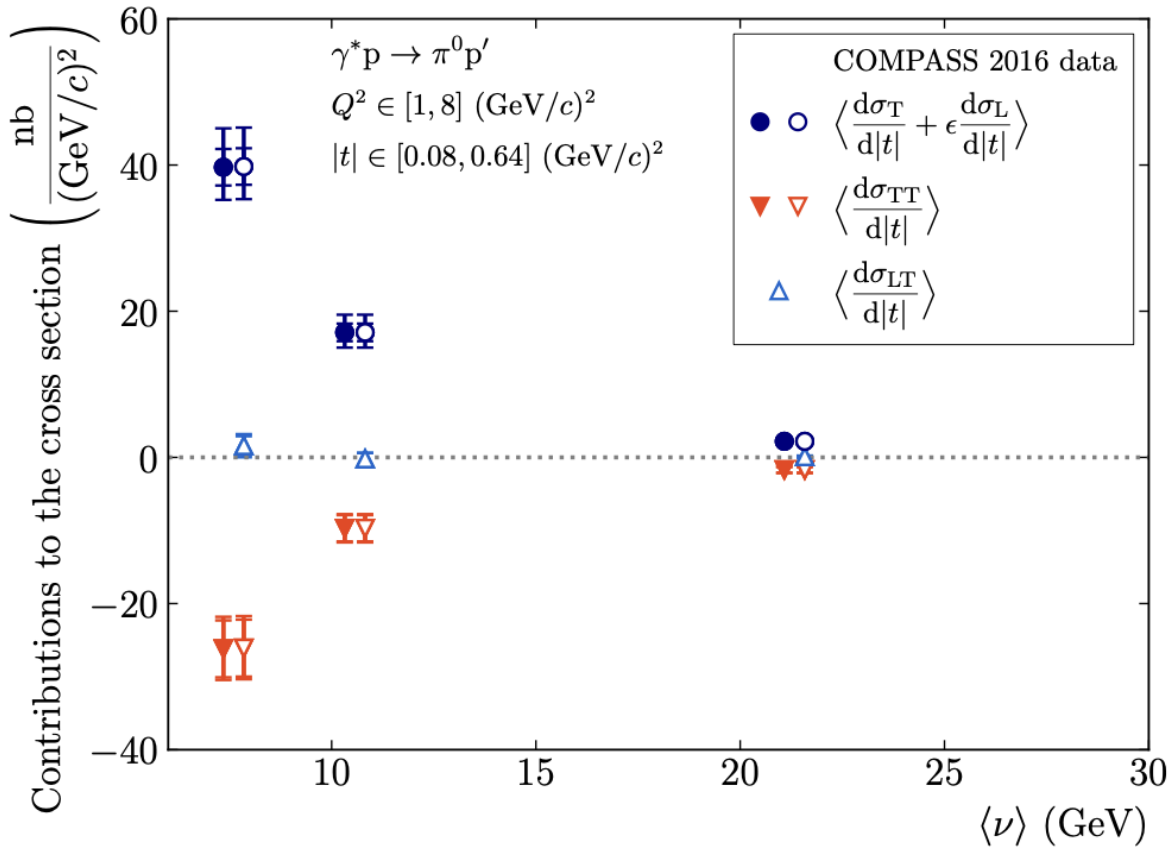


Q^2-range	$\langle Q^2 \rangle$ [(GeV/c)^2]	$\langle \nu \rangle$ [GeV]	$\langle \lvert t \rvert \rangle$ [(GeV/c)^2]	$\langle W \rangle$ [GeV/c^2]	$\langle x_{Bj} \rangle$	$\langle y \rangle$	$\langle \varepsilon \rangle$
1.0 – 1.5	1.22	10.54	0.27	4.29	0.072	0.067	0.997
1.5 – 2.1	1.77	9.81	0.27	4.09	0.109	0.062	0.997
2.1 – 3.2	2.58	9.82	0.31	4.00	0.157	0.062	0.997
3.2 – 8.0	4.33	10.39	0.33	3.90	0.247	0.065	0.997
		$\nu \in [6.4, 40]$	$\lvert t \rvert \in [0.08, 0.64]$				

Phys. Lett. B 870 (2025) 139832

New 2016 Evolution of the Structure Functions





- For both $\sigma_T + \epsilon\sigma_L$ and σ_{TT} → Relatively larger evolution in ν, smaller in Q^2
- σ_{LT} consistent with 0
- **Valuable inputs for new model calculations!**

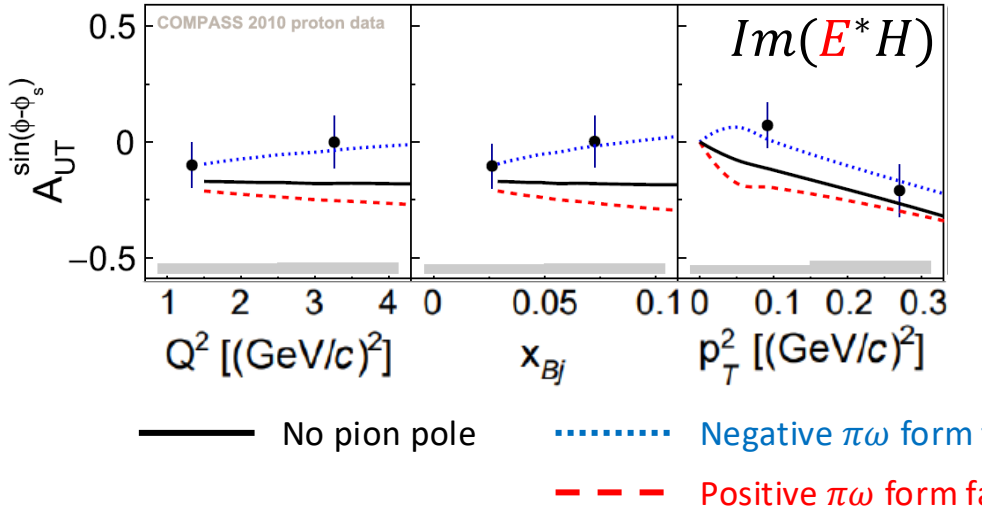
Phys. Lett. B 870 (2025) 139832

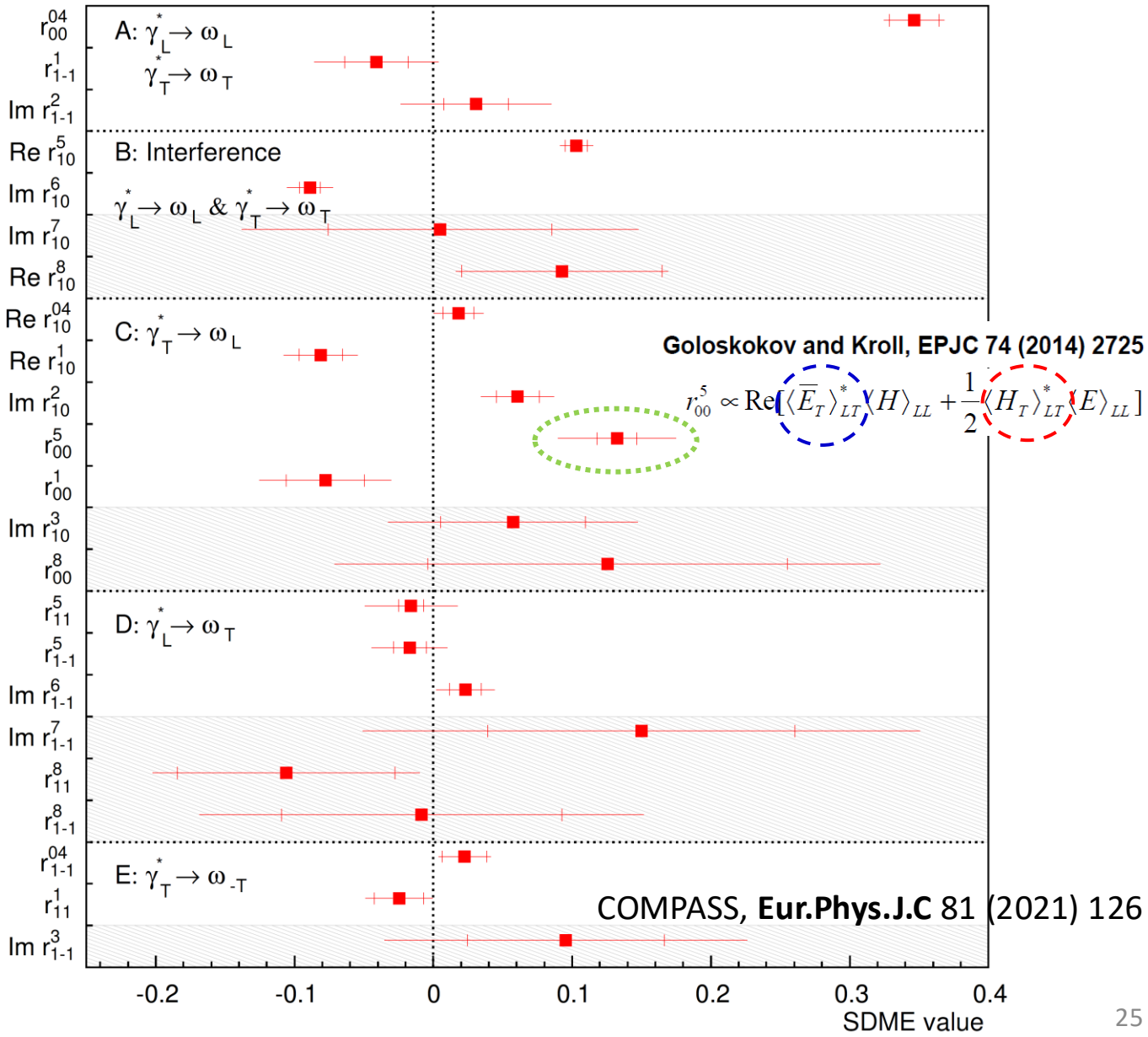
DVMP of Vector Mesons

COMPASS, **NPB** 865 (2012) 1-20, **PLB** 731 (2014) 19

$$\omega \rightarrow \pi^+\pi^-\pi^0$$

$$E_\omega = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}E^g/x\right)$$





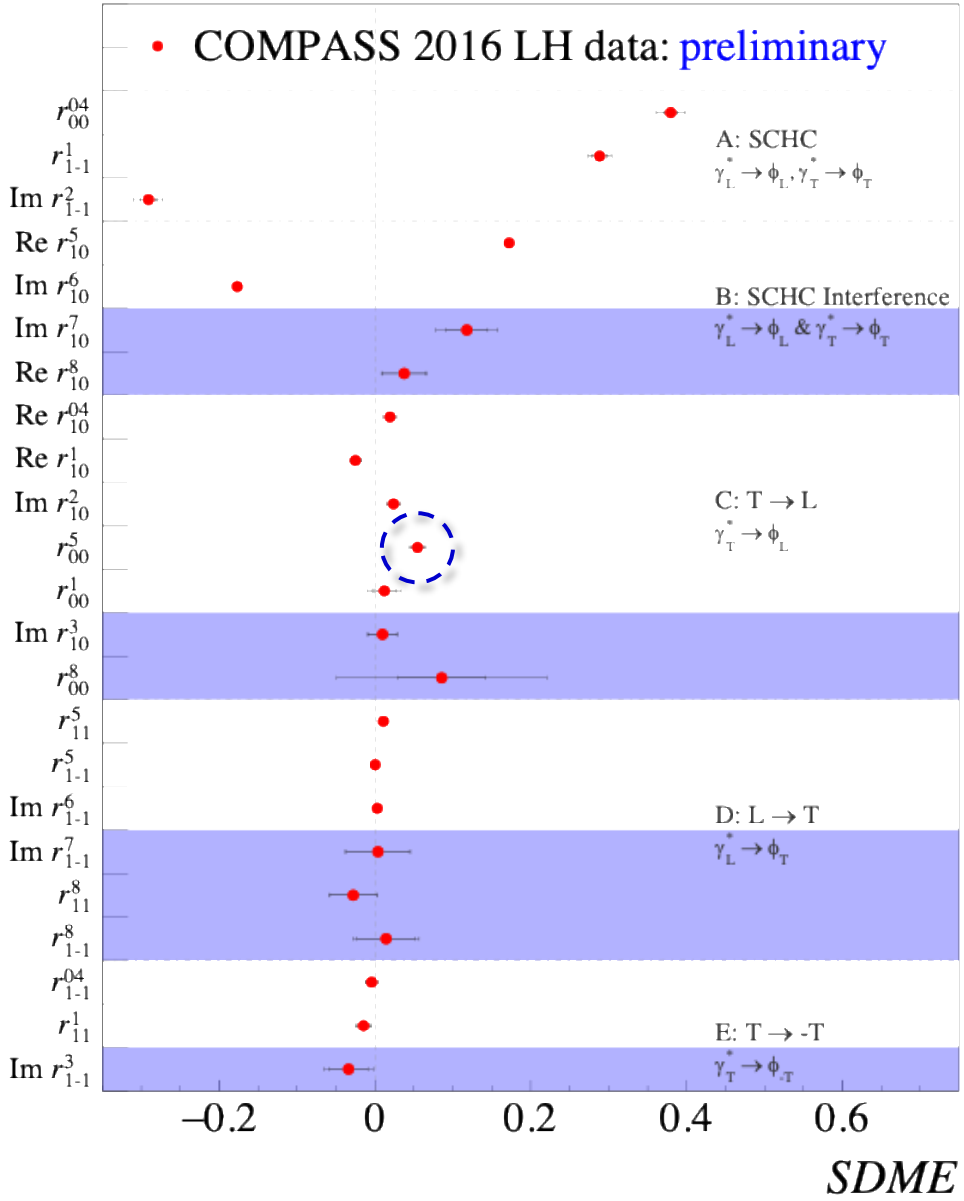
Goloskokov and Kroll, EPJC 74 (2014) 2725

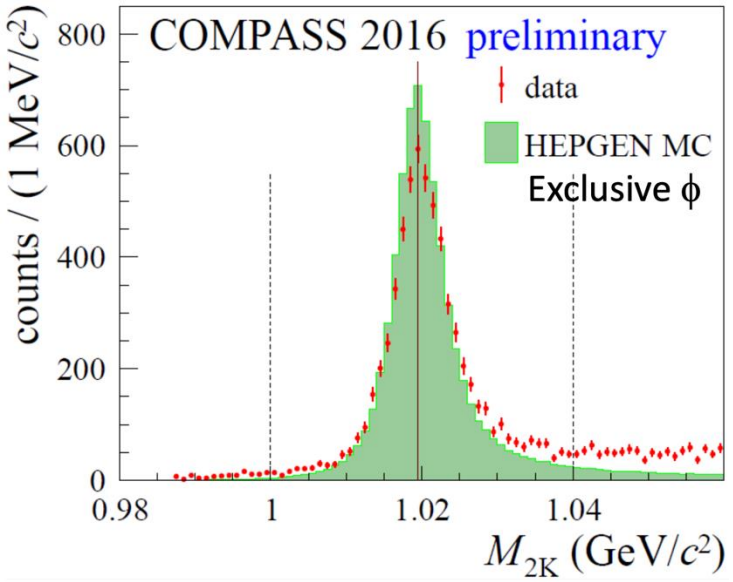
$$r^5_{00} \propto \mathrm{Re}\left[\langle \bar{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2}\langle H_T \rangle^*_{LT} \langle E \rangle_{LL}\right]$$

COMPASS, **Eur.Phys.J.C** 81 (2021) 126

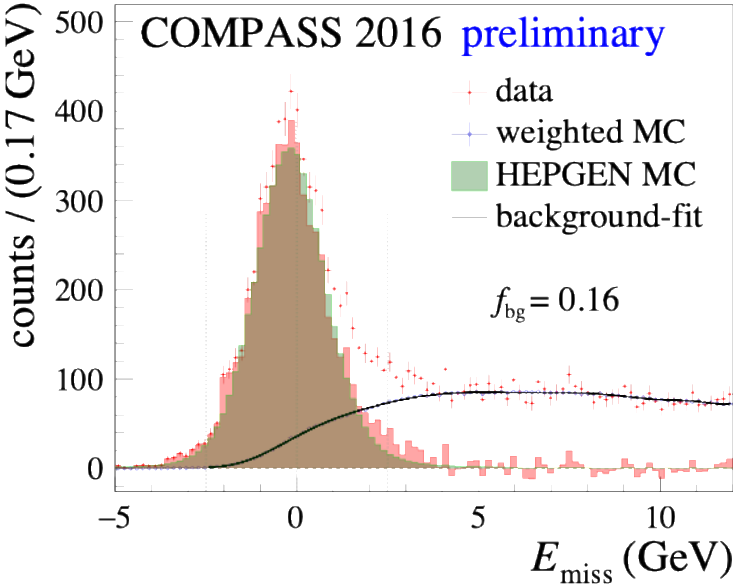
- Single spin asymmetry with polarized target and SDMEs of unpolarized target in the exclusive ρ and ω meson productions have provided fruitful inputs.

DVMP of Vector Mesons – Exclusive ϕ



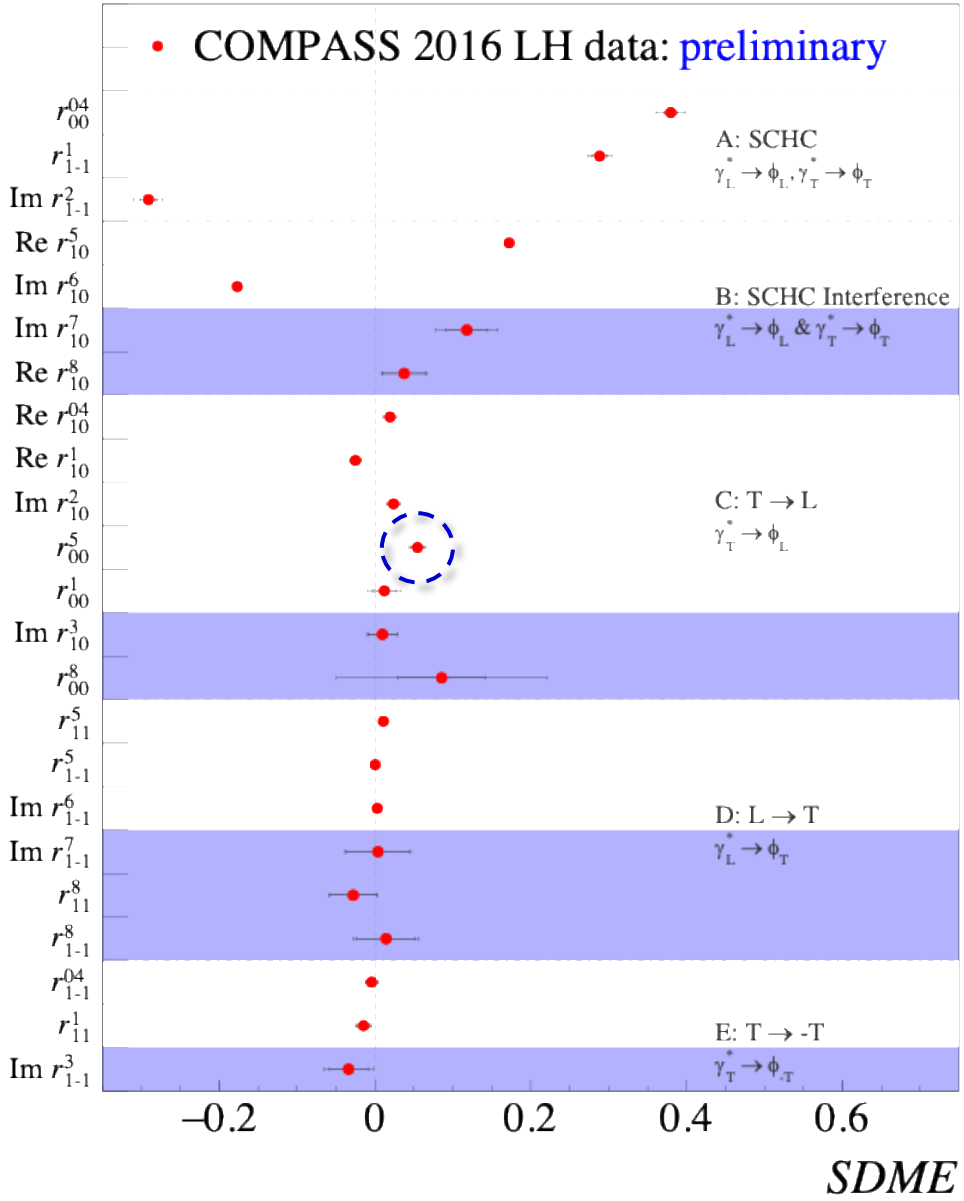


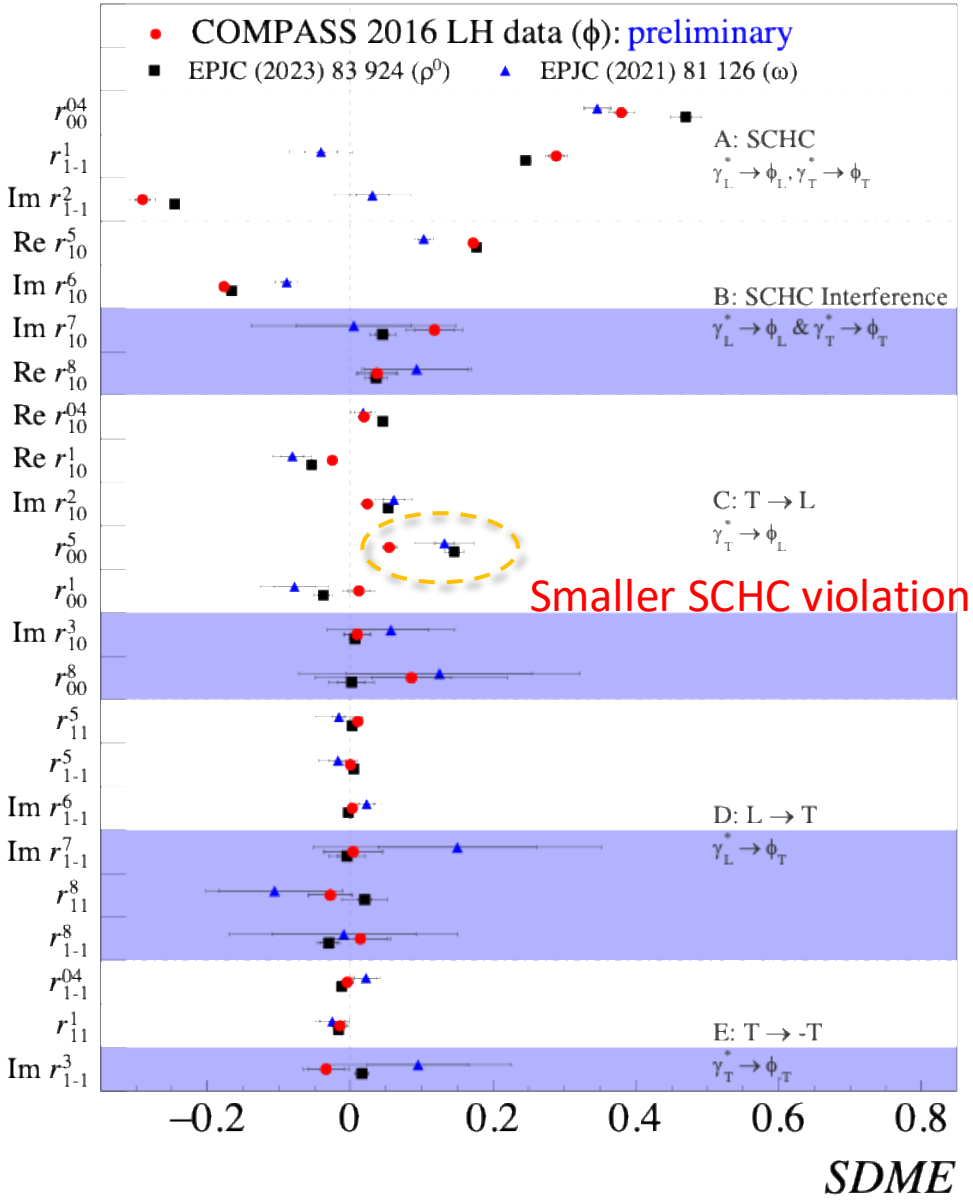
$1.00 < M_{2K} < 1.04$ GeV



$-2.5 < E_{miss} = \frac{M_X^2 - M_p^2}{2M_p} < 2.5$ GeV

DVMP of Vector Mesons – Exclusive ϕ





Smaller SCHC violation for ϕ

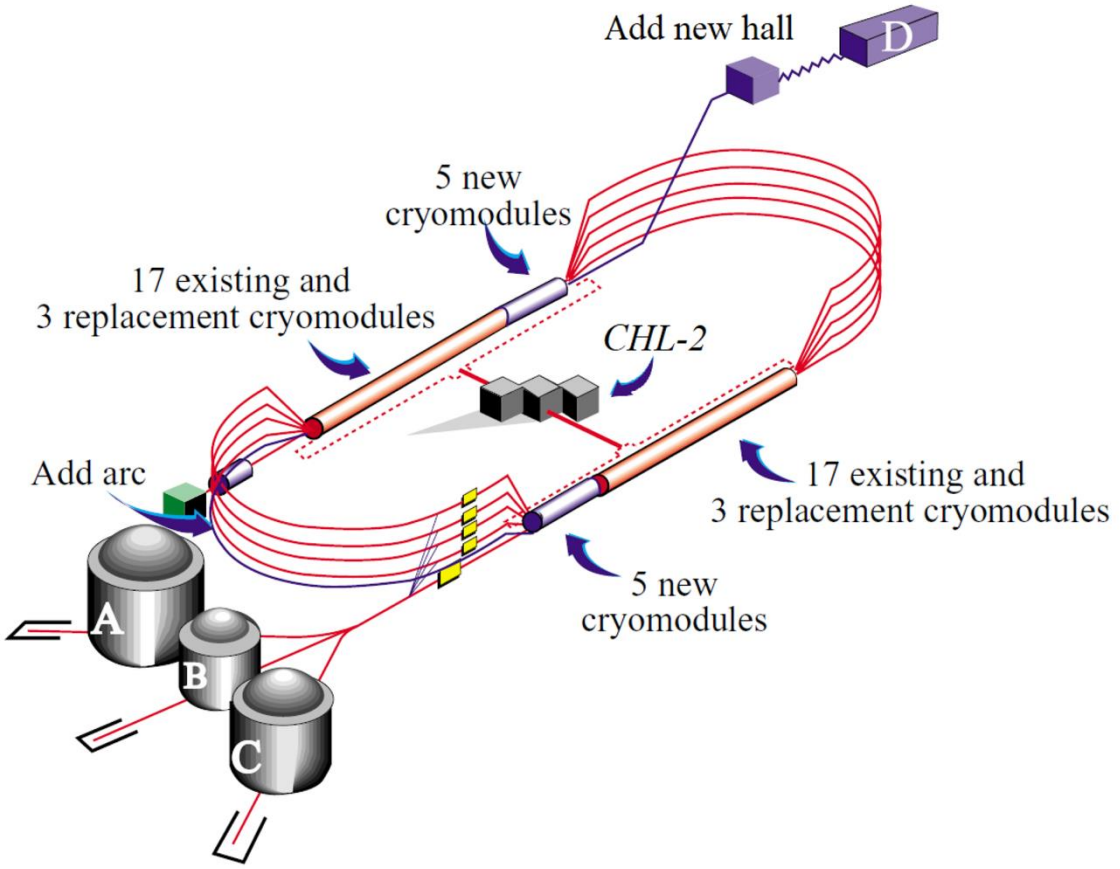


Jefferson Lab Hall A/C

Jefferson Lab and Continuous Electron Beam Accelerator Facility



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

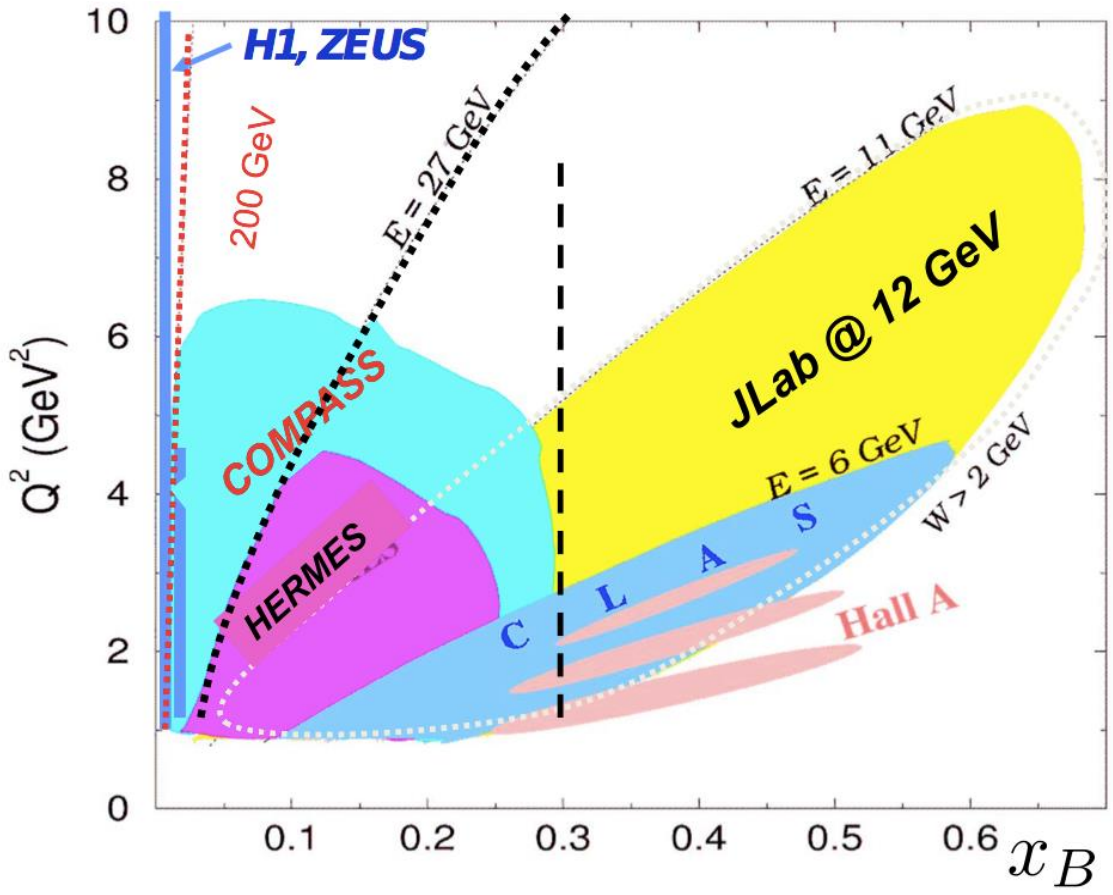


- Continuous Electron Beam Acclerator Facility (CEBAF)
  - Polarized electrons up to 12 GeV beam energy
  - Simultaneous beam delivery to different halls

JLab Exclusive Reactions for GPDs program

Measurement	Hall
DVCS Polarized beam and/or target	A,B,C
nDVCS Deuterium/He3	B, C, A(Solid)
DVCS w/ e+	B, C
TCS	A (Solid), B, C
Excl. π^0	A,B,C
Excl. π^-	A (Solid), (B)
Excl. ϕ, η	B
L/T separation (K, π+)	C
WACS (γ, π^0)	A, C
Backwards π^0	C

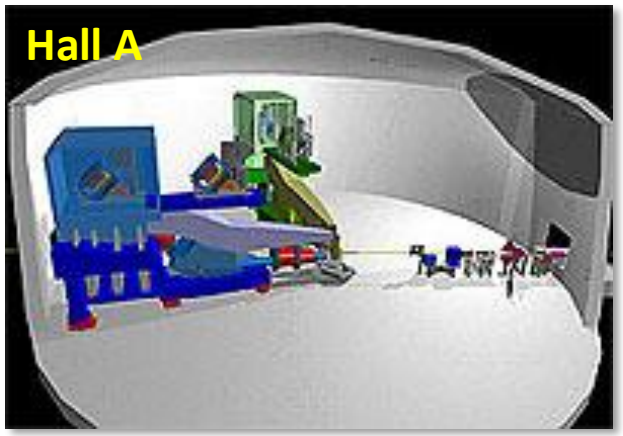
Tables by C. Munoz-Camacho

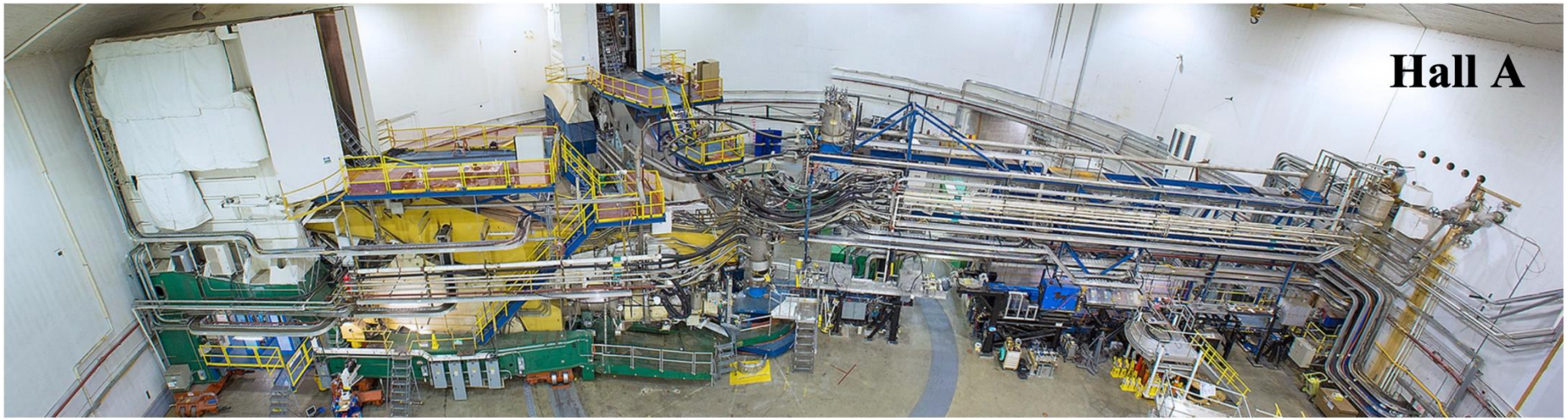


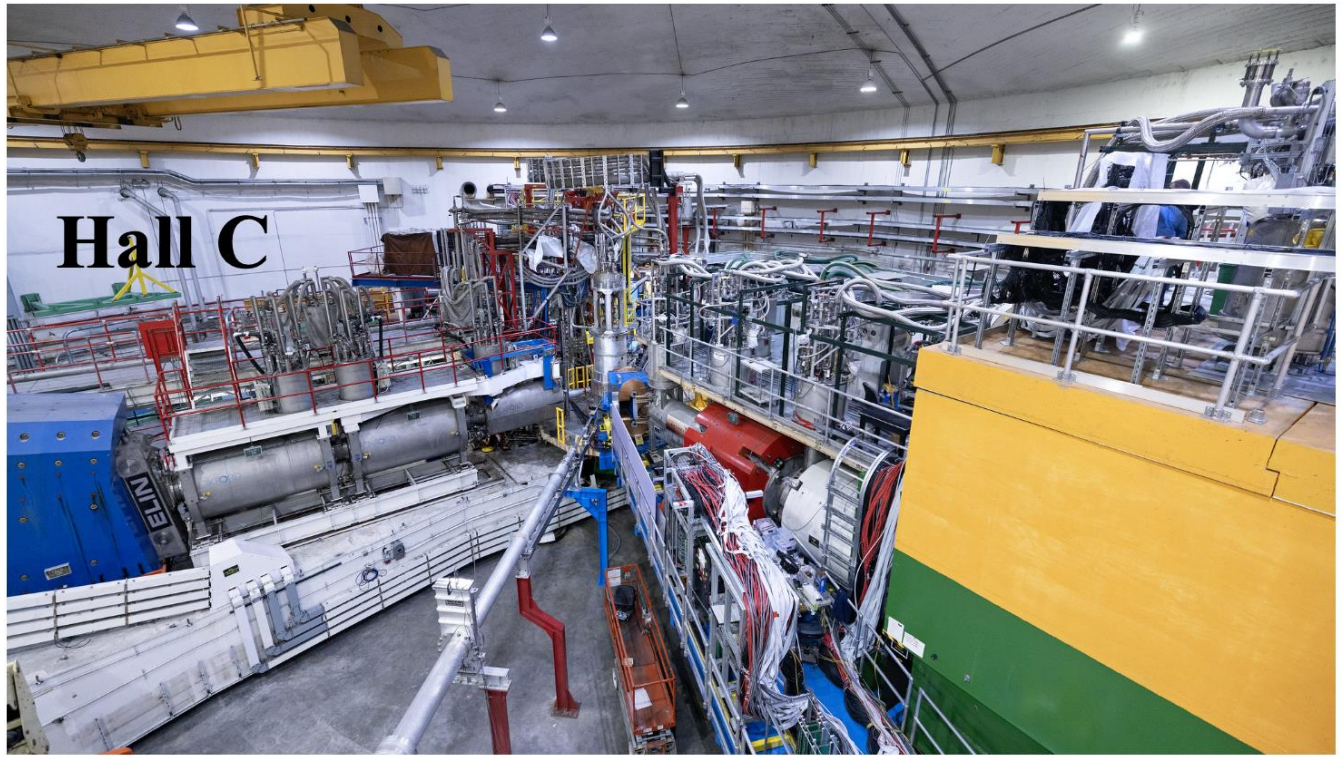
In the valence region (JLab 6 and JLab 12)

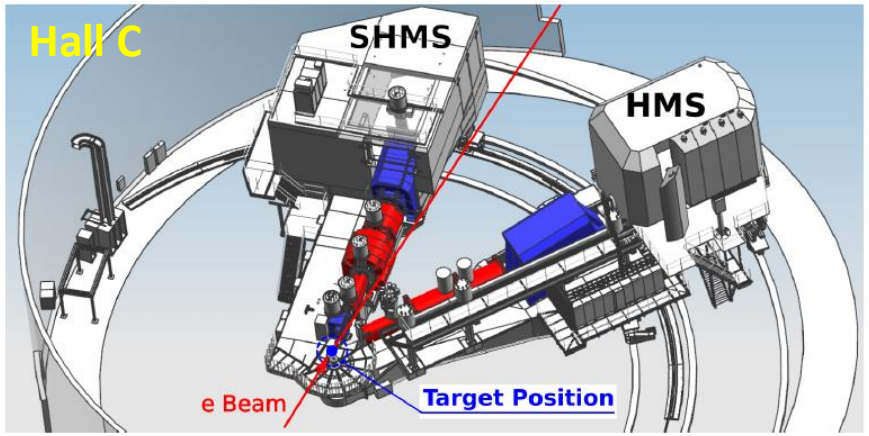
Partially complimentary, overlapping

Hall A/C



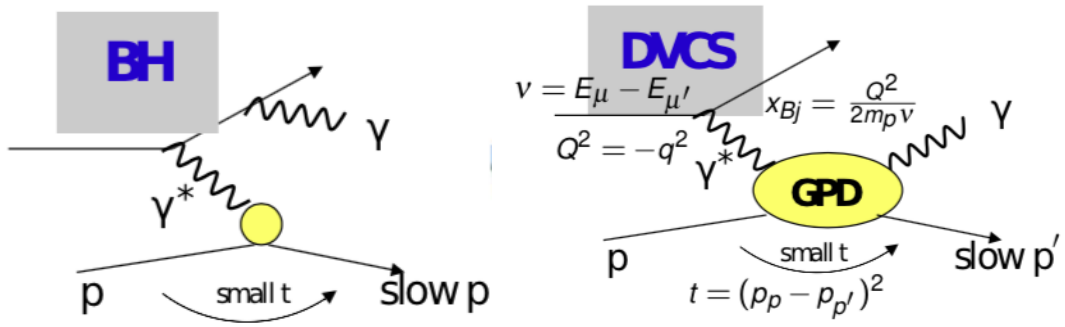


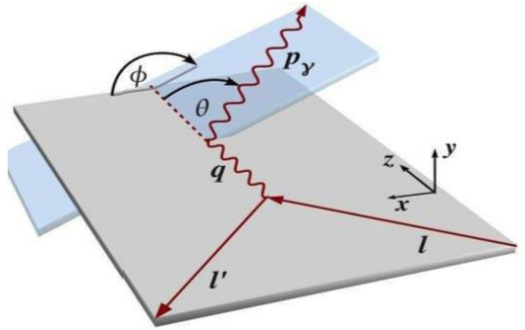




- Limited kinematic coverage
- High luminosity → about 10^{38} /(cm^2 s)
  → Test validity of formalism

Measurements at Hall A/C





DVCS $\sigma(ep \to e'p'\gamma) \propto |T_{BH}|^2 + \underbrace{|T_{DVCS}|^2}_{\propto E_{beam}^2} + \underbrace{I(BH \cdot DVCS)}_{\propto E_{beam}^3}$

DVMP-π^0 $$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\underbrace{\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right)}_{\text{L-T separation}} + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

- Multiple available beam energies allow for the exploration of E_{beam} dependence and thus separation of terms

DVCS and DVMP- π^0 with Hall A/C

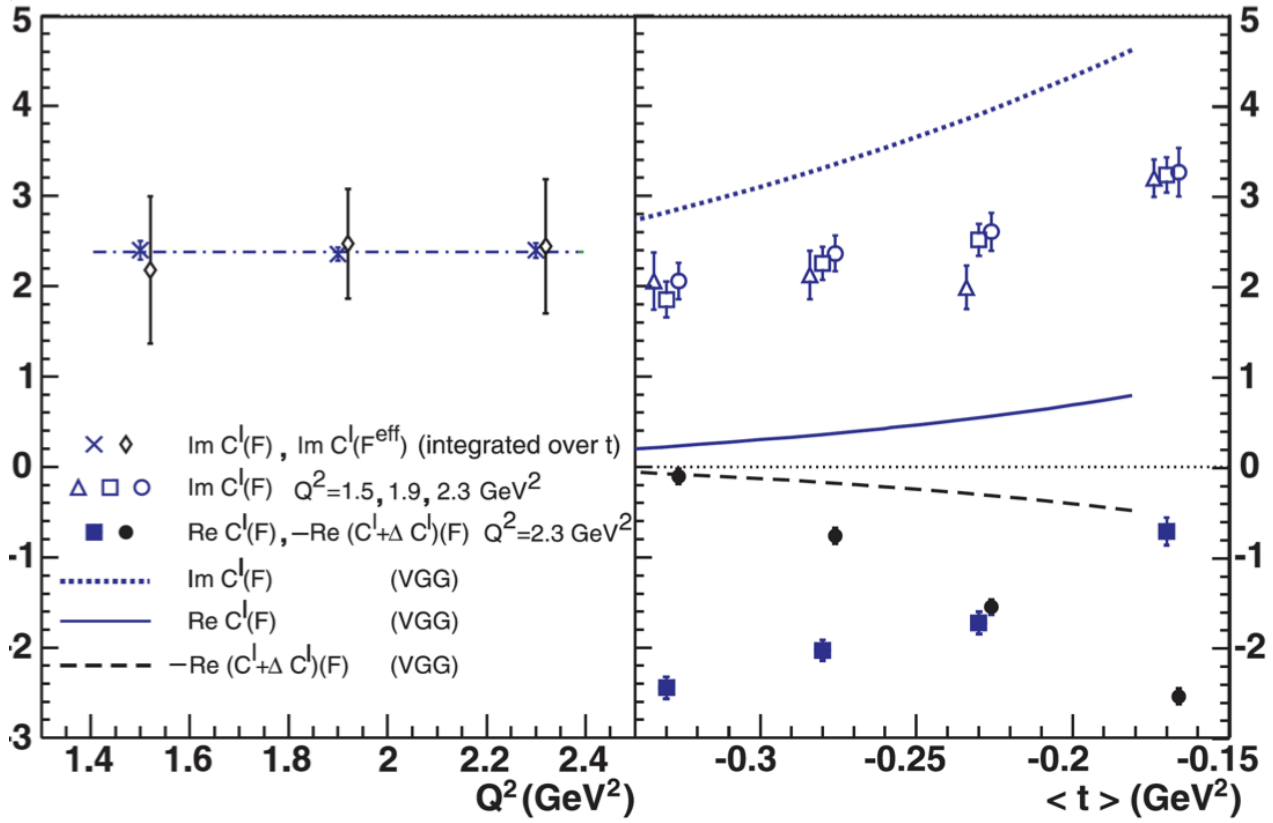
Experiment	PAC	Goal	Results
E00-110	PAC18	1st dedicated DVCS experiment at JLab	PRL97 (2006), PRC83 (2011), PRC92 (2015)
E03-106	PAC24	1st neutron DVCS experiment	PRL99 (2007)

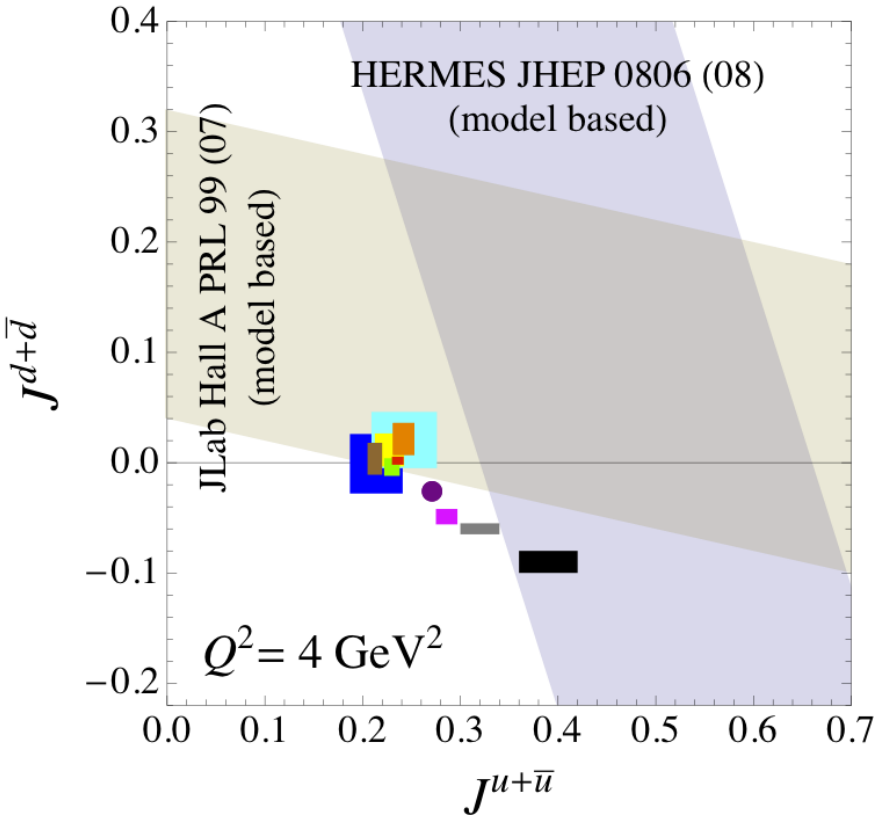
6 GeV

1st Generation (2004)

Q^2 dependence study (of leading terms)

DVCS





DVCS and DVMP-π^0 with Hall A/C

Experiment	PAC	Goal	Results
E00-110	PAC18	1st dedicated DVCS experiment at JLab	PRL97 (2006), PRC83 (2011), PRC92 (2015)
E03-106	PAC24	1st neutron DVCS experiment	PRL99 (2007)
E07-007	PAC31	DVCS Rosenbluth-like separation (proton)	PRL117 (2016), Nature Commun. 8 (2017)
E08-025	PAC33	DVCS Rosenbluth-like separation (neutron)	PRL118 (2017), Nature Physics 16 (2020)

6 GeV

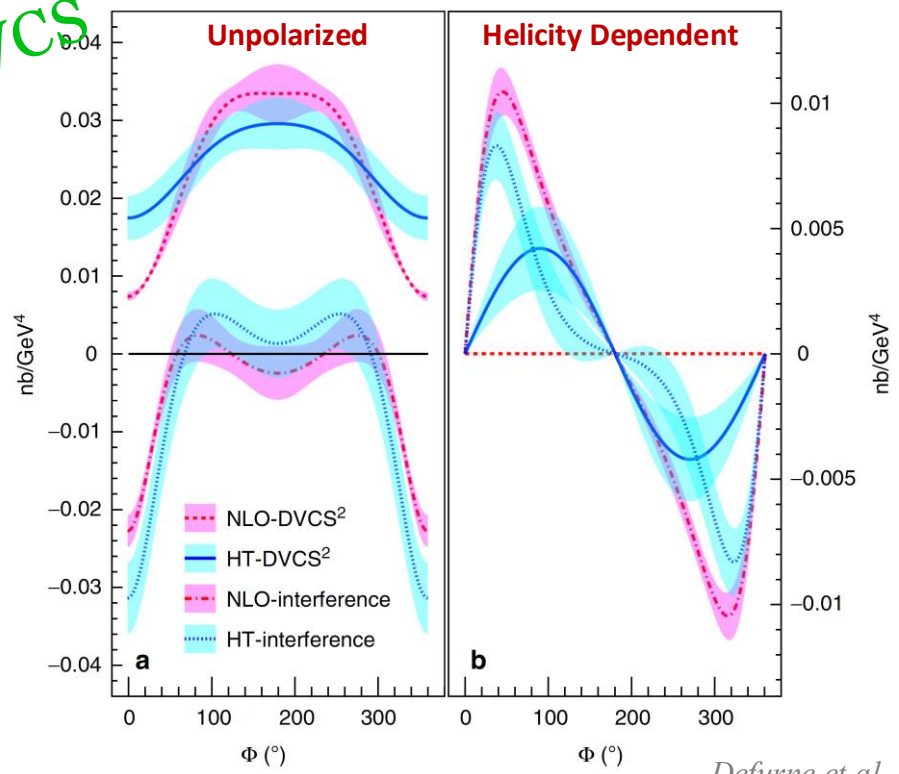
1st Generation (2004)

Q^2 dependence study (of leading terms)

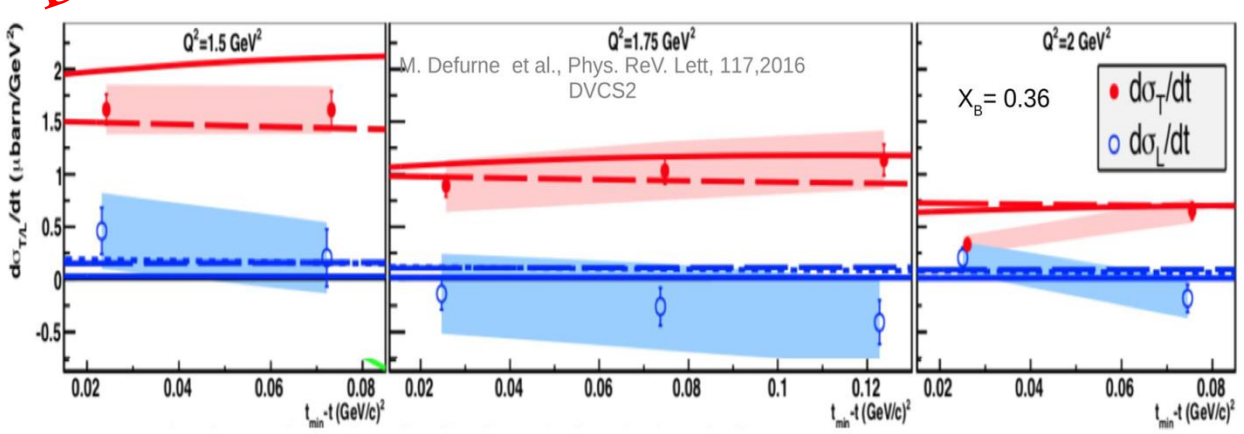
2nd Generation (2010)

2 Different E_{beam} → Beam energy dependence study at fixed x_B and Q^2

DVCS



DVMP-π^0



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

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

Defurne et al., Nature Communications 8 (2017) 1408

DVCS and DVMP-π^0 with Hall A/C

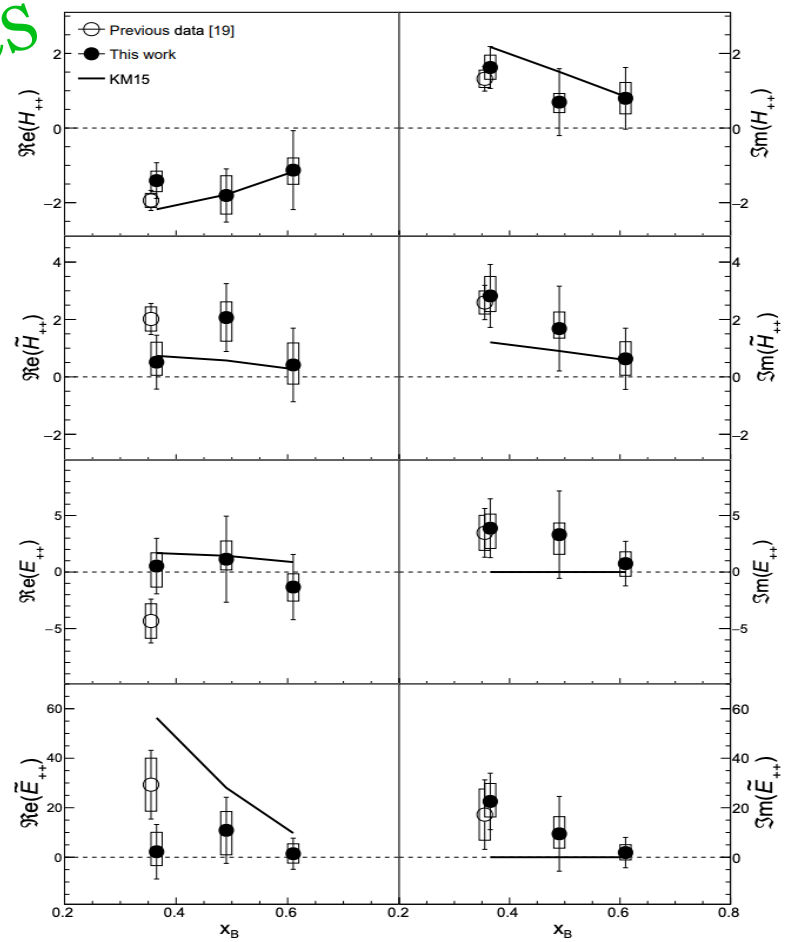
Experiment	PAC	Goal	Results
E12-06-114	PAC30+38+41+47	1st 12 GeV experiment	PRL127 (2021), PRL128 (2022)

12 GeV

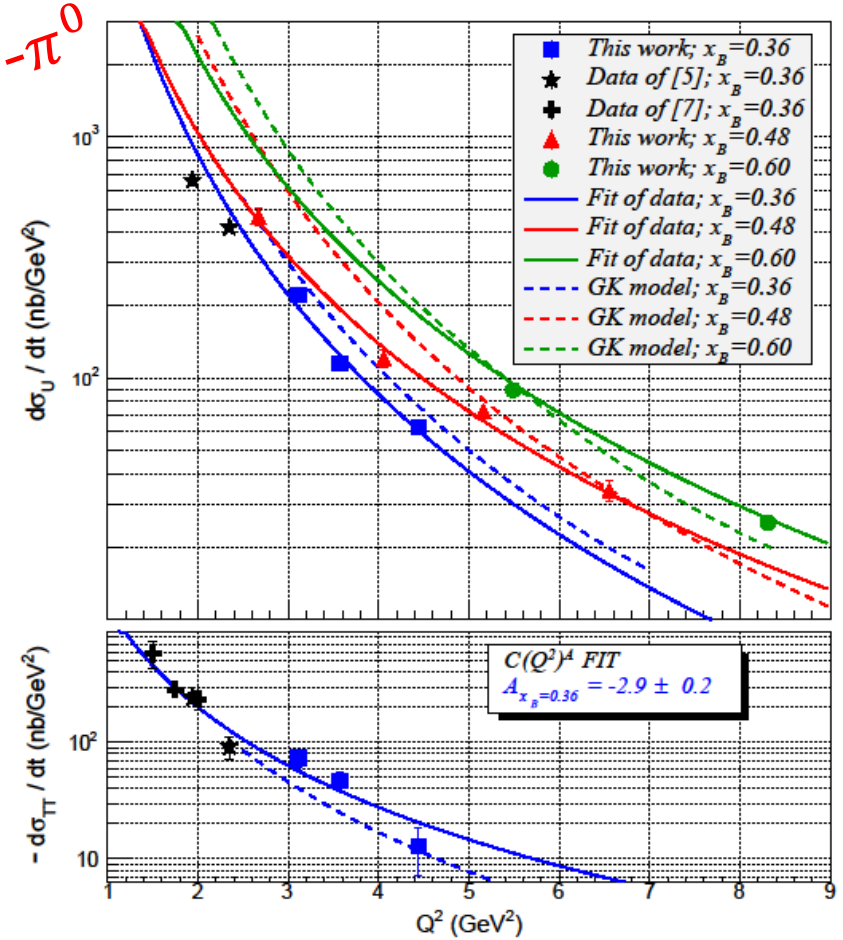
3rd Generation (2014-2016)

Multiple x_B and Q^2 measurements

DVCS



DVMP-π^0



- First experimental extraction of all four helicity-conserving CFFs

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

- Cross-section terms extracted for 9 different kinematics

M. Dlamini et al, Phys. Rev. Lett 127, 152301 (2021)

Science Programs of NPS at Hall C

Run Group 1a (NPS at small angles and HMS - SHMS used as carriage for NPS):

- **E12-13-010** (Run status: complete): Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C Link
- **E12-13-007** (Run Status: complete): Measurement of Semi-Inclusive pi0 Production as Validation of Factorization Link
- **E12-22-006** (Run status: complete): Deeply Virtual Compton Scattering off the neutron with the Neutral Particle Spectrometer in Hall C Link
- **E12-23-014** (Run status: complete): Measurements of the Ratio R = sigmaL/sigmaT p/d ratios, Pt dependence, and azimuthal asymmetries in Semi-Inclusive DIS pi0 production form proton and deuteron targets using the NPS in Hall C Link

Run Group 1b (NPS at small angles and HMS - SHMS used as carriage for NPS):

- **E12-06-114** (35 days moved to Hall C): Measurements of the electron-helicity dependent cross-sections of deeply virtual Compton scattering

Run Group 2 (NPS at large angles and HMS - SHMS used as carriage for NPS):

- **E12-14-003**: Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies Link
- **E12-14-005**: Wide Angle Exclusive Photoproduction of pi-zero Mesons Link

Run Group 3 (NPS+CPS - SHMS used as carriage for NPS)

- **E12-17-008**: Polarization Observables in Wide-Angle Compton Scattering at large s, t, and u Link

Run Group 4 (NPS reconfigured as part of an ECAL+HCAL system downstream from target)

- **E12-23-004**: A Search for a Nonzero Strange Form Factor of the Proton at 2.5 (GeV/c)^2 Link

Run Group 5 (NPS+Positrons)

- **C12-20-012** (status C2): Deeply Virtual Compton Scattering using a positron beam in Hall C Link

LOIs and proposal being developed

- LOI12-23-003: GluToNY: Gluon tomography in nucleons by gamma-polarimetry
- LOI12-23-014: Recoil Nucleon Polarization in Deeply Virtual Compton Scattering and Neutral Pion Electroproduction in Hall C
- C12-18-005: Timelike Compton Scattering Off a Transversely Polarized Proton Link (requires NPS + CPS)

NPS Run Group 1a: NPS at small angle

- Simultaneous data taking with measurements of exclusive and semi-exclusive processes.
- Data taking: September 2023 – May 2024, data analysis starting

Extended Measurements at Hall C

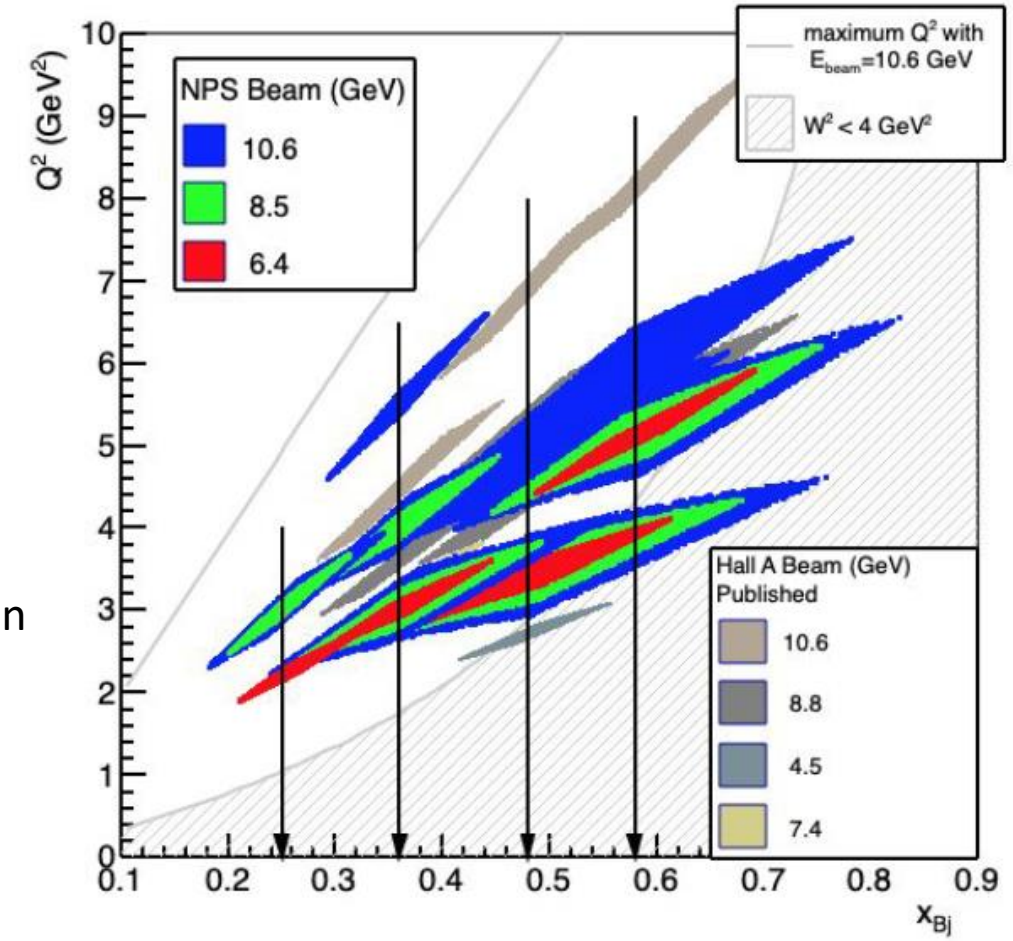
- **Expanded kinematic coverage compared to Hall A**
- **Multiple beam energies for most kinematic settings (6.4, 8.5, 10.5 GeV)**

DVCS:

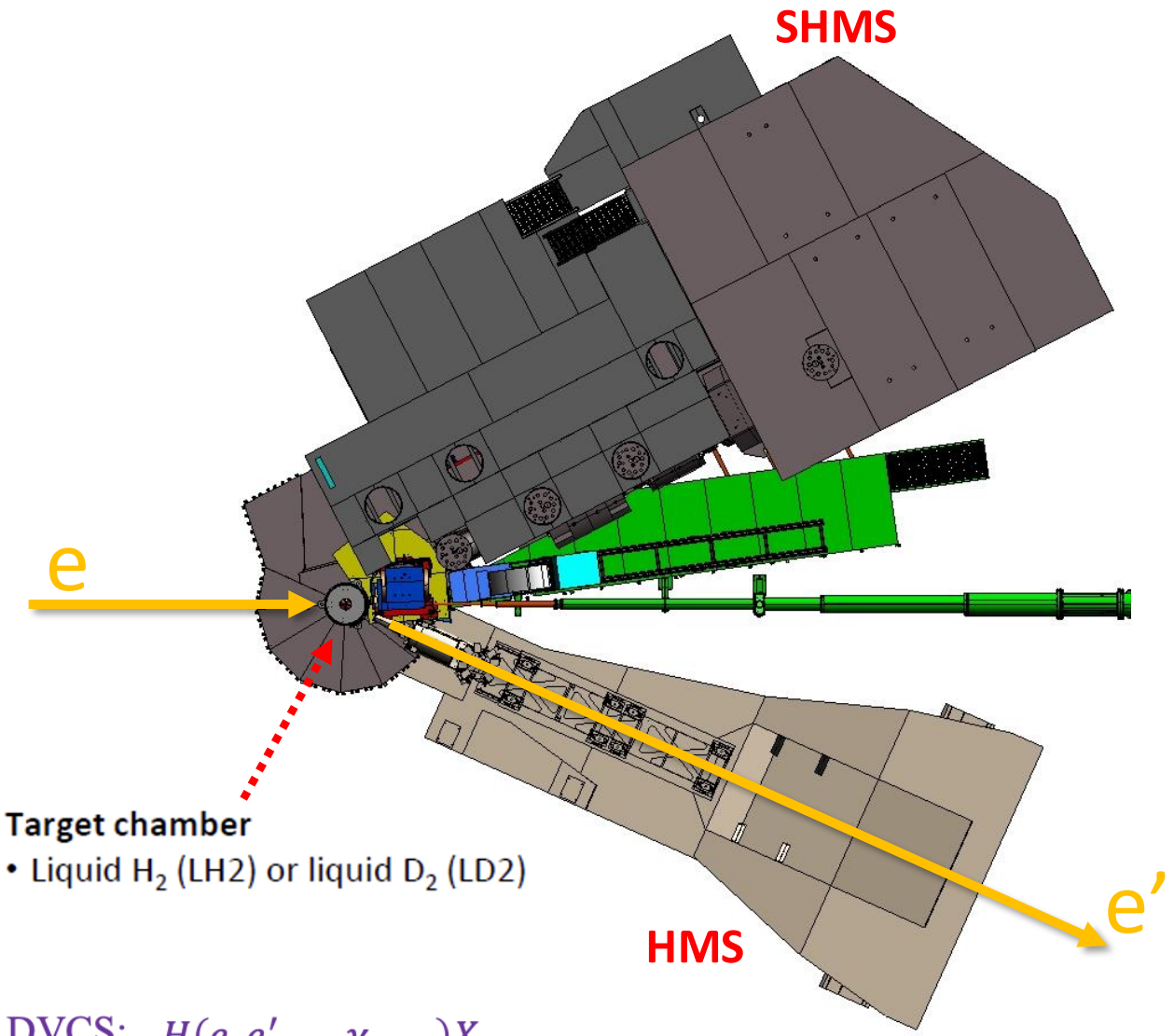
- Disentangle all Fourier moments of the cross-section
  → E and ϕ dependence
- Quantify the size of higher-twist corrections
  → Q^2 dependence
- Disentangle the imaginary and real part of the DVCS amplitude
  → helicity dependence

Exclusive π^0 electroprdution:

- Disentangle the longitudinal/transverse contribution to the cross section
  → E dependence
- Measure the Q^2 evolution of σ_L and σ_T
  → Q^2 dependence



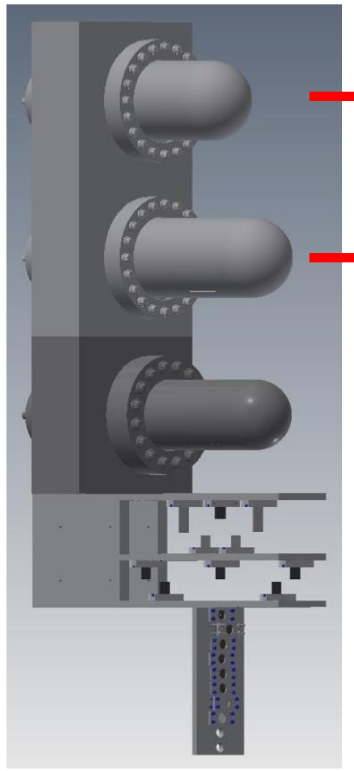
NPS Experimental Setup at Hall C



DVCS: $H(e, e'_{HMS}, \gamma_{Calo})X$

DVMP: $H(e, e'_{HMS}, \pi^0 \rightarrow \gamma\gamma)X$

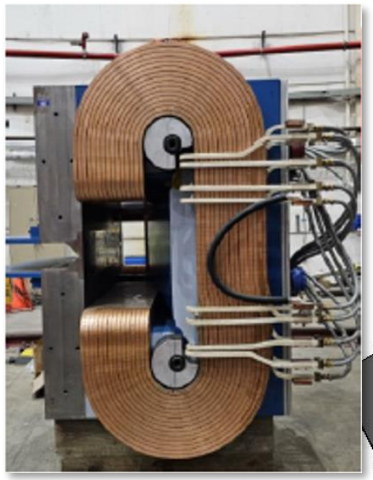
- Target chamber



➢ High Momentum Spectrometer (HMS)

- Particle identification
- e' Tracking
- Event trigger

NPS Experimental Setup at Hall C



Sweep magnet

Target chamber

- Liquid H_2 (LH2) or liquid D_2 (LD2)

DVCS: $H(e, e'_{HMS}, \gamma_{Calo})X$

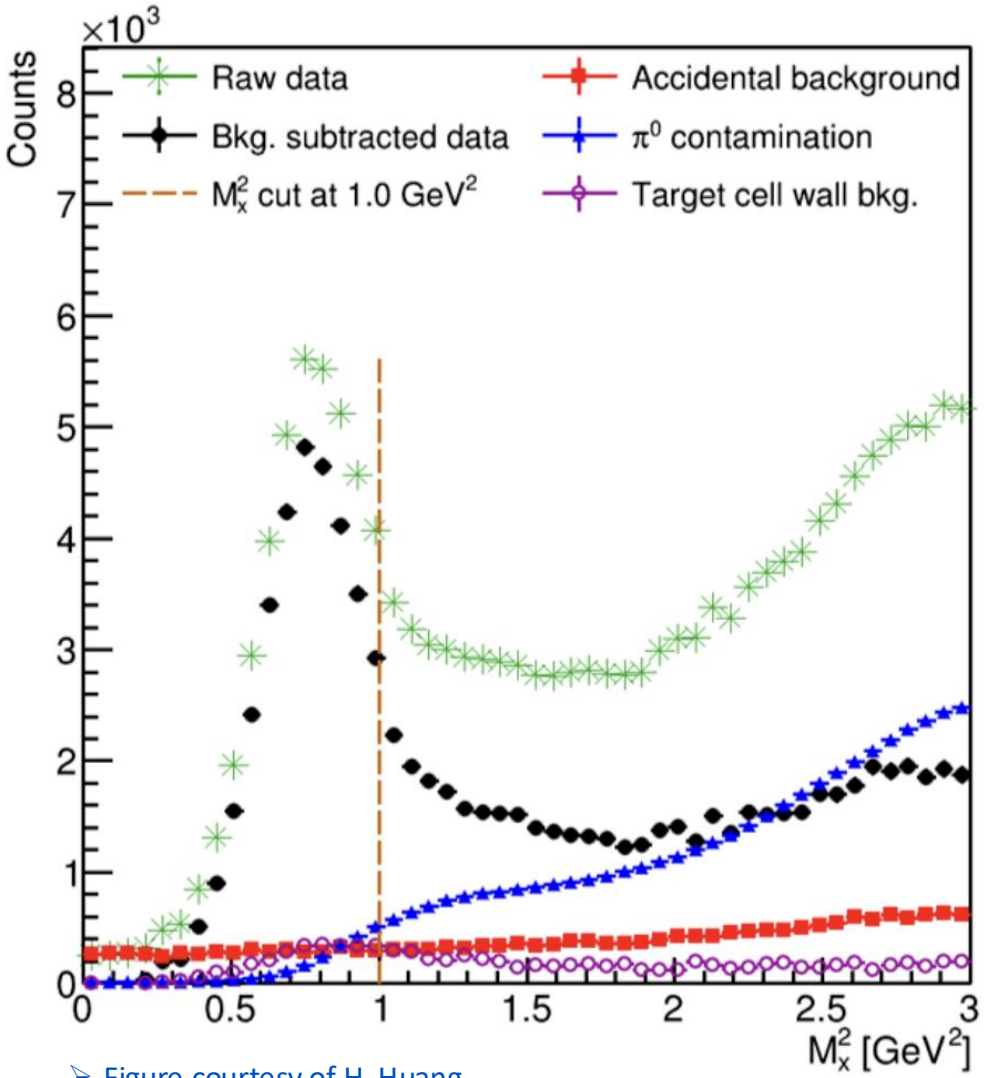
DVMP: $H(e, e'_{HMS}, \pi^0 \rightarrow \gamma\gamma)X$

- Sweep magnet:
  - 0.3 T magnetic field
  - Reduce low-energy electron background
- Neutral Particle Spectrometer (NPS):
  - Photon detection
  - A total of 30×36 (1080) PbWO4 crystals
  - PbWO4 crystals size $2\times2\times20$ cm^3





Preliminary Results of DVCS Extraction



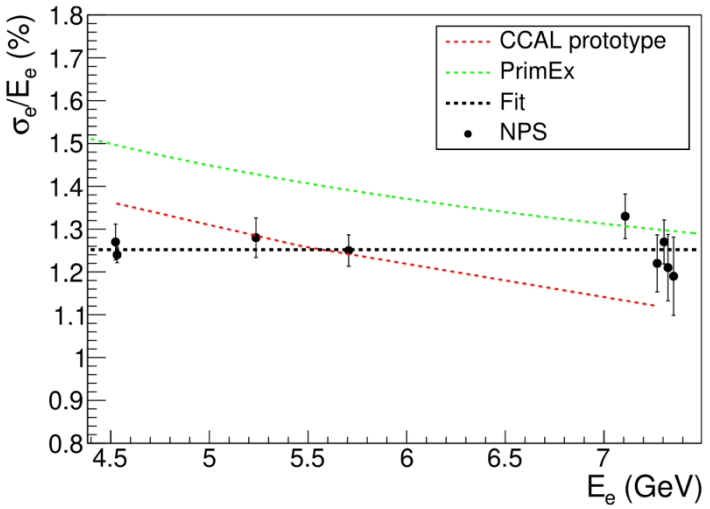
➢ Figure courtesy of H. Huang

➢ Recoil proton not detected

→ Determine the exclusivity of an event by the missing mass

$$M_X^2 = \left(k_e + P_p - k'_e - q_\gamma\right)^2$$

→ Decent photon energy resolution is essential for the separation of exclusive events from background .



➢ σ_e/E_e at of 1.2% to 1.3% between 4.5 GeV and 7.3 GeV

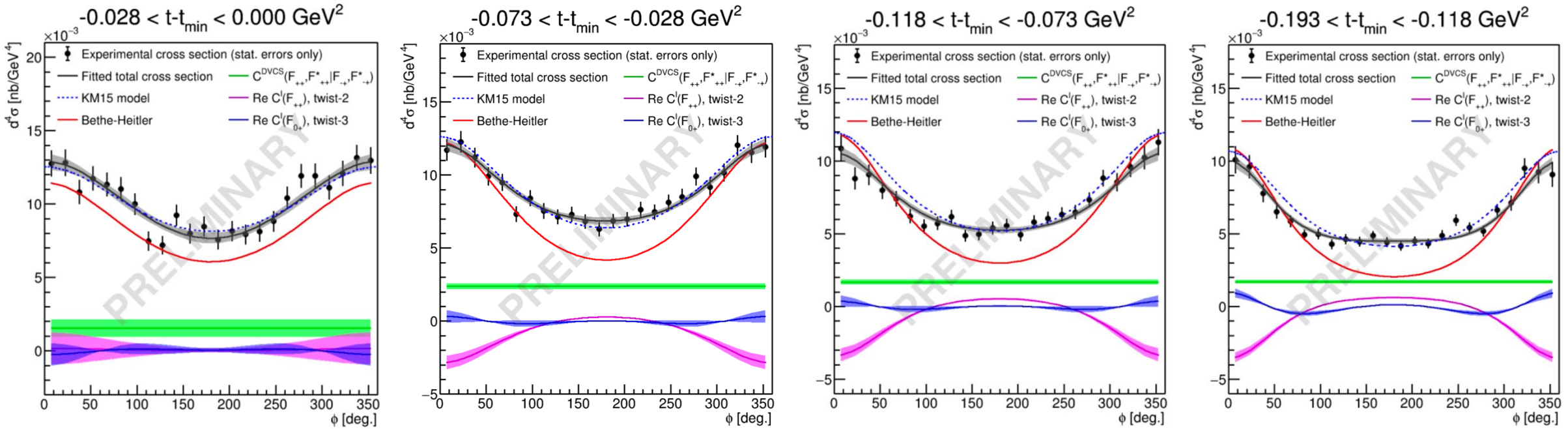
NIM A 1086 (2026) 171323

Preliminary Results of DVCS Extraction

- Kinematics: $\langle Q^2 \rangle = 4$ GeV², $\langle x_{Bj} \rangle^2 = 0.36$, $E_{beam} = 10.54$ GeV
- Background subtracted & detector efficiency corrected.

- Statistical errors only
- Good agreement with KM15 model

Helicity Independent



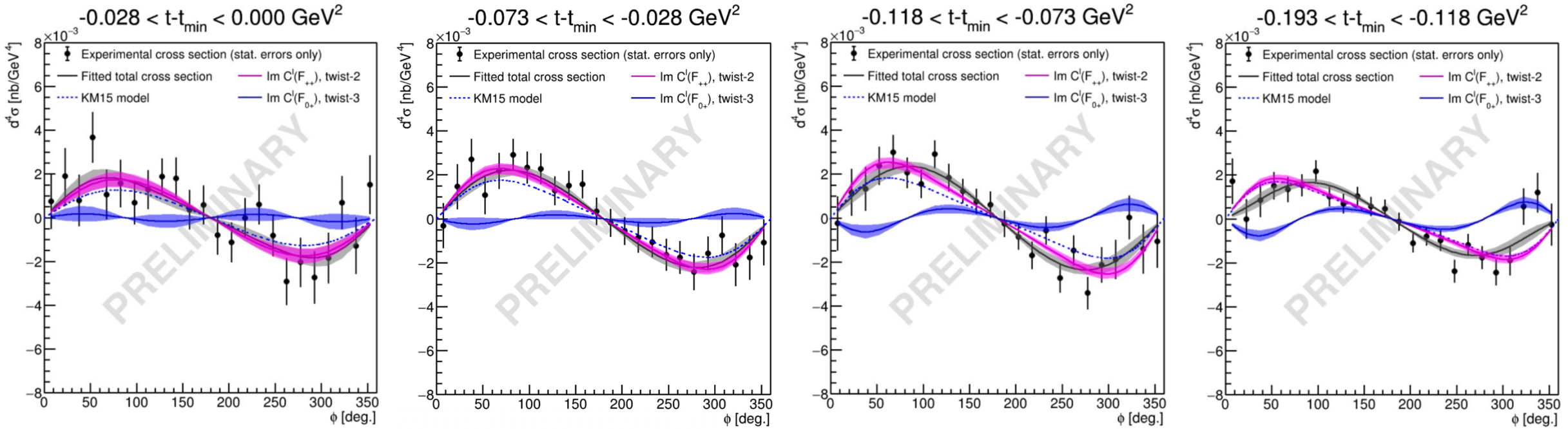
- Figure courtesy of H. Huang

Preliminary Results of DVCS Extraction

- Kinematics: $\langle Q^2 \rangle = 4$ GeV², $\langle x_{Bj} \rangle^2 = 0.36$, $E_{beam} = 10.54$ GeV
- Background subtracted & detector efficiency corrected.

- Statistical errors only
- Good agreement with KM15 model

Helicity Dependent



- Figure courtesy of H. Huang

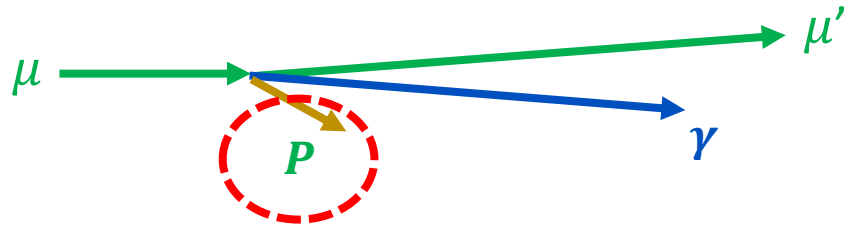
Summary

- **GPD study can provide interesting insights into the nucleon properties. And the experimental extraction of GPDs via exclusive processes is quite challenging.**

- **GPD Measurements at COMPASS & JLab Hall A/C NPS have been providing fruitful and complementary inputs for GPD study. Expect more to come in the near future.**

Backup Slides

COMPASS 2016 Preliminary Results



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

Proton azimuthal angle

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

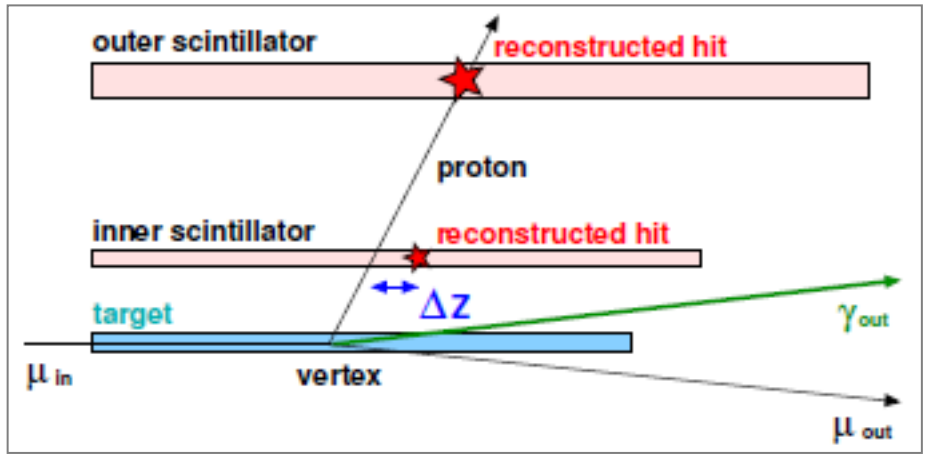
Proton momentum

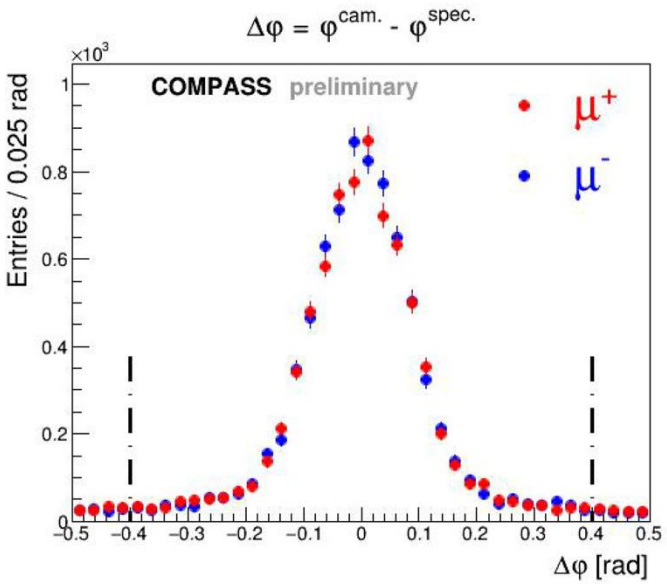
$\Delta z_A = z_A^{cam.} - z_A^{spec.}$

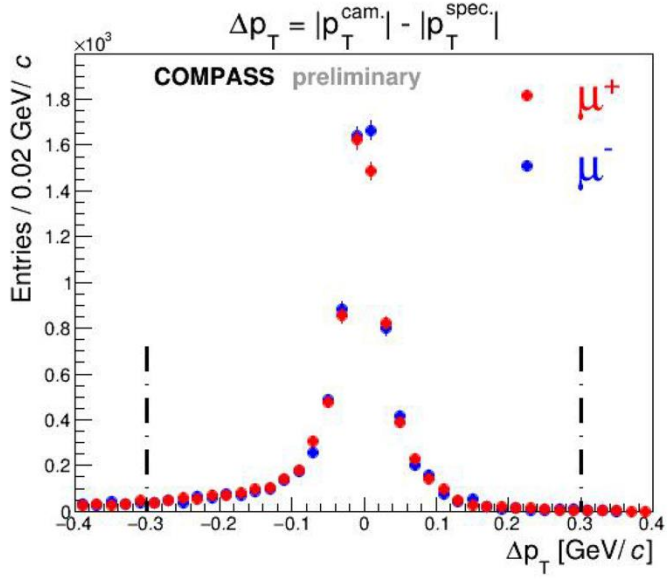
Proton track position

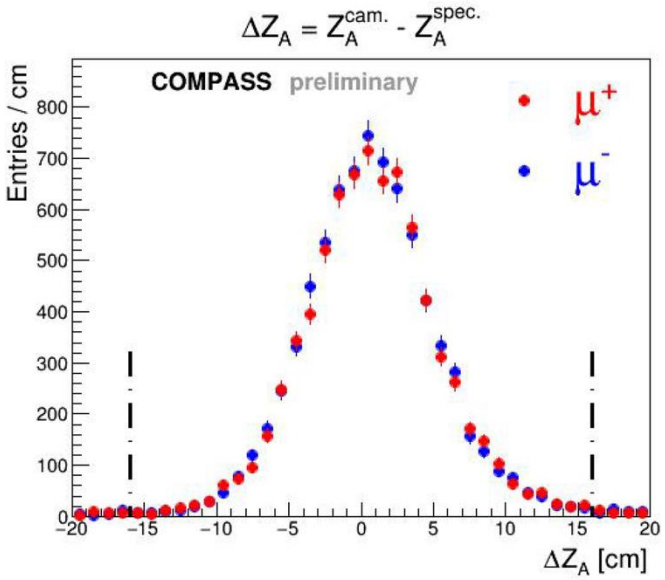
$M^2_{undet} = (k + p - k' - q' - p')^2$

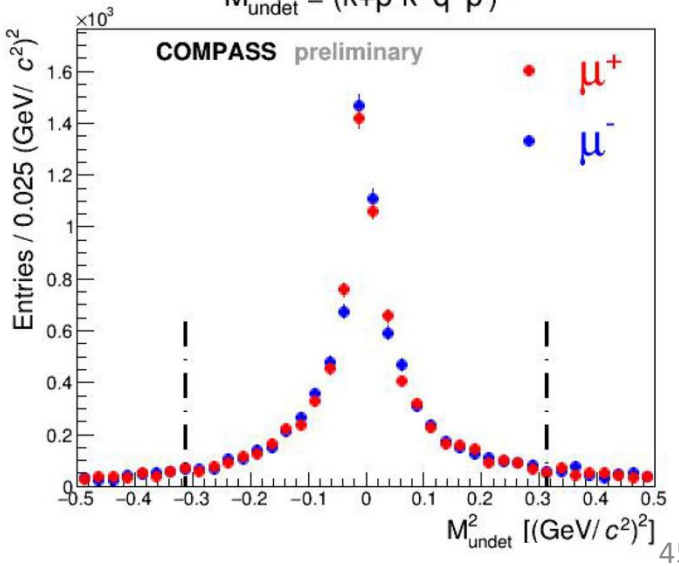
Energy momentum balance



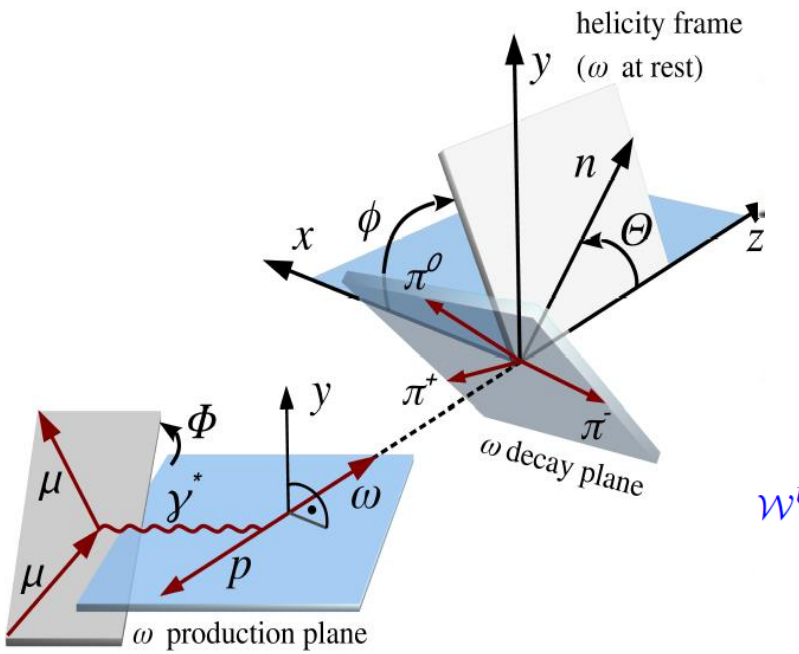








Exclusive ω Production on Unpolarized Proton



Experimental angular distributions

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

15 unpolarized SDMEs in $\mathcal{W}^U$ and 8 polarized in $\mathcal{W}^L$

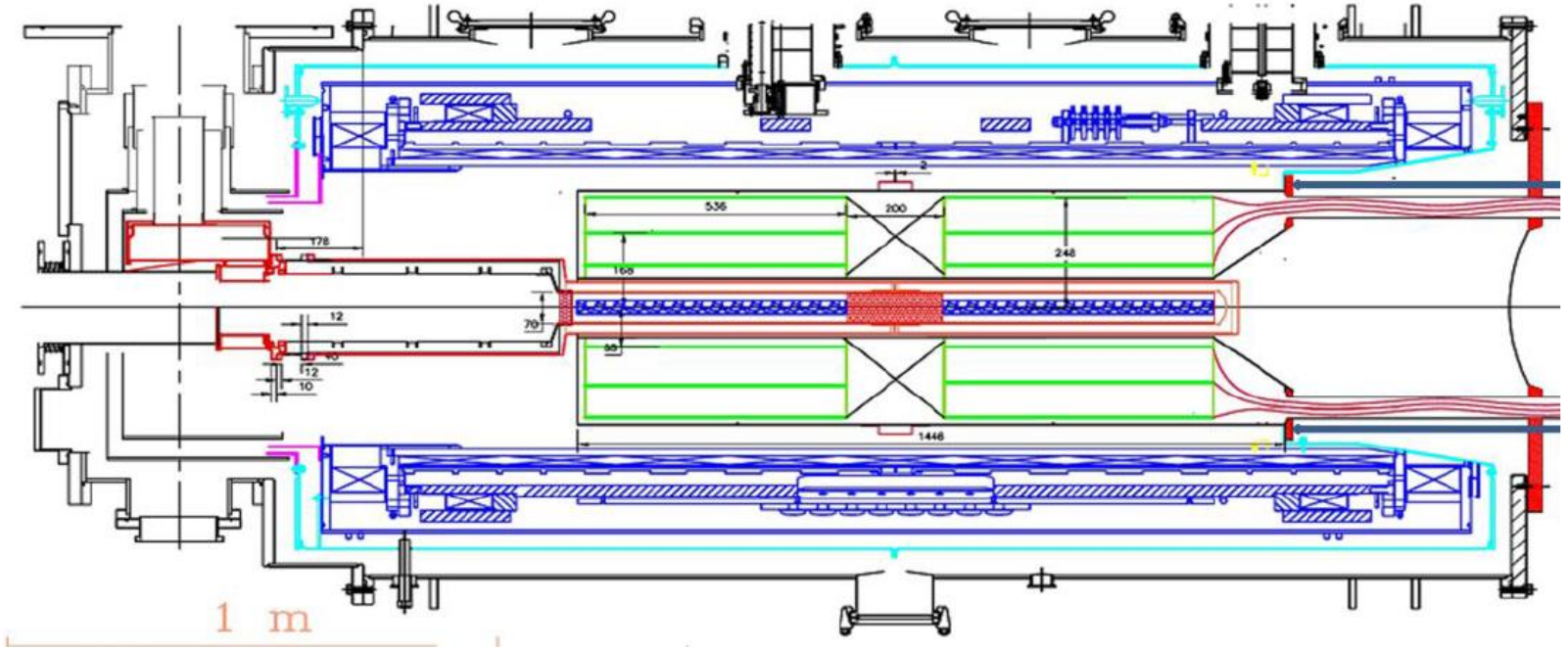
$$\mathcal{W}^{U}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\left[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi\right.$$
$$-\epsilon\cos 2\Phi\left(r^{1}_{11}\sin^2\Theta + r^{1}_{00}\cos^2\Theta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

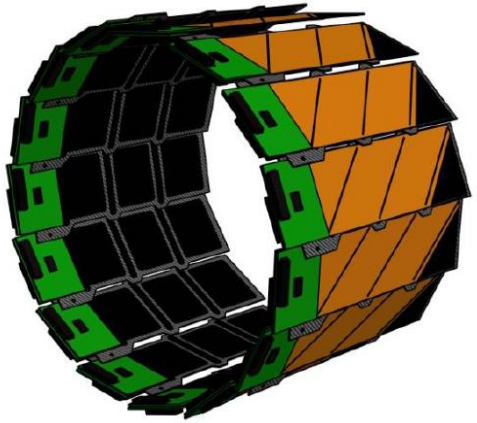
$$\mathcal{W}^{L}(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\left[\sqrt{1-\epsilon^2}\left(\sqrt{2}\mathrm{Im}\{r^{3}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{3}_{1-1}\}\sin^2\Theta\sin 2\phi\right)\right.$$
$$+\sqrt{2\epsilon(1-\epsilon)}\cos\Phi\left(\sqrt{2}\mathrm{Im}\{r^{7}_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^{7}_{1-1}\}\sin^2\Theta\sin 2\phi\right)$$
$$\left.+\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^{8}_{11}\sin^2\Theta + r^{8}_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^{8}_{10}\}\sin 2\Theta\cos\phi - r^{8}_{1-1}\sin^2\Theta\cos 2\phi\right)\right]$$

➢ $\epsilon \to 1$, small $\mathcal{W}^L$

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