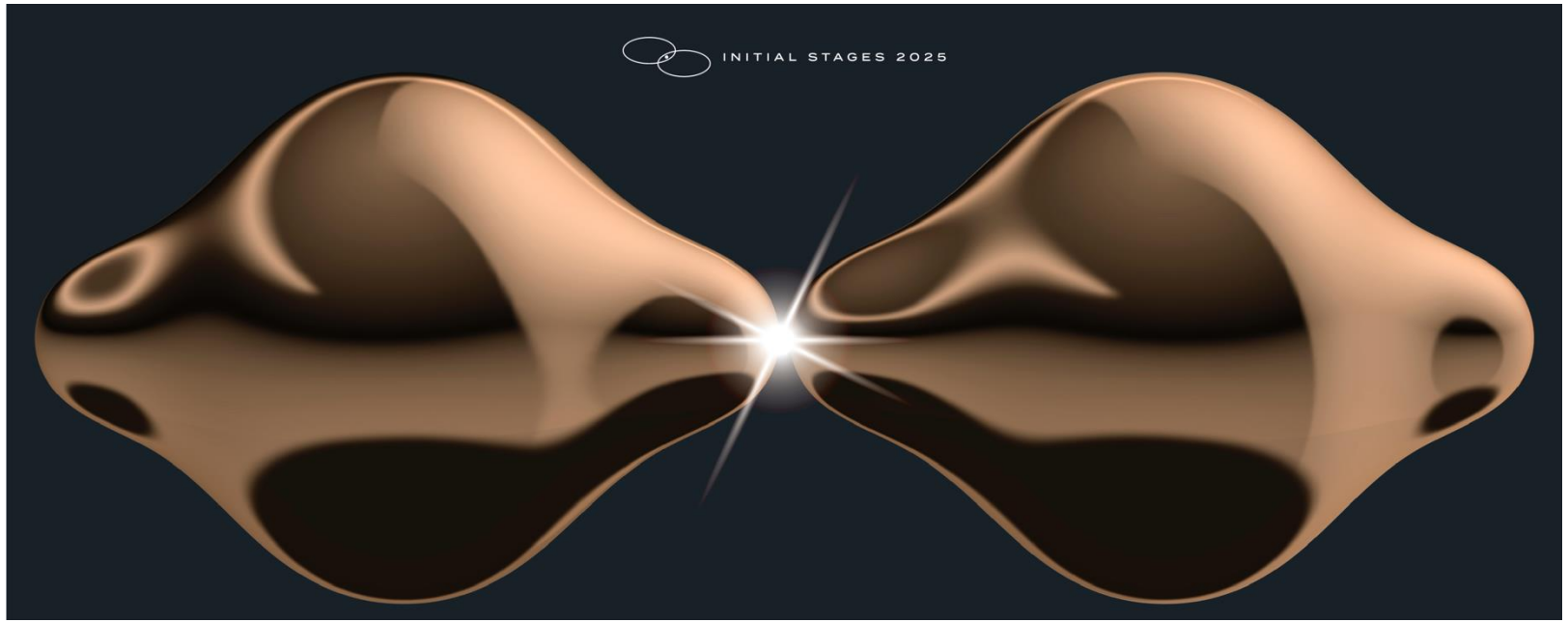


Measurement of the Hard Exclusive π^0 Muoproduction at COMPASS

Initial Stages 2025

Taipei, Taiwan

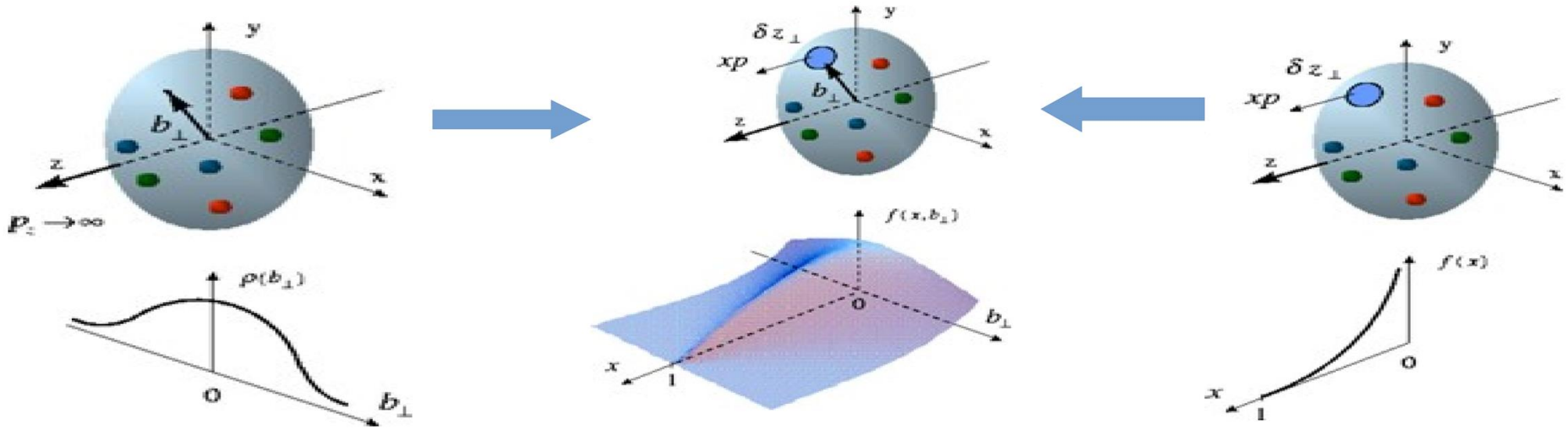
September 10th , 2025

Po-Ju Lin

Department of Physics, National Central University

On behalf of the COMPASS Collaboration

Multi-dimensional Partonic Structures



- **Form Factors (FFs)**
  - ✔ Spatial distribution
  - ✗ Momentum distribution

- **Generalized Parton Distributions (GPDs)**
  - ✔ Spatial distribution
  - ✔ Longitudinal momentum distribution

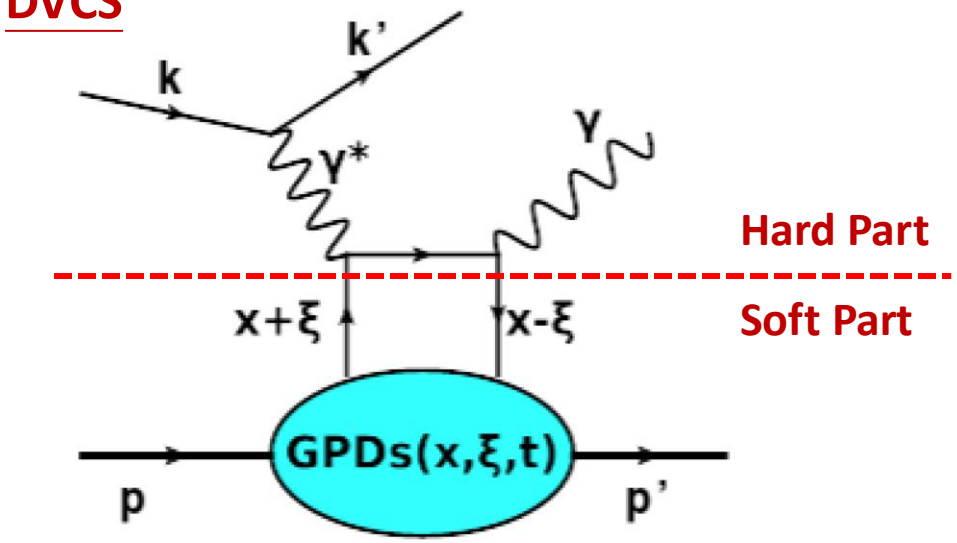
- **Parton Distribution Functions (PDFs)**
  - ✔ Longitudinal momentum distribution
  - ✗ Spatial distribution

GPDs

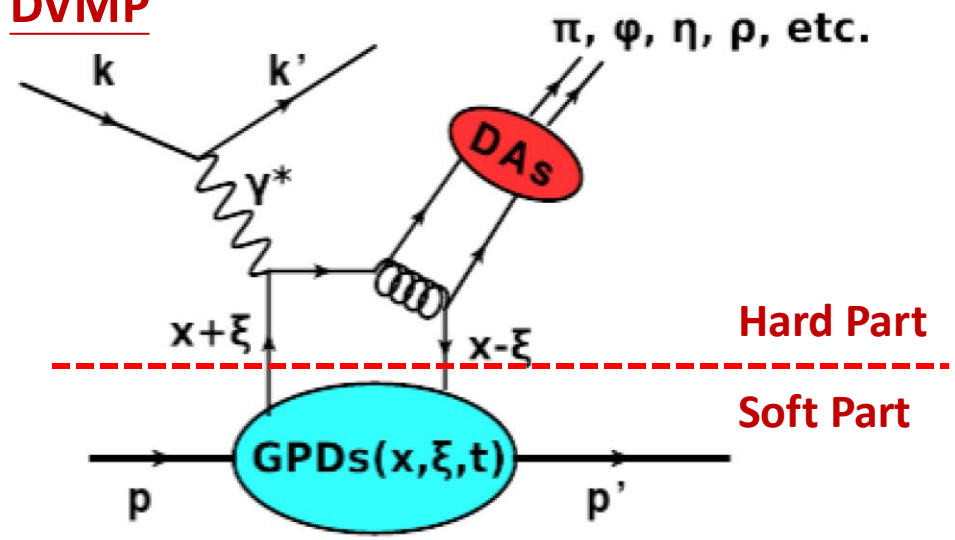
- **Correlate the transverse position to the longitudinal momentum of the partons and thus provides a 3-D information of the nucleon.**
- **Accessible through exclusive processes.**

Deep Exclusive Processes

DVCS



DVMP



- The GPDs depend on the variables at fixed Q^2:
  - x: average longitudinal momentum frac.
  - ξ: longitudinal momentum diff. $\approx x_B/(2-x_B)$
  - t: four momentum transfer

➢ Deeply Virtual Compton Scattering (DVCS) & Deeply Virtual Meson Production (DVMP)

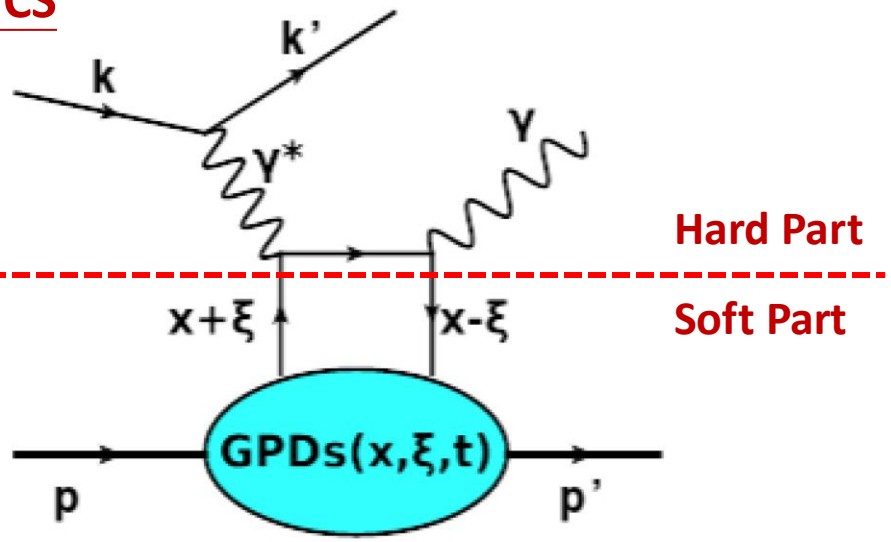
- Hard exclusive production of a single photon or meson

➢ In Bjorken limit (Q^2 & $\nu \to \infty$ at fixed x_B)

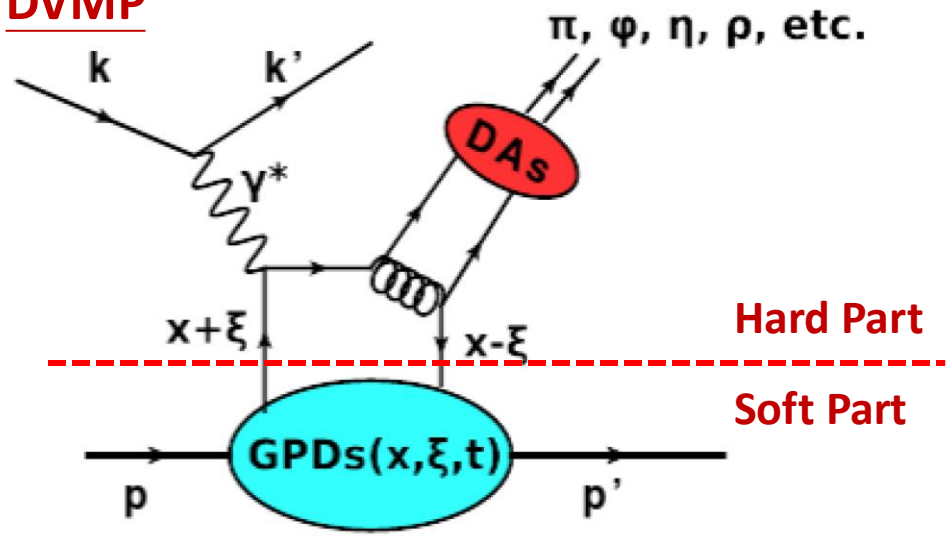
- Hard Part: Calculable perturbatively
- Soft Part: Nucleon structure described by GPDs

Deeply Virtual Meson Production (DVMP)

DVCS



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

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

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

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

- 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 on Unpolarized Proton

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

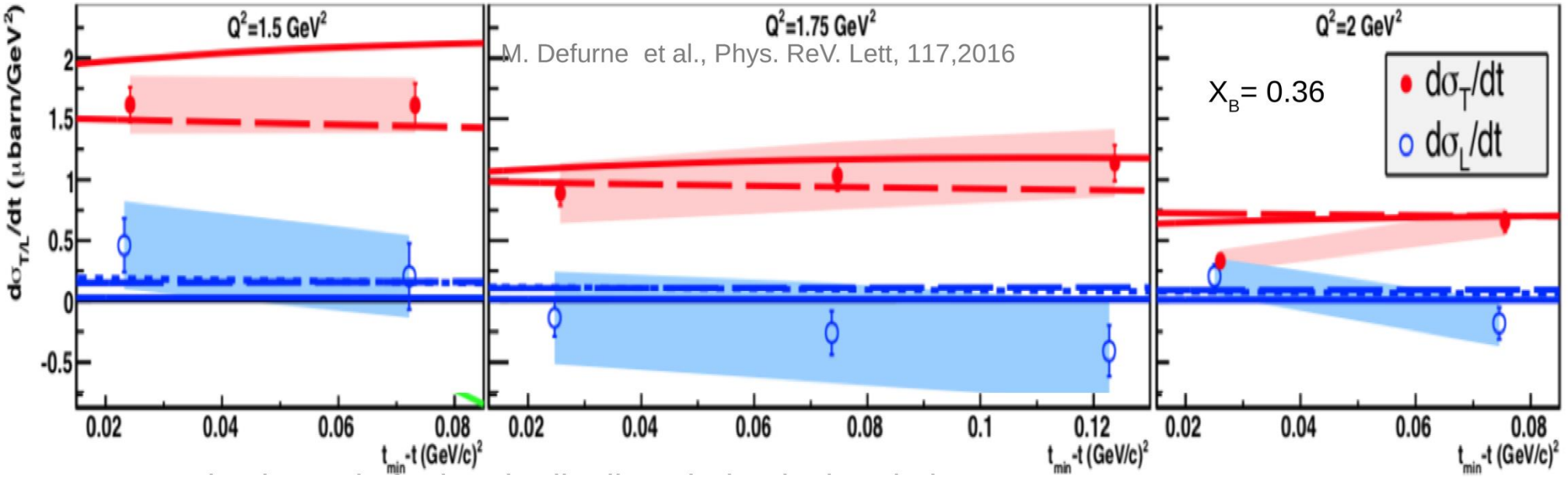
$$\frac{d^2\sigma}{dt d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

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 $\frac{d\sigma_T}{dt}$



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 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 $\frac{d\sigma_T}{dt}$

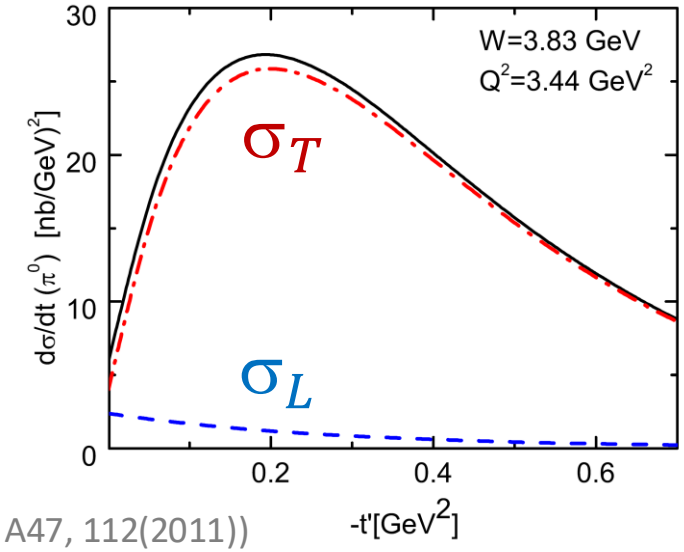
The other contributions arise from coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

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

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

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

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



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

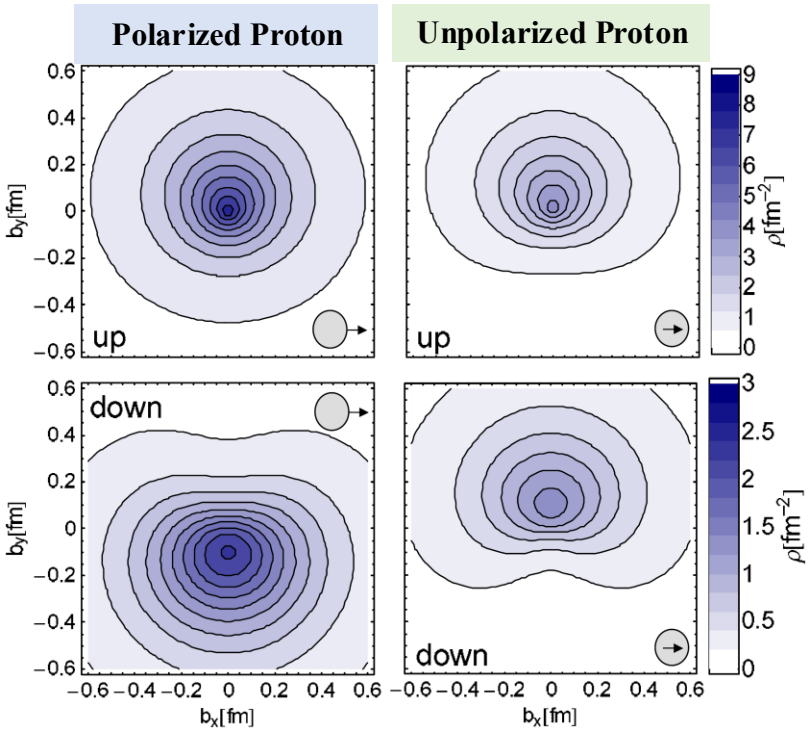
Exclusive π^0 Production on Unpolarized Proton

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

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

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

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



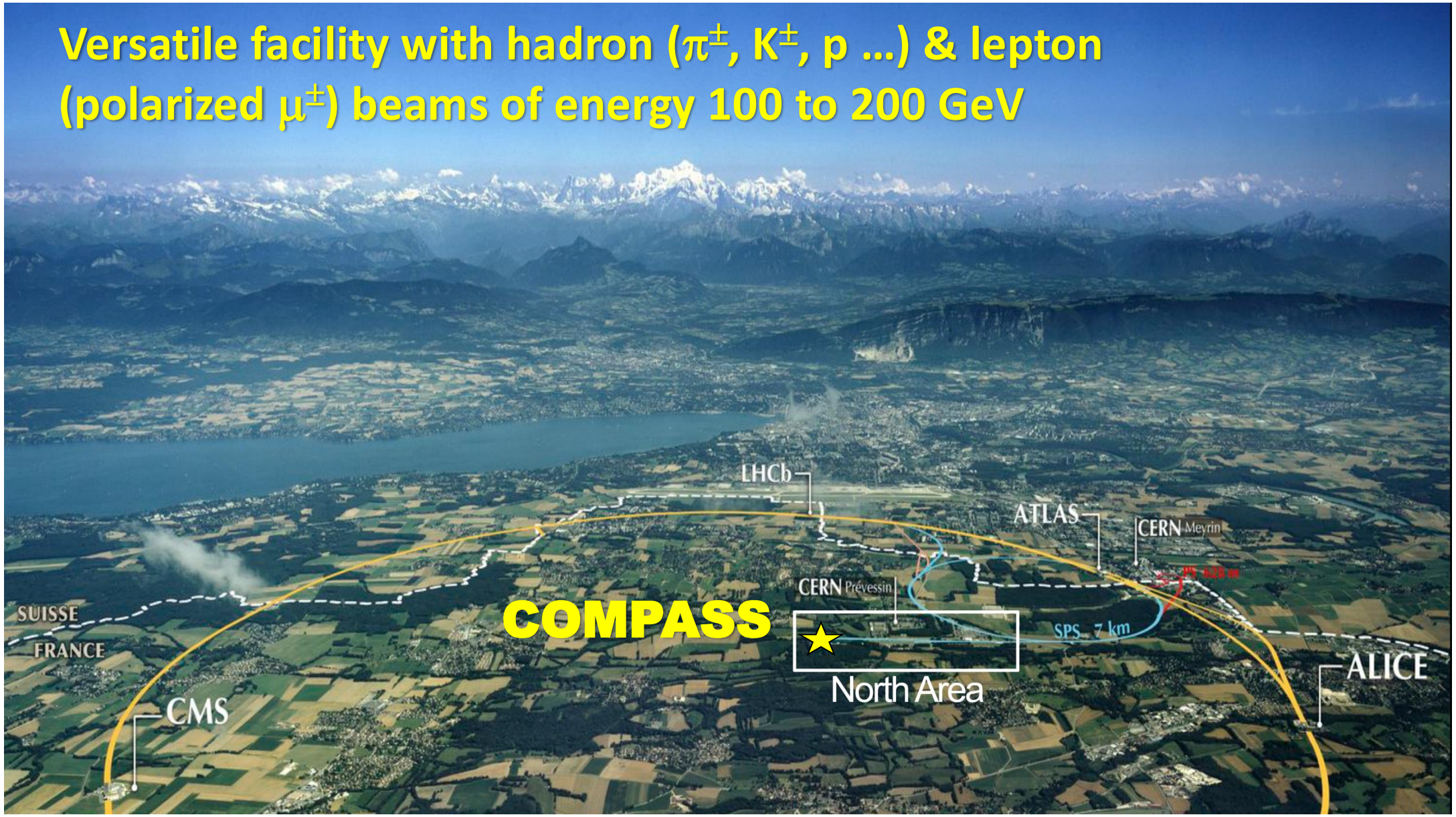
Described by E Described by $\bar{E}_T = 2\tilde{H}_T + E_T$

Lattice Calculation: Gockeler *PRL* 222001 (2007)

H_T: Generalization of transversity distribution
$h_1(x)$ → related to the transverse spin structure

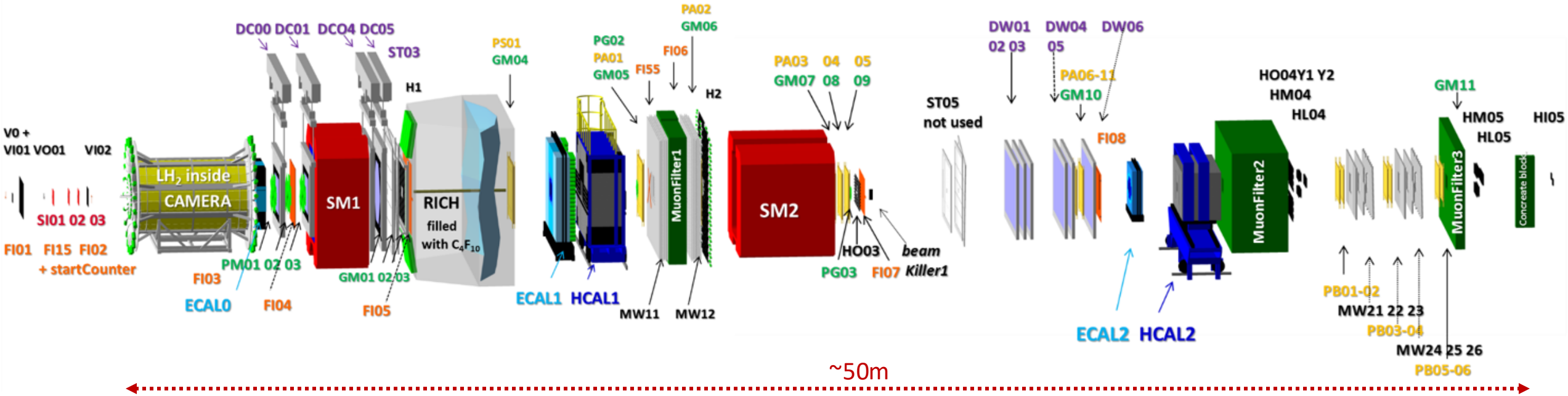
COMPASS Experiment

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 Experimental Setup



- 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

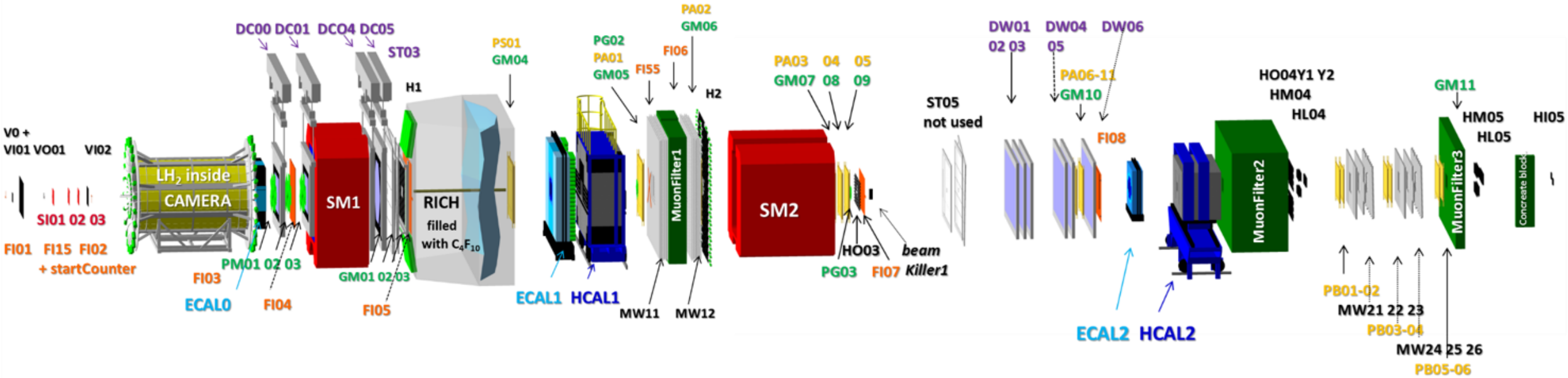
- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC, DC, straw
- PID – CEDARs, RICH, calorimeters, Muon Walls

Various targets:

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

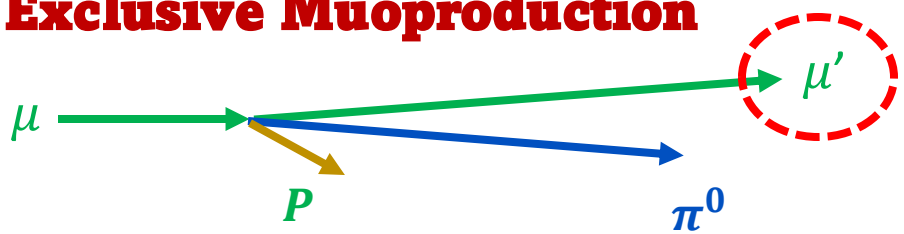
❖ NIM A 577 (2007) & NIM A 779 (2015) 69

COMPASS Setup for Exclusive Processes

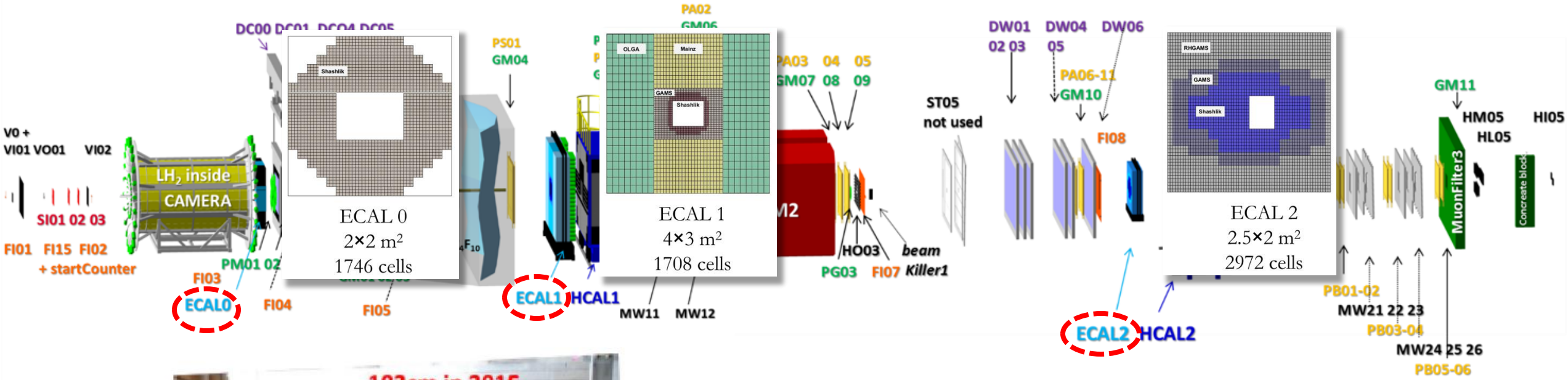


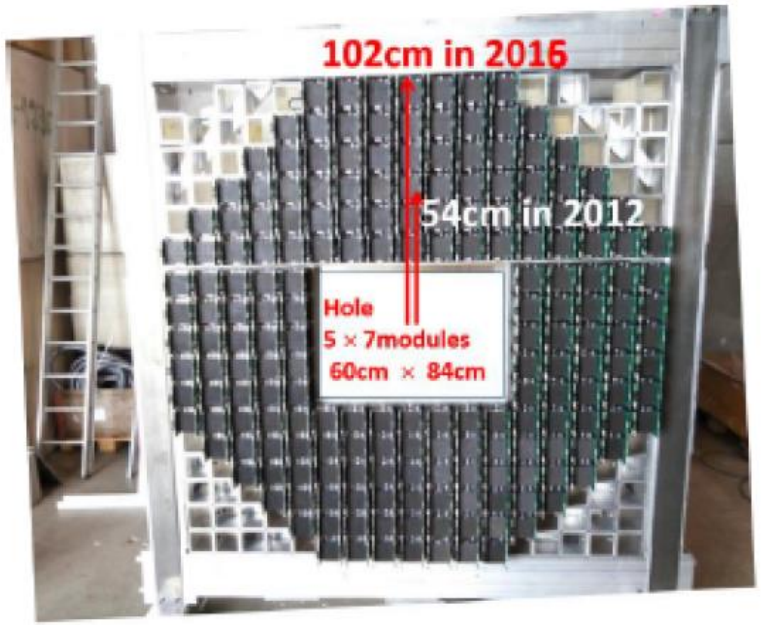
- Priamary beam – 400 GeV p from SPS
  - Impinging on Be production target
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% π^+, 24% p, 1% K^+
- **160 GeV tertiary muon beams**
  - **$\mu^\pm$ longitudinally polarized**

Exclusive Muoproduction

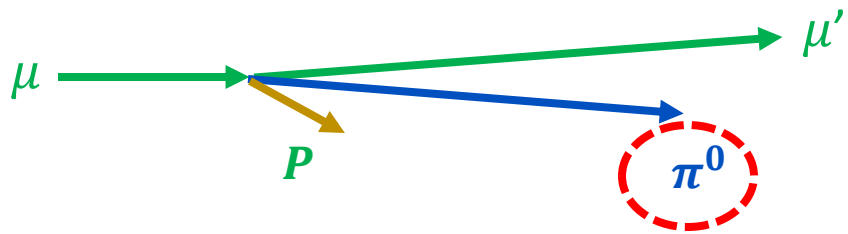


COMPASS Setup for Exclusive Processes

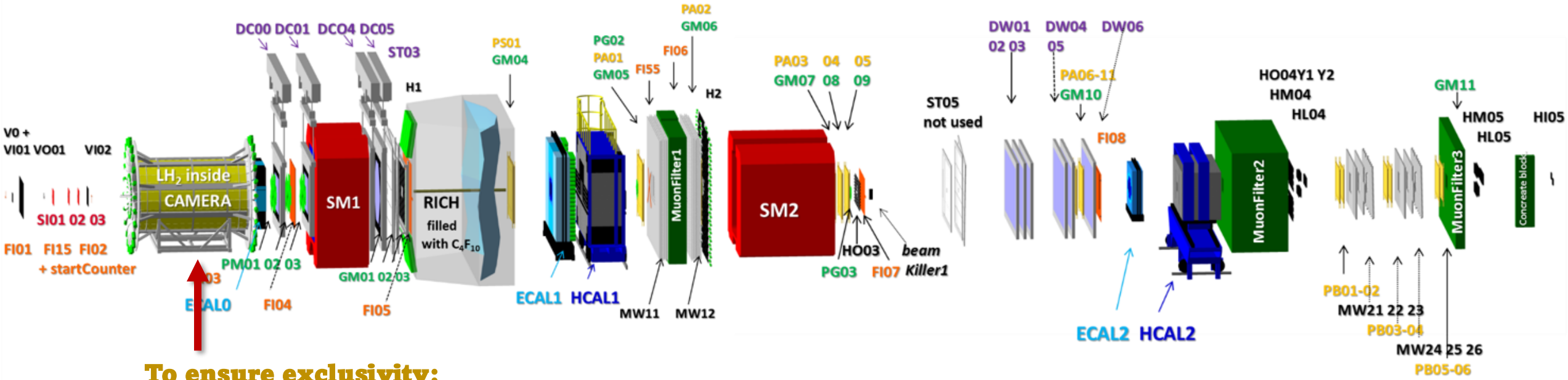




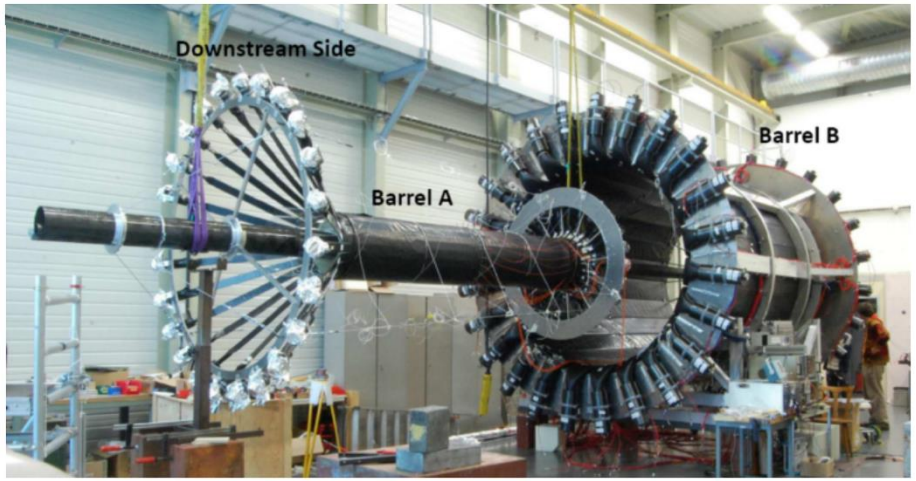
Exclusive Muoproduction



COMPASS Setup for Exclusive Processes

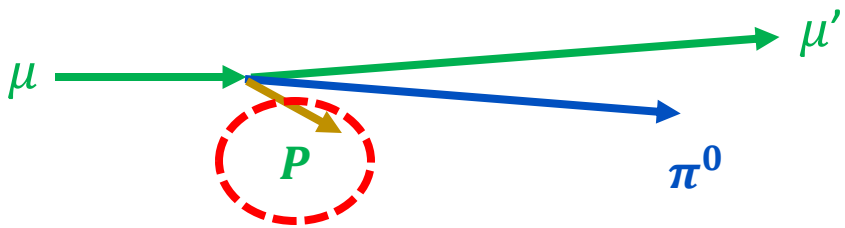


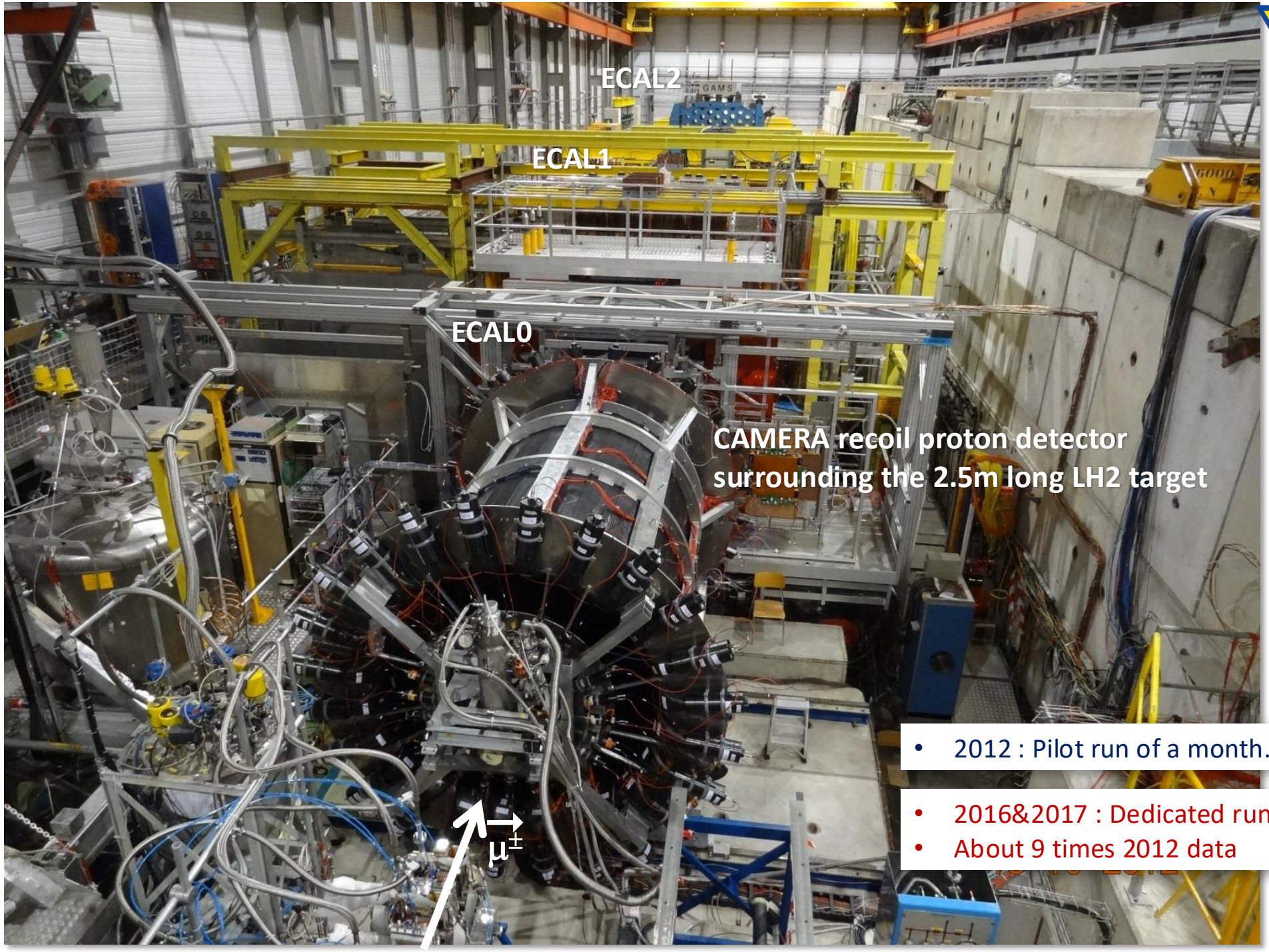
To ensure exclusivity:



CAMERA recoil proton detector

Exclusive Muoproduction



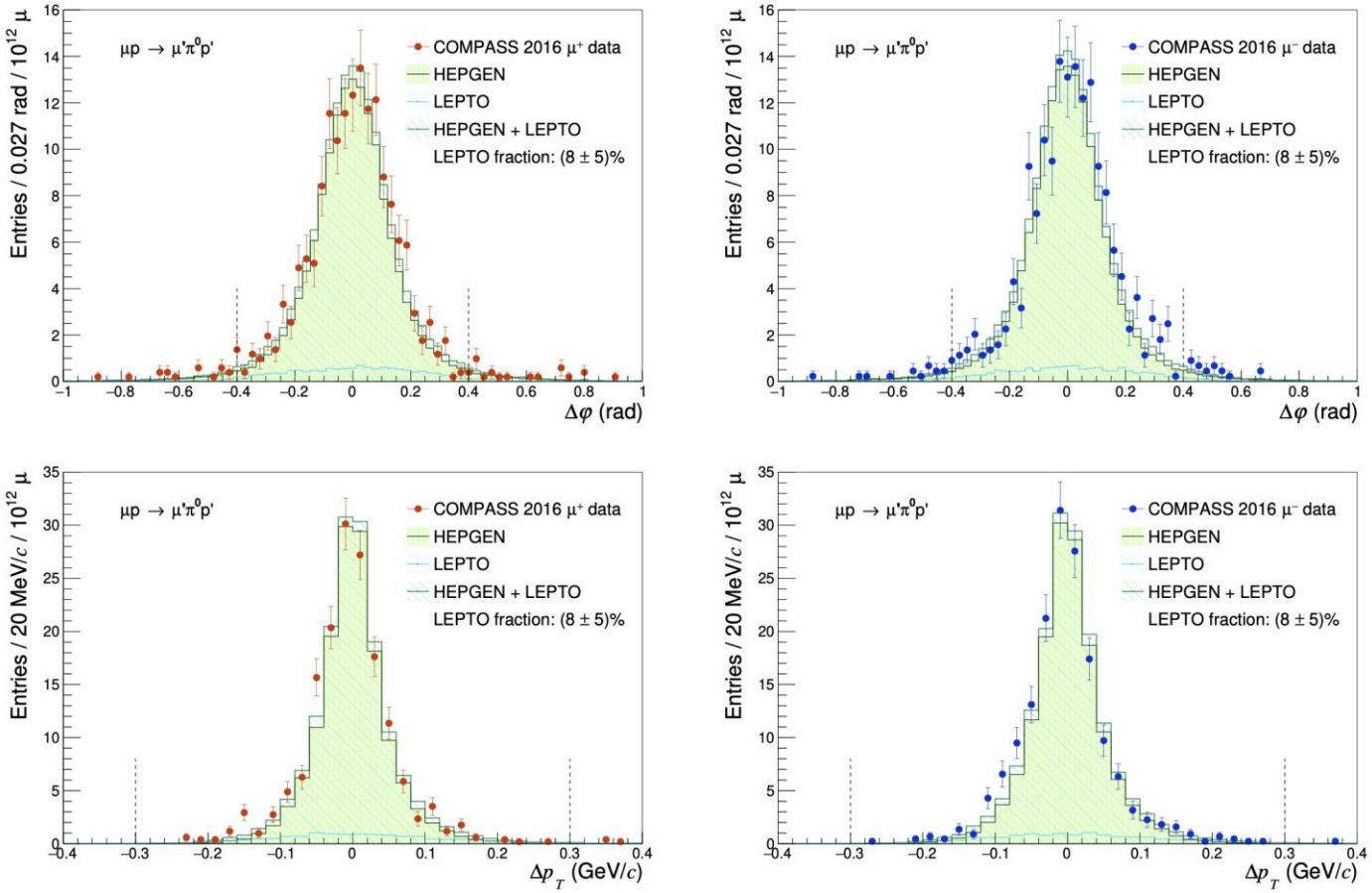


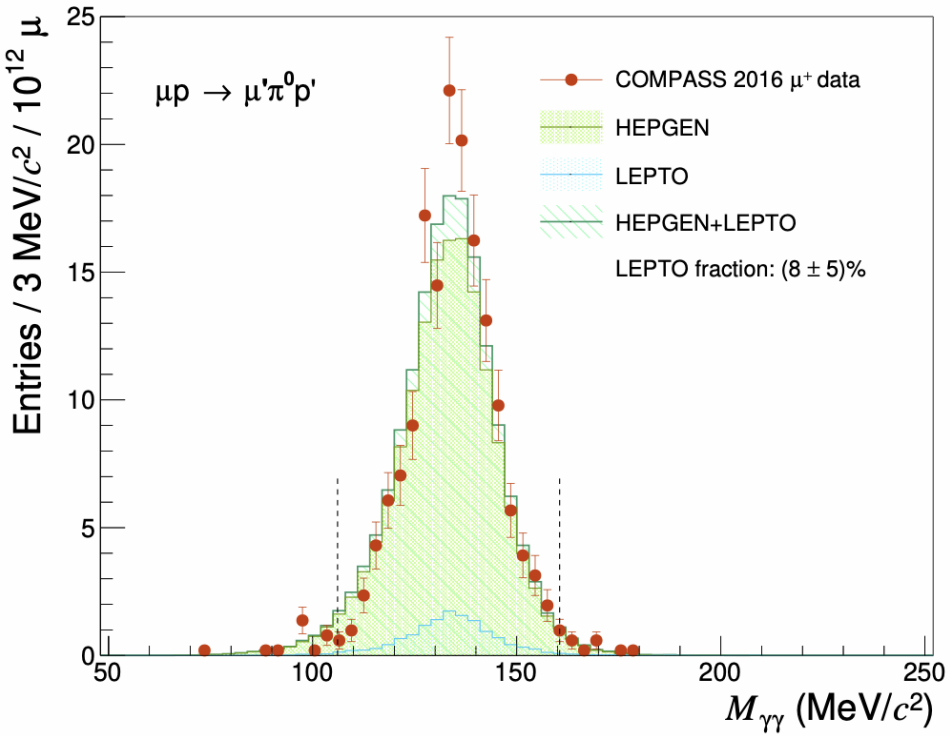
- 2012 : Pilot run of a month.

- 2016&2017 : Dedicated run of 2x6 months
- About 9 times 2012 data

Exclusive π^0 Selection and Background Estimation

- Exclusivity ensured by cuts on *exclusivity variables*.
- Background fraction determined by fitting the exclusivity variables with Monte Carlo simulations.
  - *LEPTO* for non-exclusive background
  - *HEPGEN* of exclusive π^0 for signal



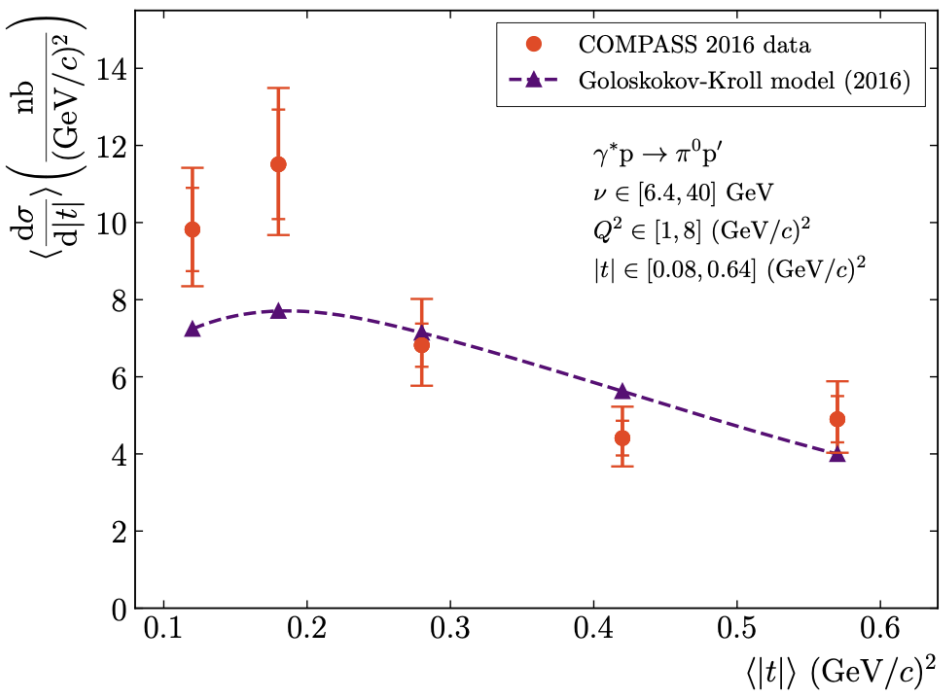


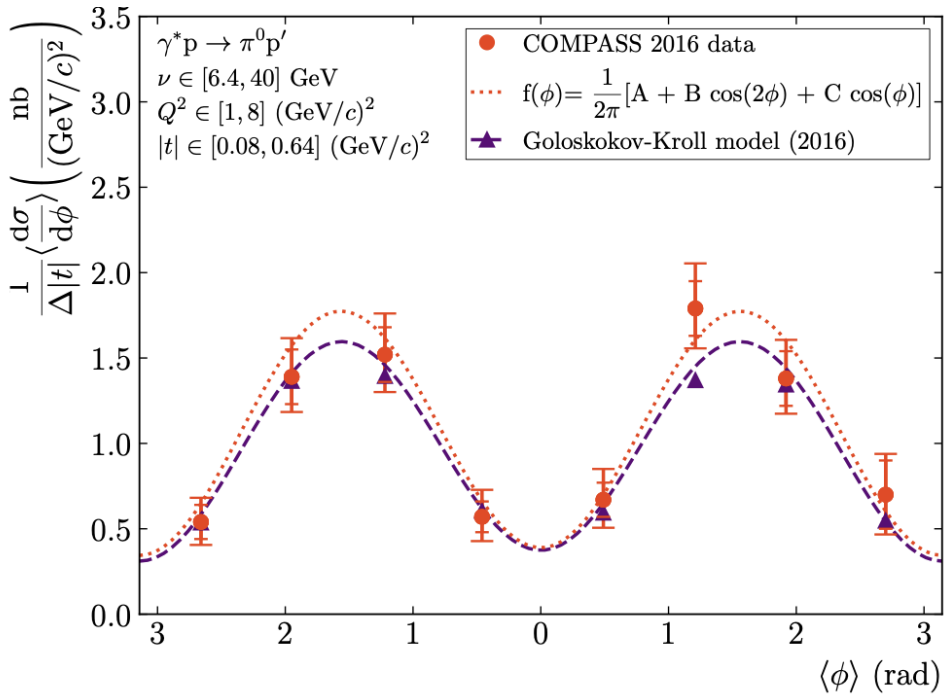
- In 2016 data, non-exclusive background fraction in data → 8 ± 5 %

New 2016 Exclusive π^0 Prod. on Unpolarized Proton

Accepted by PLB.

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





$\mu p \to \mu \pi^0 p$

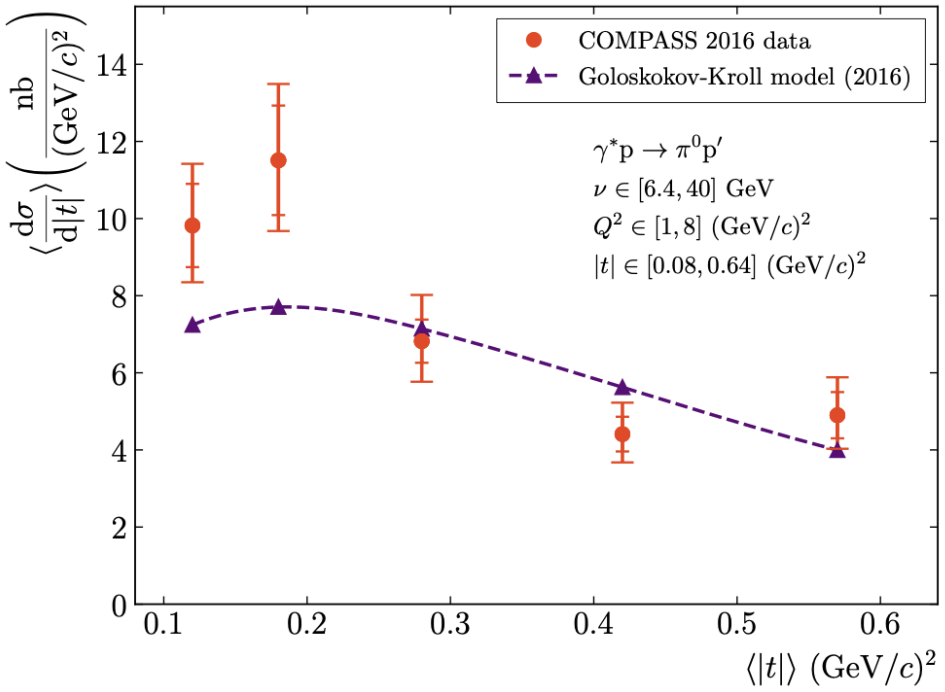
$$\frac{d^2\sigma}{dt d\phi_\pi} = \frac{1}{2\pi}\left[\left(\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}\right) + \epsilon \cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

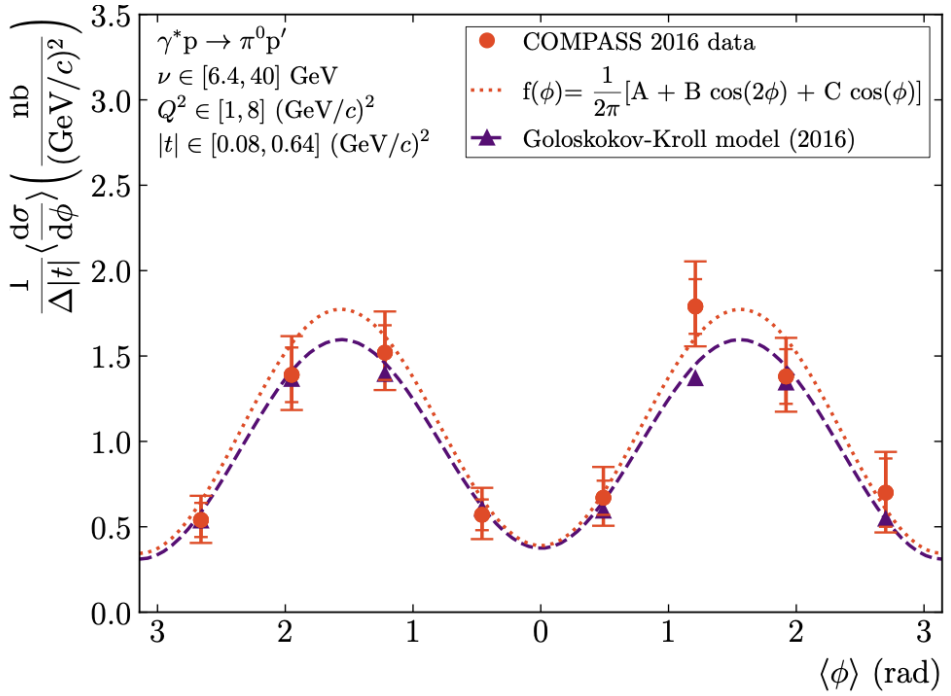
Chiral-odd GPDs

New 2016 Exclusive π^0 Prod. on Unpolarized Proton

Accepted by PLB.

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





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

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

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

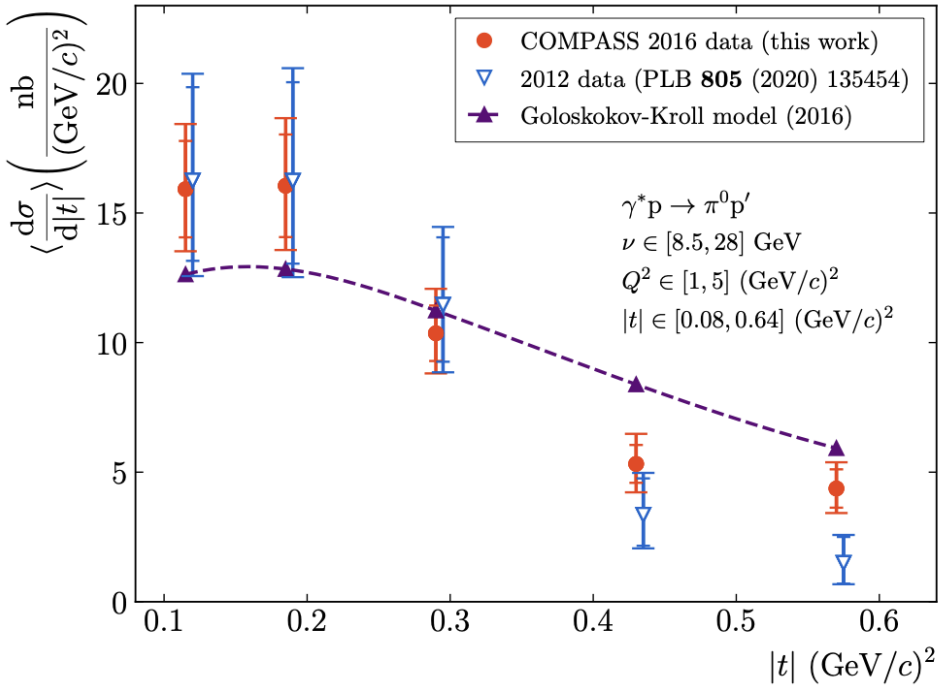
$\langle \epsilon \rangle = 0.997$

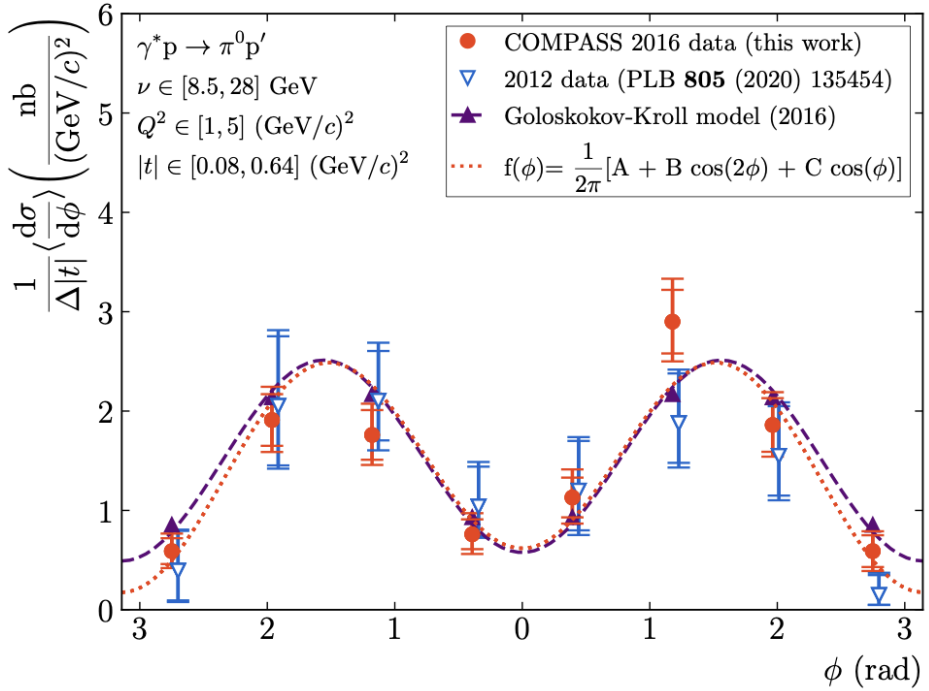
- Cross section extracted in a larger (ν, Q^2) domain, compared with the 2012 result. (COMPASS, **PLB** 805 (2020) 135454)
- Comparable $|\sigma_{TT}|$ and $\sigma_T + \epsilon\sigma_L$

2012-16 Exclusive π^0 Prod. Comparison

Accepted by PLB.

- 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:

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

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

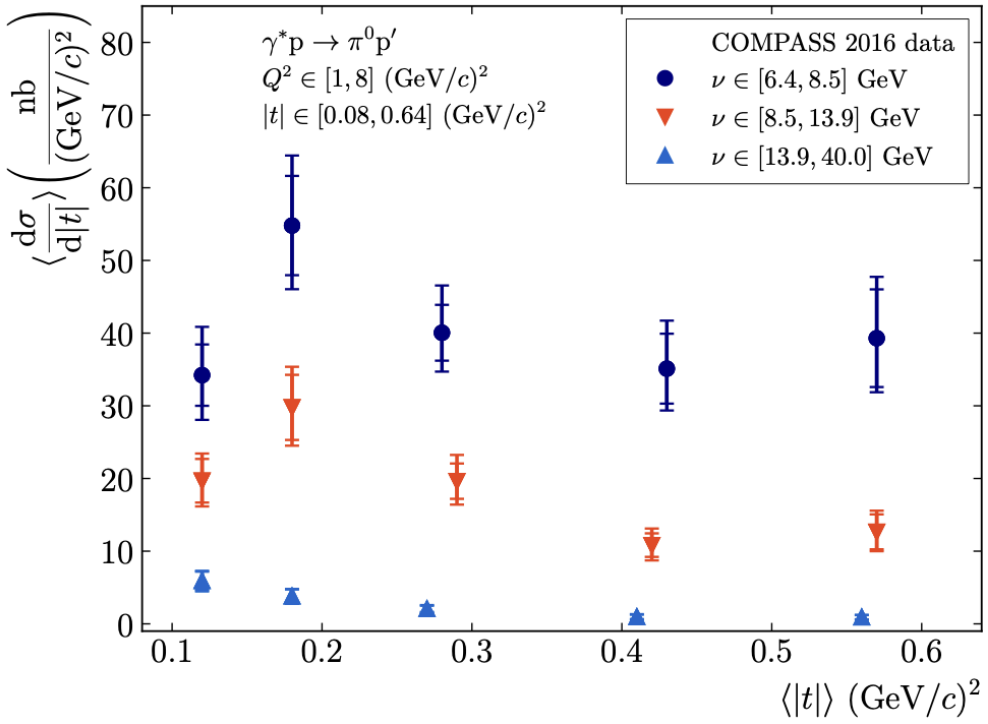
$$\left\langle \frac{d\sigma_{LT}}{dt} \right\rangle = \left(1.4 \pm 0.5_{stat}{}^{+0.3}_{-0.2}\Big|_{sys}\right) \frac{nb}{(GeV/c)^2}$$

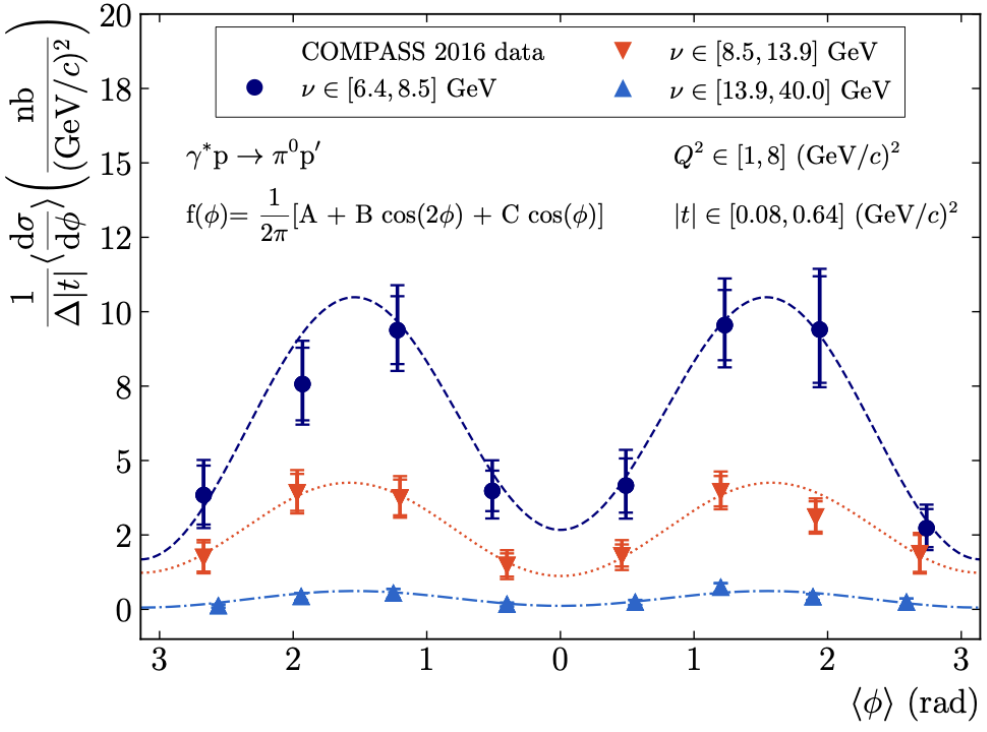
$$\langle \epsilon \rangle = 0.996$$

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

Accepted by PLB.

- Cross section decreases with increasing ν



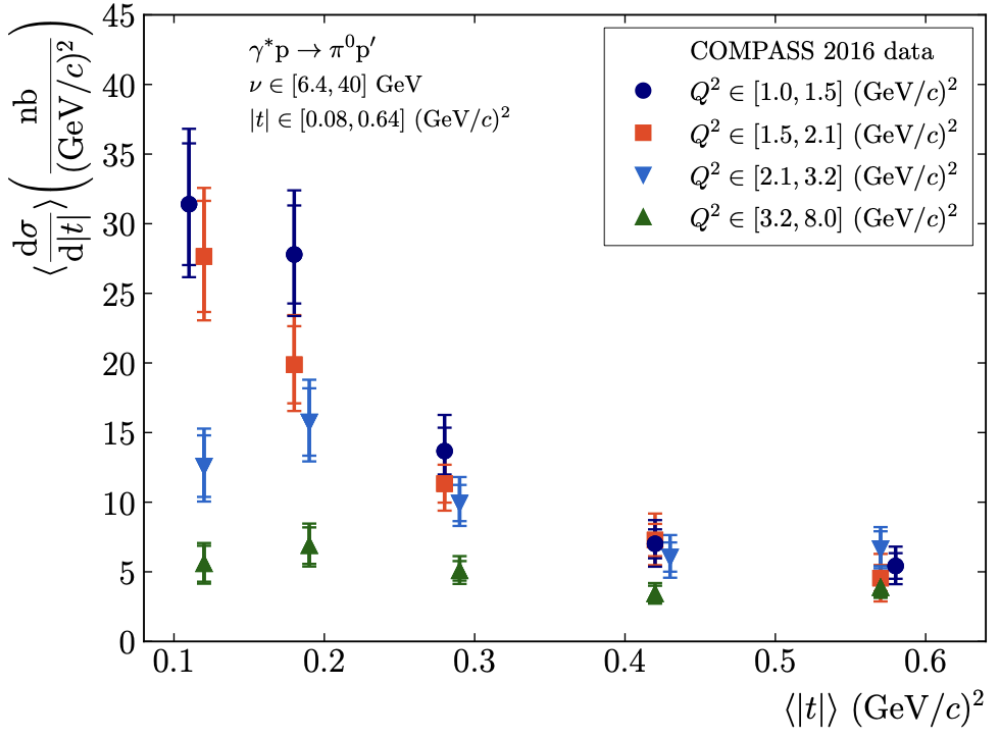


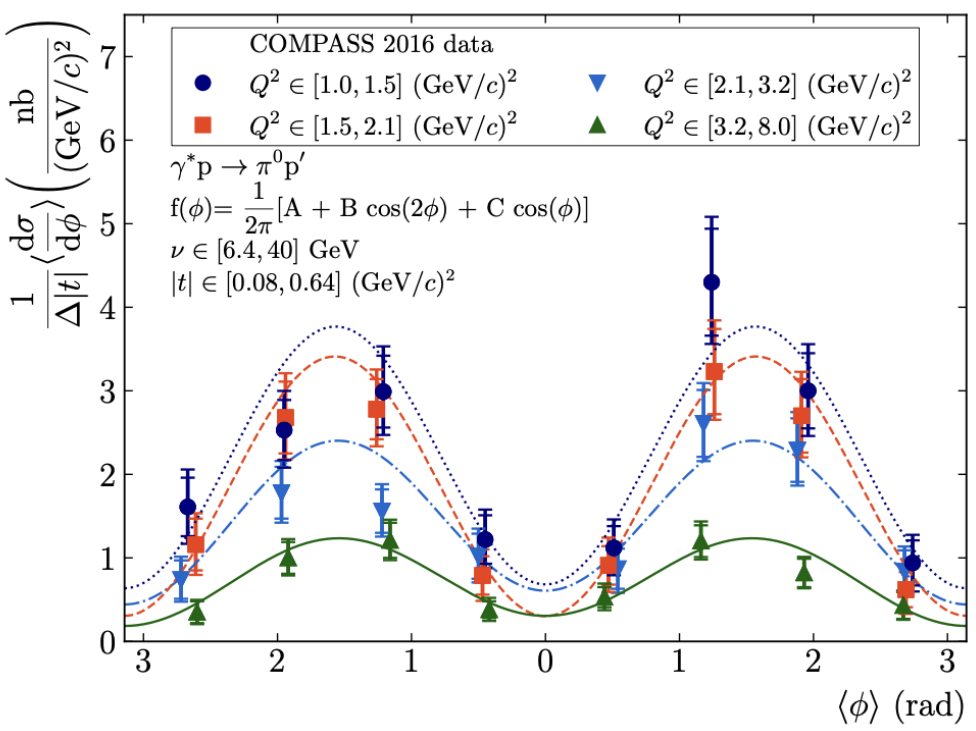
ν-range	$\langle Q^2 \rangle$ [(GeV/c)^2]	$\langle \nu \rangle$ [GeV]	$\langle \lvert t \rvert \rangle$ [(GeV/c)^2]	$\langle W \rangle$ [GeV/c^2]	$\langle x_{Bj} \rangle$	$\langle y \rangle$	$\langle \varepsilon \rangle$
6.4 – 8.5	2.15	7.35	0.31	3.53	0.156	0.046	0.999
8.5 – 13.9	2.50	10.32	0.29	4.20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

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

Accepted by PLB.

- Cross section decreases with increasing Q^2

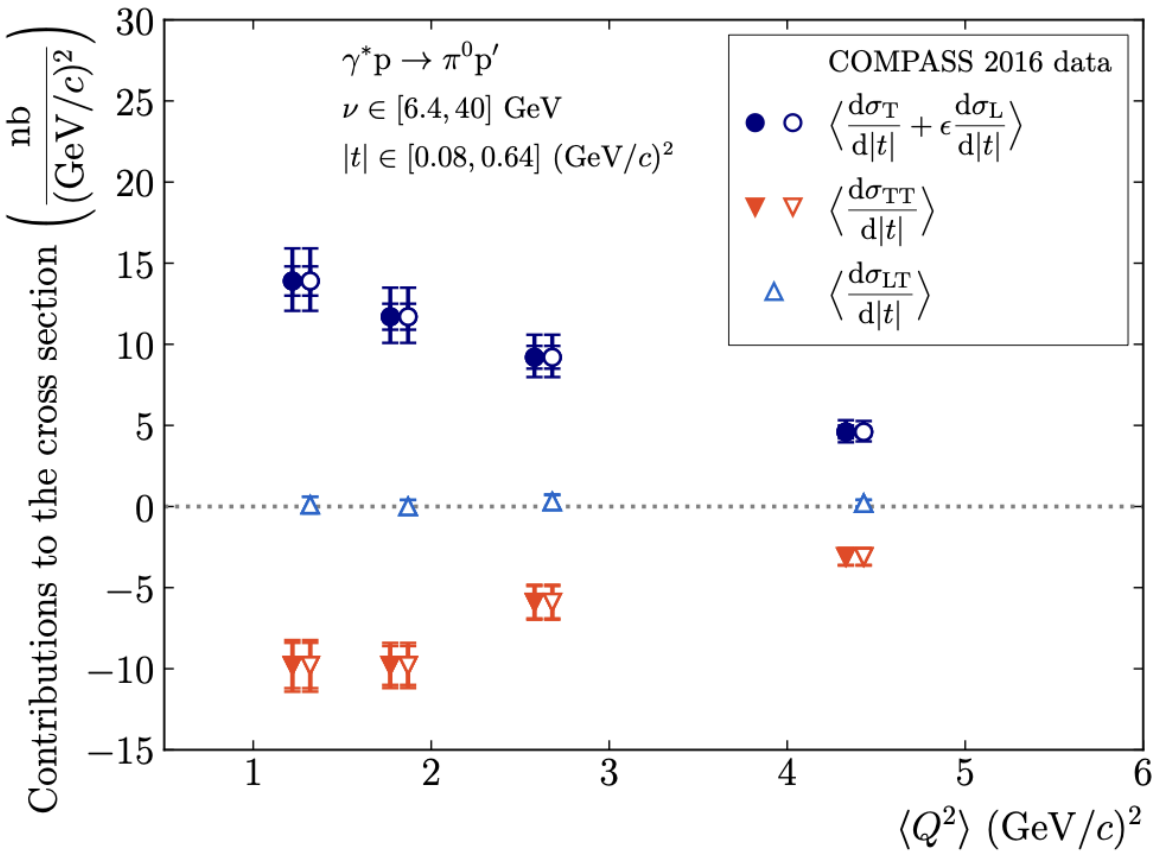


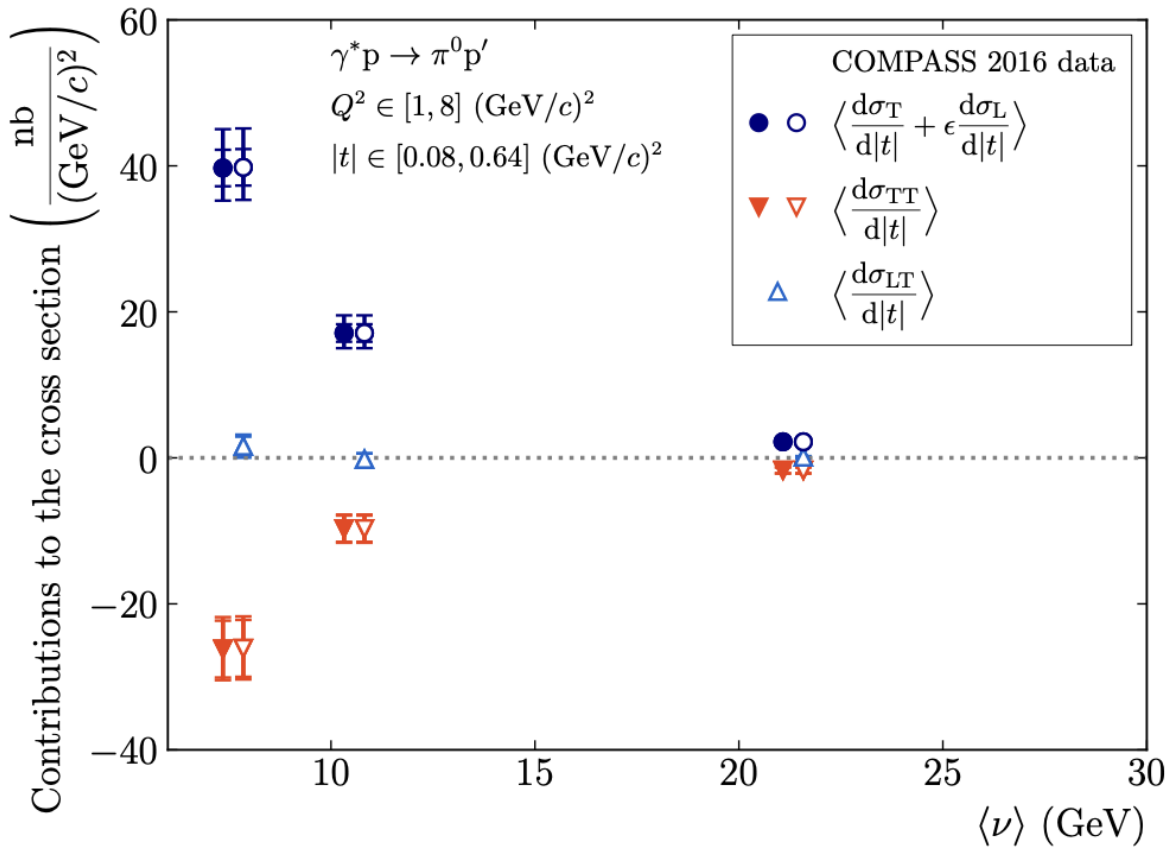


Q^2-range	$\langle Q^2 \rangle$ [(GeV/c)^2]	$\langle \nu \rangle$ [GeV]	$\langle \lvert t \rvert \rangle$ [(GeV/c)^2]	$\langle W \rangle$ [GeV/c^2]	$\langle x_{Bj} \rangle$	$\langle y \rangle$	$\langle \varepsilon \rangle$
1.0 – 1.5	1.22	10.54	0.27	4.29	0.072	0.067	0.997
1.5 – 2.1	1.77	9.81	0.27	4.09	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
		$\nu \in [6.4, 40]$	$\lvert t \rvert \in [0.08, 0.64]$				

New 2016 Evolution of the Structure Functions

Accepted by PLB.





- 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!**

Summary & Prospects

Hard Exclusive π^0 production at COMPASS

- An important probe for transversity GPDs, which cannot be accessed via DVCS
  - → Asymmetry in distribution of polarized parton in a unpolarized proton
  - → Transversity distribution

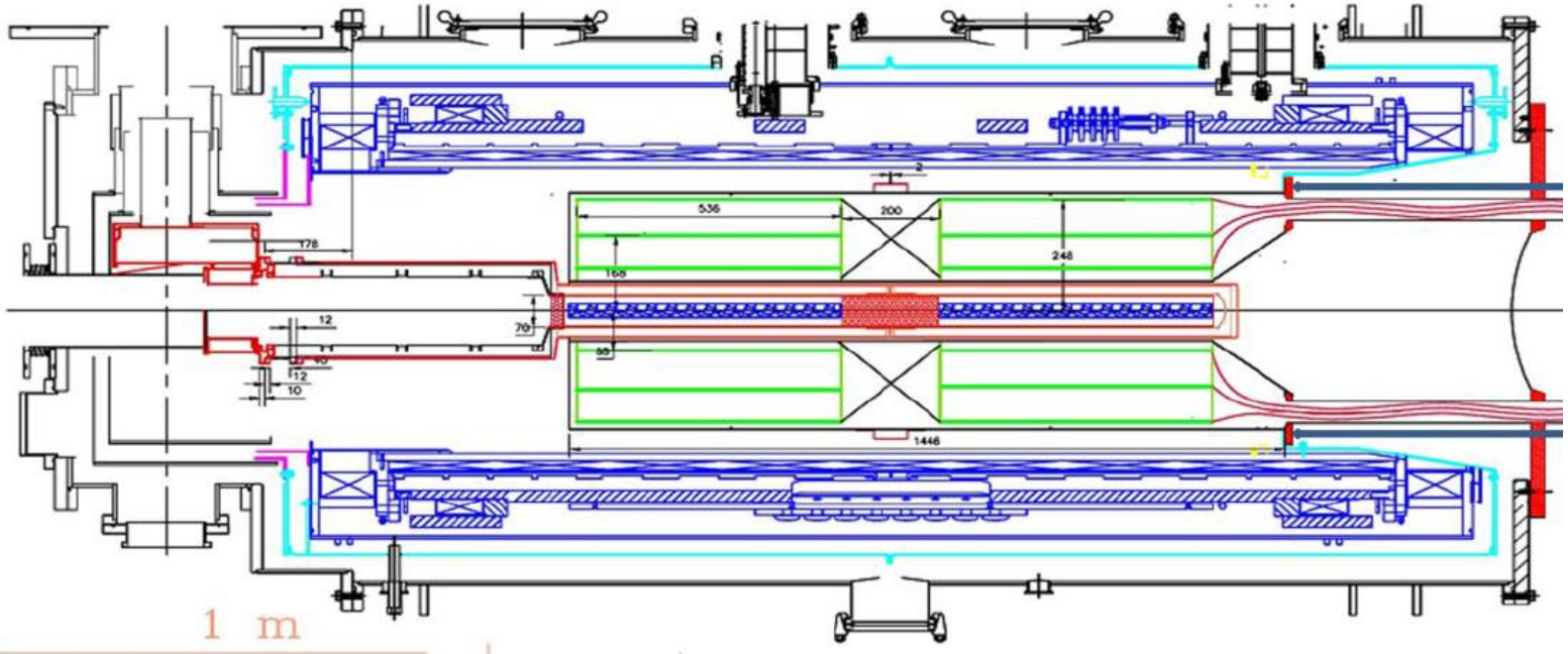
- COMPASS measurements serve as important inputs for modeling
  - → **New 2016-data results Accepted by PLB on August 17**
  - → Consistent with previous release using 2012 data, statistically better
  - → Q^2 and ν and dependence of the structure functions evaluated.

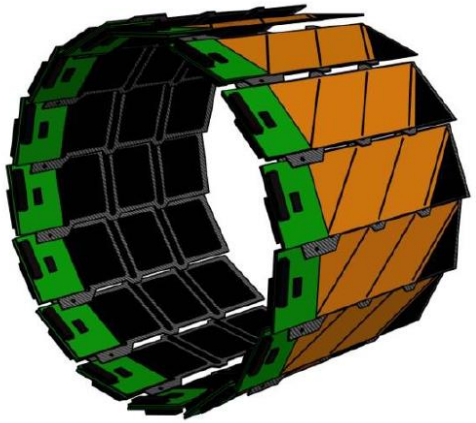
COMPASS has entered its analysis phase.
Expect more from us soon!

Backup Slides

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