

Recent TMD Highlights from COMPASS and the Path to AMBER

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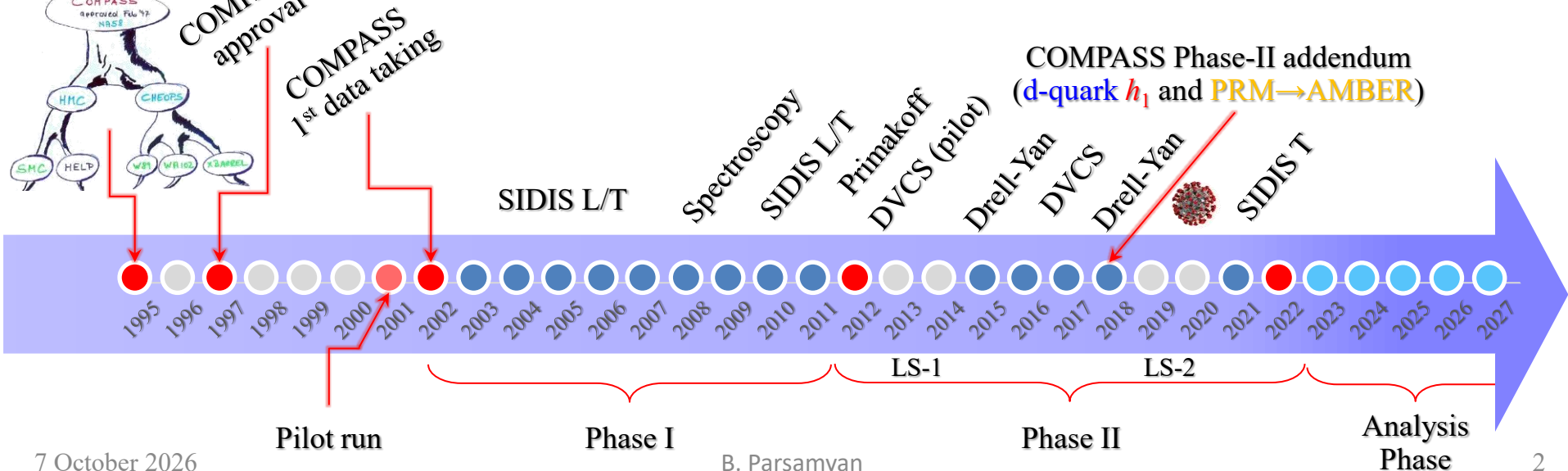


“Workshop on the Physics Program with High Luminosity Facilities”
5-10 October 2026, Jlab, US

An aerial photograph of the CERN facility in Geneva, Switzerland. The Large Hadron Collider (LHC) is shown as a large white oval. The Super Proton Synchrotron (SPS) is shown as a red oval. The COMPASS experiment is highlighted with a blue circle and a red arrow pointing to it. The text "COMPASS" is written in blue above the circle, and "SPS" is written in red above the oval. The text "LHC" is written in white at the bottom left. The URL "http://wwwcompass.cern.ch" is written in white at the bottom.

- 33** institutions from **15** countries: ~ 200 members

Many studies that can be done at future experiments can be studied at COMPASS
Key problems are in common: rad. corrections, MC generator tunings, the role of
exclusive diffractive VMs, analysis methods, etc.



AMBER timeline

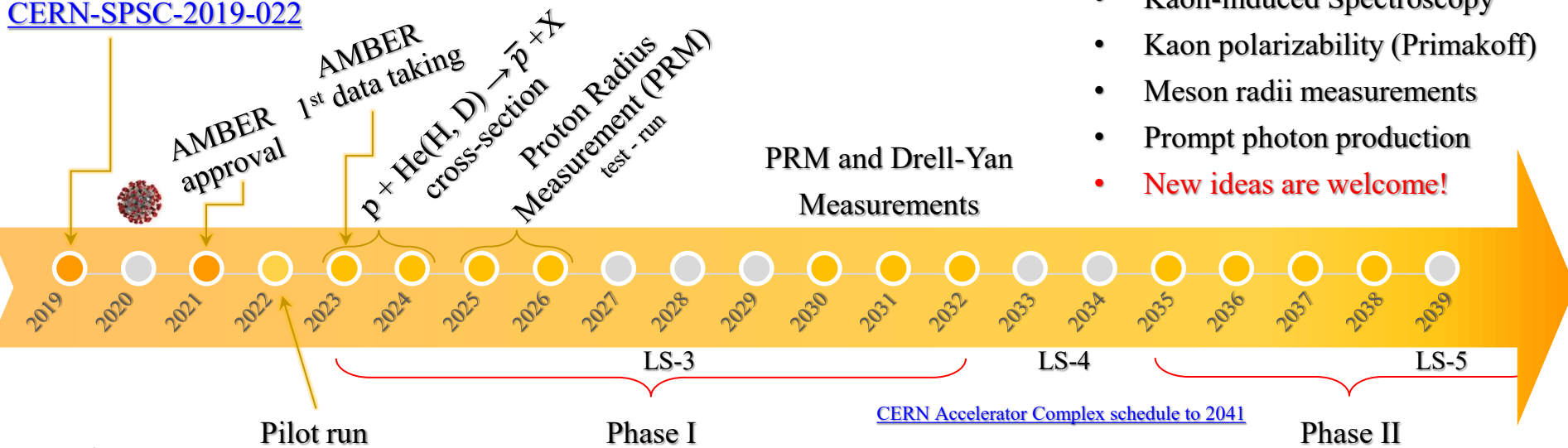
- CERN SPS north area – M2 beamline
- Successor of COMPASS
- Approved in 2019
- Taking data since 2023
- Phase-I is planned to continue after LS3

36 institutions from 14 countries: ~ 150 members

New collaborators are Welcome!



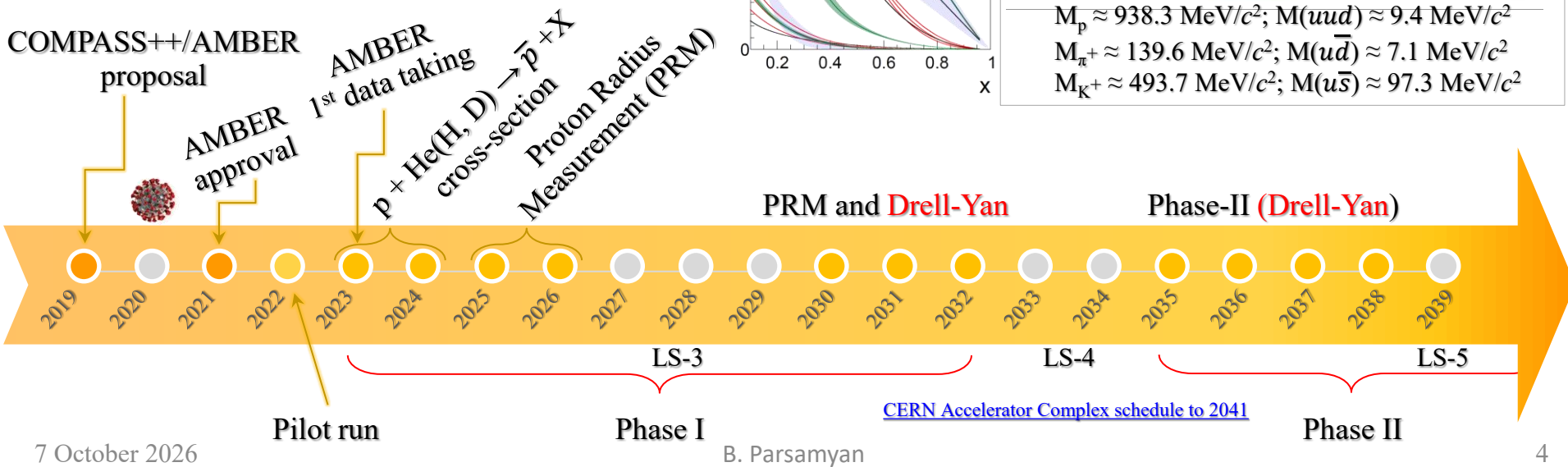
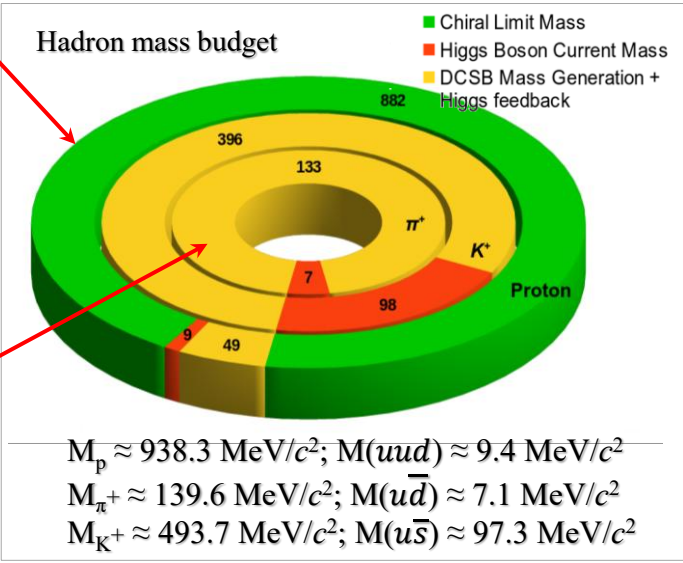
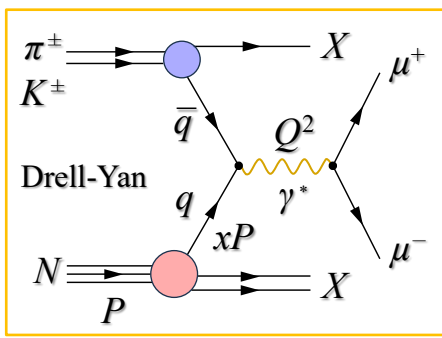
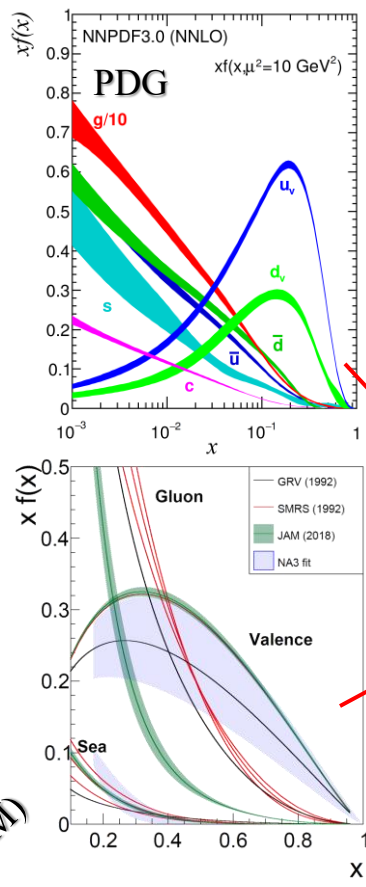
COMPASS++/AMBER proposal
[CERN-SPSC-2019-022](#)



- Phase II proposal draft
- Kaon-induced Drell-Yan and J/ψ production
 - Kaon-induced Spectroscopy
 - Kaon polarizability (Primakoff)
 - Meson radii measurements
 - Prompt photon production
 - New ideas are welcome!

AMBER measurements 2023-2024: Drell-Yan

- $\pi^\pm, K^\pm$ induced dimuon production: Drell-Yan, J/ψ (and ψ')**
- Study of pion and kaon PDFs
 - Crucial input for the study of the Emergent Hadron Mass (EHM)
 - Possibility to collect unique balanced π^+/π^- induced DY data
 - Measurement of λ, μ and ν (DY, J/ψ)
 - J/ψ production mechanisms ($q\bar{q}, gg$)
 - Carbon and tungsten targets
 - Improved vertex/mass resolution
 - Updated setup, new TL DAQ



COMPASS experimental setup

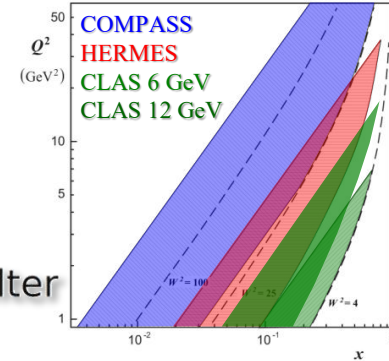
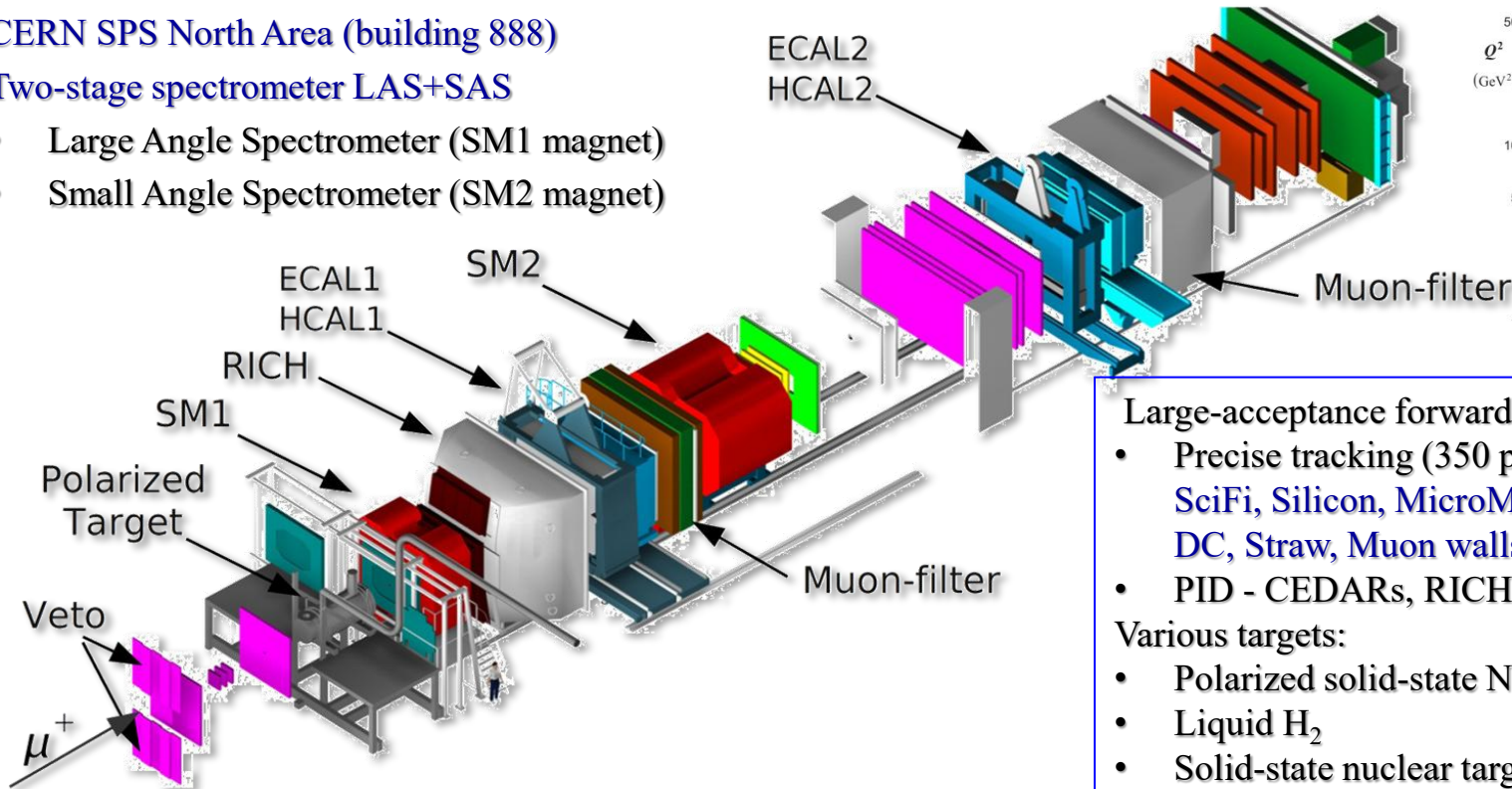


Common Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



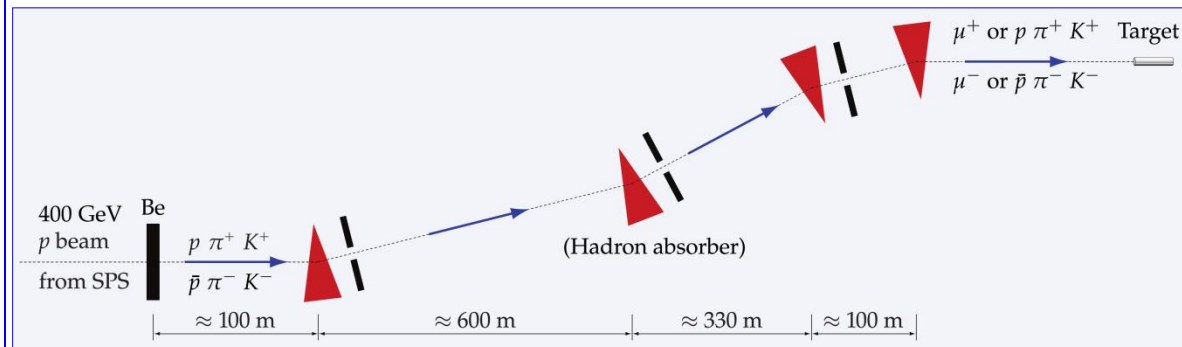
Large-acceptance forward spectrometer

- Precise tracking (350 planes)
SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon walls
- PID - CEDARs, RICH, calorimeters, MWs

Various targets:

- Polarized solid-state NH_3 or ^6LiD
- Liquid H_2
- Solid-state nuclear targets (e.g. Ni, W, Pb)

- Primary beam - 400 GeV p from SPS
 - impinging on Be production target (T6)
- 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



COMPASS experimental setup: Phase II (SIDIS program)

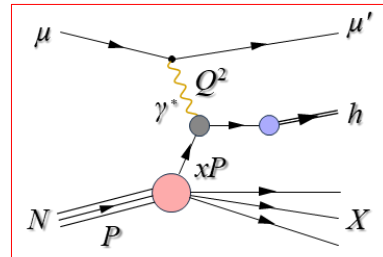
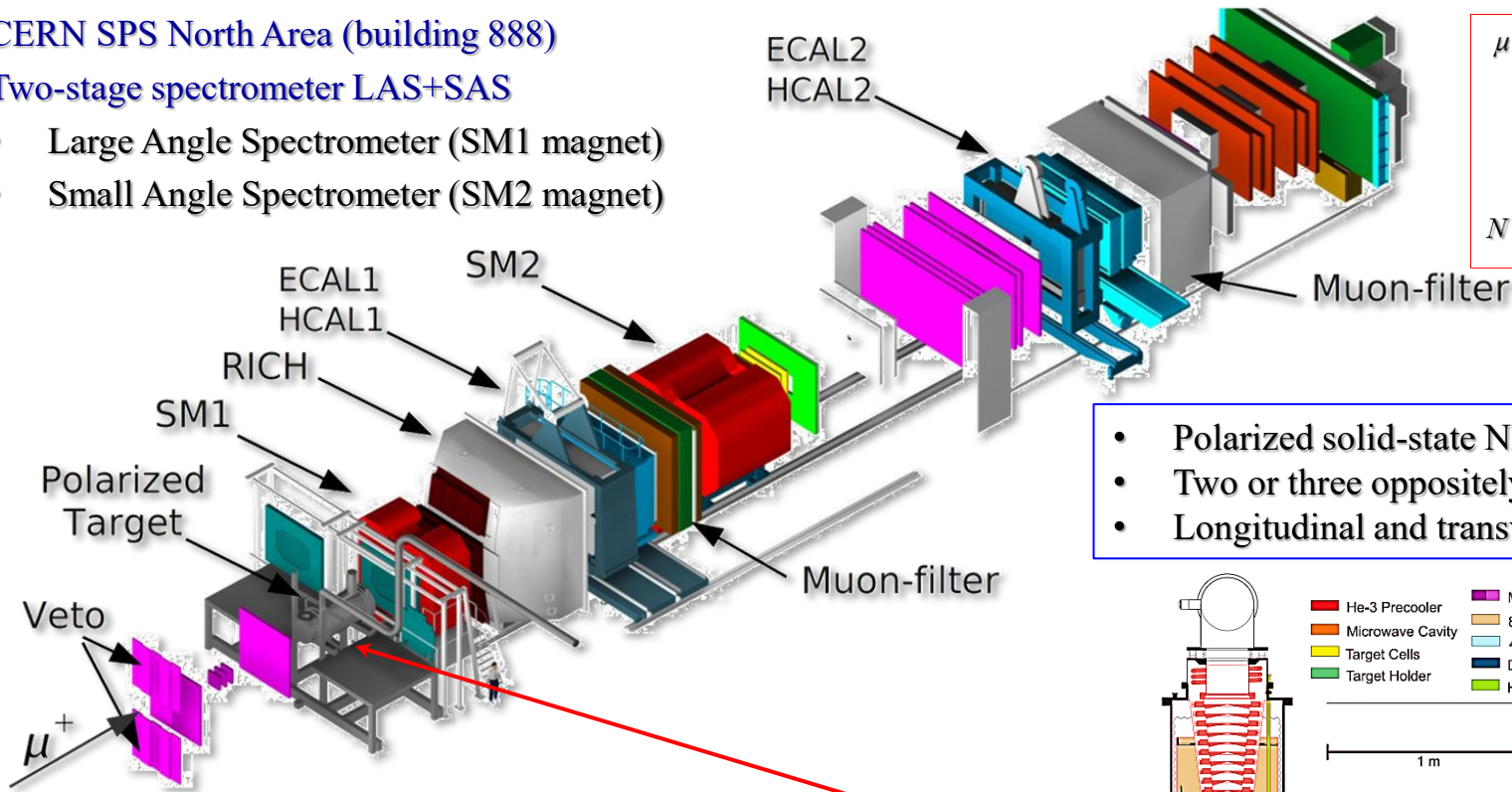


Common Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

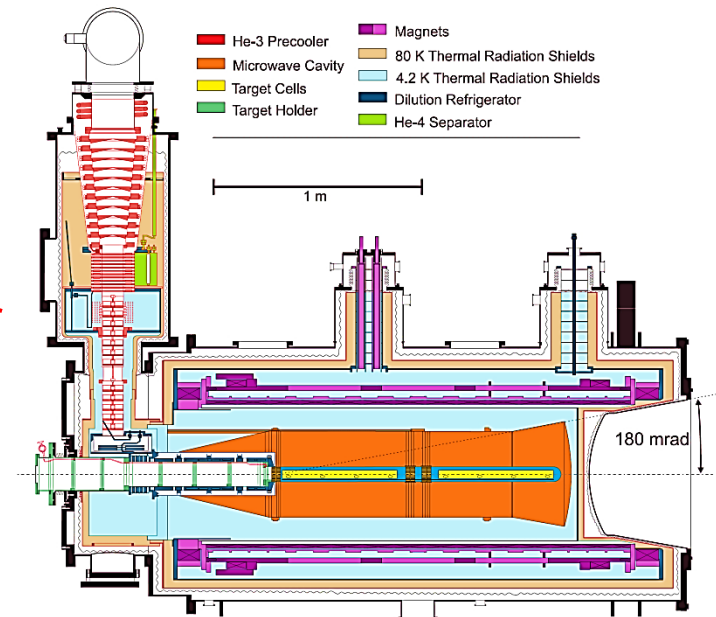
Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



- Polarized solid-state NH_3 or ${}^6\text{LiD}$
- Two or three oppositely polarized cells
- Longitudinal and transverse polarization

- Primary beam - 400 GeV p from SPS
 - impinging on Be production target (T6)
- 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
 - μ^+ longitudinally polarized



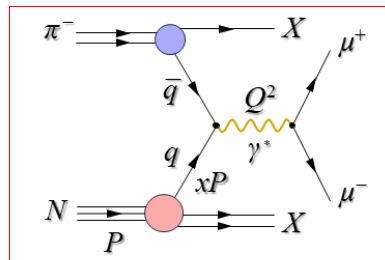
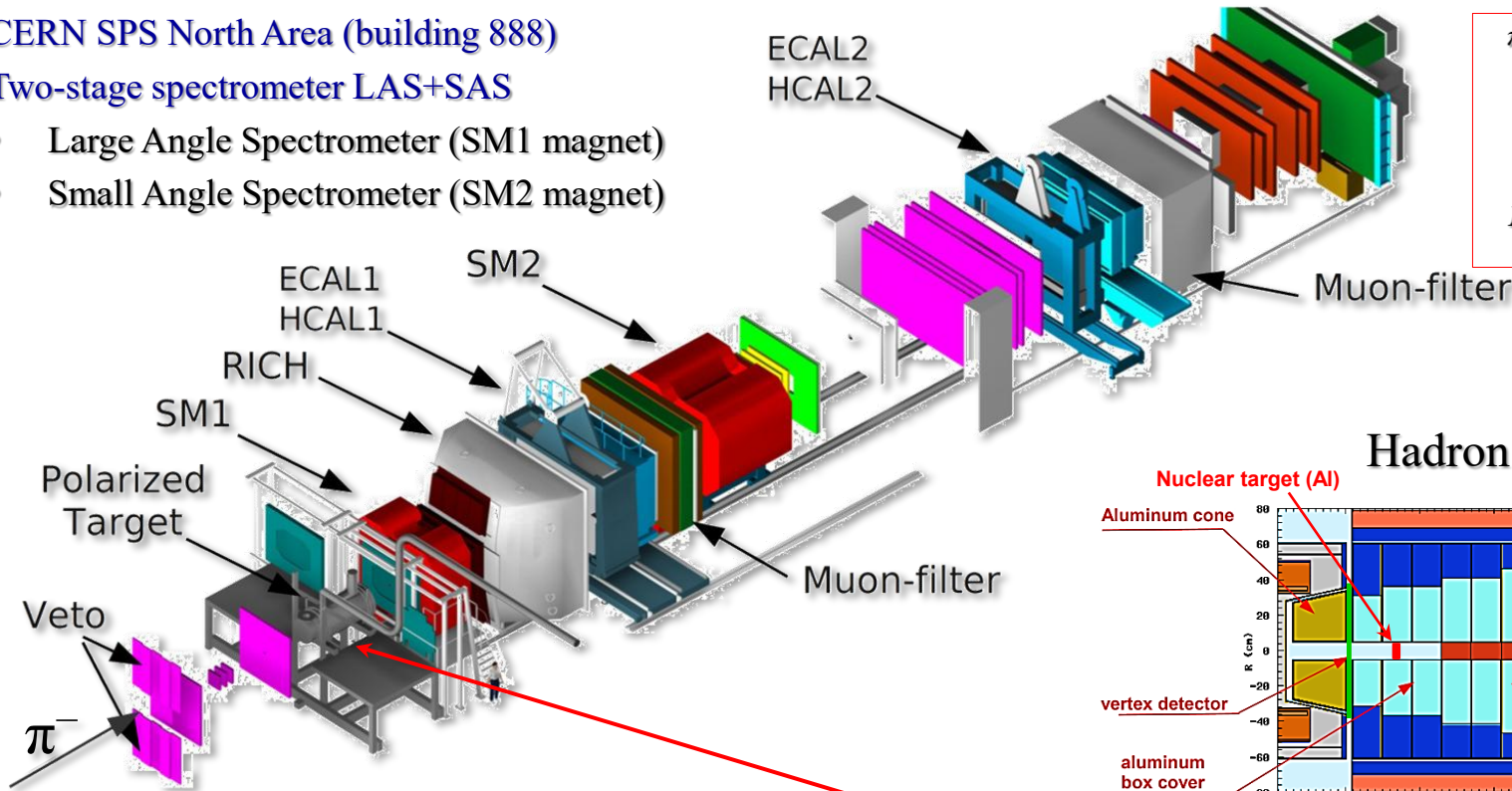
COMPASS experimental setup: Phase II (DY program)

Common Muon Proton Apparatus for Structure and Spectroscopy

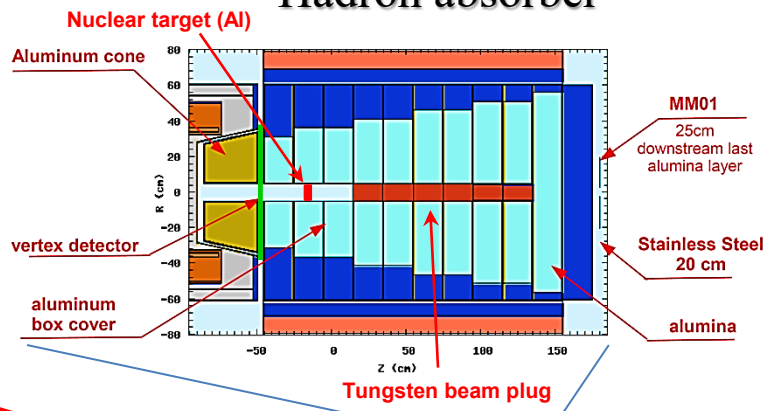
CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

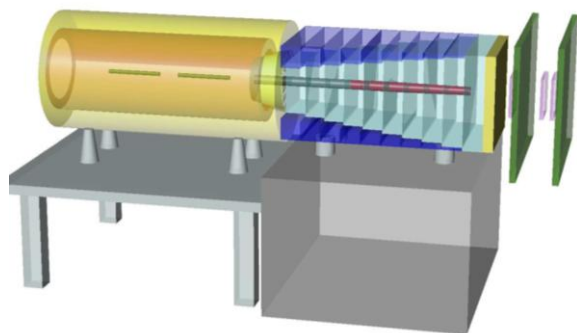
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



Hadron absorber



- Primary beam - 400 GeV p from SPS
 - impinging on Be production target (T6)
- 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



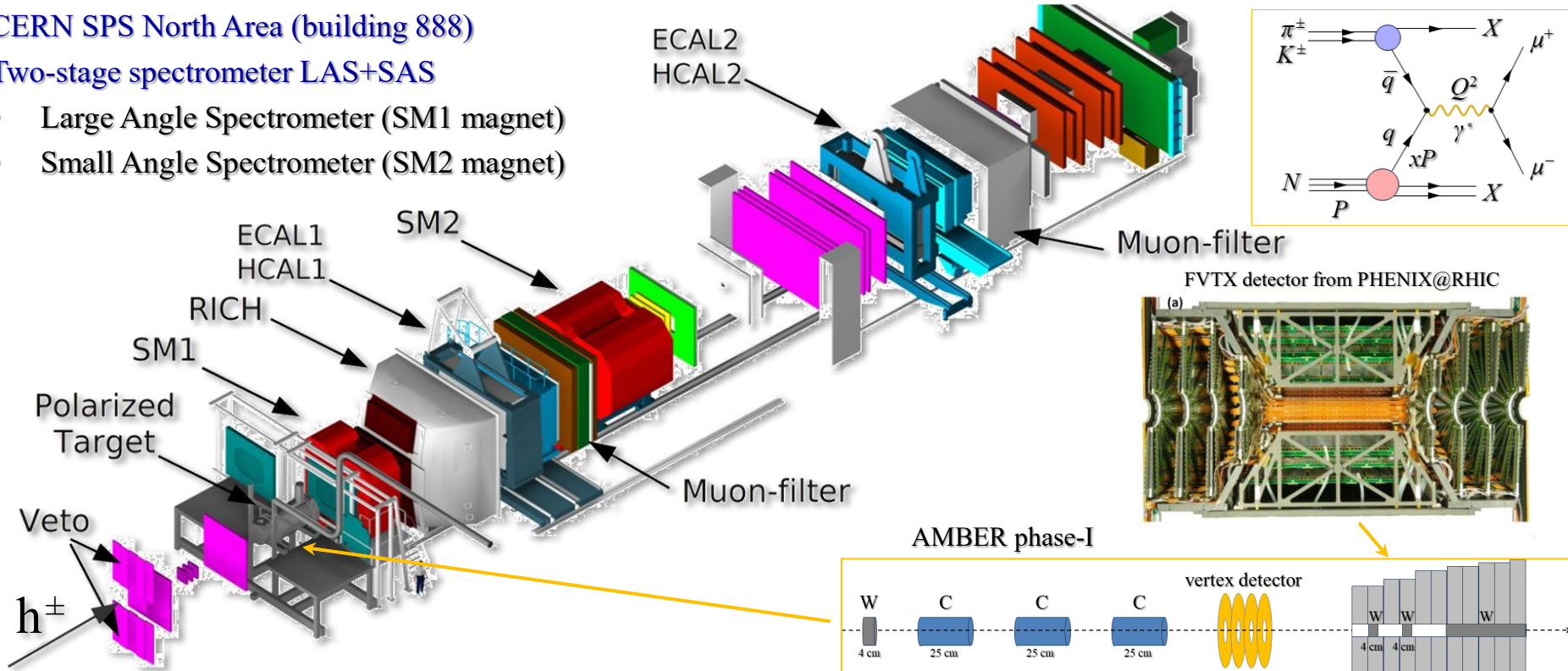
AMBER Phase I-II: DY program setup

Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

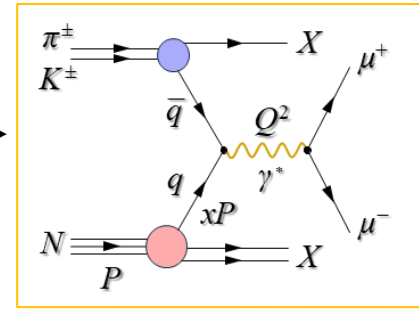
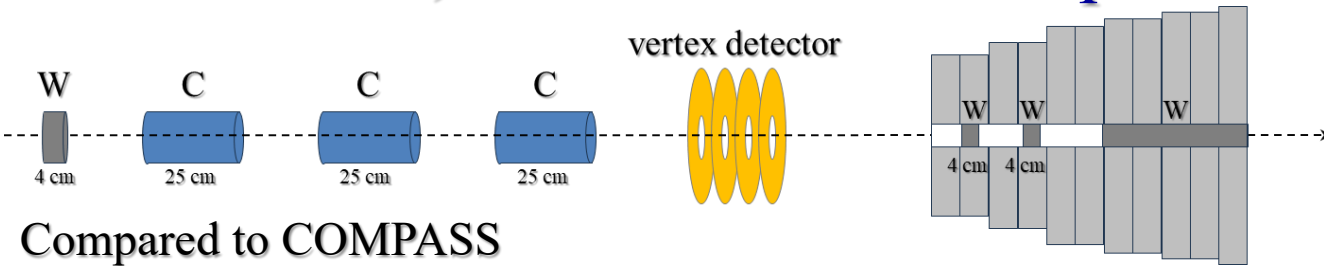
Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)



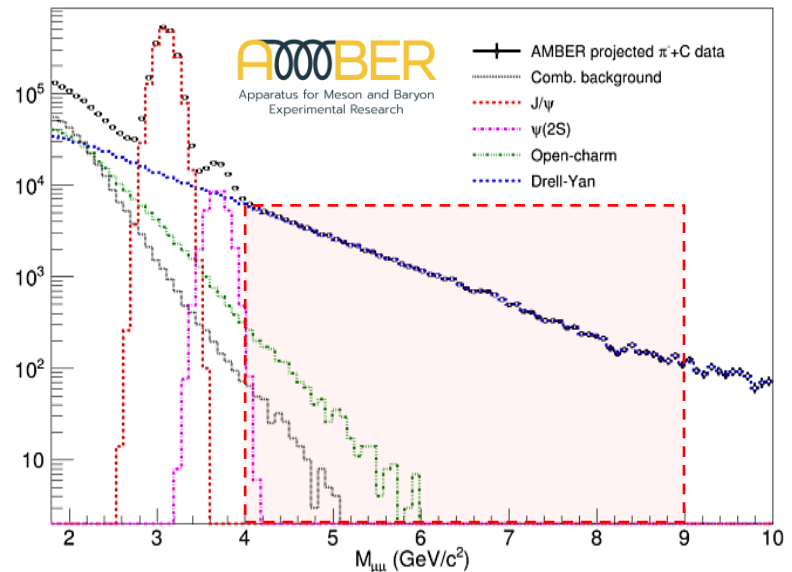
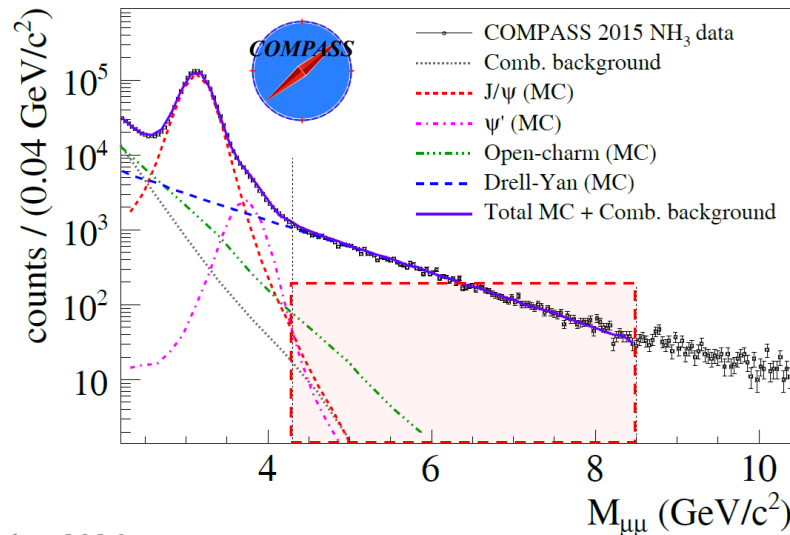
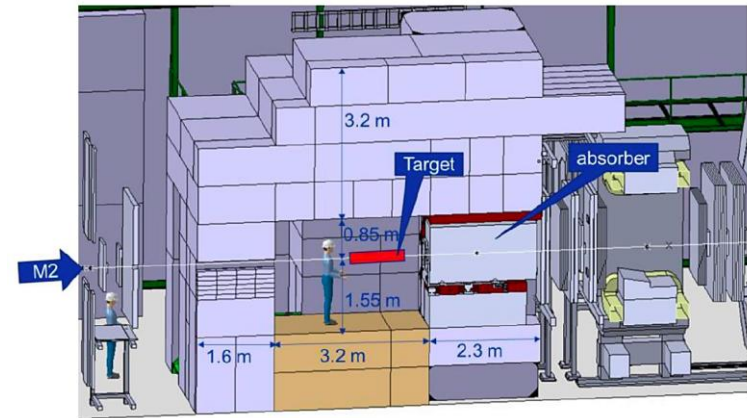
- Secondary $h^\pm$ beam: ($\pi^\pm$, $K^\pm$, $p/\bar{p}$)
- Improved beam PID (CEDARs)
 - enabling kaon physics
- Isoscalar target (C 3x25 cm) and W
- Vertex detector: improve Z and $M_{\mu\mu}$ resolution
- New trigger-less DAQ,
- Revised setup, new detectors

AMBER – $\pi^\pm, K^\pm$ induced dimuon production on C/W

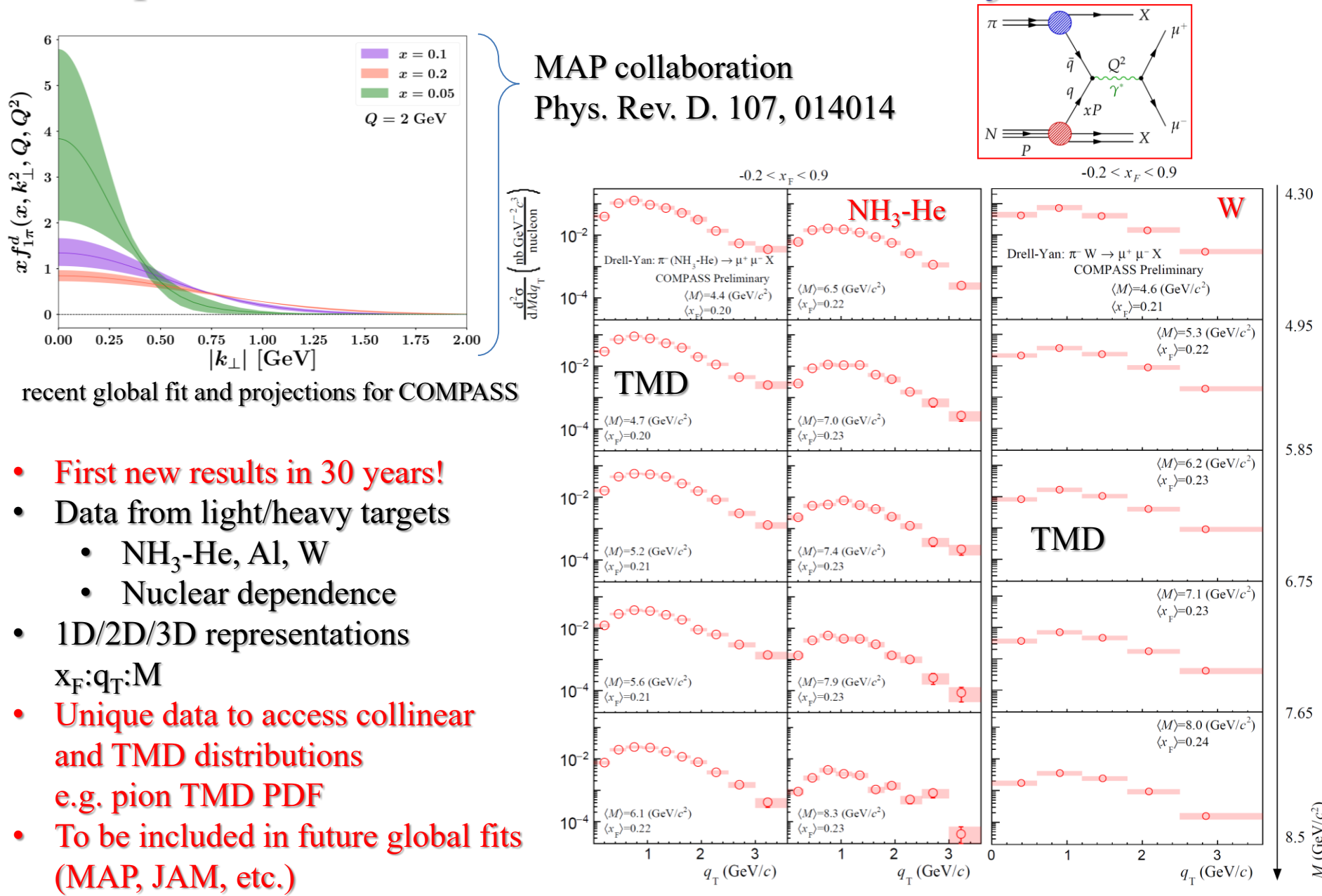


Compared to COMPASS

- Light isoscalar target (carbon) instead of NH_3 -He mix
- Improved mass resolution ($\sim 100 \text{ MeV}/c^2$)
 - Lower background $\rightarrow$ enlarge DY mass range
 - J/ψ and $\psi(2S)$ studies
- Wider beam choice: $\pi^\pm, K^\pm, p/\bar{p}$, CEDARs (PID)
- Unique complementary measurements: $\pi^\pm, K^\pm$
- Higher beam intensity (RP upgrades)
- Revised spectrometer, Triggerless DAQ

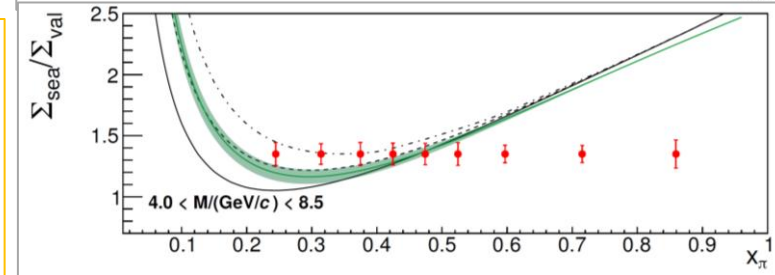
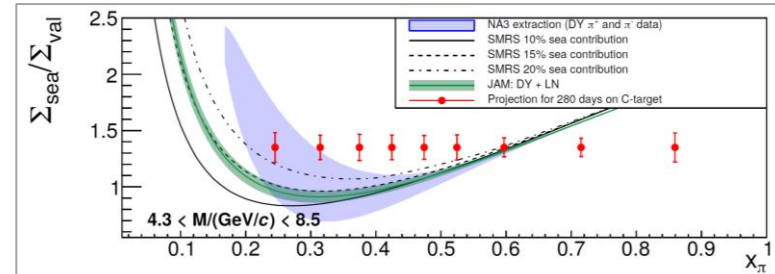
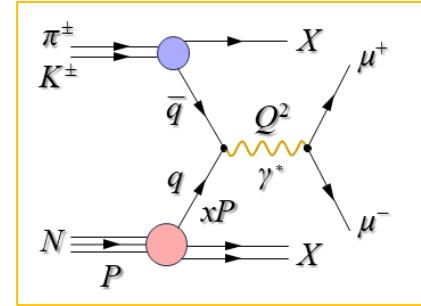


3D unpolarized Drell-Yan cross section on NH₃ and W



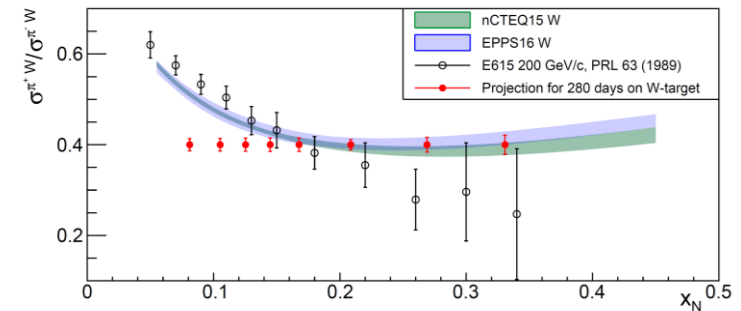
AMBER – $\pi^\pm, K^\pm$ induced dimuon production on C/W

- Unique complementary measurements: $\pi^\pm, K^\pm$
 - Cross-sections, pion and kaon PDFs
 - Data for both collinear and TMD PDF studies
 - Drell-Yan, J/ψ and potentially ψ' channels
 - Study of nuclear effects with C and W



$$\Sigma_{val} = \sigma^{\pi^- C} - \sigma^{\pi^+ C}: \text{only valence-valence}$$

$$\Sigma_{sea} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}: \text{no valence-valence}$$



AMBER	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c ²)	DY events
E615	20 cm W	252	π^+	17.6×10^7	4.05 – 8.55	5000
			π^-	18.6×10^7		30000
NA3	30 cm H ₂	200	π^+	2.0×10^7	4.1 – 8.5	40
			π^-	3.0×10^7		121
	6 cm Pt	200	π^+	2.0×10^7	4.2 – 8.5	1767
			π^-	3.0×10^7		4961
NA10	120 cm D ₂	286	π^-	65×10^7	4.2 – 8.5	7800
		140			4.35 – 8.5	3200
	12 cm W	286	π^-	65×10^7	4.2 – 8.5	49600
		194			4.07 – 8.5	155000
		140			4.35 – 8.5	29300
COMPASS 2015	110 cm NH ₃	190	π^-	7.0×10^7	4.3 – 8.5	35000
COMPASS 2018						52000
AMBER	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5	21700
			π^-		4.0 – 8.5	31000
		190	π^+	6.8×10^7	4.3 – 8.5	67000
			π^-		4.0 – 8.5	91100
	12 cm W	190	π^+	0.4×10^7	4.3 – 8.5	8300
			π^-		4.0 – 8.5	11700
		190	π^+	1.6×10^7	4.3 – 8.5	24100
			π^-		4.0 – 8.5	32100

An aerial photograph of the CERN facility in Switzerland, featuring the large, copper-clad dome of the Large Hadron Collider (LHC) on the left. The image is overlaid with several particle physics graphics. In the top left, a large, glowing sphere contains three quarks: two green 'u' quarks and one red 'd' quark, connected by wavy lines representing gluons. In the top right, a similar sphere contains an anti-up quark 'u-bar' and a down quark 'd'. In the center, two large, glowing spheres represent muons: a blue one with a minus sign 'μ⁻' and a red one with a plus sign 'μ⁺'. Two long, cylindrical particle beams, one blue and one red, extend from the top right towards the center, where they appear to interact with the muon beams. The background shows the lush green landscape of the CERN site, with roads, parking lots, and various buildings. The sky is a mix of orange and blue, suggesting a sunset or sunrise.

Polarized Drell–Yan at CERN and Around the Globe

<https://indico.cern.ch/e/comap20>

5-6 October, 2026
CERN



Goals of the workshop

Assess the present status of polarized Drell-Yan

- What have COMPASS, RHIC/STAR and other measurements already established?
- What do current phenomenological and global-fit studies tell us?

Clarify whether the key TMD tests are already within reach

- Is the evidence for the predicted sign change of T-odd TMDs becoming conclusive?
- Are existing and planned measurements sufficient, or are important ambiguities likely to remain?

Identify what additional measurements would add

- Which observables, kinematic regions, or flavor combinations are still poorly constrained?
- What is the complementarity of pp measurements, with stronger sensitivity to sea quarks, and πN measurements, with direct access to the valence region?

Evaluate realistic future opportunities

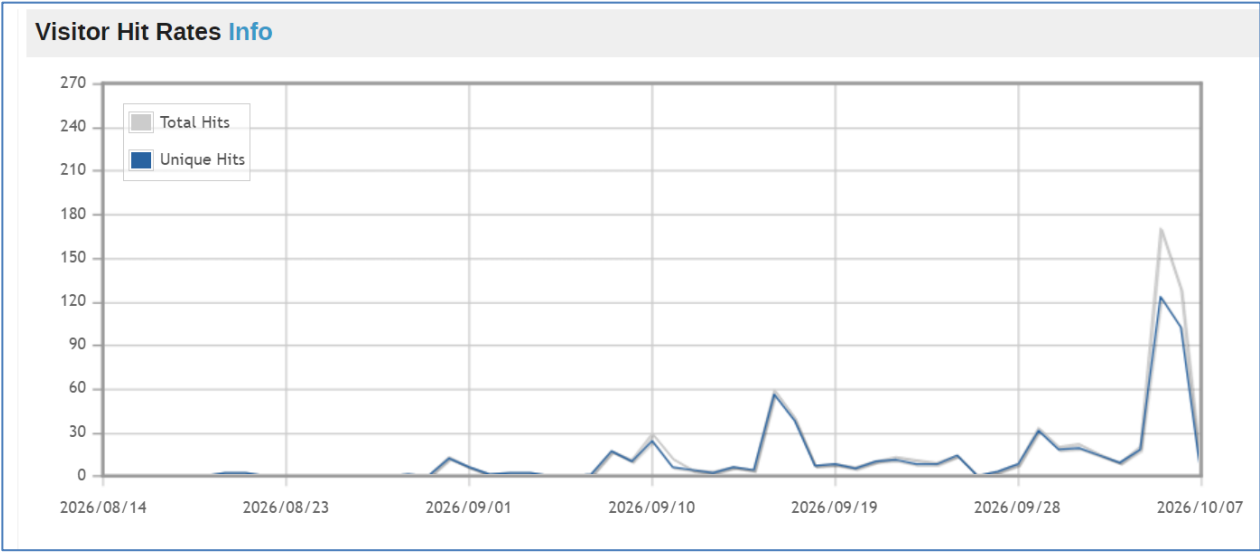
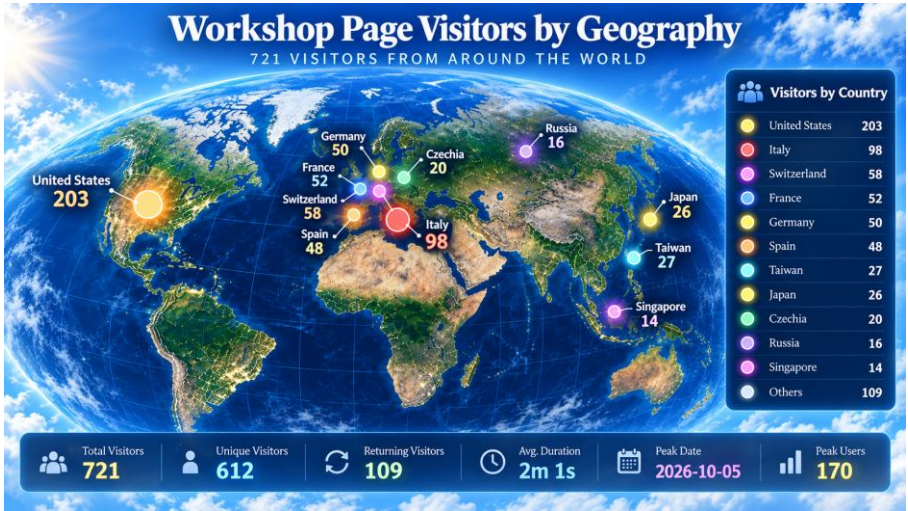
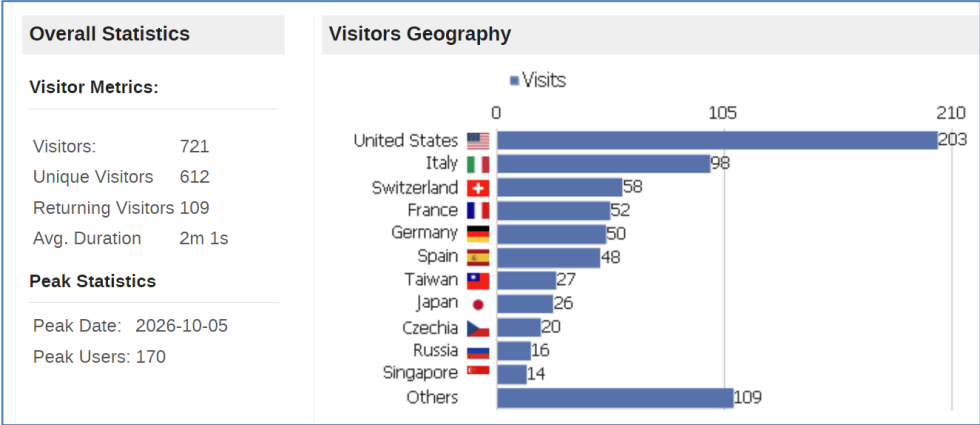
- If new measurements are needed, which beam-target configurations would be most effective?
- What could a new polarized pion-induced Drell-Yan programme at the CERN M2 beamline realistically contribute?
- A roadmap for potential EOI/LOI

Opening	<i>Dr Bakur Parsamyan</i>
892/1-D20, CERN	13:00 - 13:05
Testing TMD process dependence with polarized Drell-Yan: theory status and are new measurements needed?	
<i>Alexei Prokudin</i>	
Global fits from MAP: what have we learned so far?	<i>Dr Lorenzo Rossi</i>
892/1-D20, CERN	13:30 - 13:55
Recent studies of Sivers, Boer-Mulders and sign change	<i>Alexey Vladimirov</i>
892/1-D20, CERN	13:55 - 14:20
JAM TMD fits: do we need polarized Drell-Yan data	<i>Daniel Pitonyak et al.</i>
892/1-D20, CERN	14:20 - 14:45
Boer-Mulders TMD PDF in SIDIS and Drell-Yan	<i>Jen-Chieh Peng et al.</i>
892/1-D20, CERN	14:45 - 15:10
TMD PDF extractions using AI/ML tools	<i>Ishara Fernando</i>
892/1-D20, CERN	15:10 - 15:35
Quarkonia as a tool: what can we learn?	<i>Carlo Flore et al.</i>
892/1-D20, CERN	15:35 - 16:00

STAR: Transverse-spin asymmetries in W and Z production at STAR: constraints on TMD process dependence	<i>Oleg Eyser</i>
SpinQuest: Polarized Drell-Yan at SpinQuest: probing sea-quark TMDs and the Sivers effect	<i>Forhad Hossain</i>
892/1-D20, CERN	13:25 - 13:50
LHCspin: Polarized fixed-target physics with LHCspin: prospects for Drell-Yan and TMD studies	<i>Luciano Libero Pappalardo</i>
Prospects for Drell-Yan and hadron-structure studies at J-PARC	<i>Wen-Chen Chang</i>
892/1-D20, CERN	14:15 - 14:40
COMPASS: Polarized pion-induced Drell-Yan at COMPASS: status of the TMD sign-change test	<i>Dr Bakur Parsamyan</i>
892/1-D20, CERN	14:40 - 15:05
AMBER unpolarized Drell-Yan program highlights	
892/1-D20, CERN	15:05 - 15:30
From COMPASS to AMBER: polarized-target capabilities and future measurement opportunities	<i>Norihiro Doshita</i>
892/1-D20, CERN	15:30 - 15:55

Workshop page visitor hit rates and geography

- 128 registered participants
- Leading experts in theory and phenomenology
- Representatives from major spin-physics experiments
- Interested members of the AMBER and COMPASS collaborations



Top Referrers

Traffic Inbound Top 10:

Referrer	Visits	Actions	Visit Length
Direct Entry	651	1237	1d 6h 51m 50s
Websites	34	123	2h 37m 20s
Search Engines	22	51	2h 40m 21s
Social Networks	13	30	1h 4m 34s
AI Assistants	1	6	49m 49s

- Recent SIDIS highlights from COMPASS

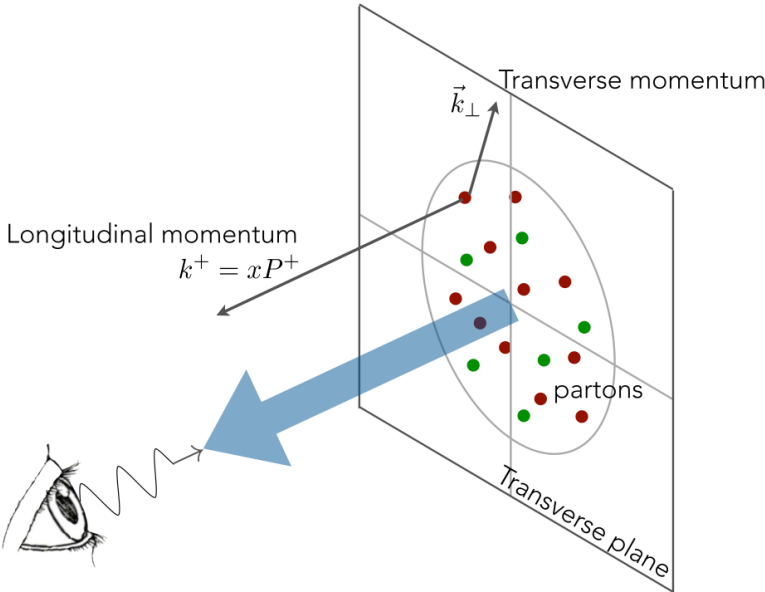
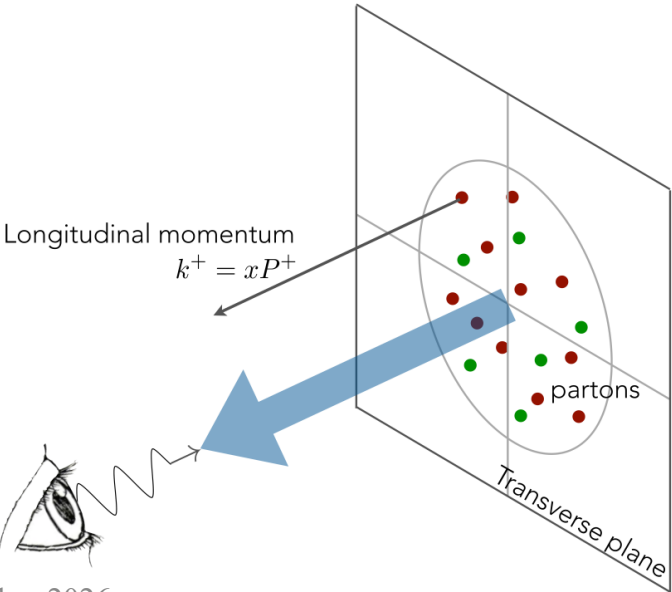
Nucleon spin structure (twist-2): collinear approach $\leftrightarrow$ TMDs

		quark		
		U	L	T
nucleon	U	$f_1^q(x)$ number density		
	L		$g_1^q(x)$ helicity	
	T			$h_1^q(x)$ transversity

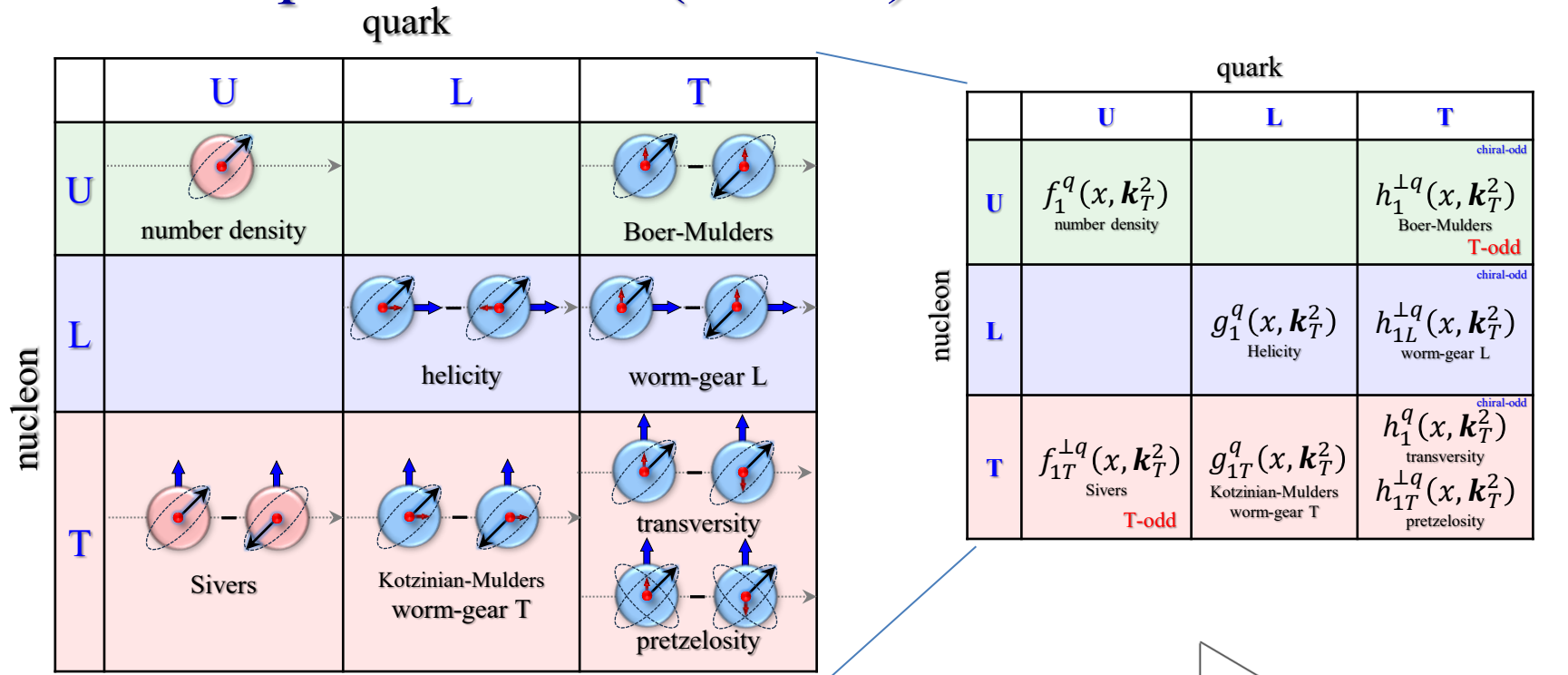
$\longleftrightarrow$

		quark		
		U	L	T
nucleon	U	$f_1^q(x, k_T^2)$ number density		$h_1^{\perp q}(x, k_T^2)$ Boer-Mulders T-odd chiral-odd
	L		$g_1^q(x, k_T^2)$ Helicity	$h_{1L}^{\perp q}(x, k_T^2)$ worm-gear L chiral-odd
	T	$f_{1T}^{\perp q}(x, k_T^2)$ Sivers T-odd	$g_{1T}^q(x, k_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x, k_T^2)$ transversity $h_{1T}^{\perp q}(x, k_T^2)$ pretzelocity chiral-odd

- PDFs – universal (process independent) objects; **T-odd PDFs – conditionally universal**



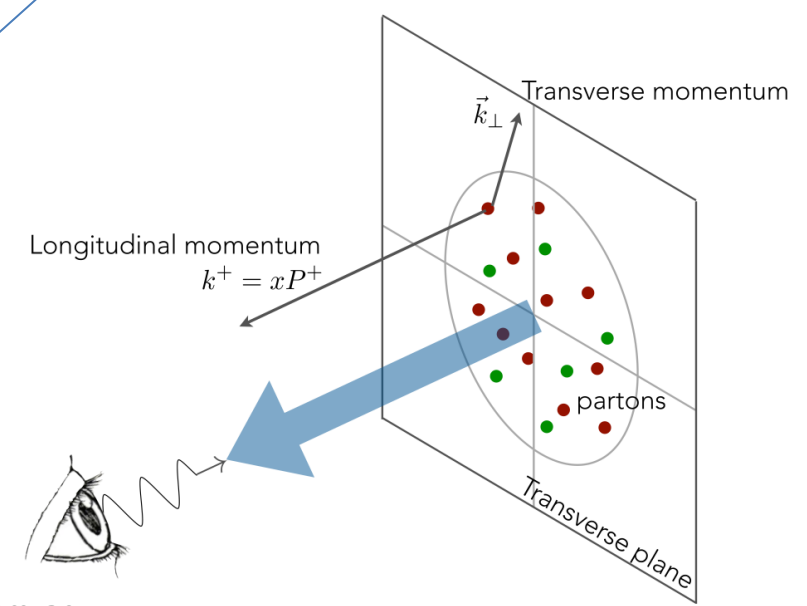
Nucleon spin structure (twist-2): TMDs



- spin of the nucleon;
 - spin of the quark
 - k_T

Direction of the motion of the nucleon

Transverse orbital motion of the quarks



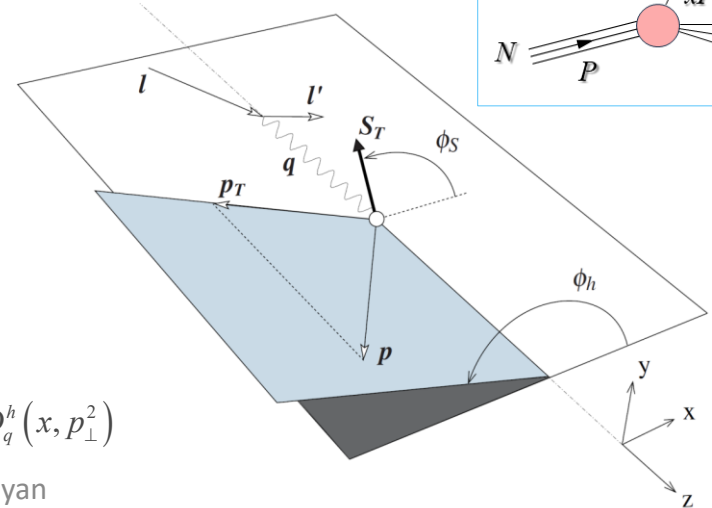
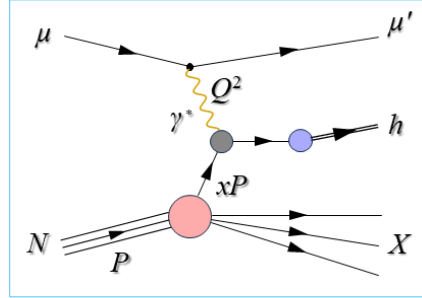
SIDIS x-section and TMDs at twist-2

$$\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times \left\{ \begin{aligned} & 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \\ & + S_T \left[\begin{aligned} & A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ & + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \end{aligned} \right] \\ & + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \right] \end{aligned} \right\}$$

		quark		
		U	L	T
nucleon	U	$f_1^q(x, k_T^2)$ number density		$h_1^{\perp q}(x, k_T^2)$ Boer-Mulders T-odd
	L		$g_1^q(x, k_T^2)$ Helicity	$h_{1L}^{\perp q}(x, k_T^2)$ worm-gear L
	T	$f_{1T}^{\perp q}(x, k_T^2)$ Sivers T-odd	$g_{1T}^q(x, k_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x, k_T^2)$ transversity $h_{1T}^{\perp q}(x, k_T^2)$ pretzelosity

$$\begin{aligned} A_{UU}^{\cos 2\phi_h} &\propto \underline{h_1^{\perp q}} \otimes \underline{H_{1q}^{\perp h}} && \text{Boer-Mulders (T-odd)} \\ A_{UT}^{\sin(\phi_h-\phi_S)} &\propto \underline{f_{1T}^{\perp q}} \otimes D_{1q}^h && \text{Sivers (T-odd)} \\ A_{UT}^{\sin(\phi_h+\phi_S)} &\propto \underline{h_1^q} \otimes \underline{H_{1q}^{\perp h}} && \text{Transversity} \\ A_{UT}^{\sin(3\phi_h-\phi_S)} &\propto \underline{h_{1T}^{\perp q}} \otimes \underline{H_{1q}^{\perp h}} && \text{Pretzelosity} \end{aligned}$$



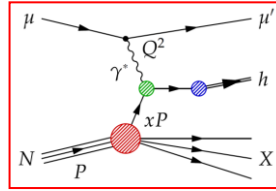
$$\otimes \equiv \mathbb{C}[wfD] = x \sum_q e_q^2 \int d^2 k_T d^2 p_\perp \delta^{(2)}(z k_T + p_\perp - P_h) w(k_T, p_\perp) f^q(x, k_T^2) D_q^h(x, p_\perp^2)$$

Hadron multiplicities; $h^\pm$, $\pi^\pm$ and $K^\pm$ (2016 data)

collinear

A set of complex corrections:

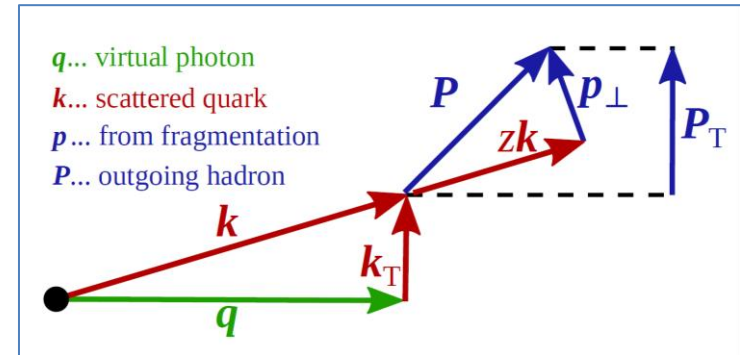
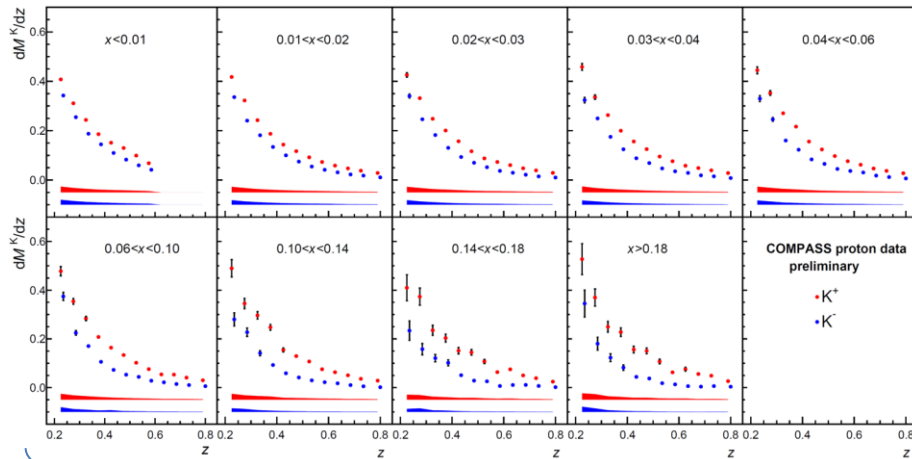
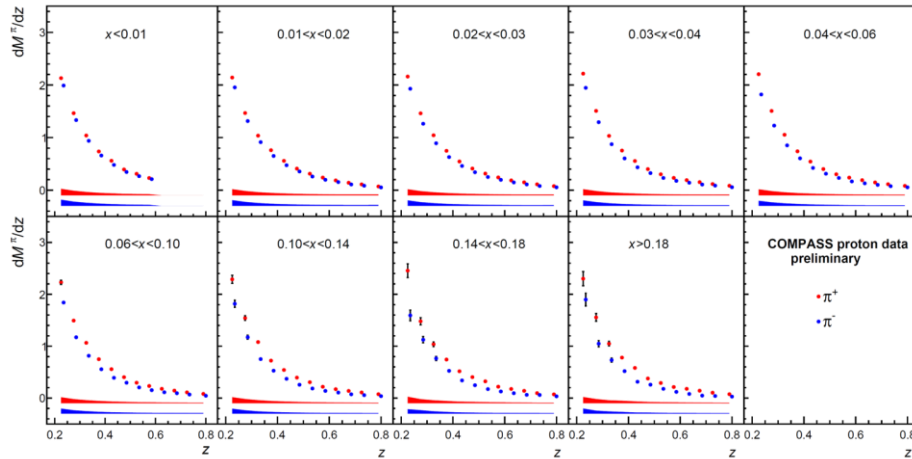
- Acceptance, rad. corrections, PID, diffractive VMs, etc.



TMD

$$f_1^q(x, k_T^2)$$

number density



New radiative corrections (DJANGO)

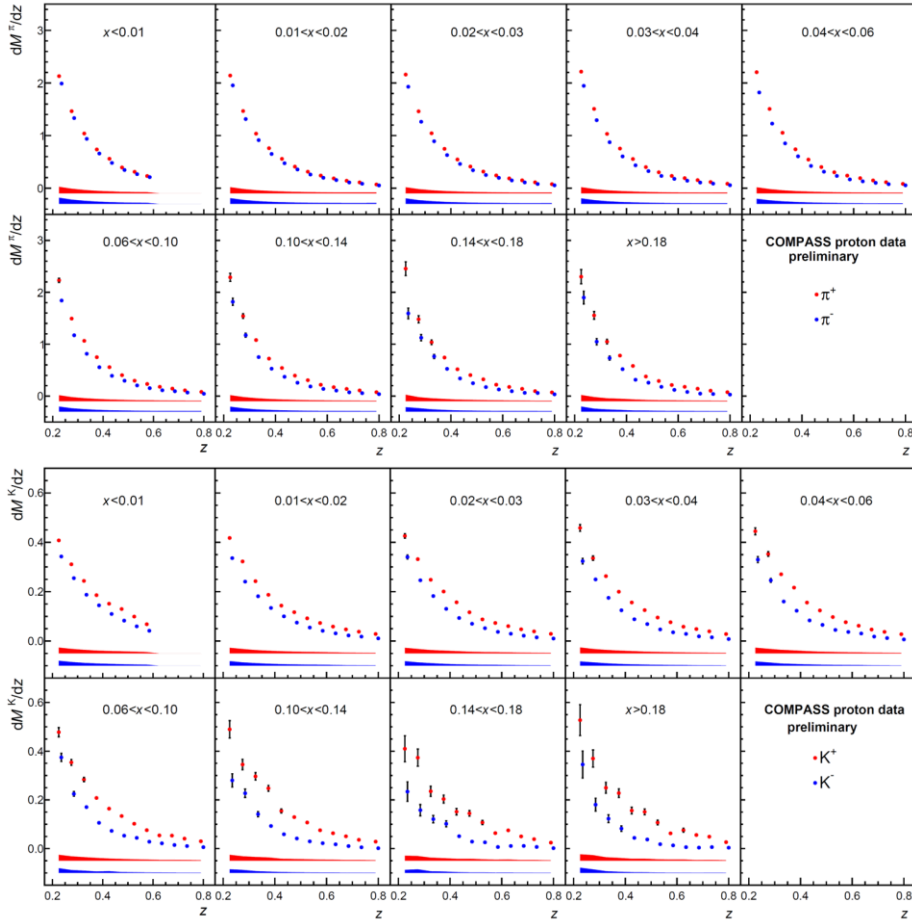
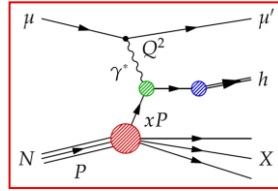
PRD 112 (2025) 012002

Hadron multiplicities; $h^\pm$, $\pi^\pm$ and $K^\pm$ (2016 data)

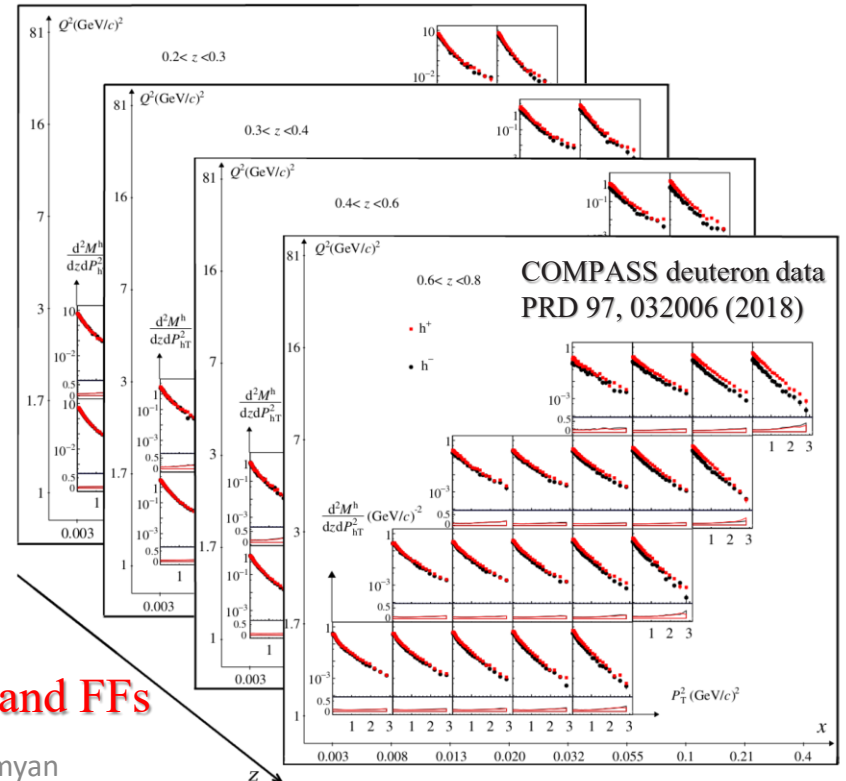
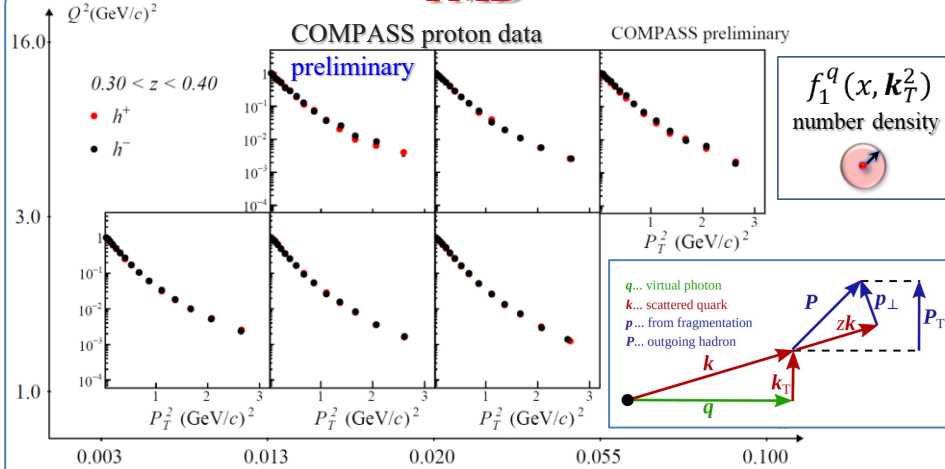
collinear

A set of complex corrections:

- Acceptance, rad. corrections, PID, diffractive VMs, etc.



TMD



New radiative corrections being applied

Multi-D is crucial to explore all features of PDFs and FFs

Hadron multiplicities; $h^\pm$, $\pi^\pm$ and $K^\pm$ (2016 data)

collinear

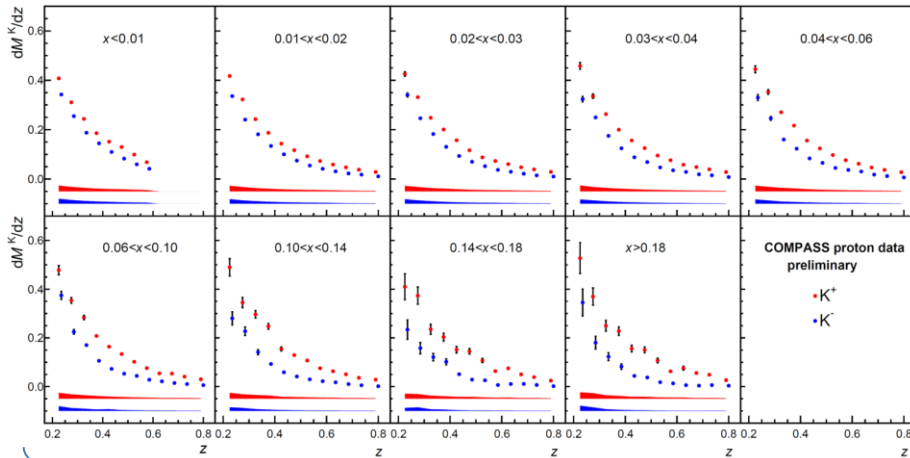
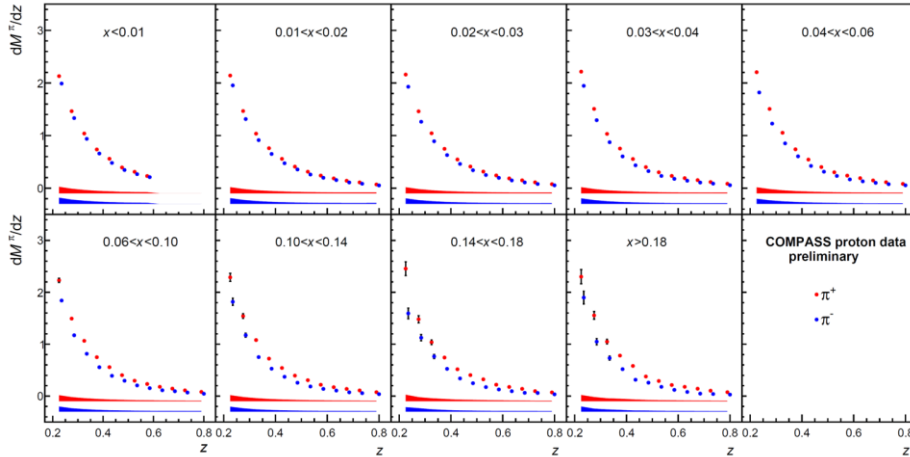
$$f_1^q(x, k_T^2)$$

number density



A set of complex corrections:

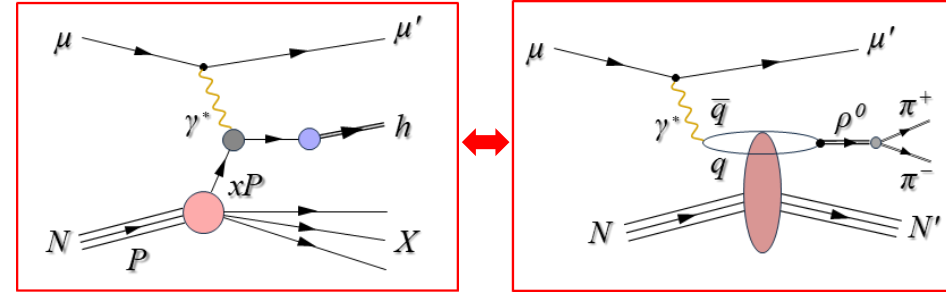
- Acceptance, rad. corrections, PID, diffractive VMs, etc.



New radiative corrections (DJANGO)

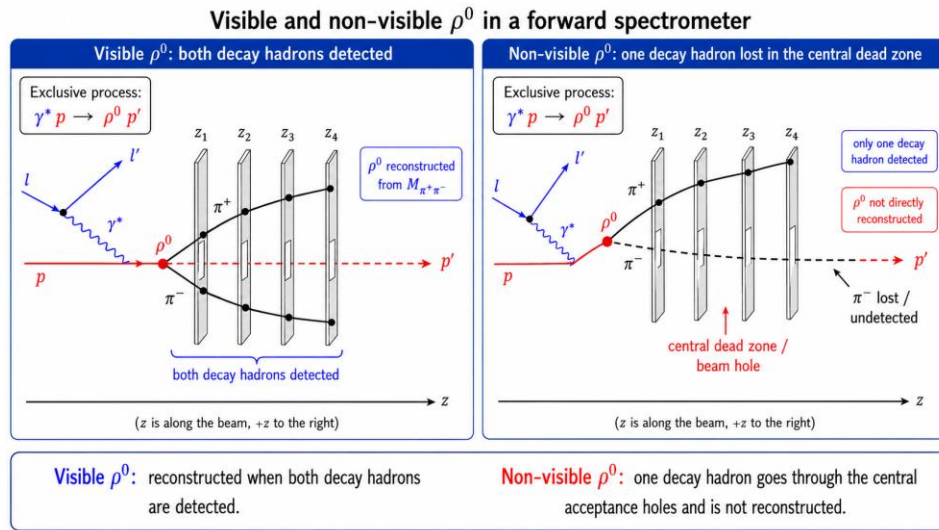
PRD 112 (2025) 012002

7 October 2026



Diffractive VM production

- In DIS γ^* interacts with a single quark
- DVMP - γ^* fluctuates into a VM
 - VM then interacts diffractively with the nucleon through multiple gluon exchange



Hadron multiplicities; $h^\pm$, $\pi^\pm$ and $K^\pm$ (2016 data)

$$f_1^q(x, k_T^2)$$

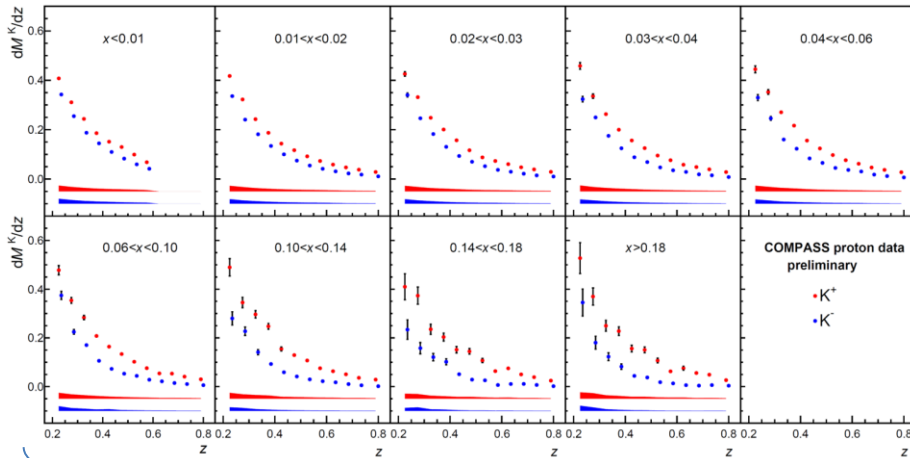
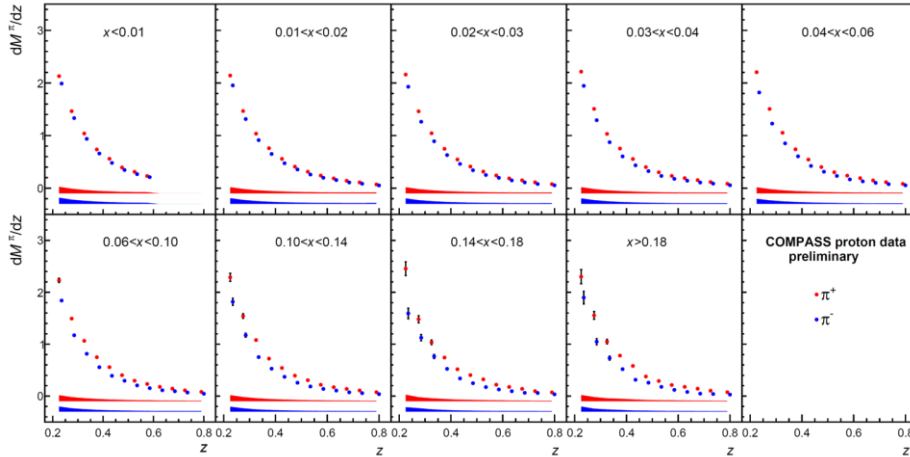
number density



collinear

A set of complex corrections:

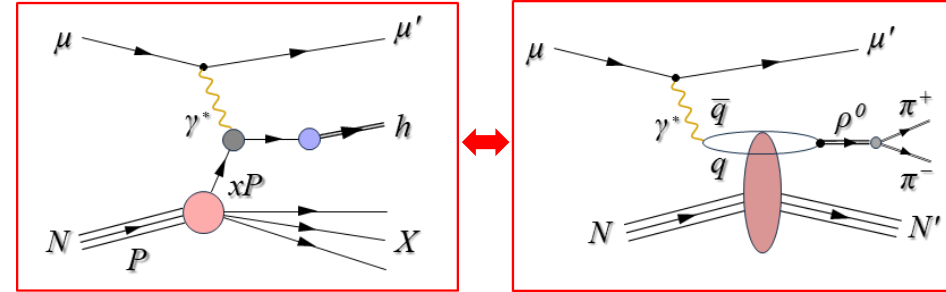
- Acceptance, rad. corrections, PID, diffractive VMs, etc.



New radiative corrections (DJANGOH)

PRD 112 (2025) 012002

7 October 2026



Diffractive VM production

- In DIS γ^* interacts with a single quark
- DVMP - γ^* fluctuates into a VM
 - VM then interacts diffractively with the nucleon through multiple gluon exchange

- DVMP correction: two MC samples are used

SIDIS

- LEPTO 6.5 MC (diffractive contributions off)

Diffractive ρ^0 and ϕ mesons

- HEPGEN generator

Diffractive events enhance at low x and Q^2

- Pions from ρ^0 decay (at high z)

For pions maximum correction can reach even 50%

- Kaons from ϕ decay ($0.4 < z < 0.6$)

For kaons maximum correction $\sim 24\%$

for ($z \approx 0.6$ and $Q^2 \approx 1 \text{ (GeV/c)}^2$).

Cahn effect in SIDIS: Diffractive VMs contribution

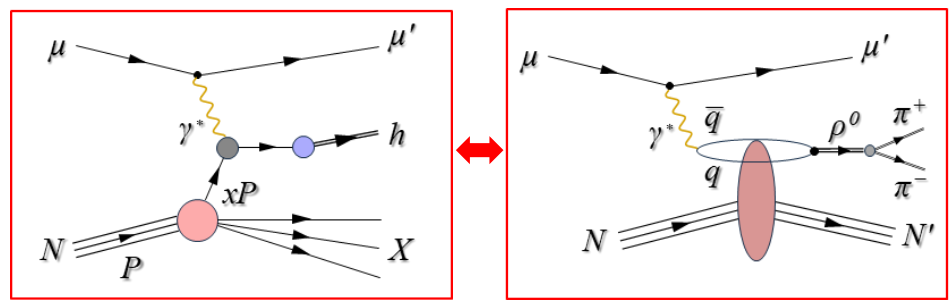
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times (1 + \underbrace{\sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h}_{\text{Cahn effect}} + \dots)$$



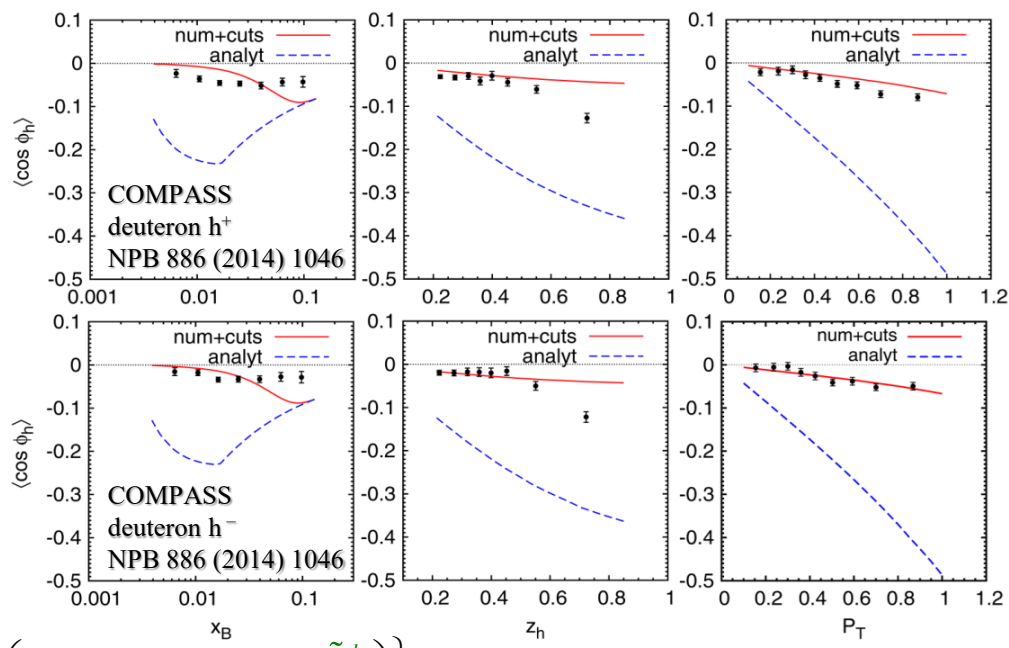
Cahn effect

$f_1^q(x, k_T^2)$
 number density
 

- As of 1978 – simplistic kinematic effect:
- non-zero k_T induces an azimuthal modulation
- As of 2023 – complex SF (twist-2/3 functions)
- Measurements by different experiments



?



$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q} C \left\{ -\frac{\hat{h} \cdot p_T}{M_h} \left(x h_{1q}^{\perp h} + \frac{M_h}{M} f_1^q \frac{\tilde{D}_q^{\perp h}}{z} \right) - \frac{\hat{h} \cdot k_T}{M} \left(x f^{\perp q} D_{1q}^h + \frac{M_h}{M} h_1^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$

Cahn effect in SIDIS: Diffractive VMs contribution

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times (1 + \underbrace{\sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h}_{\text{Cahn effect}} + \dots)$$

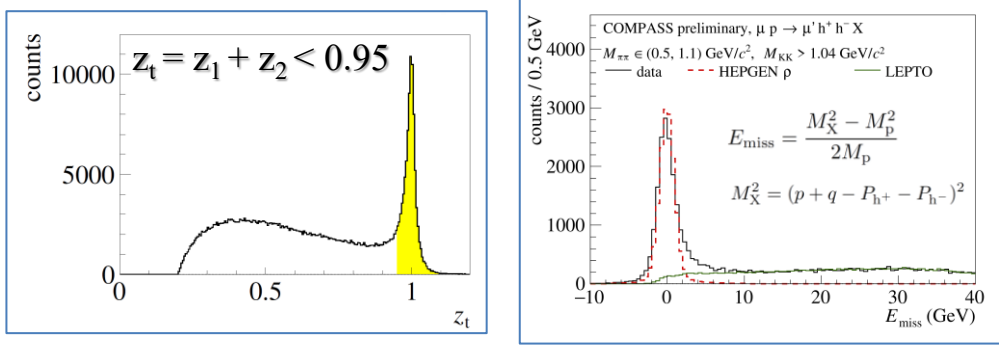
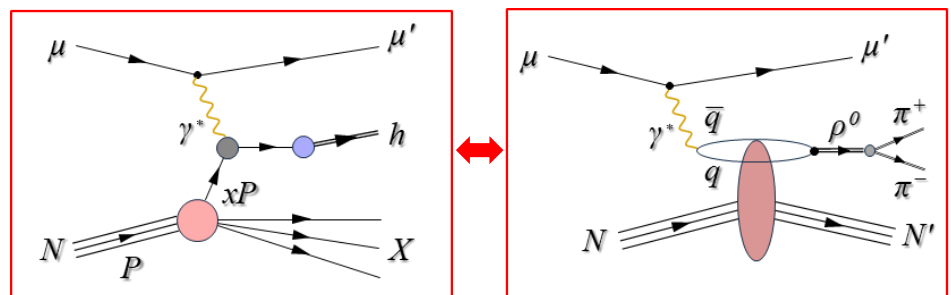


Cahn effect

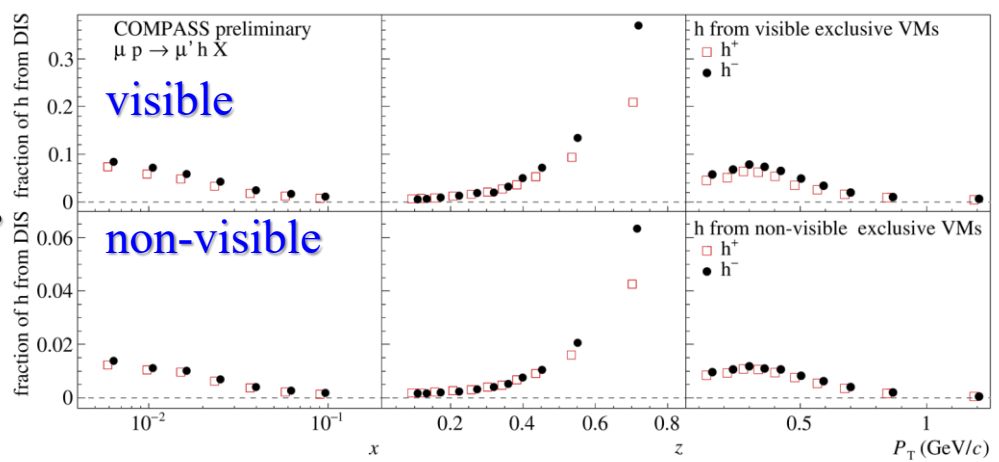
$f_1^q(x, k_T^2)$
 number density
 

- As of 1978 – simplistic kinematic effect:
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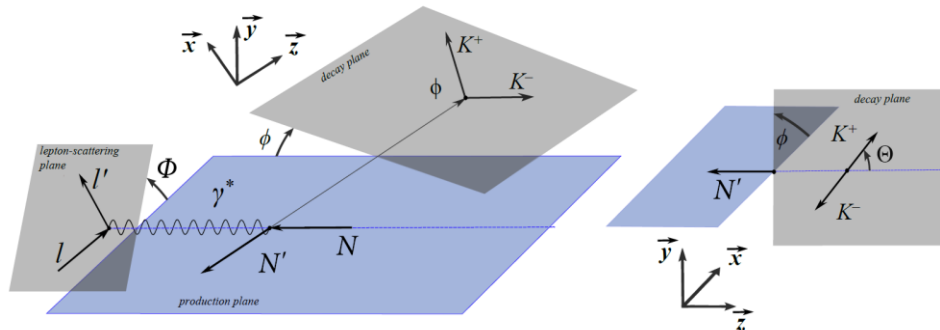
- As of 2023 – complex SF (twist-2/3 functions)
- Measurements by different experiments
 - Complex multi-D kinematic dependences
 - So far, no comprehensive interpretation
 - A set of complex corrections:
 - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.



VM fractions



Spin Density Matrix Elements from photon to a VM

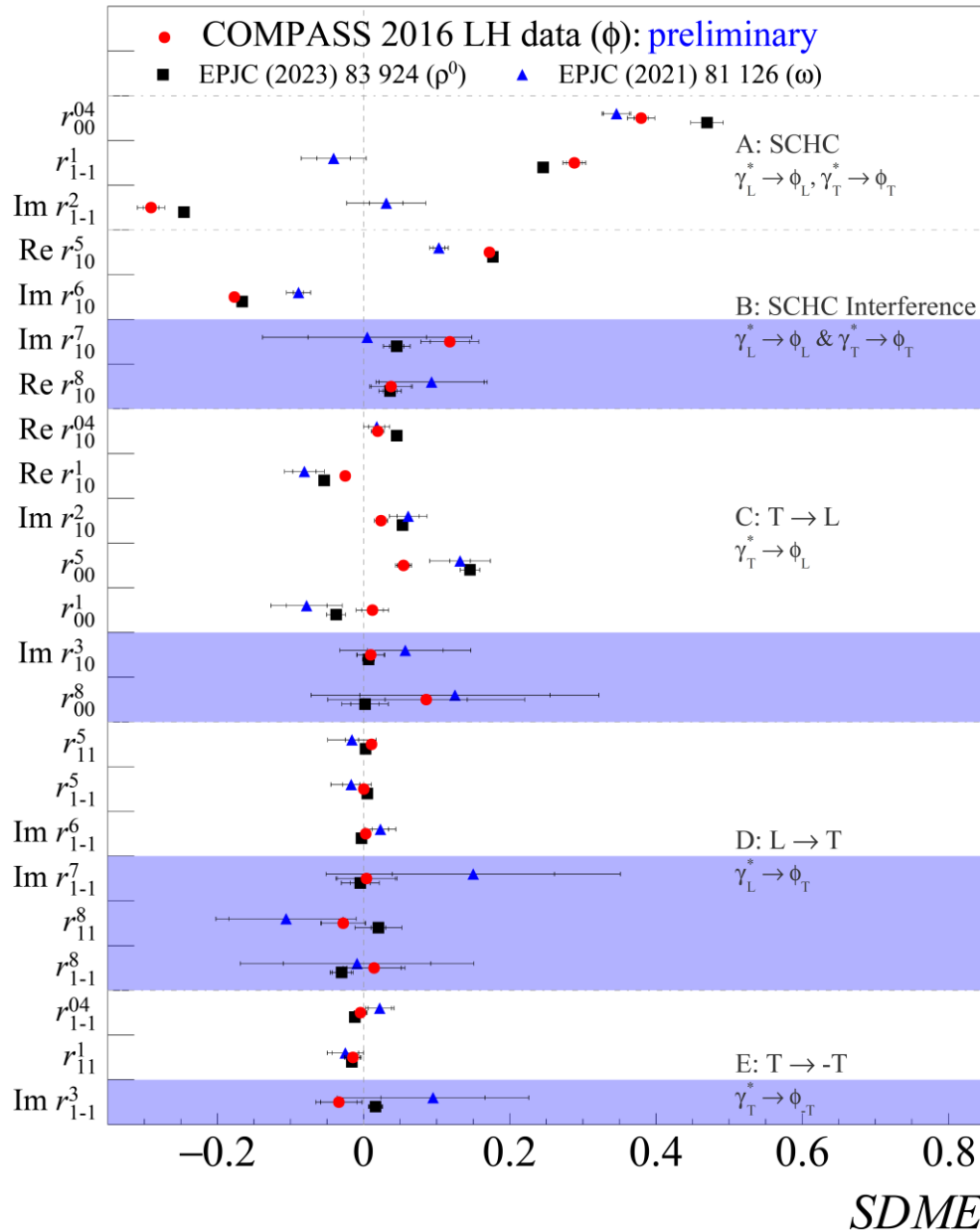


Spin Density Matrix Elements.

- SDMEs describe the spin state of a produced vector meson for example ρ^0 , ϕ , J/ψ .
- SDMEs tell how the spin of the virtual photon is transferred to the vector meson, and which helicity amplitudes contribute to the production process. SDMEs are extracted from angular distributions of the decay products and provide information on helicity transitions, natural/unnatural parity exchange, and s-channel helicity conservation.
- SDMEs are not cross sections themselves; they are normalized spin-observables describing the polarization and helicity structure of vector-meson production.

$$W_U(\phi, \Phi, \cos \theta) = \frac{3}{8\pi^2} \left[\begin{aligned} & \frac{1}{2}(1 - r_{00}^{04}) + \frac{1}{2}(3r_{00}^{04} - 1)\cos^2 \theta - \\ & \sqrt{2}\text{Re}\{r_{10}^{04}\}\sin 2\theta \cos \phi - \\ & r_{1-1}^{04}\sin^2 \theta \cos 2\phi - \\ & \varepsilon \cos 2\Phi \left(\begin{aligned} & r_{11}^1 \sin^2 \theta + \\ & r_{00}^1 \cos^2 \theta - \\ & \sqrt{2}\text{Re}\{r_{10}^1\}\sin 2\theta \cos \phi - \\ & r_{1-1}^1 \sin^2 \theta \cos 2\phi \end{aligned} \right) - \\ & \varepsilon \sin 2\Phi \left(\begin{aligned} & \sqrt{2}\text{Im}\{r_{10}^2\}\sin 2\theta \sin \phi + \\ & \text{Im}\{r_{1-1}^2\}\sin^2 \theta \sin 2\phi \end{aligned} \right) + \\ & \sqrt{2\varepsilon(1+\varepsilon)} \cos \Phi \left(\begin{aligned} & r_{11}^5 \sin^2 \theta + r_{00}^5 \cos^2 \theta - \\ & \sqrt{2}\text{Re}\{r_{10}^5\}\sin 2\theta \cos \phi - \\ & r_{1-1}^5 \sin^2 \theta \cos 2\phi \end{aligned} \right) + \\ & \sqrt{2\varepsilon(1+\varepsilon)} \sin \Phi \left(\begin{aligned} & \sqrt{2}\text{Im}\{r_{10}^6\}\sin 2\theta \sin \phi + \\ & \text{Im}\{r_{1-1}^6\}\sin^2 \theta \sin 2\phi \end{aligned} \right) \end{aligned} \right] \\ \\ W_L(\phi, \cos \theta) = \frac{3}{8\pi^2} \left[\begin{aligned} & \sqrt{1-\varepsilon^2} \left(\begin{aligned} & \sqrt{2}\text{Im}\{r_{10}^3\}\sin 2\theta \sin \phi + \\ & \text{Im}\{r_{1-1}^3\}\sin^2 \theta \sin 2\phi \end{aligned} \right) + \\ & \sqrt{2\varepsilon(1-\varepsilon)} \cos \Phi \left(\begin{aligned} & \sqrt{2}\text{Im}\{r_{10}^7\}\sin 2\theta \sin \phi + \\ & \text{Im}\{r_{1-1}^7\}\sin^2 \theta \sin 2\phi \end{aligned} \right) + \\ & \sqrt{2\varepsilon(1-\varepsilon)} \sin \Phi \left(\begin{aligned} & r_{11}^8 \sin^2 \theta + \\ & r_{00}^8 \cos^2 \theta - \\ & \sqrt{2}\text{Re}\{r_{10}^8\}\sin 2\theta \cos \phi - \\ & r_{1-1}^8 \sin^2 \theta \cos 2\phi \end{aligned} \right) \end{aligned} \right]$$

Spin Density Matrix Elements from photon to a VM



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

$$W_L(\phi, \cos \theta) = \frac{3}{8\pi^2} \left[\begin{aligned} & \sqrt{1-\varepsilon^2} \left(\begin{aligned} & \sqrt{2}\text{Im}\{r_{10}^3\}\sin 2\theta \sin \phi + \\ & \text{Im}\{r_{1-1}^3\}\sin^2 \theta \sin 2\phi \end{aligned} \right) + \\ & \sqrt{2\varepsilon(1-\varepsilon)} \cos \Phi \left(\begin{aligned} & \sqrt{2}\text{Im}\{r_{10}^7\}\sin 2\theta \sin \phi + \\ & \text{Im}\{r_{1-1}^7\}\sin^2 \theta \sin 2\phi \end{aligned} \right) + \\ & \sqrt{2\varepsilon(1-\varepsilon)} \sin \Phi \left(\begin{aligned} & r_{11}^8 \sin^2 \theta + \\ & r_{00}^8 \cos^2 \theta - \\ & \sqrt{2}\text{Re}\{r_{10}^8\}\sin 2\theta \cos \phi - \\ & r_{1-1}^8 \sin^2 \theta \cos 2\phi \end{aligned} \right) \end{aligned} \right] .$$

Cahn effect in SIDIS: DVMs

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \left(1 + \underbrace{\sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h}}_{\text{Cahn effect}} \cos\phi_h + \dots \right)$$



Cahn effect

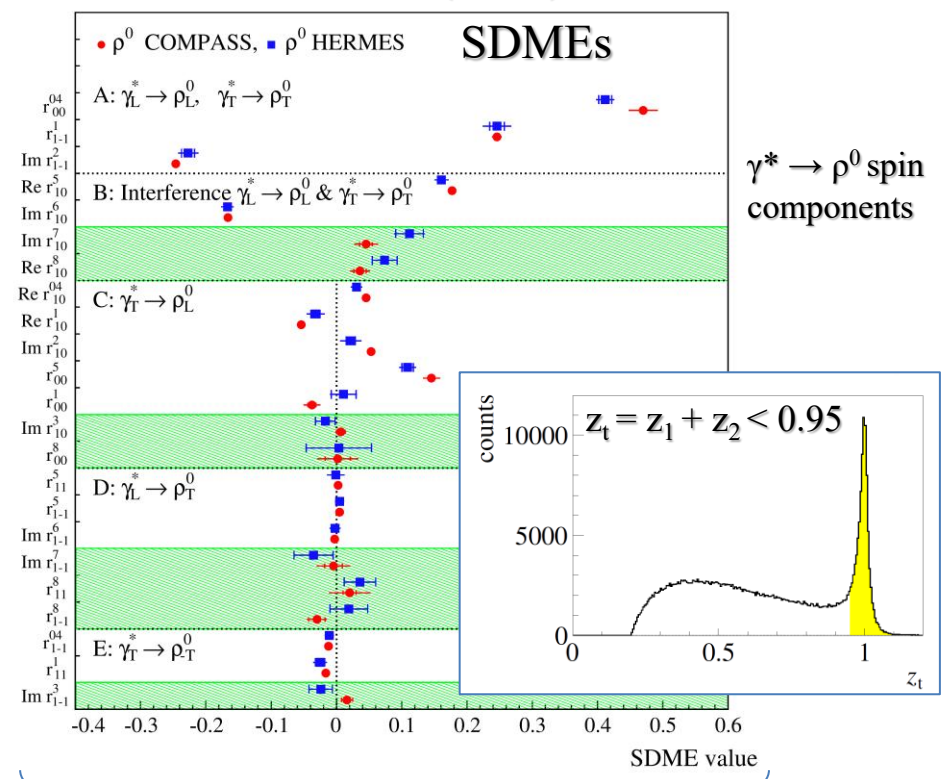
$f_1^q(x, k_T^2)$
 number density
 

- As of 1978 – simplistic kinematic effect:
- non-zero k_T induces an azimuthal modulation

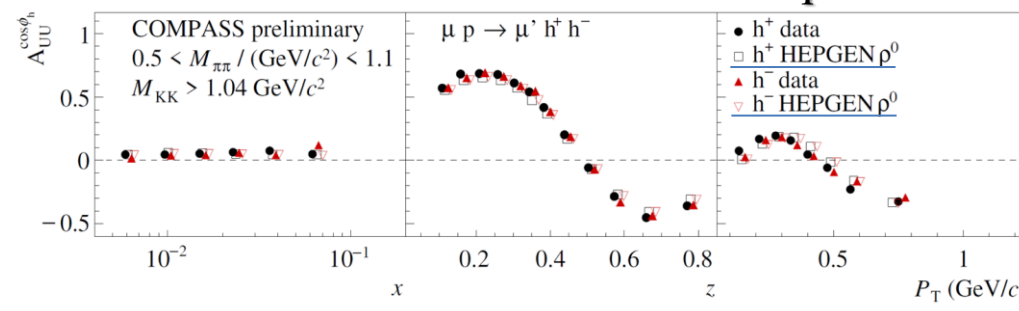
“Visible” hadron pairs

- Both hadrons reconstructed
- Removed by selecting: $z_t = z_{h^+} + z_{h^-} < 0.95$

COMPASS, EPJC (2023) 83 924



VM contribution “amplitudes”



Only “average” SDMEs are implemented in HEPgen
 They seem to describe the data well

Cahn effect in SIDIS: DVMs

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \underbrace{\left(1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \dots \right)}_{\text{Cahn effect}}$$



Cahn effect

$f_1^q(x, k_T^2)$
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- As of 1978 – simplistic kinematic effect:
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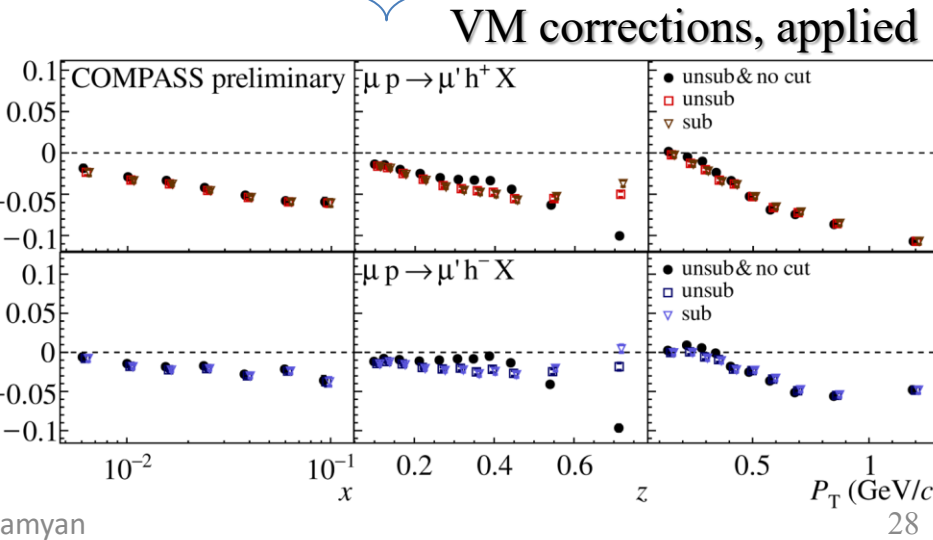
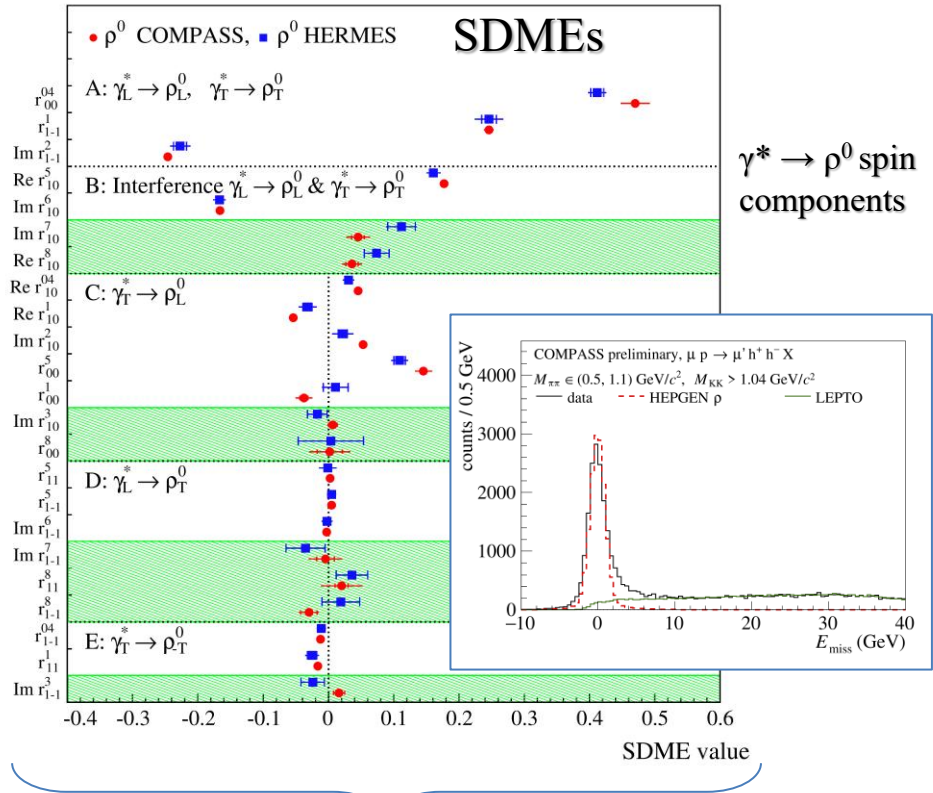
“Visible” hadron pairs

- Both hadrons reconstructed
- Removed by selecting: $z_t = z_{h^+} + z_{h^-} < 0.95$

“Invisible” hadron pairs

- Only one hadron out of two is reconstructed
- Subtraction done at the level of ϕ_h using simulated HEPGEN distribution for VMs
- HEPGEN and Lepto are normalized to the data using E_{miss} distribution, SIDIS tail is subtracted

COMPASS, EPJC (2023) 83 924

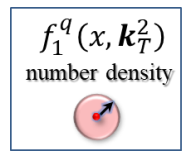


Cahn effect in SIDIS: DVMs and RCs

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L}) \times \underbrace{\left(1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \dots \right)}_{\text{Cahn effect}}$$



Cahn effect



As of 1978 – simplistic kinematic effect:
 • non-zero k_T induces an azimuthal modulation

- As of 2023 – complex SF (twist-2/3 functions)
- Measurements by different experiments
 - Complex multi-D kinematic dependences
 - So far, no comprehensive interpretation
 - A set of complex corrections:
 - Acceptance, **diffractively produced VMs**, radiative corrections (RC), etc.
 - Strong Q^2 dependence – unexplained
 - Do not seem to come from RCs
 - Transition TMD $\leftrightarrow$ collinear regions?

RC corrections, applied

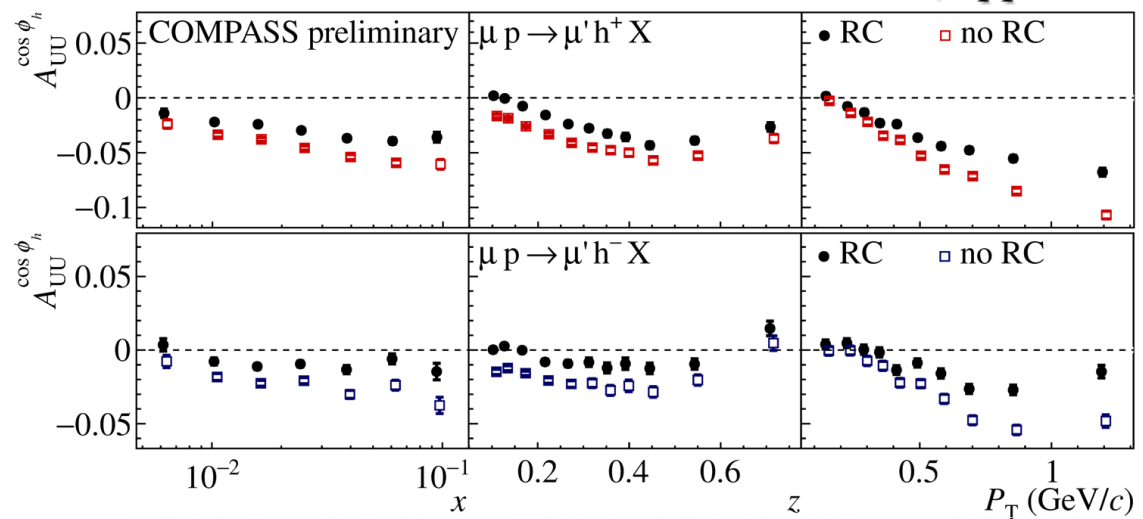
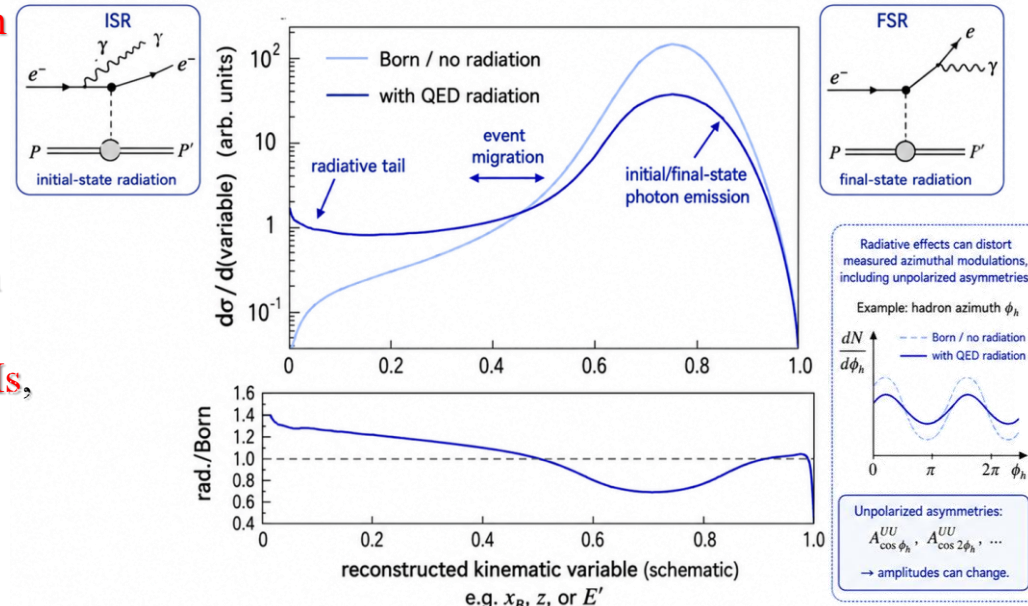


Illustration of QED radiative effects



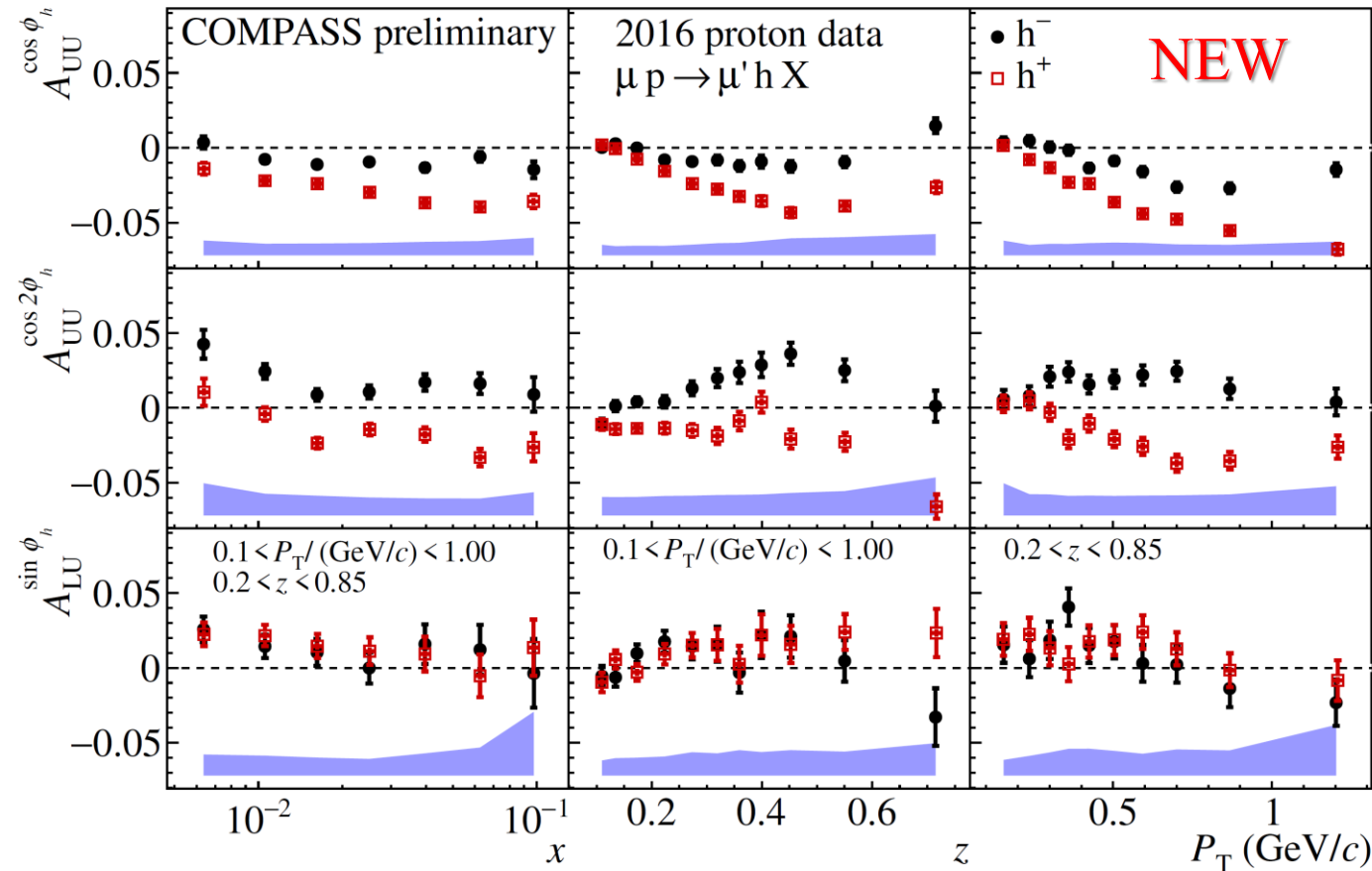
Bremsstrahlung is mass-suppressed. Since $m_\mu \gg m_e$
 QED radiative effects are smaller for muon beams.

Azimuthal effects in unpolarized SIDIS

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times (1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h + \dots)$$

Target spin independent part of the cross-section: three asymmetries



Cahn effect
Different for h⁺, h⁻
Non-trivial Q² dependence

Boer-Mulders effect
Collins-like behavior
(h⁺h⁻ - mirror symmetry)

Beam-spin asymmetry
higher-twist effect
non-zero, positive trend

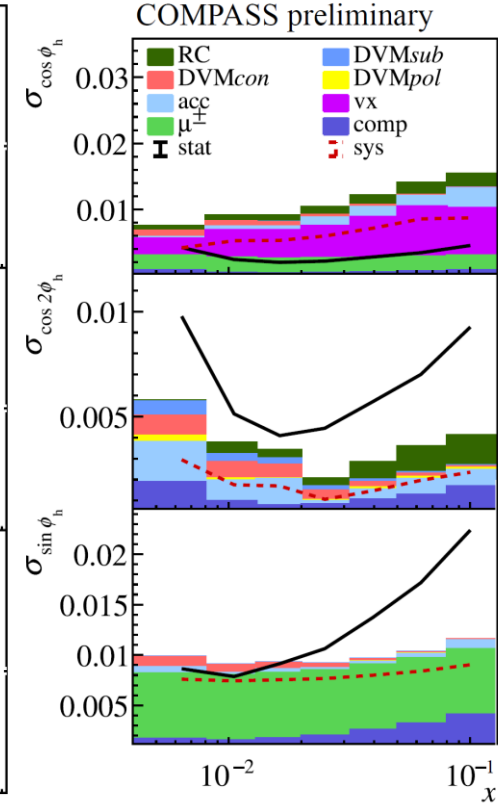
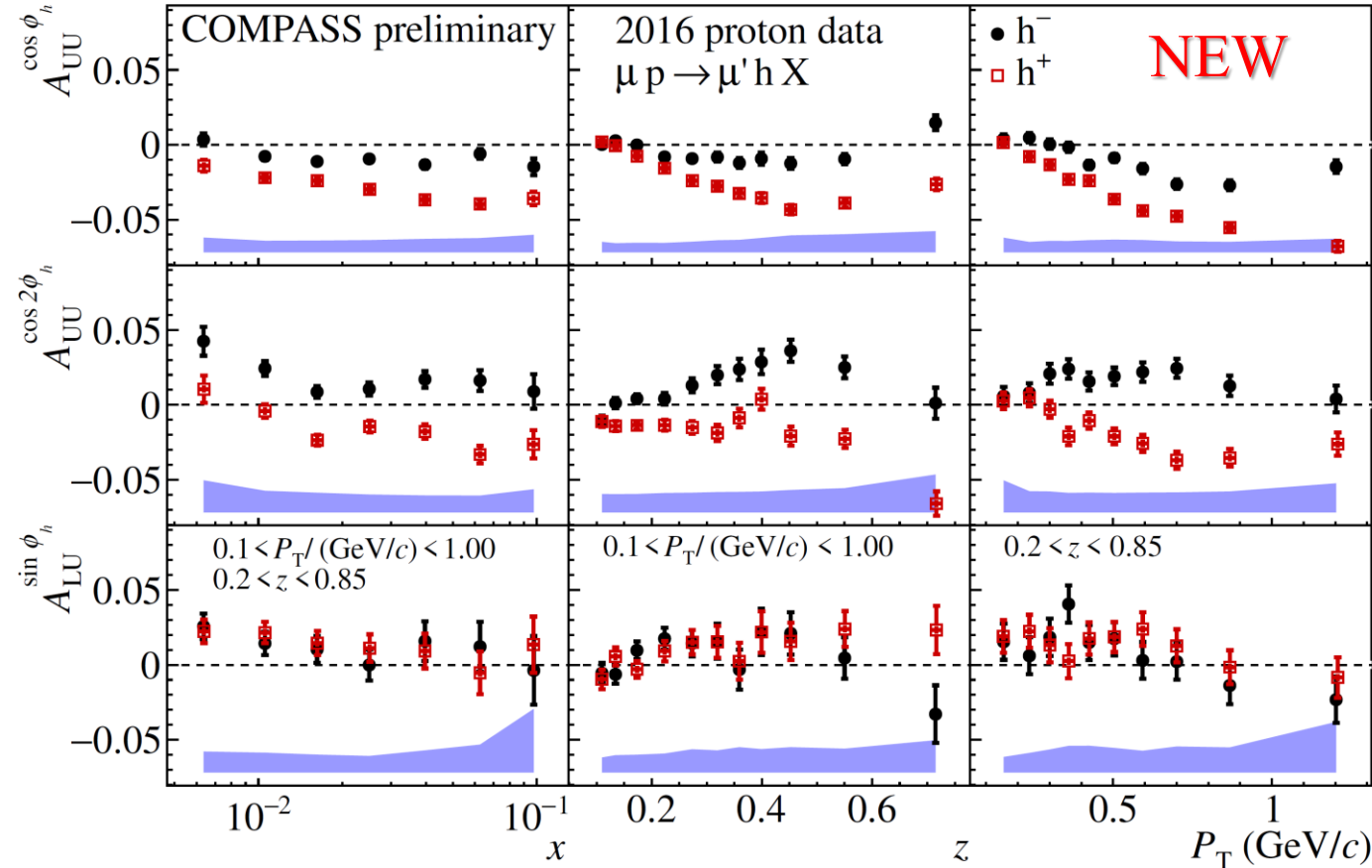
Working on 3D kinematic dependences

Azimuthal effects in unpolarized SIDIS

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times (1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h + \dots)$$

Target spin independent part of the cross-section: three asymmetries



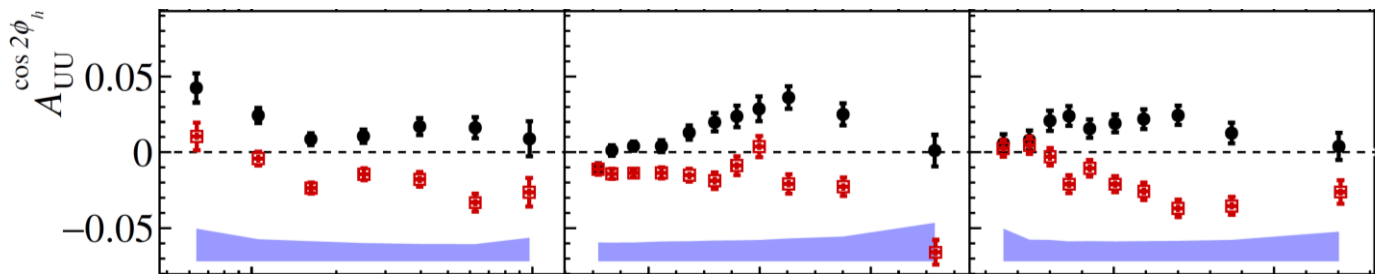
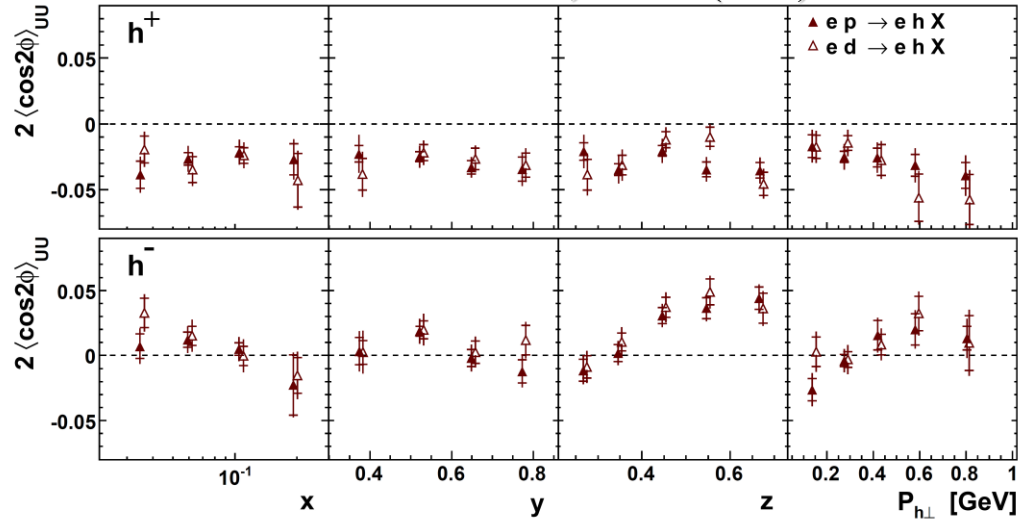
Working on 3D kinematic dependences

Azimuthal effects in unpolarized SIDIS: HERMES

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times (1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h)$$

HERMES PRD 87, 012010 (2013)



Boer-Mulders effect
Collins-like behavior
(h^+h^- - mirror symmetry)



Boer-Mulders-Collins effect
D. Boer and P. J. Mulders, PRD 57 (1998)
Boer-Mulders effect + twist-4 Cahn effect

Boer-Mulders PDF Collins FF

Cahn effect



$$F_{UU}^{\cos 2\phi_h} = C \left\{ -\frac{2(\hat{h} \cdot p_T)(\hat{h} \cdot k_T) - p_T \cdot k_T}{MM_h} h_1^{\perp q} H_{1q}^{\perp h} \right\} + \left(\frac{M}{Q} \right)^2 C \left\{ -\frac{2(\hat{h} \cdot k_T)^2 - k_T^2}{M^2} f_1^q D_{1q}^h + \dots \right\}$$

Azimuthal effects in unpolarized SIDIS: COMPASS

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} =$$

$$\left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

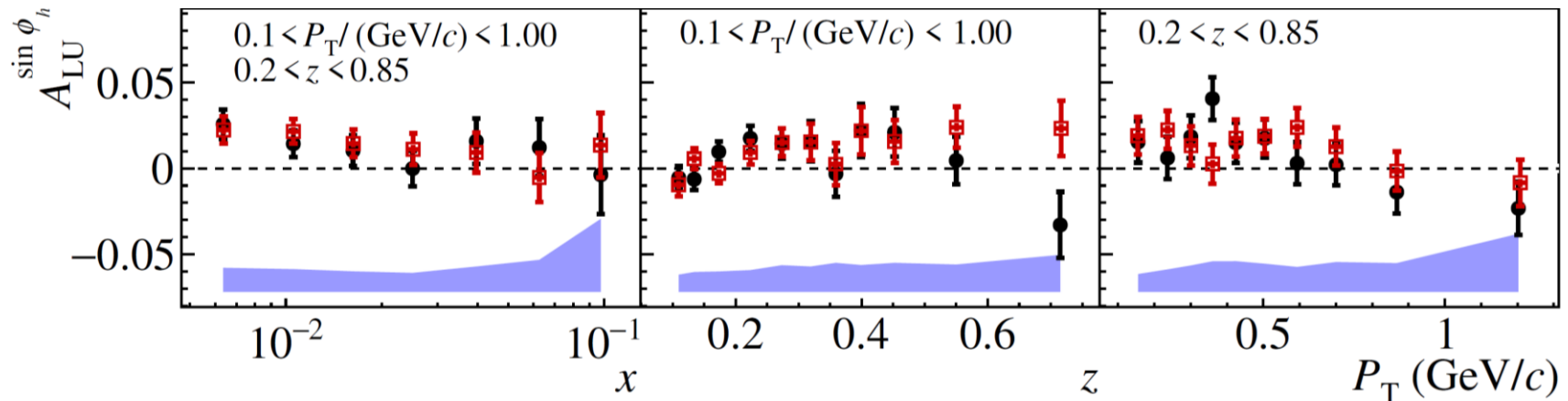
$$\times \left(1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h + \dots \right)$$

Target spin independent part of the cross-section: three asymmetries

Beam-spin asymmetry
higher-twist effect

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q} C \left\{ -\frac{\hat{h} \cdot p_T}{M_h} \left(x e H_{1q}^{\perp h} + \frac{M_h}{M} f_1^q \frac{\tilde{G}_q^{\perp h}}{z} \right) + \frac{\hat{h} \cdot k_T}{M} \left(x g^{\perp q} D_{1q}^h + \frac{M_h}{M} h_1^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$

Complex structure function involving twist-2 and twist-3 functions



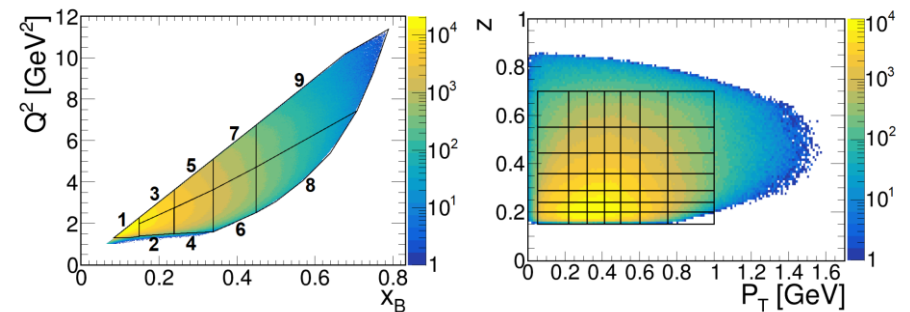
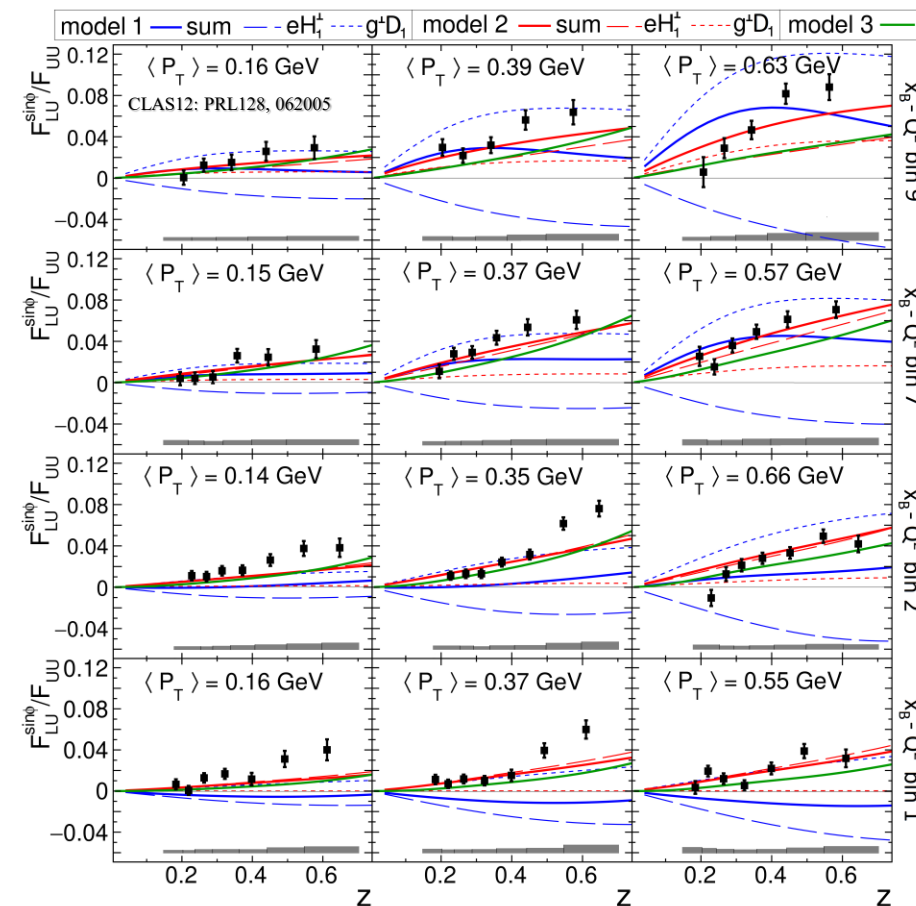
Azimuthal effects in unpolarized SIDIS: BSA CLAS12

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

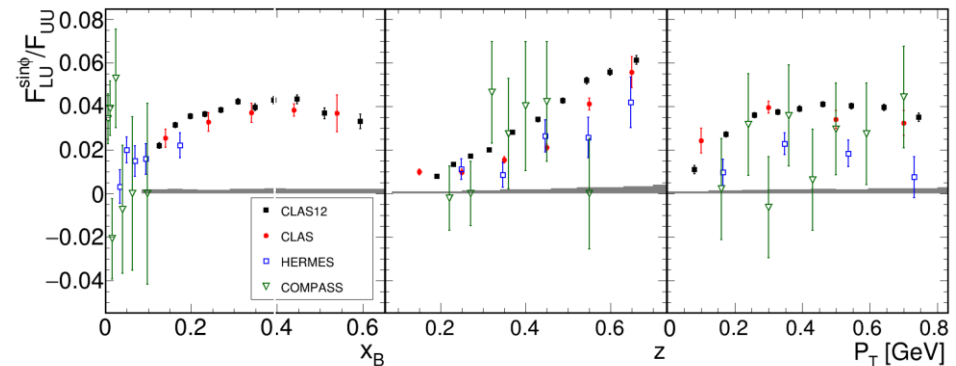
$$\times \left(1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h + \dots \right)$$

Target spin independent part of the cross-section: three asymmetries

Beam-spin asymmetry
higher-twist effect
non-zero, positive trend
Quite large at CLAS12 (lower Q^2)



CLAS12: PRL128, 062005



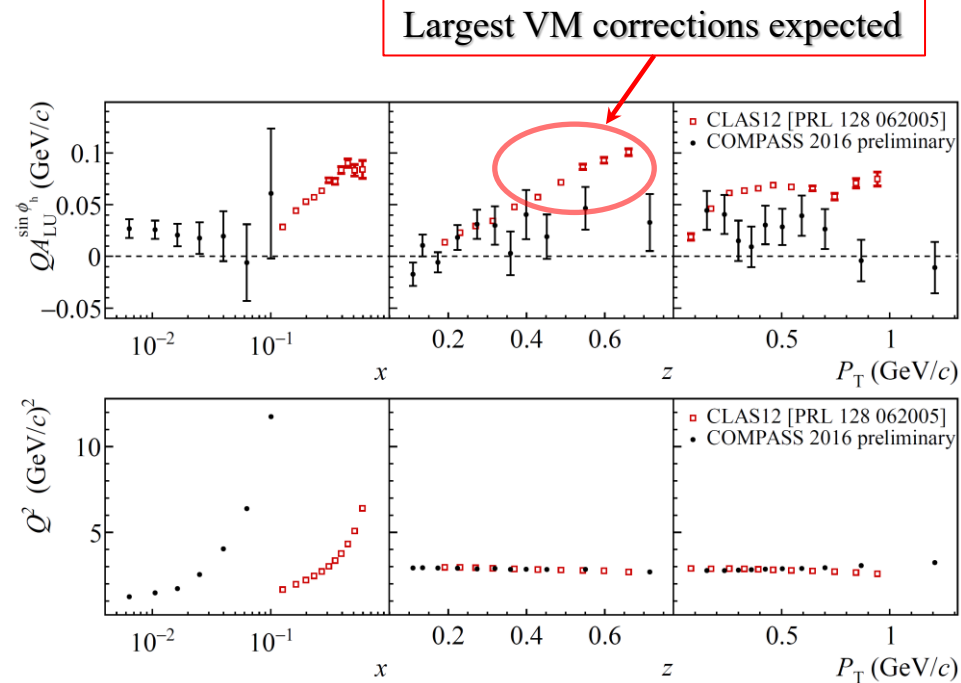
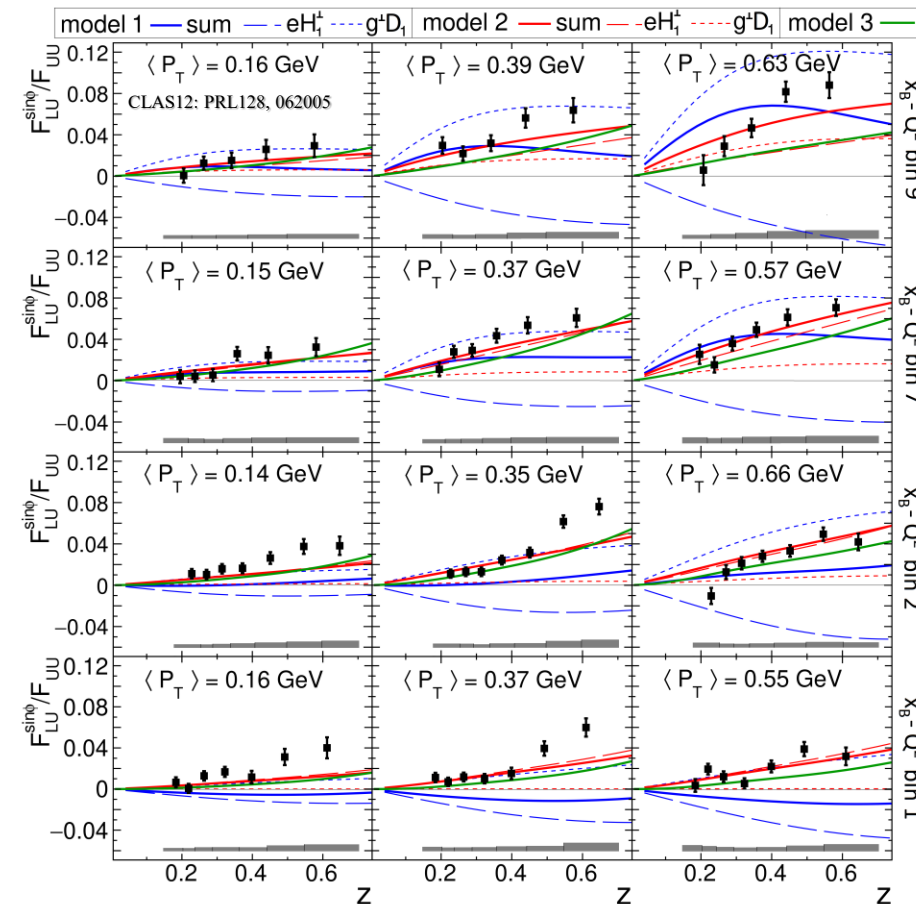
Azimuthal effects in unpolarized SIDIS: BSA CLAS12

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times \left(1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h + \dots \right)$$

Target spin independent part of the cross-section: three asymmetries

Beam-spin asymmetry
higher-twist effect
non-zero, positive trend
Quite large at CLAS12 (lower Q^2)



CLAS12 results are not corrected for the VM contribution

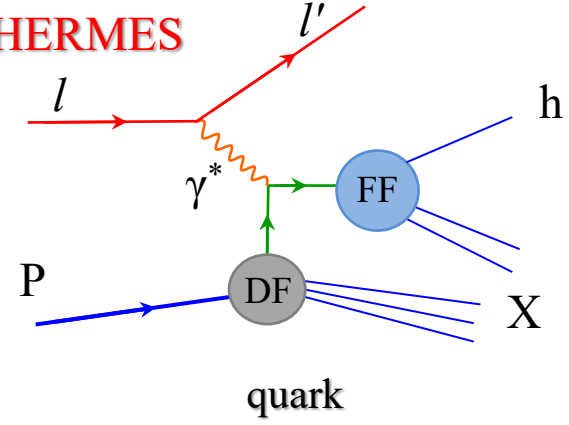
SIDIS x-section and TMDs at twist-2

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} =$$

All measured by COMPASS and HERMES

$$\left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times \left\{ \begin{aligned} & 1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \\ & + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ & + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ & + S_T \left[\begin{aligned} & A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ & + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \end{aligned} \right] \\ & + S_T \lambda \left[\begin{aligned} & \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \end{aligned} \right] \end{aligned} \right\}$$



	U	L	T
U	 number density		 Boer-Mulders
L		 helicity	 worm-gear L
T	 Sivers	 Kotzinian-Mulders worm-gear T	 transversity pretzelosity



spin of the nucleon

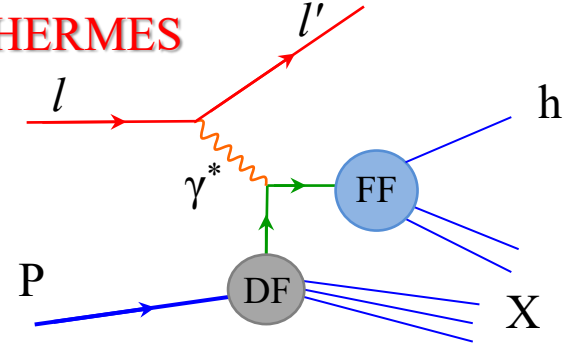


spin of the quark



SIDIS x-section and TMDs at twist-2: TSAs

All measured by COMPASS and HERMES



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times \left\{ \begin{aligned} & \left[1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right. \\ & \quad \left. + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \right] \\ & + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ & + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ & + S_T \left[\begin{aligned} & A_{UT}^{\sin(\phi_h-\phi_s)} \sin(\phi_h-\phi_s) \\ & + \varepsilon A_{UT}^{\sin(\phi_h+\phi_s)} \sin(\phi_h+\phi_s) \\ & + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_s)} \sin(3\phi_h-\phi_s) \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_s} \sin\phi_s \\ & + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_s)} \sin(2\phi_h-\phi_s) \end{aligned} \right] \\ & + S_T \lambda \left[\begin{aligned} & \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_s)} \cos(\phi_h-\phi_s) \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_s} \cos\phi_s \\ & + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_s)} \cos(2\phi_h-\phi_s) \end{aligned} \right] \end{aligned} \right\}$$

$$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h \quad \text{Sivers}$$

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h} \quad \text{Collins}$$

$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$A_{UT}^{\sin(\phi_s)} \propto Q^{-1} \left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots \right)$$

$$A_{UT}^{\sin(2\phi_h-\phi_s)} \propto Q^{-1} \left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h + \dots \right)$$

$$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$A_{LT}^{\cos(\phi_s)} \propto Q^{-1} \left(g_{1T}^q \otimes D_{1q}^h + \dots \right)$$

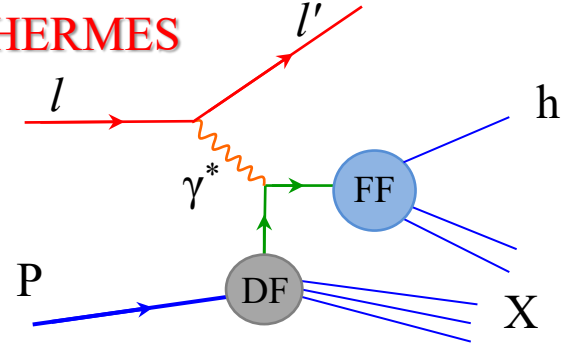
$$A_{LT}^{\cos(2\phi_h-\phi_s)} \propto Q^{-1} \left(g_{1T}^q \otimes D_{1q}^h + \dots \right)$$

Twist-2

Twist-3

SIDIS x-section and TMDs at twist-2: TSAs

All measured by COMPASS and HERMES



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} =$$

$$\left[\frac{\alpha}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times \left\{ \begin{array}{l} \left[1 + \sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right. \\ \left. + \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LU}^{\sin\phi_h} \sin\phi_h \right] \\ + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \end{array} \right] \\ + S_T \lambda \left[\begin{array}{l} \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos\phi_S} \cos\phi_S \\ + \sqrt{2\varepsilon(1-\varepsilon)} A_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \end{array} \right] \end{array} \right\}$$

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C \left\{ \left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) - \frac{\mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z} \right) \right] \right\}$$

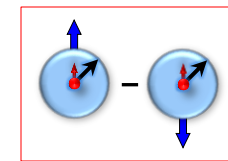
$$F_{UT}^{\sin(2\phi_h-\phi_S)} = \frac{2M}{Q} C \left\{ \frac{2(\hat{\mathbf{h}} \cdot \mathbf{k}_T)^2 - \mathbf{k}_T^2}{2M^2} \left(x f_T^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1T}^q \frac{\tilde{H}_q^h}{z} \right) - \frac{2(\hat{\mathbf{h}} \cdot \mathbf{p}_T)(\hat{\mathbf{h}} \cdot \mathbf{k}_T) - \mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) + \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z} \right) \right] \right\}$$

$$F_{LT}^{\cos\phi_S} = \frac{2M}{Q} C \left\{ - \left(x g_T^q D_{1q}^h + \frac{M_h}{M} h_1^q \frac{\tilde{E}_q^h}{z} \right) + \frac{\mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[\left(x e_T^q H_{1q}^{\perp h} - \frac{M_h}{M} g_{1T}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) + \left(x e_T^{\perp q} H_{1q}^{\perp h} + \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{G}_q^{\perp h}}{z} \right) \right] \right\}$$

$$F_{LT}^{\cos(2\phi_h-\phi_S)} = \frac{2M}{Q} C \left\{ - \frac{2(\hat{\mathbf{h}} \cdot \mathbf{k}_T)^2 - \mathbf{k}_T^2}{2M^2} \left(x g_T^{\perp q} D_{1q}^h + \frac{M_h}{M} h_{1T}^q \frac{\tilde{E}_q^h}{z} \right) + \frac{2(\hat{\mathbf{h}} \cdot \mathbf{p}_T)(\hat{\mathbf{h}} \cdot \mathbf{k}_T) - \mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[\left(x e_T^q H_{1q}^{\perp h} - \frac{M_h}{M} g_{1T}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) - \left(x e_T^{\perp q} H_{1q}^{\perp h} + \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{G}_q^{\perp h}}{z} \right) \right] \right\}$$

Twist-3

SIDIS TSAs: Collins effect and Transversity



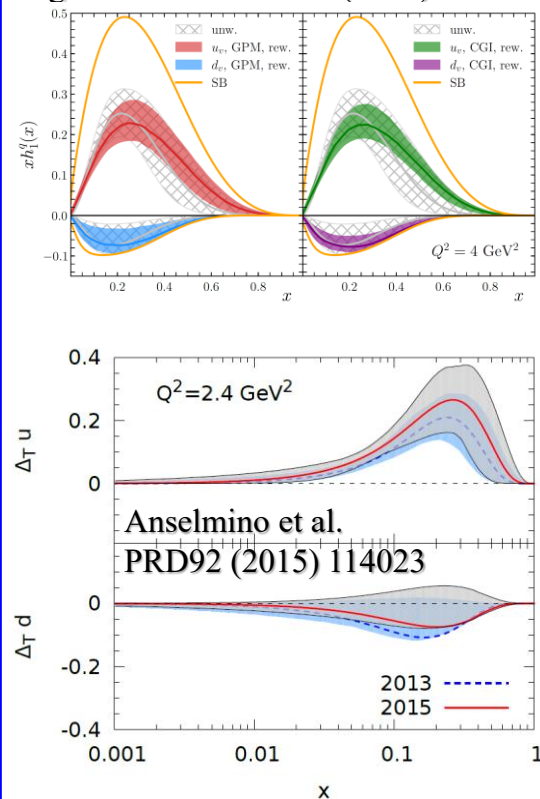
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot p_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$

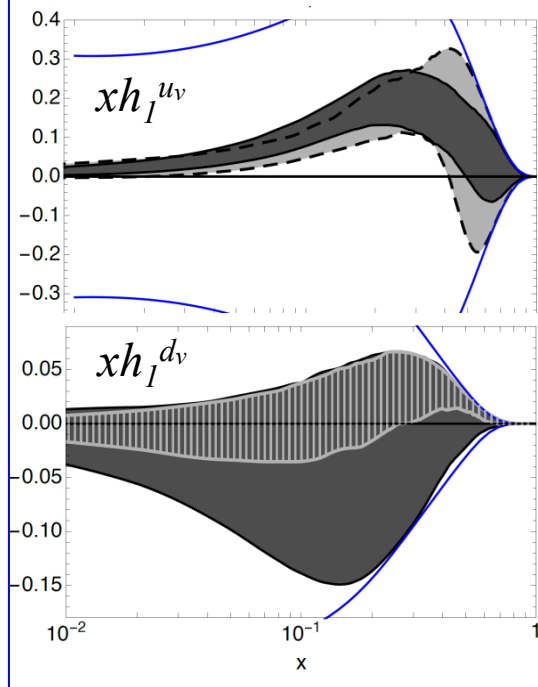


- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of $\sim 2-3$)
- **No impact from Q^2 -evolution? Clear signal at STAR energies**
- Extensive phenomenological studies and various global fits by different groups

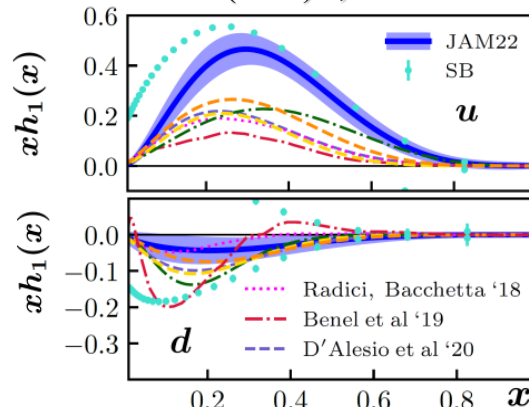
Boglionne et al. PLB 854 (2024) 138712



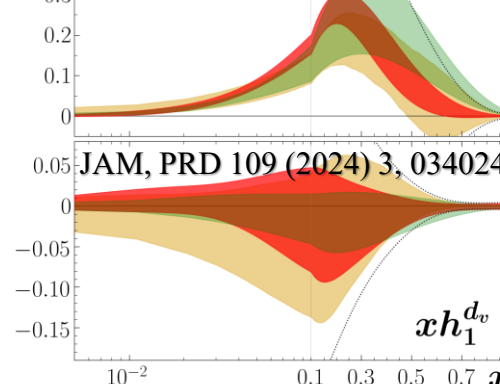
M. Radici and A. Bacchetta
PRL 120 (2018) no.19, 192001



JAM PRD 106 (2022) 3, 034014

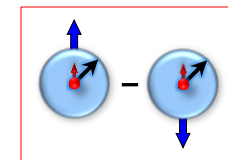


JAMDiFF (no LQCD)
JAM3D* (no LQCD)
Radici, Bacchetta (2018)



JAM, PRD 109 (2024) 3, 034024

SIDIS TSAs: Collins effect and Transversity

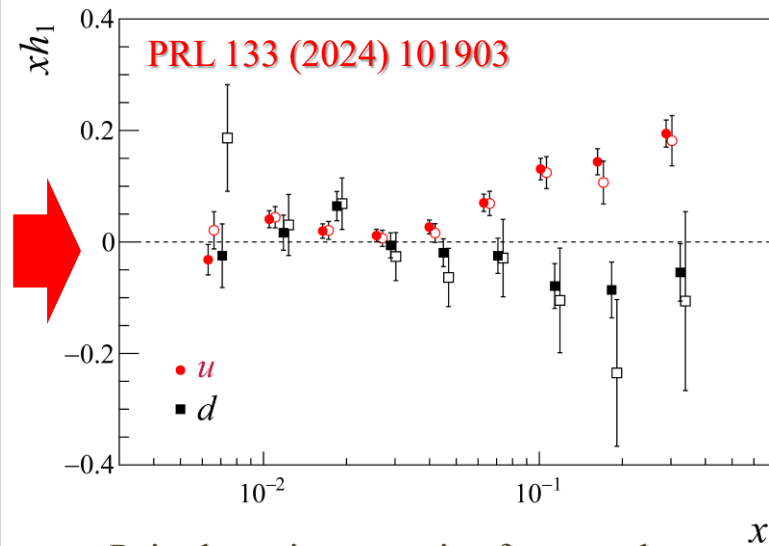
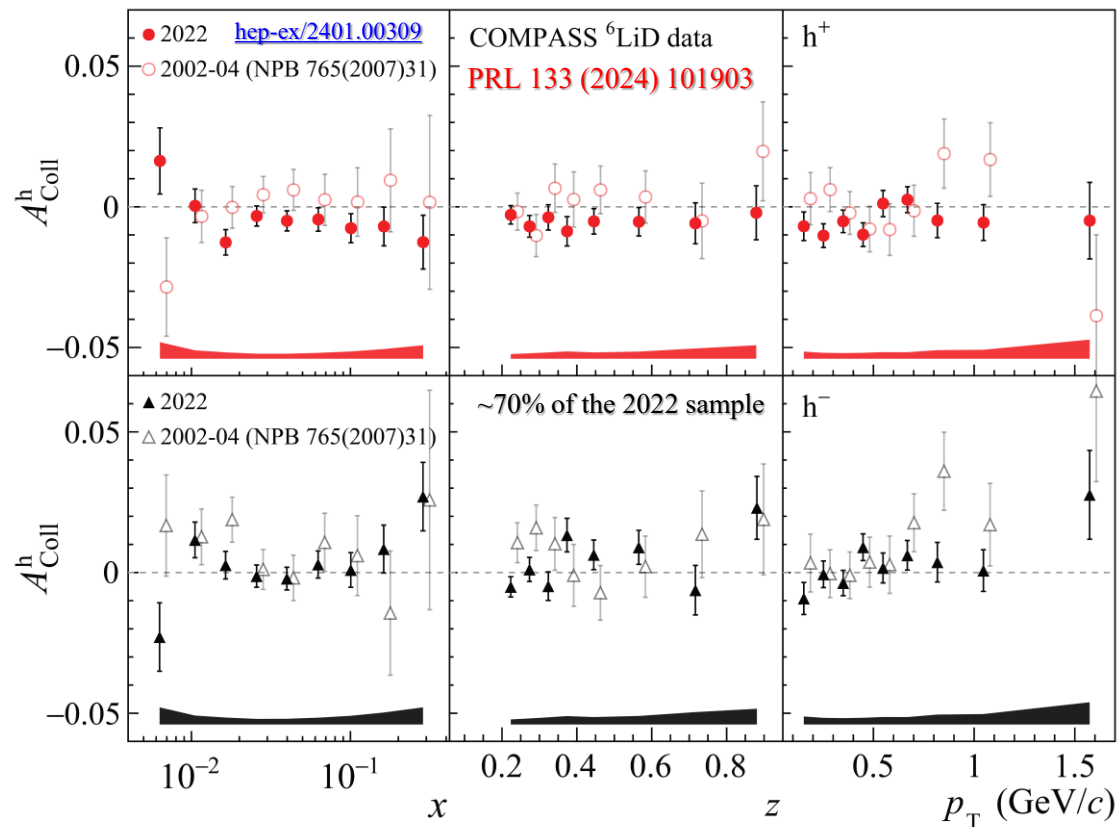


$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot p_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$



- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of $\sim 2-3$)
- **New deuteron data crucial to constrain d -quark transversity**

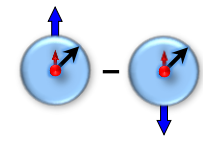


Point-by-point extraction framework
A. Martin et al. PRD **91**, 014034 (2015)
A. Martin et al. PRD **95**, 094024 (2017)

COMPASS 2022 run – highly successful data-taking!

- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades

Dihadron Collins effect and Transversity

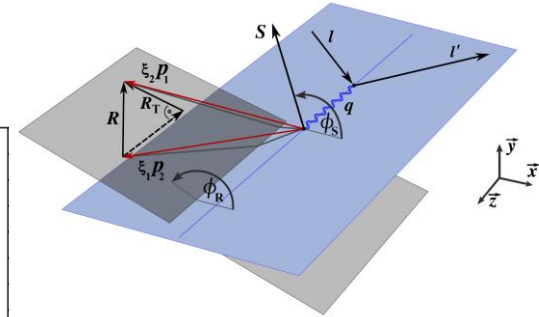
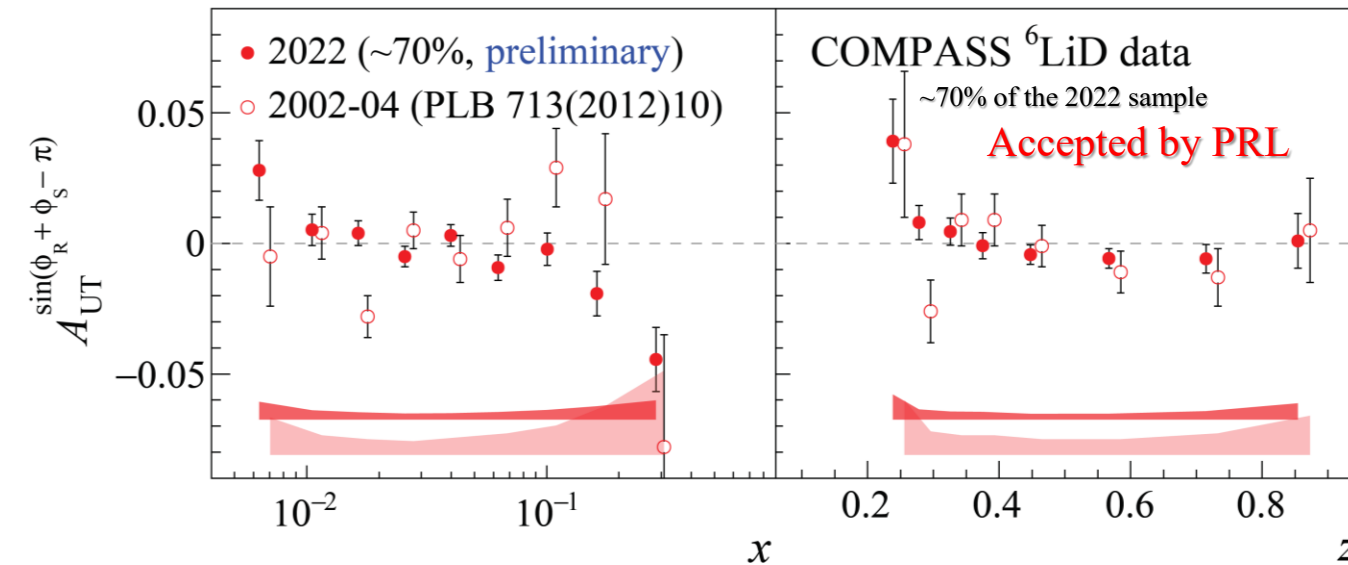


$$\frac{d^7 \sigma}{d \cos \theta d M_{hh} d \phi_R d z d x d y d \phi_S} =$$

$$\frac{\alpha^2}{2\pi Q^2 y} \left((1-y + \frac{y^2}{2}) \sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{hh}^2, \cos \theta) + \right.$$

$$\left. S_{\perp} (1-y) \sum_q e_q^2 \frac{|\mathbf{p}_1 - \mathbf{p}_2|}{2M_{hh}} \sin \theta \sin \phi_{RS} h_1^q(x) H_{1,q}^{\triangleleft}(z, M_{hh}^2, \cos \theta) \right)$$

$$A_{UT}^{\sin \phi_{RS}} = \frac{|\mathbf{p}_1 - \mathbf{p}_2|}{2M_{hh}} \frac{\sum_q e_q^2 h_1^q(x) H_{1,q}^{\triangleleft}(z, M_{hh}^2, \cos \theta)}{\sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{hh}^2, \cos \theta)}$$

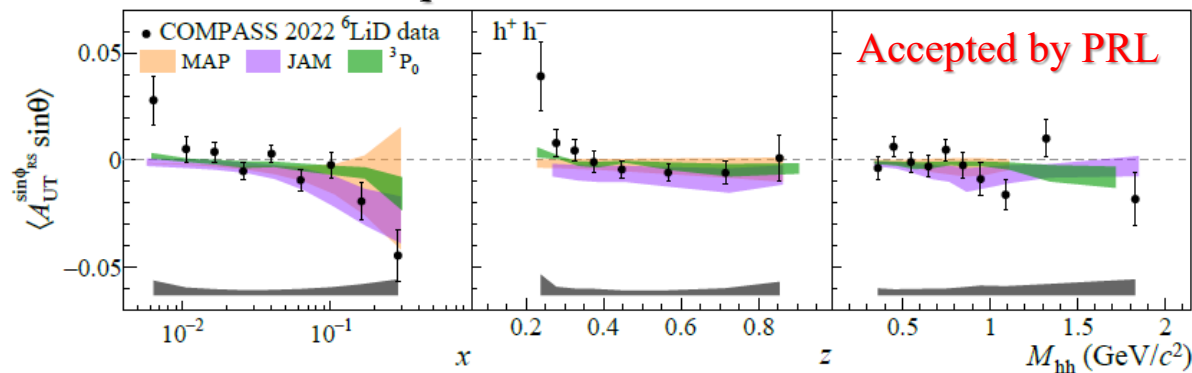


COMPASS 2022 run – highly successful data-taking!

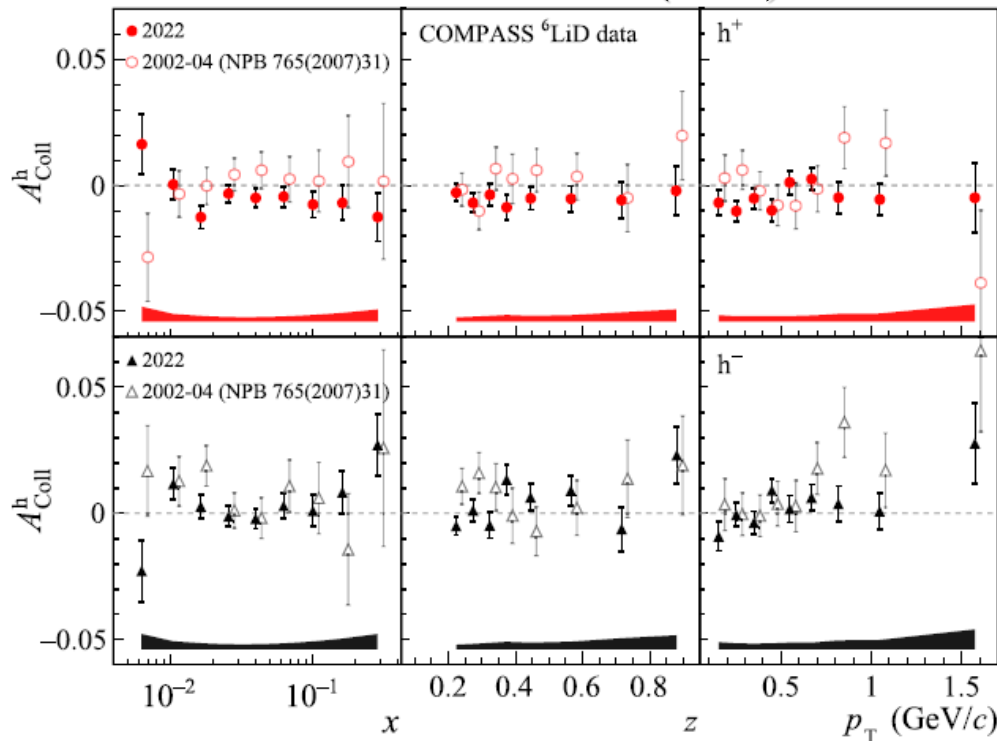
- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades
- **New results – dihadron Collins-like asymmetries**
- Access to collinear transversity PDF; Non-zero trend at large x
- Precision comparable with proton results

COMPASS data: access to collinear and TMD transversity

COMPASS hep-ex/2512.22311

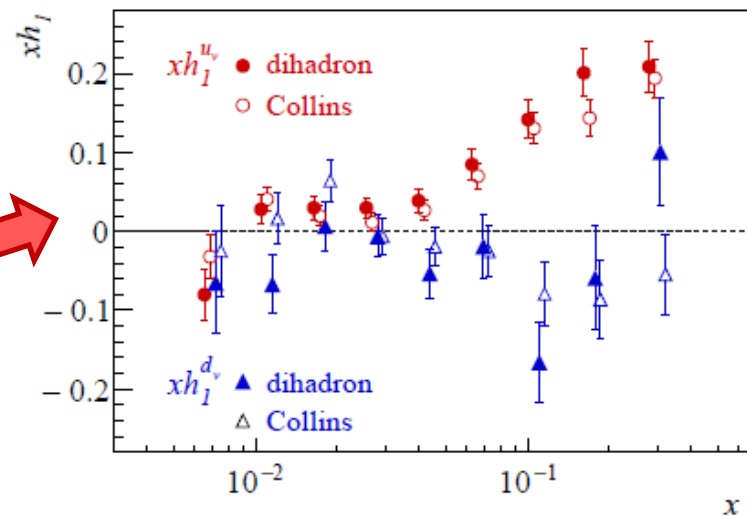


COMPASS PRL 133 (2024) 101903



Accepted by PRL

COMPASS hep-ex/2512.22311



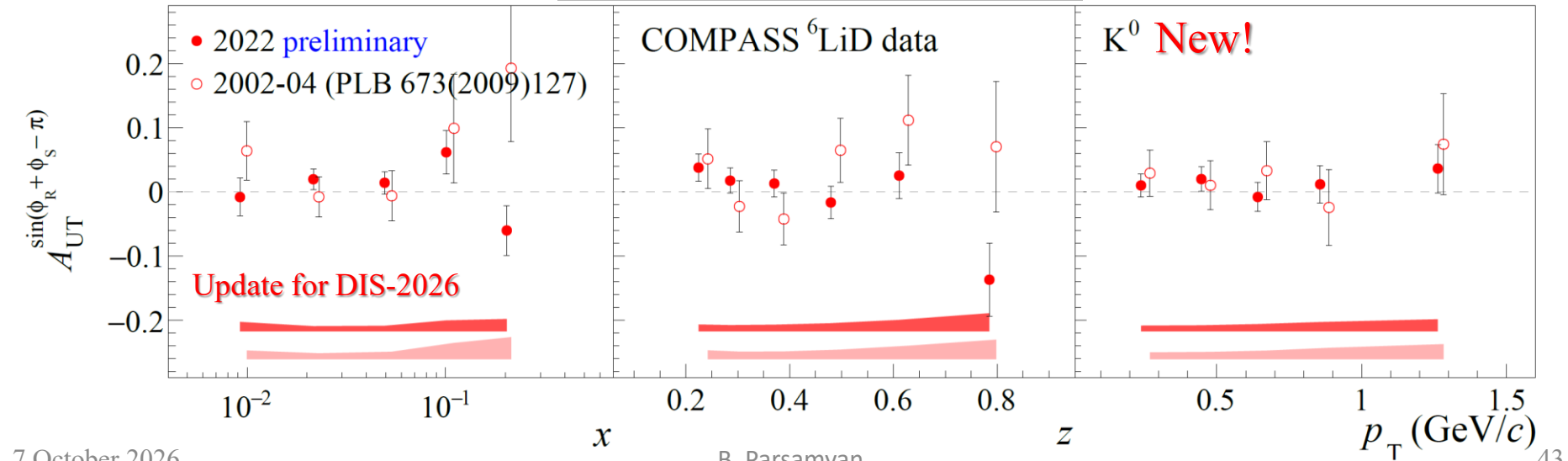
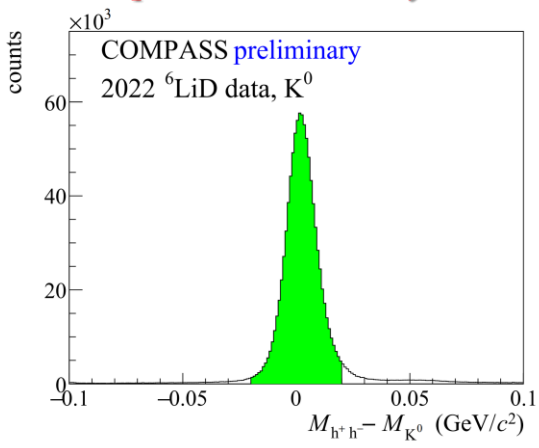
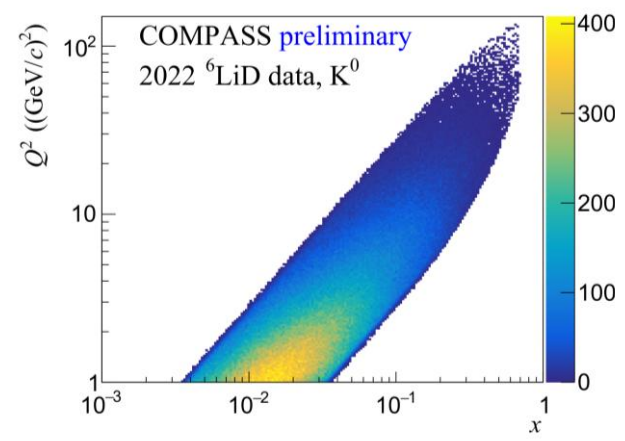
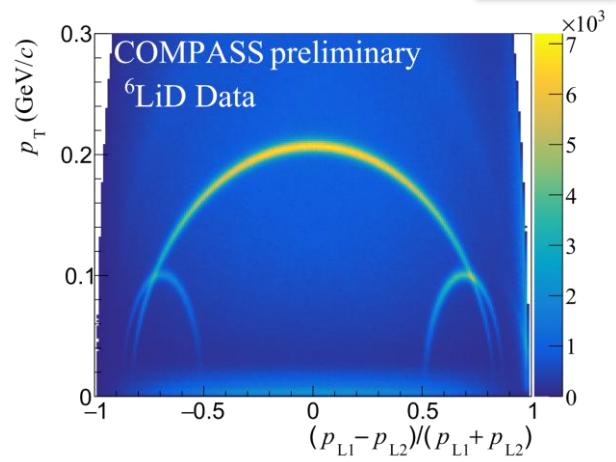
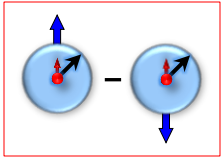
SIDIS TSAs: Collins effect for K^0

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

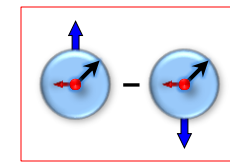
$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot p_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$



- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of $\sim 2-3$)
- **New deuteron data crucial to constrain d -quark transversity**



SIDIS TSAs: Kotzinian-Mulders asymmetry



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + \lambda S_T \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + \dots \right\}$$

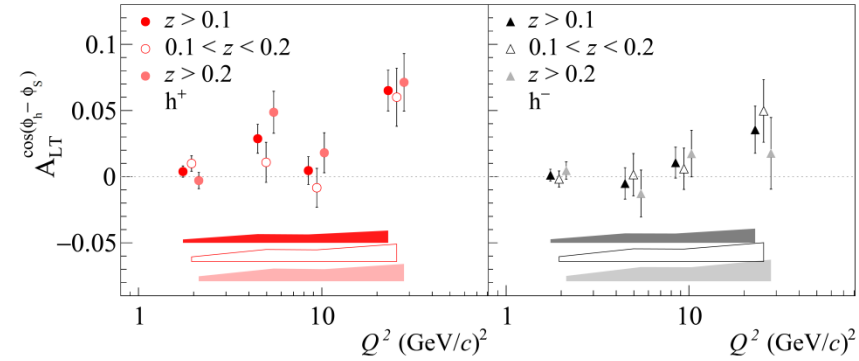
$$F_{LT}^{\cos(\phi_h - \phi_S)} = C \left[\frac{\hat{h} \cdot \mathbf{k}_T}{M} g_{1T}^q D_{1q}^h \right]$$



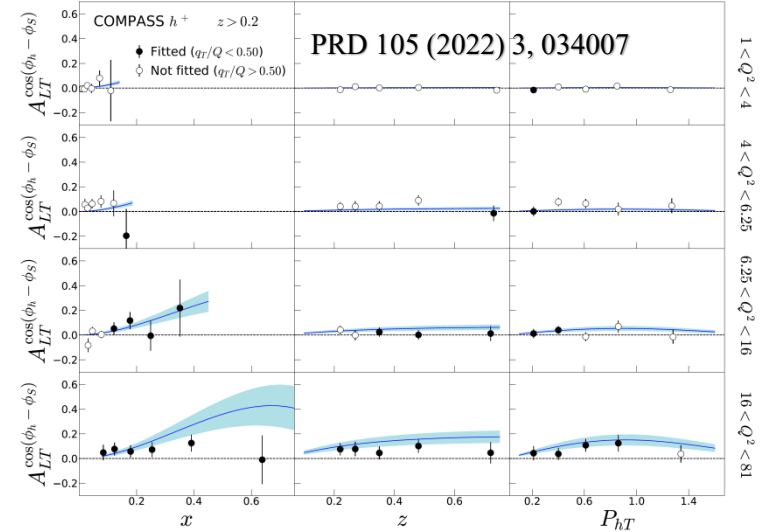
COMPASS/HERMES/CLAS6 results

$$A_{LT}^{\cos(\phi_h - \phi_S)}$$

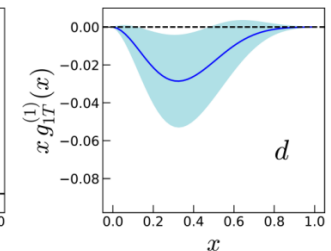
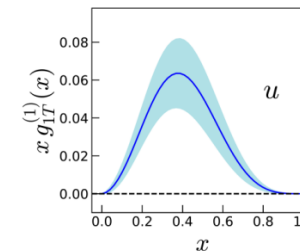
- Only “twist-2” ingredients
- **Sizable non-zero effect for h^+ !**
- **Similar effect at HERMES**



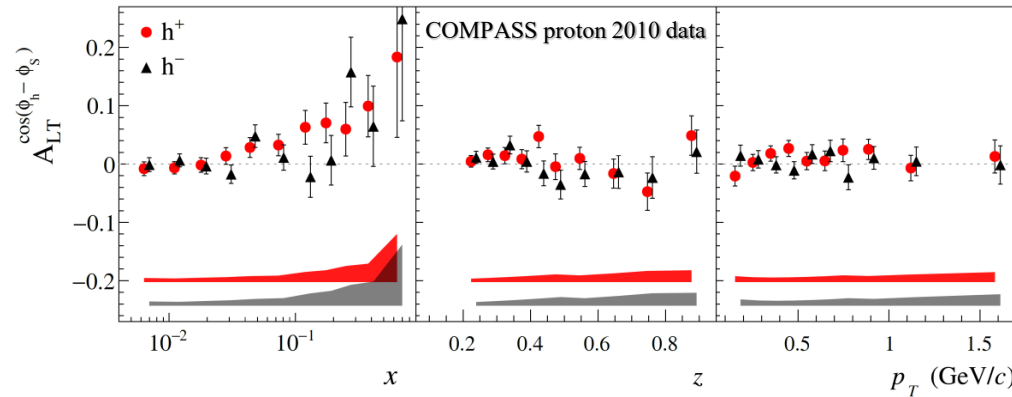
First global QCD analysis of the g_{1T} TMD PDF using SIDIS data



$1 < Q^2 < 4$
 $4 < Q^2 < 6.25$
 $6.25 < Q^2 < 16$
 $16 < Q^2 < 81$

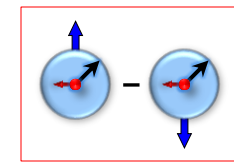


COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



See also, PRD 107, (2023) 034016 – global fit by:
M. Horstmann, A. Schafer and A. Vladimirov

SIDIS TSAs: Kotzinian-Mulders asymmetry



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + \lambda S_T \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + \dots \right\}$$

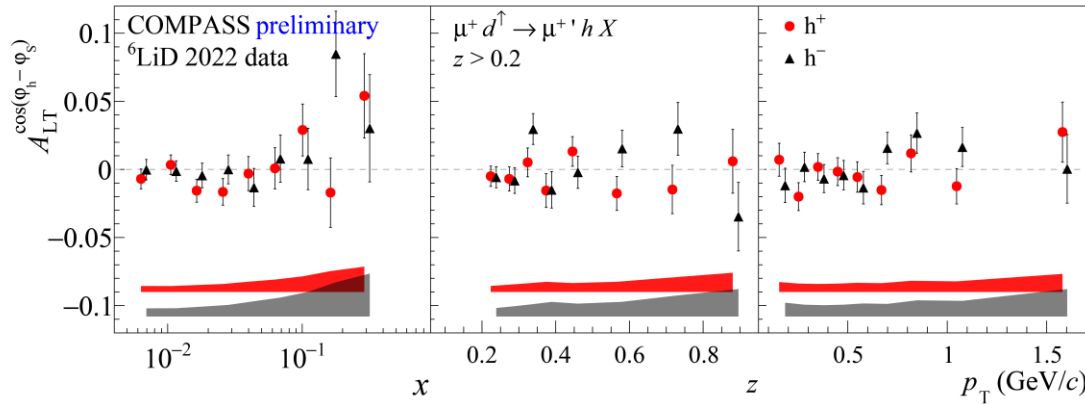
$$F_{LT}^{\cos(\phi_h - \phi_S)} = C \left[\frac{\hat{h} \cdot k_T}{M} g_{1T}^q D_{1q}^h \right]$$



COMPASS/HERMES/CLAS6 results

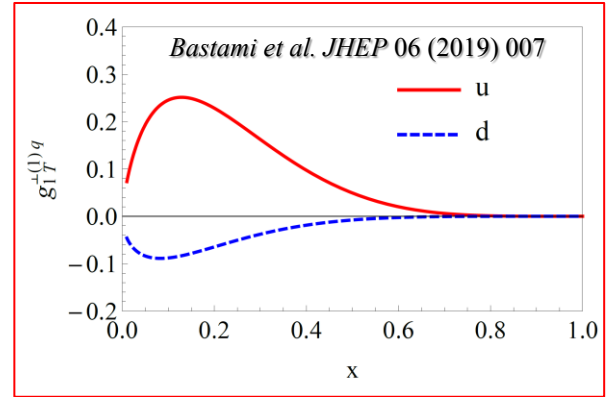
$$A_{LT}^{\cos(\phi_h - \phi_S)}$$

- Only “twist-2” ingredients
- **Sizable non-zero effect for h^+ !**
- **Similar effect at HERMES**

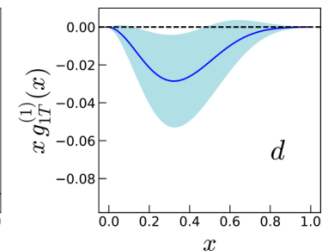
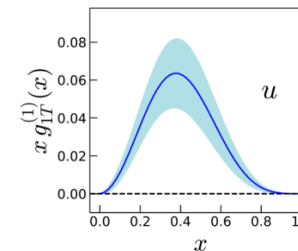
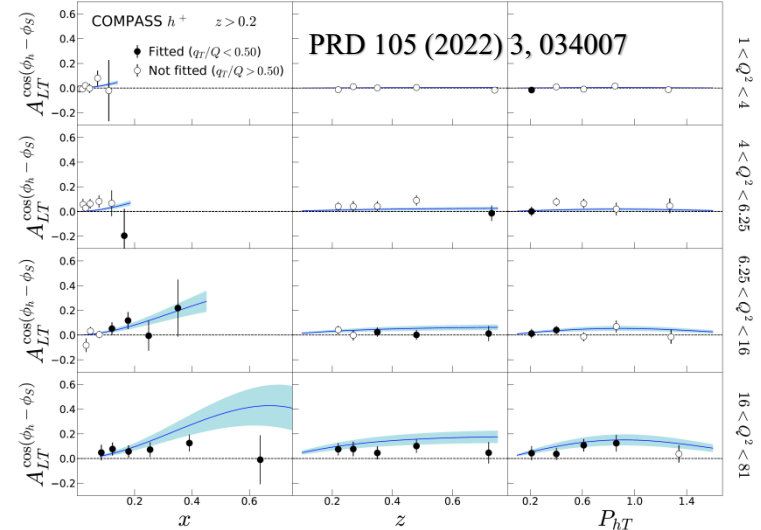


New COMPASS 2022 deuteron data

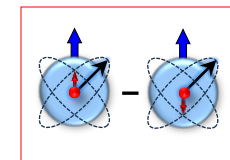
- The asymmetry is compatible with zero within the uncertainties
- Some hints for a non-zero signal at large x
- Potential signal is compatible with model expectations



First global QCD analysis of the g_{1T} TMD PDF using SIDIS data



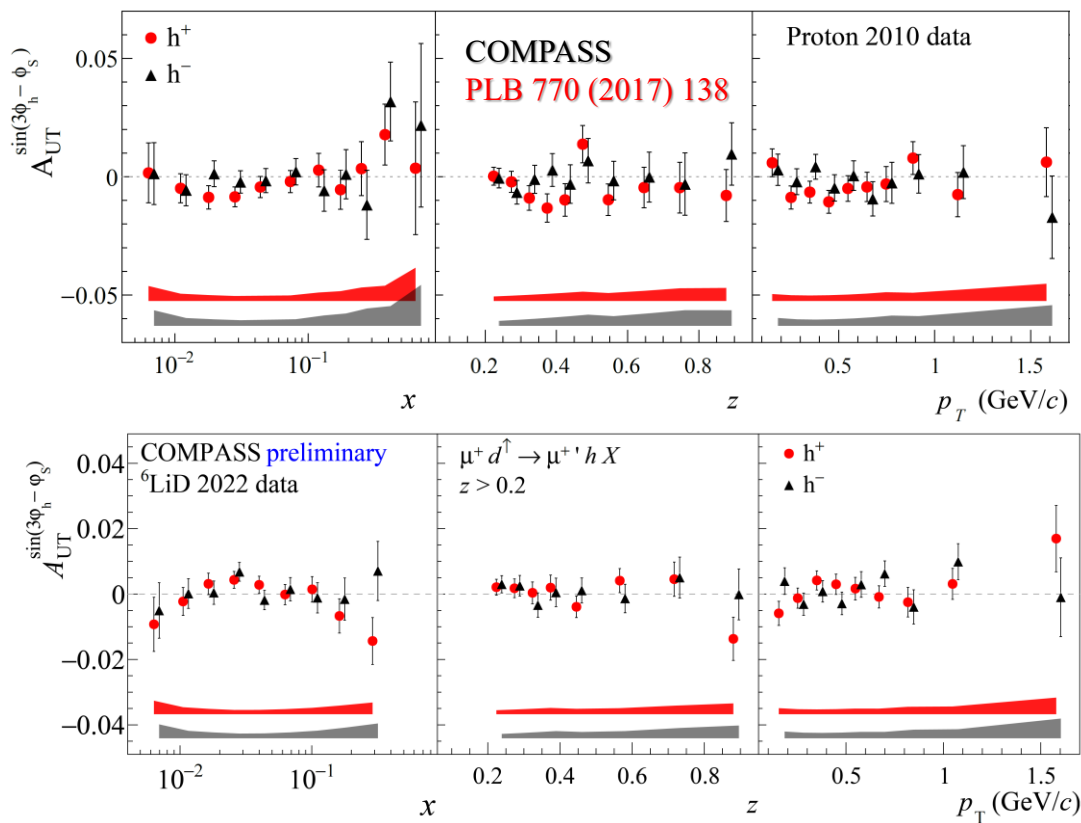
SIDIS TSAs: Pretzelosity TSA



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(3\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

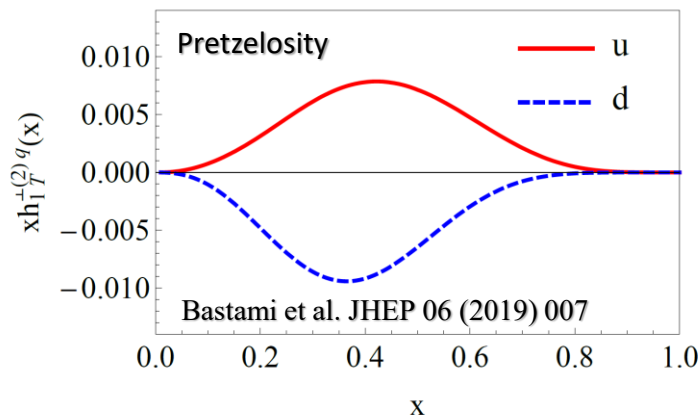
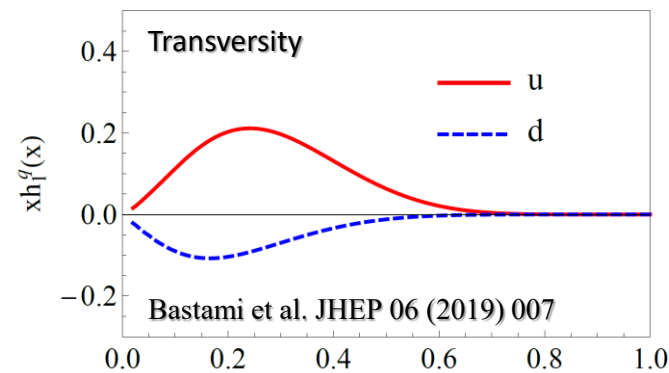
$$F_{UT}^{\sin(3\phi_h - \phi_S)} = C \left[\frac{2(\hat{h} \cdot k_T)(k_T \cdot p_T) + k_T^2(\hat{h} \cdot p_T) - 4(\hat{h} \cdot k_T)^2(\hat{h} \cdot p_T)}{2M^2 M_h} h_{1T}^{\perp q} H_{1q}^{\perp h} \right]$$

- Only “twist-2” ingredients
- p_T^2 -suppressed compared to Siverts and Collins
- The PDF is expected to be small
- Small, compatible with zero asymmetry



COMPASS/HERMES results with proton target

- Proton asymmetry is small (below 1-2 %)
- TSA is compatible with zero for both h^+ and h^-
- The measurements are compatible with models



SIDIS TSAs: subleading twist effects

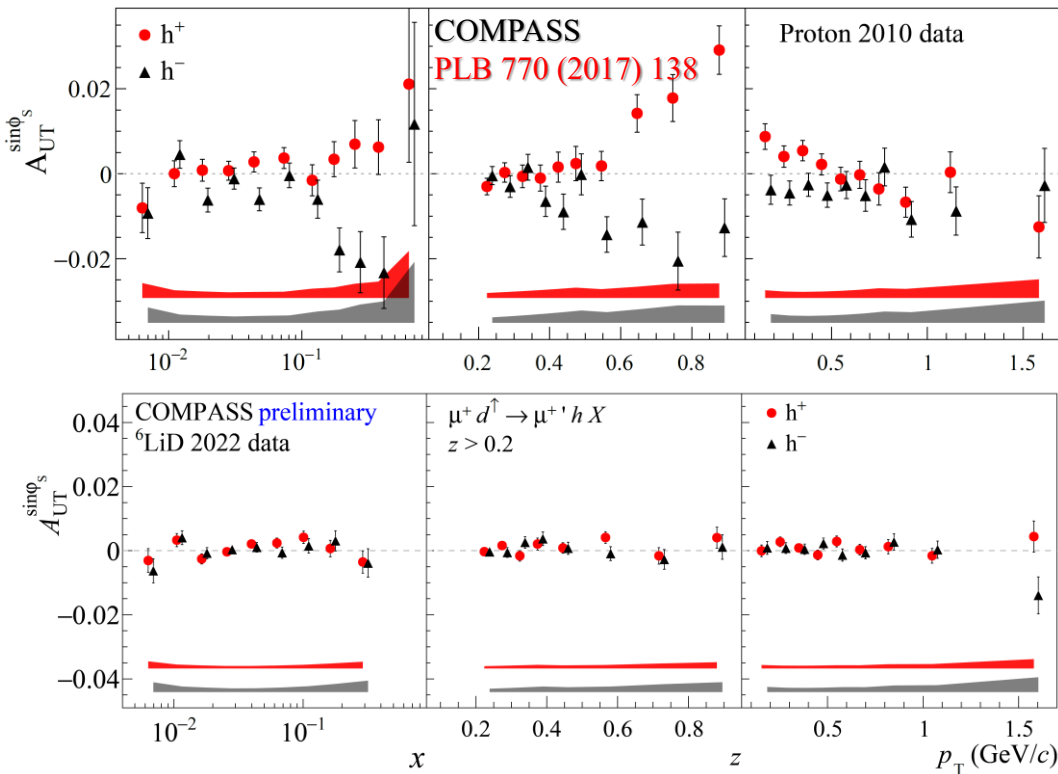
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \sqrt{2\varepsilon(1-\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \dots \right\}$$

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C \left\{ \left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) - \frac{\mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) \right] \right\}$$

- Complex SF, various “twist-2” and “twist-3” ingredients,
 Q^{-1} and other suppressions
- Expected to be zero in WW approximation

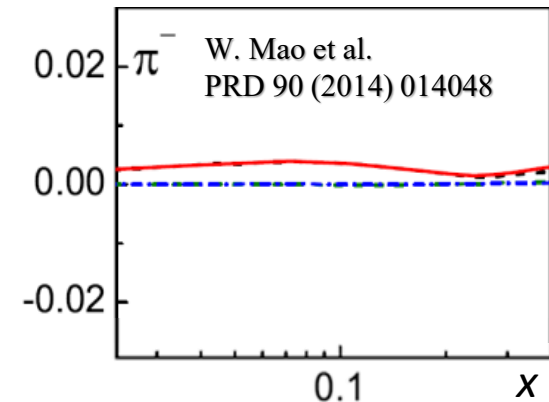
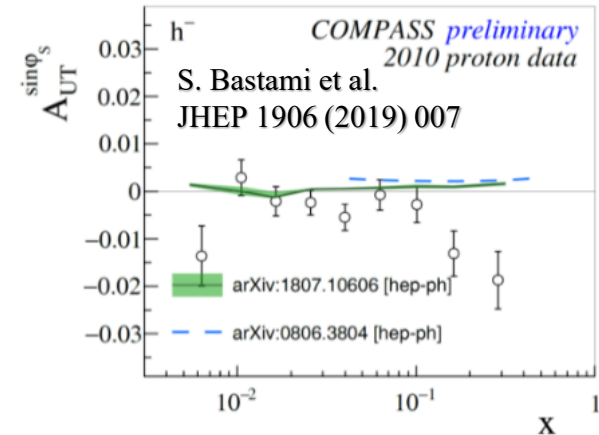
COMPASS/HERMES results with proton target

- Small TSA; signal at large z for both h^+ and h^-
 - Can large- z signal be induced by DVMs?

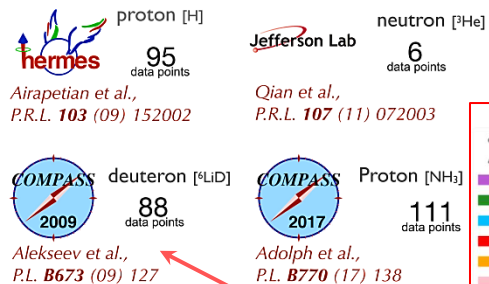


New COMPASS 2022 deuteron data

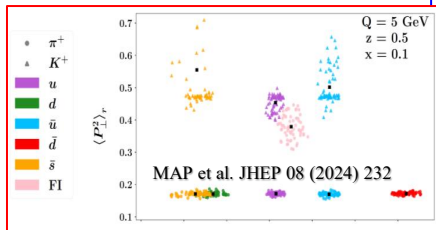
- The asymmetry is compatible with zero within the uncertainties
- The measured amplitudes are below 1%



COMPASS 2022 run: new unique deuteron data



Pavia group fits



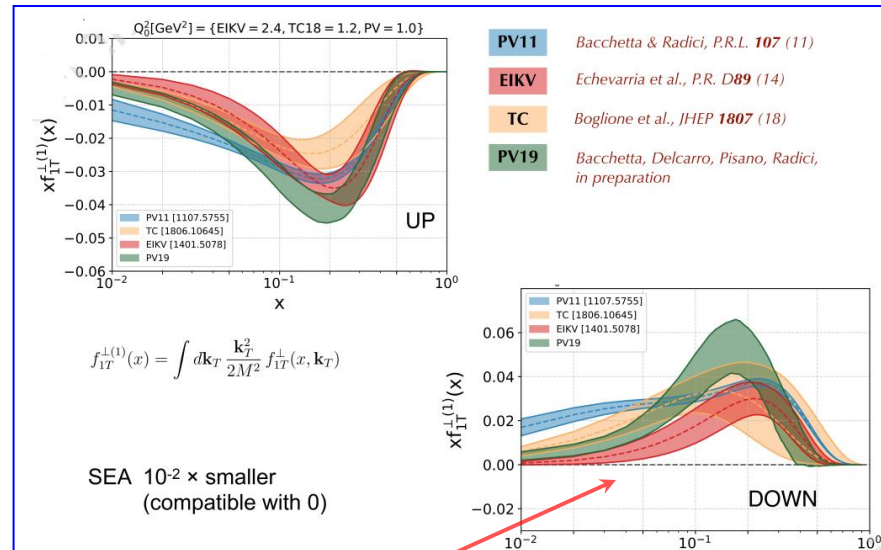
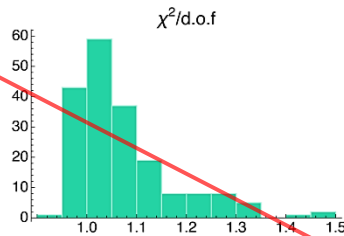
Same **kinematic cuts** applied to unpolarized

~~x, z, P_{HT} data projections~~

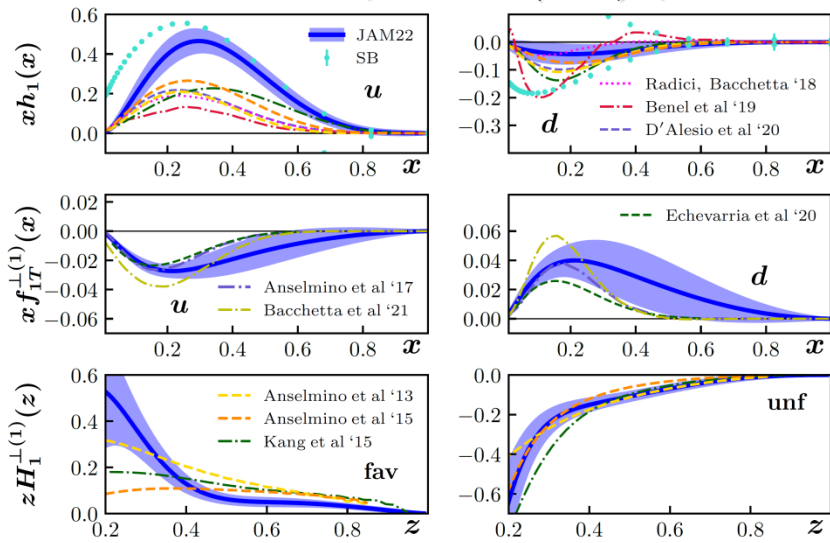
$$Q^2 \geq 1.4 \text{ GeV}^2 \quad 0.2 \leq z \leq 0.7$$

$$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5 \text{ GeV}$$

300 data points $\rightarrow$ **118** data fitted
14 free parameters
 $\chi^2/\text{d.o.f.} = \mathbf{1.06 \pm 0.10}$

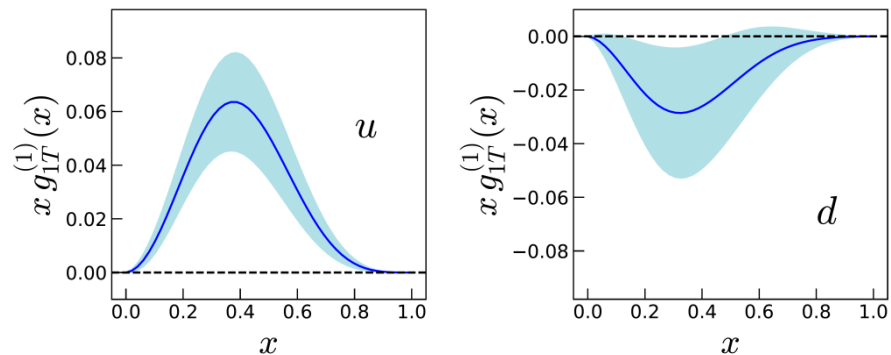


JAM Collaboration, PRD 106 (2022) 3, 034014



COMPASS 2022 deuteron run

S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D. Pitonyak
PRD 105 (2022) 3, 034007



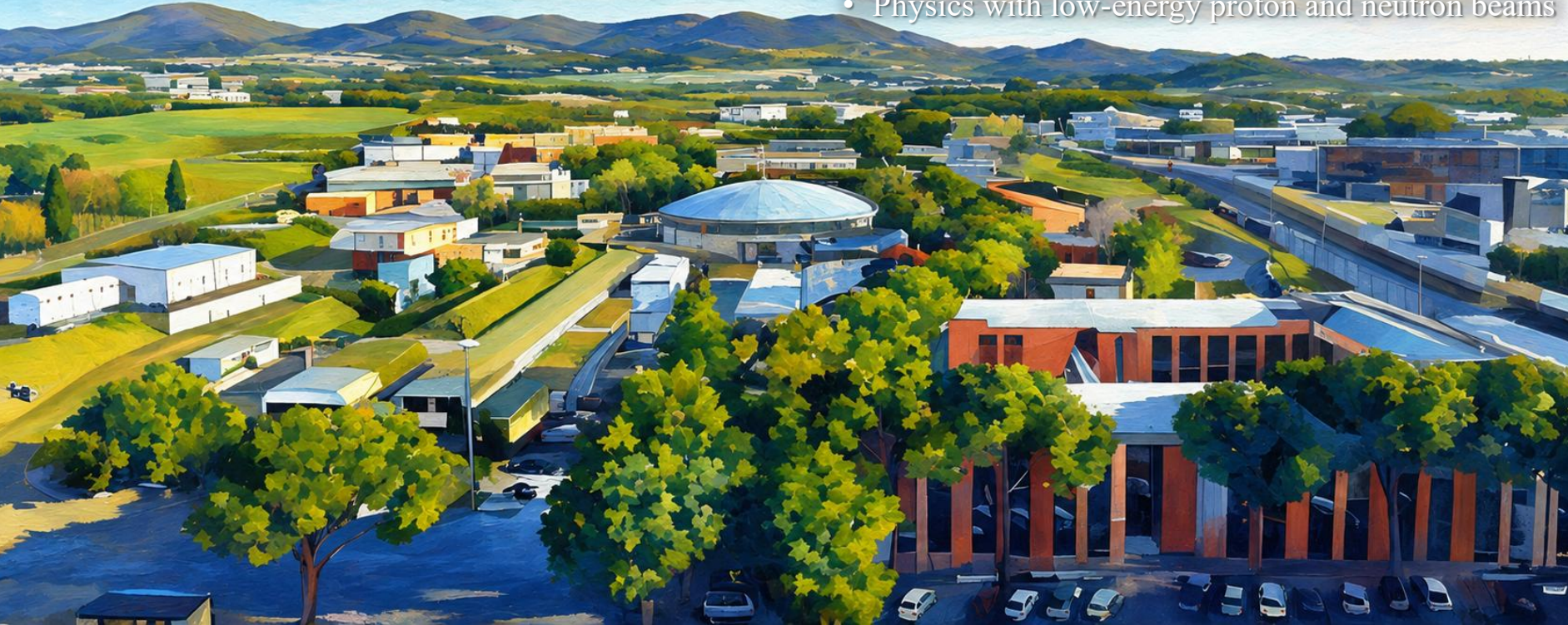
Conclusions

- **COMPASS – one of CERN's longest-running fixed-target experiments**
 - Around 20 years of data taking
 - A rich physics programme covering spectroscopy, (SI)DIS, Drell-Yan, DVCS and HEMP
 - Petabytes of data remain available for analysis
- **Broad and distinctive kinematic coverage**
 - Access to low x and relatively large Q^2
 - A kinematic domain that is expected to remain highly competitive for at least the next decade
 - The highly successful 2022 deuteron SIDIS run is yielding many new and distinctive results
- **Strong complementarity with the JLab high-luminosity programme**
 - COMPASS provides a broad set of measurements in a complementary kinematic regime
 - Growing interest in knowledge transfer, joint analyses and collaborative initiatives
 - Increasing number of joint workshops and task-force activities
- **Since 2023, COMPASS has entered its Analysis Phase**
 - Four new groups have joined during this phase
 - The COMPASS spectrometer has been transferred to the AMBER collaboration
- **AMBER has already started its experimental programme**
 - First data taken in 2023-2024 for antiproton production
 - 2025-2026: proton-radius measurement pilot programme
 - Phase I foresees distinctive Drell-Yan measurements after LS3
- **A long-term AMBER physics programme is now being developed**
 - The Phase II proposal is currently being drafted
 - An EOI for a polarized Drell-Yan programme at AMBER is now also being prepared

Thank You!



- 3-D structure and QCD
- Extraction of 3-D parton distributions
- Partonic structure beyond simple densities
- Experimental efforts
- Confinement QCD and fundamental symmetries
- Software tools for nuclear-physics data analysis
- Physics with low-energy proton and neutron beams



Correlations in Partonic and Hadronic Interactions 2026

14–18 December 2026

Laboratori Nazionali di Frascati

<https://indico.cern.ch/e/CPHI2026>

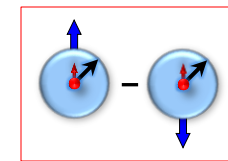
Workshop Organizers

Local Organizers: M. Mirazita (INFN LNF), P. Rossi (INFN LNF, JLab, [co-chair](#))

Organizing Committee: H. Avakian (JLab, [co-chair](#)), A. Bacchetta (Pavia U.), C. Flore (Cagliari U.), L. Gamberg (Penn State U.), B. Parsamyan (AANL, INFN, CERN, [co-chair](#)), A. Vossen (Duke U)

- Spare slides

SIDIS TSAs: Collins effect and Transversity



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

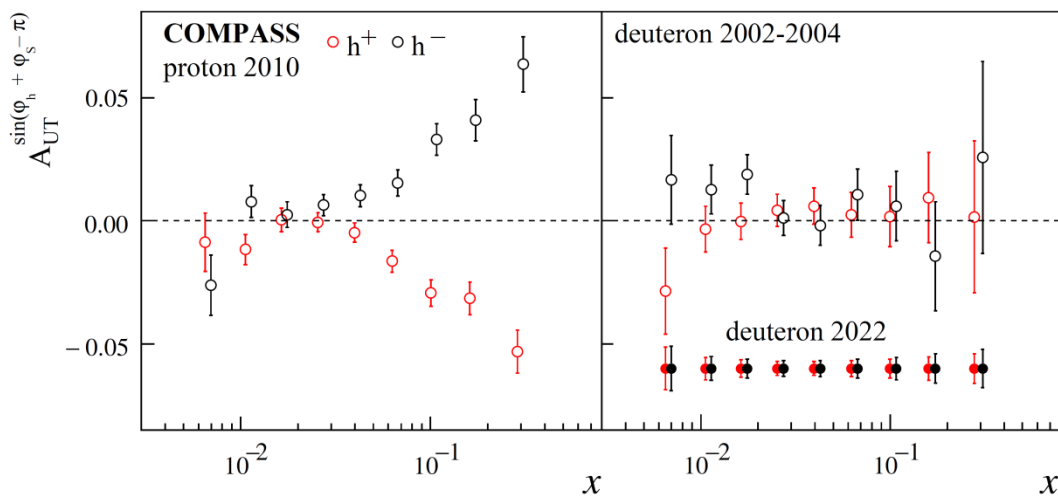
$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot p_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$



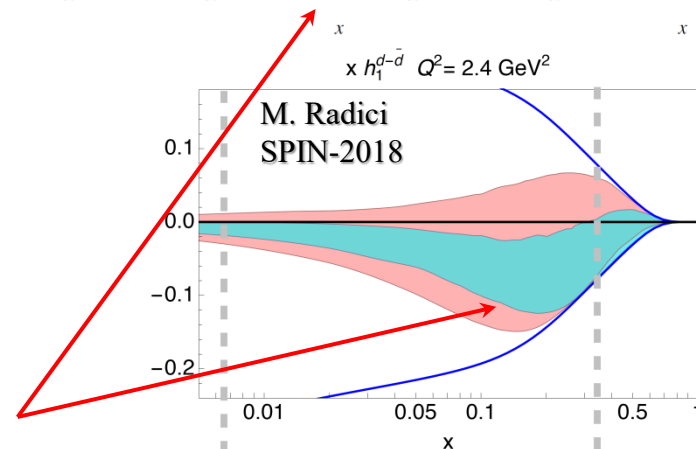
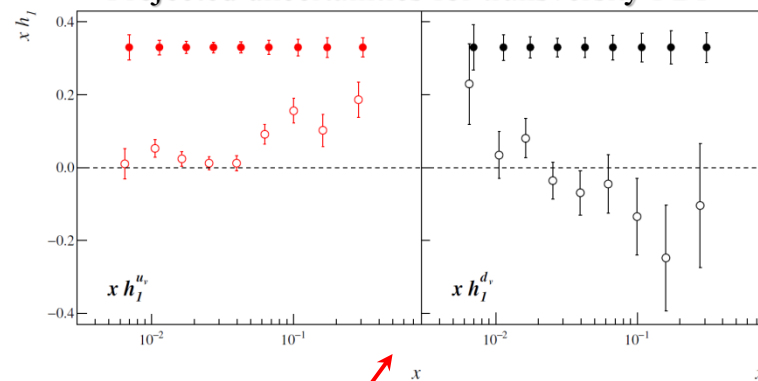
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of $\sim 2-3$)
- **New deuteron data crucial to constrain d -quark transversity**

[Addendum to the COMPASS-II Proposal]

Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF



COMPASS-II (2022)

- **2nd COMPASS deuteron measurements performed**
- **Crucial to constrain the transversity TMD PDF for the d -quark**

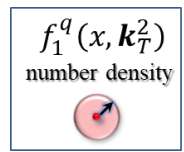
Cahn effect in SIDIS: DVMs

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xy Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x} \right) \right] (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\times \left(1 + \underbrace{\sqrt{2\varepsilon(1+\varepsilon)} A_{UU}^{\cos\phi_h}}_{\text{Cahn effect}} \cos\phi_h + \dots \right)$$



Cahn effect



As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

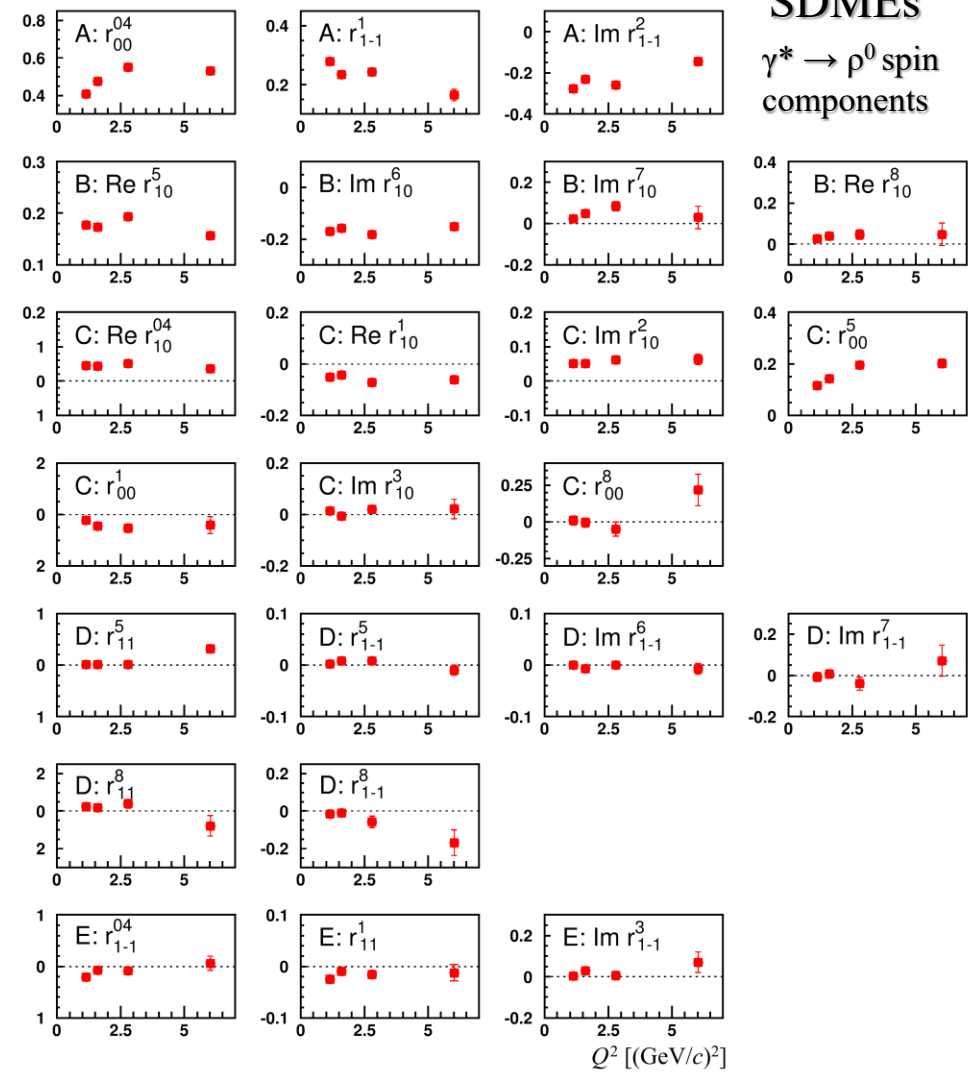
As of 2023 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
 - So far, no comprehensive interpretation
- A set of complex corrections:
 - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.

COMPASS, EPJC (2023) 83 924

SDMEs

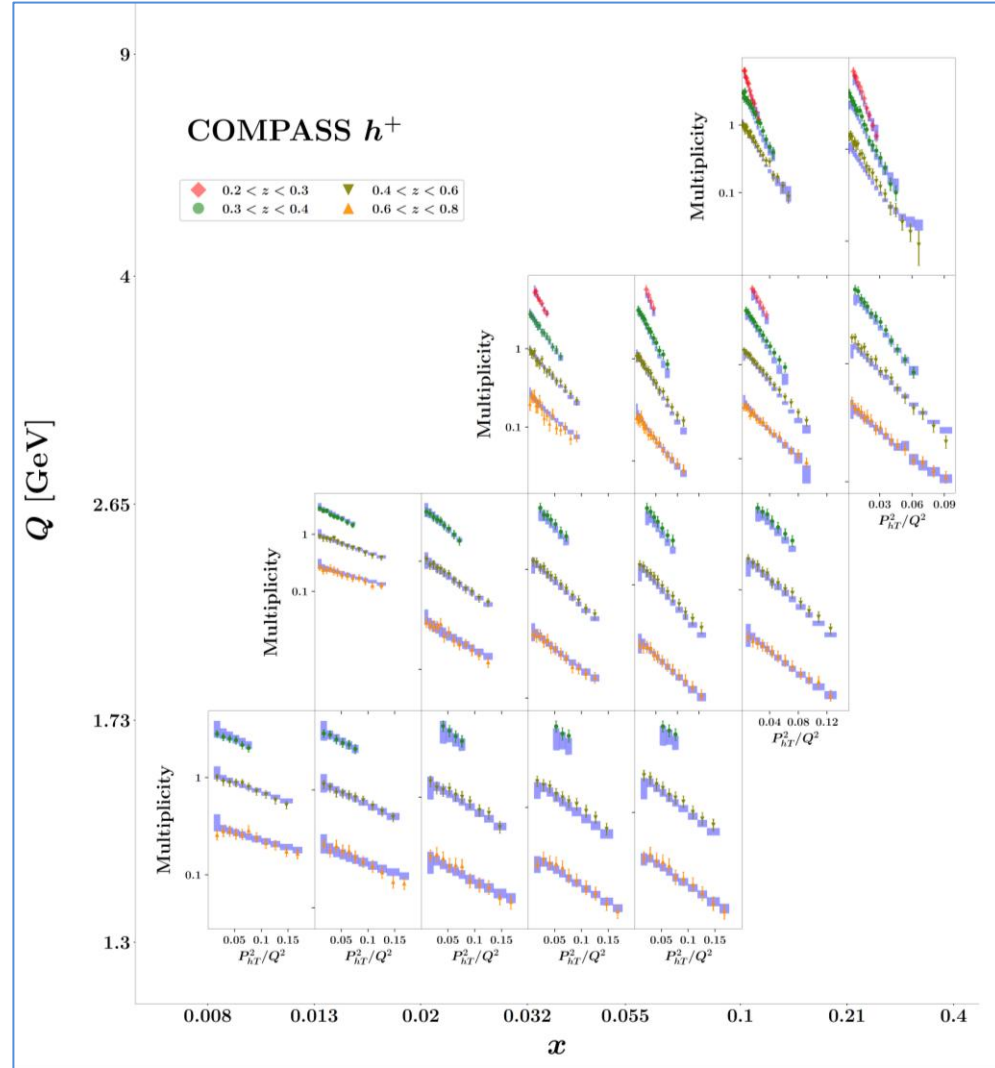
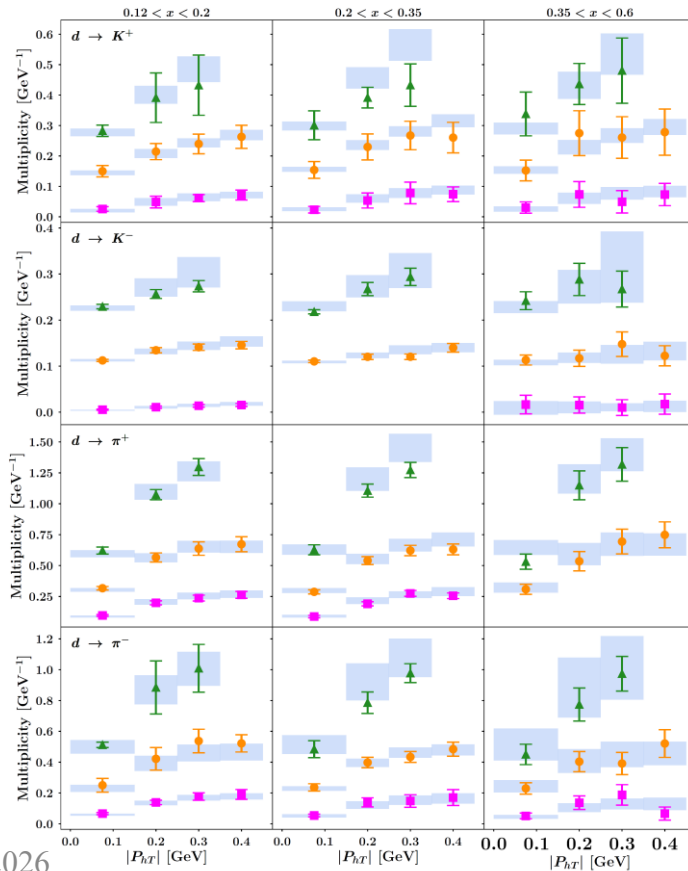
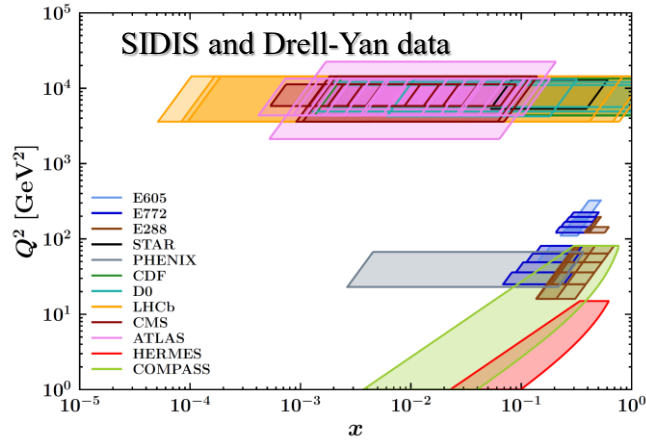
$\gamma^* \rightarrow \rho^0$ spin components



Kinematic dependences of SDMEs
Measured (1D), not yet implemented in HEPgen

Flavor dependence of unpolarized quarks: MAP global fit

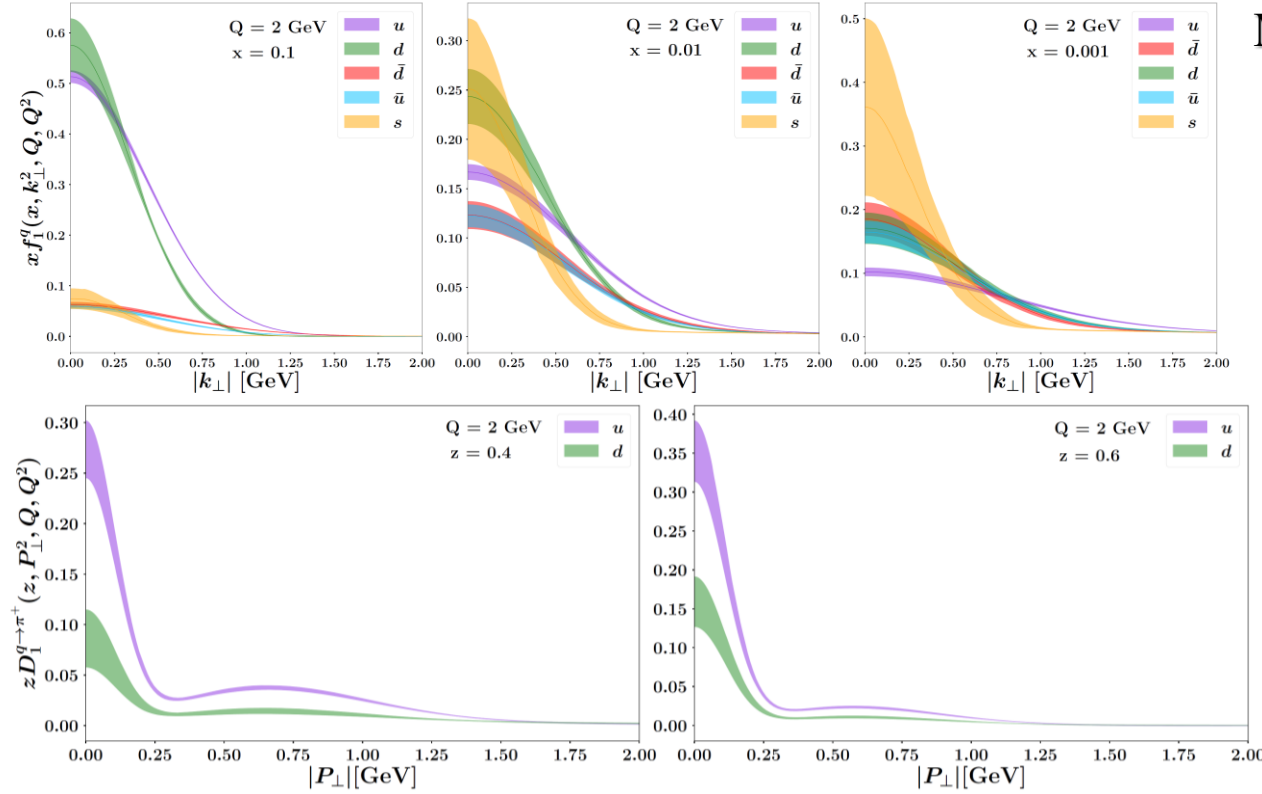
MAP et al. JHEP 08 (2024) 232



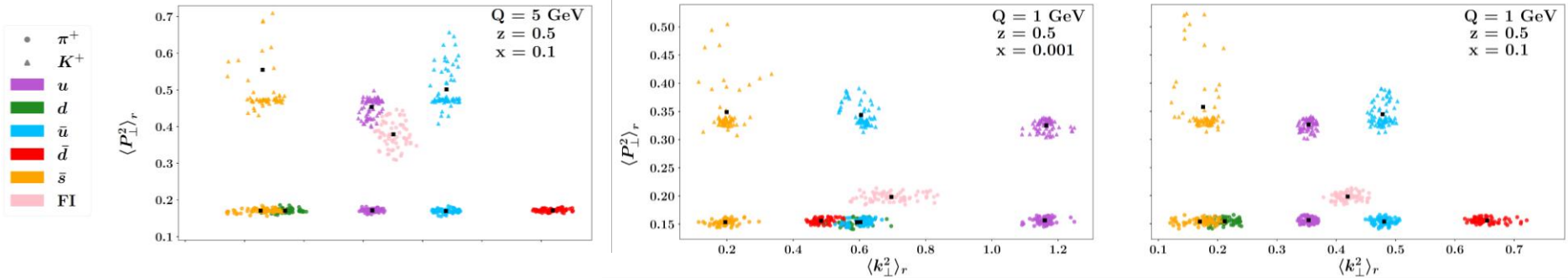
Simultaneous fit of large samples from different experiments

Flavor dependence of unpolarized quarks: MAP global fit

MAP et al. JHEP 08 (2024) 232

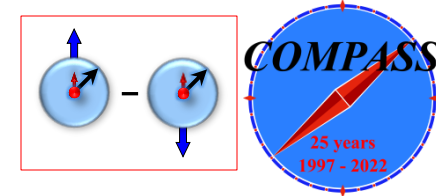


Data set	N ³ LL			
	N_{dat}	χ_D^2	χ_λ^2	χ_0^2
Tevatron total	71	1.10	0.07	1.17
LHCb total	21	3.56	0.96	4.52
ATLAS total	72	3.54	0.82	4.36
CMS total	78	0.38	0.05	0.43
PHENIX 200	2	2.76	1.04	3.80
STAR 510	7	1.12	0.26	1.38
<i>DY collider total</i>	251	1.37	0.28	1.65
E288 200 GeV	30	0.13	0.40	0.53
E288 300 GeV	39	0.16	0.26	0.42
E288 400 GeV	61	0.11	0.08	0.19
E772	53	0.88	0.20	1.08
E605	50	0.70	0.22	0.92
<i>DY fixed-target total</i>	233	0.63	0.31	0.94
<i>DY total</i>	484	1.02	0.29	1.31
HERMES total	344	0.81	0.24	1.05
COMPASS total	1203	0.67	0.27	0.94
<i>SIDIS total</i>	1547	0.70	0.26	0.96
Total	2031	0.81	0.27	1.08



Global TMD extraction: simultaneous fit of DY/Z/W and SIDIS data to determine unpolarized TMD PDFs $f_1^q(x, k_T^2)$ and TMD FFs $D_1^{q \rightarrow h}(z, P_\perp^2)$. The result provides flavor-, x - and z -dependent TMD distributions of partons and fragmentation.

SIDIS TSAs: Collins effect and Transversity



$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

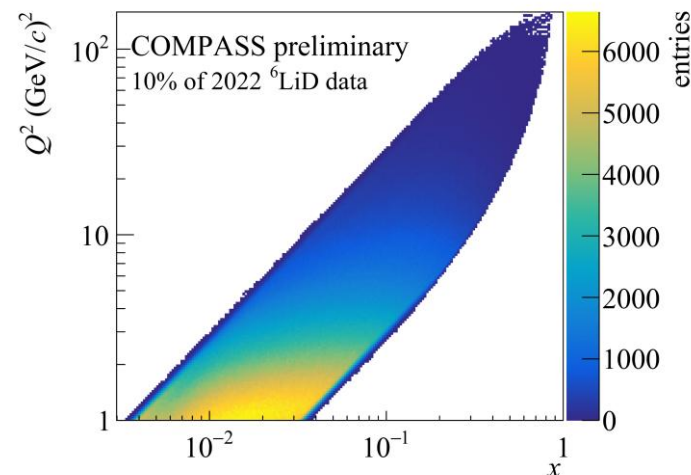
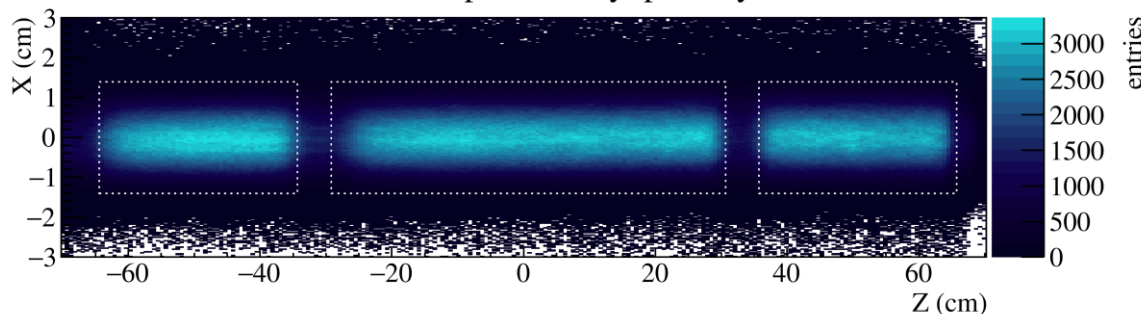
$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot p_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$



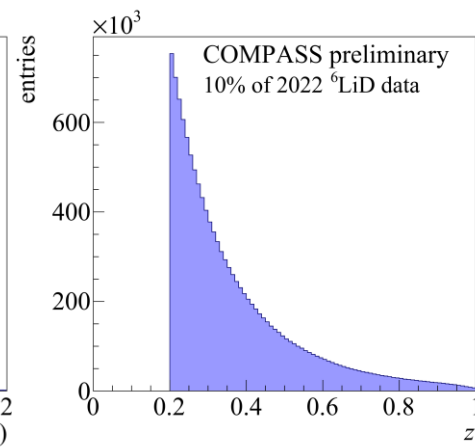
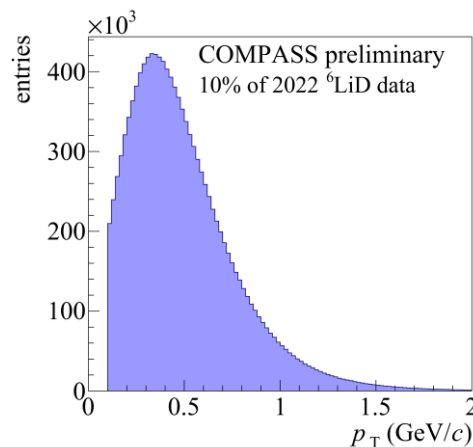
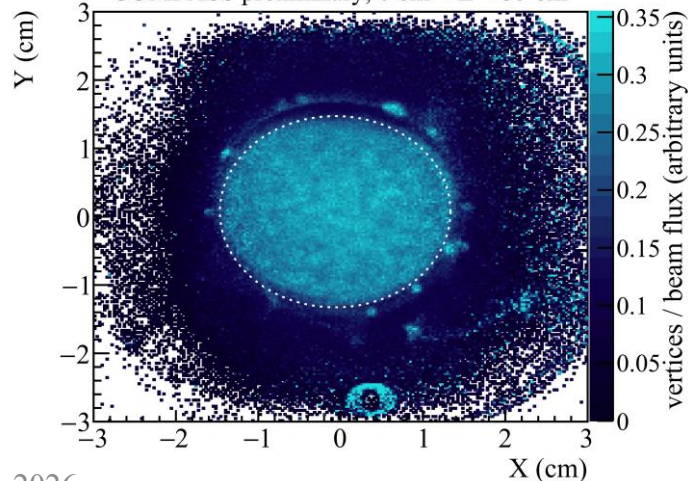
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of $\sim 2-3$)
- New deuteron data crucial to constrain d -quark transversity

Highly successful
Run in 2022!

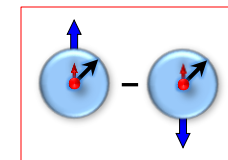
COMPASS preliminary, primary vertices



COMPASS preliminary, 0 cm < Z < 35 cm



SIDIS TSAs: Collins effect and Transversity



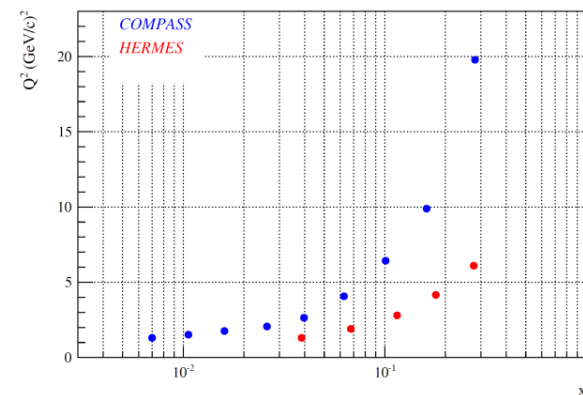
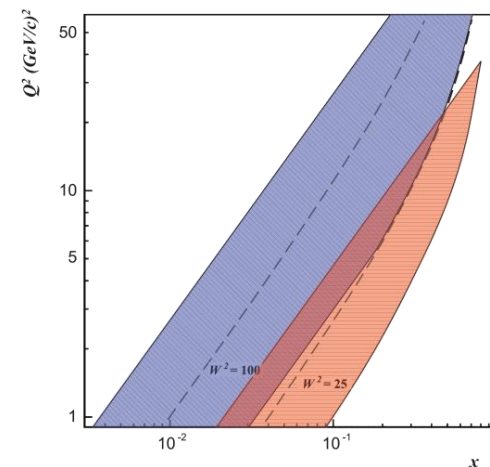
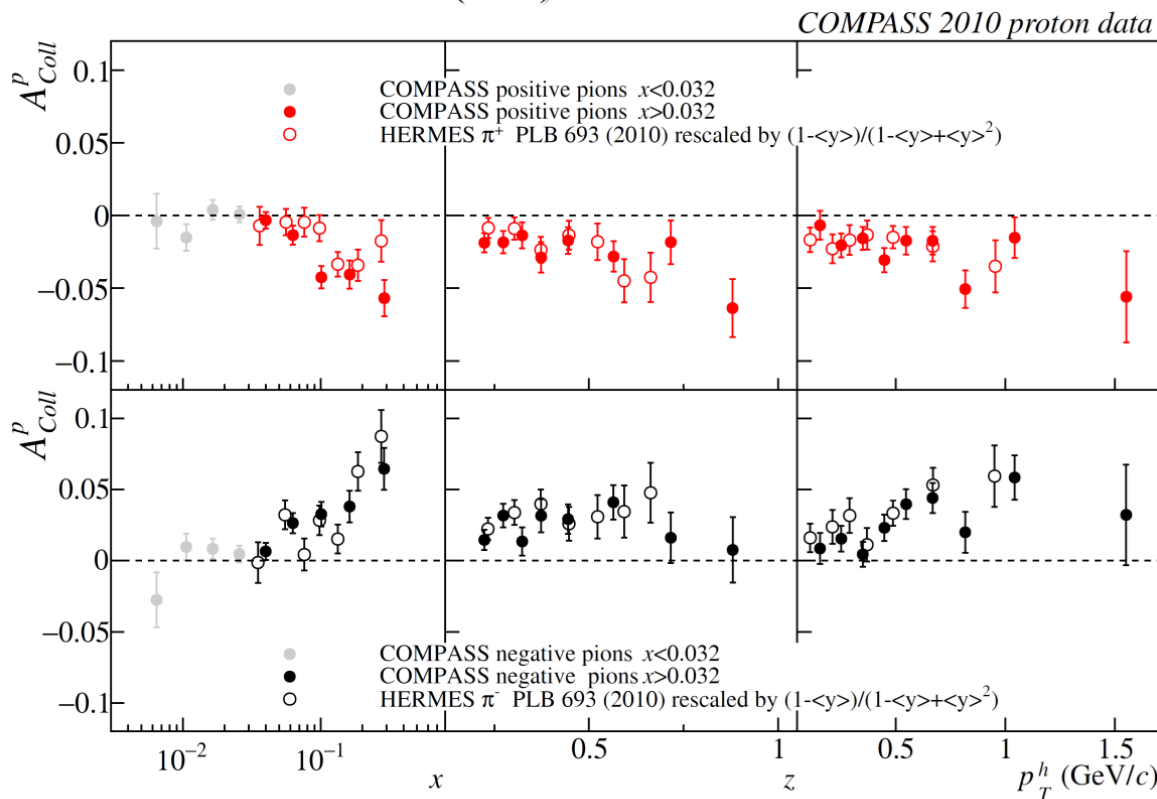
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot p_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$



- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of $\sim 2-3$)
- No impact from Q^2 -evolution? Clear signal at STAR energies

COMPASS PLB 744 (2015) 250



SIDIS Siverts TSA in COMPASS Drell-Yan Q²-ranges

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L} \right) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h \right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$



- COMPASS-HERMES discrepancy
- Q²-evolution effect?

1st COMPASS multi-D fit done for all eight TSAs

