Mapping the Transverse Structure of the Nucleon at CERN: Recent COMPASS Results and Beyond

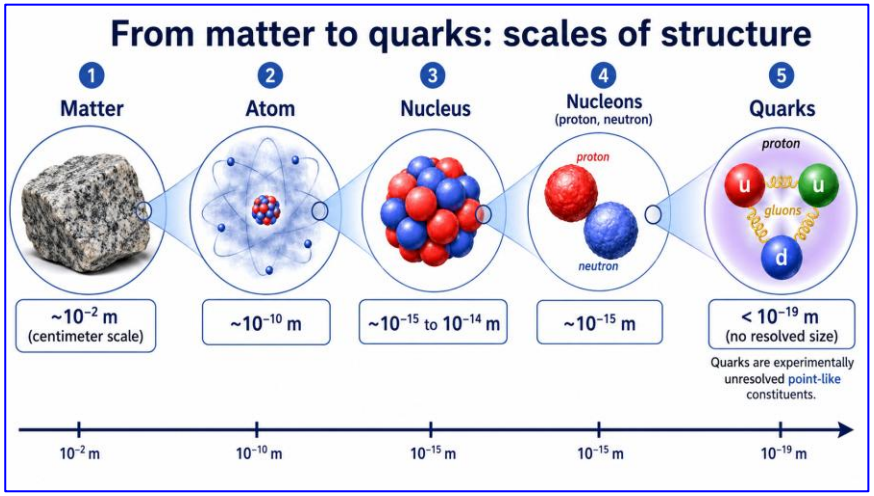
Bakur Parsamyan

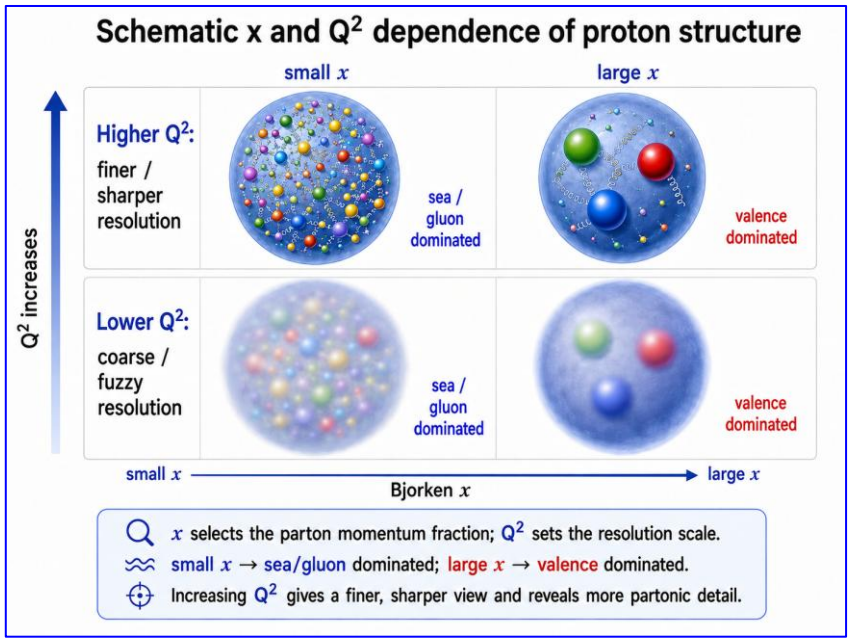
AANL (Yerevan), CERN,
INFN (Torino) and Yamagata University



PacificSPIN 2026 - The 13th Circum-Pan-Pacific Symposium on High Energy Spin Physics
October 27 - 30, 2026, Institute of Physics, Academia Sinica, Taipei

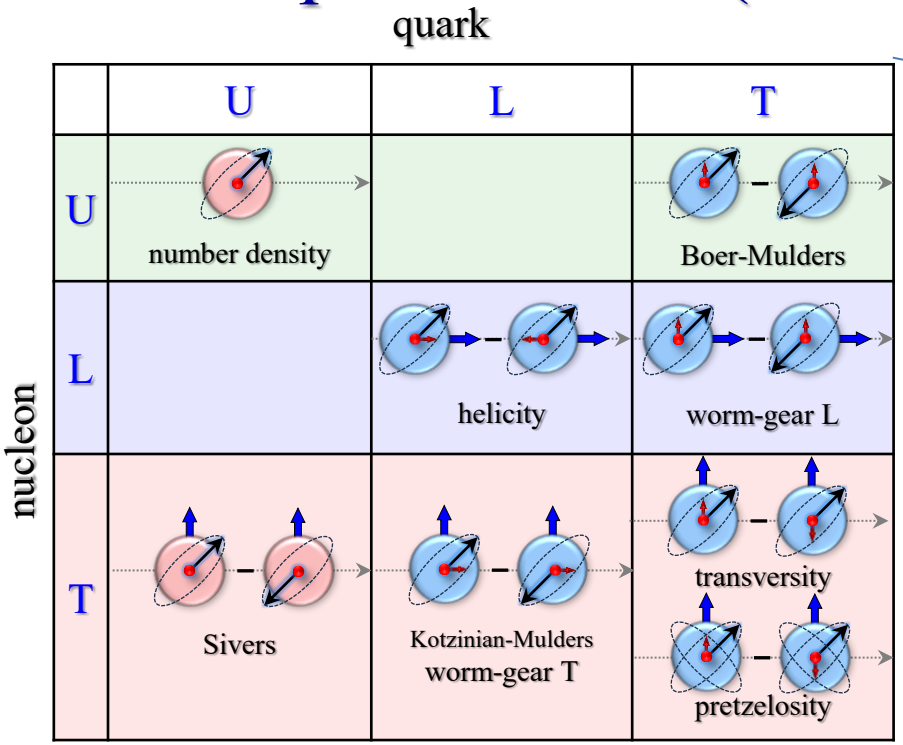
The beginning - scattering experiments in early XXth century







Nucleon spin structure (twist-2): TMDs



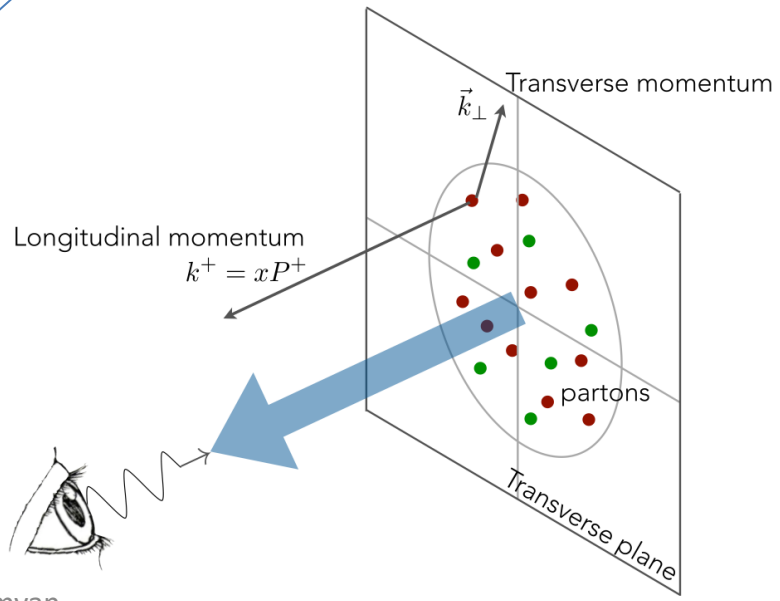
quark

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

- 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

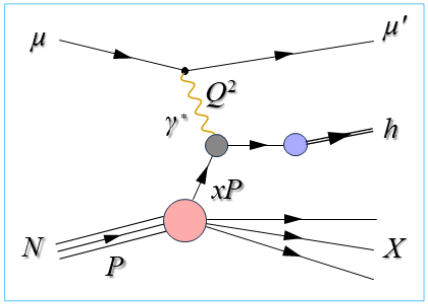
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$

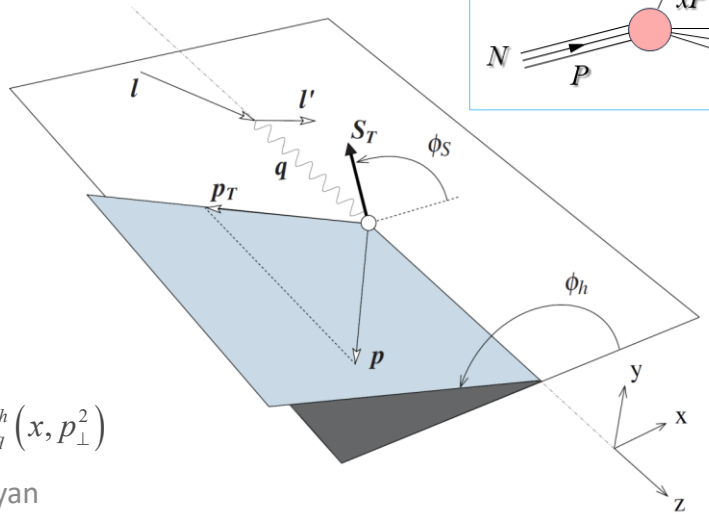
$$\times \Big\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} + S_T \Big[A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \Big] + S_T \lambda \Big[\sqrt{(1-\varepsilon^2)}\, A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \Big] \Big\}$$

quark

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

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





$$\otimes \equiv \mathbb{C}[wfD] = x\sum_q e_q^2 \int d^2\boldsymbol{k}_T d^2\boldsymbol{p}_\perp \delta^{(2)}\left(z\boldsymbol{k}_T + \boldsymbol{p}_\perp - \boldsymbol{P}_h\right) w(\boldsymbol{k}_T, \boldsymbol{p}_\perp) f^q\left(x, k_T^2\right) D_q^h\left(x, p_\perp^2\right)$$

Single-polarized Drell-Yan x-section and twist-2 TMDs

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{\left[\sin^2\theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{\left[\sin^2\theta_{CS}\right]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin\left(2\varphi_{CS}+\varphi_S\right) \end{array} \right) \end{array} \right] \end{array} \right\}$$

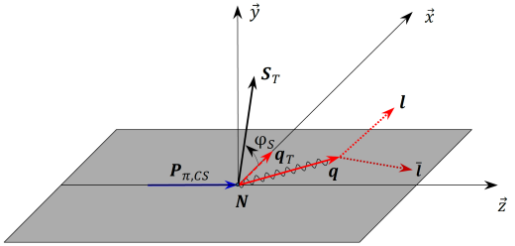
where $D_{\left[\sin^2\theta_{CS}\right]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

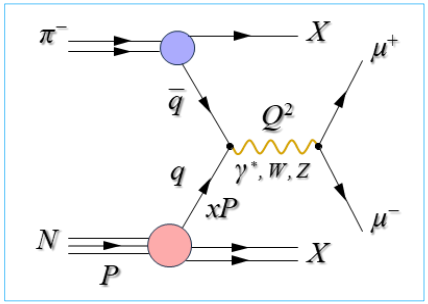
nucleon \ quark	U	L	T
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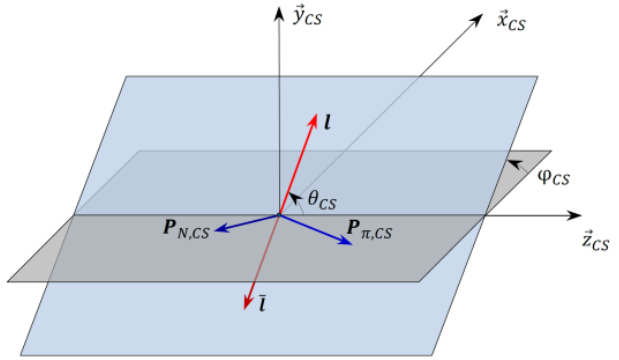
$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$	Boer-Mulders (T-odd)
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	Sivers (T-odd)
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$	Transversity
$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$	Pretzelosity

SIDIS ↔ Drell-Yan sign-change of the T-odd TMD PDFs

Fundamental quest: COMPASS, STAR, SpinQuest, LHCspin, etc.

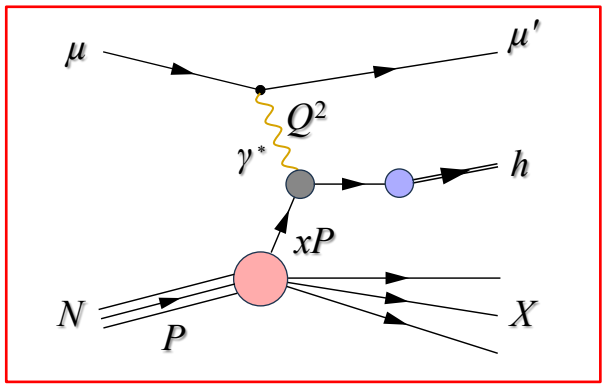






Polarized SIDIS and DY – factorization and kinematic regions

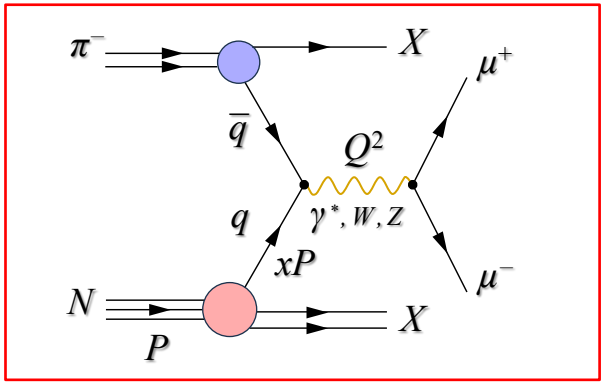
Semi-inclusive DIS



T-odd TMD PDFs

sign change

Drell-Yan process



High q_T – Collinear factorization
Low q_T – TMD factorization

$q_T \geq Q$

Current fragmentation
Collinear factorization

High x_F – Current fragmentation
Low x_F – Target fragmentation

Target fragmentation
TMD factorization
Fracture Functions

Soft region

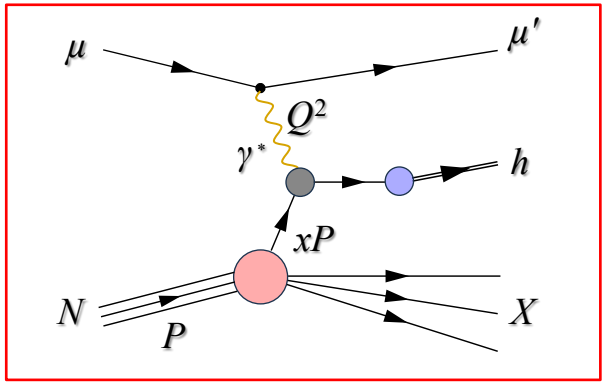
Current fragmentation
TMD factorization
PDFs, FFs

$q_T << Q$

x_F

Main TMD tools - universality and synergies

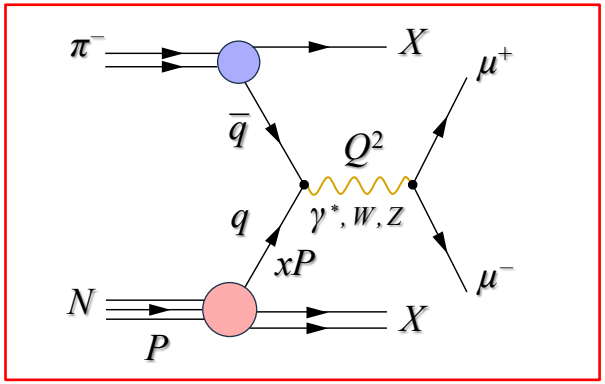
Semi-inclusive DIS



T-odd TMD PDFs

sign change

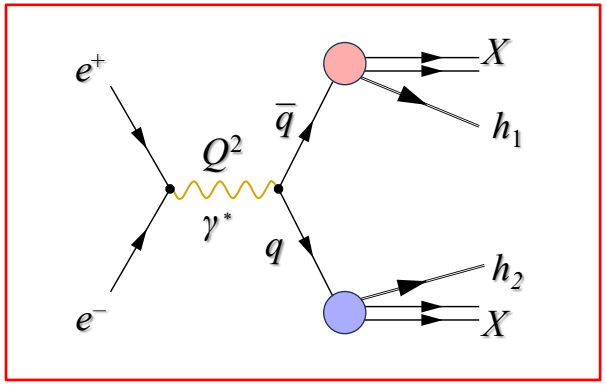
Drell-Yan process



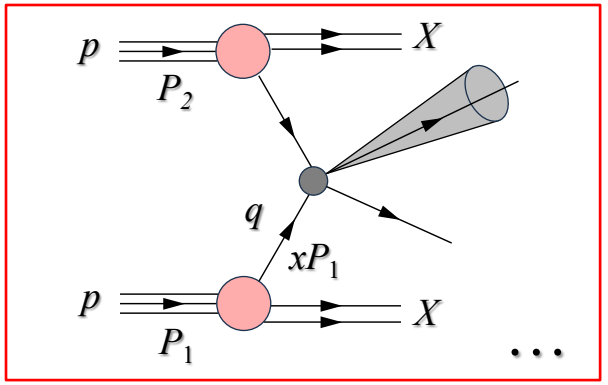
Fragmentation Functions

Parton Distribution Functions

Electron-positron annihilation



pp, pA-scattering, jet production, etc.

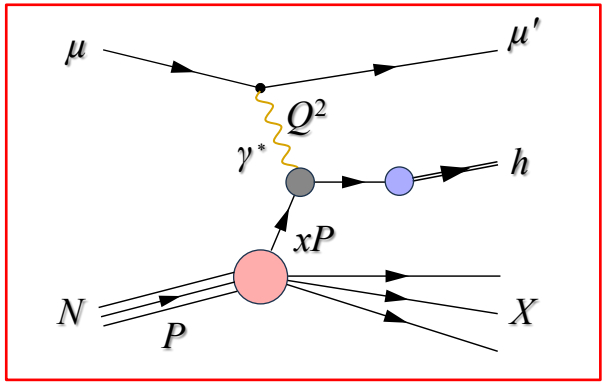


Cleanest access to hadronization/fragmentation

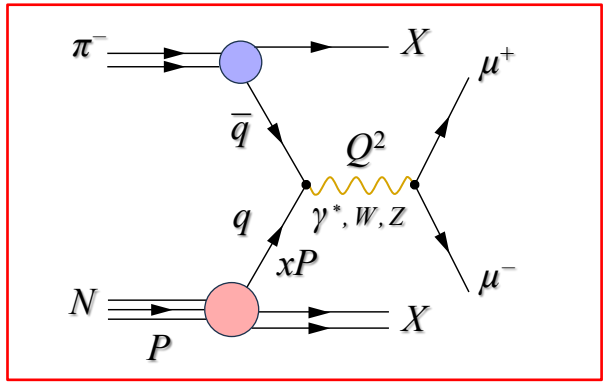
Hybrid collinear-TMD approach. The wealth of pp data allows studies of: TMD universality, evolution, expected factorization breaking

Main TMD tools - list of experiments (non exhaustive)

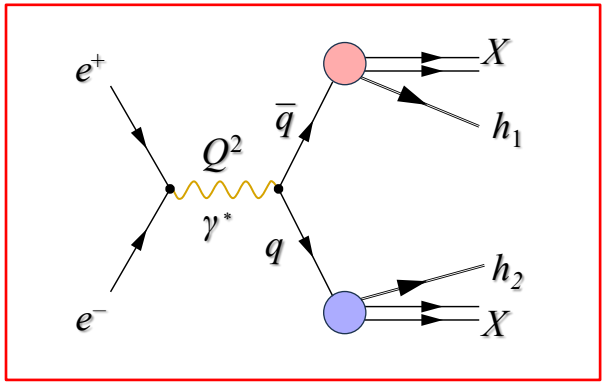
Semi-inclusive DIS



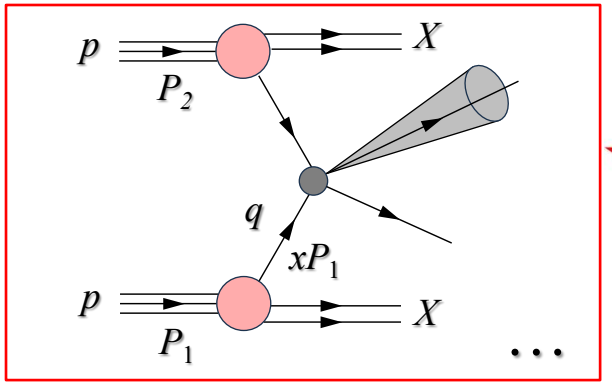
Drell-Yan process



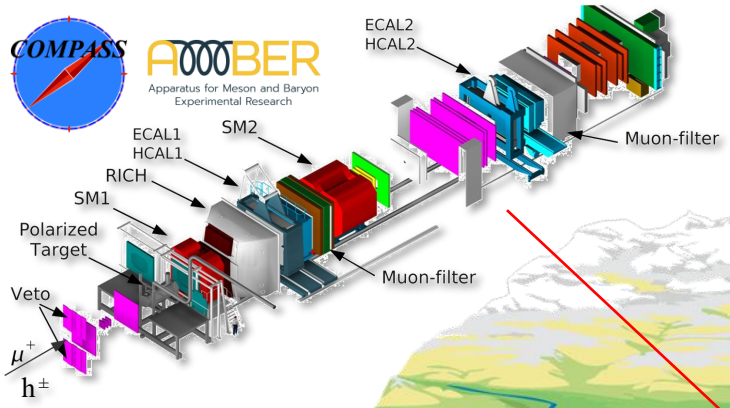
Electron-positron annihilation

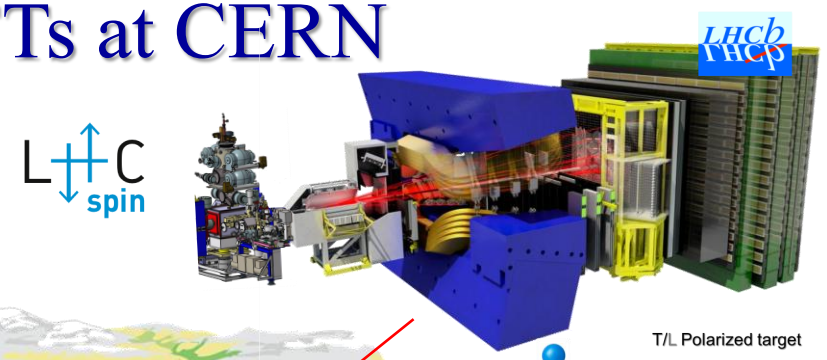


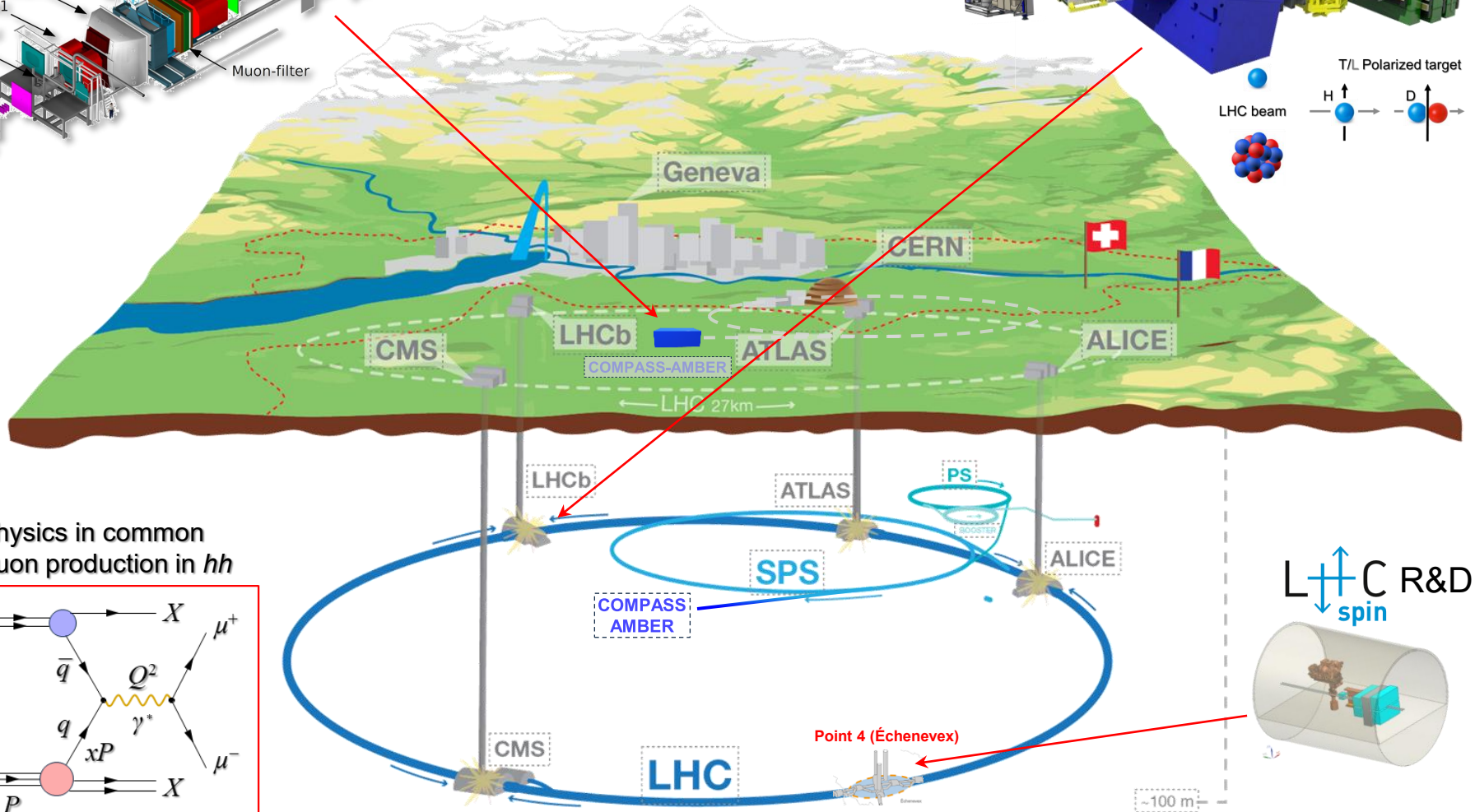
pp, pA-scattering, jet production, etc.



COMPASS-AMBER-LHCspin FTs at CERN





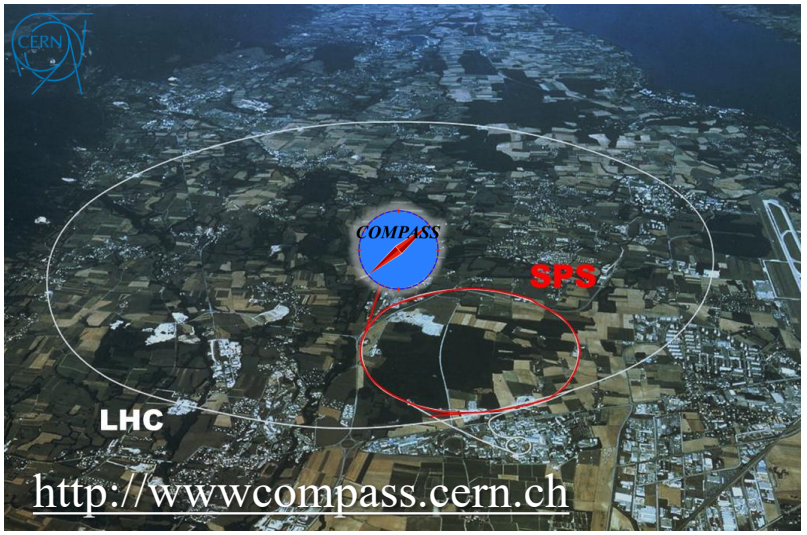


physics in common dimuon production in *hh*

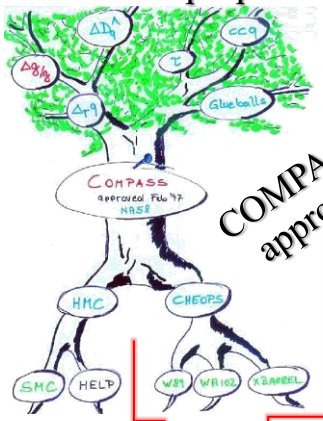
COMPASS timeline

- CERN SPS north area – M2 beamline
- Fixed target experiment
- Approved in 1997
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

33 institutions from 15 countries: ~ 200 members
4 new groups joined in the analysis phase!
Get in touch if interested!



COMPASS proposal



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.

COMPASS approval

COMPASS 1st data taking

For the COMPASS-GPD programme see Po-Ju's talk

COMPASS Phase-II addendum (d-quark h_1 and PRM→AMBER)

SIDIS L/T

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

Drell-Yan

DVCS

Drell-Yan

SIDIS T

1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

LS-1

LS-2

Pilot run

Phase I

Phase II

Analysis Phase

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!

- Polarized Drell-Yan?
- Polarized SIDIS?

For details, see Kun Liu's talk

COMPASS++/AMBER proposal CERN-SPSC-2019-022

AMBER approval

AMBER 1st data taking

$p + He(H, D) \rightarrow \bar{p} + X$ cross-section

Proton Radius Measurement (PRM) test - run

PRM and Drell-Yan Measurements

Phase II proposal potential ideas

- Kaon-induced unpolarized DY
- Kaon-induced Spectroscopy
- Meson radii measurements
- Prompt photon production

2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039

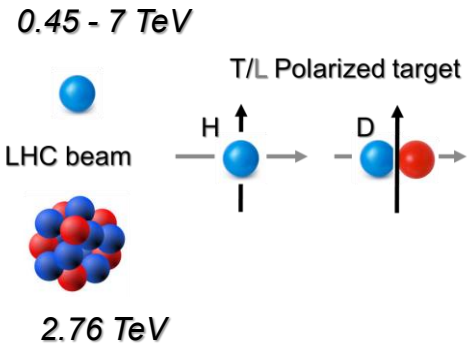
LS-3 LS-4 LS-5

Pilot run Phase I Phase II

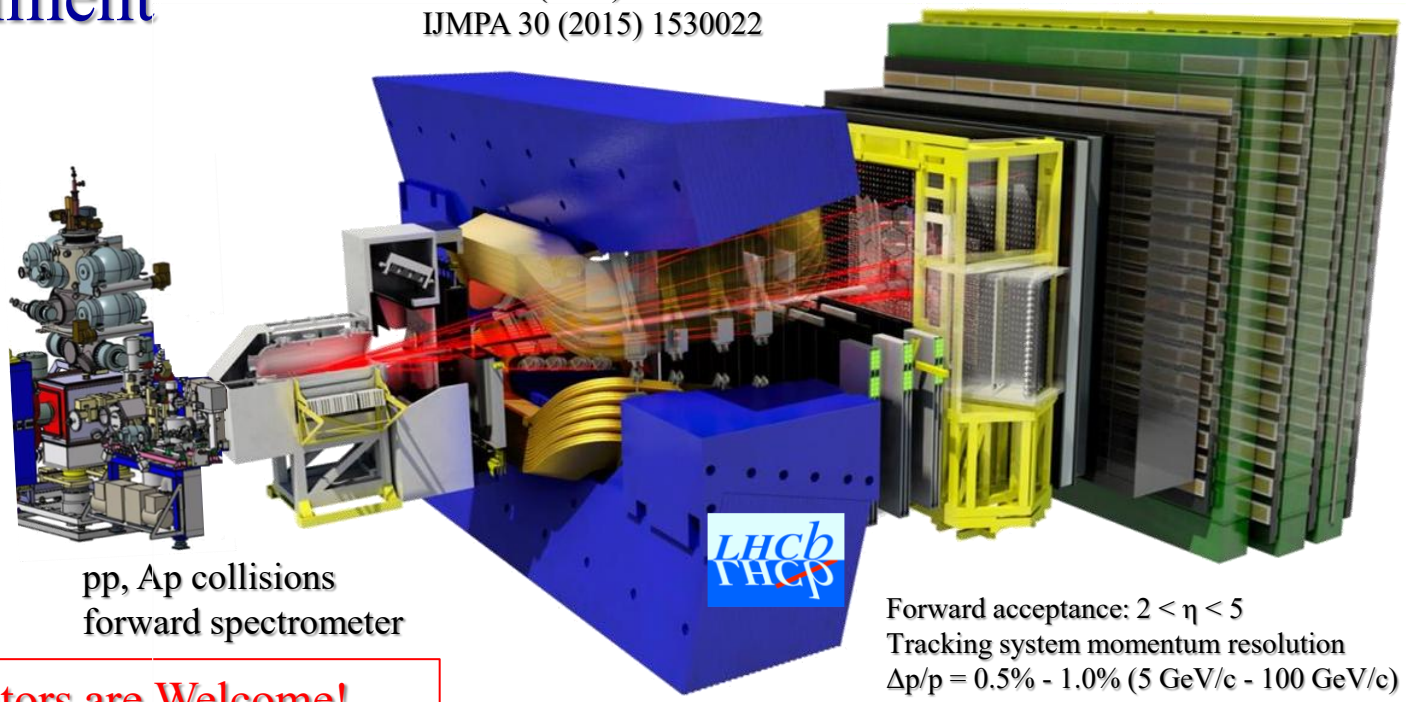
CERN Accelerator Complex schedule to 2041

LHCspin experiment

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



pp: $\sqrt{s} \simeq 29 - 115$ GeV
Ap: $\sqrt{s} \simeq 72$ GeV

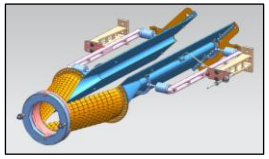


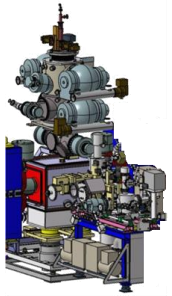
pp, Ap collisions
forward spectrometer

Forward acceptance: $2 < \eta < 5$
Tracking system momentum resolution
$\Delta p/p = 0.5\% - 1.0\%$ (5 GeV/c - 100 GeV/c)

New collaborators are Welcome!

Timeline





LHCspin R&D

As a group independent
from LHCb collaboration

LHCspin

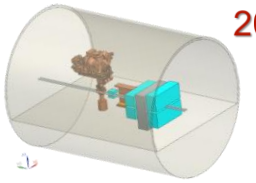
LHC Run4
data taking at the IR4

LHCspin Run5+6
data taking at LHCb

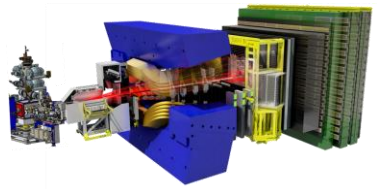
2024 2025 2026 2027 2030 2033 2035

SMOG2

LHC LS3
installation of the
apparatus at the IR4



LHC LS4
installing the
target at LHCb



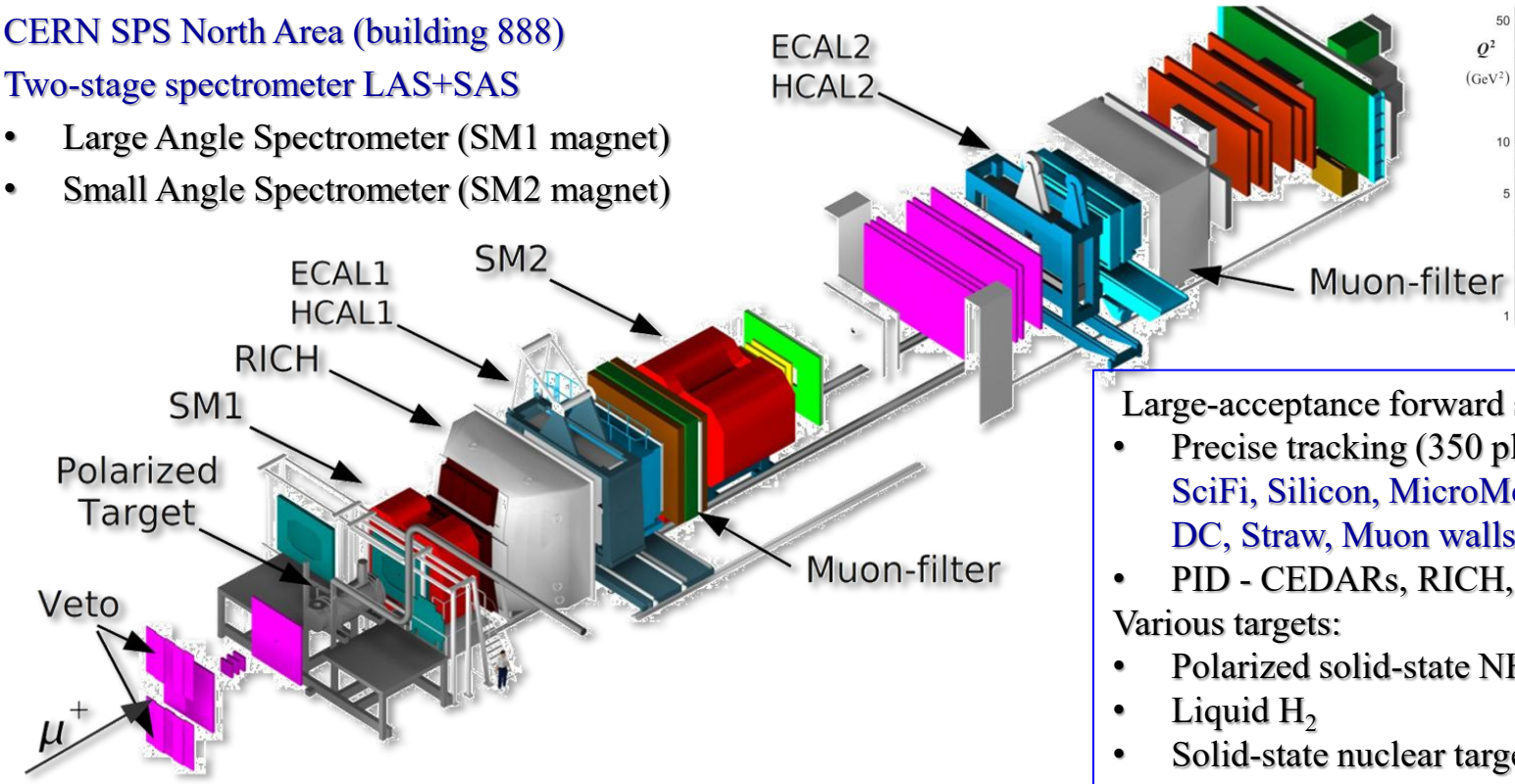
COMPASS experimental setup

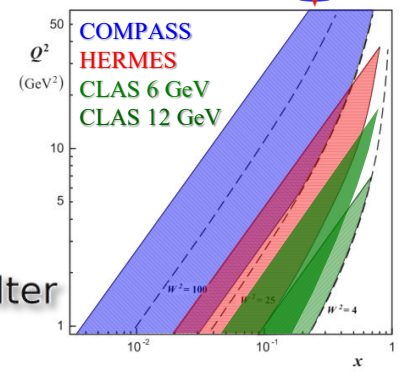
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





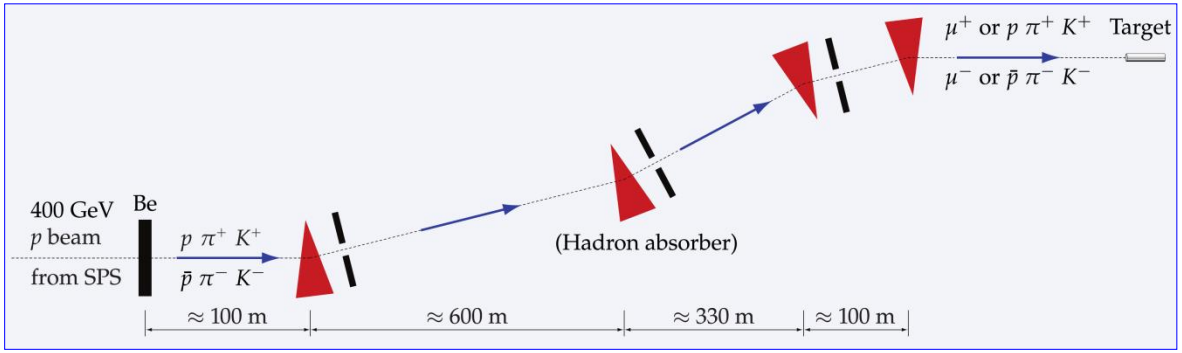
Large-acceptance forward spectrometer

- 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



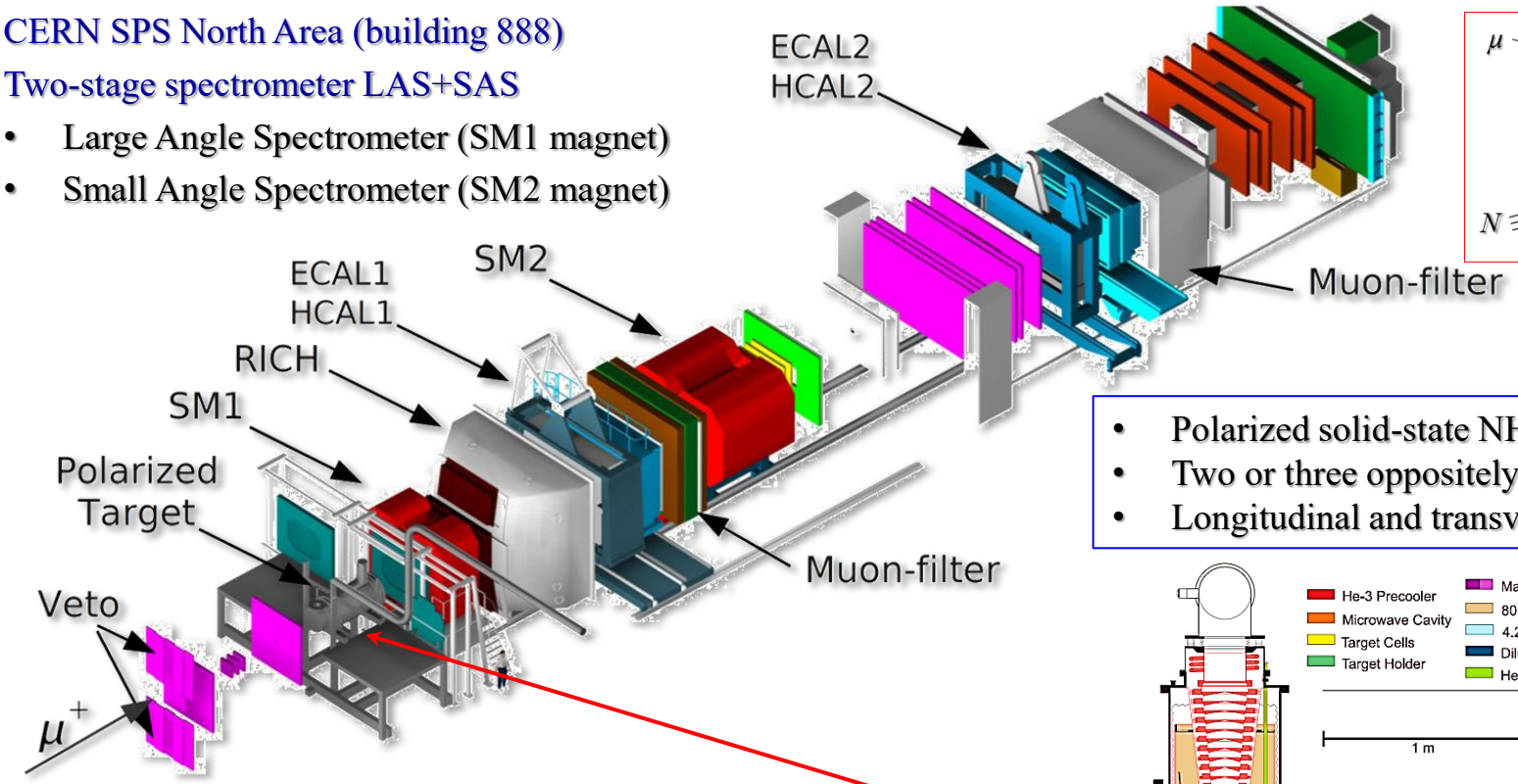
COMPASS experimental setup: Phase II (SIDIS program)

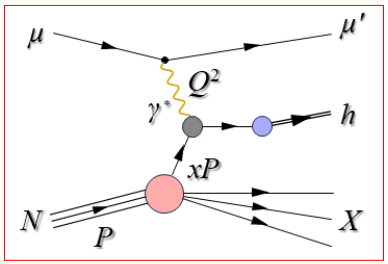
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

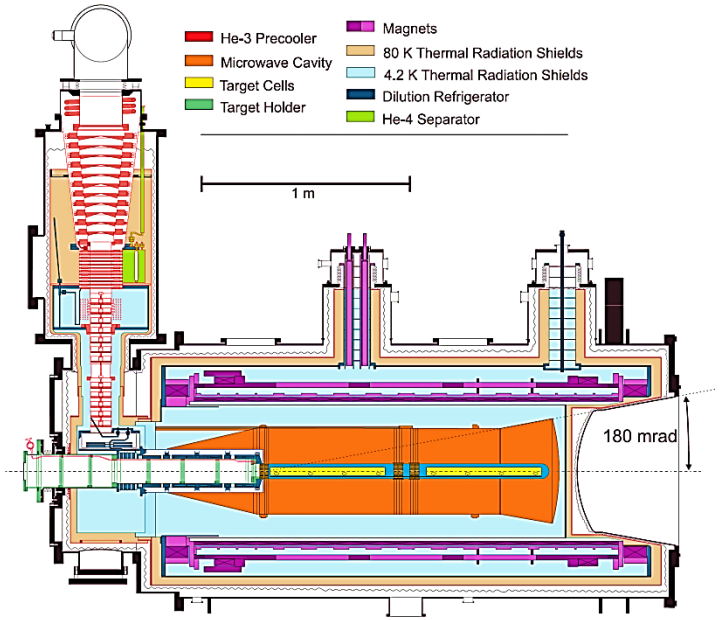
Two-stage spectrometer LAS+SAS

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





- Polarized solid-state NH_3 or ^6LiD
- 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

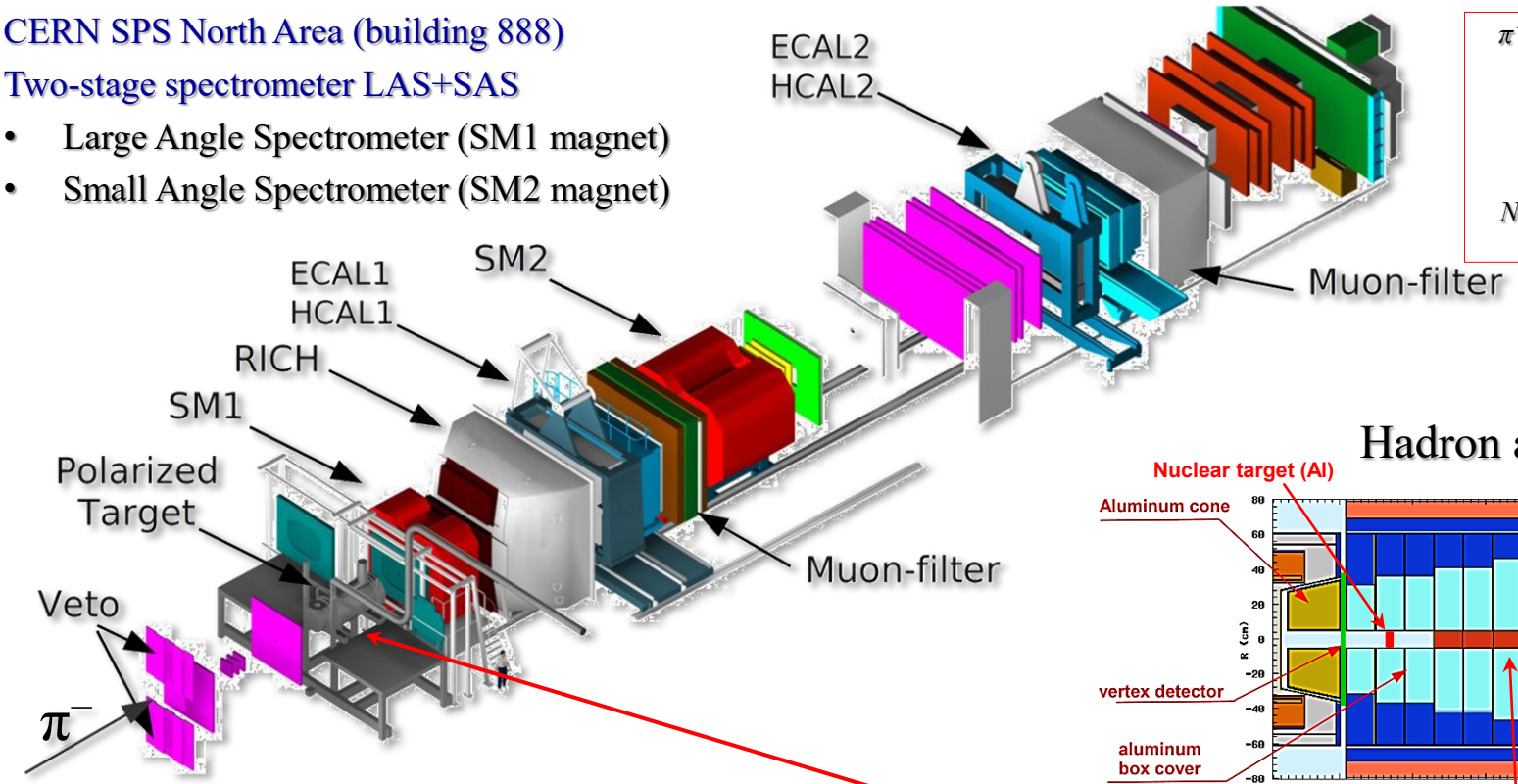
COMPASS experimental setup: Phase II (DY program)

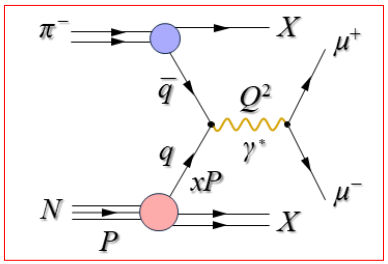
COmmon Muon Proton Apparatus for Structure and Spectroscopy

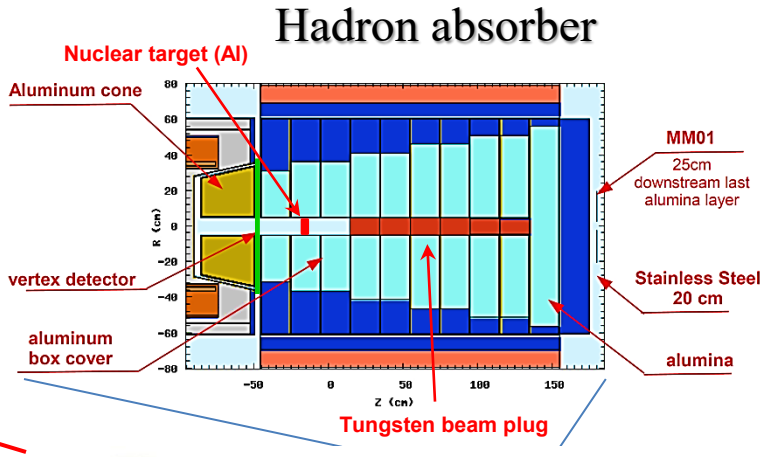
CERN SPS North Area (building 888)

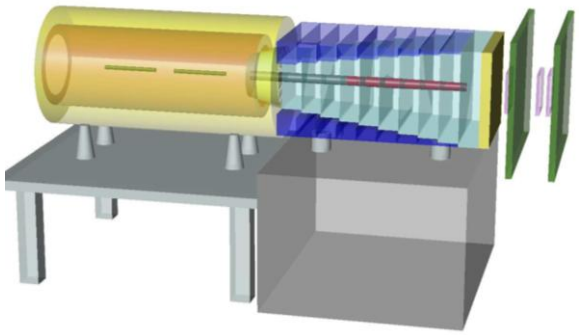
Two-stage spectrometer LAS+SAS

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- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

AMBER Phase I-II: DY program setup

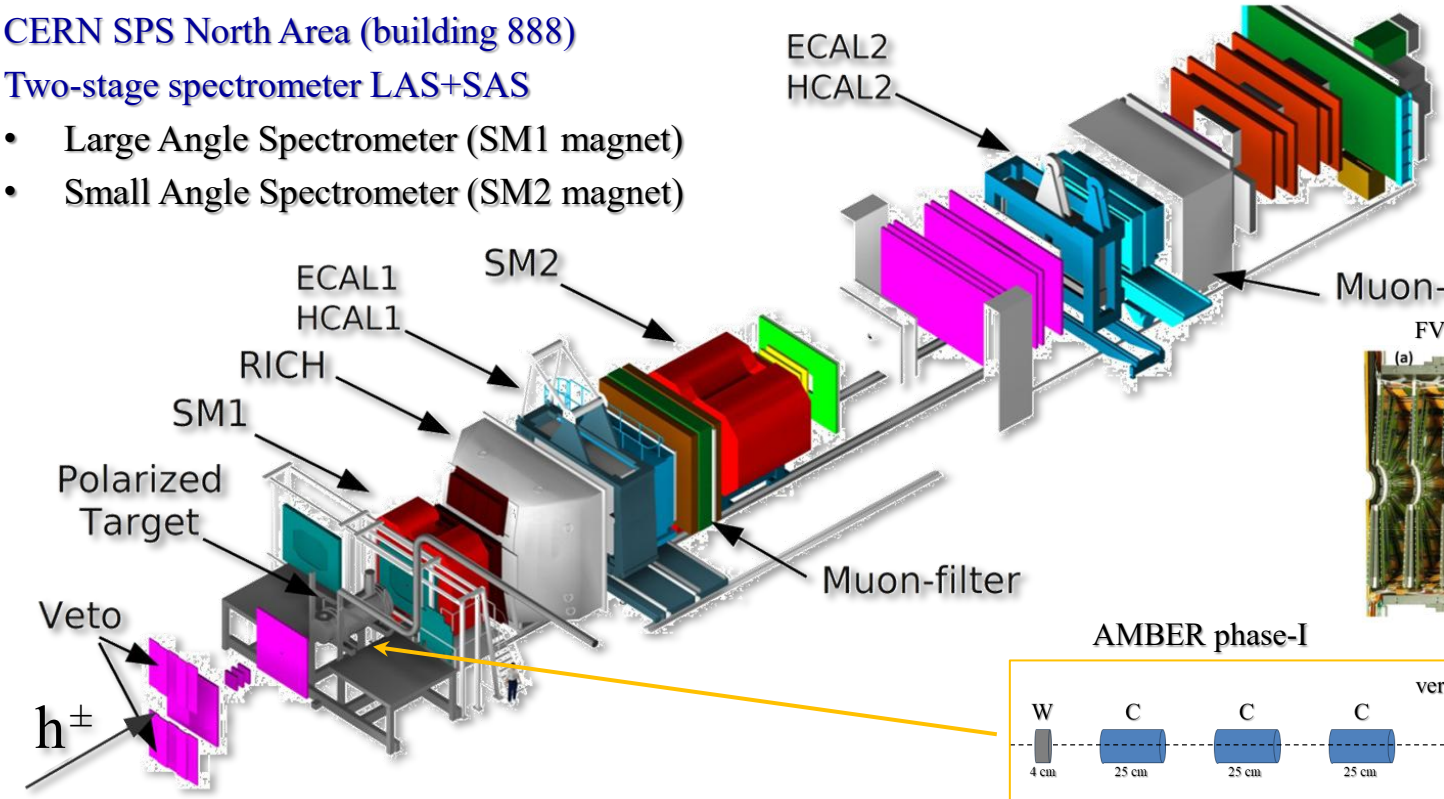
AMBER
Apparatus for Meson and Baryon Experimental Research

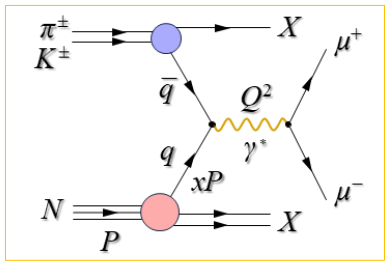
Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

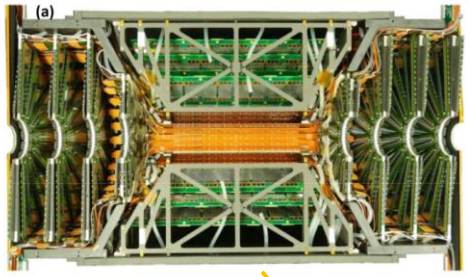
Two-stage spectrometer LAS+SAS

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

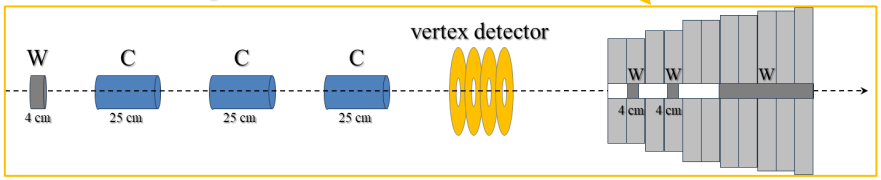


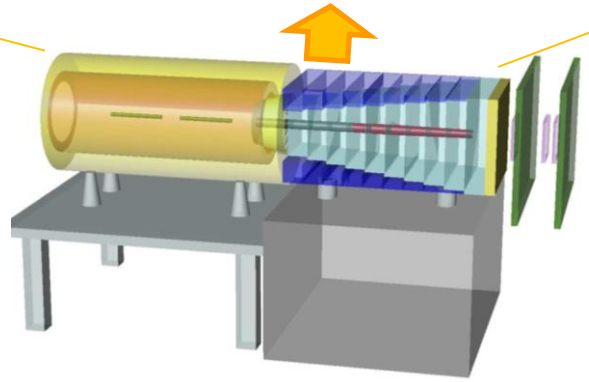


FVTX detector from PHENIX@RHIC



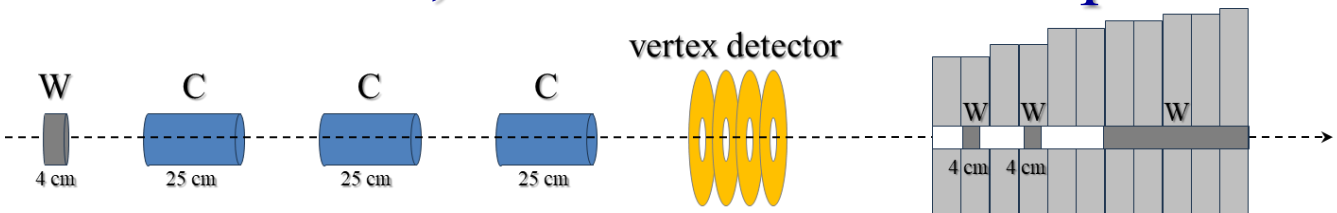
AMBER phase-I

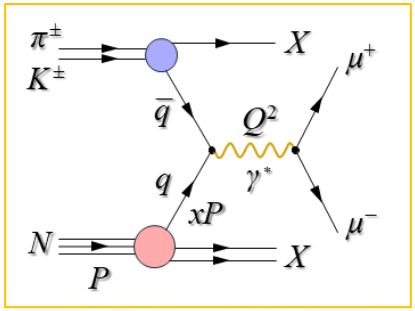




- Secondary h ± beam: ($\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$)
- Improved beam PID (CEDARs)
  - enabling kaon physics
- Isoscalar target (C 3x25 cm) and W
- Vertex detector: improve Z and $M_{\mu\mu}$ resolution
- New trigger-less DAQ,
- Revised setup, new detectors

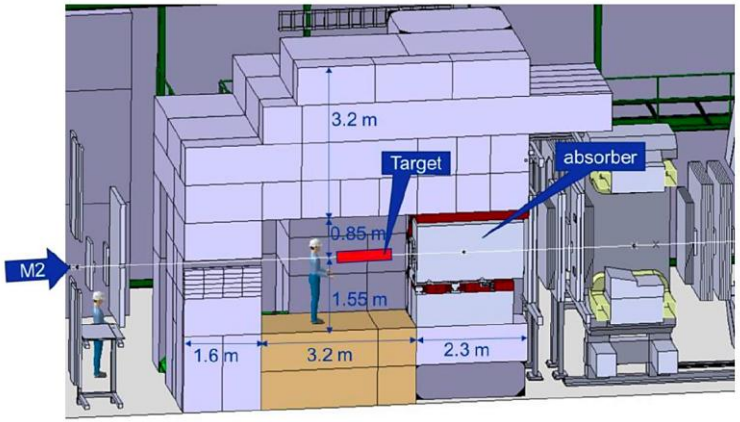
AMBER – $\pi^{\pm}$, $K^{\pm}$ induced dimuon production on C/W

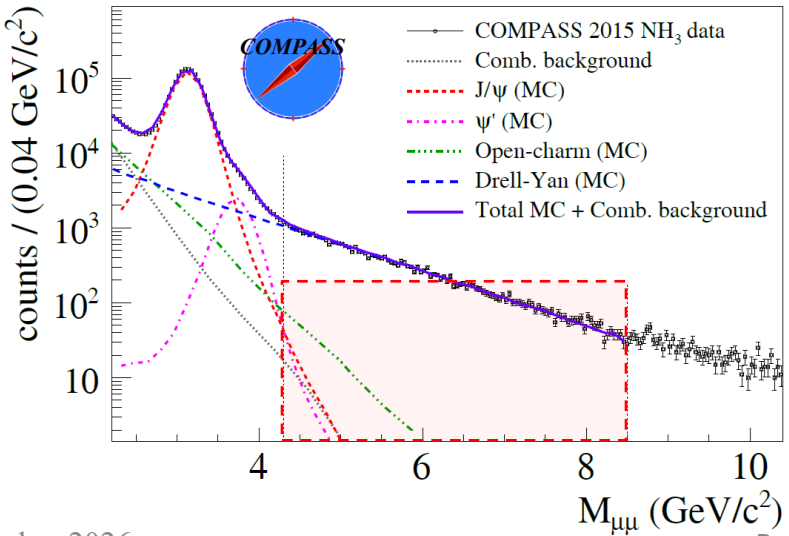


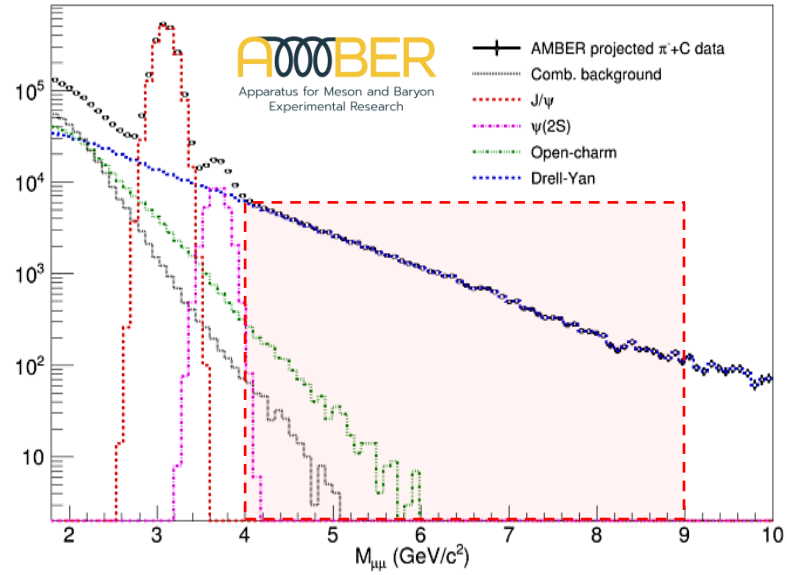


Compared to COMPASS

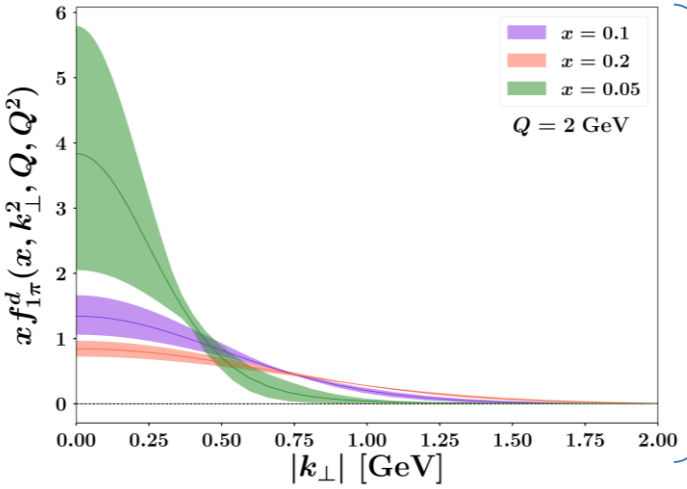
- Light isocalar target (carbon) instead of NH_3-He mix
- Improved mass resolution (~ 100 MeV/c^2)
  - Lower background → enlarge DY mass range
  - J/ψ and ψ(2S) studies
- Wider beam choice: $\pi^{\pm}$, $K^{\pm}$, p / $\bar{p}$, CEDARs (PID)
- Unique complementary measurements: $\pi^{\pm}$, $K^{\pm}$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





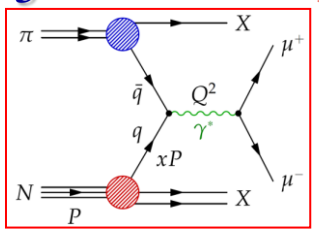


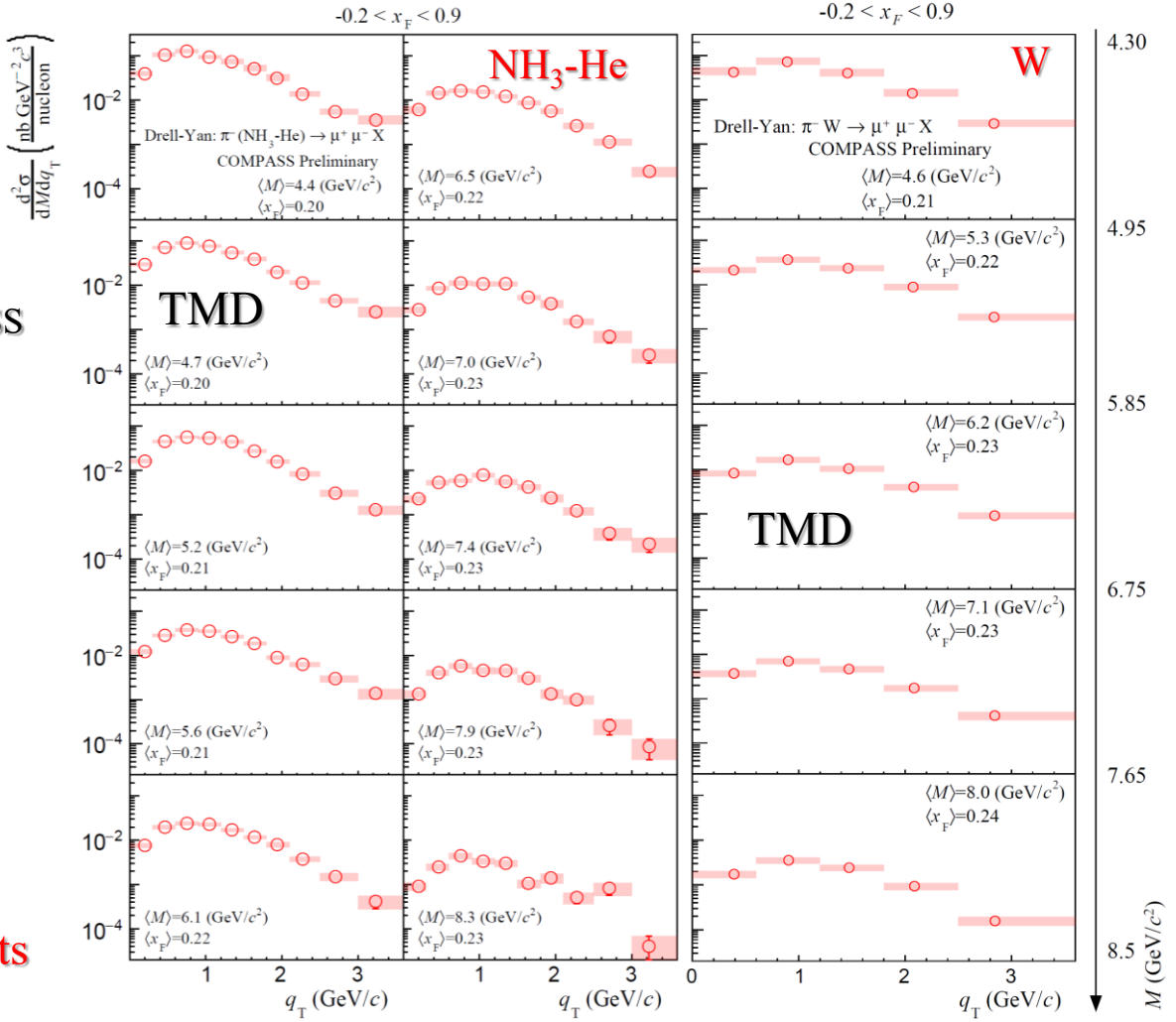
3D unpolarized Drell-Yan cross section on NH_3 and W



MAP collaboration
Phys. Rev. D. 107, 014014

recent global fit and projections for COMPASS



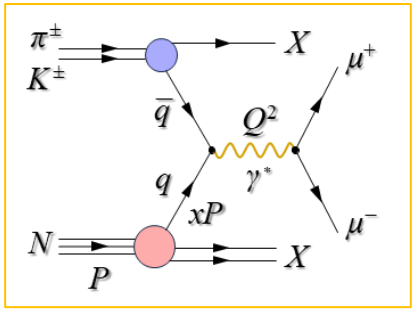


- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations
  x_F:q_T:M
- Unique data to access collinear and TMD distributions
  e.g. pion TMD PDF
- To be included in future global fits (MAP, JAM, etc.)

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

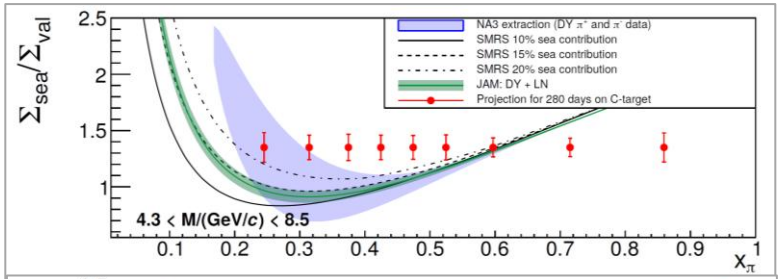
- Unique complementary measurements: $\pi^{\pm}$, $K^{\pm}$
  - Cross-sections, pion and kaon PDFs
    - Data for both collinear and TMD PDF studies
  - Drell-Yan, J/ψ and potentially ψ' channels
  - Study of nuclear effects with C and W

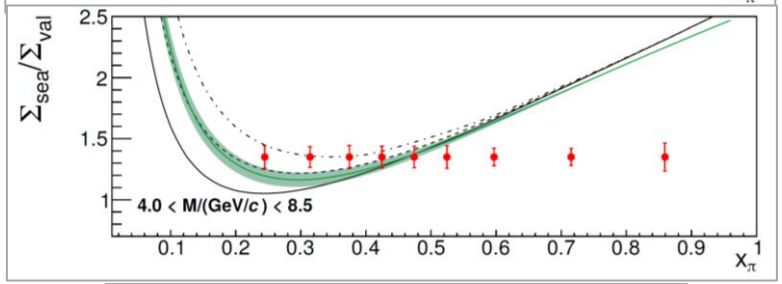
For details, see Kun Liu's talk



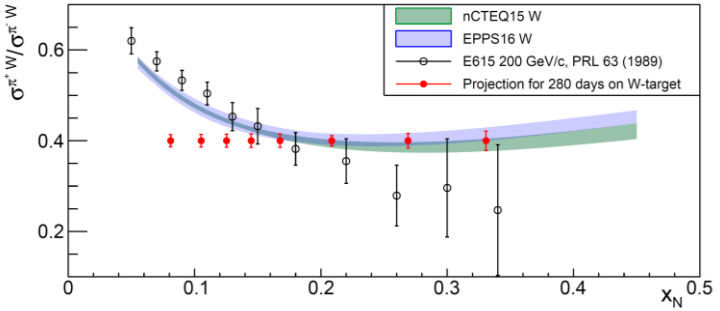
AMBER J/ψ events	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

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 COMPASS 2018	110 cm NH_3	190	π^-	7.0×10^7	4.3 – 8.5	35000 52000
AMBER	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5	21700
					4.0 – 8.5	31000
		190	π^-	6.8×10^7	4.3 – 8.5	67000
					4.0 – 8.5	91100
	12 cm W	190	π^+	0.4×10^7	4.3 – 8.5	8300
					4.0 – 8.5	11700
		190	π^-	1.6×10^7	4.3 – 8.5	24100
					4.0 – 8.5	32100

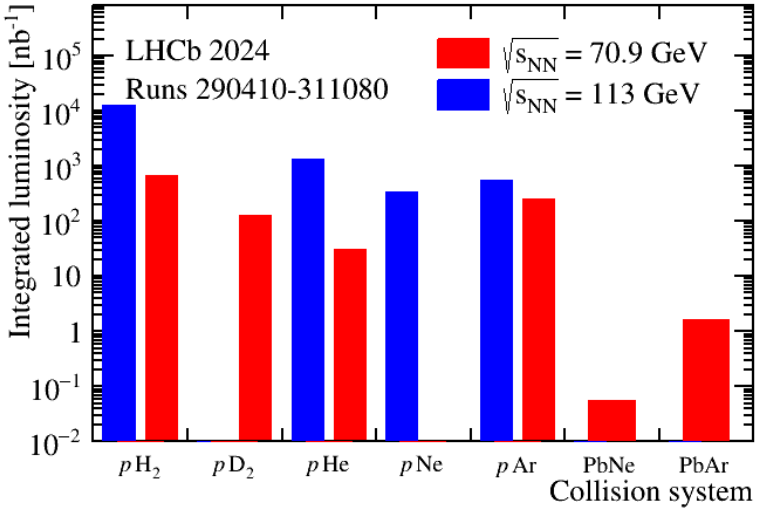


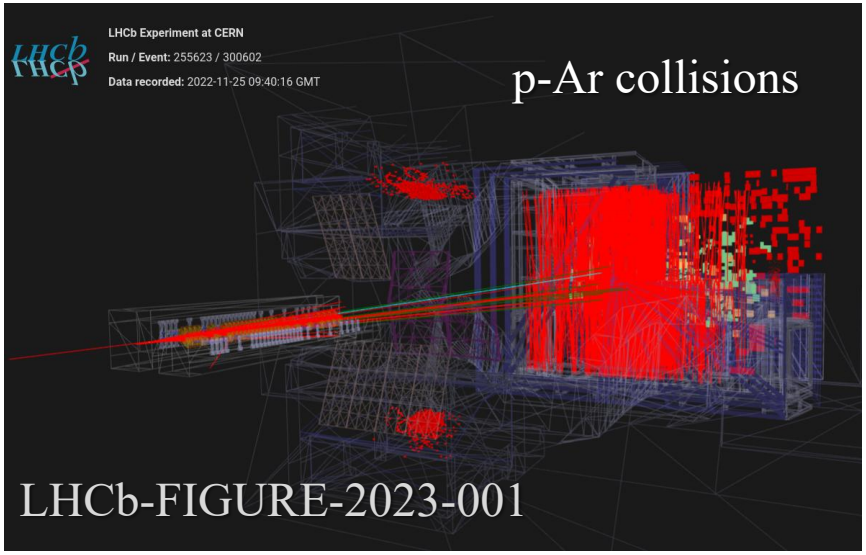


$\Sigma_{val} = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence
$\Sigma_{sea} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence



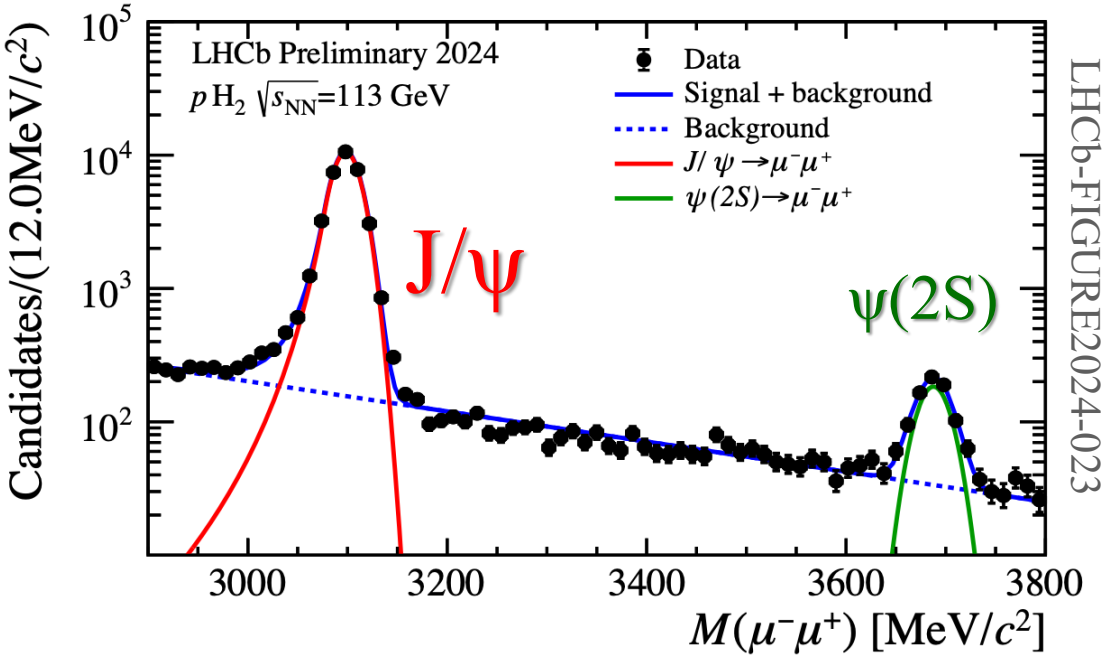
LHC - SMOG2 early data - fantastic precision





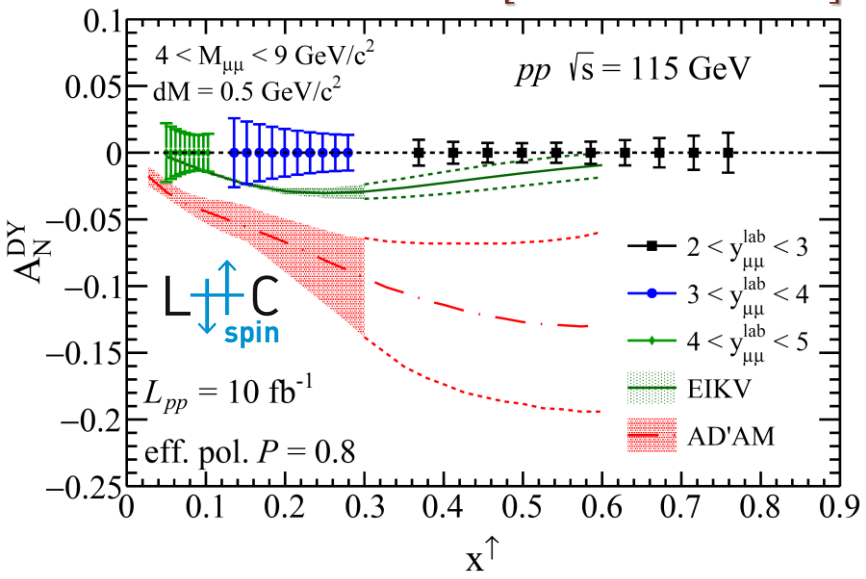
A wealth of unique data collected in 2024





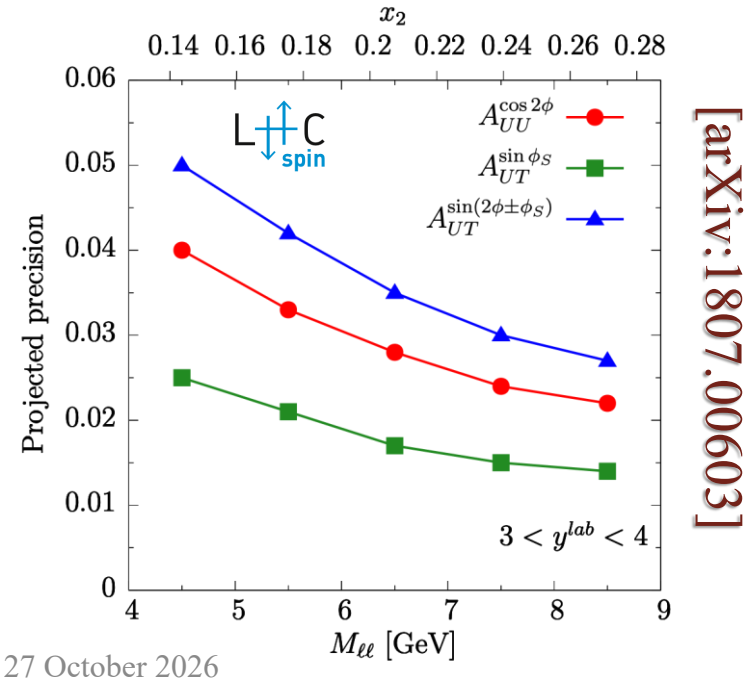
LHCspin experiment

[arXiv:1807.00603]

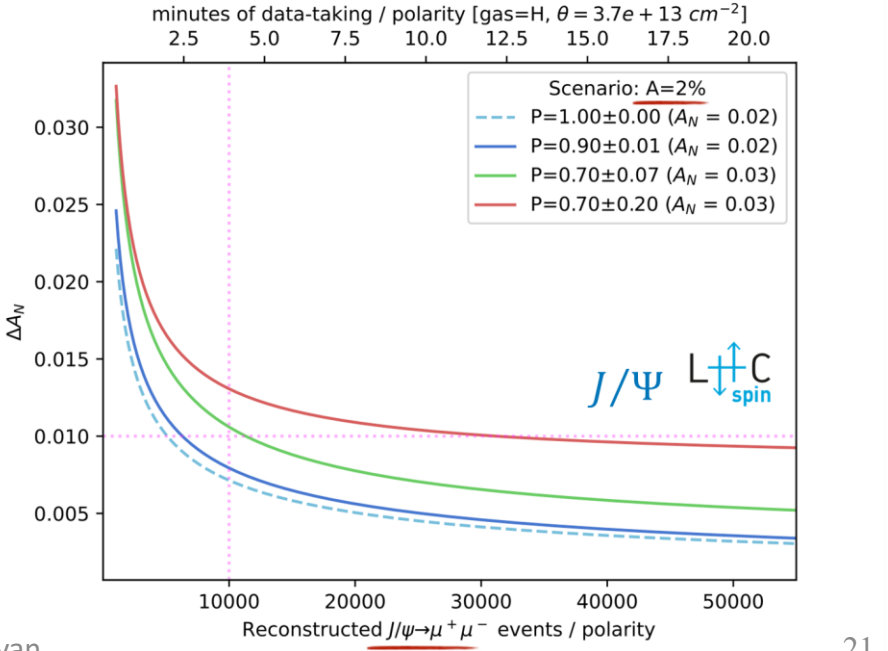


Channel	Events / week	Total yield
$J/\psi \to \mu^+\mu^-$	1.3×10^7 !!	1.5×10^9
$D^0 \to K^-\pi^+$	6.5×10^7	7.8×10^9
$\psi(2S) \to \mu^+\mu^-$	2.3×10^5	2.8×10^7
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	8.5	1.0×10^3
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	2.5×10^1	3.1×10^3
Drell Yan ($5 < M_{\mu\mu} < 9$ GeV)	7.4×10^3	8.8×10^5
$\Upsilon \to \mu^+\mu^-$	5.6×10^3	6.7×10^5
$\Lambda_c^+ \to pK^-\pi^+$	1.3×10^6	1.5×10^8

- Precise *spin asymmetry* on $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ for $pH^{\uparrow}$ collisions in just few weeks
- Inclusive quarkonia production in (un)polarized pp interactions - ideal observable to access gTMDs
- Flavor separation using H/D, EMC effect
- Spin physics in heavy-ion collisions and a lot more!



[arXiv:1807.00603]





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

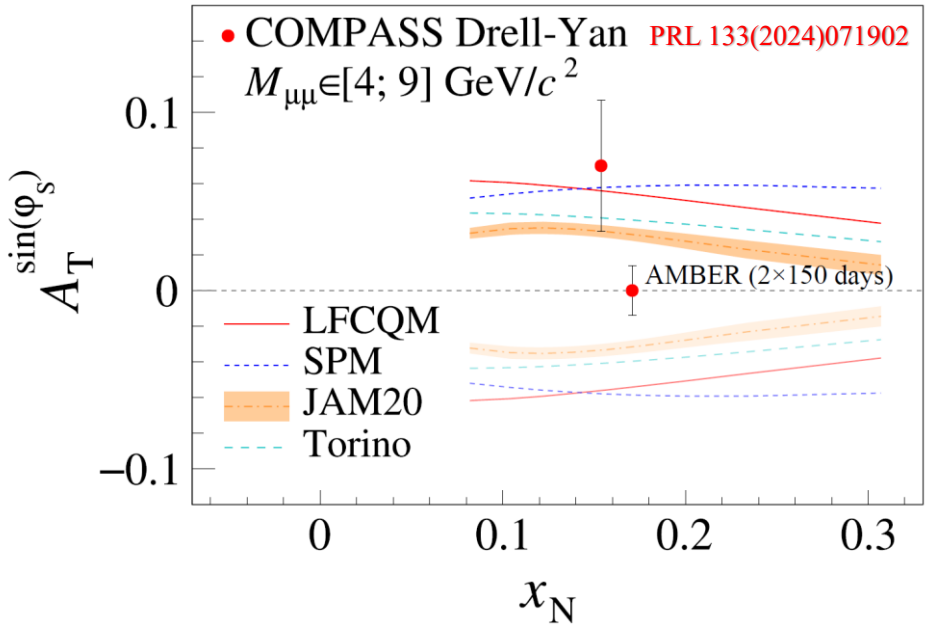
Opening	*Dr Bakur Parsamyan*	
892/1-D20, CERN		13:00 - 13:05
Testing TMD process dependence with polarized Drell-Yan: theory status and are new measurements needed?		
Alexei Prokudin		
Global fits from MAP:what have we learned so far?	*Dr Lorenzo Rossi*	
892/1-D20, CERN		13:30 - 13:55
Recent studies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

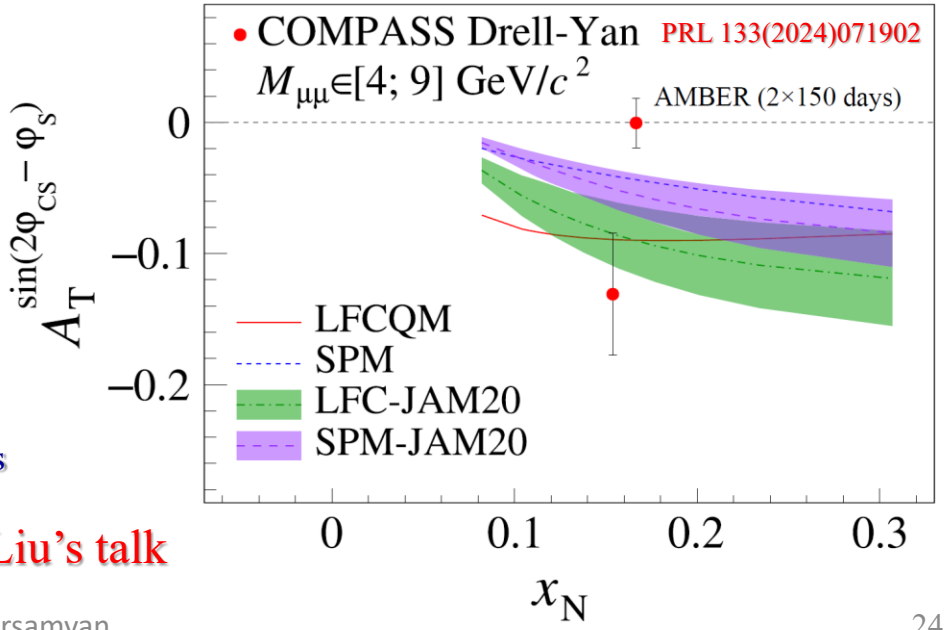
STAR: Transverse-spin asymmetries in W and Z production at STAR: constraints on TMD process dependence		
Oleg Eyser		
SpinQuest: Polarized Drell–Yan at SpinQuest: probing sea-quark TMDs and the Sivers effect	*Forhad Hossain*	
892/1-D20, CERN		13:25 - 13:50
LHCspin: Polarized fixed-target physics with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

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

Polarized Drell-Yan: from COMPASS to AMBER

- Exclusive possibilities at the M2 beamline (AMBER)
- Unique access to valence PDFs with pion beams
- Important complementarity to the sea-quark sensitivity of $pp^{\uparrow}$ measurements
- Sivers and Transversity TSAs in DY and J/ψ channels
  - Definite answer to the sign-change prediction via measurement of two TSAs
  - Accessing 1D-2D kinematic dependences
- Access to π and proton BM via ν from the same data
  - Verifying theory expectations for BM TMD PDF (collinear and TMD parts)
  - Sizable transversity TSA → non-zero π BM
- Improved mass resolution → access to ψ' and ϒ mesons
- Cross-section studies with NH_3-He (x-check of COMPASS/AMBER)
- Checking the expectations for the Pretzelosity PDF
- Accessing twist-3 distributions in Drell-Yan
  - In SIDIS higher twist effect are often quite large
- AMBER groups interested in polarized physics
  - Interesting potential for target system development
    - New polarized target magnet system
  - Many possibilities for common projects and studies





For details, see Kun Liu's talk

- Recent SIDIS highlights from COMPASS

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

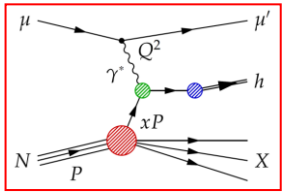
collinear

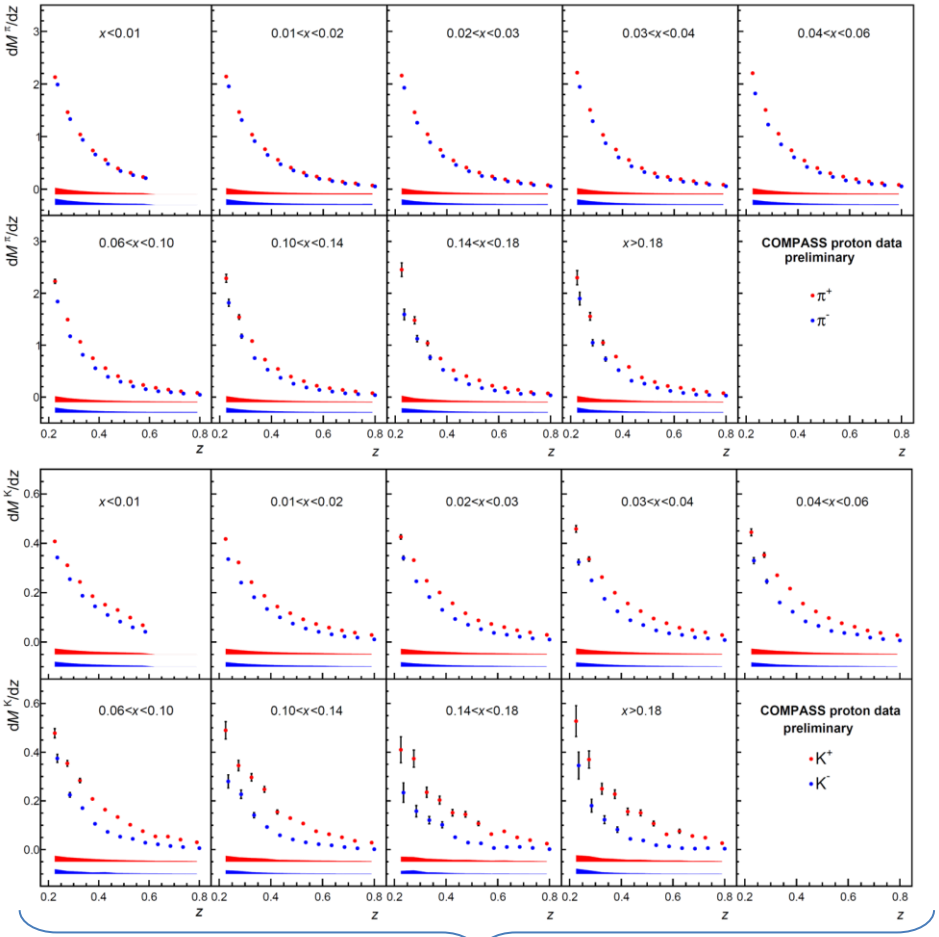
TMD

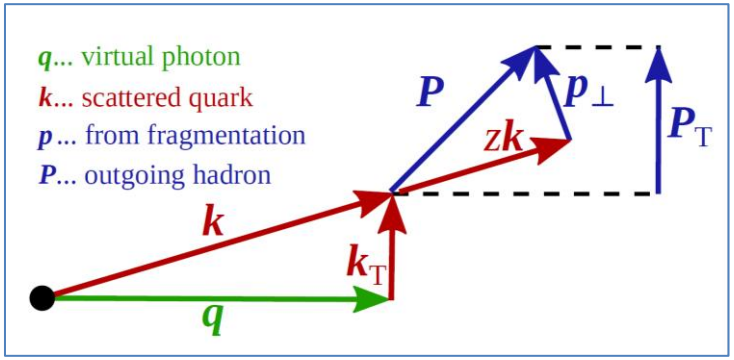
$f_1^q(x, k_T^2)$ number density

A set of complex corrections:

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







New radiative corrections (DJANGOH)
PRD 112 (2025) 012002

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

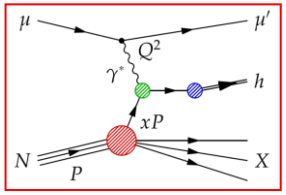
$f_1^q(x, k_T^2)$ number density

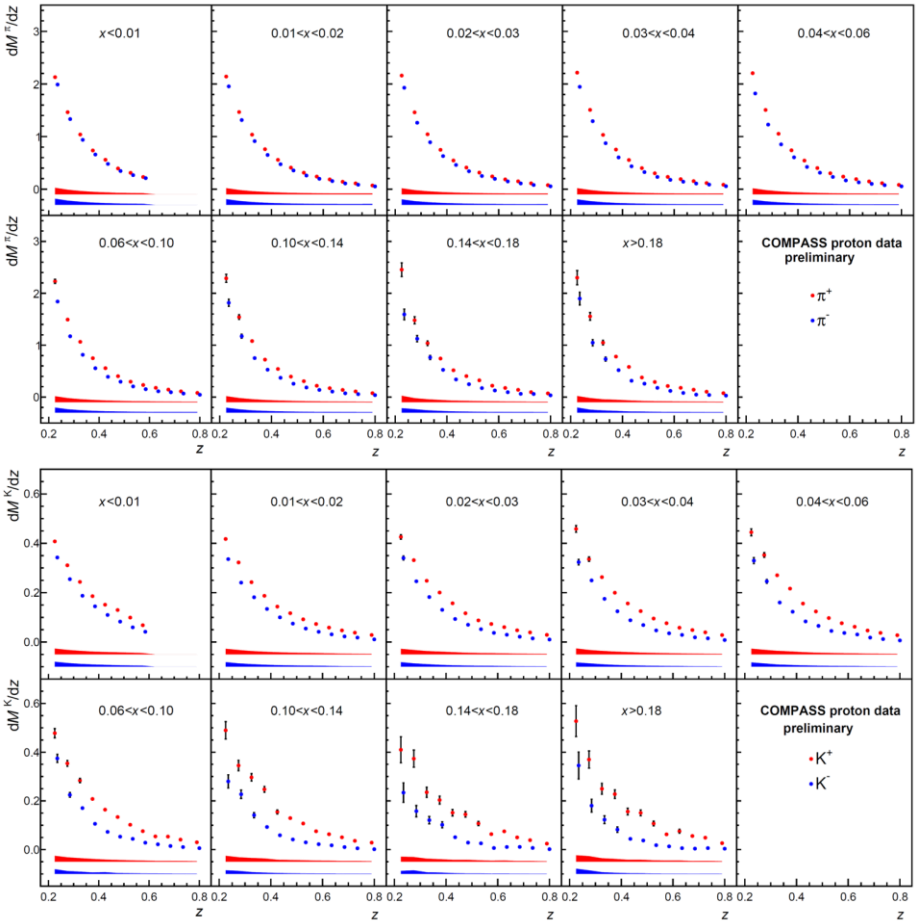
COMPASS 25 years 1997 - 2022

collinear

A set of complex corrections:

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

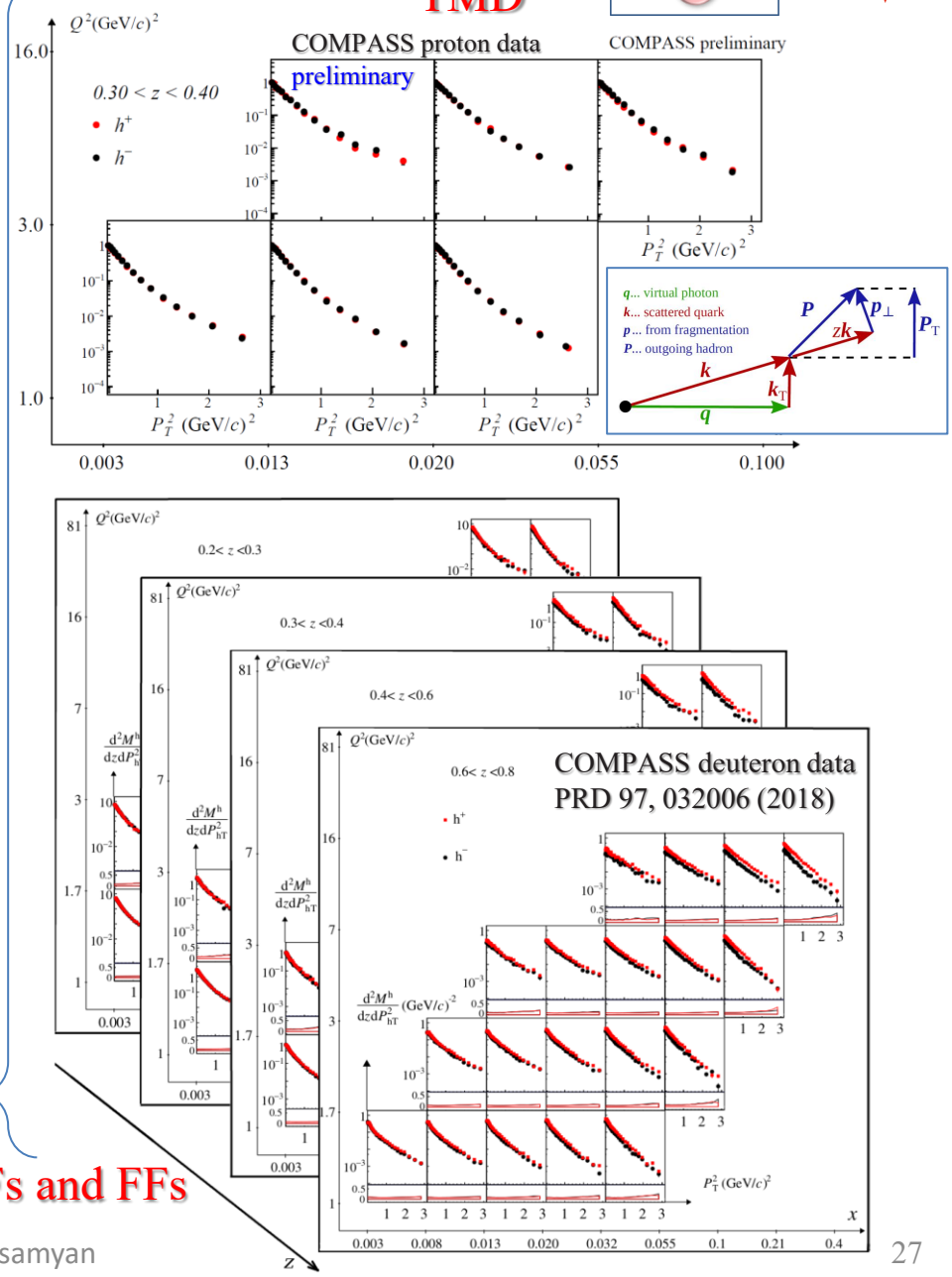




New radiative corrections being applied

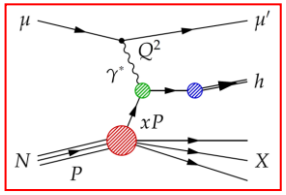
Multi-D is crucial to explore all features of PDFs and FFs

TMD

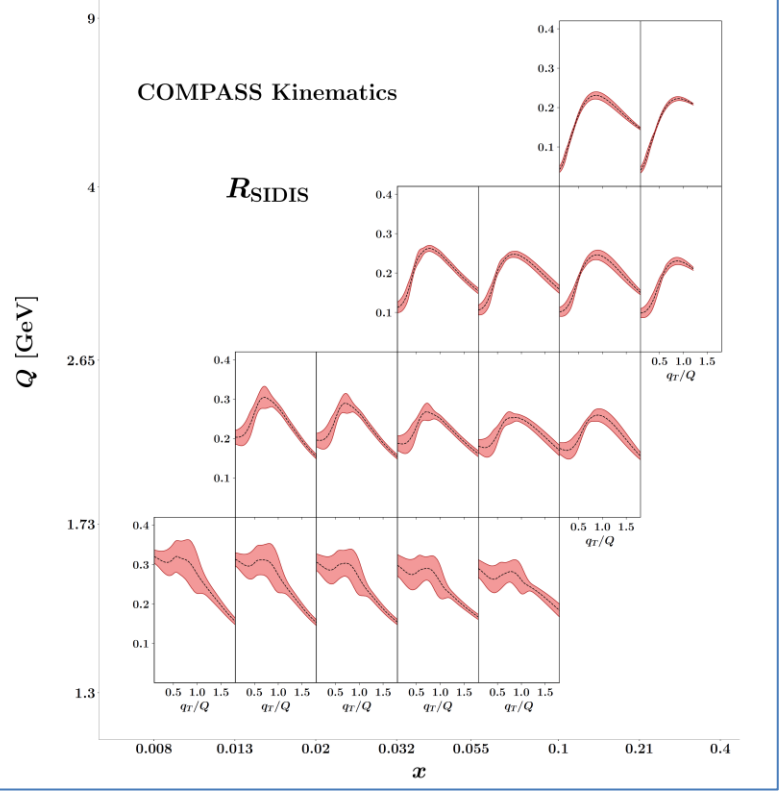


Hadron multiplicities; $h^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ (2016 data)

- Non-negligible $F_{UU,L}$ in COMPASS kinematics?
  $R_{SIDIS} = F_{UU,L} / F_{UU,T}$ can reach ~30% at low Q and low q_T



A. Bacchetta and L. Gamberg at EMMI-RRTF at CERN
e-Print: 2610.06628 [hep-ph]

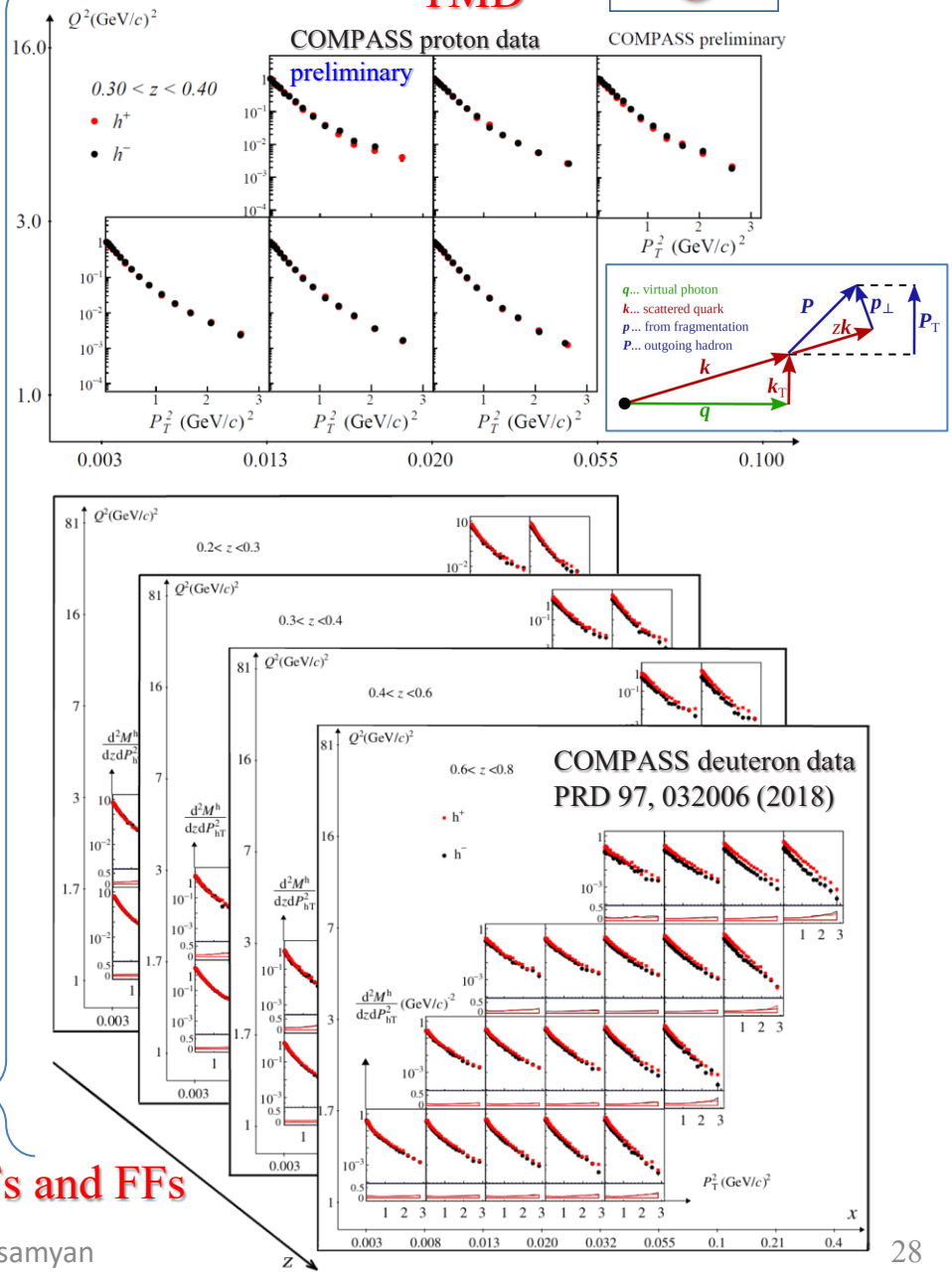


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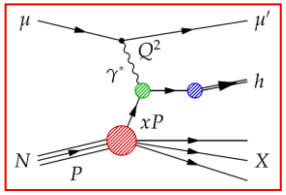
TMD

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

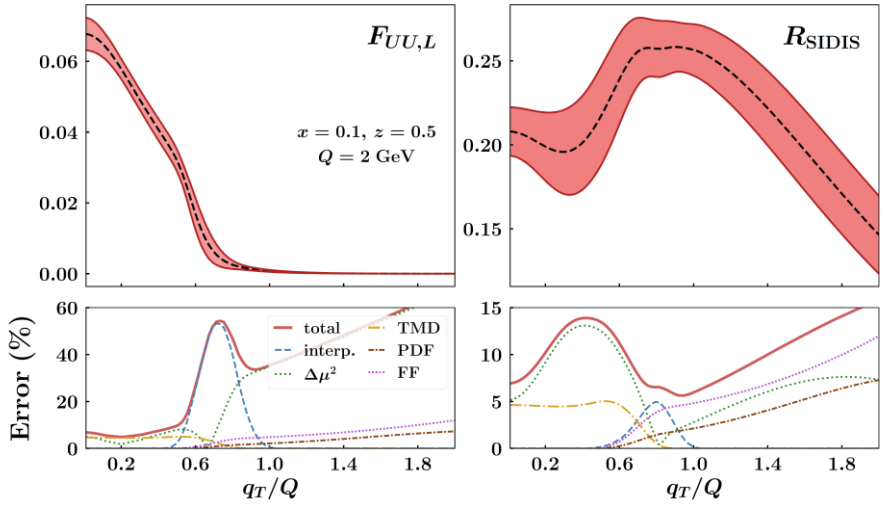


Hadron multiplicities; $h^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ (2016 data)

- Non-negligible $F_{UU,L}$ in COMPASS kinematics?
  $R_{SIDIS} = F_{UU,L} / F_{UU,T}$ can reach ~30% at low Q and low q_T
- Neglecting $F_{UU,L}$ affects the interpretation of SIDIS multiplicities and unpolarized TMD extractions
- The same effect propagates into TSAs through the denominator $F_{UU,T} + \varepsilon F_{UU,L}$
- For the Sivers asymmetry:
  $A_{Siv} = (F_{UT,T}^{Siv} + \varepsilon F_{UT,L}^{Siv}) / (F_{UU,T} + \varepsilon F_{UU,L})$



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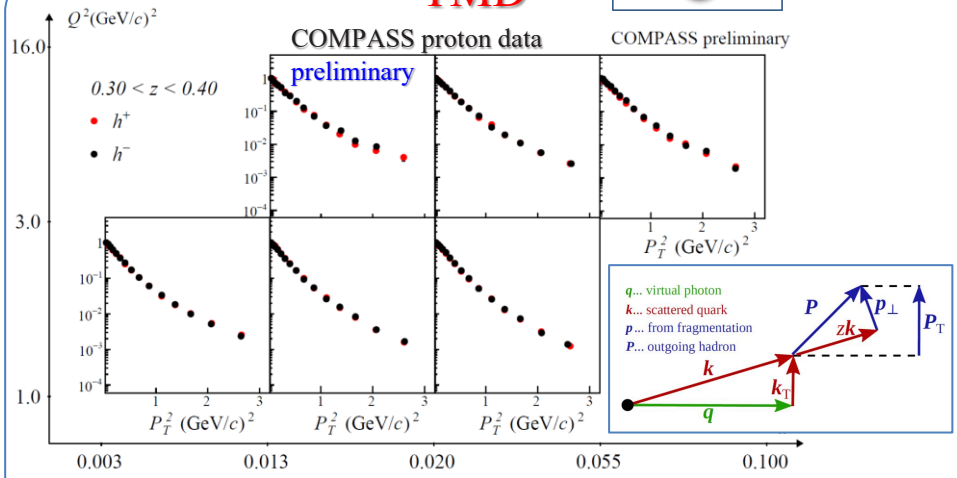


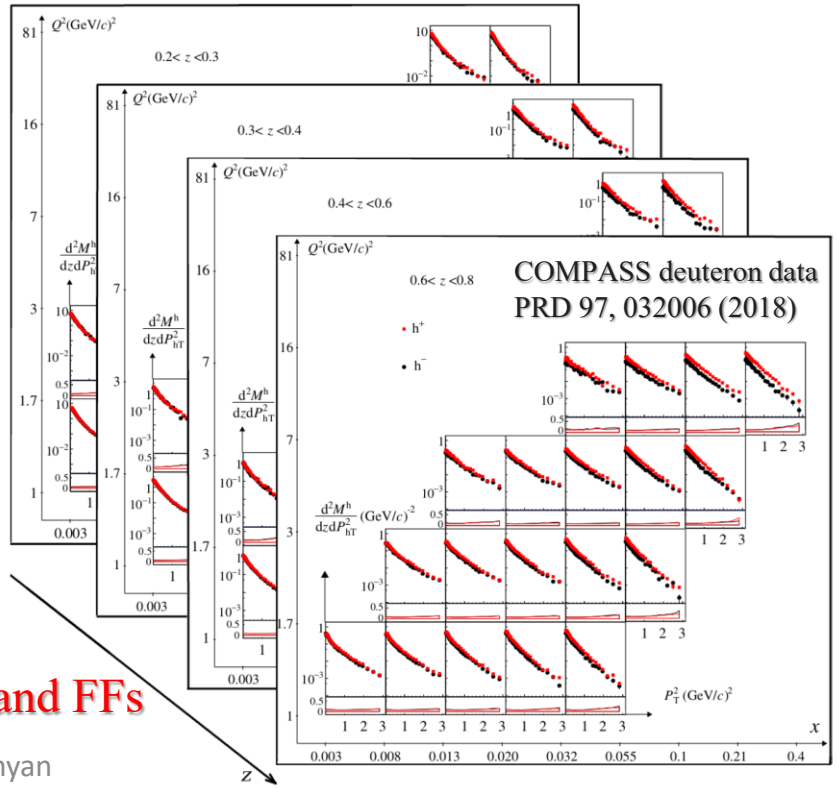
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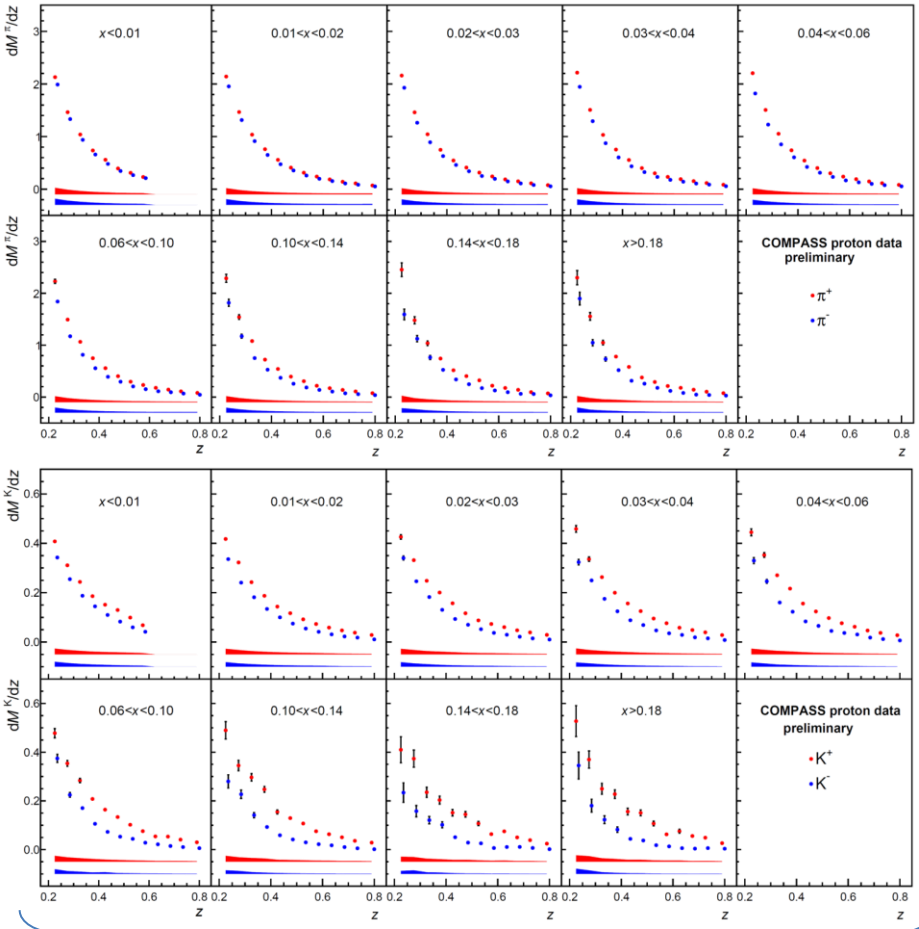
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COMPASS 25 years 1997 - 2022

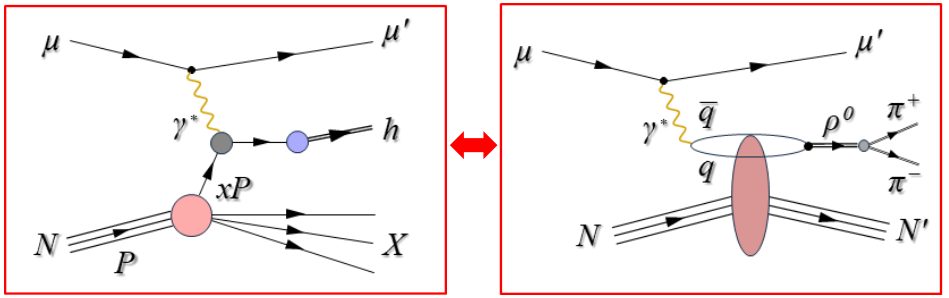
collinear

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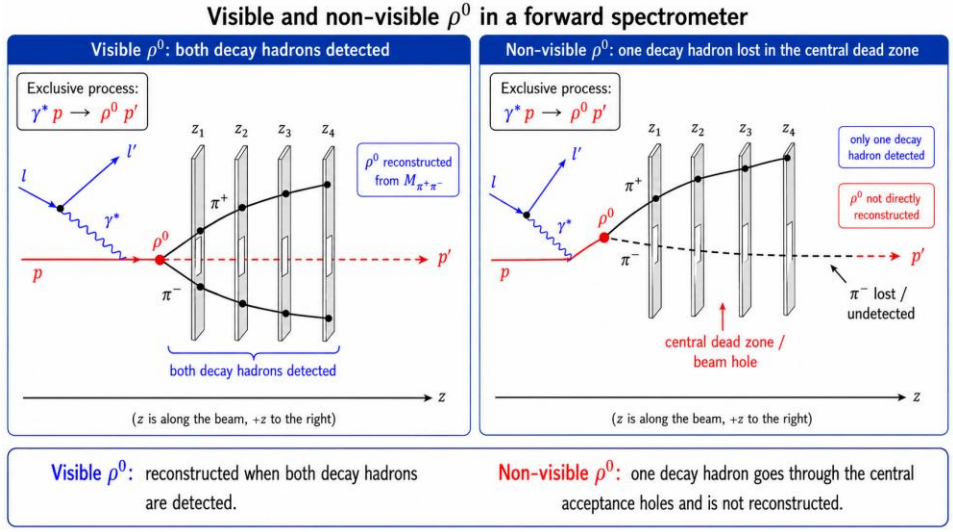


New radiative corrections (DJANGOH)
PRD 112 (2025) 012002



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



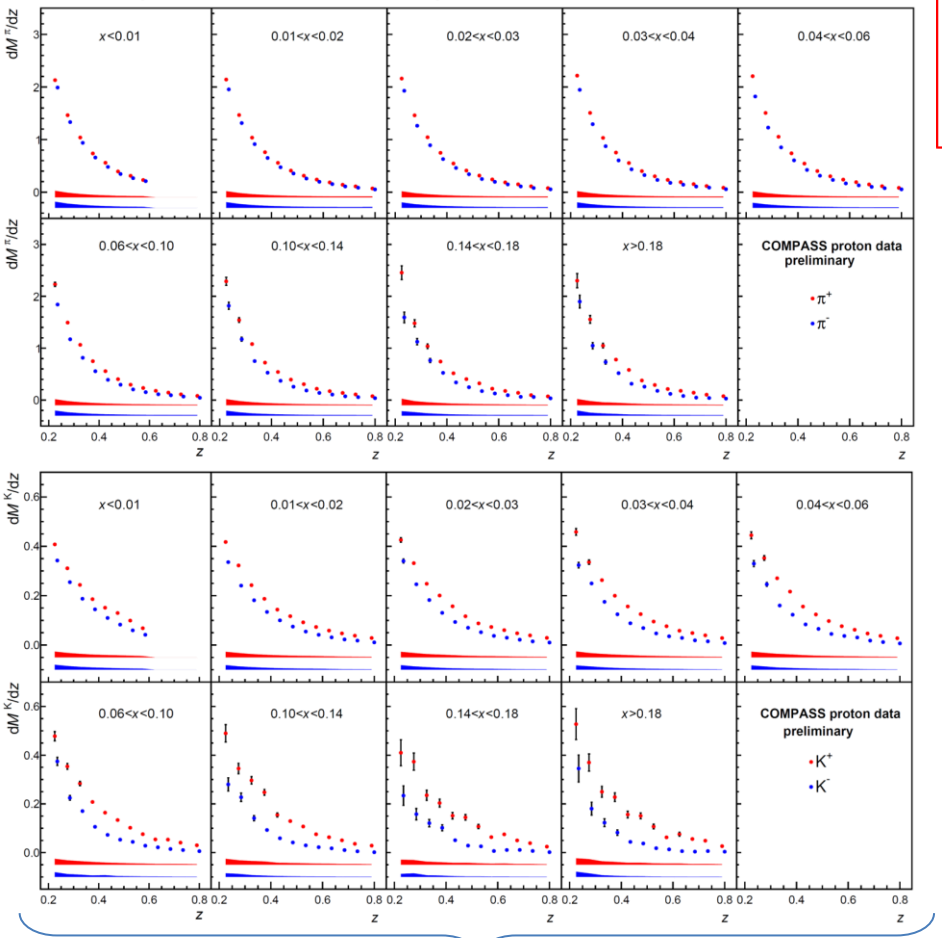
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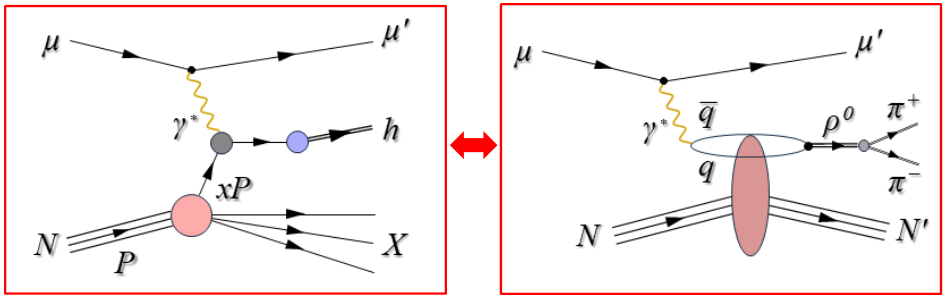
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Diffractive VM production

- 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 ~24%
for ($z \approx 0.6$ and $Q^2 \approx 1$ (GeV/c)^2.

Cahn effect in SIDIS: Diffractive VMs contribution

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

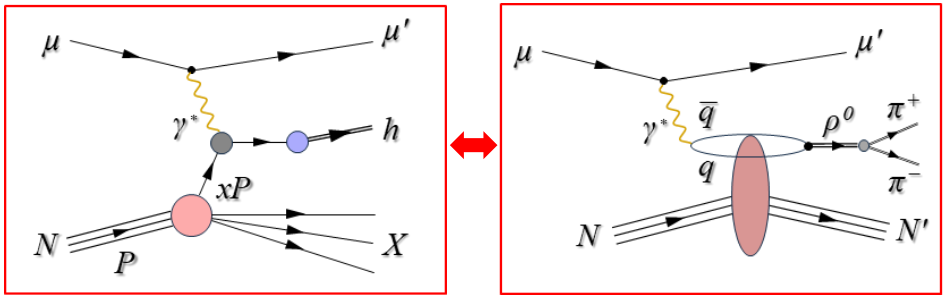
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

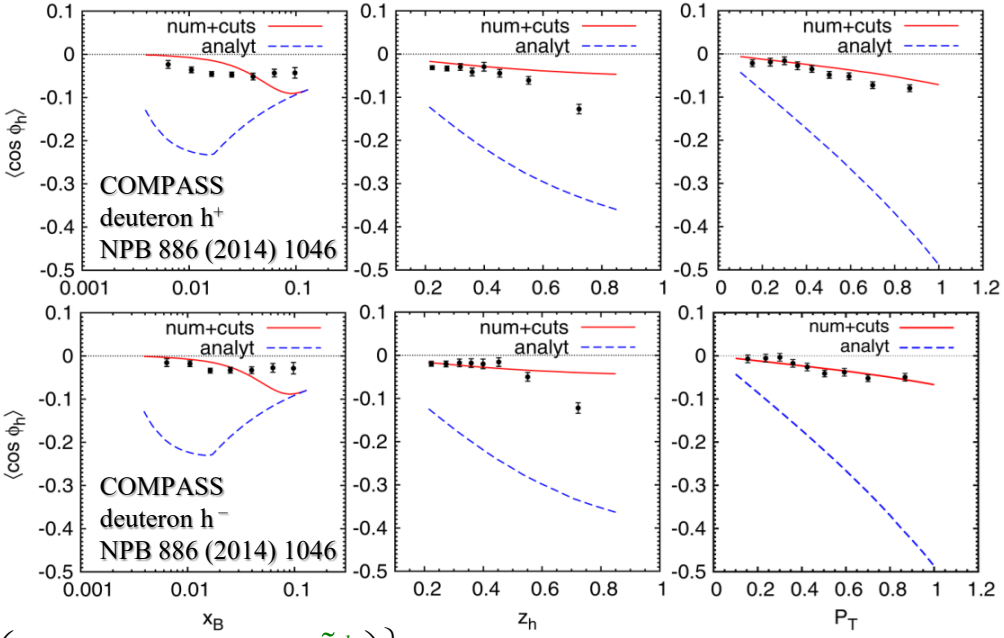
Cahn effect



$f_1^q(x,\boldsymbol{k}_T^2)$
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

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

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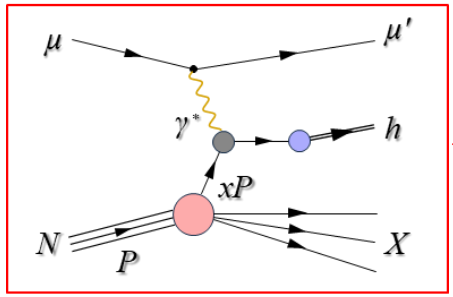
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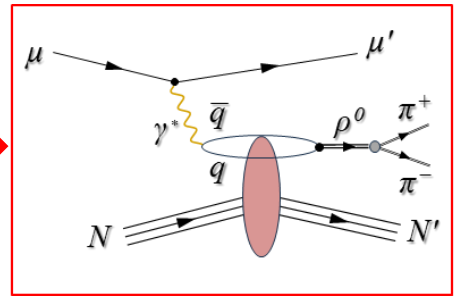
$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\ldots\right)$$

Cahn effect



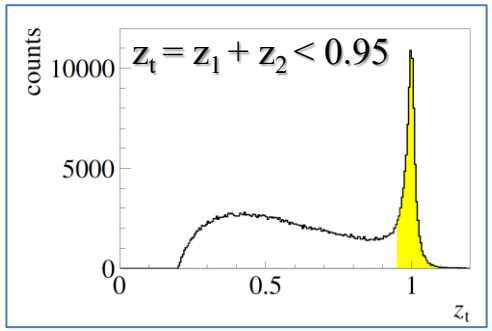
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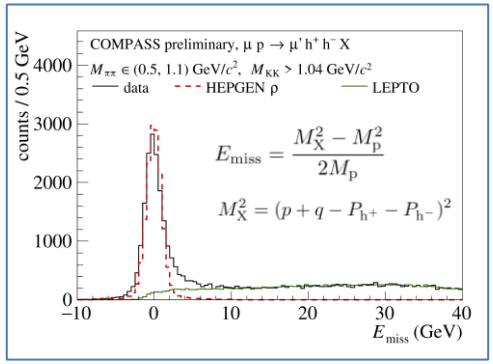




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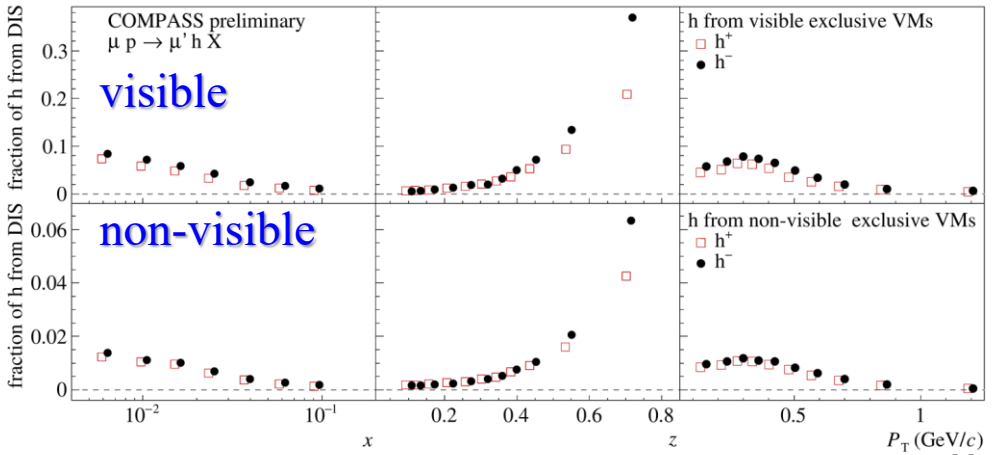




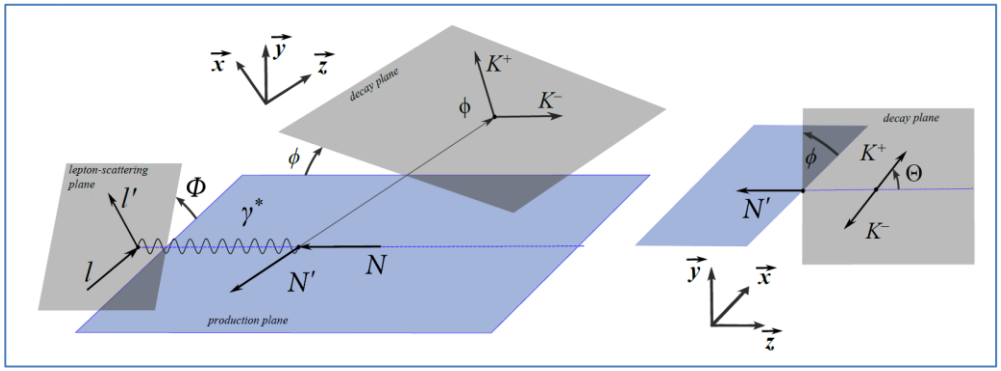
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- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
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VM fractions



Spin Density Matrix Elements from photon to a VM



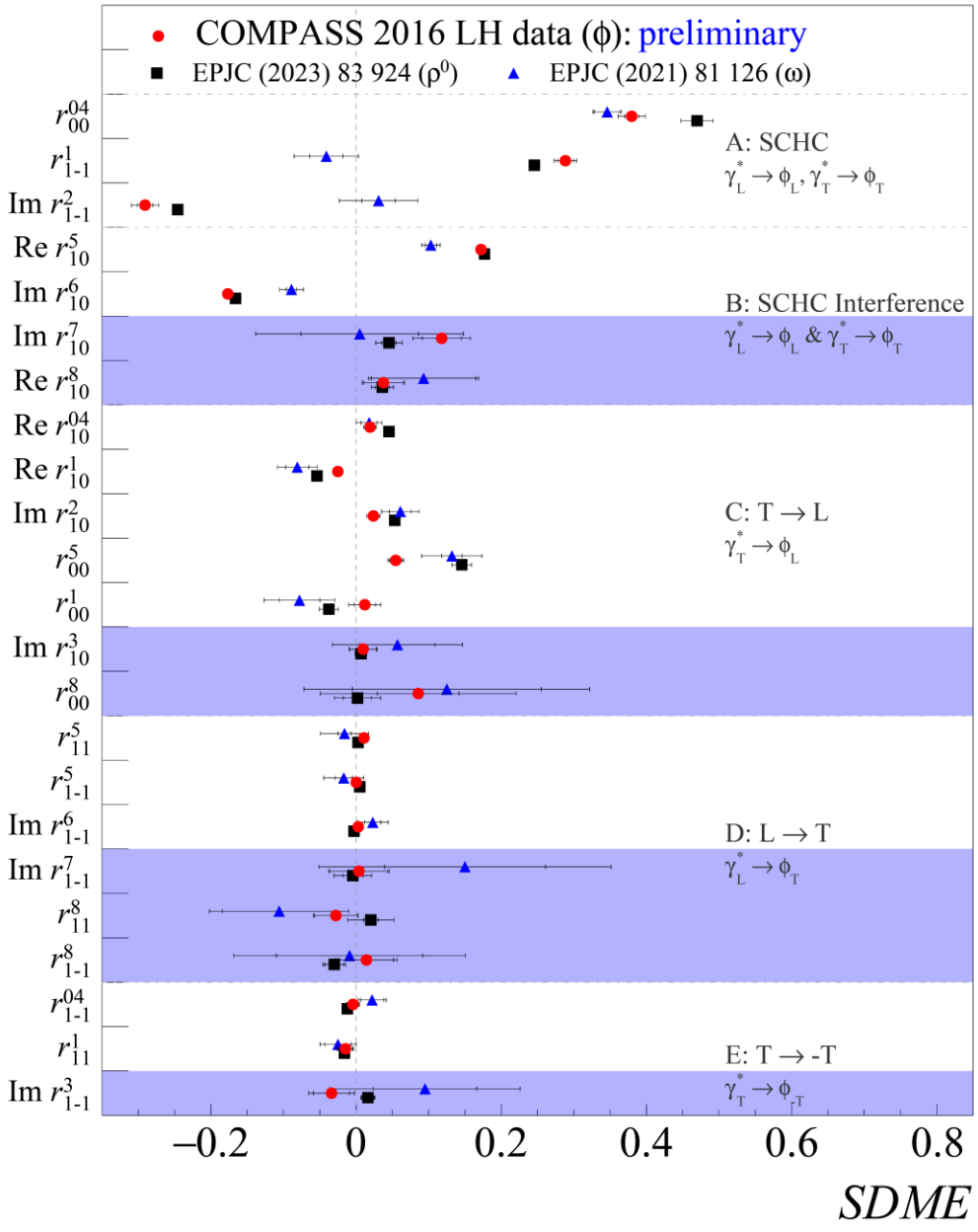
Spin Density Matrix Elements.

- SDMEs describe the spin state of a produced vector meson for example ρ^0, ϕ, J/ψ.
- SDMEs tells 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.

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

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

Spin Density Matrix Elements from photon to a VM



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

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Cahn effect in SIDIS: DVMs

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

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

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



Cahn effect

$f_1^q(x,\boldsymbol{k}_T^2)$
number density



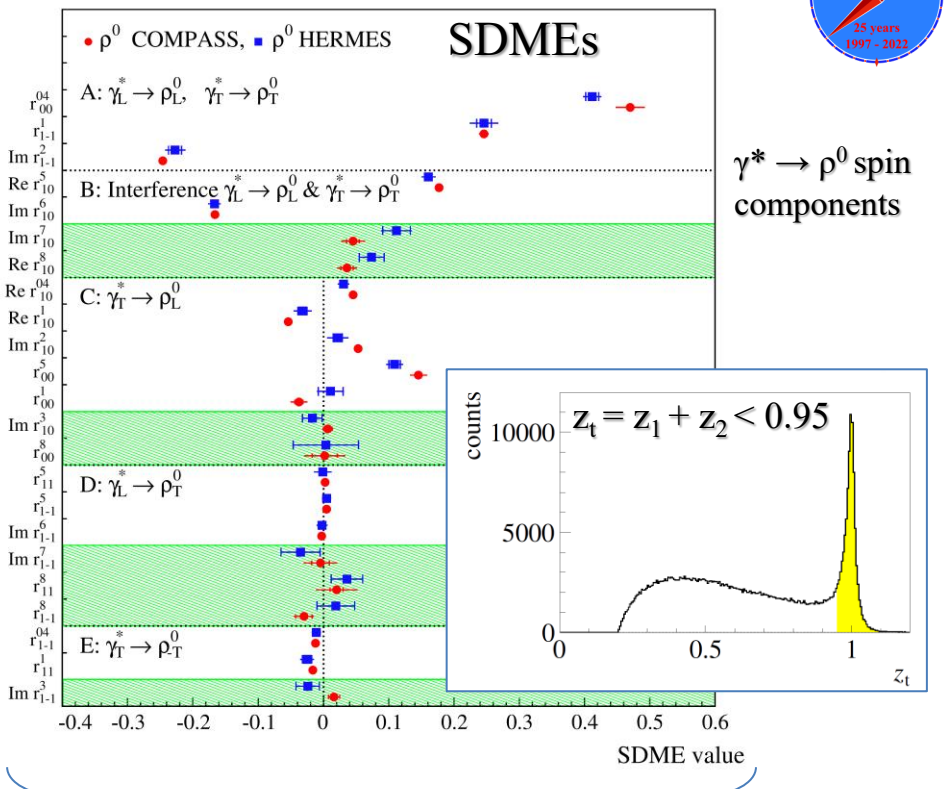
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

"Visible" hadron pairs

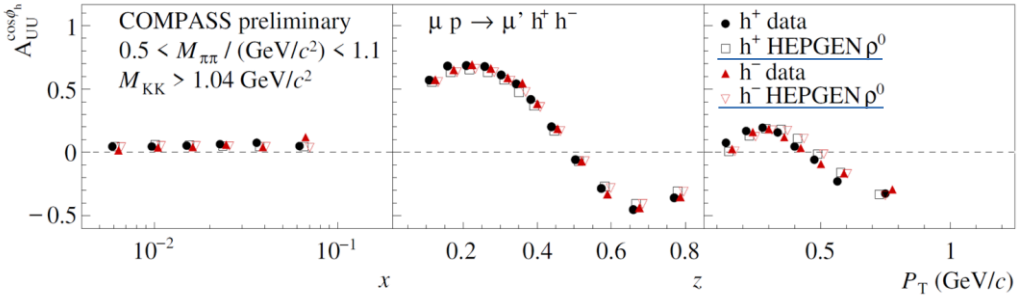
- Both hadrons reconstructed
- Removed by selecting: $z_t = z_{h+} + z_{h-} < 0.95$

COMPASS, EPJC (2023) 83 924



γ* → ρ⁰ spin components

VM contribution "amplitudes"



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

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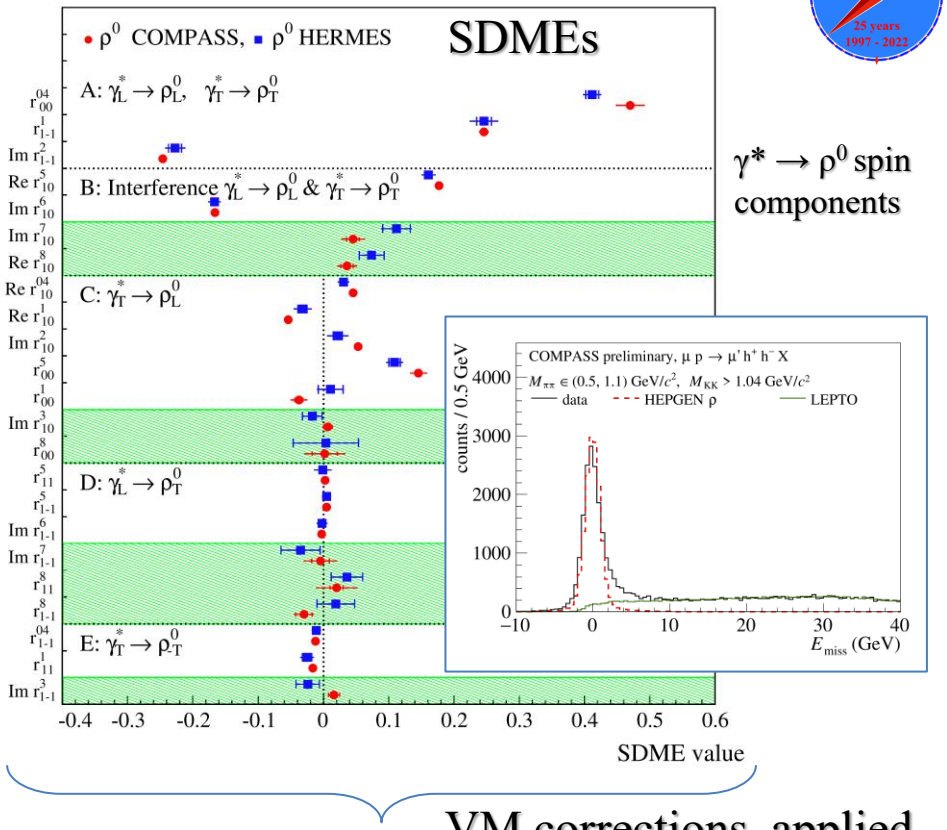
"Invisible" hadron pairs

- 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

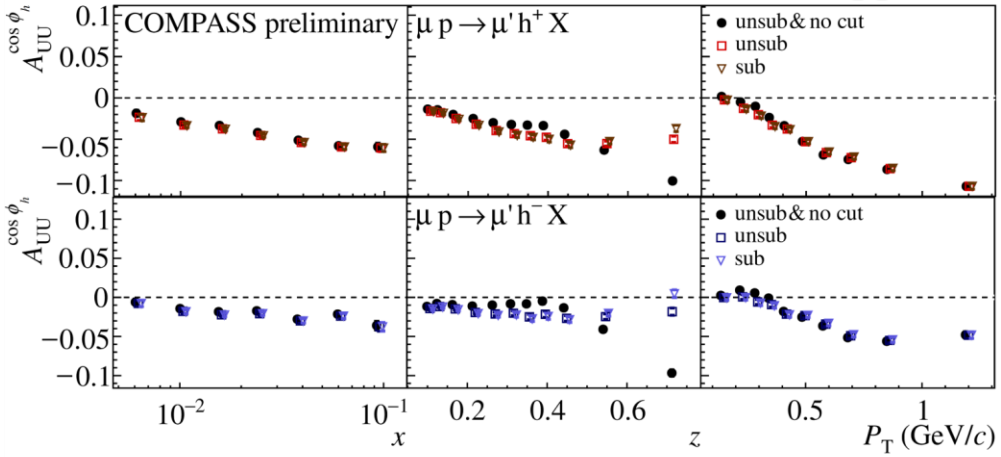


SDMEs



γ* → ρ⁰ spin components

VM corrections, applied



Cahn effect in SIDIS: DVMs and RCs

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

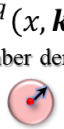
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

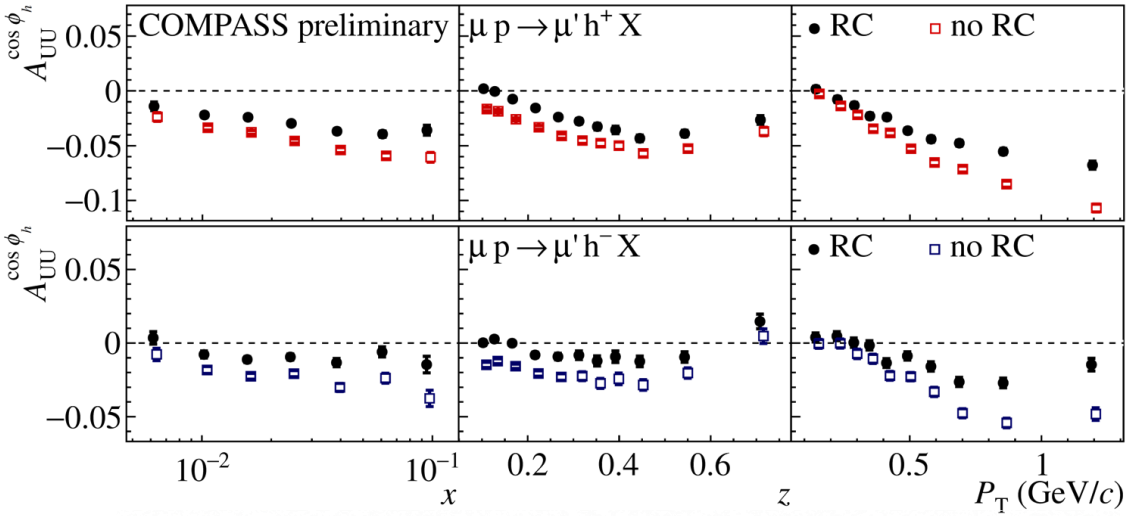
Cahn effect



$f_1^q(x,\boldsymbol{k}_T^2)$
number density



RC corrections, applied



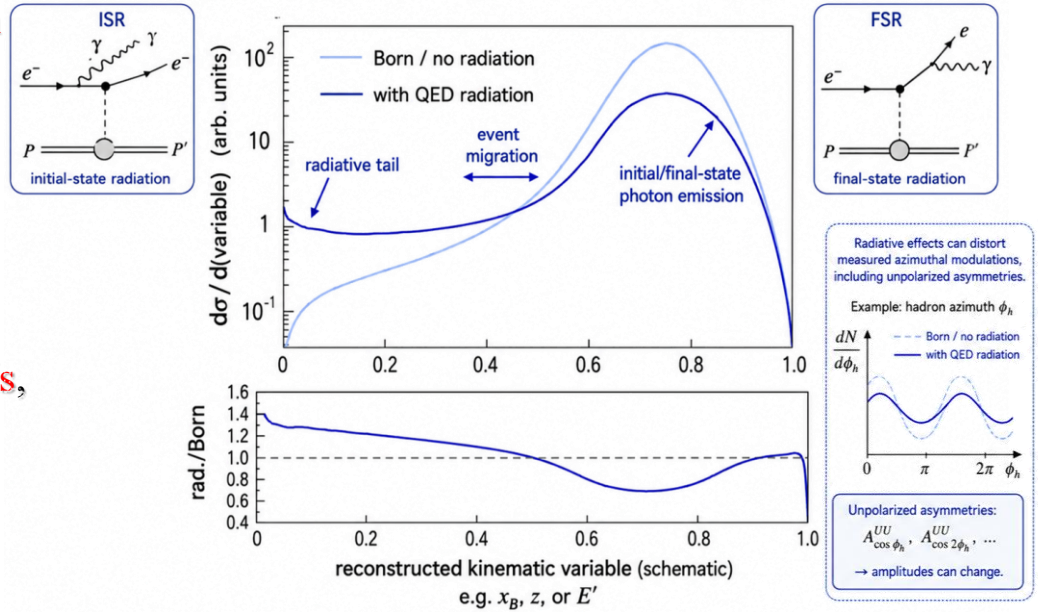
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- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
- Strong Q^2 dependence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

Illustration of QED radiative effects



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

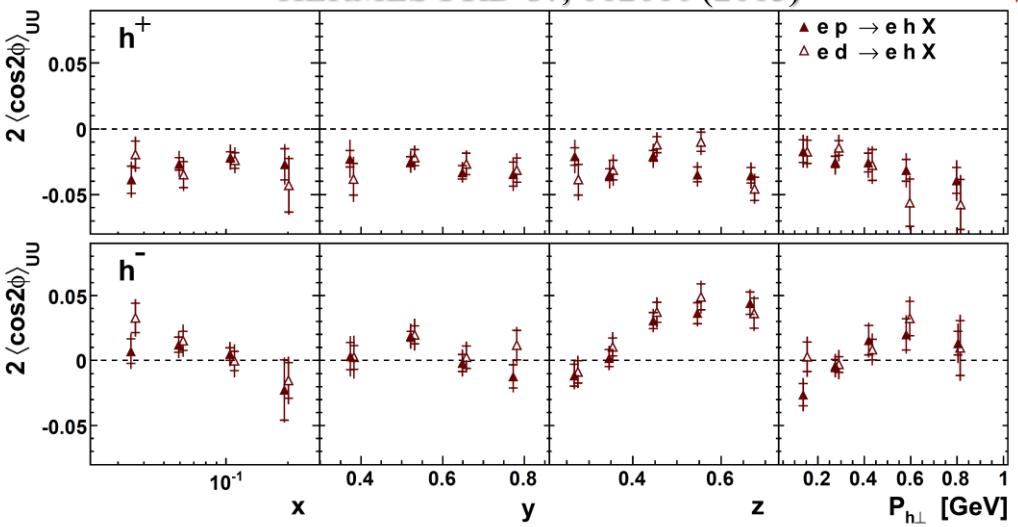
Azimuthal effects in unpolarized SIDIS: HERMES

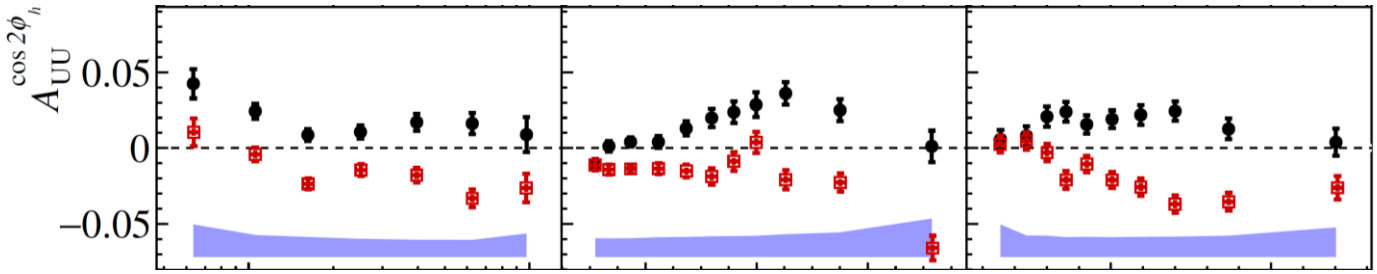
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

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

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

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

Cahn effect

Boer-Mulders PDF Collins FF

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

Azimuthal effects in unpolarized SIDIS: COMPASS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

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

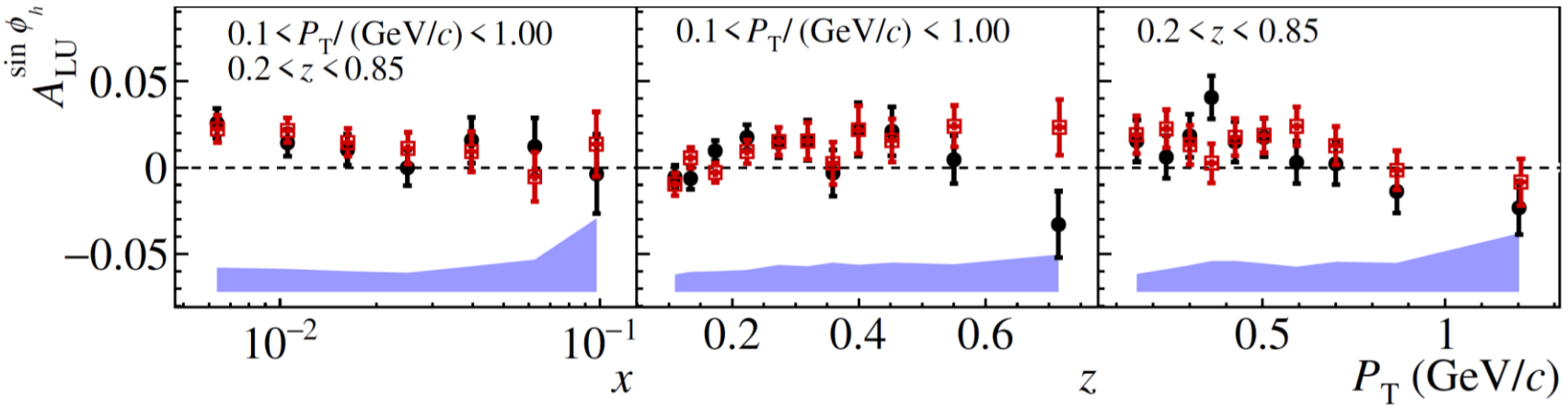
Target spin independent part of the cross-section: three asymmetries

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

Beam-spin asymmetry higher-twist effect

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

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



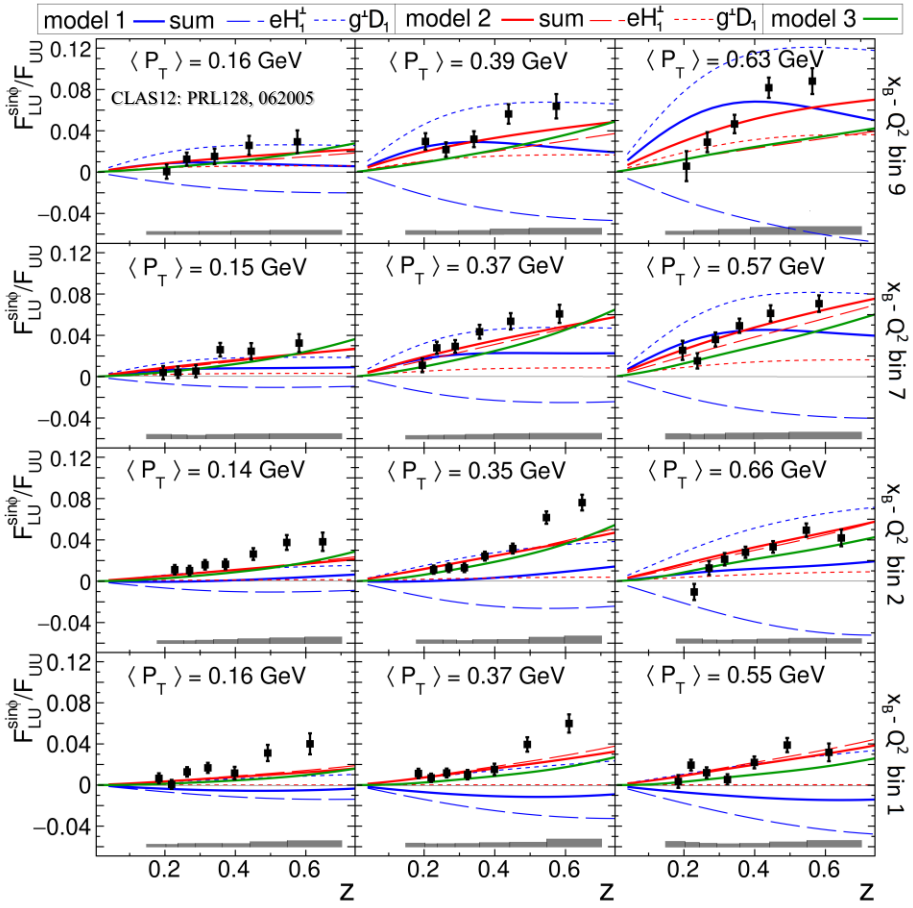
Azimuthal effects in unpolarized SIDIS: BSA CLAS12

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

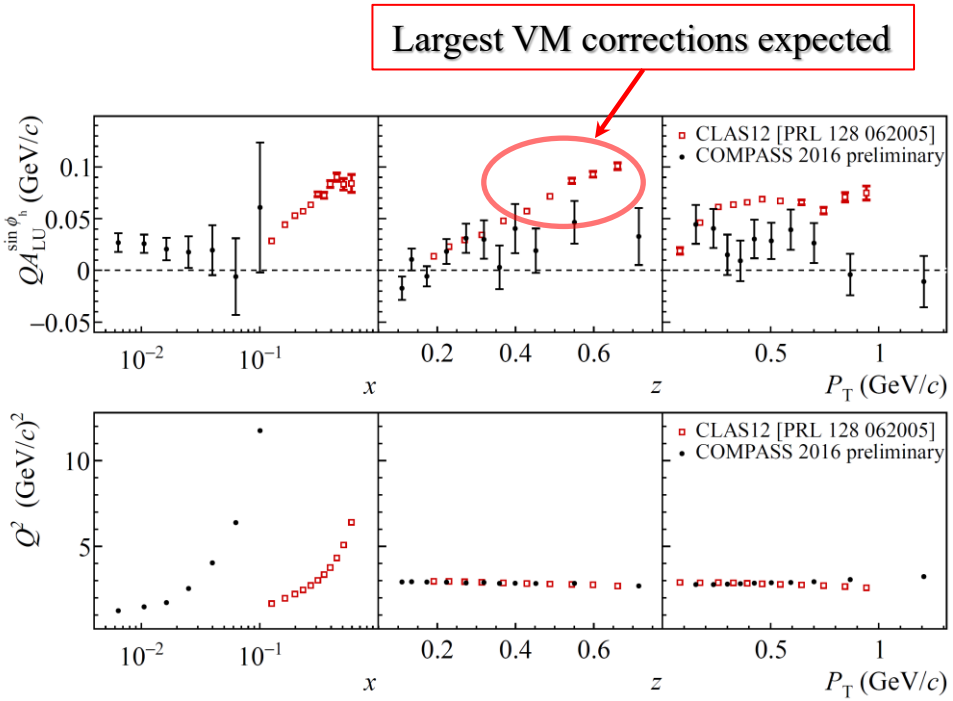
$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h+\ldots\right)$$

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?)



Largest VM corrections expected



CLAS12 results are not corrected for the VM contribution

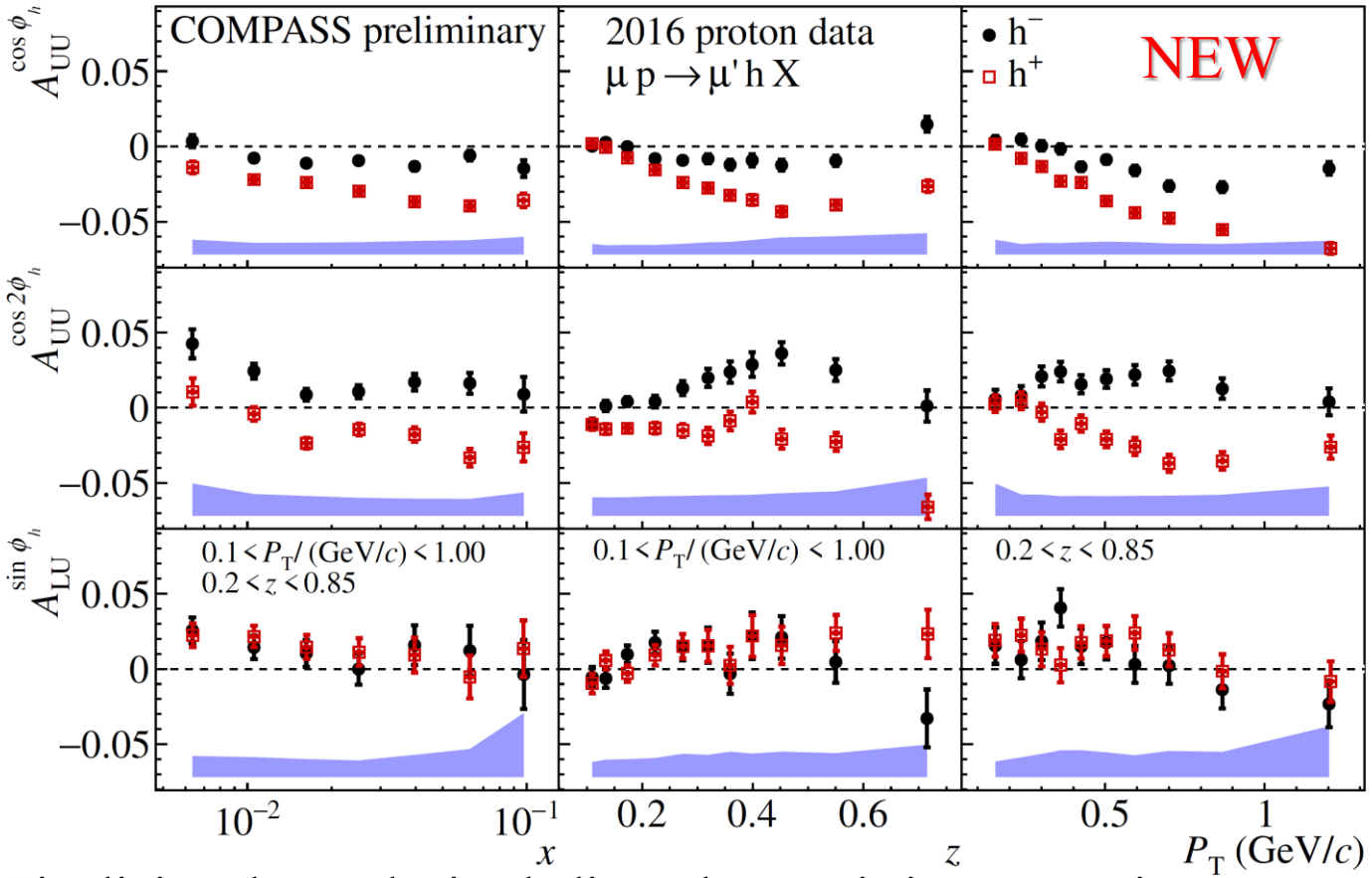
Azimuthal effects in unpolarized SIDIS: COMPASS

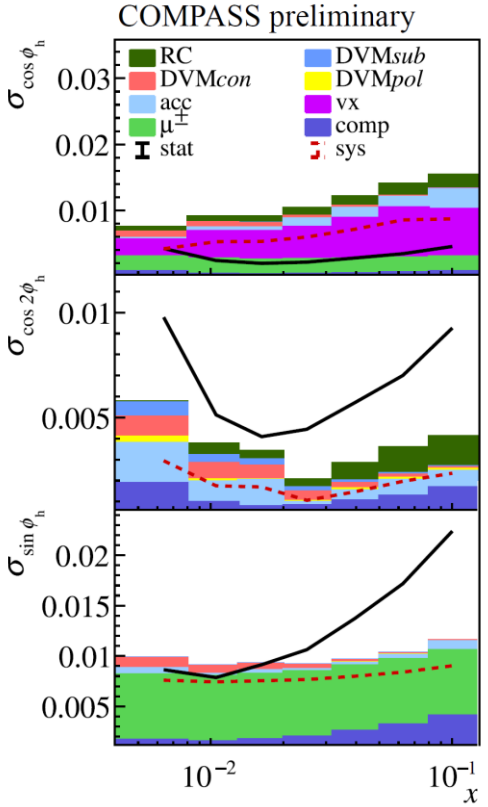
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

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

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

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





Finalizing the analysis, dedicated paper is in preparation

SIDIS x-section and TMDs at twist-2

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

All measured by COMPASS and HERMES

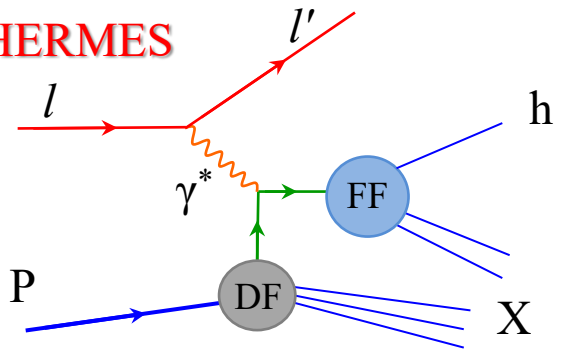
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

$$+ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UL}^{\sin\phi_h}\sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\,A_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

$$+ S_T\left[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\right]$$

$$+ S_T\lambda\left[\sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) + \sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\right]\Big\}$$



quark

nucleon

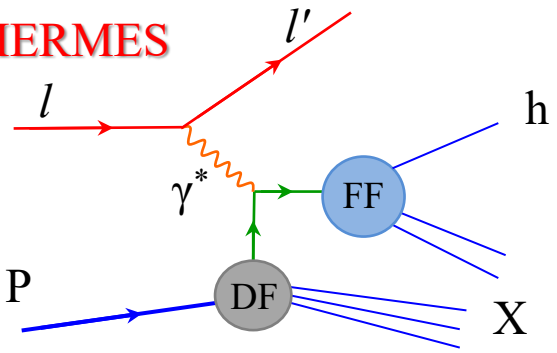
	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L
T	Sivers	Kotzinian-Mulders worm-gear T	transversity, pretzelosity

spin of the nucleon spin of the quark k_T

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

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

All measured by COMPASS and HERMES



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

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

$$+ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]$$

$$+ S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

$$+ S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ + \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\end{array}\right]$$

$$+ S_T\lambda\left[\begin{array}{l}\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ + \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\end{array}\right]\Bigg\}$$

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

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

Twist-2

Twist-3

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

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

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

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

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

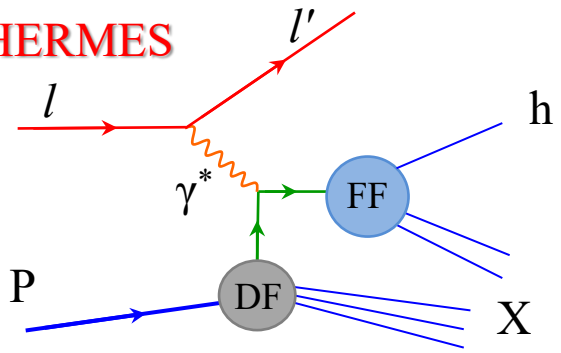
$A_{LT}^{\cos(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^{q}\otimes D_{1q}^{h}+\ldots\right)$

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

All measured by COMPASS and HERMES

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

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



$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q}C\left\{\left(xf_T^q D_{1q}^h - \frac{M_h}{M}h_1^q\frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(xh_T^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1T}^q\frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(xh_T^{\perp q}H_{1q}^{\perp h} - \frac{M_h}{M}f_{1T}^{\perp q}\frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

$$F_{UT}^{\sin(2\phi_h-\phi_S)} = \frac{2M}{Q}C\left\{\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T})^2-\boldsymbol{k_T^2}}{2M^2}\left(xf_T^{\perp q}D_{1q}^h - \frac{M_h}{M}h_{1T}^{\perp q}\frac{\tilde{H}_q^h}{z}\right) - \frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T})(\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T})-\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(xh_T^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1T}^q\frac{\tilde{G}_q^{\perp h}}{z}\right) + \left(xh_T^{\perp q}H_{1q}^{\perp h} - \frac{M_h}{M}f_{1T}^{\perp q}\frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

Twist-3

$$F_{LT}^{\cos\phi_S} = \frac{2M}{Q}C\left\{-\left(xg_T^q D_{1q}^h + \frac{M_h}{M}h_1^q\frac{\tilde{E}_q^h}{z}\right) + \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(xe_T^q H_{1q}^{\perp h} - \frac{M_h}{M}g_{1T}^q\frac{\tilde{D}_q^{\perp h}}{z}\right) + \left(xe_T^{\perp q}H_{1q}^{\perp h} + \frac{M_h}{M}f_{1T}^{\perp q}\frac{\tilde{G}_q^{\perp h}}{z}\right)\right]\right\}$$

$$F_{LT}^{\cos(2\phi_h-\phi_S)} = \frac{2M}{Q}C\left\{-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T})^2-\boldsymbol{k_T^2}}{2M^2}\left(xg_T^{\perp q}D_{1q}^h + \frac{M_h}{M}h_{1T}^{\perp q}\frac{\tilde{E}_q^h}{z}\right) + \frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T})(\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T})-\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(xe_T^q H_{1q}^{\perp h} - \frac{M_h}{M}g_{1T}^q\frac{\tilde{D}_q^{\perp h}}{z}\right) - \left(xe_T^{\perp q}H_{1q}^{\perp h} + \frac{M_h}{M}f_{1T}^{\perp q}\frac{\tilde{G}_q^{\perp h}}{z}\right)\right]\right\}$$

SIDIS TSAs: Collins effect and Transversity

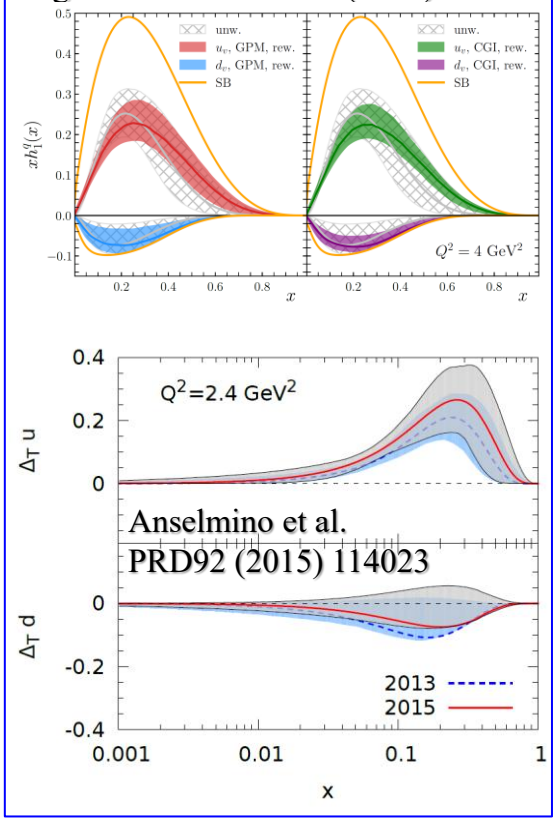
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon\, A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\right\}$$

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

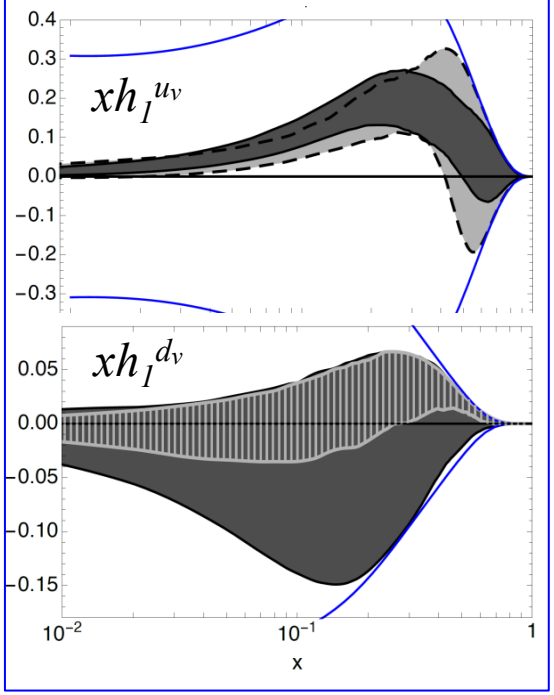


- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution? Clear signal at STAR energies
- Extensive phenomenological studies and various global fits by different groups

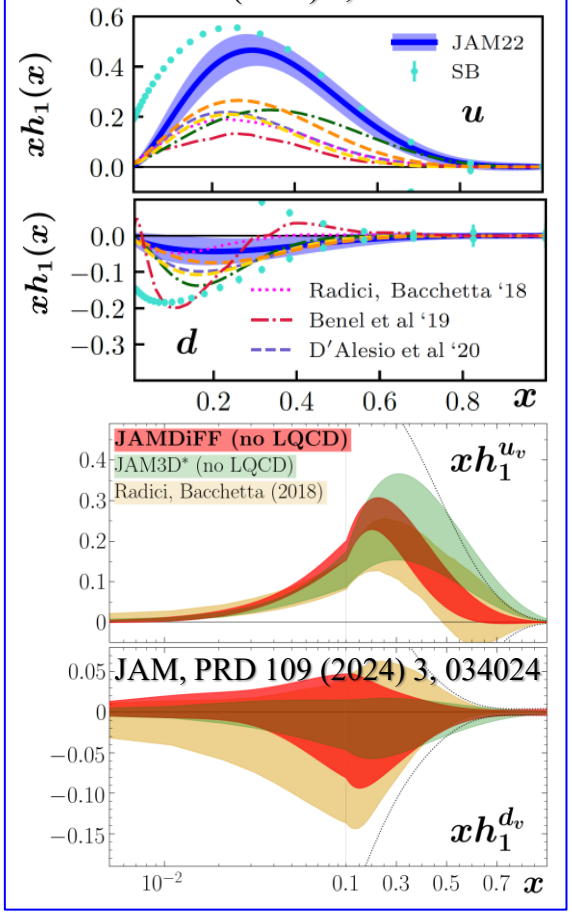
Boglione et al. PLB 854 (2024) 138712



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



JAM PRD 106 (2022) 3, 034014



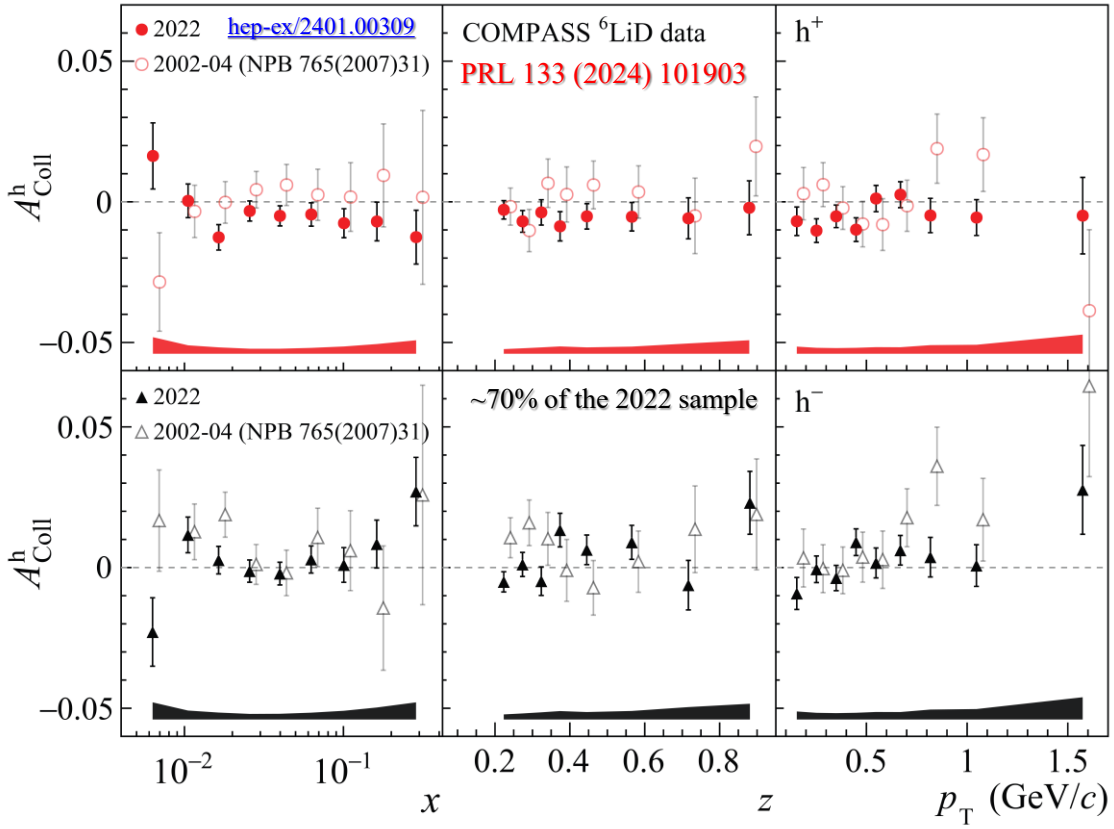
SIDIS TSAs: Collins effect and Transversity

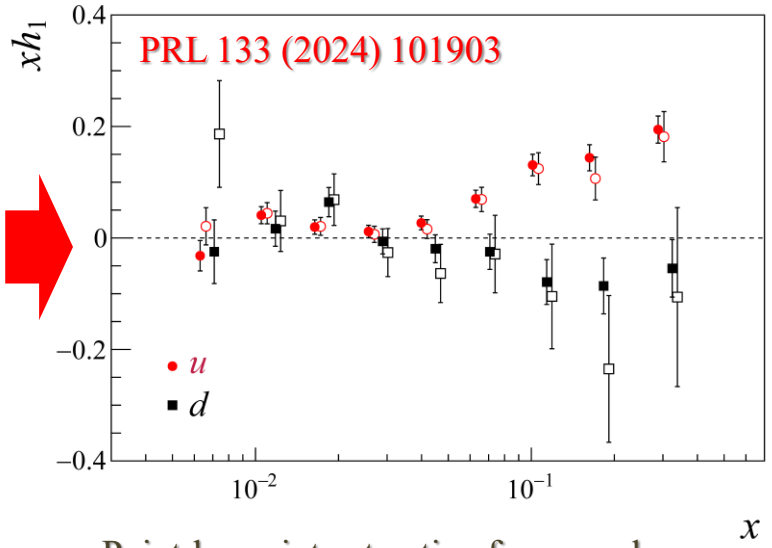
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon\, A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\right\}$$

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



- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~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)

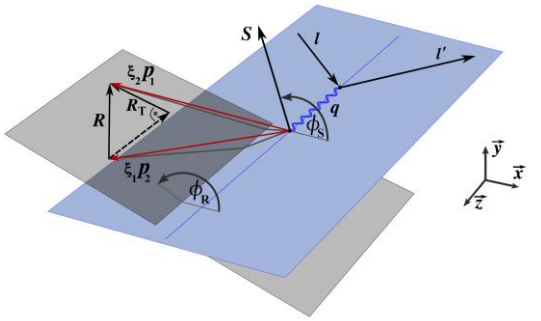
COMPASS 2022 run – highly successful data-taking!

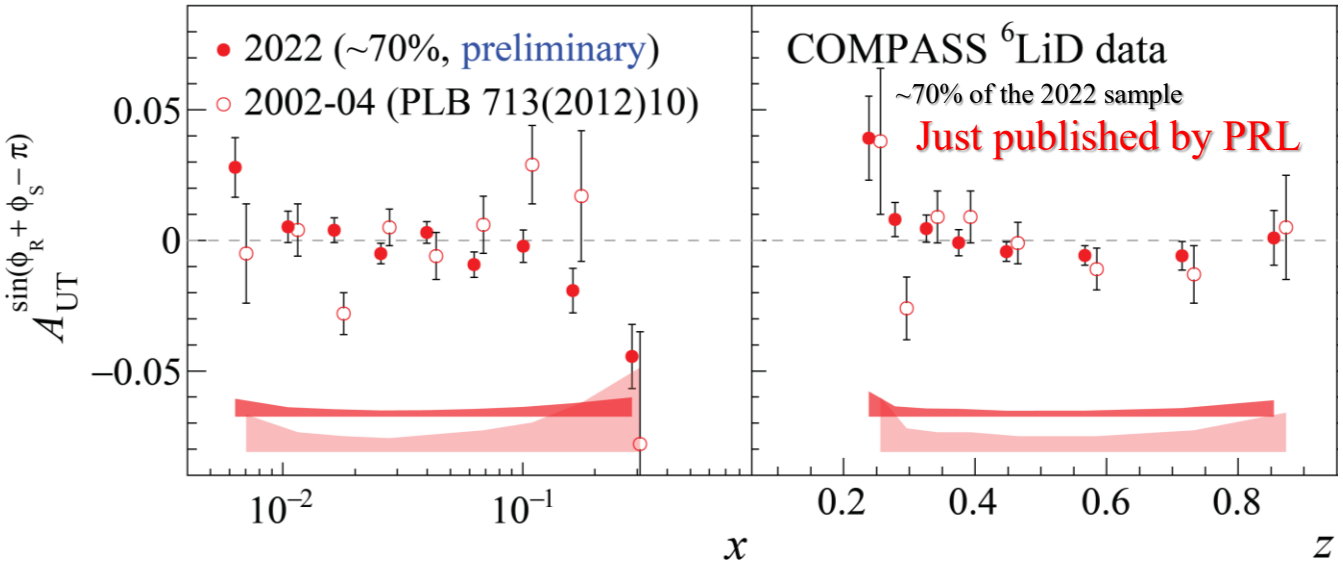
- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades

Dihadron Collins effect and Transversity

$$\frac{d^7\sigma}{d\cos\theta\, dM_{hh}\, d\phi_R\, dz\, dx\, dy\, d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y}\left((1-y+\frac{y^2}{2})\sum_q e_q^2\, f_1^q(x)\, D_{1,q}(z, M_{hh}^2, \cos\theta) + S_\perp(1-y)\sum_q e_q^2 \frac{|\mathbf{p}_1-\mathbf{p}_2|}{2M_{hh}} \sin\theta\, \sin\phi_{RS}\, h_1^q(x)\, H_{1,q}^{\sphericalangle}(z, M_{hh}^2, \cos\theta)\right)$$

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



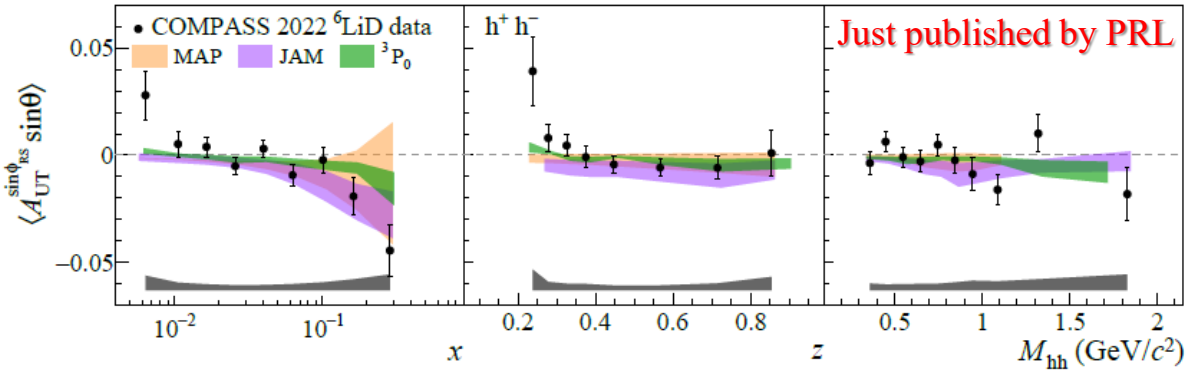


COMPASS 2022 run – highly successful data-taking!

- 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

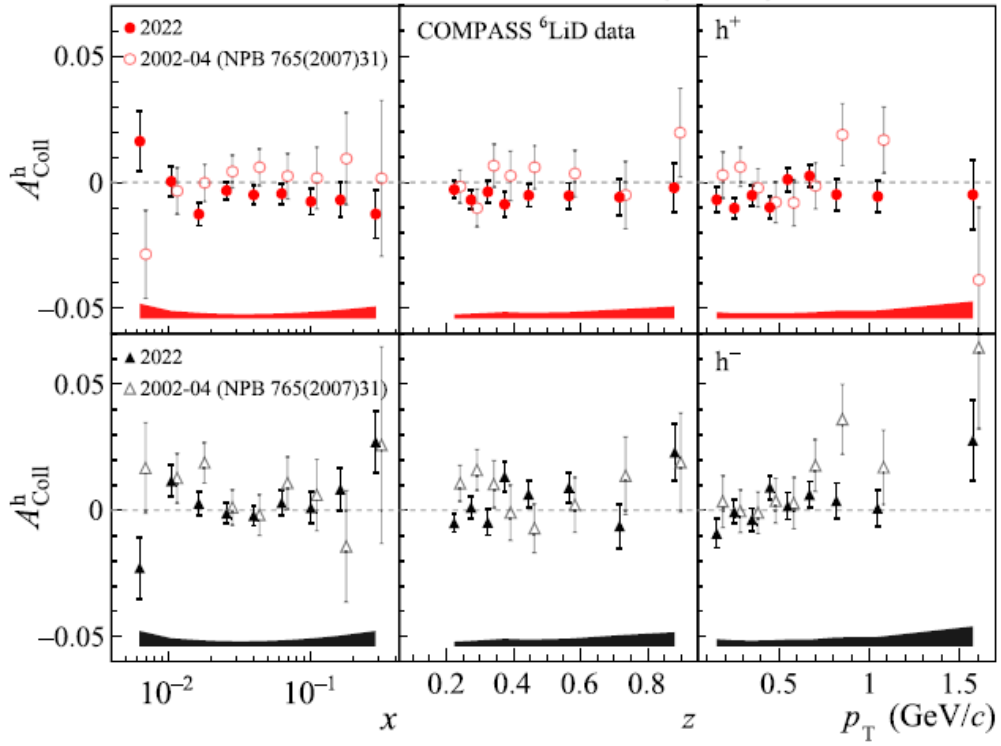
COMPASS data: access to collinear and TMD transversity

COMPASS PRL 137 (2026) 171903



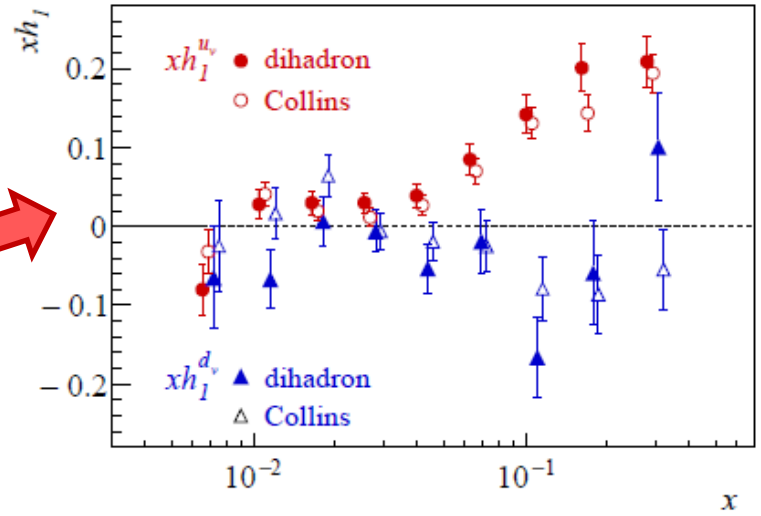
Just published by PRL

COMPASS PRL 133 (2024) 101903



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COMPASS PRL 137 (2026) 171903



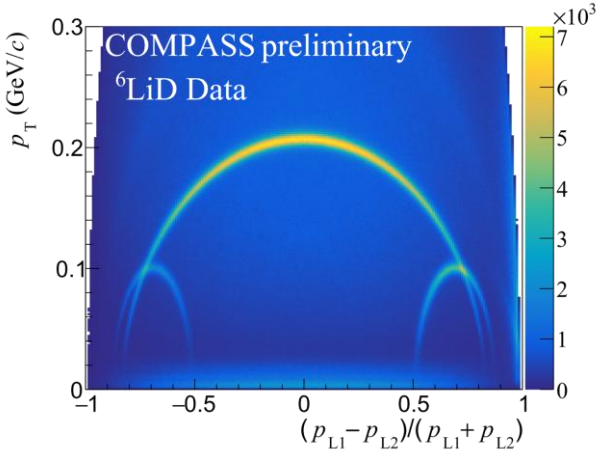
SIDIS TSAs: Collins effect for K^0

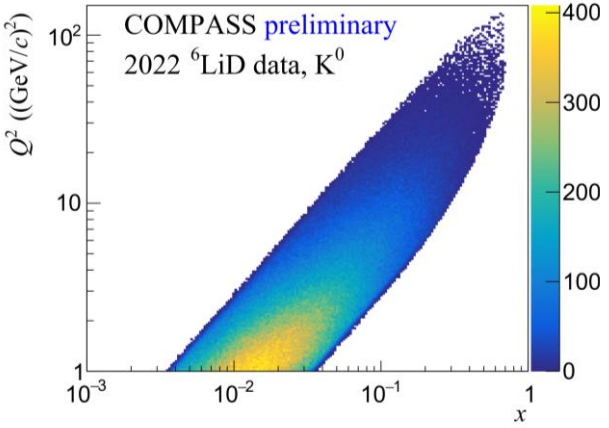
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon\, A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\right\}$$

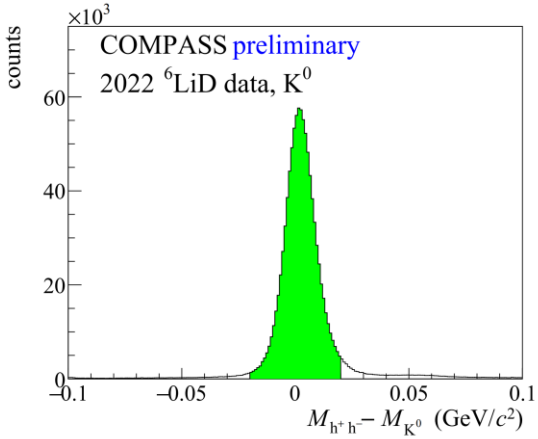
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

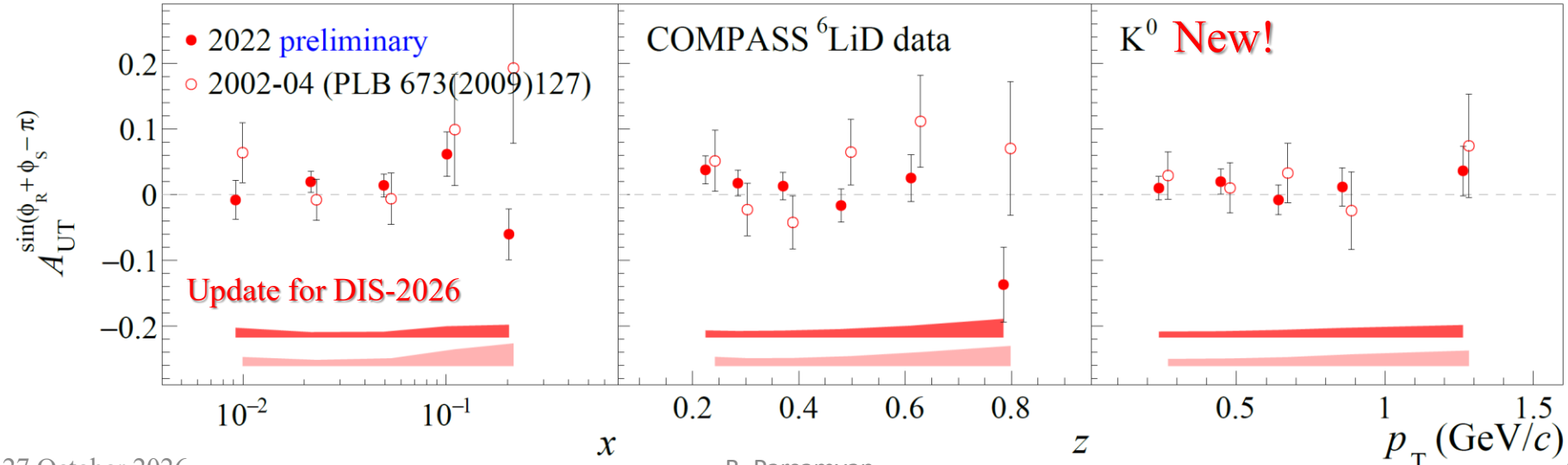


- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity









SIDIS TSAs: Kotzinian-Mulders asymmetry

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

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

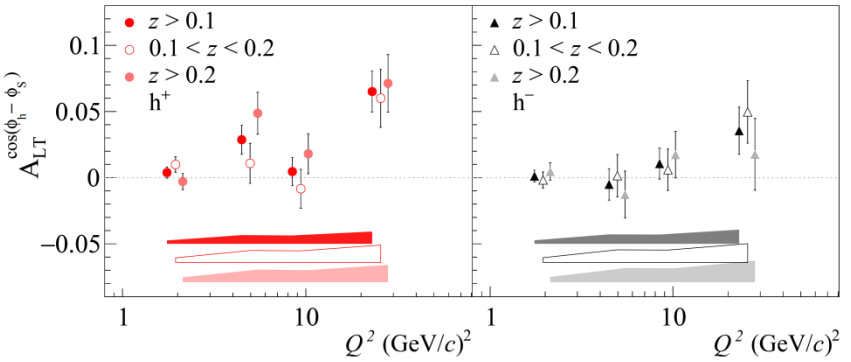




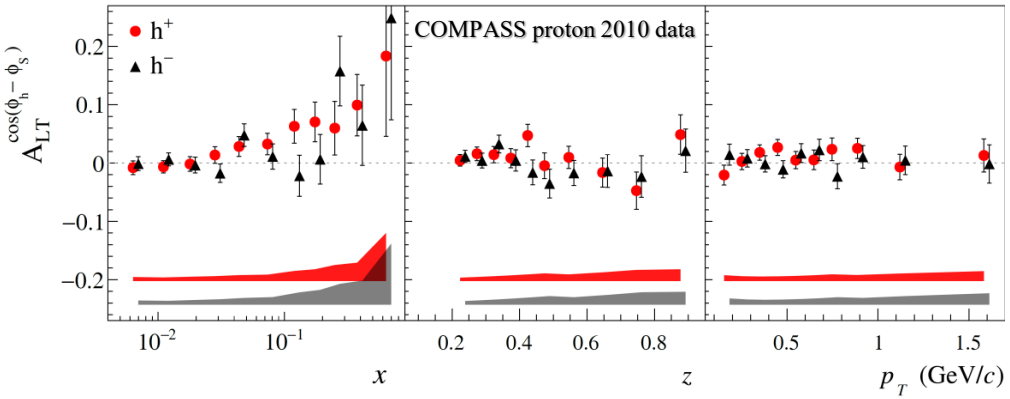
COMPASS/HERMES/CLAS6 results

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

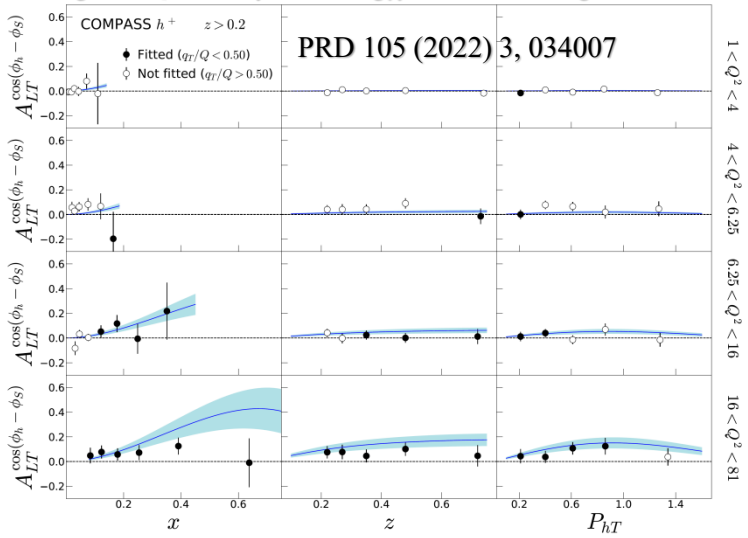
- Only "twist-2" ingredients
- Sizable non-zero effect for h^+ !
- Similar effect at HERMES

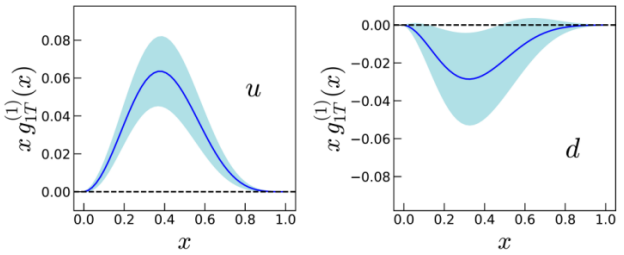


COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



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





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

SIDIS TSAs: Kotzinian-Mulders asymmetry

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

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

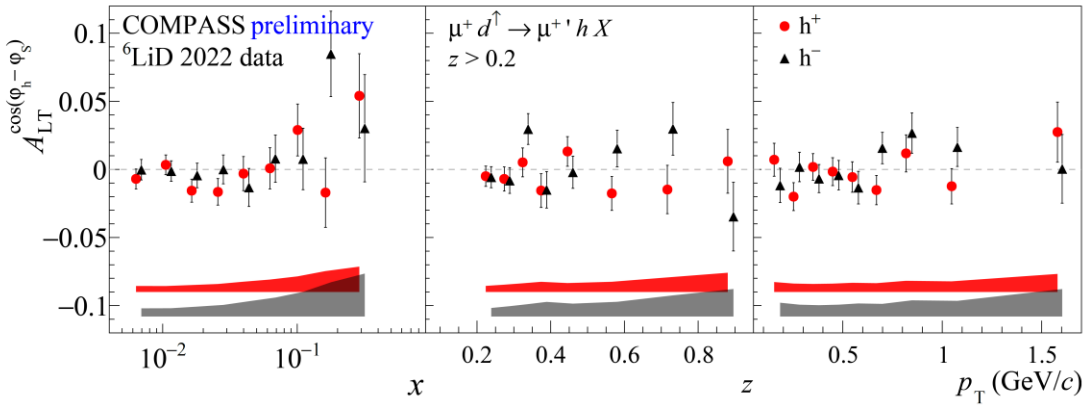




COMPASS/HERMES/CLAS6 results

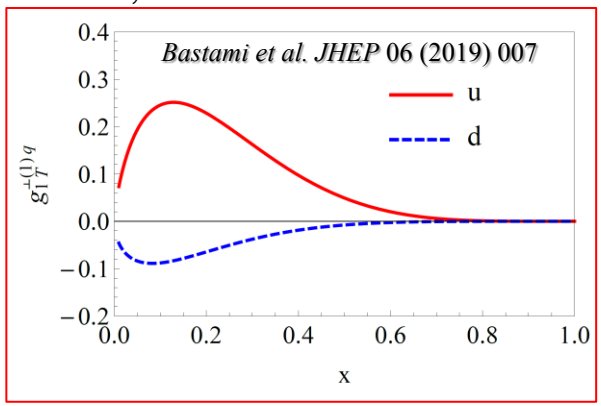
$A_{LT}^{\cos(\phi_h-\phi_S)}$

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

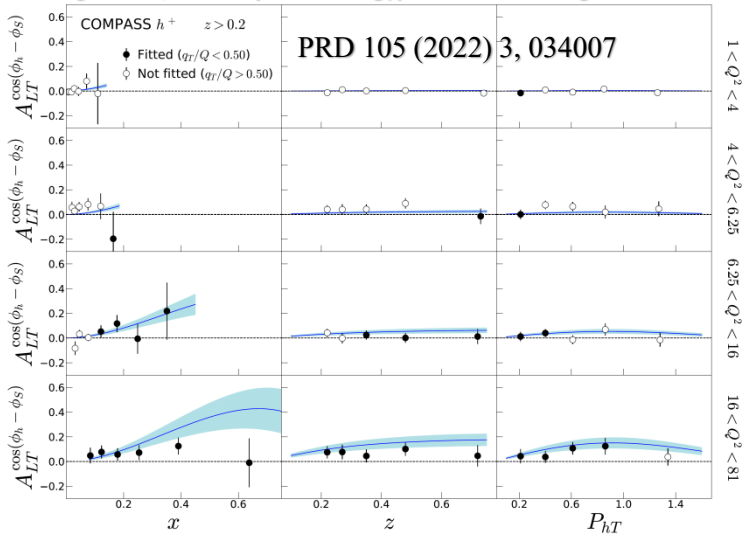


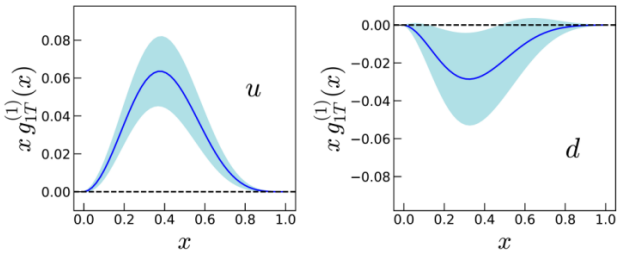
New COMPASS 2022 deuteron data

- 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



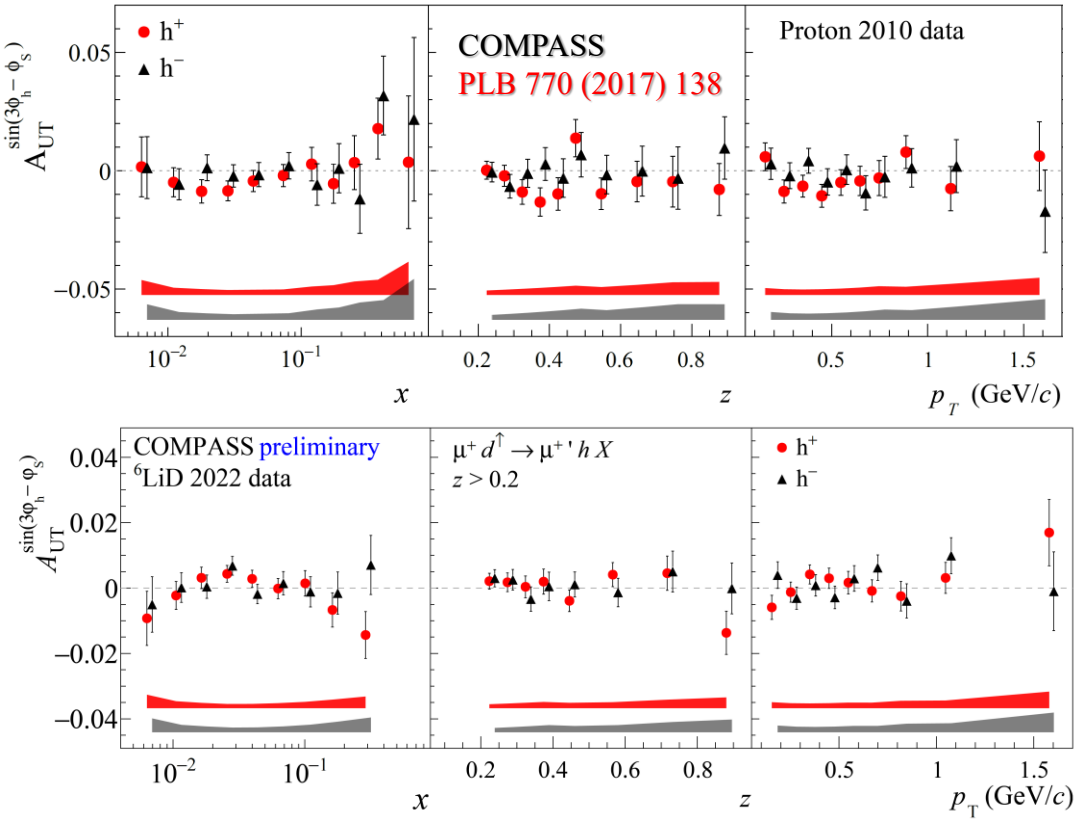


SIDIS TSAs: Pretzelosity TSA

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

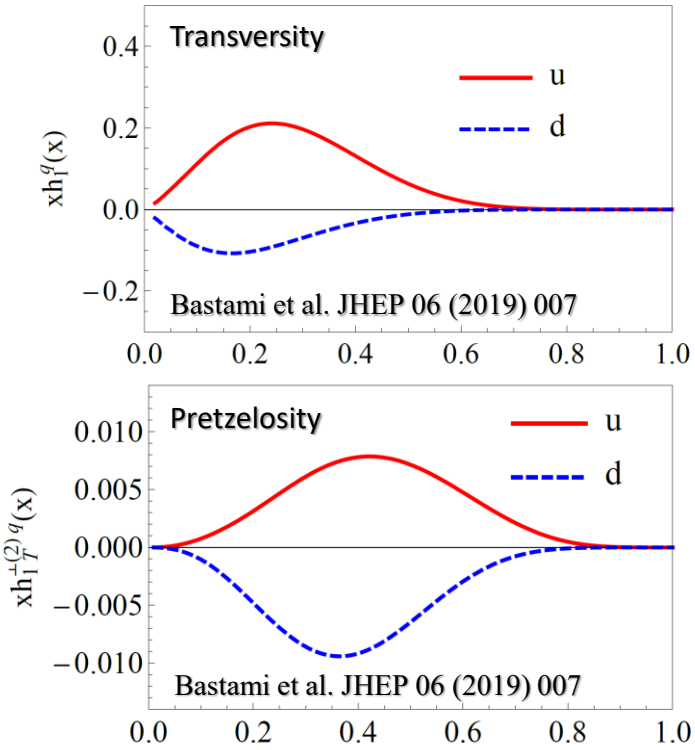
$$F_{UT}^{\sin(3\phi_h-\phi_S)} = C\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\boldsymbol{k}_T\cdot\boldsymbol{p}_T\right) + \boldsymbol{k}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right) - 4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)}{2M^2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

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



COMPASS/HERMES results with proton target

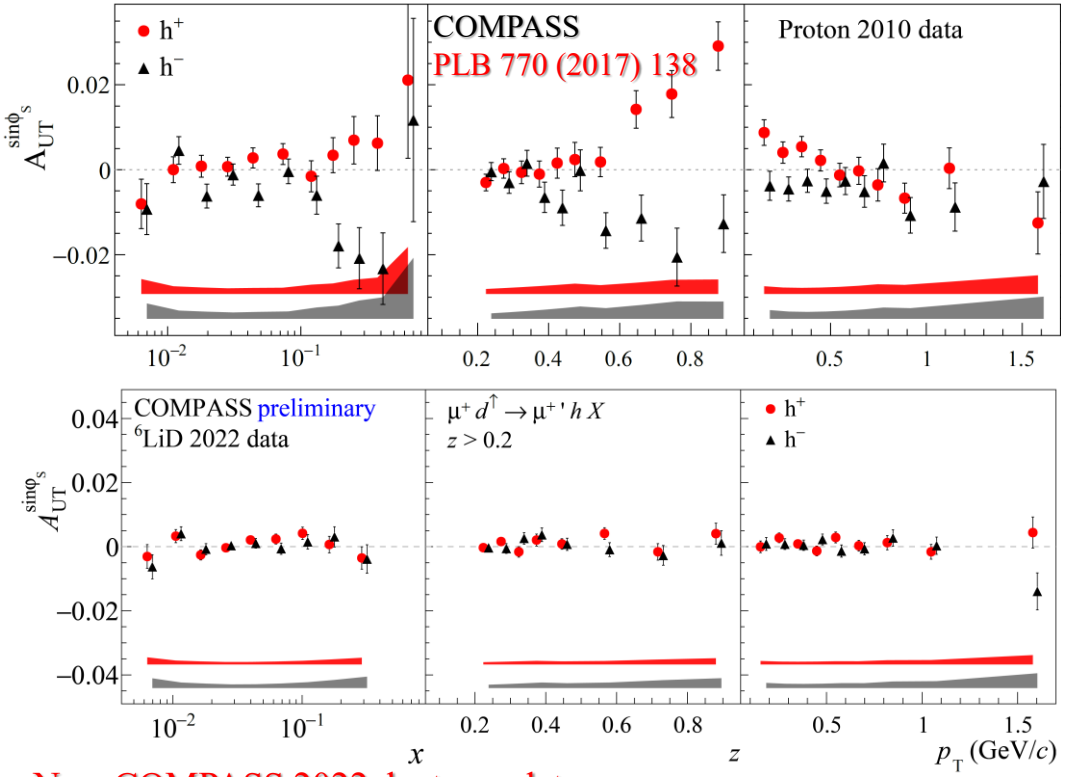
- Proton asymmetry is small (below 1-2 %)
- TSA is compatible with zero for both h^+ and h^-
- The measurements are compatible with models



SIDIS TSAs: subleading twist effects

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

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



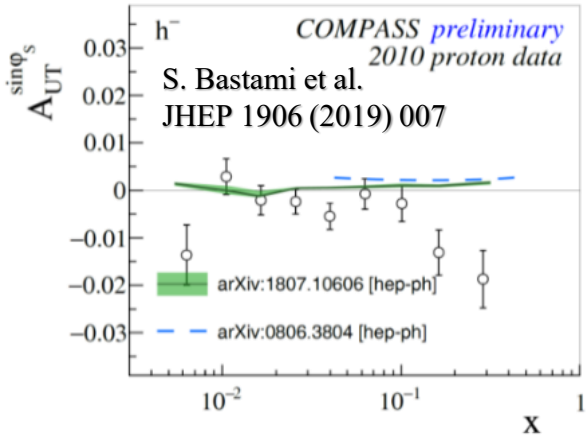
New COMPASS 2022 deuteron data

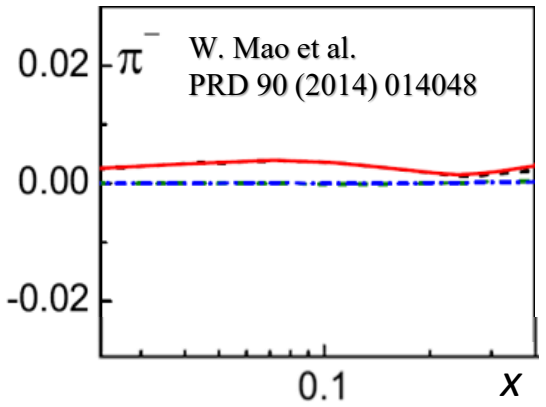
- The asymmetry is compatible with zero within the uncertainties
- The measured amplitudes are below 1%

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

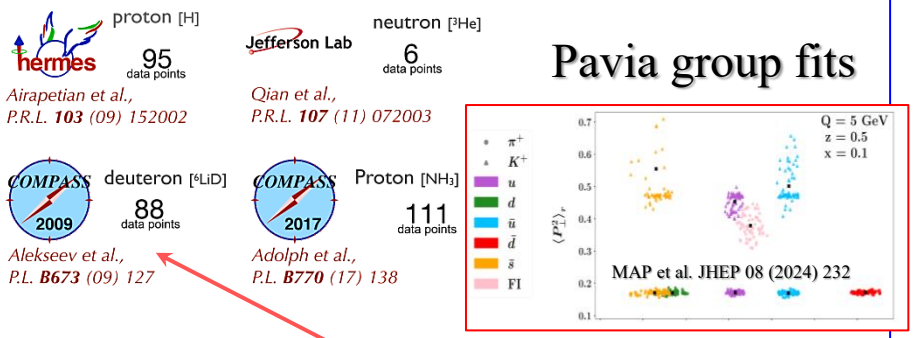
COMPASS/HERMES results with proton target

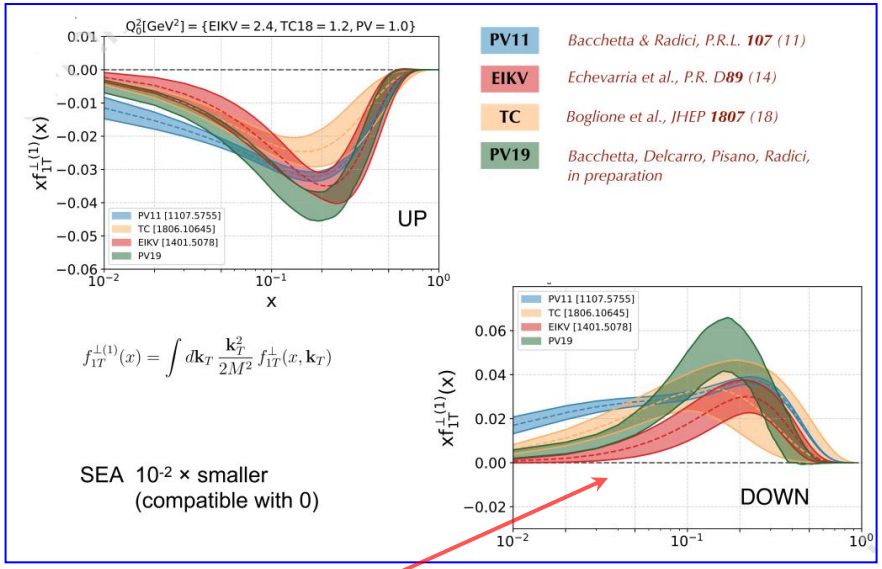
- Small TSA; signal at large z for both h^+ and h^-
  - Can large-z signal be induced by DVMs?



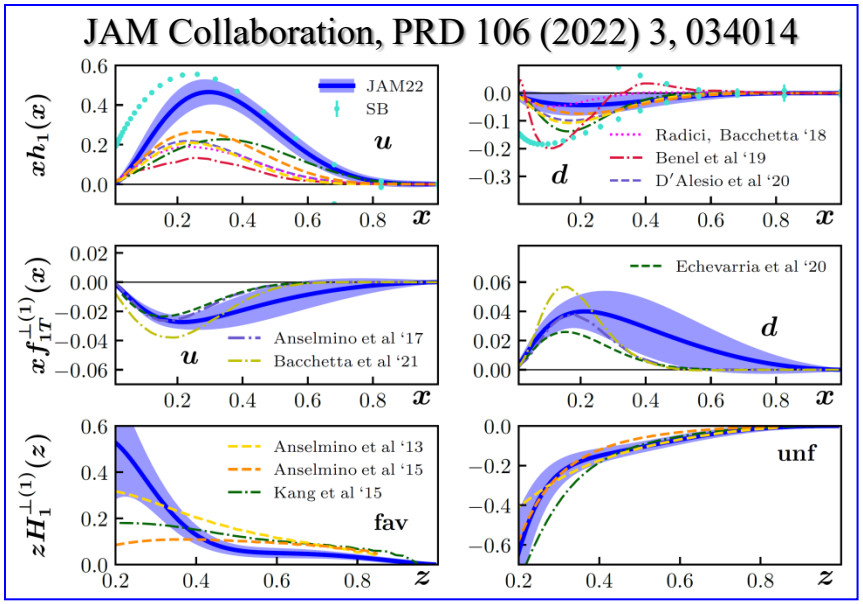


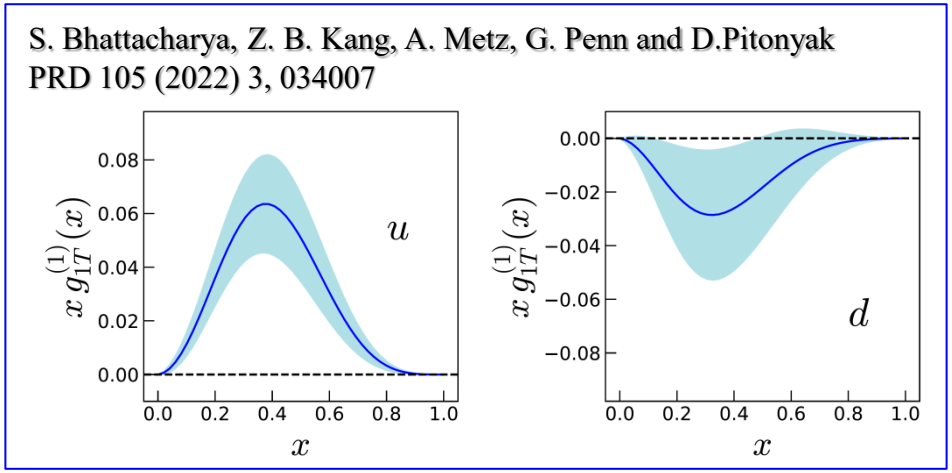
COMPASS 2022 run: new unique deuteron data





COMPASS 2022 deuteron run



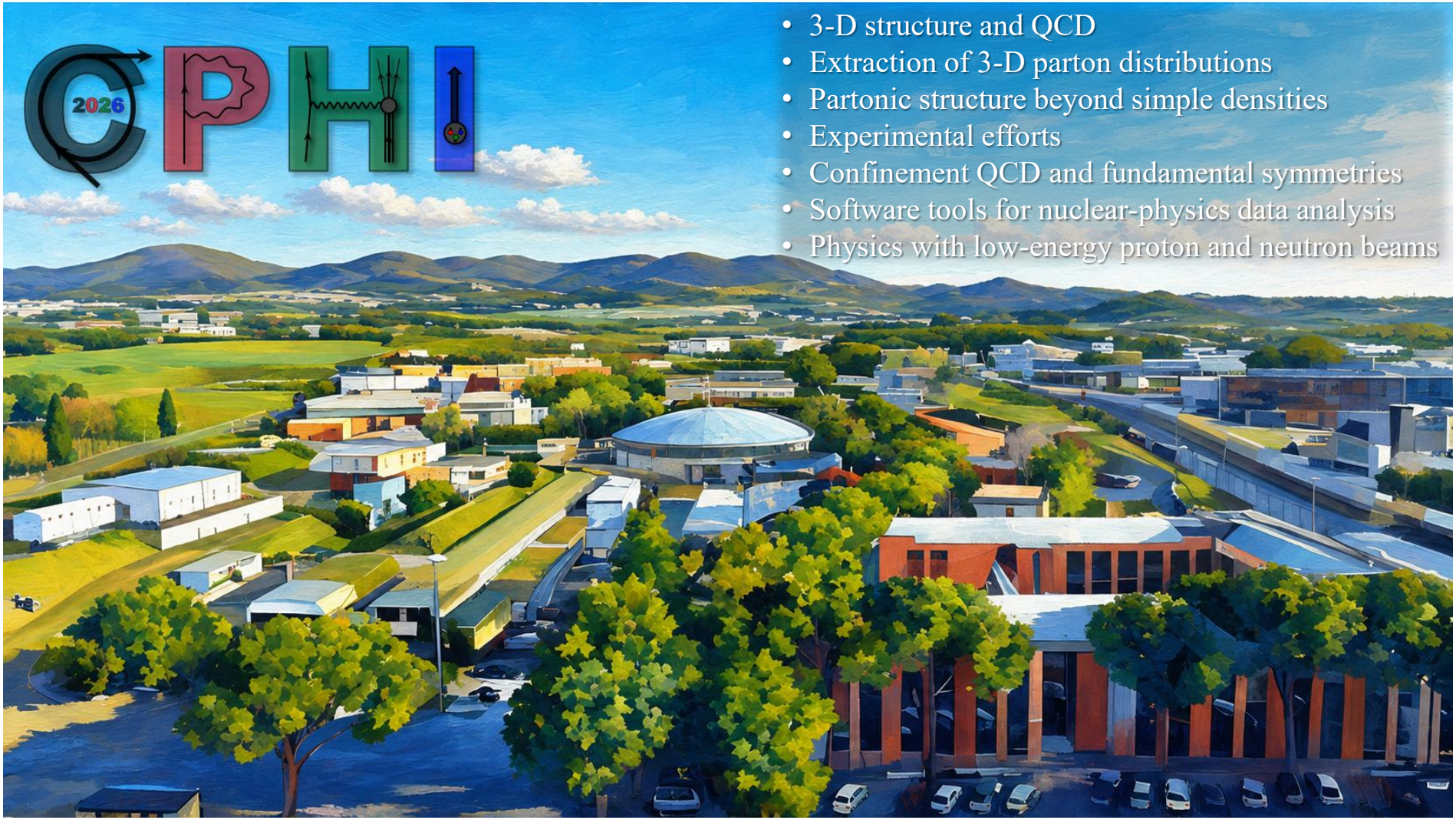


More news soon…

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 → competitive domain 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 and with EIC
  - COMPASS provides a broad set of measurements in a complementary kinematic regime
  - Growing interest in knowledge transfer, joint analyses and collaborative initiatives
- Since 2023, COMPASS has entered its Analysis Phase → Four new groups have joined
  - 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
  - Collecting inputs for the Phase II proposal
  - An EOI for a polarized Drell-Yan programme at AMBER is now also being prepared
- LHCspin – bringing polarized fixed-target physics to the LHC
  - Building on the successful SMOG2 programme at LHCb
  - Development of a polarized H/D gas target, with a staged R&D and implementation programme
  - Unique opportunities to explore quark and gluon spin structure at unprecedented FT energies
  - Strong complementarity with COMPASS, AMBER and future EIC measurement

Thank You!



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)