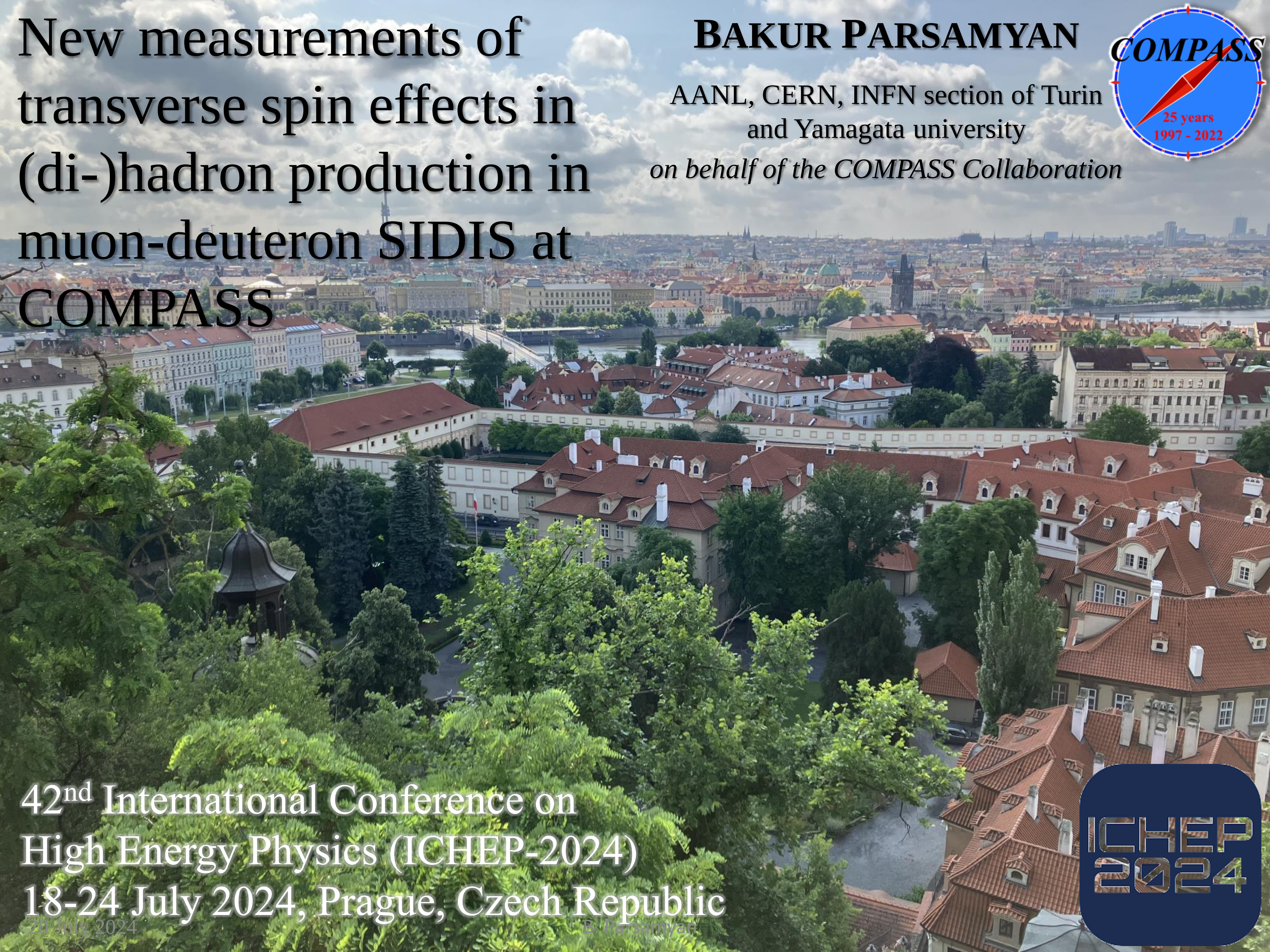
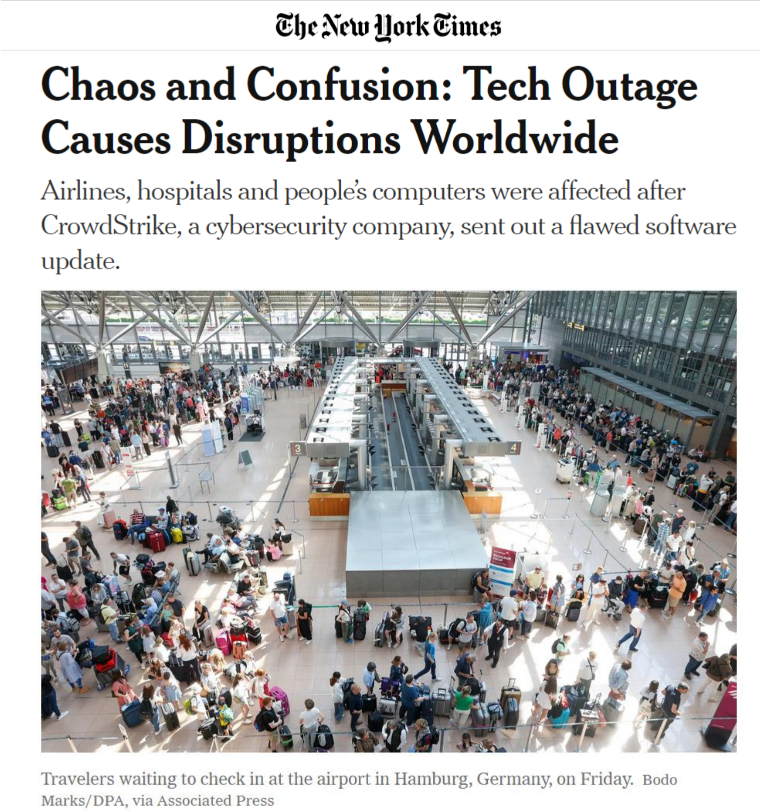


New measurements of transverse spin effects in (di-)hadron production in muon-deuteron SIDIS at COMPASS

BAKUR PARSAMYAN

AANL, CERN, INFN section of Turin
and Yamagata university
on behalf of the COMPASS Collaboration

42nd International Conference on
High Energy Physics (ICHEP-2024)
18-24 July 2024, Prague, Czech Republic


The New York Times

Chaos and Confusion: Tech Outage Causes Disruptions Worldwide

Airlines, hospitals and people's computers were affected after CrowdStrike, a cybersecurity company, sent out a flawed software update.

Travelers waiting to check in at the airport in Hamburg, Germany, on Friday. Bodo Marks/DPA, via Associated Press


aaron @aaronoleary

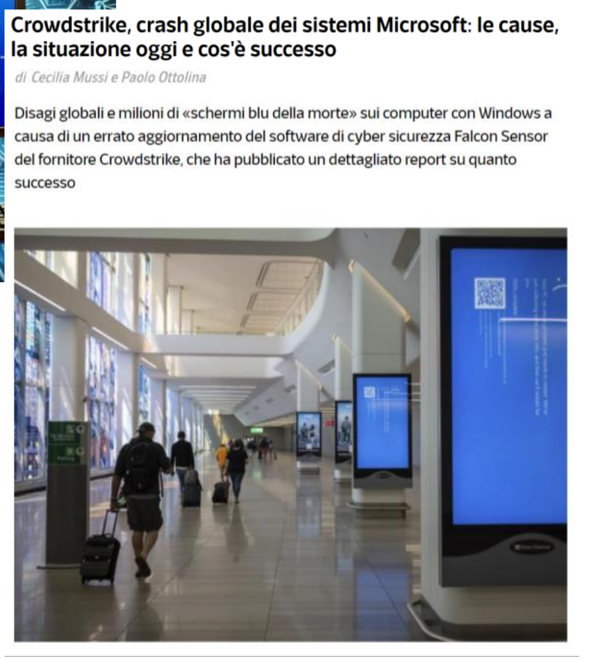
They got the vegas ball. It's all over. We lost.


sophie @netcapgirl

crowdstrike intern after pushing to prod

5:54 AM · Jul 19, 2024 · **370.2K** Views

CrowdStrike Update Causing Blue Screen of Death and Microsoft 365/Azure Outage


Crowdstrike, crash globale dei sistemi Microsoft: le cause, la situazione oggi e cos'è successo

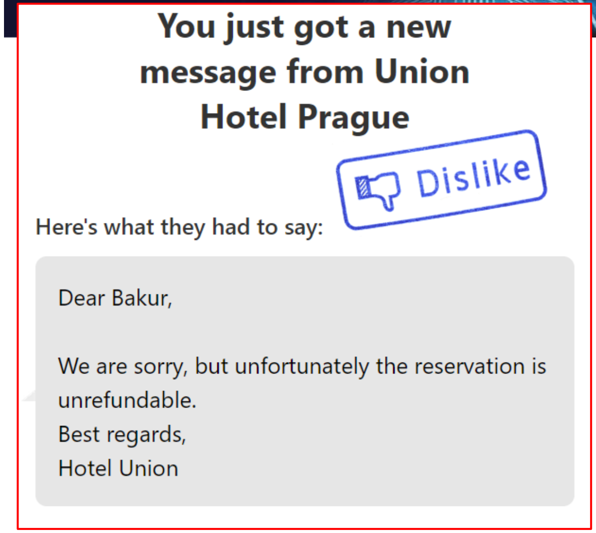
di Cecilia Mussi e Paolo Ottolina

Disagi globali e milioni di «schermi blu della morte» sui computer con Windows a causa di un errato aggiornamento del software di cyber sicurezza Falcon Sensor del fornitore Crowdstrike, che ha pubblicato un dettagliato report su quanto successo


The Guardian

Microsoft IT outage live: expert says 'worst is over' but world likely to see more outages

Global travel has been severely affected by the IT outage. Photograph: Edna Leshowitz/ZUMA Press Wire/REX/Shutterstock


You just got a new message from Union Hotel Prague

Here's what they had to say:

Dear Bakur,

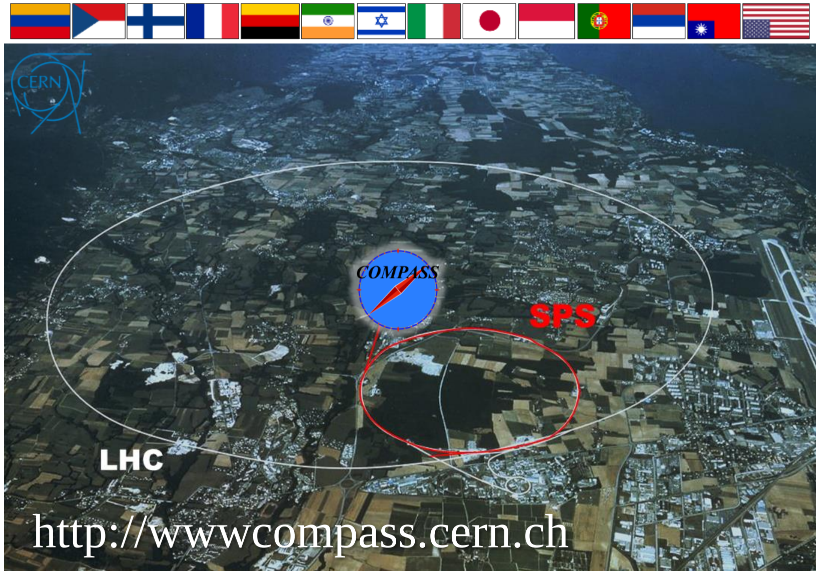
We are sorry, but unfortunately the reservation is unrefundable.
Best regards,
Hotel Union

COMPASS timeline

- CERN SPS north area
- Fixed target experiment
- Approved in 1997 (25 years)
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

28 institutions from 14 countries: nearly 210 physicists

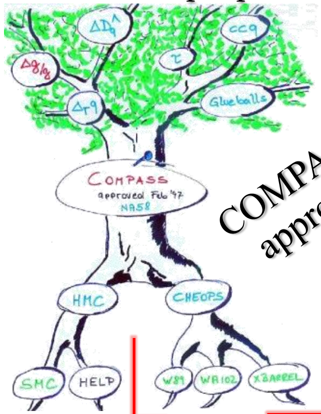
3 new groups joined the COMPASS in 2023
UCon (US), AANL (Armenia), NCU (Taiwan)



http://wwwcompass.cern.ch

See talks by: M. Niemiec, M. Peskova and D. Giordano (for AMBER)

COMPASS proposal



COMPASS approval

COMPASS 1st data taking

SIDIS L/T

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

COMPASS++/AMBER proposal

Drell-Yan

DVCS

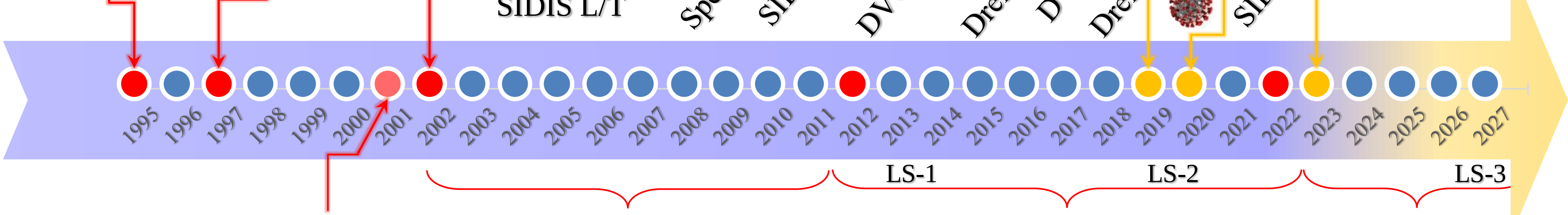
Drell-Yan

AMBER approval

SIDIS T

AMBER
Apparatus for Meson and Baryon Experimental Research

AMBER 1st data taking



Pilot run

Phase I

Phase II

Analysis Phase

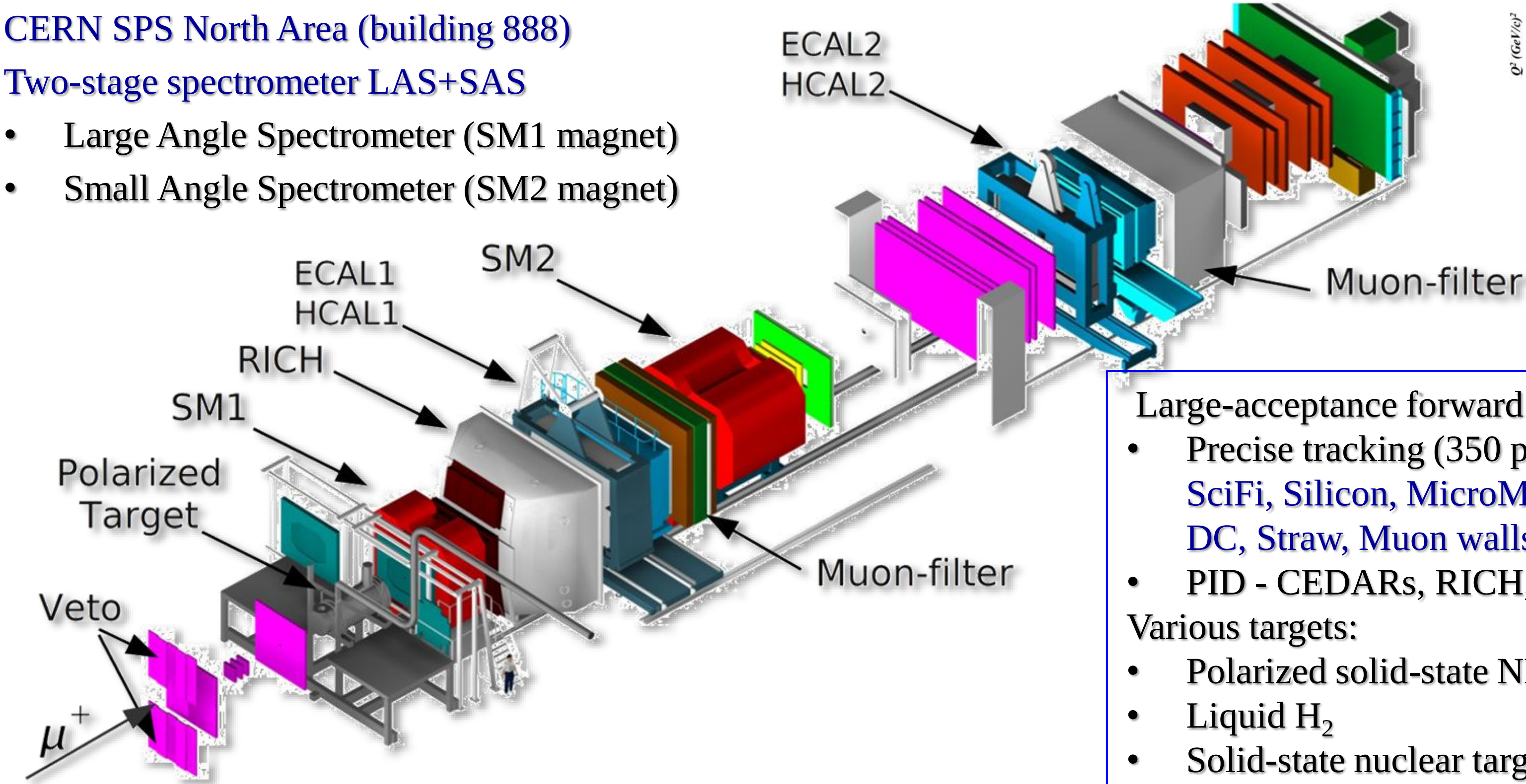
COMPASS experimental setup

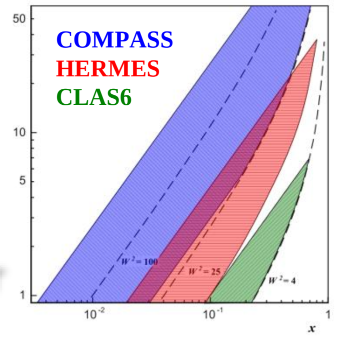
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





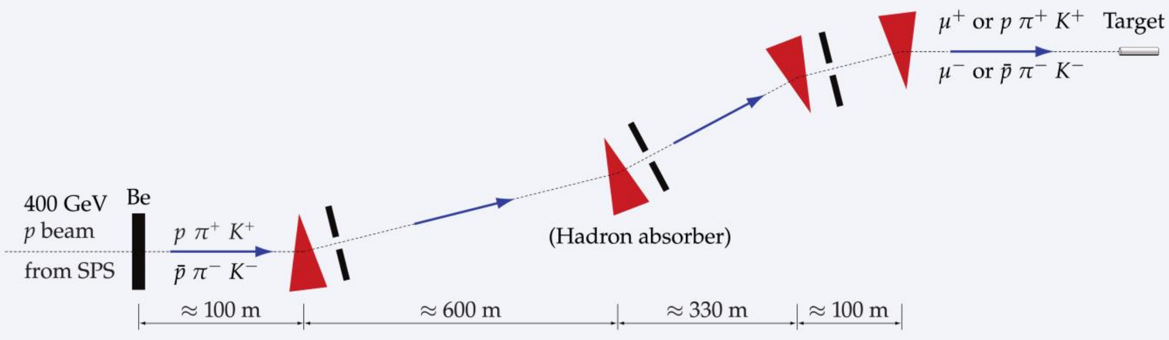
Large-acceptance forward spectrometer

- 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 ^{6}LiD
- 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



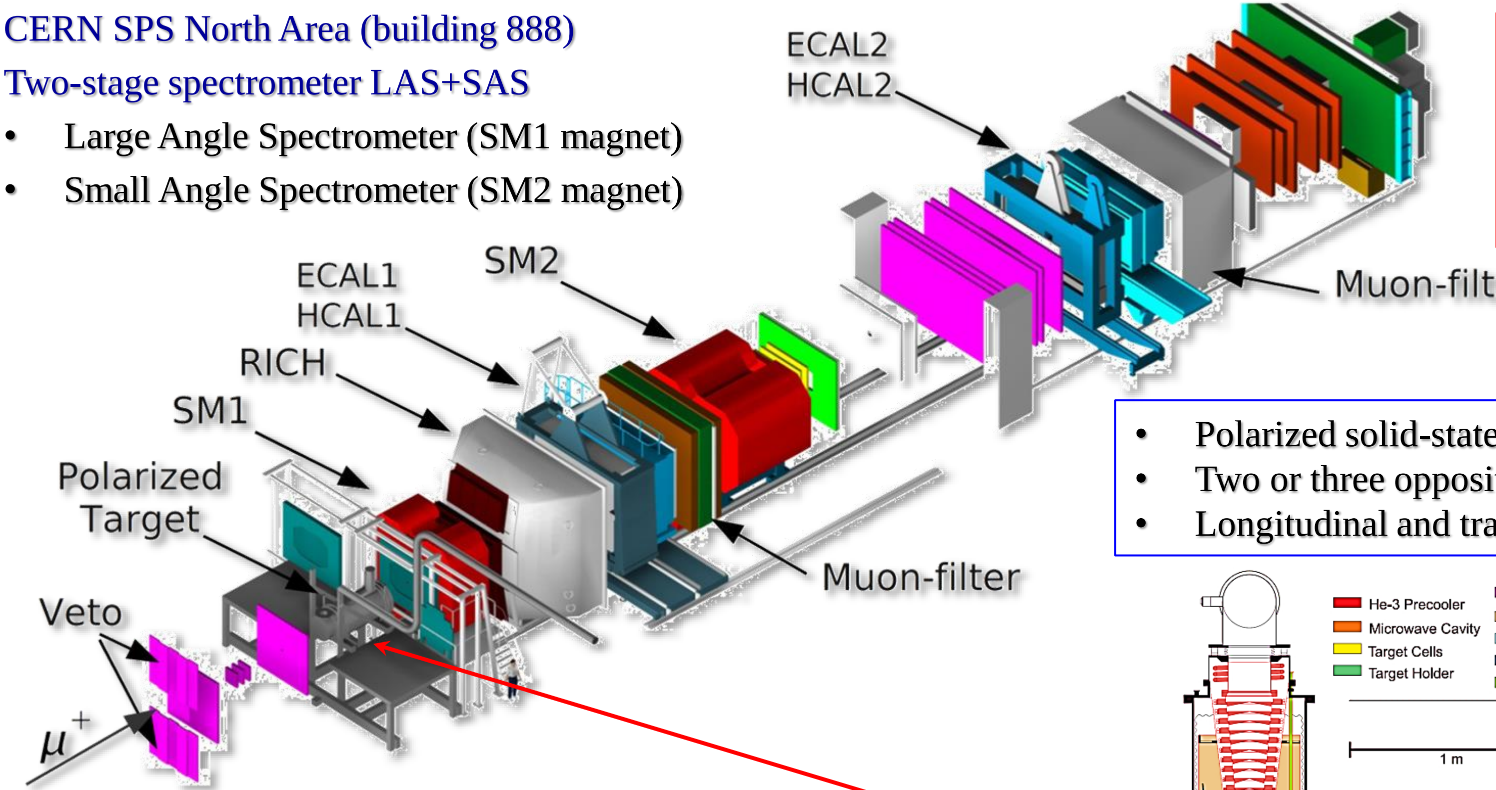
COMPASS experimental setup: Phase II (SIDIS programme)

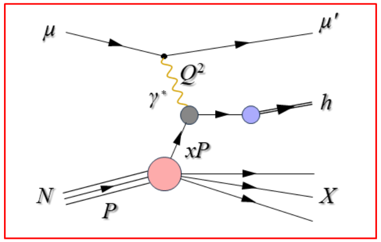
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

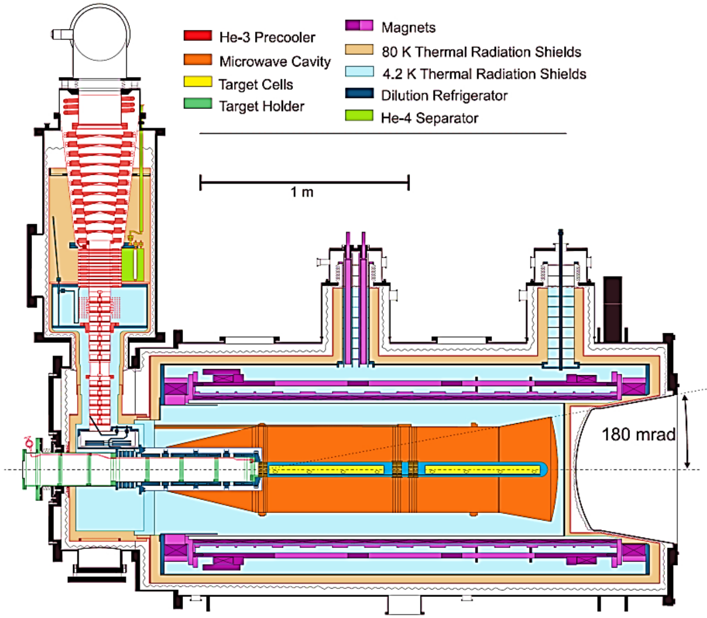
Two-stage spectrometer LAS+SAS

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





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



- Primary beam - 400 GeV *p* from SPS
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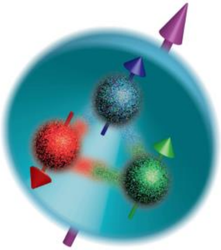
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - μ^+ longitudinally polarized

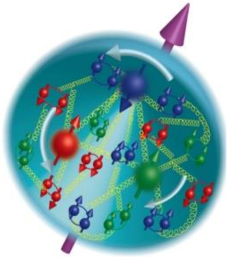
Nucleon spin structure: transverse effects



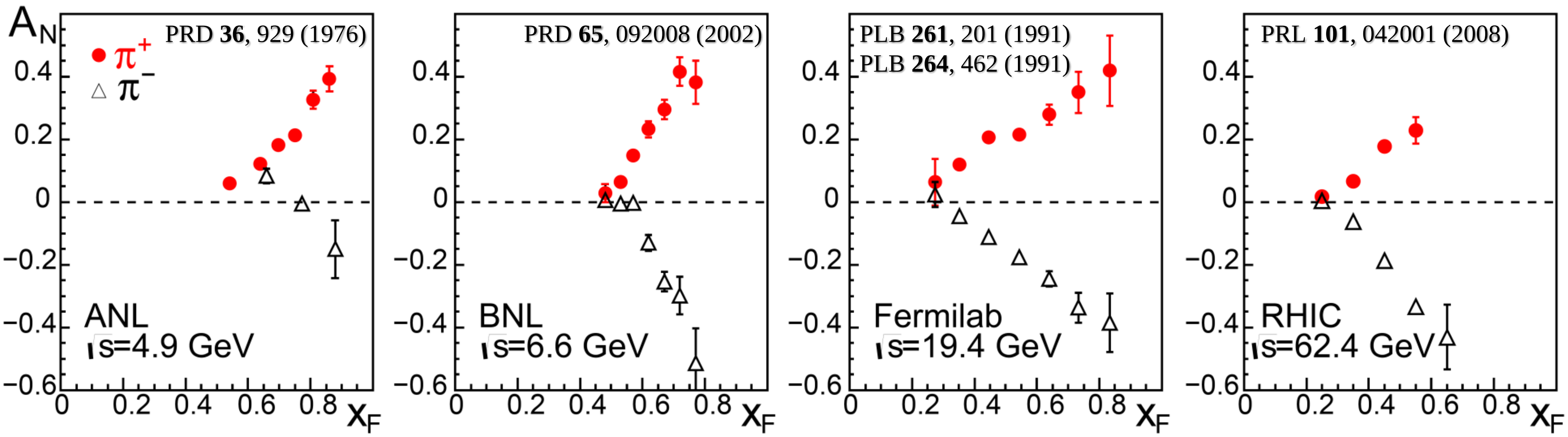
- 1964 Quark model

- 1969 Parton model

- 1973 asymptotic freedom and QCD

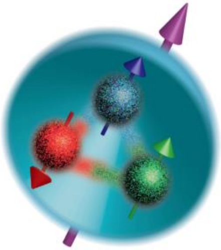


- 1976 large transverse single spin asymmetry in forward $\pi^{\pm}$ production



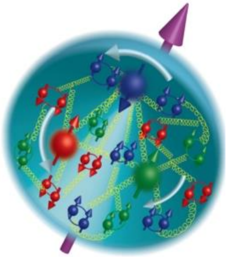
Nucleon spin structure: TMD effects

- 1964 Quark model

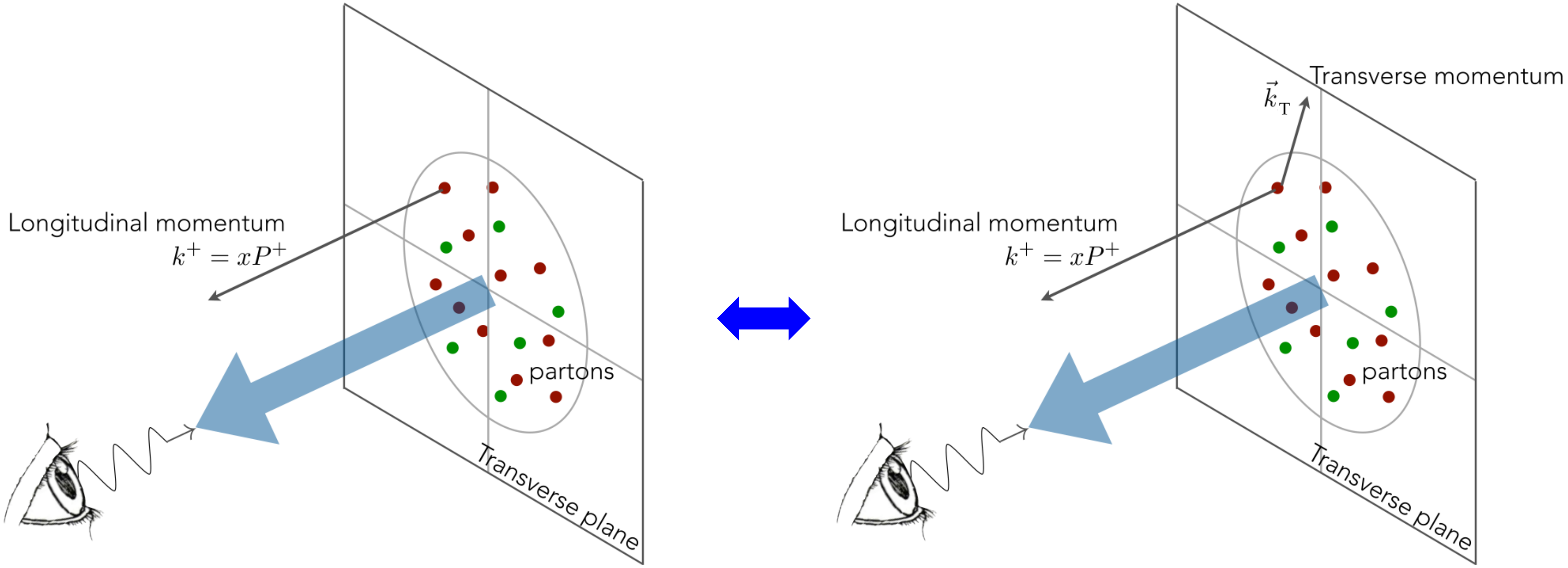


- 1969 Parton model

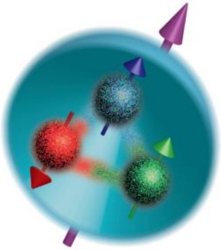
- 1973 asymptotic freedom and QCD



- 1976 large transverse single spin asymmetry in forward $\pi^{\pm}$ production

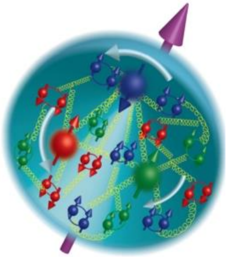


Nucleon spin structure: TMD Cahn effect



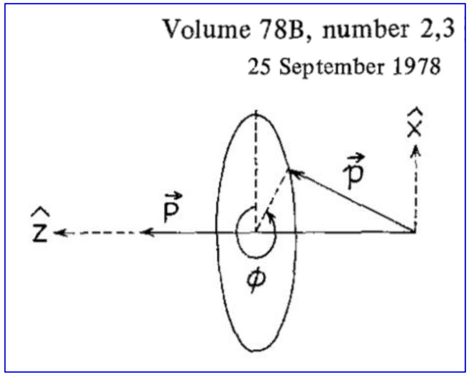
- 1964 Quark model

- 1969 Parton model

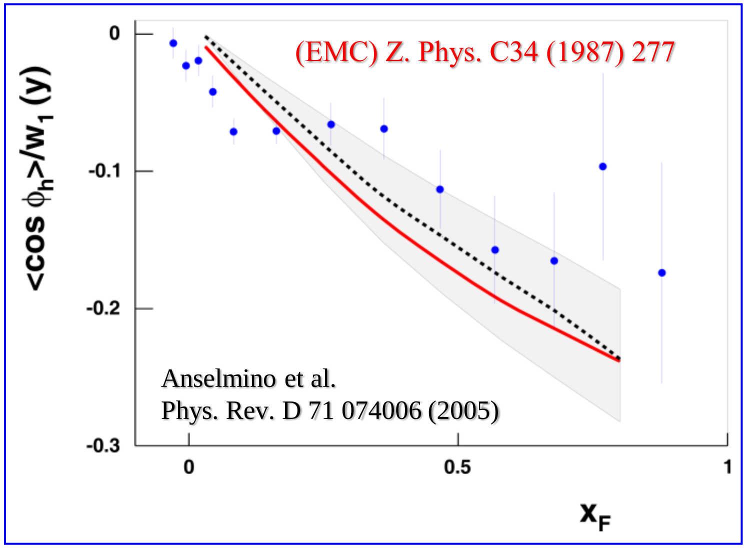


- 1973 asymptotic freedom and QCD

- 1976 large transverse single spin asymmetry in forward $\pi^{\pm}$ production
- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries



Volume 78B, number 2,3
25 September 1978



(EMC) Z. Phys. C34 (1987) 277

Anselmino et al.
Phys. Rev. D 71 074006 (2005)

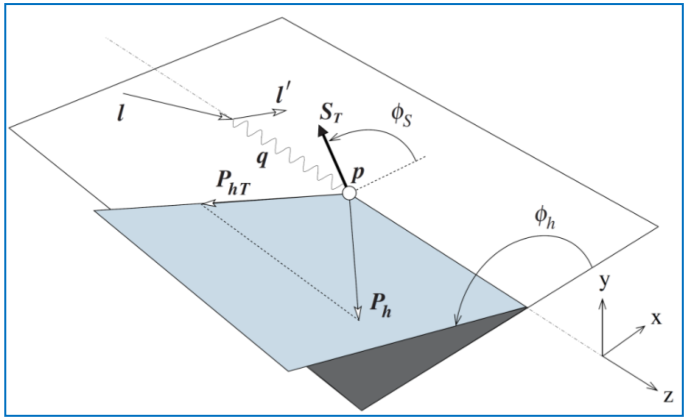
(SLAC) Phys. Rev. Lett. 31, 786 (1973)
(EMC) Phys. Lett. B 130 (1983) 118,
(EMC) Z. Phys. C34 (1987) 277
(EMC) Z. Phys. C52, 361 (1991).
(E665) Phys. Rev. D48 (1993) 5057
(ZEUS) Eur. Phys. J. C11, 251 (1999)
(ZEUS) Phys. Lett. B 481, 199 (2000)
(H1) Phys. Lett. B654, 148 (2007)

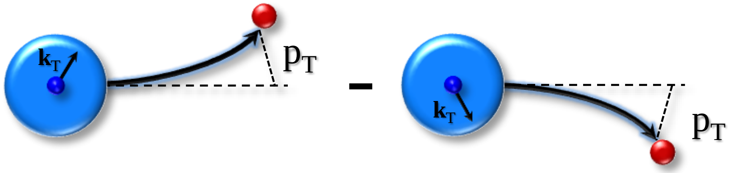
Cahn effect in SIDIS

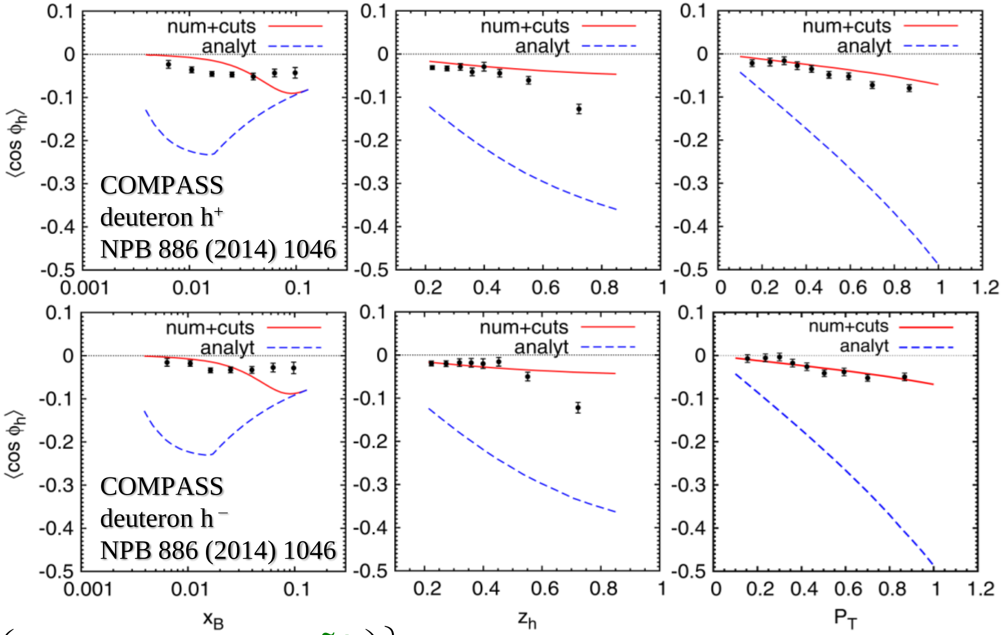
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

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

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

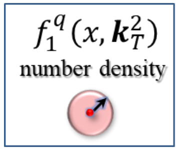
Cahn effect in SIDIS

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

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

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

Cahn effect



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

number density

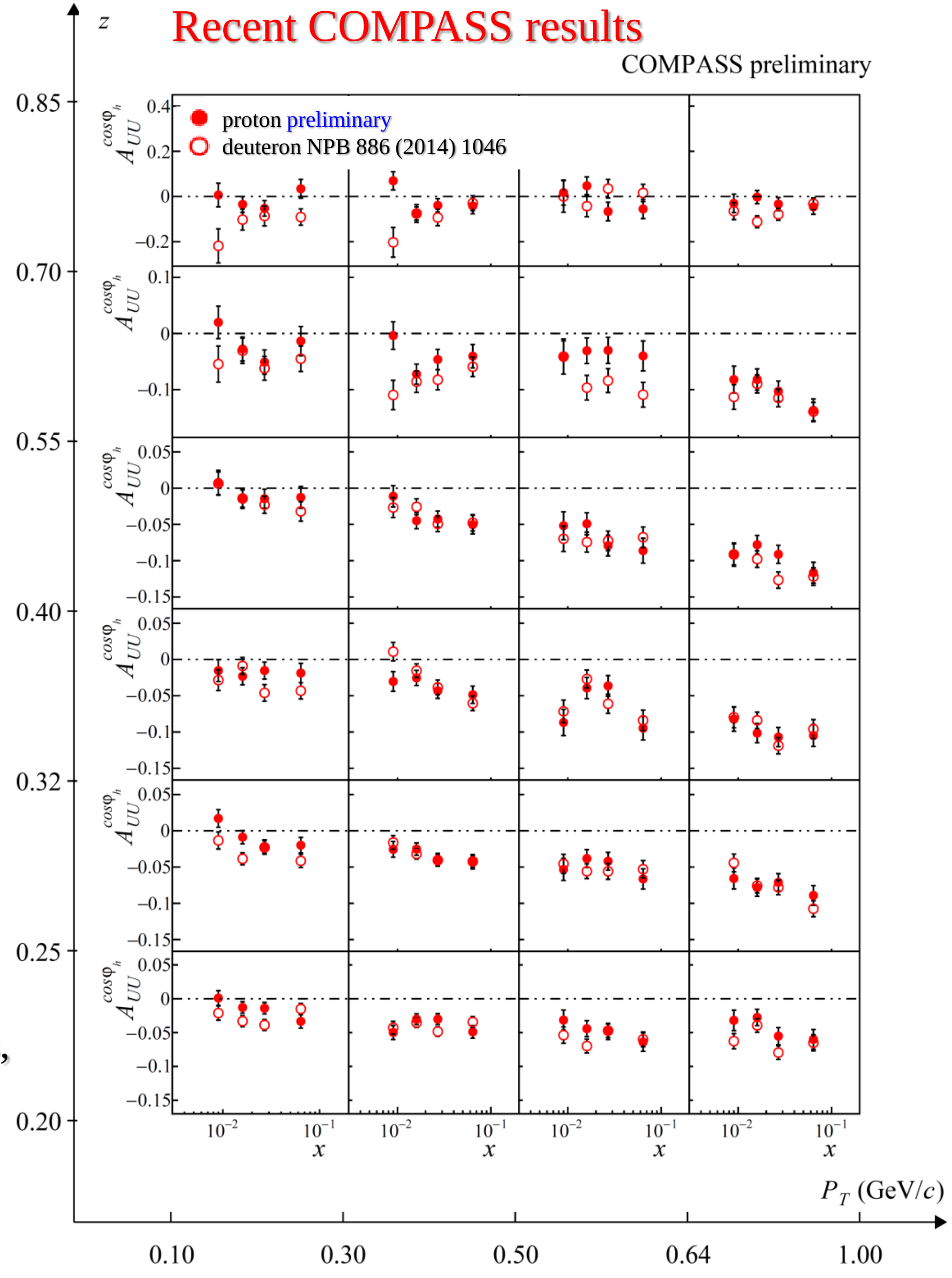
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

- Measurements by different experiments
- 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

Recent COMPASS results



Nucleon spin structure: collinear approach ↔TMDs

quark

nucleon

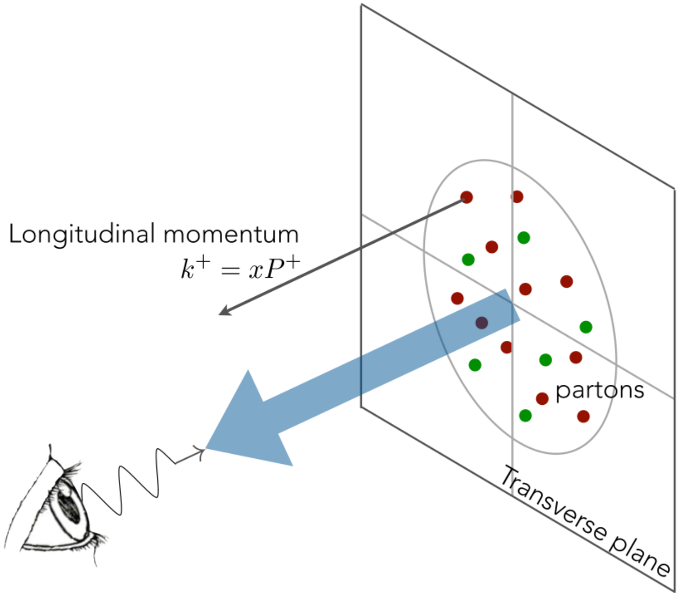
	U	L	T
U	$f_1^q(x)$ number density		
L		$g_1^q(x)$ Helicity	
T			$h_1^q(x)$ transversity

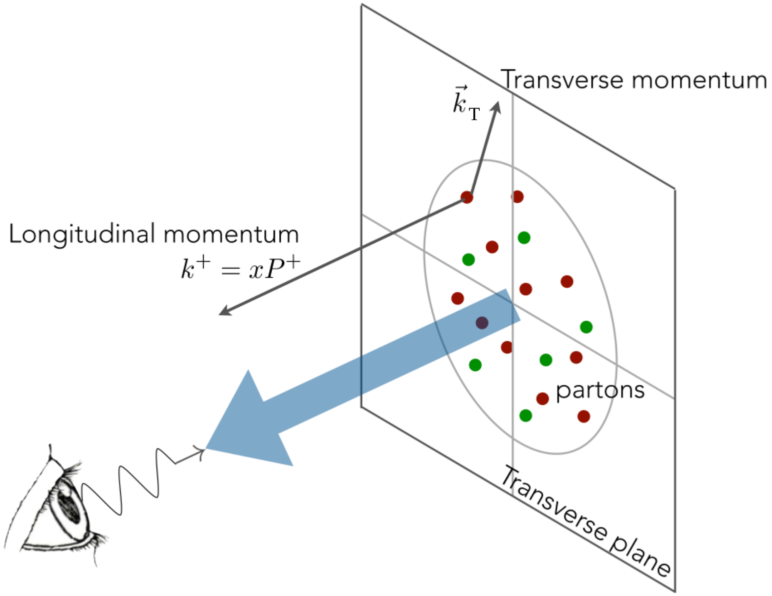
quark

nucleon

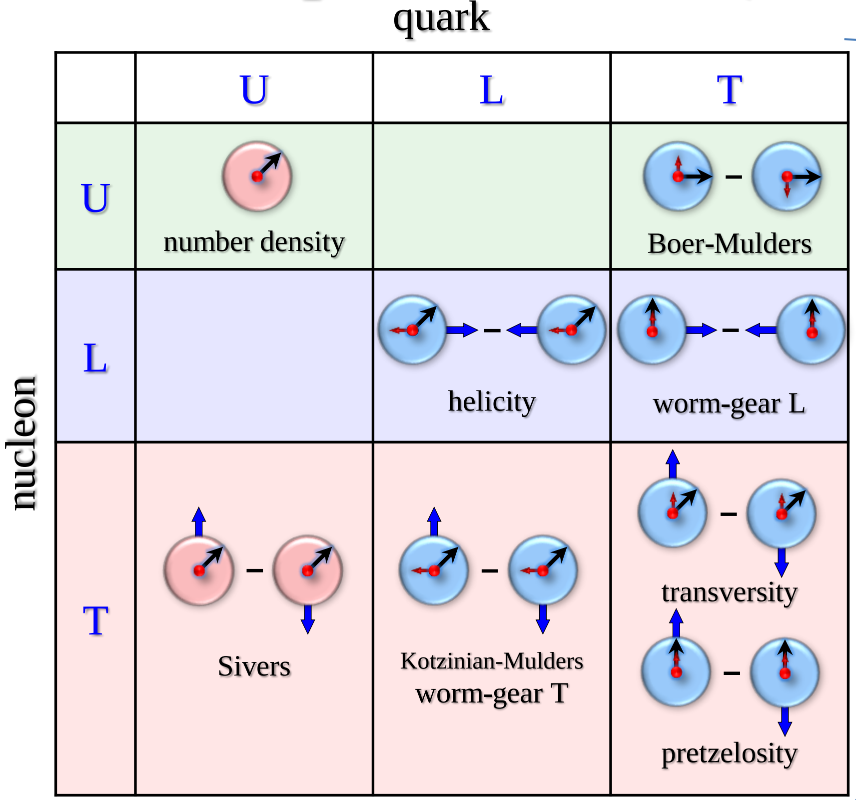
	U	L	T
U	$f_1^q(x, \boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ Boer-Mulders T-odd
L		$g_1^q(x, \boldsymbol{k}_T^2)$ Helicity	$h_{1L}^{\perp q}(x, \boldsymbol{k}_T^2)$ worm-gear L
T	$f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x, \boldsymbol{k}_T^2)$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

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





Nucleon spin structure (twist-2): TMDs

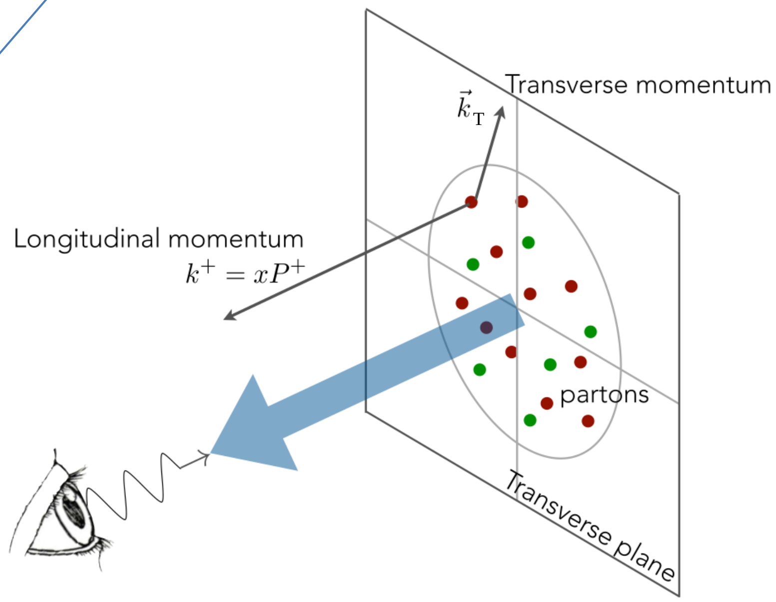


↑ - spin of the nucleon; ↑ - spin of the quark ↗ - k_T

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
L		$g_1^q(x, \boldsymbol{k}_T^2)$ Helicity	$h_{1L}^{\perp q}(x, \boldsymbol{k}_T^2)$ 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	$h_1^q(x, \boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ pretzelosity

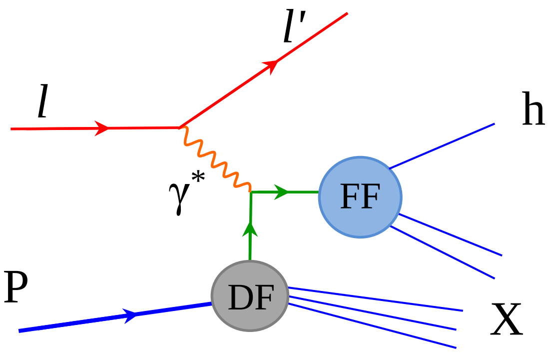


SIDIS x-section and TMDs at twist-2: TSAs

All measured by COMPASS

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

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



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

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

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

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

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

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

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

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

Twist-2

Twist-3

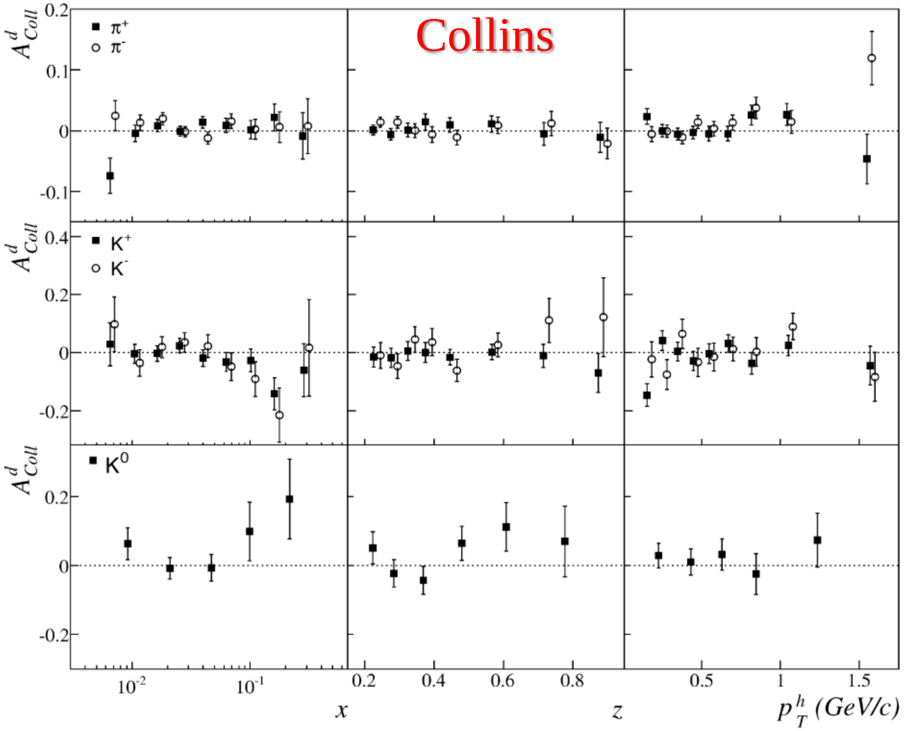
SIDIS TSAs: Collins and Sivers effects (deuteron)

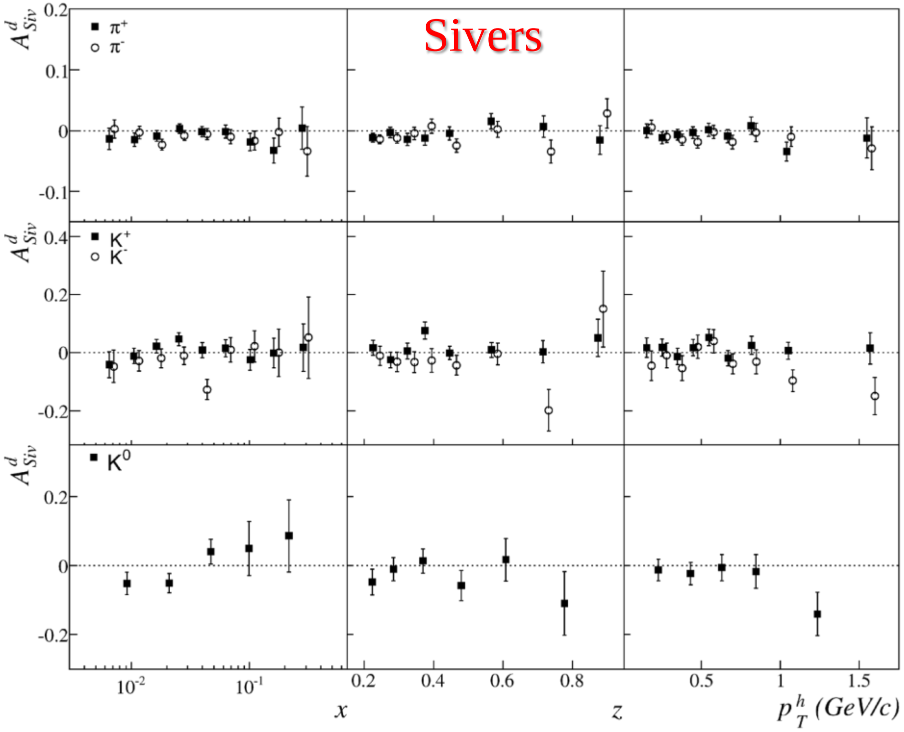
$$\frac{d\sigma}{dxdydzdp_T^2\, d\phi_h\, d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_{\mathrm{T}}\, A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h - \phi_S\right) + S_{\mathrm{T}}\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) \ldots\right\}$$

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

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

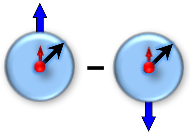
COMPASS PLB 673 (2009) 127





- 1st COMPASS deuteron measurements
- Collins and Sivers asymmetries compatible with zero within uncertainties.

SIDIS TSAs: Collins effect and Transversity



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

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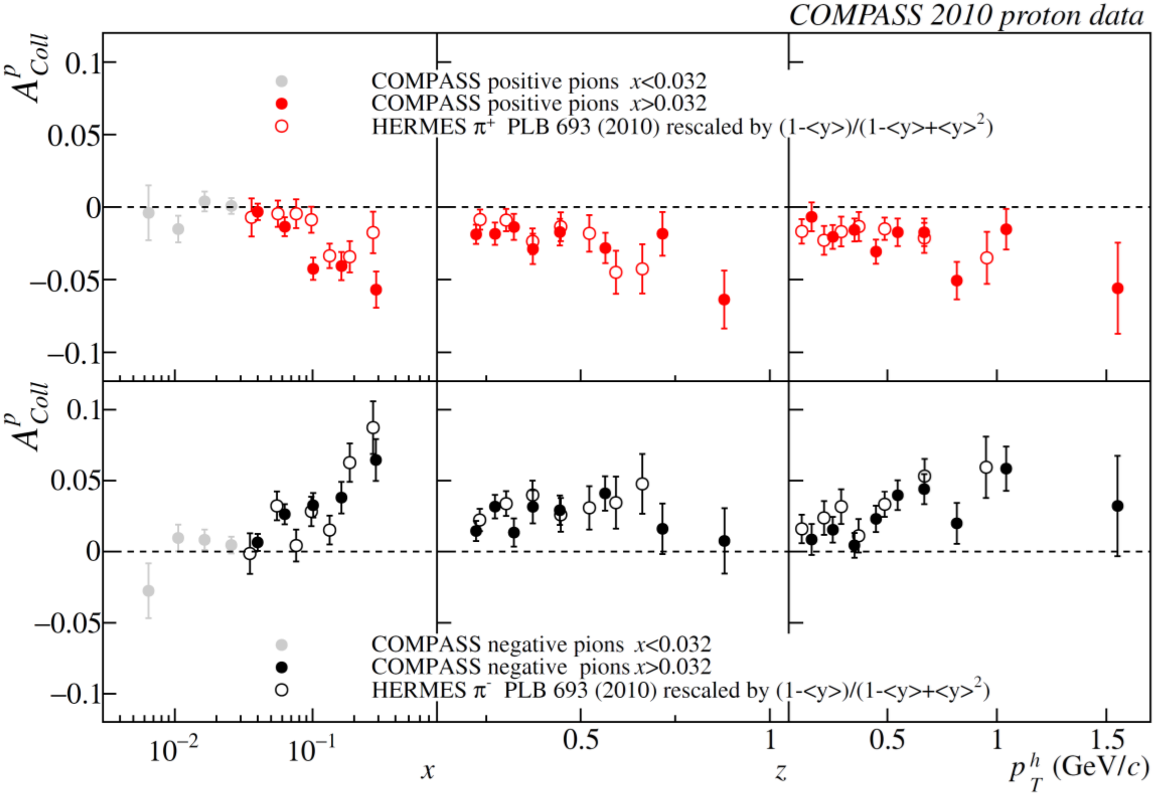
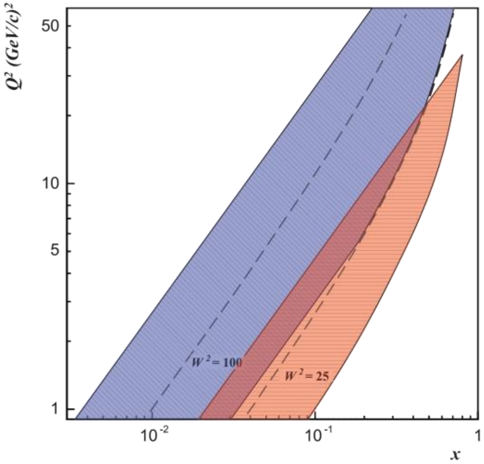
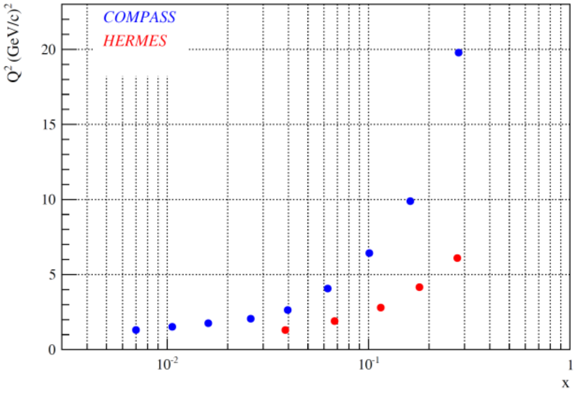
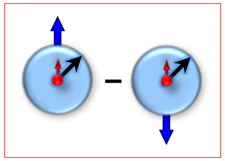
COMPASS PLB 744 (2015) 250







SIDIS TSAs: Collins effect and Transversity



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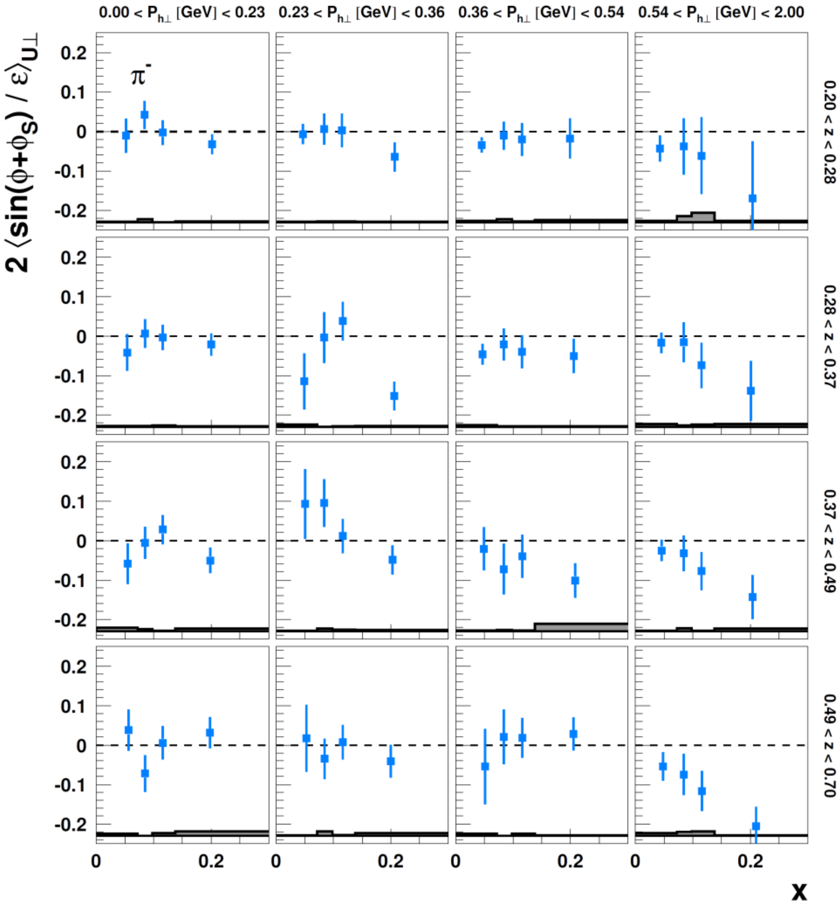
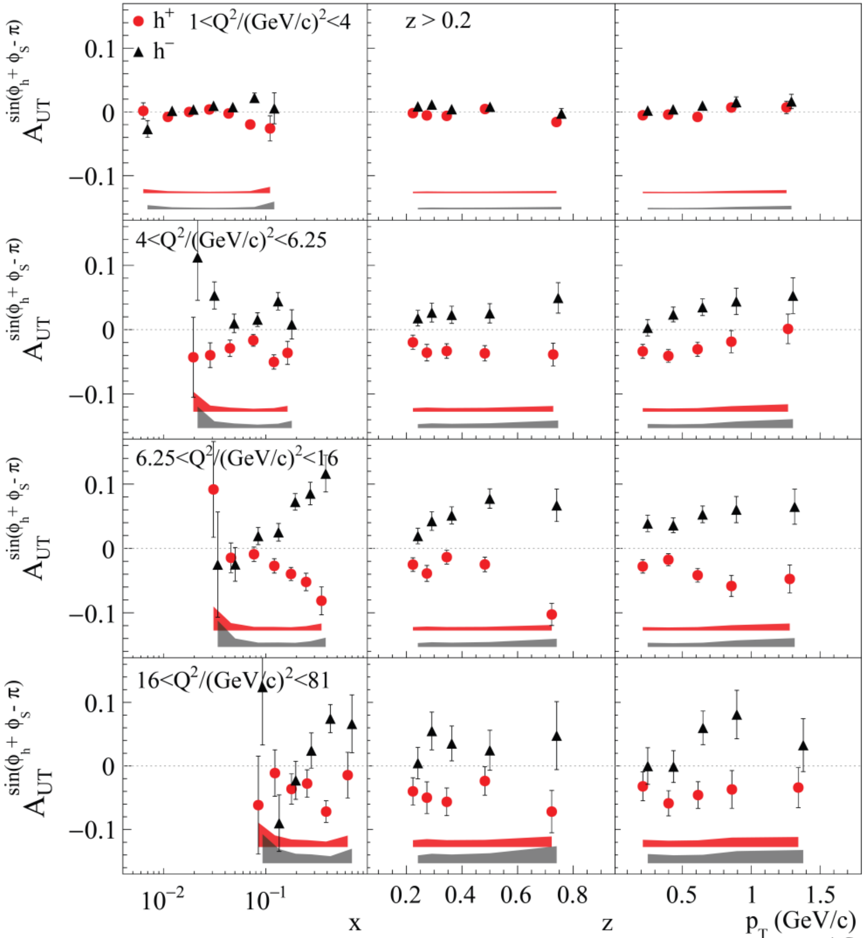
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



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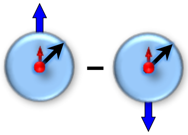

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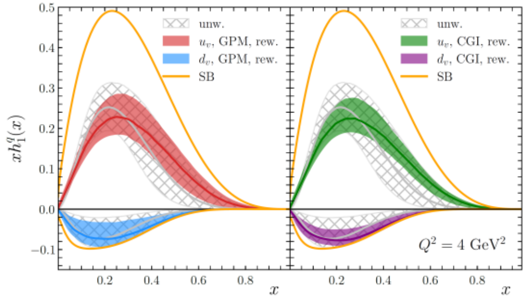
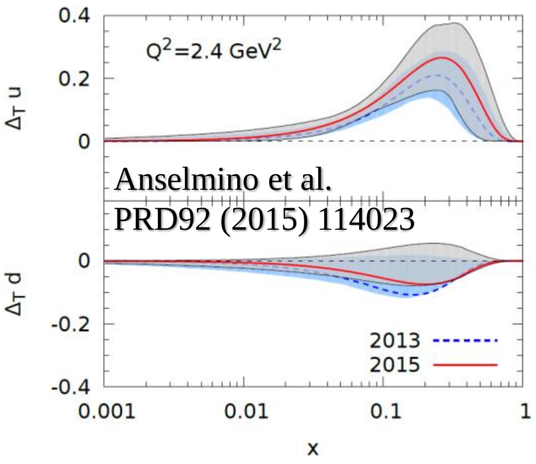
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution? Clear signal at STAR energies
- Extensive phenomenological studies and various global fits by different groups

Boglione et al. PLB 854 (2024) 138712

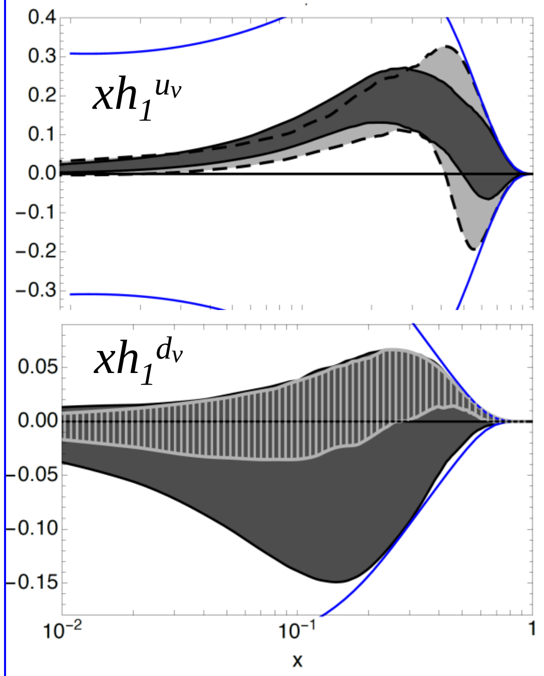


See Carlo Flore’s talk

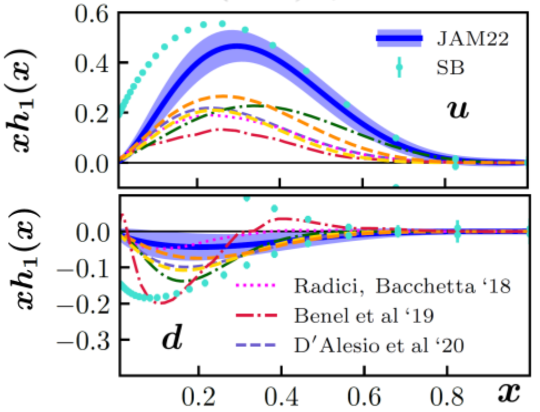


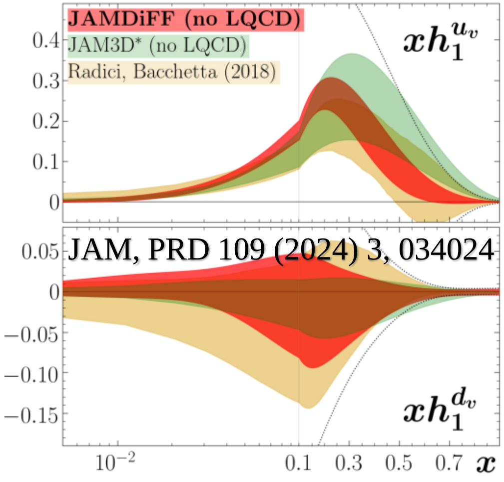
Anselmino et al.
PRD92 (2015) 114023

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



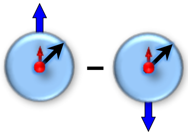
JAM PRD 106 (2022) 3, 034014





JAM, PRD 109 (2024) 3, 034024

SIDIS TSAs: Collins effect and Transversity



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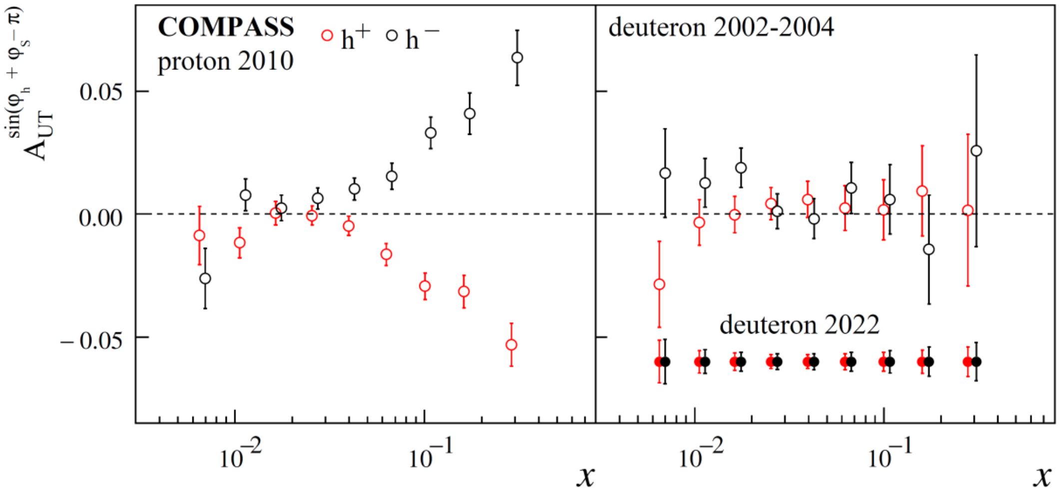
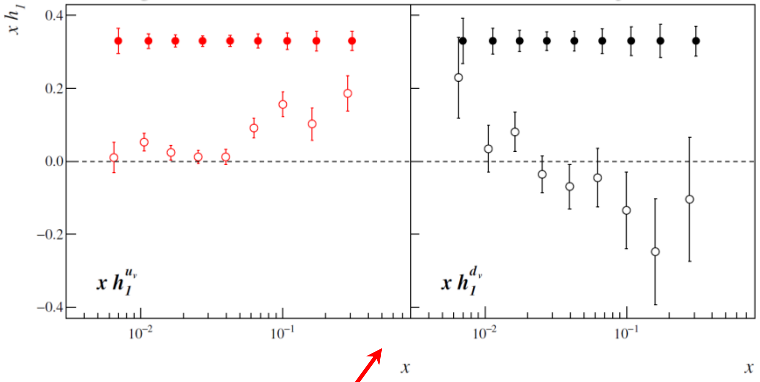
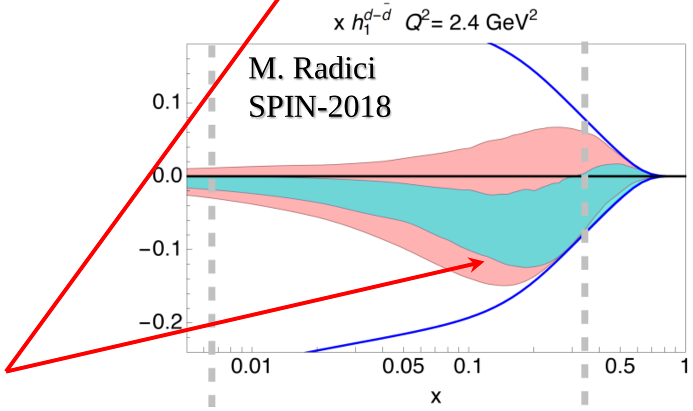
[Addendum to the COMPASS-II Proposal]

Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF



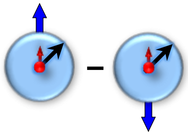


M. Radici
SPIN-2018

COMPASS-II (2022)

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

SIDIS TSAs: Collins effect and Transversity



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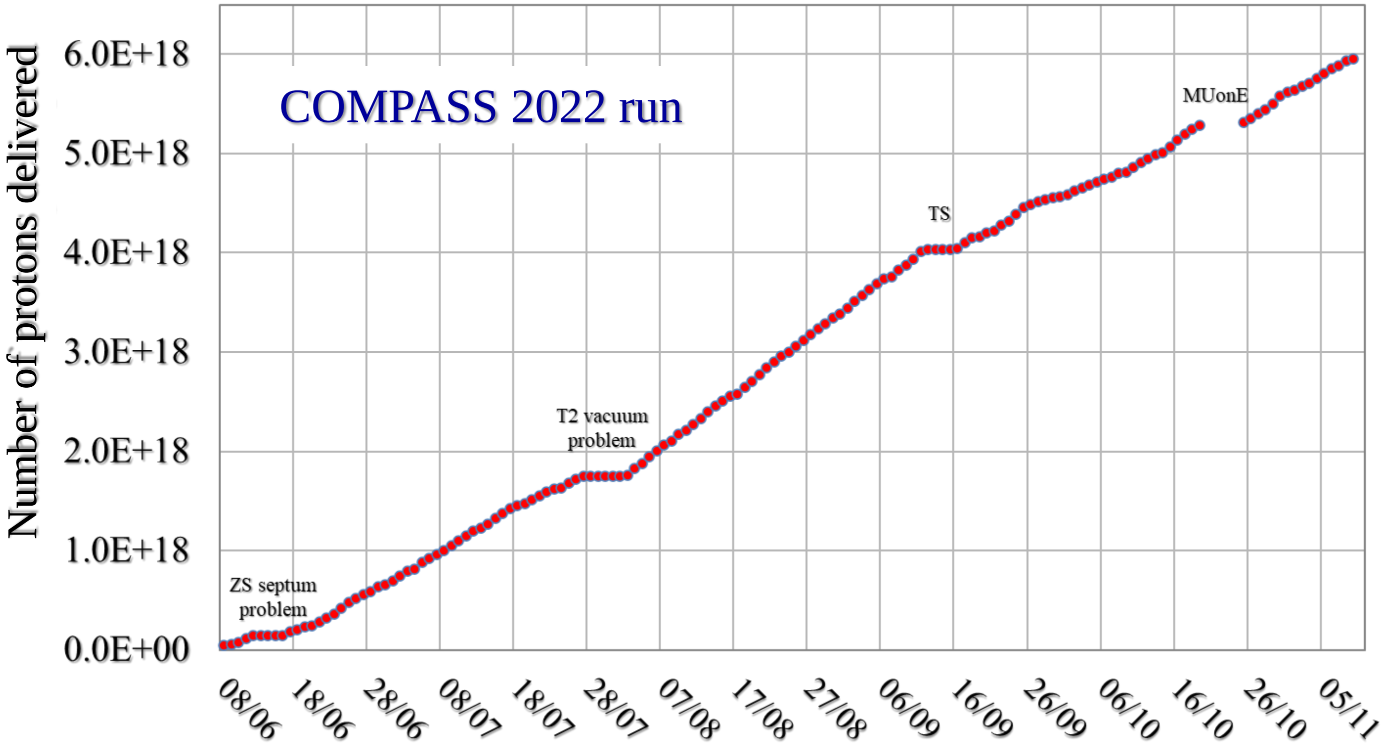
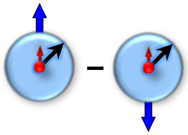
Total protons delivered on the production target: ~5.95×10^{18} (98% of the request) in ~150 days



SPS efficiency: ~ 73%
Spectrometer efficiency: ~ 90%
Physics data collection efficiency: ~ 75%

Highly successful Run in 2022!

SIDIS TSAs: Collins effect and Transversity



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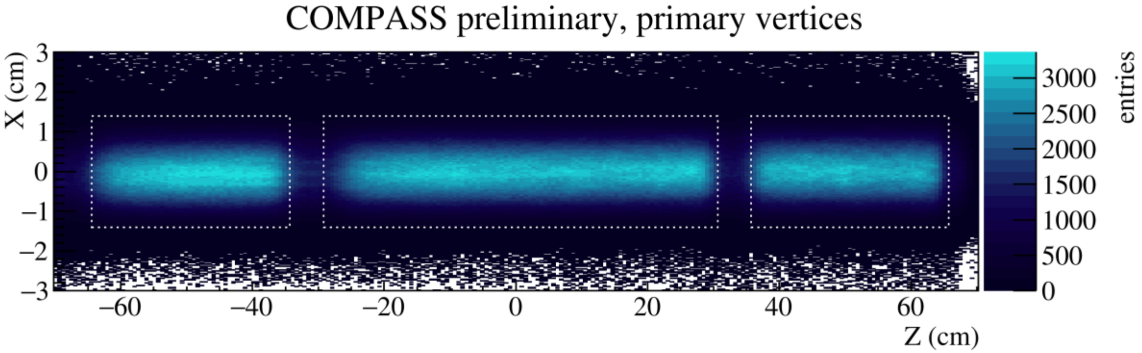

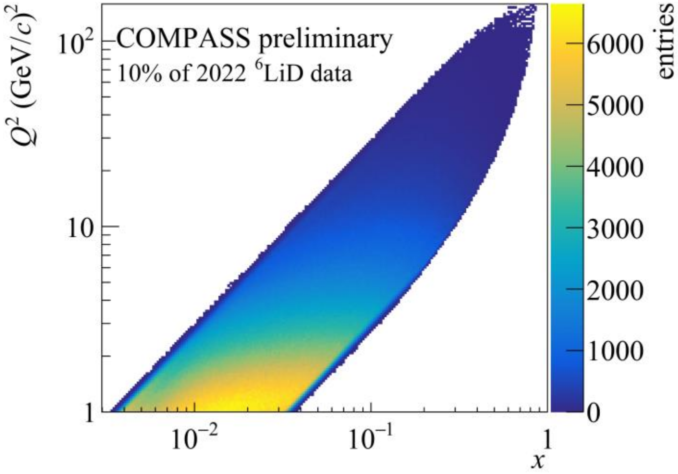

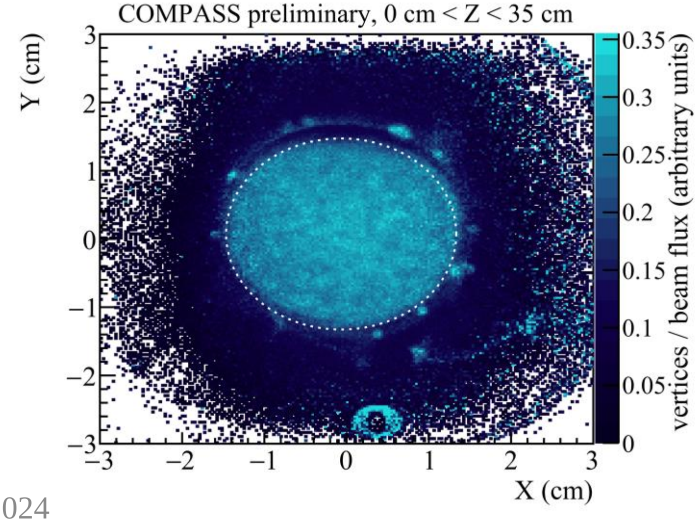

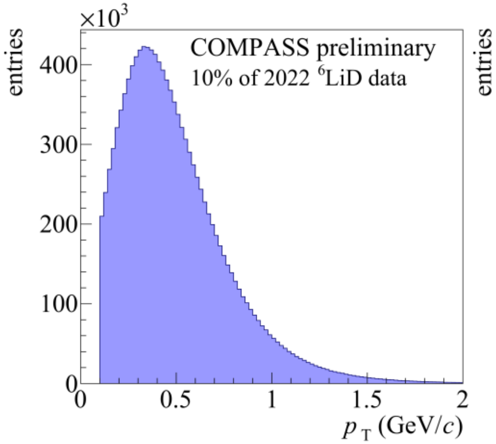

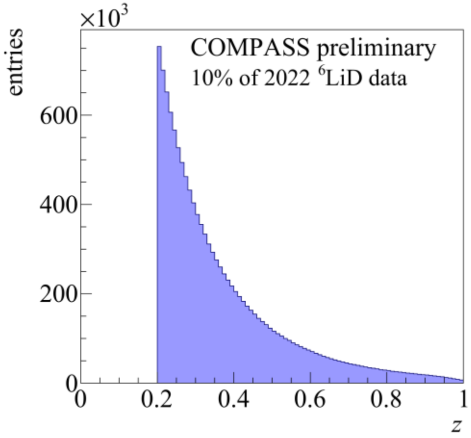

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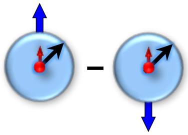

COMPASS
25 years
1997 - 2022

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

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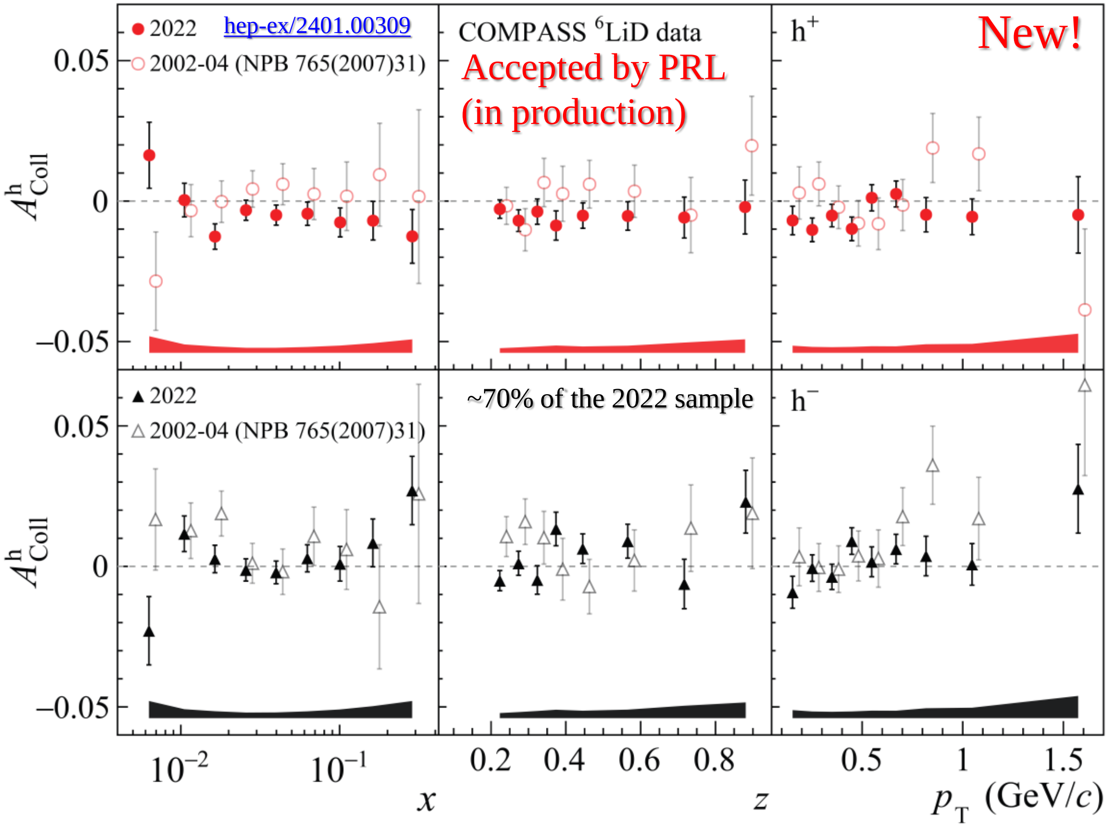


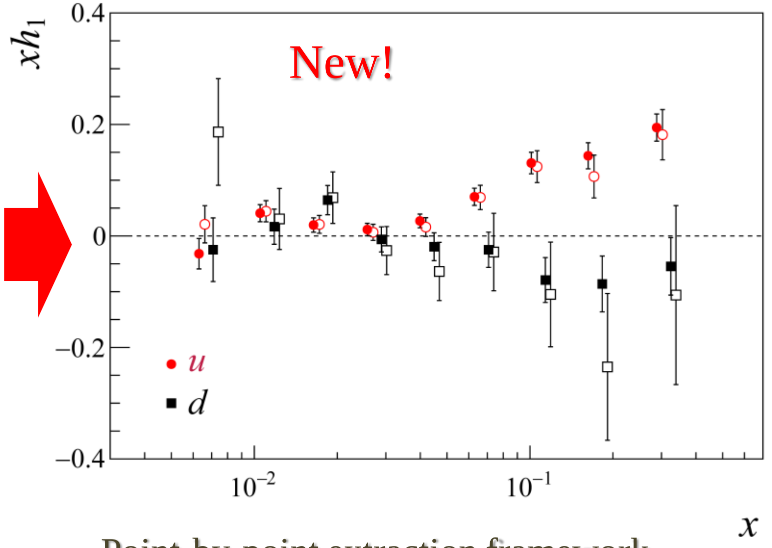
hep-ex/2401.00309

COMPASS ^{6}LiD data

Accepted by PRL (in production)

New!

~70% of the 2022 sample



New!

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

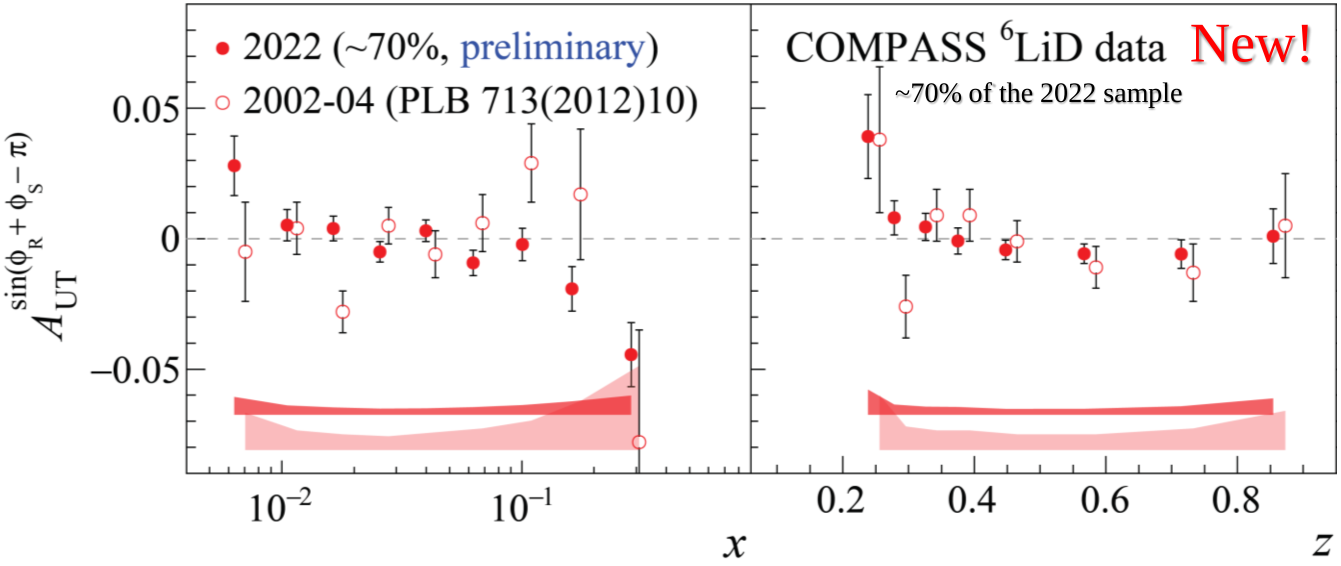
COMPASS 2022 run – highly successful data-taking!

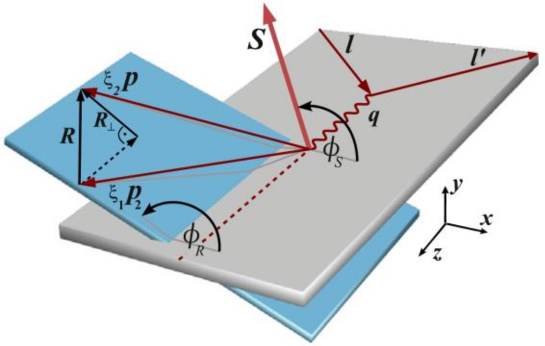
- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades

Dihadron Collins effect and Transversity

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

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

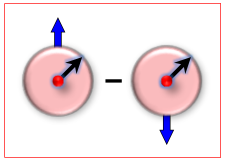




COMPASS 2022 run – highly successful data-taking!

- 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

SIDIS TSAs: Sivers effect



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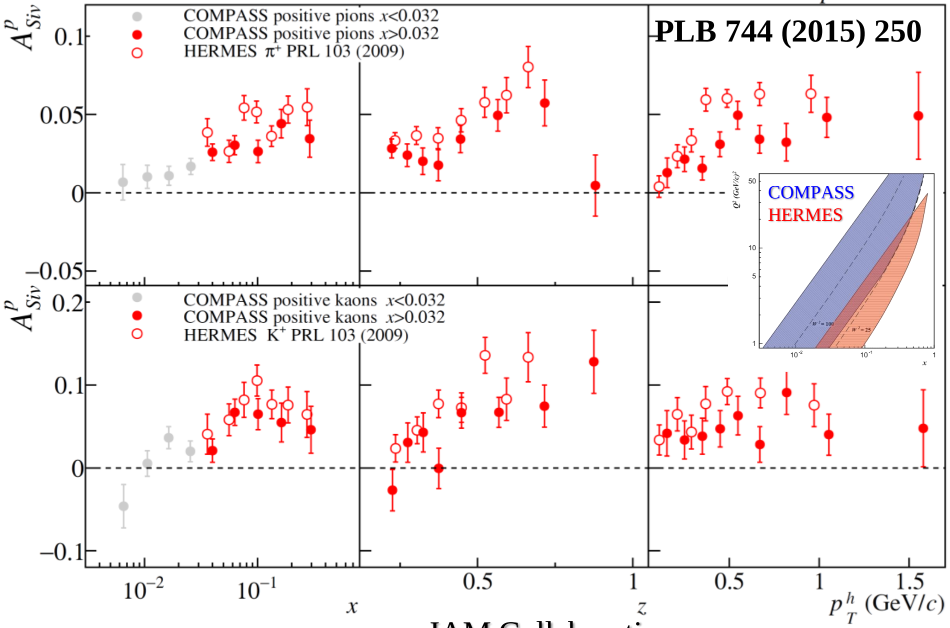
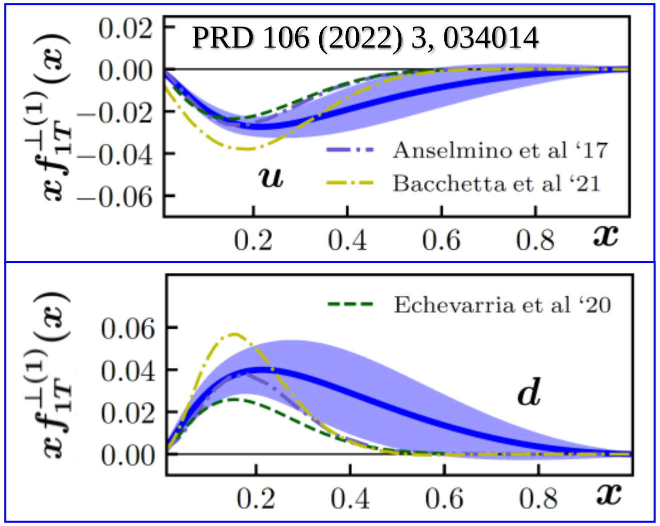
- COMPASS-HERMES discrepancy
- T-oddness: sign-change (SIDIS ↔ Drell-Yan)
    - Explored by COMPASS

COMPASS 2010 proton data



JAM Collaboration



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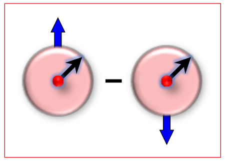

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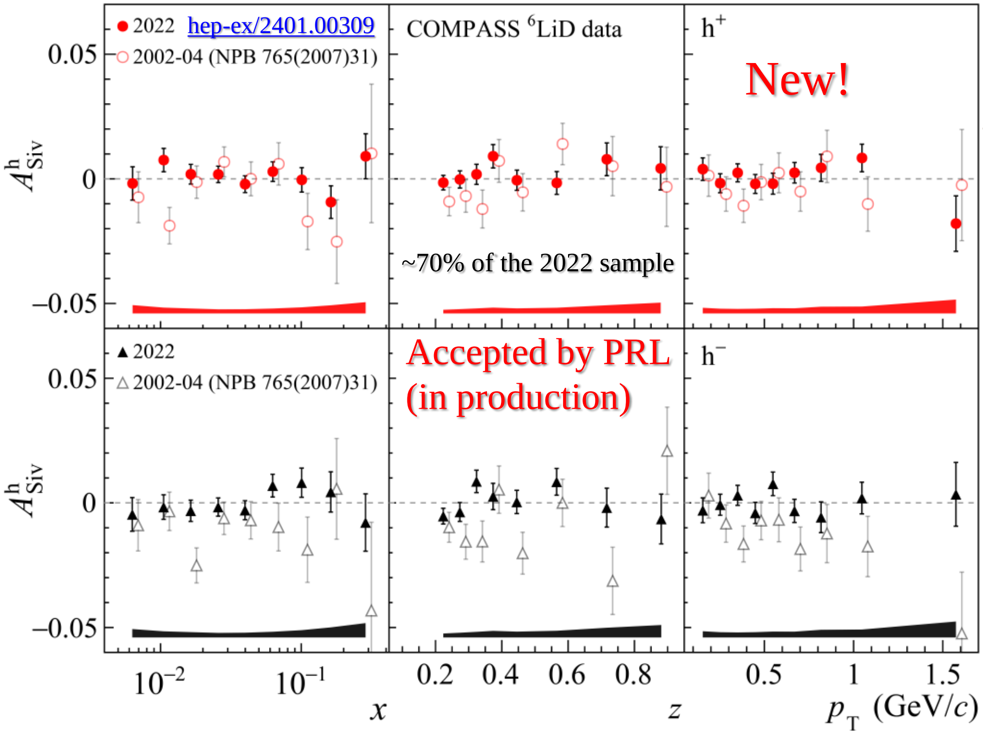
- COMPASS-HERMES discrepancy
- T-oddness: sign-change (SIDIS ↔ Drell-Yan)
  - Explored by COMPASS
- New precise deuteron data from COMPASS
  - Unique input to constrain Sivers PDF



New!

Accepted by PRL (in production)

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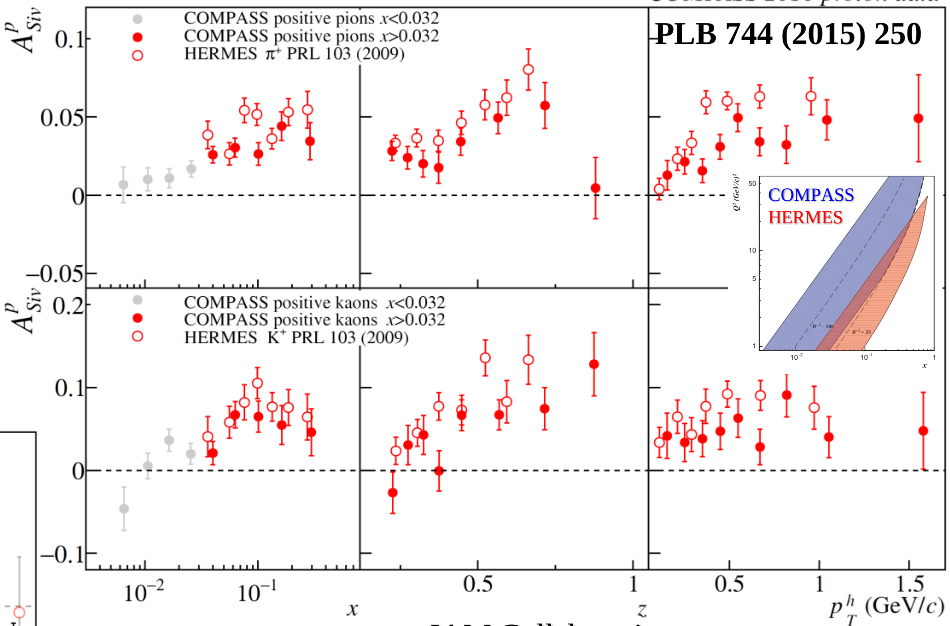
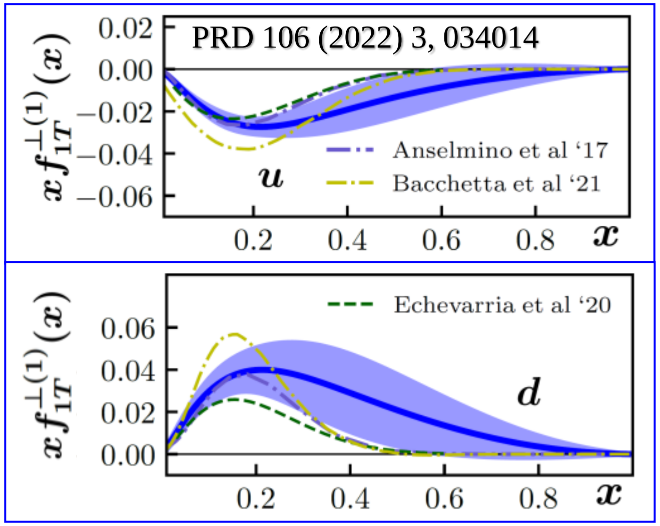


JAM Collaboration



COMPASS 2022 run: new unique deuteron data

hermes proton [H]
95 data points
Airapetian et al.,
*P.R.L. **103** (09) 152002*

Jefferson Lab neutron [^{3}He]
6 data points
Qian et al.,
*P.R.L. **107** (11) 072003*

COMPASS 2009 deuteron [^{6}LiD]
88 data points
Alekseev et al.,
*P.L. **B673** (09) 127*

COMPASS 2017 Proton [NH_3]
111 data points
Adolph et al.,
*P.L. **B770** (17) 138*

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici,
in preparation

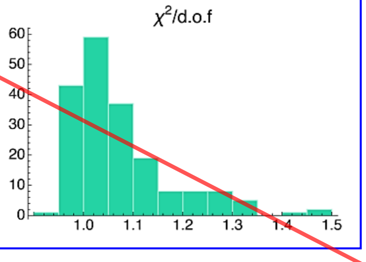
analysis of statistical error
with replica method (200)
68% confidence level

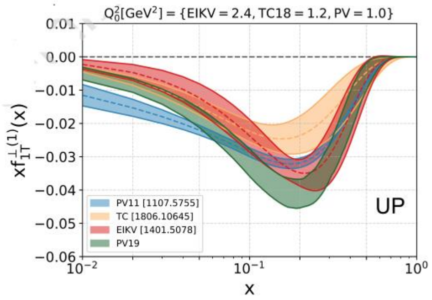
Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

$Q^2 \geq 1.4$ GeV^2 $0.2 \leq z \leq 0.7$
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

300 data points → **118** data fitted
14 free parameters
χ^2/d.o.f. = 1.06 ± 0.10

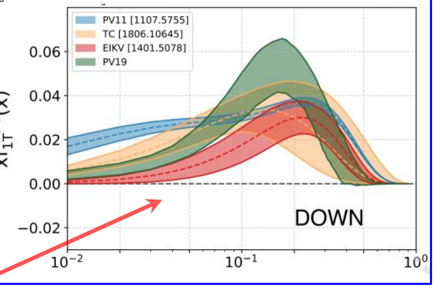




PV11	*Bacchetta & Radici, P.R.L. **107** (11)*
EIKV	*Echevarria et al., P.R. D**89** (14)*
TC	*Boglione et al., JHEP **1807** (18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

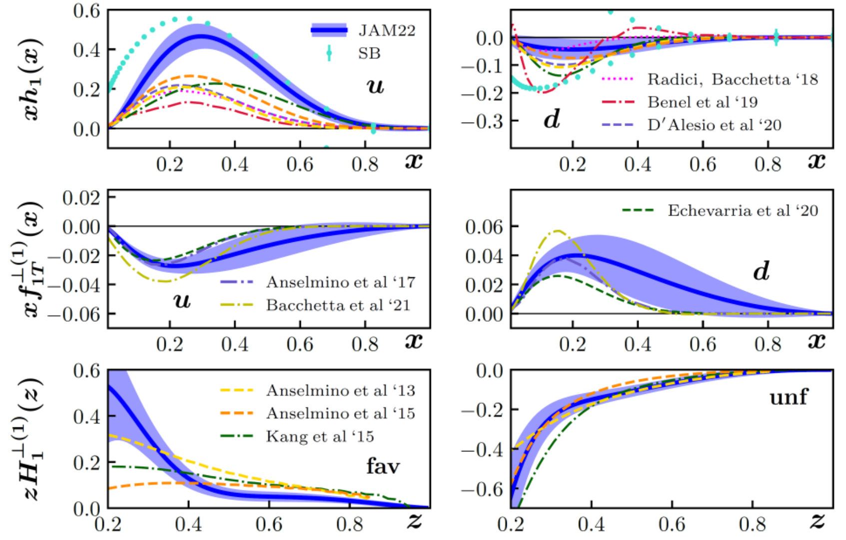
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \, \frac{\mathbf{k}_T^2}{2M^2} \, f_{1T}^{\perp}(x, \mathbf{k}_T)$$

SEA 10^{-2} × smaller
(compatible with 0)

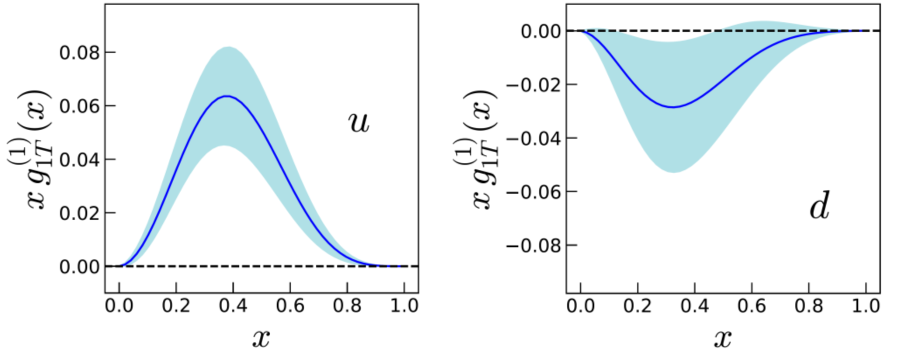


COMPASS 2022 deuteron run

JAM Collaboration, PRD 106 (2022) 3, 034014

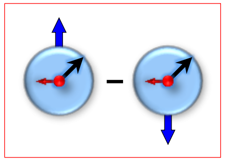


S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D.Pitonyak
PRD 105 (2022) 3, 034007



More news soon…

SIDIS TSAs: Kotzinian-Mulders asymmetry

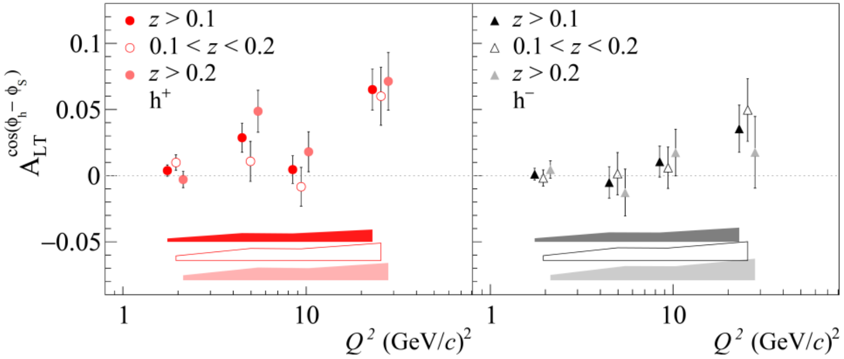


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ \lambda S_T\sqrt{\left(1-\varepsilon^2\right)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos\left(\phi_h-\phi_S\right)+\ldots\right\}$$

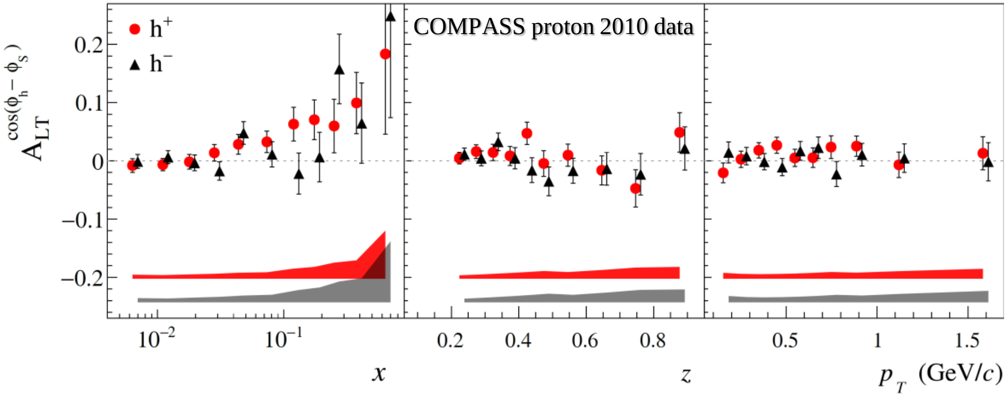
$$\boxed{F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M} g_{1T}^q D_{1q}^h\right]}$$

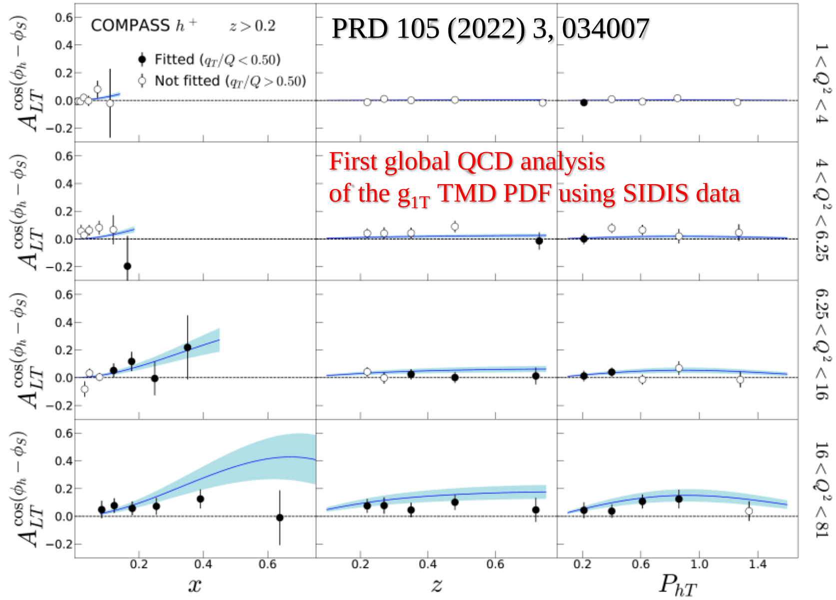
COMPASS/HERMES/CLAS6 results $A_{LT}^{\cos(\phi_h-\phi_S)}$

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



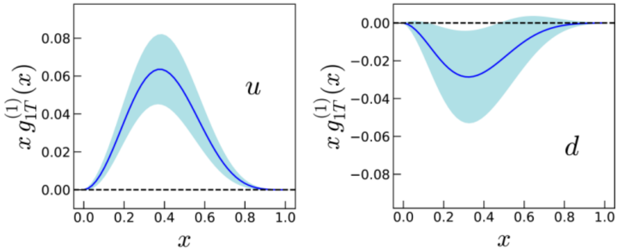
COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042





PRD 105 (2022) 3, 034007

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

Conclusions

COMPASS
25 years
1997 - 2022

- COMPASS holds the record for the longest-running CERN experiment (20 years of data-taking)
- Series of successful and important measurements addressing nucleon spin-structure
  - Inclusive measurements, unpolarized and polarized SIDIS (longitudinal/transverse)
  - First-ever polarized Drell-Yan measurements
- A wealth of (SI)DIS, Drell-Yan, DVCS, HEMP data collected across the years
  - Petabytes of data available for analysis
- Wide and unique kinematic domain accessing low x and large Q^2
  - Will remain unique for at least another decade
- World-unique SIDIS deuteron data collected in 2022
  - Highly successful run, promising first results (2/3 of the sample) – soon in PRL
- Since 2023 the experiment entered the Analysis Phase
  - The spectrometer has been transferred to the COMPASS successor in the M2 beamline – the AMBER collaboration
  - 3 new groups joined COMPASS in the course of 2023 for the Analysis Phase
  - If you are interested – don’t hesitate to get in touch!

Thank You!

Joint XX-th International Workshop on Hadron Structure and Spectroscopy and 5-th Workshop on Correlations in Partonic and Hadronic Interactions

2024
30/09 - 04/10

Yerevan Armenia

Yerevan, Armenia

30 September – 4 October, 2024

https://indico.cern.ch/e/IWHSS-CPHI-2024

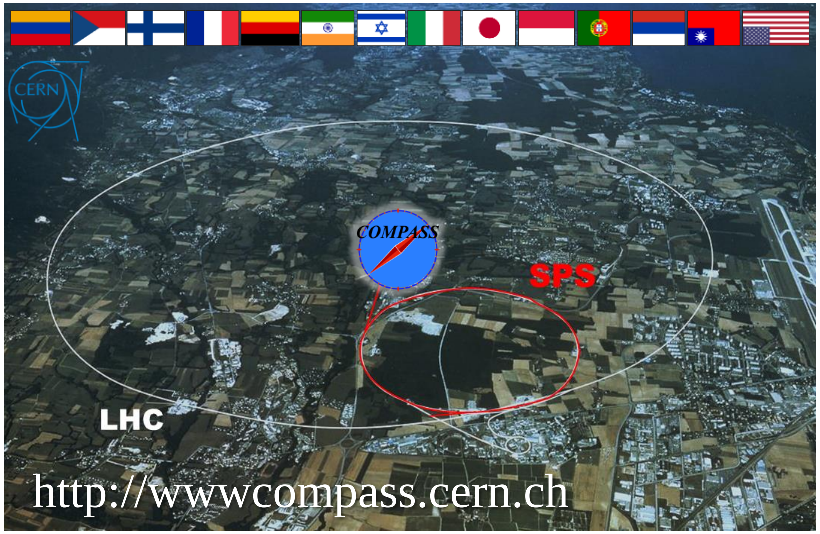
- Spare slides

COMPASS timeline

- CERN SPS north area
- Fixed target experiment
- Approved in 1997 (25 years)
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

28 institutions from 14 countries: nearly 210 physicists

3 new groups joined the COMPASS in 2023
UCon (US), AANL (Armenia), NCU (Taiwan)



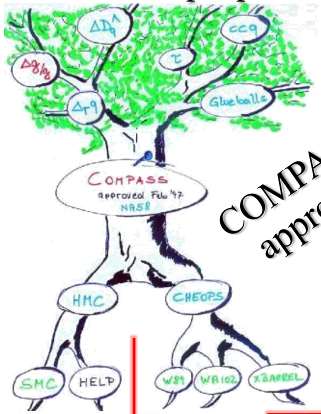
Wide physics program

COMPASS-I
- Data taking 2002-2011
- Muon and hadron beams
- Nucleon spin structure
- Spectroscopy

COMPASS-II
- Data taking 2012-2022
- Primakoff
- DVCS (GPD+SIDIS)
- Polarized Drell-Yan
- Transverse deuteron SIDIS 2022

See talks by: M. Niemiec, M. Peskova and D. Giordano (for AMBER)

COMPASS proposal



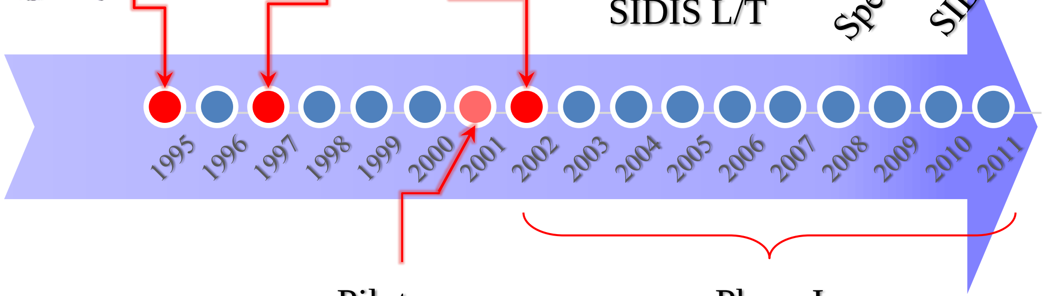
COMPASS approval

COMPASS 1st data taking

SIDIS L/T

Spectroscopy

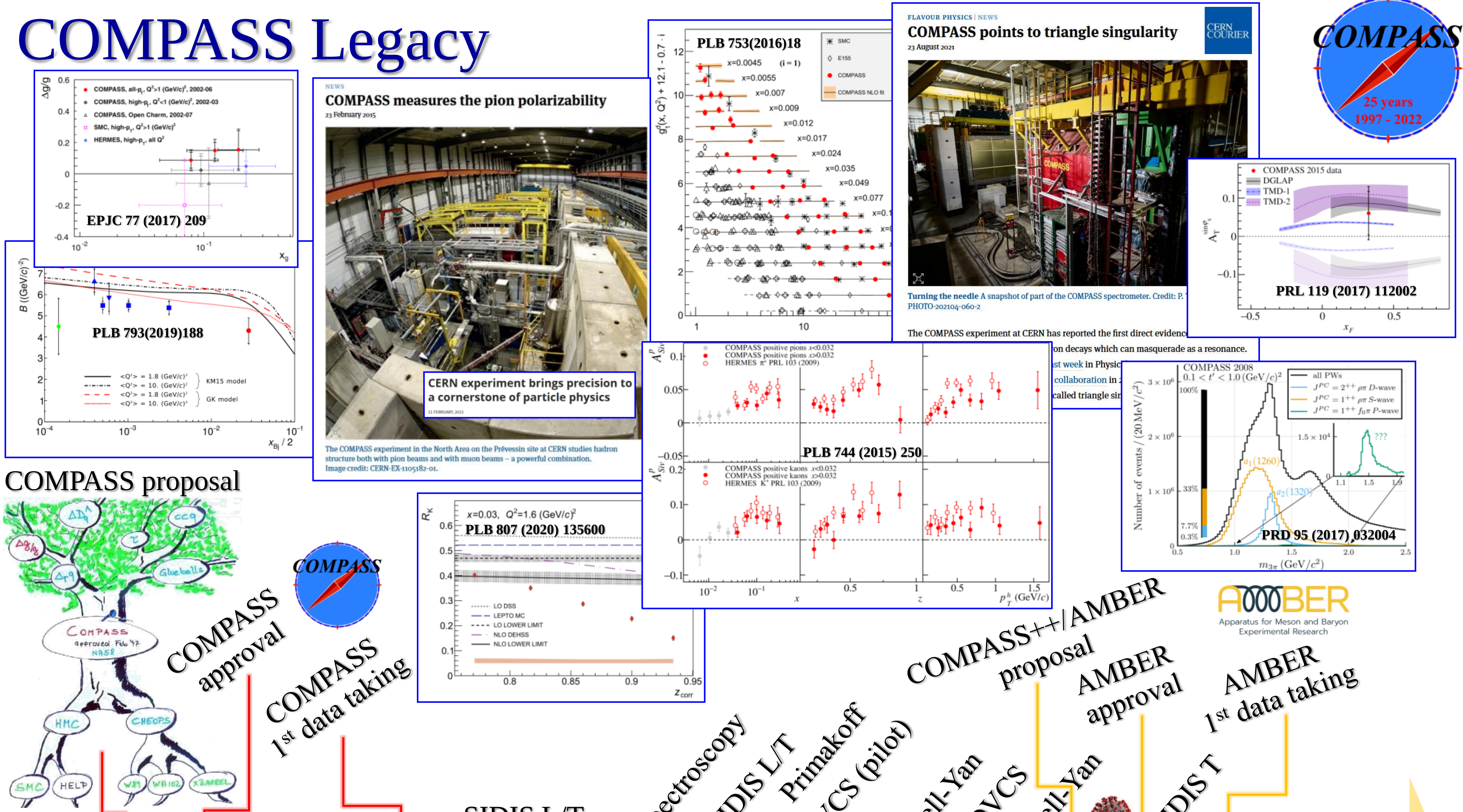
SIDIS L/T



Pilot run

Phase I

COMPASS Legacy



NEWS

COMPASS measures the pion polarizability

23 February 2015

CERN experiment brings precision to a cornerstone of particle physics

11 FEBRUARY, 2015

The COMPASS experiment in the North Area on the Prévessin site at CERN studies hadron structure both with pion beams and with muon beams – a powerful combination. Image credit: CERN-EX-1105182-01.

FLAVOUR PHYSICS | NEWS

CERN COURIER

COMPASS points to triangle singularity

23 August 2021

Turning the needle A snapshot of part of the COMPASS spectrometer. Credit: P.
PHOTO-202104-060-2

The COMPASS experiment at CERN has reported the first direct evidenc
on decays which can masquerade as a resonance.
st week in Physic
collaboration in
called triangle sin

COMPASS proposal

COMPASS approval

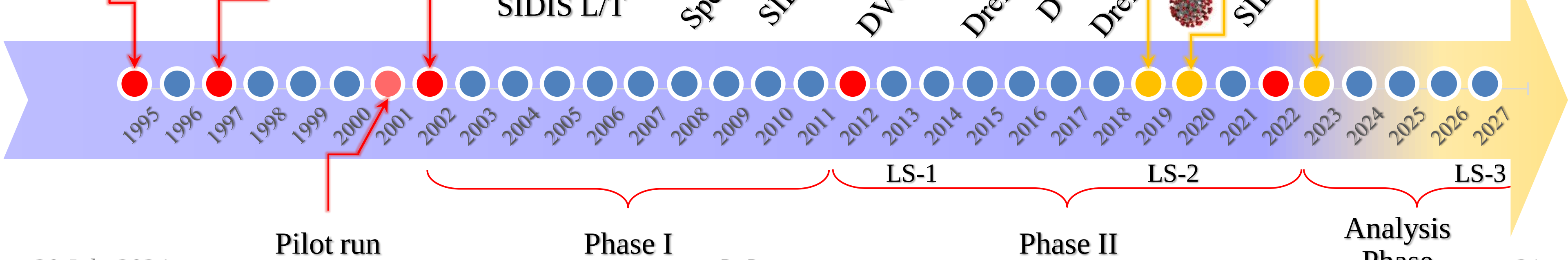
COMPASS 1st data taking

COMPASS++/AMBER proposal

AMBER approval

AMBER 1st data taking

AMBER
Apparatus for Meson and Baryon Experimental Research



Pilot run

Phase I

Phase II

Analysis Phase

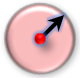
Cahn effect in SIDIS

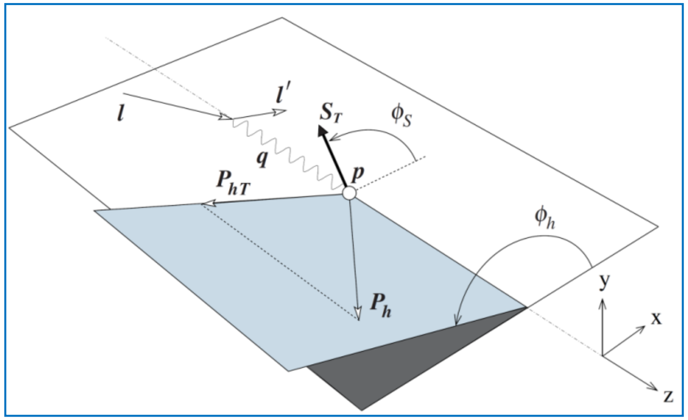
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

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

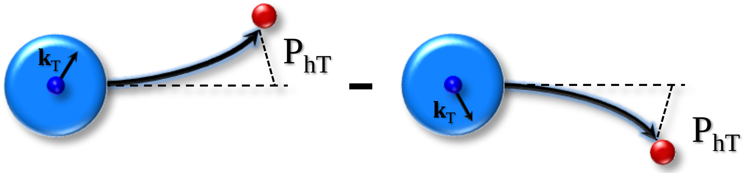
number density



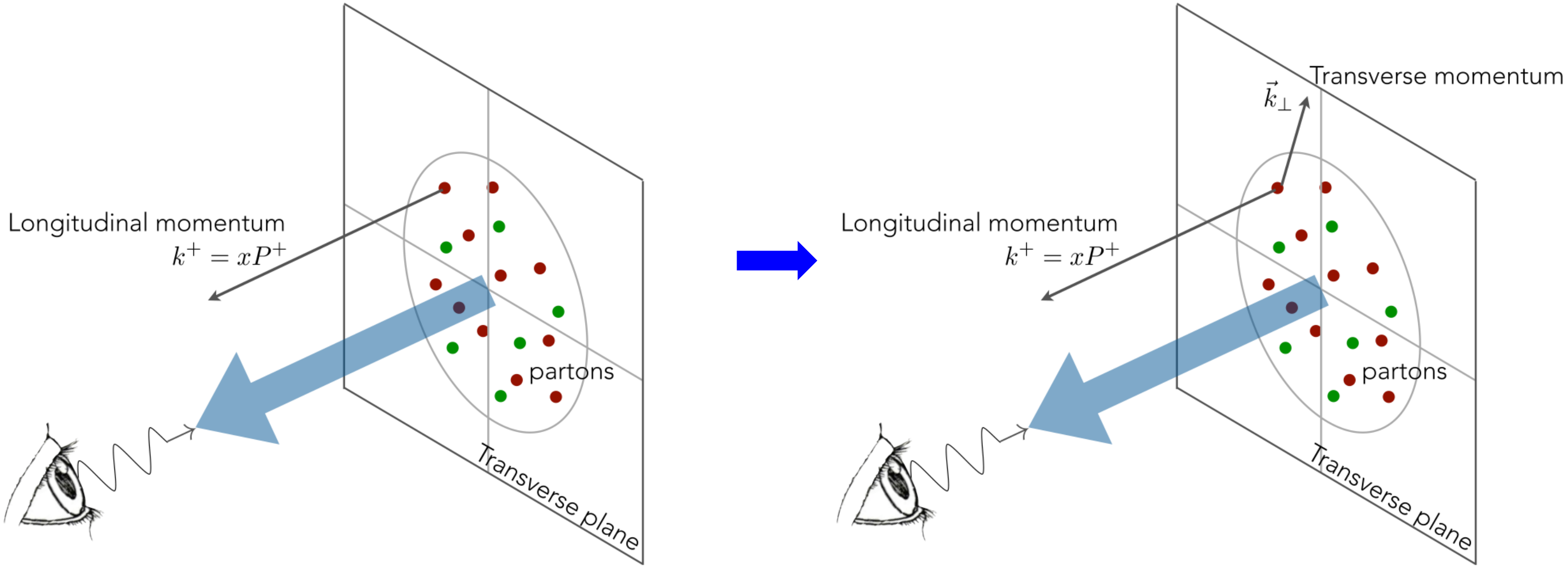


Cahn effect - R. N. Cahn, PLB 78 (1978)

The point that there are azimuthal dependences, which arise from the transverse momenta of the partons was clearly stated in this papers: T.P. Cheng and A. Zee, **Phys. Rev. D6** (1972) 885; F. Ravndal, **Phys. Lett. 43B** (1973) 301.R.L. Kingsley, **Phys. Rev. D10** (1974) 1580; A.M. Kotsinyan, **Teor. Mat. Fiz. 24** (1975) 206;



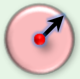
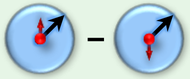
$$k_T \rightarrow \cos\varphi_q \rightarrow \cos\varphi_h$$



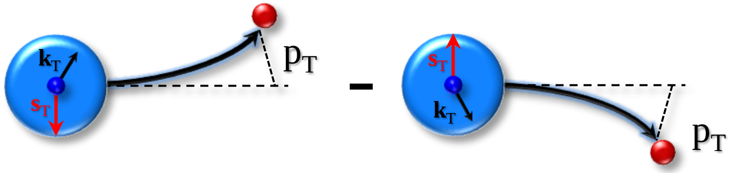
Boer-Mulders effect in SIDIS

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

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

Quark / **Nucleon**	**U**		**T**
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density** 		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders** 

Arises due to the correlation between quark transverse spin and intrinsic transverse momentum

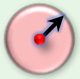
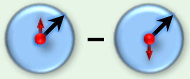


$$F_{UU}^{\cos 2\phi_h} = C\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-\boldsymbol{p}_T\cdot\boldsymbol{k}_T}{MM_h}h_1^{\perp q}H_{1q}^{\perp h}\right]$$

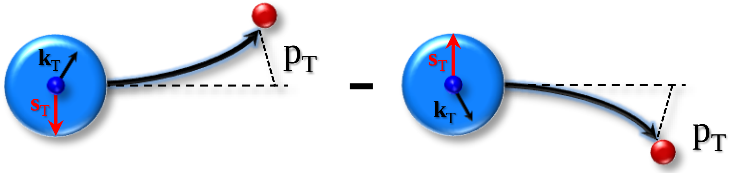
Boer-Mulders effect in SIDIS

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

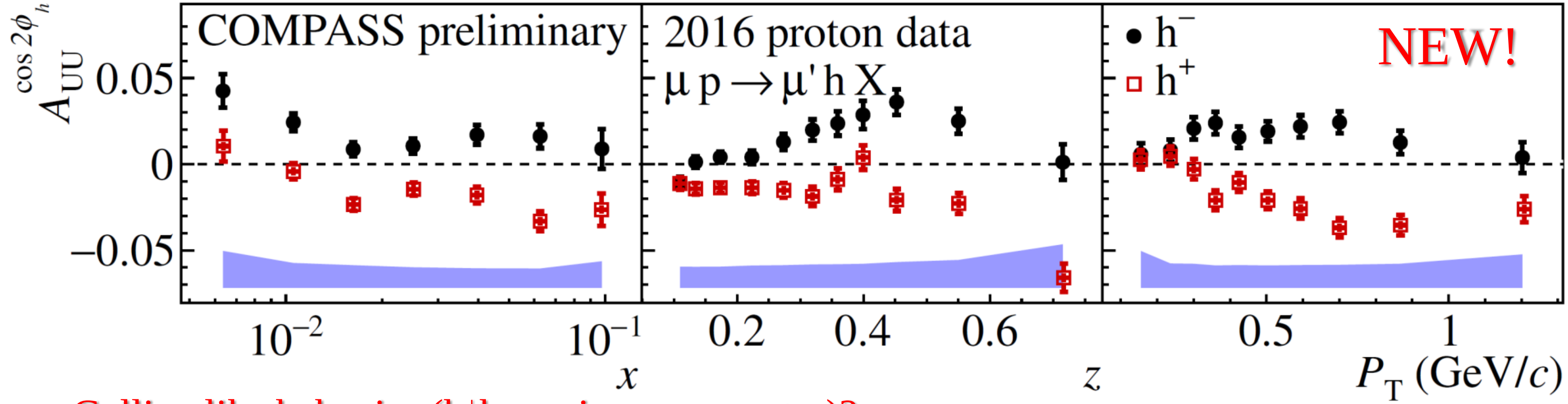
$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\ldots\right)$$

Quark / Nucleon	U		T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density** 		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders** 

Arises due to the correlation between quark transverse spin and intrinsic transverse momentum



$$F_{UU}^{\cos 2\phi_h} = C\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-\boldsymbol{p}_T\cdot\boldsymbol{k}_T}{MM_h}h_1^{\perp q}H_{1q}^{\perp h}\right]$$



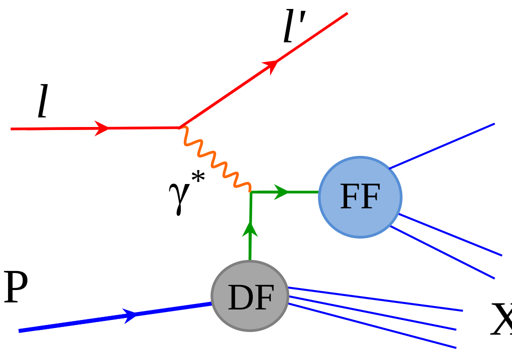
- Collins-like behavior (h^+h^- - mirror symmetry)?

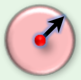
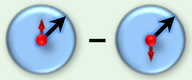
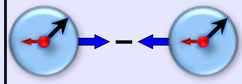
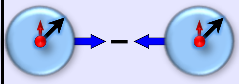
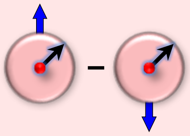
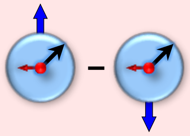
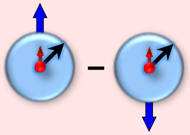
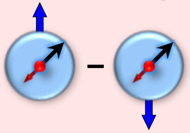
SIDIS x-section and TMDs at twist-2

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

All measured by COMPASS

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



Nucleon \ **Quark**	**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** ↗ $\mathbf{k_T}$

The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

Nucleon structure

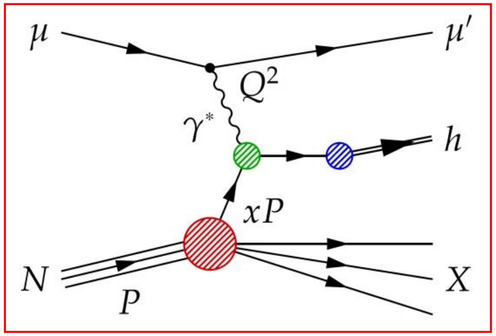
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

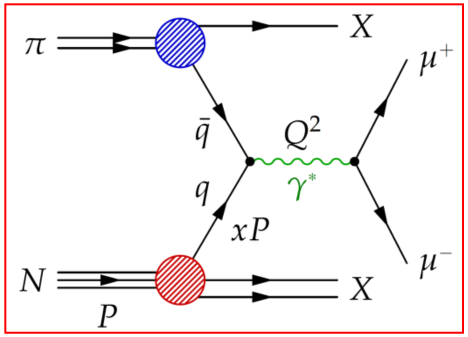
Hadron spectroscopy

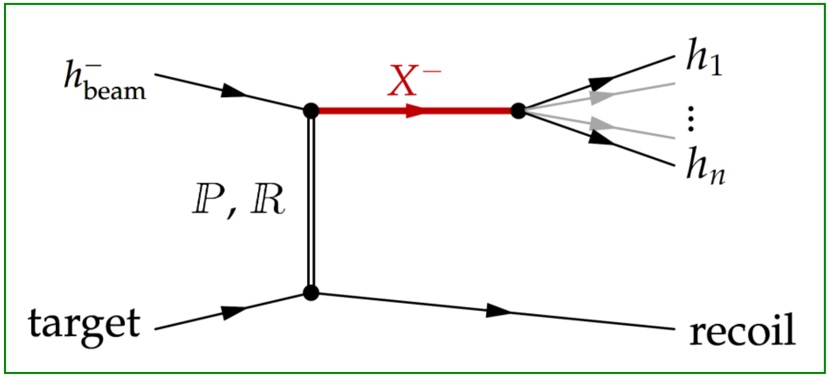
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

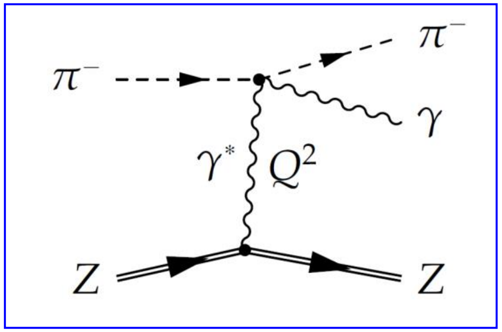
Chiral dynamics

- Test chiral perturbation theory in $\pi(K)$ γ reactions
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
- Chiral anomaly $F_{3\pi}$









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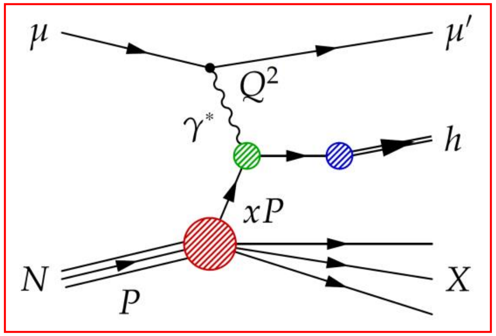
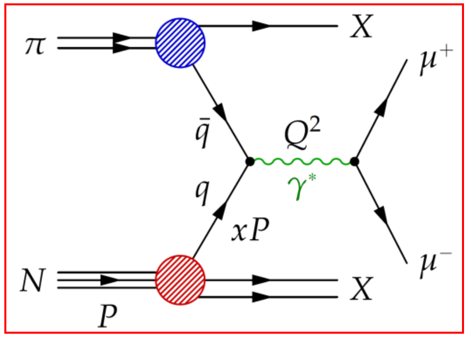
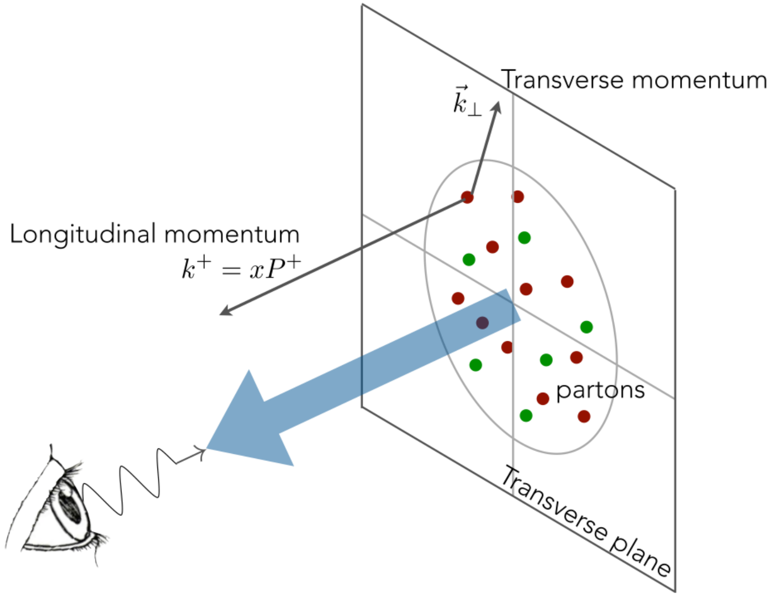




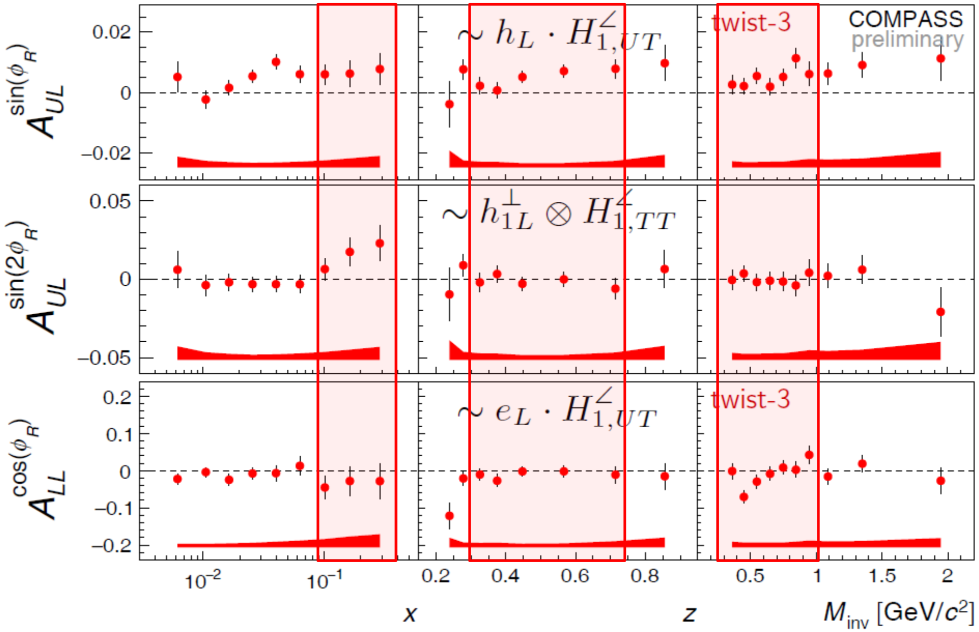


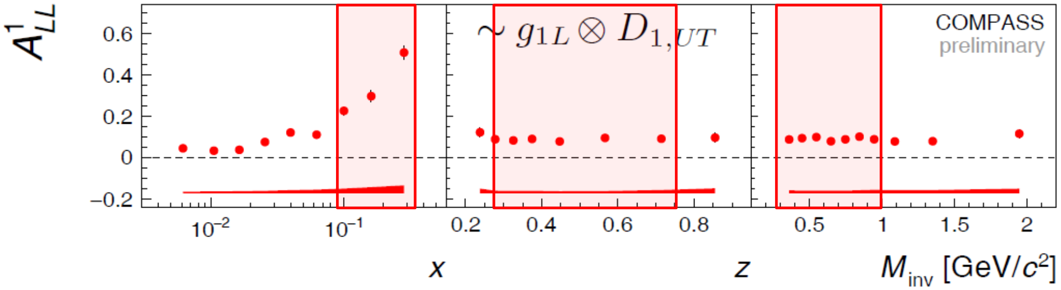
COMPASS data taking campaigns

Beam	Target	year	Physics programme
μ^+	Polarized deuteron (^6LiD)	2002 2003 2004	80% Longitudinal | 20% Transverse SIDIS
		2006	Longitudinal SIDIS
	Polarized proton (NH_3)	2007	50% Longitudinal | 50% Transverse SIDIS
π | K | p	LH_2, Ni, Pb, W	2008 2009	Spectroscopy
μ^+	Polarized proton (NH_3)	2010	Transverse SIDIS
		2011	Longitudinal SIDIS
π | K | p	Ni	2012	Primakoff
$\mu^\pm$	LH_2	2012	Pilot DVCS & HEMP & unpolarized SIDIS
π^-	Polarized proton (NH_3)	2014	Pilot Drell-Yan
		2015 2018	Transverse Drell-Yan
$\mu^\pm$	LH_2	2016 2017	DVCS & HEMP & unpolarized SIDIS
μ^+	Polarized deuteron (^6LiD)	2021 2022	Transverse SIDIS

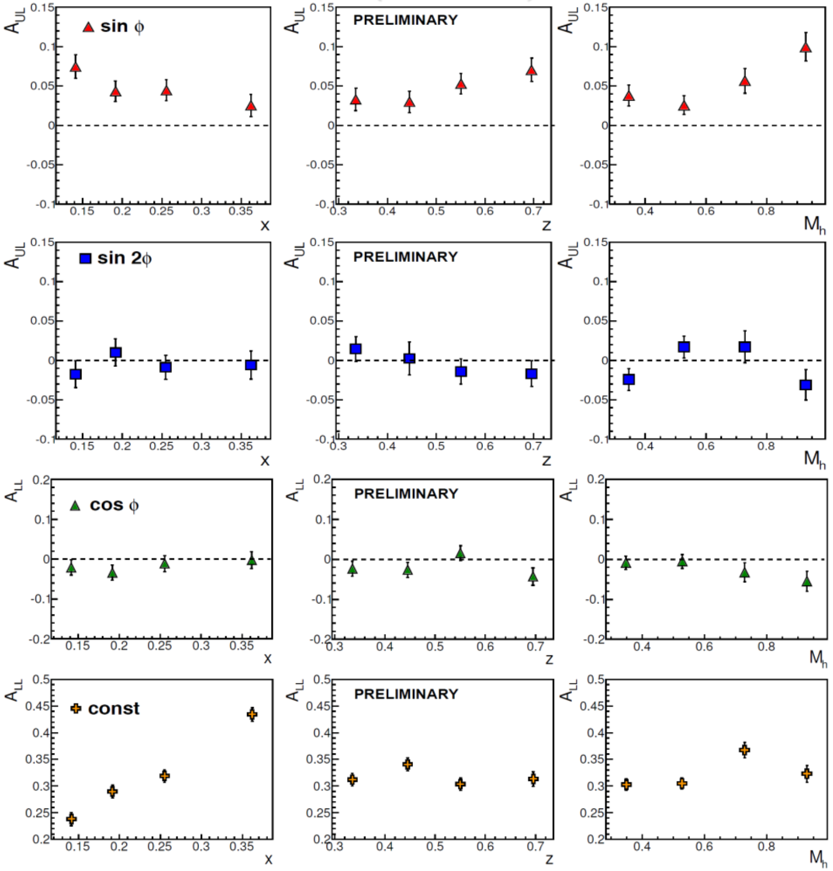
Selected results for di-hadron LSAs

COMPASS (NH_3) 2007+2011 data: preliminary

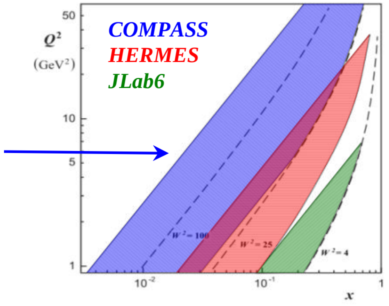




CLAS 6 GeV (NH_3)
S. A. Pereira: PoS (DIS 2014) 231

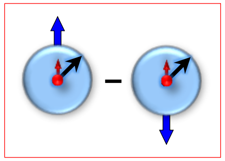


$Q^2 > 1\,(\mathrm{GeV}/c)^2$
$0.0025 < x < 0.7$
$0.1 < y < 0.9$
$W > 5\,\mathrm{GeV}/c^2$



- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A_{LL}^{1}
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?

SIDIS TSAs: Collins effect and Transversity

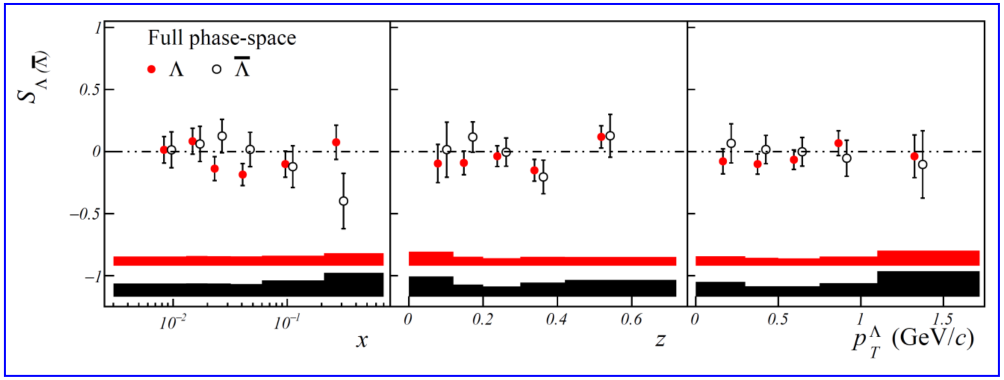


$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\ \right\}$$

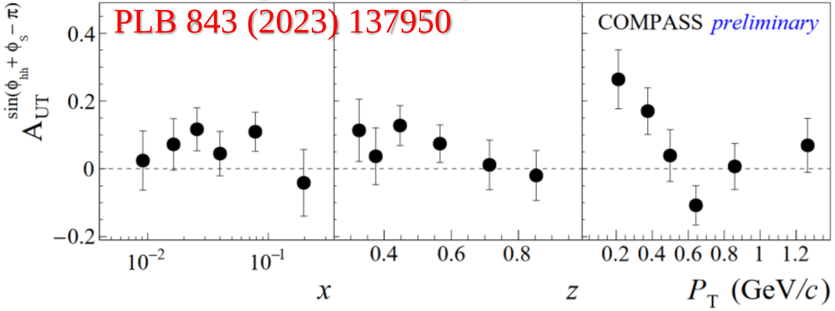
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\,h_1^q H_{1q}^{\perp h}\right]}$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

PLB 824 (2022) 136834

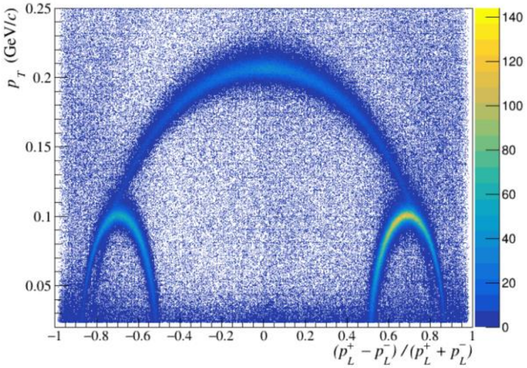


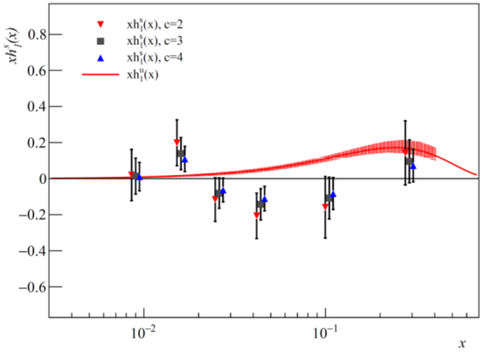
Inclusive $\boldsymbol{\rho^0}$ Collins asymmetry

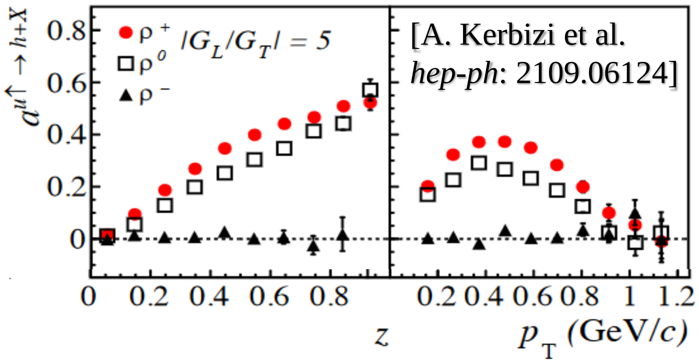


PLB 843 (2023) 137950

- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T







[A. Kerbizi et al. *hep-ph*: 2109.06124]