TMD effects in polarized processes: COMPASS selected highlights

BAKUR PARSAMYAN

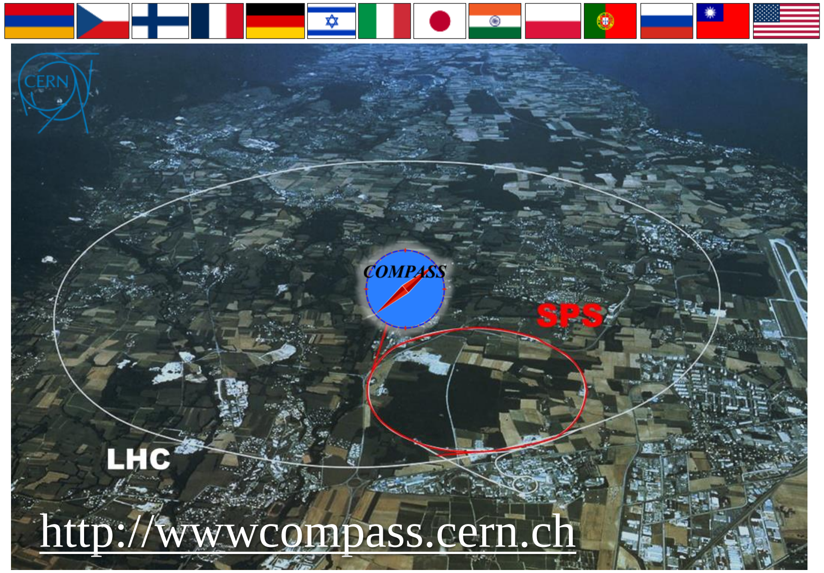
AANL, CERN, INFN (Turin) and
Yamagata University

Joint "20th *International Workshop on Hadron Structure and Spectroscopy*" and
5th workshop on "*Correlations in Partonic and Hadronic Interactions*"
September 30 – October 4, Yerevan, Armenia

COMPASS timeline

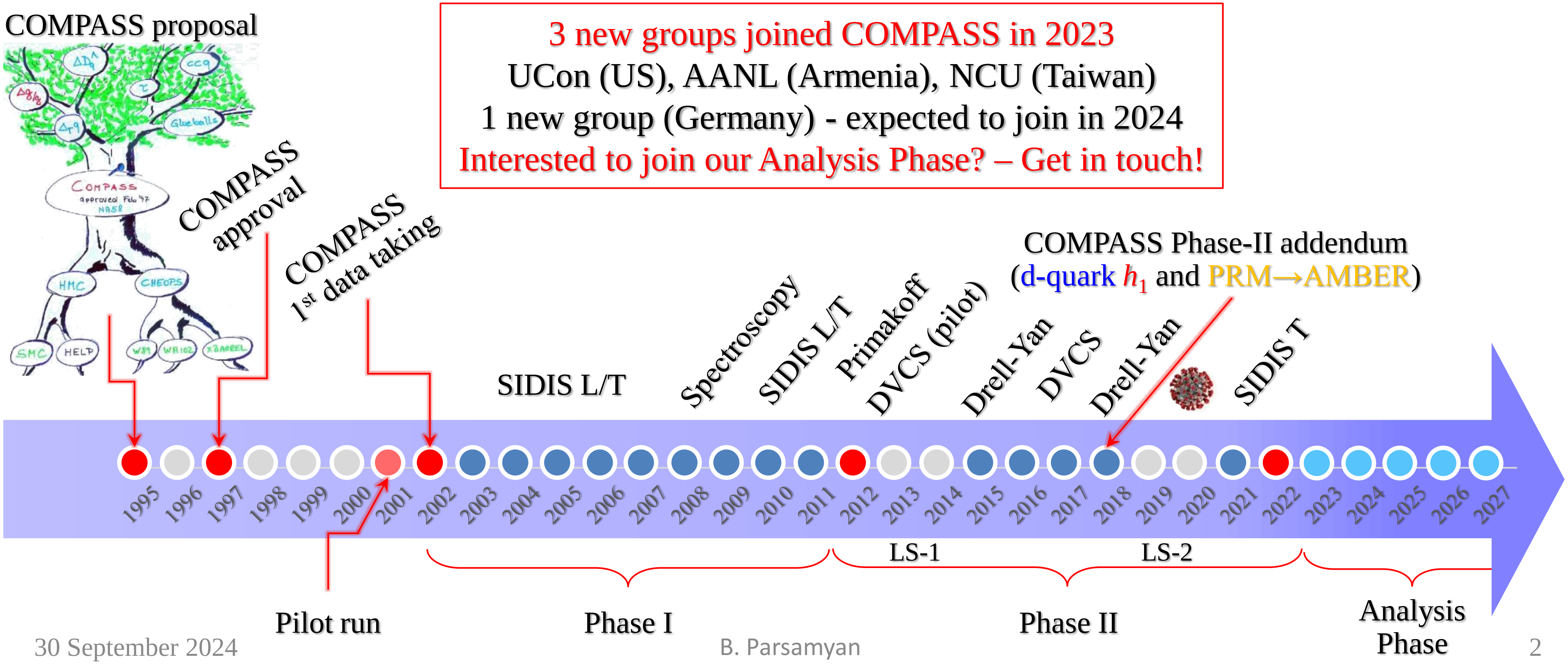
- CERN SPS north area – M2 beamline
- Fixed target experiment
- Approved in 1997
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

33 institutions from 15 countries: ~ 200 members



http://wwwcompass.cern.ch

3 new groups joined COMPASS in 2023
UCon (US), AANL (Armenia), NCU (Taiwan)
1 new group (Germany) - expected to join in 2024
Interested to join our Analysis Phase? – Get in touch!



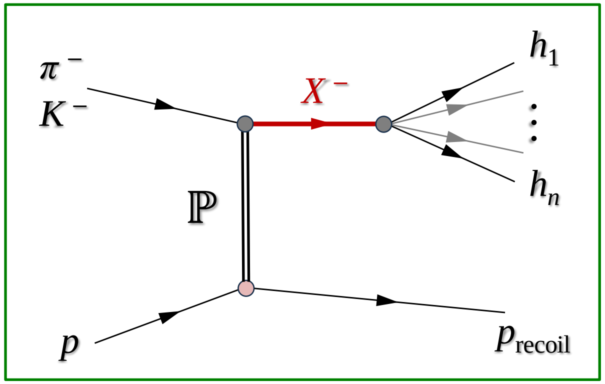
COMPASS Physics Program

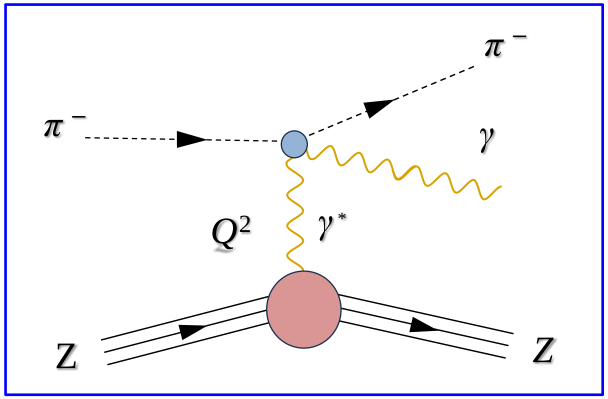
Hadron spectroscopy

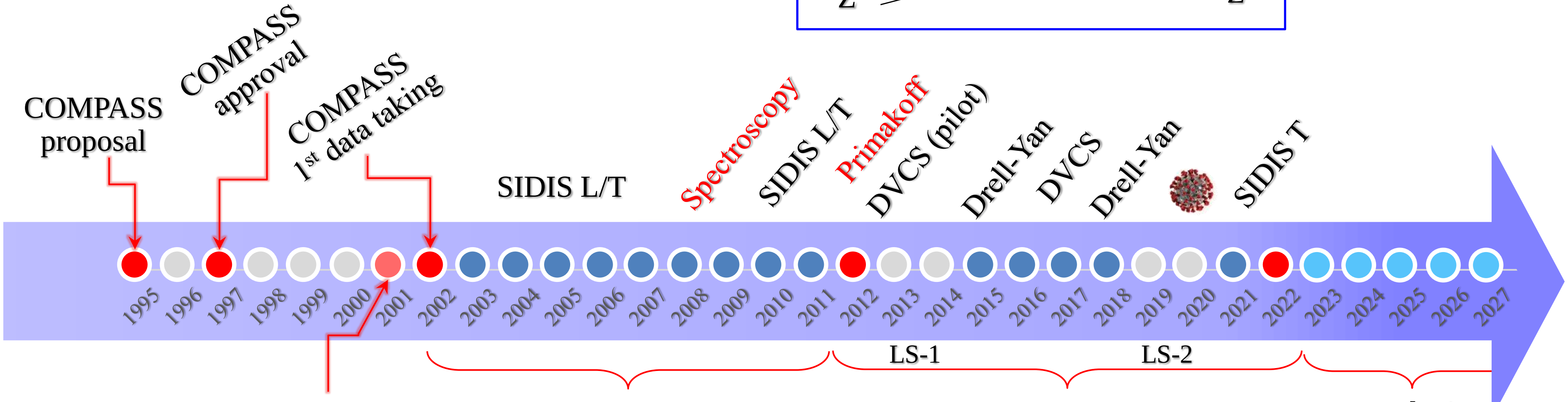
- Diffractive *π(K)* dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

Chiral dynamics

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







Pilot run

Phase I

Phase II

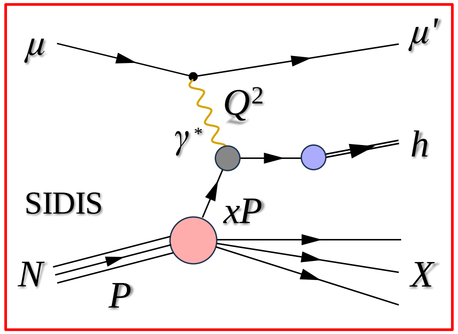
Analysis Phase

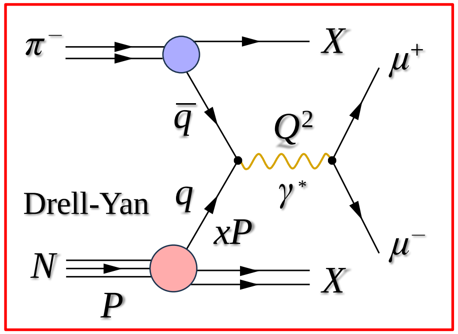
COMPASS Physics Program

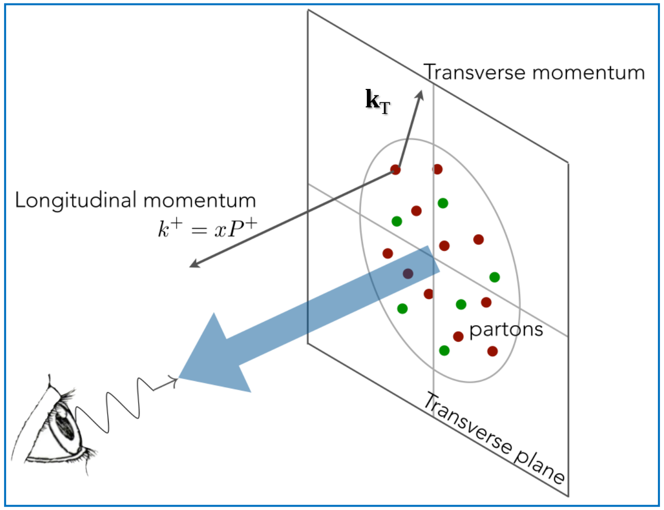
Nucleon structure

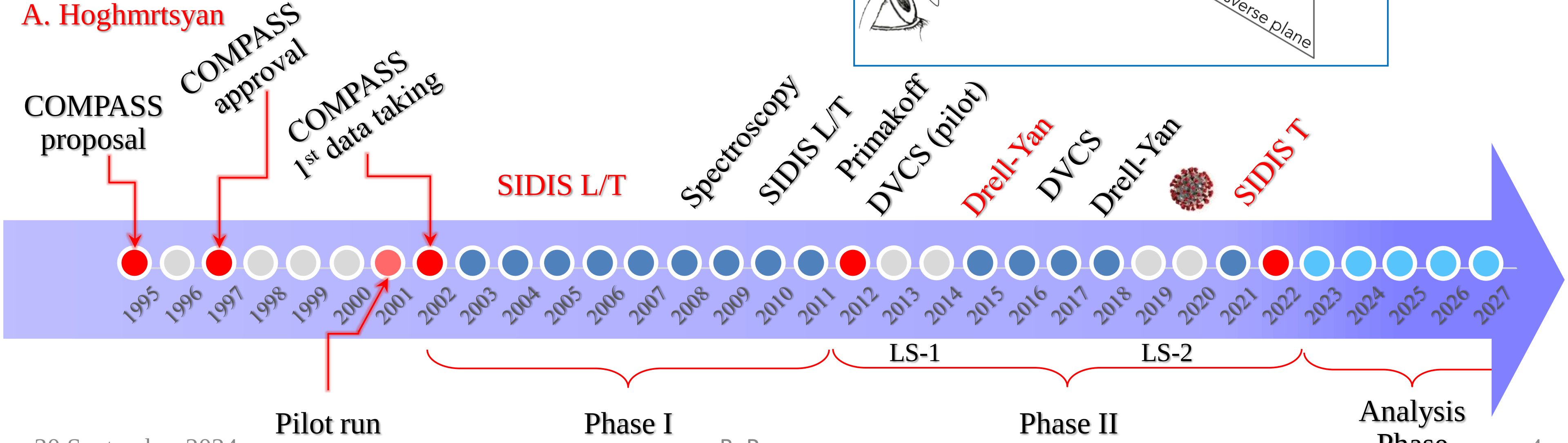
- Hard scattering of $\mu^\pm$ and π^- off (un)polarized P/D targets
- Inclusive and Semi-Inclusive DIS
- Drell-Yan and J/ψ production
- Study of nucleon spin structure
  - Longitudinal and Transverse
- Collinear and TMD pictures
- Parton distribution functions and fragmentation functions
- Last COMPASS measurement: 2022 run – transverse SIDIS

See talks by V. Benesova, M. Niemiec, S. Asatryan and A. Hoghmrtsyan





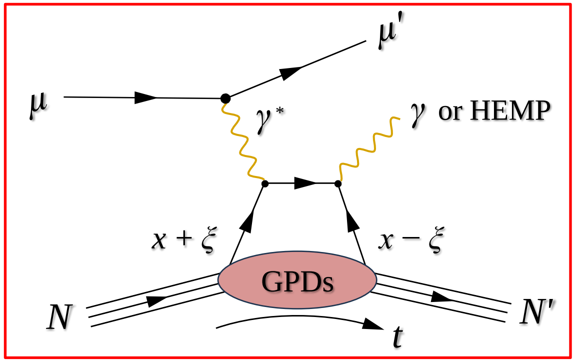




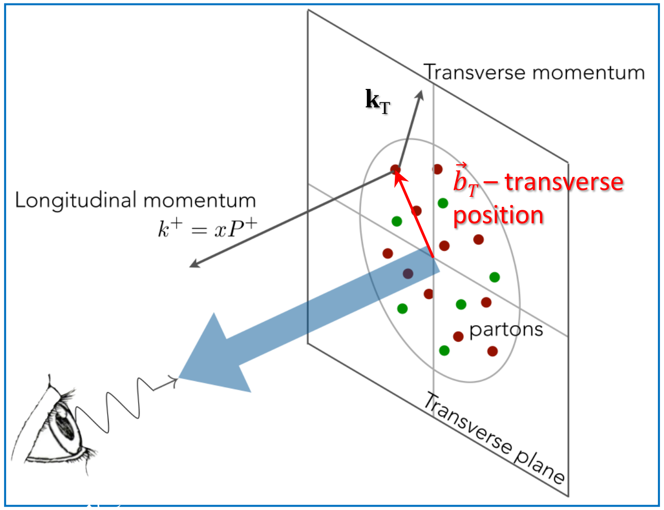
COMPASS Physics Program

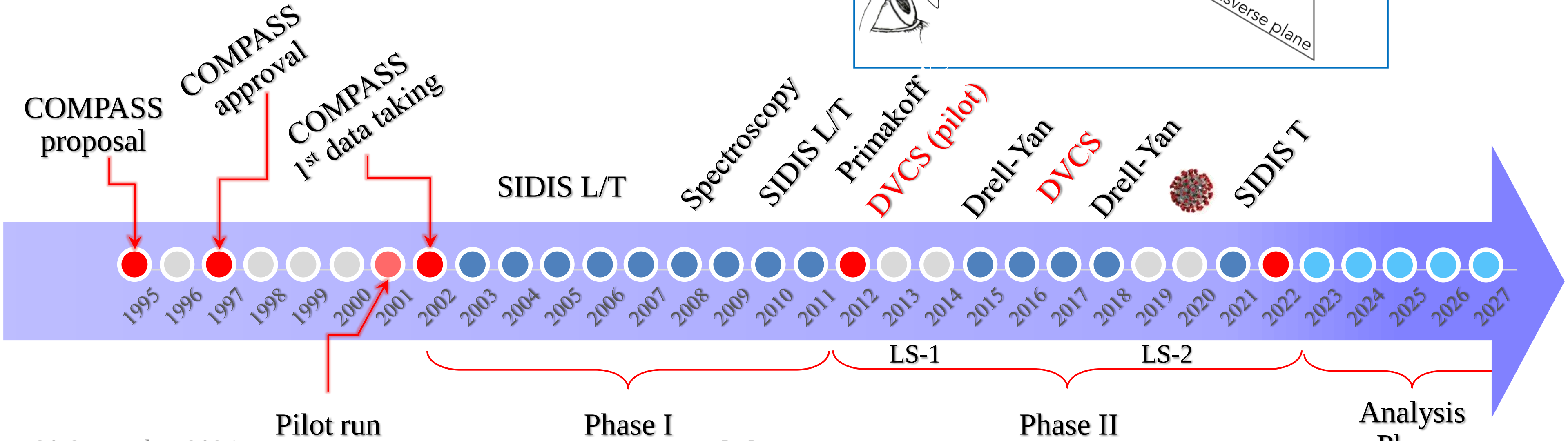
GPDs

- Transverse position $\vec{b}_T$ of partons
  - 8 GPDs - correlation between $\vec{b}_T$ and x
  - Complementary to TMD PDFs
  - Contain information about parton orbital angular momentum
- Accessed via exclusive processes:
  - Deeply virtual Compton scattering (DVCS): $\mu + \mathrm{N} \rightarrow \mu + \gamma + \mathrm{N}$
  - Hard exclusive meson production (HEMP): $\mu + \mathrm{N} \rightarrow \mu + \mathrm{M} + \mathrm{N}$ with $\mathrm{M} = \pi^0, \rho(770), \omega(782)$,..



see Nicole's talk

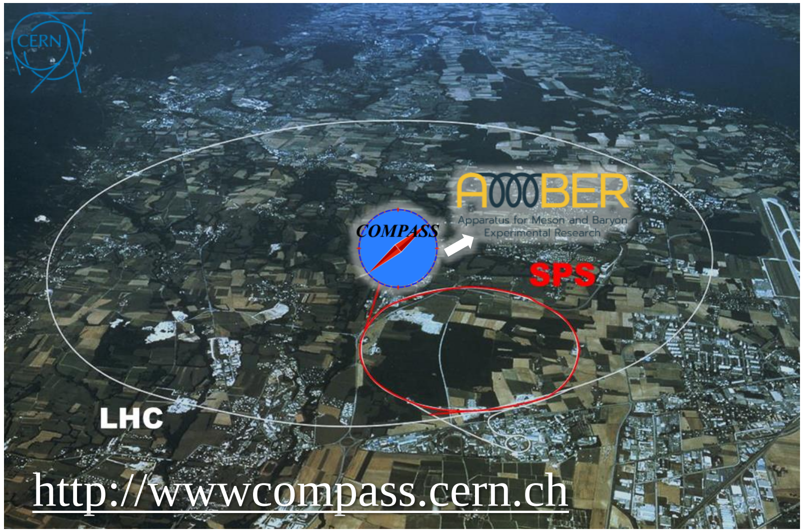




COMPASS-AMBER timeline

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

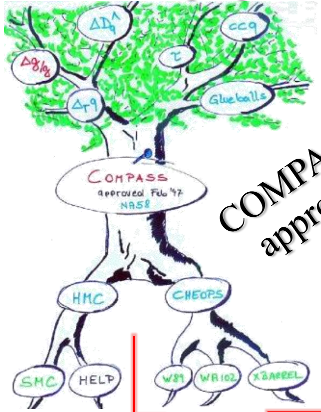
33 institutions from 15 countries: ~ 200 members

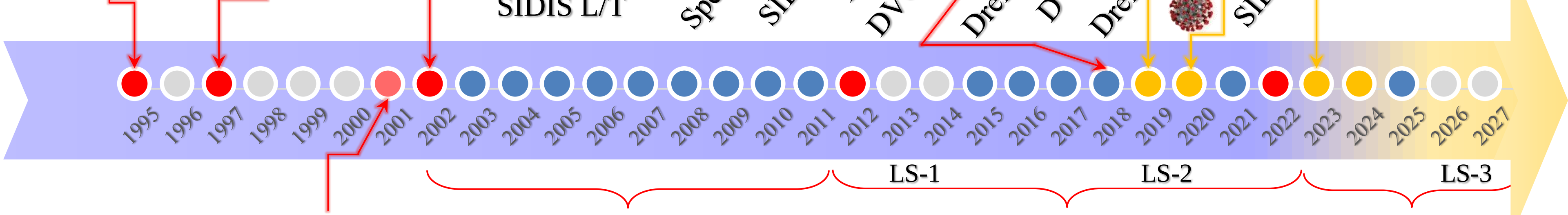


http://wwwcompass.cern.ch

AMBER
Apparatus for Meson and Baryon Experimental Research

COMPASS proposal





COMPASS approval

COMPASS

COMPASS 1st data taking

SIDIS L/T

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

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

Drell-Yan

DVCS

Drell-Yan

COMPASS++/AMBER proposal

AMBER approval

SIDIS T

AMBER
Apparatus for Meson and Baryon Experimental Research

AMBER 1st data taking

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!

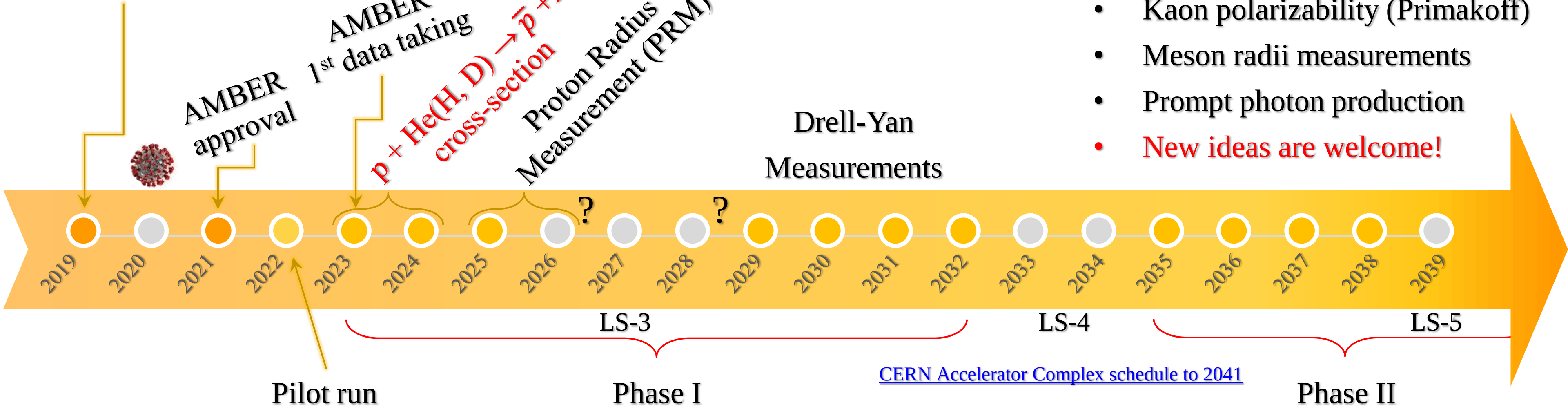
https://amber.web.cern.ch

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

see D. Giordano’s talk

Phase II proposal draft

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



CERN Accelerator Complex schedule to 2041

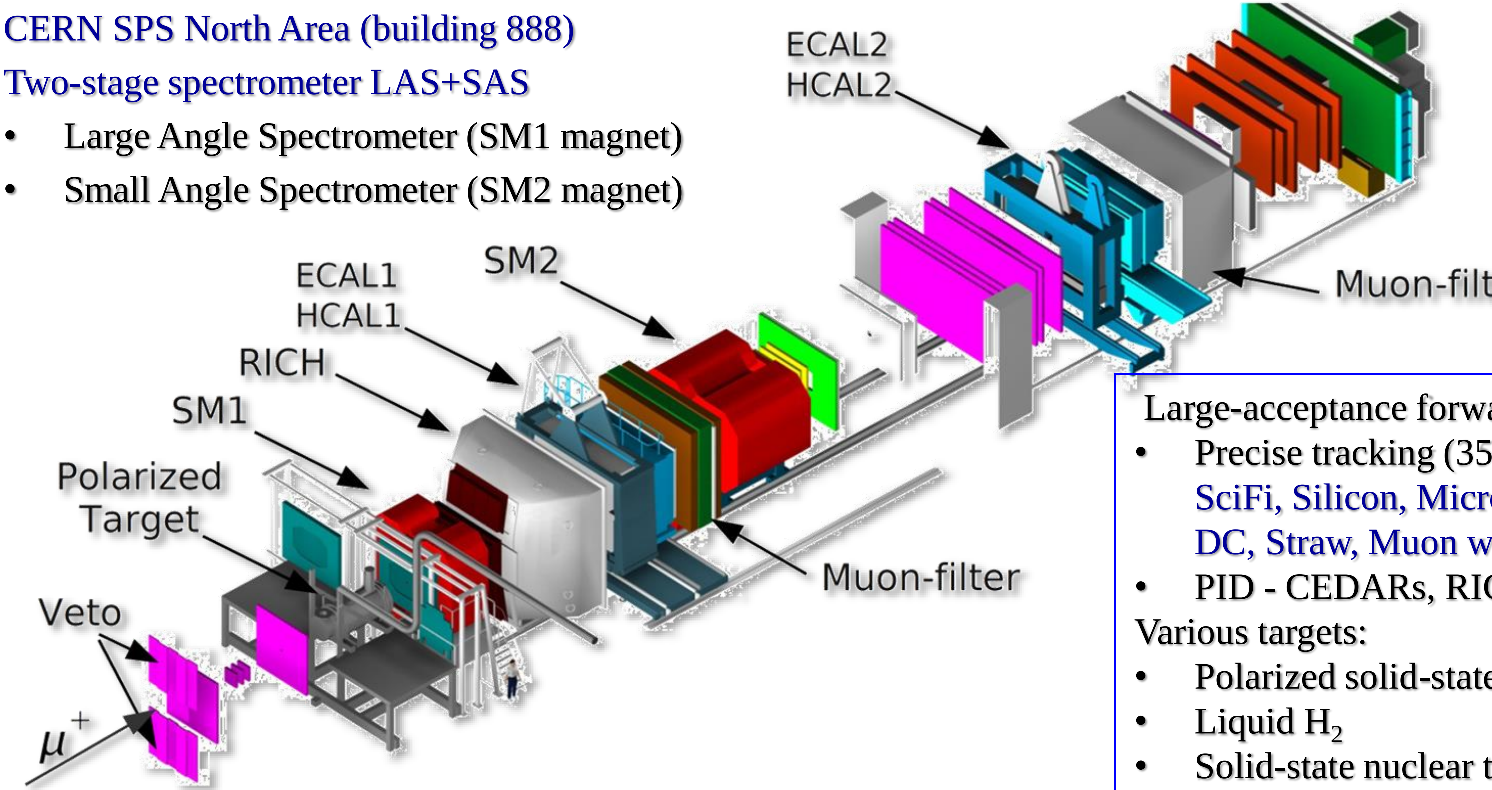
COMPASS experimental setup

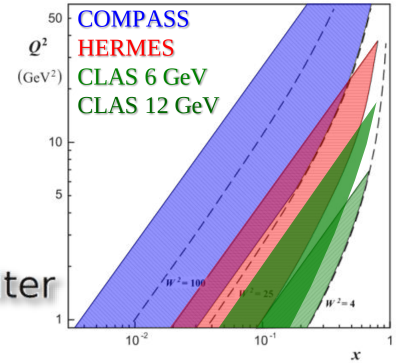
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





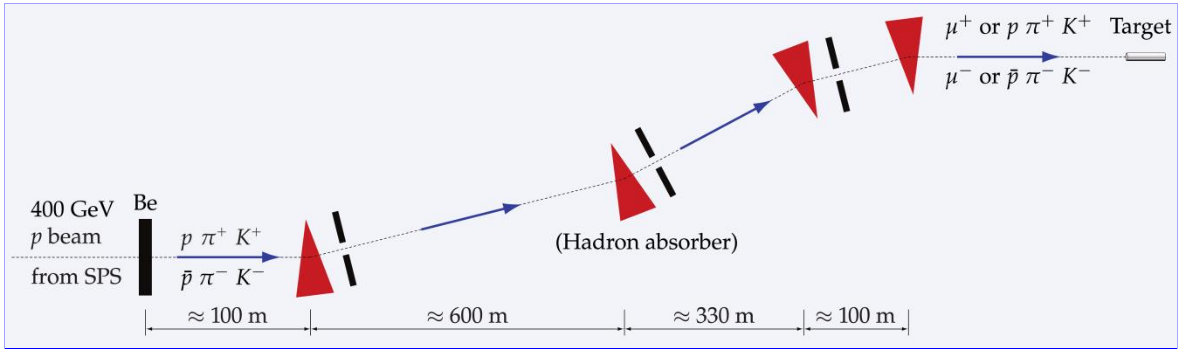
Large-acceptance forward spectrometer

- 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 program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

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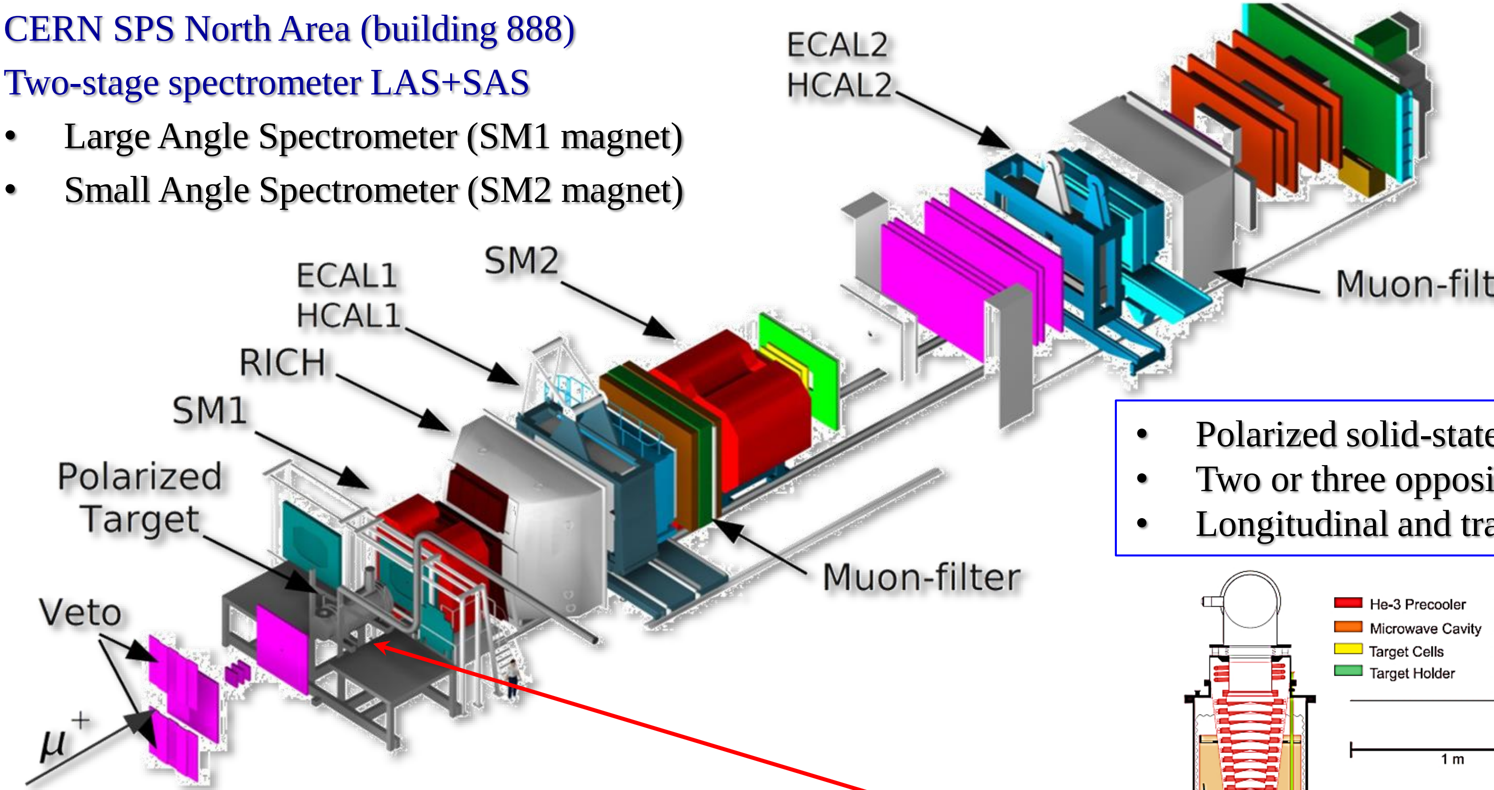
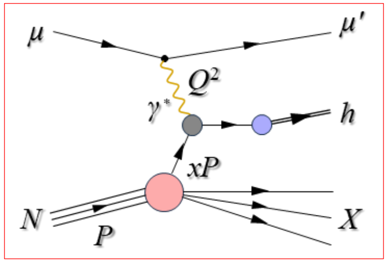
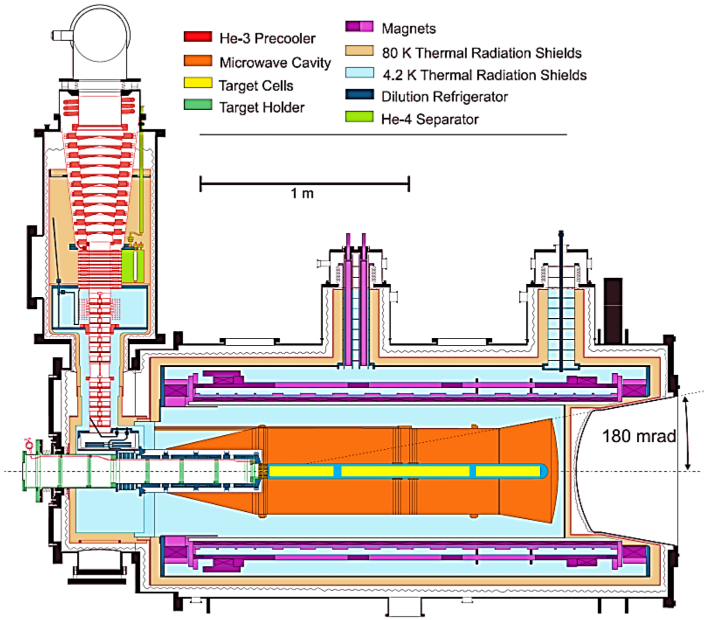




- Polarized solid-state NH_3 or ^{6}LiD
- Two or three oppositely polarized cells
- Longitudinal and transverse polarization



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  - 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

AMBER Phase I: $\bar{p}$ cross-section, 2023 He-target setup

Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

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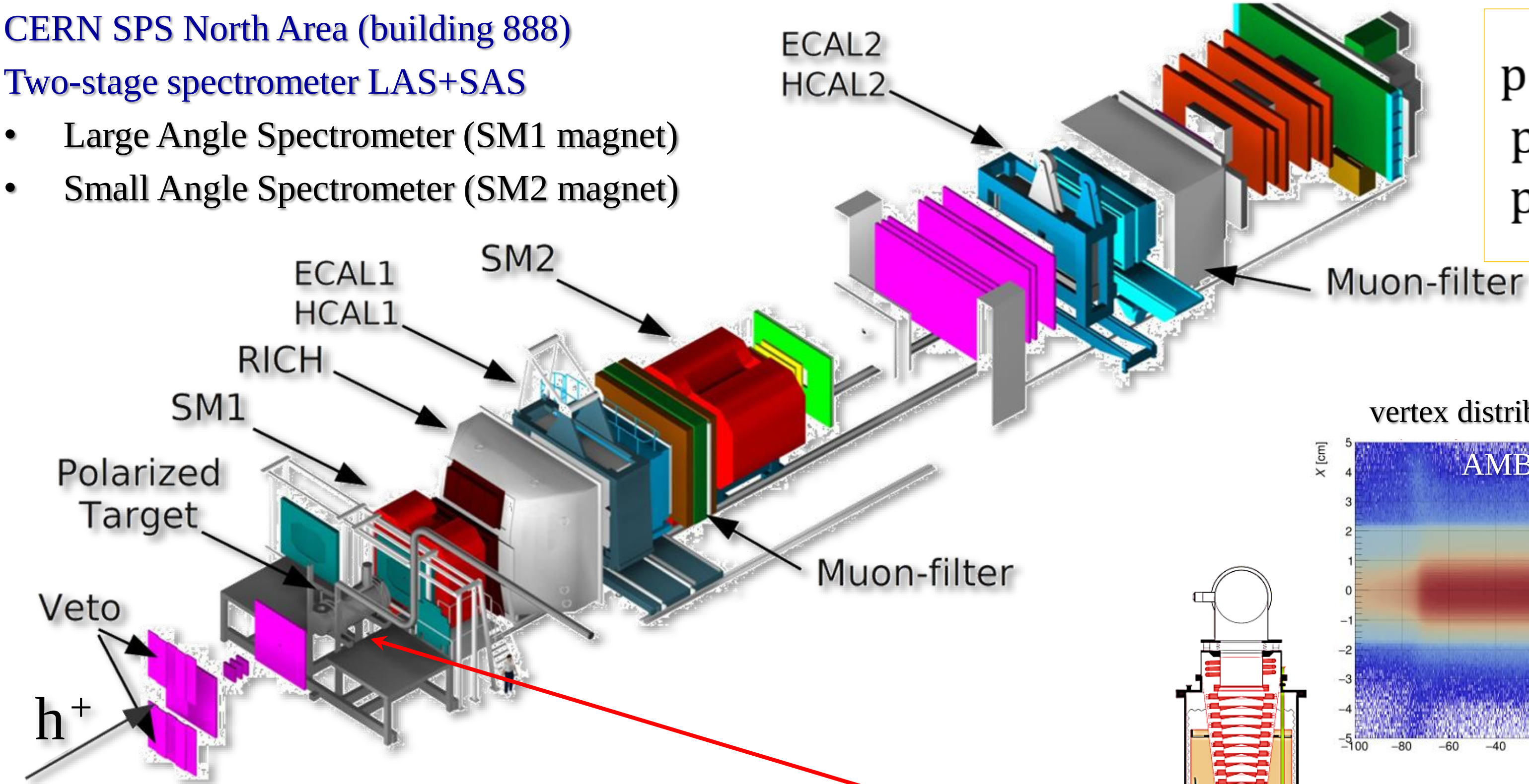
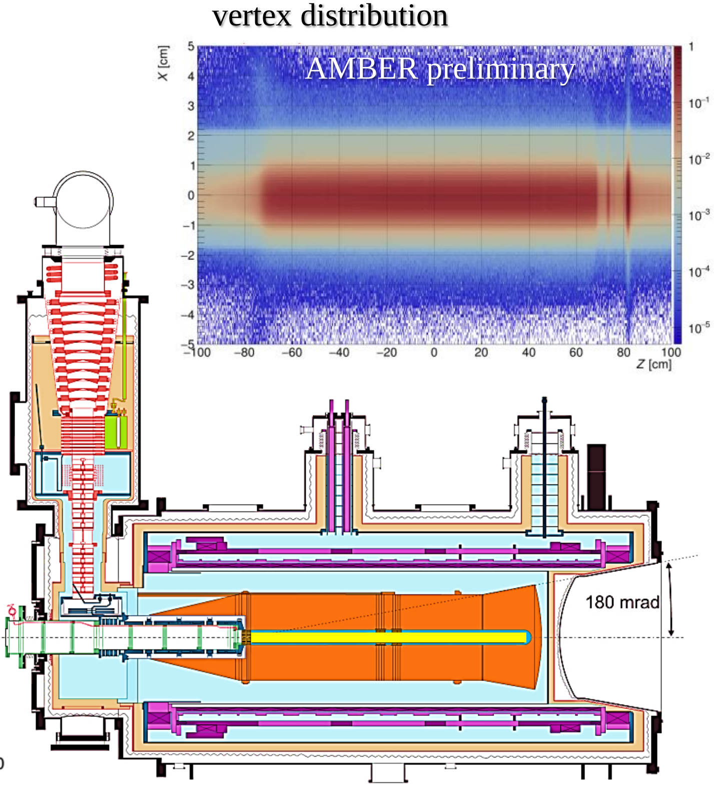
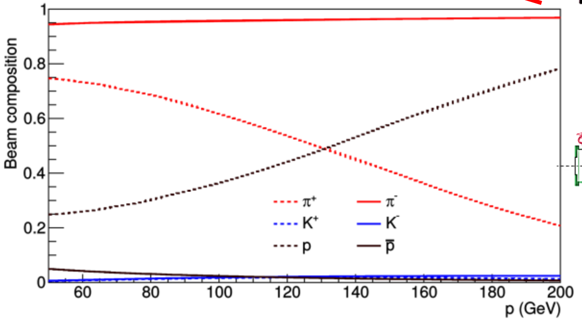


$$p + \mathrm{He} \rightarrow \bar{p} + X$$
$$p + \mathrm{H} \rightarrow \bar{p} + X$$
$$p + \mathrm{D} \rightarrow \bar{p} + X$$


vertex distribution

- h^+ beam: 60, 80, 100, 160, 190 and 250 GeV/c;
  Intensity: $25{\cdot}10^3$ h/s
- Beam PID: 2 CEDAR detectors
- Target: He (2023), H/D (2024)
- Data-taking ~2 months/year
- Dedicated trigger and beam-killer systems



COMPASS experimental setup: Phase II (DY program)

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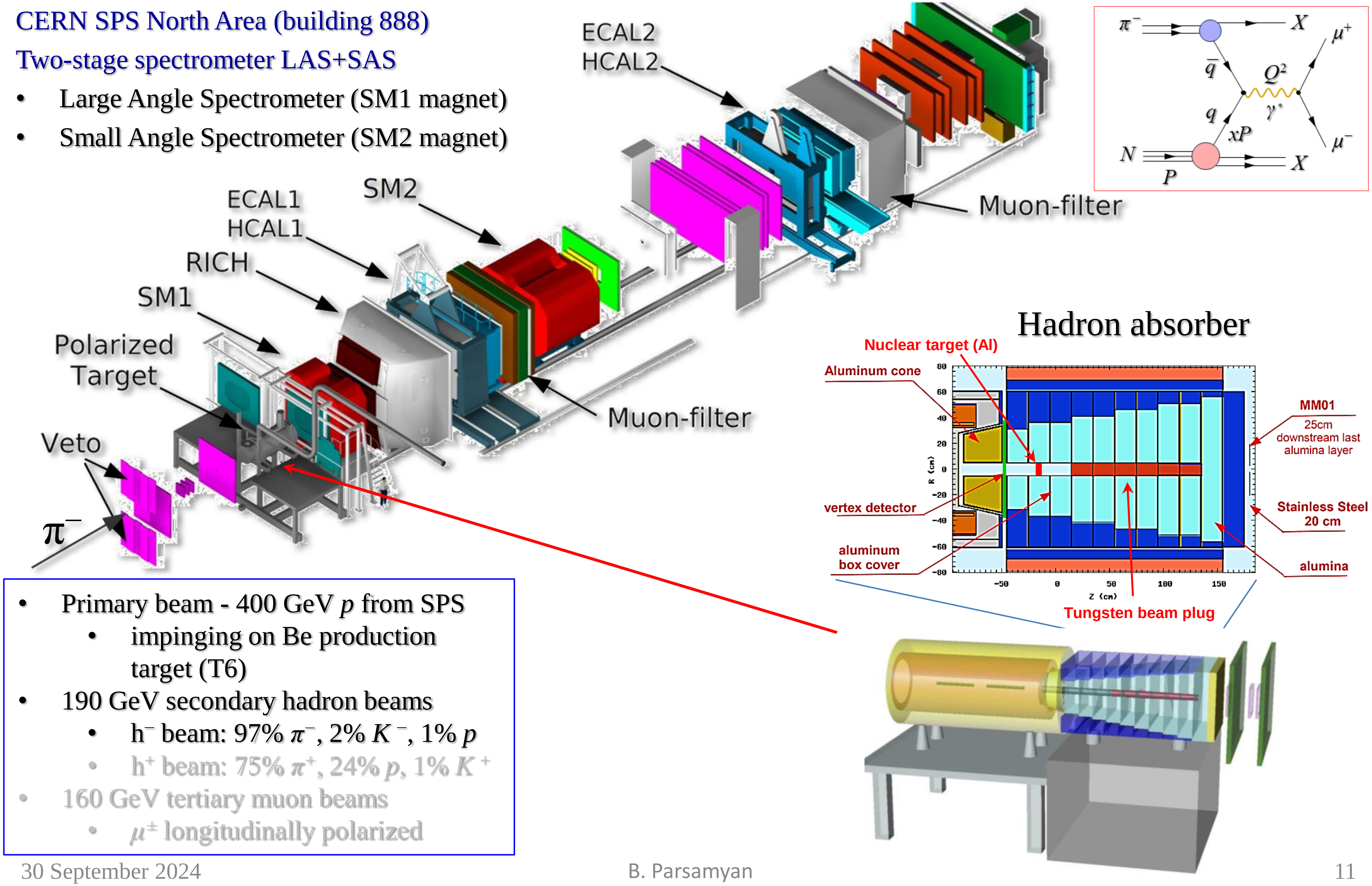

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    - h^- beam: 97% π^-, 2% K^-, 1% p
    - h^+ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
    - $\mu^\pm$ longitudinally polarized

AMBER Phase I-II: DY program setup

Apparatus for Meson and Baryon Experimental Research

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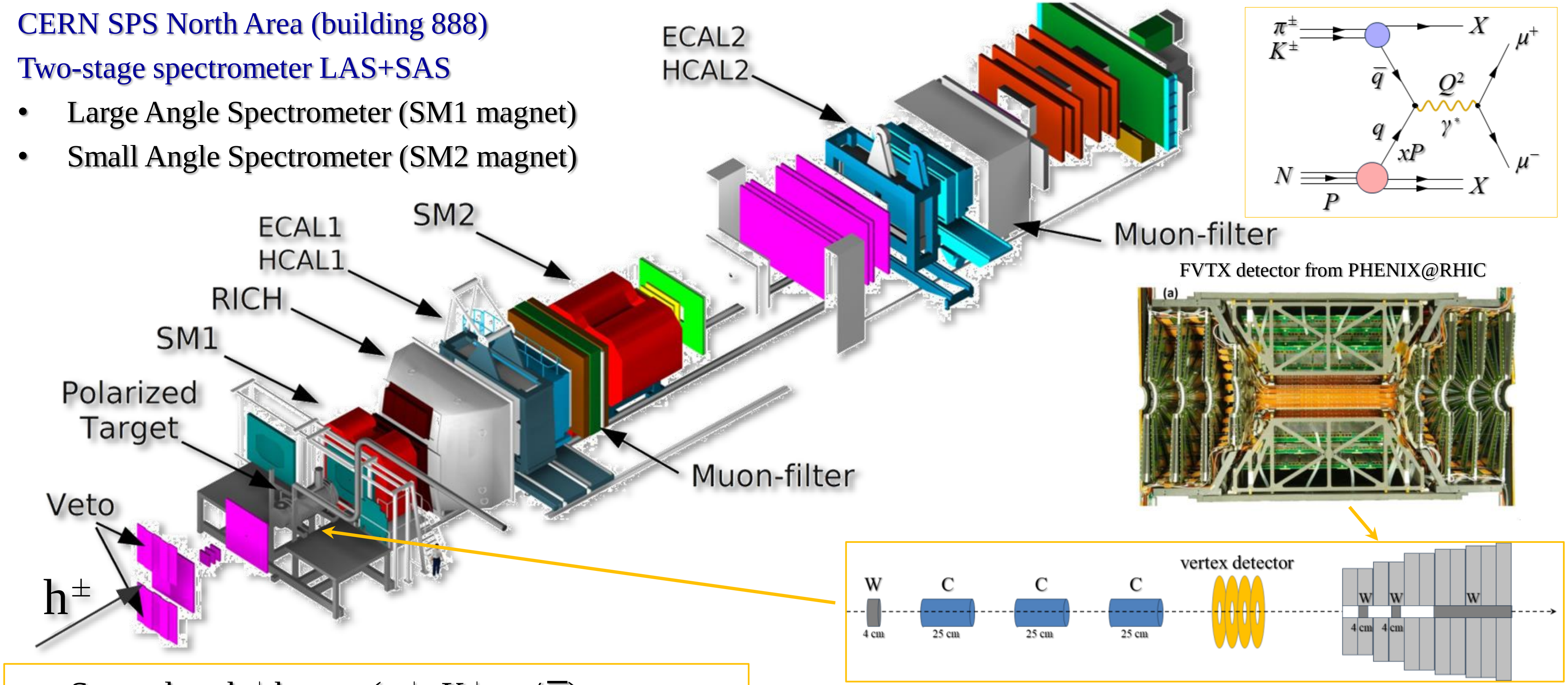
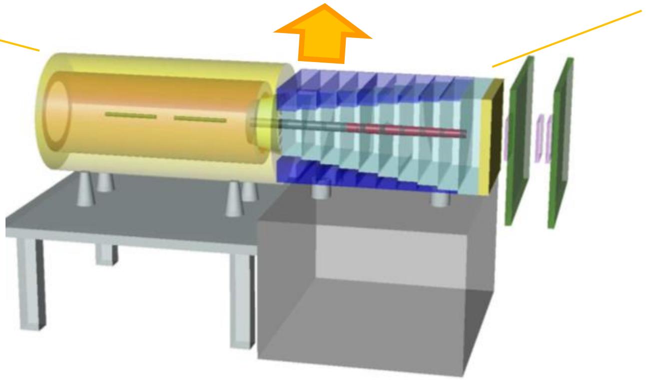


FVTX detector from PHENIX@RHIC

- Secondary $h^{\pm}$ beam: ($\pi^{\pm}$, $K^{\pm}$, $p\,/\,\overline{p}$)
- 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 Phase I-II: DY program setup

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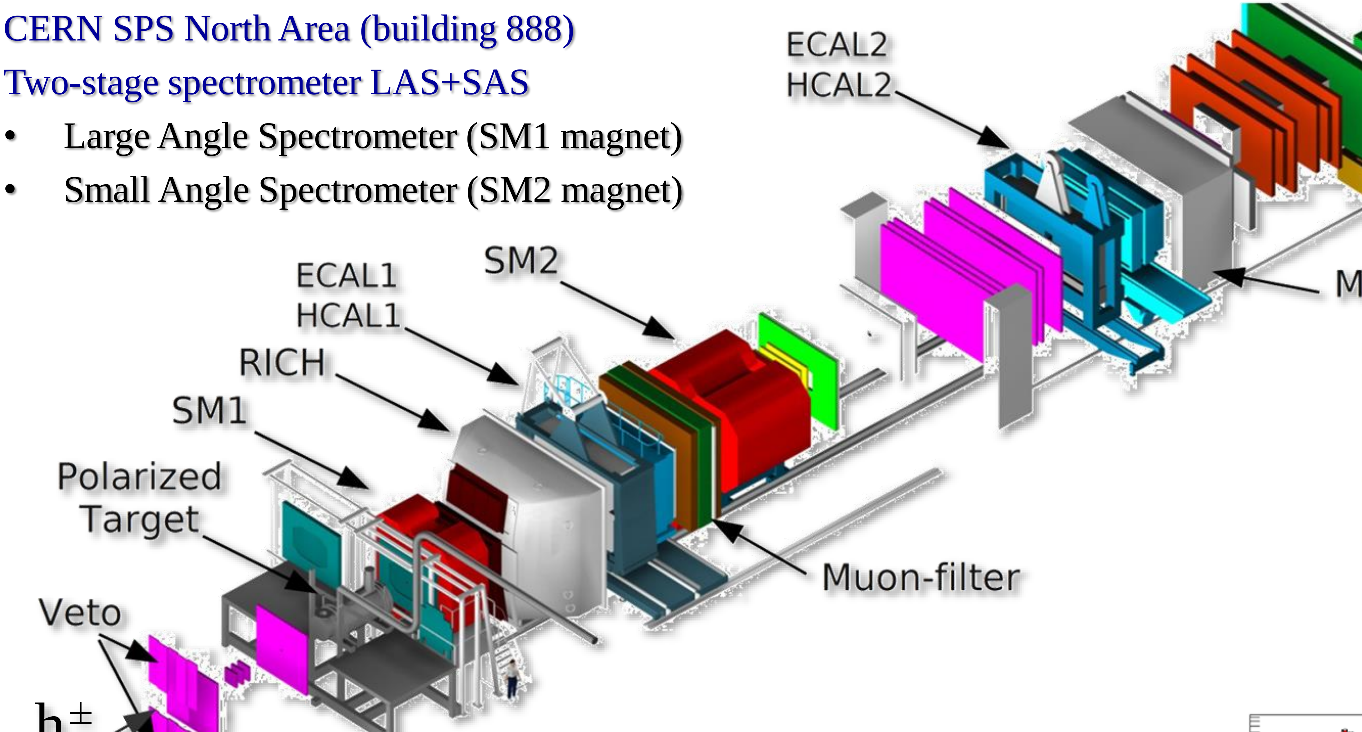

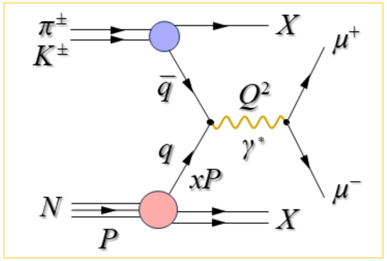

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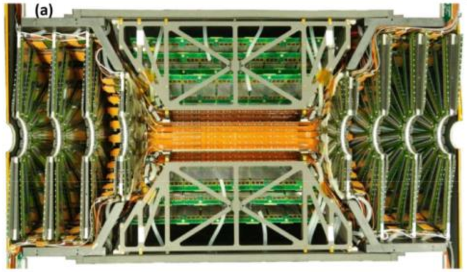
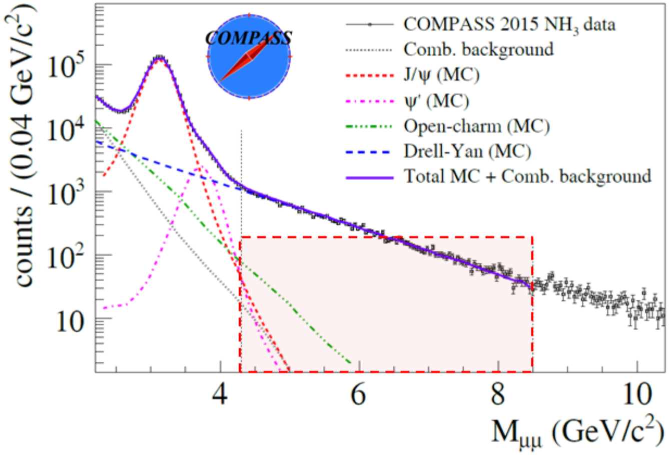
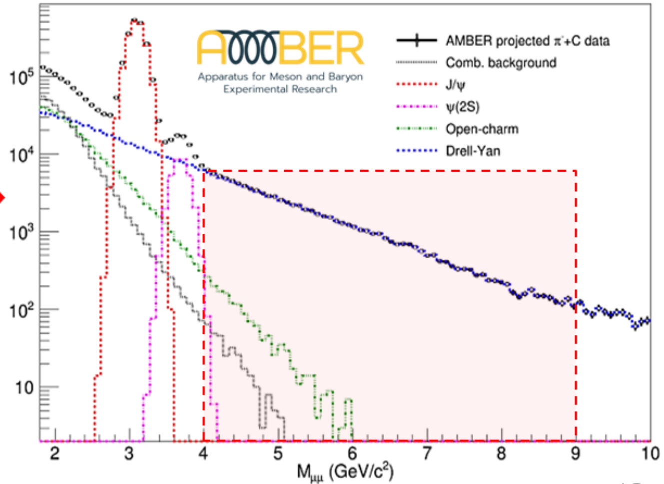


From COMPASS to AMBER





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

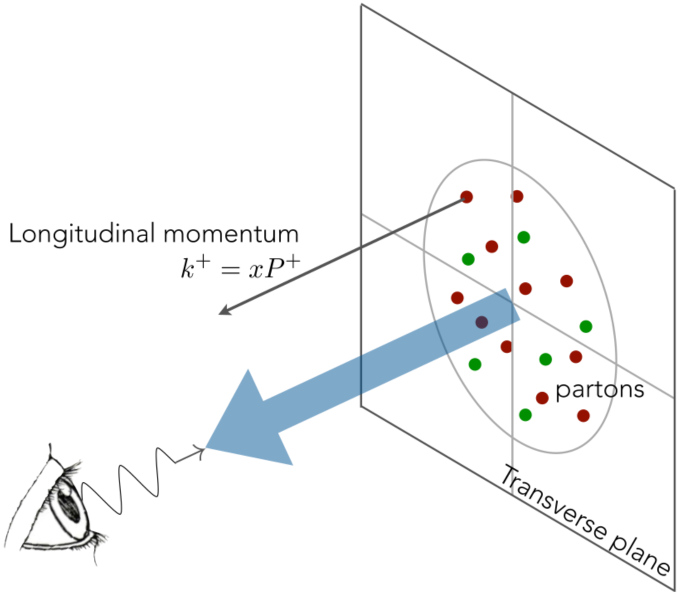
↔

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
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	$g_{1T}^q(x, \boldsymbol{k}_T^2)$ 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



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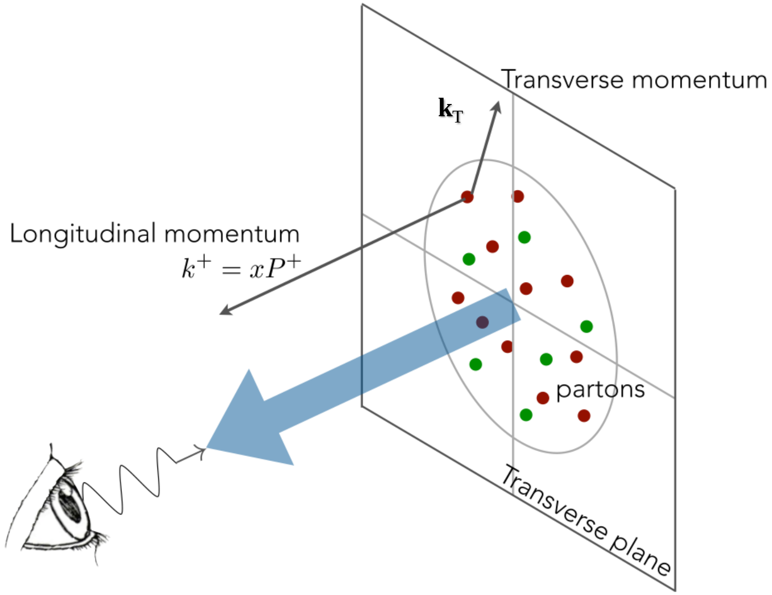
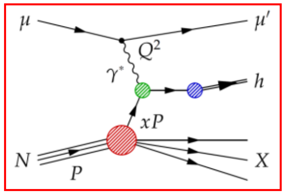


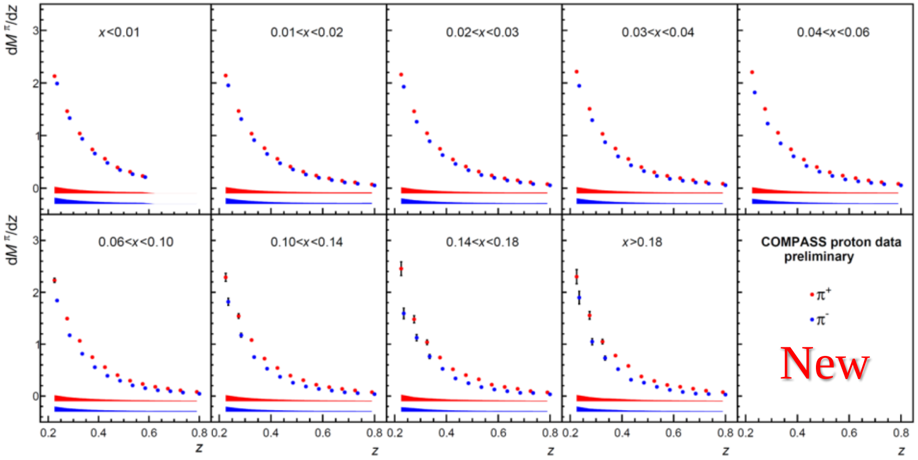
Hadron multiplicities; h±, π± and K± (2016 data)

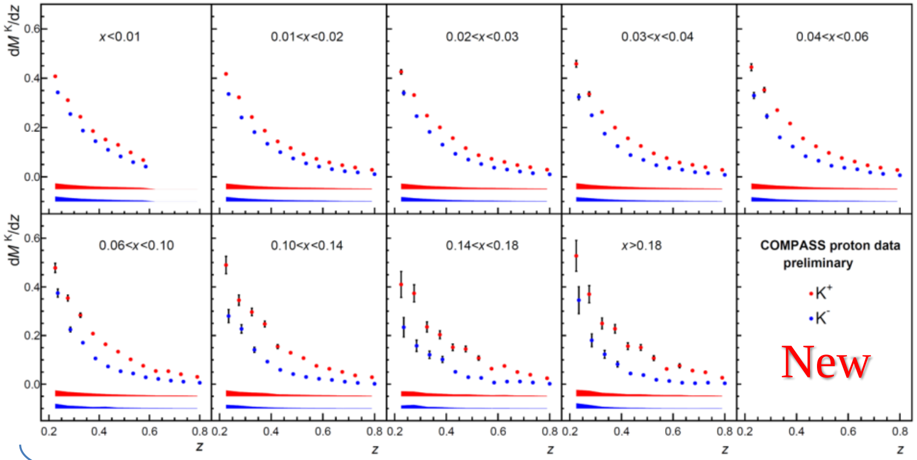
collinear

A set of complex corrections:

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



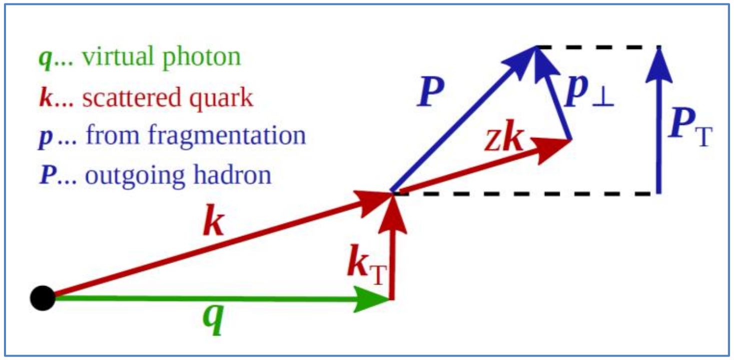




New radiative corrections (DJANGOH)
Soon on arXiv, submission to PRD

TMD

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



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

collinear

A set of complex corrections:

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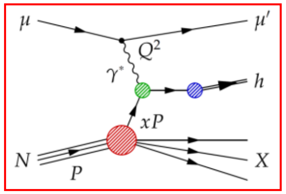
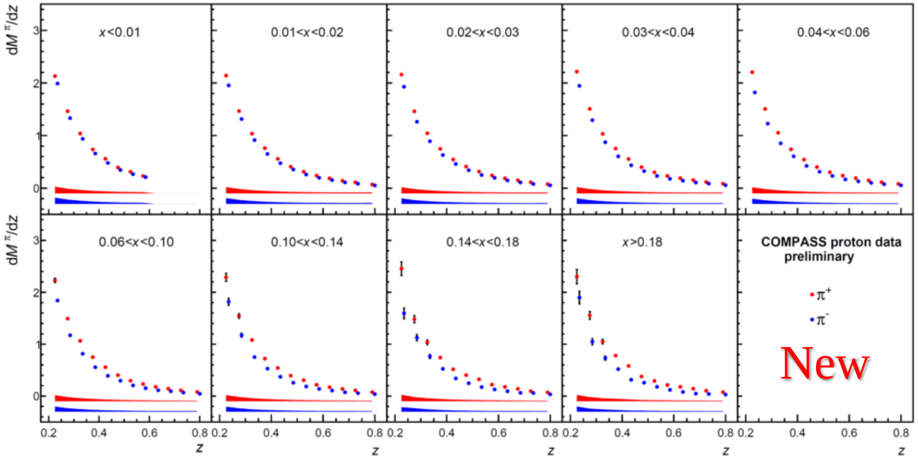
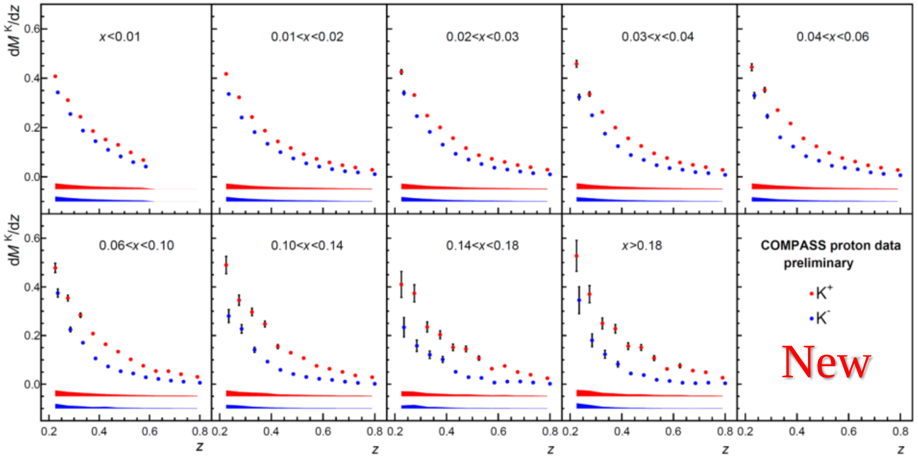
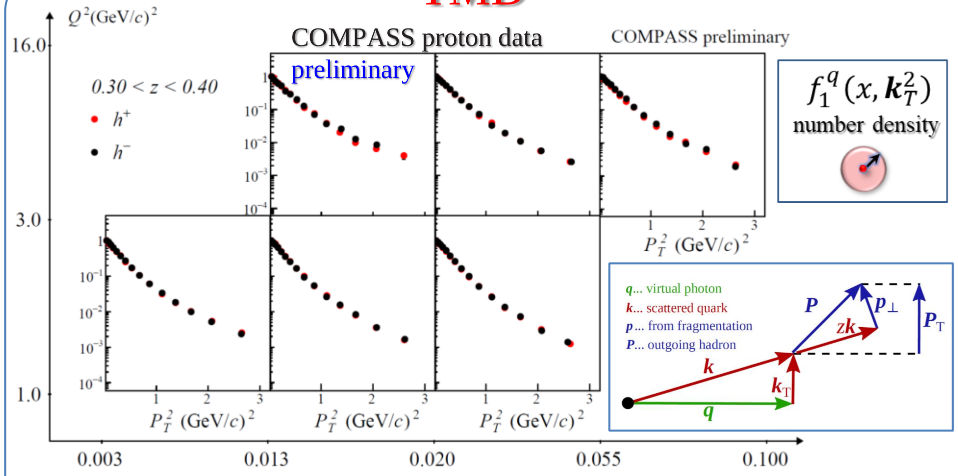
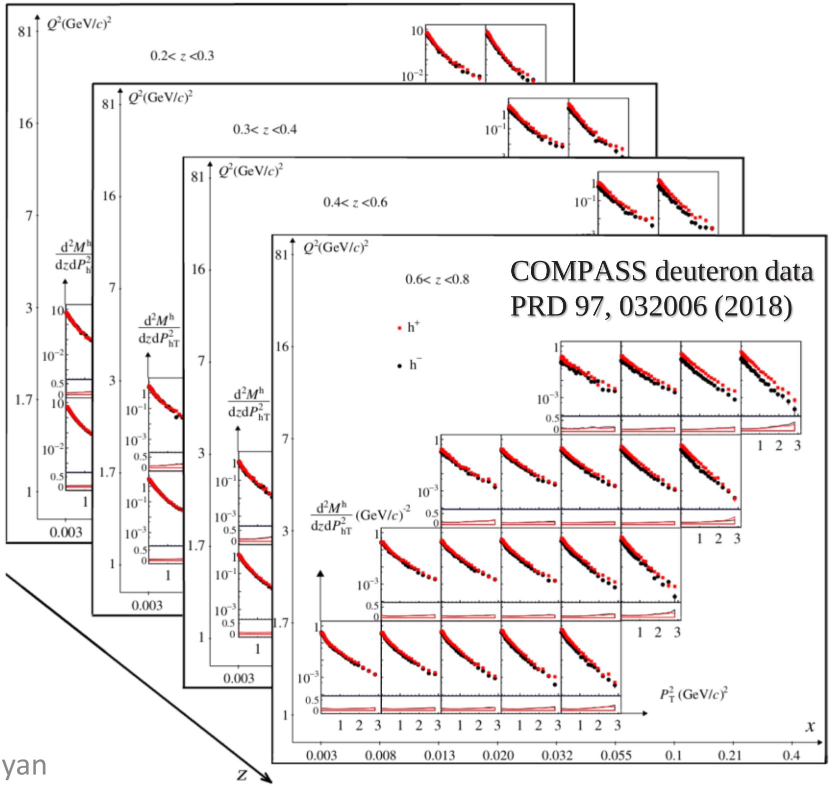






TMD



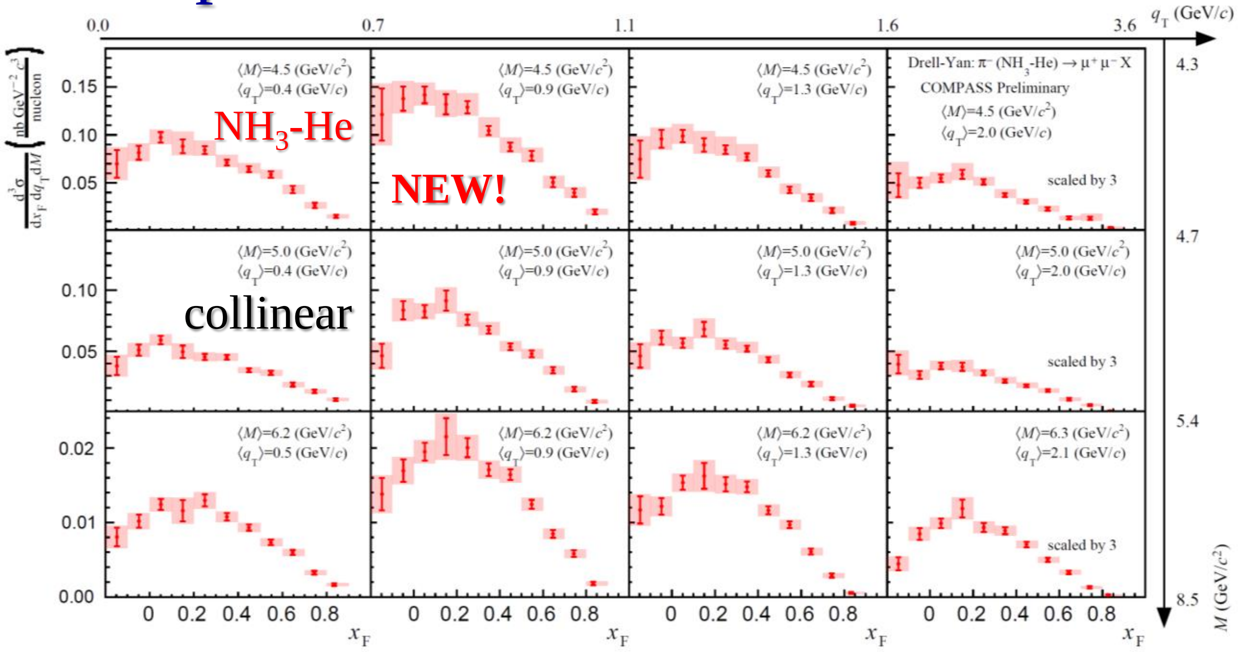


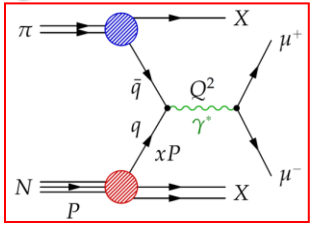
COMPASS deuteron data
PRD 97, 032006 (2018)

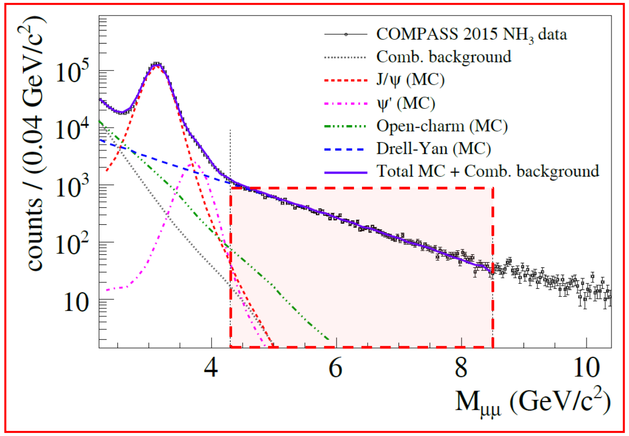
New radiative corrections being applied

See V. Benesova's talk on Friday

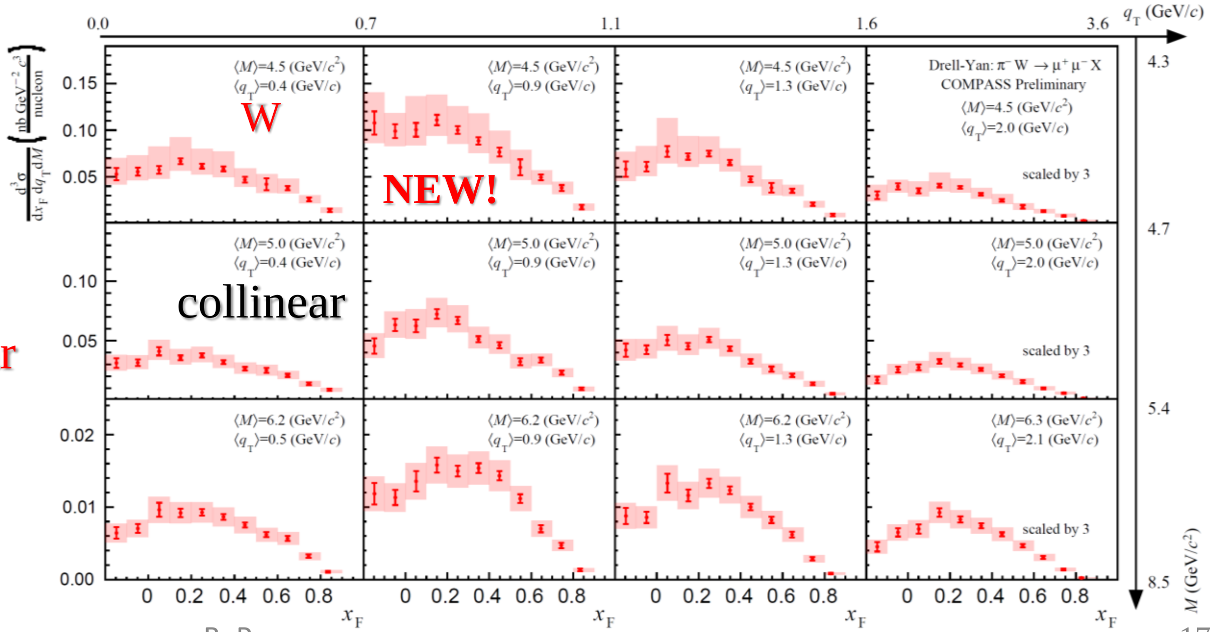
3D unpolarized Drell-Yan cross section on NH_3 and W



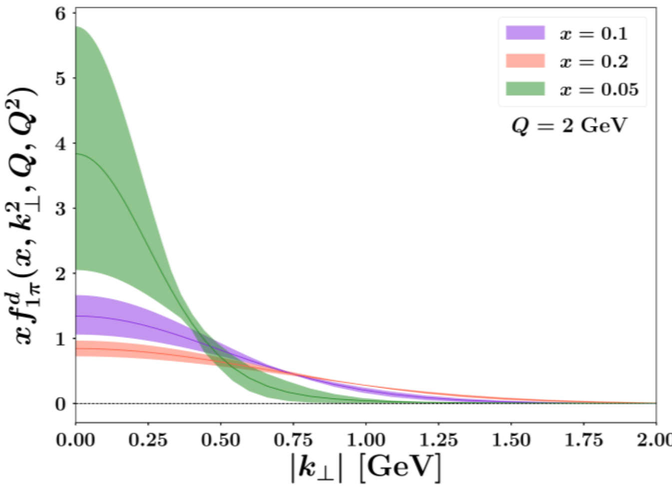




- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF

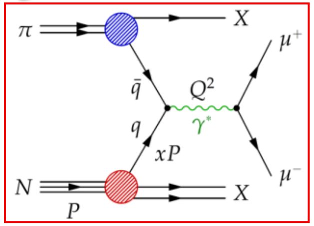


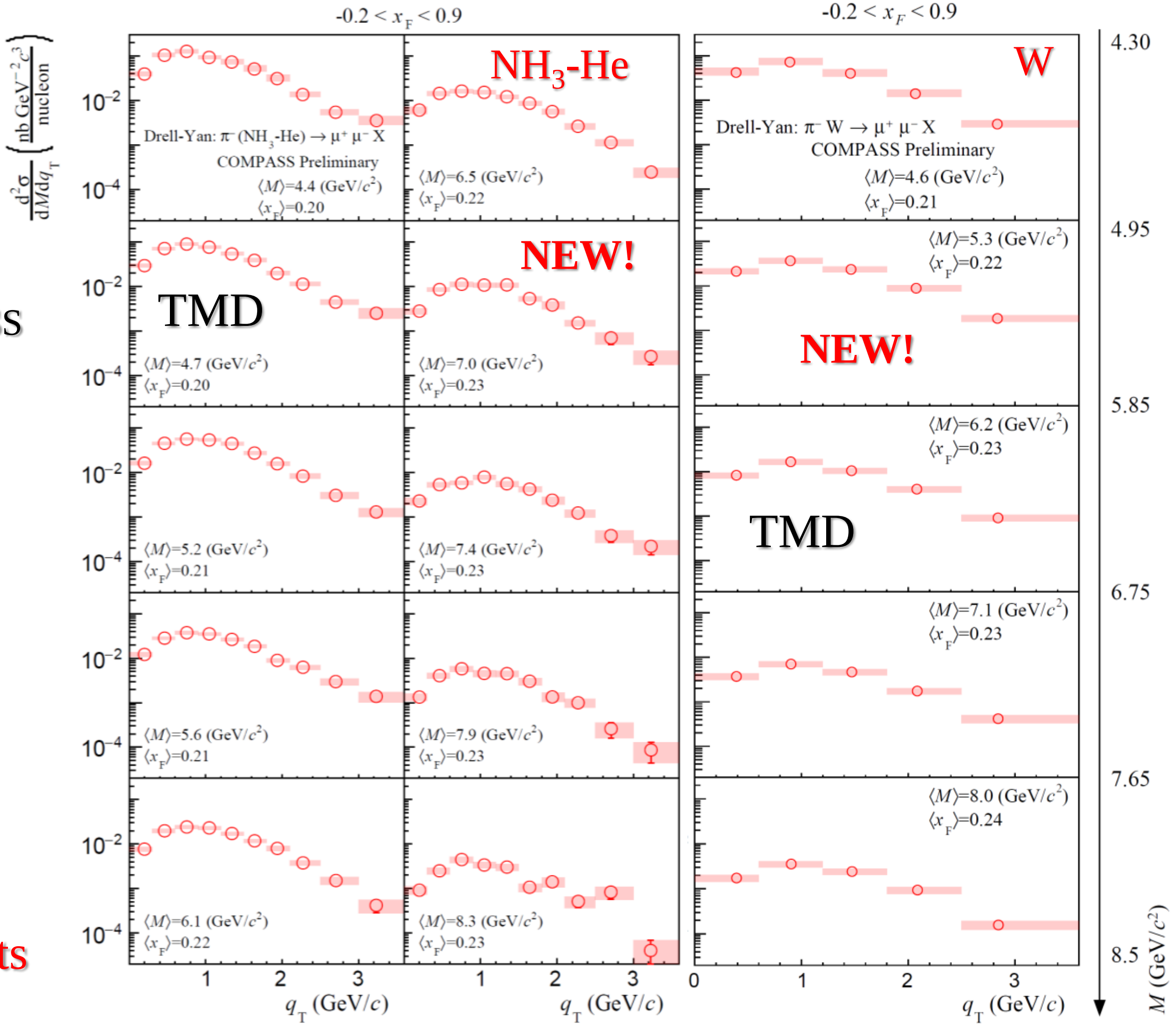
3D unpolarized Drell-Yan cross section on NH_3 and W



MAP collaboration
Phys. Rev. D. 107, 014014

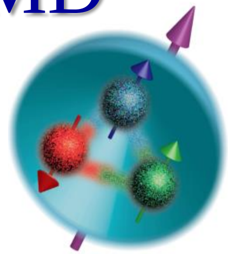
recent global fit and projections for COMPASS





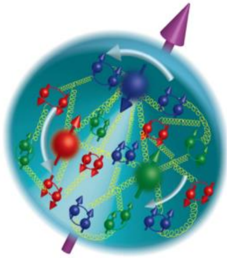
- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF
- To be included in future global fits (MAP, JAM, etc.)

Nucleon spin structure: TMD



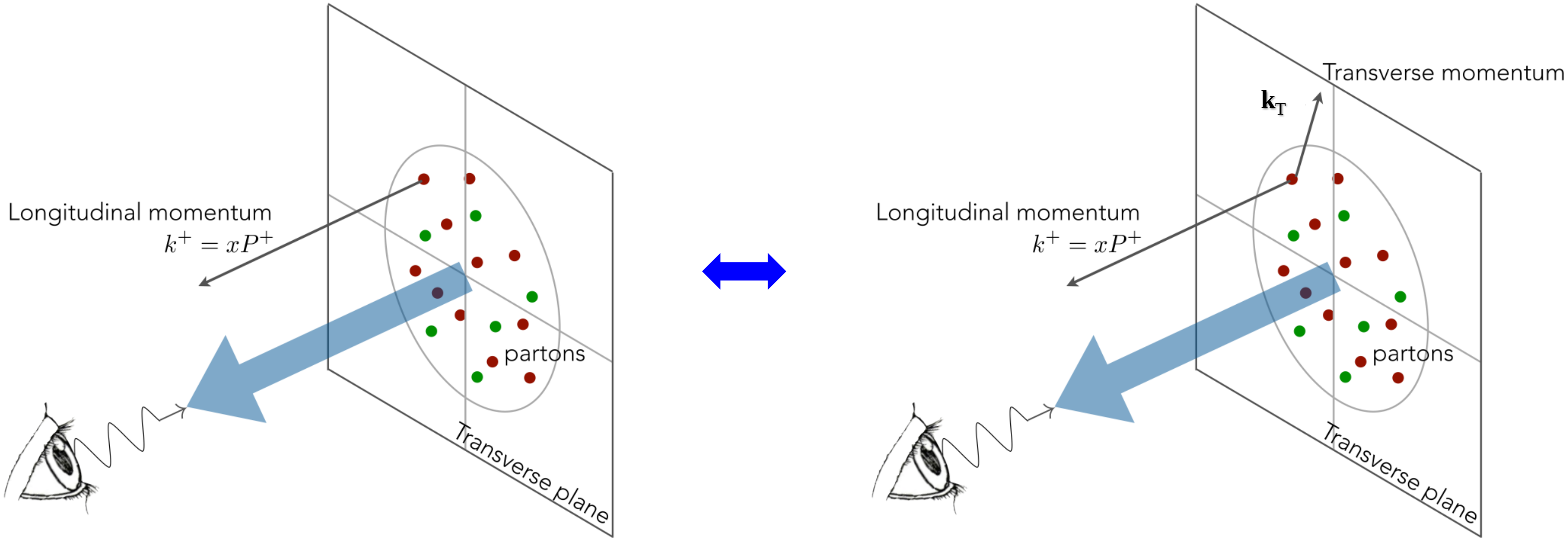
- 1964 Quark model

- 1969 Parton model

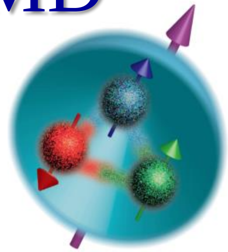


- 1973 asymptotic freedom and QCD

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



Nucleon spin structure: TMD



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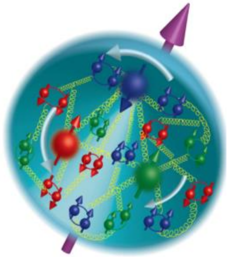

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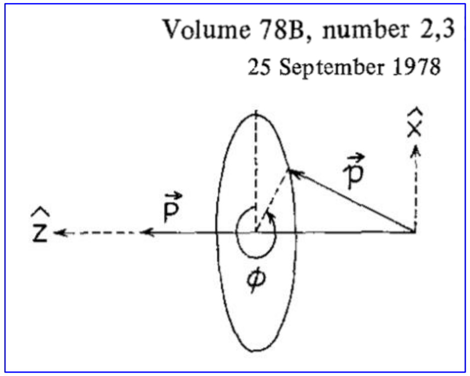
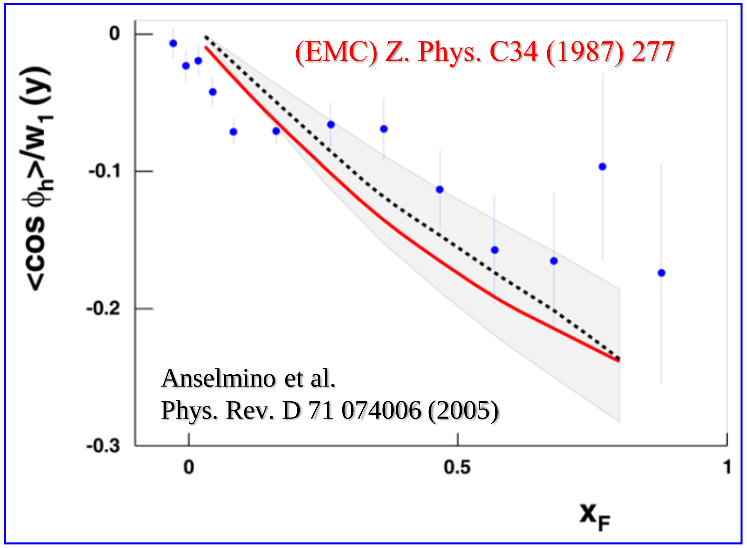


Volume 78B, number 2,3

25 September 1978



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

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

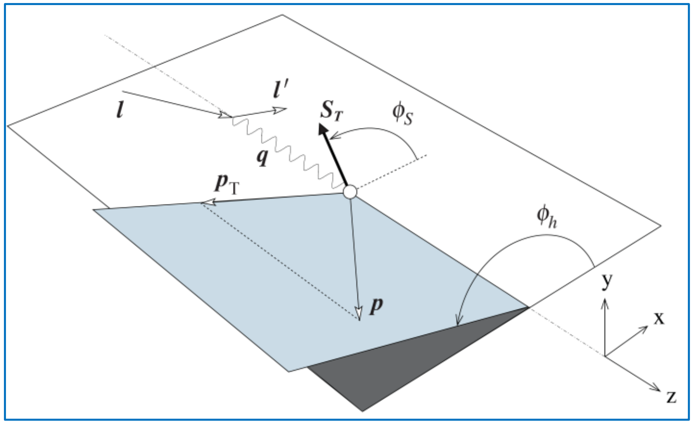
(SLAC) Phys. Rev. Lett. 31, 786 (1973)
(EMC) Phys. Lett. B 130 (1983) 118,
(EMC) Z. Phys. C34 (1987) 277
(EMC) Z. Phys. C52, 361 (1991).
(E665) Phys. Rev. D48 (1993) 5057
(ZEUS) Eur. Phys. J. C11, 251 (1999)
(ZEUS) Phys. Lett. B 481, 199 (2000)
(H1) Phys. Lett. B654, 148 (2007)

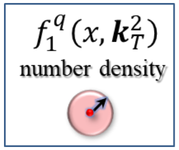
Cahn effect in SIDIS

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

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

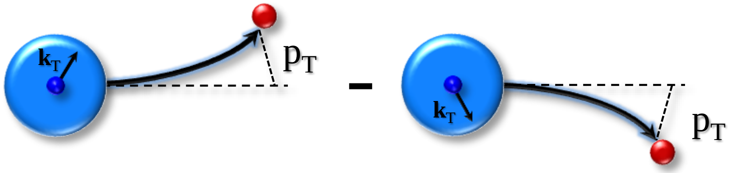
$$\times\left(\ 1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}\ +\ldots\right)$$





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

number density

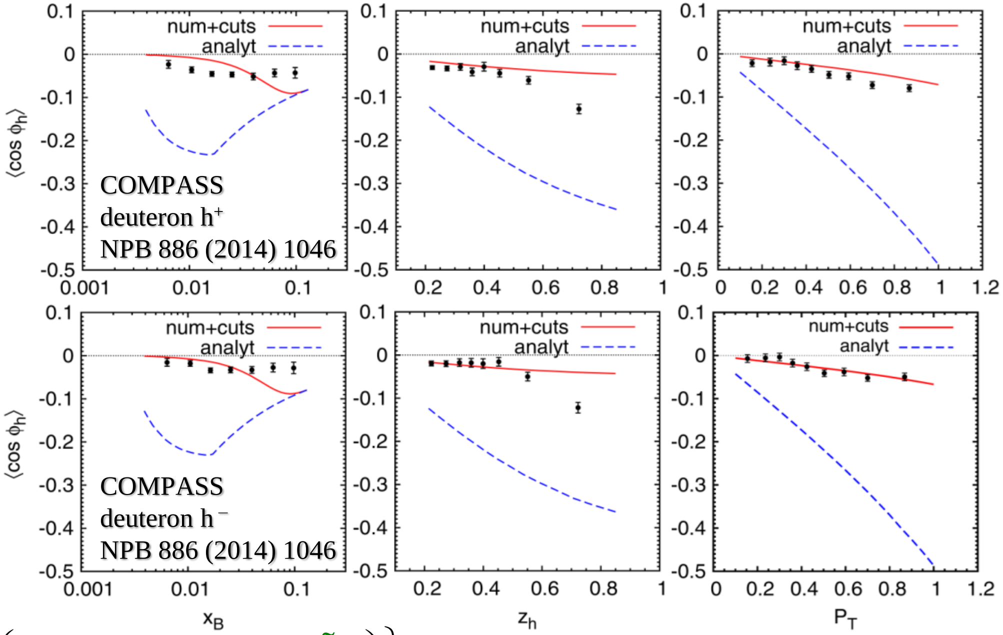


As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

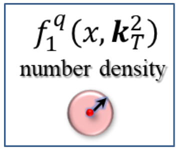
- Measurements by different experiments



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

Cahn effect in SIDIS

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



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    - So far, no comprehensive interpretation
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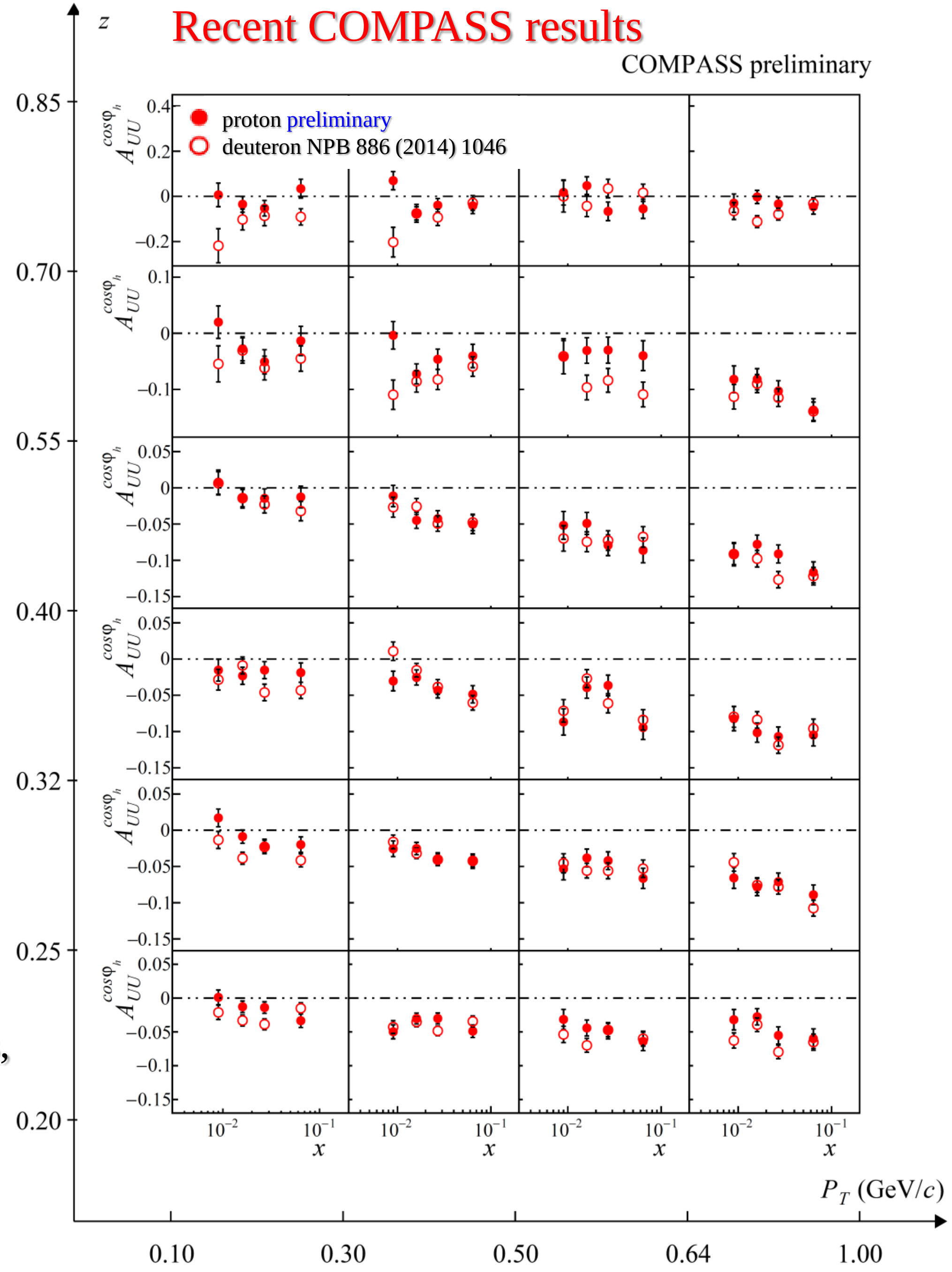
    - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
- Strong Q^2 dependence – unexplained

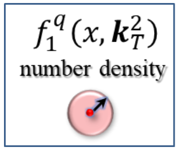
Recent COMPASS results



Cahn effect in SIDIS

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

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



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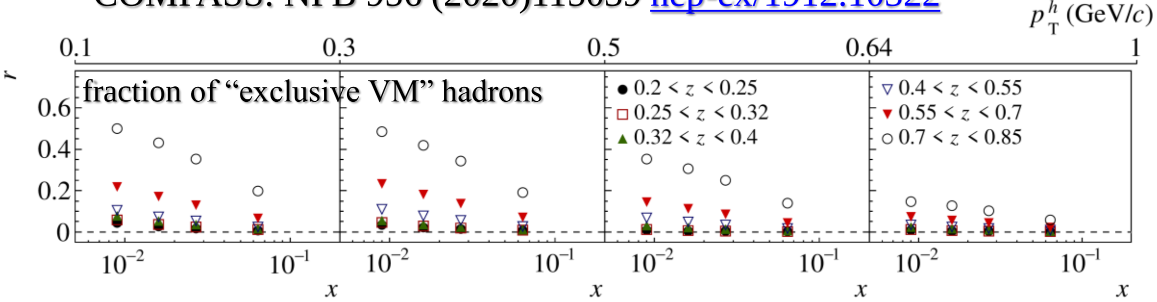
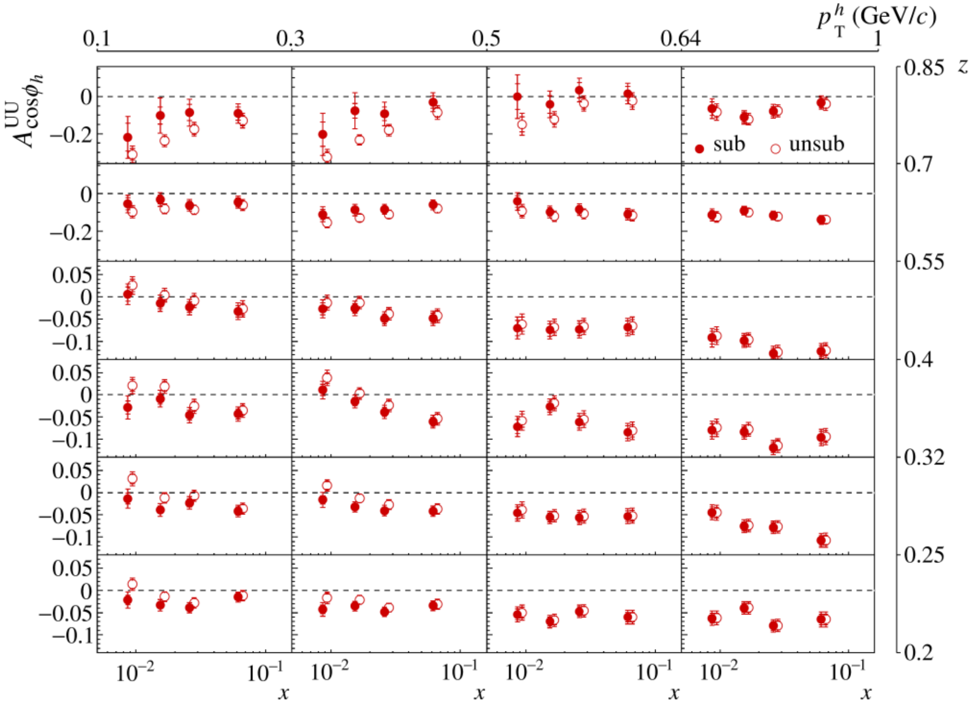
Contribution of exclusive diffractive processes to the measured azimuthal asymmetries in SIDIS

COMPASS: NPB 956 (2020)115039 hep-ex/1912.10322





Cahn effect in SIDIS

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

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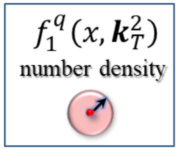

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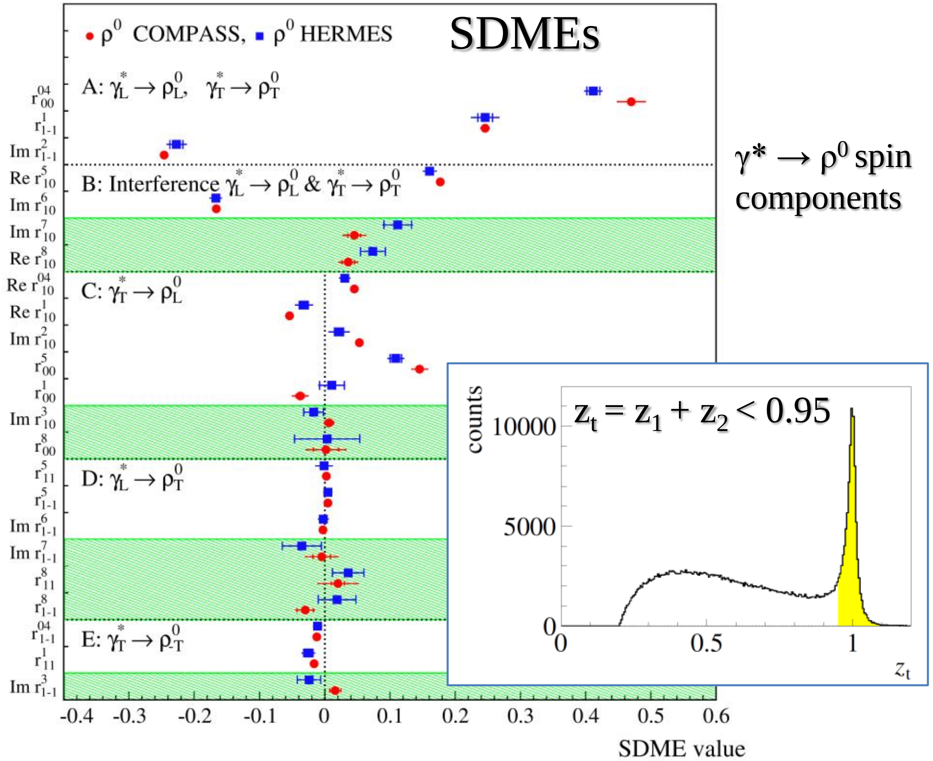
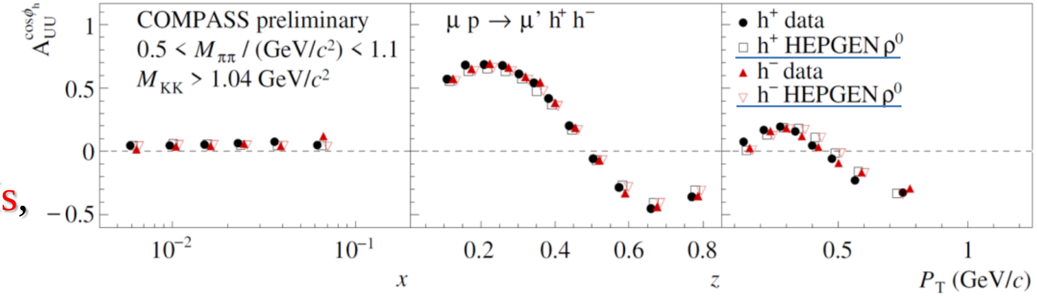
COMPASS, EPJC (2023) 83 924



γ* → ρ0 spin components

VM contribution



Cahn effect in SIDIS

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

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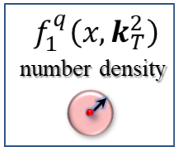

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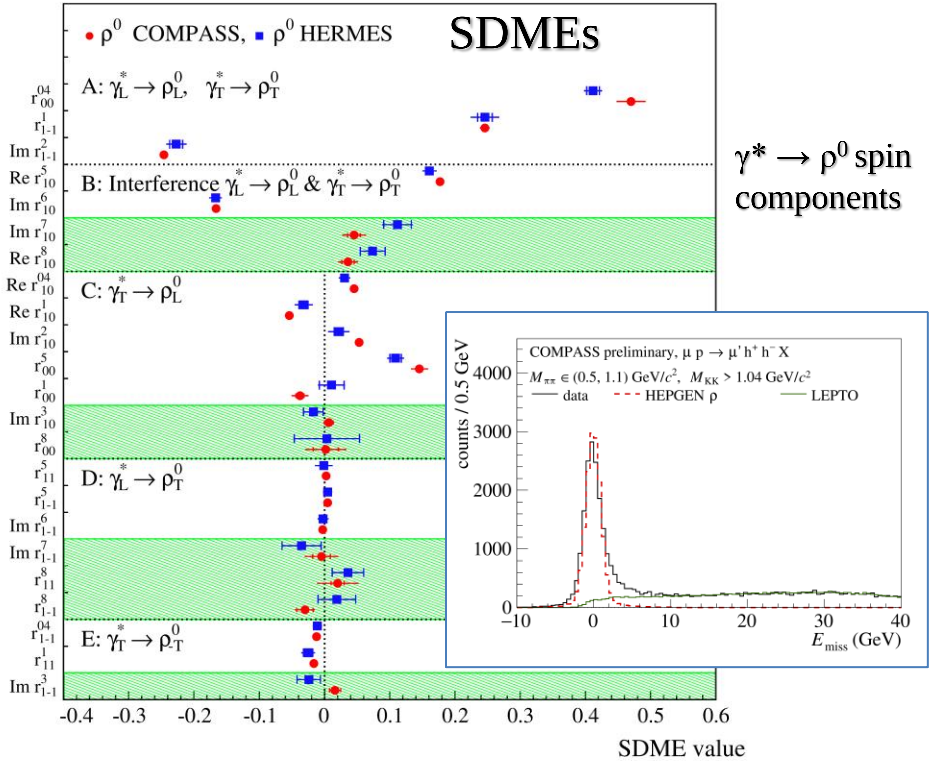
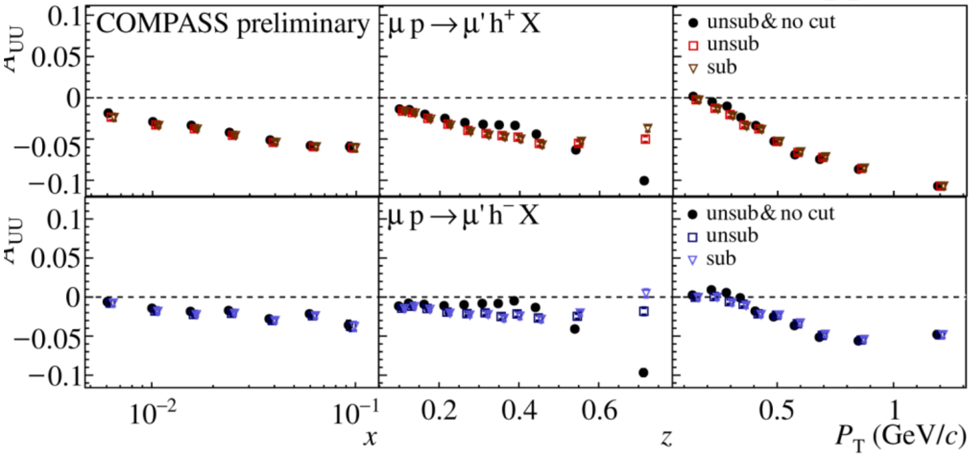
COMPASS, EPJC (2023) 83 924



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

VM corrections, applied



Cahn effect in SIDIS

See V. Benesova's talk on Friday

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

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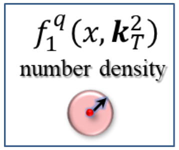
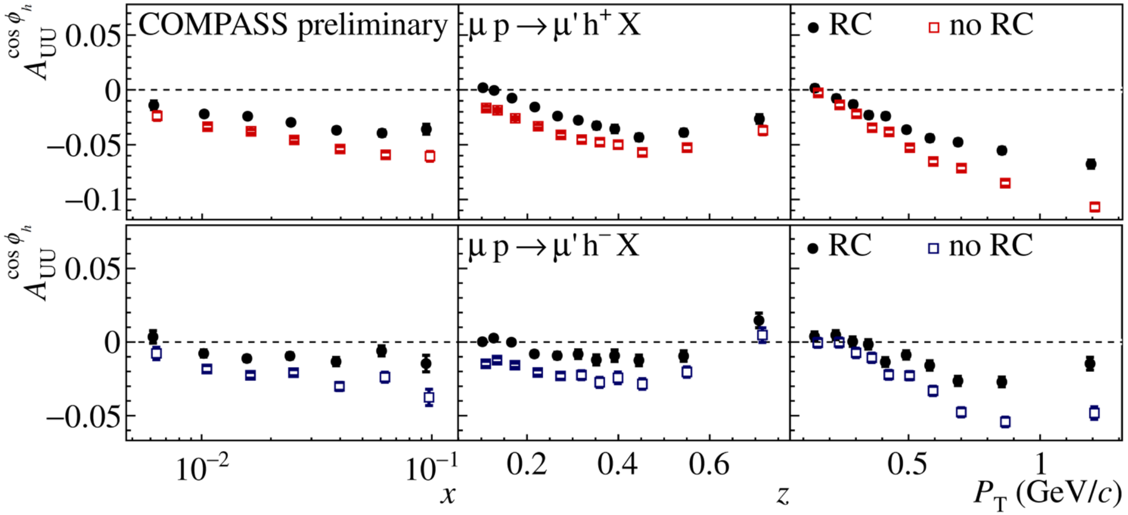


RC corrections, applied



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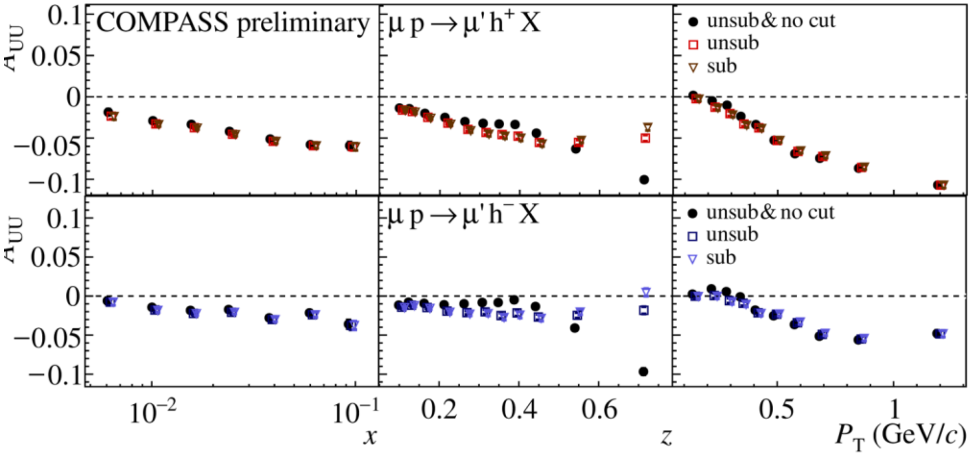
- Strong Q^2 dependence – unexplained
    - Do not seem to come from RCs
    - Transition TMD ↔ collinear regions?

VM corrections, applied

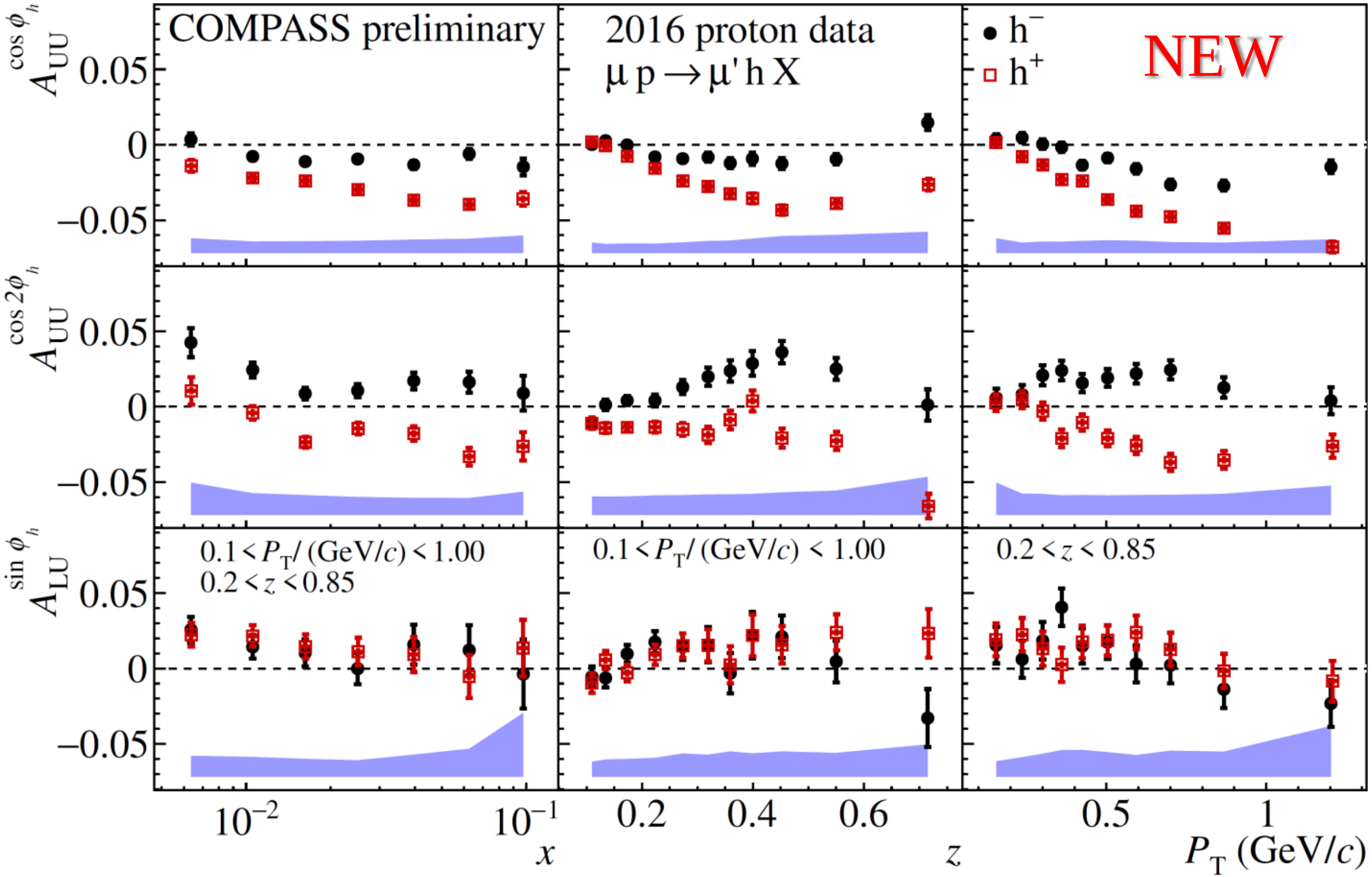


Boer-Mulders effect in SIDIS

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

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

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



Cahn effect
Different for h+, h⁻
Non-trivial Q^2 dependence

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

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

Working on 3D kinematic dependences

Nucleon spin structure (twist-2): 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

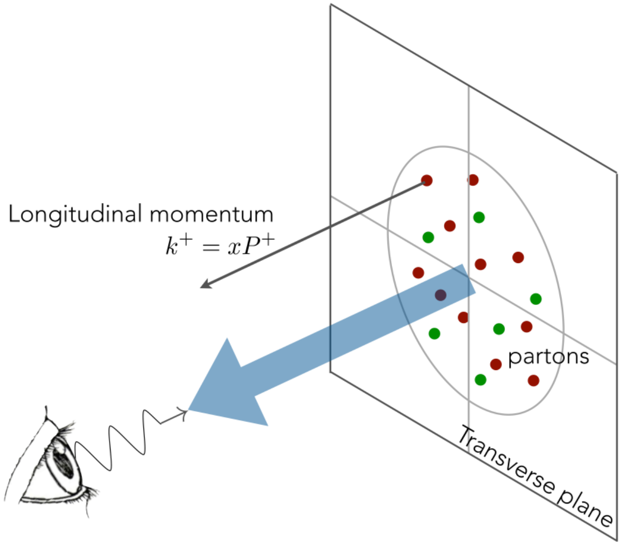
↔

quark

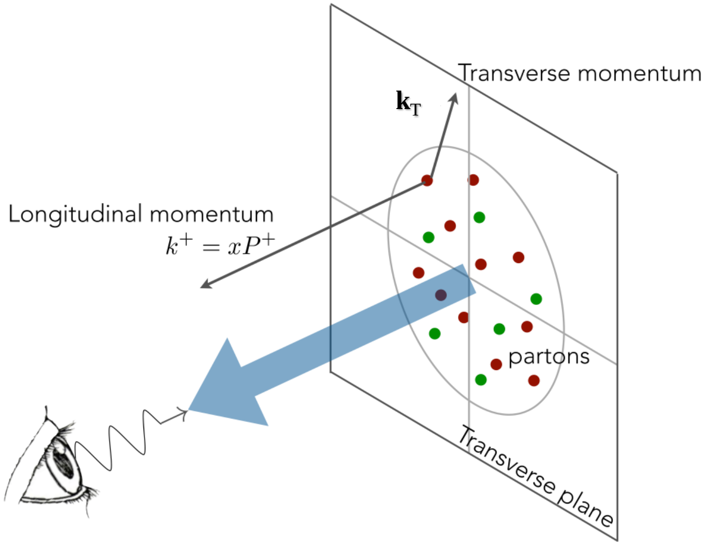
nucleon

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

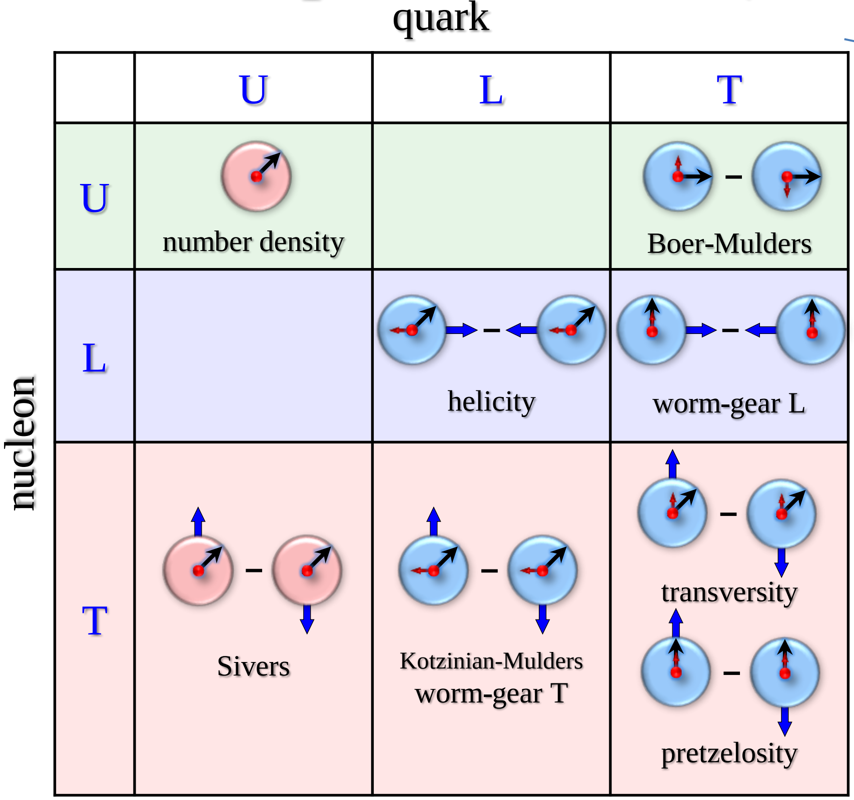
- PDFs – universal (process independent) objects; T-odd PDFs – conditionally universal



↔



Nucleon spin structure (twist-2): TMDs



quark

nucleon

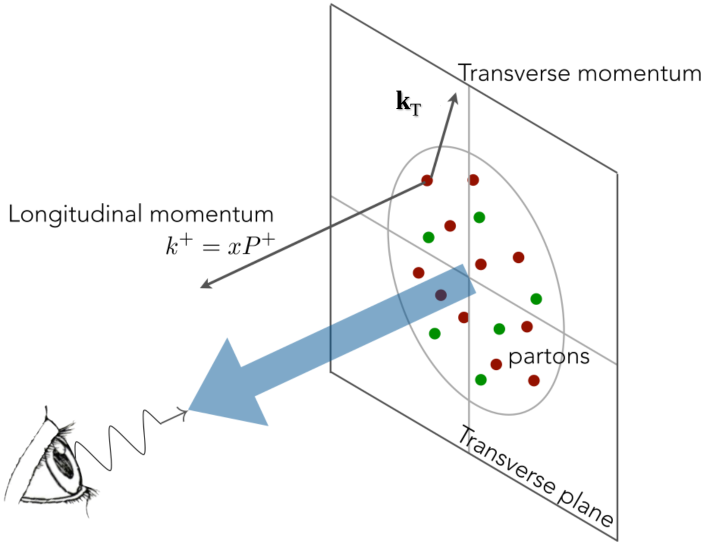
	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L
T	Sivers	Kotzinian-Mulders worm-gear T	transversity pretzelosity

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

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



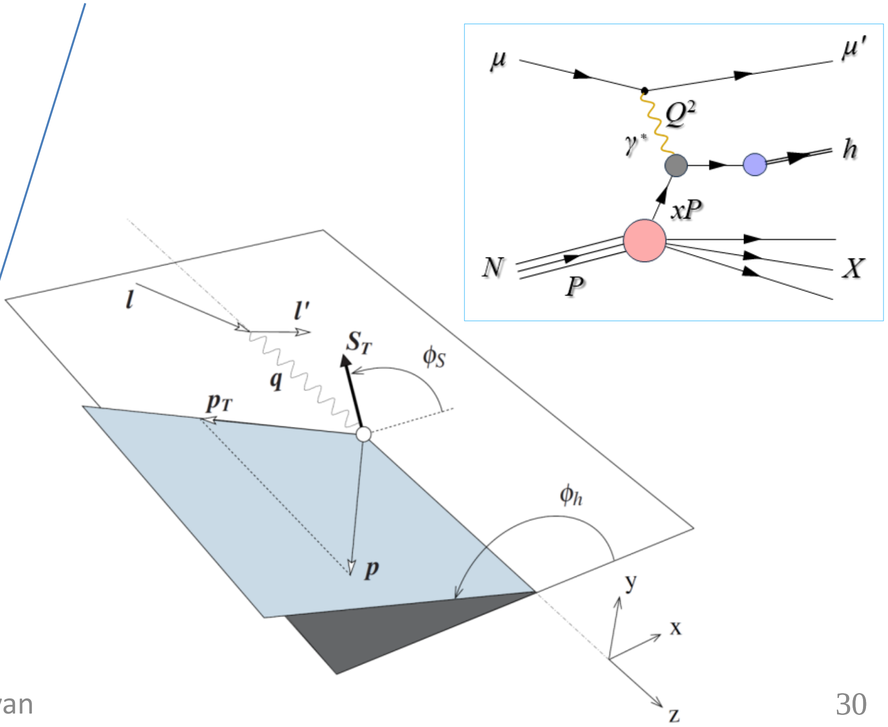
SIDIS x-section and TMDs at twist-2

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

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

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

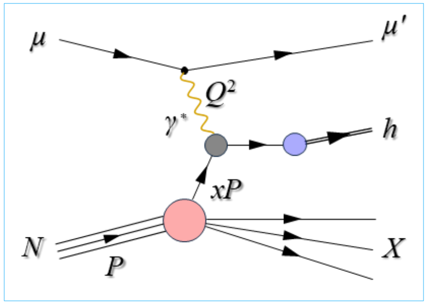


SIDIS x-section and TMDs at twist-2

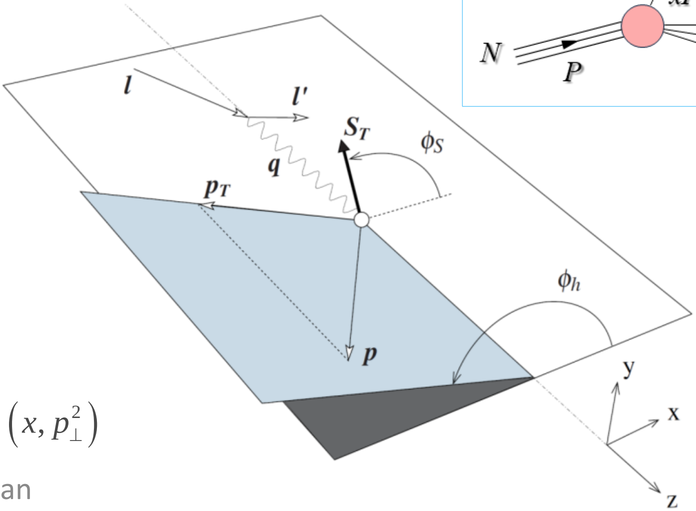
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$

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

		quark		
		U	**L**	**T**
nucleon	**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



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



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

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

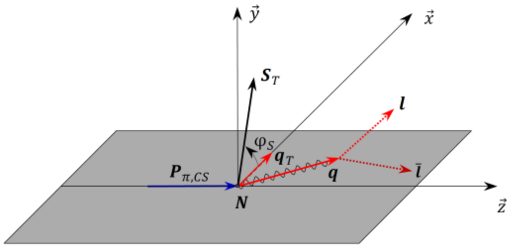
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right) \times \left\{ 1 + D_{\left[\sin^2\theta_{CS}\right]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{\left[\sin^2\theta_{CS}\right]}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

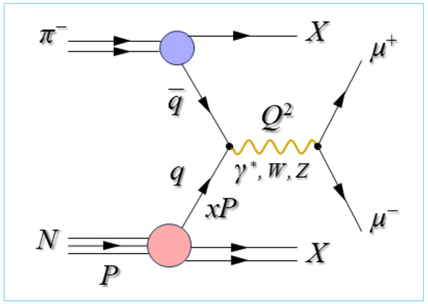
where $D_{\left[\sin^2\theta_{CS}\right]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

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



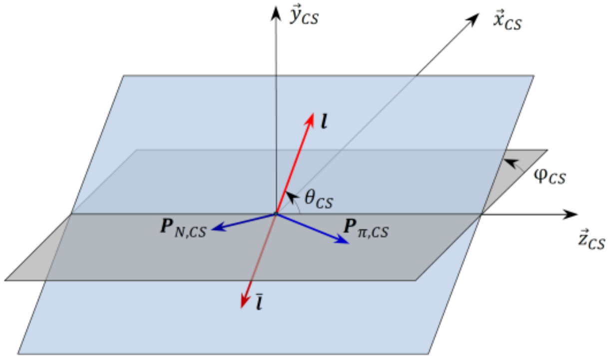


$A_U^{\cos 2\varphi_{CS}} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{\perp q}}$ Boer-Mulders (T-odd)

$A_T^{\sin\varphi_S} \propto \underline{f_{1,\pi}^{q}} \otimes \underline{f_{1T,p}^{\perp q}}$ Sivers (T-odd)

$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{q}}$ Transversity

$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1T,p}^{\perp q}}$ Pretzelosity



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

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

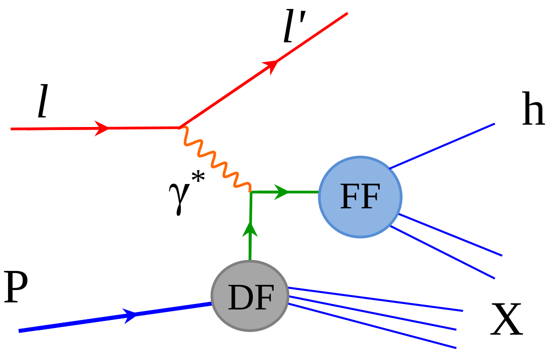
See talks by P. Di Nezza, L. Diaz, M. Niemiec

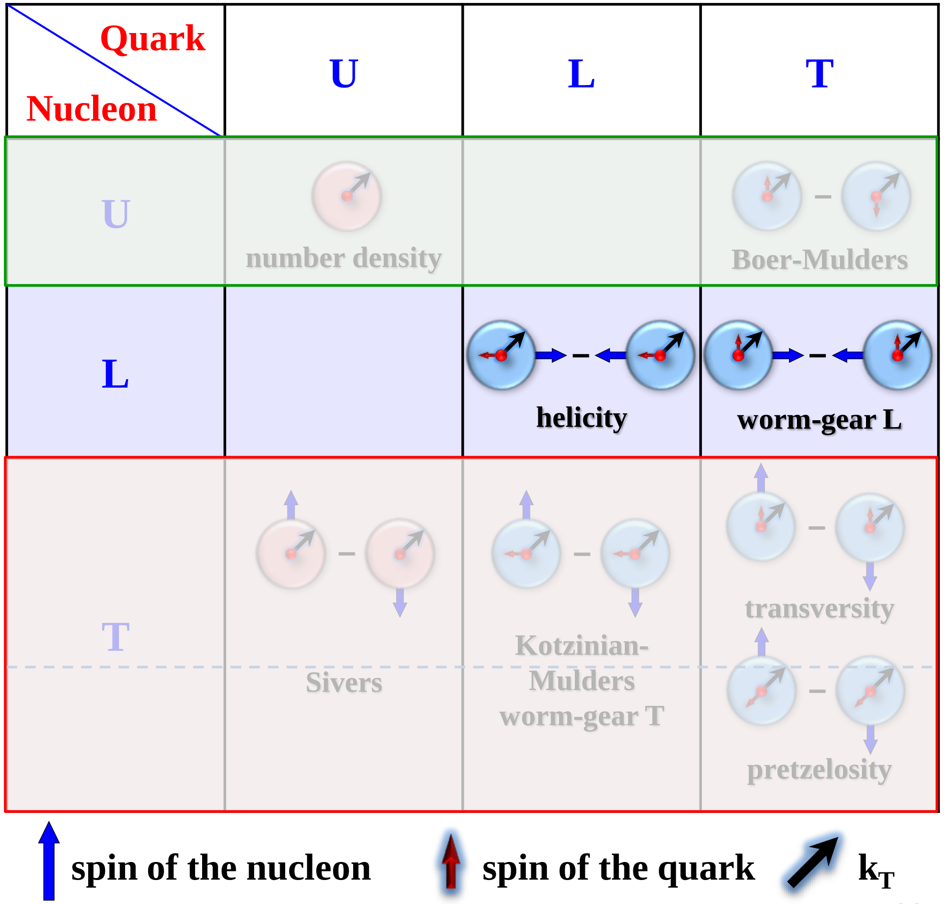
SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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





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: target longitudinal spin dependent asymmetries

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

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

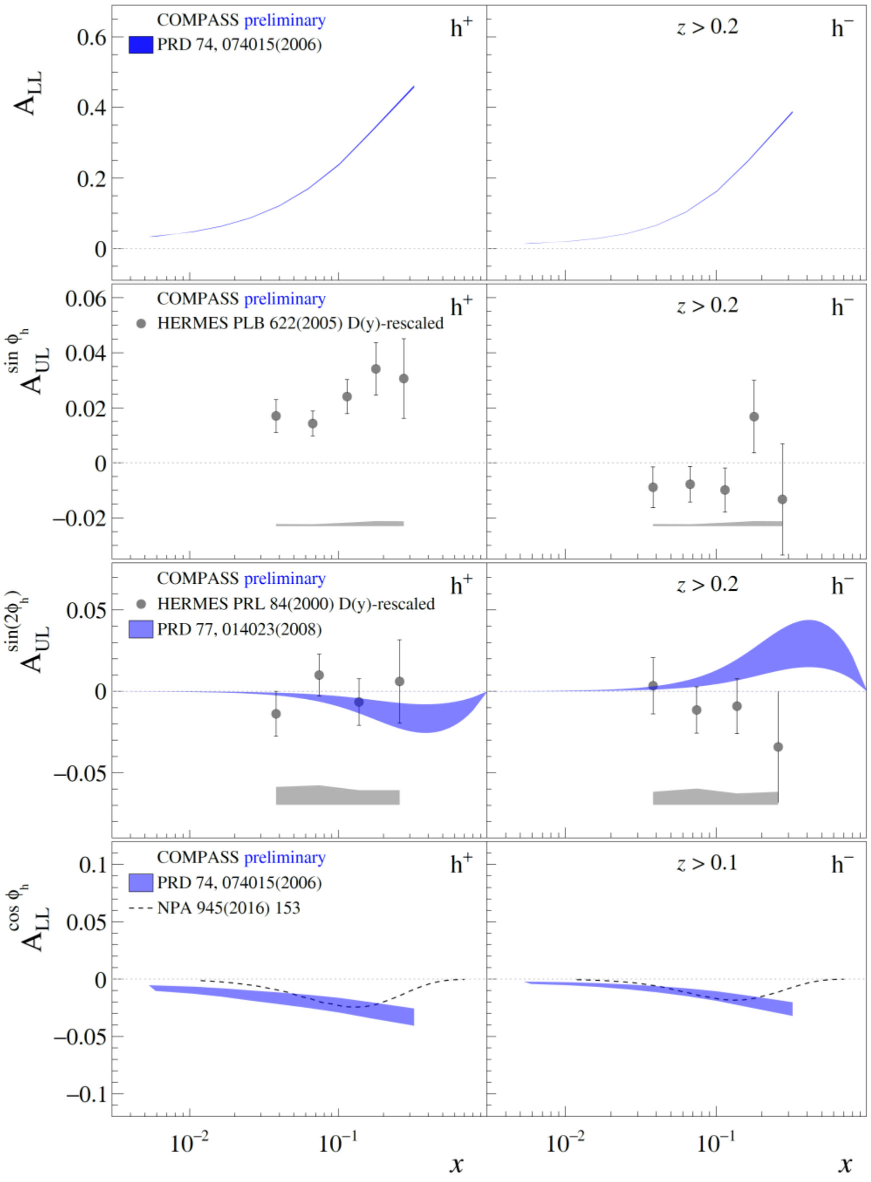
$$\left. + \; S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL} + \sqrt{2\varepsilon\left(1-\varepsilon\right)}\,A_{LL}^{\cos\phi_h}\,\cos\phi_h\right]\right\}$$

$$F_{LL}^{1} = \mathbb{C}\left\{g_{1L}^{q} D_{1q}^{h}\right\}$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathbb{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(x h_L^{q} H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^{q}\frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(x f_L^{\perp q} D_{1q}^{h} - \frac{M_h}{M} h_{1L}^{\perp q}\frac{\tilde{H}_q^{h}}{z}\right)\right\}$$

$$F_{UL}^{\sin 2\phi_h} = \mathbb{C}\left\{-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}\right) - \boldsymbol{p_T}\cdot\boldsymbol{k_T}}{MM_h} h_{1L}^{\perp q} H_{1q}^{\perp h}\right\}$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathbb{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(x e_L^{q} H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^{q}\frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(x g_L^{\perp q} D_{1q}^{h} - \frac{M_h}{M} h_{1L}^{\perp q}\frac{\tilde{E}_q^{h}}{z}\right)\right\}$$



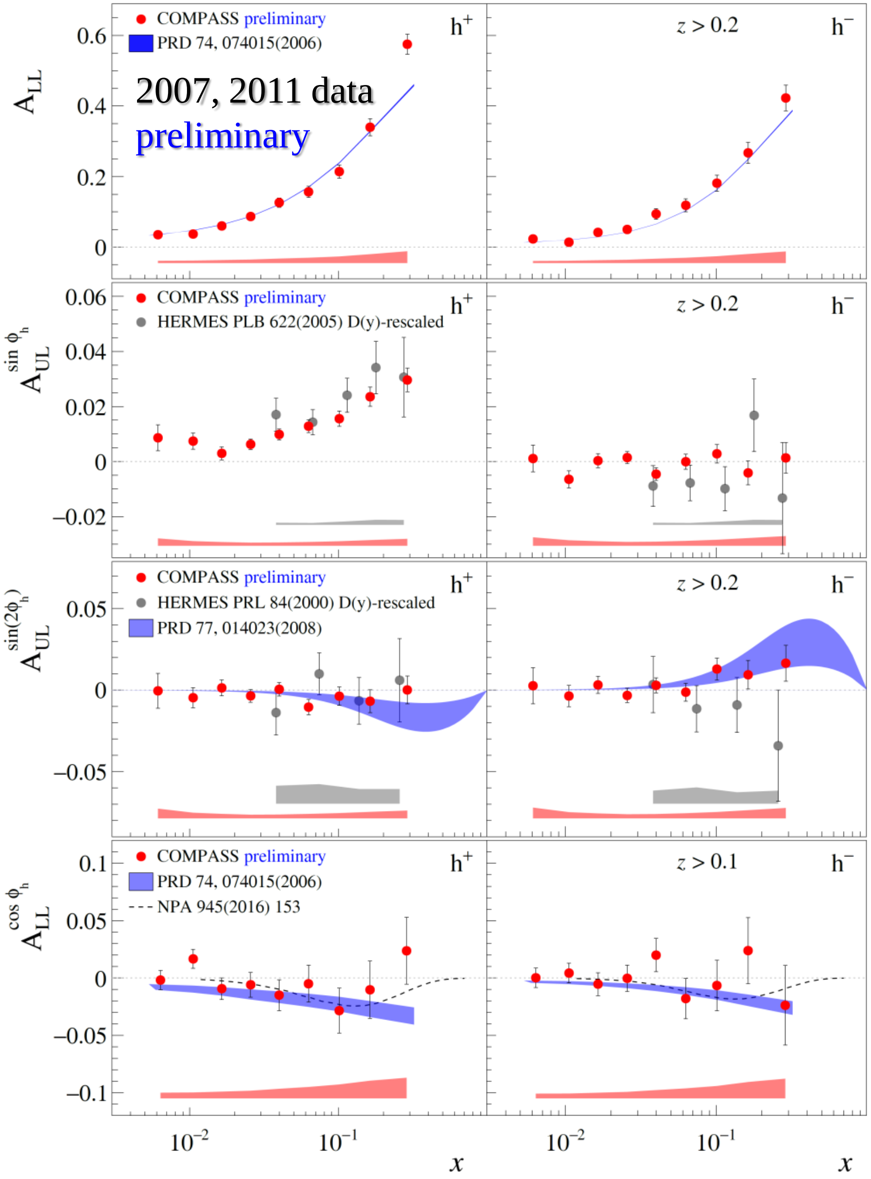
SIDIS: target longitudinal spin dependent asymmetries

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

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

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

B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex]



COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

$A_{UL}^{\sin\phi_h}$

- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- Significant h$^+$ asymmetry, clear *z*-dependence
- h$^-$ compatible with zero

$A_{UL}^{\sin2\phi_h}$

- Only "twist-2" ingredients
- Additional p$_T$-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

$A_{LL}^{\cos\phi_h}$

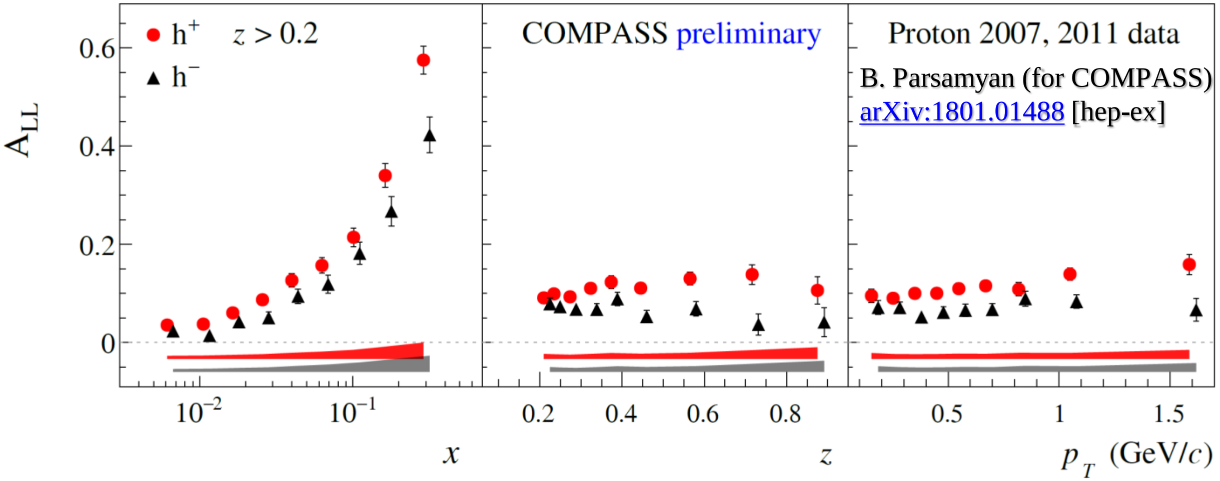
- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models

SIDIS: target longitudinal spin dependent asymmetries

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

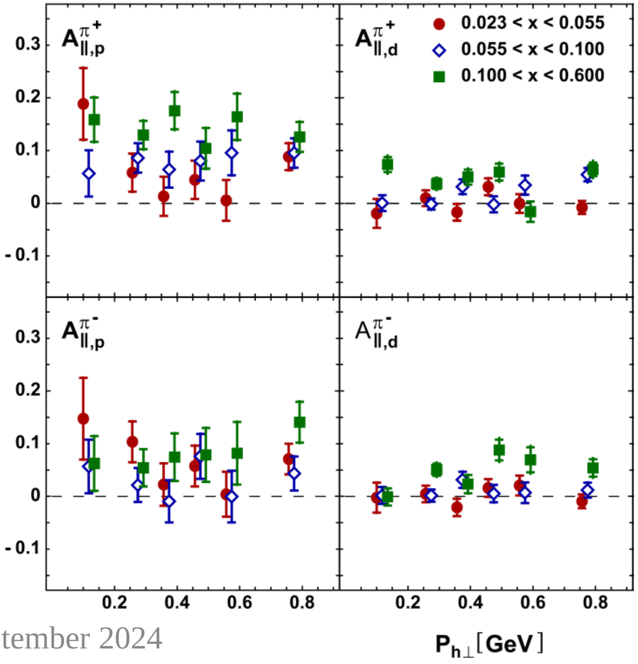
$$\boxed{F_{LL}^{1} = \mathcal{C}\left\{g_{1L}^{q} D_{1q}^{h}\right\}}$$

- Measurement of (semi-)inclusive A_1(A_{LL}) is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed

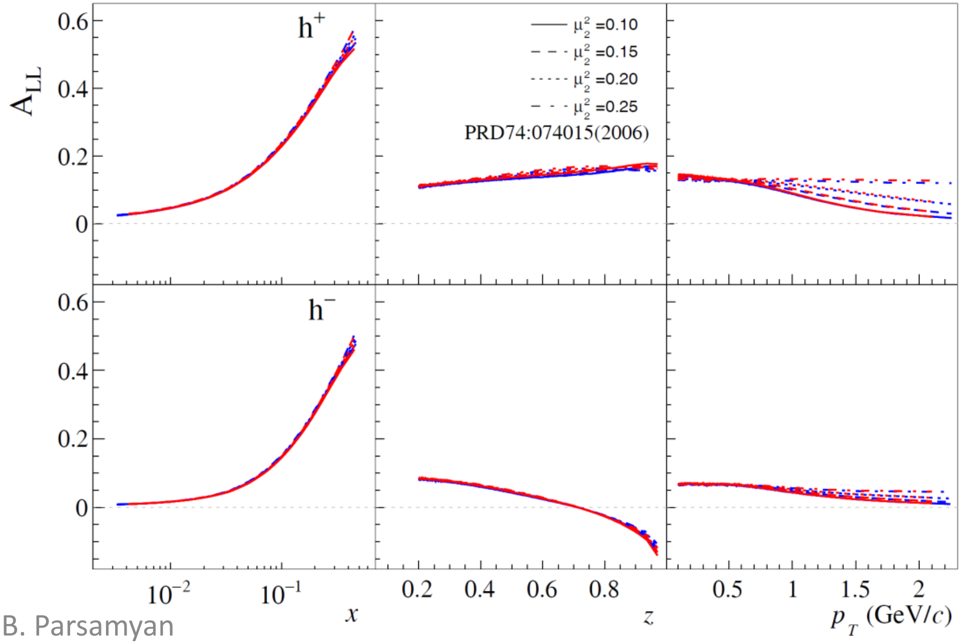


B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]

HERMES: PRD 99, 112001 (2019)



COMPASS Proton-2007, -2011 kinematics



SIDIS: target longitudinal spin dependent asymmetries

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

$$\boxed{F_{LL}^1 = \mathbb{C}\left\{g_{1L}^q D_{1q}^h\right\}}$$

- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of HERMES/COMPASS
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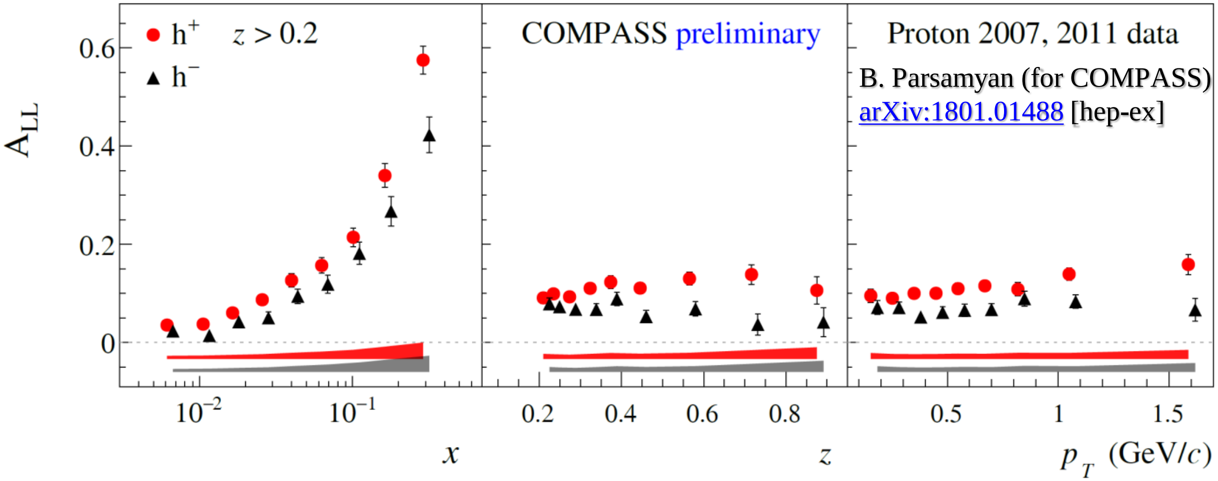
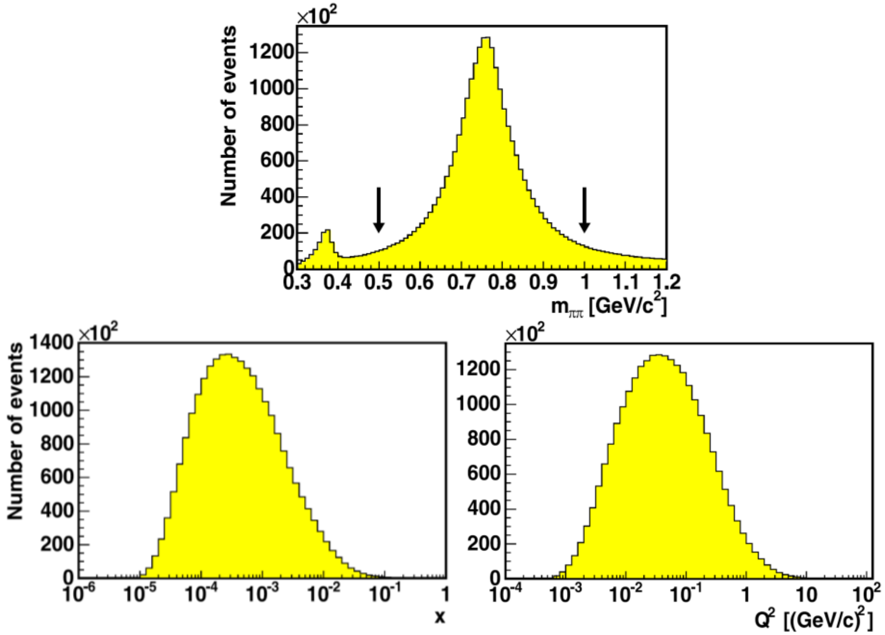
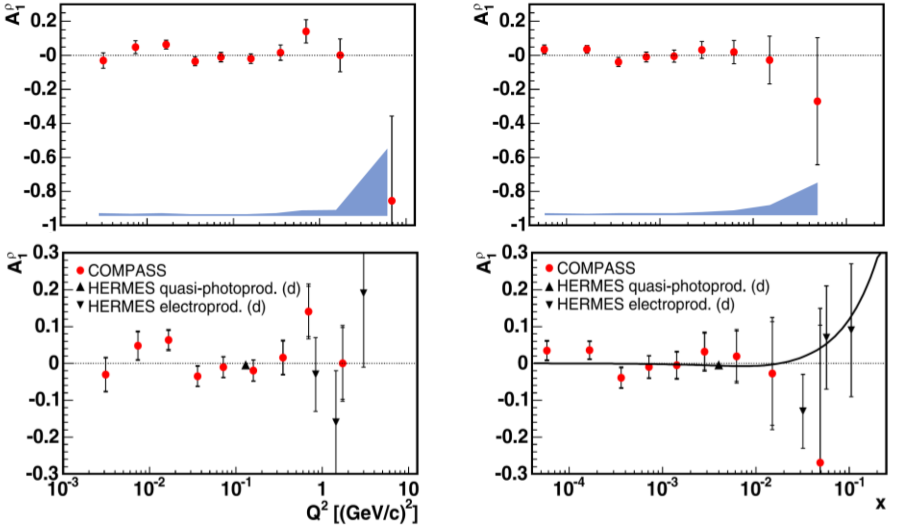
- No P_T-dependence observed



B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex]



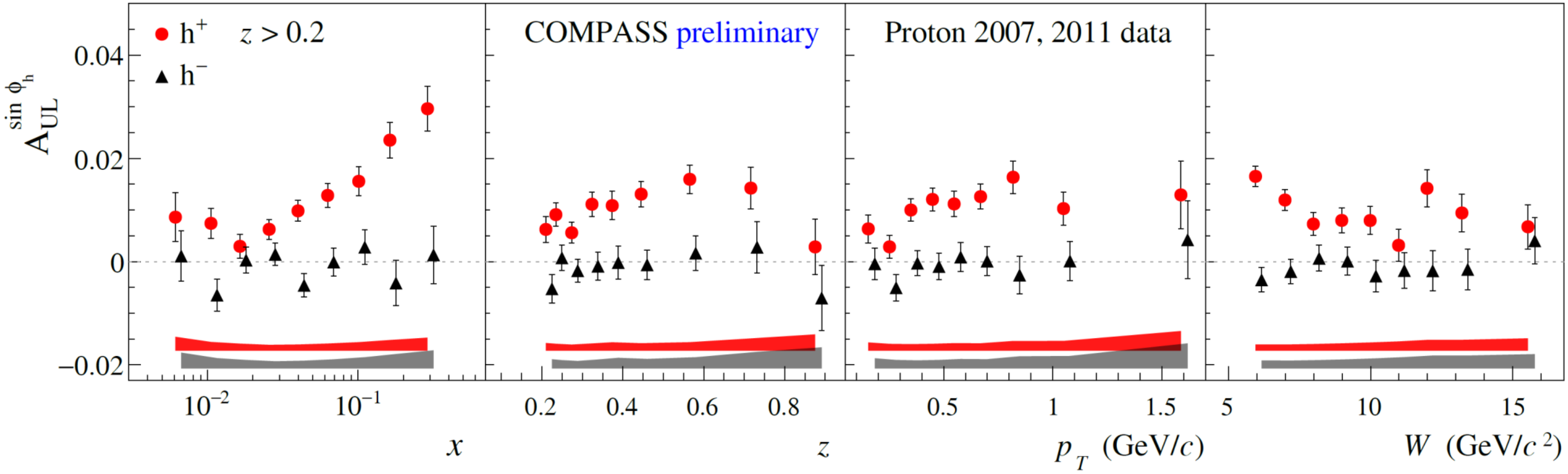
Double spin asymmetry in exclusive ρ^0 muoproduction at COMPASS EPJ C52 (2007) 255



SIDIS TSAs: subleading twist effects

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

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathbb{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^q H_{1q}^{\perp h} + \frac{M_h}{M}g_{1L}^q\frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q}D_{1q}^h - \frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$



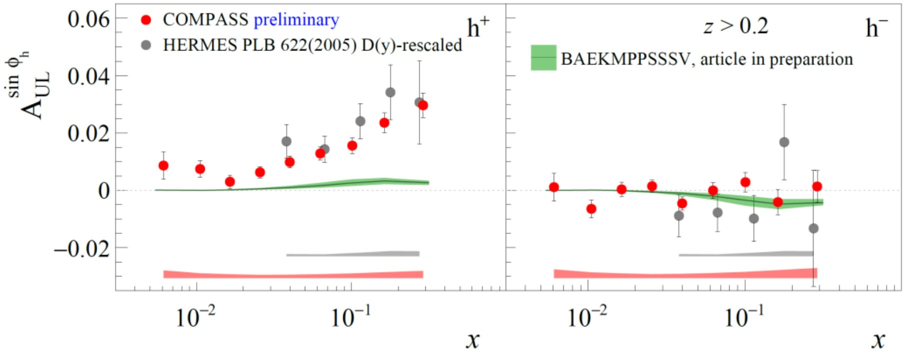
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- Non-zero trend for h⁺, h⁻ compatible with zero

SIDIS TSAs: subleading twist effects

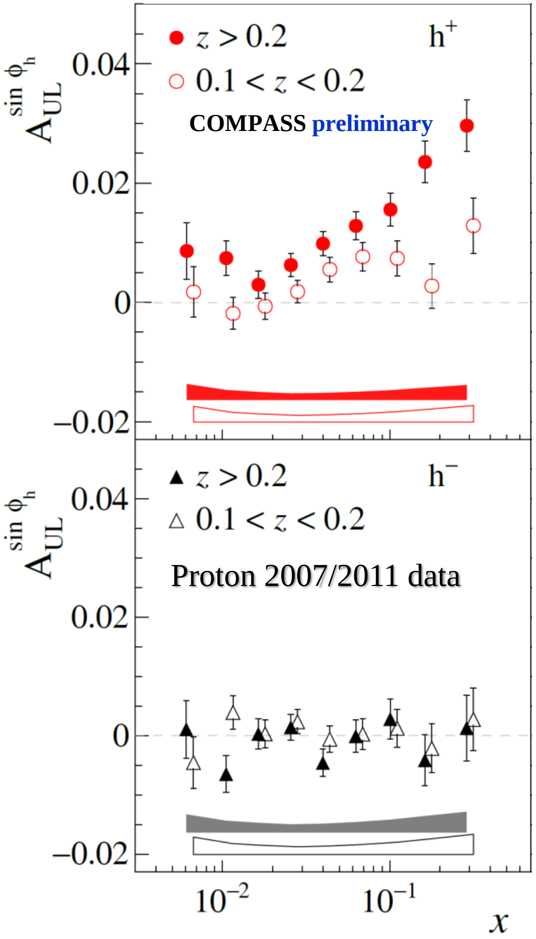
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_L\sqrt{2\varepsilon\left(1+\varepsilon\right)}A_{UL}^{\sin\phi_h}\sin\phi_h+\ldots\right\}$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^q H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{G}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

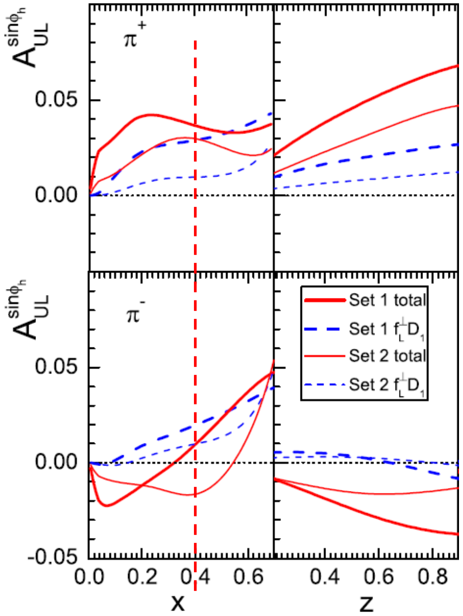
S. Bastami et al. JHEP 1906 (2019) 007:
"SIDIS in Wandzura-Wilczek-type approximation"



B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]



Zhun Lu
Phys. Rev. D 90, 014037(2014)



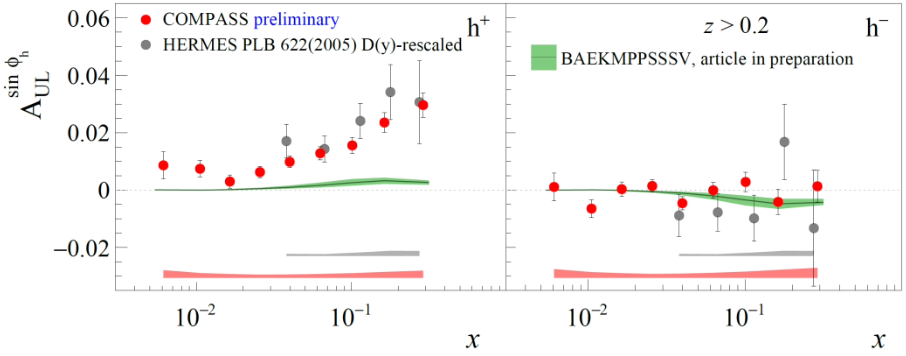
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h^+, h^- compatible with zero, clear z-dependence

SIDIS TSAs: subleading twist effects

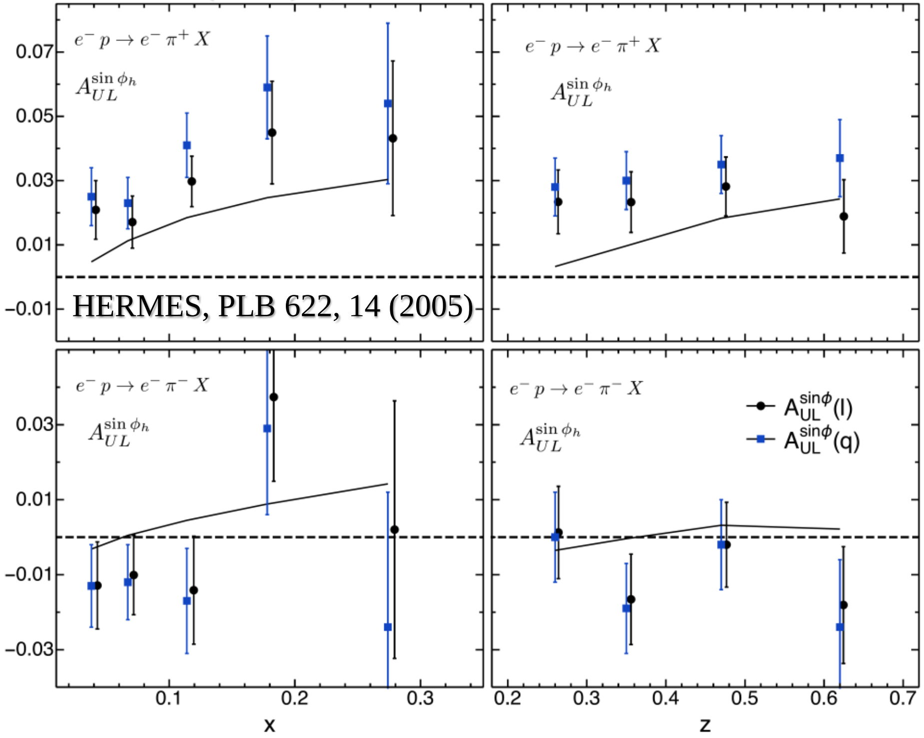
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_L\sqrt{2\varepsilon\left(1+\varepsilon\right)}A_{UL}^{\sin\phi_h}\sin\phi_h+\ldots\right\}$$

$$\boxed{F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^q H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{G}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}}$$

S. Bastami et al. JHEP 1906 (2019) 007:
"SIDIS in Wandzura-Wilczek-type approximation"



M.Abele, M.Aicher, F.Piacenza, A.Schäfer, W.Vogelsang
PRD 106 (2022) 1, 014020



HERMES, PLB 622, 14 (2005)

- Calculations in collinear factorization (lowest order of pQCD)
  - T-odd effect for photon exchange
  - Contributions from QCD loop effects
  - Related to proton helicity
- To be compared to predictions within TMD formalism

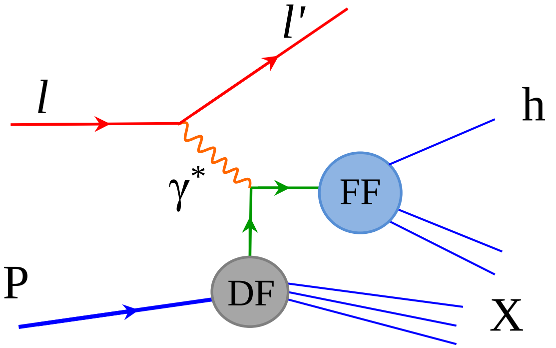
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h$^+$, h$^-$ compatible with zero, clear *z*-dependence

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

All measured by COMPASS

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

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



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

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

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

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

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

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

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

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

🟥 Twist-2

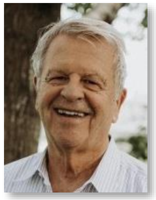
🟦 Twist-3

SIDIS TSAs: Collins and Sivers effects (deuteron)

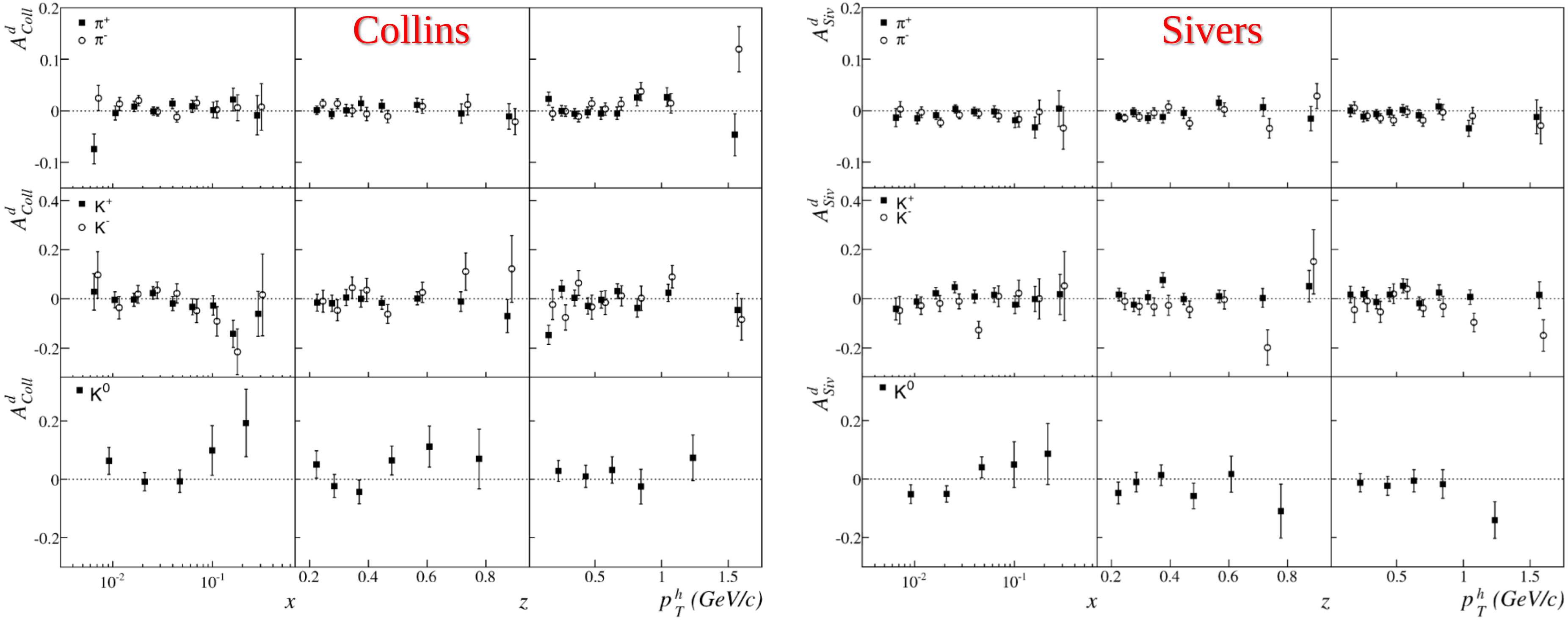
$$\frac{d\sigma}{dxdydzdp_T^2\, d\phi_h\, d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_{\mathrm{T}}\, A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h - \phi_S\right) + S_{\mathrm{T}}\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) \ldots\right\}$$

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

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



COMPASS PLB 673 (2009) 127



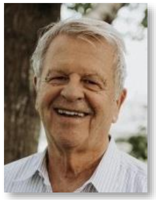
- 1st COMPASS deuteron measurements
- Collins and Sivers asymmetries compatible with zero within uncertainties.

SIDIS TSAs: Collins and Sivers effects (proton)

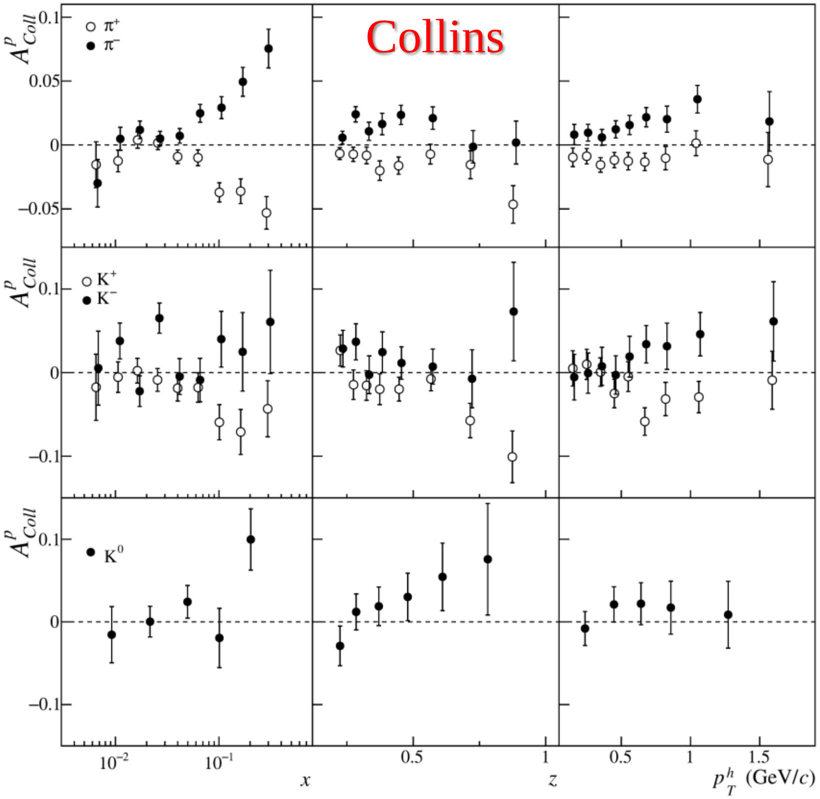
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_{\mathrm{T}}\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+S_{\mathrm{T}}\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)\ldots\right\}$$

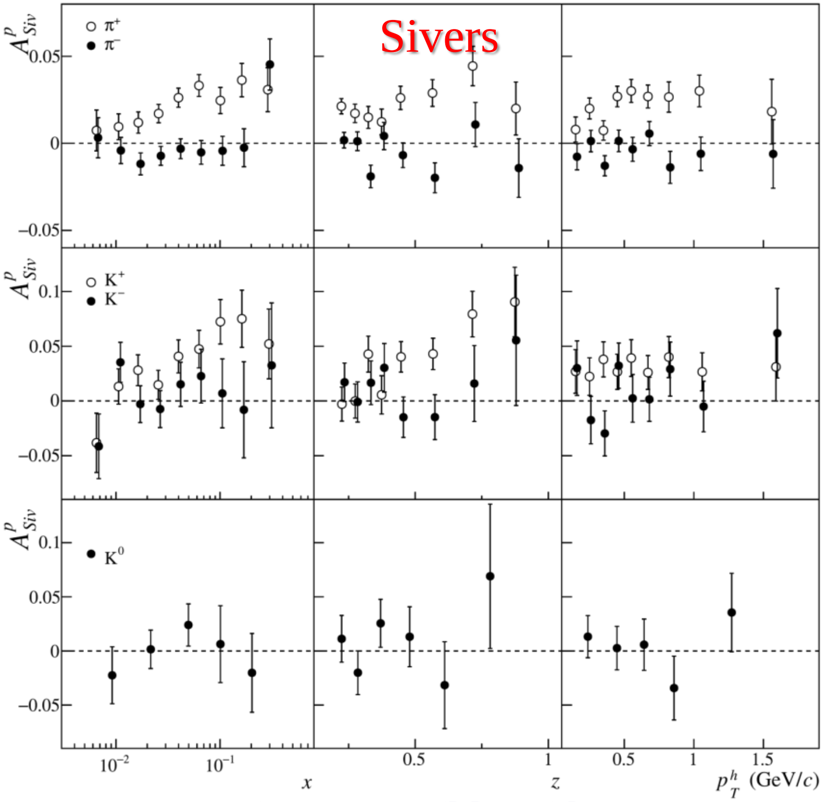
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\,h_1^q H_{1q}^{\perp h}\right]$$

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



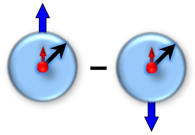
COMPASS PLB 744(2015)250





- 1st COMPASS deuteron measurements – Collins and Sivers asymmetries compatible with zero
- COMPASS proton measurements – clear non-zero signal for both asymmetries

SIDIS TSAs: Collins effect and Transversity

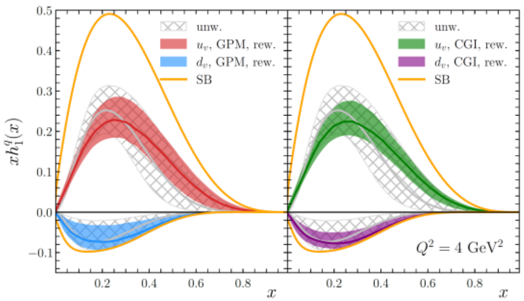


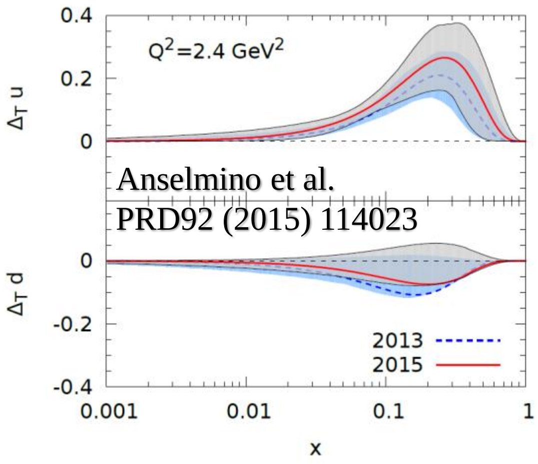
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\ \right\}$$

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

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results 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

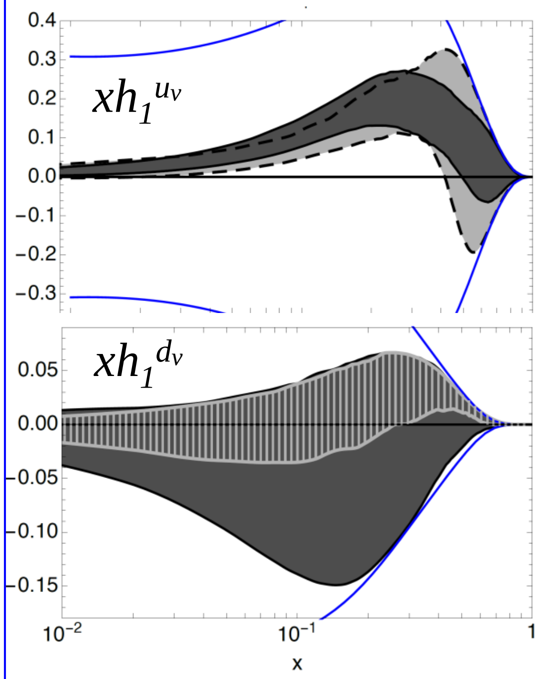
Boglione et al. PLB 854 (2024) 138712



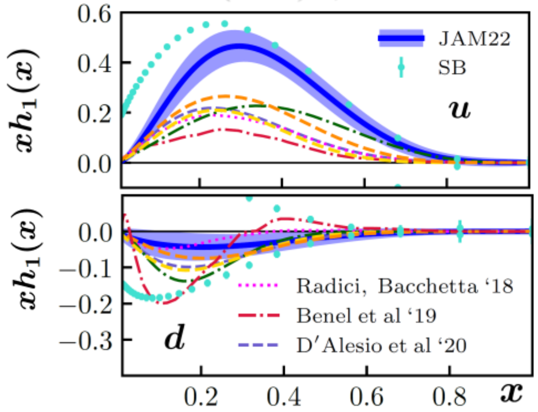


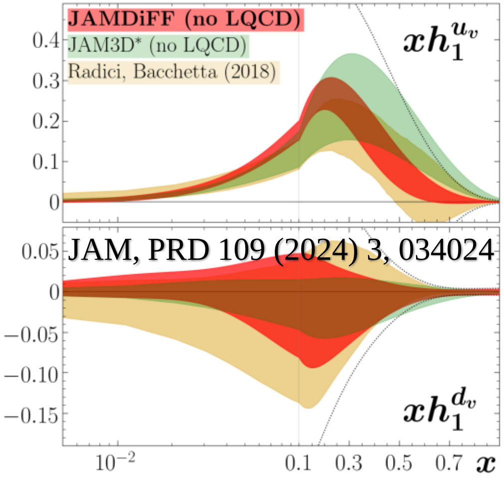
Anselmino et al. PRD92 (2015) 114023

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



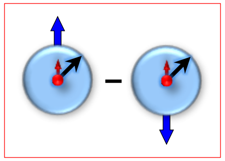
JAM PRD 106 (2022) 3, 034014





JAM, PRD 109 (2024) 3, 034024

SIDIS TSAs: Collins effect and Transversity



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

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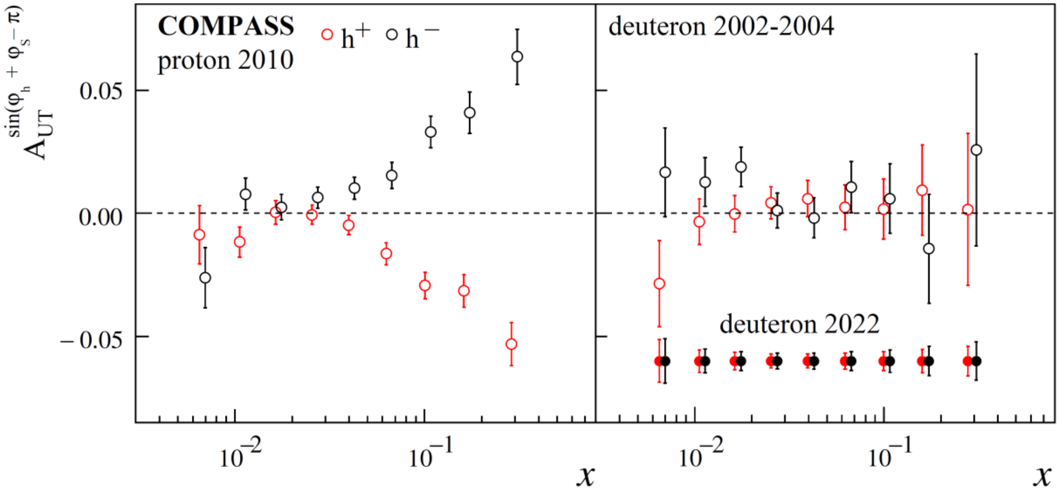
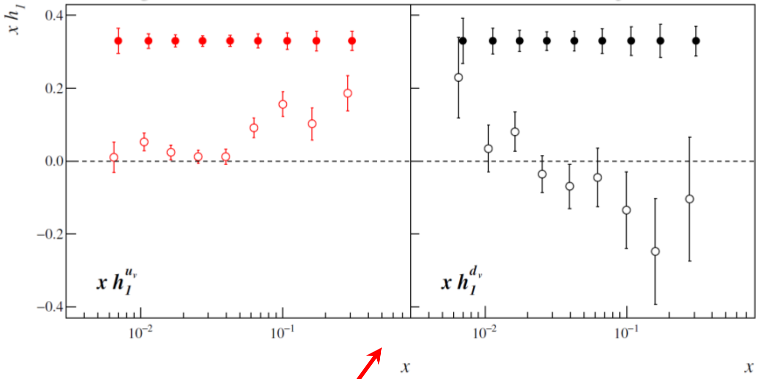
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS
  (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity

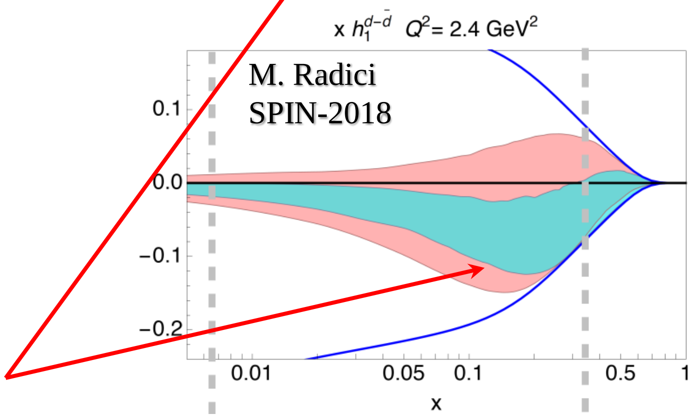
[Addendum to the COMPASS-II Proposal]

Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF



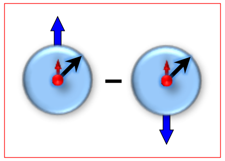


M. Radici
SPIN-2018

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



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

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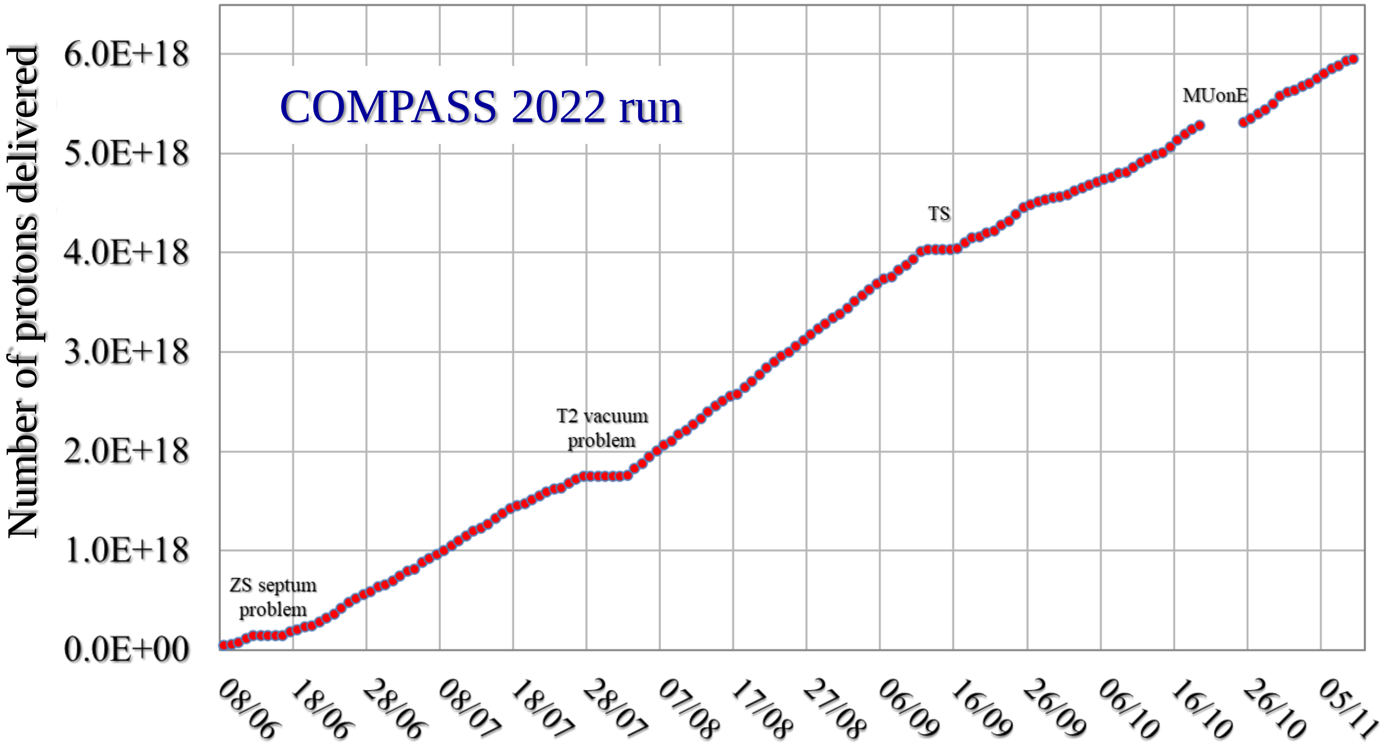
- New deuteron data crucial to constrain *d*-quark transversity

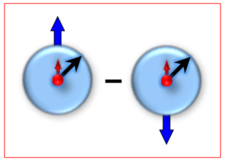
Total protons delivered on the production target: ~5.95×10^{18} (98% of the request) in ~150 days



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

Highly successful Run in 2022!

SIDIS TSAs: Collins effect and Transversity



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

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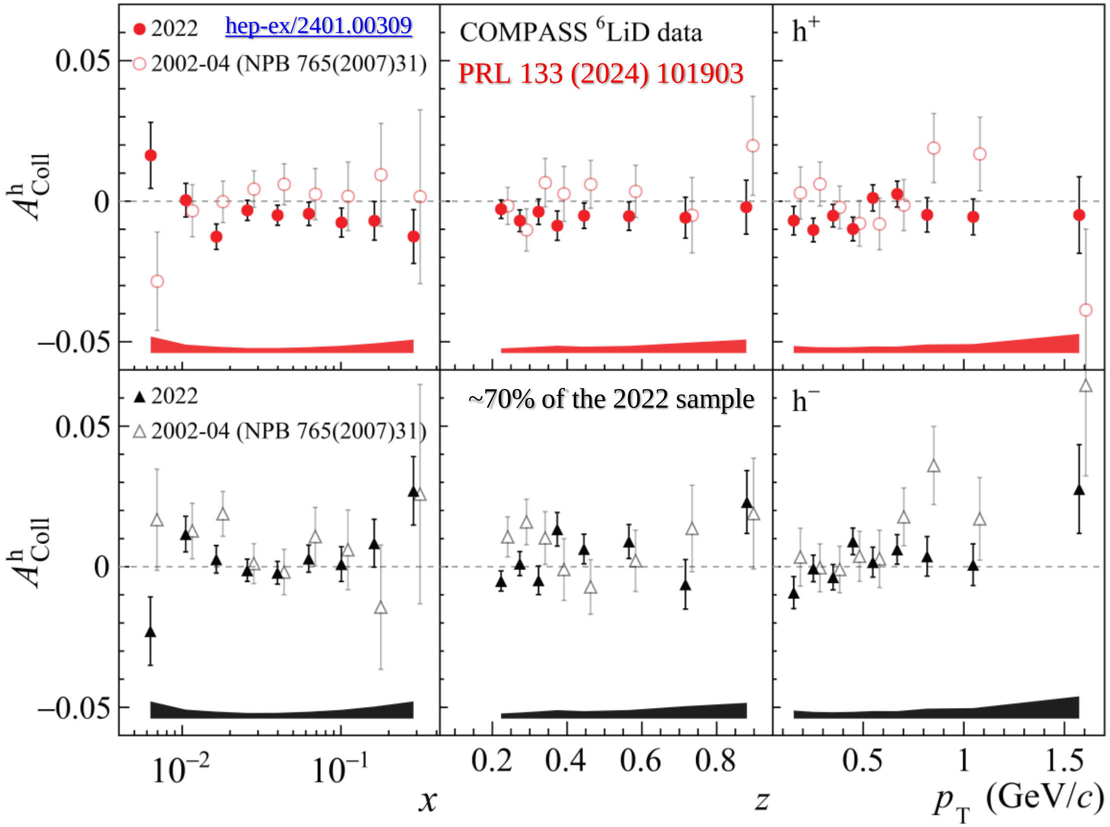
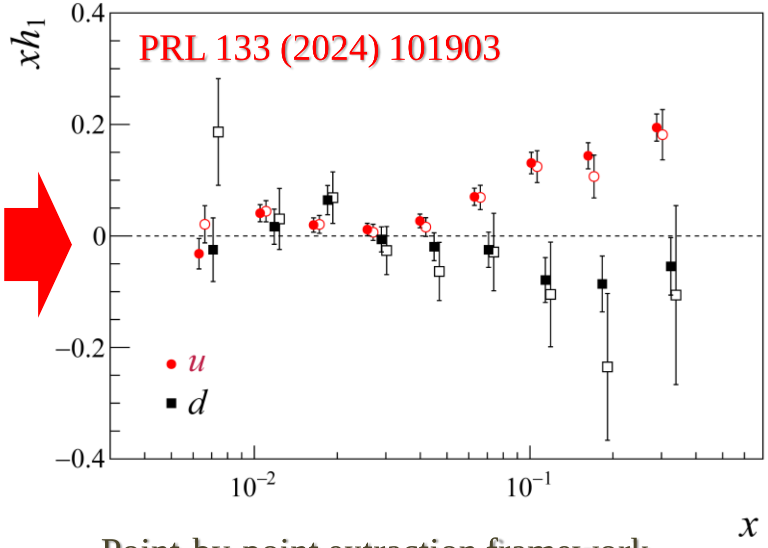


See S. Asatryan’s talk

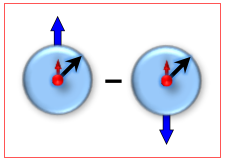


Point-by-point extraction framework
A. Martin et al. PRD **91**, 014034 (2015)
A. Martin et al. PRD **95**, 094024 (2017)

COMPASS 2022 run – highly successful data-taking!

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

SIDIS TSAs: Collins effect for K^0



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

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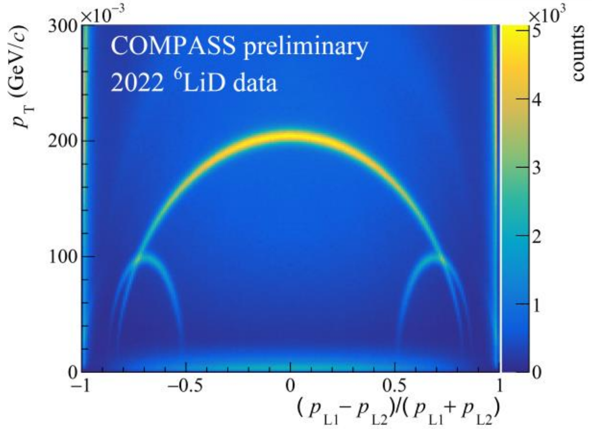
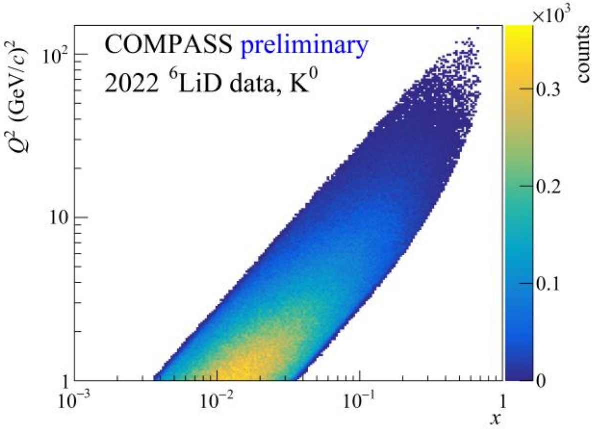
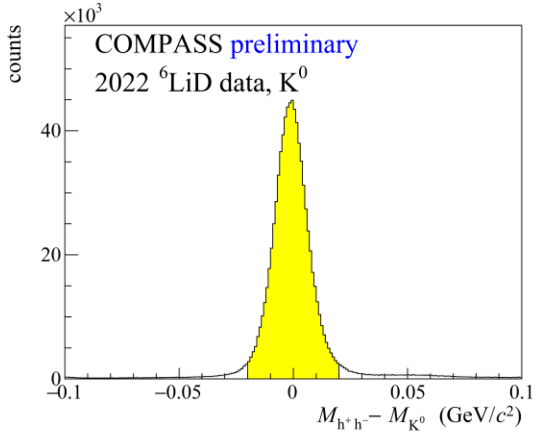
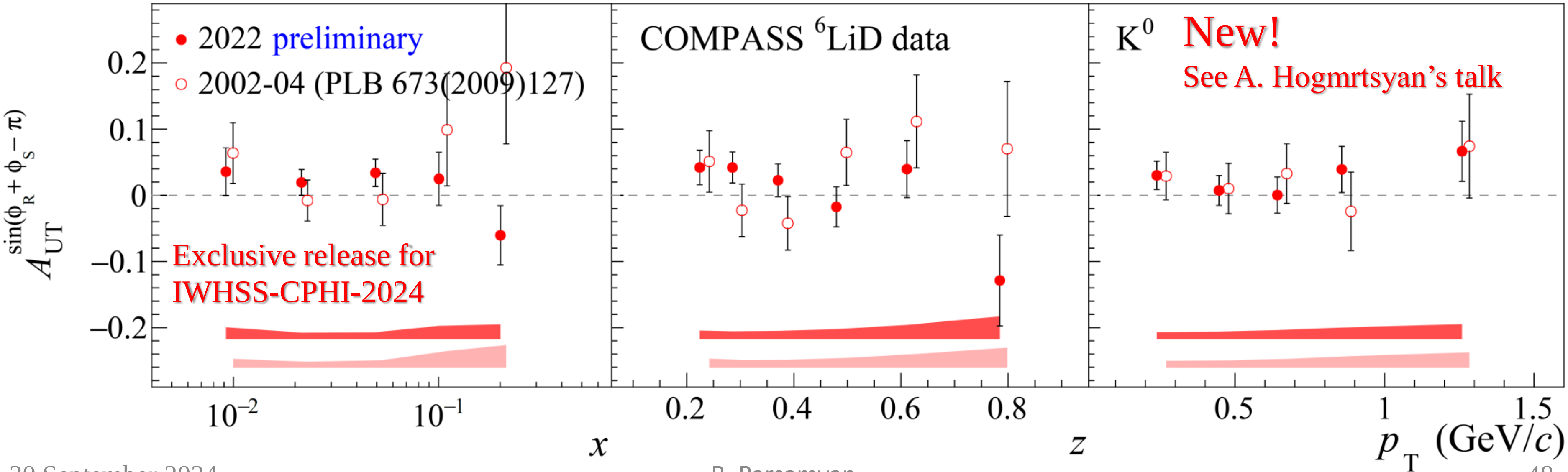




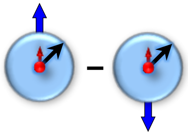




Exclusive release for IWHSS-CPHI-2024

New!
See A. Hogmrtsyan's talk

Dihadron Collins effect and Transversity

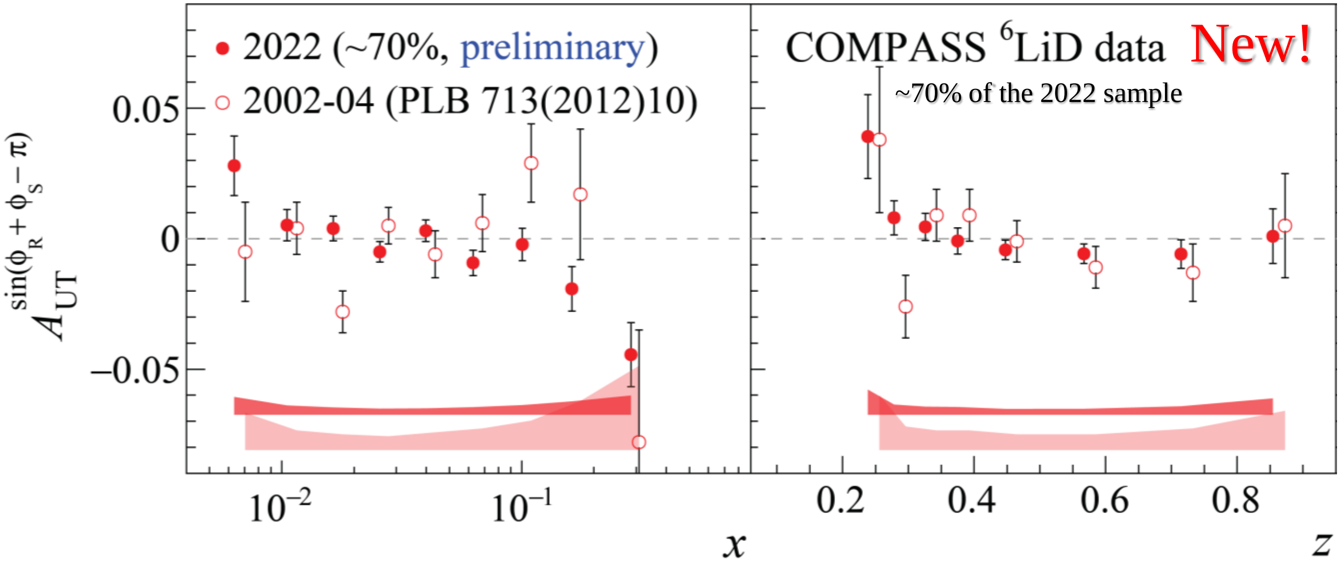


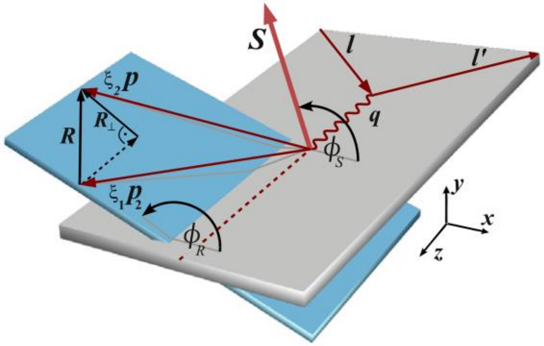
$$\frac{d^7\sigma}{d\cos\theta\, d M_{hh}\, d\phi_R\, d z\, d x\, d y\, d\phi_S} =$$

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

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

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



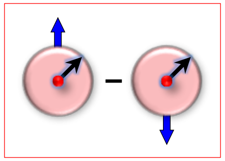


See S. Asatryan's talk

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

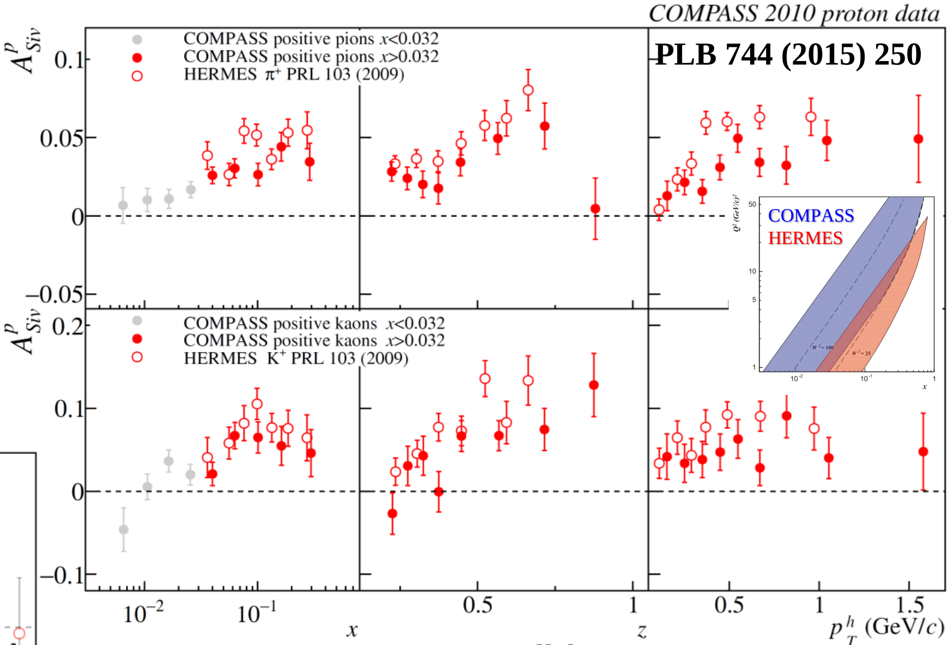
SIDIS TSAs: Sivers effect

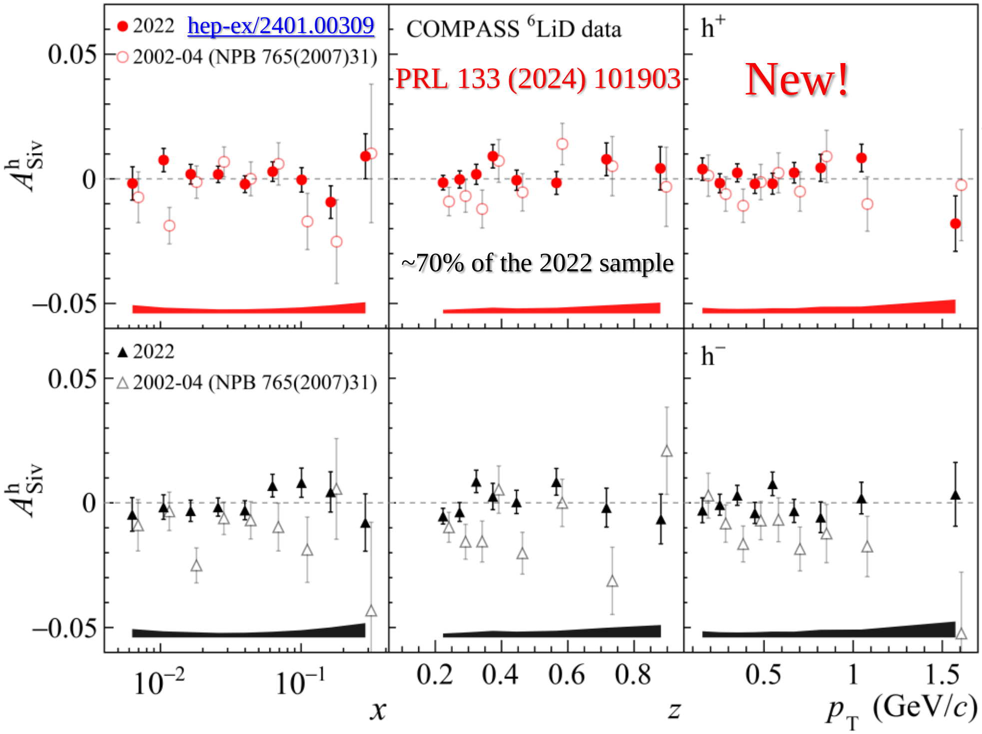


$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\;S_T\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+\ldots\right\}$$

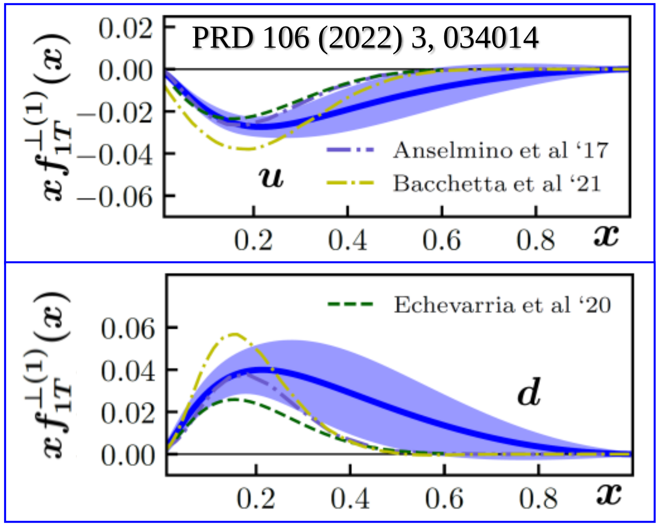
$$\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\,f_{1T}^{\perp q}D_{1q}^{h}\right],\; F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0}$$

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





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

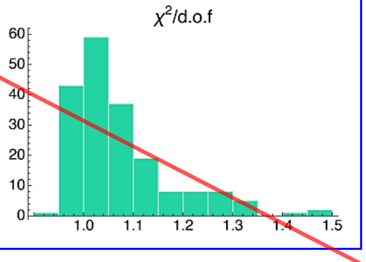
$Q^2 \geq 1.4$ GeV^2 $0.2 \leq z \leq 0.7$

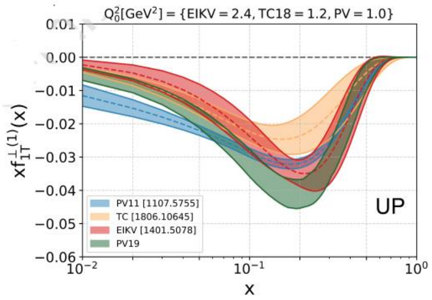
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

300 data points → **118** data fitted

14 free parameters

χ^2/d.o.f. = 1.06 ± 0.10

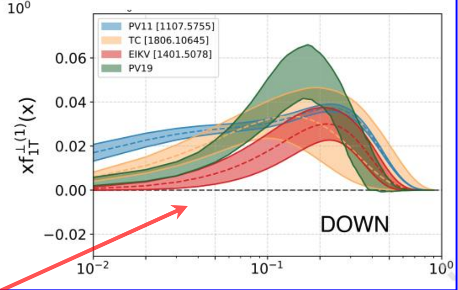




PV11	*Bacchetta & Radici, P.R.L.* ***107*** *(11)*
EIKV	*Echevarria et al., P.R. D****89*** *(14)*
TC	*Boglione et al., JHEP* ***1807*** *(18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

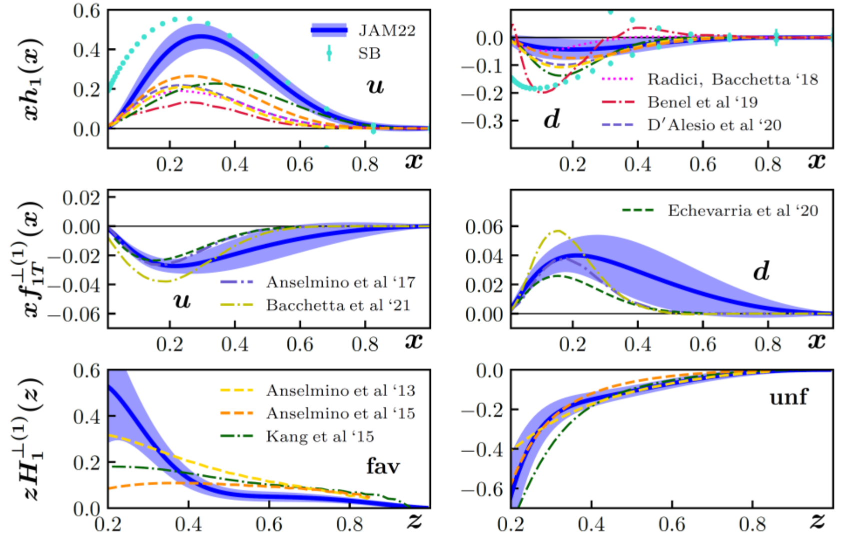
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \, \frac{\mathbf{k}_T^2}{2M^2} \, f_{1T}^{\perp}(x, \mathbf{k}_T)$$

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

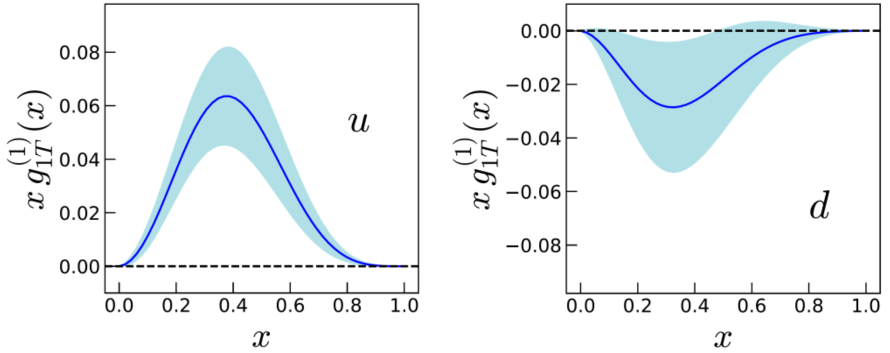


COMPASS 2022 deuteron run

JAM Collaboration, PRD 106 (2022) 3, 034014

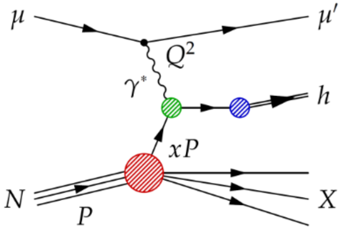


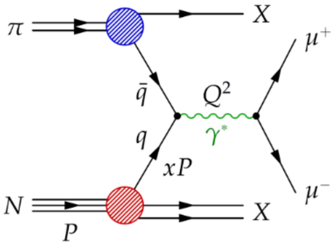
S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D.Pitonyak
PRD 105 (2022) 3, 034007



More news soon…

COMPASS bridge

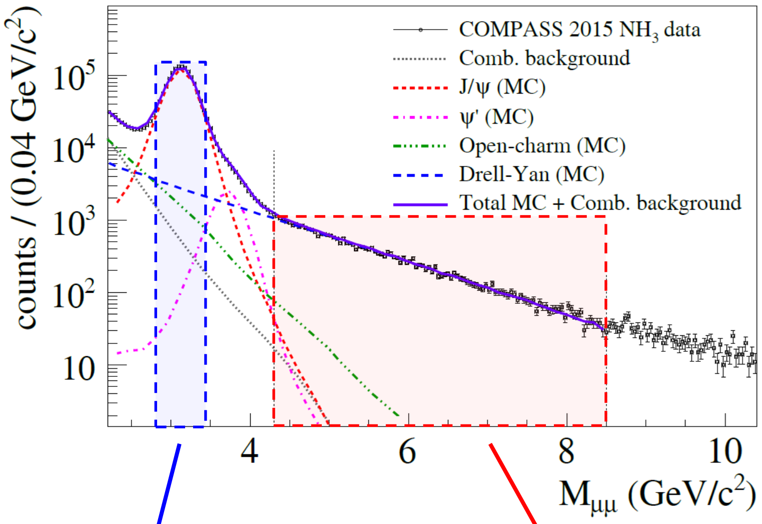


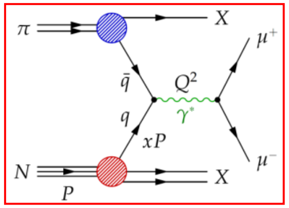


Drell-Yan

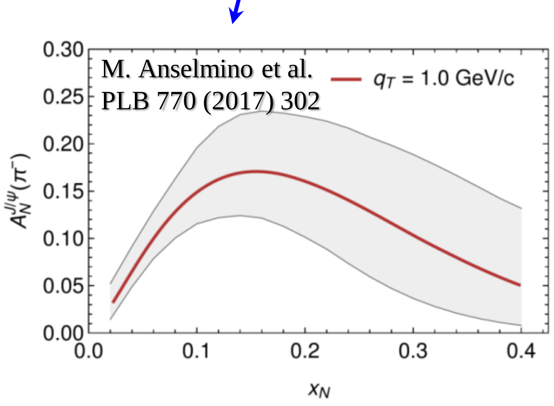
SIDIS

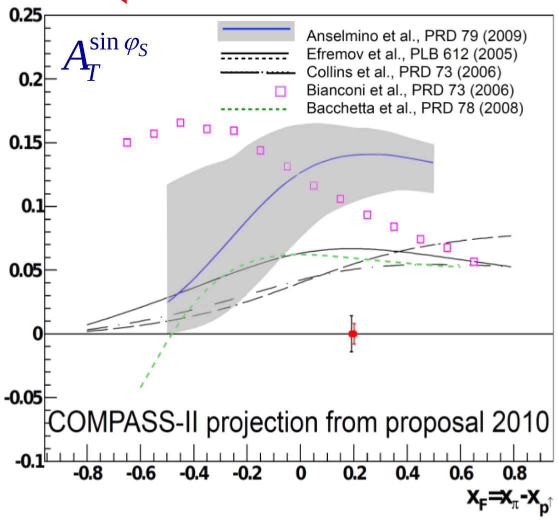
Single-polarized Drell-Yan cross-section at twist-2 (LO)





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





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

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

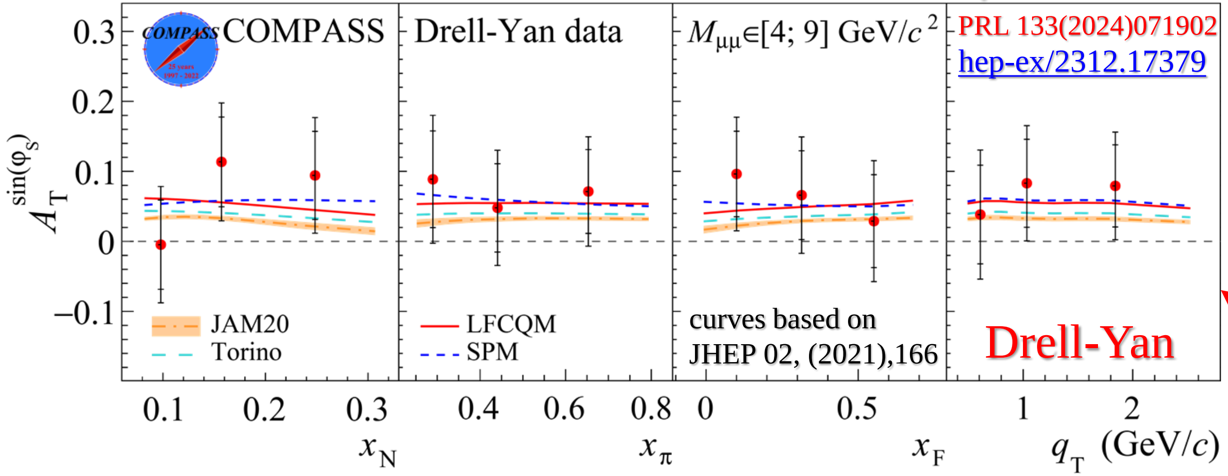
COMPASS phase-II proposal submitted in 2010 (Drell-Yan, DVCS,…)

Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS → sign change test

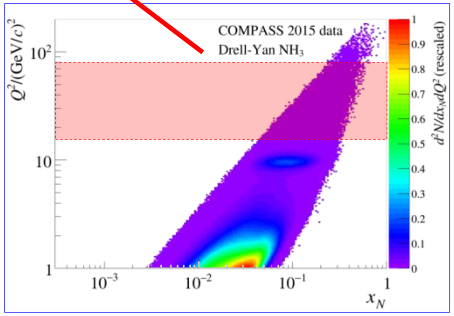
Sivers effect: Drell-Yan and J/ψ

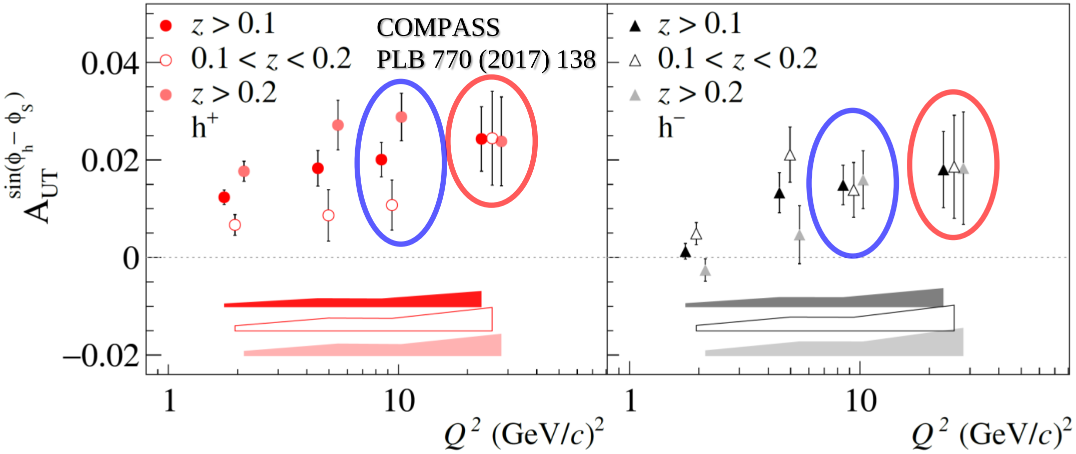
Sivers DY TSA

$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$



- The Drell-Yan Sivers asymmetry tends to be positive (~1.5 s.d.)





Sivers SIDIS TSA

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

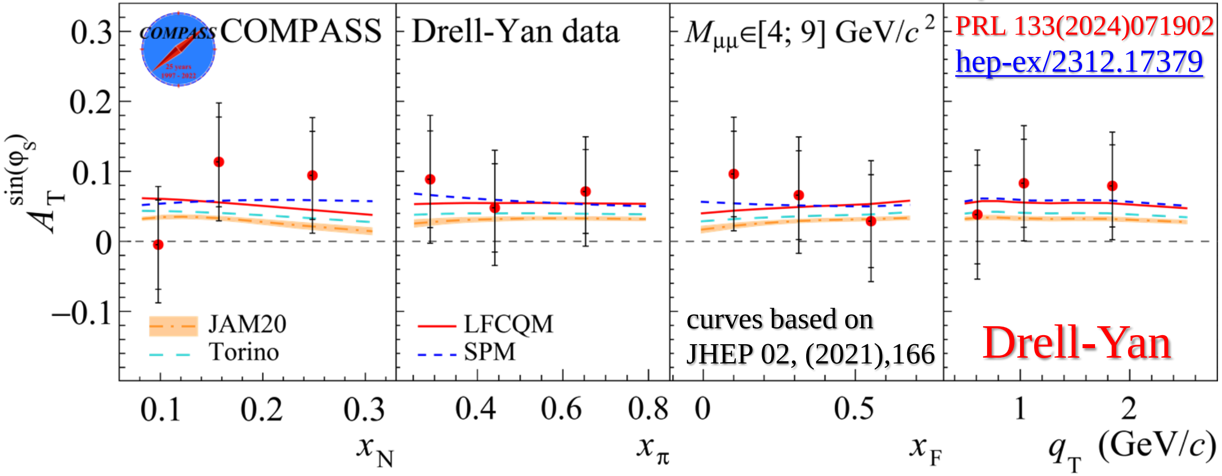
COMPASS proton Sivers measurements

- Clear signal in the matching Q² ranges

Sivers effect: Drell-Yan and J/ψ

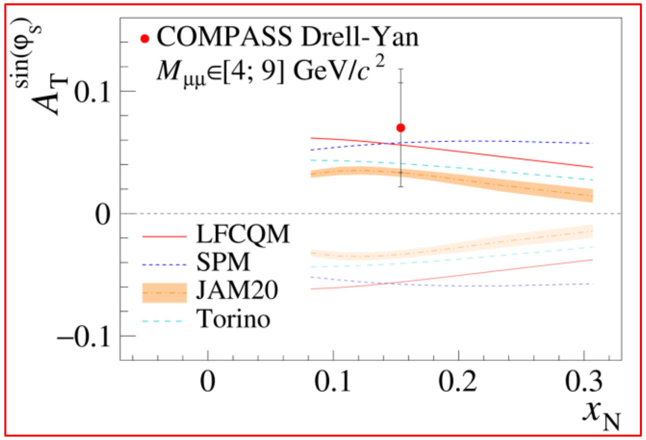
Sivers DY TSA

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$$

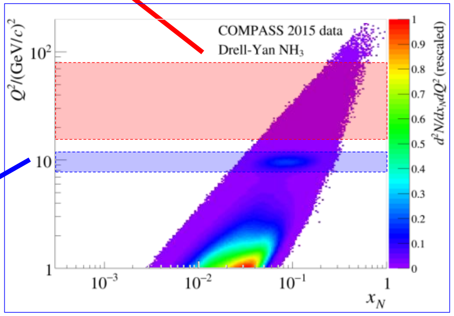


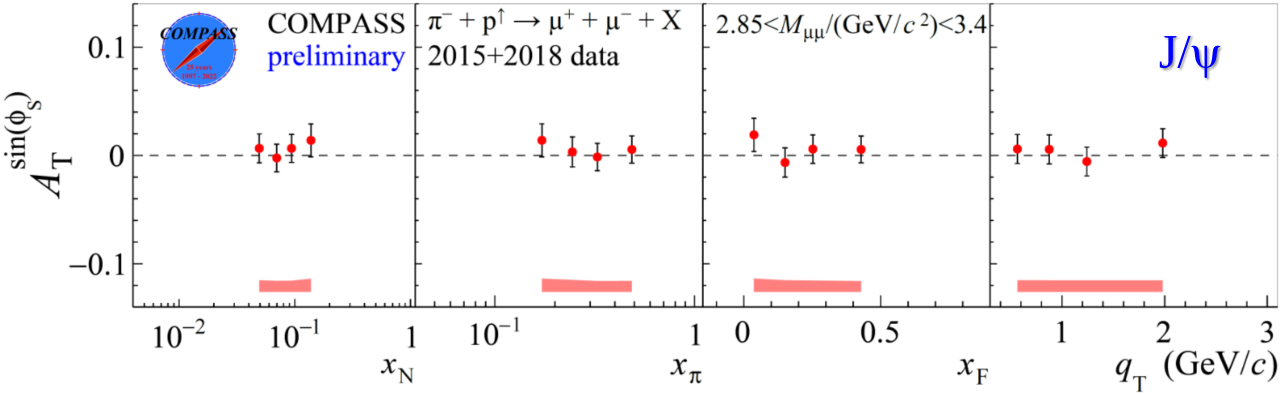
PRL 133(2024)071902
hep-ex/2312.17379

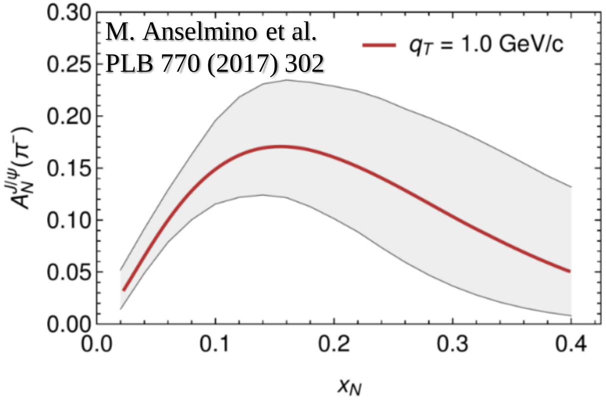
curves based on
JHEP 02, (2021),166



- The Drell-Yan Sivers asymmetry tends to be positive (~1.5 s.d.)







M. Anselmino et al.
PLB 770 (2017) 302

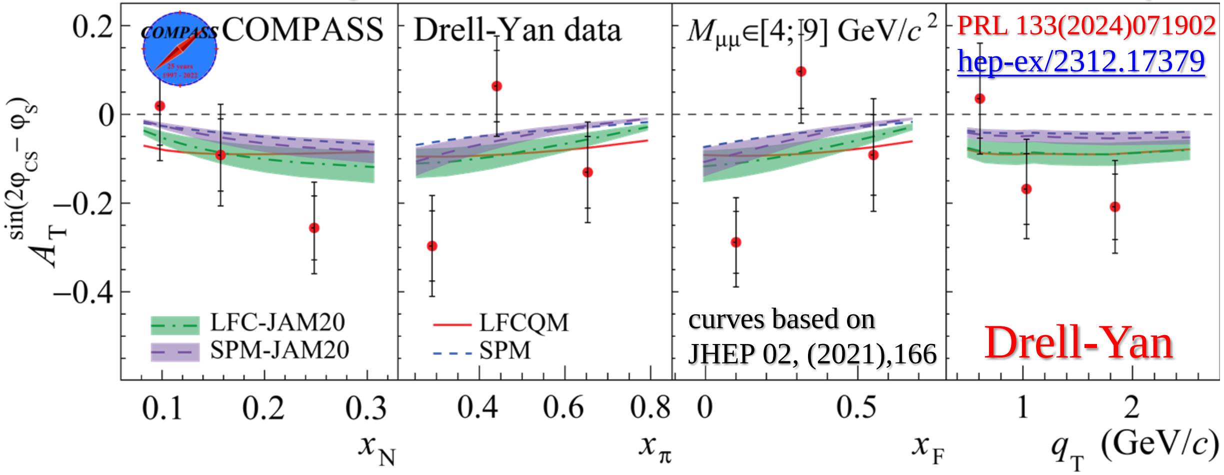
- J/ψ Sivers asymmetry is compatible with zero (within ~ 1%)
- Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS

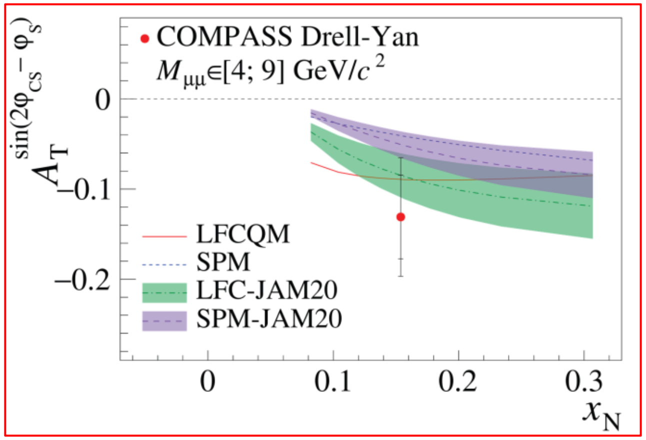
- Hint that J/ψ production might go via gg fusion in COMPASS?
- Access to small gluon TMDs?

Transversity TSA: Drell-Yan and J/ψ

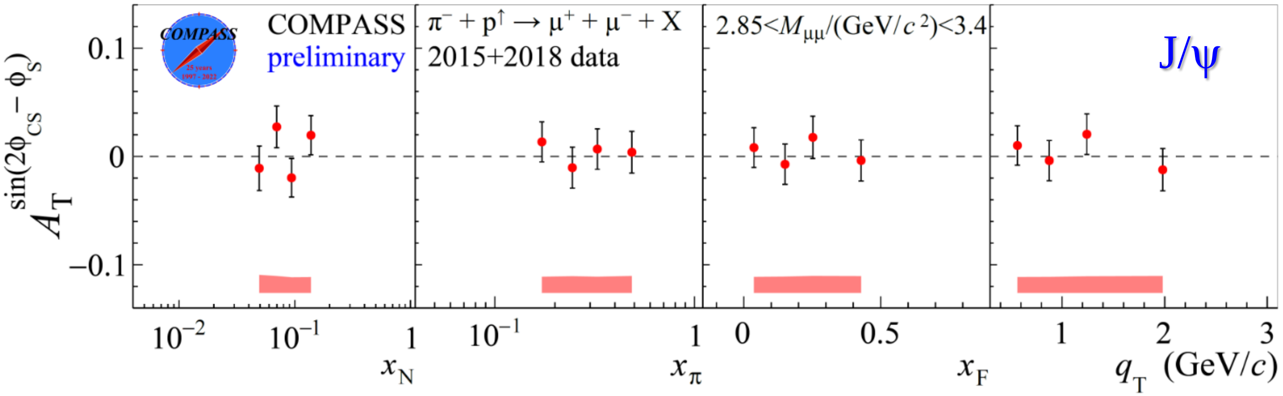
Transversity DY TSA

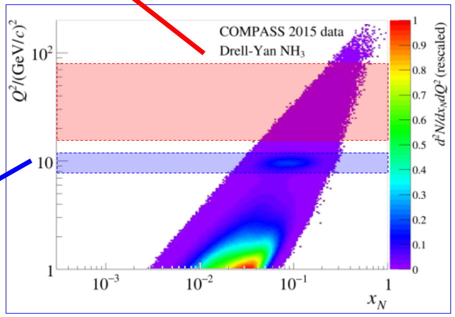
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$

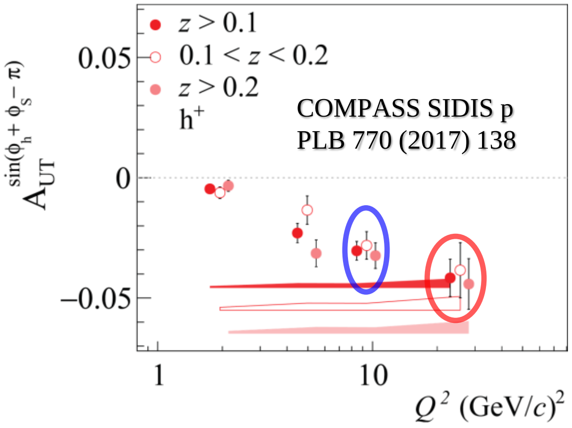




- The Drell-Yan Transversity asymmetry is negative (~2 s.d.)



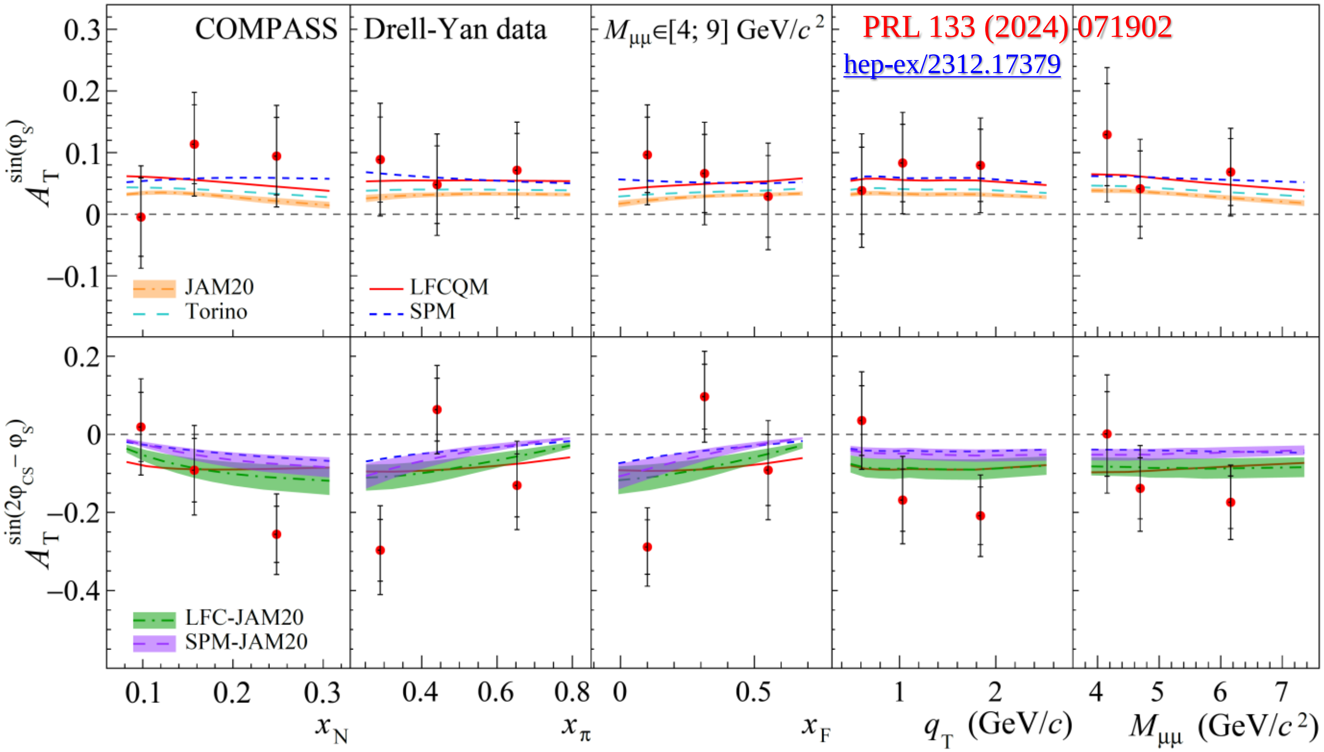




- J/ψ Sivers asymmetry is compatible with zero (within ~ 1%)
- Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS
- J/ψ Transversity TSA is also compatible with zero
- Hint that J/ψ production might go via gg fusion in COMPASS?
- Access to small gluon TMDs?

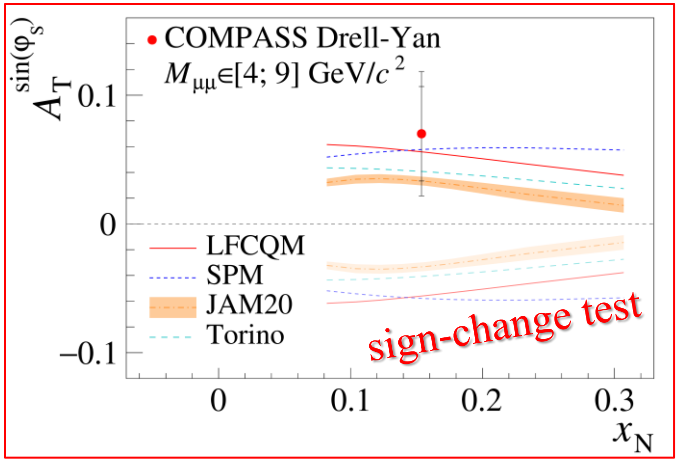
Transverse-spin asymmetries in $\pi^- p^\uparrow$ scattering

Theory curves based on S. Bastami et al. JHEP 02, (2021),166

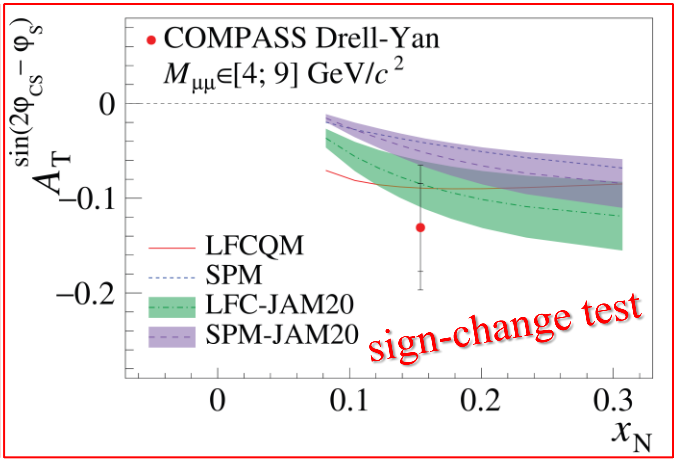


PRL 133 (2024) 071902

hep-ex/2312.17379



sign-change test



sign-change test

Drell-Yan measurements

- Ruled out predictions for large asymmetries
- General agreement with currently available model calculations
- COMPASS data favors the sign-change hypothesis for the Sivers TMD PDF
- COMPASS data also favors proton Boer-Mulders TMD PDF sign-change (indirect, model-based)

J/ψ production channel

- All TSAs are small and compatible with zero
- Hint that J/ψ production might go via gluon-gluon fusion in COMPASS
- Access to small gluon TMDs?

Conclusions

- COMPASS - 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 Spectroscopy, (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 preliminary results
- Since 2023 the experiment entered the Analysis Phase
  - 3 new groups joined COMPASS in the course of 2023 for the Analysis Phase
  - The spectrometer has been transferred to the COMPASS successor in the M2 beamline – the AMBER collaboration
- AMBER took its first data in 2023-2024!
  - Antiproton production studies and input for DM search
- AMBER phase one comprises also PRM and unique Drell-Yan measurements
  - Phase I will be resumed after LS3
- Long AMBER program is being developed: Phase-II proposal is being drafted

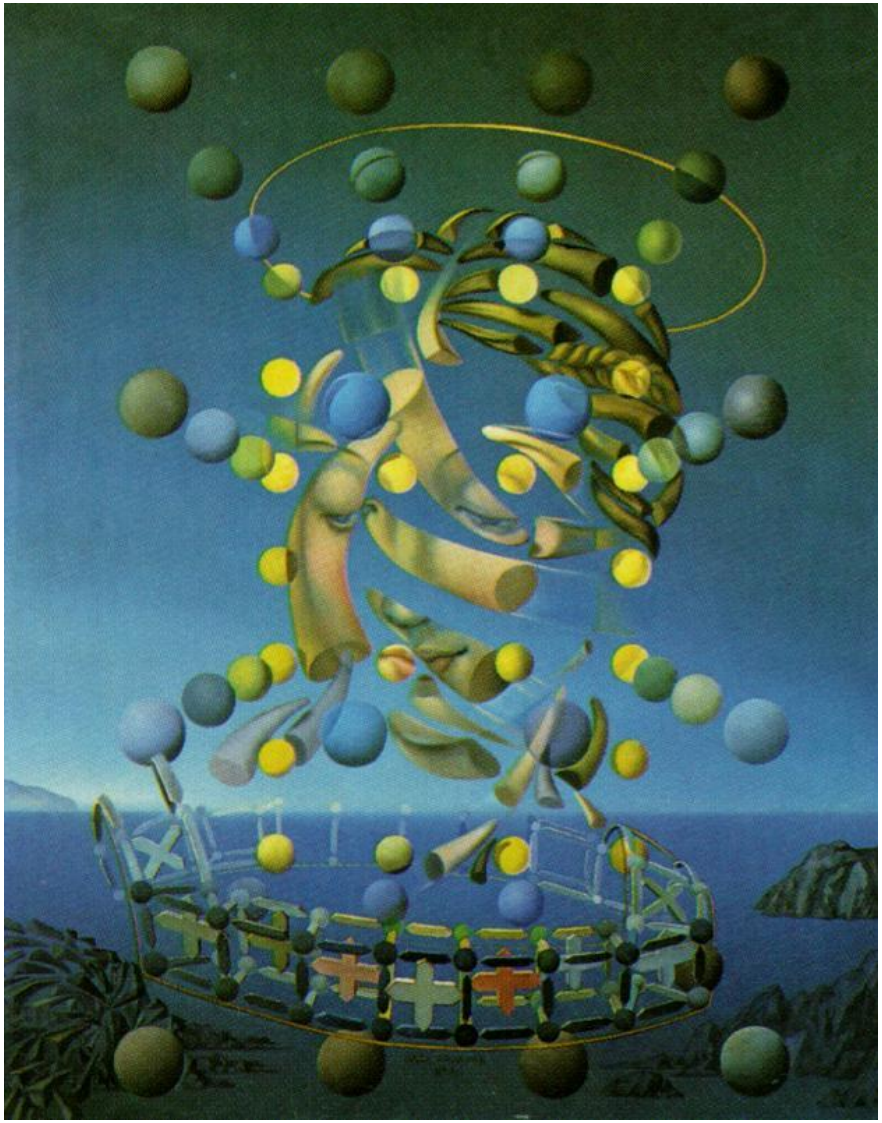
If you are interested in joining COMPASS or AMBER – don’t hesitate to get in touch!

Thank You!

“Nature”

Raphael “Madonna del Prato”

“1D”

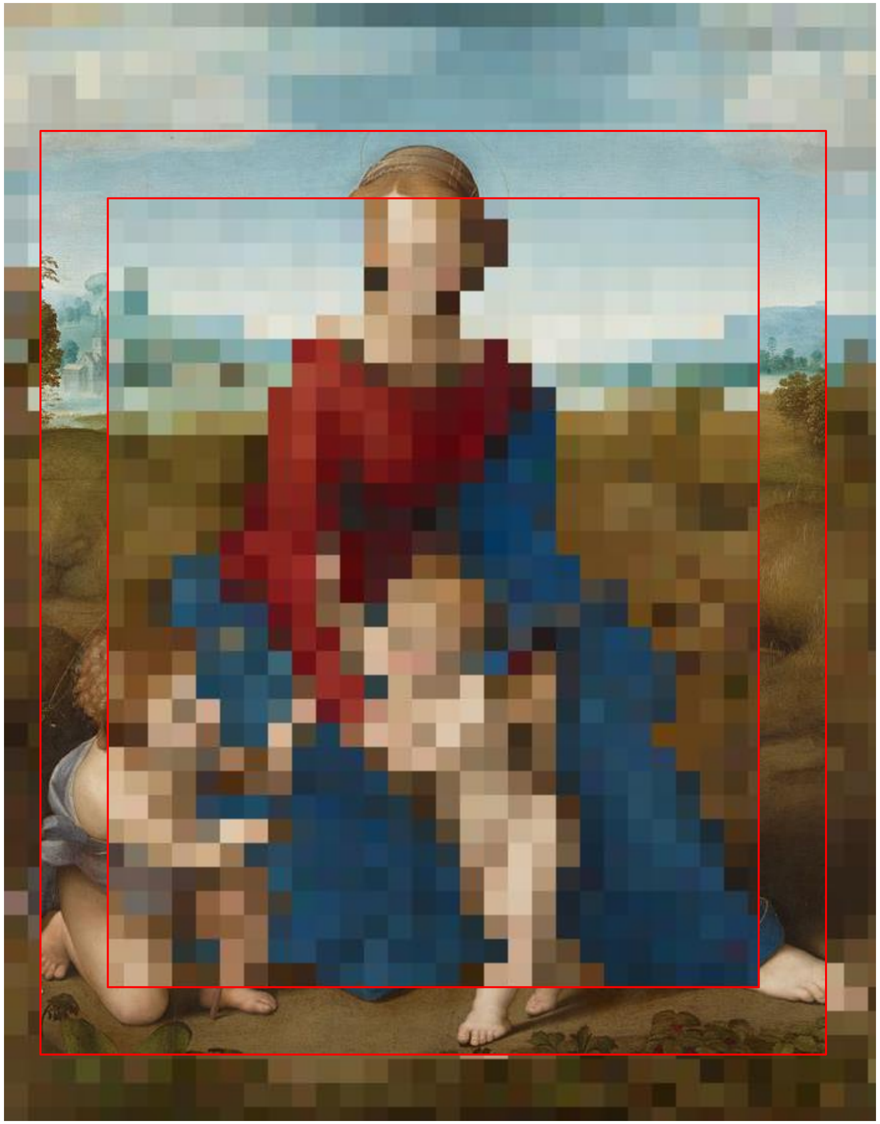


Salvador Dali “Maximum Speed of Raphael's Madonna”

“Nature”

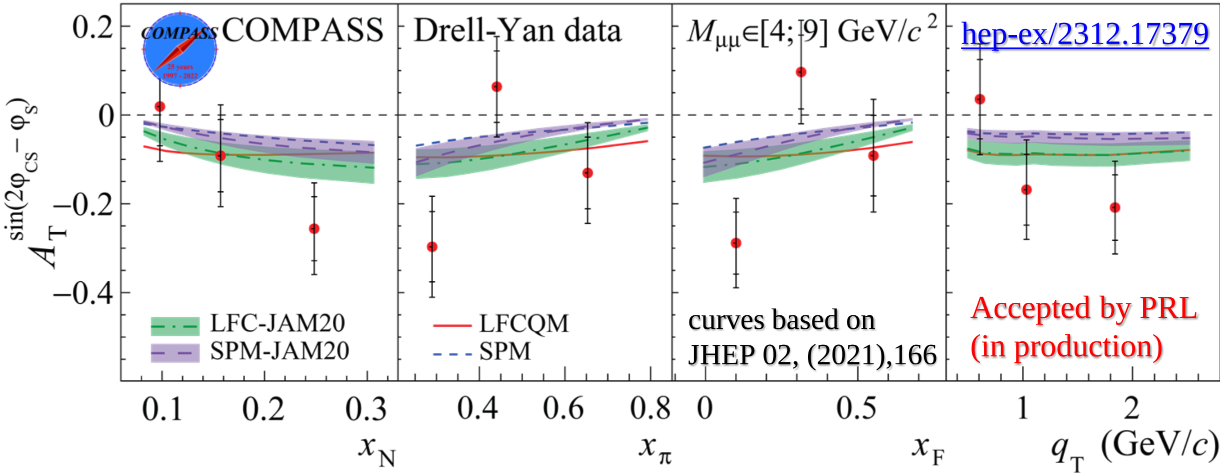
Raphael “Madonna del Prato”

“multi-D” with available statistics



Raphael “Madonna del Prato” (poor resolution)

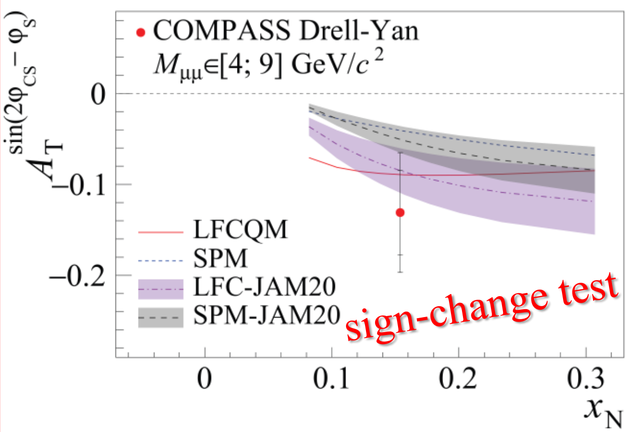
Boer-Mulders TMD PDF: sign change



hep-ex/2312.17379

curves based on
JHEP 02, (2021),166

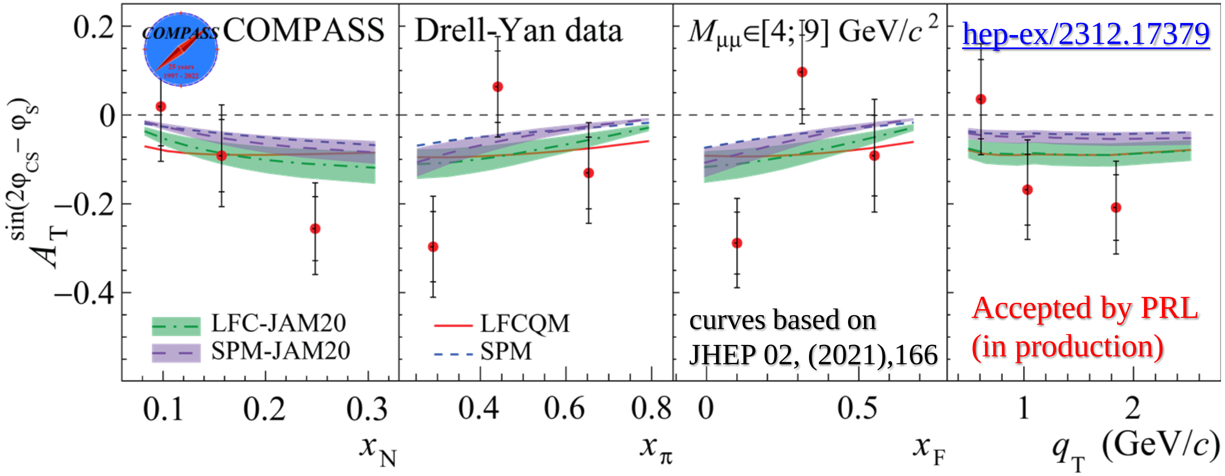
Accepted by PRL
(in production)



sign-change test

DY: $A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto -\left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,\mathrm{p}}^{u}\right\} < 0 \Rightarrow h_{1,\pi^-}^{\perp\bar{u}} > 0$

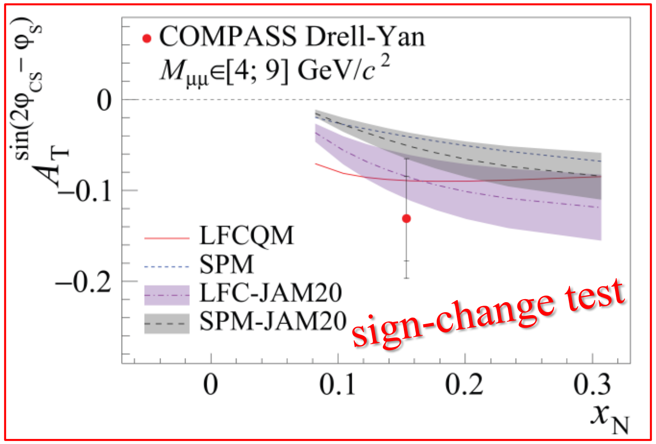
Boer-Mulders TMD PDF: sign change



hep-ex/2312.17379

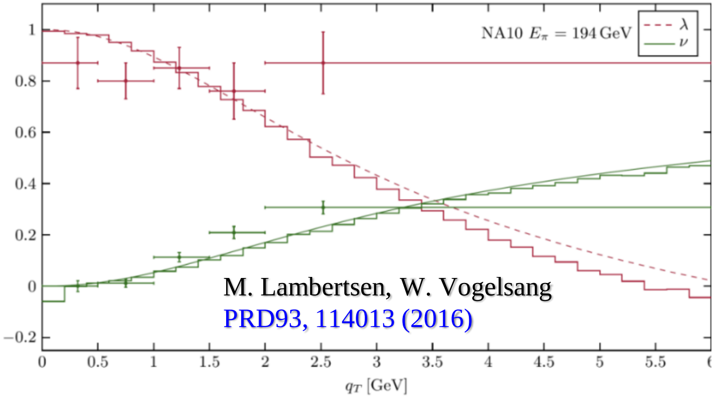
curves based on JHEP 02, (2021),166

Accepted by PRL (in production)

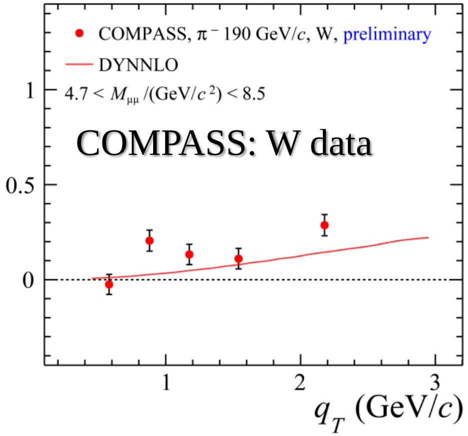


sign-change test

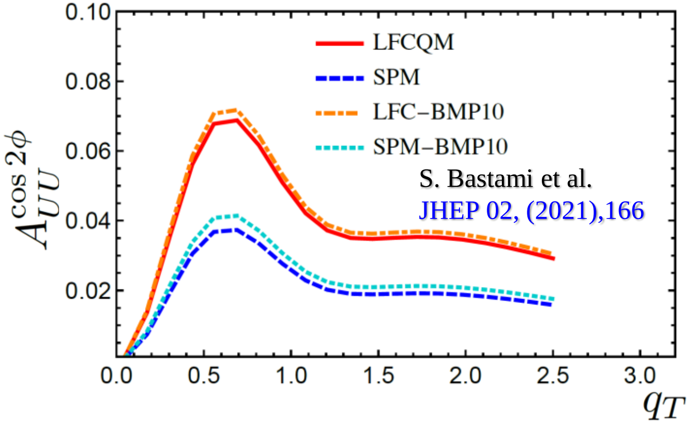
$$\text{DY: } A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto -\left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,\text{p}}^{u}\right\} < 0 \Rightarrow h_{1,\pi^-}^{\perp\bar{u}} > 0$$



M. Lambertsen, W. Vogelsang
PRD93, 114013 (2016)



COMPASS: W data



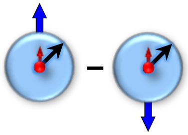
S. Bastami et al.
JHEP 02, (2021),166

$$\text{DY: } A_T^{\sin 2\varphi_{CS}} \propto \left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,p}^{\perp u}\right\} > 0 \Rightarrow h_{1,p}^{\perp u} > 0 \overset{\text{sign-change}}{\Leftrightarrow} \text{SIDIS: } h_{1,p}^{\perp u} < 0$$

$h_{1,p}^{\perp u} < 0 \to$ SIDIS fits
V. Barone, et al.
PRD 82 (2010) 114025

- COMPASS data favors proton Boer-Mulders TMD PDF sign-change

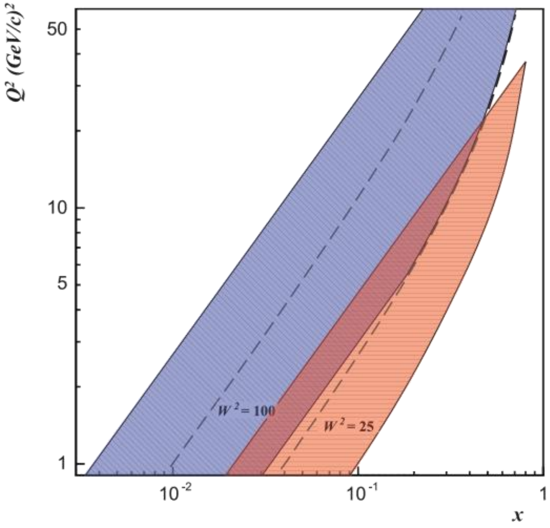
SIDIS TSAs: Collins effect and Transversity



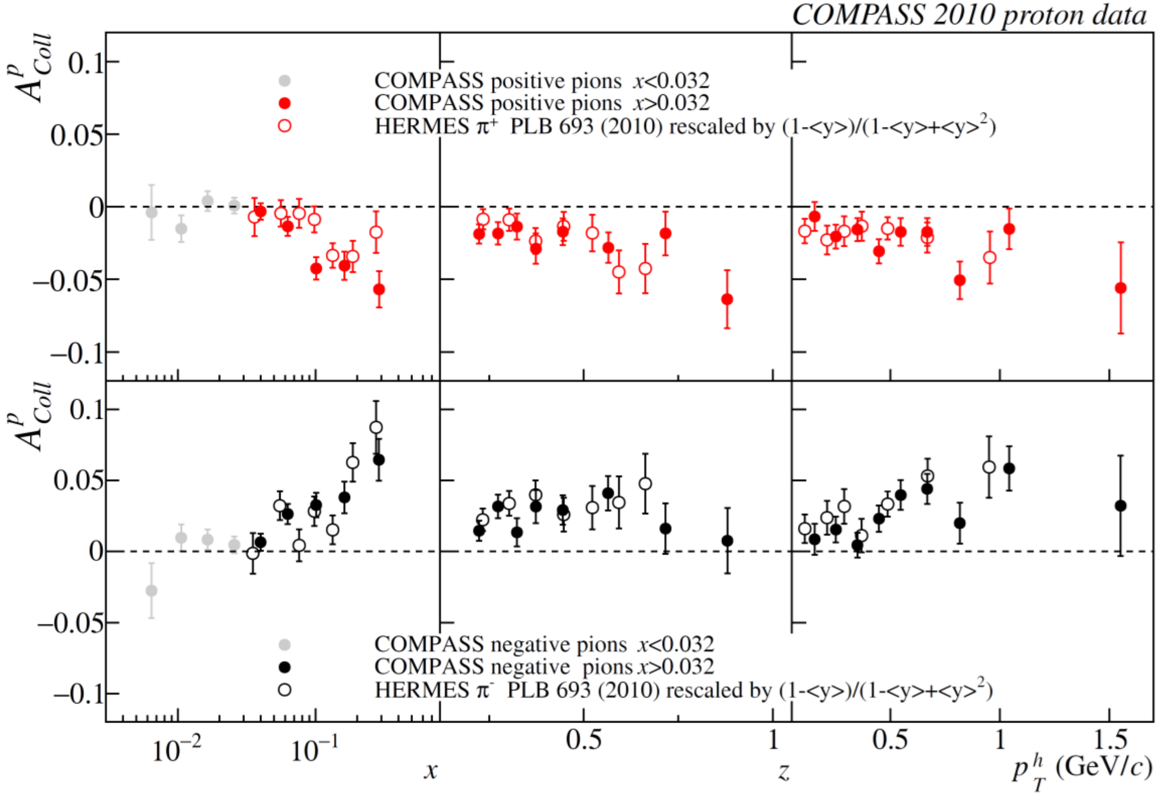
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

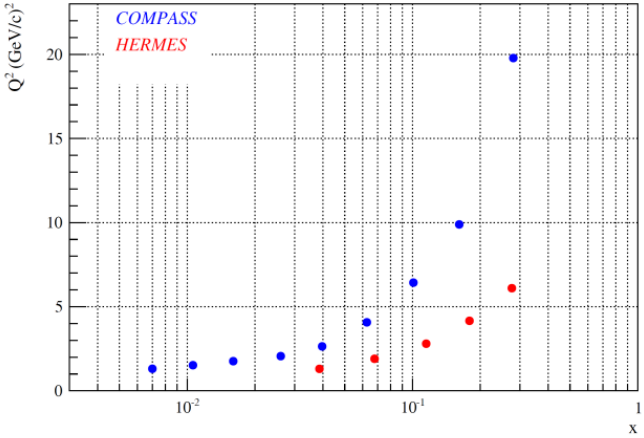
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

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

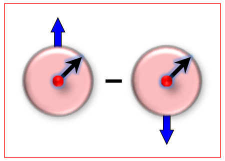


COMPASS PLB 744 (2015) 250





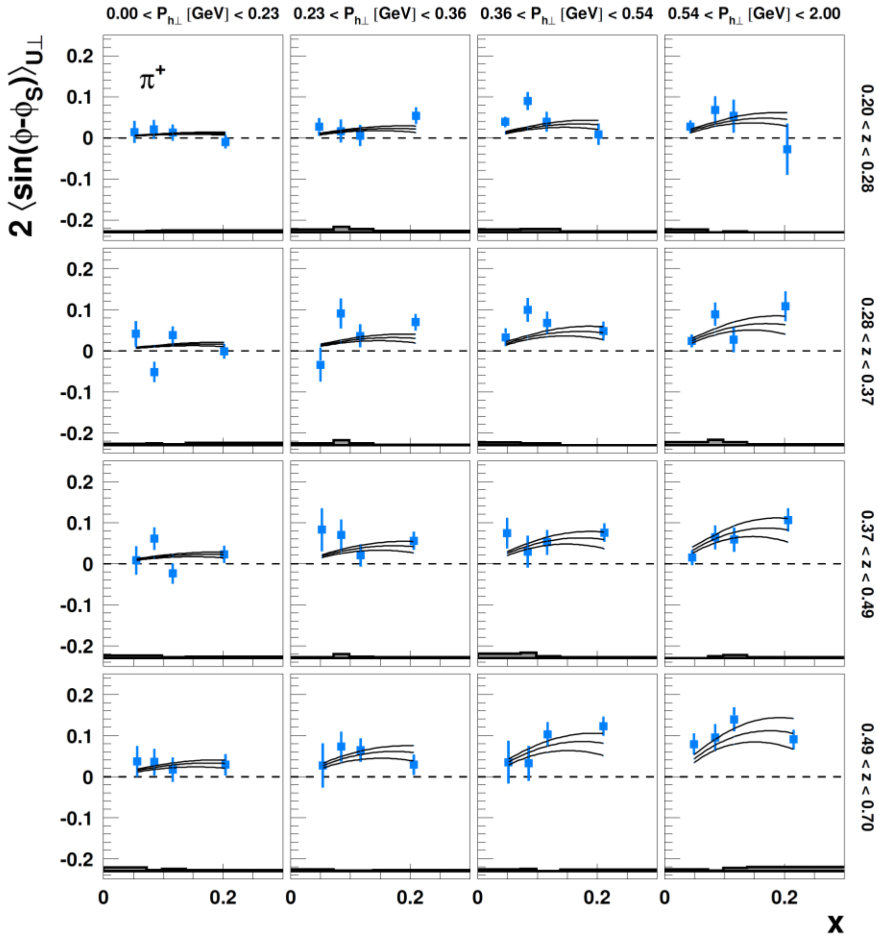
SIDIS TSAs: Sivers effect



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

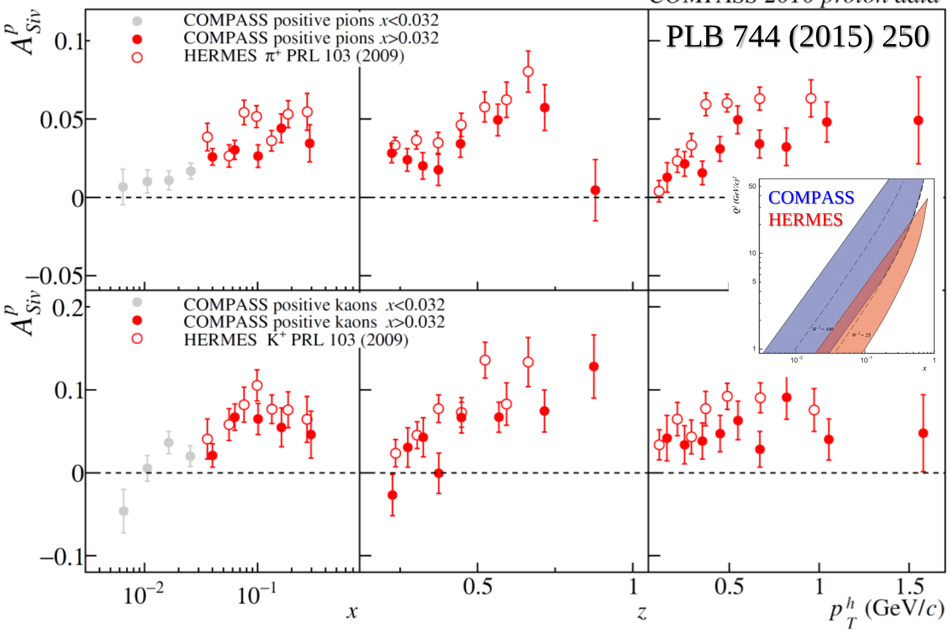
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\, f_{1T}^{\perp q} D_{1q}^{h}\right],\; F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

- COMPASS-HERMES discrepancy
- Q^2-evolution effect?

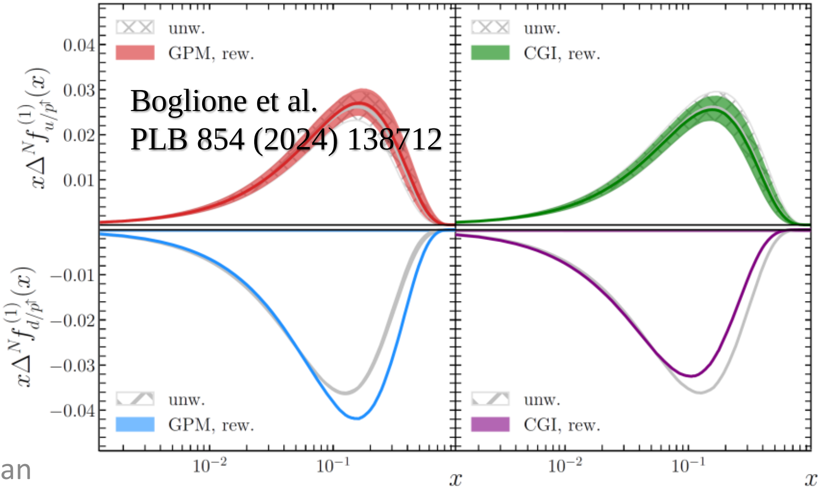


COMPASS 2010 proton data

PLB 744 (2015) 250



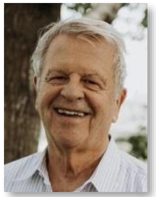
Boglione et al.
PLB 854 (2024) 138712



SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

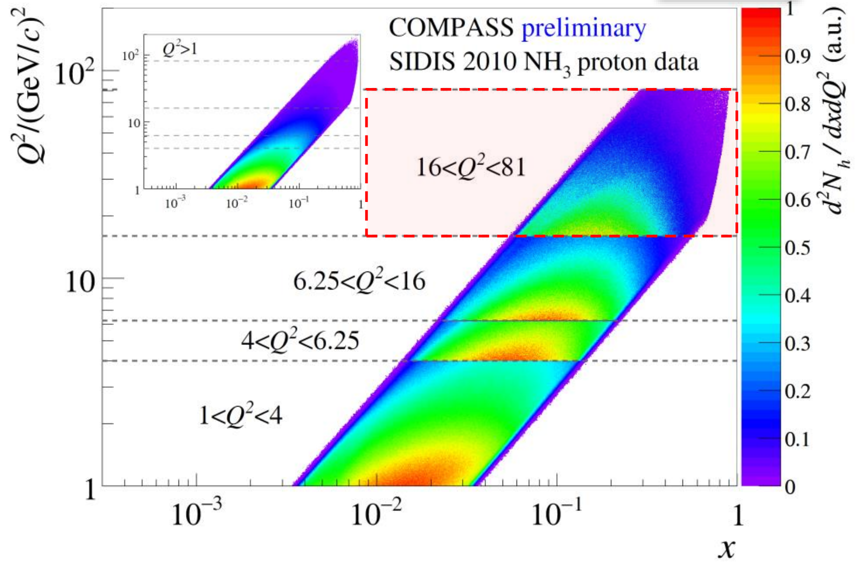
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\;S_T\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+\ldots\right\}$$

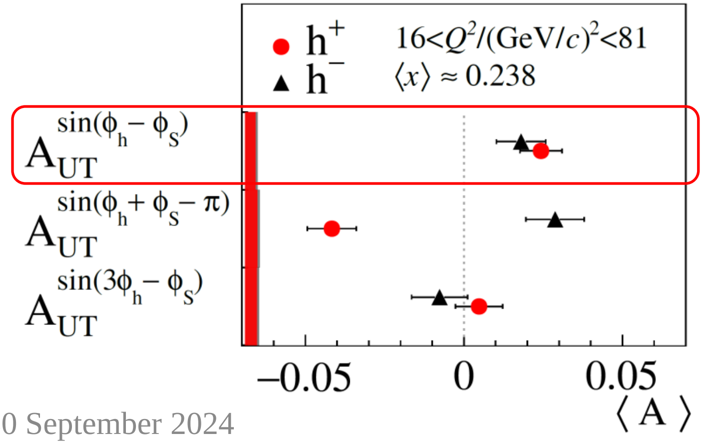
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\,f_{1T}^{\perp q}D_{1q}^{h}\right],\;F_{UT,L}^{\sin(\phi_h-\phi_S)}=0$$

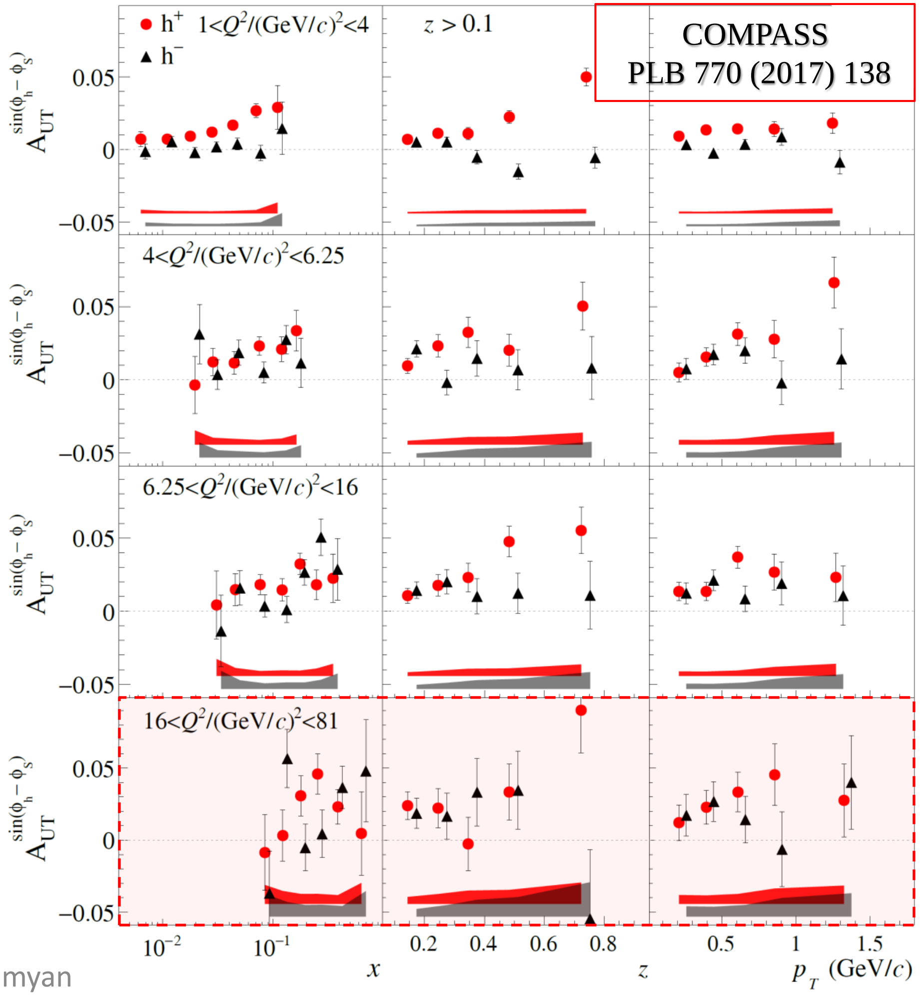


- COMPASS-HERMES discrepancy
- Q^2-evolution effect?

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

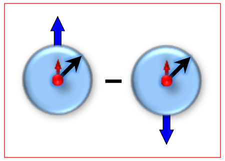






SIDIS TSAs: Collins effect and Transversity

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

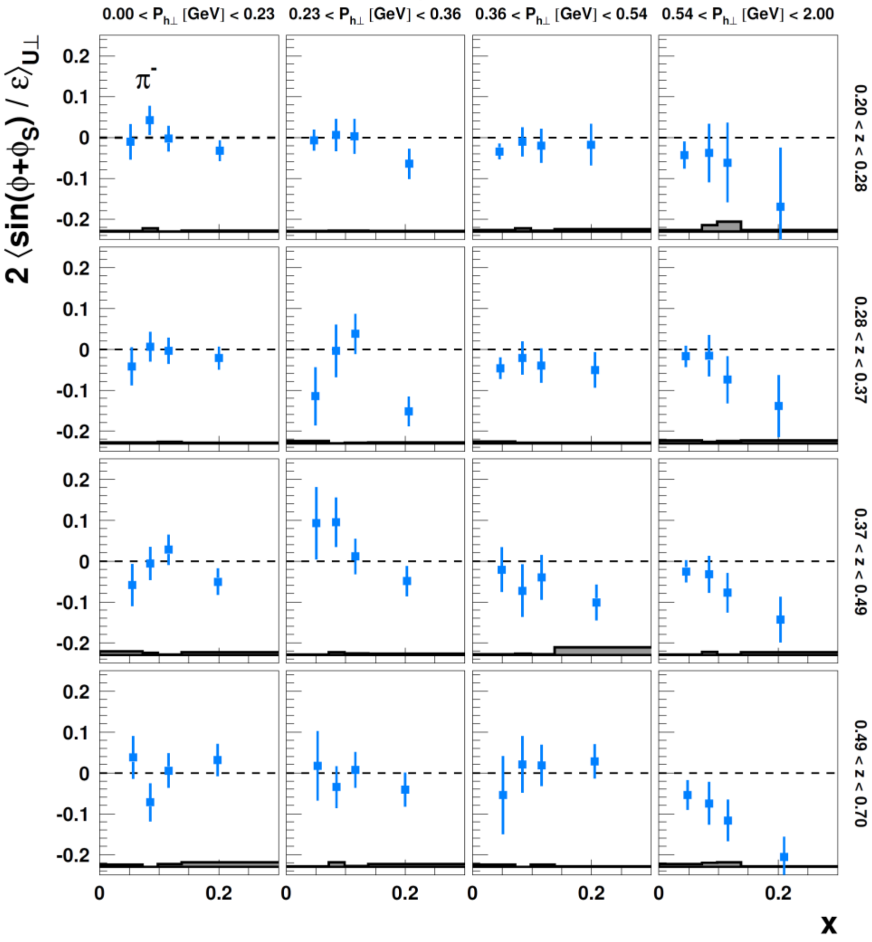


$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

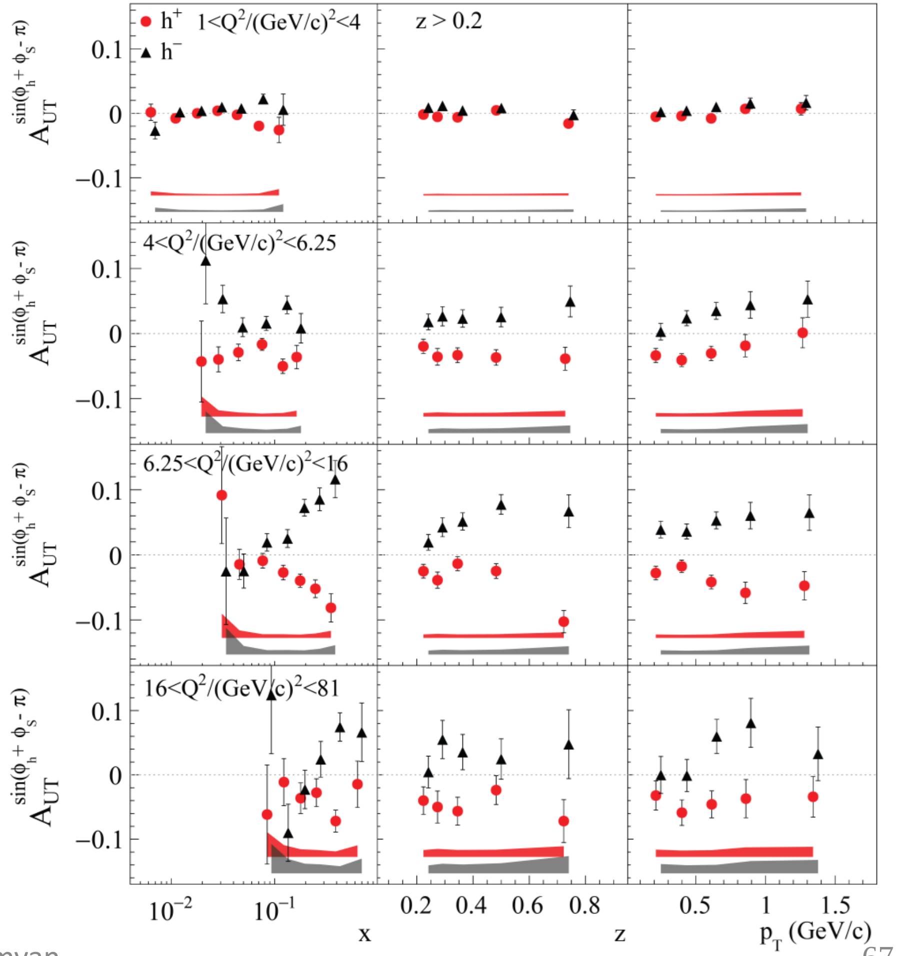
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

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

HERMES, JHEP 12 (2020) 010



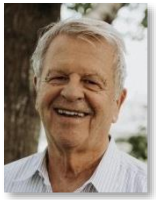
COMPASS, PBL 770 (2017) 138



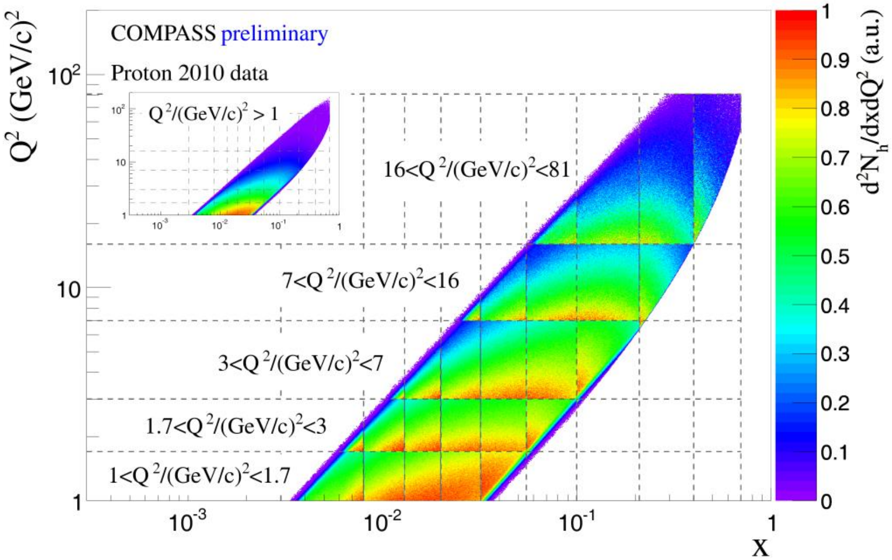
COMPASS Multi-D TSA analyses

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

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



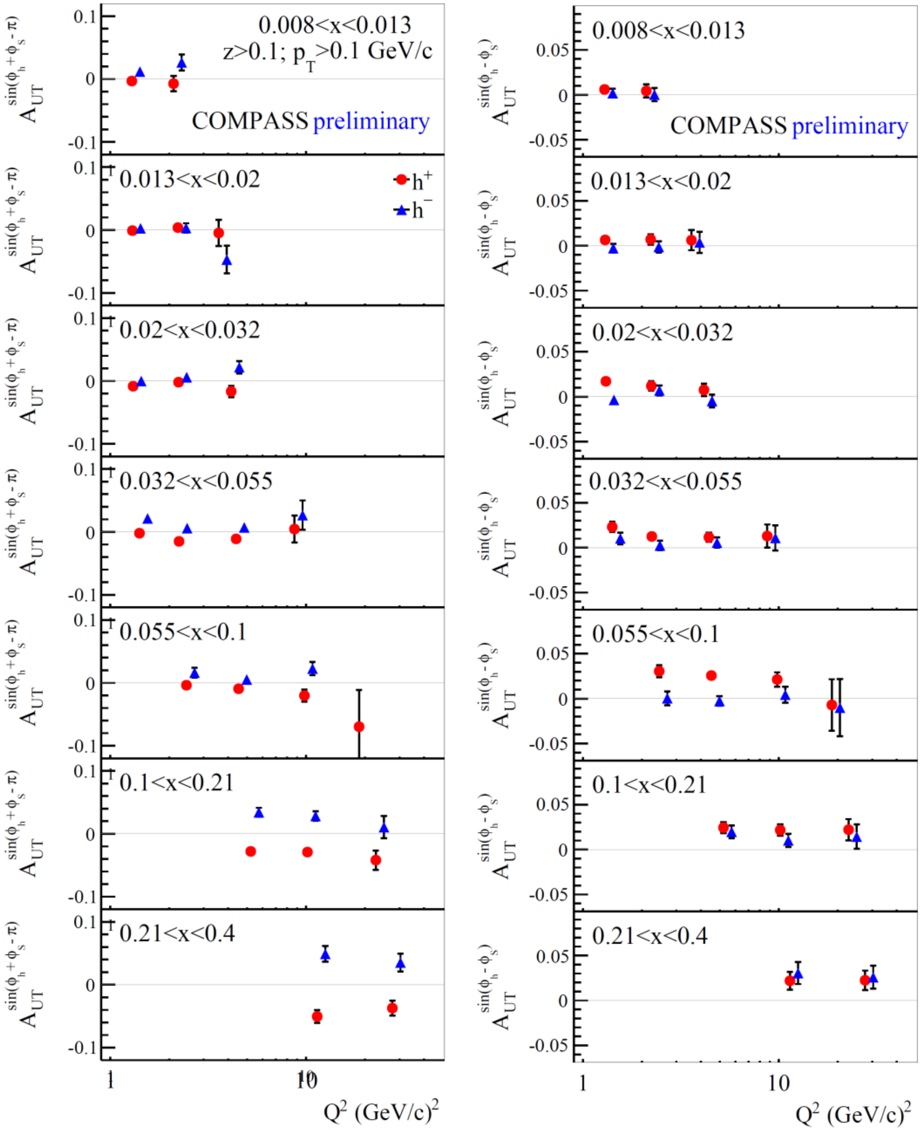
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\,h_1^{q}H_{1q}^{\perp h}\right]$$



3D $x{:}Q^2{:}z$ or $x{:}Q^2{:}p_T$ $x{:}z{:}p_T$

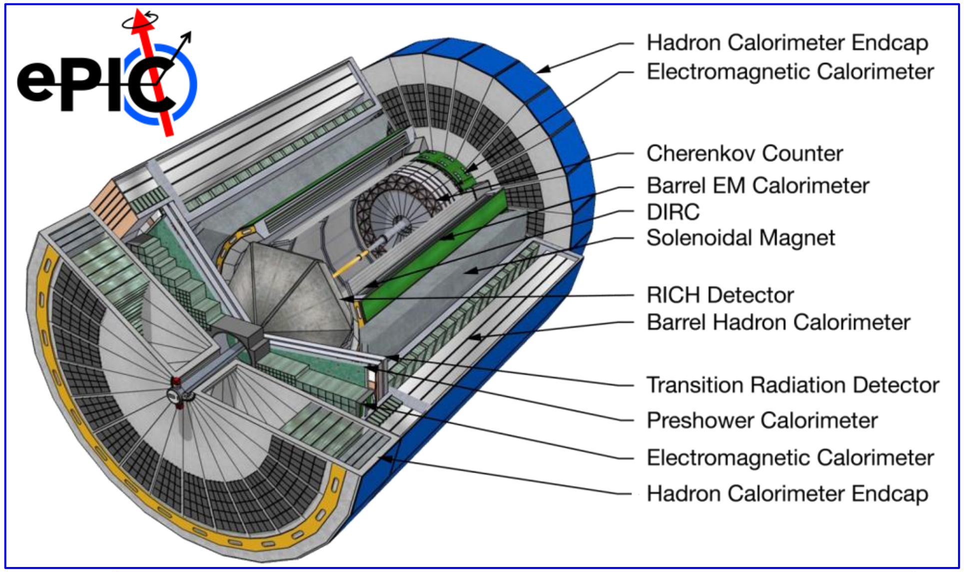
- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

B.Parsamyan (for COMPASS) arXiv:1504.01599 [hep-ex] (SPIN-2014)

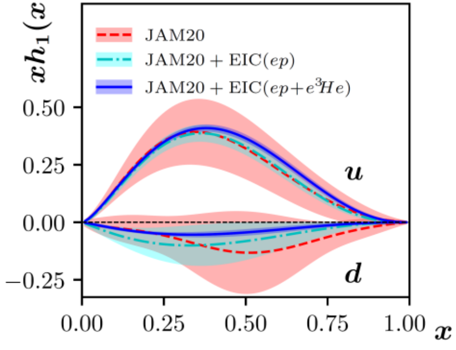


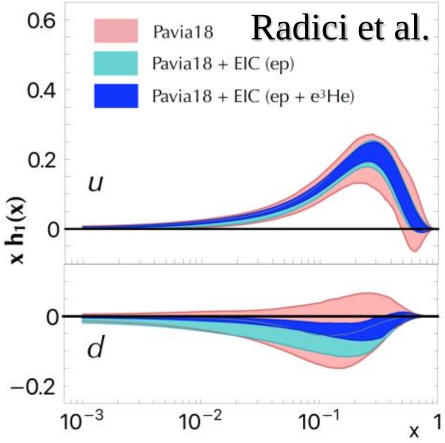
Electron Ion Collider(s): EIC

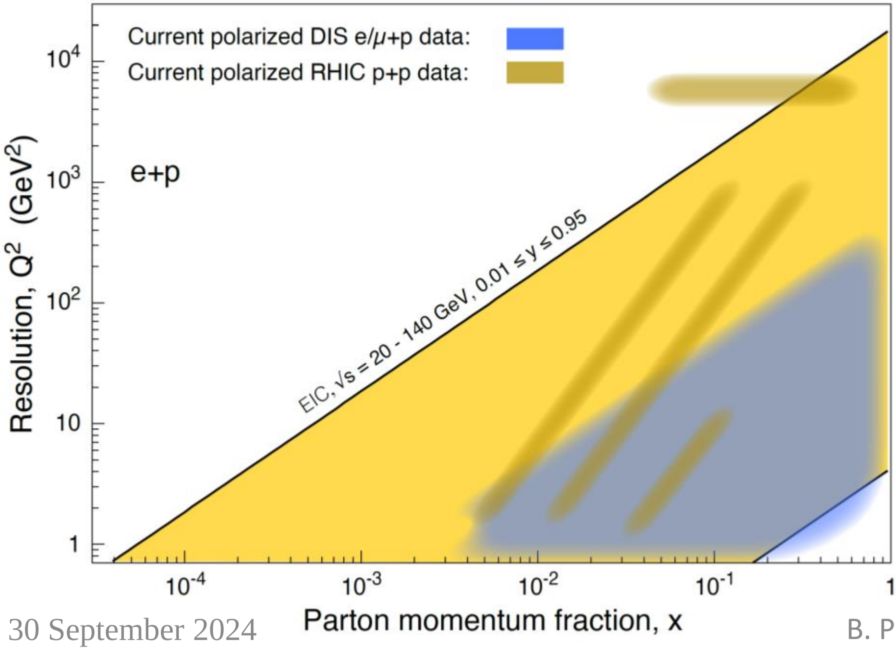
EIC WP, arXiv:1212.1701 [nucl-ex],
EIC YR, arXiv:2103.05419 [physics.ins-det]

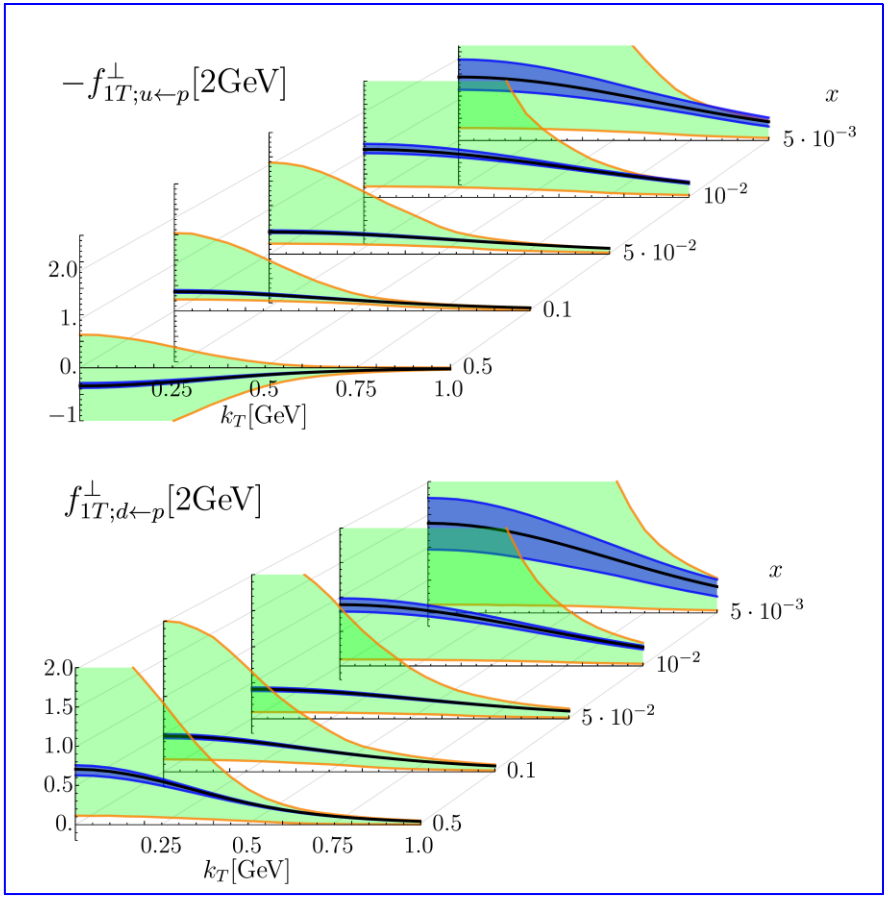


Gamberg et al. (JAM)
PLB 816 (2021) 136255




Radici et al.

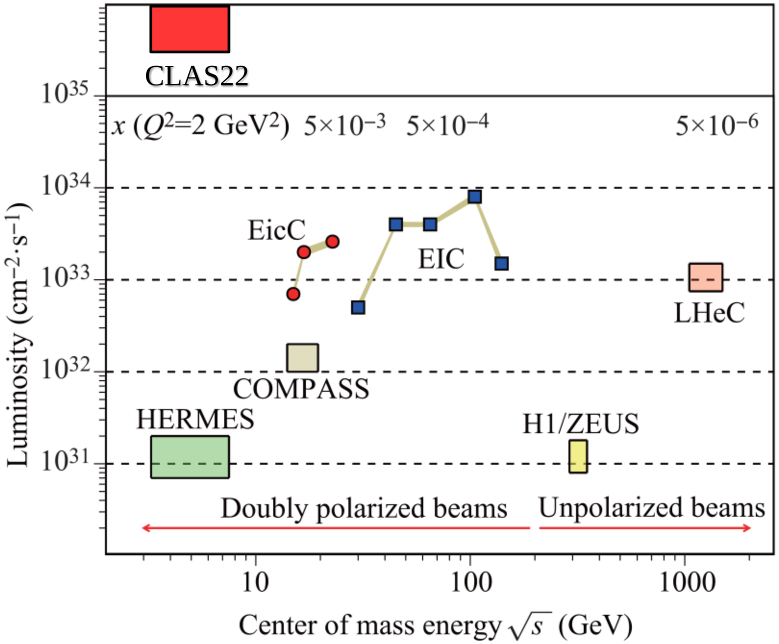


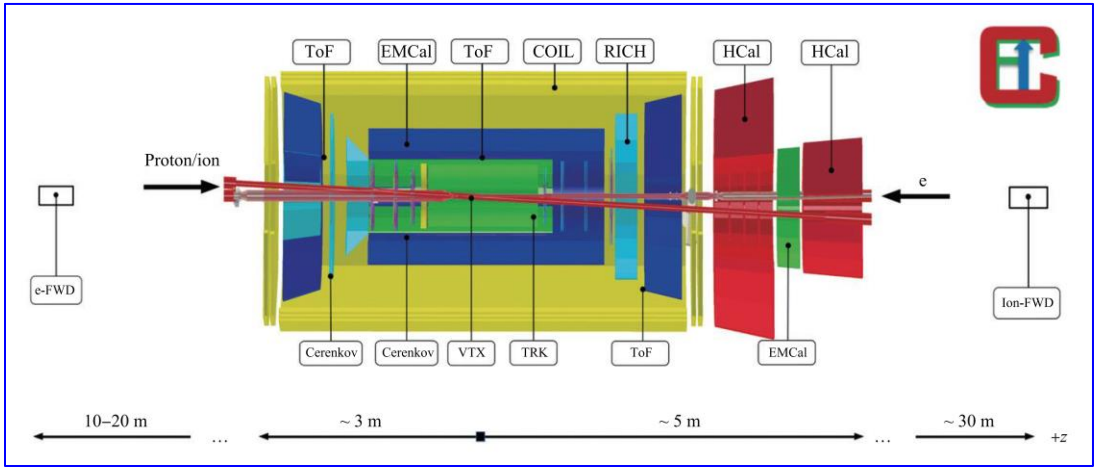


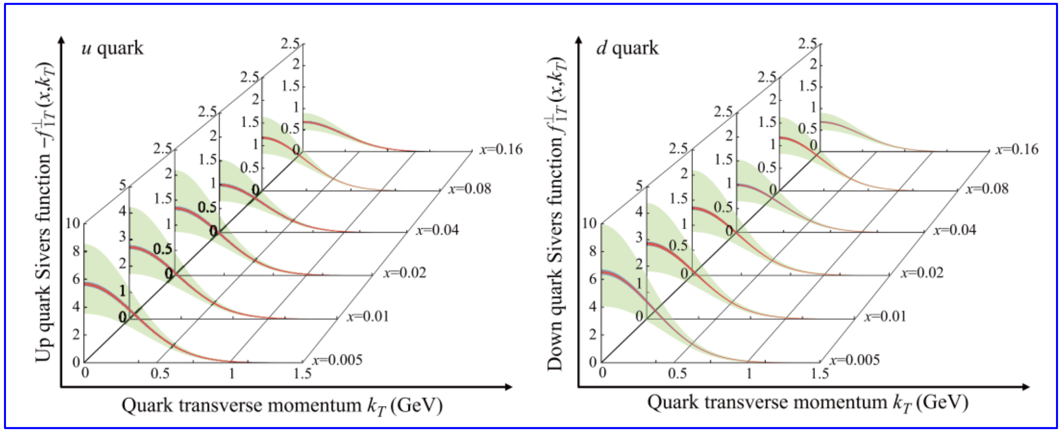
See Elke Aschenauer's talk

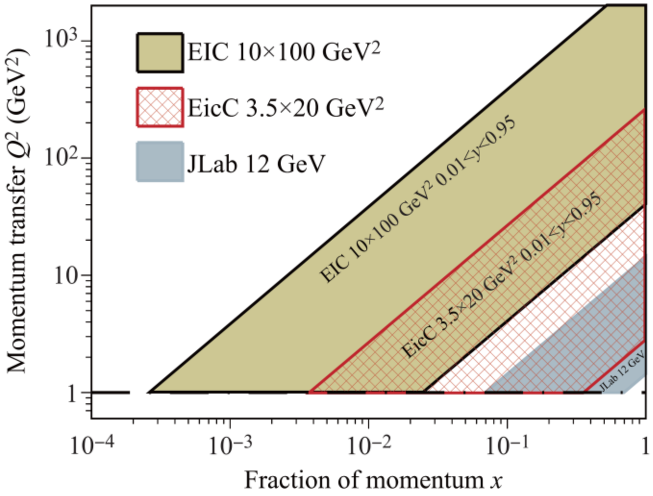
Electron Ion Collider(s): EICc

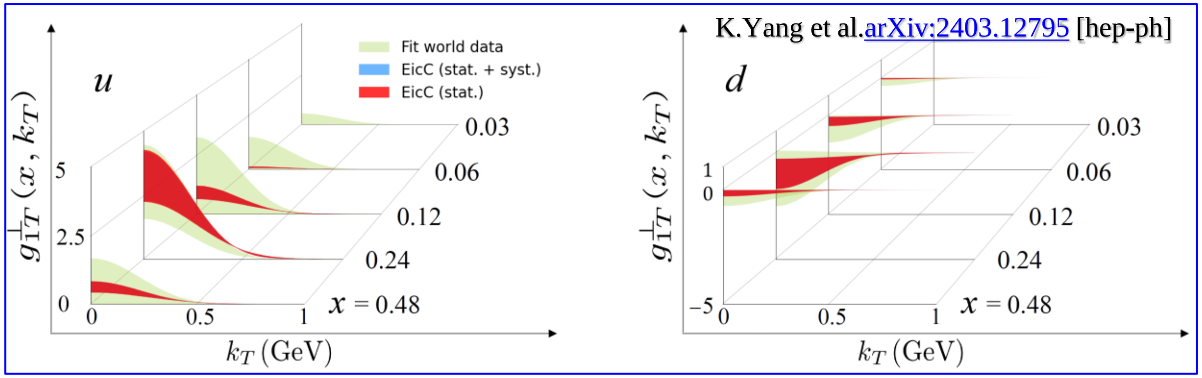
EICc, FP16(6), 64701 (2021), arXiv:2102.09222 [nucl-ex]







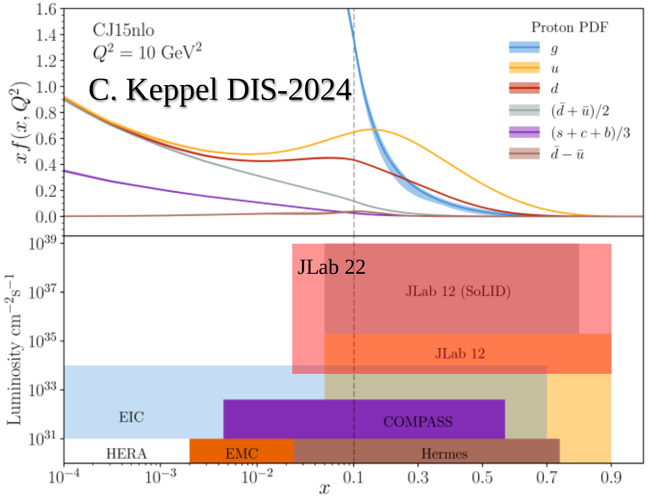




K.Yang et al.arXiv:2403.12795 [hep-ph]

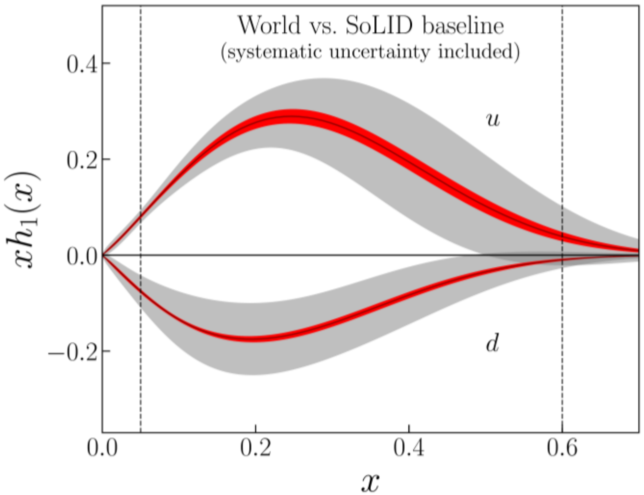
See Yuxiang Zhao's talk

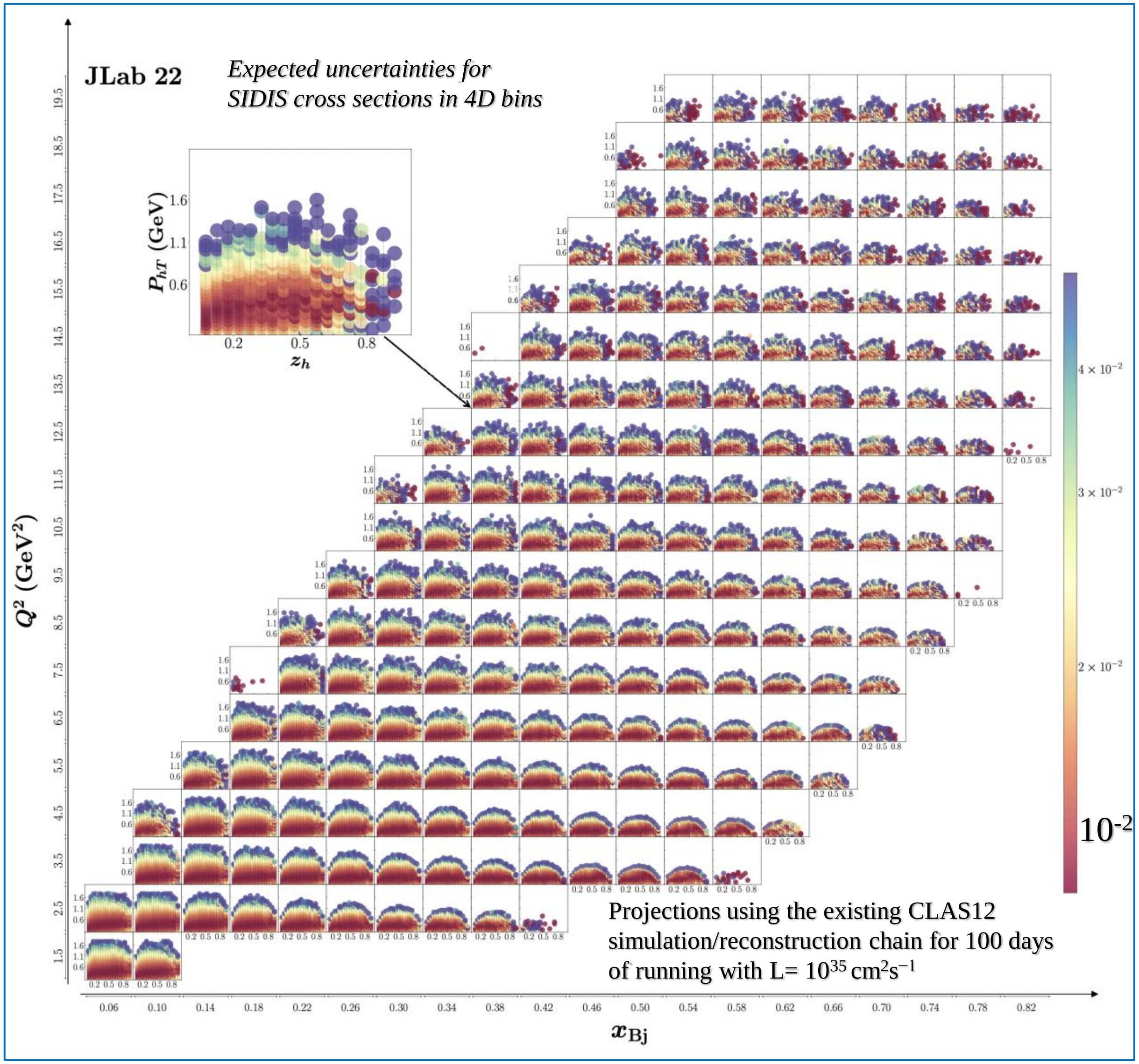
JLab from 12 GeV, SoLID to 22 GeV



C. Keppel DIS-2024

CEBAF at 12 GeV and Future opportunities
arXiv:2112.00060 [nucl-ex]




JLab 22

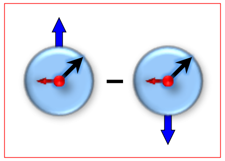
Expected uncertainties for SIDIS cross sections in 4D bins

Projections using the existing CLAS12 simulation/reconstruction chain for 100 days of running with L= 10^{35} cm^{2}s^{-1}

- High luminosity, complementary kinematic coverages, evolution studies, all TMDs, etc.
- Together with EIC/EICc - complete picture!

See Harut Avagyan’s talk

SIDIS TSAs: Kotzinian-Mulders asymmetry



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

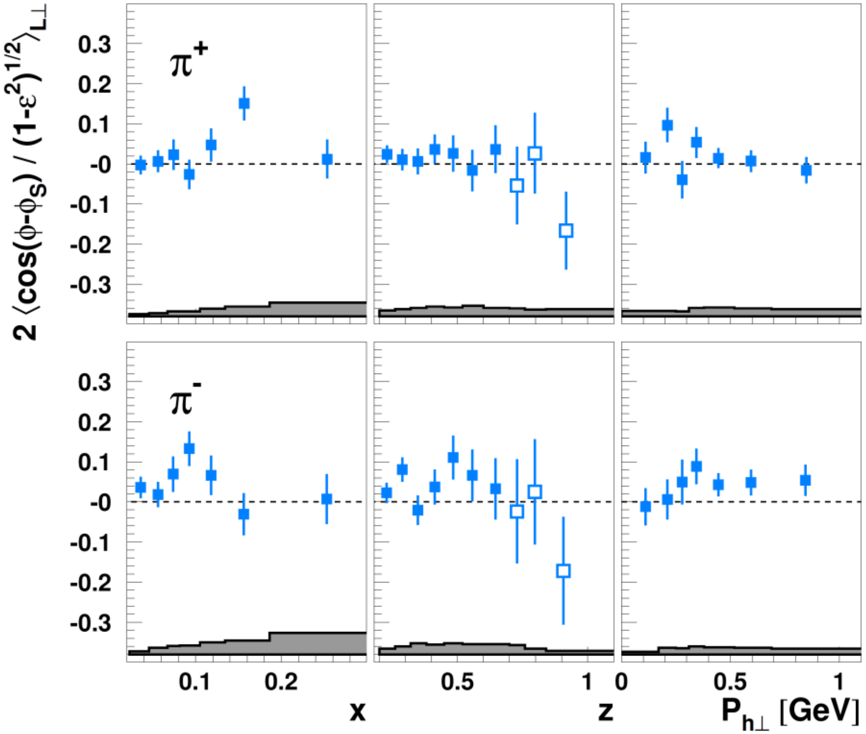
$$\boxed{F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\, g_{1T}^{q} D_{1q}^{h}\right]}$$

COMPASS/HERMES/CLAS6 results

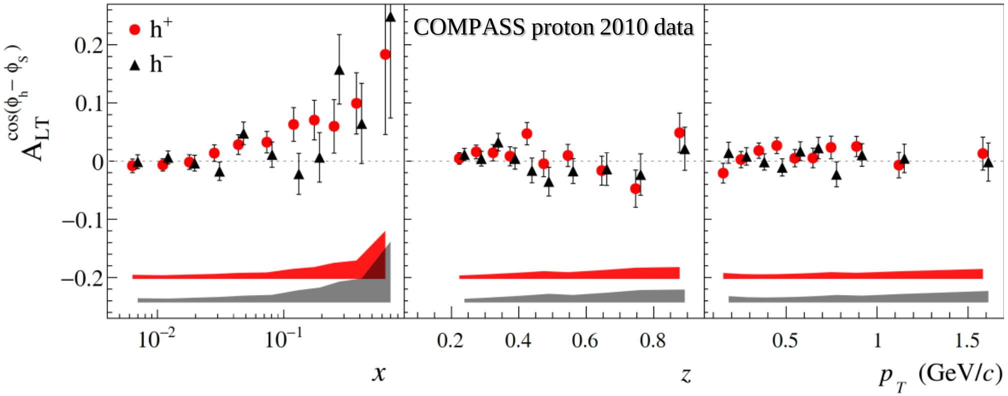
$A_{LT}^{\cos(\phi_h-\phi_S)}$

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

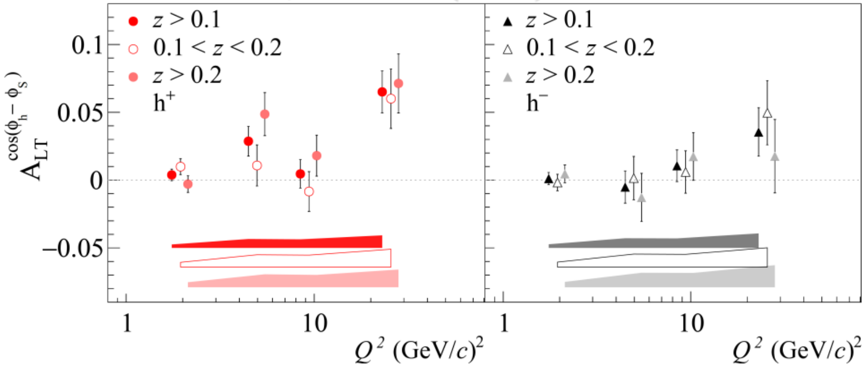
HERMES, JHEP 12 (2020) 010



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

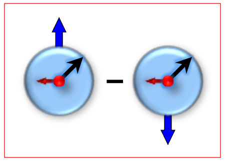


COMPASS, PBL 770 (2017) 138



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

SIDIS TSAs: Kotzinian-Mulders asymmetry



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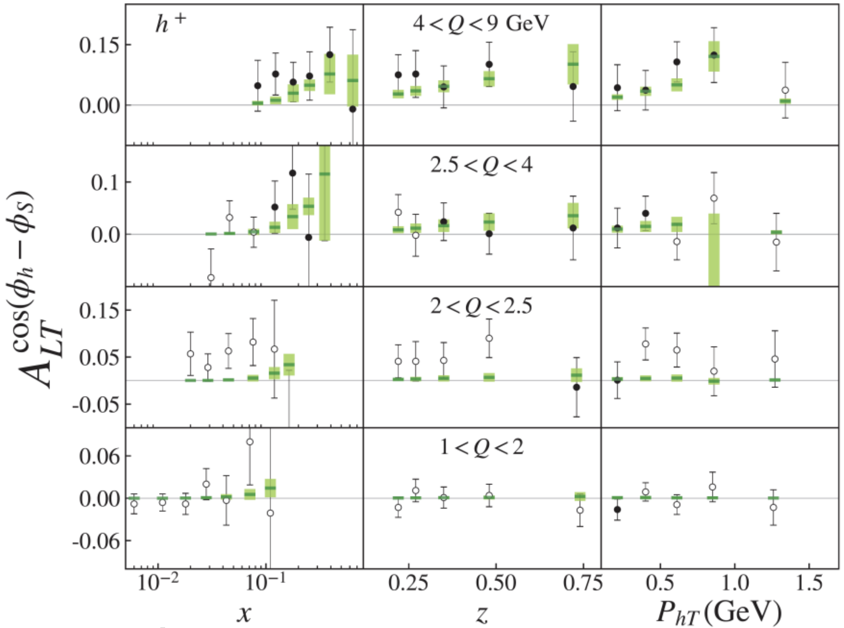
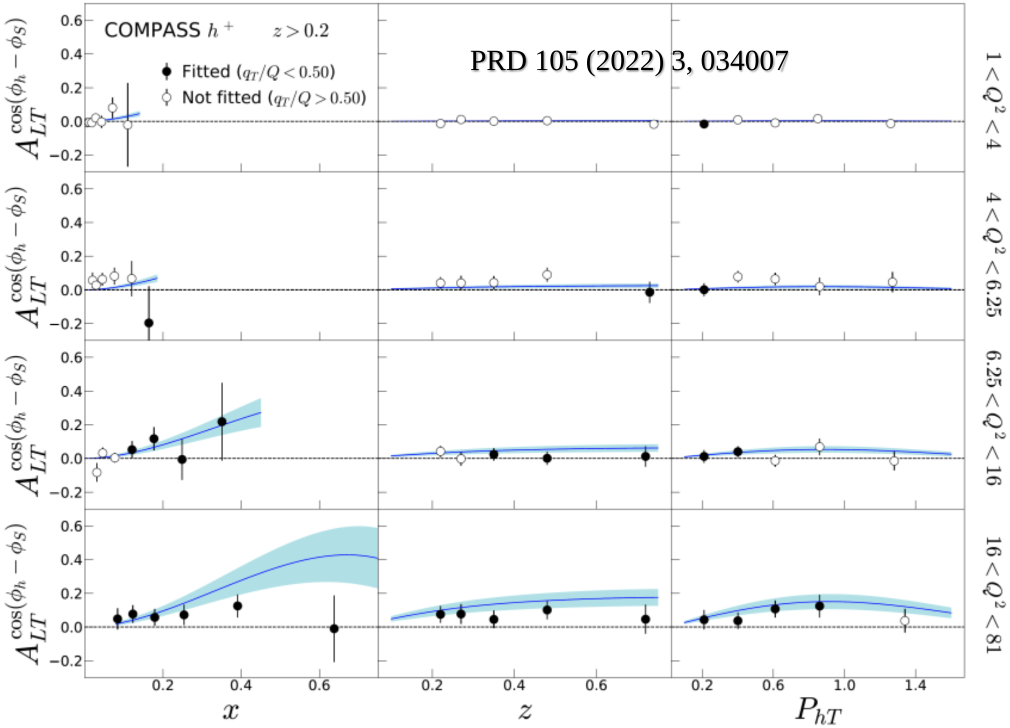
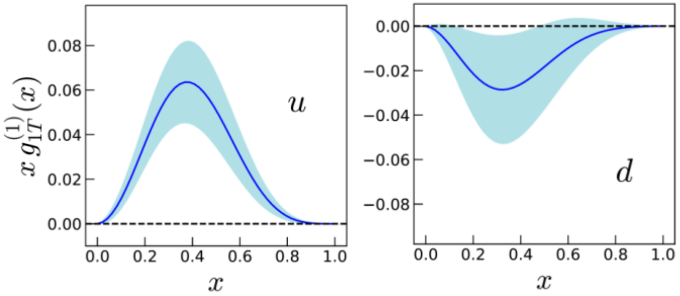


First global QCD analysis of the g_{1T} TMD PDF using SIDIS data



PRD 105 (2022) 3, 034007



See also, PRD 107, (2023) 034016 – global fit by:
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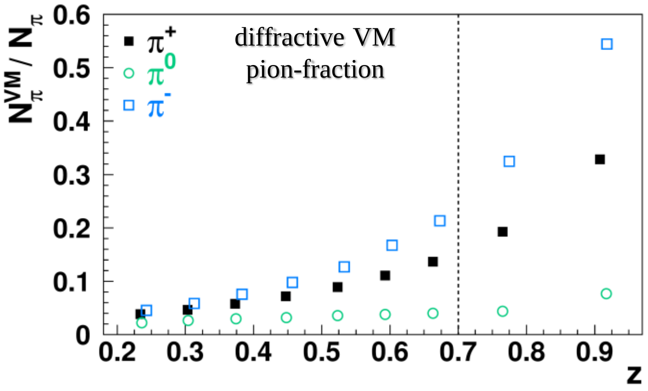
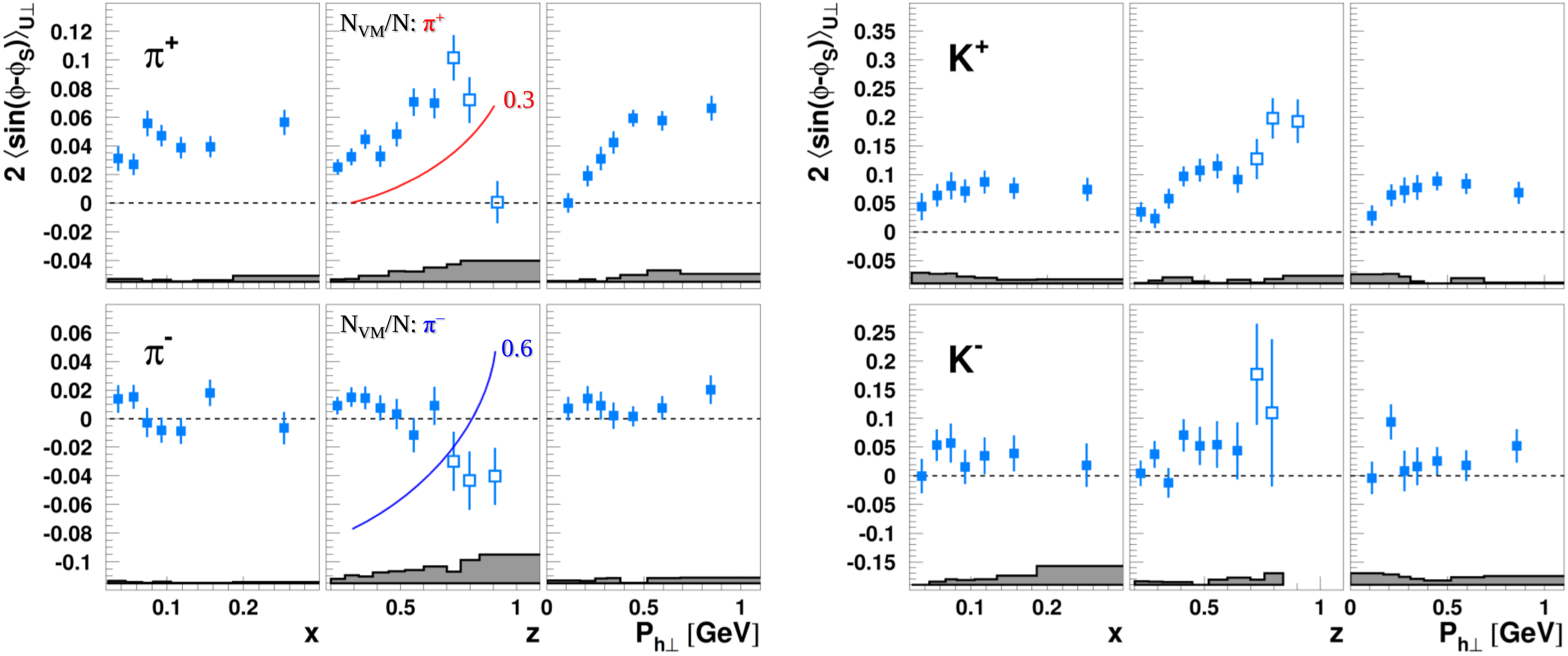
HERMES: Sivers effect and diffractive VMs

- The asymmetry drops at large z for pion
    - Not the case for kaons
- Can it be caused by exclusive diffractive VMs?
- The contamination indeed grows with *z* for pions
    - At the level of 10% for kaons



HERMES: JHEP 12(2020)010 [hep-ex/2007.07755](https://arxiv.org/abs/2007.07755)



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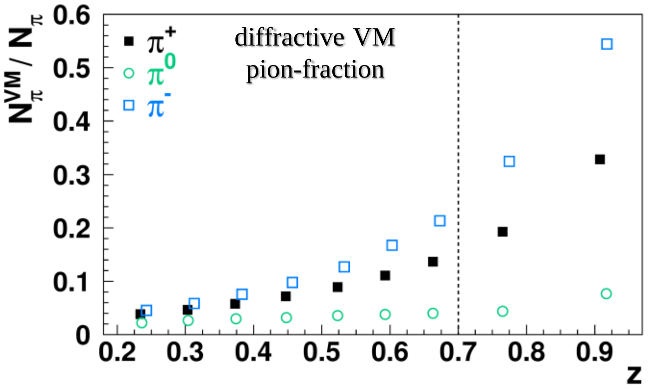
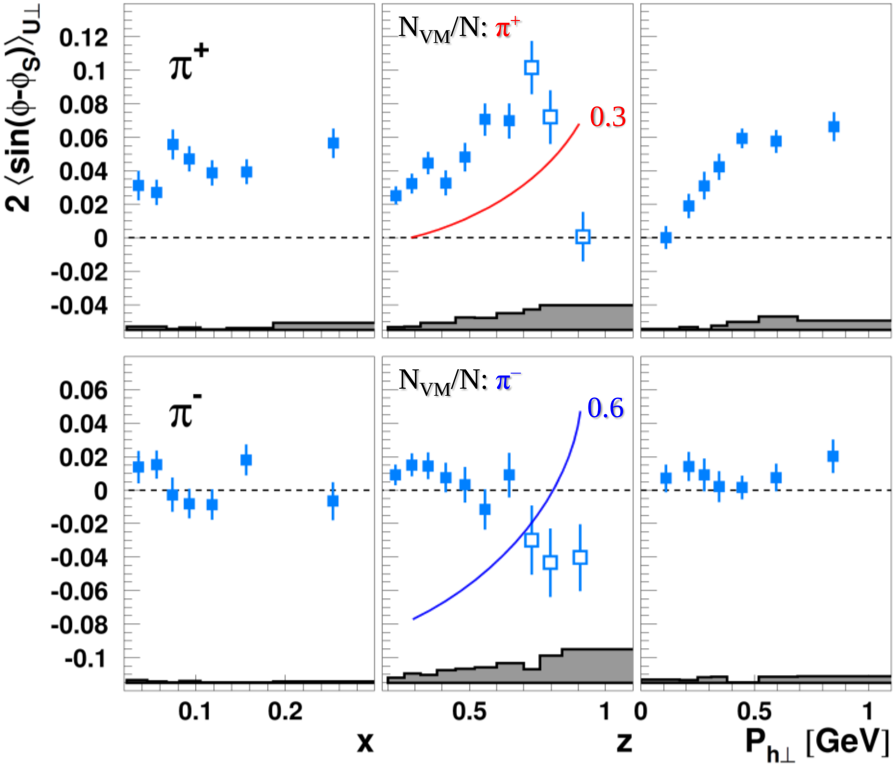
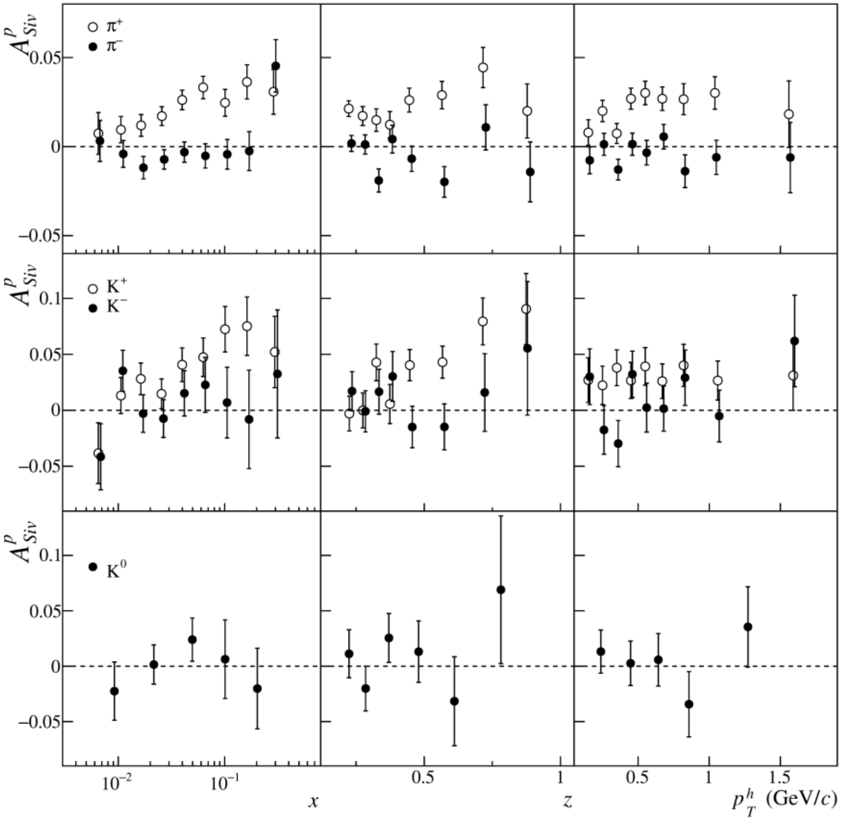


HERMES: JHEP 12(2020)010 hep-ex/2007.07755



COMPASS: PLB 744 (2015) 250



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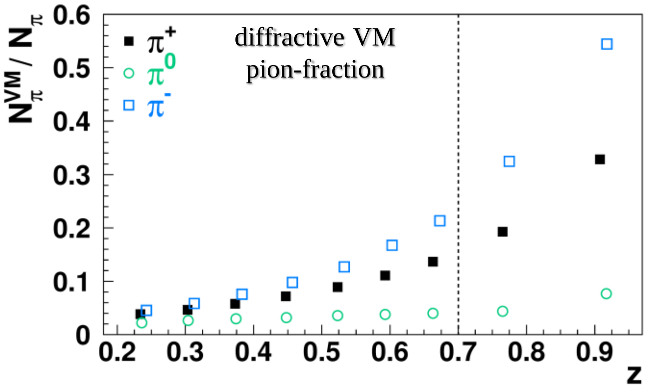
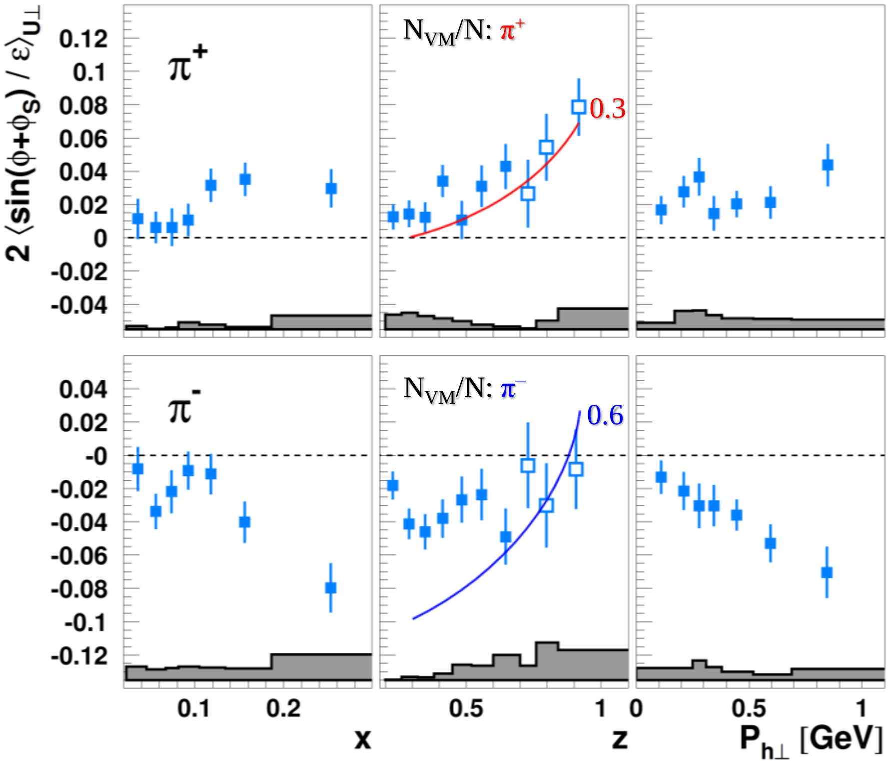
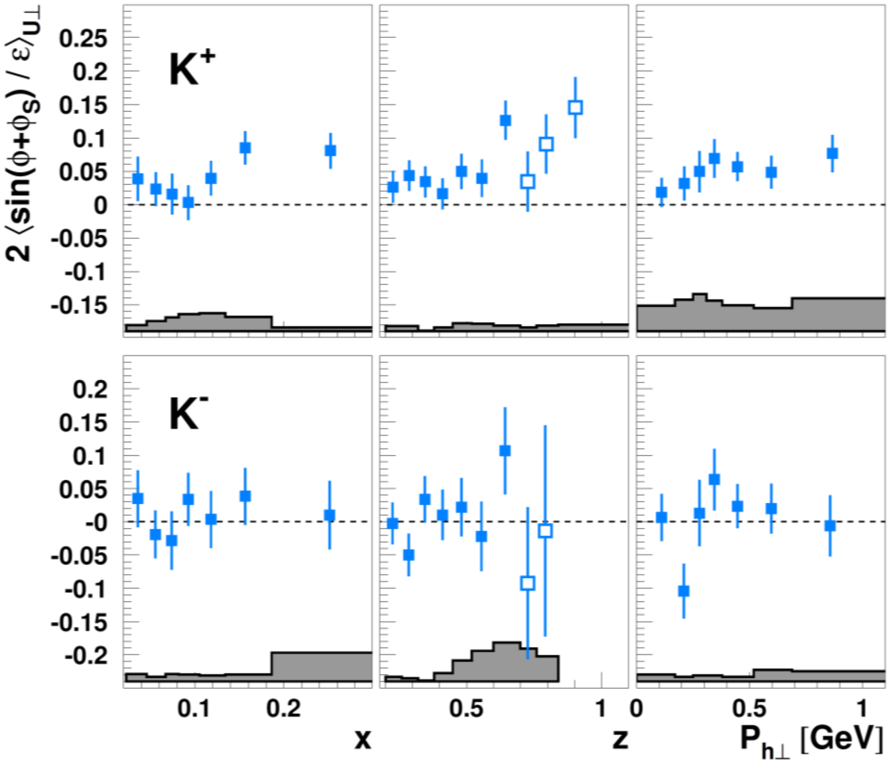
- Not clear with Collins







HERMES: Sivers effect and diffractive VMs

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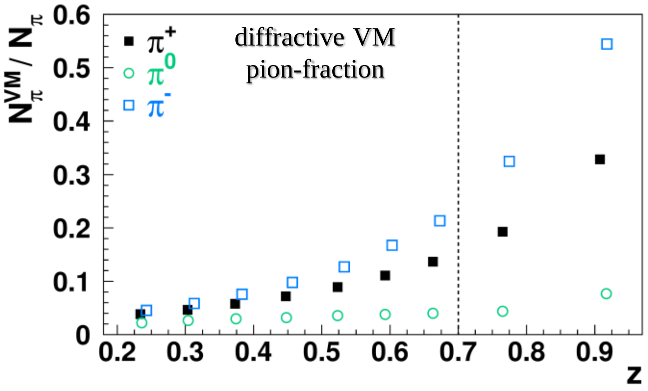
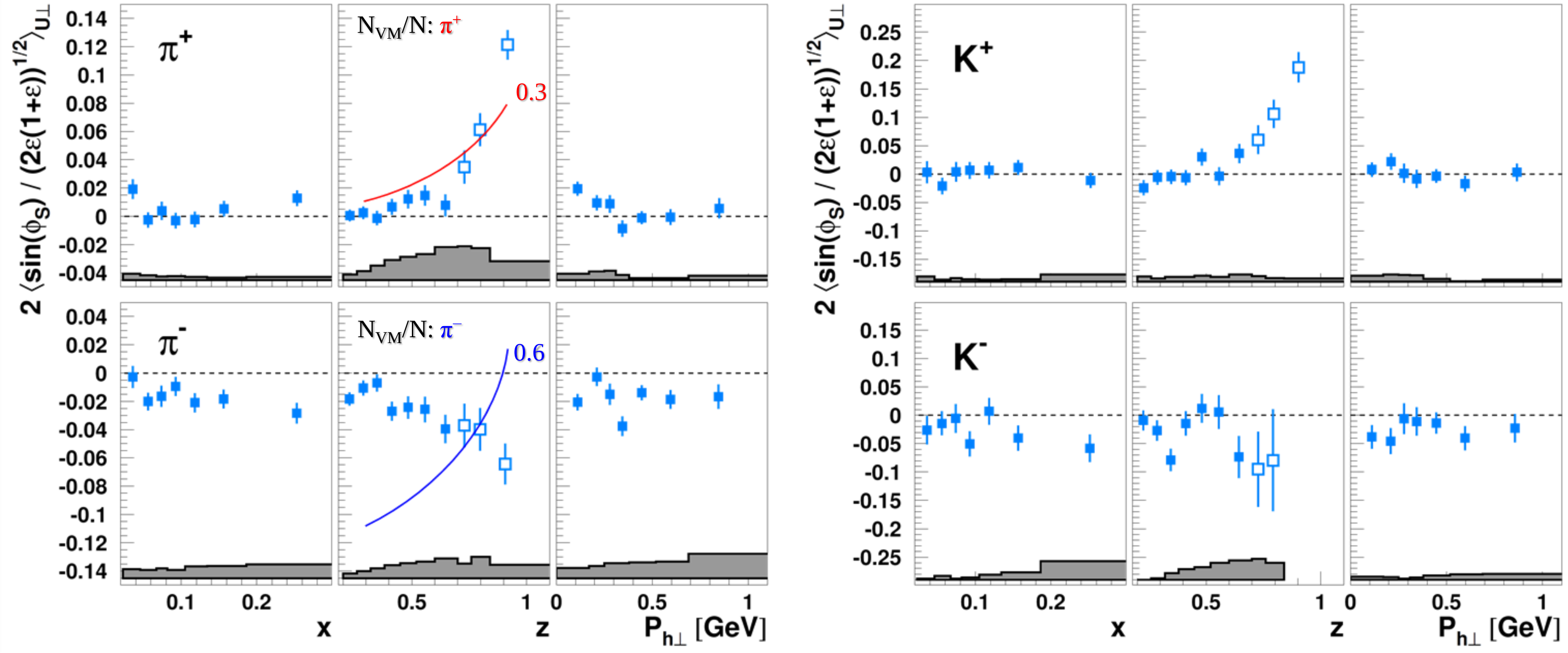
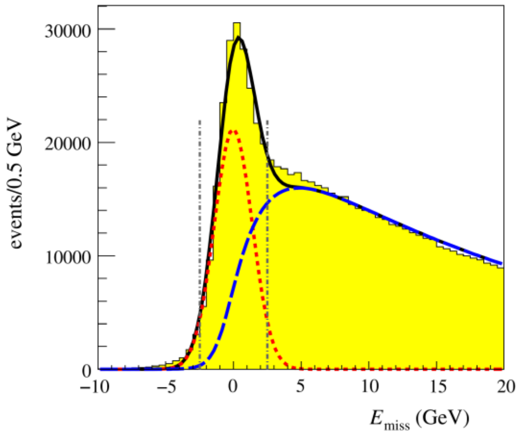
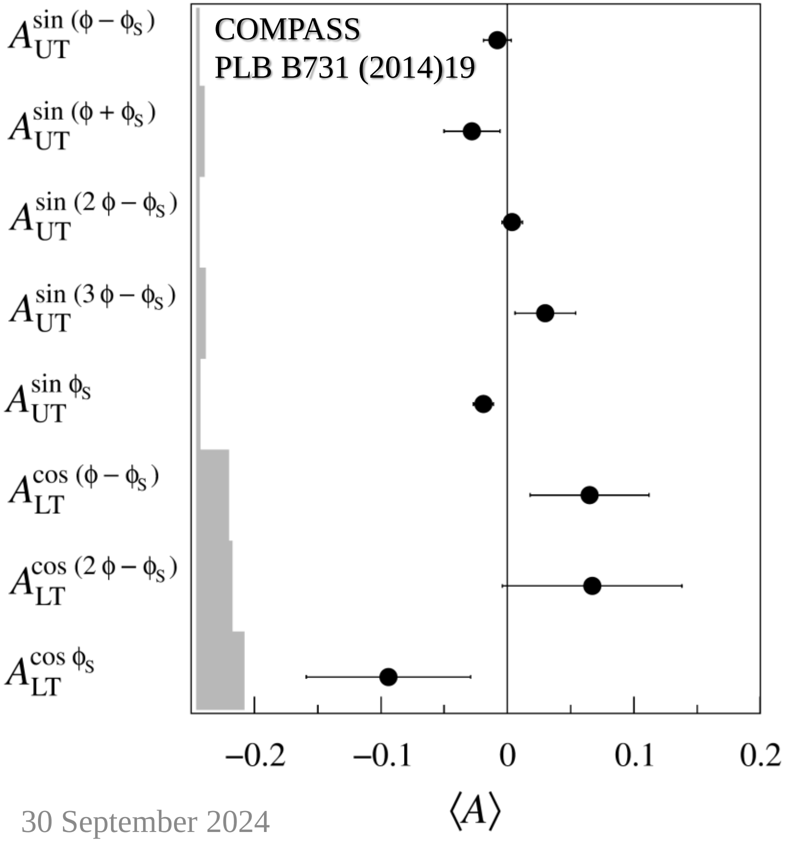




COMPASS: Exclusive ρ^0 TSAs

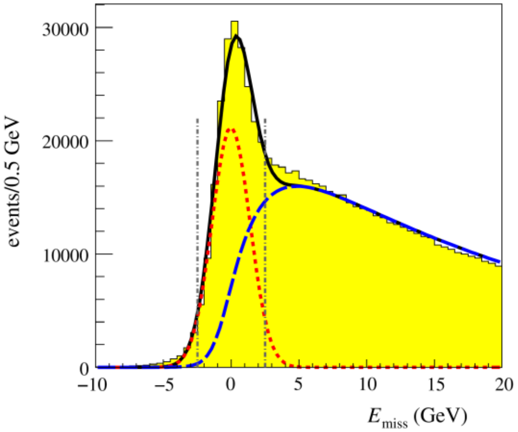


exclusive



- Both Collins and Sivers TSAs are small an compatible with zero
  - $\sin(\varphi_S)$ is small, but possibly non zero
  - Can VM pion asymmetries still be large?

COMPASS: Exclusive ρ^0 TSAs



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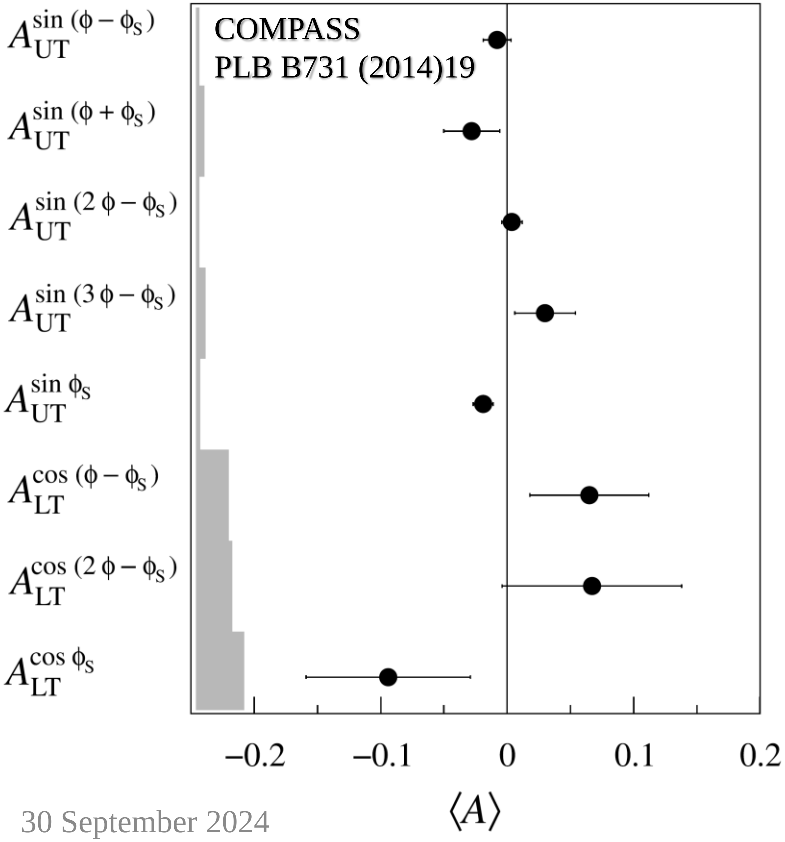
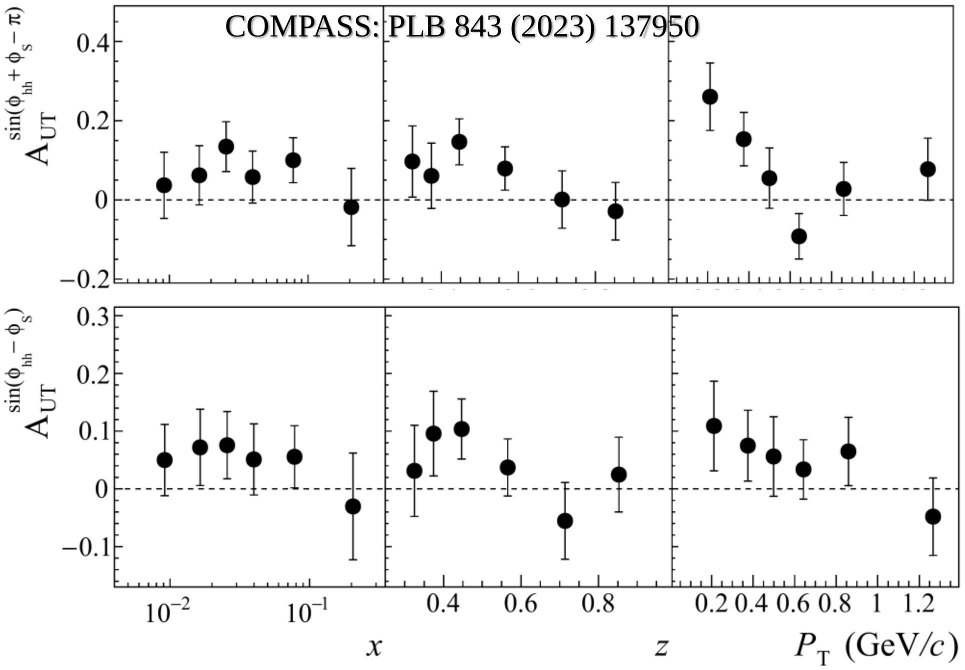
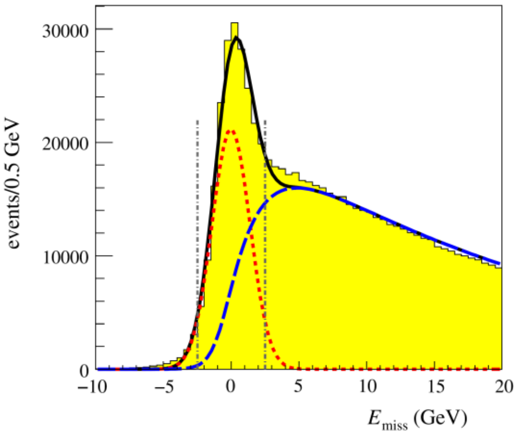


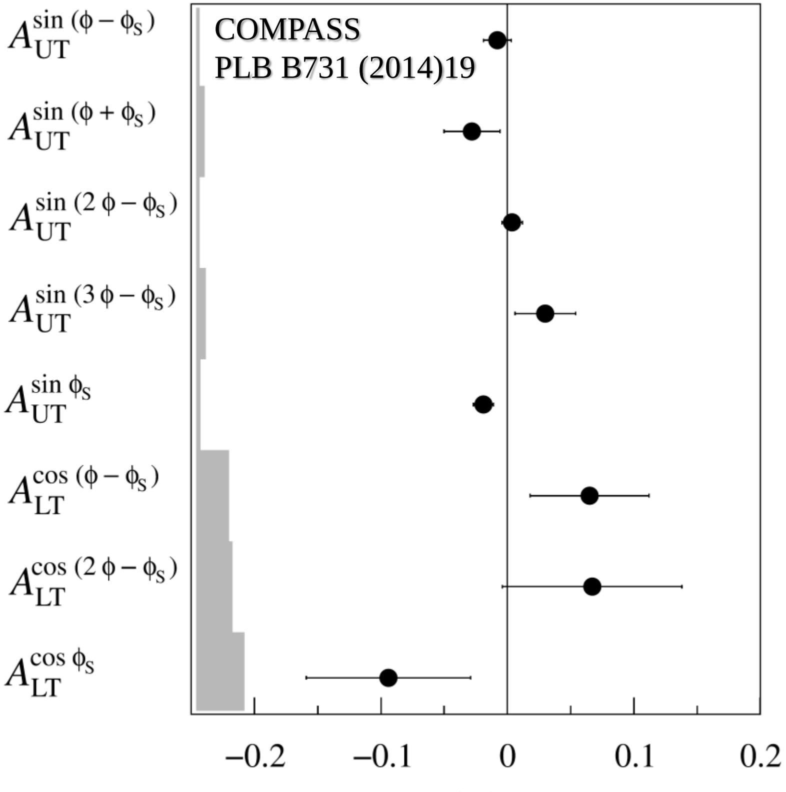
- Both Collins and Sivers TSAs are small an compatible with zero
  - $\sin(\varphi_S)$ is small, but possibly non zero
  - Can VM pion asymmetries still be large?
- COMPASS has checked also the inclusive ρ^0 Collins and Sivers asymmetries
  - Both tend to be positive
  - The fraction of inclusive ρ^0 in the selected dihadron sample is below 20%
  - Further checks needed, StringSpinner?

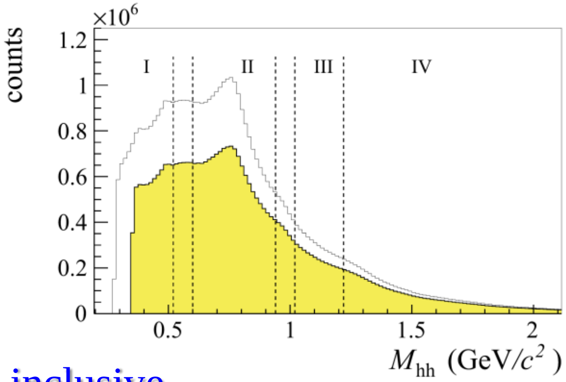


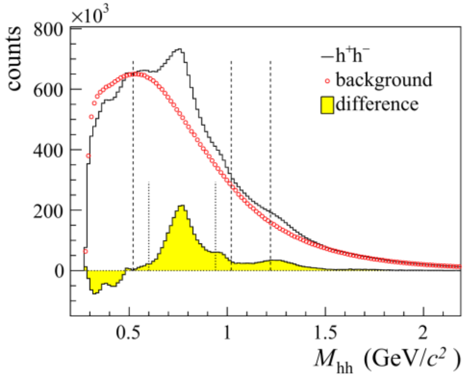
COMPASS: Exclusive and Inclusive ρ^0 TSAs



exclusive







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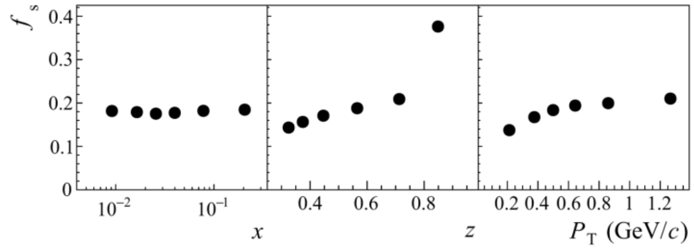
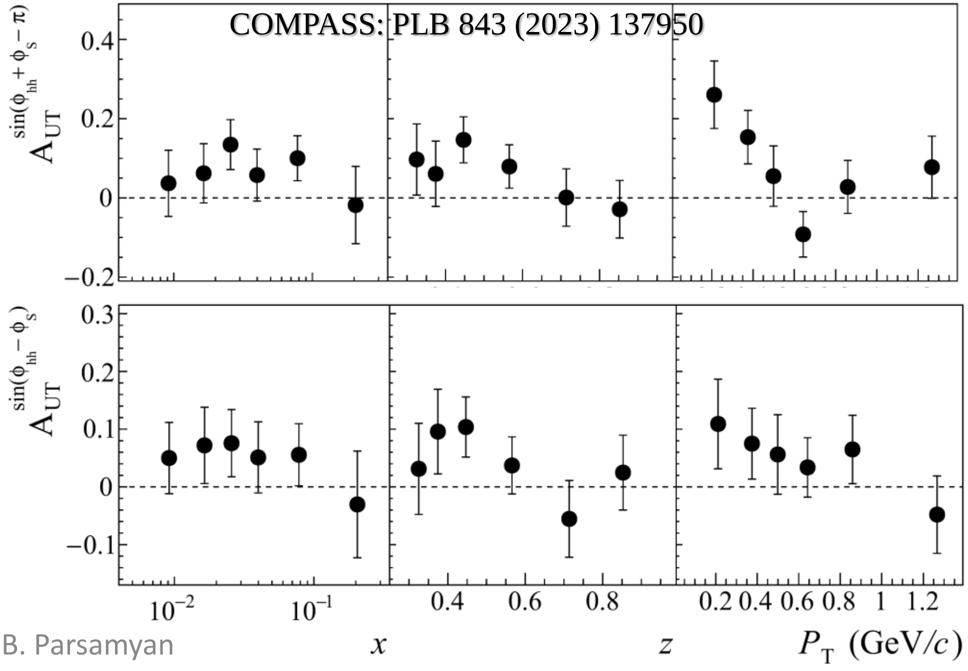


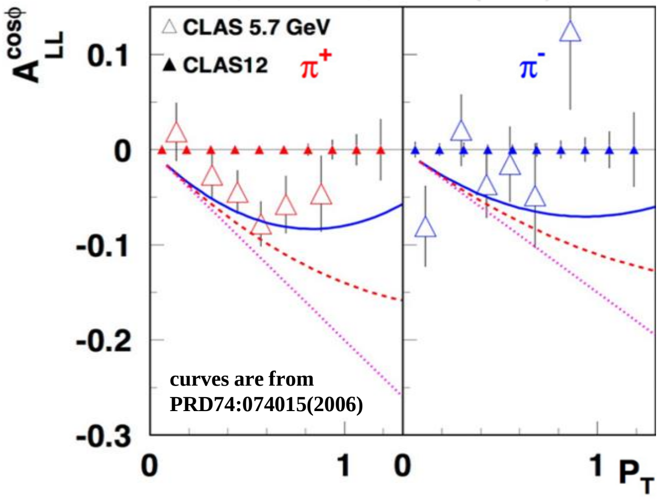


SIDIS TSAs: subleading twist effects

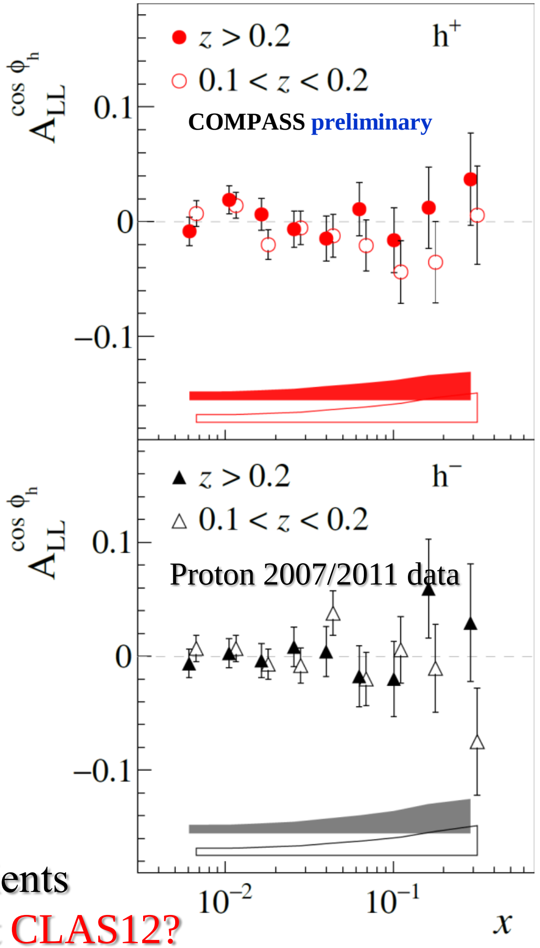
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\; S_L\lambda\sqrt{2\varepsilon\left(1-\varepsilon\right)}A_{LL}^{\cos\phi_h}\cos\phi_h+\ldots\right\}$$

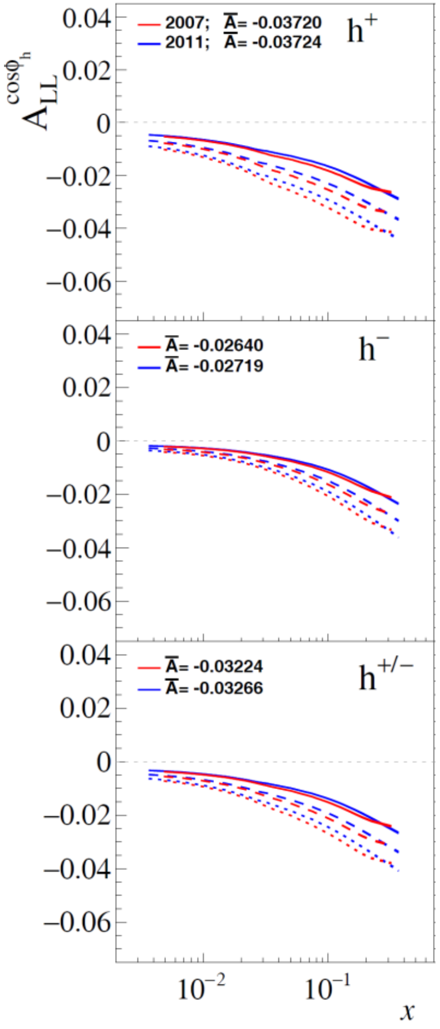
$$\boxed{\begin{aligned}F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathbb{C}\Bigg\{&-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xe_L^q H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{D}_q^{\perp h}}{z}\right)\\ &+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xg_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{E}_q^h}{z}\right)\Bigg\}\end{aligned}}$$

CLAS, PRL 105,262002(2010)



B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]





- Q-suppression, various different “twist” ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

SIDIS TSAs: subleading twist effects

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

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

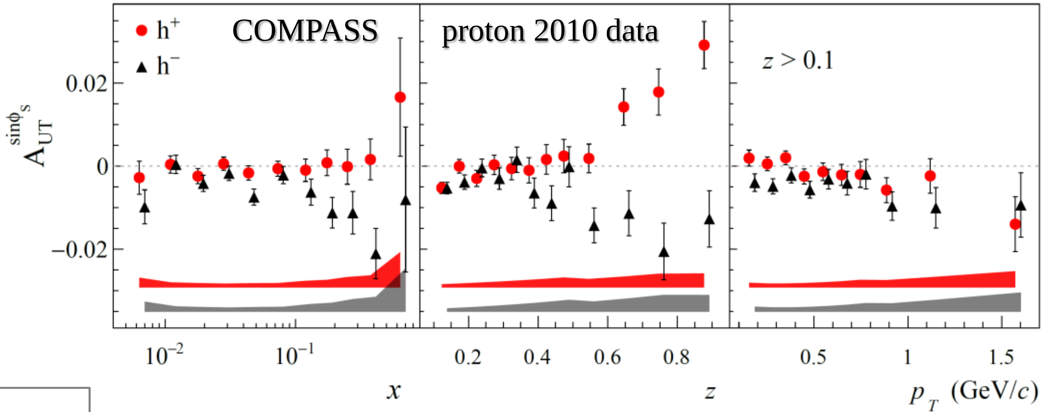
COMPASS/HERMES results

$A_{UT}^{\sin\phi_S}$

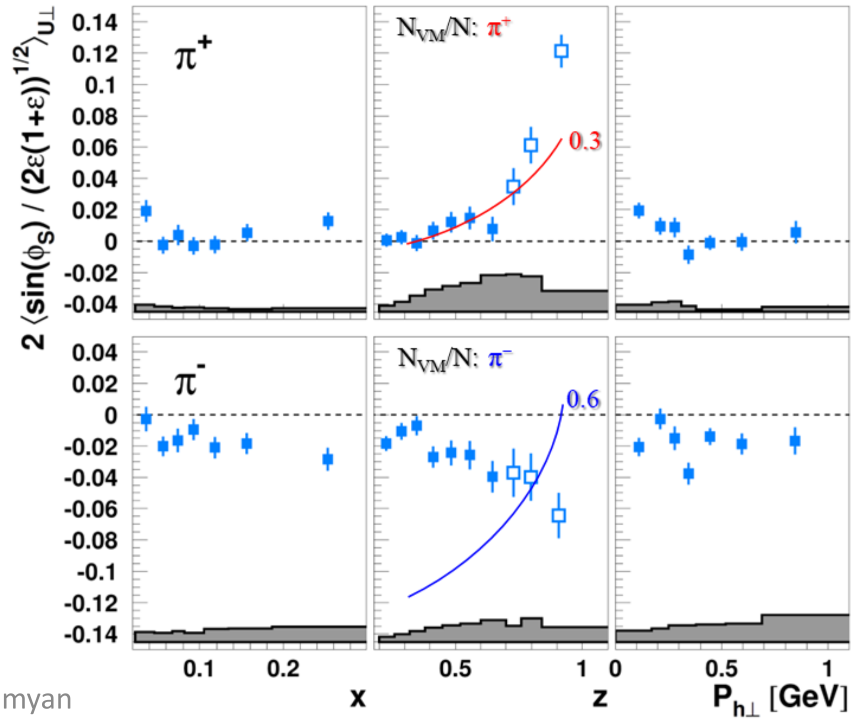
- Q-suppression
- various “twist-2/3” ingredients
- non-zero signal for h$^{\pm}$ at large z?
- Survives integration of hadron p$_T$
    - gives access to transversity PDF (without involving convolution over k$_T$)

See Daniel Pitonyak’s talk

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



HERMES, JHEP 12 (2020) 010



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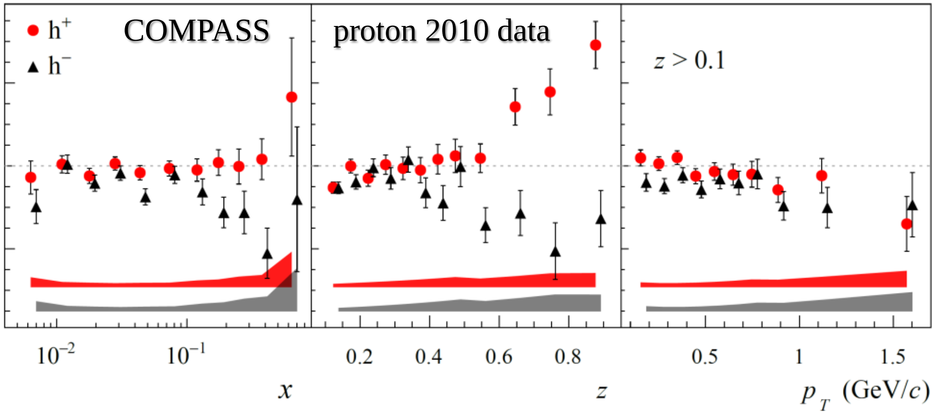
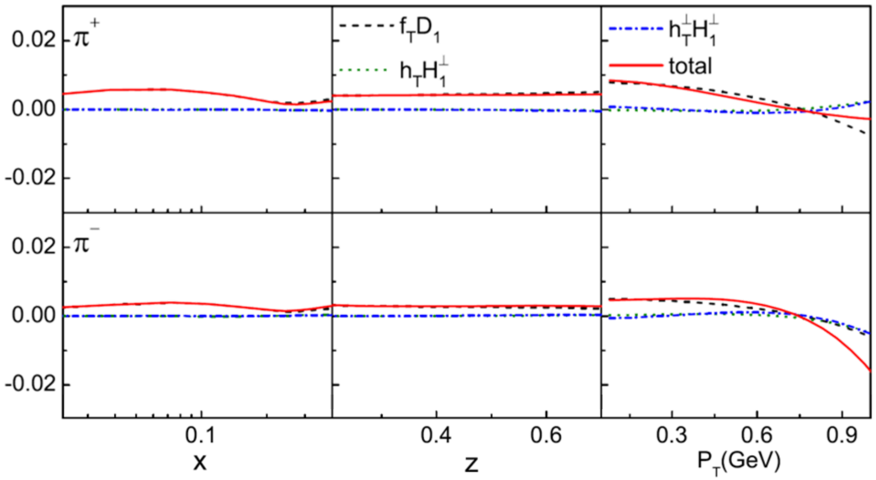
COMPASS/HERMES results $A_{UT}^{\sin\phi_S}$

- Q-suppression
- various “twist-2/3” ingredients
- non-zero signal for h± at large z?

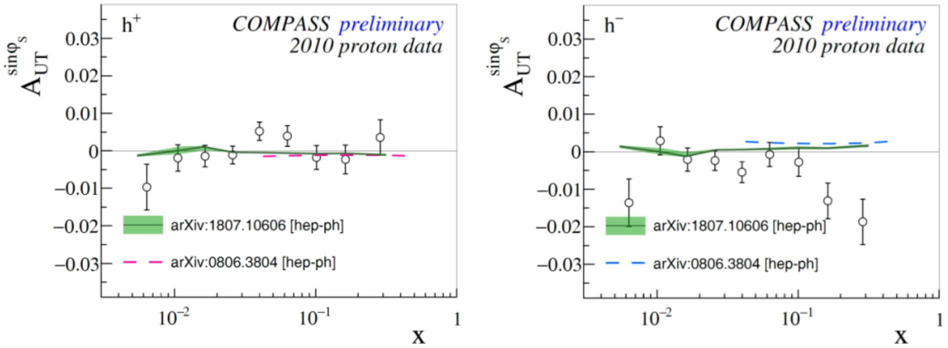
COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



W. Mao, Z. Lu and B.Q. Ma Phys.Rev. D 90 (2014) 014048



S. Bastami et al. JHEP 1906 (2019) 007

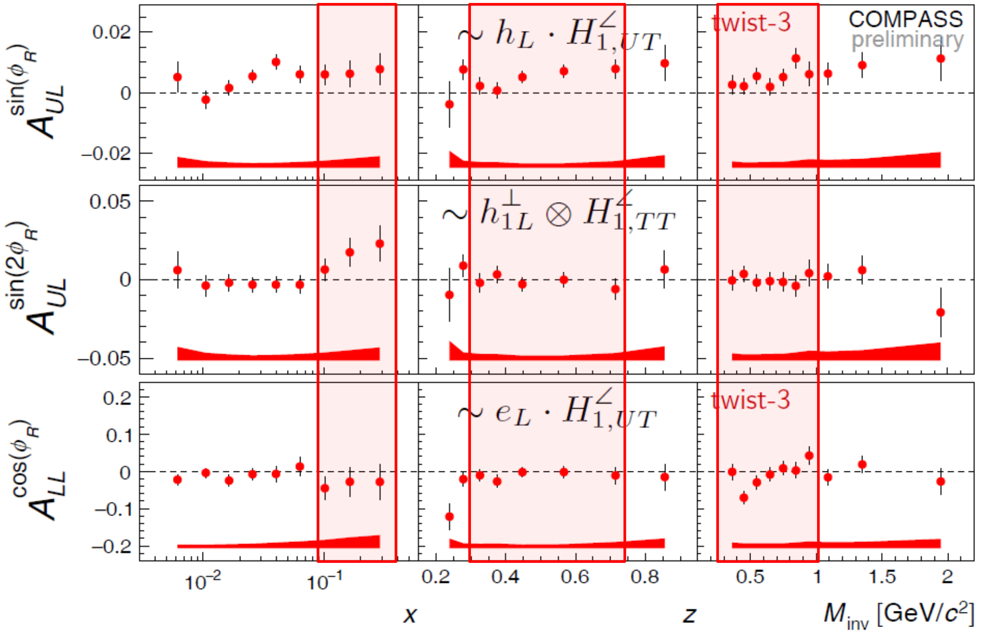


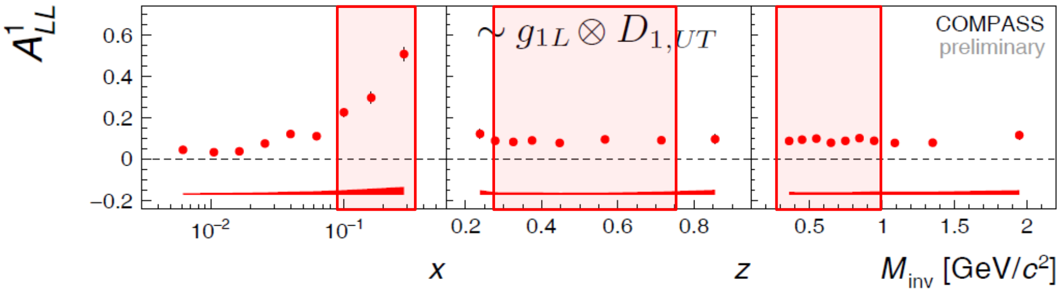
Moving towards Open Data and Data Preservation

- There is an increasing interest in making experimental data Open
- Becoming more relevant for CERN
- Important for CERN to be play a leading role in Open Science
    - Recent Open Science policy released by CERN
- The latest European Strategy report encouraged the development of internal policies on Open Data and Data preservation
- The policy has been broken down into the 4 levels of data as defined in the
- DHEP study on data preservation:
    - Level 1 – Scientific publications, and associated additional data
    - Level 2 – Data useful for Education and Outreach
    - Level 3 – Reconstruction level data useful for general physics analysis
    - Level 4 – RAW data
- All large-LHC experiments already release data for L1 and L2 in broadly similar ways
    - L4 is not practically useful
    - The discussion focused on the policy for L3 data
- Any rules relating to publicly releasing L3 data need to be approved by each experiment’s Collaboration Board
- General effort to find a good balance between:
    - Making data openly available
    - Preserving the data
    - Protecting the collaborations

Selected results for di-hadron LSAs

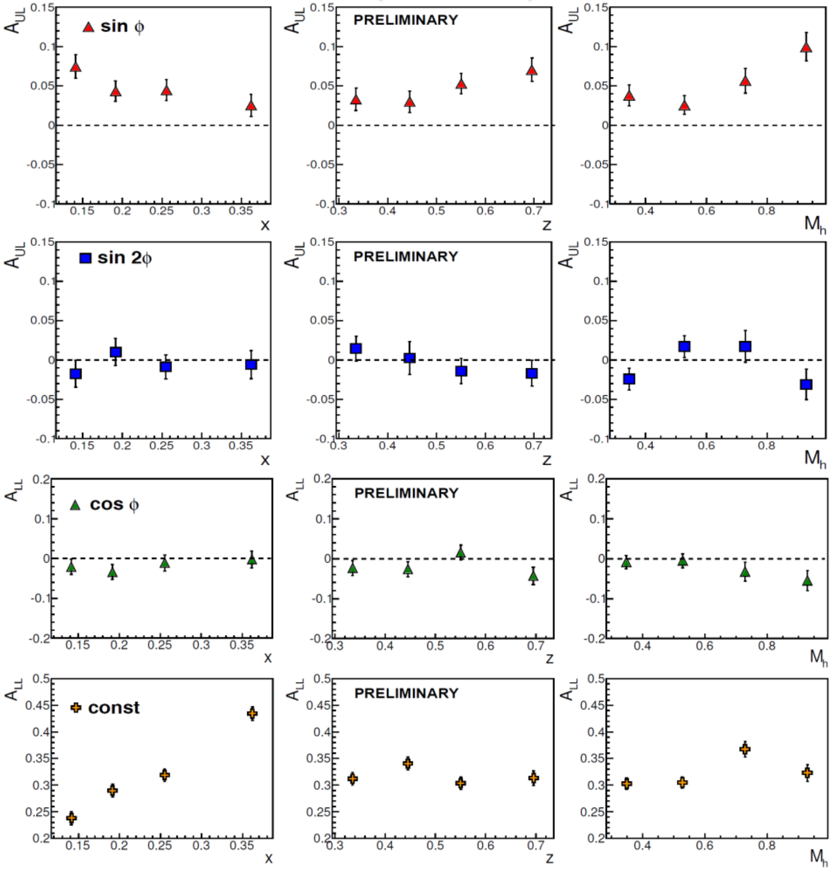
COMPASS (NH$_3$) 2007+2011 data: preliminary





CLAS 6 GeV (NH$_3$)

S. A. Pereira: PoS (DIS 2014) 231

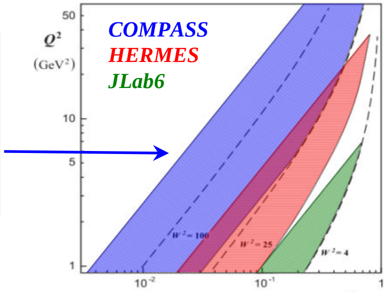


$Q^2 > 1\,(\mathrm{GeV}/c)^2$

$0.0025 < x < 0.7$

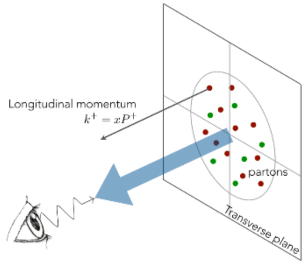
$0.1 < y < 0.9$

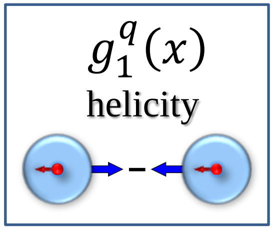
$W > 5\,\mathrm{GeV}/c^2$



- 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 $A_{UL}^{sin2\phi_R}$ at large x?

Nucleon spin structure: helicity $g_{1,d(p)}^{q}(x)$



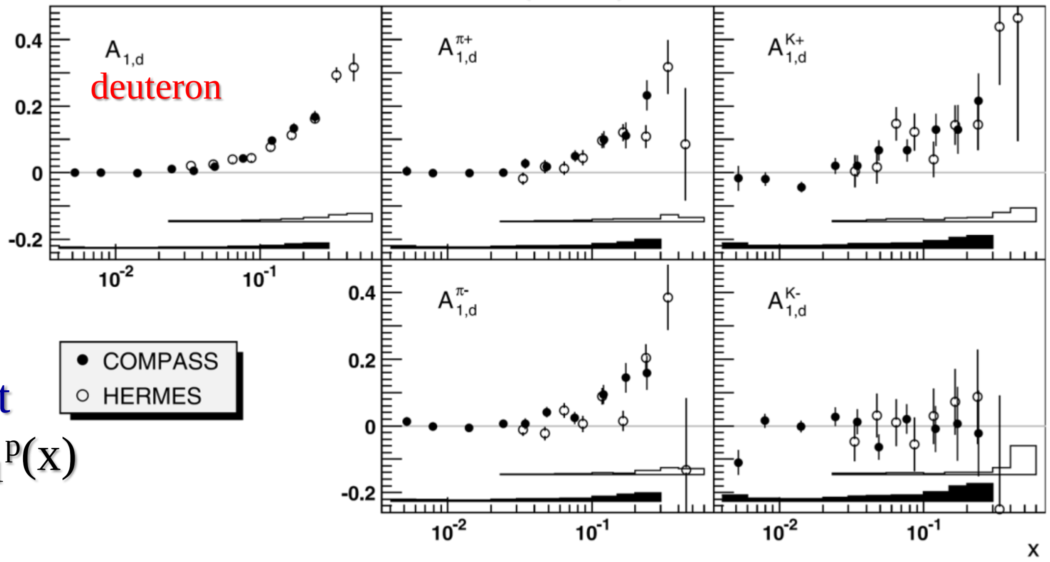


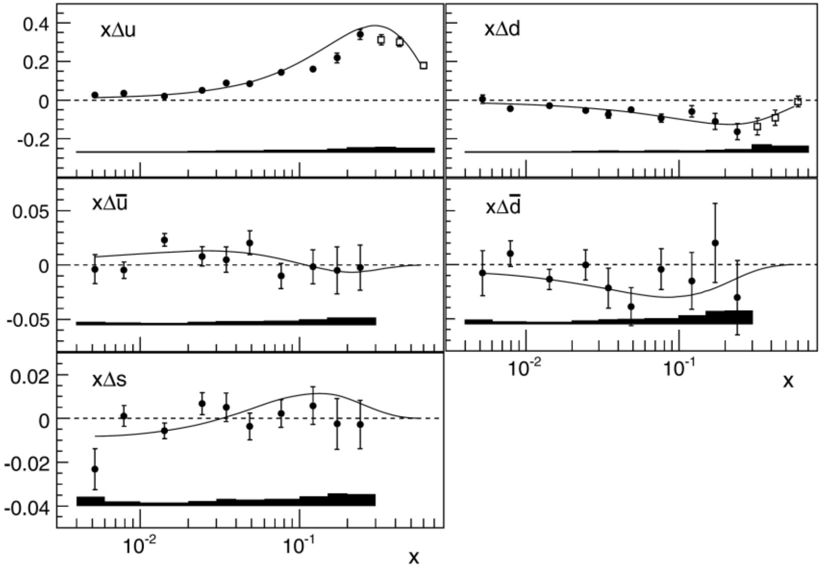
$g_1^q(x)$

helicity

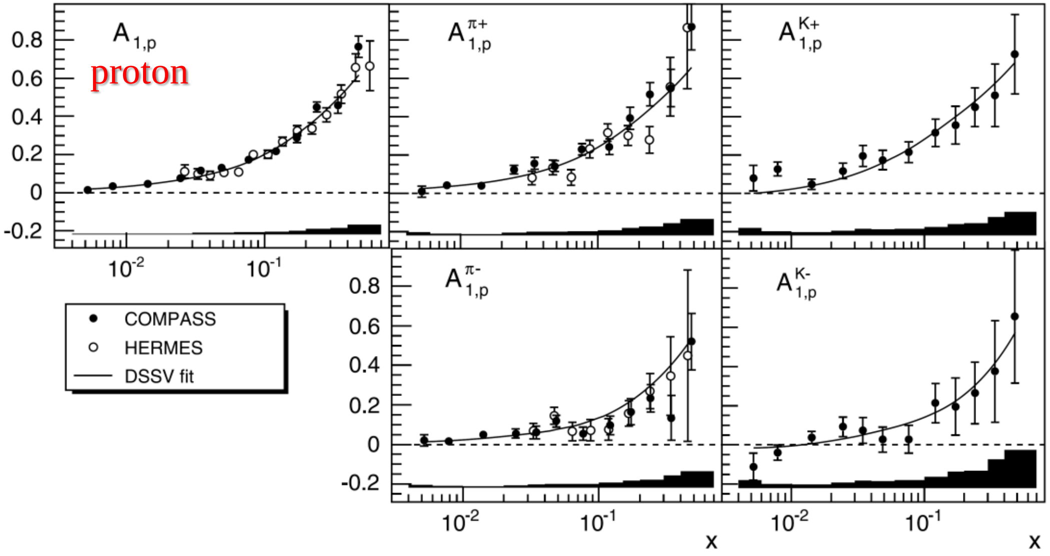
- COMPASS contribution: lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$
- Both inclusive and semi-inclusive measurements – access to flavor

COMPASS PLB 680 (2009) 217

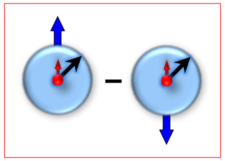




COMPASS PLB 693 (2010) 227



SIDIS TSAs: Collins effect and Transversity

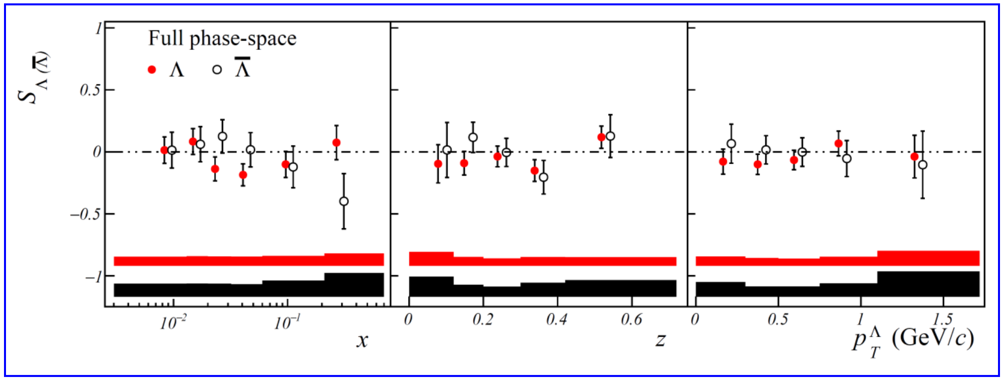


$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\; S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

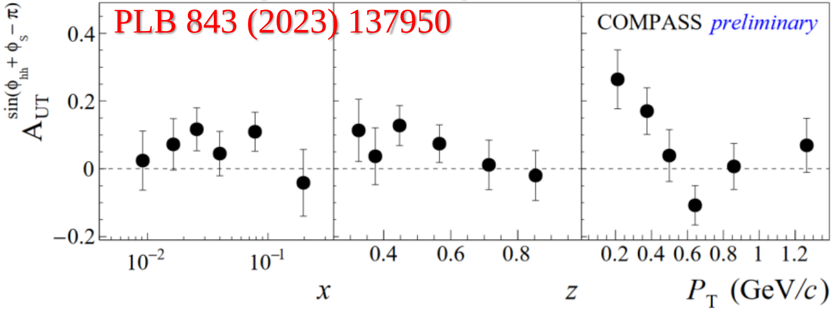
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\,h_1^q H_{1q}^{\perp h}\right]}$$

- 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?

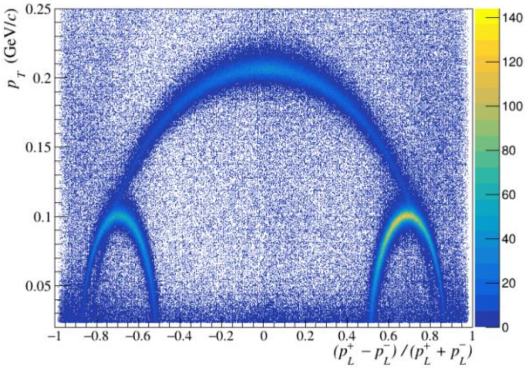
PLB 824 (2022) 136834

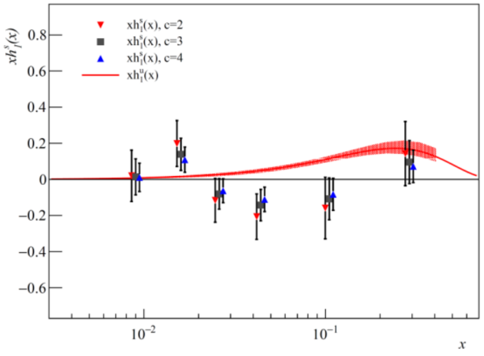


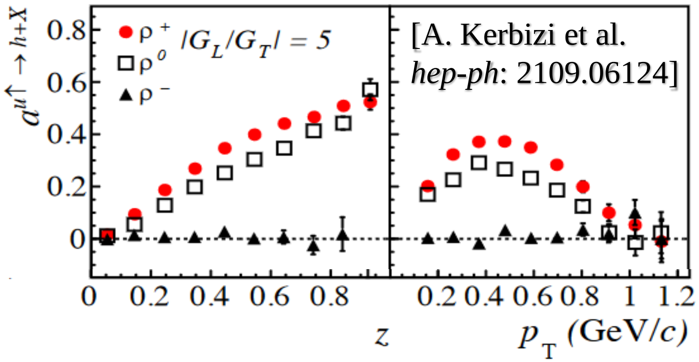
Inclusive $\boldsymbol{\rho^0}$ Collins asymmetry


PLB 843 (2023) 137950

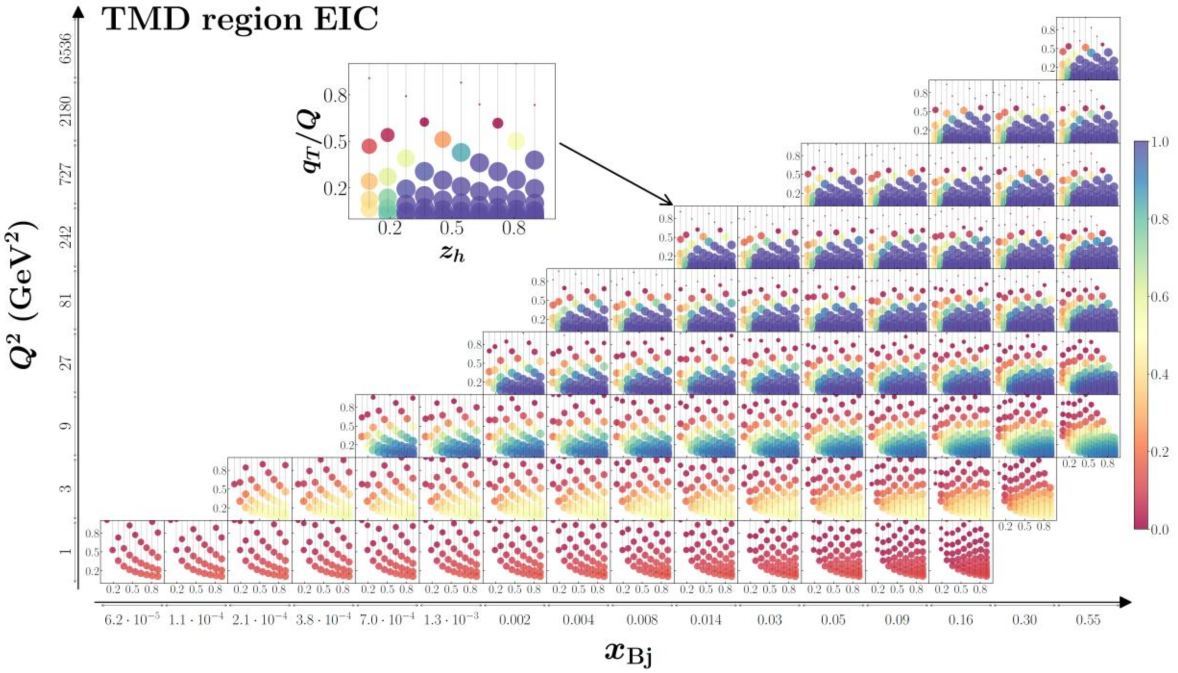
- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T



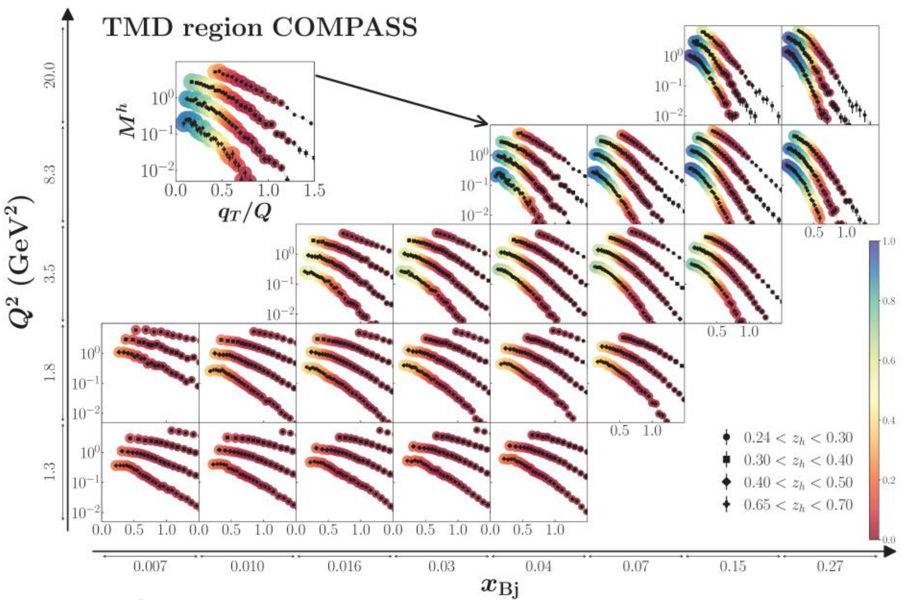


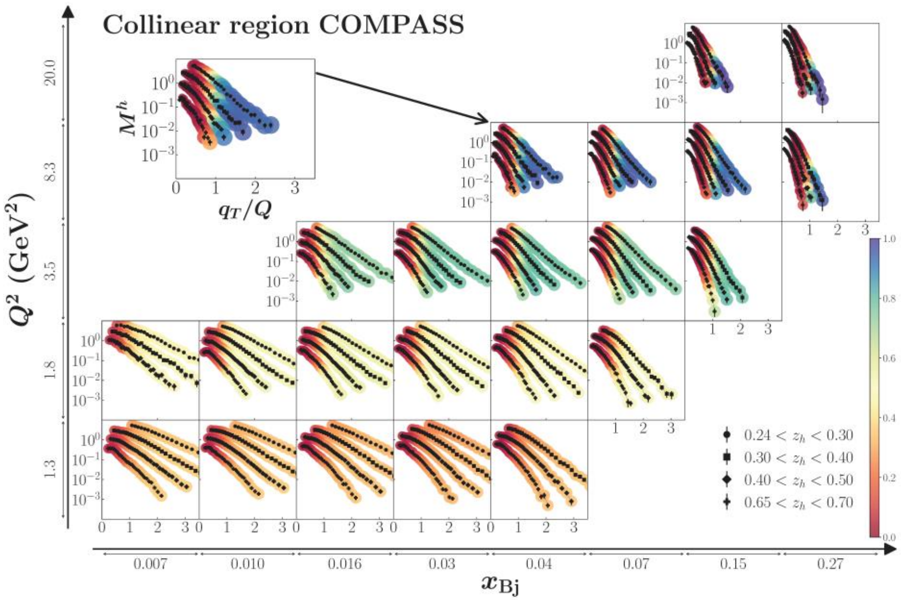

[A. Kerbizi et al. *hep-ph*: 2109.06124]

Polarized SIDIS and DY – factorization and kinematic regions

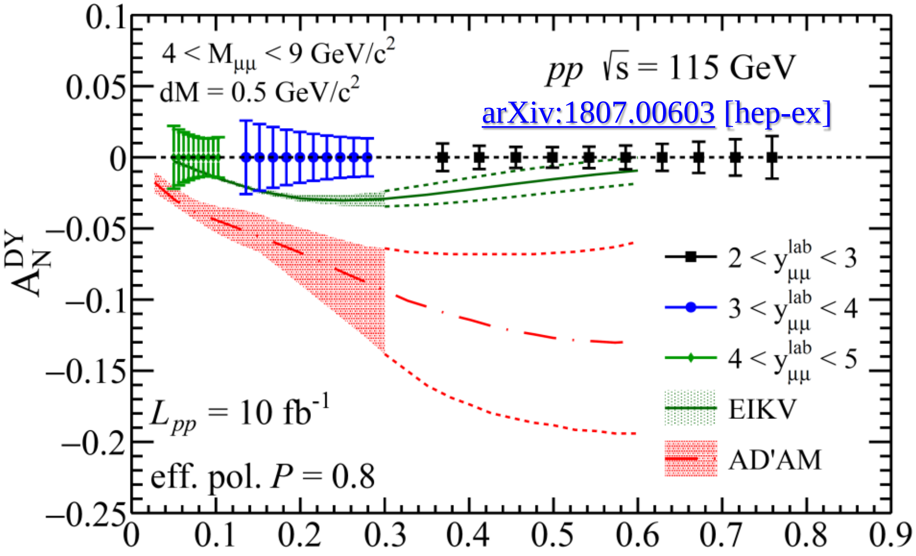


JAM, JHEP 04 (2022) 084

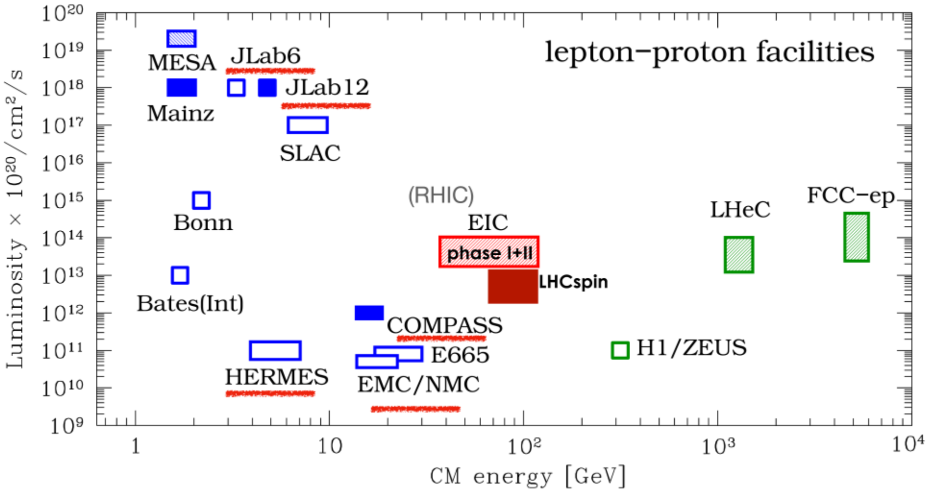




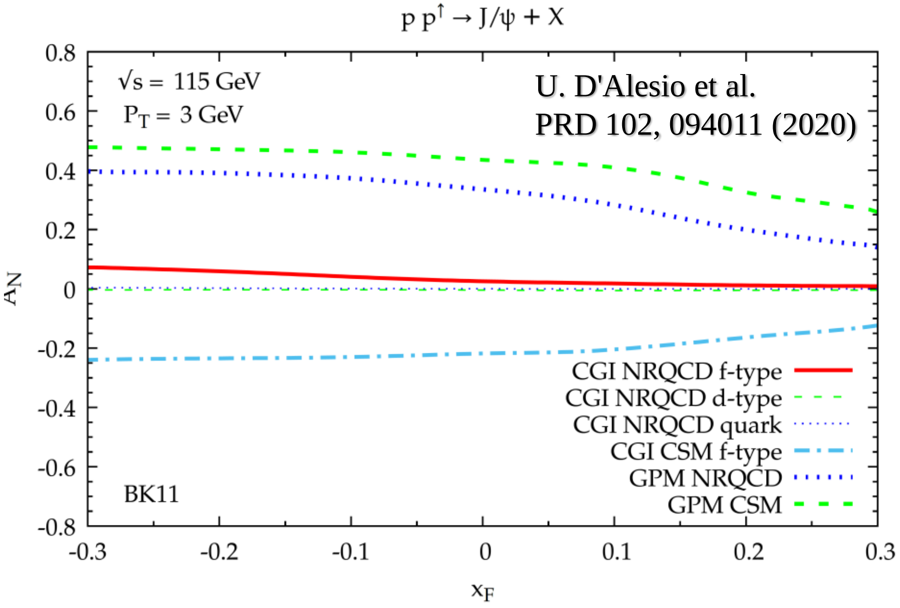
LHCspin



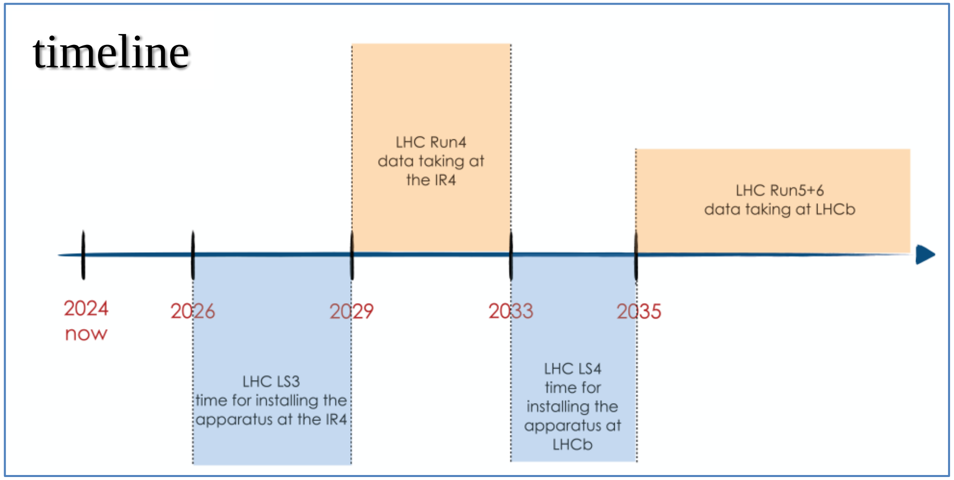
$4 < M_{\mu\mu} < 9$ GeV/c^2
dM = 0.5 GeV/c^2
pp $\sqrt{s}$ = 115 GeV
arXiv:1807.00603 [hep-ex]
L_{pp} = 10 fb^{-1}
eff. pol. P = 0.8
$2 < y^{lab}_{\mu\mu} < 3$
$3 < y^{lab}_{\mu\mu} < 4$
$4 < y^{lab}_{\mu\mu} < 5$
EIKV
AD'AM
A_N^{DY}
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.25
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9



lepton−proton facilities
Luminosity × 10^{20}/cm²/s
CM energy [GeV]
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
1
10
10^2
10^3
10^4
MESA
JLab6
Mainz
JLab12
SLAC
Bonn
Bates(Int)
HERMES
(RHIC)
EIC
phase I+II
LHCspin
COMPASS
E665
EMC/NMC
H1/ZEUS
LHeC
FCC−ep



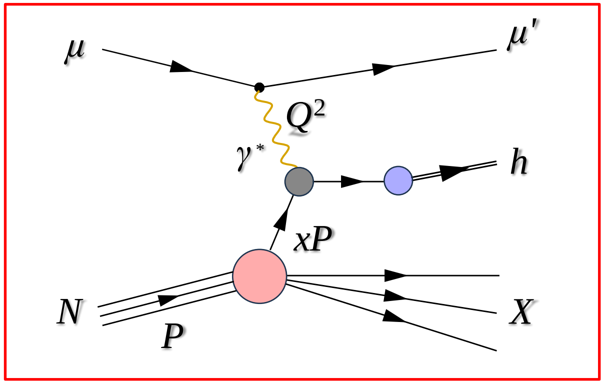
p p$^\uparrow$ → J/ψ + X
$\sqrt{s}$ = 115 GeV
P_T = 3 GeV
U. D'Alesio et al.
PRD 102, 094011 (2020)
BK11
CGI NRQCD f-type
CGI NRQCD d-type
CGI NRQCD quark
CGI CSM f-type
GPM NRQCD
GPM CSM
A_N
x_F
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.3
-0.2
-0.1
0
0.1
0.2
0.3



timeline
LHC Run4
data taking at
the IR4
LHC Run5+6
data taking at LHCb
2024
now
2026
2029
2033
2035
LHC LS3
time for installing the
apparatus at the IR4
LHC LS4
time for
installing the
apparatus at
LHCb

Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS

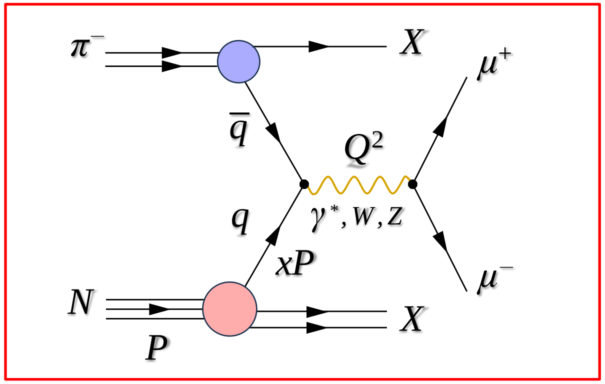


T-odd TMD PDFs

⟷

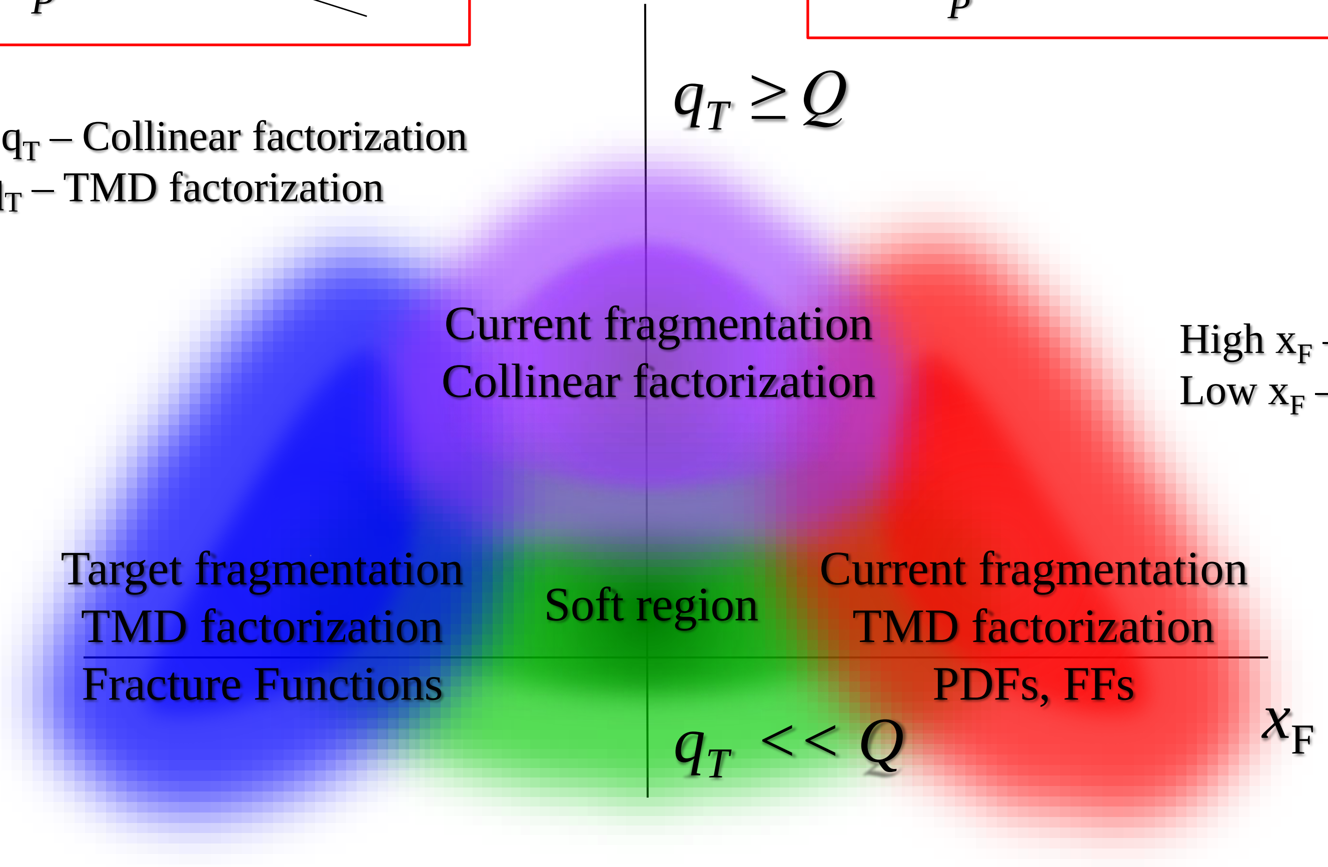
sign change

Drell-Yan process



High q_T – Collinear factorization
Low q_T – TMD factorization

High x_F – Current fragmentation
Low x_F – Target fragmentation



$q_T \geq Q$

Current fragmentation
Collinear factorization

Target fragmentation
TMD factorization
Fracture Functions

Soft region

Current fragmentation
TMD factorization
PDFs, FFs

x_F

$q_T << Q$