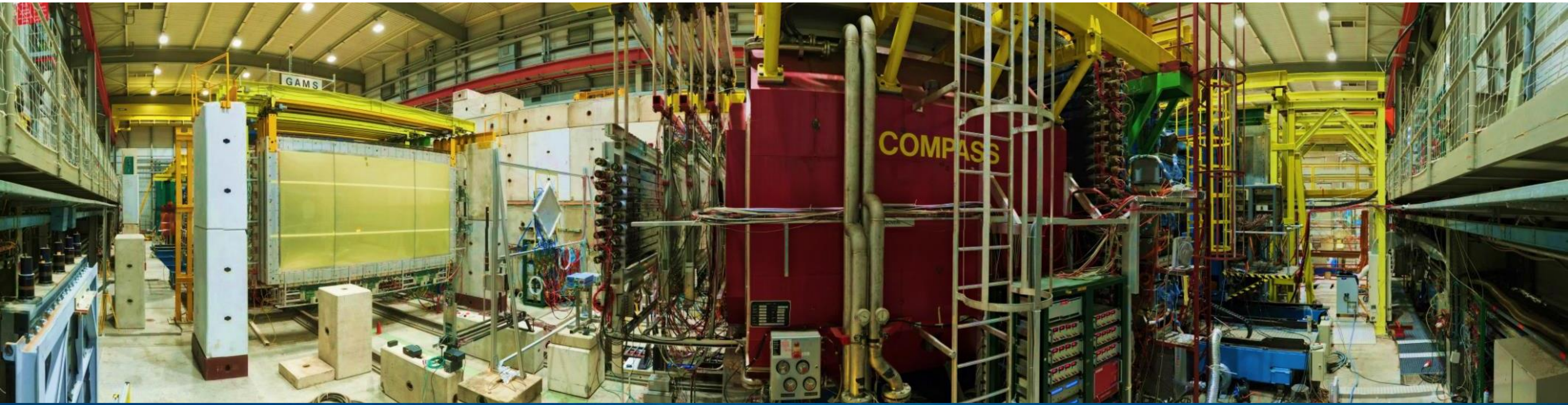
Longitudinal and transverse PDFs of hadrons: from COMPASS to AMBER

Bakur Parsamyan

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



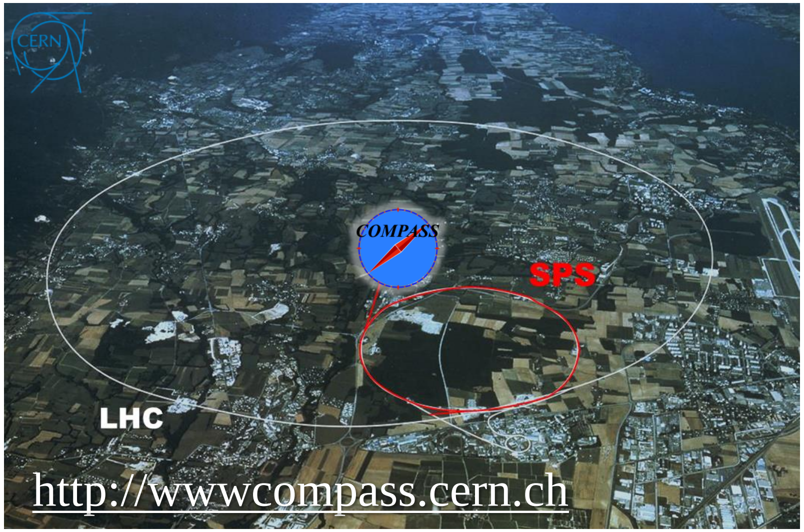
XVIth Quark Confinement and the Hadron Spectrum Conference (QCHSC 2024)

August 18–24, 2024,
Cairns, Queensland, Australia

COMPASS timeline

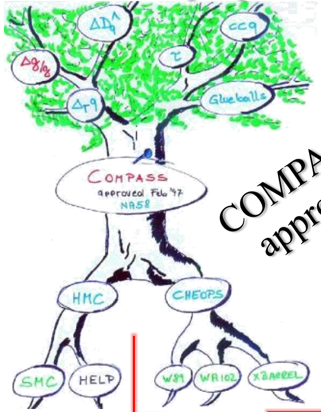
- CERN SPS north area – M2 beamline
- Fixed target experiment
- Approved in 1997
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

33 institutions from 15 countries: ~ 200 members

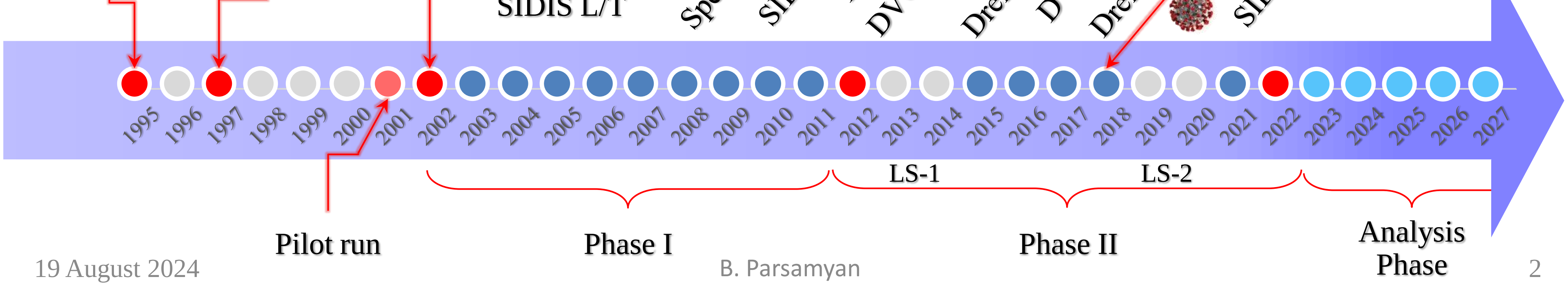


http://wwwcompass.cern.ch

COMPASS proposal



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

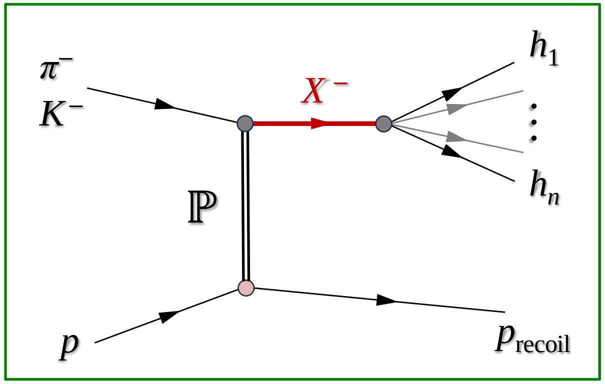
Hadron spectroscopy

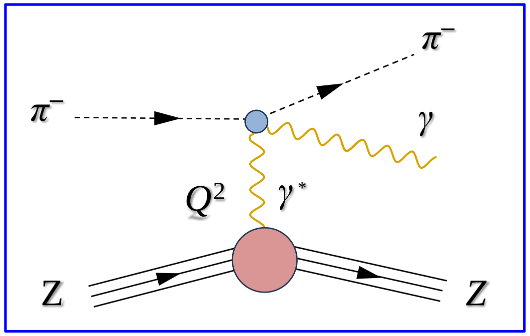
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

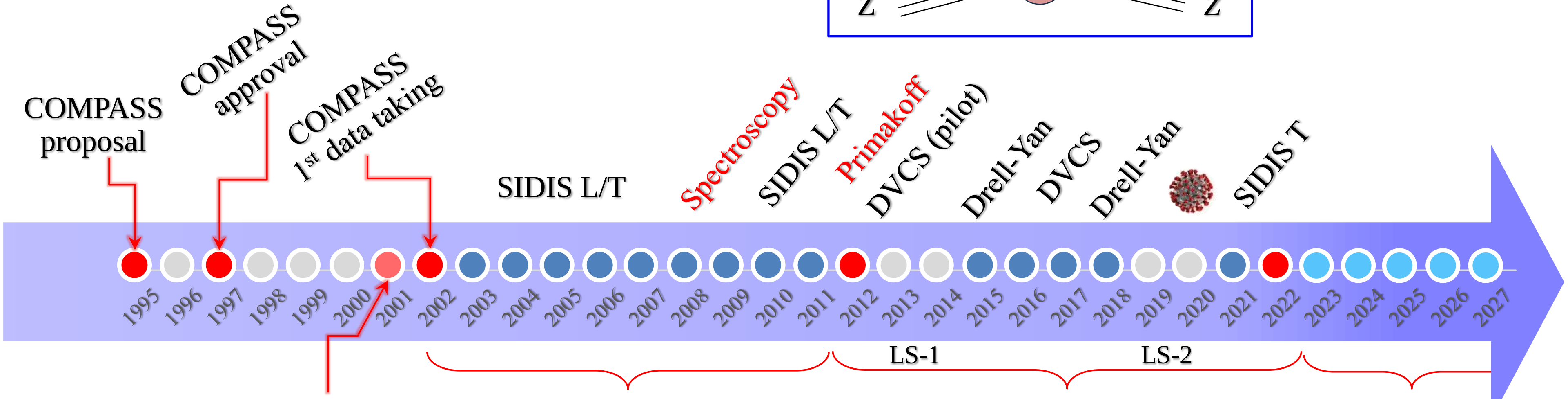
Chiral dynamics

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

See Stefan Wallner's talk (Wednesday)







COMPASS proposal

COMPASS approval

COMPASS 1st data taking

SIDIS L/T

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

Drell-Yan

DVCS

Drell-Yan

SIDIS T

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

LS-1

LS-2

Pilot run

Phase I

Phase II

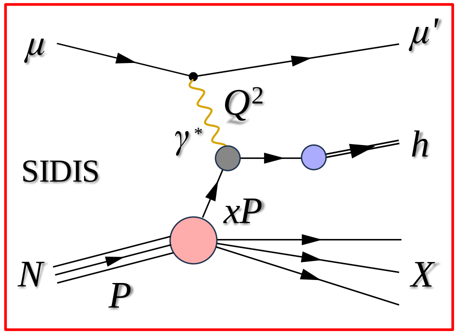
Analysis Phase

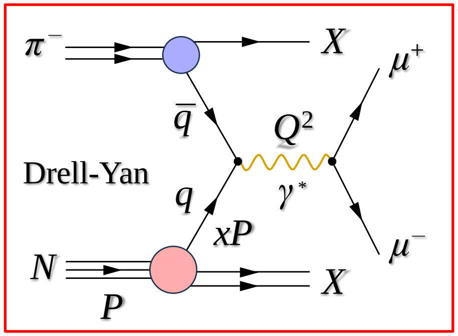
COMPASS Physics Program

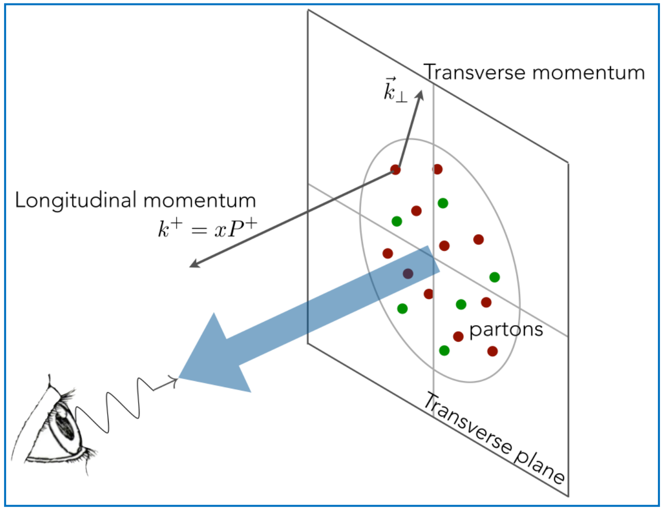
This talk

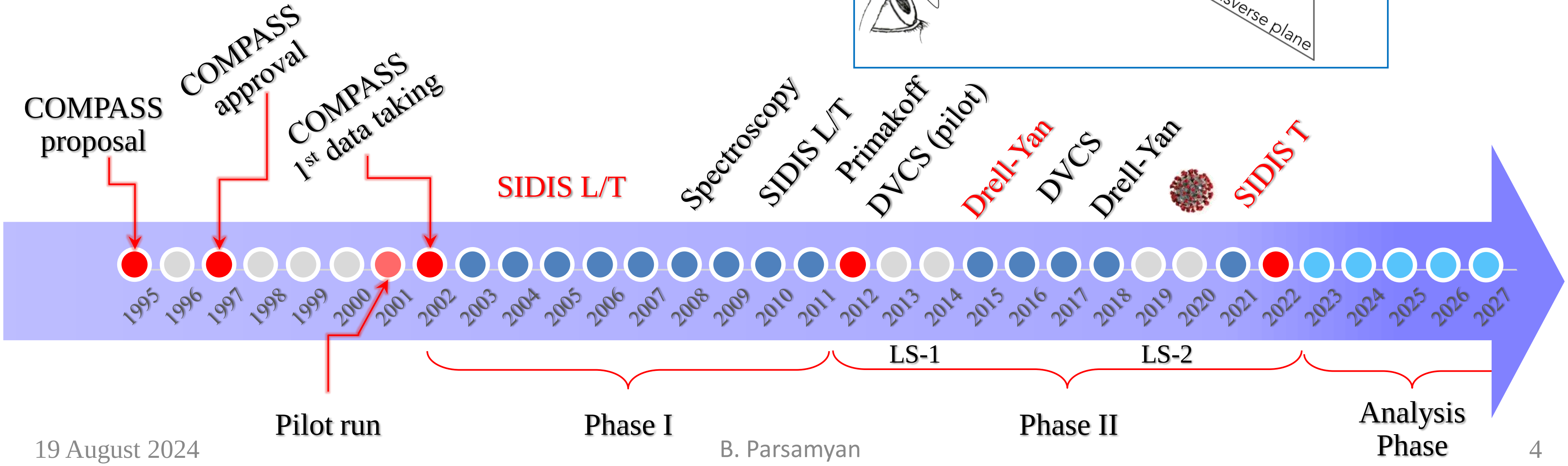
Nucleon structure

- Hard scattering of μ± 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





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Spectroscopy

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Primakoff

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Drell-Yan

DVCS

Drell-Yan

SIDIS T

LS-1

LS-2

Pilot run

Phase I

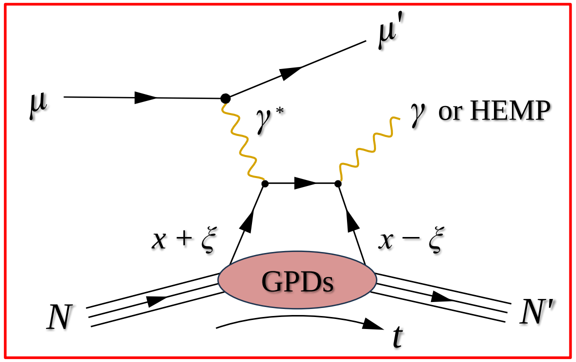
Phase II

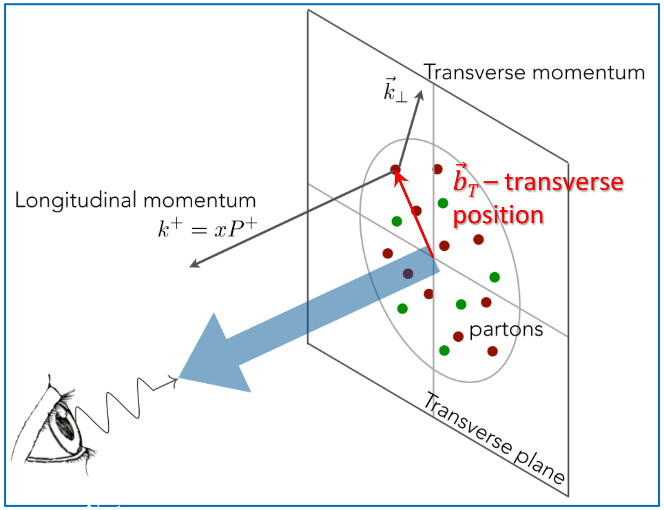
Analysis Phase

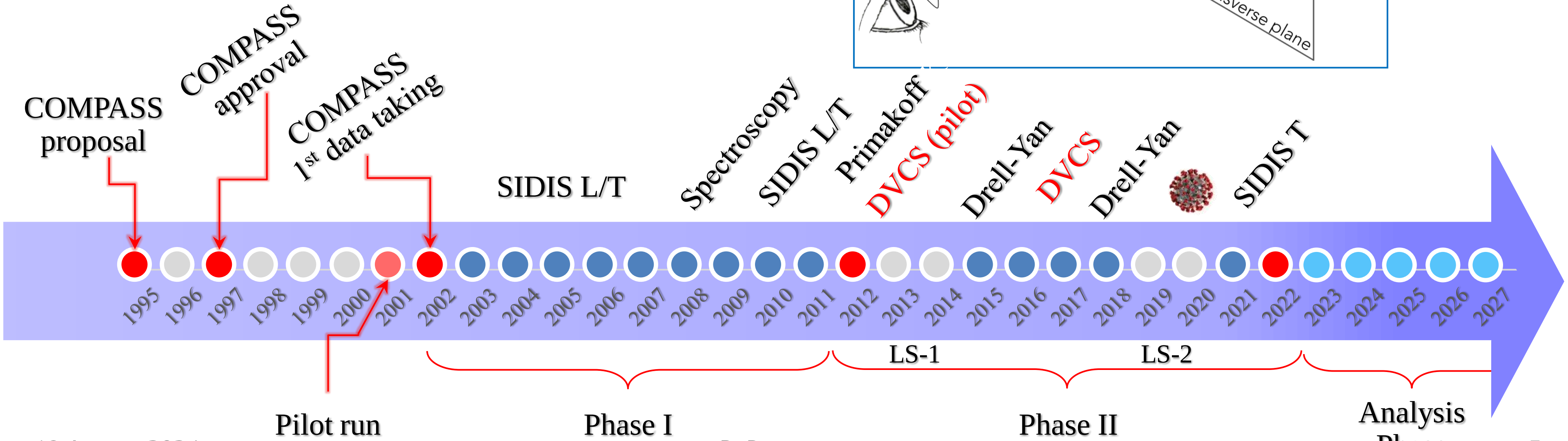
COMPASS Physics Program

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 M = π^0, $\rho(770)$, $\omega(782)$,..







COMPASS proposal

COMPASS approval

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LS-1

LS-2

Pilot run

Phase I

Phase II

Analysis Phase

COMPASS-AMBER timeline

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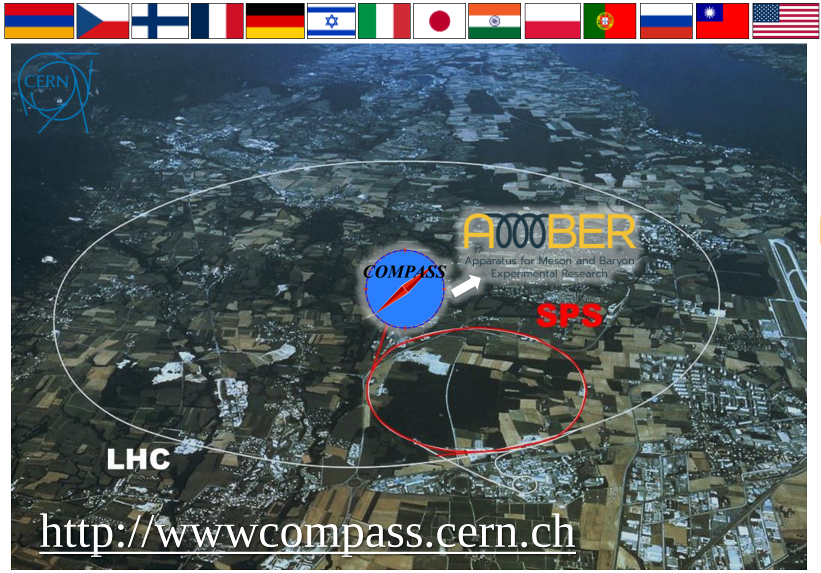
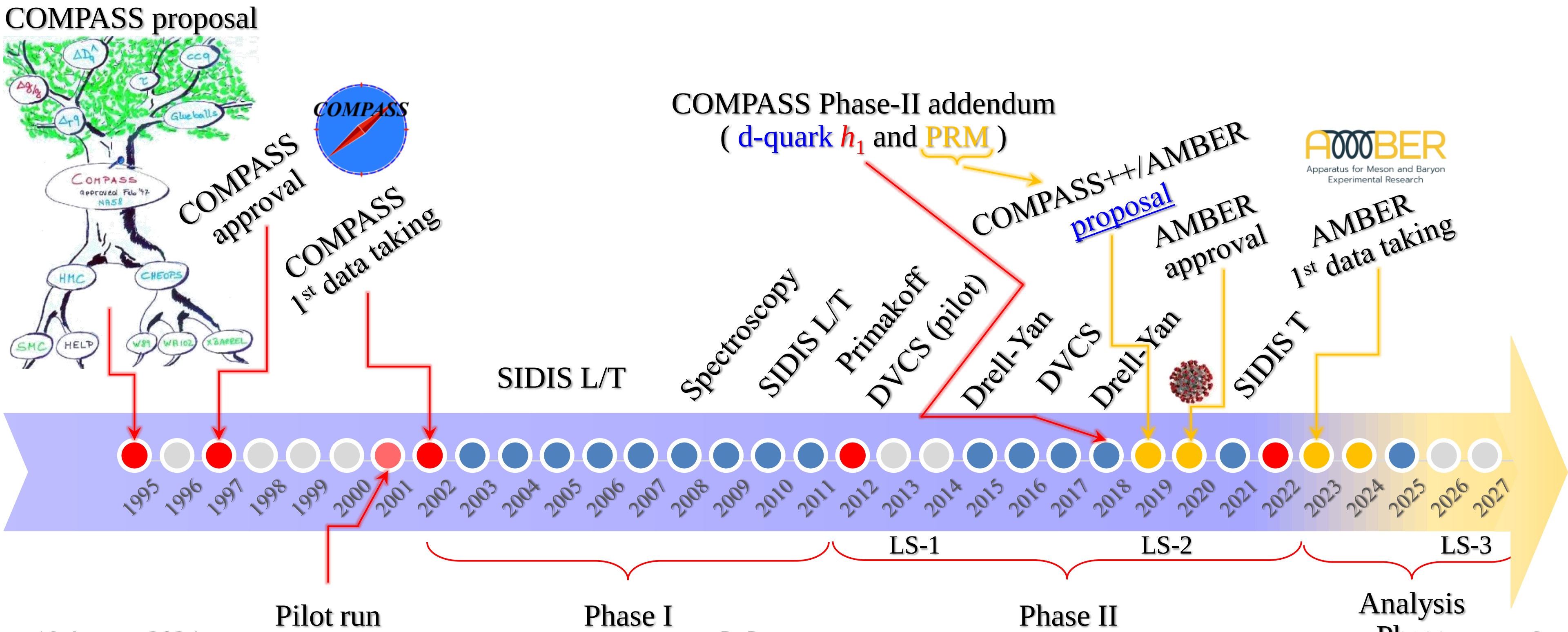
33 institutions from 15 countries: ~ 200 members



http://wwwcompass.cern.ch

COMPASS 25 years 1997 - 2022



COMPASS proposal

COMPASS approval

COMPASS 1st data taking

Pilot run

SIDIS L/T

Spectroscopy

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Drell-Yan

DVCS

Drell-Yan

SIDIS T

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

COMPASS++/AMBER proposal

AMBER approval

AMBER 1st data taking

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

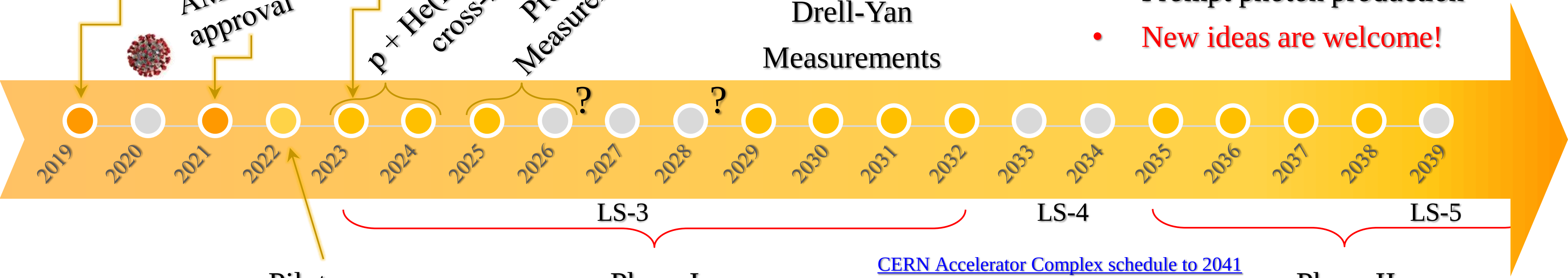
New collaborators are Welcome!

https://amber.web.cern.ch

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!

see S. Wallner's talk



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

AMBER approval

AMBER 1st data taking

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

Proton Radius Measurement (PRM)

Drell-Yan Measurements

Pilot run

LS-3

LS-4

LS-5

Phase I

Phase II

CERN Accelerator Complex schedule to 2041

AMBER measurements 2023-2024: $\overline{p}$ production cross-section

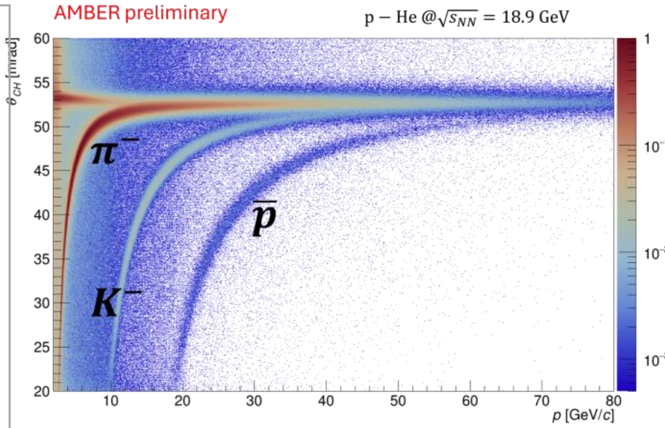
AMBER
Apparatus for Meson and Baryon Experimental Research

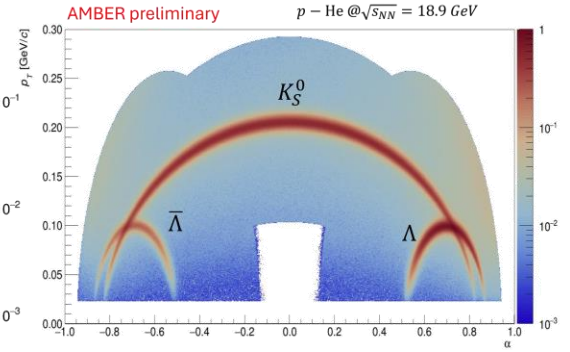
$\overline{p}$ production measurement

- $\overline{p}$ detected in the cosmic rays
  - produced in CR collisions
  - dark matter signature

Understanding the $\overline{p}$ flux:

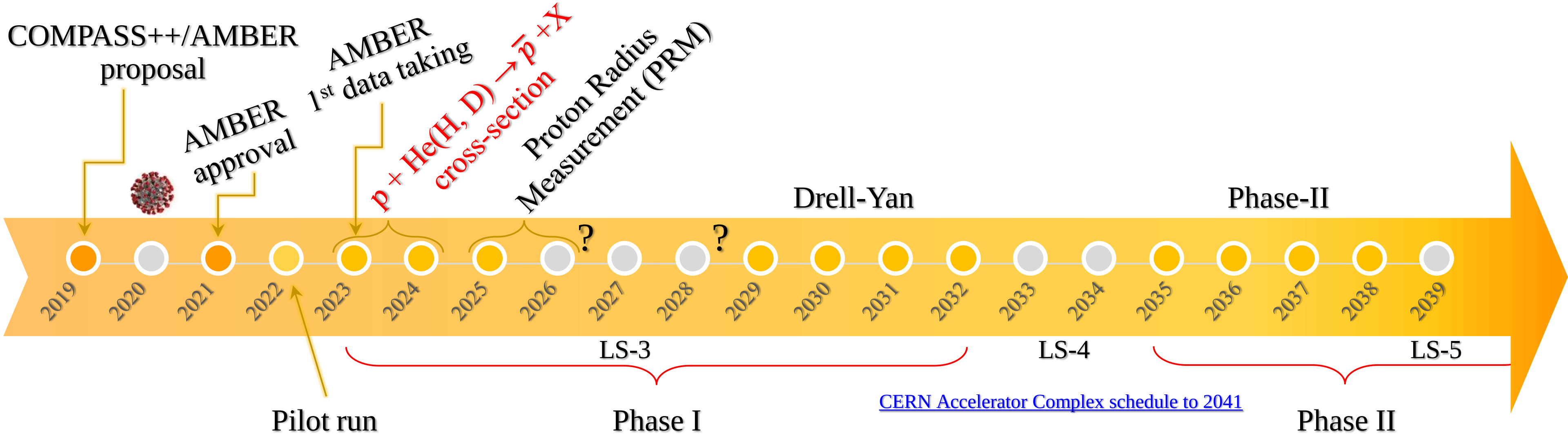
- Accurate determination of the CR-component
- Accuracy of the $\overline{p}$-production models is at ~20% level





Motivation for AMBER 2023-2024 runs

New measurements needed to determine the
$\overline{p}$ -production from cosmic-ray collisions accurately



COMPASS++/AMBER proposal

AMBER approval

AMBER 1st data taking

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

Proton Radius Measurement (PRM)

?

?

Drell-Yan

Phase-II

2019
2020
2021
2022
2023
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2025
2026
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2031
2032
2033
2034
2035
2036
2037
2038
2039

LS-3

LS-4

LS-5

Pilot run

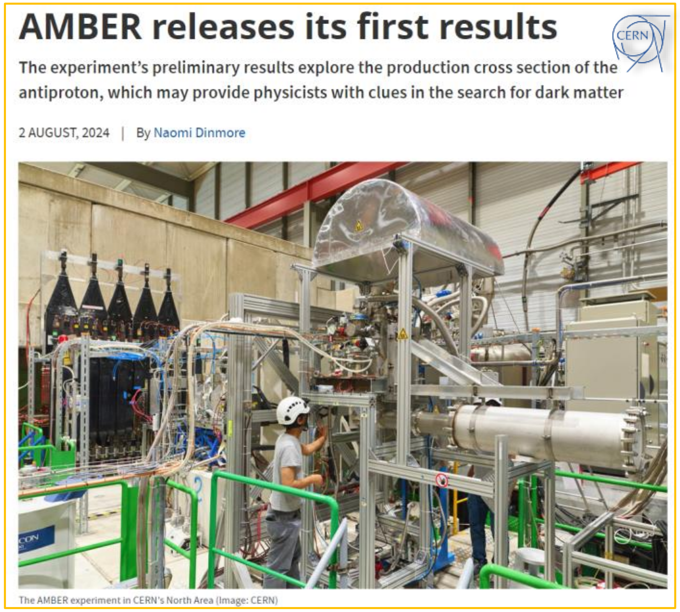
Phase I

CERN Accelerator Complex schedule to 2041

Phase II

AMBER measurements 2023-2024: $\overline{p}$ production cross-section

AMBER
Apparatus for Meson and Baryon Experimental Research

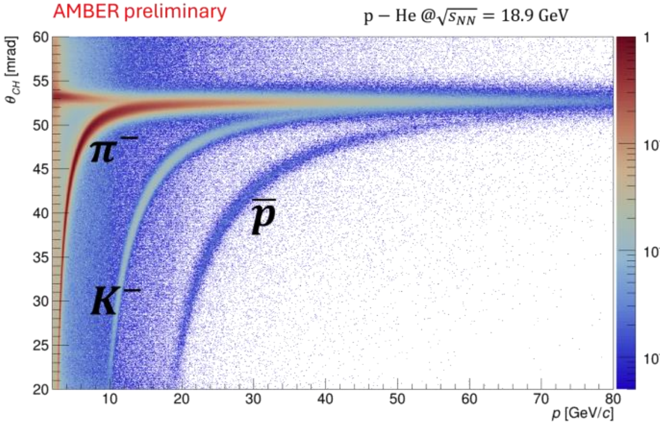


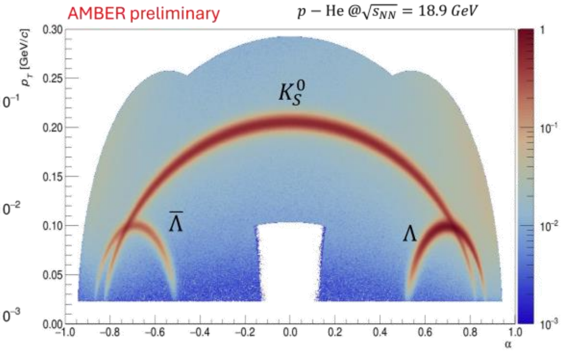
AMBER releases its first results

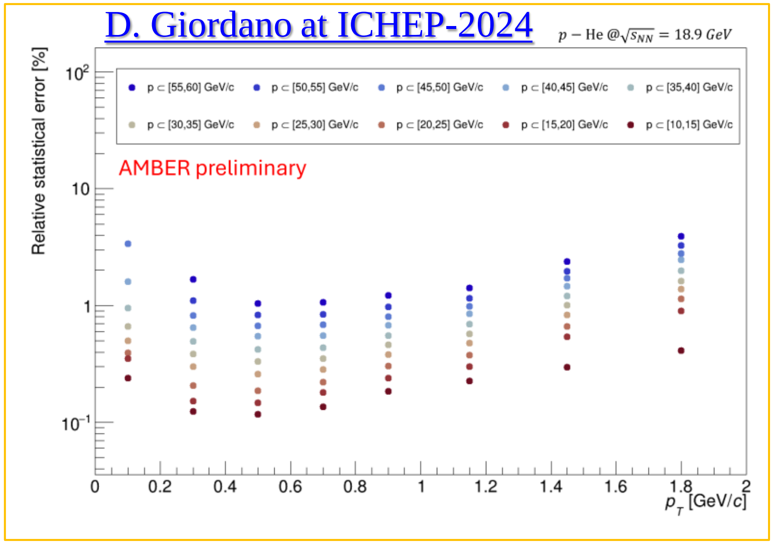
The experiment's preliminary results explore the production cross section of the antiproton, which may provide physicists with clues in the search for dark matter

2 AUGUST, 2024 | By Naomi Dinmore

The AMBER experiment in CERN's North Area (Image: CERN)






D. Giordano at ICHEP-2024

COMPASS++/AMBER proposal

AMBER approval

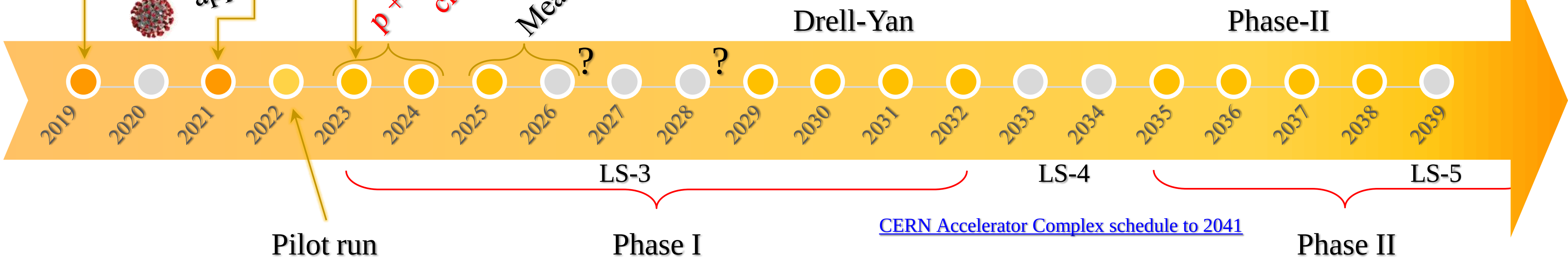
AMBER 1^{st} data taking

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

Proton Radius Measurement (PRM)

Drell-Yan

Phase-II



Pilot run

Phase I

CERN Accelerator Complex schedule to 2041

Phase II

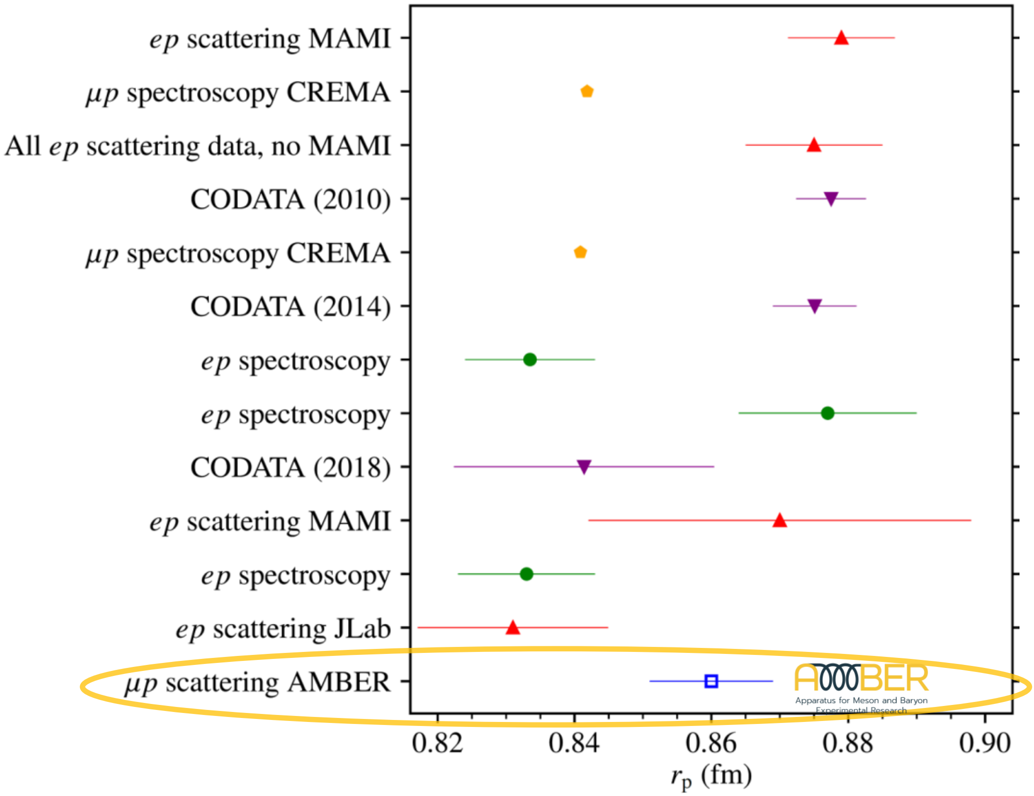
AMBER measurements 2023-2024: proton charge radius

The proton-radius puzzle

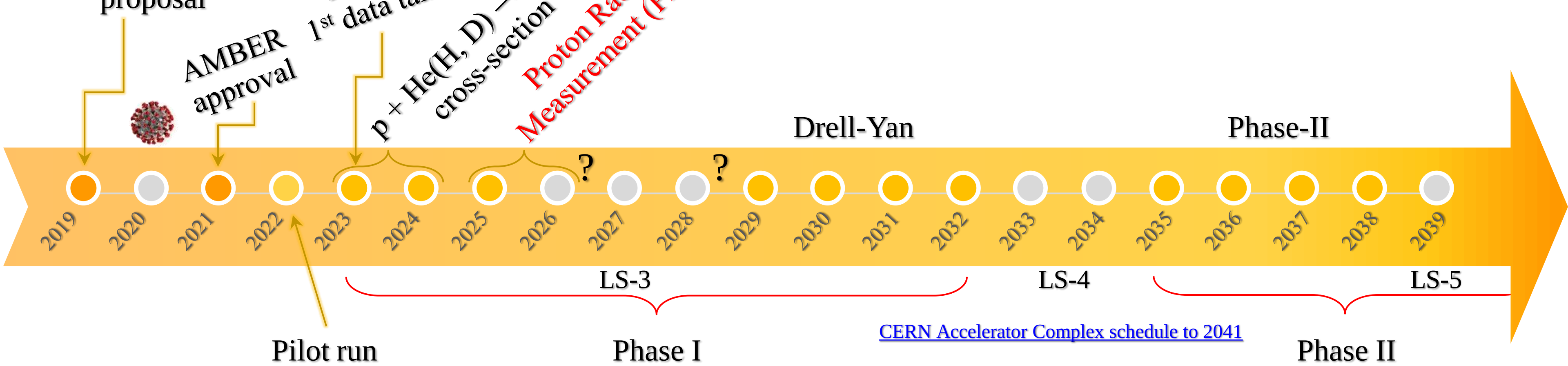
- Discrepancies between the charge-radius of the proton extracted from:
    - Electron-proton scattering
    - Hydrogen spectroscopy
    - Muonic-hydrogen spectroscopy

AMBER PRM

- Elastic muon-proton scattering
    - 100 GeV/c muon beam
    - Active-target Hydrogen TPC for proton detection



Ch. Dreisbach – CERN-THESIS-2022-286



COMPASS++/AMBER proposal

AMBER approval

AMBER 1st data taking

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

Proton Radius Measurement (PRM)

Drell-Yan

Phase-II

?

?

LS-3

LS-4

LS-5

Pilot run

Phase I

Phase II

CERN Accelerator Complex schedule to 2041

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AMBER PRM

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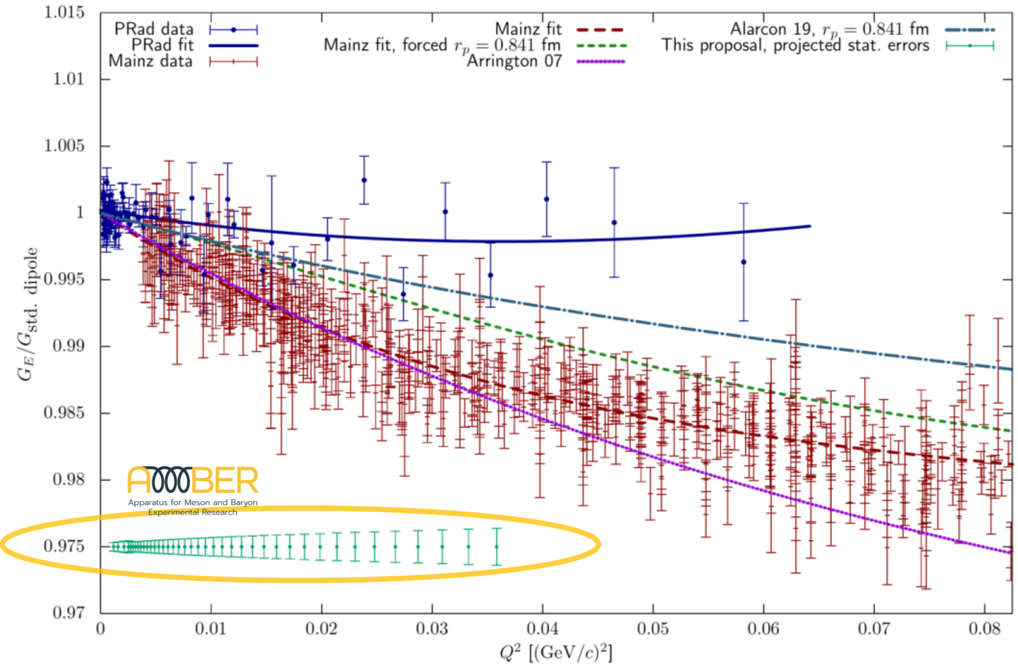
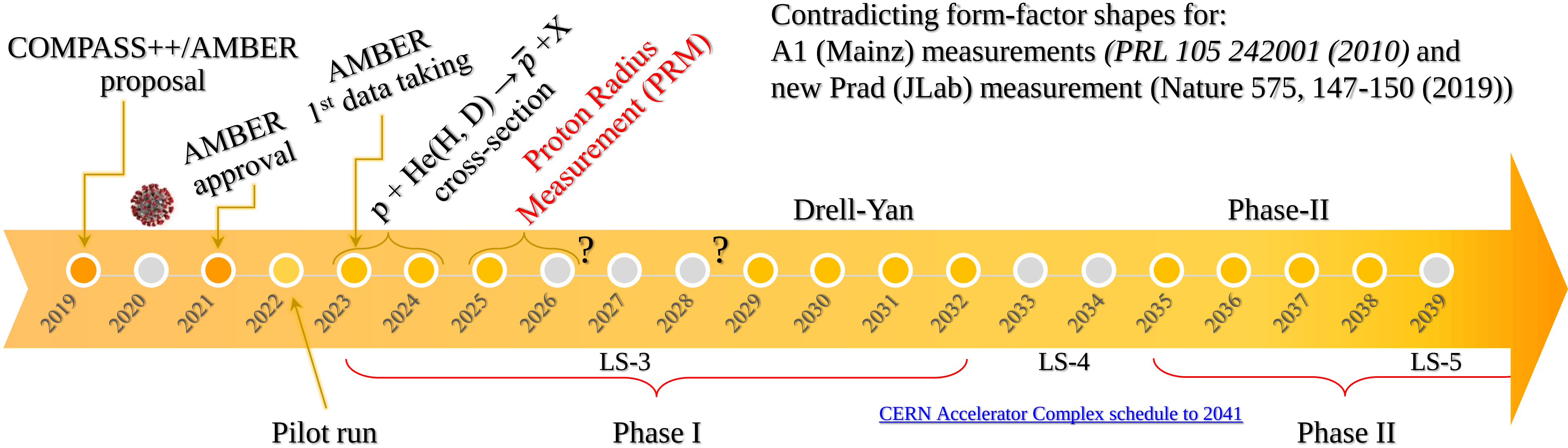
    - 100 GeV/*c* muon beam
    - Active-target Hydrogen TPC for proton detection

Phase II – meson radii measurements

Ch. Dreisbach – CERN-THESIS-2022-286



Contradicting form-factor shapes for:
A1 (Mainz) measurements *(PRL 105 242001 (2010)* and
new Prad (JLab) measurement (Nature 575, 147-150 (2019))

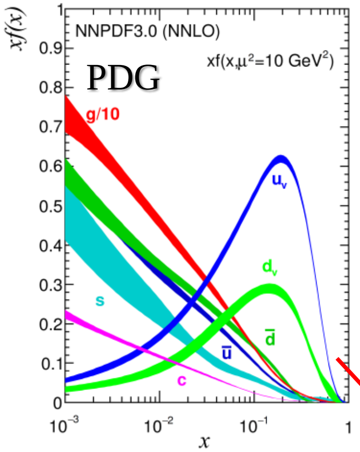


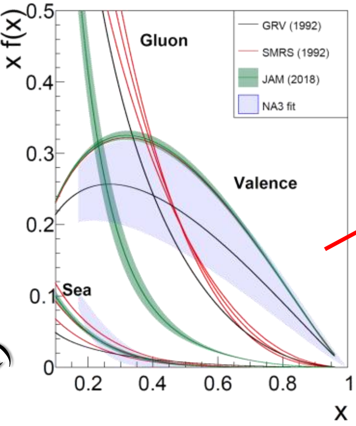
CERN Accelerator Complex schedule to 2041

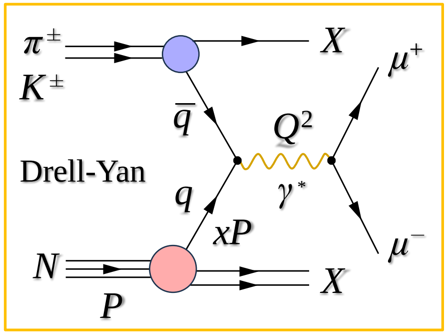
AMBER measurements 2023-2024: Drell-Yan

$\pi^{\pm}$, $K^{\pm}$ induced dimuon production: Drell-Yan, J/ψ (and ψ')

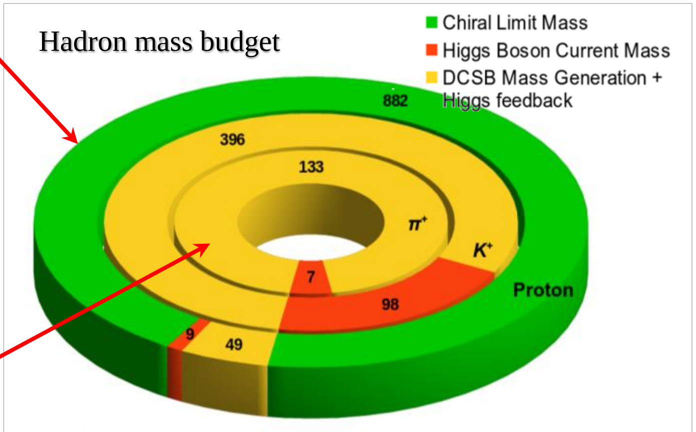
- Study of pion and kaon PDFs
  - Crucial input for the study of the Emergent Hadron Mass (EHM)
  - Possibility to collect unique balanced π^{+}/π^{-} induced DY data
- Measurement of λ, μ and ν (DY, J/ψ)
- J/ψ production mechanisms ($q\bar{q}, gg$)
- Carbon and tungsten targets
- Improved vertex/mass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







see Craig Roberts' talk



$M_p \approx 938.3$ MeV/c^2; $M(uud) \approx 9.4$ MeV/c^2

$M_{\pi^+} \approx 139.6$ MeV/c^2; $M(u\bar{d}) \approx 7.1$ MeV/c^2

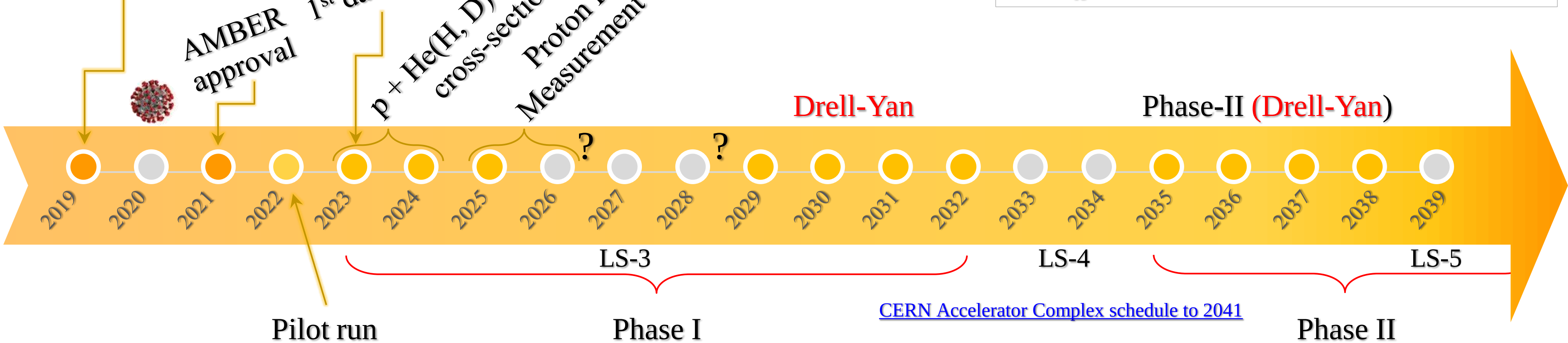
$M_{K^+} \approx 493.7$ MeV/c^2; $M(u\bar{s}) \approx 97.3$ MeV/c^2

COMPASS++/AMBER proposal

AMBER 1st data taking

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

Proton Radius Measurement (PRM)



AMBER approval

Drell-Yan

Phase-II (Drell-Yan)

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

LS-3

LS-4

LS-5

CERN Accelerator Complex schedule to 2041

Pilot run

Phase I

Phase II

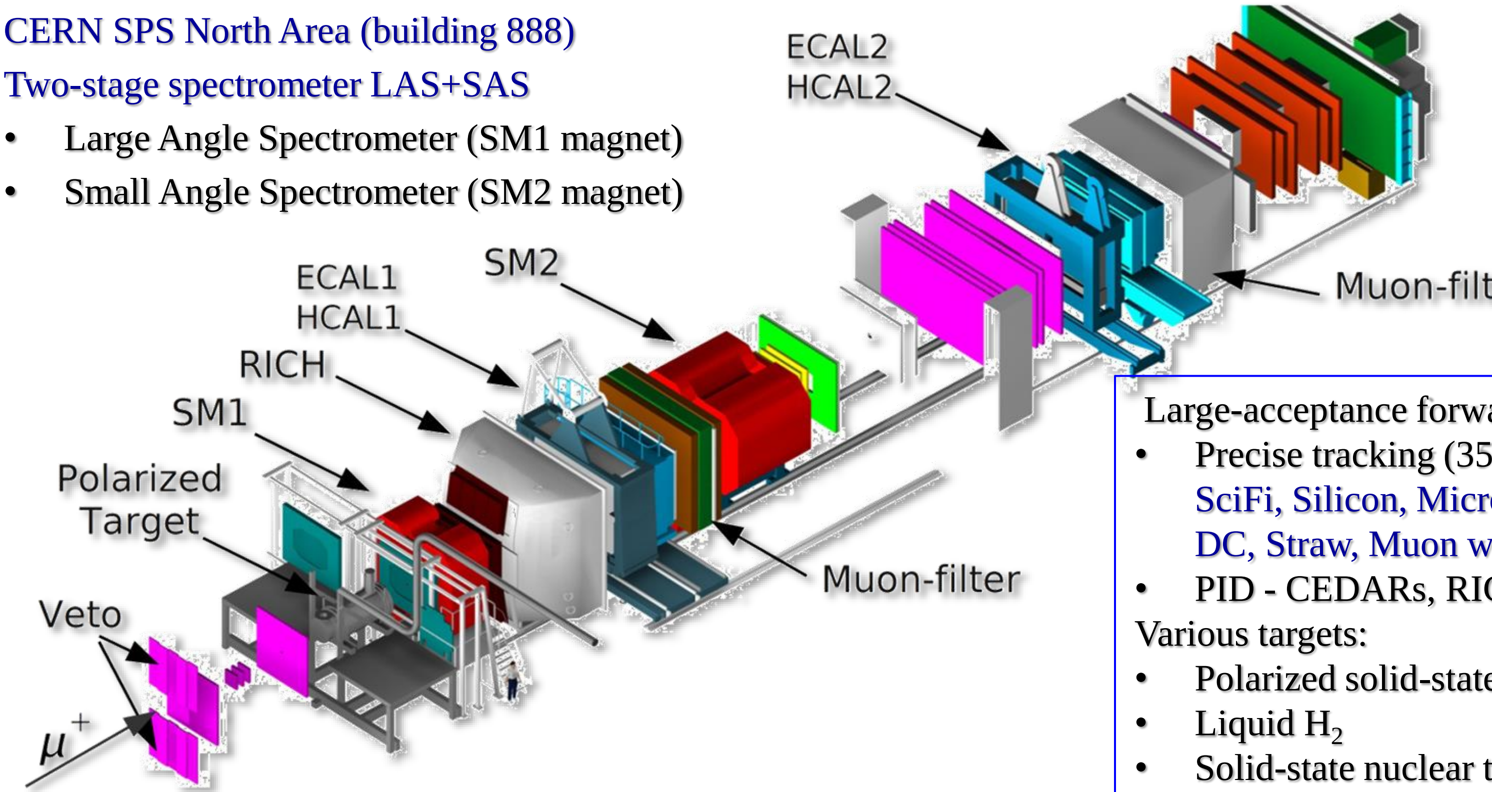
COMPASS experimental setup

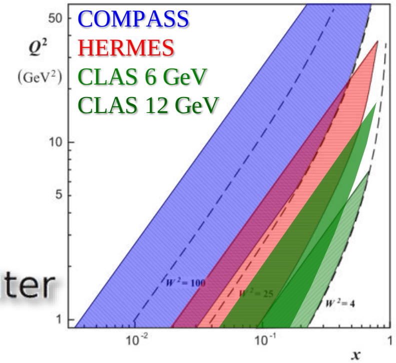
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





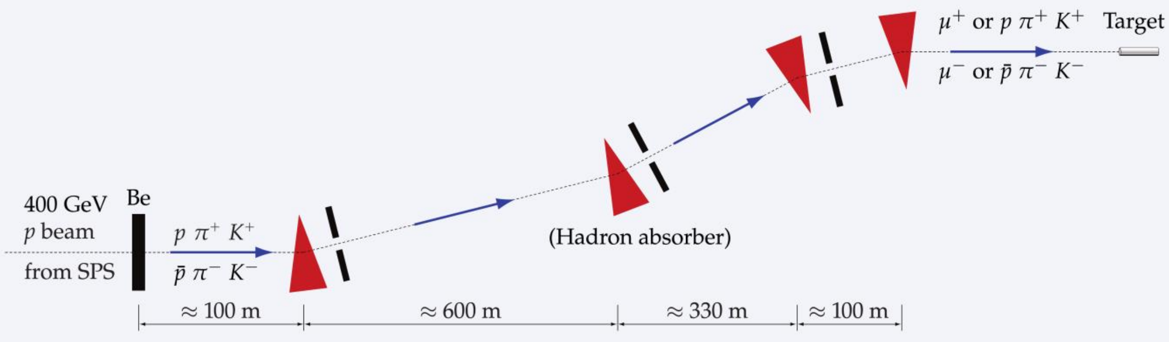
Large-acceptance forward spectrometer

- 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

CERN SPS North Area (building 888)

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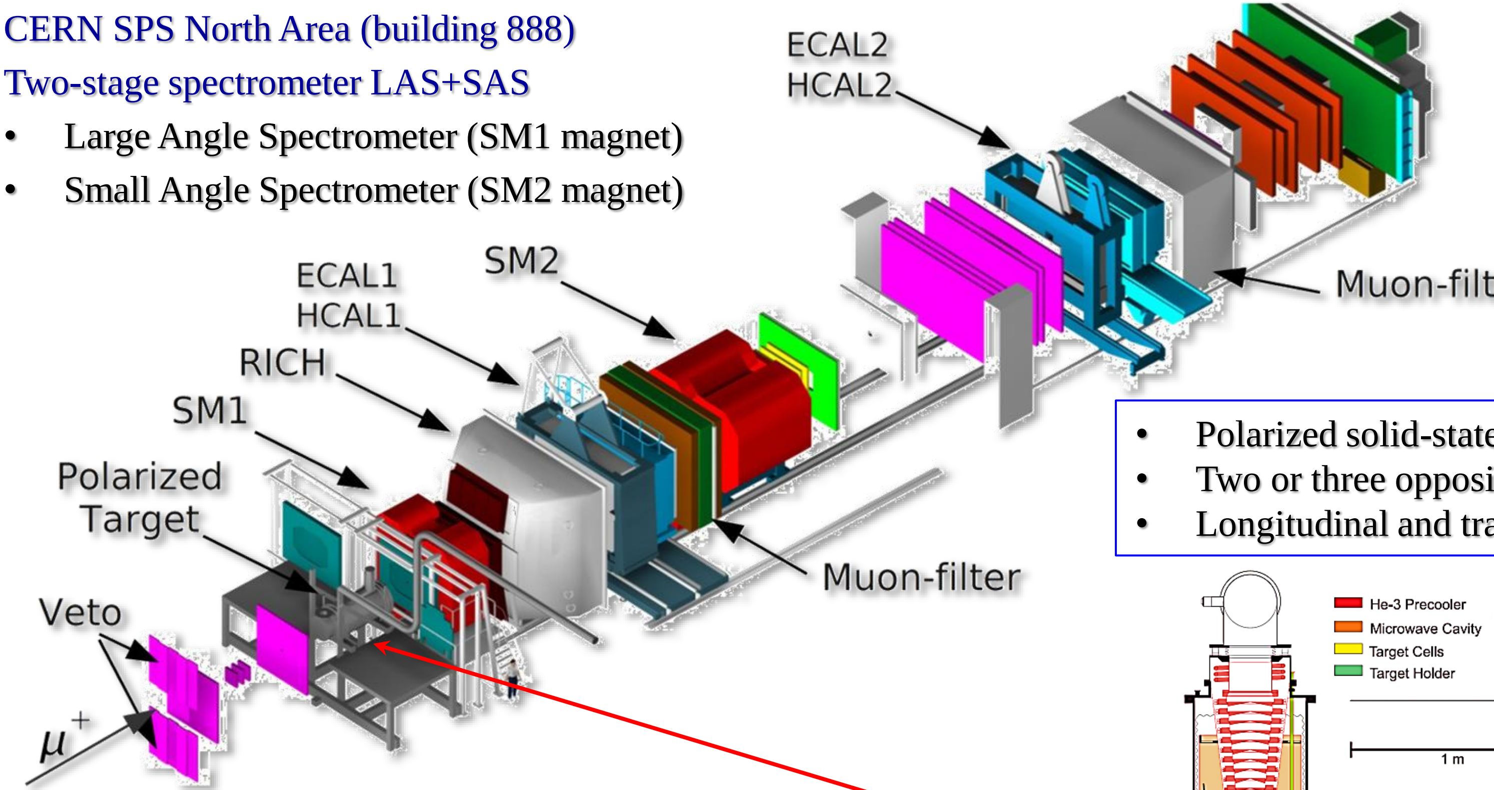
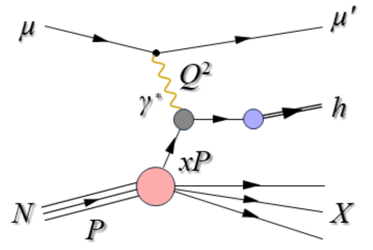
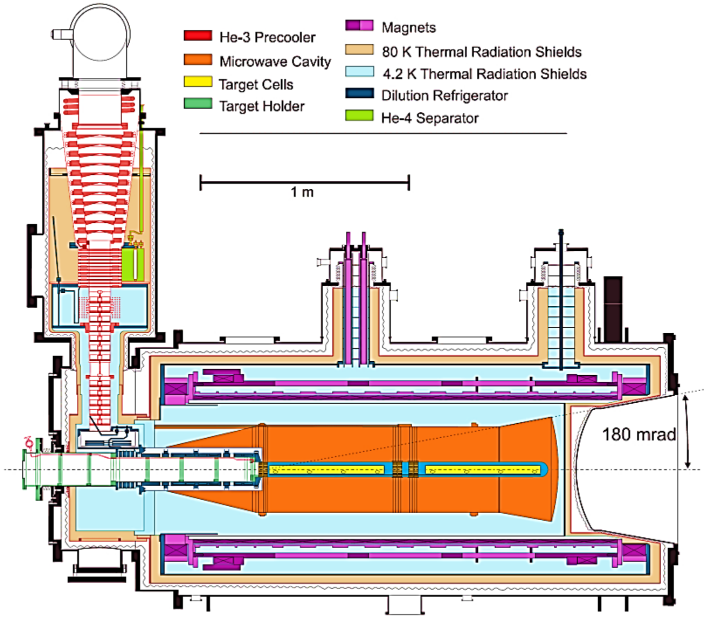




- Polarized solid-state NH_3 or ^{6}LiD
- Two or three oppositely polarized cells
- Longitudinal and transverse polarization



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  - h⁺ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - μ^+ longitudinally polarized

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

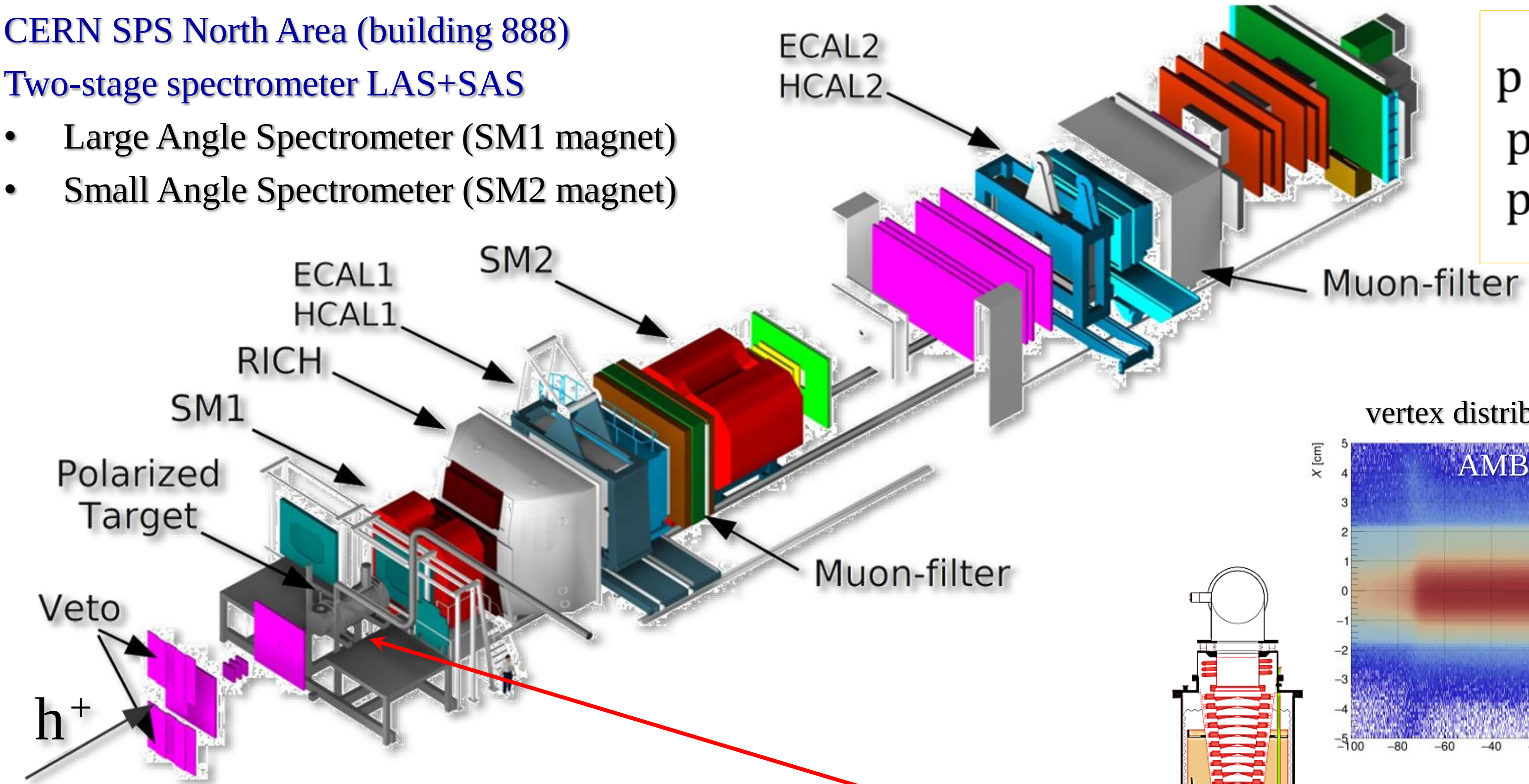
Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

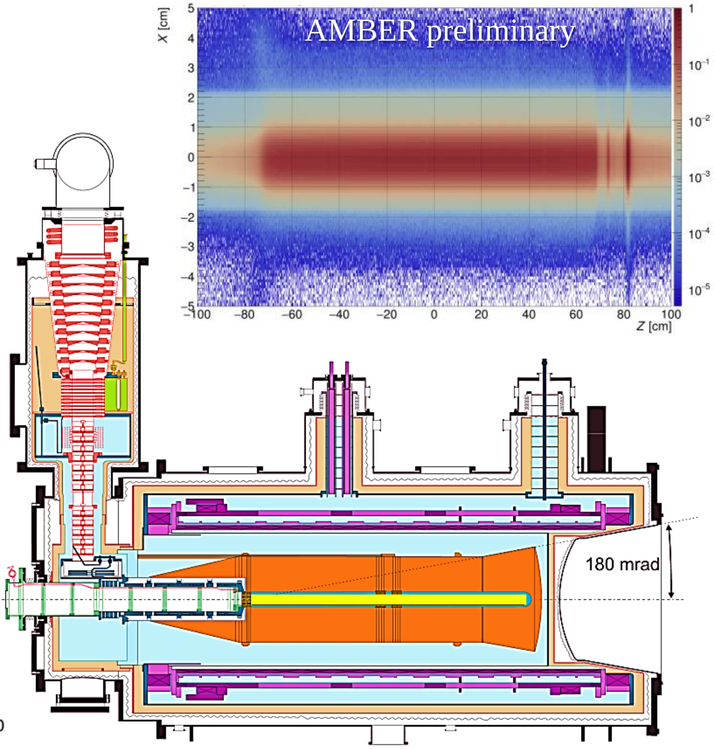
Two-stage spectrometer LAS+SAS

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

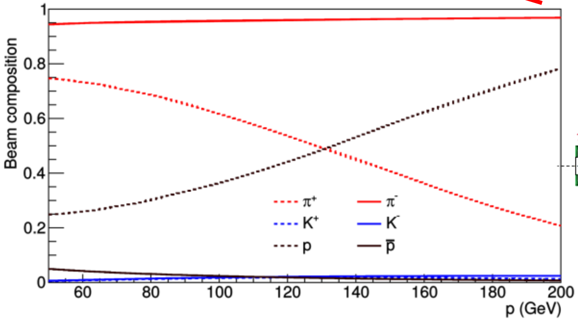
$$p + \mathrm{He} \rightarrow \bar{p} + X$$
$$p + \mathrm{H} \rightarrow \bar{p} + X$$
$$p + \mathrm{D} \rightarrow \bar{p} + X$$



vertex distribution



- h^+ beam: 60, 80, 100, 160, 190 and 250 GeV/c;
  Intensity: $25\cdot10^3$ h/s
- Beam PID: 2 CEDAR detectors
- Target: He (2023), H/D (2024)
- Data-taking ~2 months/year
- Dedicated trigger and beam-killer systems



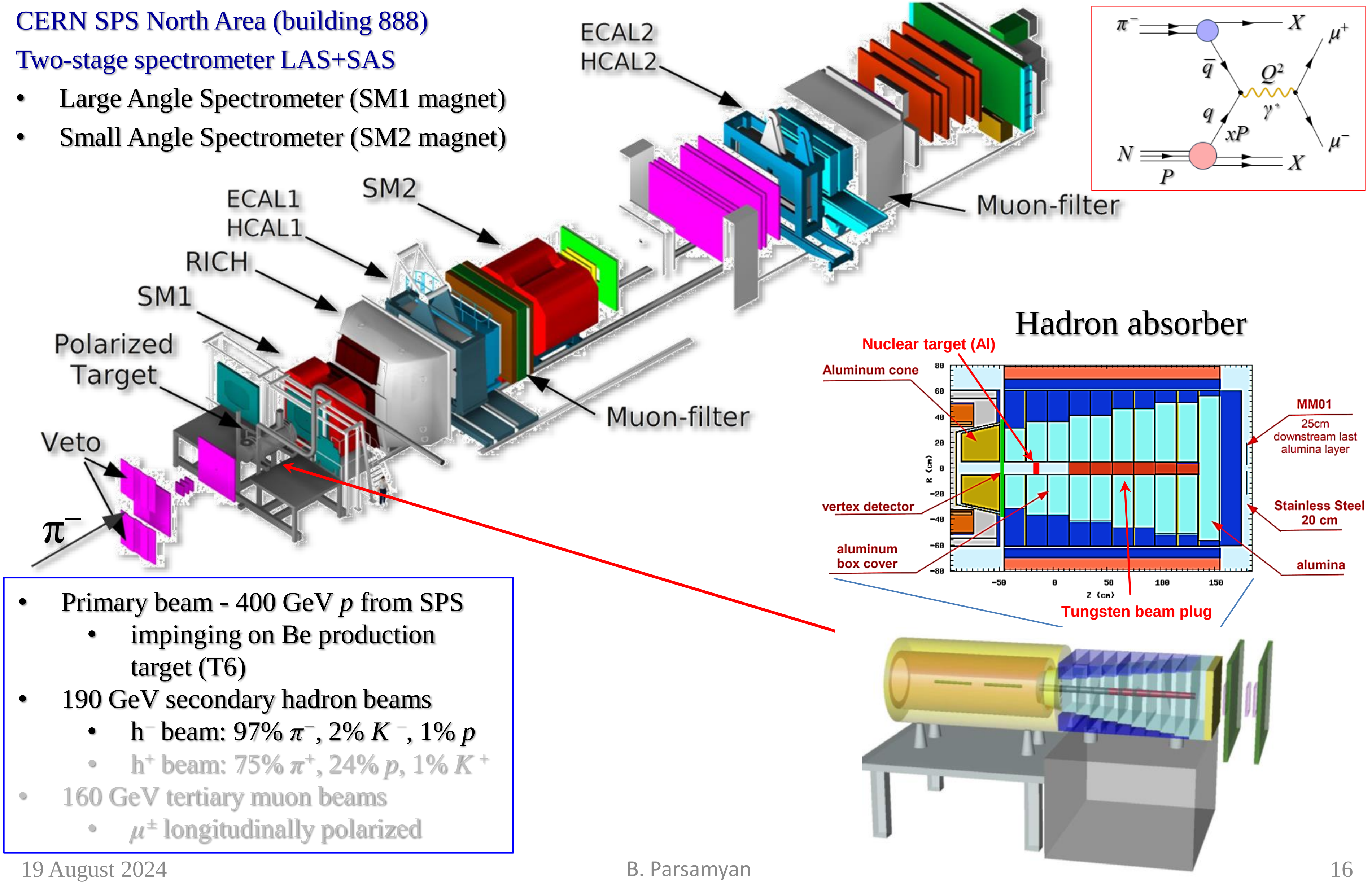
COMPASS experimental setup: Phase II (DY program)

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)



- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

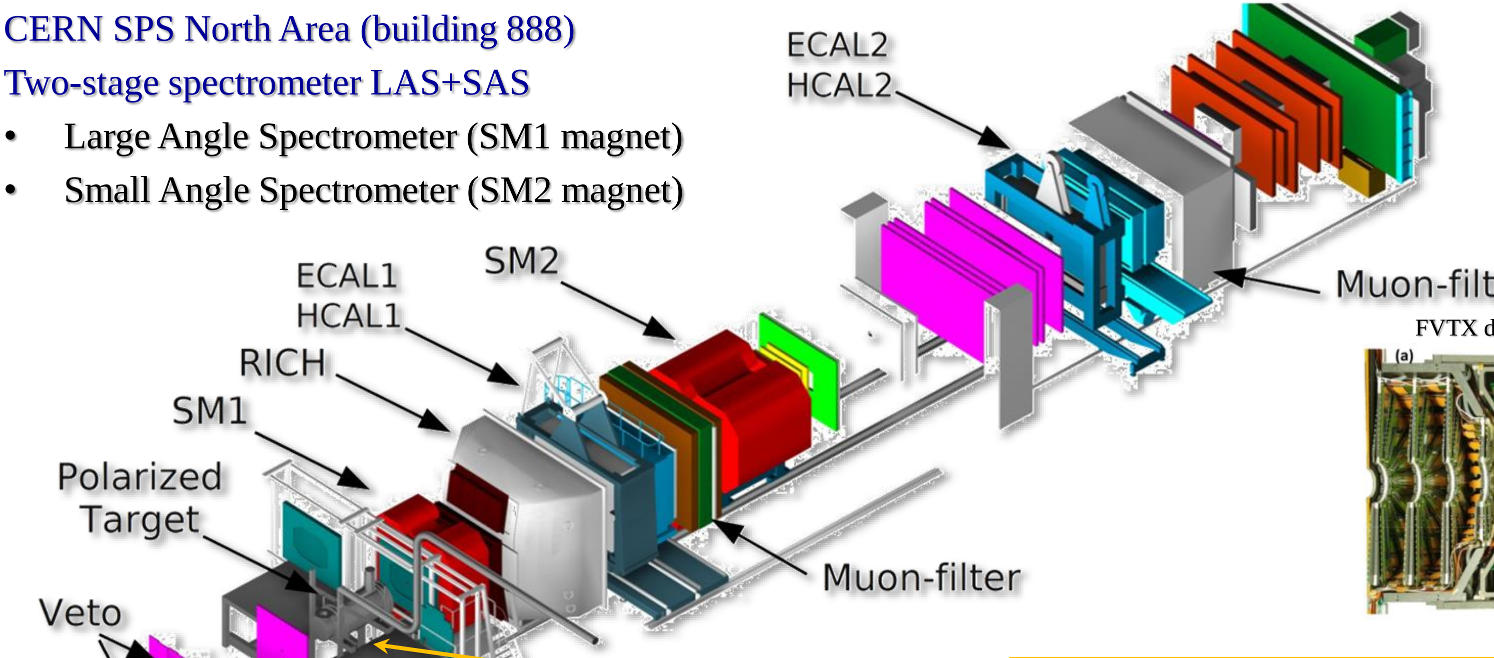
AMBER Phase I-II: DY program setup

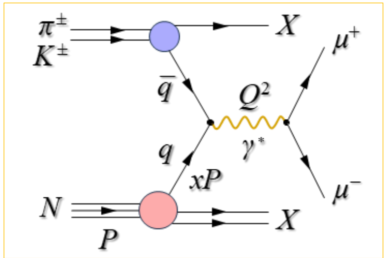
Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

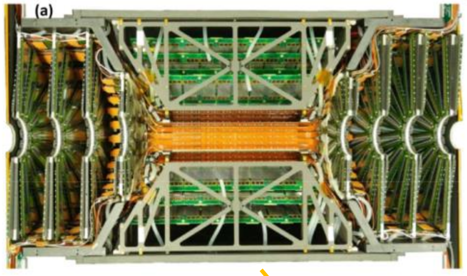
Two-stage spectrometer LAS+SAS

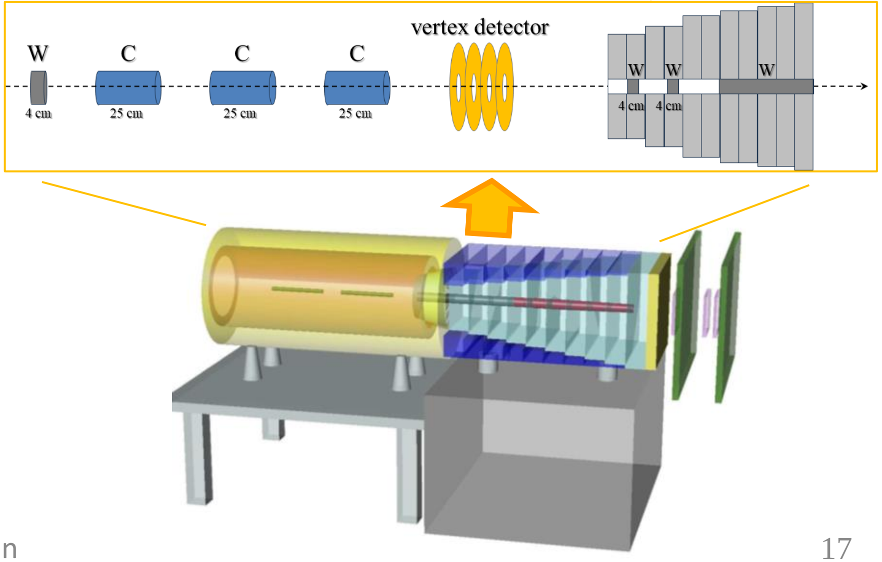
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)





FVTX detector from PHENIX@RHIC





- Secondary h ± 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

Nucleon spin structure: collinear approach ↔TMDs

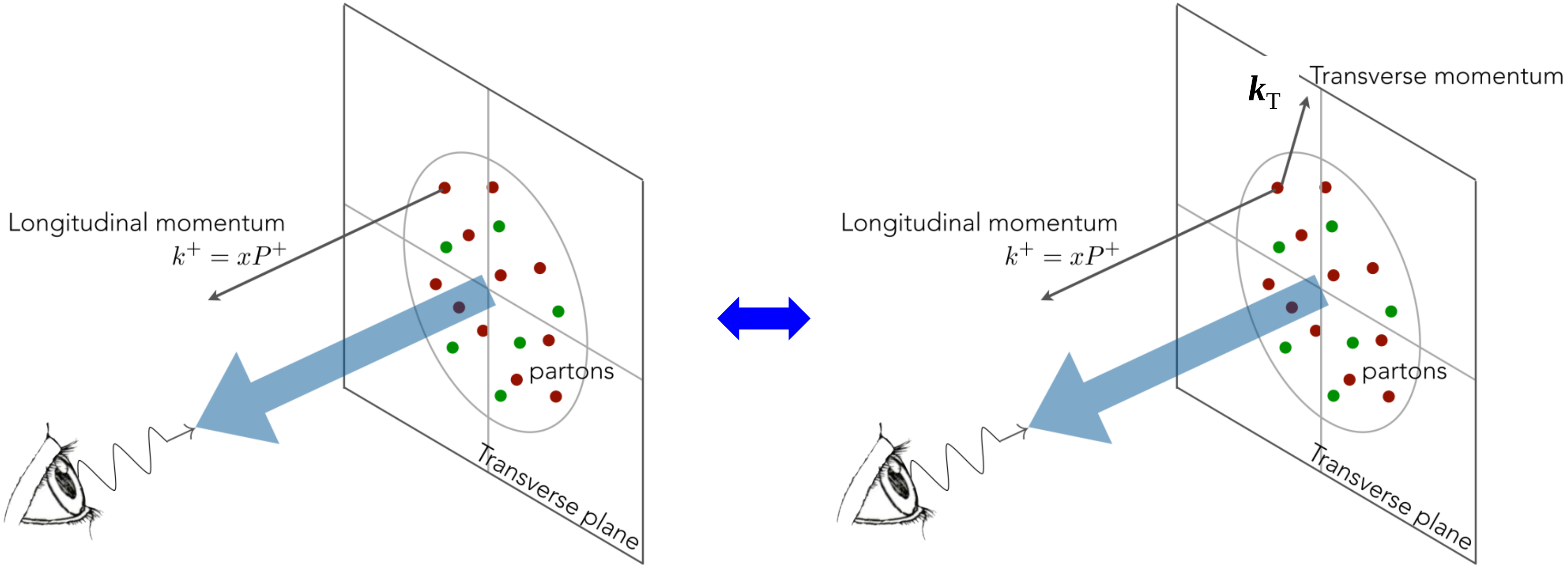
COMPASS
25 years
1997 - 2022

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

↔

		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
	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



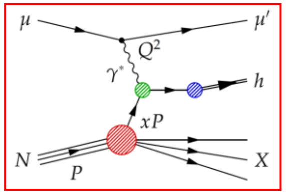
Hadron multiplicities; $h^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ (2016 data)

collinear

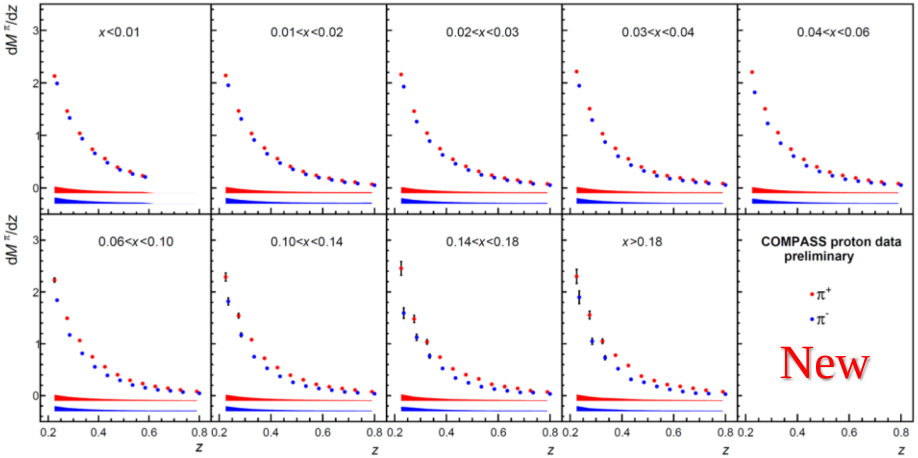
TMD

A set of complex corrections:

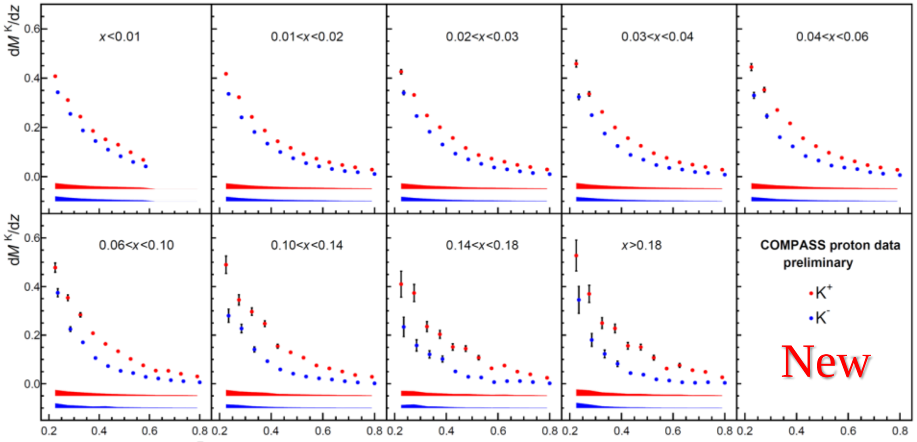
- Acceptance, rad. corrections, PID, diffractive VMs, etc.



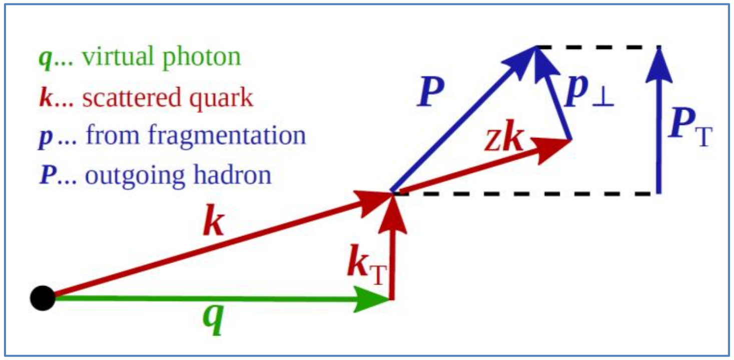
$f_1^q(x, \boldsymbol{k}_T^2)$
number density



New



New


$\boldsymbol{q}$... virtual photon

$\boldsymbol{k}$... scattered quark

$\boldsymbol{p}$... from fragmentation

$\boldsymbol{P}$... outgoing hadron

New radiative corrections

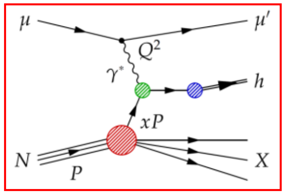
The article is in a final drafting stage

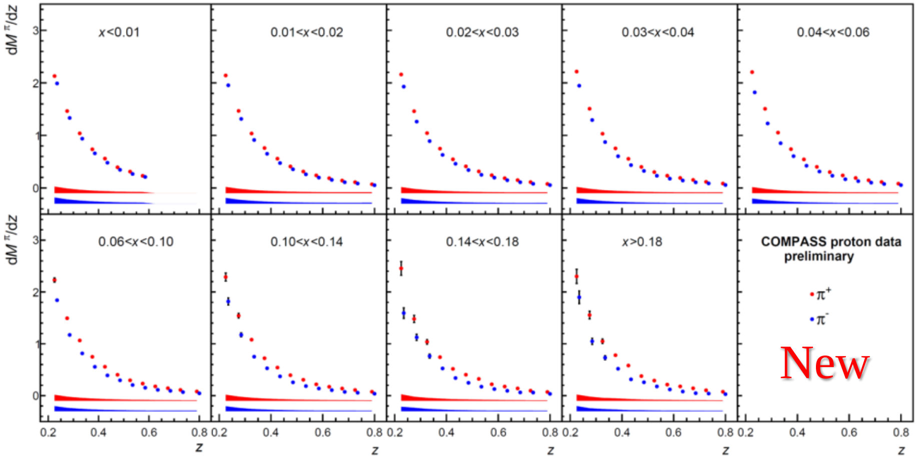
Hadron multiplicities; $h^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ (2016 data)

collinear

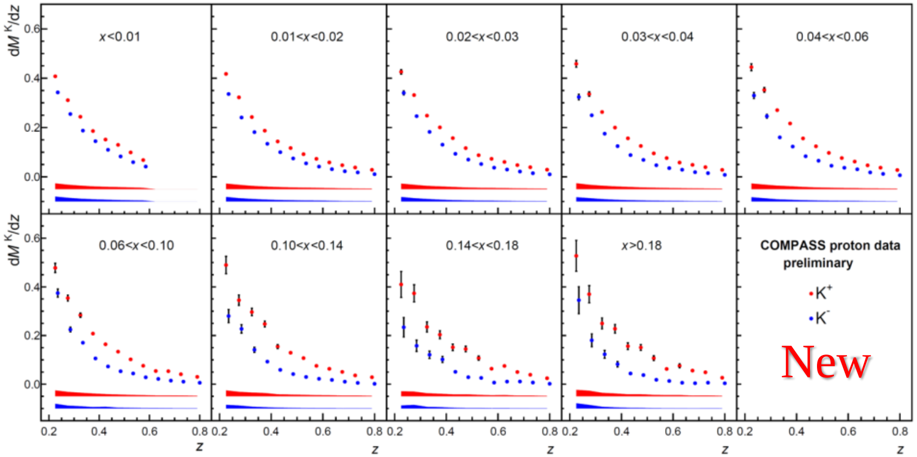
A set of complex corrections:

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





New

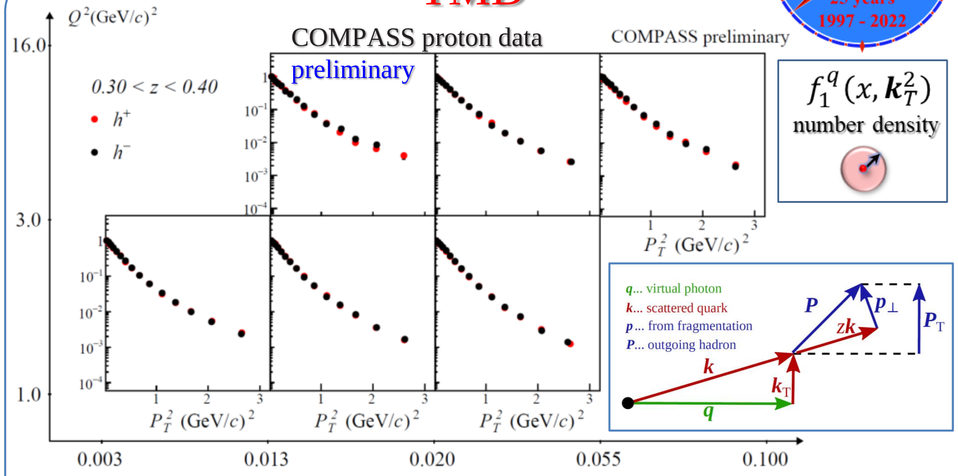


New

New radiative corrections being applied

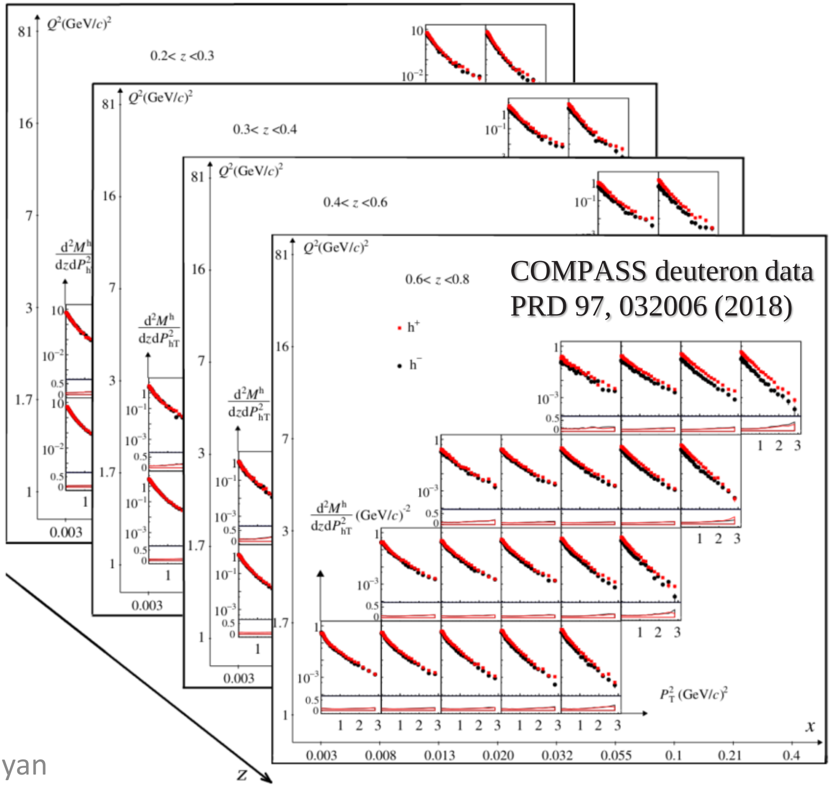
Drafting started for a dedicated article

TMD



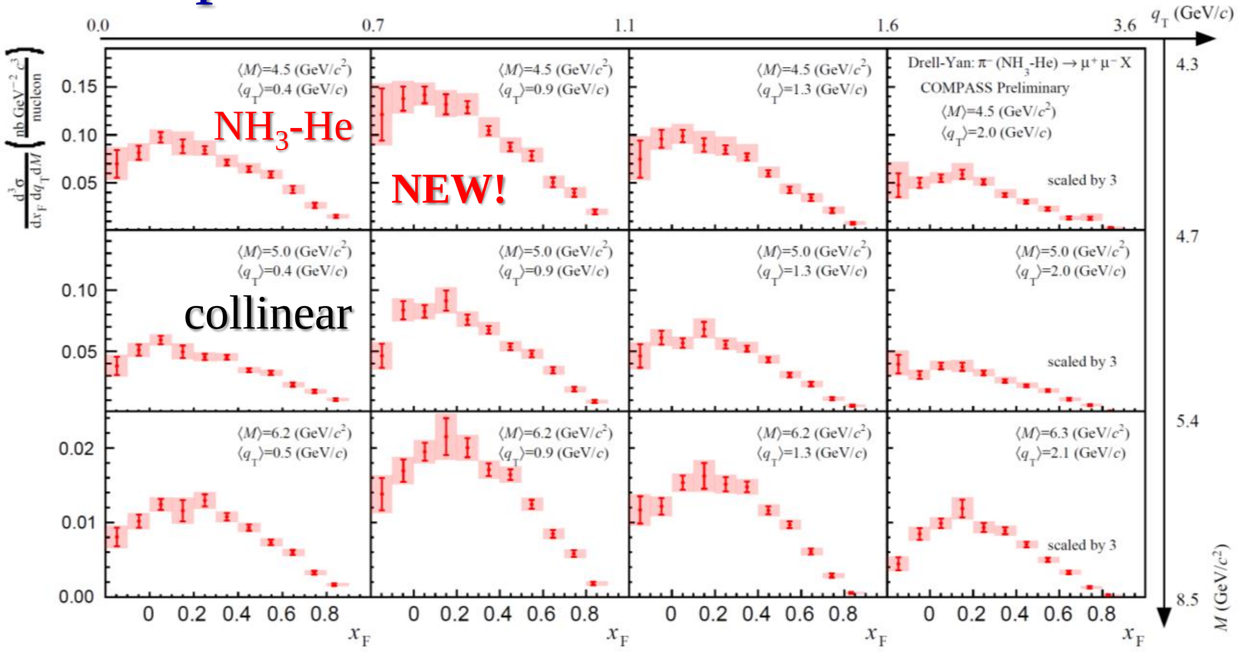
$f_1^q(x, \boldsymbol{k}_T^2)$

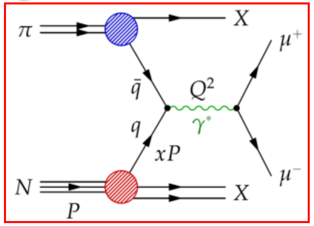
number density

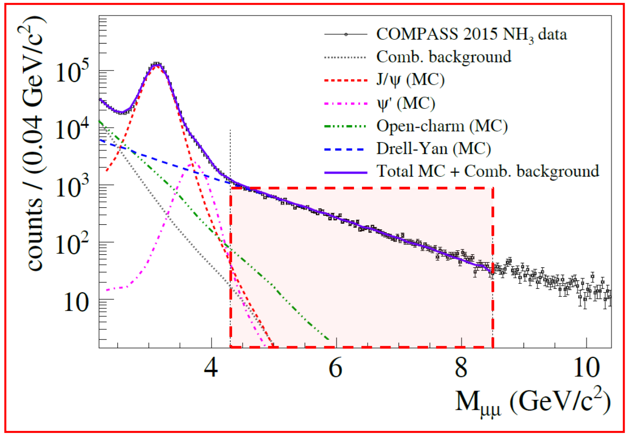


COMPASS deuteron data
PRD 97, 032006 (2018)

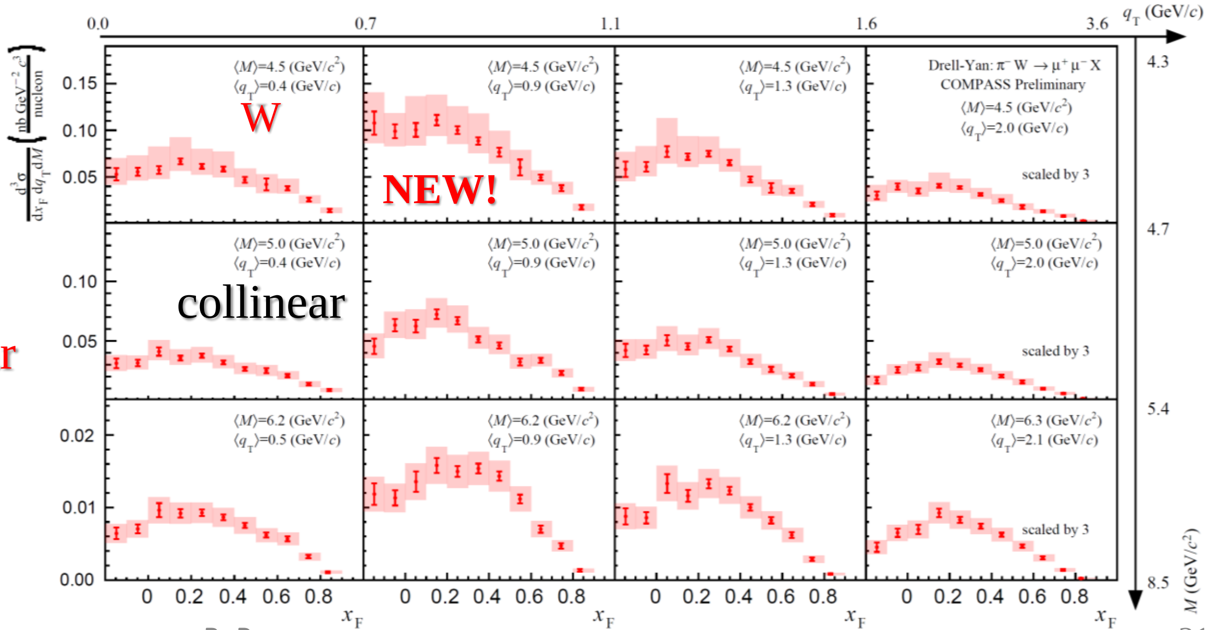
3D unpolarized Drell-Yan cross section on NH_3 and W







- 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



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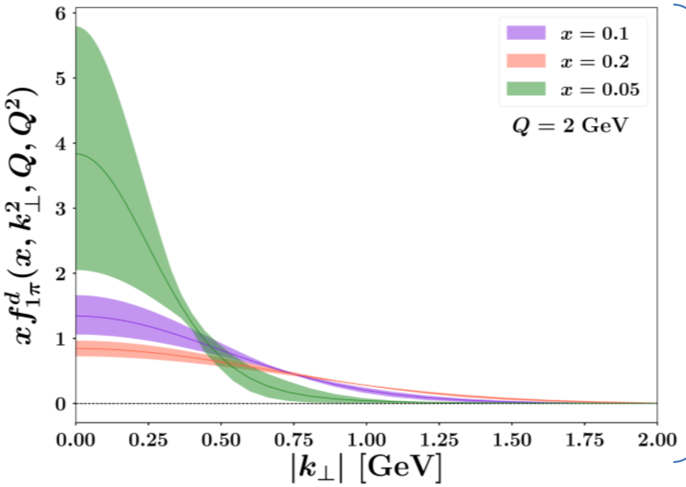
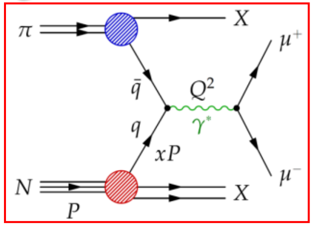
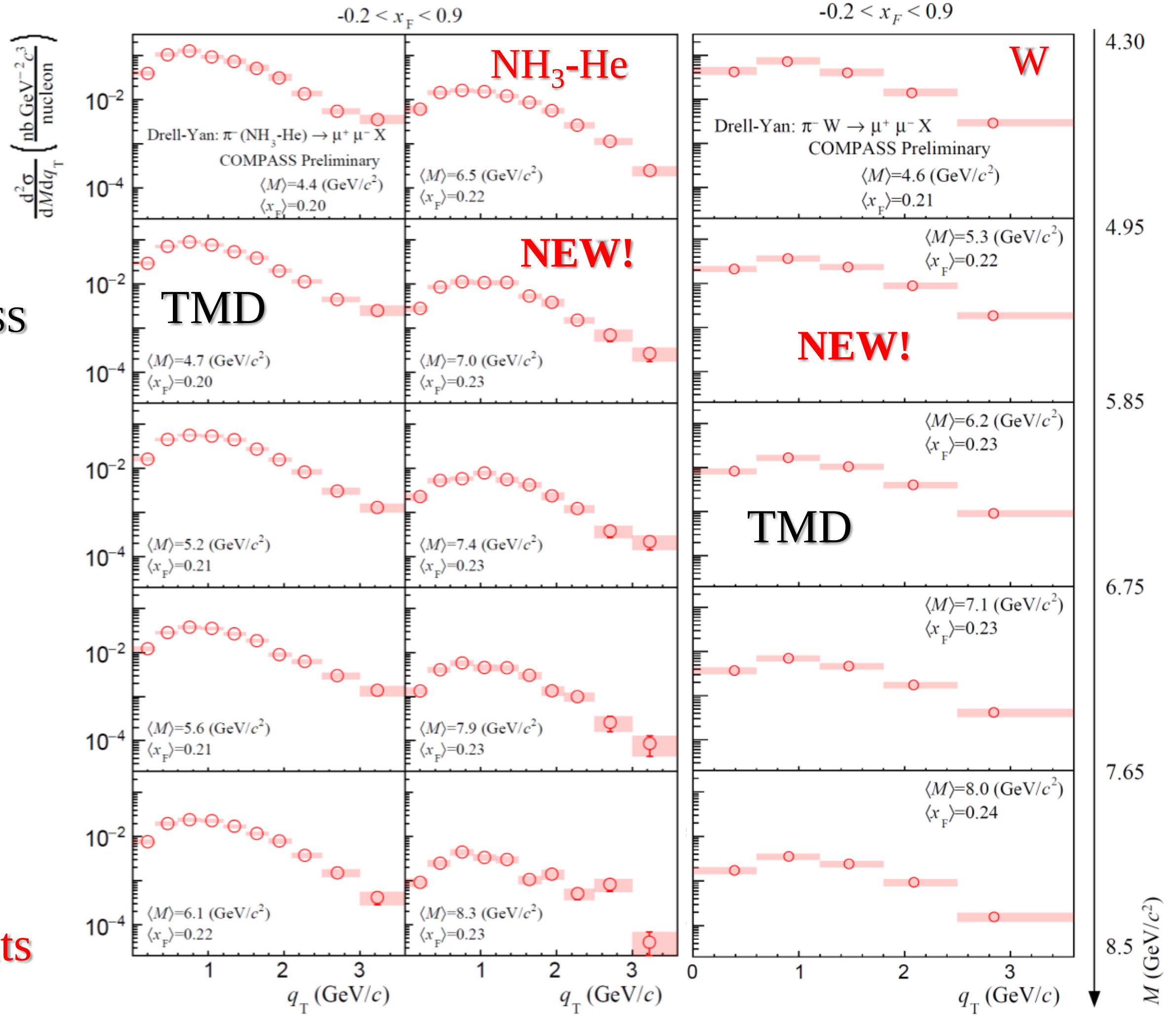


MAP collaboration
Phys. Rev. D. 107, 014014

recent global fit and projections for COMPASS





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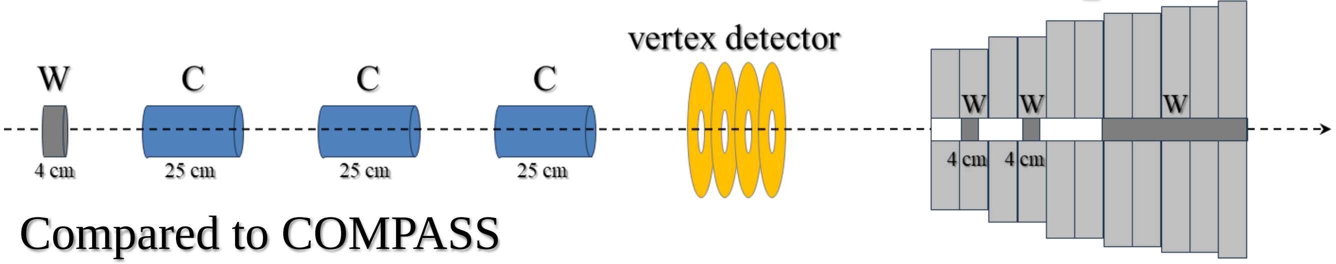
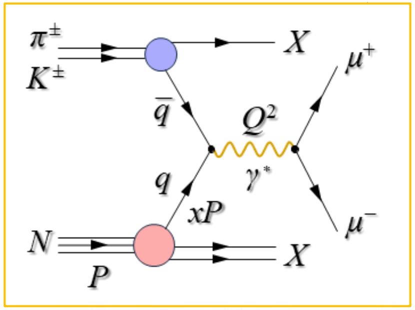
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF
- To be included in future global fits (MAP, JAM, etc.)

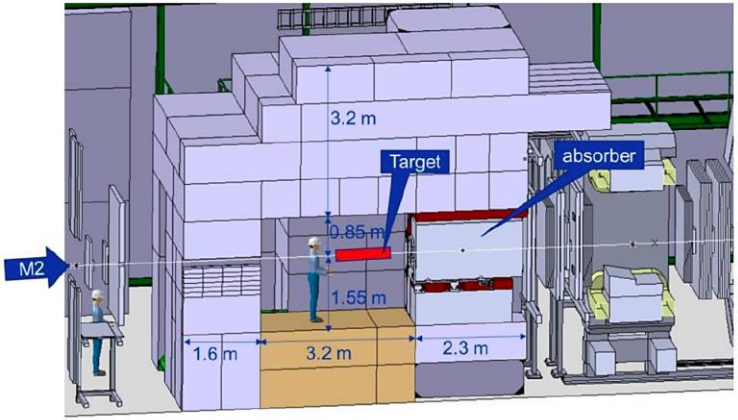
AMBER – $\pi^{\pm}$, $K^{\pm}$ induced dimuon production on C/W

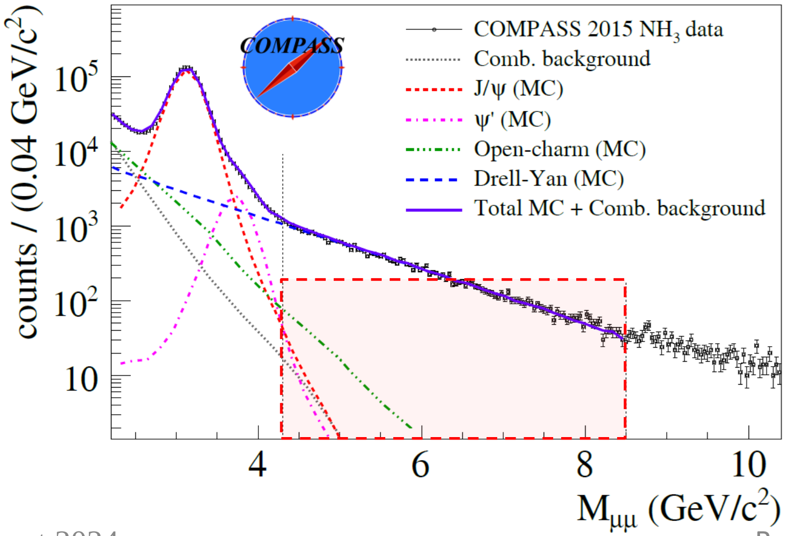


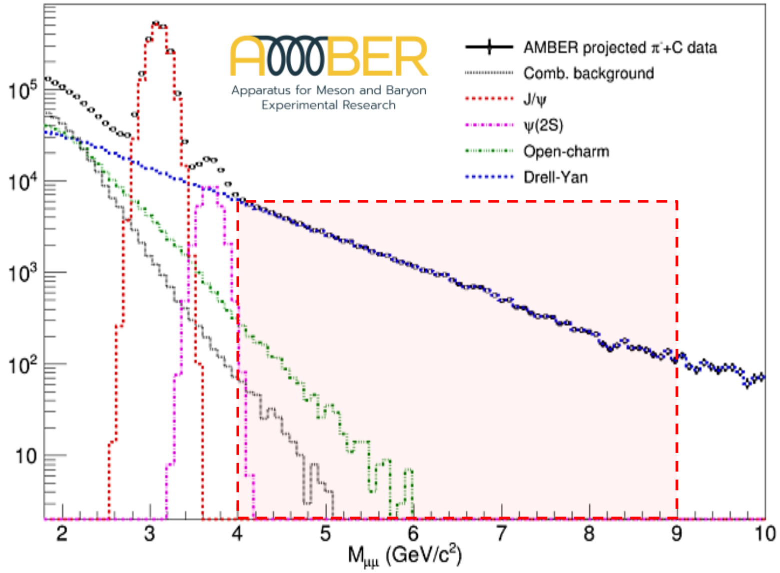


Compared to COMPASS

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

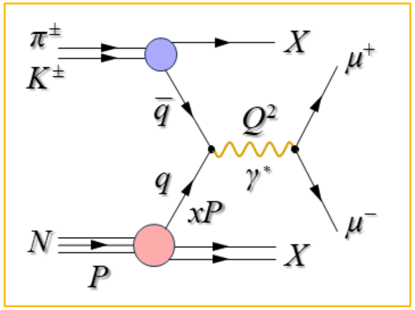






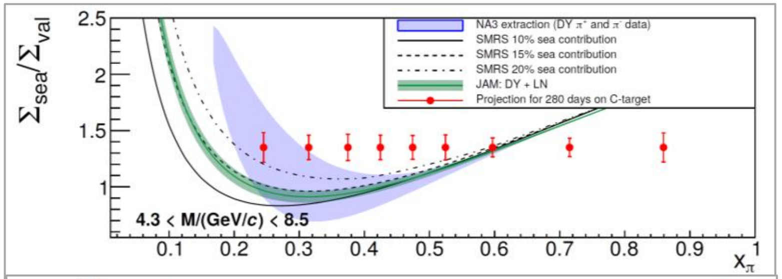
AMBER – $\pi^{\pm}$, $K^{\pm}$ induced dimuon production on C/W

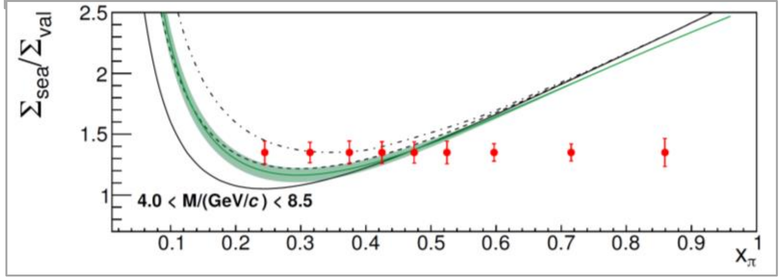
- Unique complementary measurements: $\pi^{\pm}$, $K^{\pm}$
  - Cross-sections, pion and kaon PDFs
    - Data for both collinear and TMD PDF studies
  - Drell-Yan, J/ψ and potentially ψ' channels
  - Study of nuclear effects with C and W



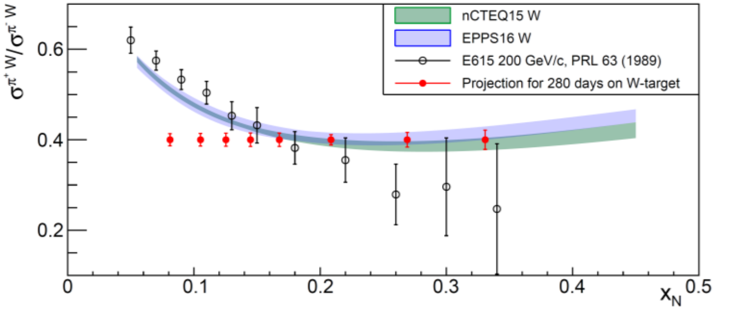
AMBER **J/ψ events**	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

Experiment	Target type	Beam energy (GeV)	Beam type	Beam intensity (part/sec)	DY mass (GeV/c^2)	DY events
E615	20 cm W	252	π^+ π^-	17.6×10^7 18.6×10^7	4.05 – 8.55	5000 30000
NA3	30 cm H$_2$	200	π^+ π^-	2.0×10^7 3.0×10^7	4.1 – 8.5	40 121
	6 cm Pt	200	π^+ π^-	2.0×10^7 3.0×10^7	4.2 – 8.5	1767 4961
NA10	120 cm D$_2$	286 140	π^-	65×10^7	4.2 – 8.5 4.35 – 8.5	7800 3200
	12 cm W	286 194 140	π^-	65×10^7	4.2 – 8.5 4.07 – 8.5 4.35 – 8.5	49600 155000 29300
COMPASS 2015 COMPASS 2018	110 cm NH$_3$	190	π^-	7.0×10^7	4.3 – 8.5	35000 52000
AMBER	75 cm C	190	π^+	1.7×10^7	4.3 – 8.5 4.0 – 8.5	21700 31000
		190	π^-	6.8×10^7	4.3 – 8.5 4.0 – 8.5	67000 91100
	12 cm W	190	π^+	0.4×10^7	4.3 – 8.5 4.0 – 8.5	8300 11700
		190	π^-	1.6×10^7	4.3 – 8.5 4.0 – 8.5	24100 32100



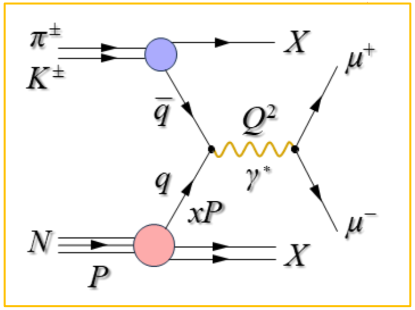


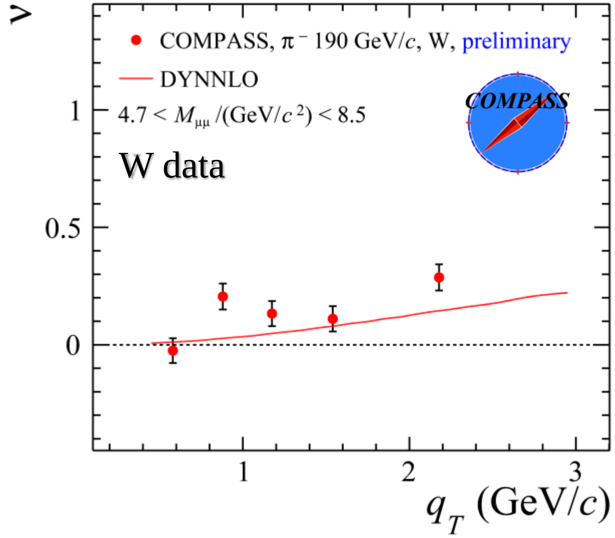
$$\Sigma_{val} = \sigma^{\pi^- C} - \sigma^{\pi^+ C}\text{: only valence-valence}$$
$$\Sigma_{sea} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}\text{: no valence-valence}$$



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

- Unique complementary measurements: $\pi^{\pm}$, $K^{\pm}$
  - Cross-sections, pion and kaon PDFs
    - Data for both collinear and TMD PDF studies
  - Drell-Yan, J/ψ and potentially ψ' channels
  - Study of nuclear effects with C and W
  - Azimuthal asymmetries (ν, μ, Lam-Tung relation)
  - J/ψ polarization measurements (λ polar angle asymmetry)
  - Study of the J/ψ production mechanisms
  - Unique kaon-induced Drell-Yan and J/ψ data
- Possibilities for polarized measurements in PHASE-II?





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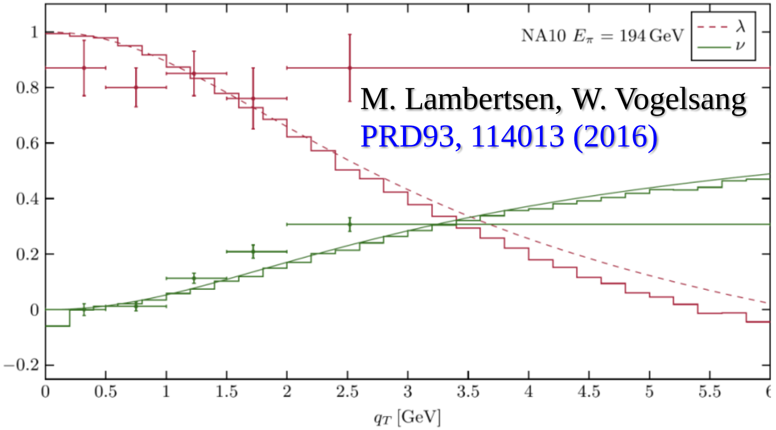
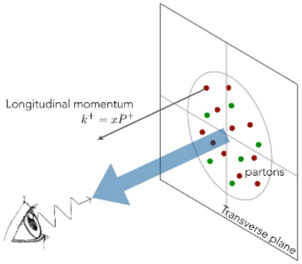
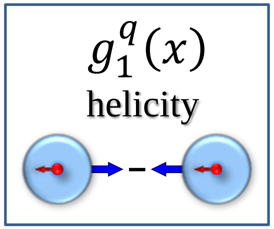


M. Lambertsen, W. Vogelsang
PRD93, 114013 (2016)

Nucleon spin structure: helicity $g^q_{1,p}(x)$

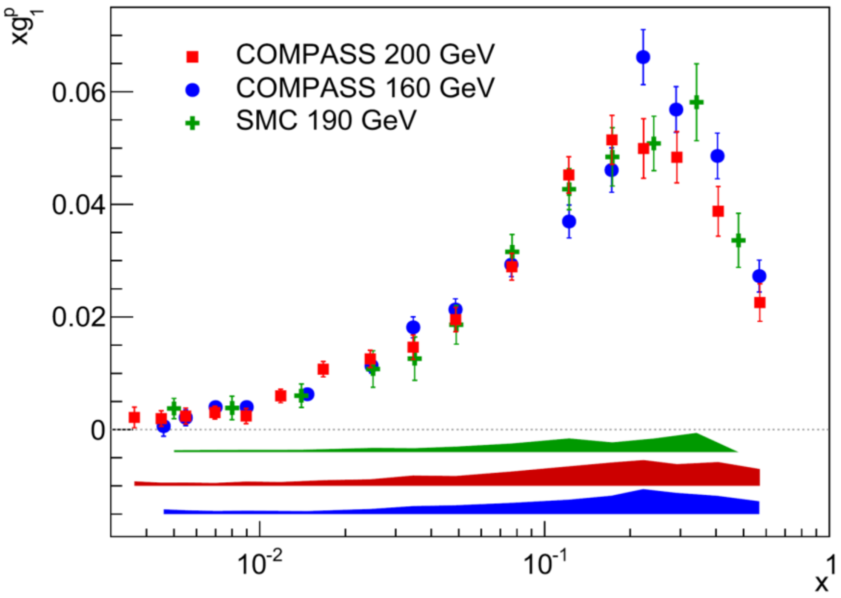




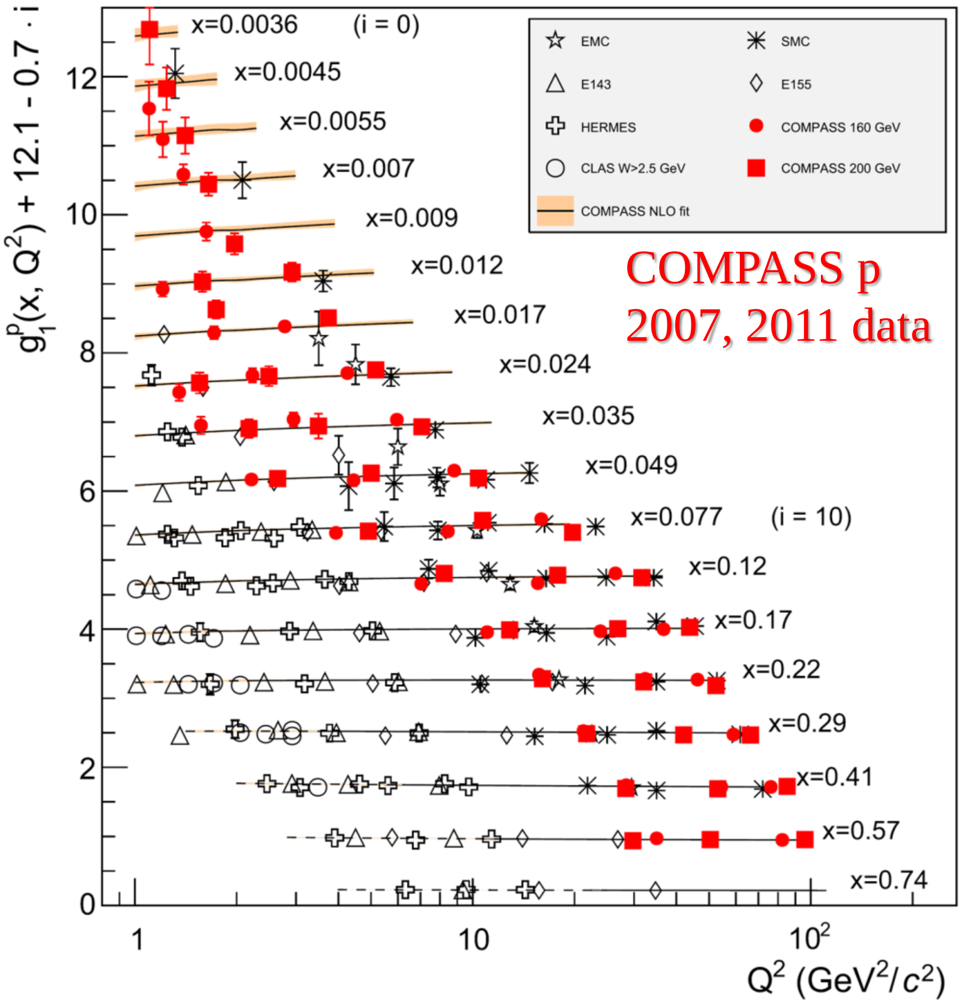
$g_1^q(x)$

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 $g_1^p(x)$

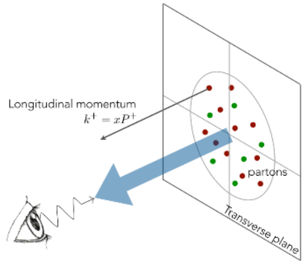


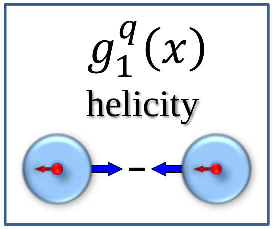
COMPASS PLB 753(2016)18



COMPASS p 2007, 2011 data

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



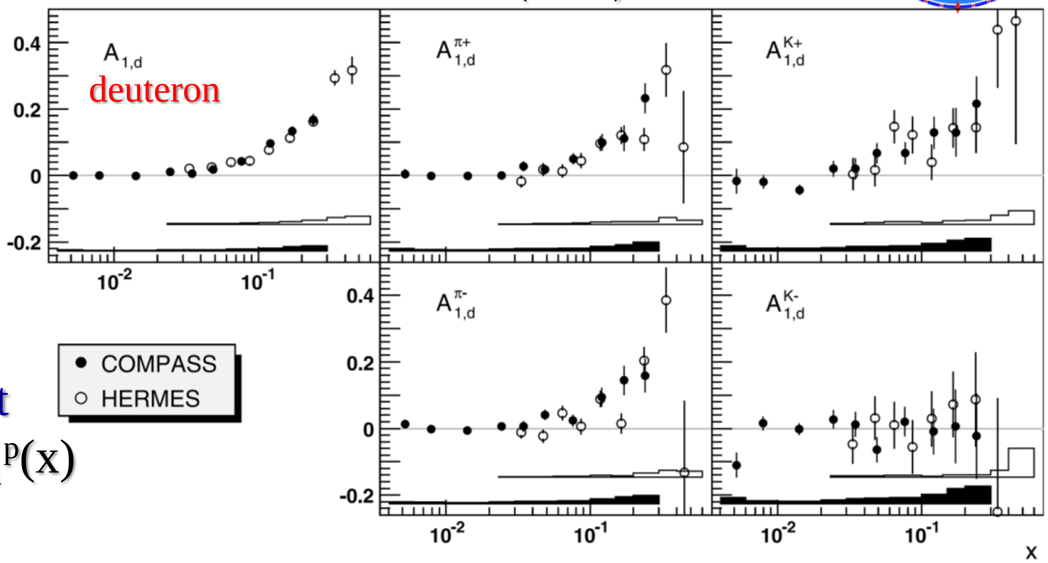


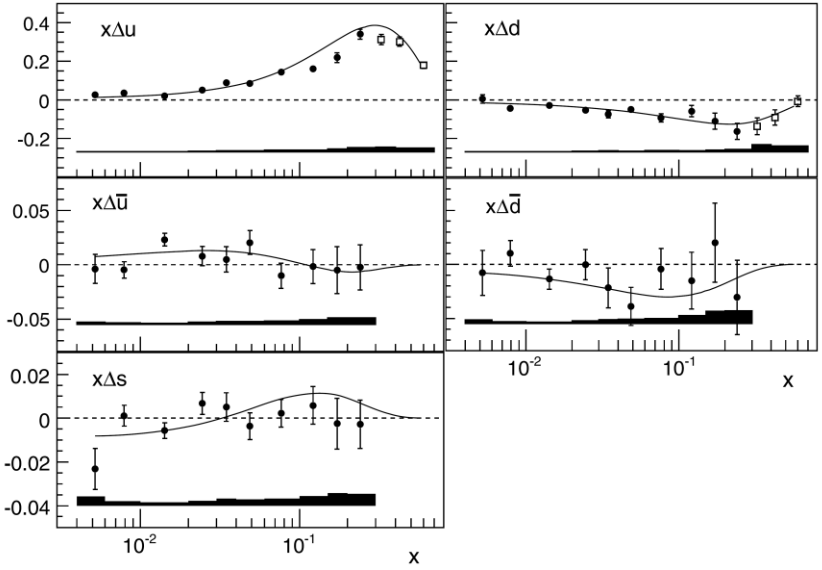
$g_1^q(x)$

helicity

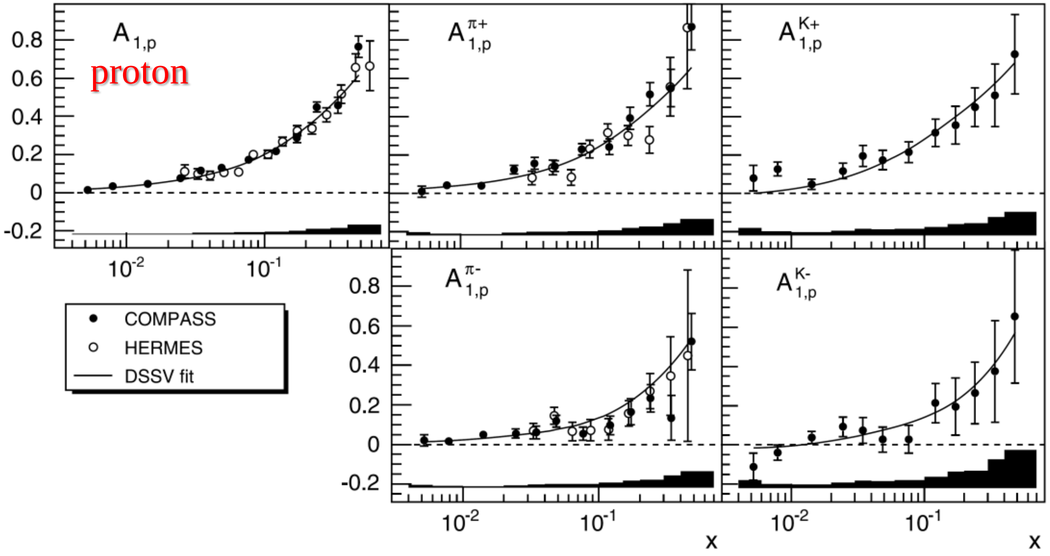
- COMPASS contribution: lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$
- Both inclusive and semi-inclusive measurements – access to flavor

COMPASS PLB 680 (2009) 217

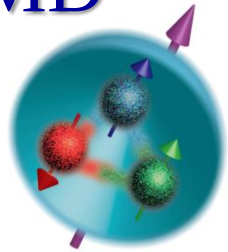




COMPASS PLB 693 (2010) 227



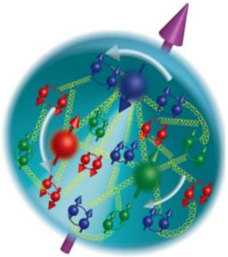
Nucleon spin structure: TMD



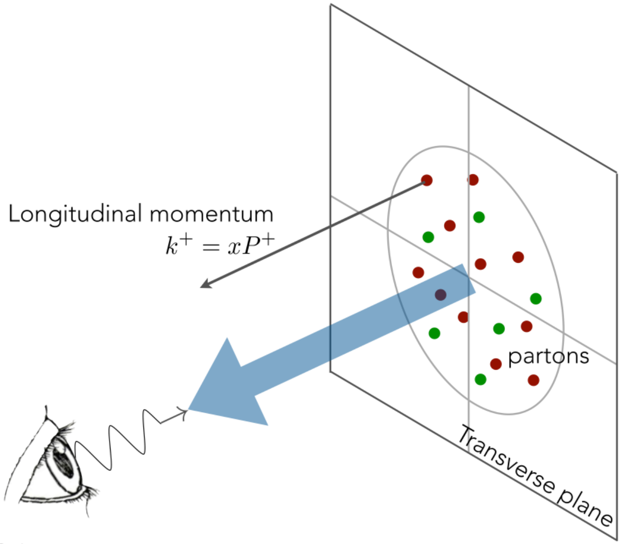
- 1964 Quark model

- 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



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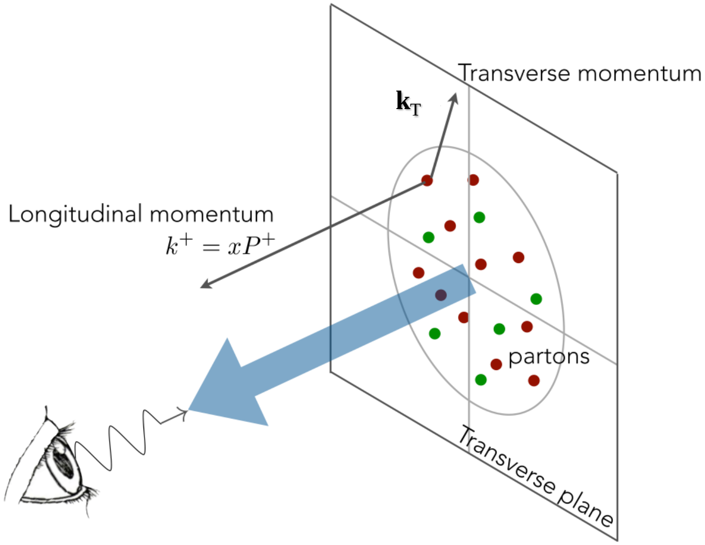

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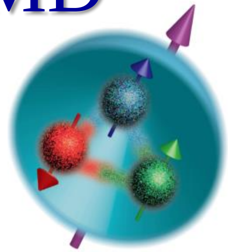
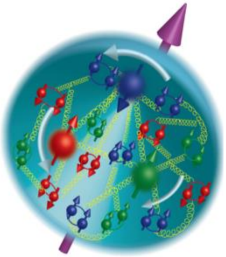


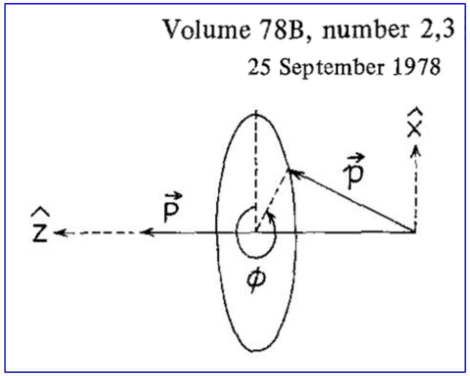
- 1964 Quark model

- 1969 Parton model

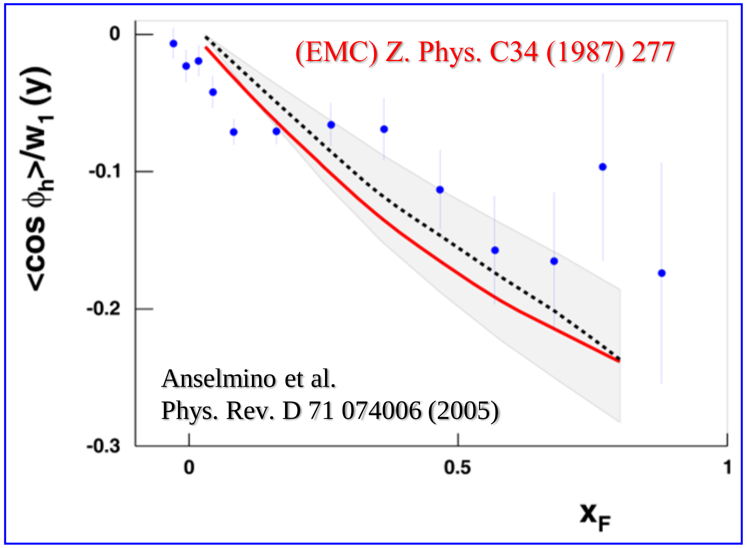


- 1973 asymptotic freedom and QCD

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



Volume 78B, number 2,3
25 September 1978



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

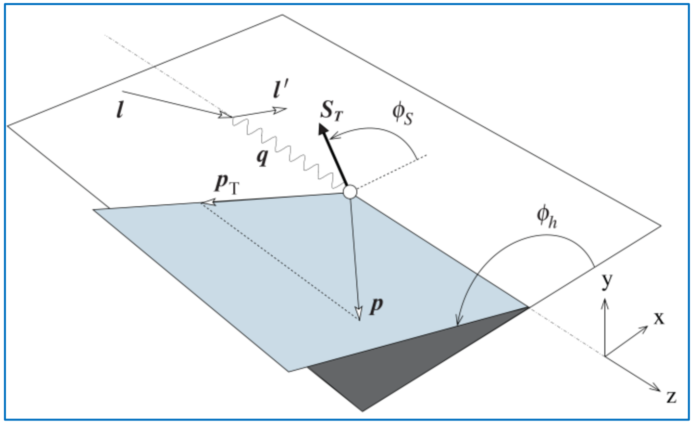
Anselmino et al.
Phys. Rev. D 71 074006 (2005)

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

Cahn effect in SIDIS

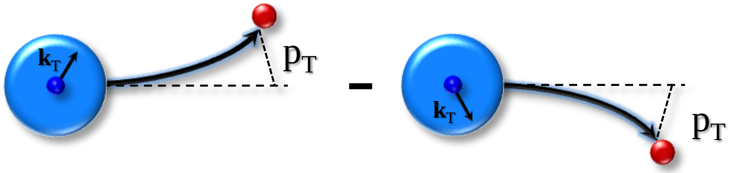
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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



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

number density

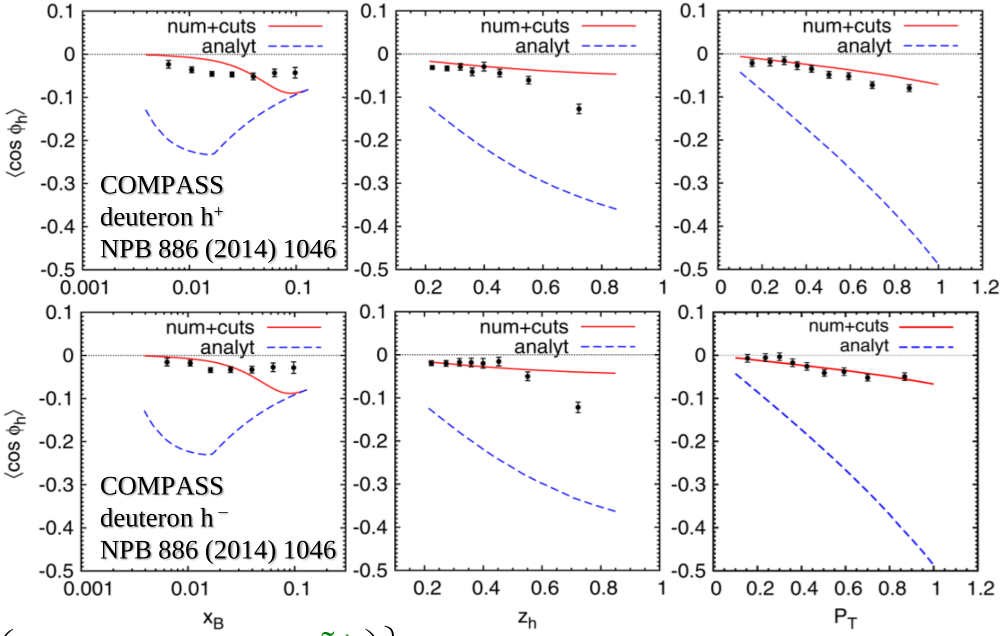


As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

- Measurements by different experiments

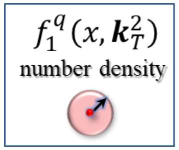


$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

Cahn effect in SIDIS

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

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


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

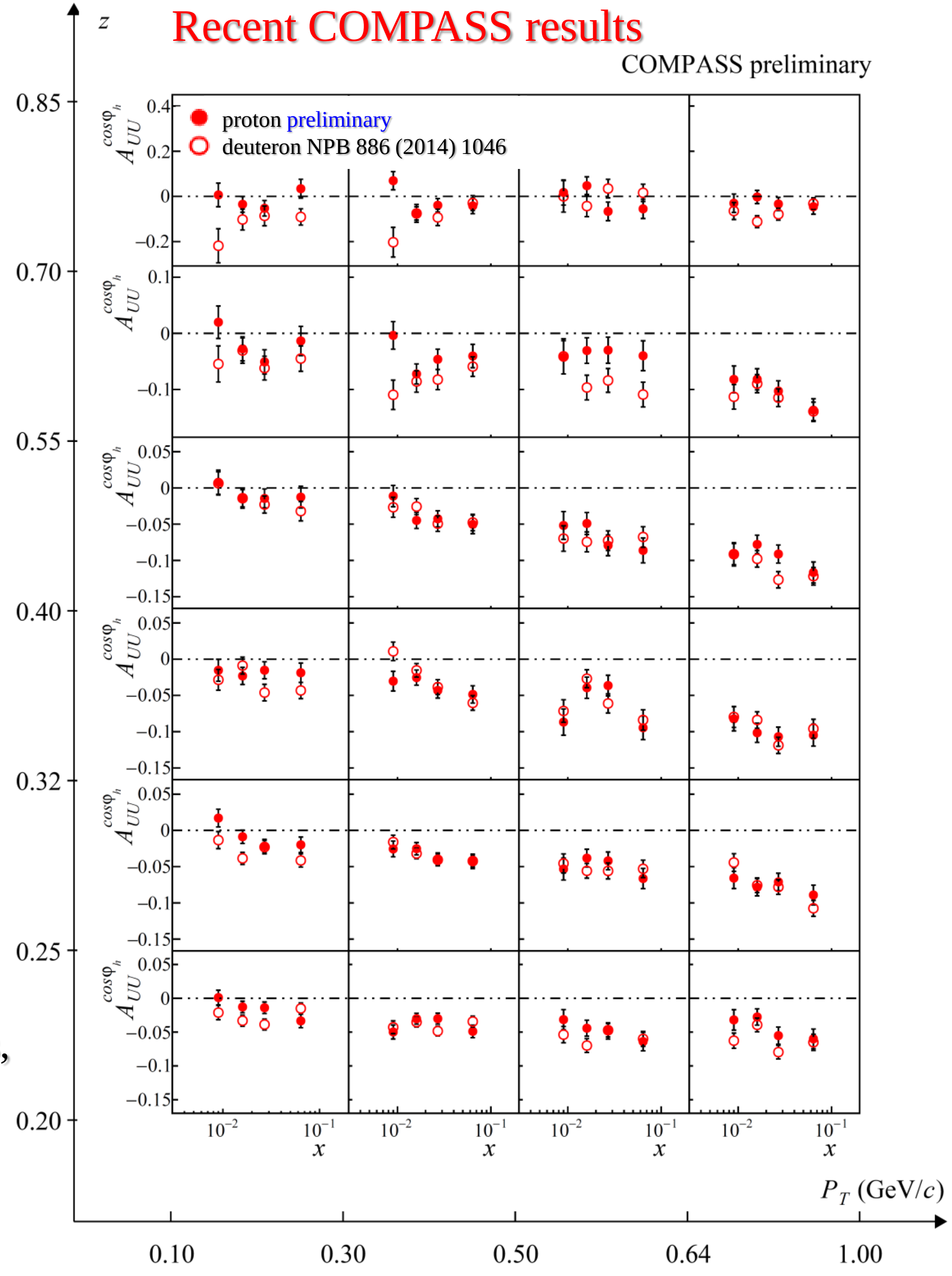
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
- Strong Q^2 dependence – unexplained

Recent COMPASS results



Nucleon spin structure (twist-2): collinear approach ↔TMDs

quark

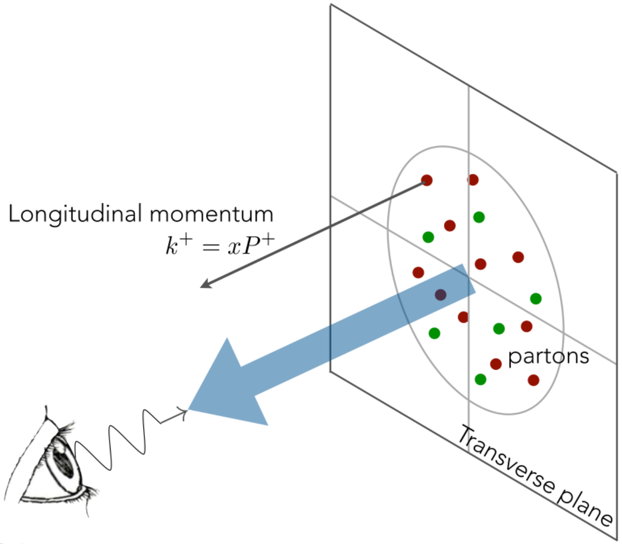
		U	L	T
nucleon	U	$f_1^q(x)$ number density		
	L		$g_1^q(x)$ helicity	
	T			$h_1^q(x)$ transversity

↔

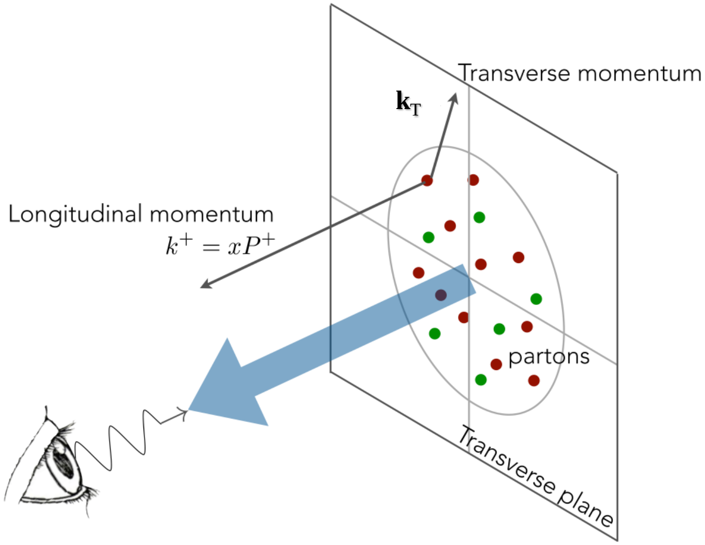
quark

		U	L	T
nucleon	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

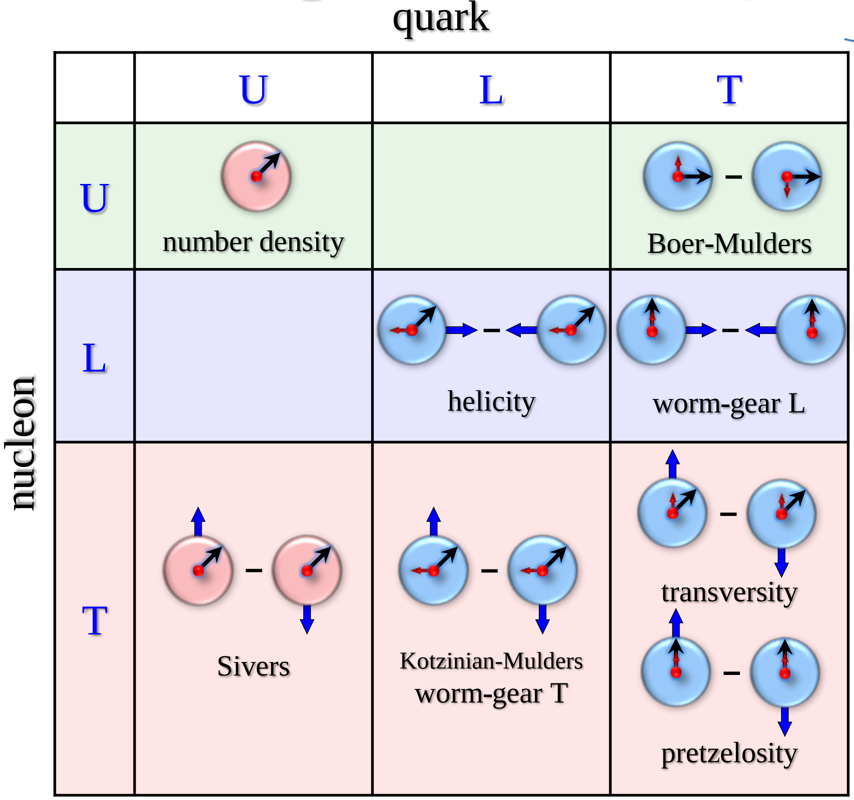
- PDFs – universal (process independent) objects; T-odd PDFs – conditionally universal



↔



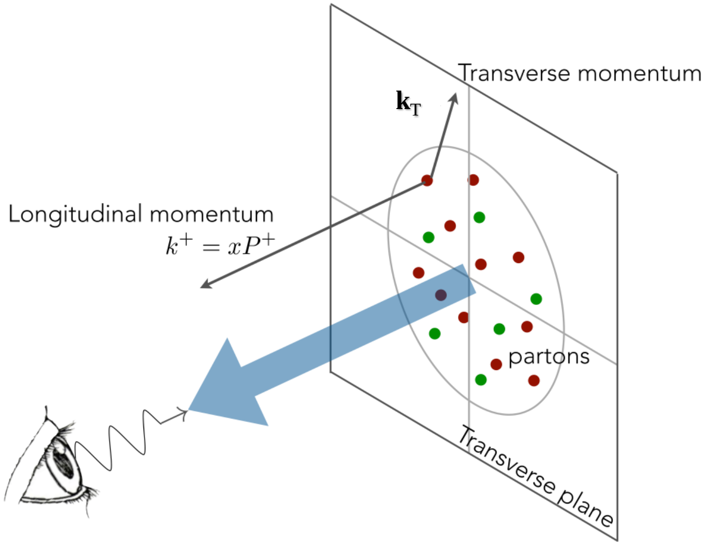
Nucleon spin structure (twist-2): TMDs



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

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

nucleon \ quark	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



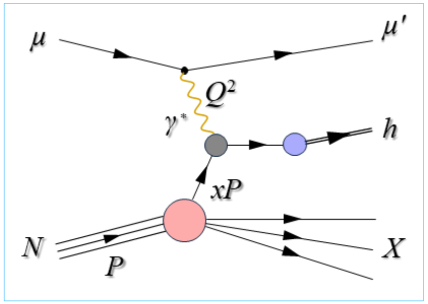
SIDIS x-section and TMDs at twist-2

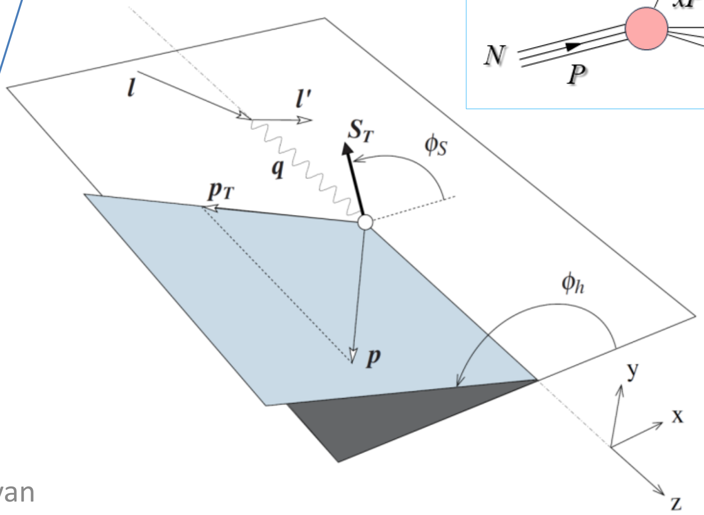
$$
\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)
$$

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

quark

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

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

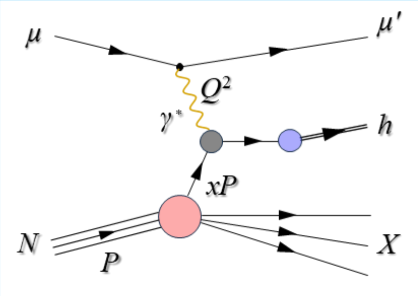
$$\times\left\{\begin{aligned}
&\boxed{1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h}\\
&\boxed{+\,S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h+S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL}}\\
&+\,S_T\left[\begin{aligned}&A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)\\&+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)\\&+\va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

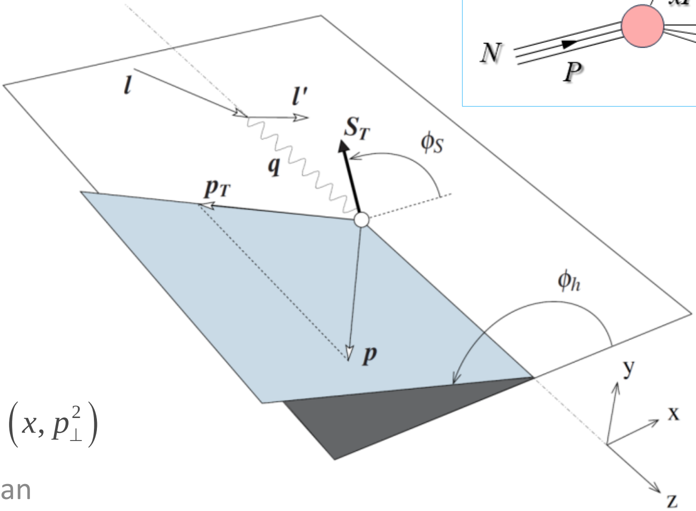
quark

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

$A_{UU}^{\cos 2\phi_h} \propto \underline{h_1^{\perp q}} \otimes \underline{H_{1q}^{\perp h}}$	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





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

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

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)$$

$$\times\left\{\begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin\left(2\varphi_{CS}+\varphi_S\right) \end{array}\right) \end{array}\right] \end{array}\right\}$$

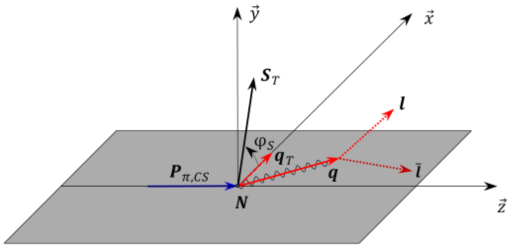
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

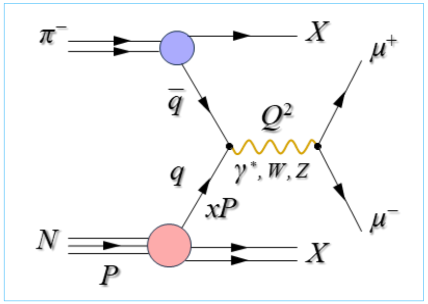
		quark		
		U	**L**	**T**
nucleon	**U**	$f_1^q(x,\boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ Boer-Mulders T-odd
	L		$g_1^q(x,\boldsymbol{k}_T^2)$ Helicity	$h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ worm-gear L
	T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x,\boldsymbol{k}_T^2)$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

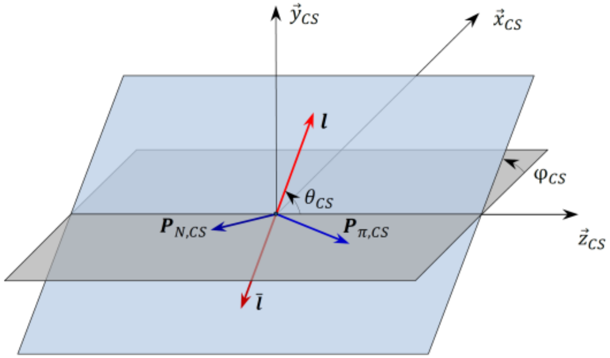
$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$	Boer-Mulders (T-odd)
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	Sivers (T-odd)
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$	Transversity
$A_T^{\sin(2\varphi_{CS}+\varphi_S)}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

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

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







SIDIS x-section and TMDs at twist-2

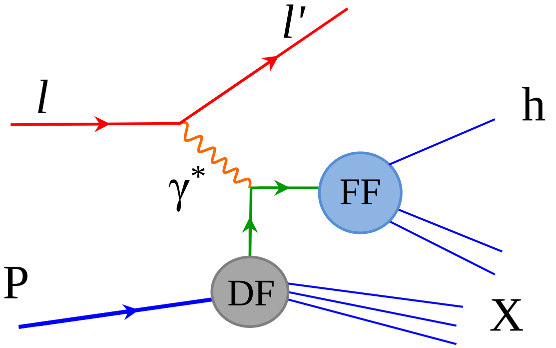
COMPASS 25 years 1997 - 2022

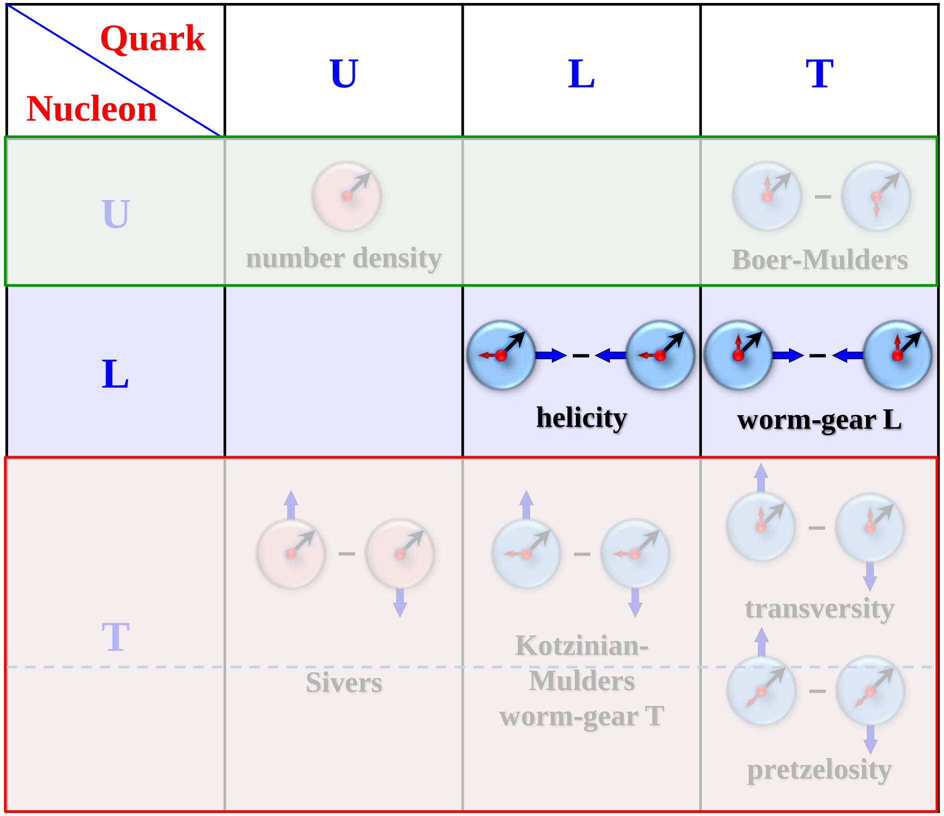
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} =$$

All measured by COMPASS

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

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





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

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

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

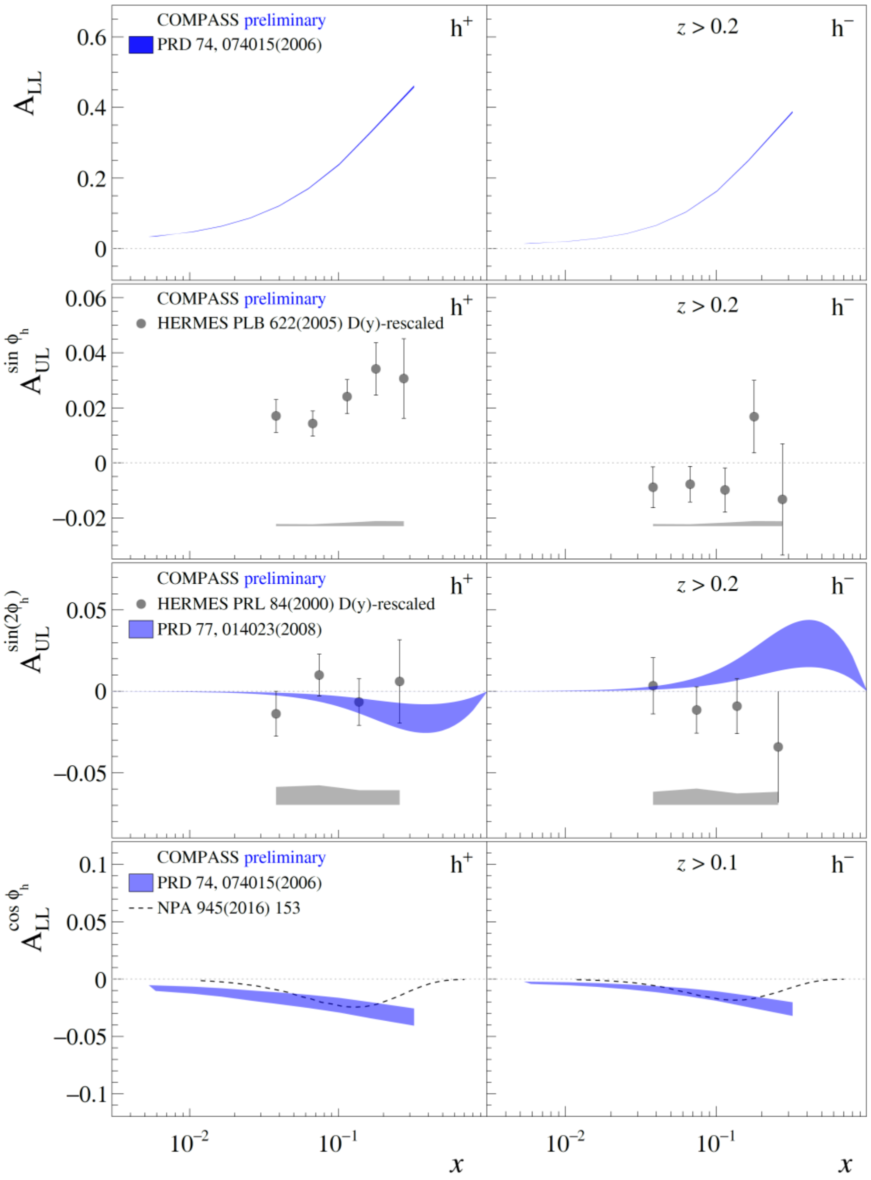
$$\left.+\;S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL}+\sqrt{2\varepsilon\left(1-\varepsilon\right)}A_{LL}^{\cos\phi_h}\,\cos\phi_h\right]\right\}$$

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

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

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

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



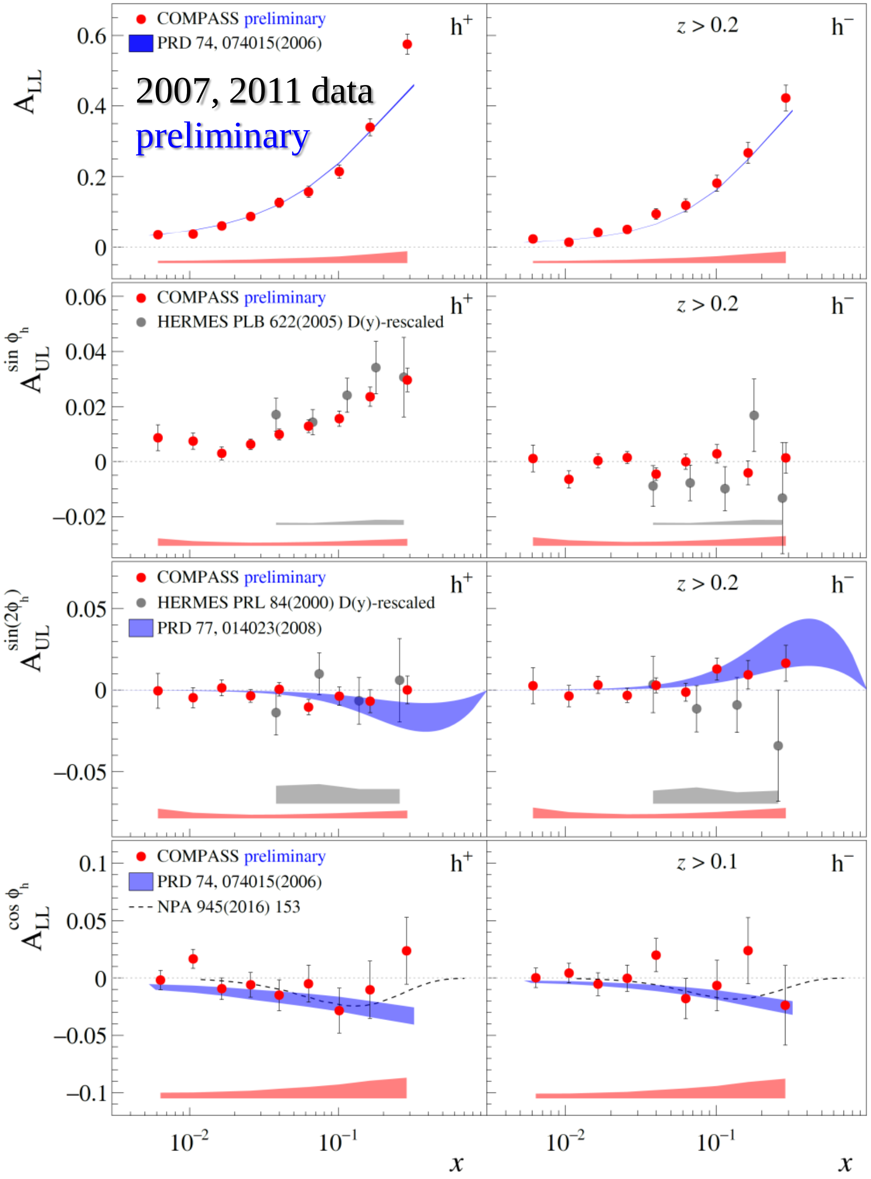
SIDIS: target longitudinal spin dependent asymmetries

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

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

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

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

$A_{UL}^{\sin 2\phi_h}$

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

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

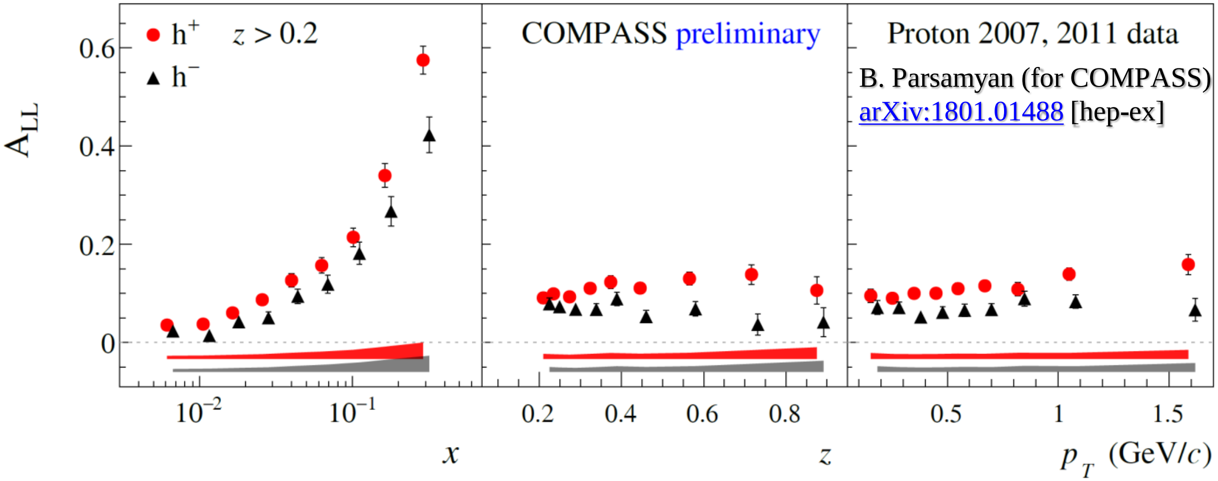
- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models

SIDIS: target longitudinal spin dependent asymmetries

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

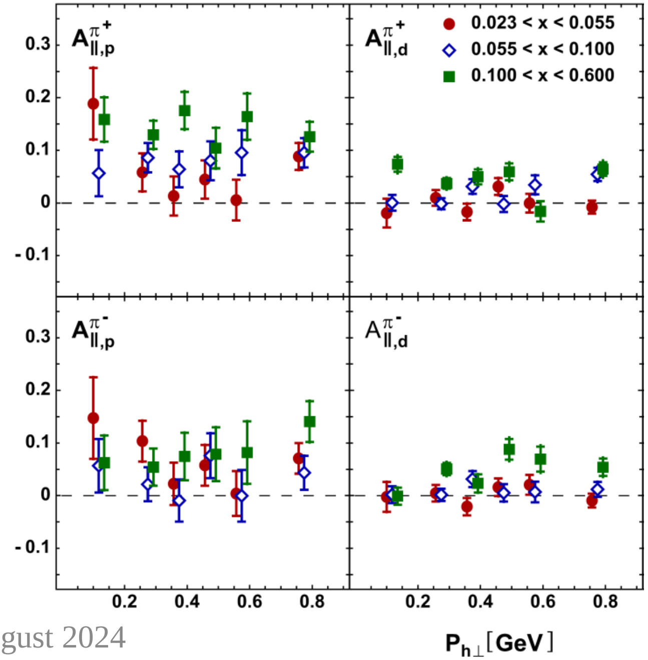
$$\boxed{F_{LL}^1 = \mathcal{C}\left\{g_{1L}^q D_{1q}^h\right\}}$$

- 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

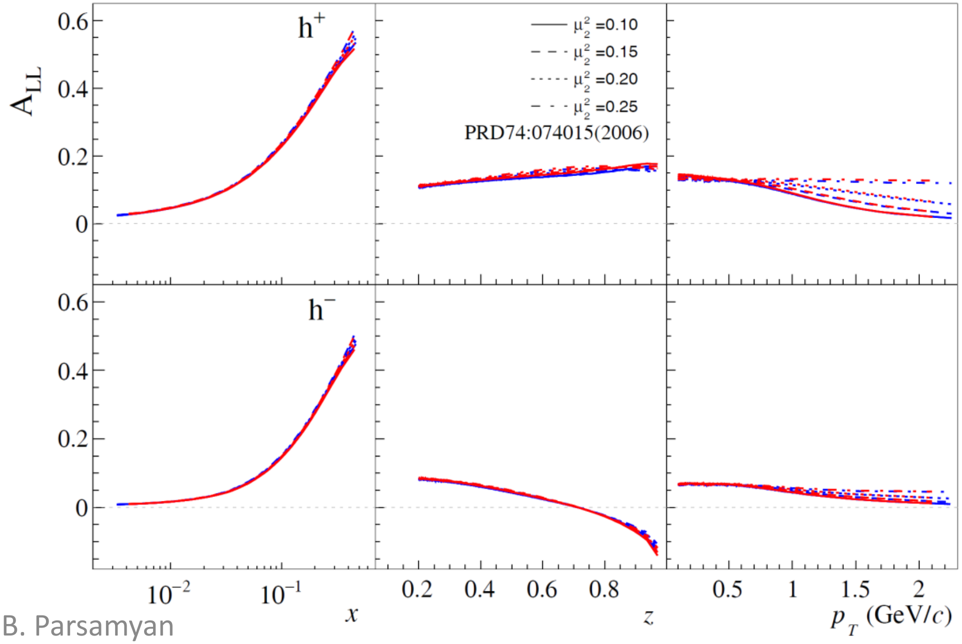


B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]

HERMES: PRD 99, 112001 (2019)



COMPASS Proton-2007, -2011 kinematics

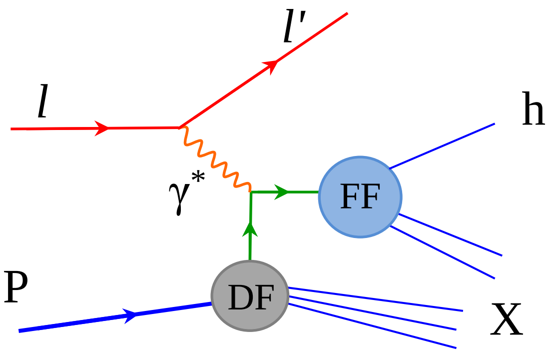


SIDIS x-section and TMDs at twist-2: TSAs

All measured by COMPASS

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

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



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

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

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

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

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

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

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

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

Twist-2

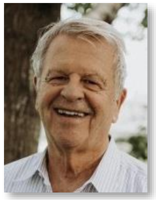
Twist-3

SIDIS TSAs: Collins and Sivers effects (deuteron)

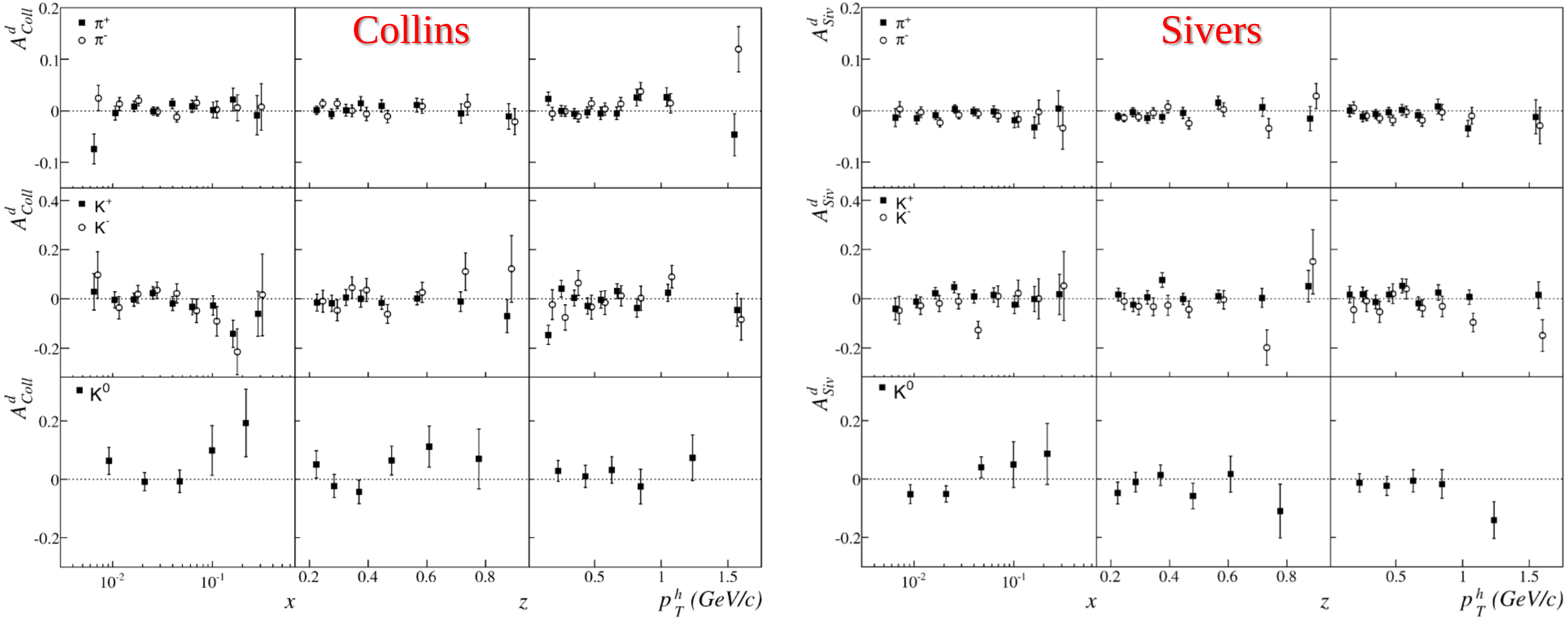
$$\frac{d\sigma}{dxdydzdp_T^2\, d\phi_h\, d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+\ldots+S_{\mathrm{T}}\, A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+S_{\mathrm{T}}\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)\ldots\right\}$$

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

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



COMPASS PLB 673 (2009) 127



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

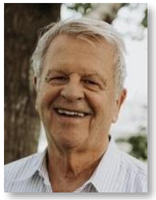
SIDIS TSAs: Collins and Sivers effects (proton)

COMPASS
25 years
1997 - 2022

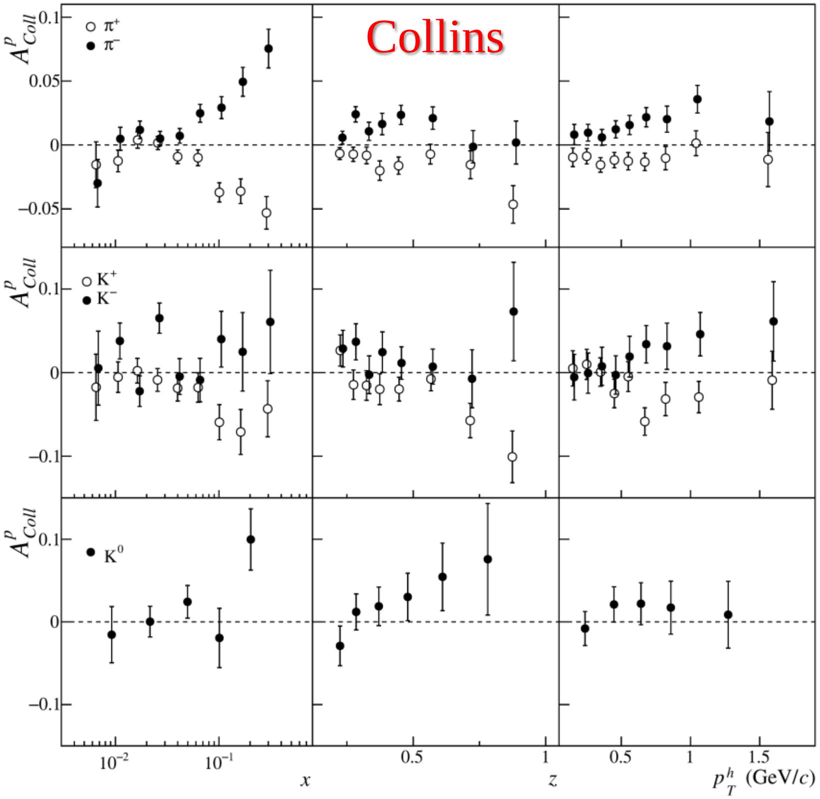
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_T\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)+S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\ldots\right\}$$

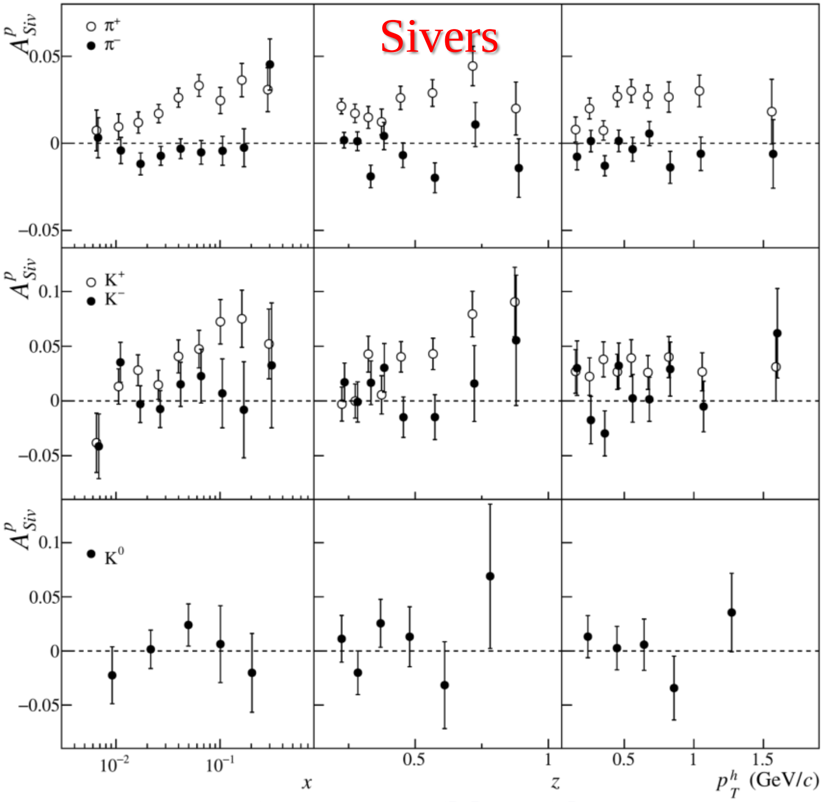
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h}\,h_1^q H_{1q}^{\perp h}\right]$$

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



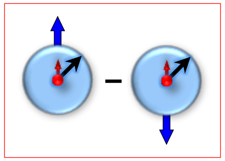
COMPASS PLB 744(2015)250





- 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

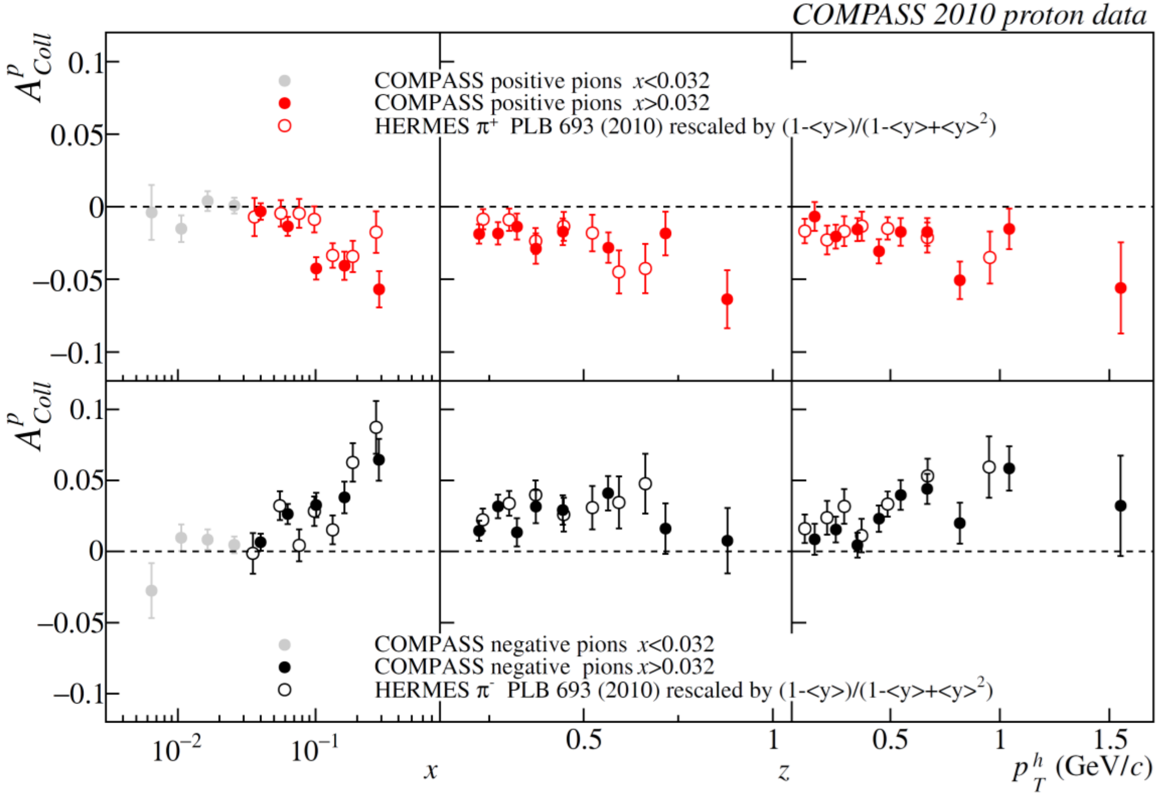


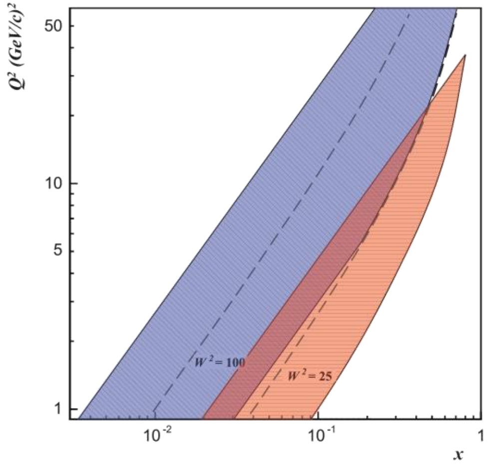
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\ \right\}$$

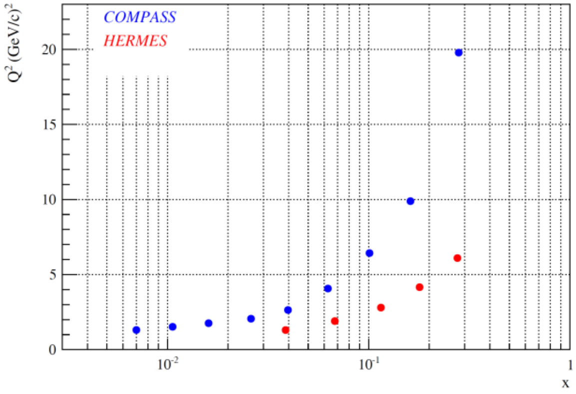
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

- 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

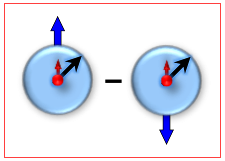
COMPASS PLB 744 (2015) 250







SIDIS TSAs: Collins effect and Transversity

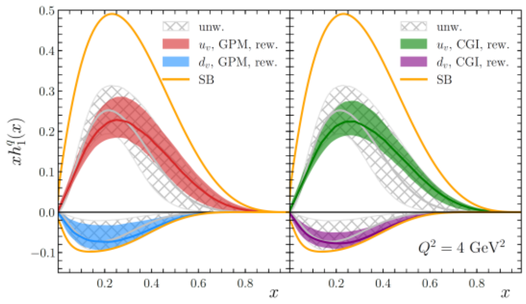


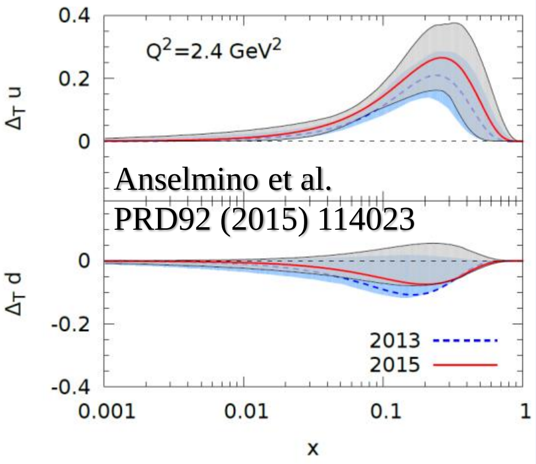
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\dots+\ S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right)+\dots\right\}$$

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

- 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

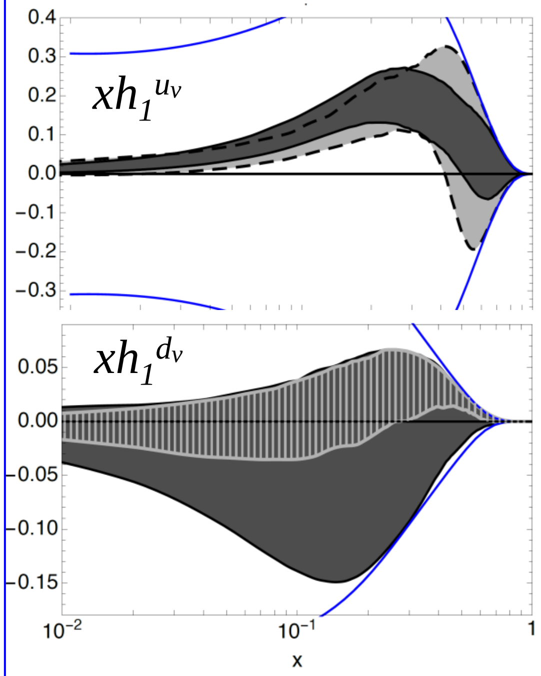
Boglione et al. PLB 854 (2024) 138712



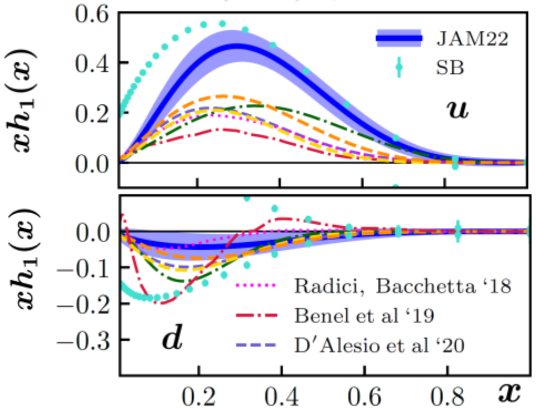


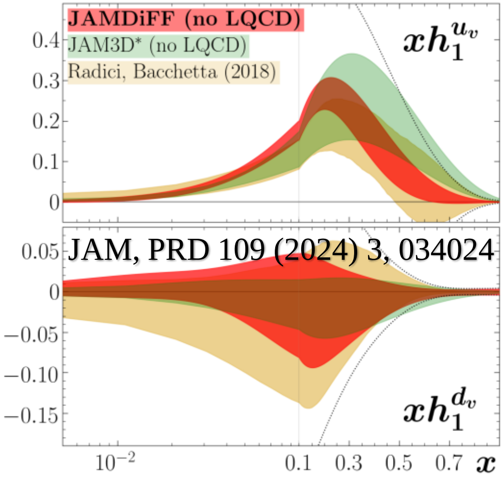
Anselmino et al.
PRD92 (2015) 114023

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



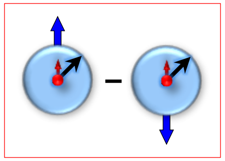
JAM PRD 106 (2022) 3, 034014





JAM, PRD 109 (2024) 3, 034024

SIDIS TSAs: Collins effect and Transversity



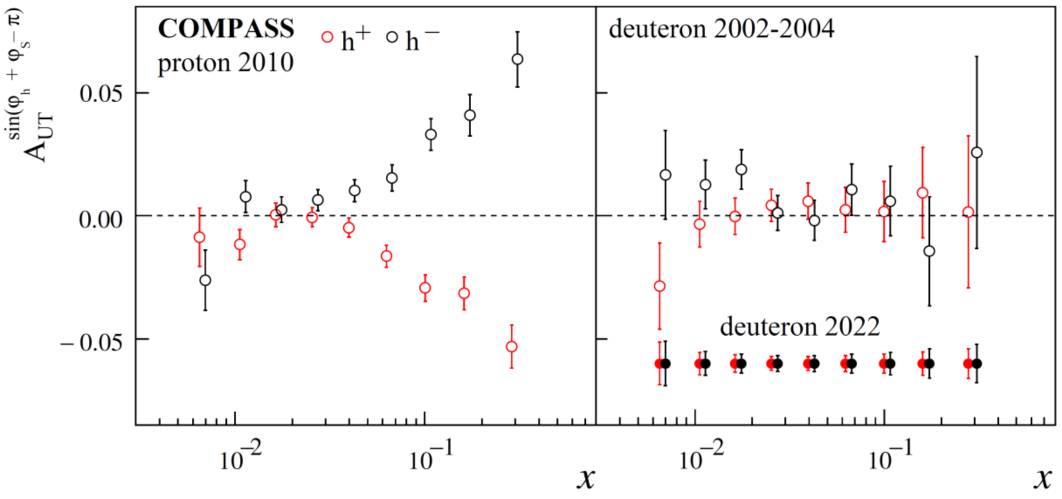
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\ \right\}$$

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

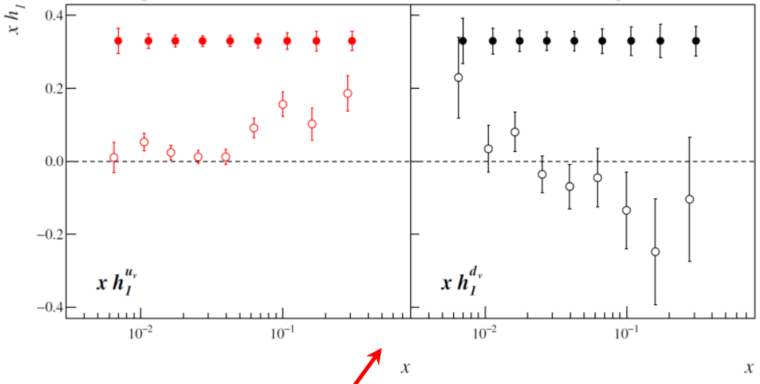
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS
  (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity

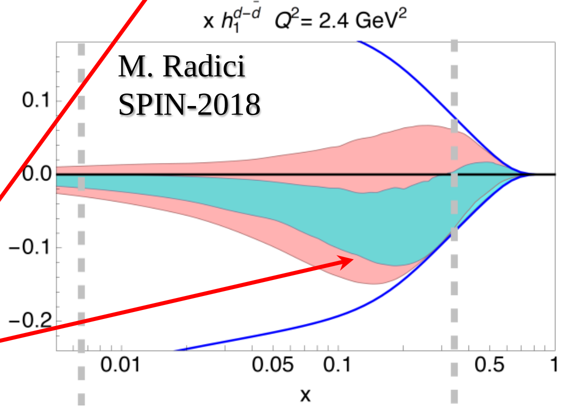
[Addendum to the COMPASS-II Proposal]

Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF

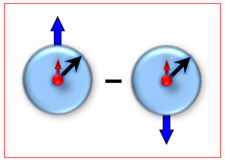




COMPASS-II (2022)

- 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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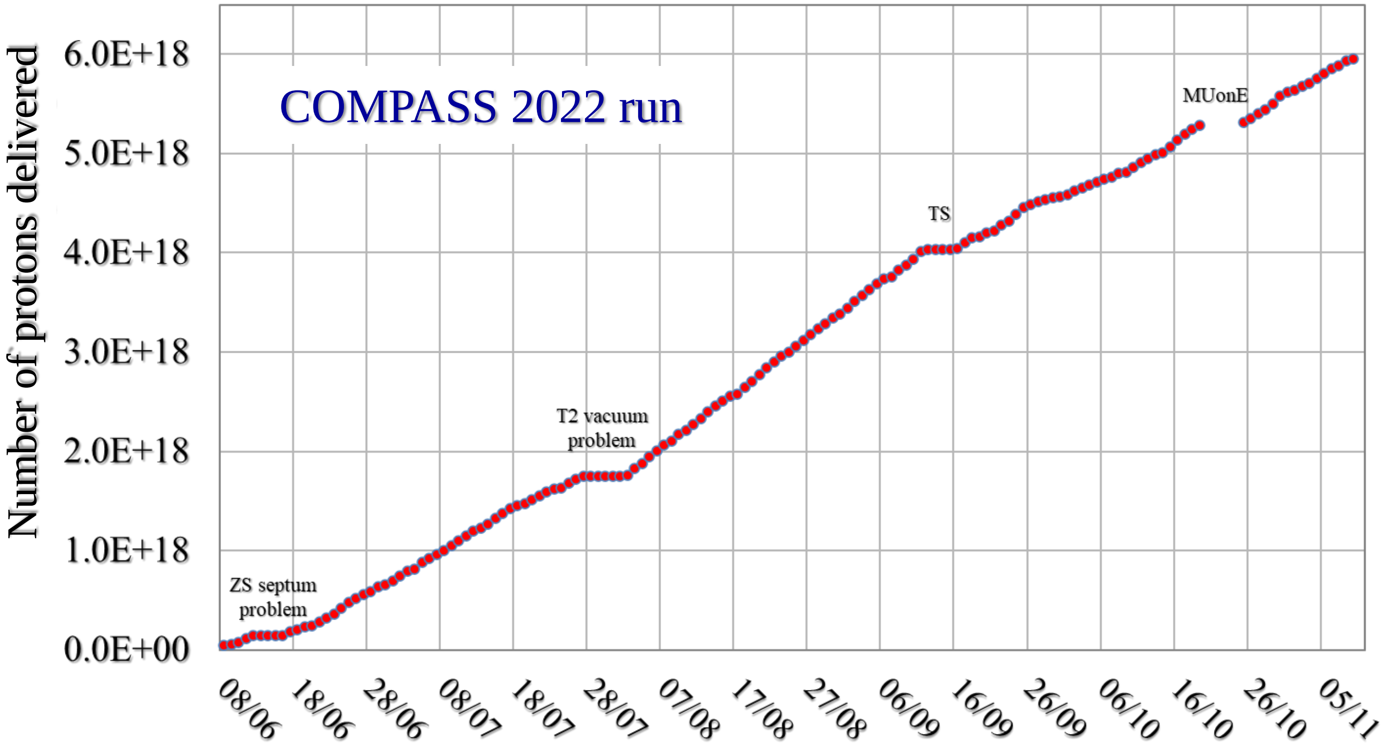
  (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity

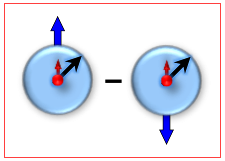
Total protons delivered on the production target: ~5.95×10^{18} (98% of the request) in ~150 days



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

Highly successful Run in 2022!

SIDIS TSAs: Collins effect and Transversity



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

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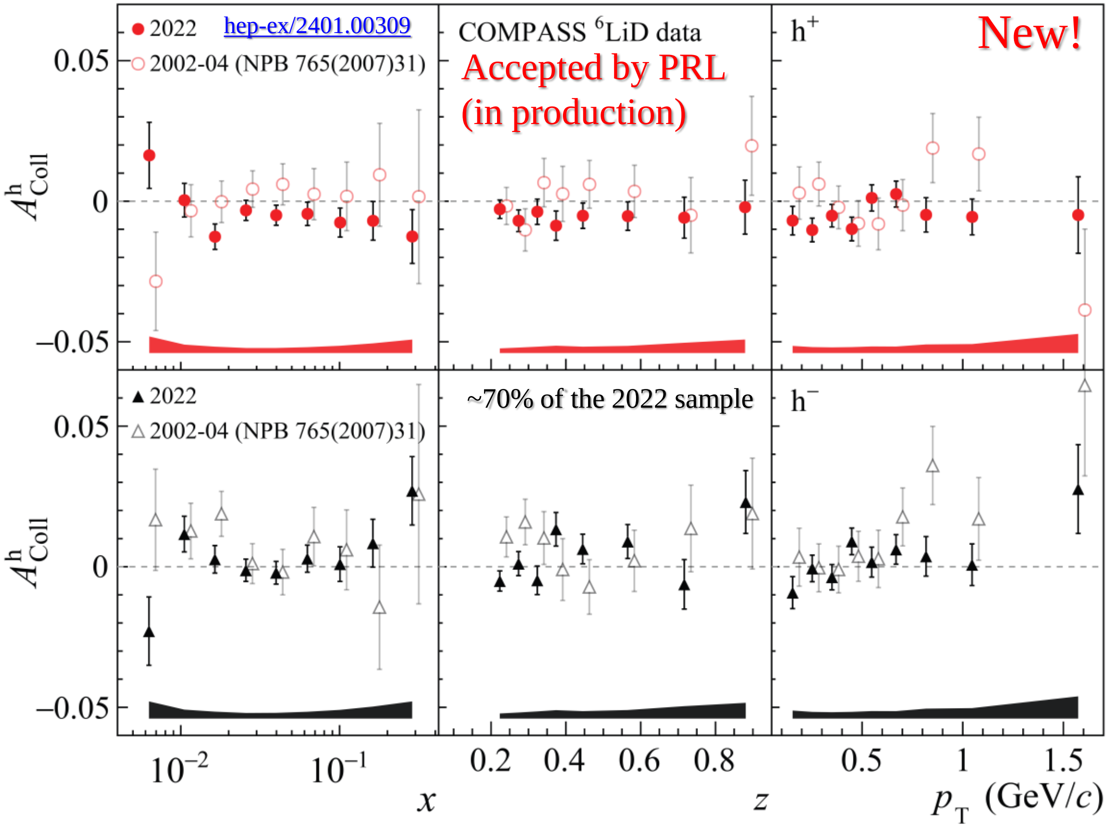
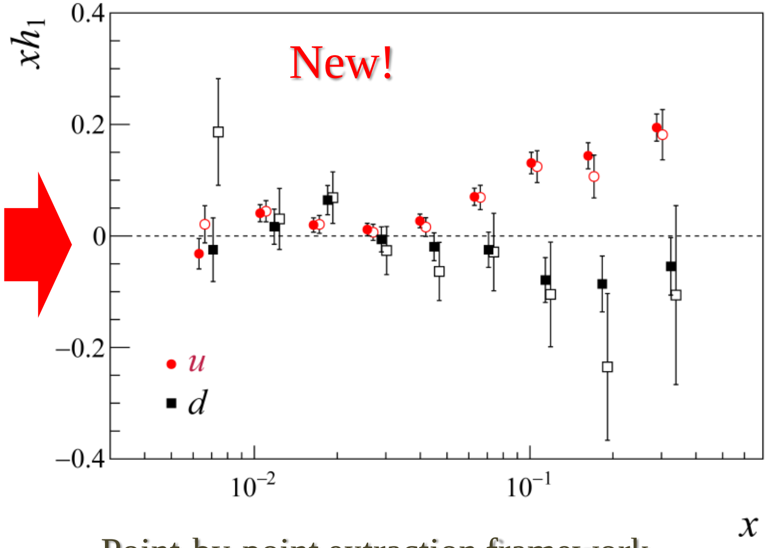


Accepted by PRL (in production)

~70% of the 2022 sample



Point-by-point extraction framework

A. Martin et al. PRD **91**, 014034 (2015)

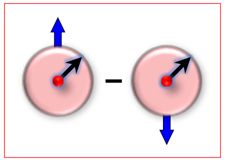
A. Martin et al. PRD **95**, 094024 (2017)

COMPASS 2022 run – highly successful data-taking!

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

SIDIS TSAs: Sivers effect

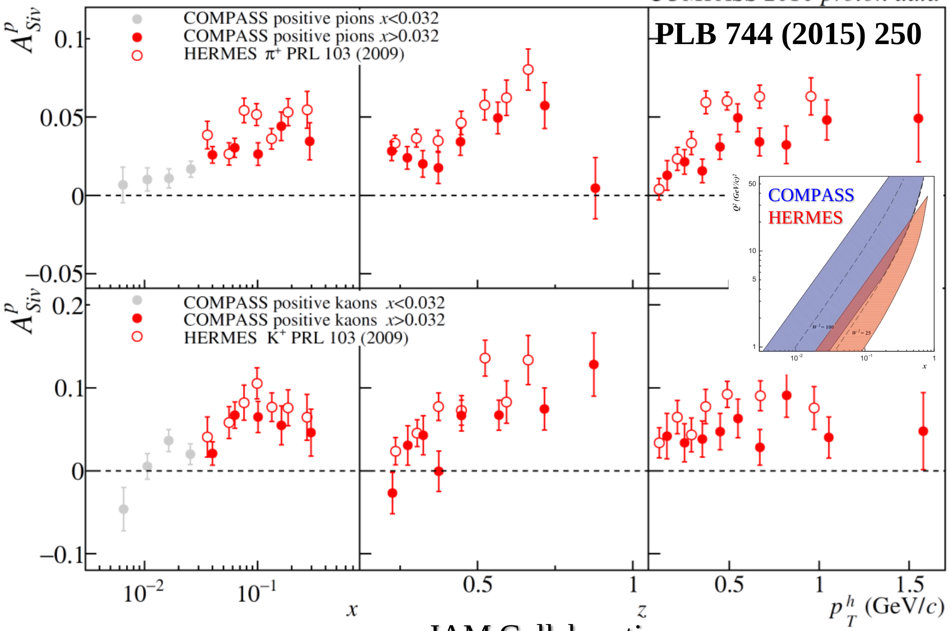
$$\frac{d\sigma}{dxdydzdp_T^2\, d\phi_h\, d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_{\mathrm{T}}\, A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h-\phi_S\right)+\ldots\right\}$$



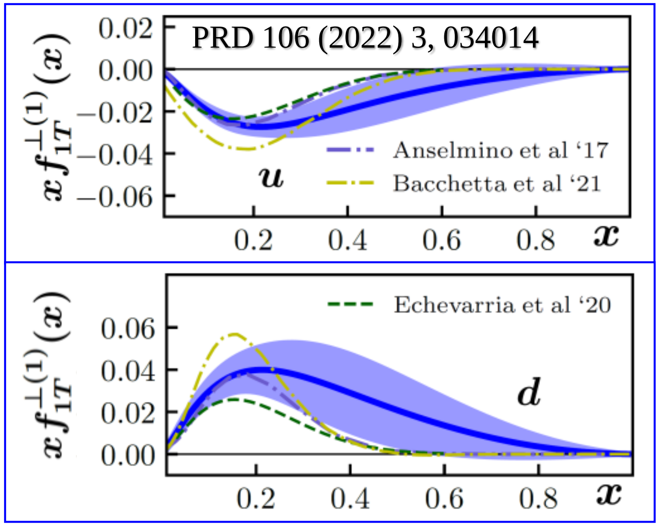
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M}\, f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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

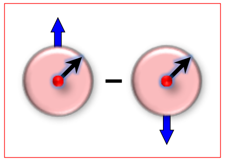
COMPASS 2010 proton data


PLB 744 (2015) 250

JAM Collaboration


PRD 106 (2022) 3, 034014

SIDIS TSAs: Sivers effect



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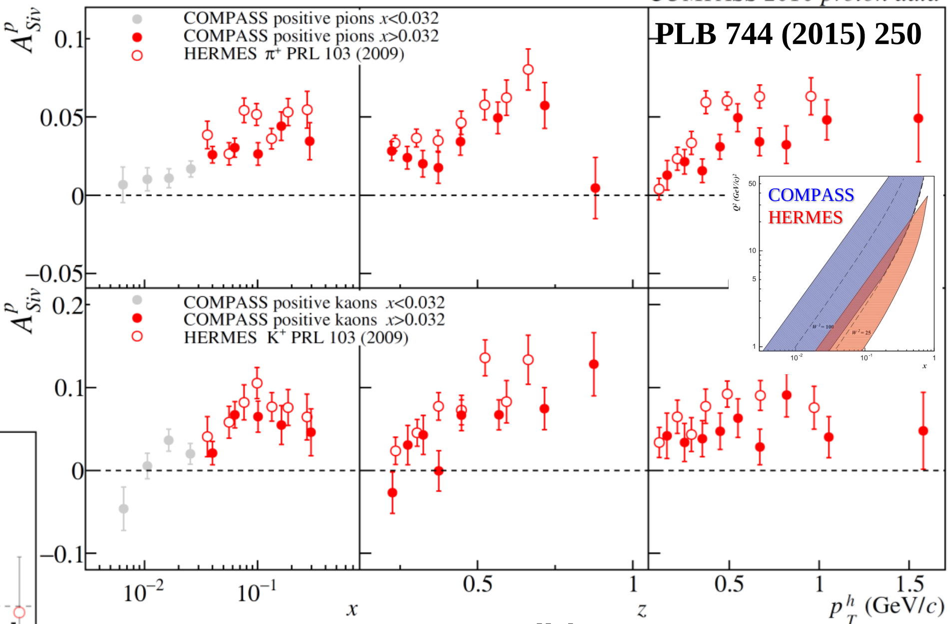
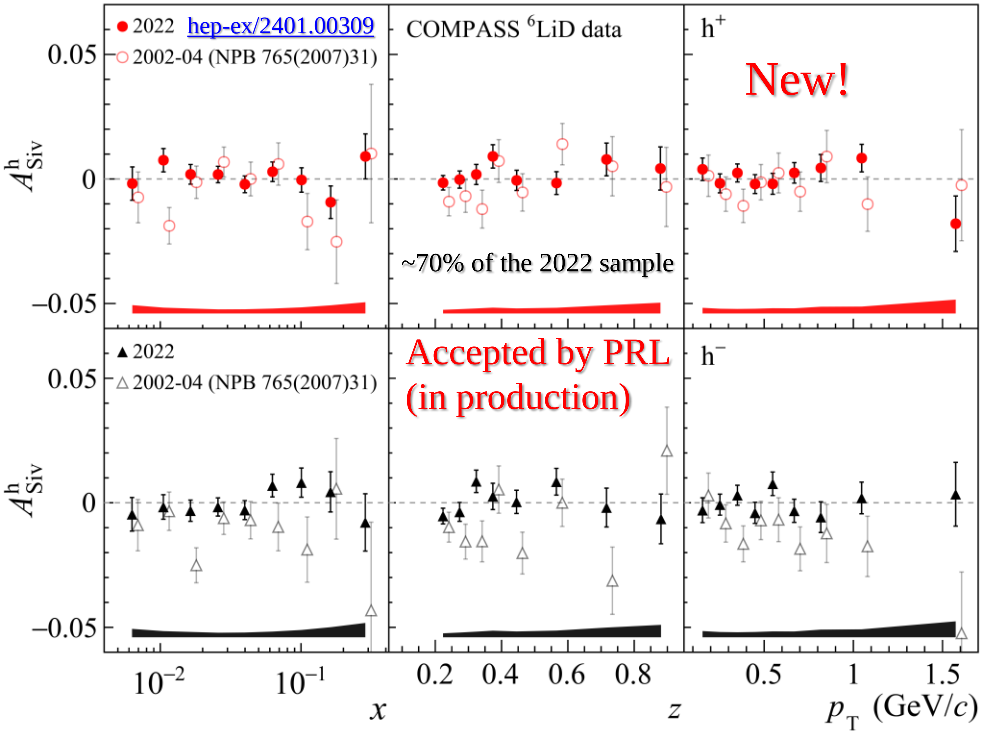
$$\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0}$$

- 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

COMPASS 2010 proton data



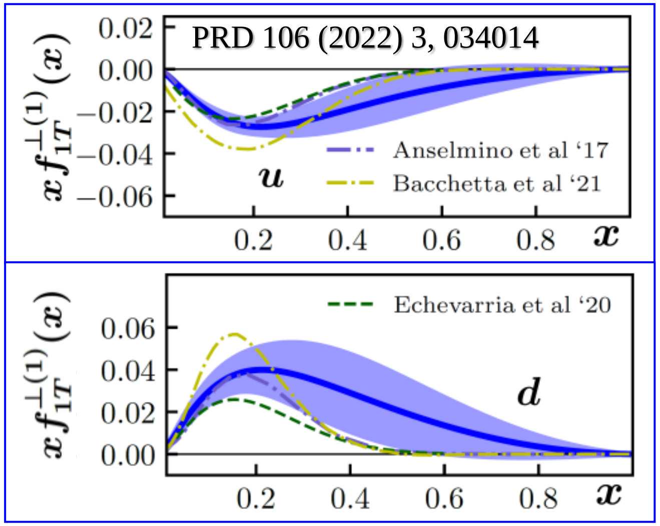
PLB 744 (2015) 250



New!

Accepted by PRL (in production)

JAM Collaboration



PRD 106 (2022) 3, 034014

COMPASS 2022 run: new unique deuteron data

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

hermes proton [H] 95 data points *Airapetian et al., P.R.L. **103** (09) 152002*	Jefferson Lab neutron [³He] 6 data points *Qian et al., P.R.L. **107** (11) 072003*
COMPASS 2009 deuteron [⁶LiD] 88 data points *Alekseev et al., P.L. **B673** (09) 127*	COMPASS 2017 Proton [NH₃] 111 data points *Adolph et al., P.L. **B770** (17) 138*

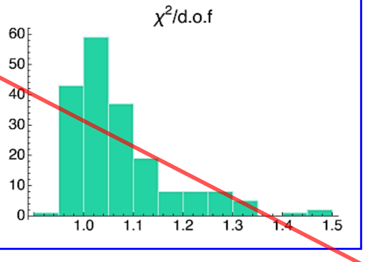
analysis of statistical error with replica method (200)
68% confidence level

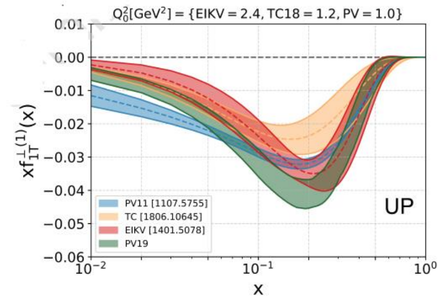
Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

$Q^2 \geq 1.4$ GeV² $\quad 0.2 \leq z \leq 0.7$
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

300 data points → **118** data fitted
14 free parameters
χ²/d.o.f. = 1.06 ± 0.10

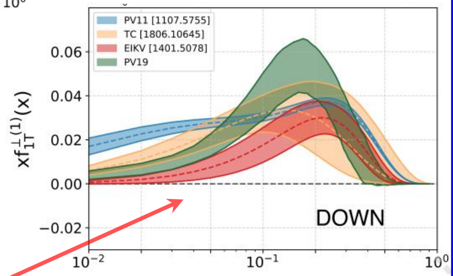




PV11	*Bacchetta & Radici, P.R.L. **107** (11)*
EIKV	*Echevarria et al., P.R. **D89** (14)*
TC	*Boglione et al., JHEP **1807** (18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

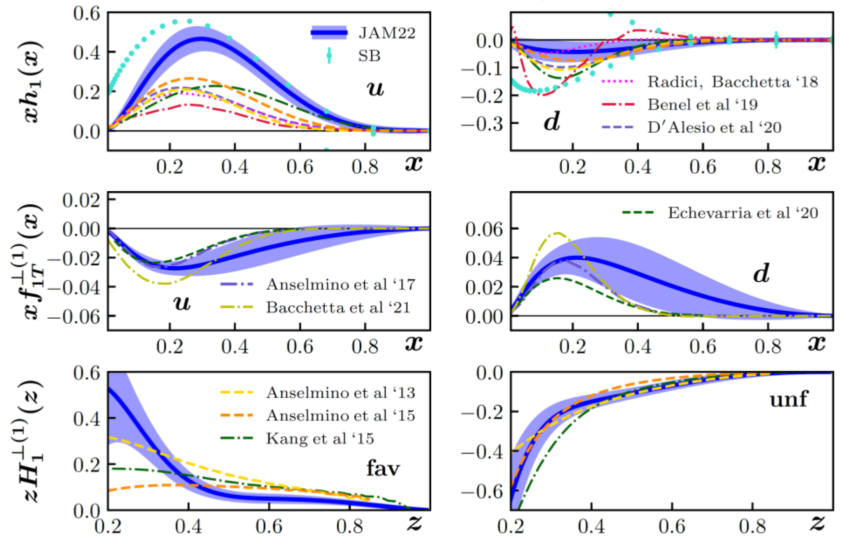
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \frac{\mathbf{k}_T^2}{2M^2} f_{1T}^{\perp}(x, \mathbf{k}_T)$$

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

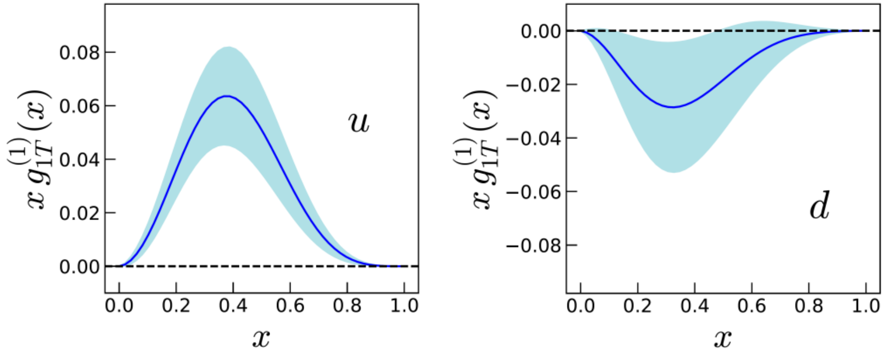


COMPASS 2022 deuteron run

JAM Collaboration, PRD 106 (2022) 3, 034014



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



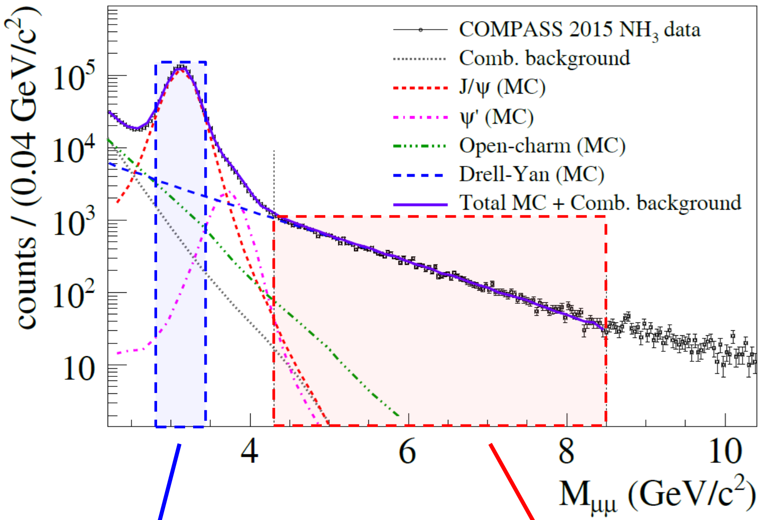
More news soon…

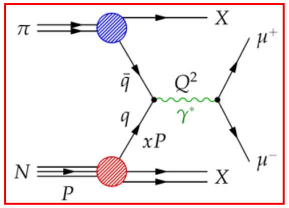
COMPASS bridge

Drell-Yan

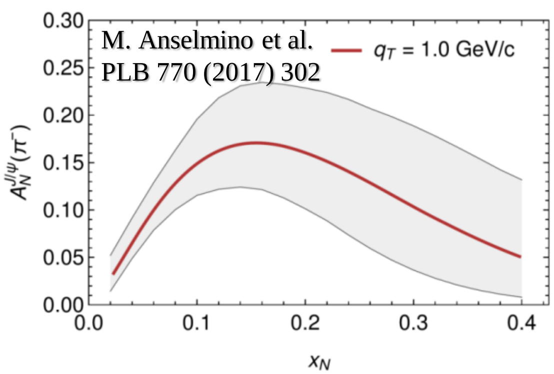
SIDIS

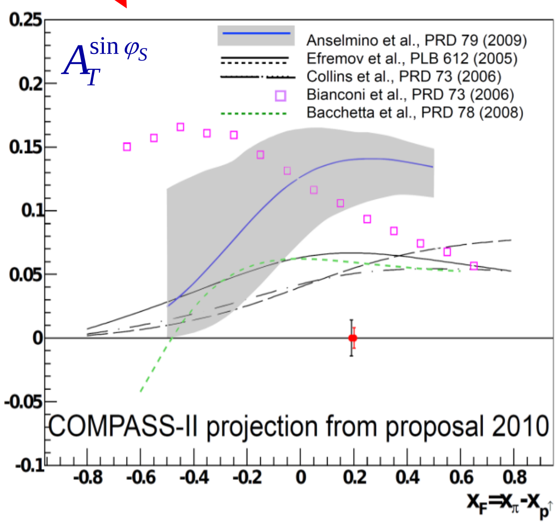
Single-polarized Drell-Yan cross-section at twist-2 (LO)





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





$A_U^{\cos 2\varphi_{CS}} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{\perp q}}$ 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

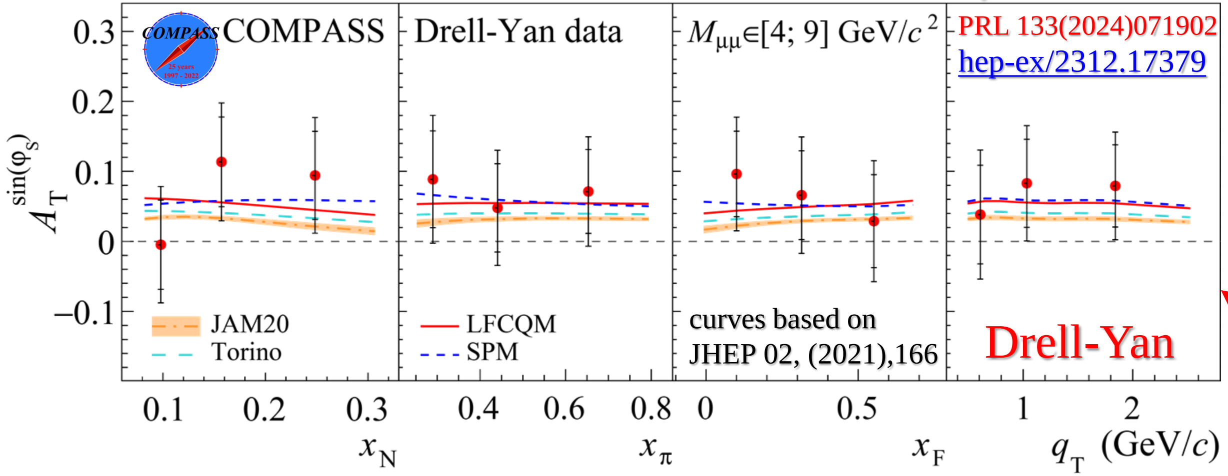
SIDIS ↔ Drell-Yan sign-change of the T-odd TMD PDFs

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

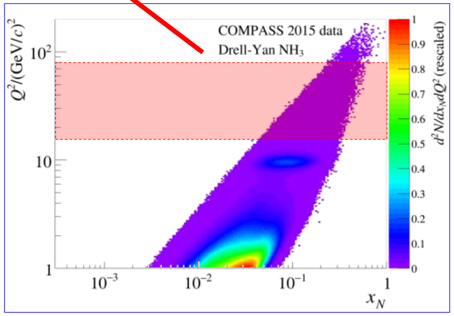
Sivers effect: Drell-Yan and J/ψ

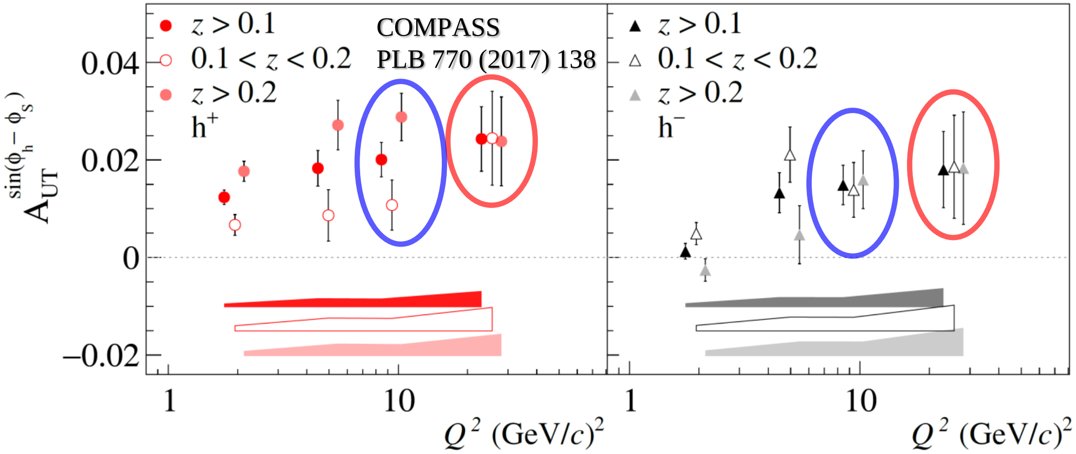
Sivers DY TSA

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



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





Sivers SIDIS TSA

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

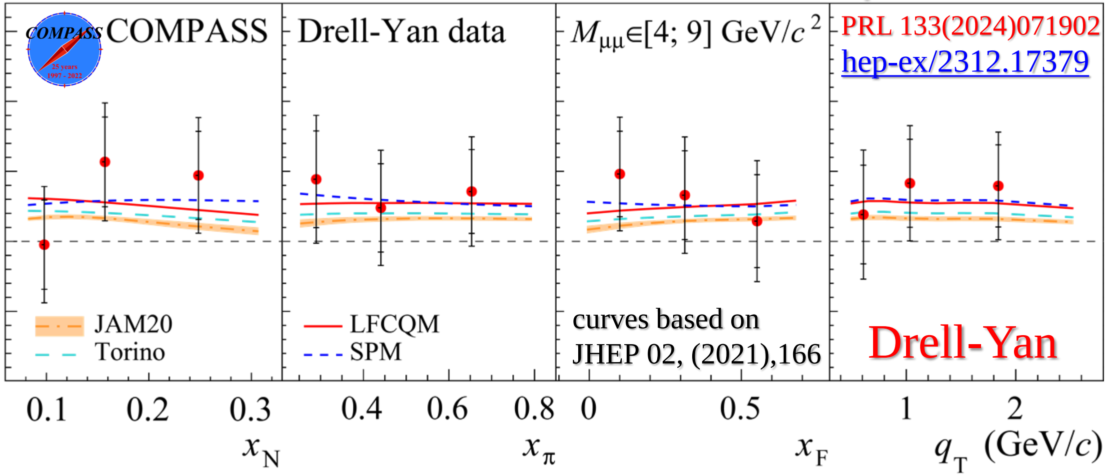
COMPASS proton Sivers measurements

- Clear signal in the matching Q^2 ranges

Sivers effect: Drell-Yan and J/ψ

Sivers DY TSA

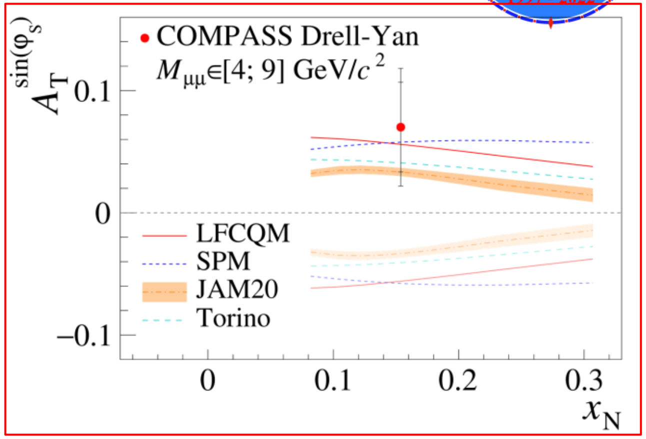
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$



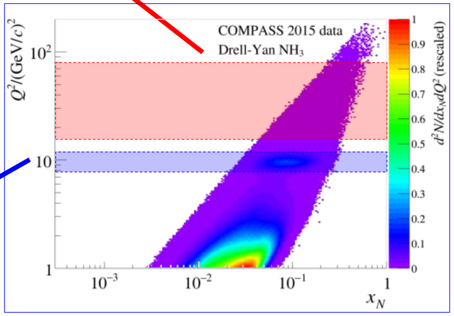
PRL 133(2024)071902
hep-ex/2312.17379

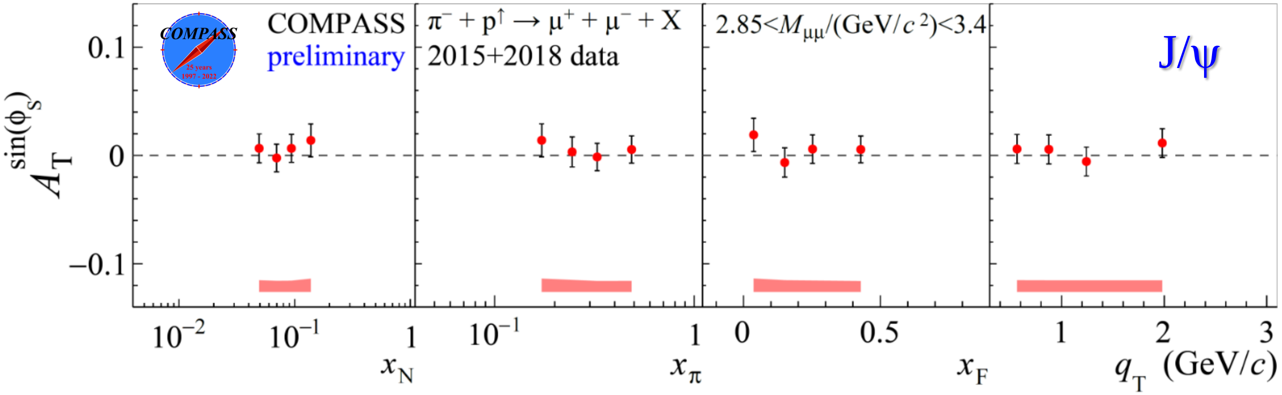
curves based on JHEP 02, (2021),166

Drell-Yan

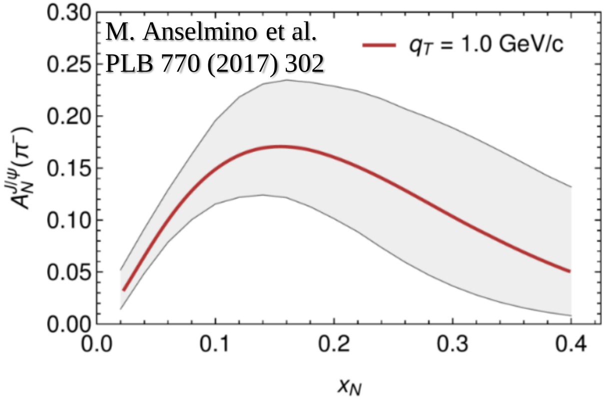


- The Drell-Yan Sivers asymmetry tends to be positive (~1.5 s.d.)





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

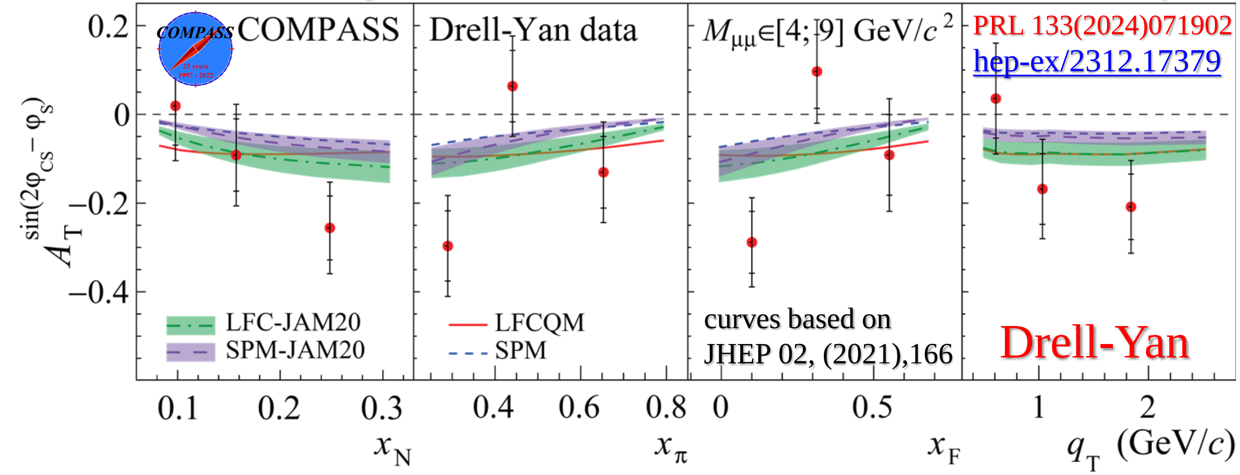

M. Anselmino et al.
PLB 770 (2017) 302

- 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

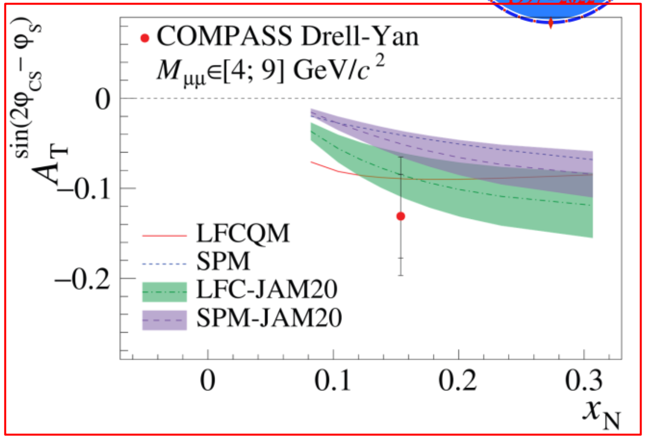
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$



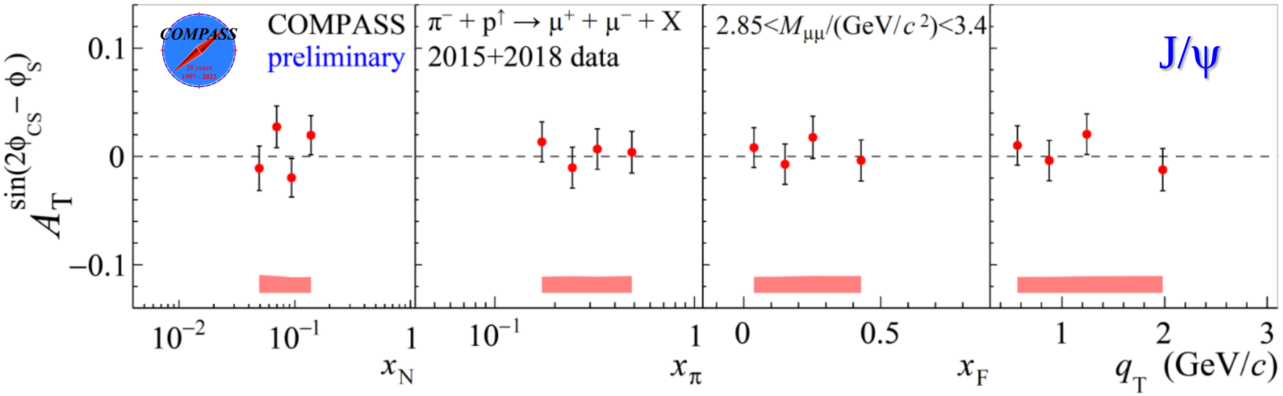
PRL 133(2024)071902

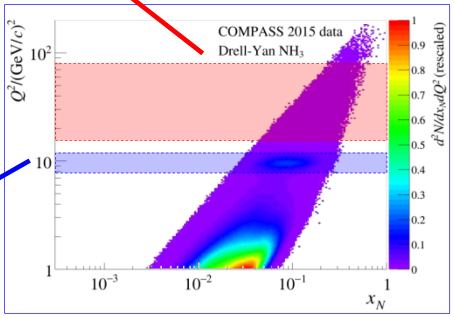
hep-ex/2312.17379

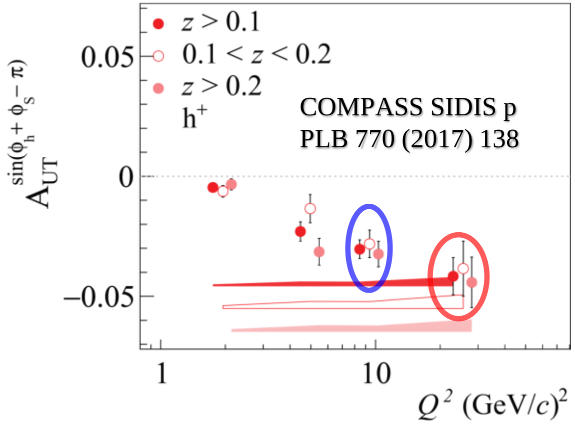
curves based on JHEP 02, (2021),166



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





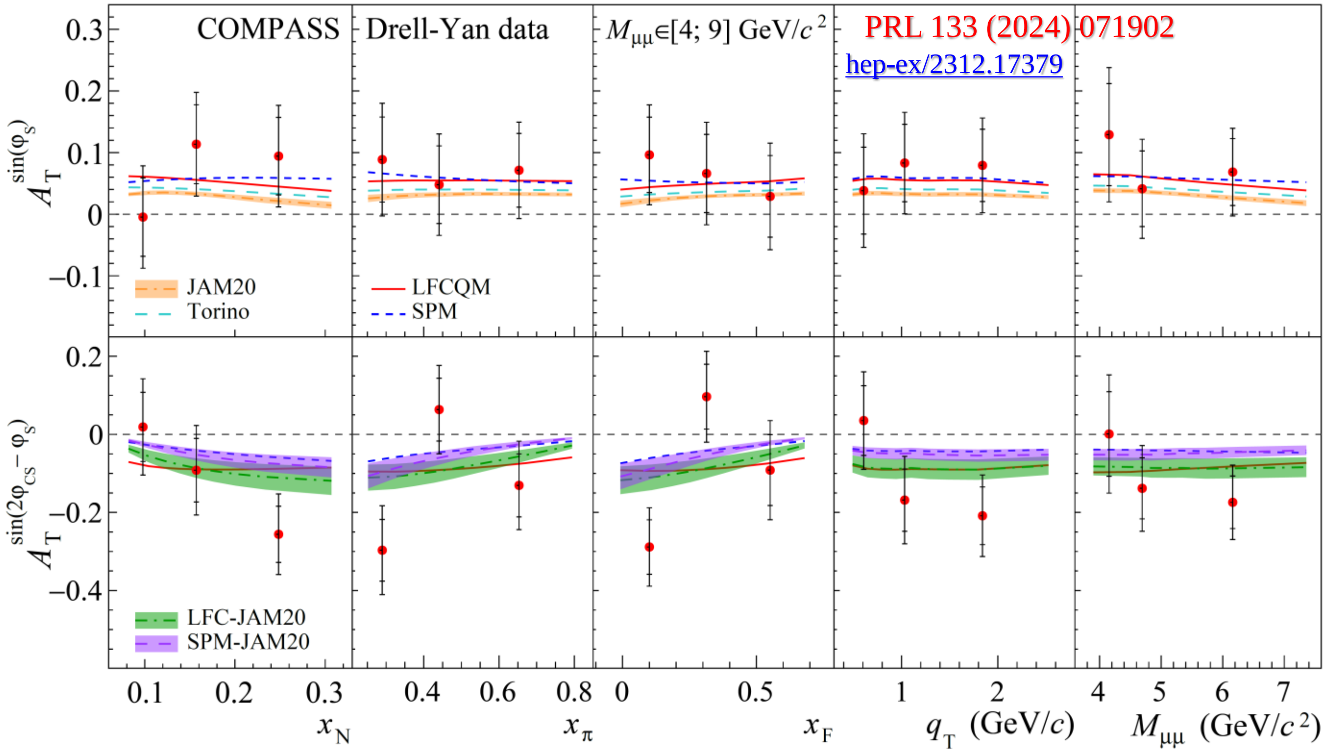


COMPASS SIDIS p
PLB 770 (2017) 138

- 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?

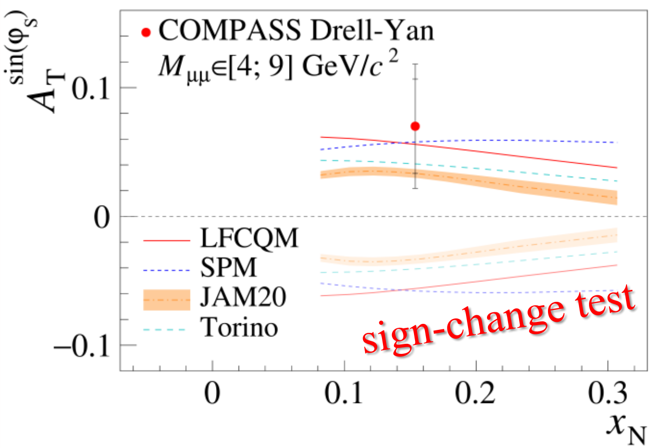
Transverse-spin asymmetries in $\pi^{-}p^{\uparrow}$ scattering

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

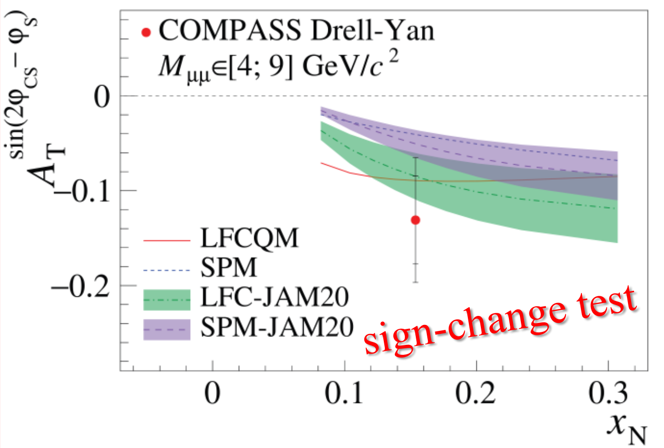


PRL 133 (2024) 071902

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!

2024
30/09 - 04/10

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

COMPASS
25 years
1997 - 2022

IWHSS
CPHI

Yerevan
Armenia

Yerevan, Armenia

30 September – 4 October, 2024

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

COMPASS Physics Program

COMPASS
25 years
1997 - 2022

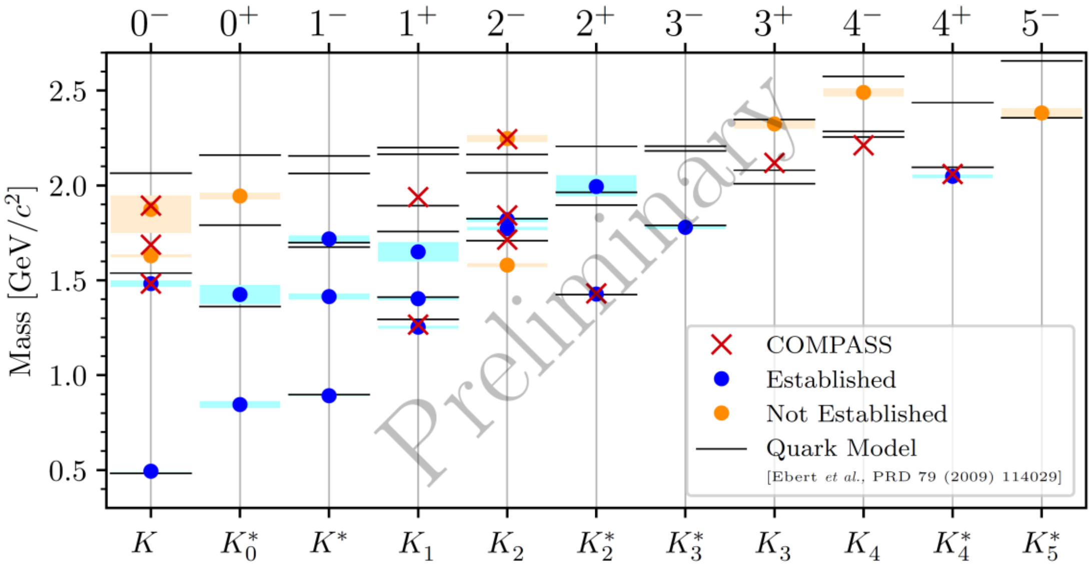
Hadron spectroscopy

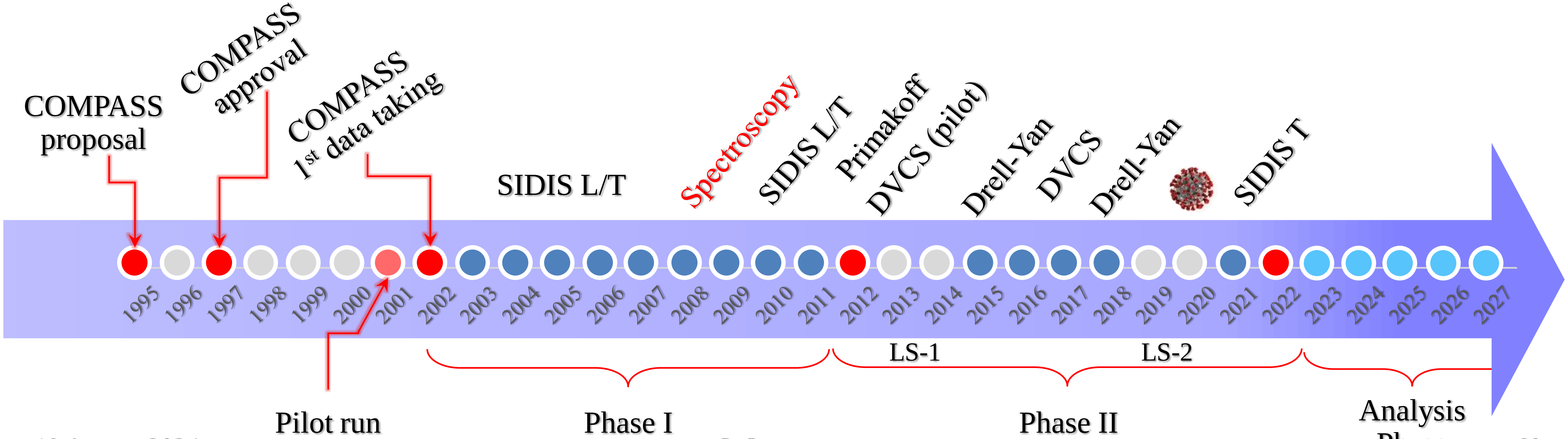
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

Chiral dynamics

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

See Stefan Wallner's talk (Wednesday)



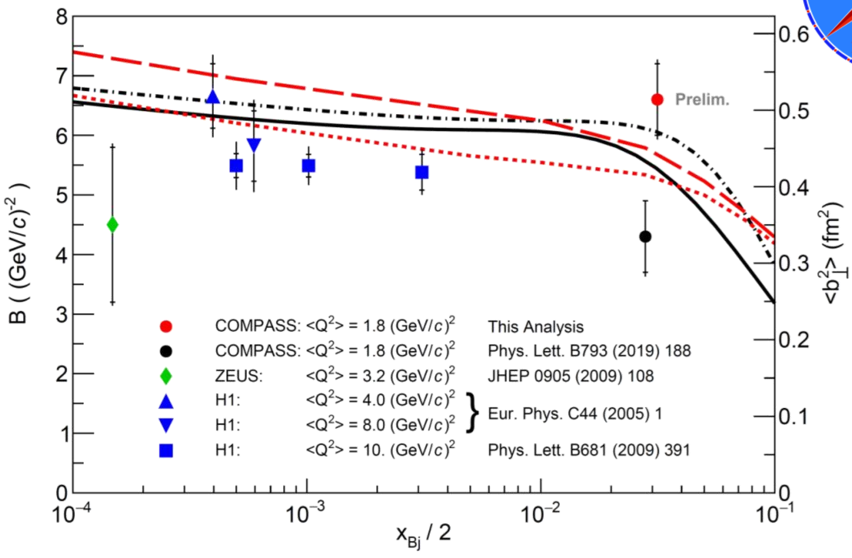


COMPASS Physics Program

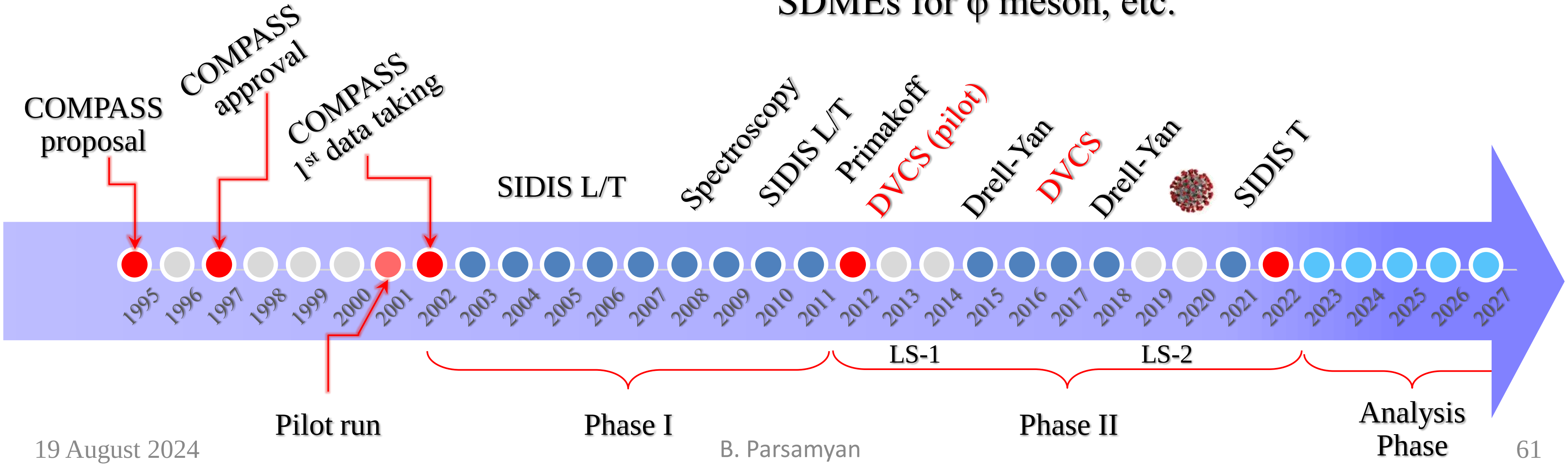
GPDs

- 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 $\mathrm{M} = \pi^0, \rho(770), \omega(782)$,..

COMPASS preliminary 2016 data (~70%)



Several ongoing analyses close to completion: exclusive π^0 cross-section, DVCS cross-section, SDMEs for φ meson, etc.



COMPASS proposal

COMPASS approval

COMPASS 1st data taking

SIDIS L/T

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

Drell-Yan

DVCS

Drell-Yan

SIDIS T

LS-1

LS-2

Pilot run

Phase I

Phase II

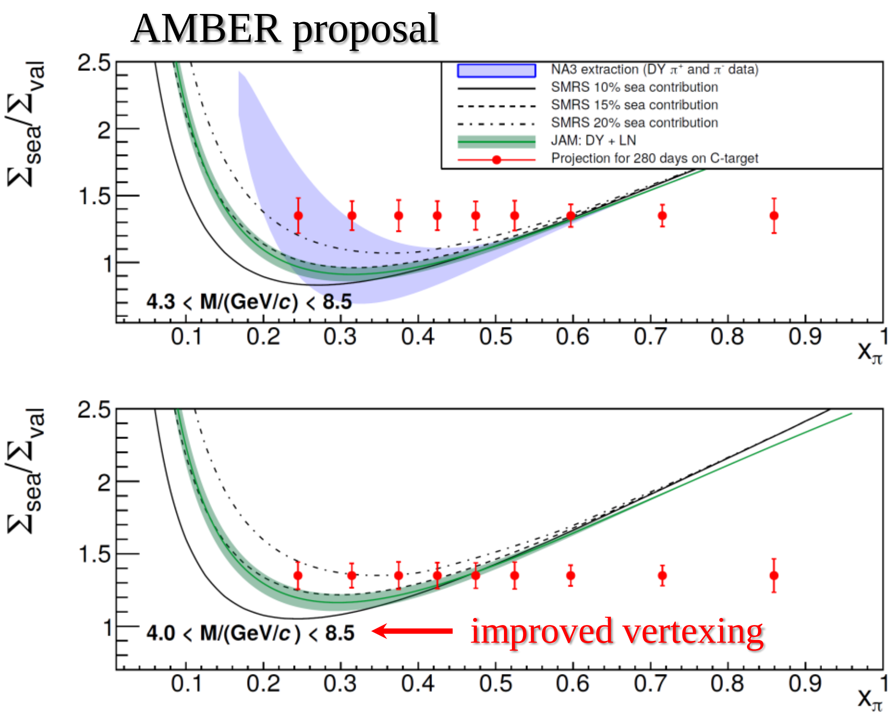
Analysis Phase

AMBER measurements 2023-2024: Drell-Yan

AMBER
Apparatus for Meson and Baryon Experimental Research

$\pi^\pm$, $K^\pm$ induced dimuon production: Drell-Yan, J/ψ (and ψ')

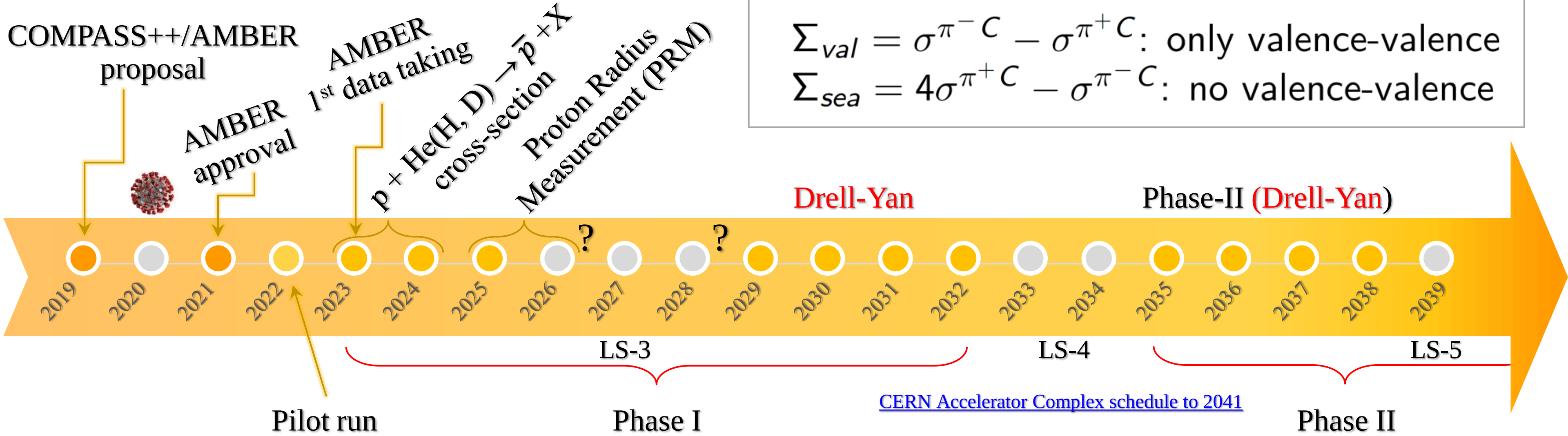
- Study of pion and kaon PDFs
    - Crucial input for the study of the Emergent Hadron Mass (EHM)
    - Possibility to collect unique balanced π^+/π^- induced DY data
- Measurement of λ, μ and ν (DY, J/ψ)
- J/ψ production mechanisms ($q\bar{q}, gg$)
- Carbon and tungsten targets
- Improved vertex/mass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



improved vertexing

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

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



COMPASS++/AMBER proposal

AMBER approval

AMBER 1st data taking

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

Proton Radius Measurement (PRM)

Drell-Yan

Phase-II (Drell-Yan)

LS-3

LS-4

LS-5

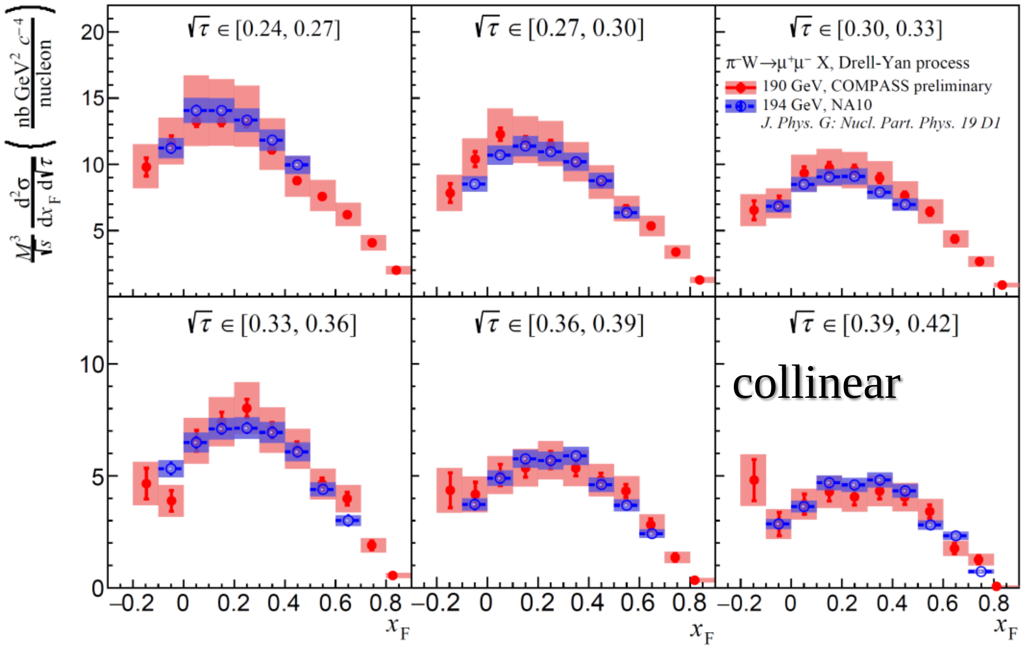
Pilot run

Phase I

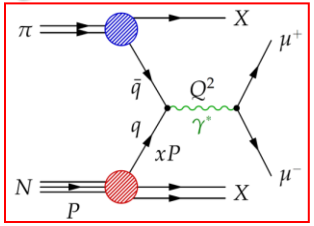
CERN Accelerator Complex schedule to 2041

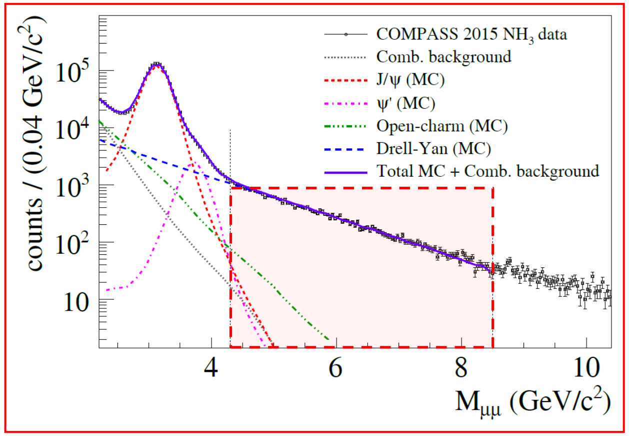
Phase II

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



collinear



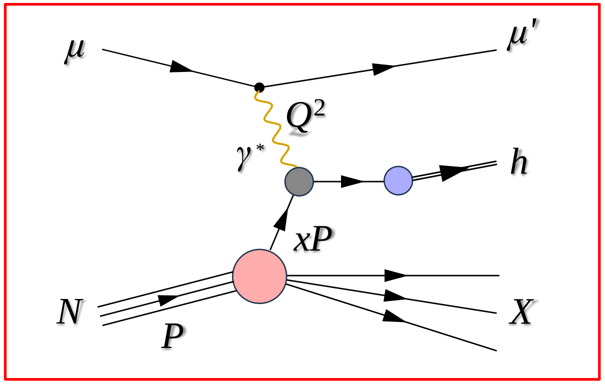


- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF

Experiment	target	number of events	systematic uncertainty	datapoints (M, x_F)
COMPASS (2018 data)	NH_3-He	36000	~5%	110
	Al	6000	~15%	50
	W	43000	~15%	50
NA10	W	155000	6.50%	59
E615	W	36000	16%	168

Polarized SIDIS and Drell-Yan: universality

Semi-inclusive DIS

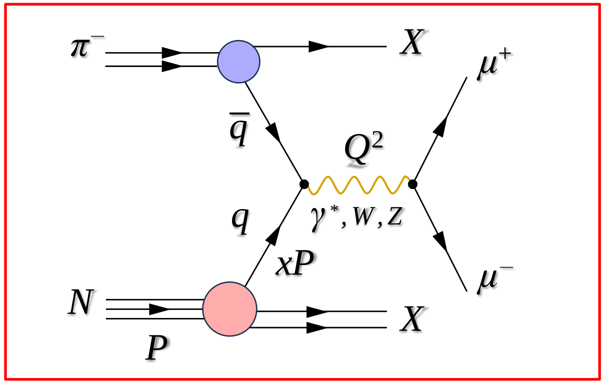


T-odd TMD PDFs

⟷

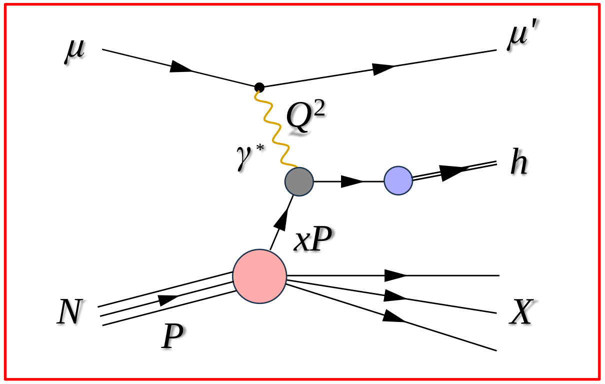
sign change

Drell-Yan process



Polarized SIDIS and DY – factorization and kinematic regions

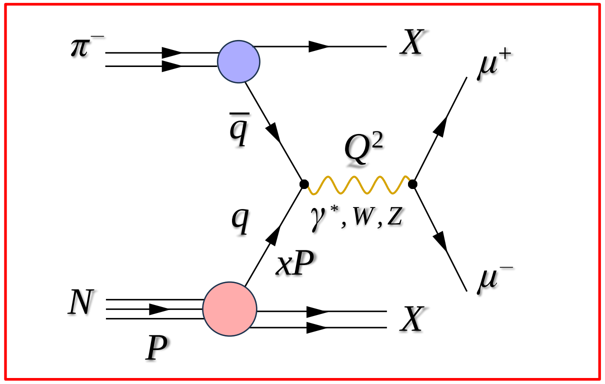
Semi-inclusive DIS



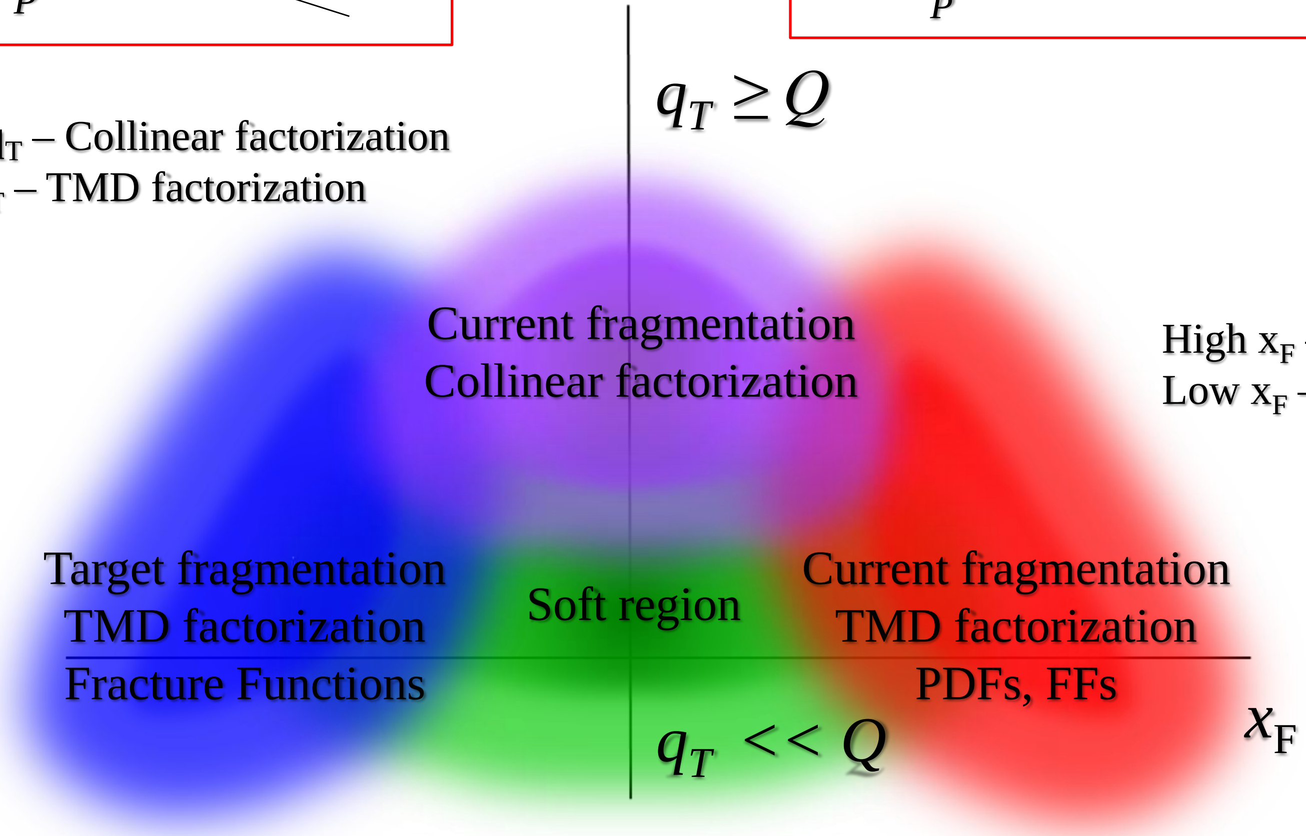
T-odd TMD PDFs

sign change

Drell-Yan process



High q_T – Collinear factorization
Low q_T – TMD factorization



Current fragmentation
Collinear factorization

Target fragmentation
TMD factorization
Fracture Functions

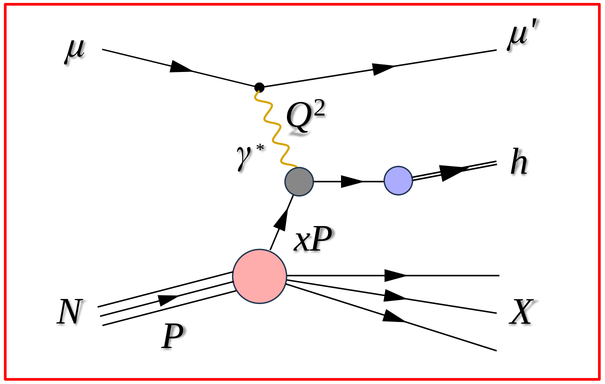
Soft region

Current fragmentation
TMD factorization
PDFs, FFs

High x_F – Current fragmentation
Low x_F – Target fragmentation

Main polarized SIDIS (Drell-Yan) inputs 1995-2022

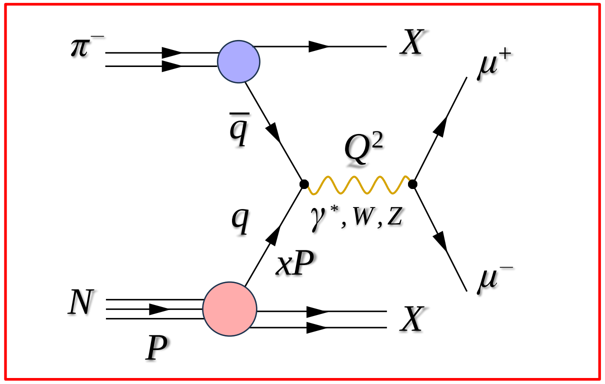
Semi-inclusive DIS

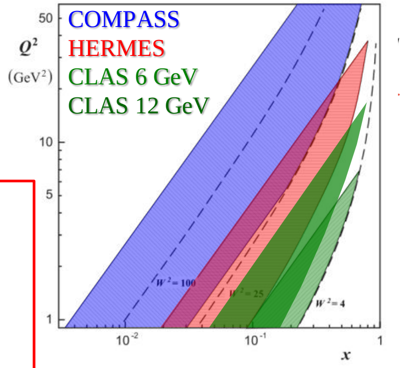


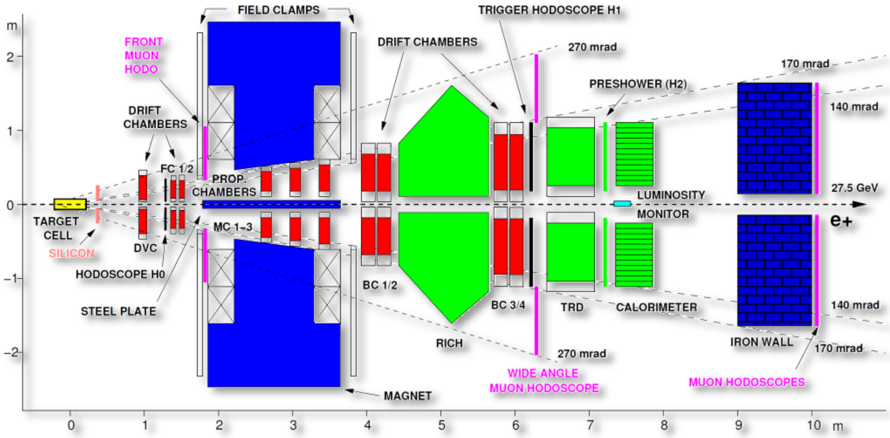
T-odd TMD PDFs

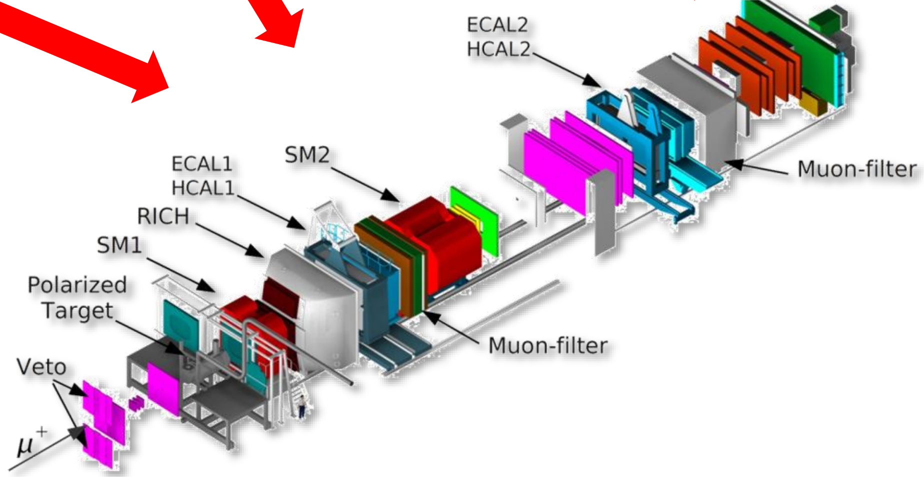
sign change

Drell-Yan process







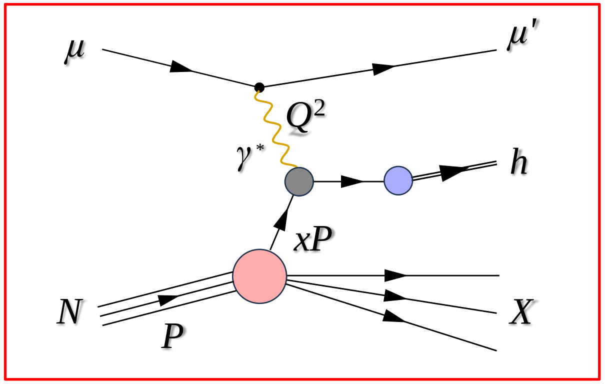


HERMES (data taking: 1995-2007)
Beam: e^+, e^- 27.6 GeV/c
L- and T- polarized proton target

COMPASS (data taking: 2002-2022)
Beam: μ^+, 160 GeV/c (DY: π^-, 190 GeV/c)
L- and T- polarized NH_3, ^6LiD targets (DY: T-NH_3)

Main TMD tools – universality and synergies

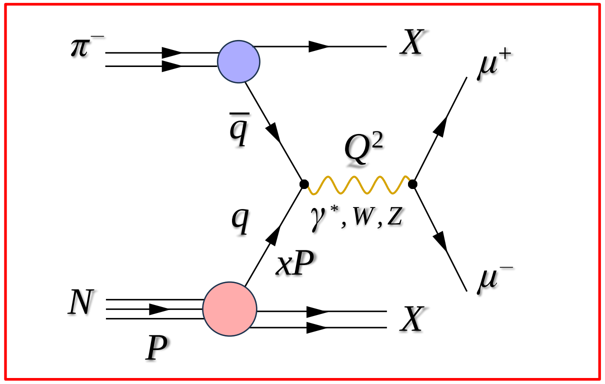
Semi-inclusive DIS



T-odd TMD PDFs

sign change

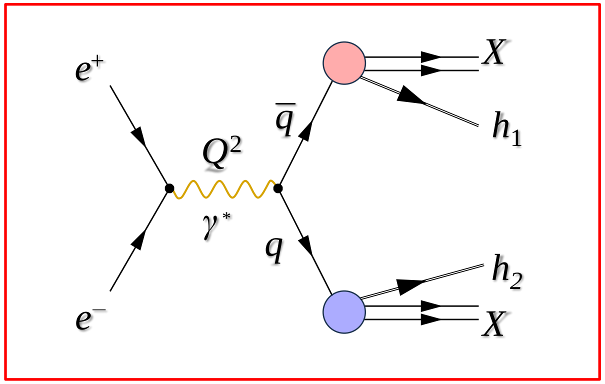
Drell-Yan process



Fragmentation Functions

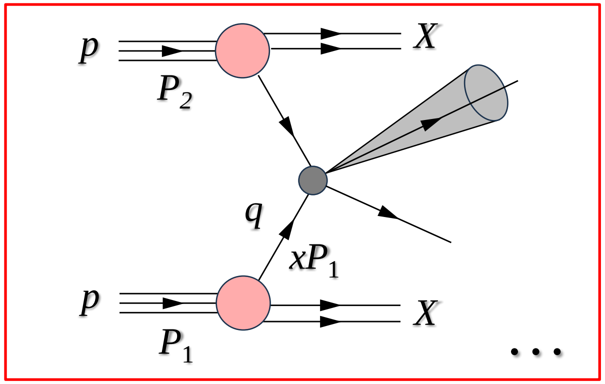
Parton Distribution Functions

Electron-positron annihilation



Cleanest access to hadronization/fragmentation

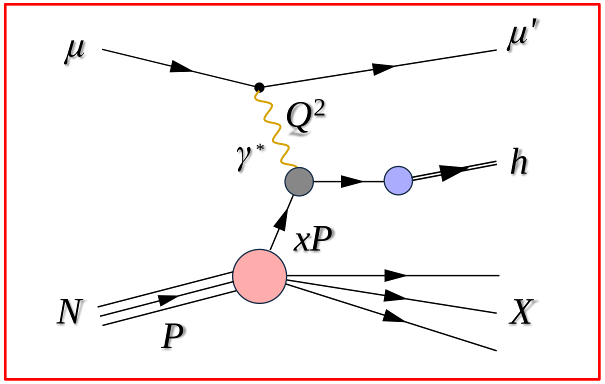
pp, pA-scattering, jet production, etc.



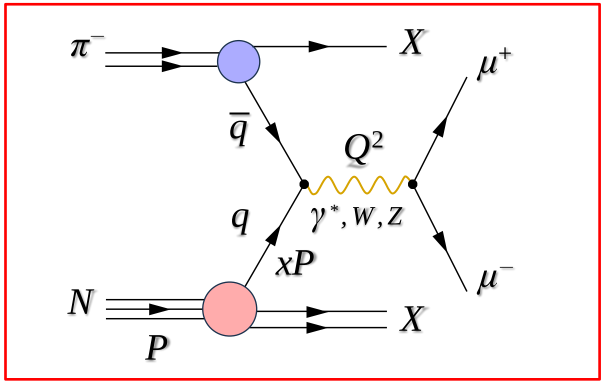
Hybrid collinear-TMD approach. The wealth of pp data allows studies of: TMD universality, evolution, expected factorization breaking

Main TMD tools – list of experiments (non exhaustive)

Semi-inclusive DIS

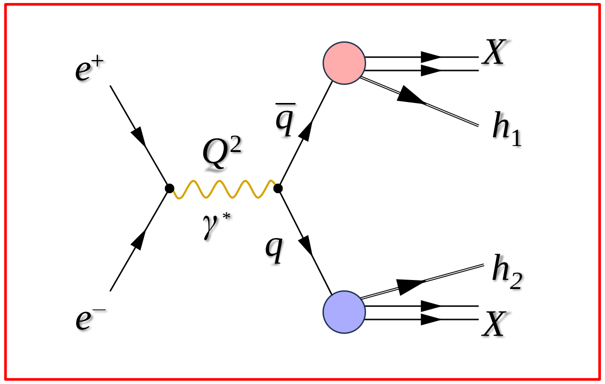


Drell-Yan process

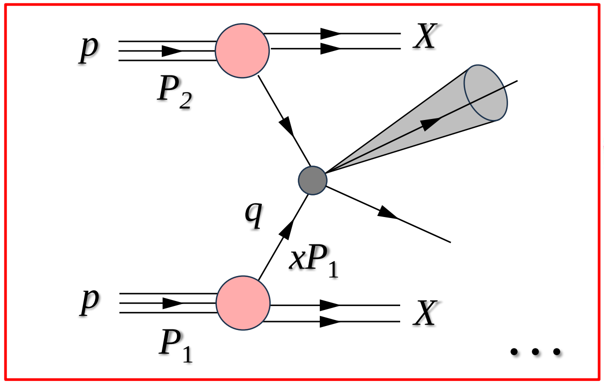


Jefferson Lab @ 22 GeV

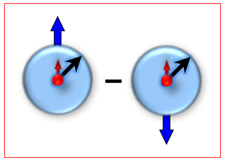
Electron-positron annihilation



pp, pA-scattering, jet production, etc.



SIDIS TSAs: Collins effect and Transversity

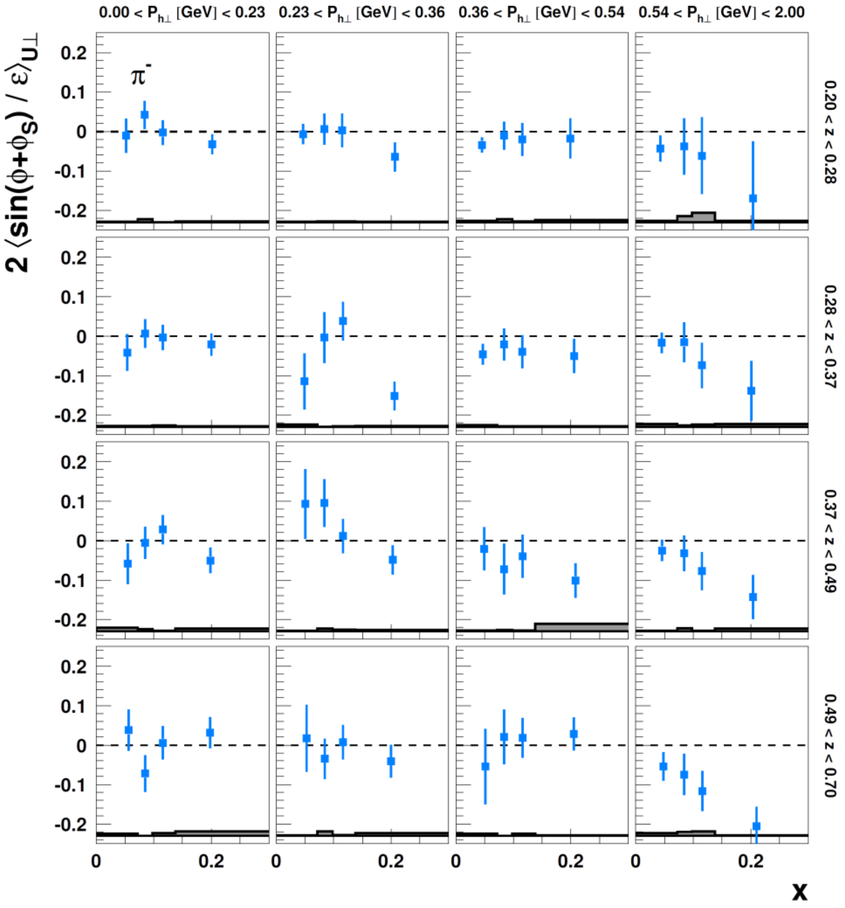


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

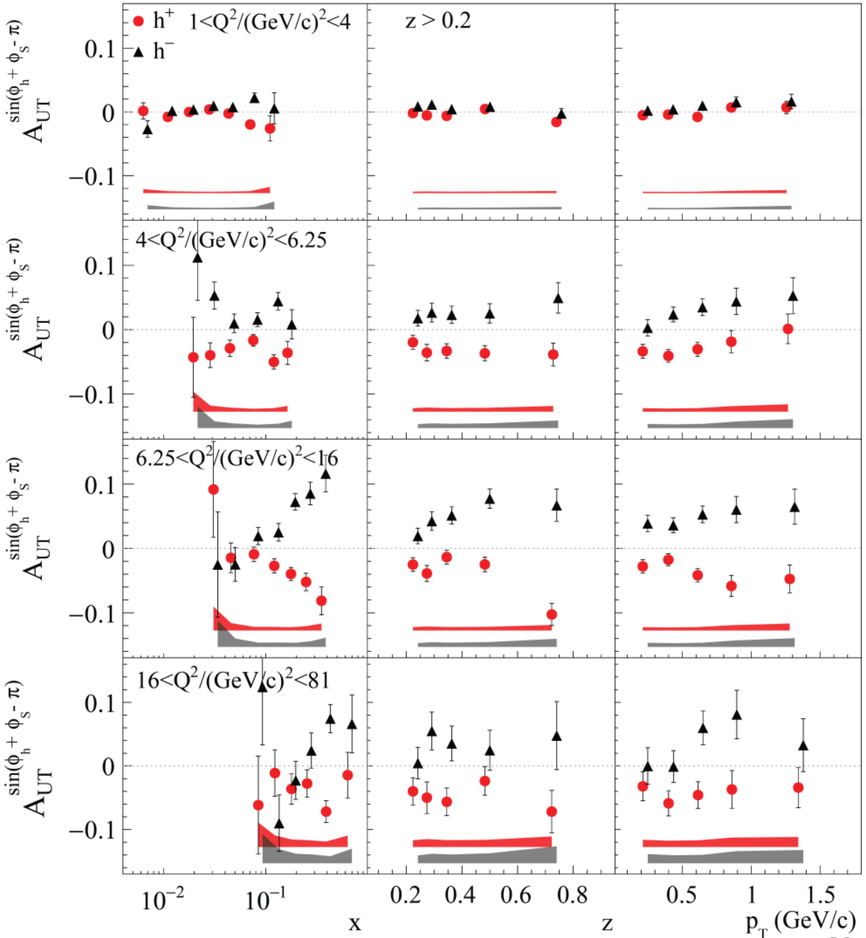
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

- 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

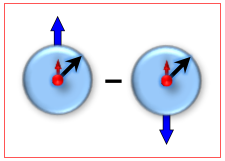
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



SIDIS TSAs: Collins effect and Transversity



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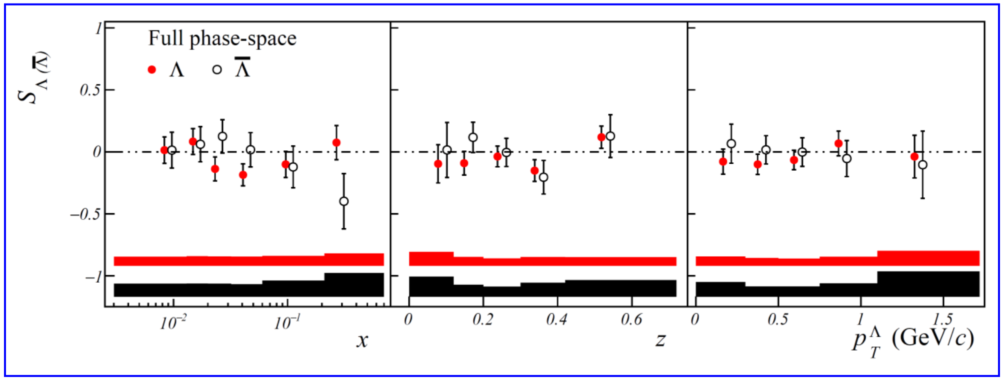
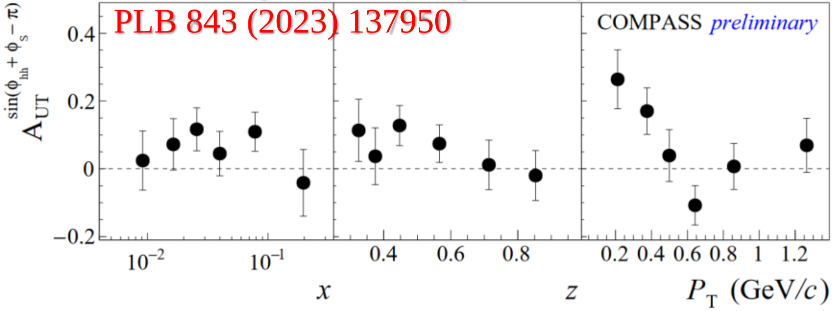
- No impact from Q^2-evolution? Clear signal at STAR energies

PLB 824 (2022) 136834

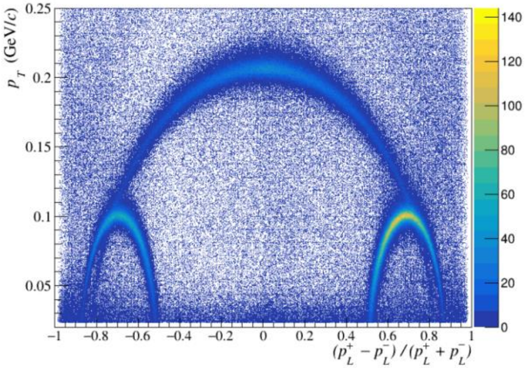


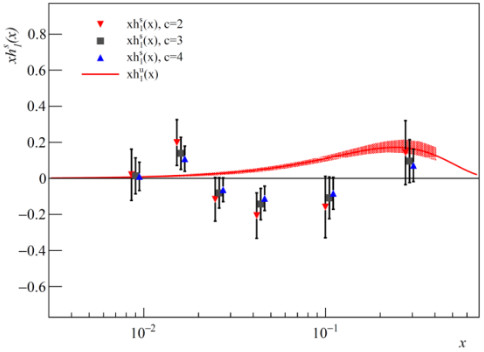
Inclusive ρ^0 Collins asymmetry

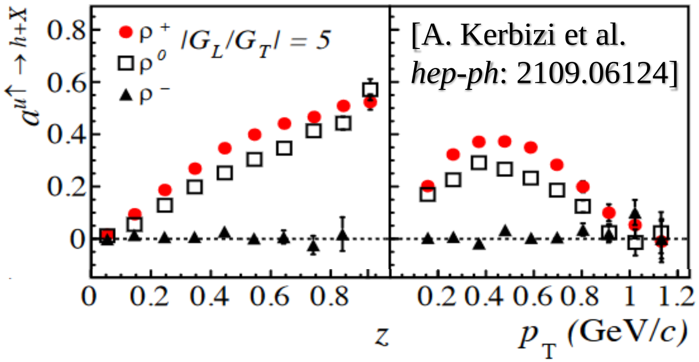


PLB 843 (2023) 137950

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

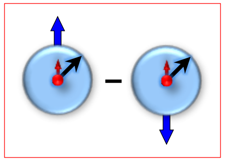






[A. Kerbizi et al.
hep-ph: 2109.06124]

SIDIS TSAs: Collins effect and Transversity



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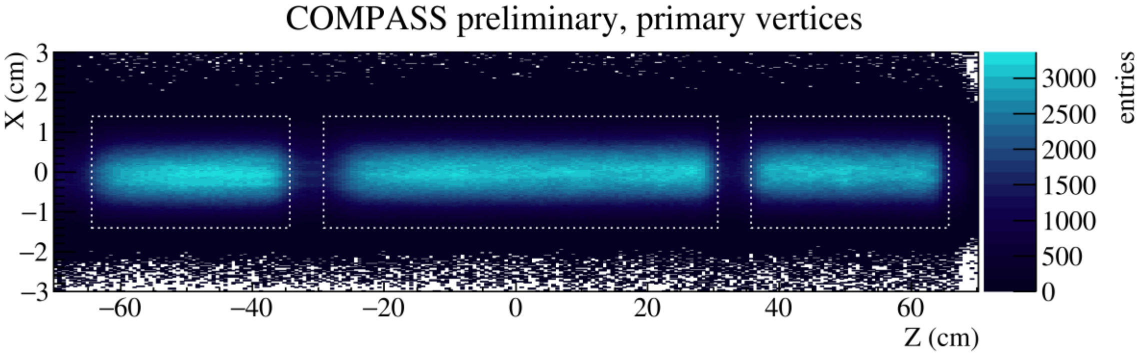
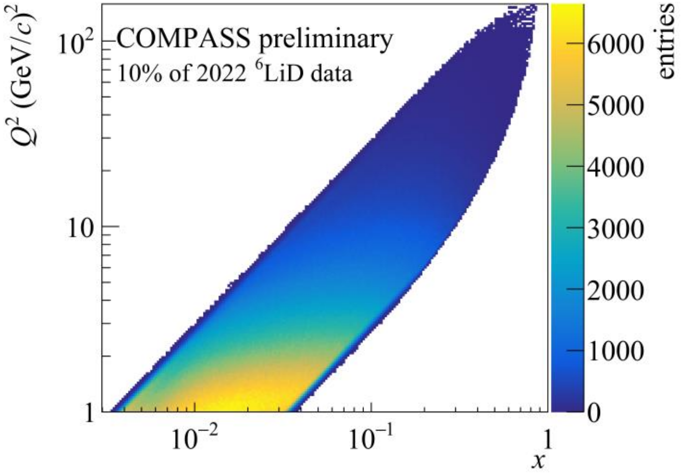
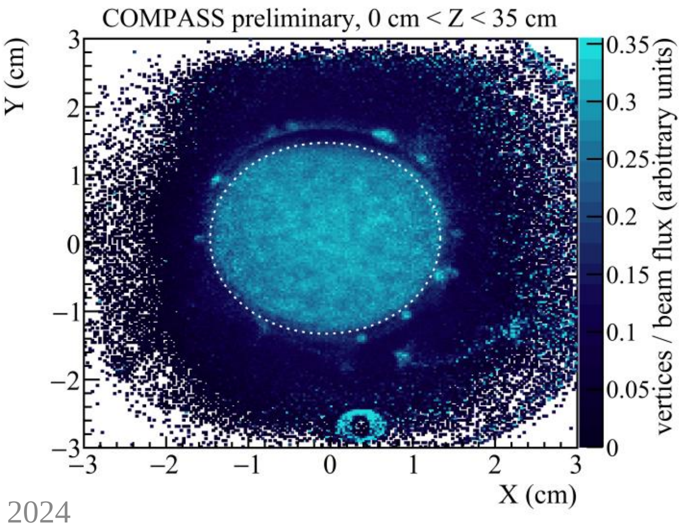
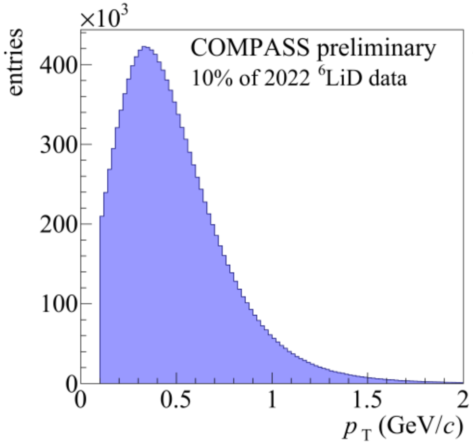
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS
  (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity

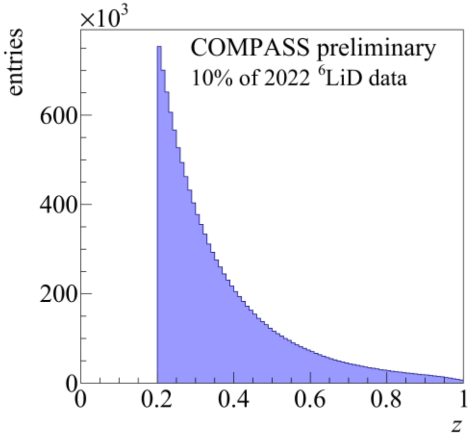
Highly successful
Run in 2022!





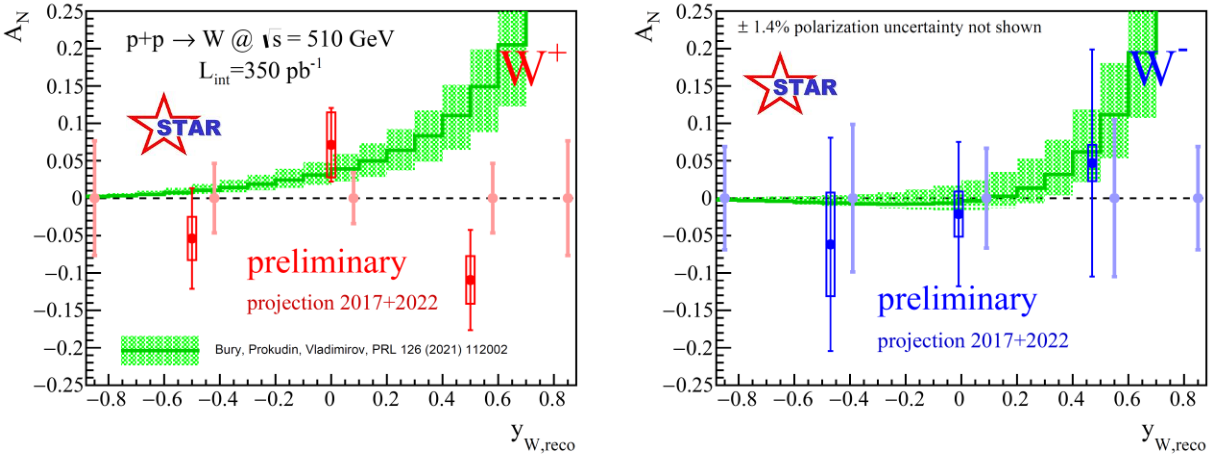




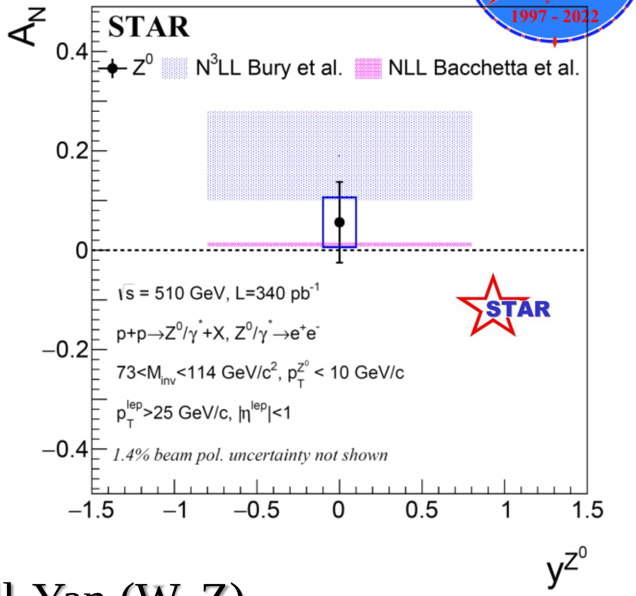


Sivers TMD PDF: sign change

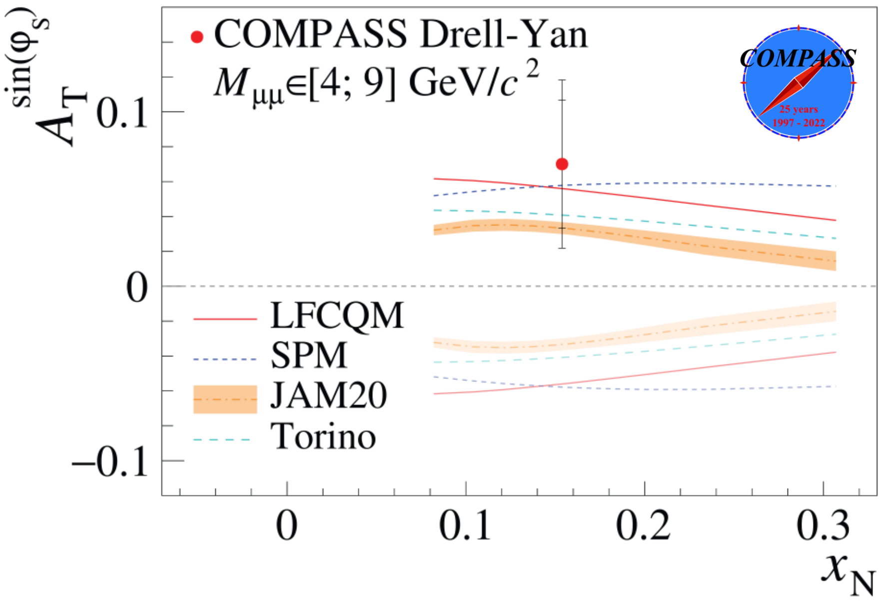
The RHIC Cold QCD program: arXiv:2302.00605 [nucl-ex]



STAR, arXiv:2308.15496 [hep-ex]



COMPASS, PRL 133 (2024) 071902

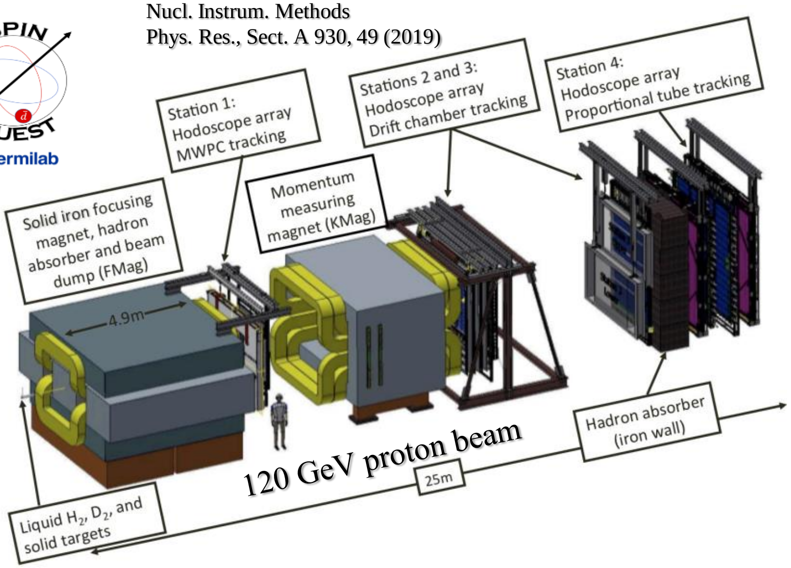


SIDIS↔Drell-Yan (W, Z)
sign change of T-odd TMD PDFs

- Difficult measurement
  - Low x-section, background
- Sivers TMD PDF
- Pioneering measurements
  - COMPASS (Drell-Yan): 2015, 2018
  - STAR (W, Z): 2011, 2017, 2022
- COMPASS data favors the sign change
  - Useful input to constrain the fits

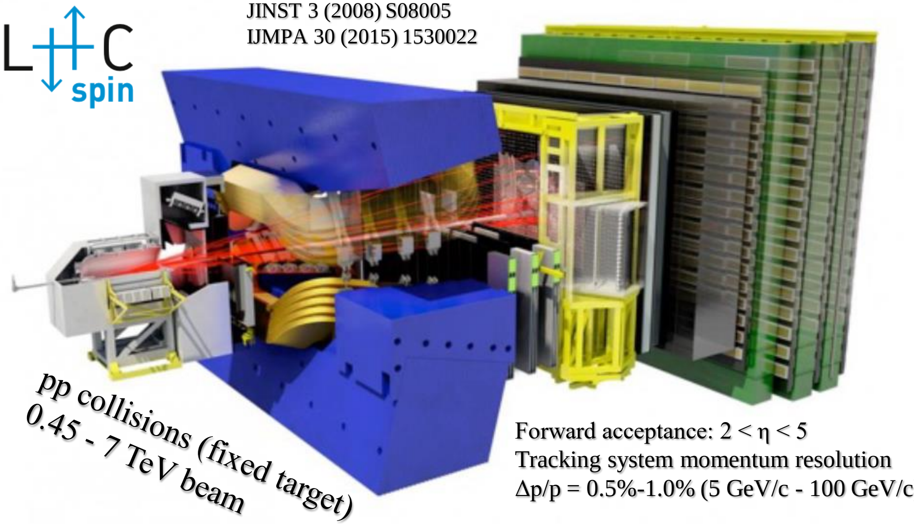
Sivers TMD PDF: sign change - future

Nucl. Instrum. Methods
Phys. Res., Sect. A 930, 49 (2019)



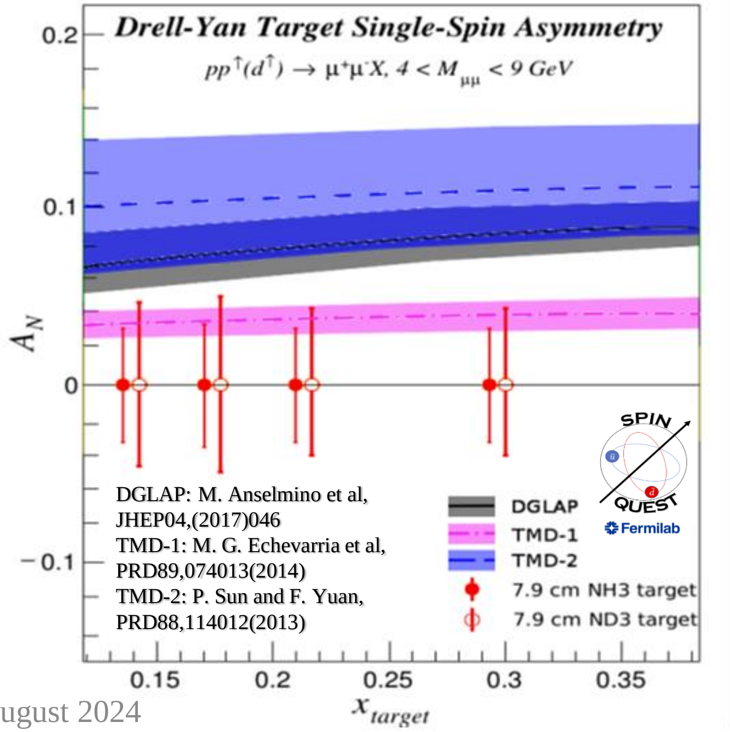
120 GeV proton beam

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

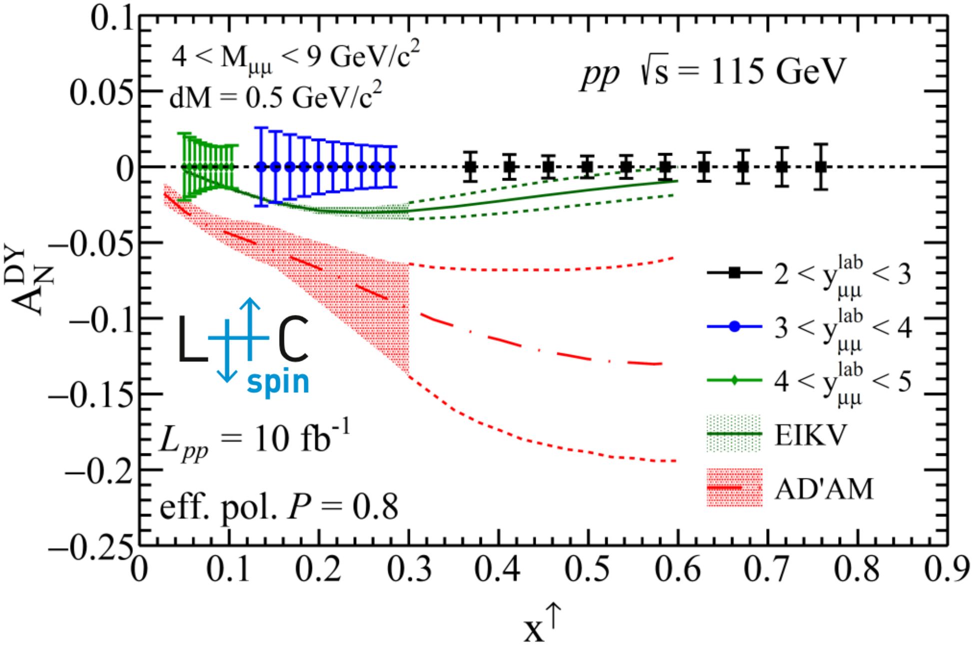


pp collisions (fixed target)
0.45 - 7 TeV beam

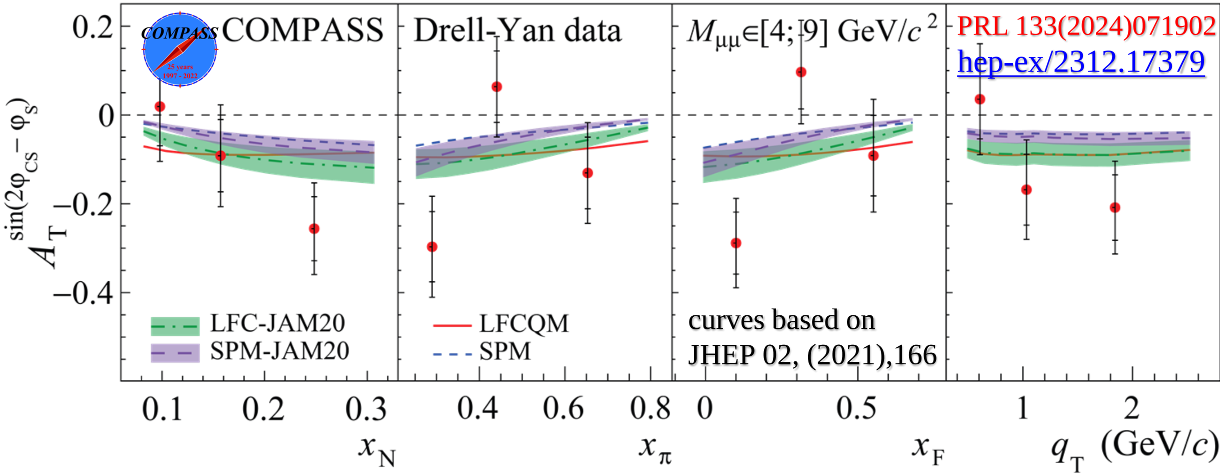
Forward acceptance: $2 < \eta < 5$
Tracking system momentum resolution
$\Delta p/p$ = 0.5%-1.0% (5 GeV/c - 100 GeV/c)



DGLAP: M. Anselmino et al, JHEP04,(2017)046
TMD-1: M. G. Echevarria et al, PRD89,074013(2014)
TMD-2: P. Sun and F. Yuan, PRD88,114012(2013)



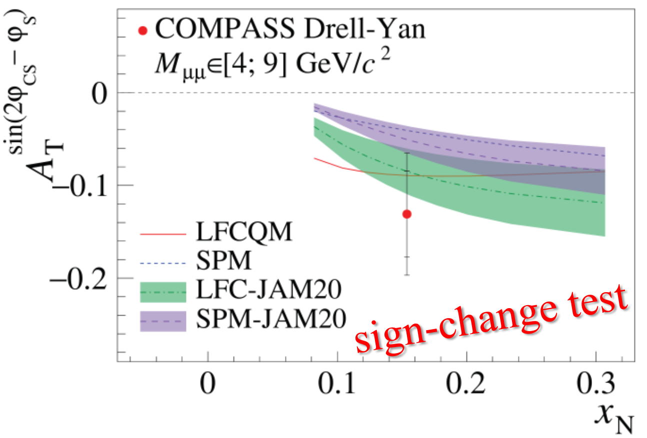
Boer-Mulders TMD PDF: sign change



curves based on JHEP 02, (2021),166

PRL 133(2024)071902

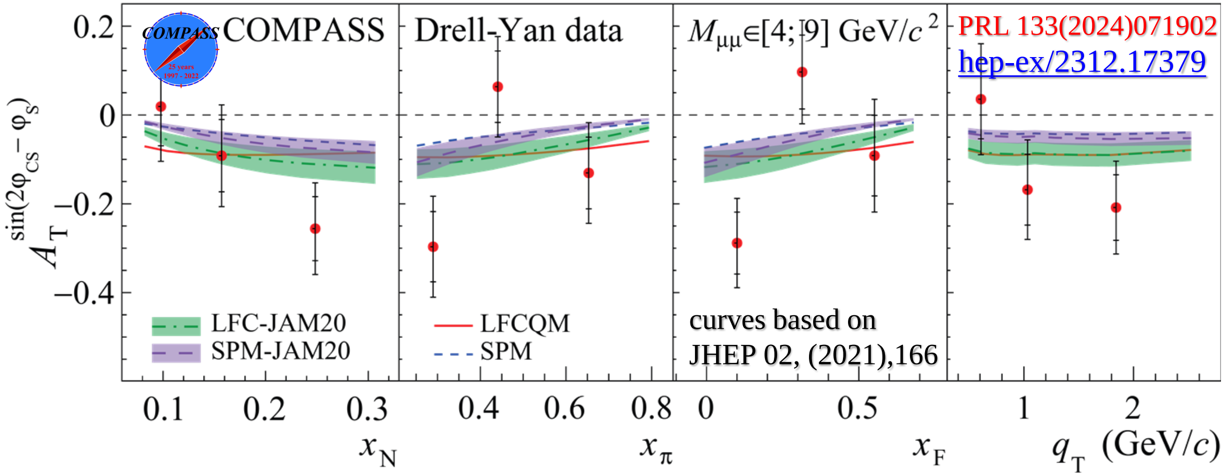
hep-ex/2312.17379



sign-change test

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

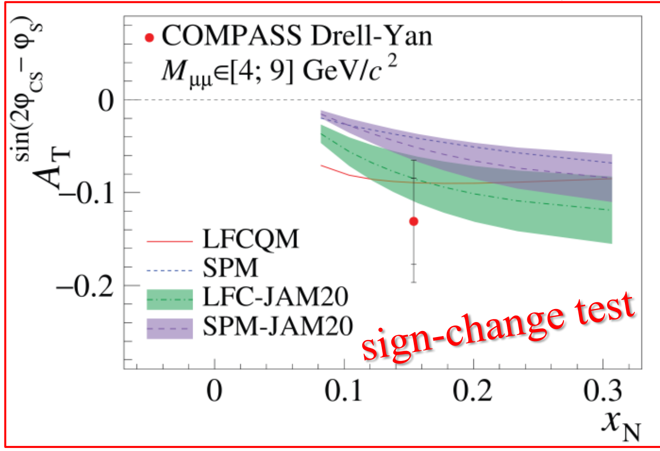
Boer-Mulders TMD PDF: sign change



PRL 133(2024)071902

hep-ex/2312.17379

curves based on JHEP 02, (2021),166



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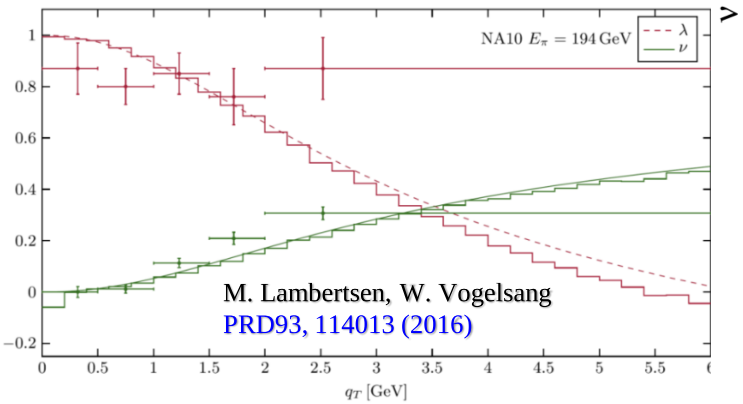
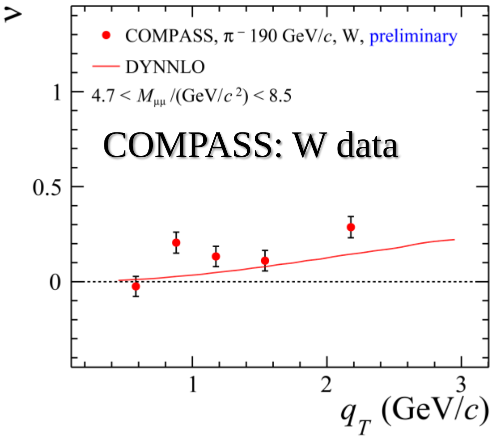
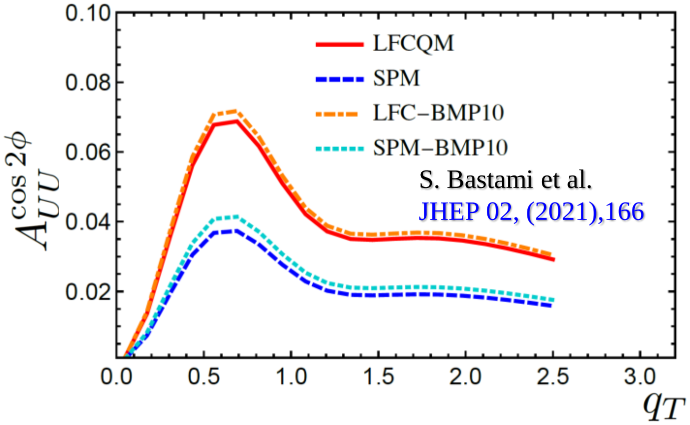


M. Lambertsen, W. Vogelsang

PRD93, 114013 (2016)



COMPASS: W data



S. Bastami et al.

JHEP 02, (2021),166

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

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

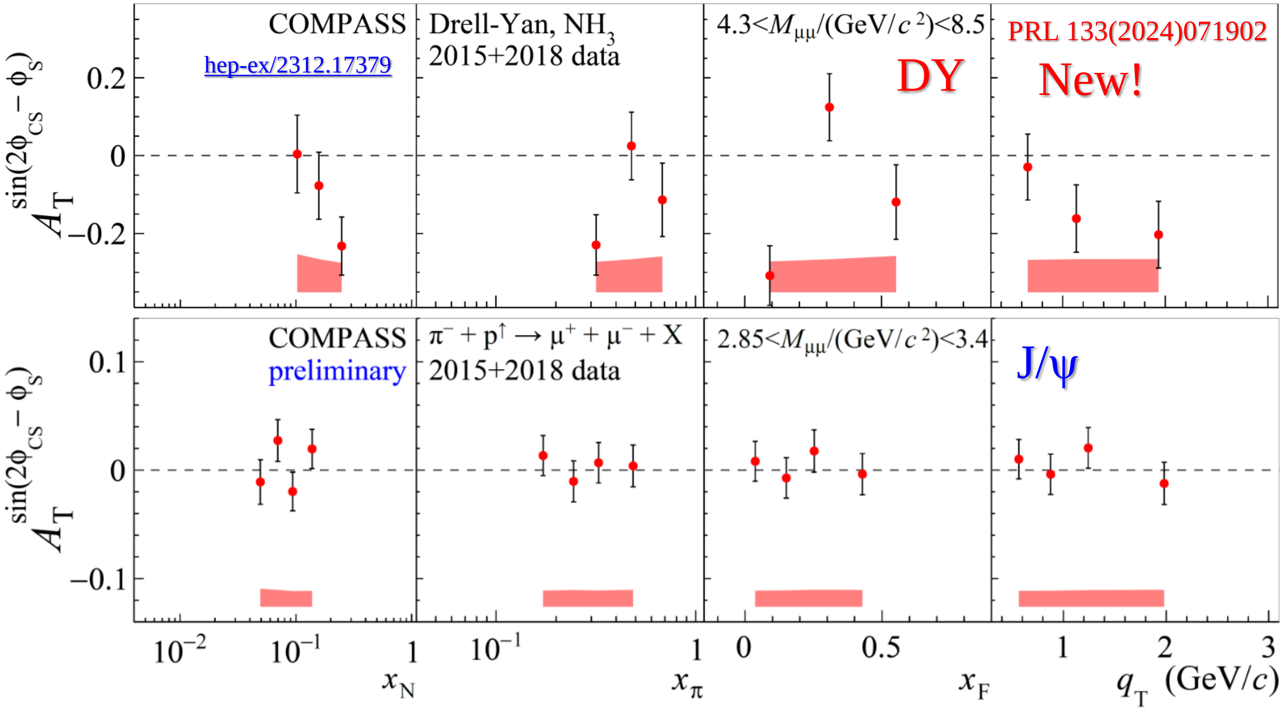
- COMPASS data favors proton Boer-Mulders TMD PDF sign-change

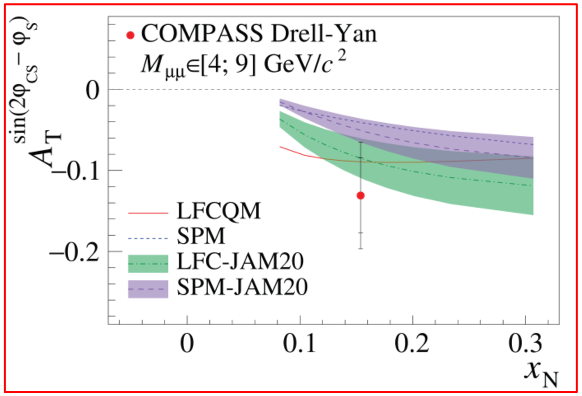
Drell-Yan TSAs – Transversity

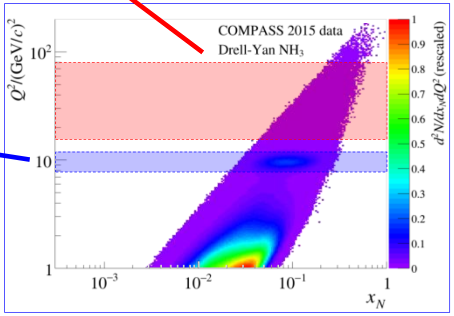
$$\frac{d\sigma}{dq^4 d\Omega} \propto 1+\ldots+ S_T\left[D_{\left[\sin^2\theta_{CS}\right]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S)+\ldots\right]$$

Transversity DY TSA

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





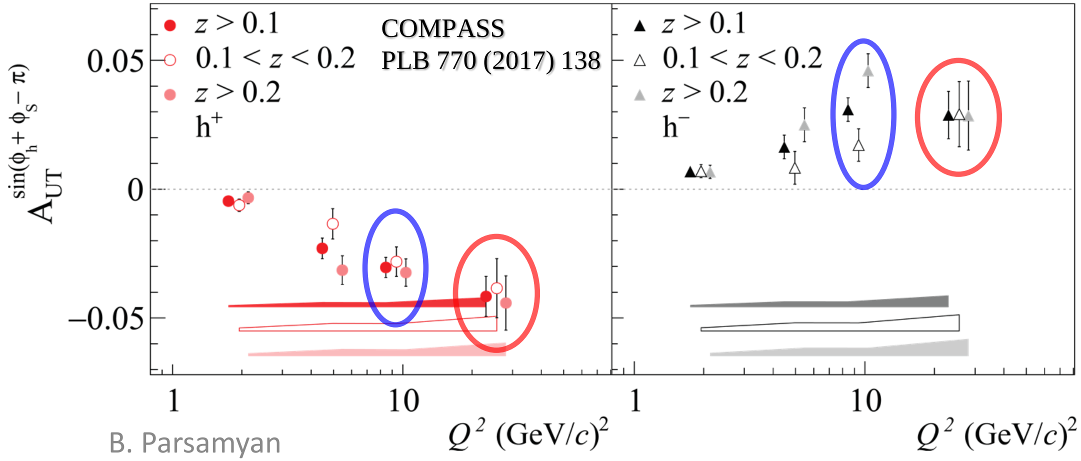


Collins SIDIS TSA

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

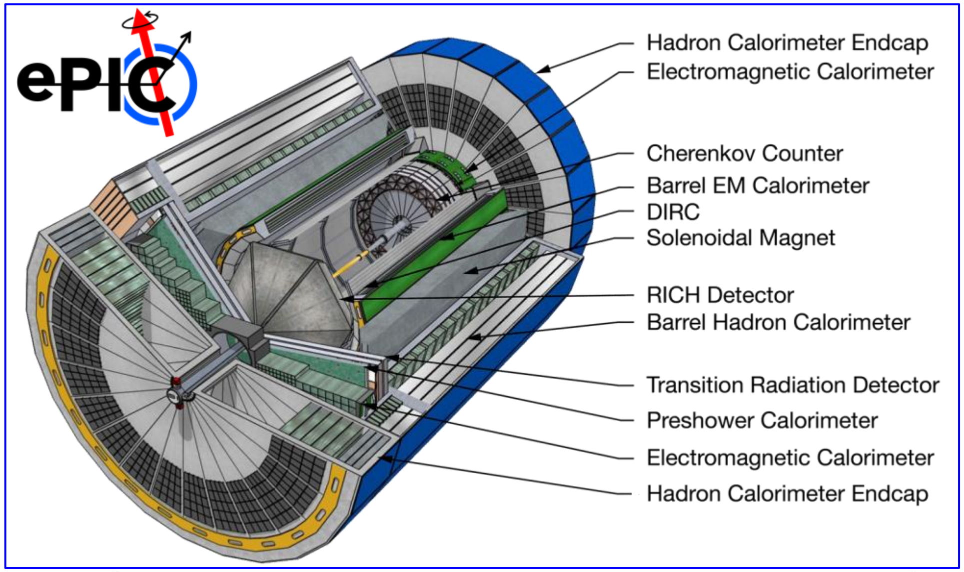
COMPASS proton Collins measurements

- Clear signal in the matching Q^2 ranges

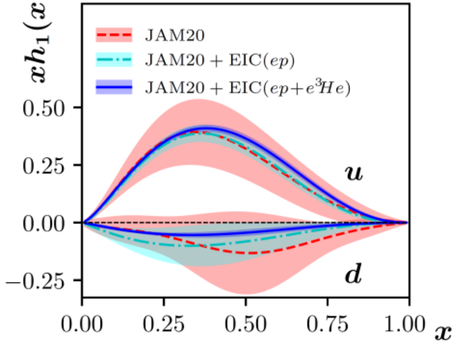


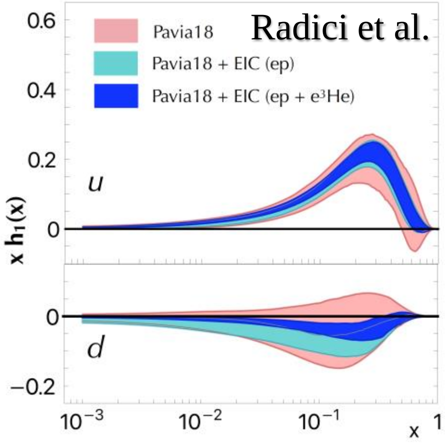
Electron Ion Collider(s): EIC

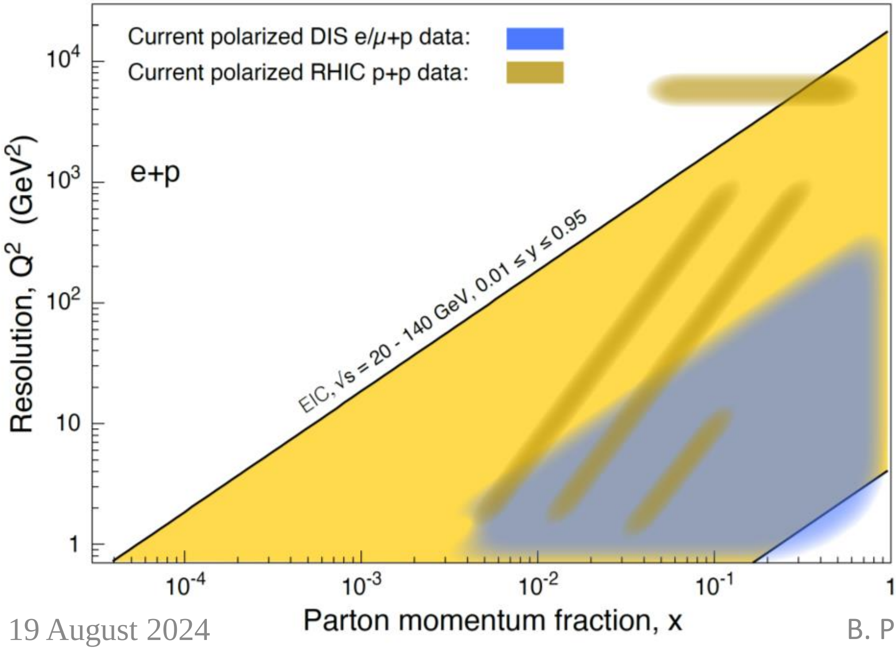
EIC WP, arXiv:1212.1701 [nucl-ex],
EIC YR, arXiv:2103.05419 [physics.ins-det]

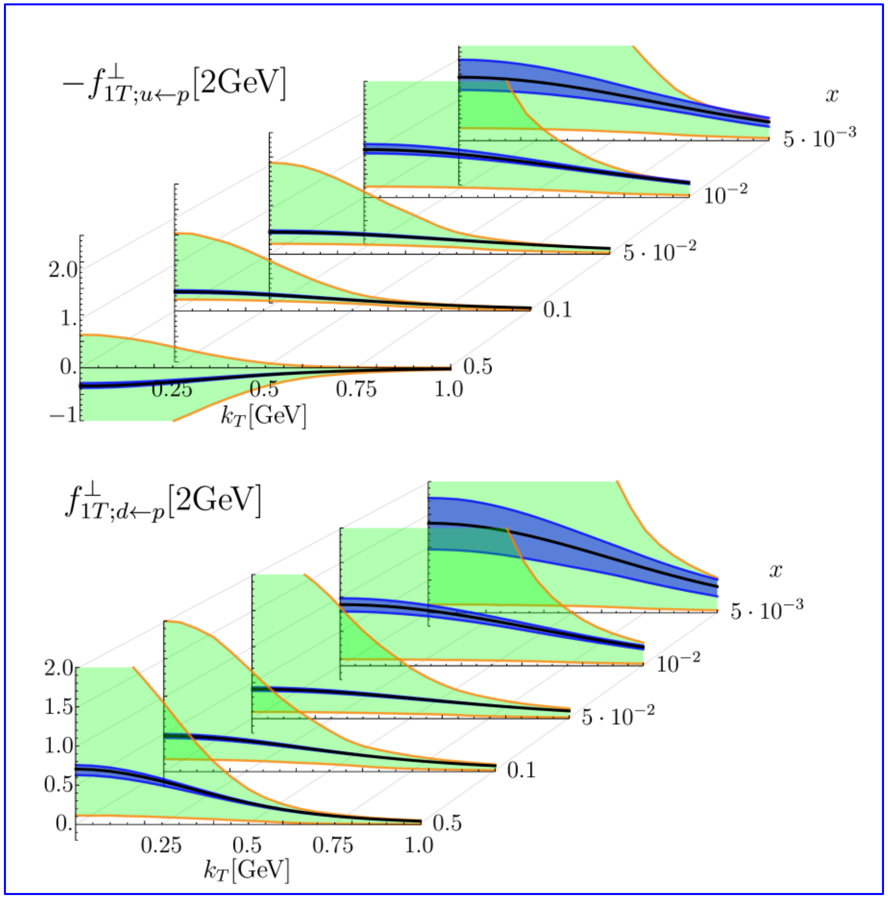


Gamberg et al. (JAM)
PLB 816 (2021) 136255



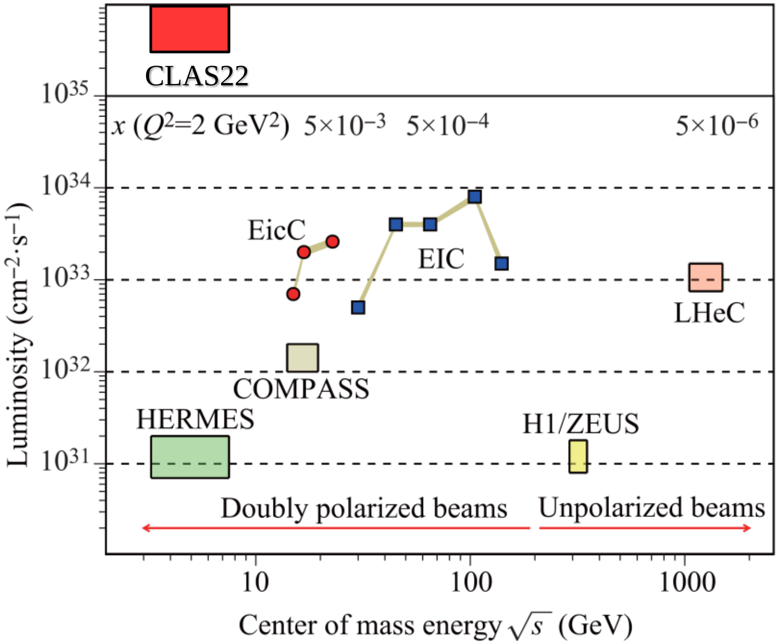


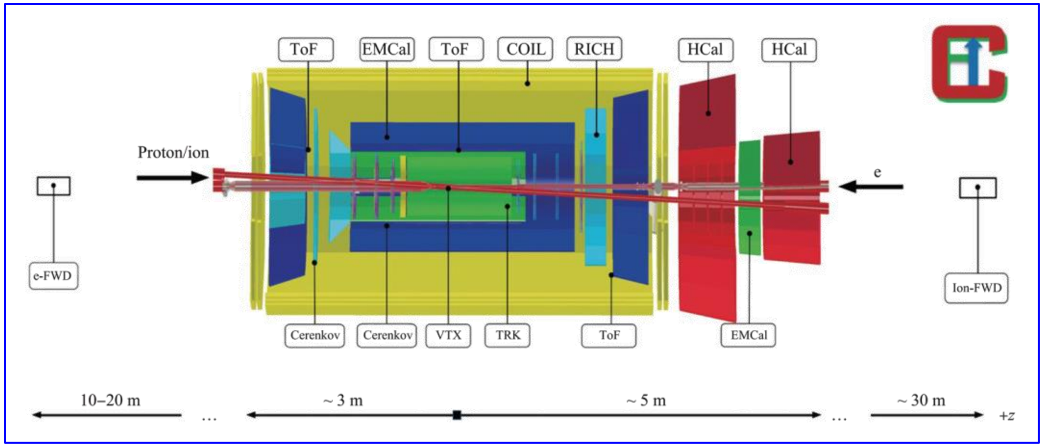


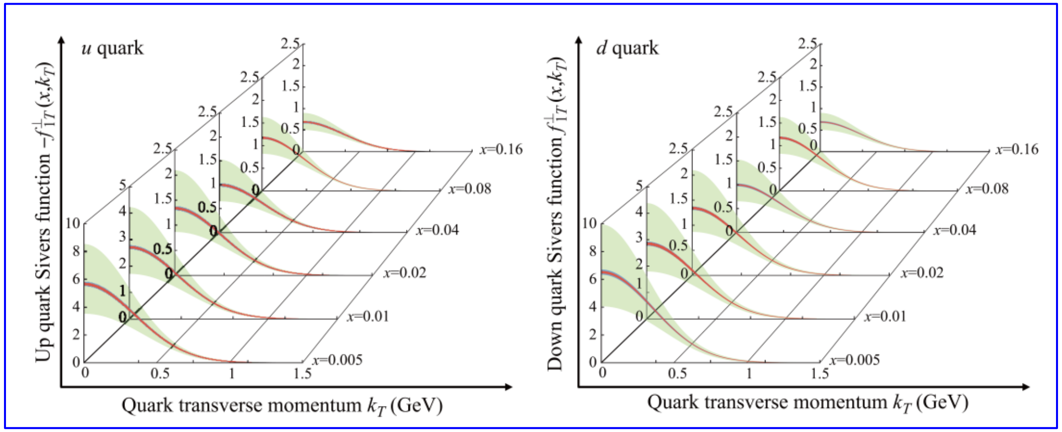


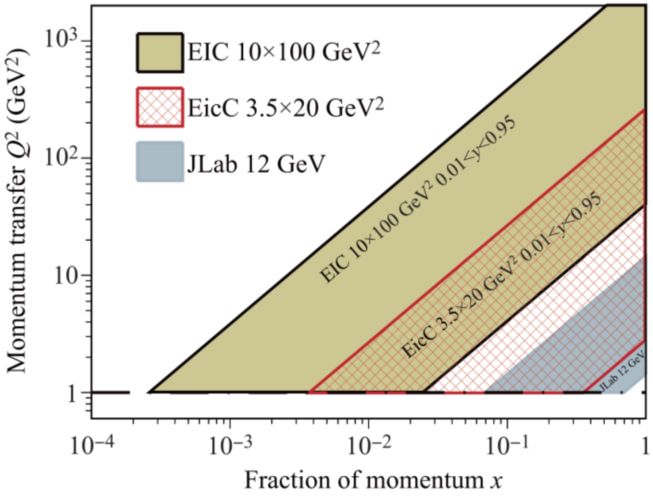
Electron Ion Collider(s): EICc

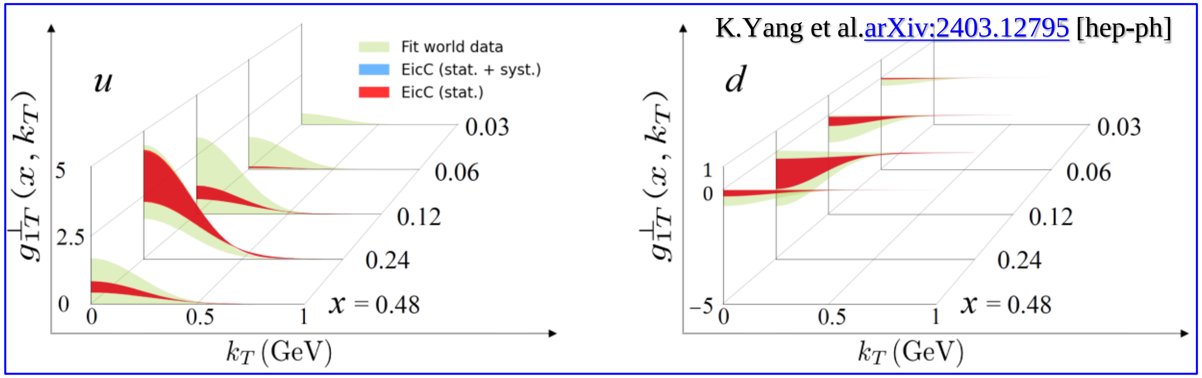
EICc, FP16(6), 64701 (2021), arXiv:2102.09222 [nucl-ex]





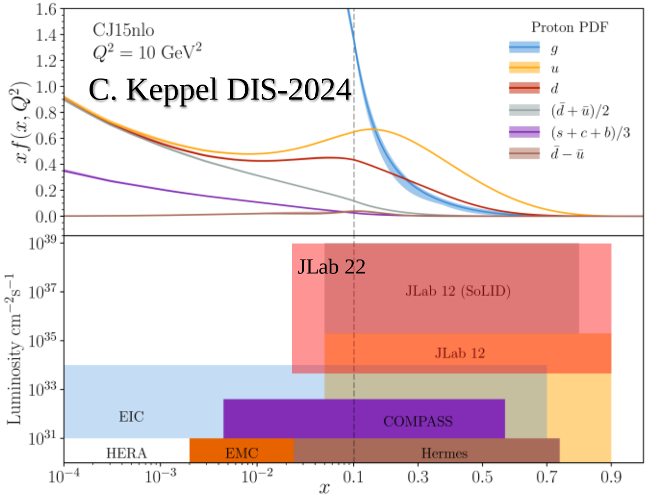






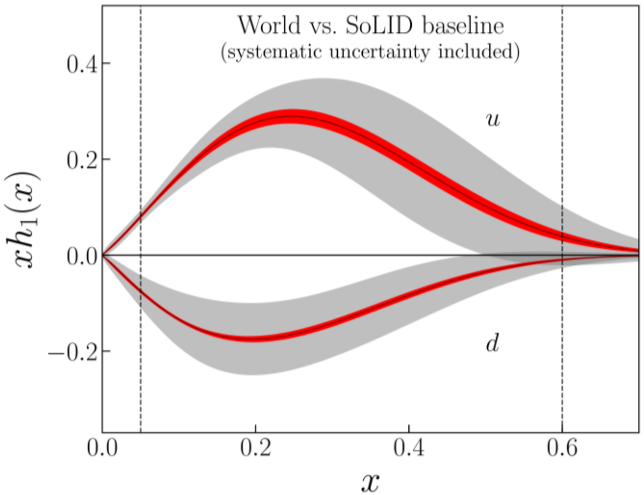
K.Yang et al.arXiv:2403.12795 [hep-ph]

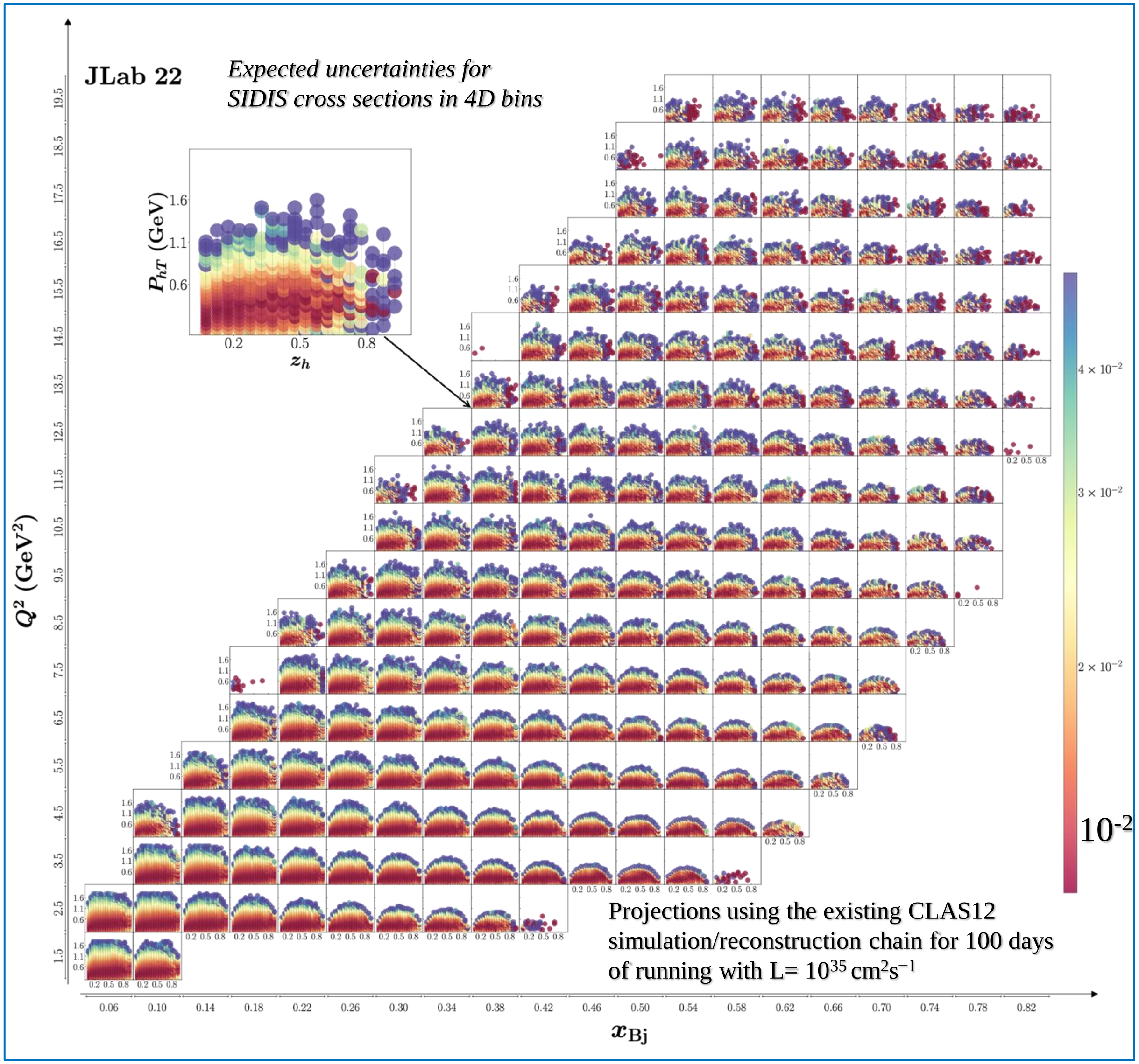
JLab from 12 GeV, SoLID to 22 GeV



C. Keppel DIS-2024

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



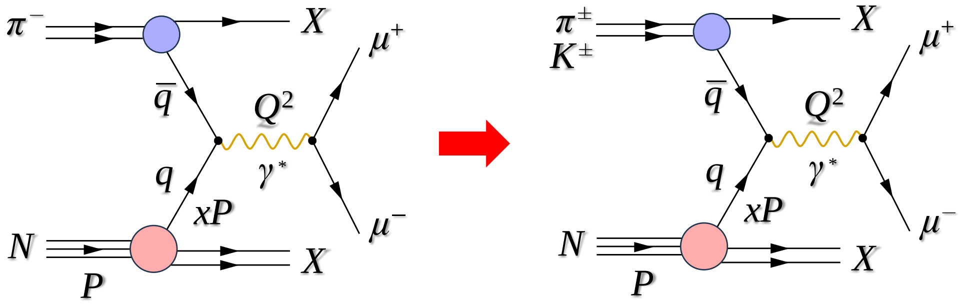


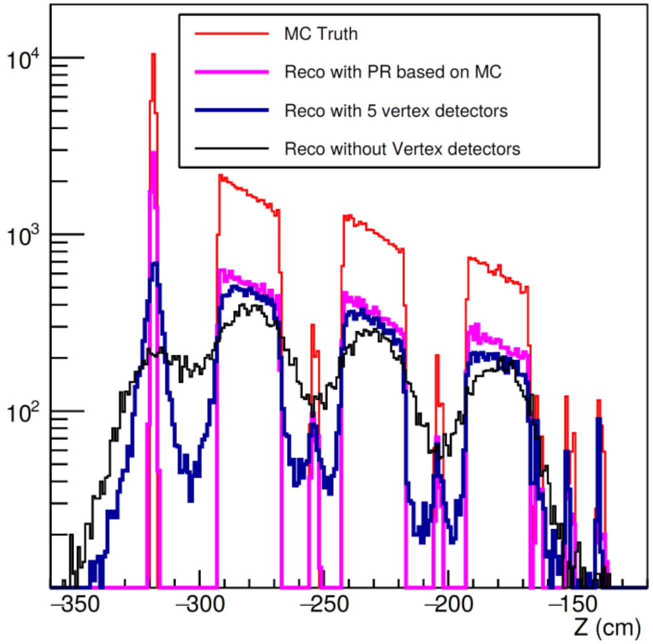
Expected uncertainties for SIDIS cross sections in 4D bins

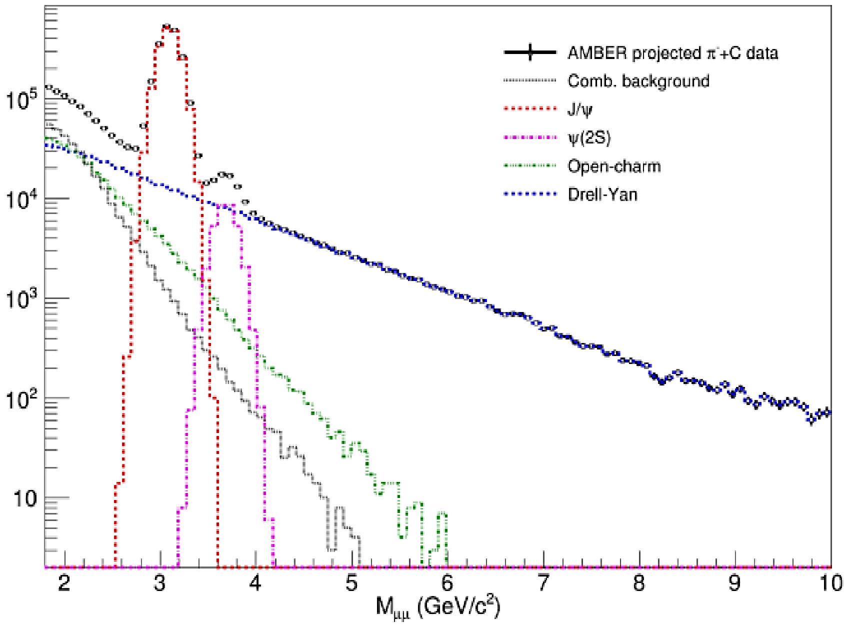
Projections using the existing CLAS12 simulation/reconstruction chain for 100 days of running with L= 10^{35} cm^{2}s^{-1}

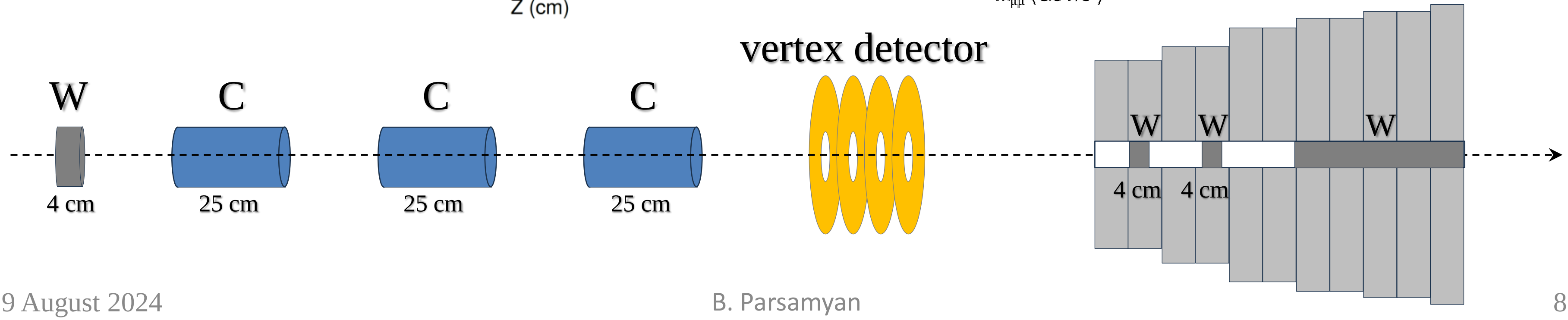
- High luminosity, complementary kinematic coverages, evolution studies, all TMDs, etc.
- Together with EIC/EICc - complete picture!

COMPASS→AMBER: Vertex detector improvements







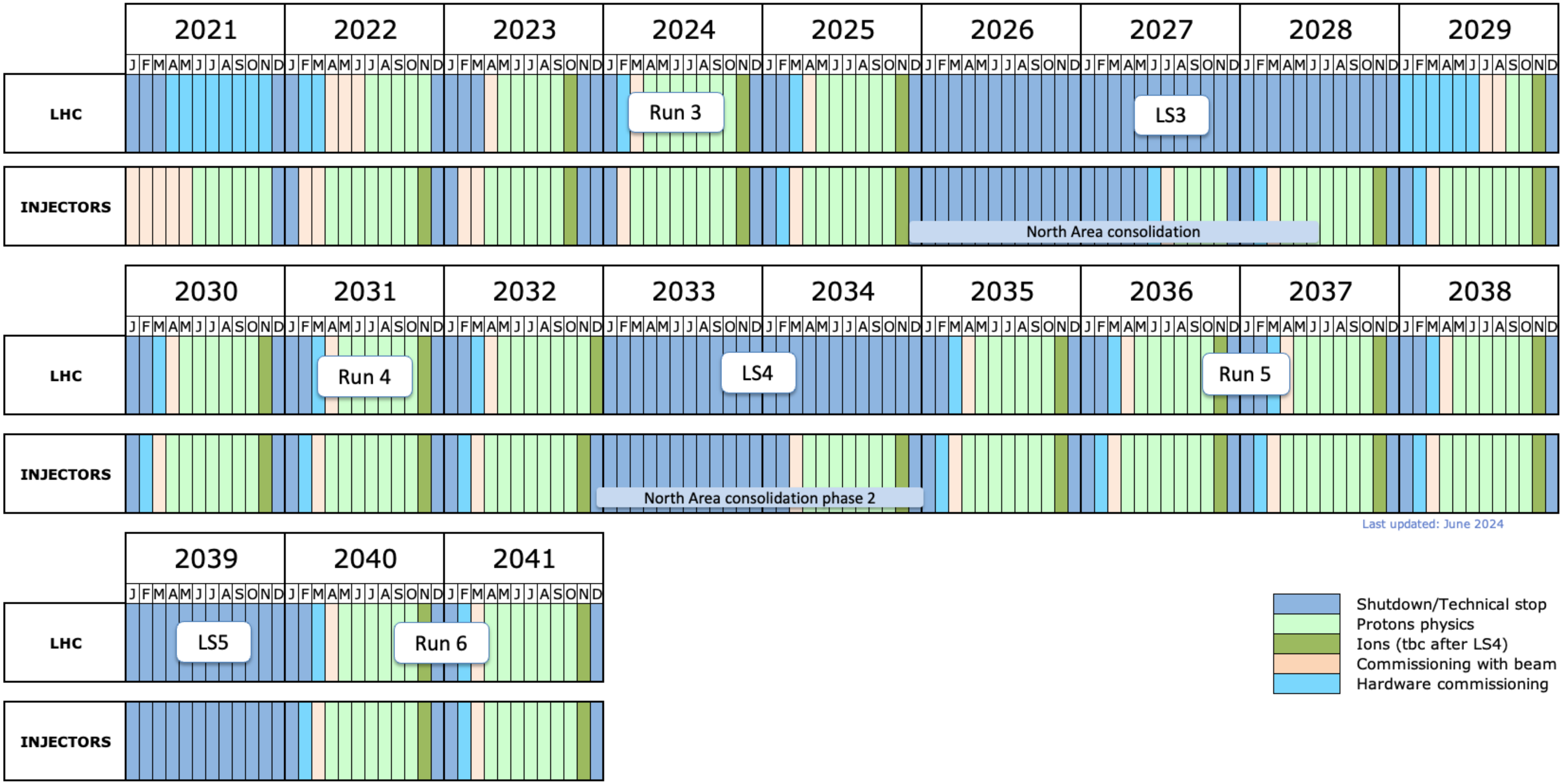


COMPASS data taking campaigns

Beam	Target	year	Physics program
μ^+	Polarized deuteron (^{6}LiD)	2002 2003 2004	80% Longitudinal | 20% Transverse SIDIS
		2006	Longitudinal SIDIS
	Polarized proton (NH$_3$)	2007	50% Longitudinal | 50% Transverse SIDIS
π | K | p	LH$_2$, Ni, Pb, W	2008 2009	Spectroscopy
μ^+	Polarized proton (NH$_3$)	2010	Transverse SIDIS
		2011	Longitudinal SIDIS
π | K | p	Ni	2012	Primakoff
$\mu^\pm$	LH$_2$	2012	Pilot DVCS & HEMP & unpolarized SIDIS
π^-	Polarized proton (NH$_3$)	2014	Pilot Drell-Yan
		2015 2018	Transverse Drell-Yan
$\mu^\pm$	LH$_2$	2016 2017	DVCS & HEMP & unpolarized SIDIS
μ^+	Polarized deuteron (^{6}LiD)	2021 2022	Transverse SIDIS

CERN LHC and NA schedules

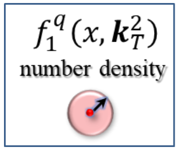
CERN Accelerator Complex schedule to 2041



Cahn effect in SIDIS

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

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



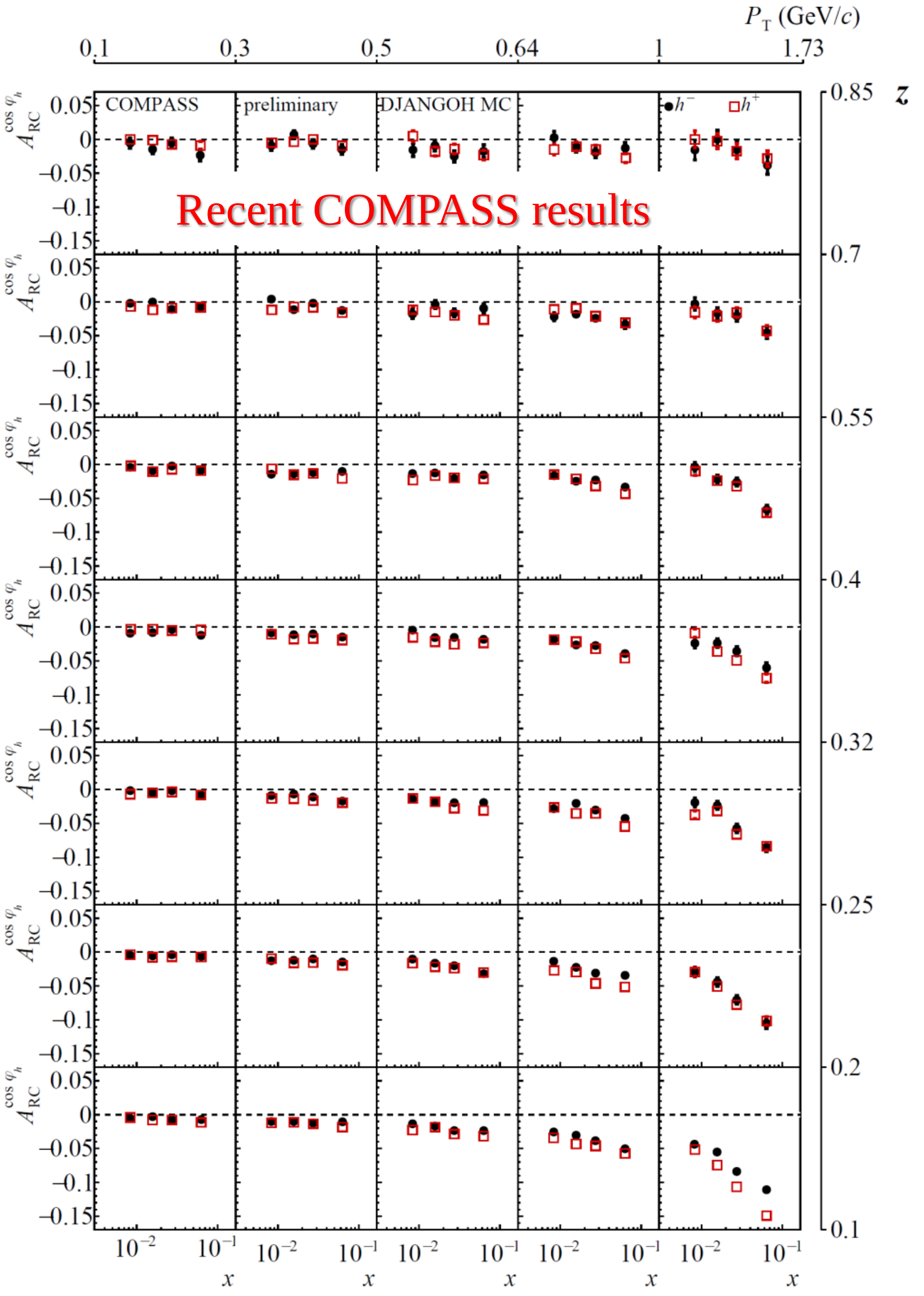
$f_1^q(x,\boldsymbol{k}_T^2)$
number density

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
- Complex multi-D kinematic dependences
    - So far, no clear interpretation
- A set of complex corrections:
    - Acceptance, diffractively produced VMs, radiative corrections, etc.



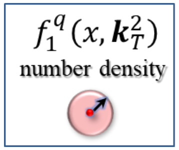
Recent COMPASS results

cosϕ_h amplitude of the radiative corrections

Cahn effect in SIDIS

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

Cahn effect



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

number density

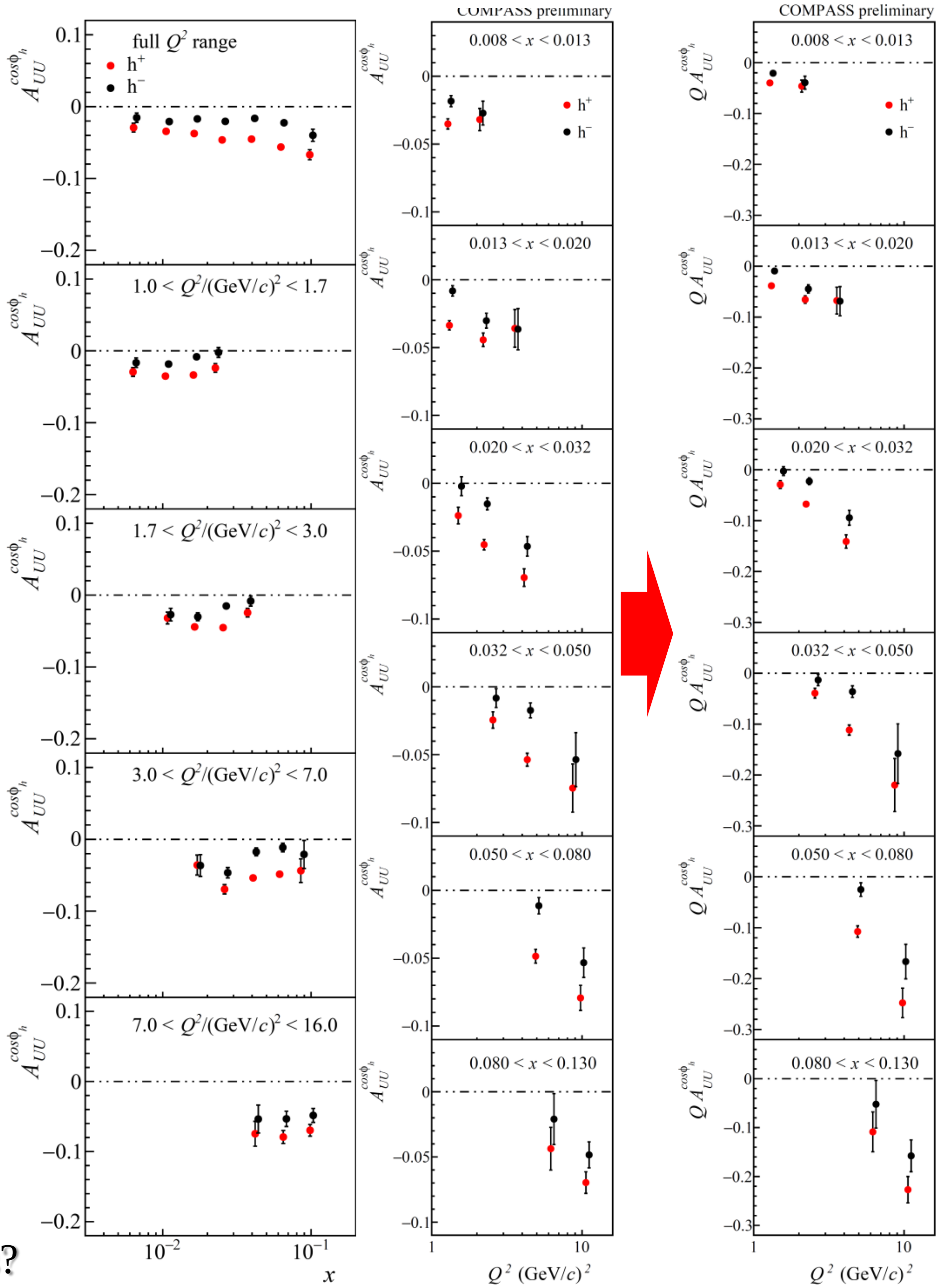
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

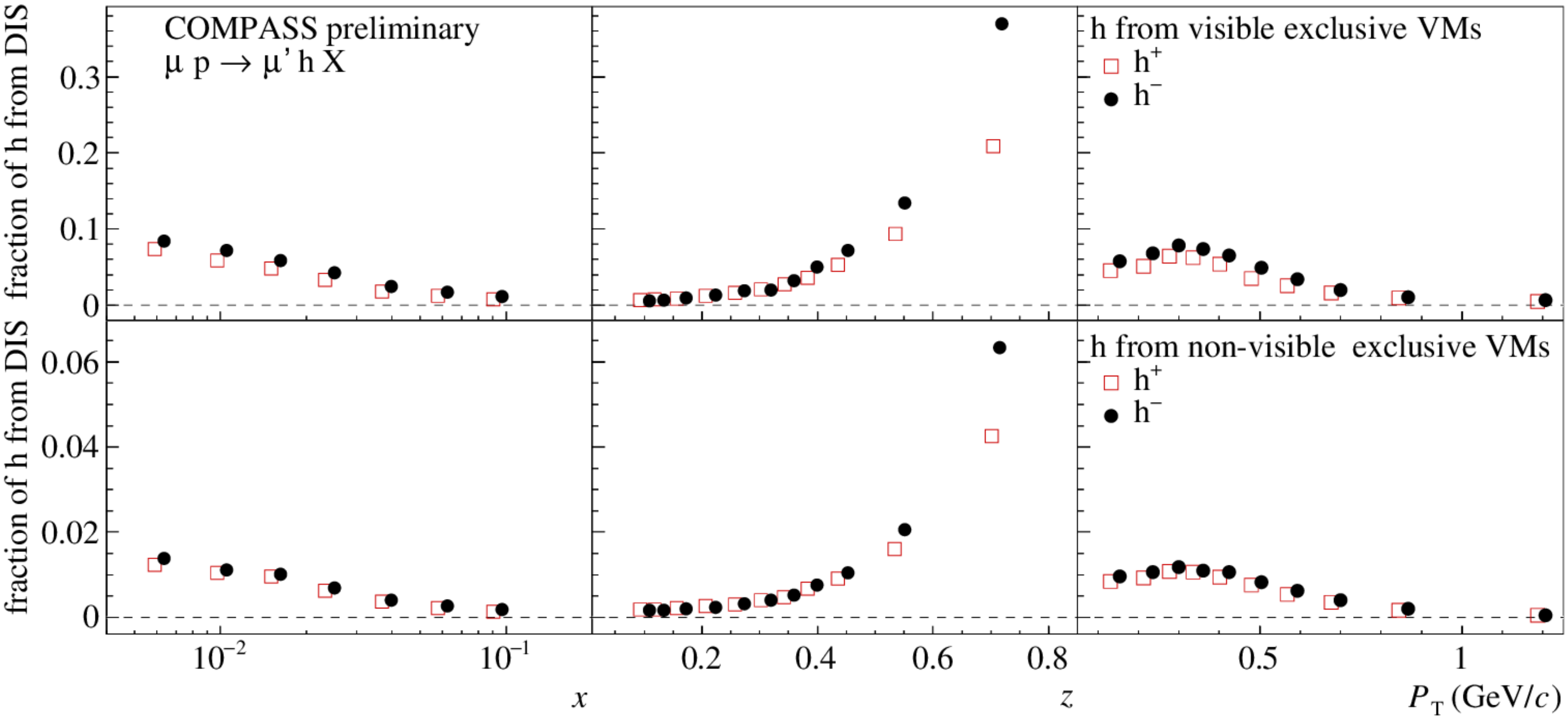
As of 2023 – complex SF (twist-2/3 functions)

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

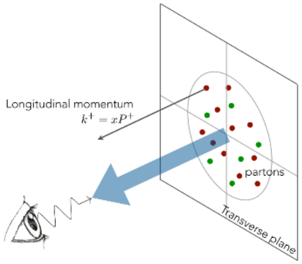
Recent COMPASS results

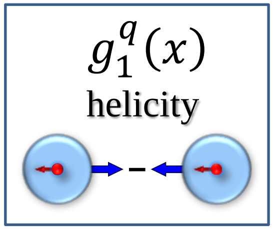


Exclusive Vector mesons in SIDIS



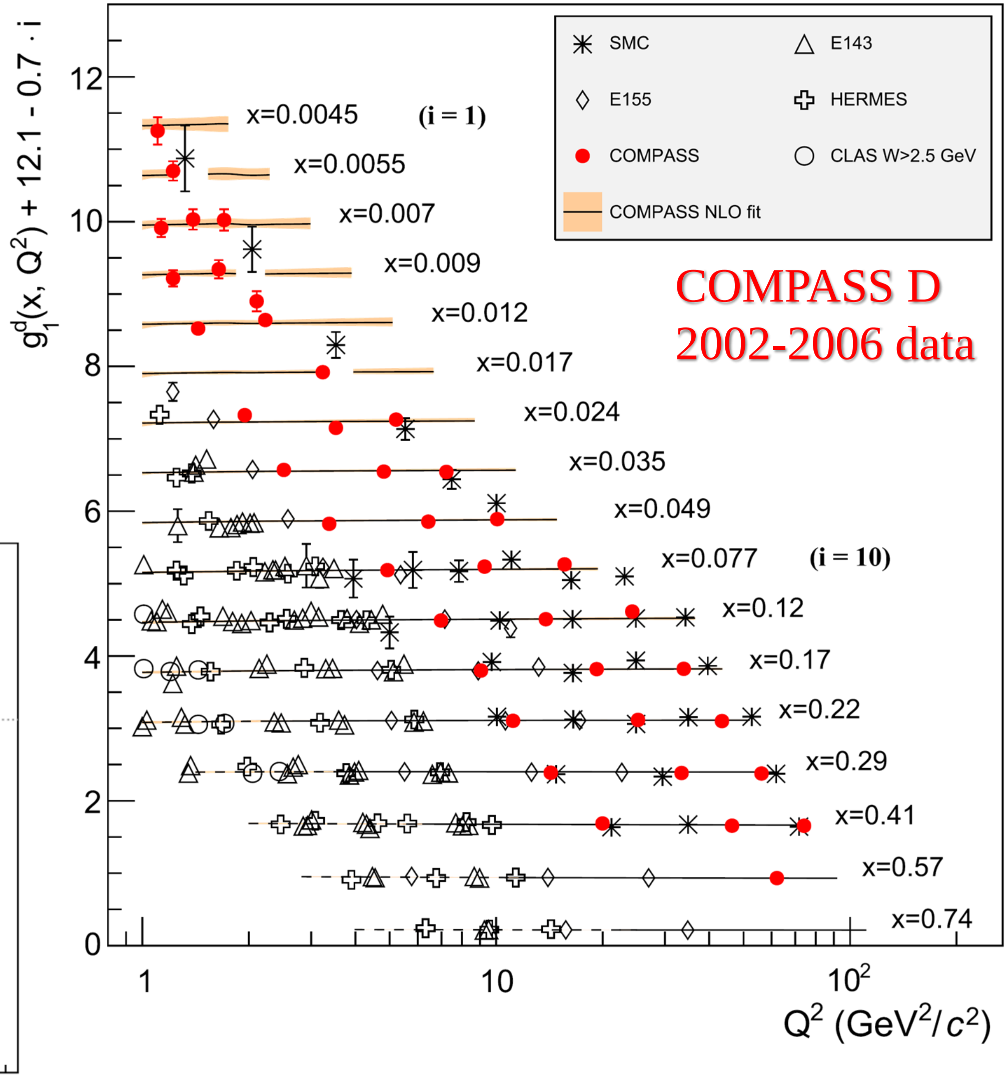
Nucleon spin structure: helicity $g_{1,d}^{q}(x)$



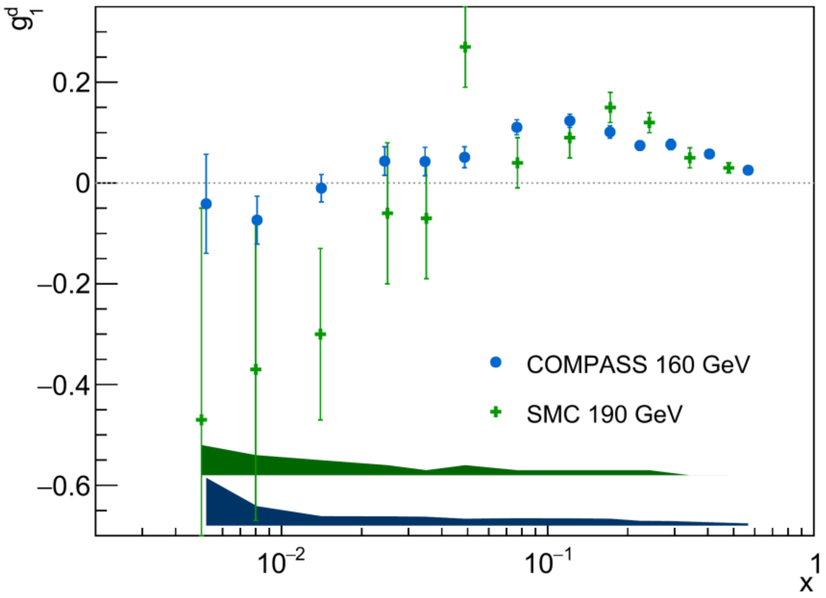

$g_1^q(x)$
helicity

- COMPASS contribution:
  lowest x and highest Q^2 regions

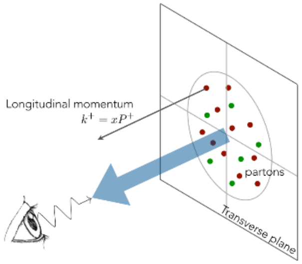
COMPASS PLB 769(2017) 34

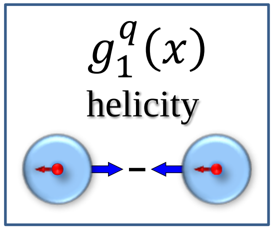


COMPASS D
2002-2006 data



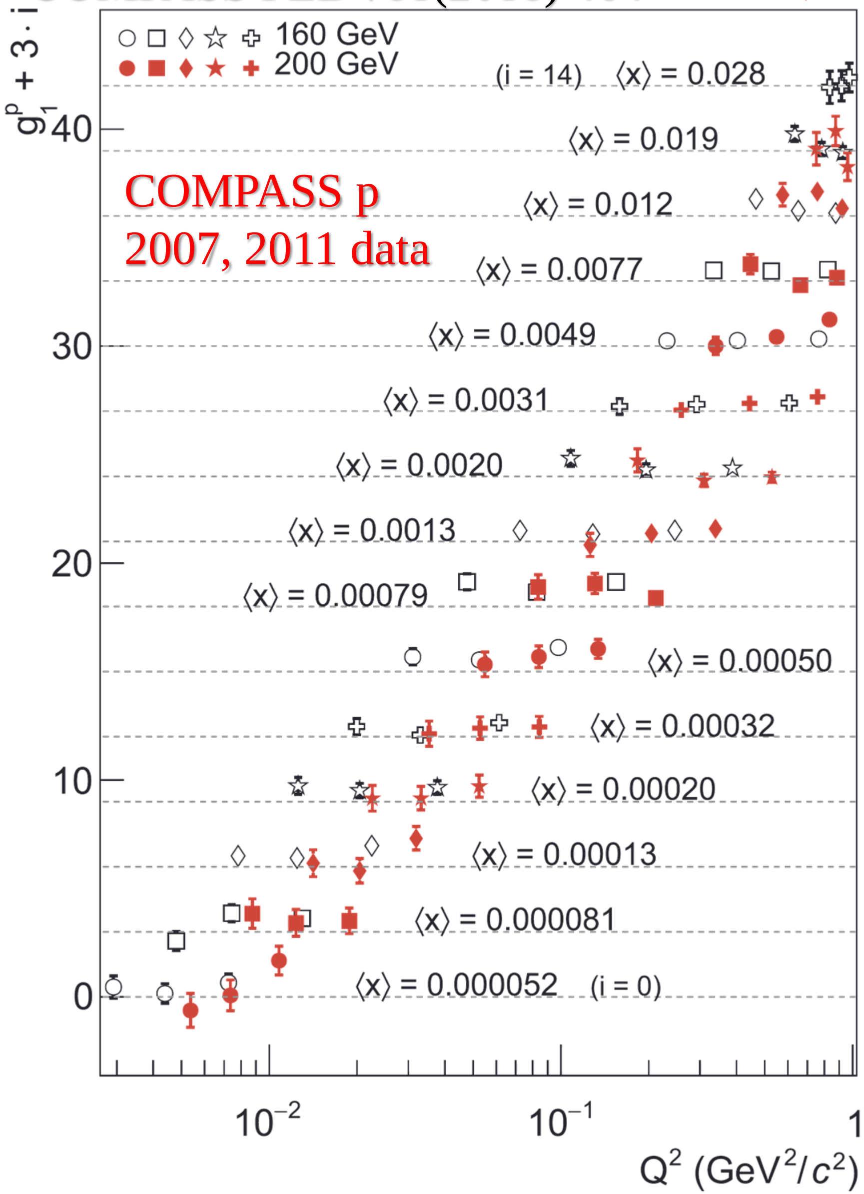
Nucleon spin structure: helicity $g_{1,p}^{q}(x)$



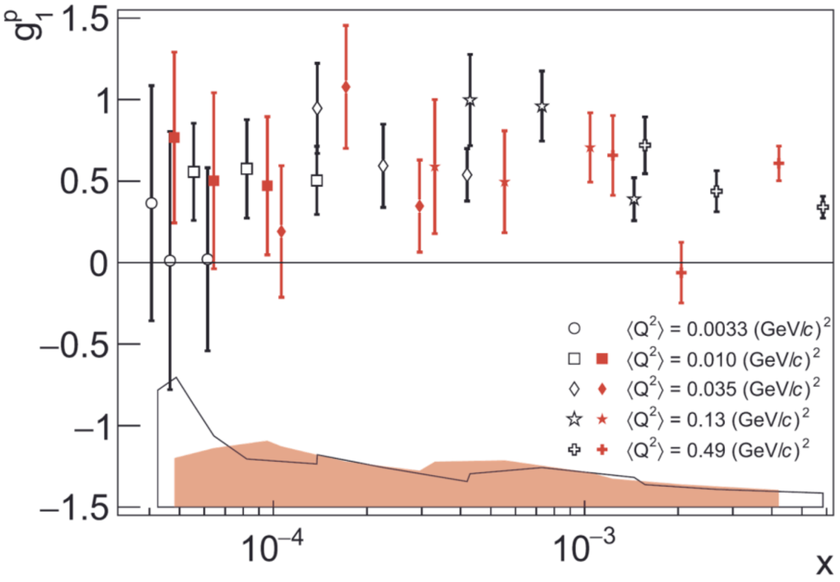


- COMPASS contribution:
  lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$

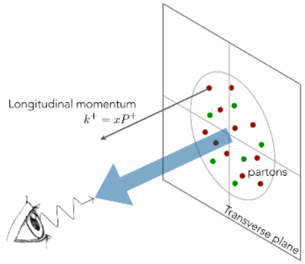
COMPASS PLB 781(2018) 464

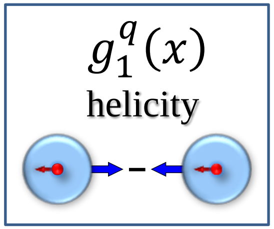


COMPASS p
2007, 2011 data



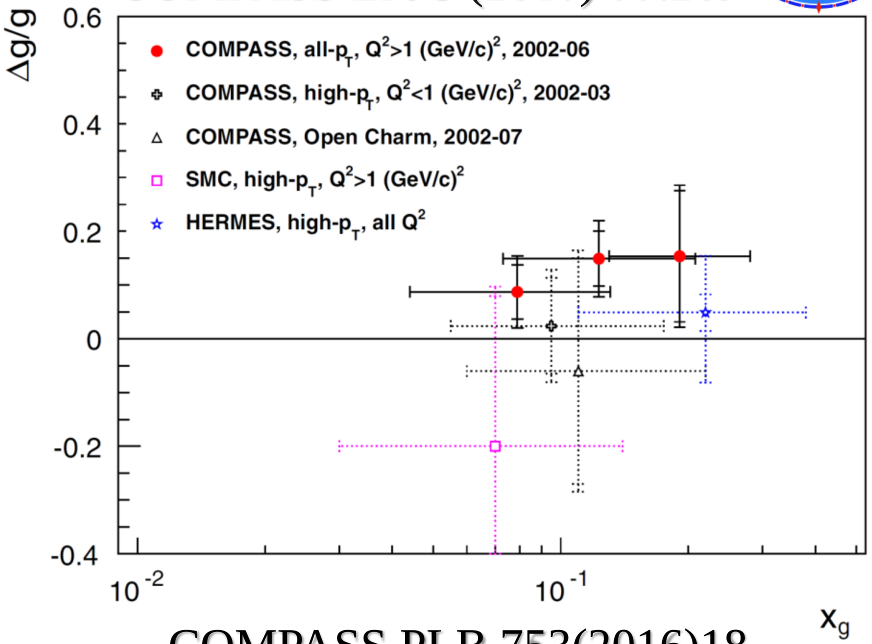
Nucleon spin structure: helicity $g_{1,d(p)}^{q}(x)$



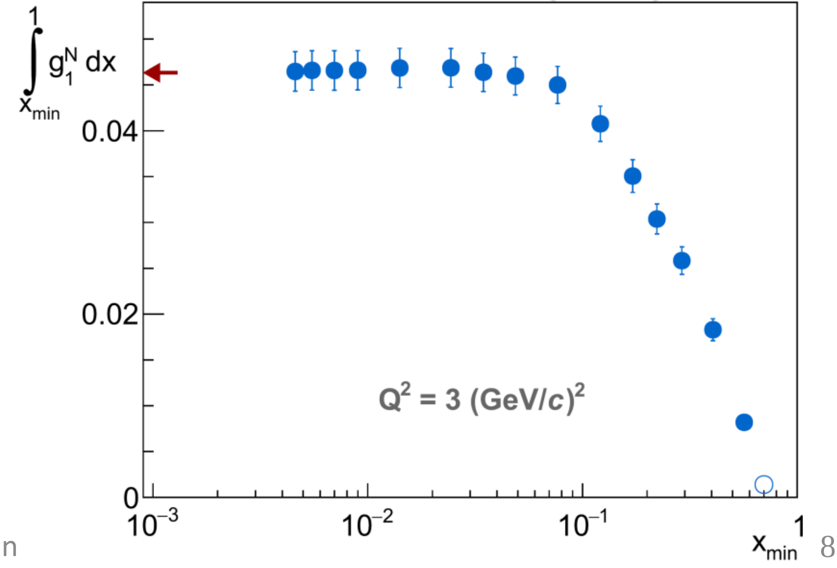


- COMPASS contribution:
  lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$
- Gluon polarization measurements
  via open charm and SIDIS
- COMPASS - first to rule out a large gluon polarization in the nucleon!
  Precise test of Bjorken sum rule (9% level)

COMPASS EPJC (2017) 77:209



COMPASS PLB 753(2016)18

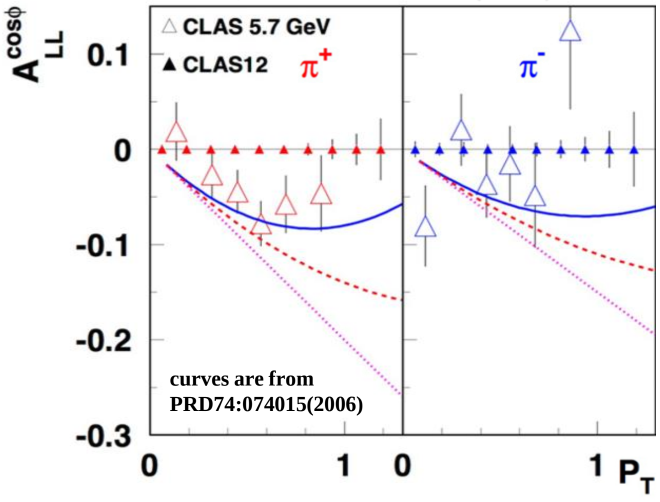


SIDIS: target longitudinal spin dependent asymmetries

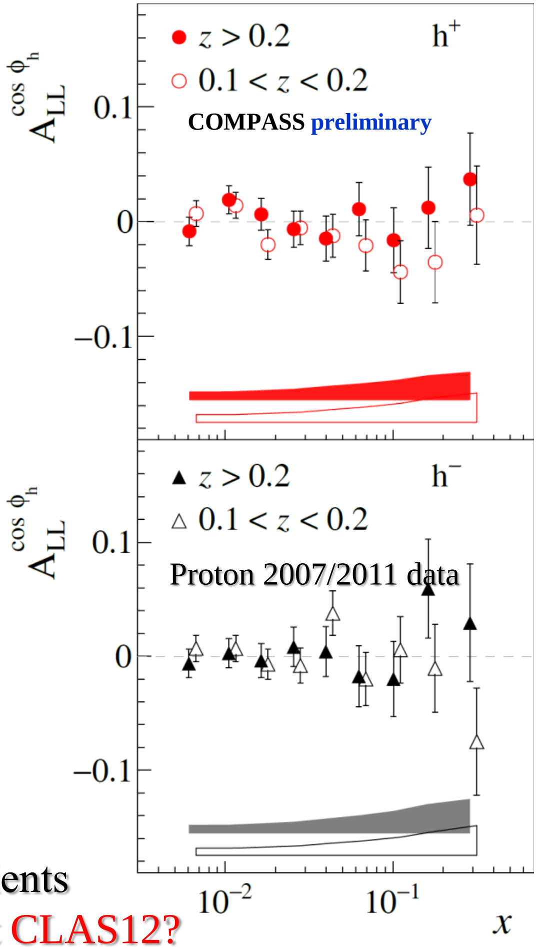
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+ S_L\lambda\sqrt{2\varepsilon\left(1-\varepsilon\right)}A_{LL}^{\cos\phi_h}\cos\phi_h+\ldots\right\}$$

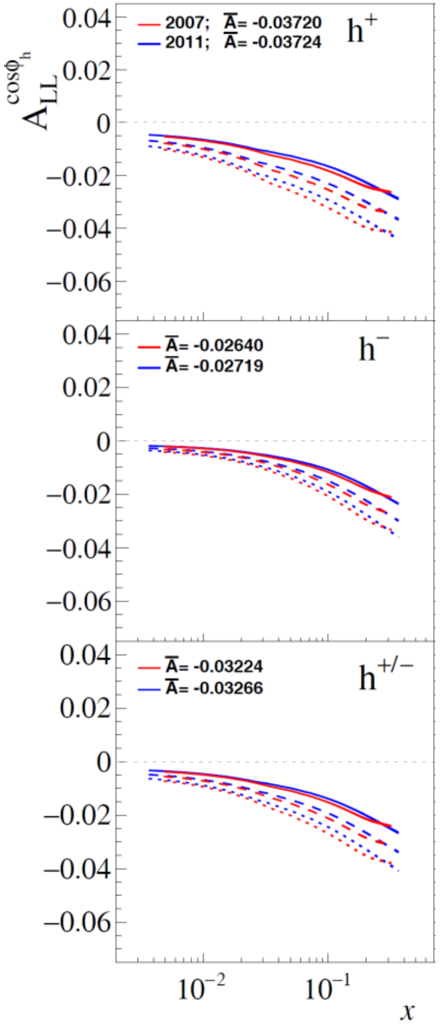
$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xe_L^q H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xg_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{E}_q^h}{z}\right)\right\}$$

CLAS, PRL 105,262002(2010)



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

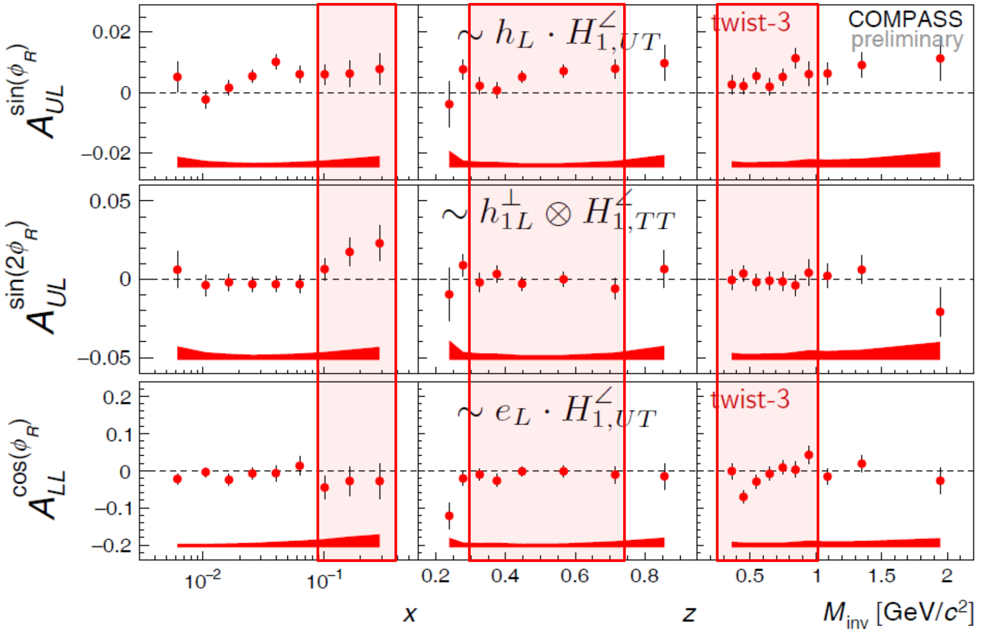


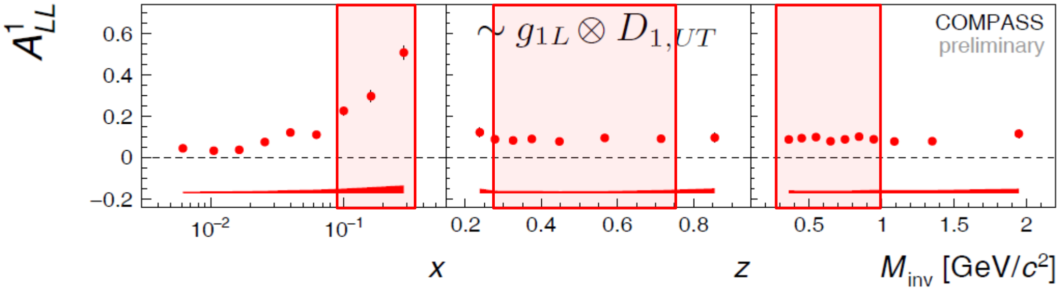


- Q-suppression, various different “twist” ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

Selected results for di-hadron LSAs

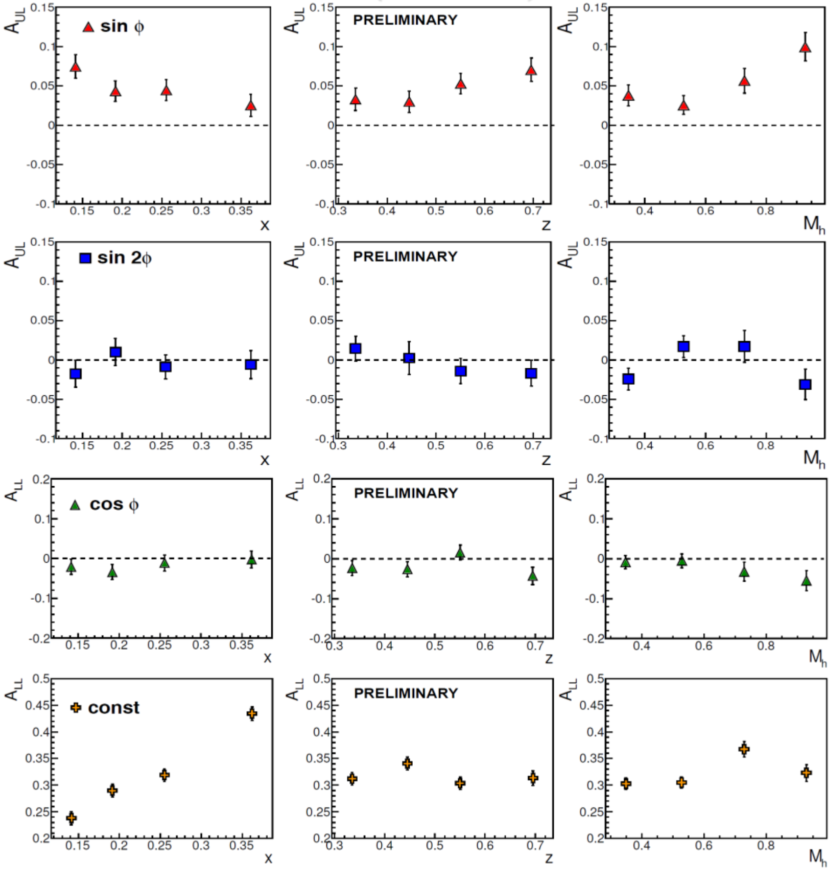
COMPASS (NH$_3$) 2007+2011 data: preliminary





CLAS 6 GeV (NH$_3$)

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

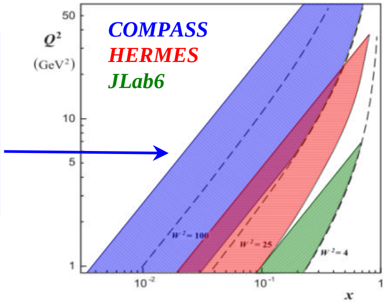


$Q^2 > 1\,(\text{GeV}/c)^2$

$0.0025 < x < 0.7$

$0.1 < y < 0.9$

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

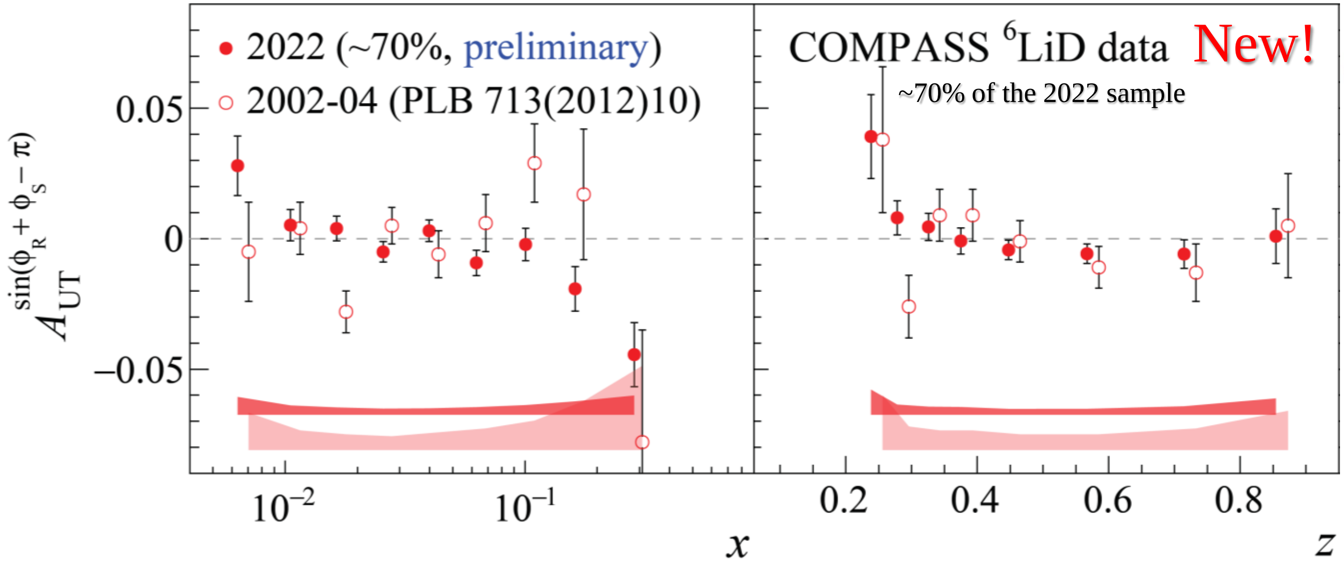


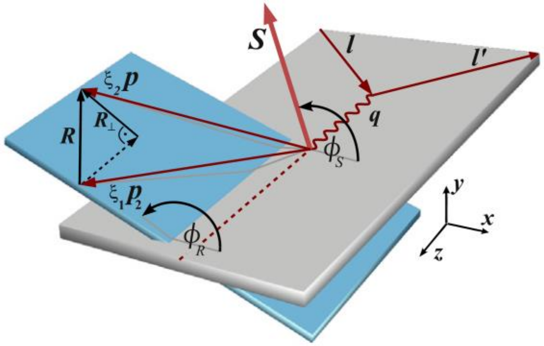
- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A_{LL}^{1}
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?

Dihadron Collins effect and Transversity

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

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

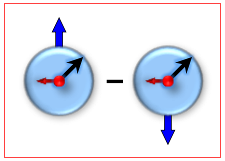




COMPASS 2022 run – highly successful data-taking!

- 2^{nd} 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: Kotzinian-Mulders asymmetry

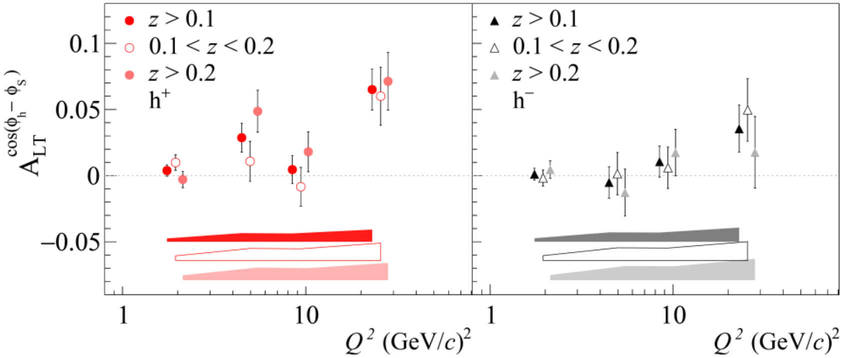


$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\lambda S_T\sqrt{\left(1-\varepsilon^2\right)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos\left(\phi_h-\phi_S\right)+\ldots\right\}$$

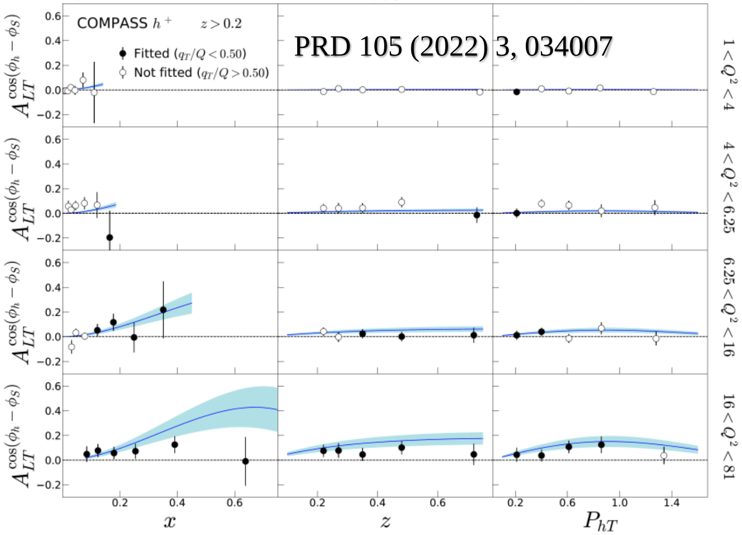
$$\boxed{F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\, g_{1T}^{q} D_{1q}^{h}\right]}$$

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

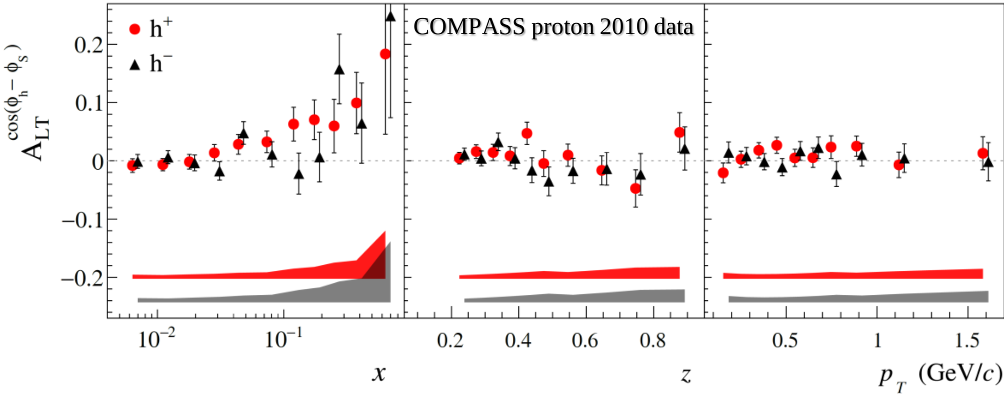


First global QCD analysis of the g_{1T} TMD PDF using SIDIS data



PRD 105 (2022) 3, 034007

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



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