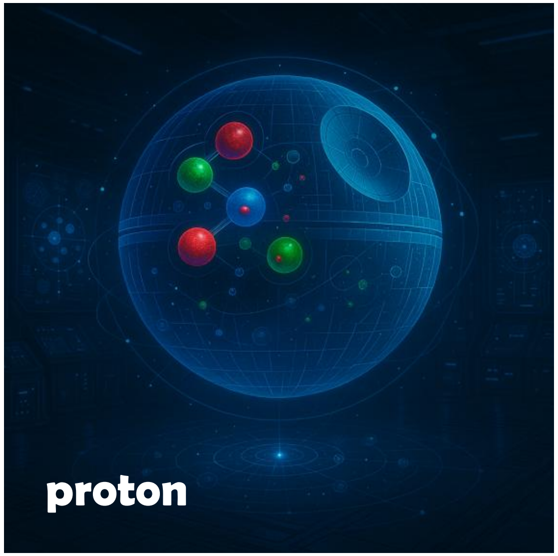
Spin, Structure, and Synergy: COMPASS and the Experiments of Tomorrow

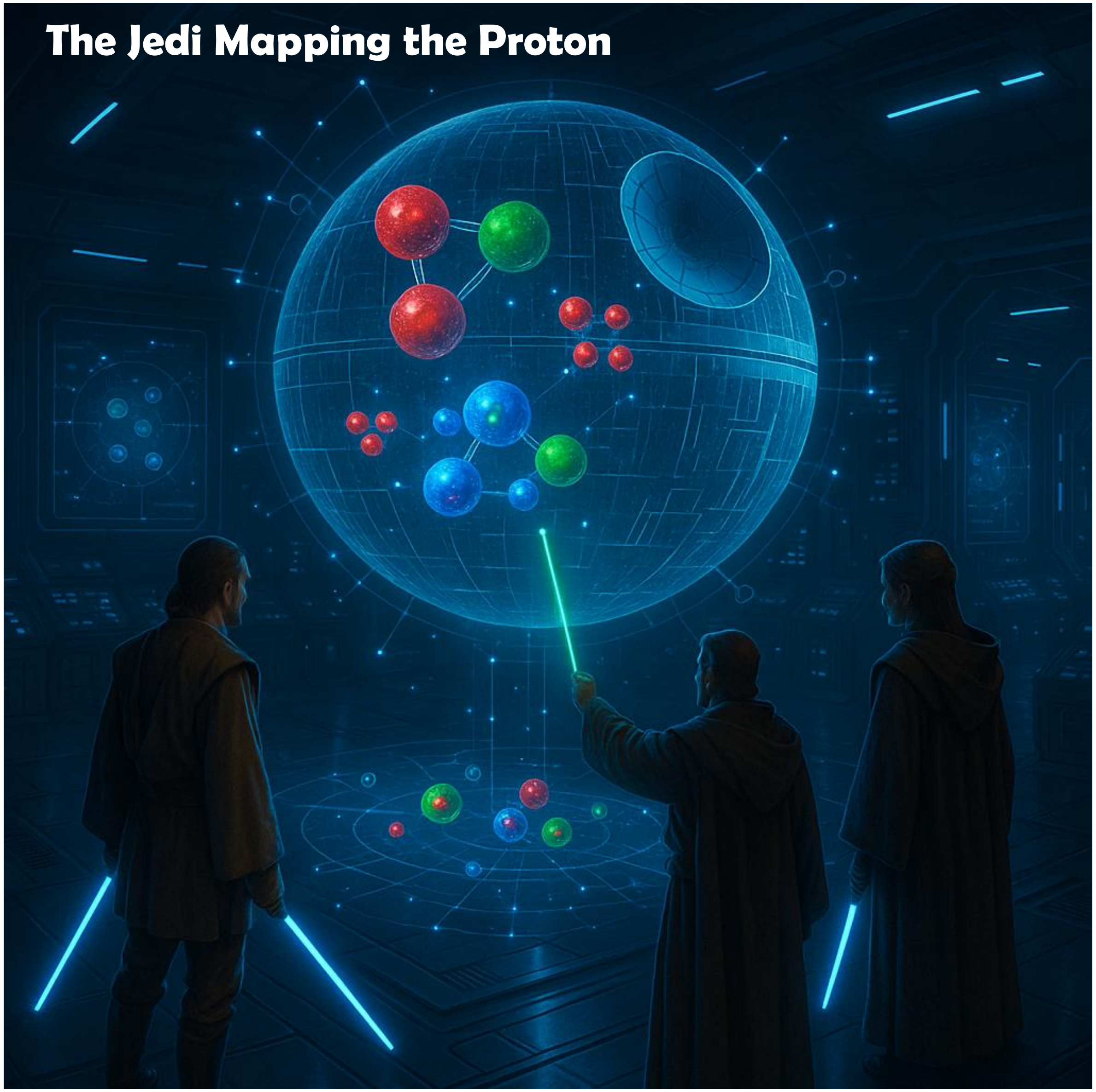
Bakur Parsamyan

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

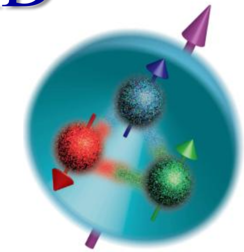
4th Sardinian Workshop on Spin and related issues
(Sar WorS 2025)
June 11–13, 2025
Pula (CA), Sardinia, Italy



May the Force be with us!

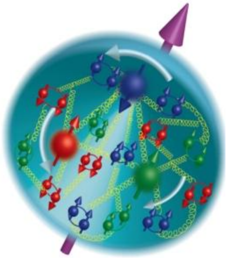


Nucleon spin structure: TMD



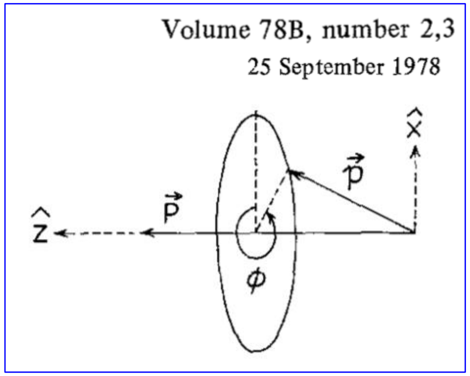
- 1964 Quark model

- 1969 Parton model



- 1973 asymptotic freedom and QCD

- 1976 large transverse single spin asymmetry in forward $\pi^{\pm}$ production ~50 years
- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries



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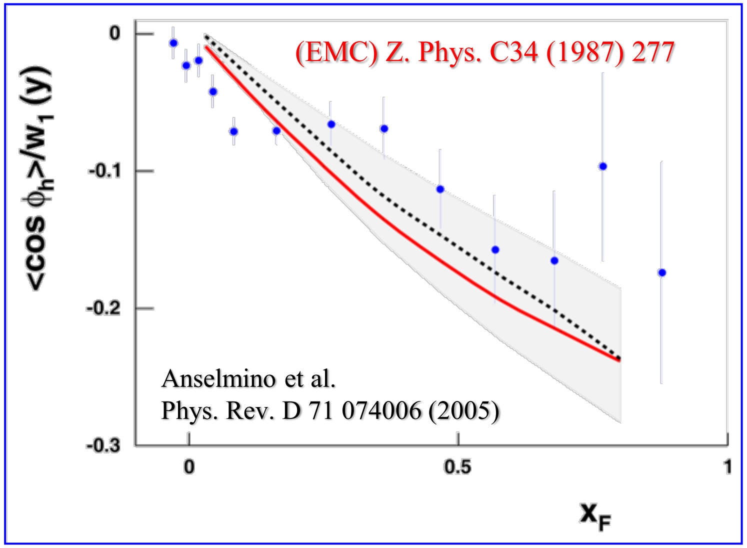
25 September 1978



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

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Phys. Rev. D 71 074006 (2005)

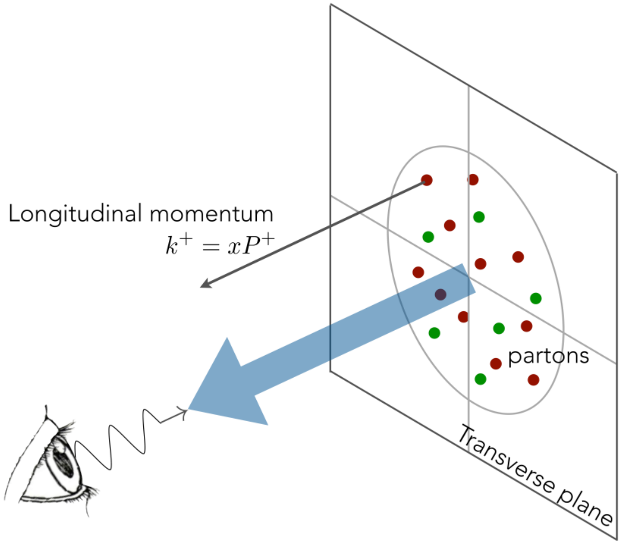
(SLAC) Phys. Rev. Lett. 31, 786 (1973)
(EMC) Phys. Lett. B 130 (1983) 118,
(EMC) Z. Phys. C34 (1987) 277
(EMC) Z. Phys. C52, 361 (1991).
(E665) Phys. Rev. D48 (1993) 5057
(ZEUS) Eur. Phys. J. C11, 251 (1999)
(ZEUS) Phys. Lett. B 481, 199 (2000)
(H1) Phys. Lett. B654, 148 (2007)

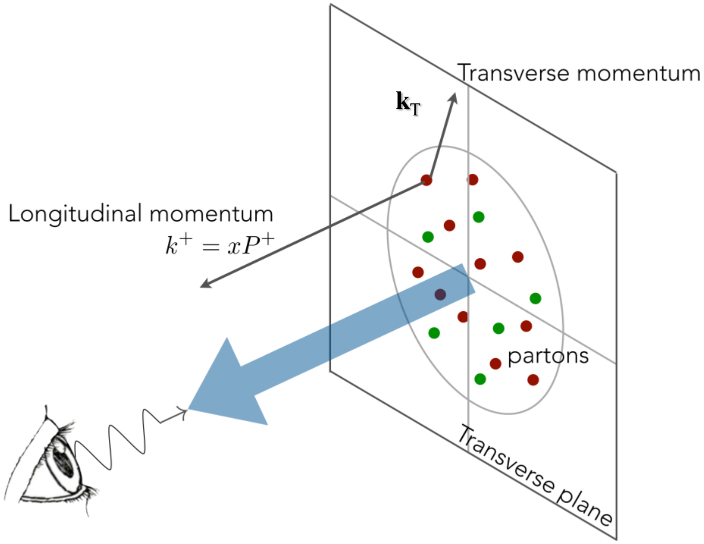
Nucleon spin structure (twist-2): collinear approach ↔TMDs

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

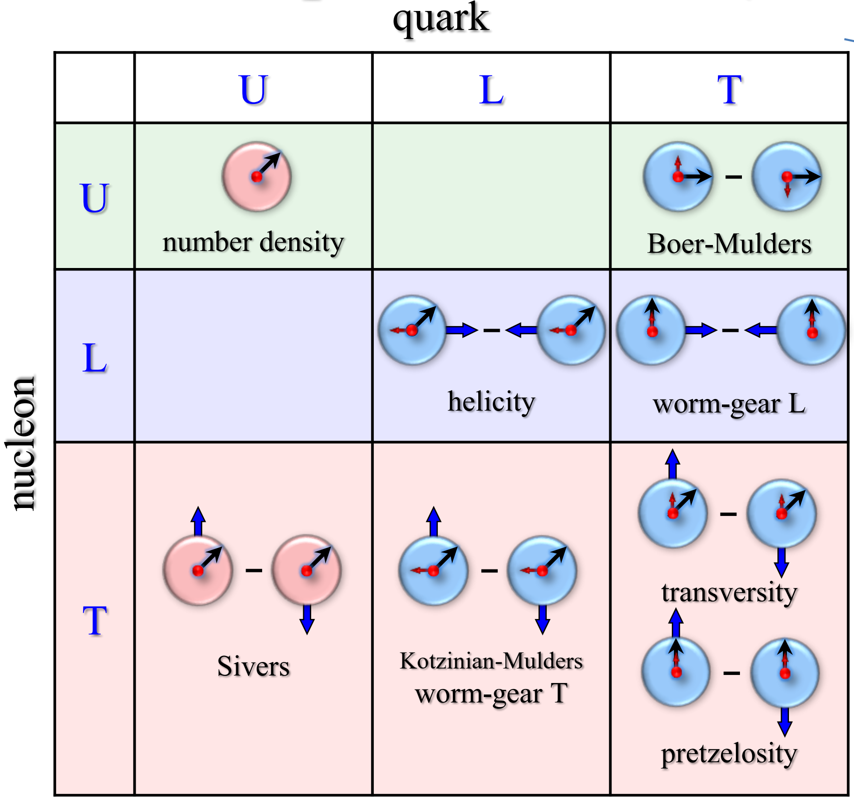
		quark		
		U	**L**	**T**
nucleon	**U**	$f_1^q(x, \boldsymbol{k}_T^2)$ number density		chiral-odd $h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ Boer-Mulders T-odd
	L		$g_1^q(x, \boldsymbol{k}_T^2)$ Helicity	chiral-odd $h_{1L}^{\perp q}(x, \boldsymbol{k}_T^2)$ worm-gear L
	T	$f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$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



quark

nucleon

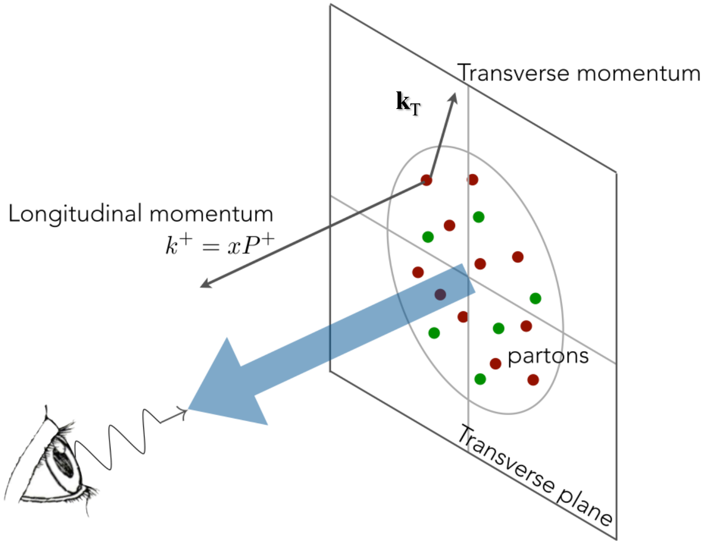
	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L
T	Sivers	Kotzinian-Mulders worm-gear T	transversity pretzelosity

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

quark

nucleon

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



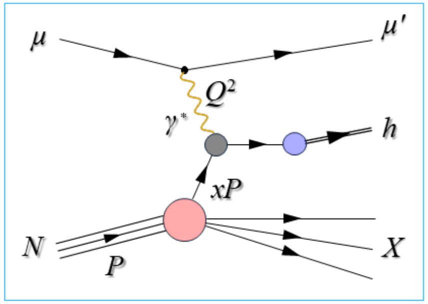
SIDIS x-section and TMDs at twist-2

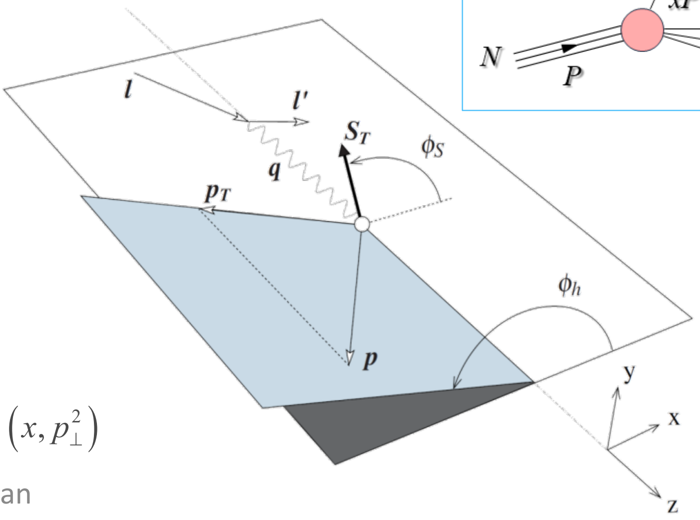
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2d\phi_hd\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

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

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





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

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

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

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

quark

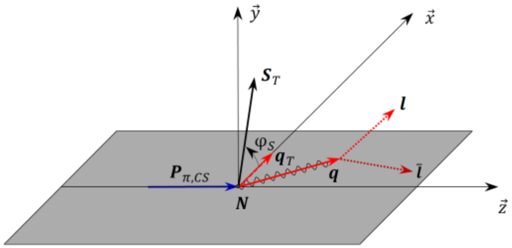
nucleon

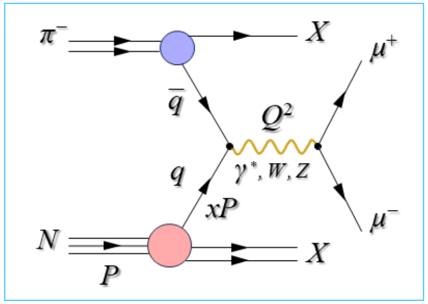
	U	**L**	**T**
U	$f_1^q(x,\boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ Boer-Mulders T-odd
L		$g_1^q(x,\boldsymbol{k}_T^2)$ Helicity	$h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ worm-gear L
T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x,\boldsymbol{k}_T^2)$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

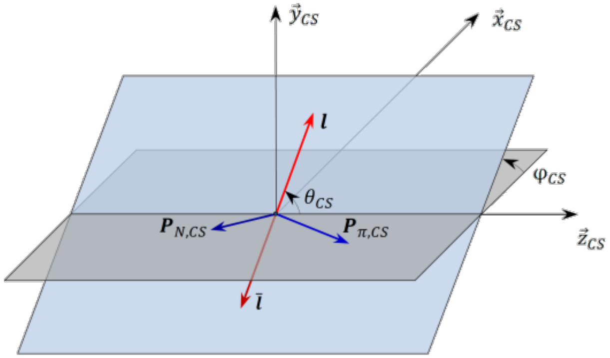
$A_U^{\cos 2\varphi_{CS}} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{\perp q}}$	Boer-Mulders (T-odd)
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes \underline{f_{1T,p}^{\perp q}}$	Sivers (T-odd)
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto \underline{h_{1,\pi}^{\perp q}}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

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

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

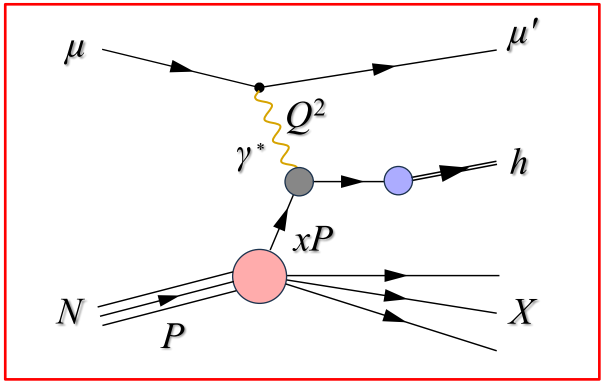






Polarized SIDIS and Drell-Yan: universality

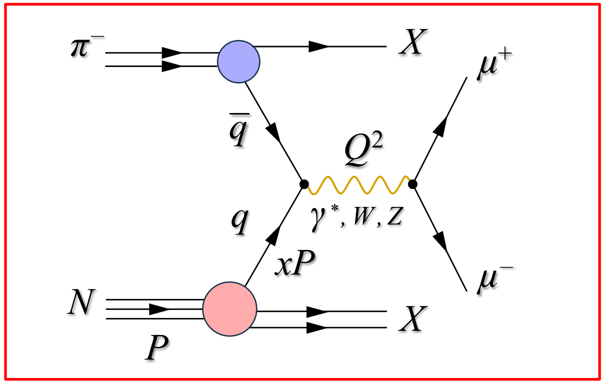
Semi-inclusive DIS



T-odd TMD PDFs

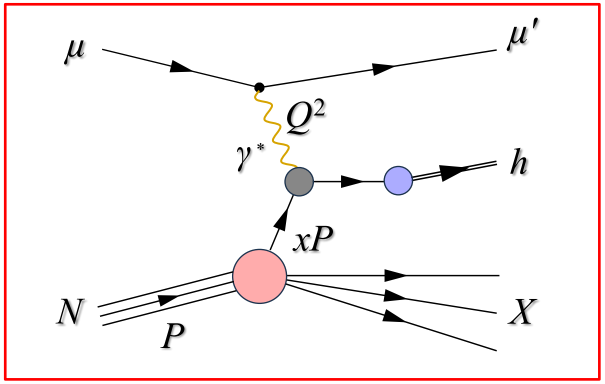
sign change

Drell-Yan process



Polarized SIDIS and DY – factorization and kinematic regions

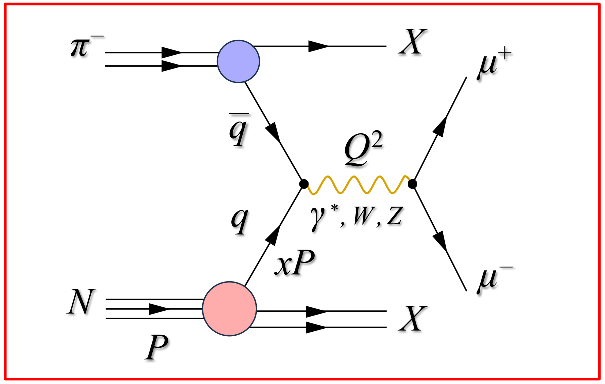
Semi-inclusive DIS



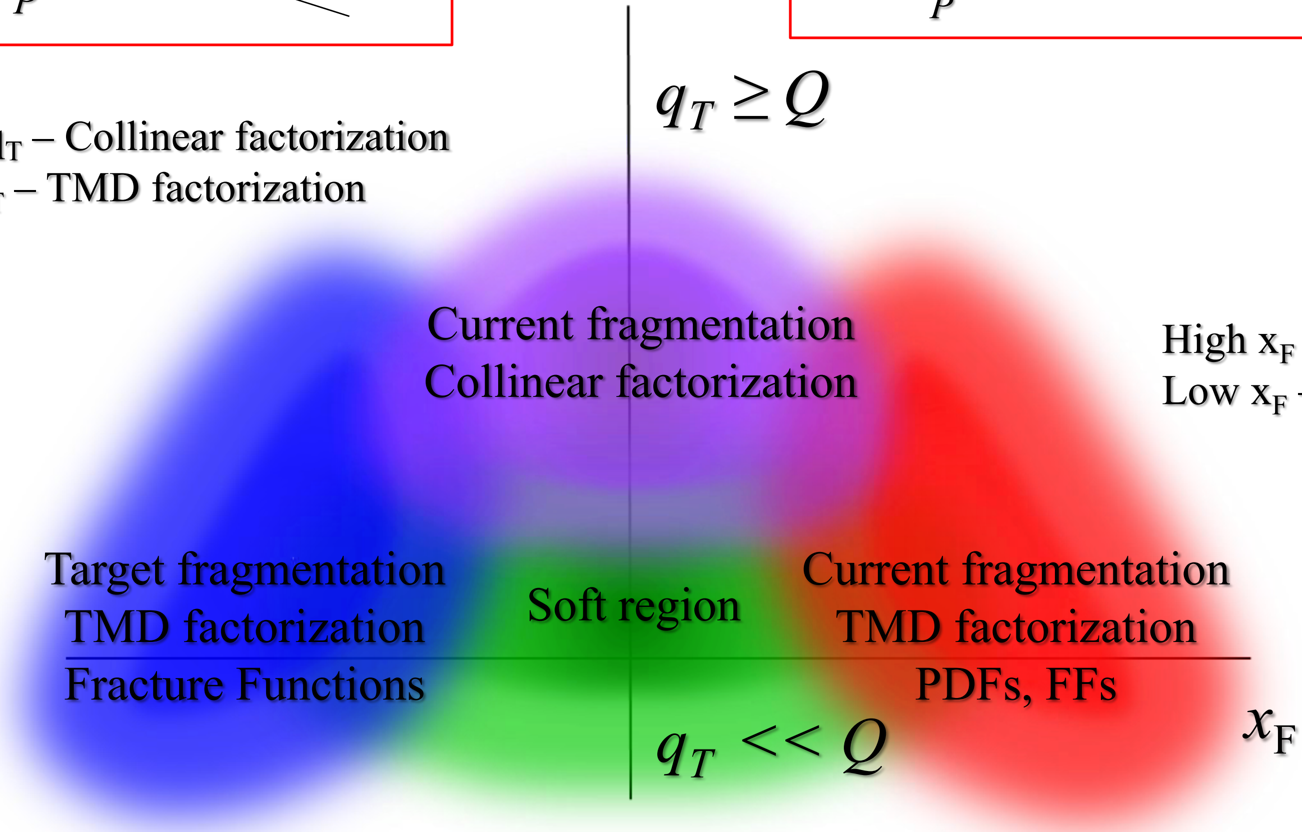
T-odd TMD PDFs

sign change

Drell-Yan process



High q_T – Collinear factorization
Low q_T – TMD factorization



$q_T \geq Q$

Current fragmentation
Collinear factorization

Target fragmentation
TMD factorization
Fracture Functions

Soft region

Current fragmentation
TMD factorization
PDFs, FFs

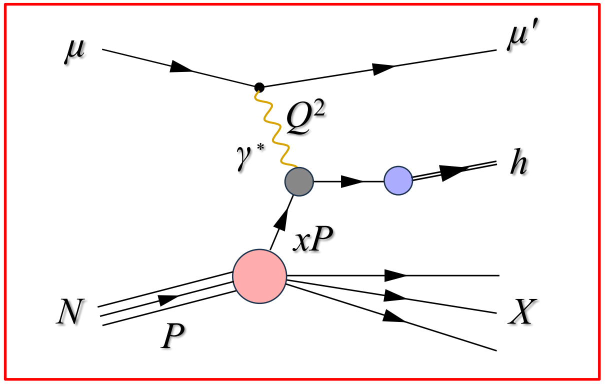
x_F

$q_T << Q$

High x_F – Current fragmentation
Low x_F – Target fragmentation

Polarized SIDIS and DY – factorization and kinematic regions

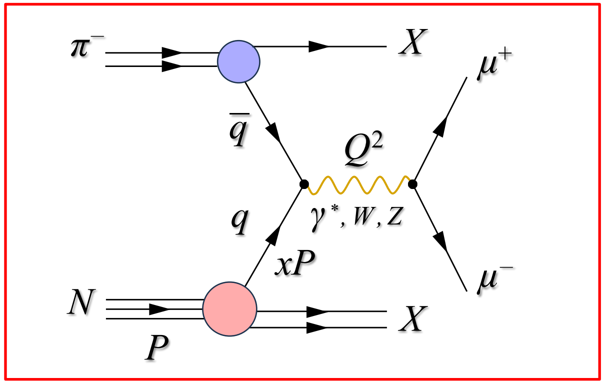
Semi-inclusive DIS

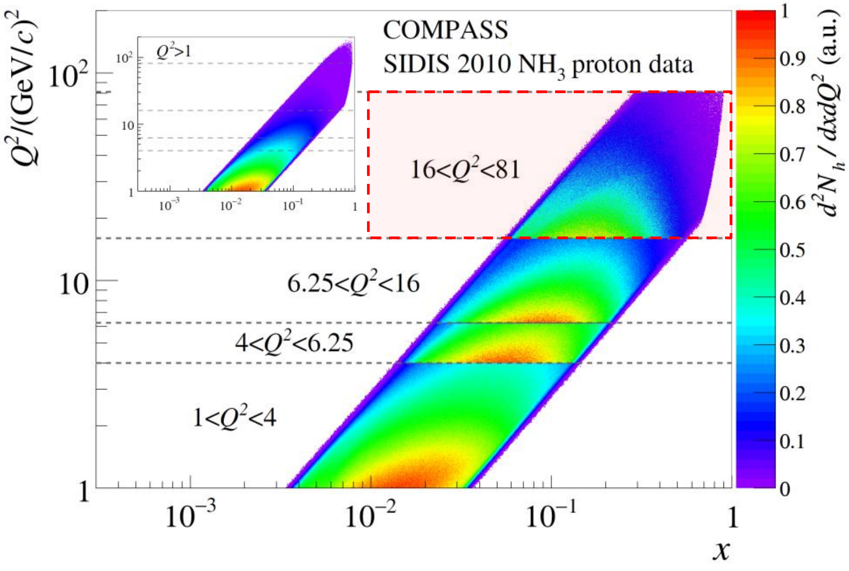


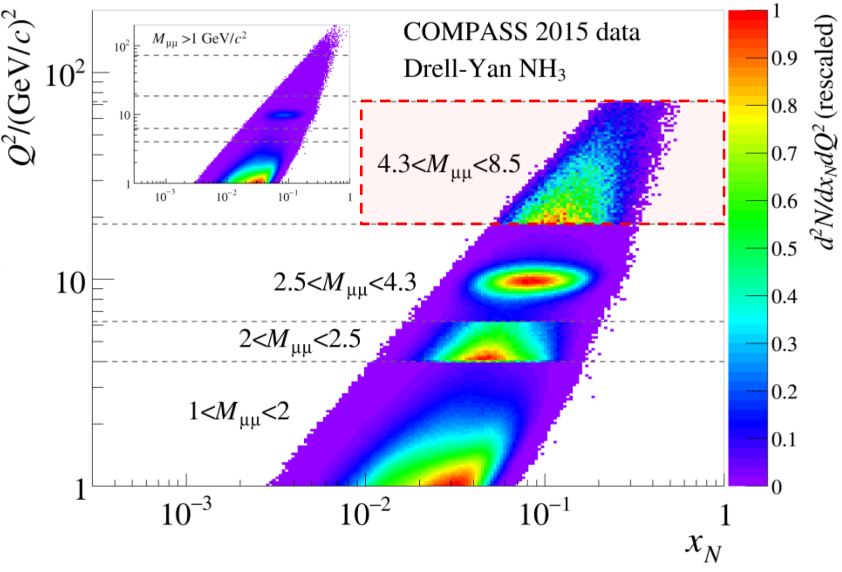
T-odd TMD PDFs

sign change

Drell-Yan process

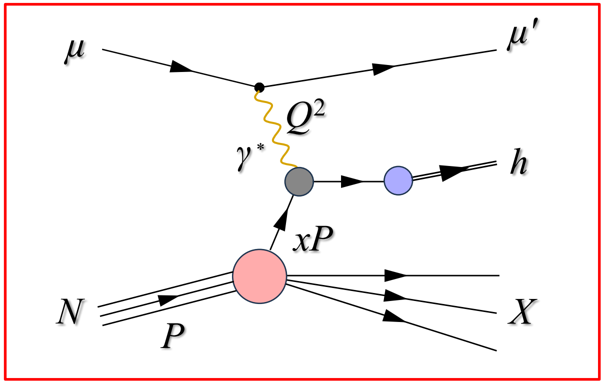






Polarized SIDIS and DY – factorization and kinematic regions

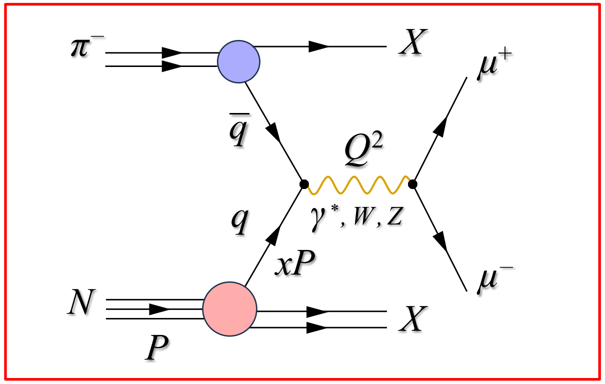
Semi-inclusive DIS

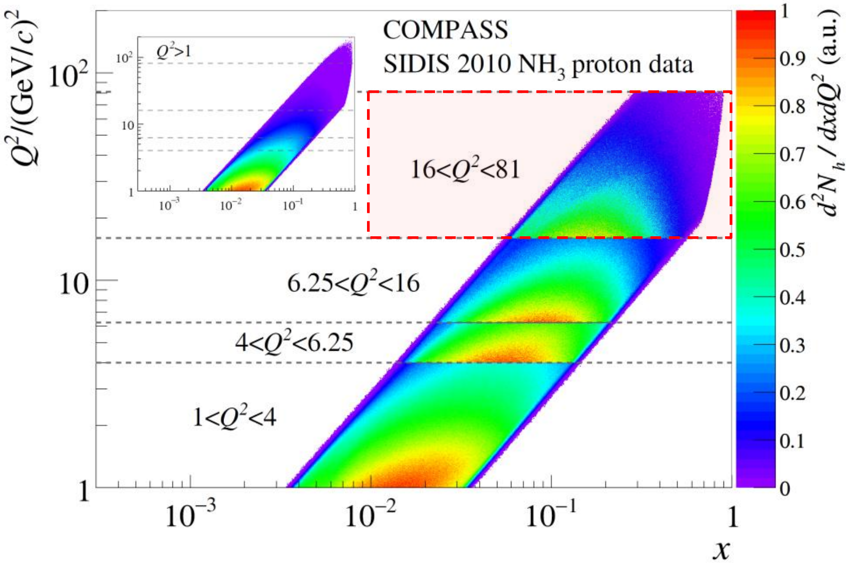


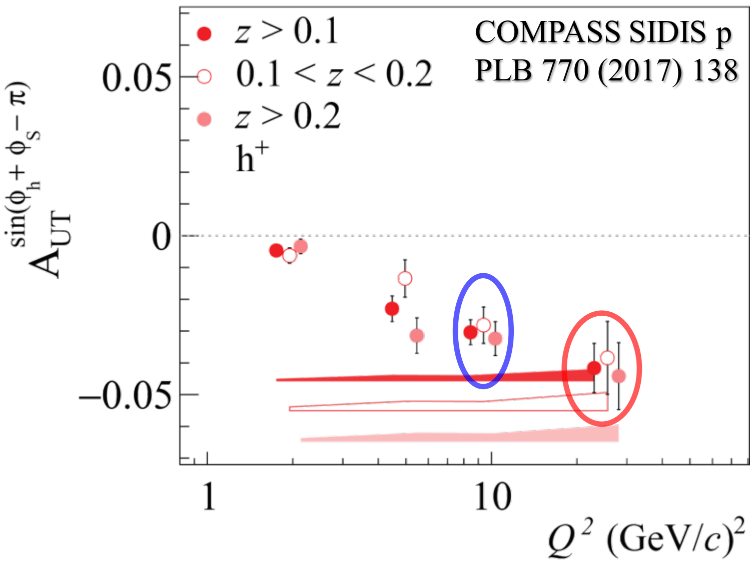
T-odd TMD PDFs

sign change

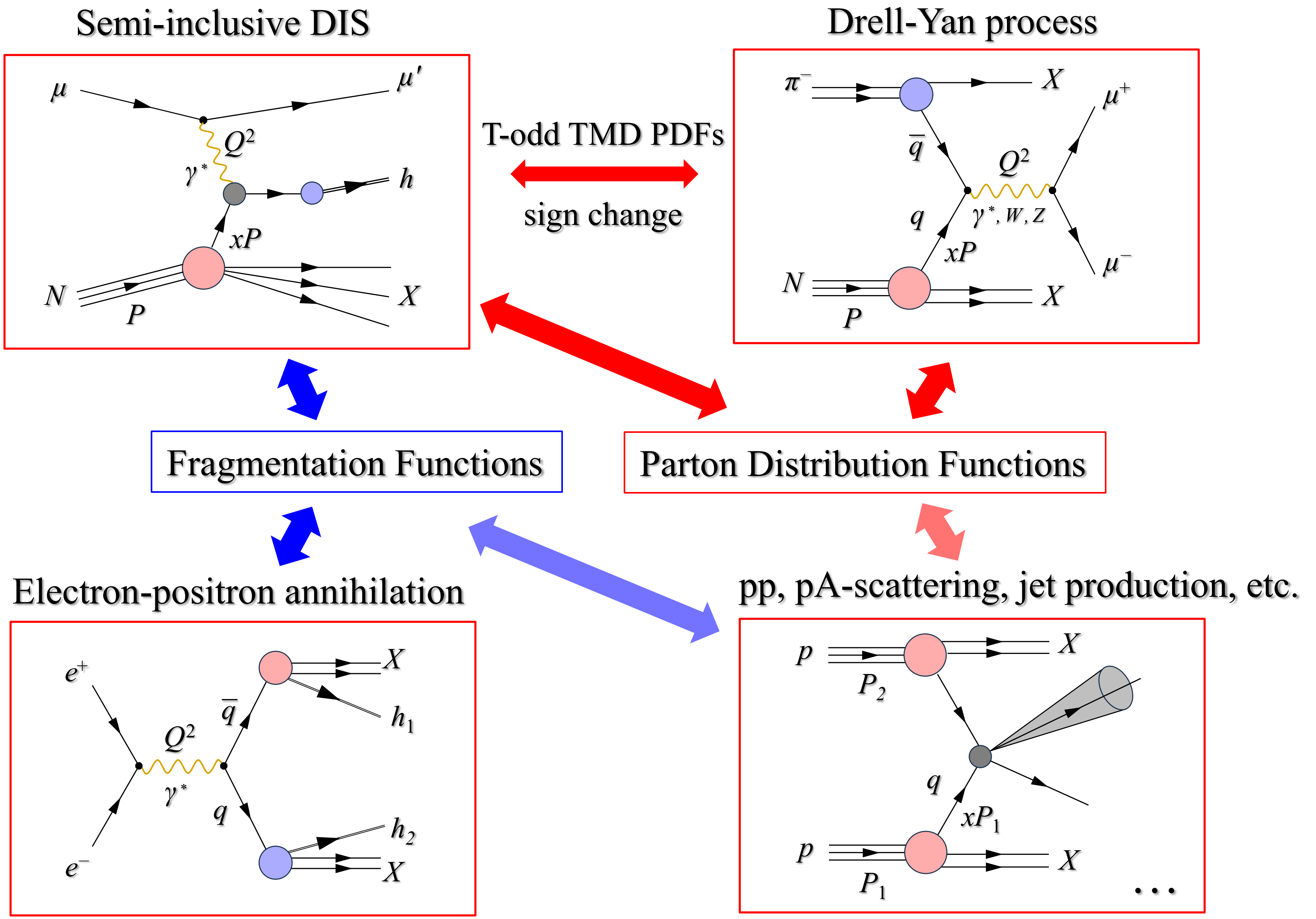
Drell-Yan process







Main TMD tools – universality and synergies


Semi-inclusive DIS

T-odd TMD PDFs

sign change

Drell-Yan process

Fragmentation Functions

Parton Distribution Functions

Electron-positron annihilation

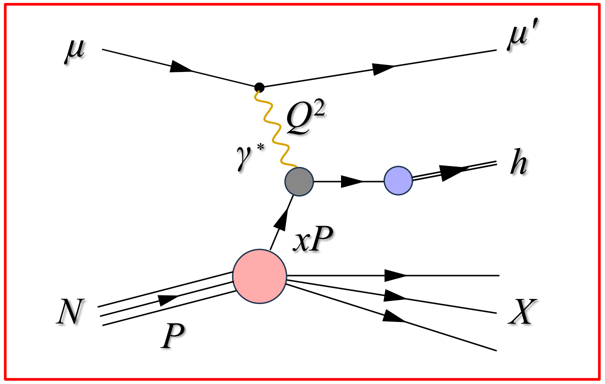
pp, pA-scattering, jet production, etc.

Cleanest access to hadronization/fragmentation

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

Main TMD tools – list of experiments (non exhaustive)

Semi-inclusive DIS



hermes DESY

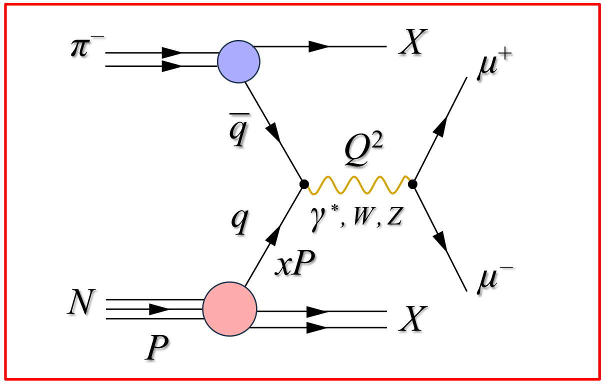
COMPASS CERN

Jefferson Lab

clas SoLID

ePIC EIC Jefferson Lab @ 22 GeV

Drell-Yan process



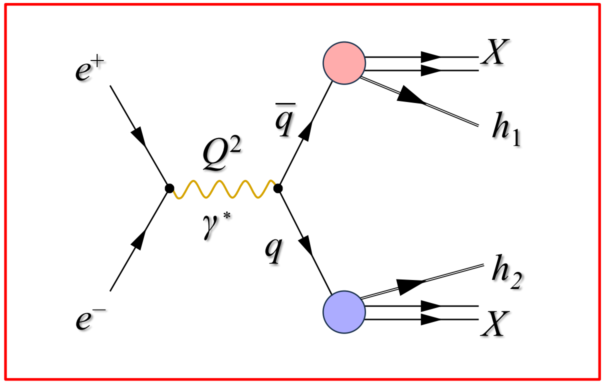
COMPASS CERN

STAR SPIN QUEST

LHC spin Fermilab

AMBER
Apparatus for Meson and Baryon Experimental Research

Electron-positron annihilation



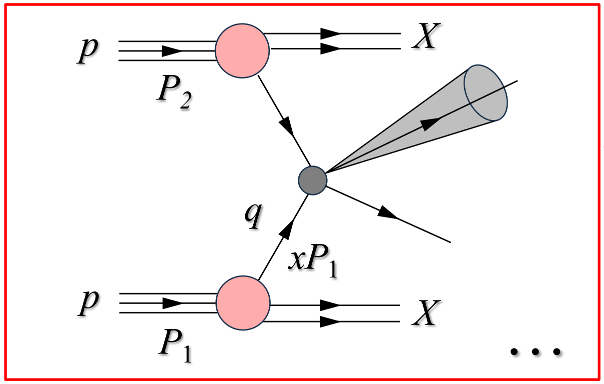
Belle KEK

BABAR

SLAC
NATIONAL ACCELERATOR LABORATORY

BESIII

pp, pA-scattering, jet production, etc.



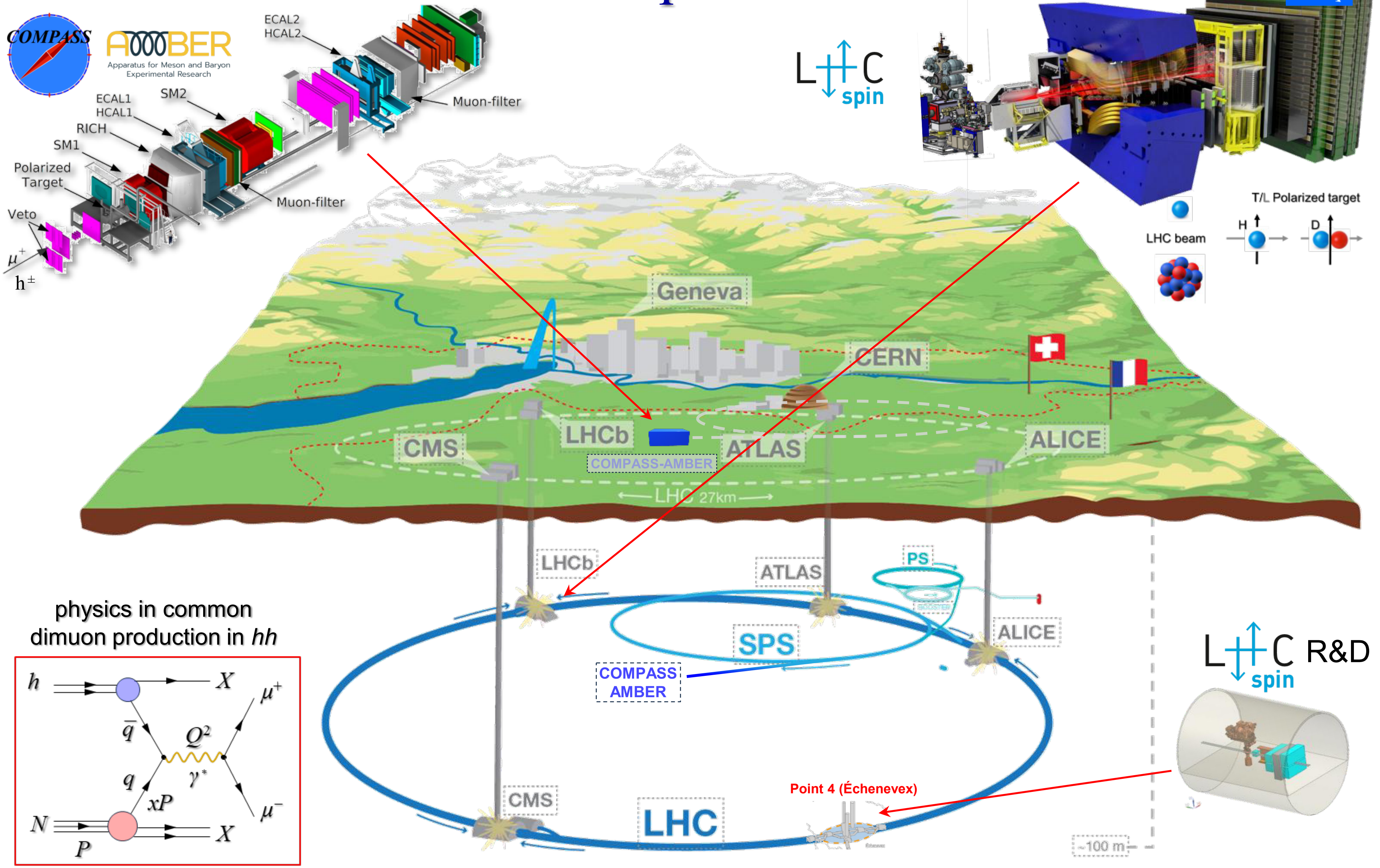
Brookhaven National Laboratory

STAR PHENIX

sPHENIX

NICA

COMPASS-AMBER-LHCspin FTs at CERN

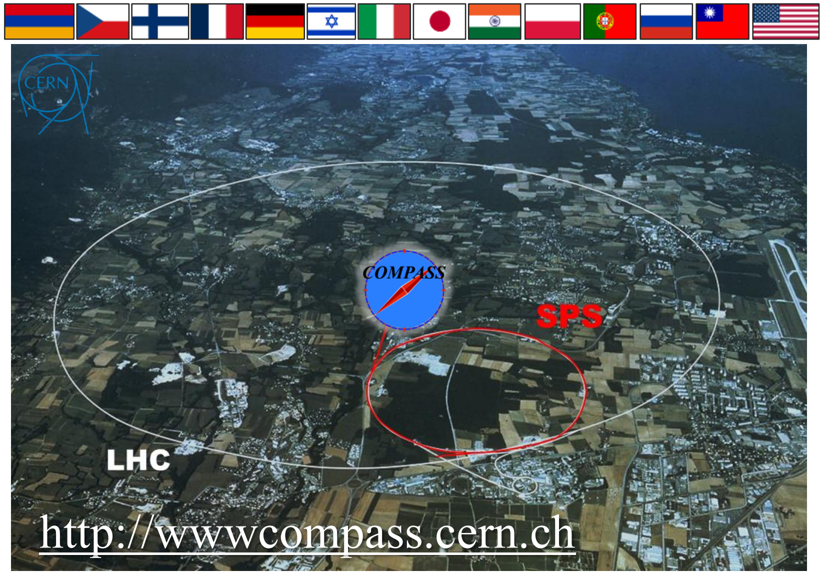


physics in common
dimuon production in *hh*

COMPASS timeline

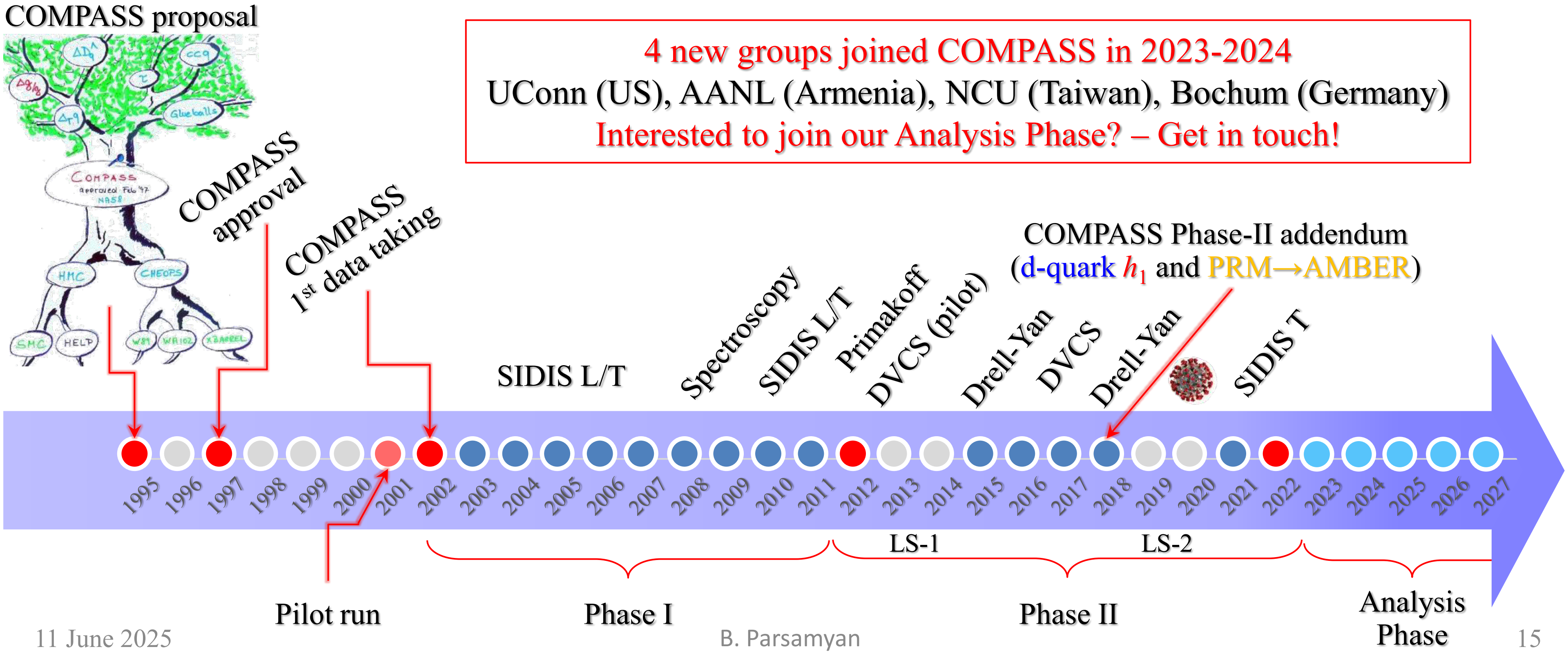
- CERN SPS north area – M2 beamline
- Fixed target experiment
- Approved in 1997
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

33 institutions from 15 countries: ~ 200 members



http://wwwcompass.cern.ch

4 new groups joined COMPASS in 2023-2024
UConn (US), AANL (Armenia), NCU (Taiwan), Bochum (Germany)
Interested to join our Analysis Phase? – Get in touch!



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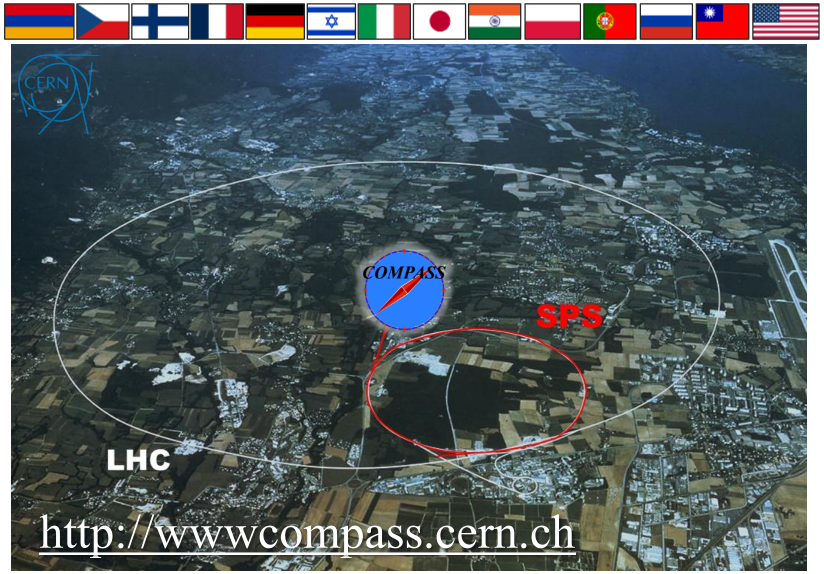
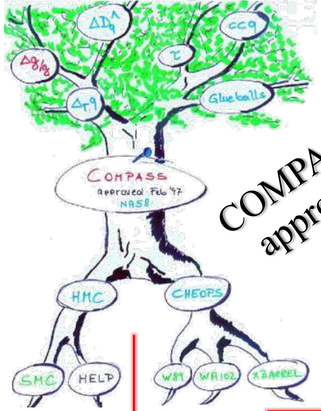
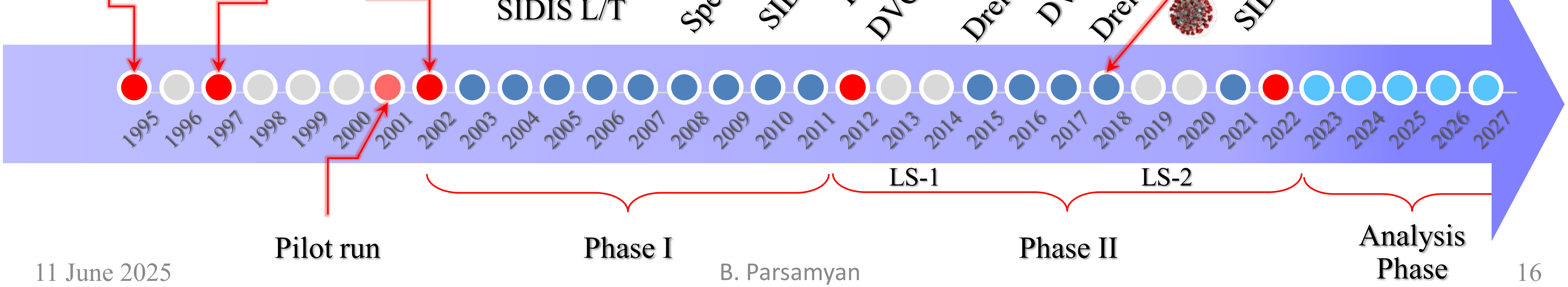


Many studies that can be done at future experiments can be studied at COMPASS
Key problems are in common: rad. corrections, MC generator tunings, the role of exclusive diffractive VMs, analysis methods, etc.

COMPASS proposal





COMPASS approval

COMPASS 1st data taking

SIDIS L/T

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

Drell-Yan

DVCS

Drell-Yan

SIDIS T

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

Pilot run

Phase I

Phase II

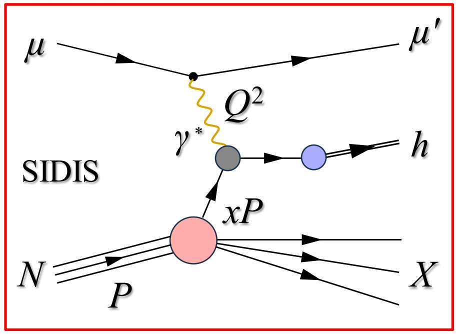
Analysis Phase

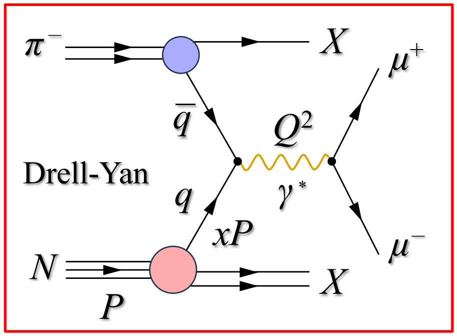
COMPASS Physics Program

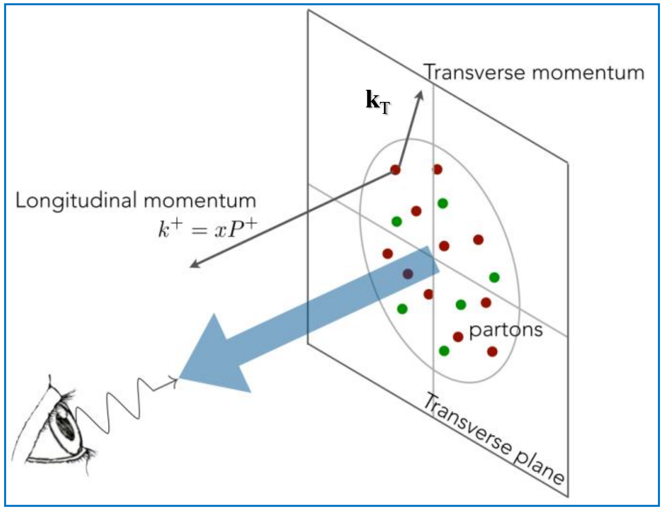
Nucleon structure

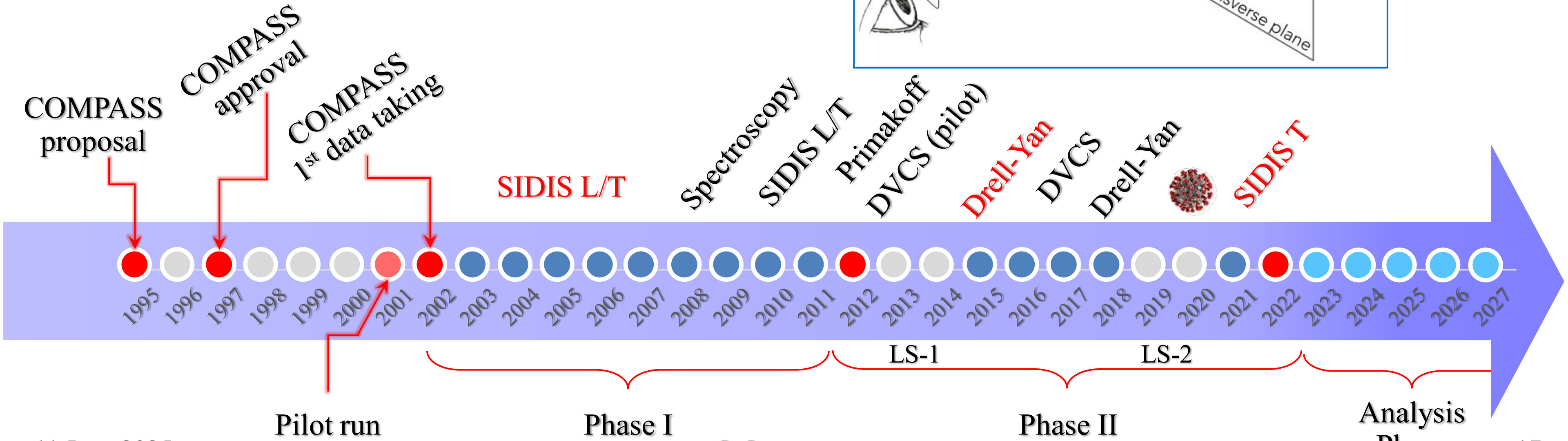
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Inclusive and Semi-Inclusive DIS
- Drell-Yan and J/ψ production
- Study of nucleon spin structure
  - Longitudinal and Transverse
- Collinear and TMD pictures
- Parton distribution functions and fragmentation functions
- Last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

This talk









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

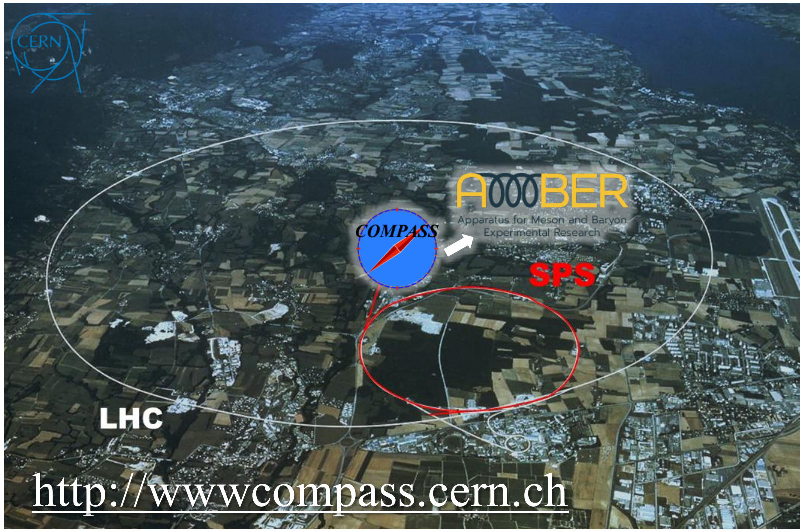
Phase II

Analysis Phase

COMPASS-AMBER timeline

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

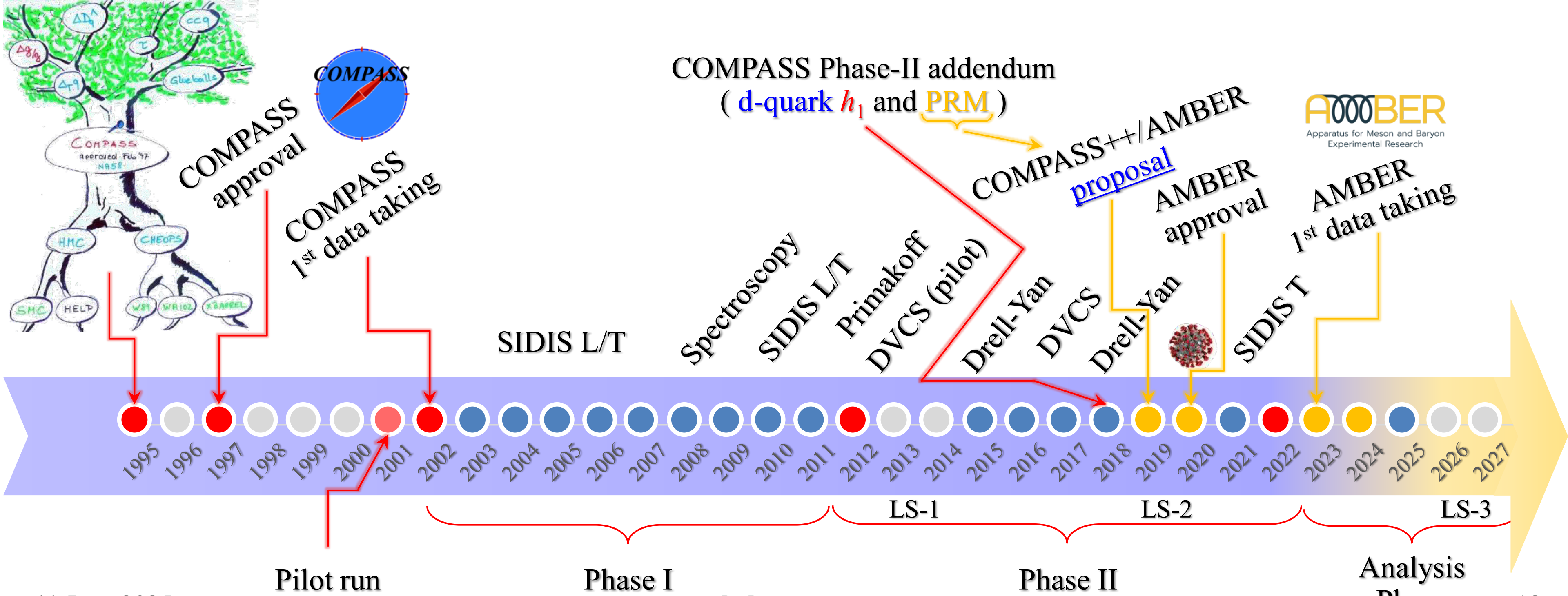
33 institutions from 15 countries: ~ 200 members



COMPASS
25 years
1997 - 2022

AMBER
Apparatus for Meson and Baryon Experimental Research

COMPASS proposal



COMPASS approval

COMPASS
1st data taking

SIDIS L/T

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

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

Drell-Yan

DVCS

Drell-Yan

COMPASS++/AMBER
proposal

AMBER
approval

SIDIS T

AMBER
1st data taking

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

LS-3

Pilot run

Phase I

Phase II

Analysis
Phase

AMBER timeline

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

36 institutions from 14 countries: ~ 150 members

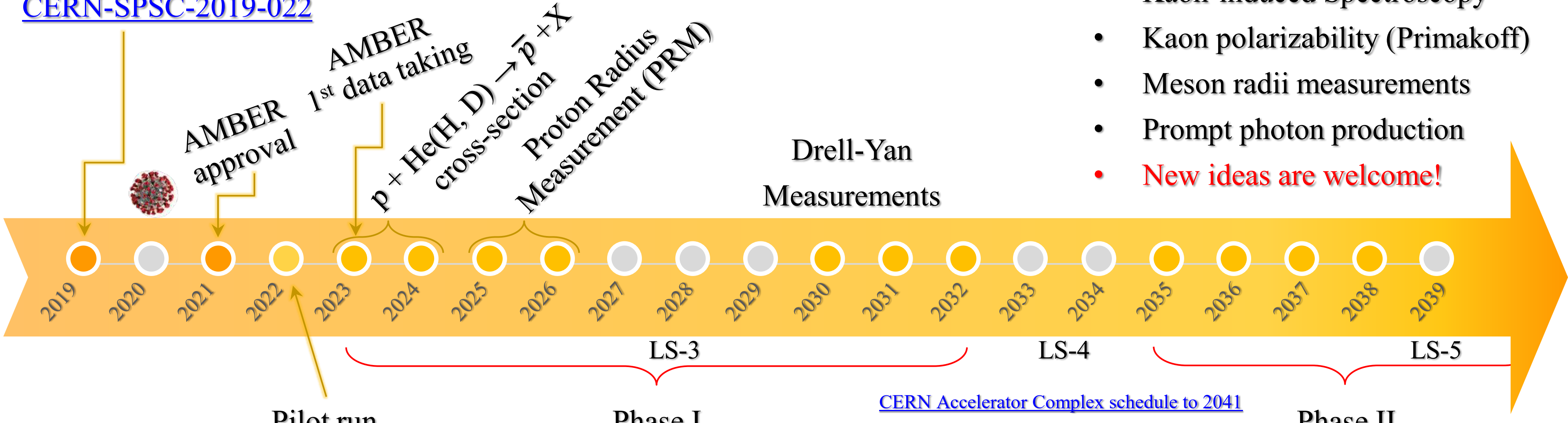
New collaborators are Welcome!

https://amber.web.cern.ch

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!

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



AMBER approval

AMBER
1^{st} data taking

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

Proton Radius
Measurement (PRM)

Drell-Yan
Measurements

Pilot run

Phase I

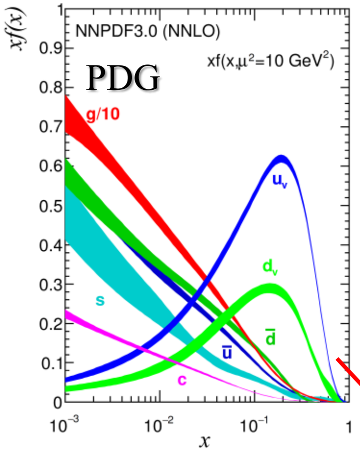
CERN Accelerator Complex schedule to 2041

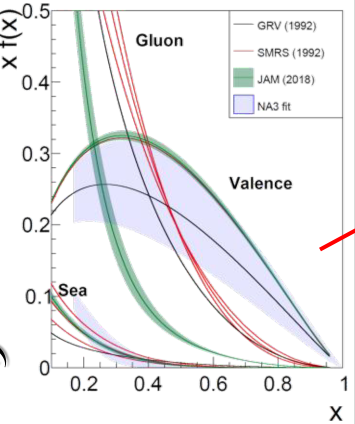
Phase II

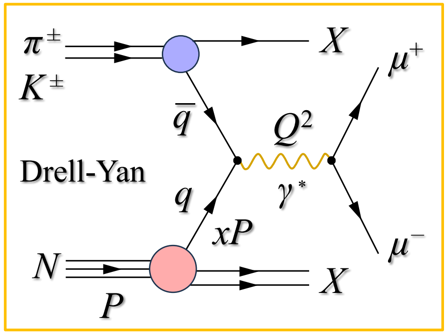
AMBER measurements 2023-2024: Drell-Yan

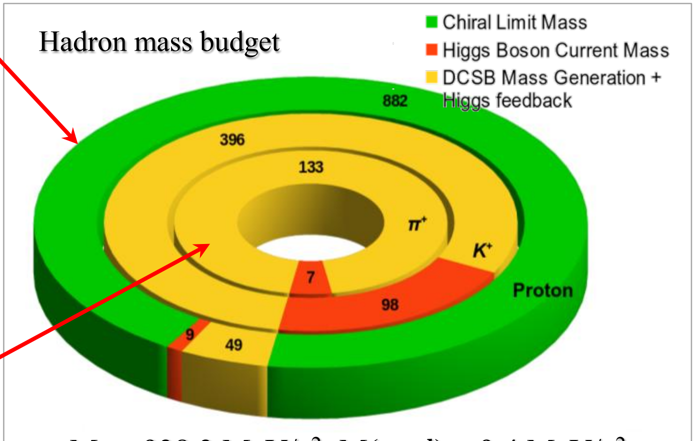
$\pi^{\pm}$, $K^{\pm}$ induced dimuon production: Drell-Yan, J/ψ (and ψ')

- 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





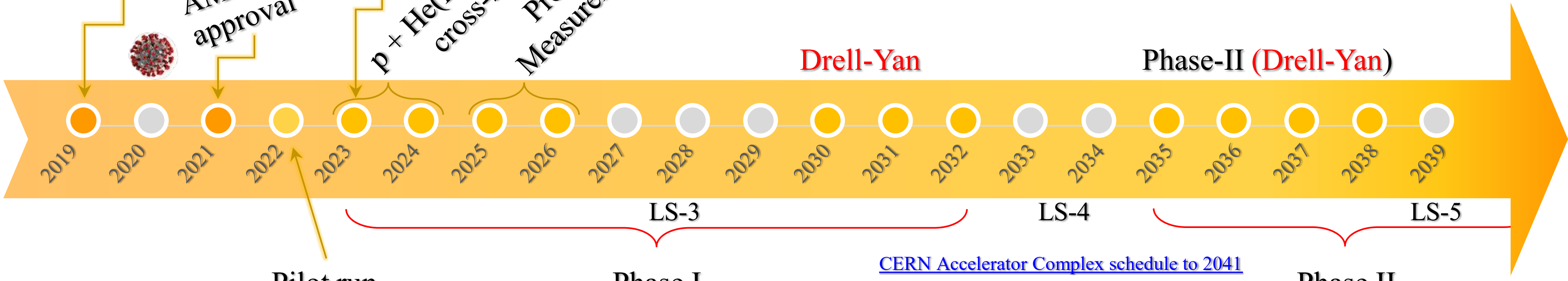




$M_p \approx 938.3$ MeV/c^2; $M(uud) \approx 9.4$ MeV/c^2

$M_{\pi^+} \approx 139.6$ 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 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)

Pilot run

Phase I

Phase II

CERN Accelerator Complex schedule to 2041

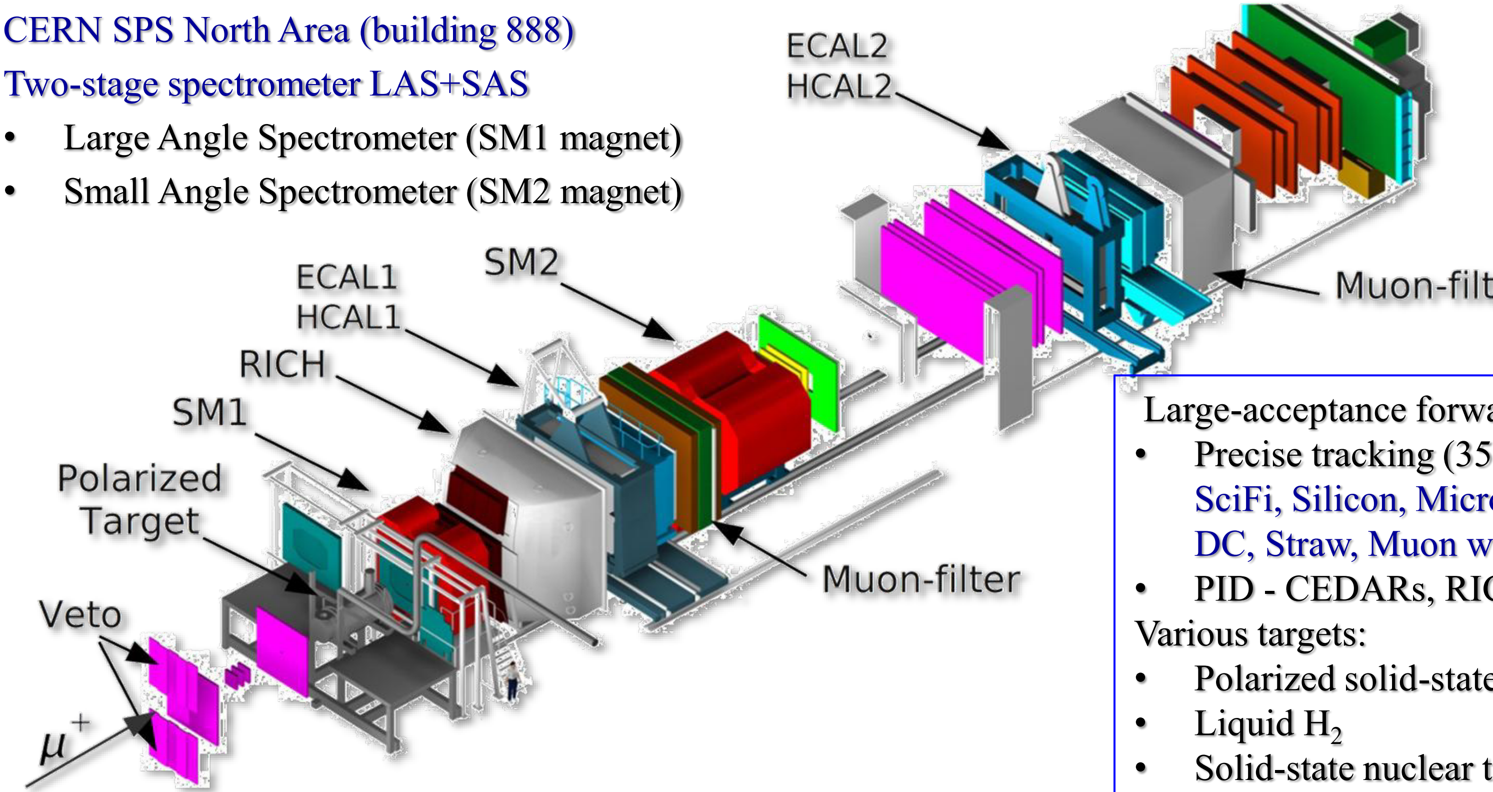
COMPASS experimental setup

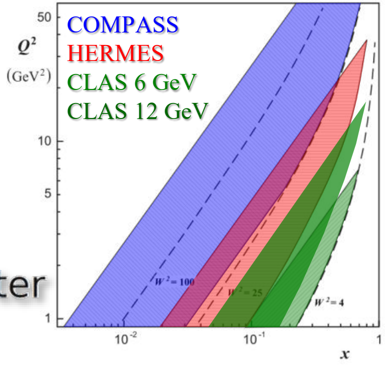
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





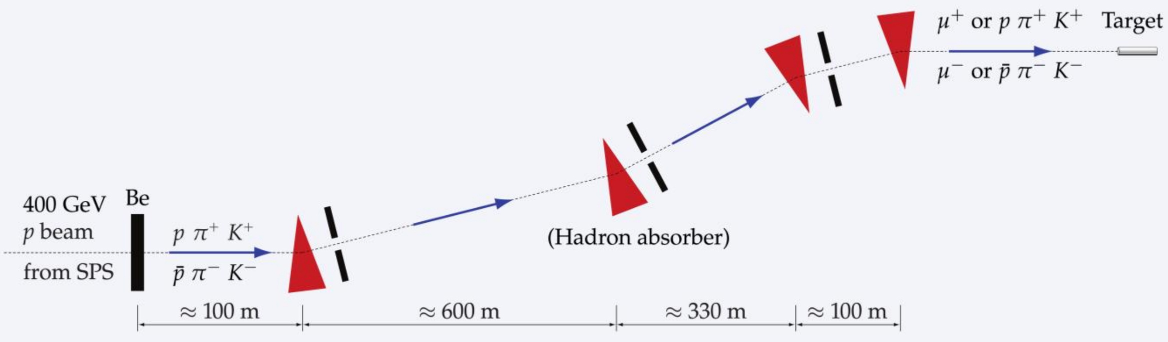
Large-acceptance forward spectrometer

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

Various targets:

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

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



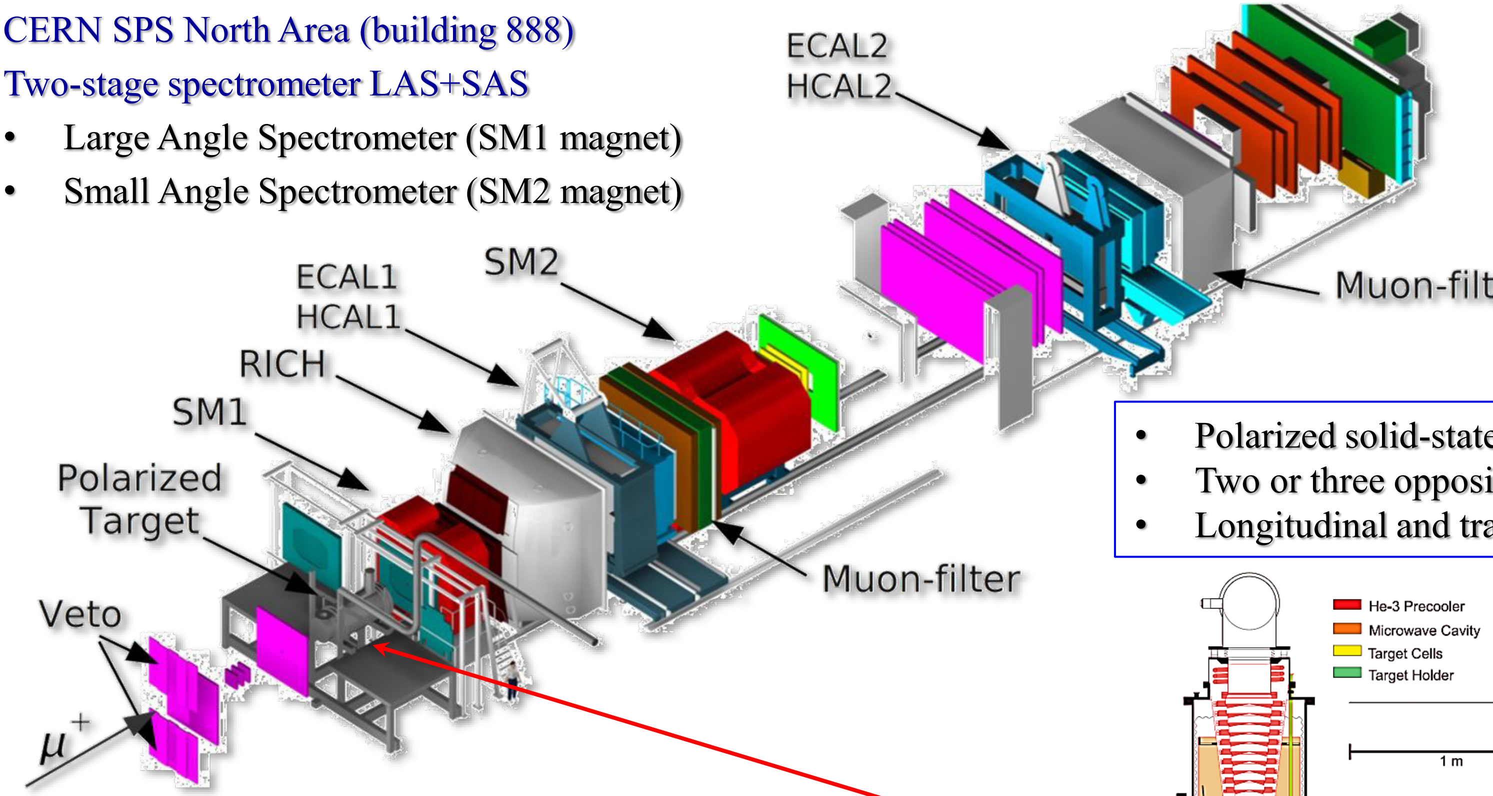
COMPASS experimental setup: Phase II (SIDIS program)

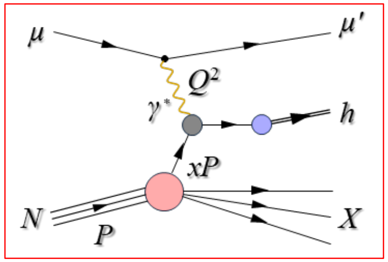
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

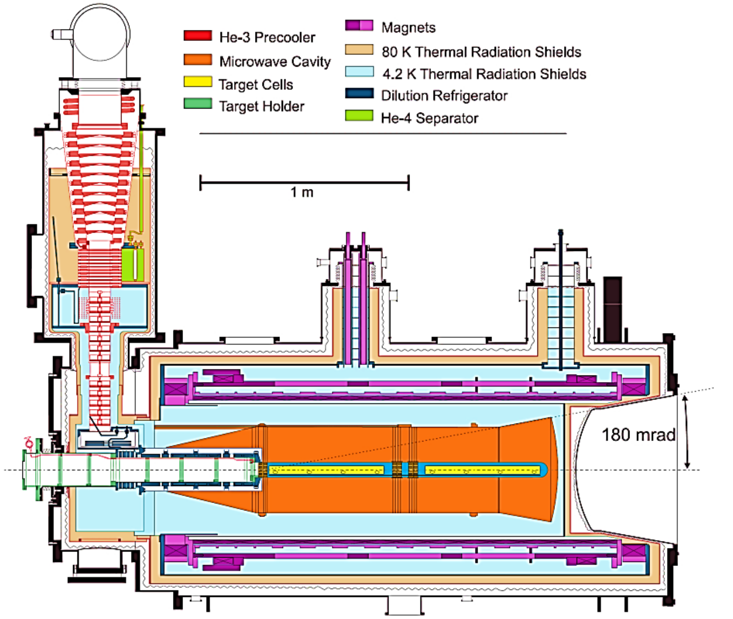
Two-stage spectrometer LAS+SAS

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





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



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

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

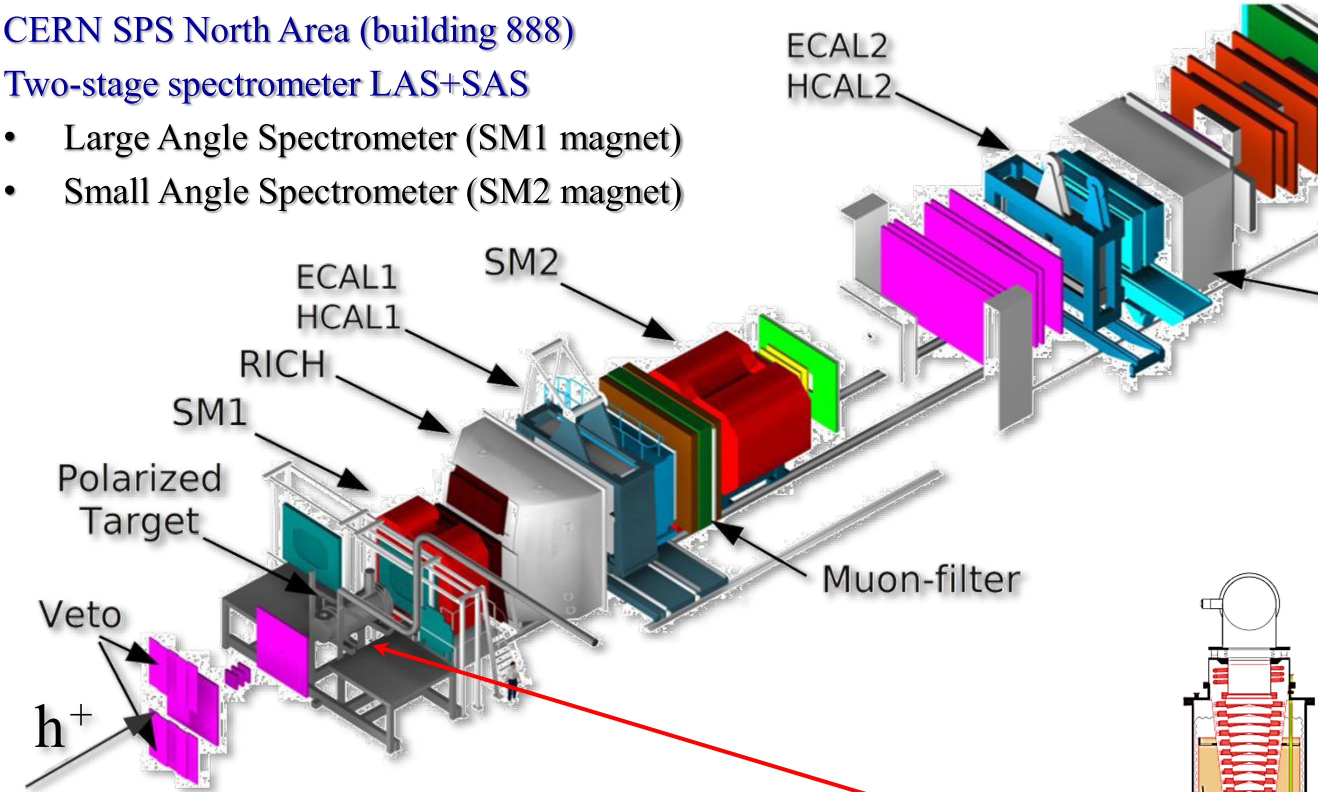
Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

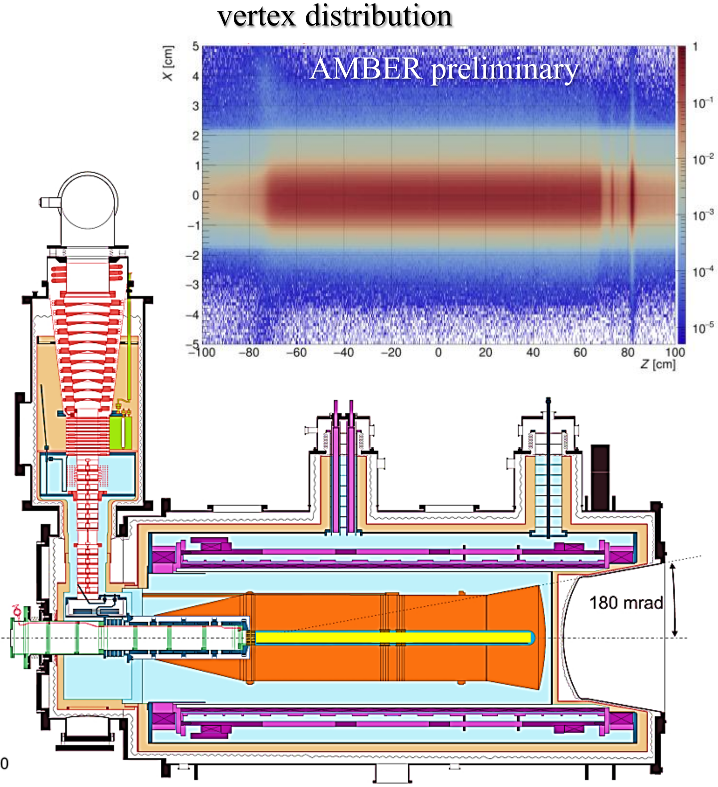
Two-stage spectrometer LAS+SAS

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

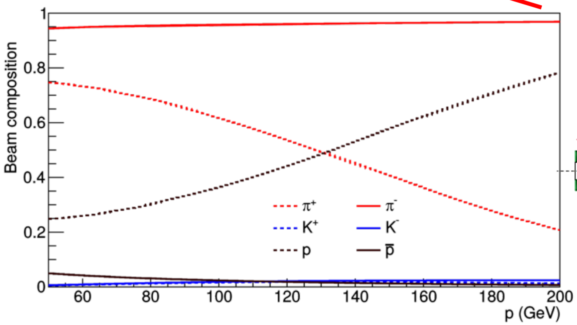
$$p + \mathrm{He} \rightarrow \bar{p} + X$$
$$p + \mathrm{H} \rightarrow \bar{p} + X$$
$$p + \mathrm{D} \rightarrow \bar{p} + X$$



vertex distribution



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



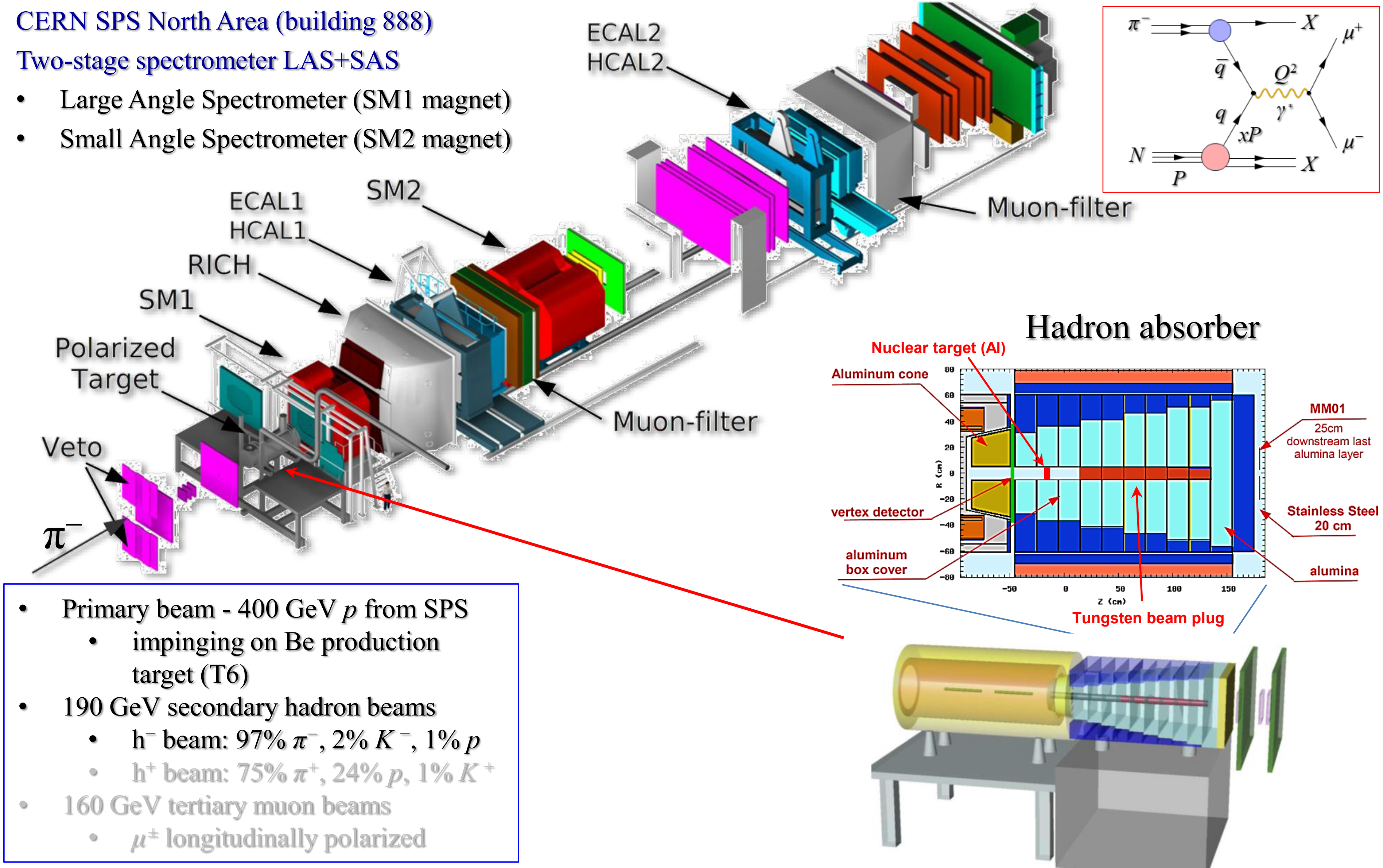
COMPASS experimental setup: Phase II (DY program)

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

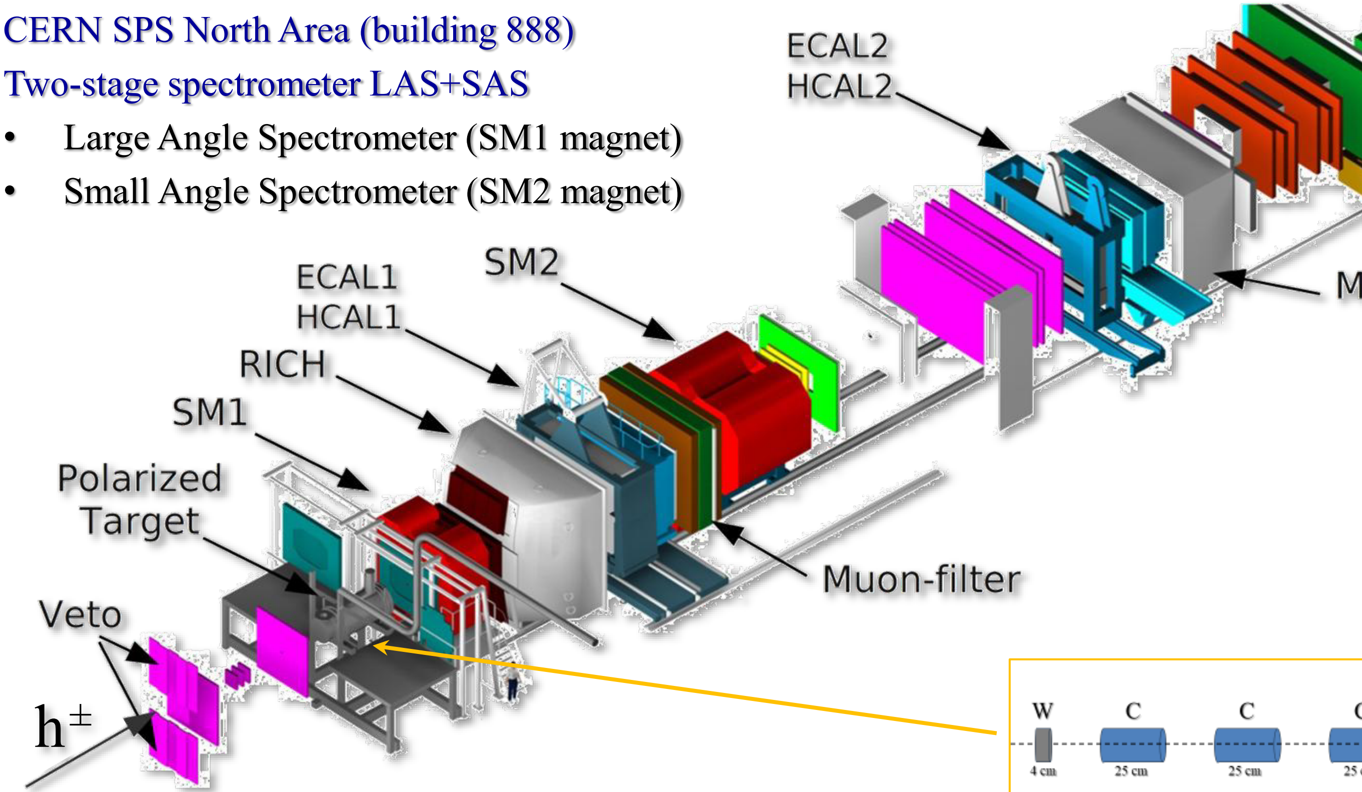
AMBER Phase I-II: DY program setup

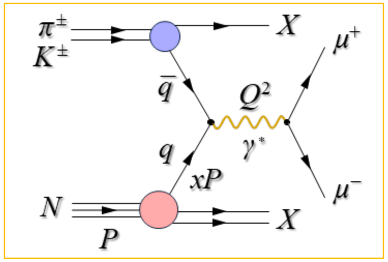
Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

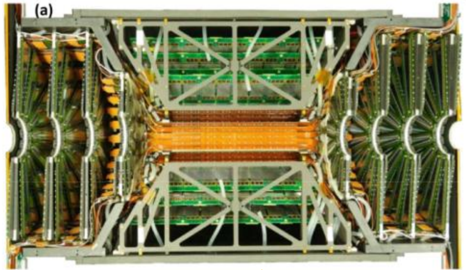
Two-stage spectrometer LAS+SAS

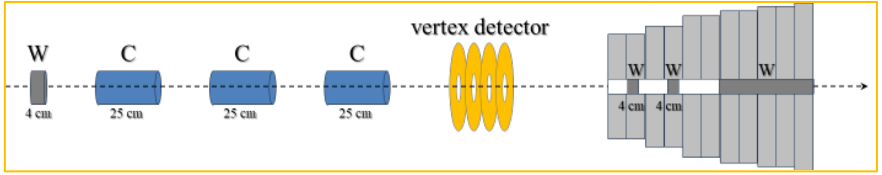
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)

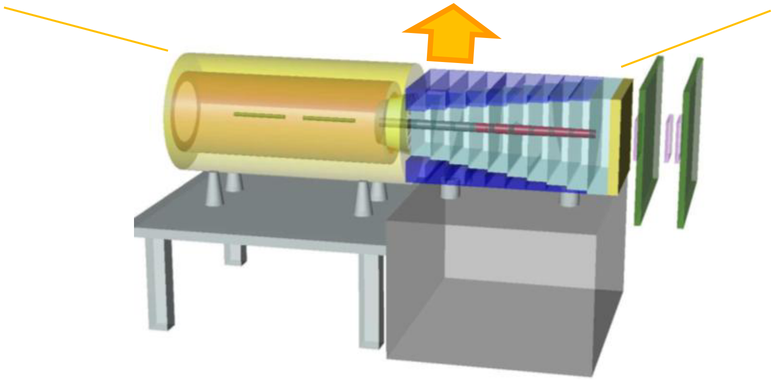




FVTX detector from PHENIX@RHIC



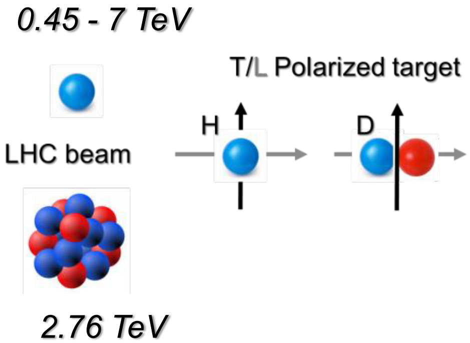




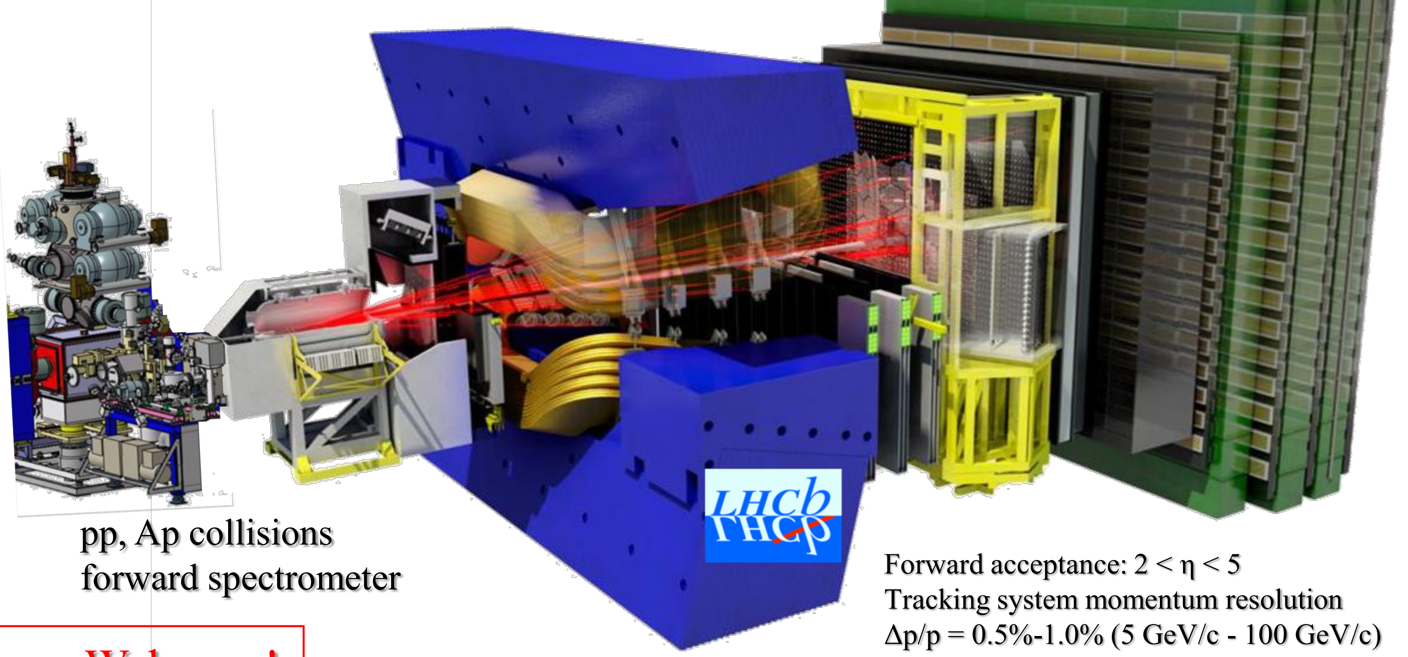
- Secondary h$^{\pm}$ beam: $(\pi^{\pm}, K^{\pm}, p\,/\,\bar{p})$
- Improved beam PID (CEDARs)
    - enabling kaon physics
- Isoscalar target (C 3x25 cm) and W
- Vertex detector: improve Z and $M_{\mu\mu}$ resolution
- New trigger-less DAQ,
- Revised setup, new detectors

LHCspin experiment

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



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

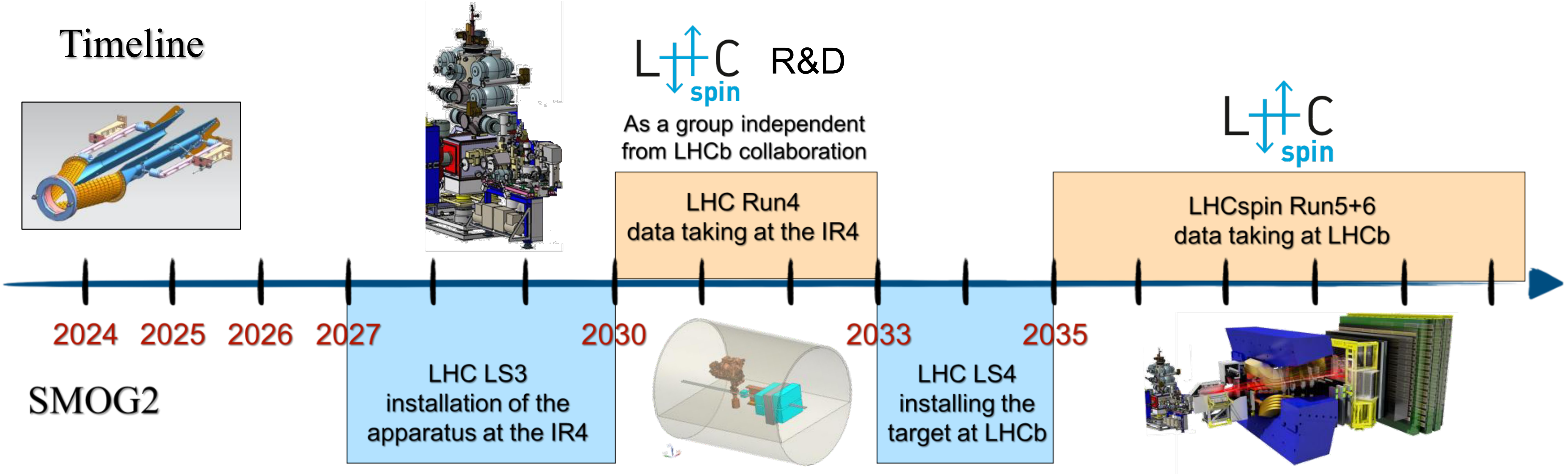


pp, Ap collisions
forward spectrometer

Forward acceptance: 2 < η < 5
Tracking system momentum resolution
Δp/p = 0.5%-1.0% (5 GeV/c - 100 GeV/c)

New collaborators are Welcome!

Timeline



As a group independent from LHCb collaboration

LHC Run4
data taking at the IR4

LHCspin Run5+6
data taking at LHCb

LHC LS3
installation of the apparatus at the IR4

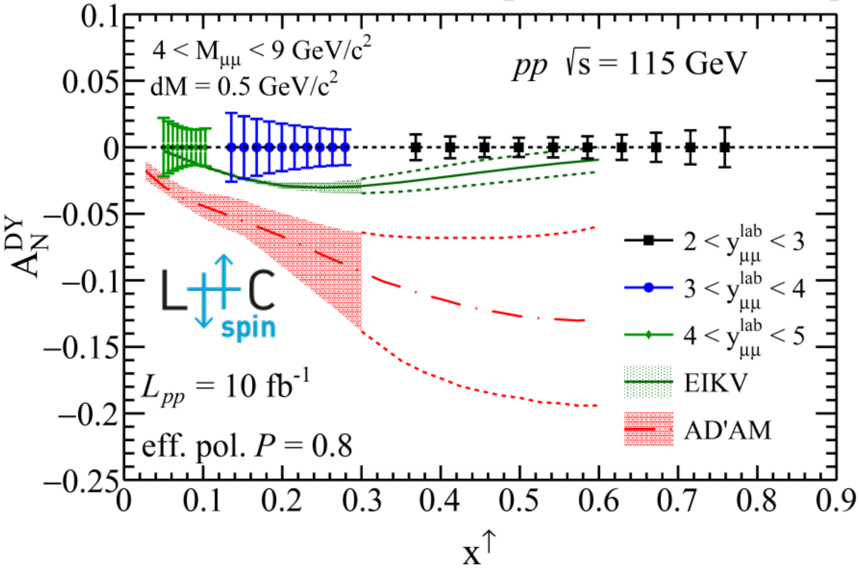
LHC LS4
installing the target at LHCb

SMOG2

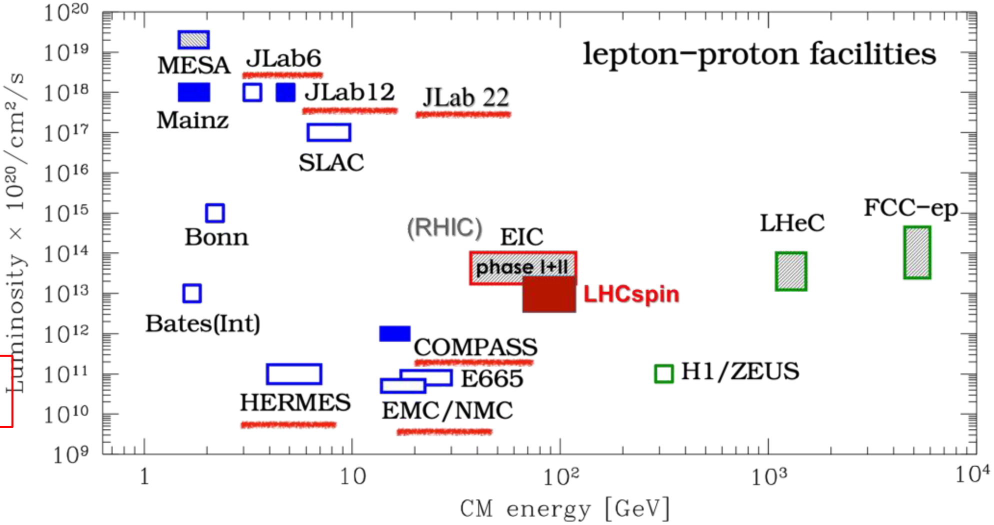
See Luciano's talk

LHCspin experiment

[arXiv:1807.00603]

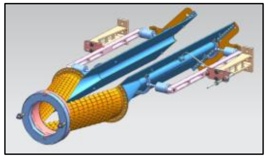


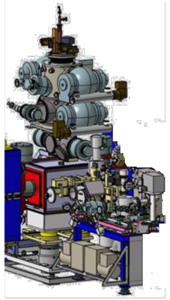
Channel	Events / week	Total yield
$J/\psi \to \mu^+\mu^-$	1.3×10^7 !!	1.5×10^9
$D^0 \to K^-\pi^+$	6.5×10^7	7.8×10^9
$\psi(2S) \to \mu^+\mu^-$	2.3×10^5	2.8×10^7
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	8.5	1.0×10^3
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	2.5×10^1	3.1×10^3
Drell Yan ($5 <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



Of course, the Sivers sign-change and much more

Timeline





As a group independent from LHCb collaboration

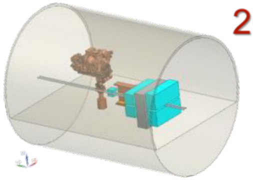
LHC Run4
data taking at the IR4

LHCspin Run5+6
data taking at LHCb

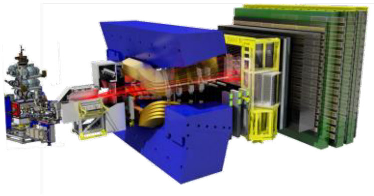
2024 2025 2026 2027 2030 2033 2035

SMOG2

LHC LS3
installation of the apparatus at the IR4

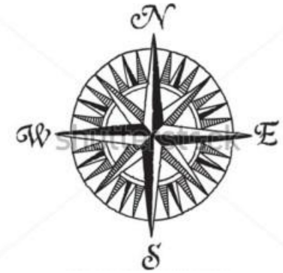


LHC LS4
installing the target at LHCb

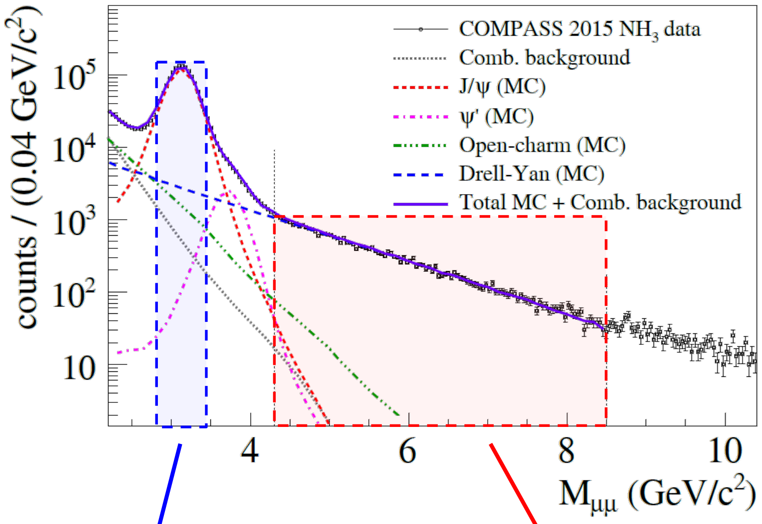


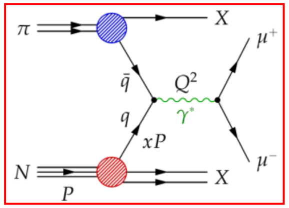
See Luciano’s talk

COMPASS bridge

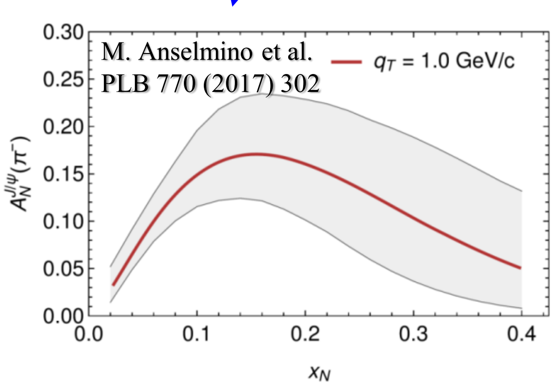


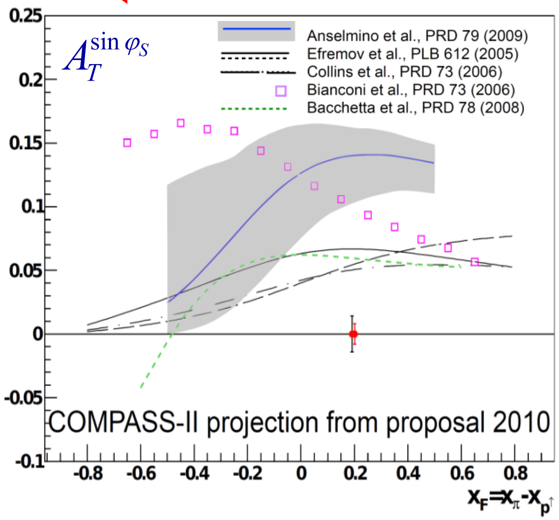
Single-polarized Drell-Yan cross-section at twist-2 (LO)





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


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


COMPASS-II projection from proposal 2010

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

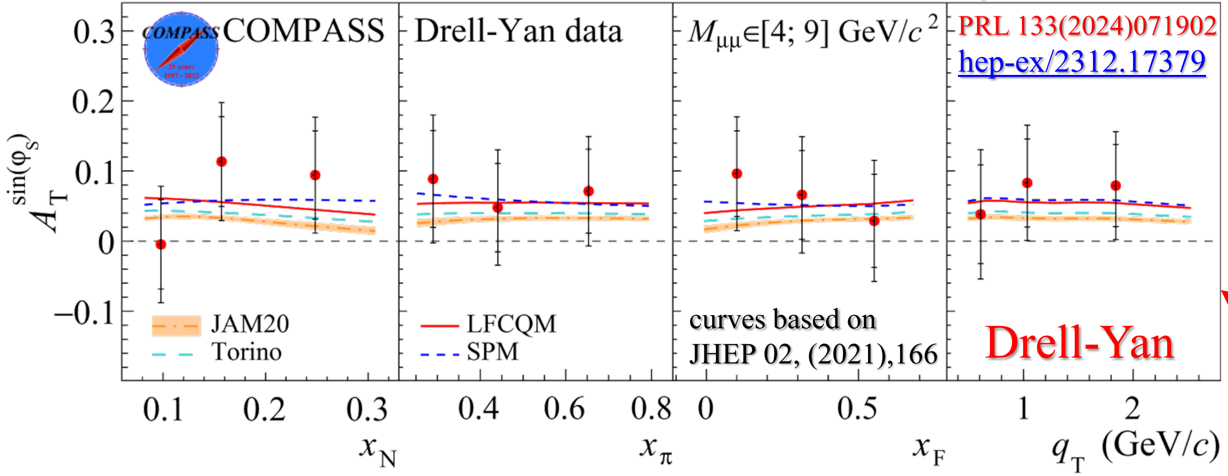
SIDIS ↔ Drell-Yan sign-change of the T-odd TMD PDFs

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

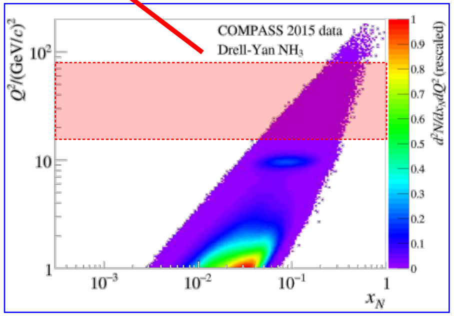
Sivers effect: Drell-Yan and J/ψ

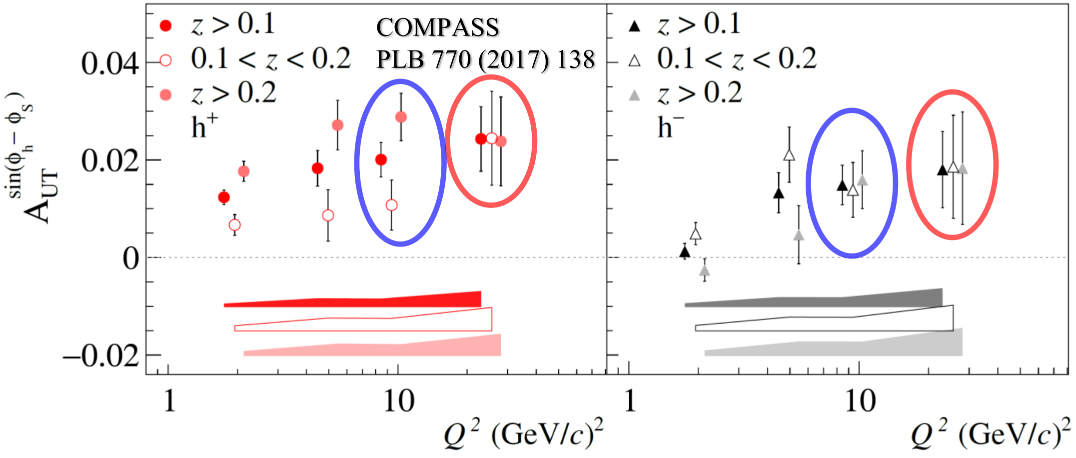
Sivers DY TSA

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



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





Sivers SIDIS TSA

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

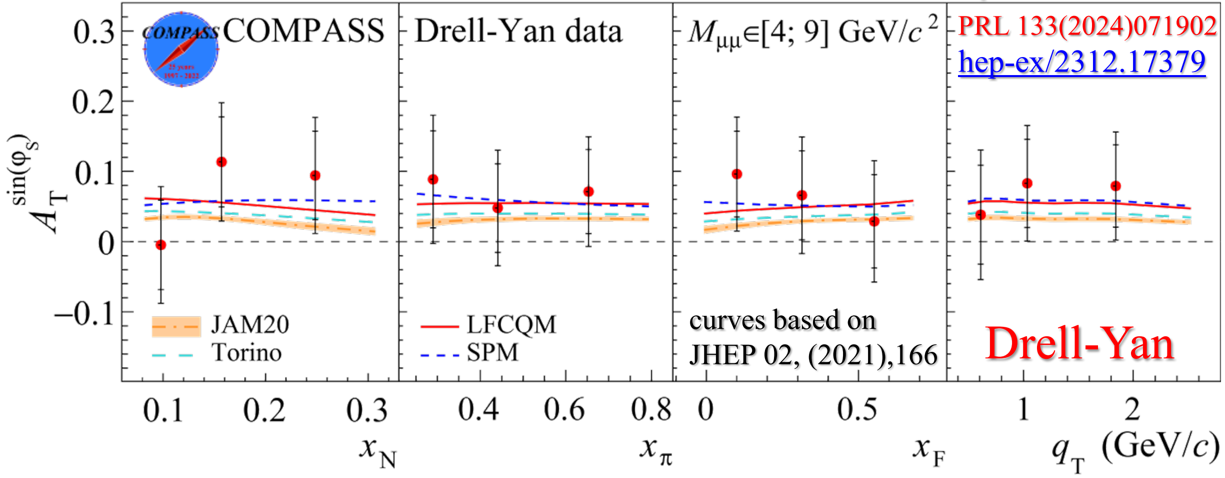
COMPASS proton Sivers measurements

- Clear signal in the matching Q^2 ranges

Sivers effect: Drell-Yan and J/ψ

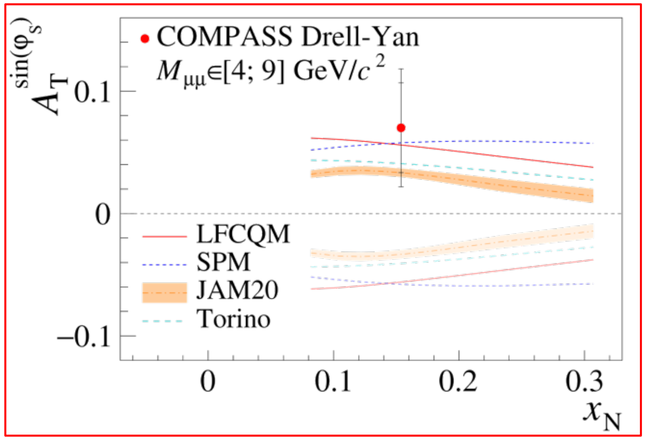
Sivers DY TSA

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

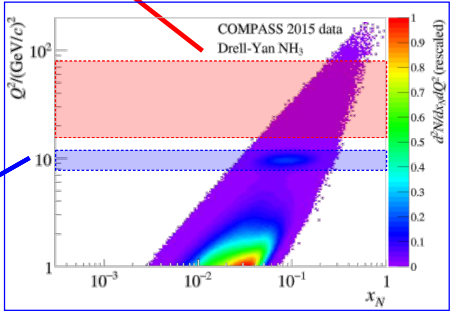


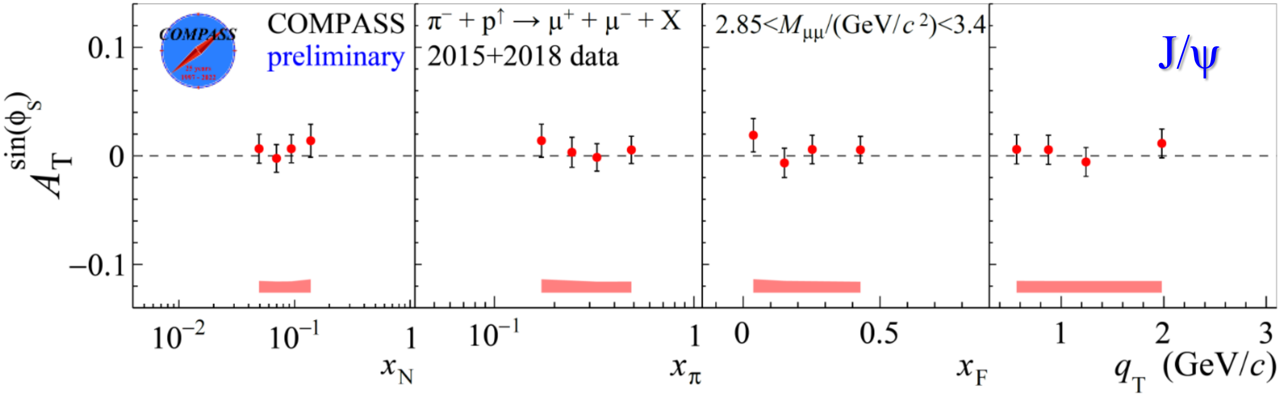
PRL 133(2024)071902
hep-ex/2312.17379

curves based on
JHEP 02, (2021),166



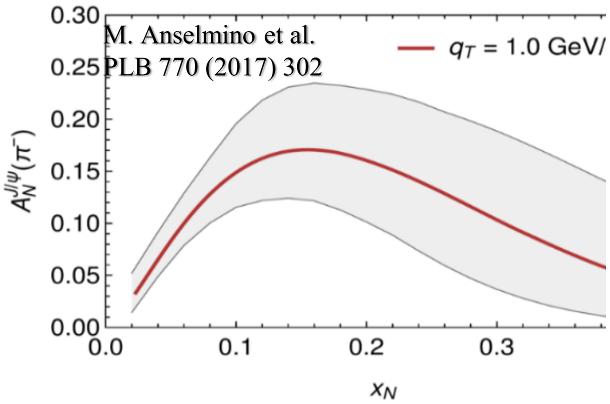
- The Drell-Yan Sivers asymmetry tends to be positive (~1.5 s.d.)





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

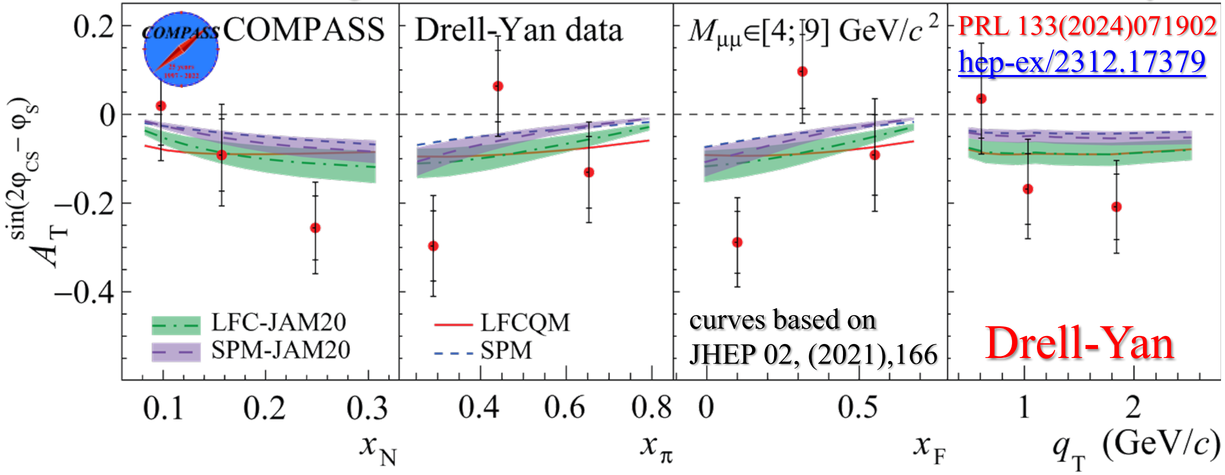
- Hint that J/ψ production might go via gg fusion in COMPASS?
- Access to small gluon TMDs?

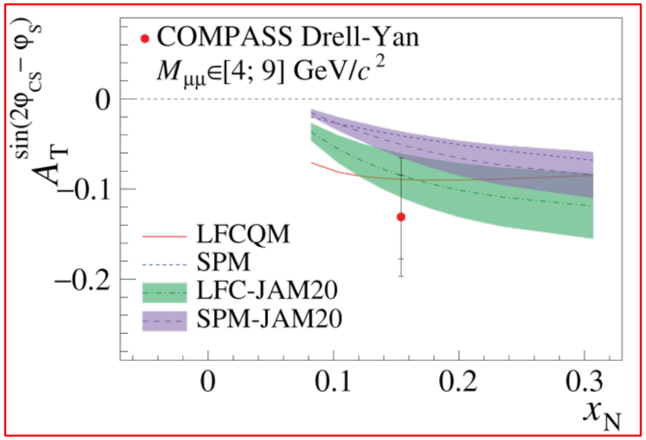


Transversity TSA: Drell-Yan and J/ψ

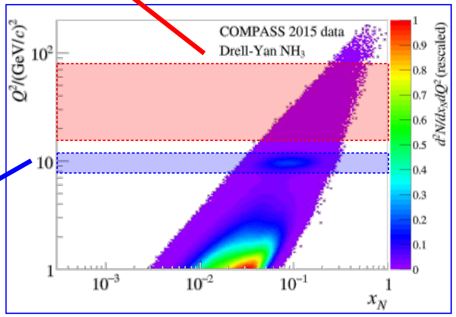
Transversity DY TSA

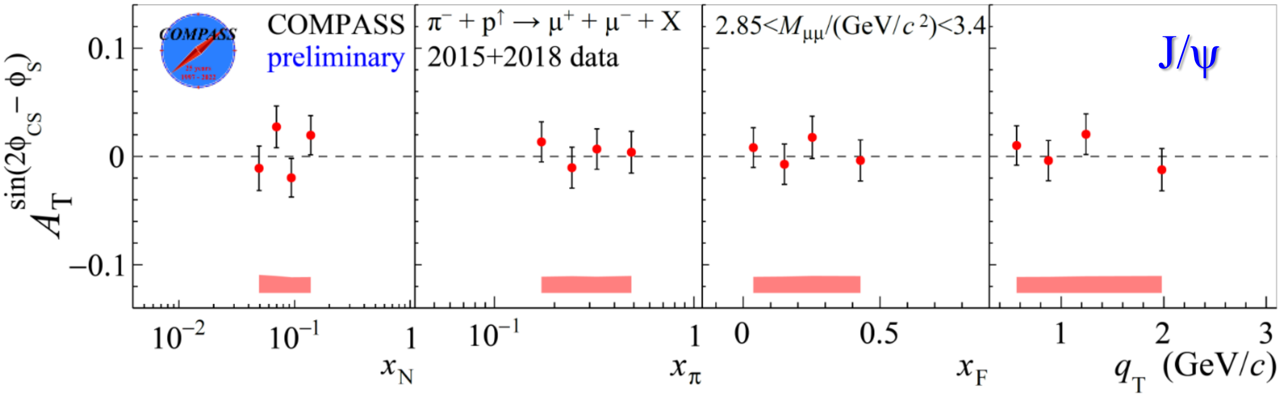
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$

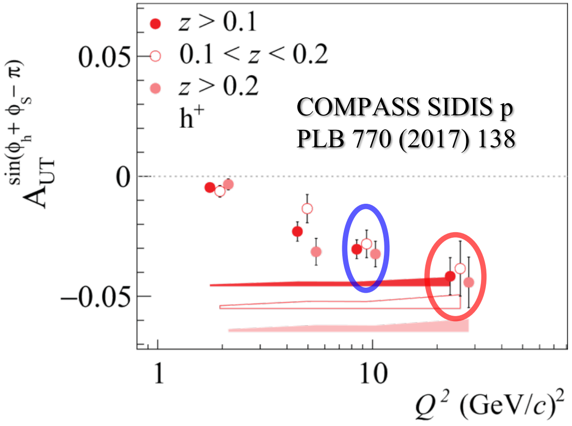




- The Drell-Yan Transversity asymmetry is negative (~2 s.d.)

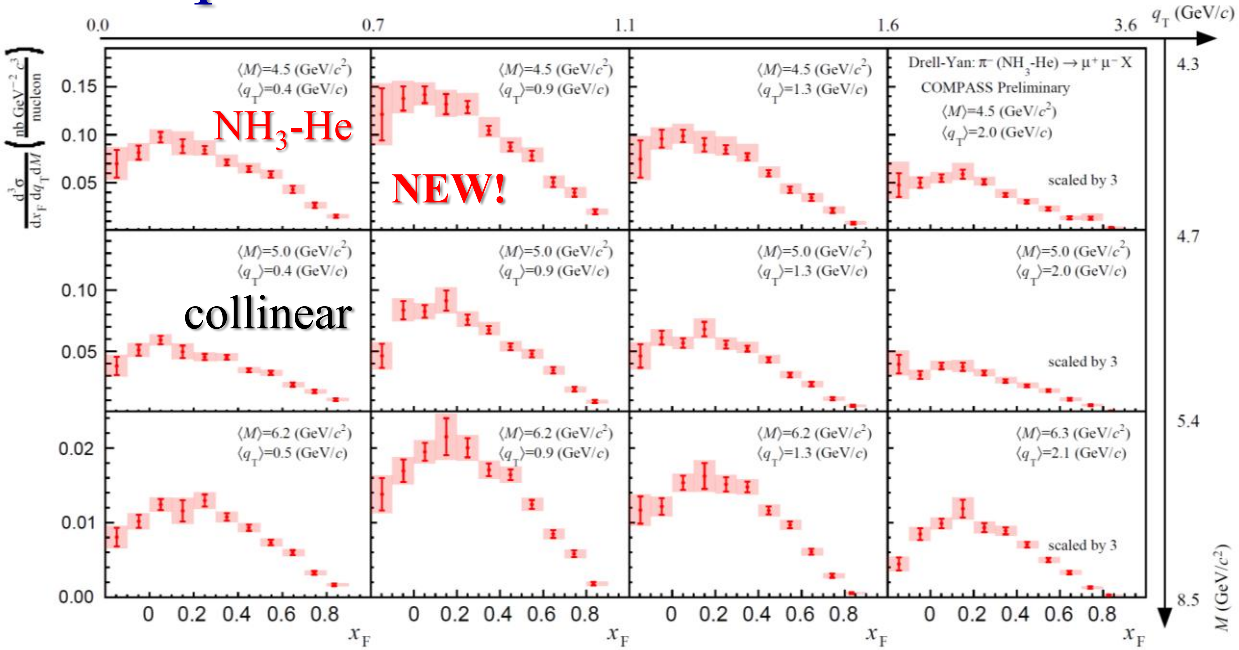


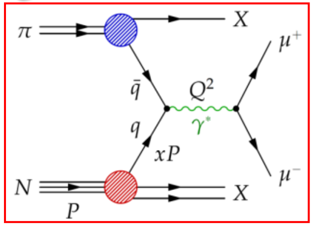


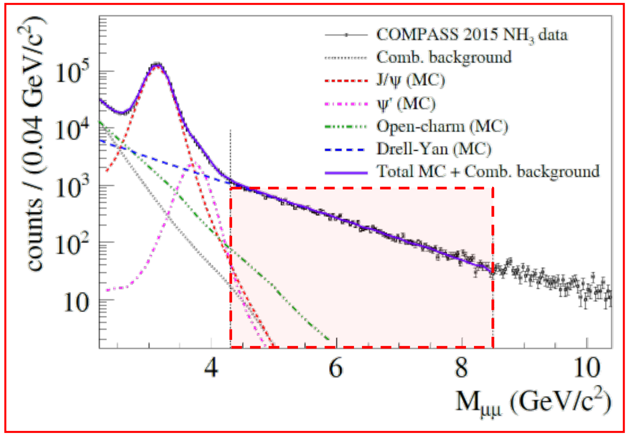


- J/ψ Sivers asymmetry is compatible with zero (within ~ 1%)
- Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS
- J/ψ Transversity TSA is also compatible with zero
- Hint that J/ψ production might go via gg fusion in COMPASS?
- Access to small gluon TMDs?

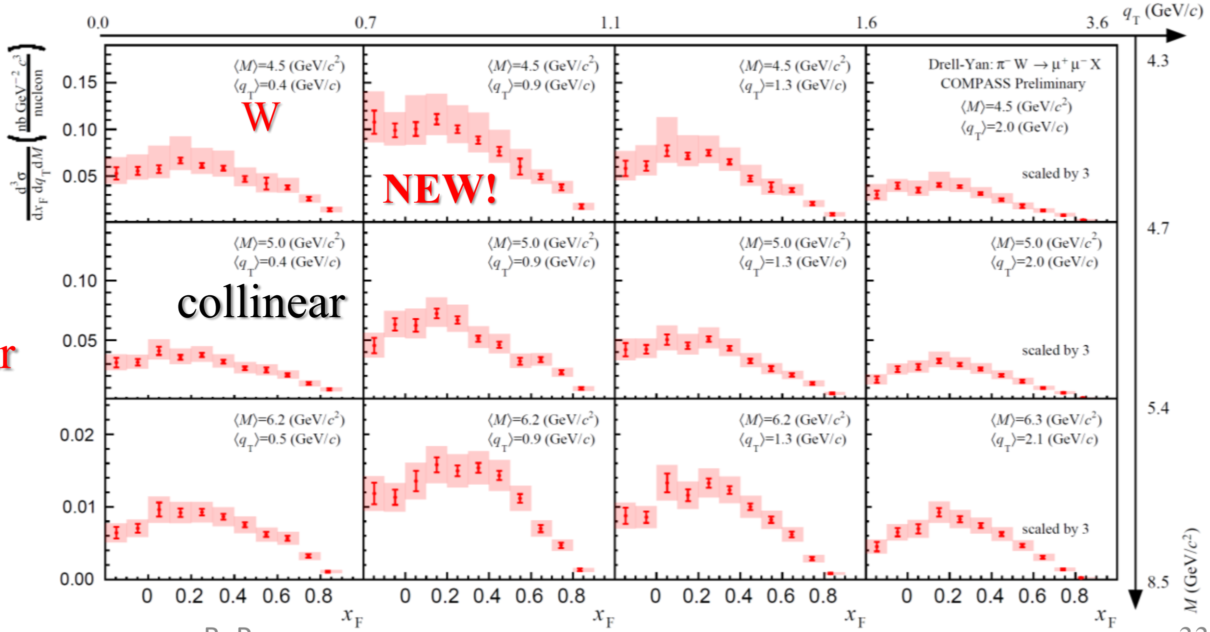
3D unpolarized Drell-Yan cross section on NH_3 and W







- 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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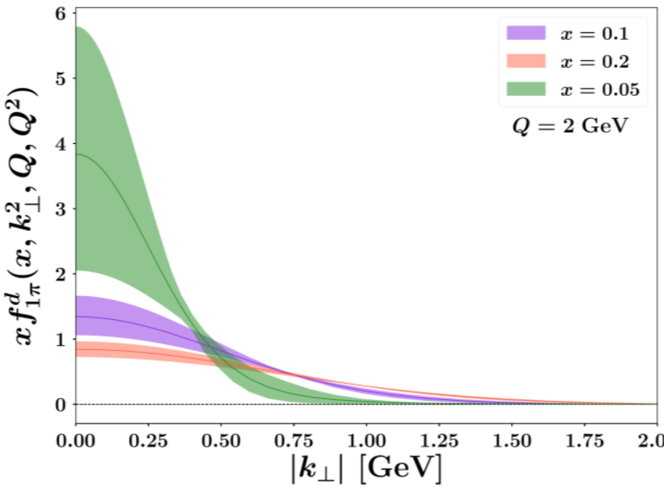
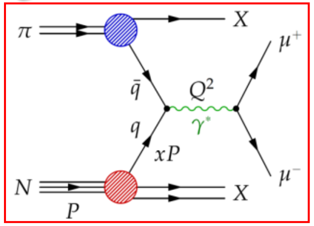
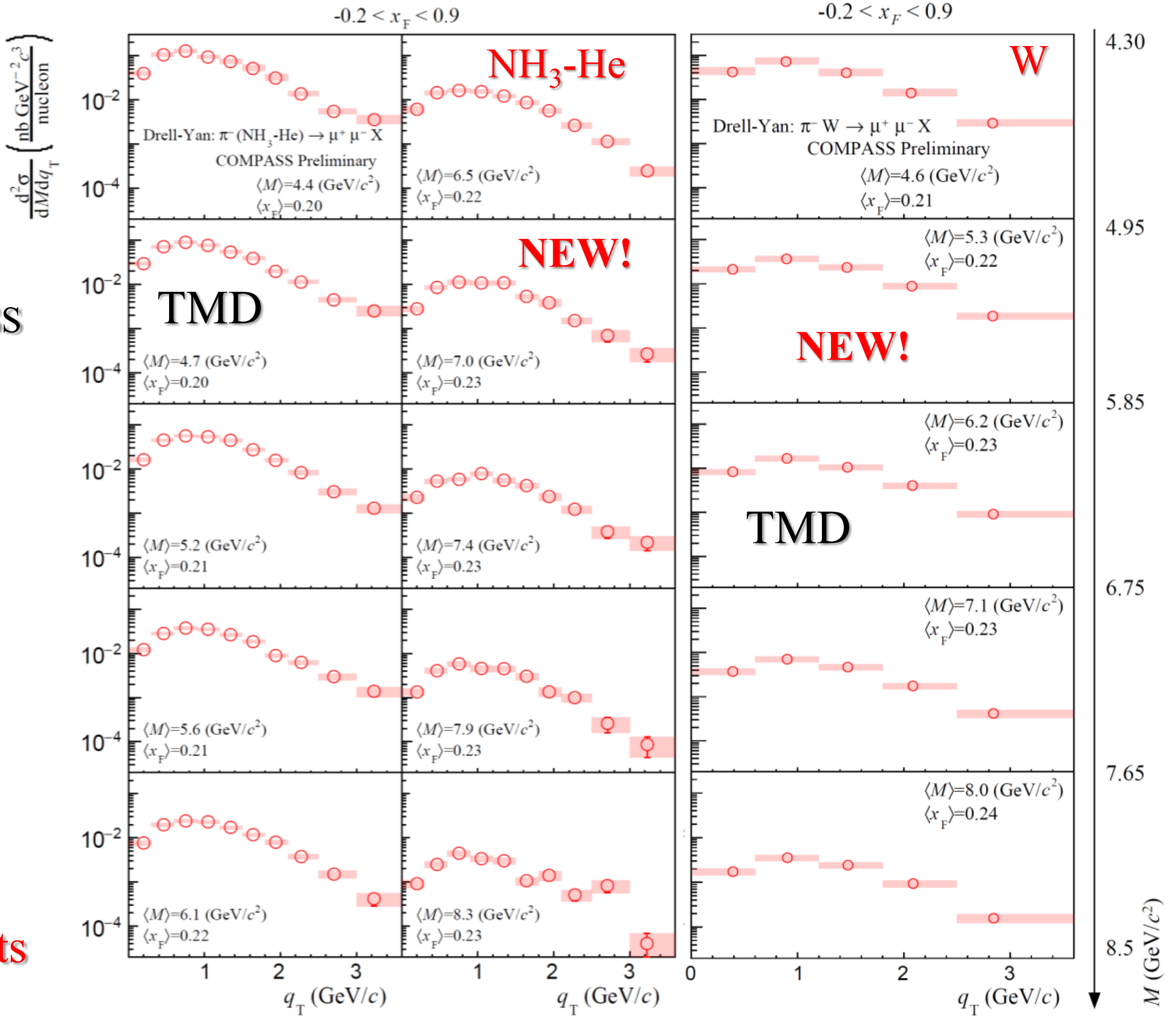


recent global fit and projections for COMPASS

MAP collaboration
Phys. Rev. D. 107, 014014





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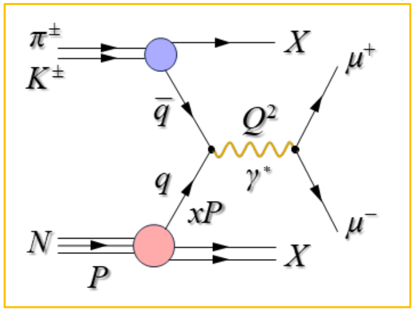
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF
- To be included in future global fits (MAP, JAM, etc.)

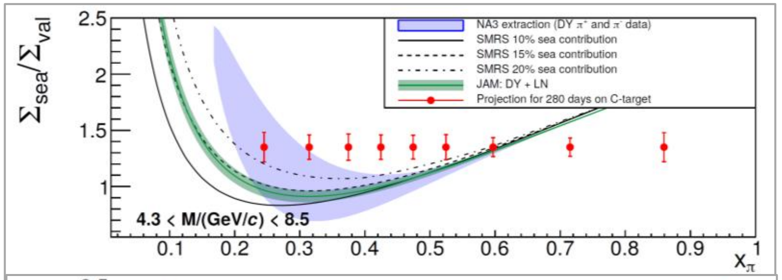
AMBER – $\pi^{\pm}$, $K^{\pm}$ induced dimuon production on C/W

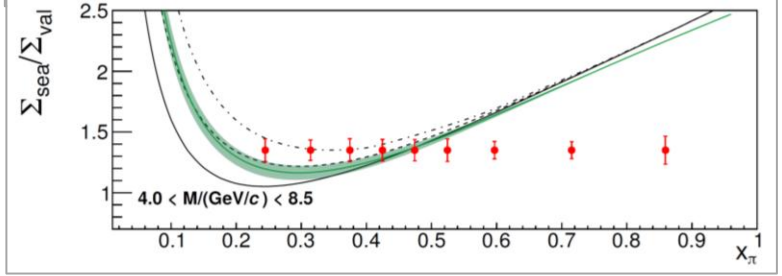
- Unique complementary measurements: $\pi^{\pm}$, $K^{\pm}$
  - Cross-sections, pion and kaon PDFs
    - Data for both collinear and TMD PDF studies
  - Drell-Yan, J/ψ and potentially ψ' channels
  - Study of nuclear effects with C and W



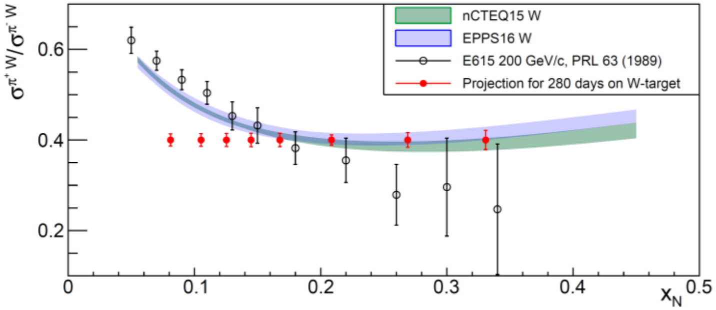
AMBER J/ψ events	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

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

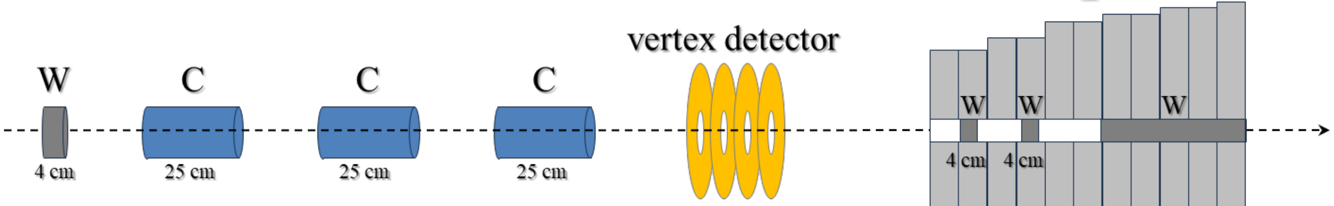


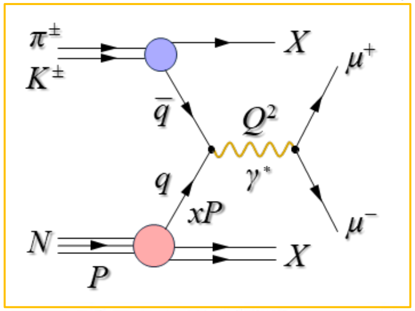


$\Sigma_{val} = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence
$\Sigma_{sea} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence



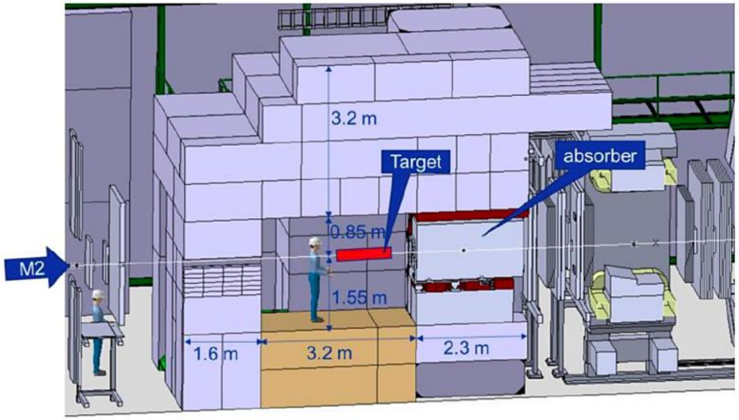
AMBER – $\pi^\pm$, $K^\pm$ induced dimuon production on C/W

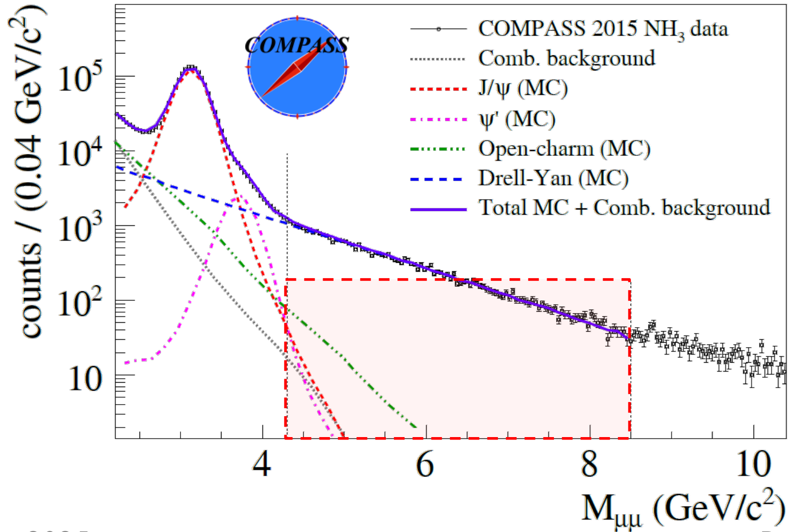


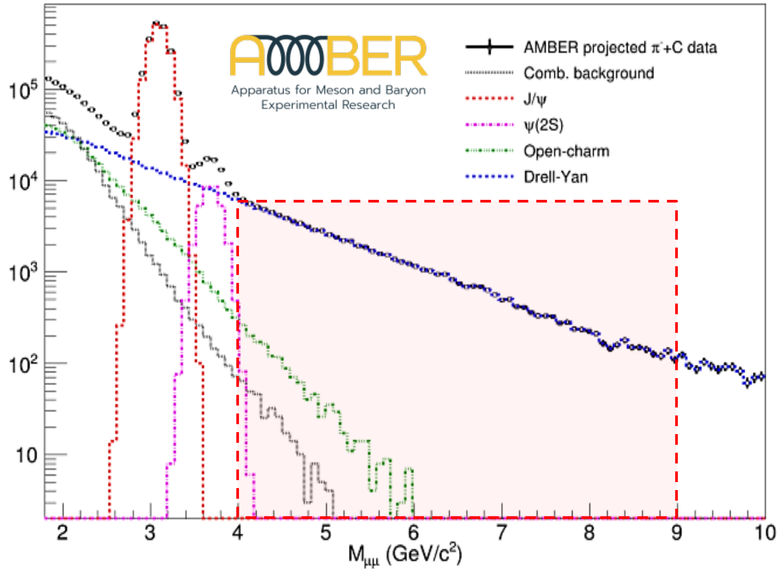


Compared to COMPASS

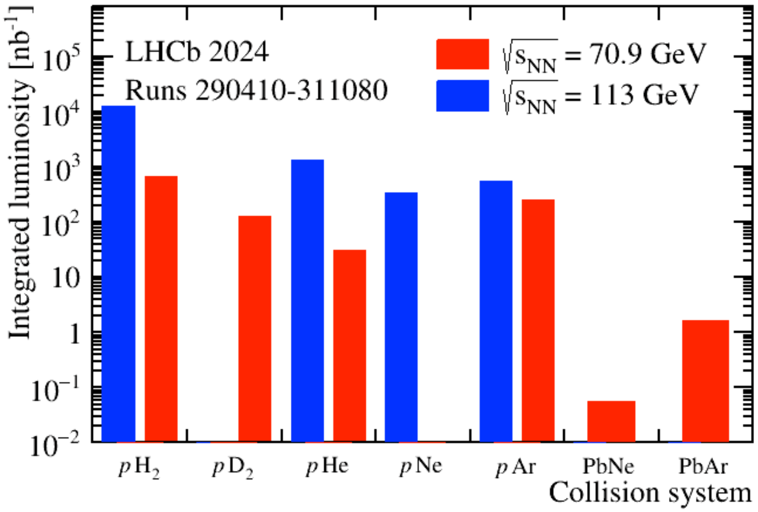
- Light isocalar target (carbon) instead of NH_3-He mix
- Improved mass resolution (~ 100 MeV/c^2)
  - Lower background → enlarge DY mass range
  - J/ψ and ψ(2S) studies
- Wider beam choice: $\pi^\pm$, $K^\pm$, $p\,/\,\overline{p}$, CEDARs (PID)
- Unique complementary measurements: $\pi^\pm$, $K^\pm$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



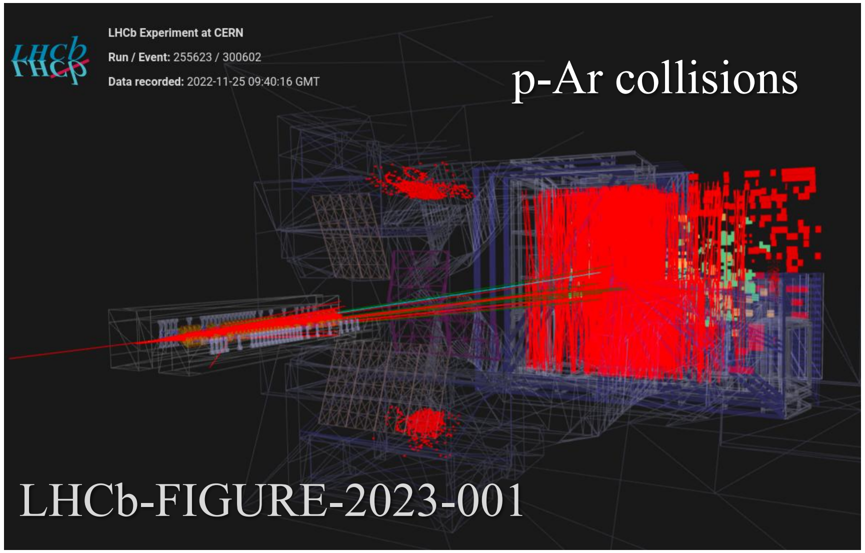




LHC – SMOG2 early data – fantastic precision



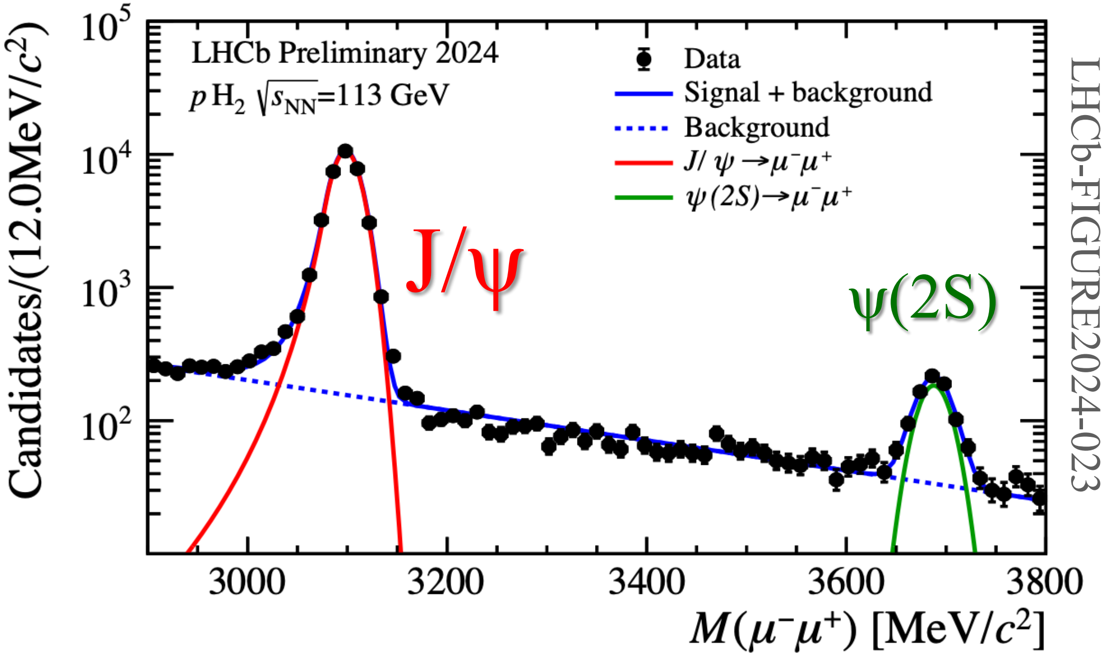
A wealth of unique data collected in 2024



p-Ar collisions

LHCb-FIGURE-2023-001

tomography of the cell:
residual gas & secondary interactions



J/ψ

ψ(2S)

LHCb-FIGURE2024-023

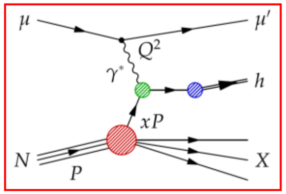
- Recent SIDIS highlights from COMPASS

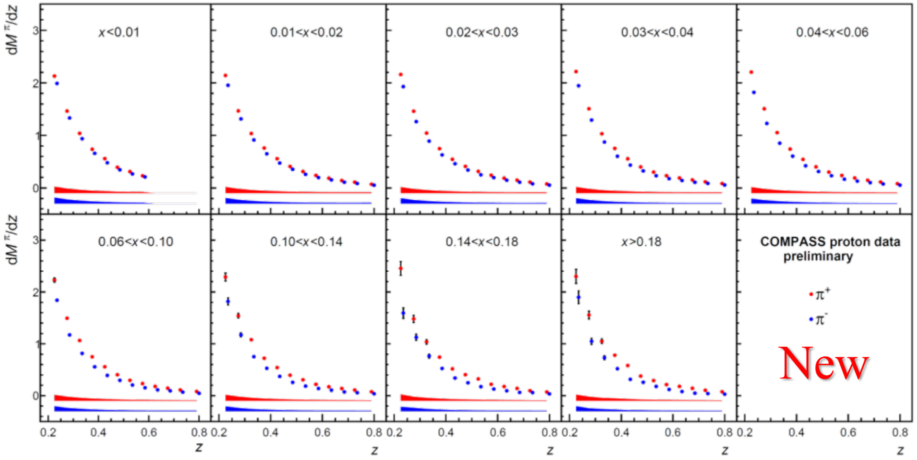
Hadron multiplicities; $h^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ (2016 data)

collinear

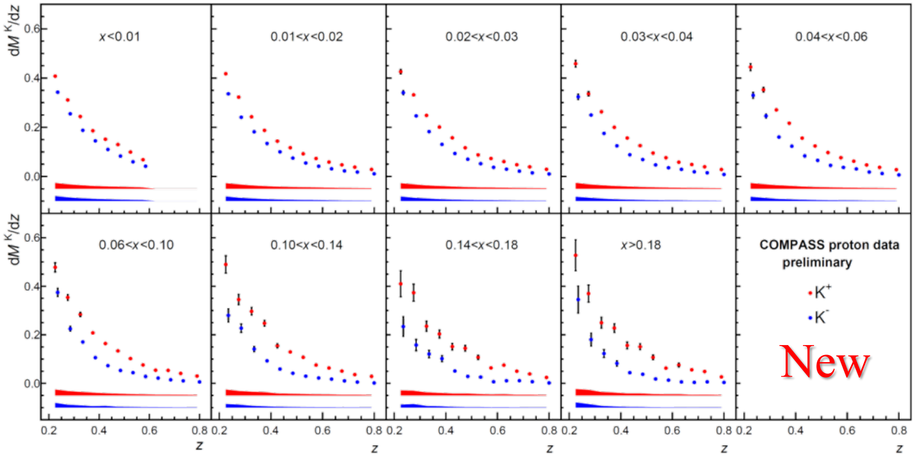
A set of complex corrections:

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



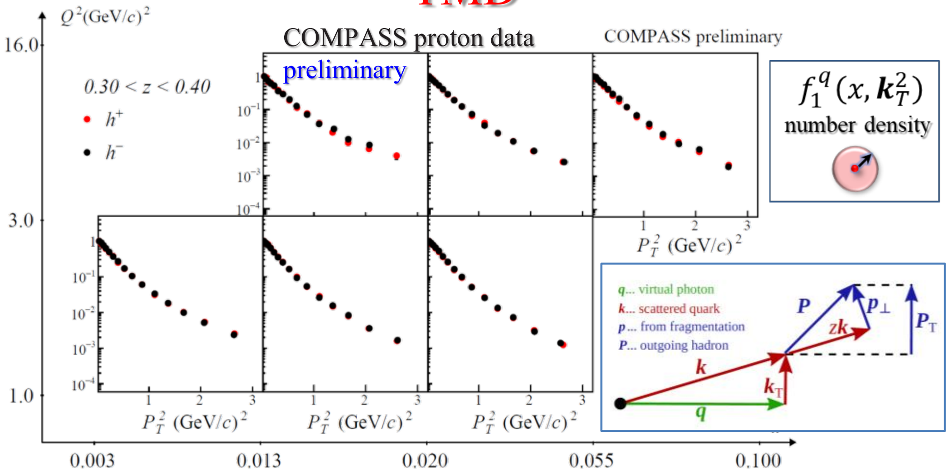


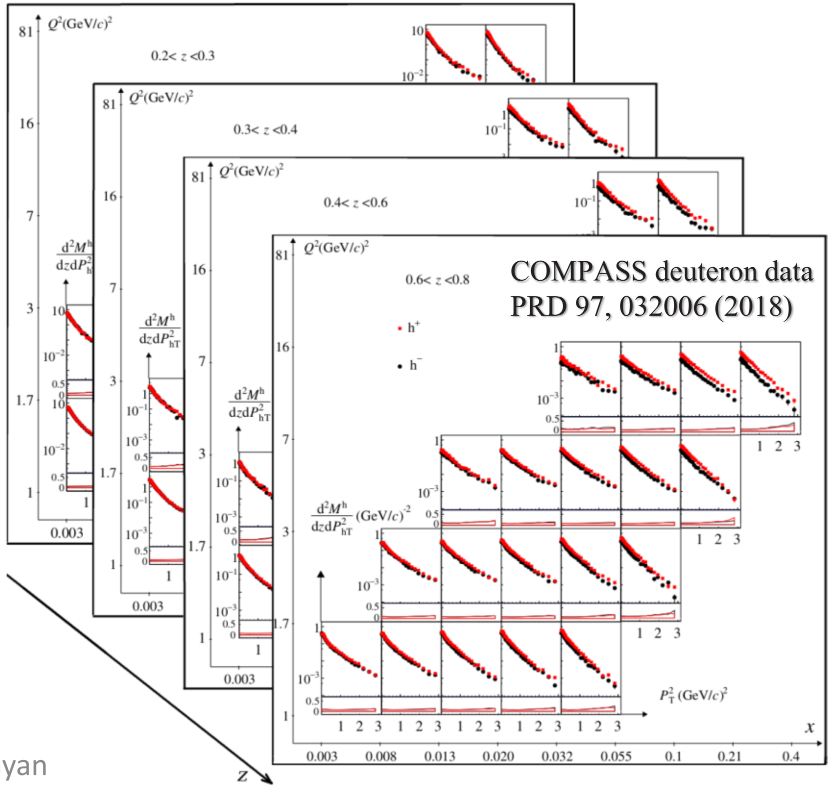
New



New

TMD



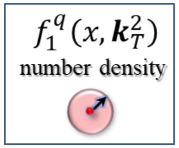


COMPASS deuteron data
PRD 97, 032006 (2018)

New radiative corrections being applied

Drafting started for a dedicated article

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



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A set of complex corrections:

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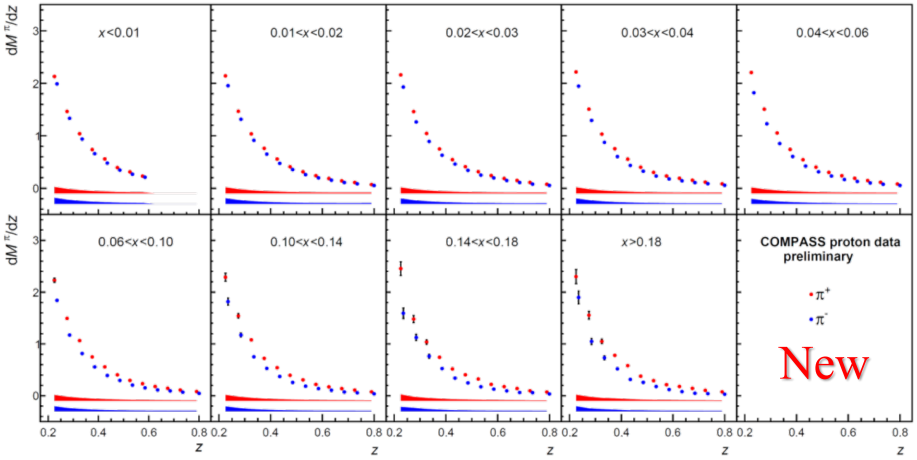
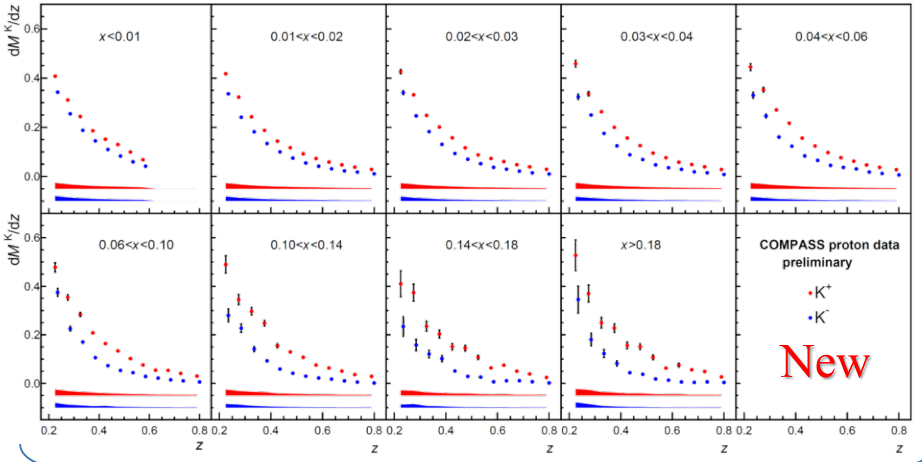
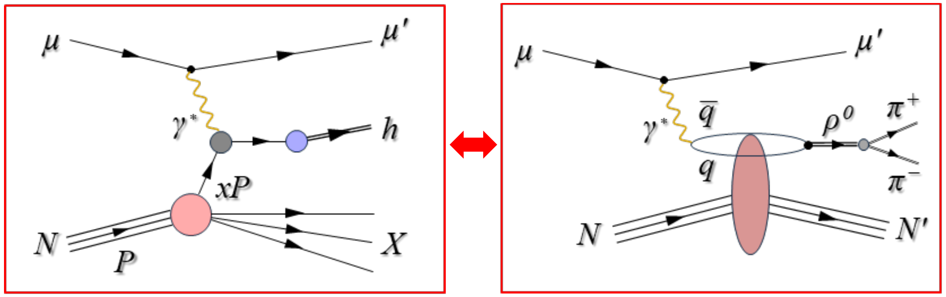




New radiative corrections (DJANGOH)

hep-ex/2410.12005 soon in PRD



Diffractive VM production

- In DIS γ^* interacts with a single quark
- DVMP - γ^* fluctuates into a VM
  - VM then interacts diffractively with the nucleon through multiple gluon exchange
- DVMP correction: two MC samples are used

SIDIS

- LEPTO 6.5 MC (diffractive contributions off)

Diffractive ρ^0 and ϕ mesons

- HEPGEN generator

Diffractive events enhance at low x and Q^2

- Pions from ρ^0 decay (at high z)

For pions maximum correction can reach even 50%

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

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

Cahn effect in SIDIS: Diffractive VMs contribution

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

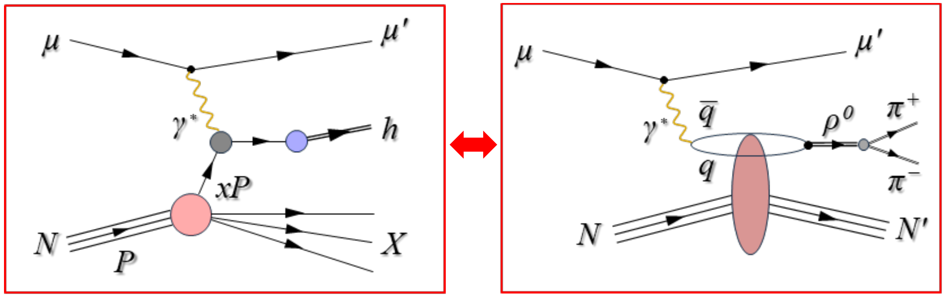
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

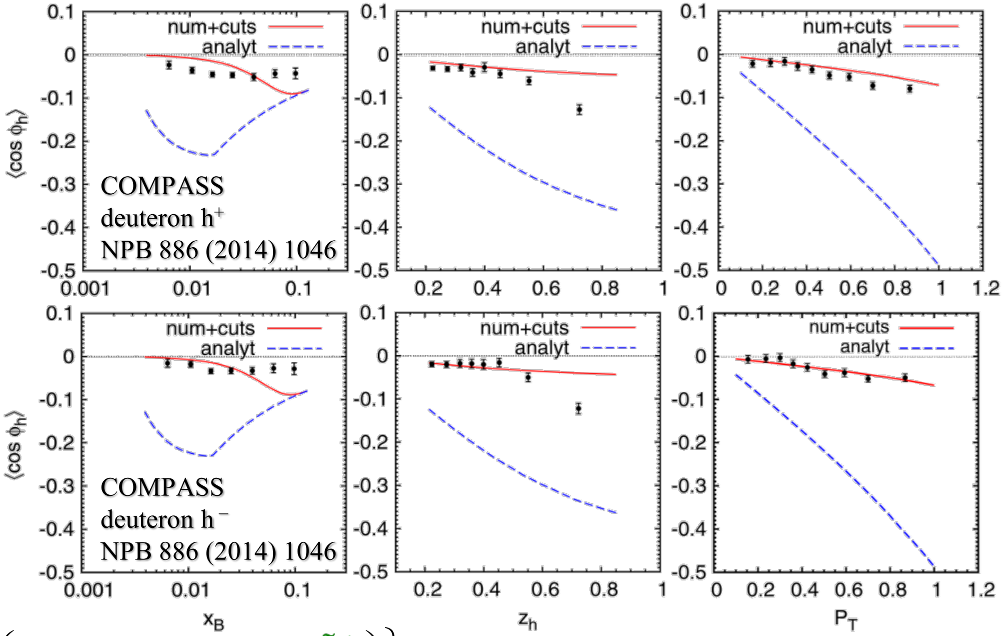
Cahn effect

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

number density



?



As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

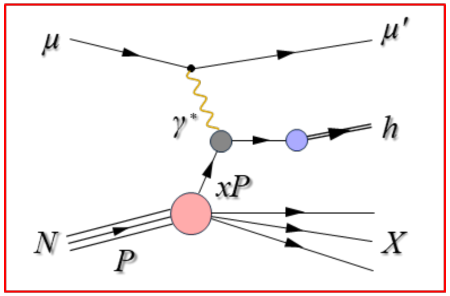
- Measurements by different experiments

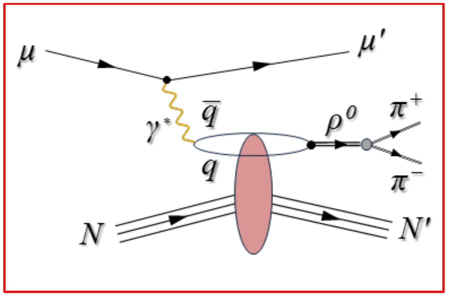
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

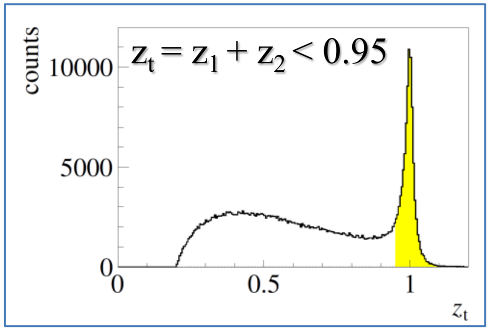
Cahn effect in SIDIS: Diffractive VMs contribution

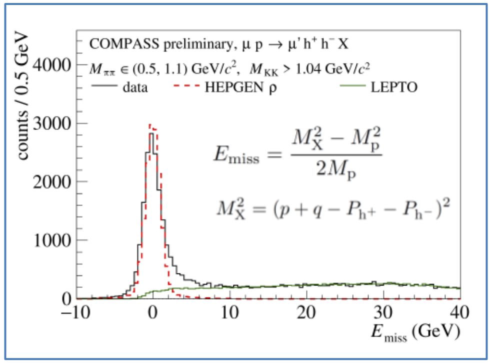
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times \left(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\ldots\right)$$

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

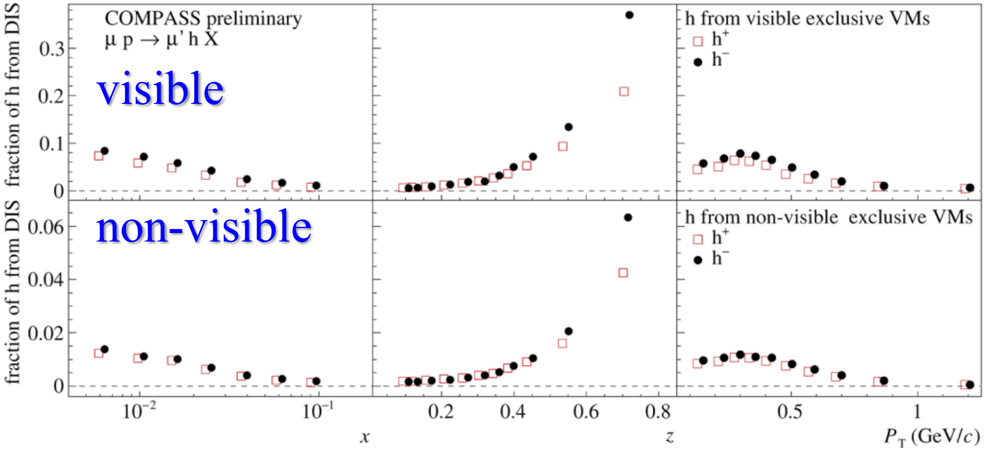








VM fractions



As of 1978 – simplistic kinematic effect:

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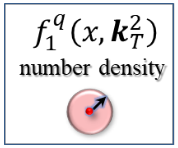
As of 2023 – complex SF (twist-2/3 functions)

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

Cahn effect in SIDIS: DVMs

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



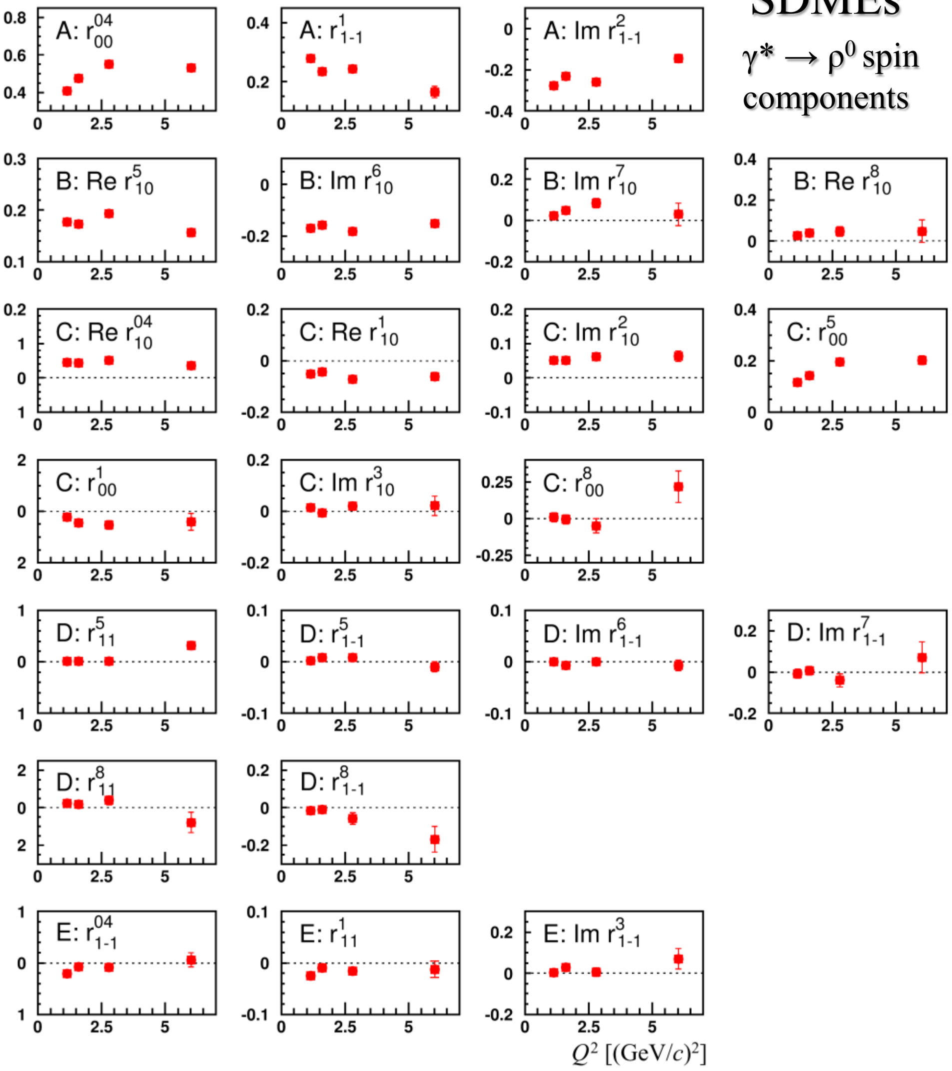
$f_1^q(x,\boldsymbol{k}_T^2)$

number density

COMPASS, EPJC (2023) 83 924

SDMEs

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



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

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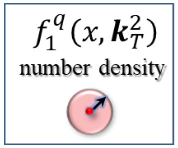
$$\times\Big(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\ldots\Big)$$



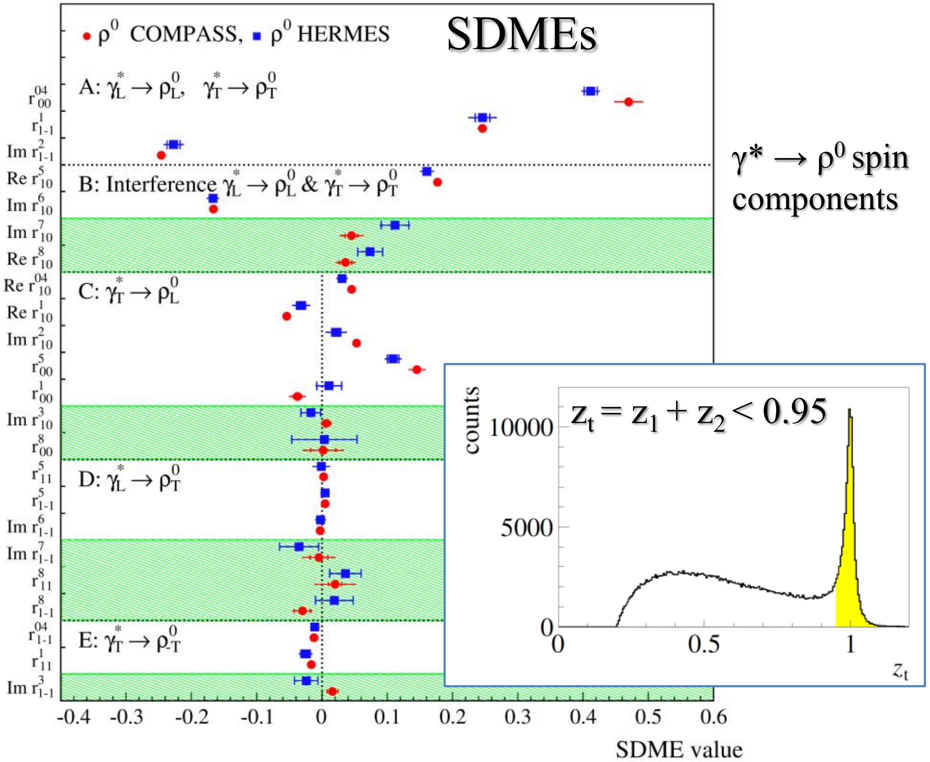
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

“Visible” hadron pairs

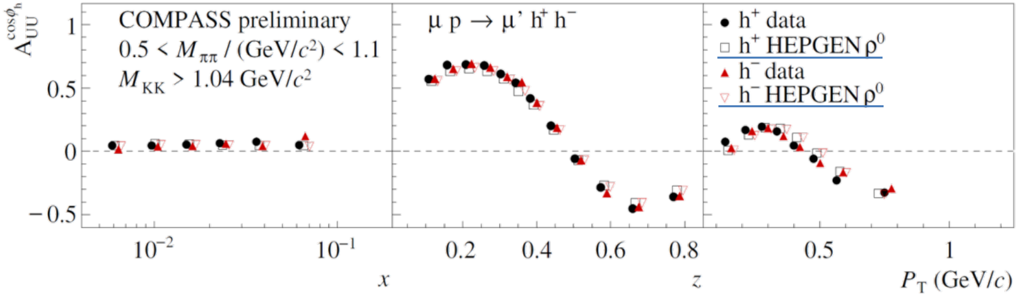
- Both hadrons reconstructed
- Removed by selecting: $z_t = z_{h+} + z_{h-} < 0.95$

COMPASS, EPJC (2023) 83 924



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

VM contribution “amplitudes”

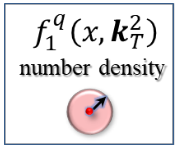


Only “average” SDMEs are implemented in HEPgen
They seem to describe the data well

Cahn effect in SIDIS: DVMs

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

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



As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

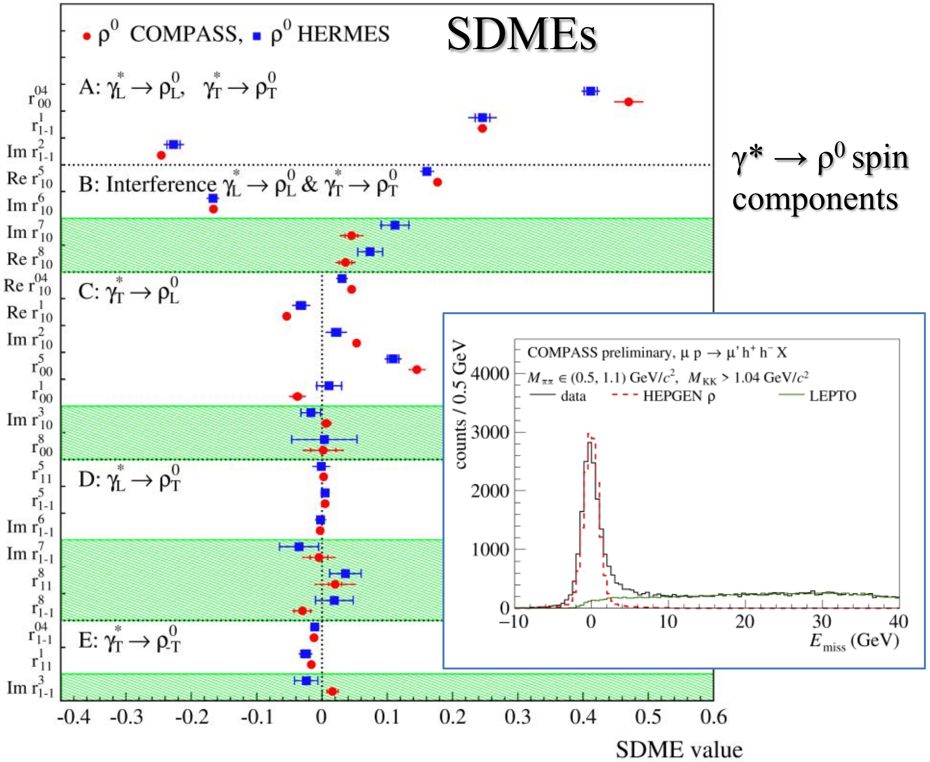
“Visible” hadron pairs

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

“Invisible” hadron pairs

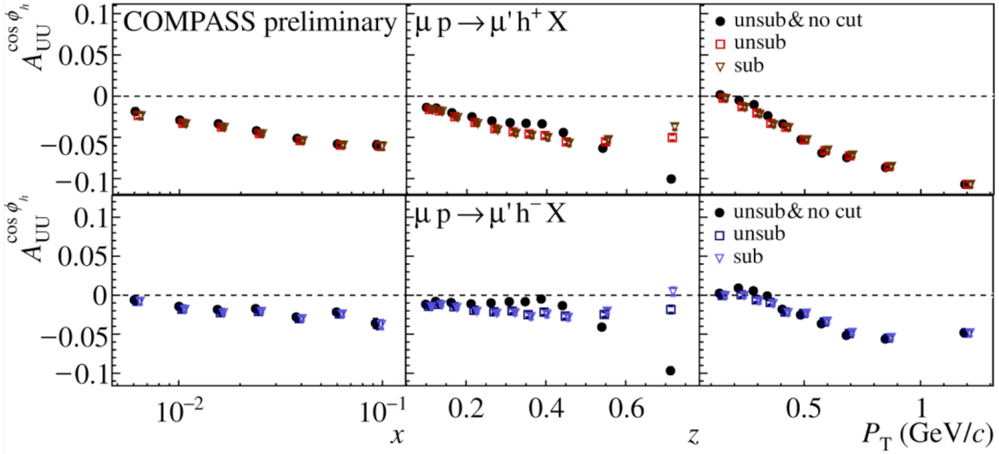
- Only one hadron out of two is reconstructed
- Subtraction done at the level of ϕ_h using simulated HEPGEN distribution for VMs
- HEPGEN and Lepto are normalized to the data using E_{miss} distribution, SIDIS tail is subtracted

COMPASS, EPJC (2023) 83 924



γ* → ρ0 spin components

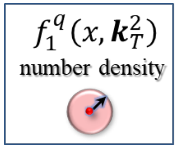
VM corrections, applied



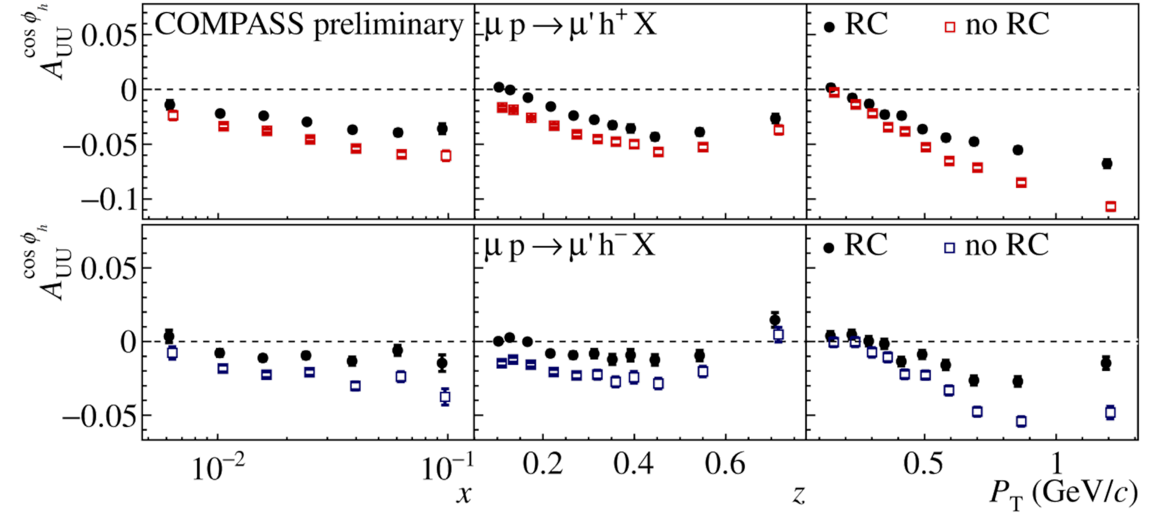
Cahn effect in SIDIS: DVMs and RCs

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

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



RC corrections, applied



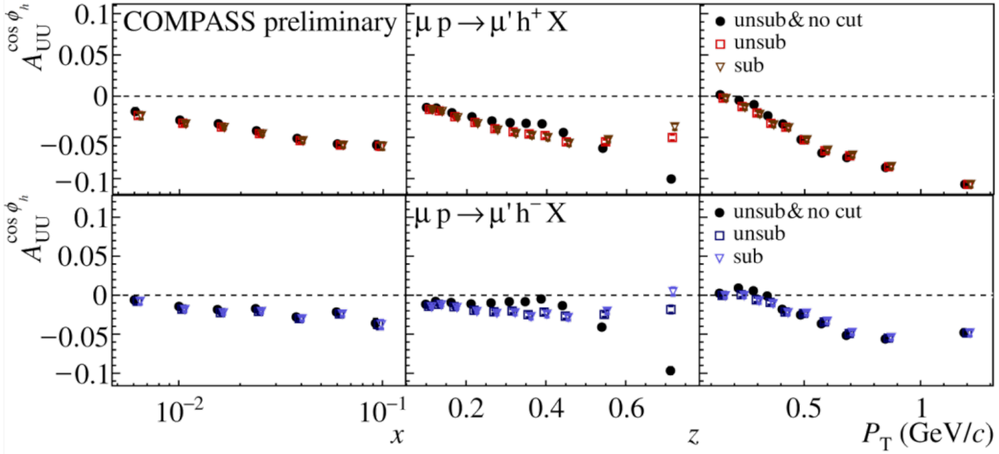
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

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

VM corrections, applied



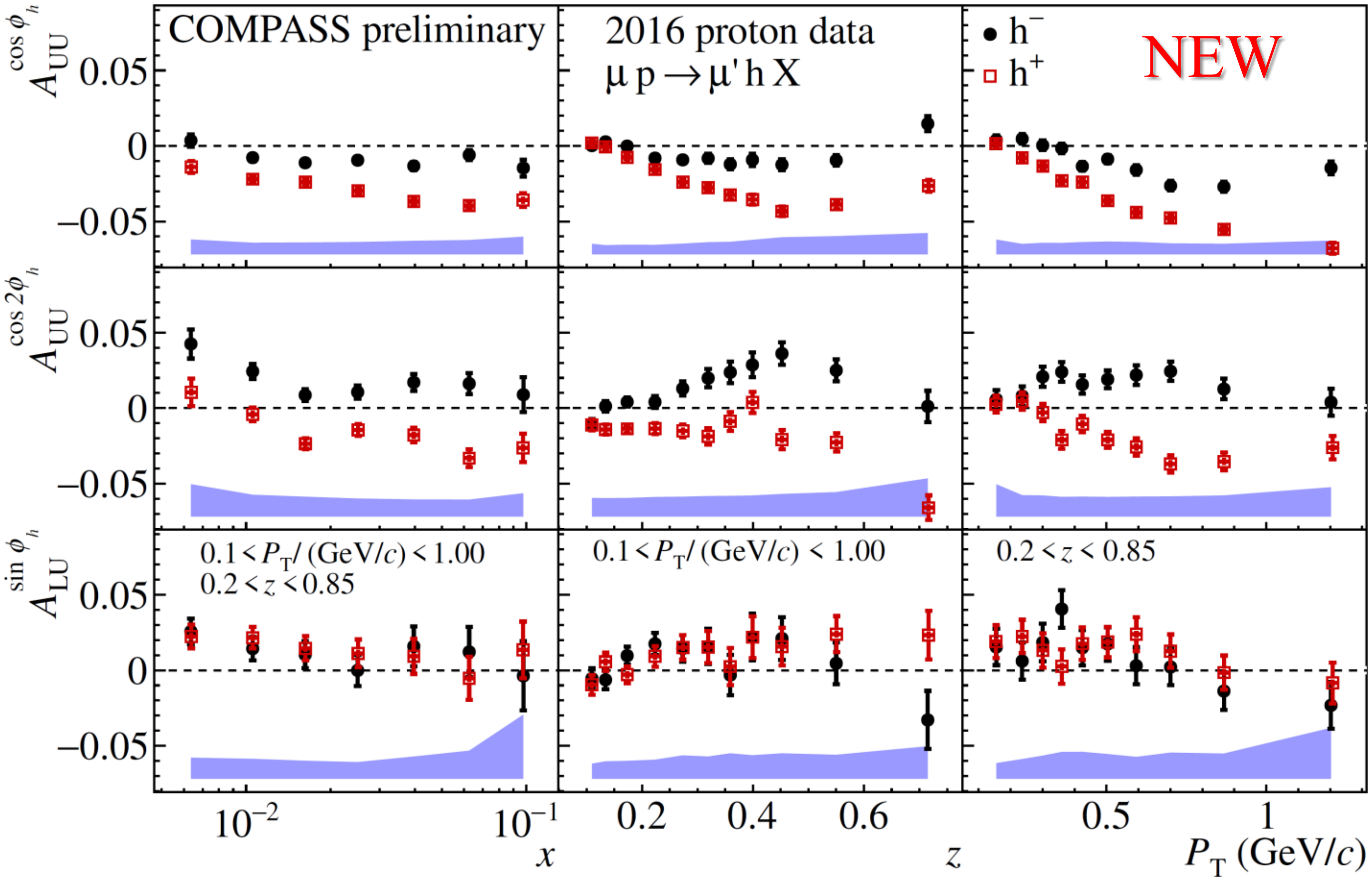
Azimuthal effects in unpolarized SIDIS

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

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

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

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



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

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

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

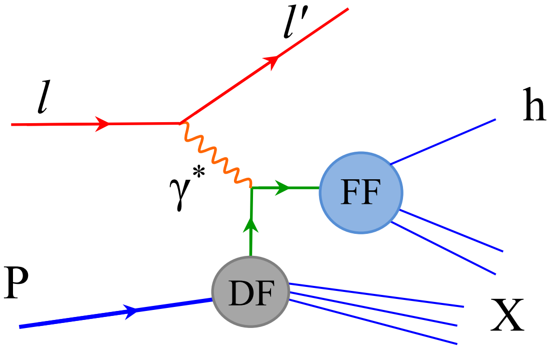
Working on 3D kinematic dependences

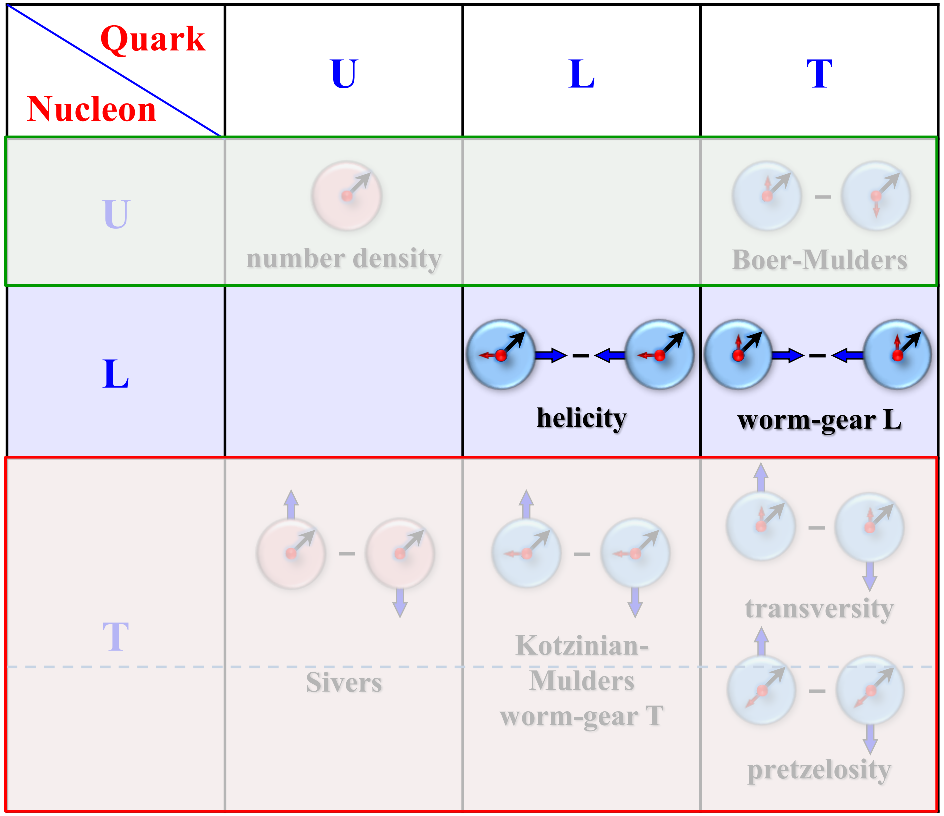
SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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





Quark / Nucleon	U	L	T
U	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**

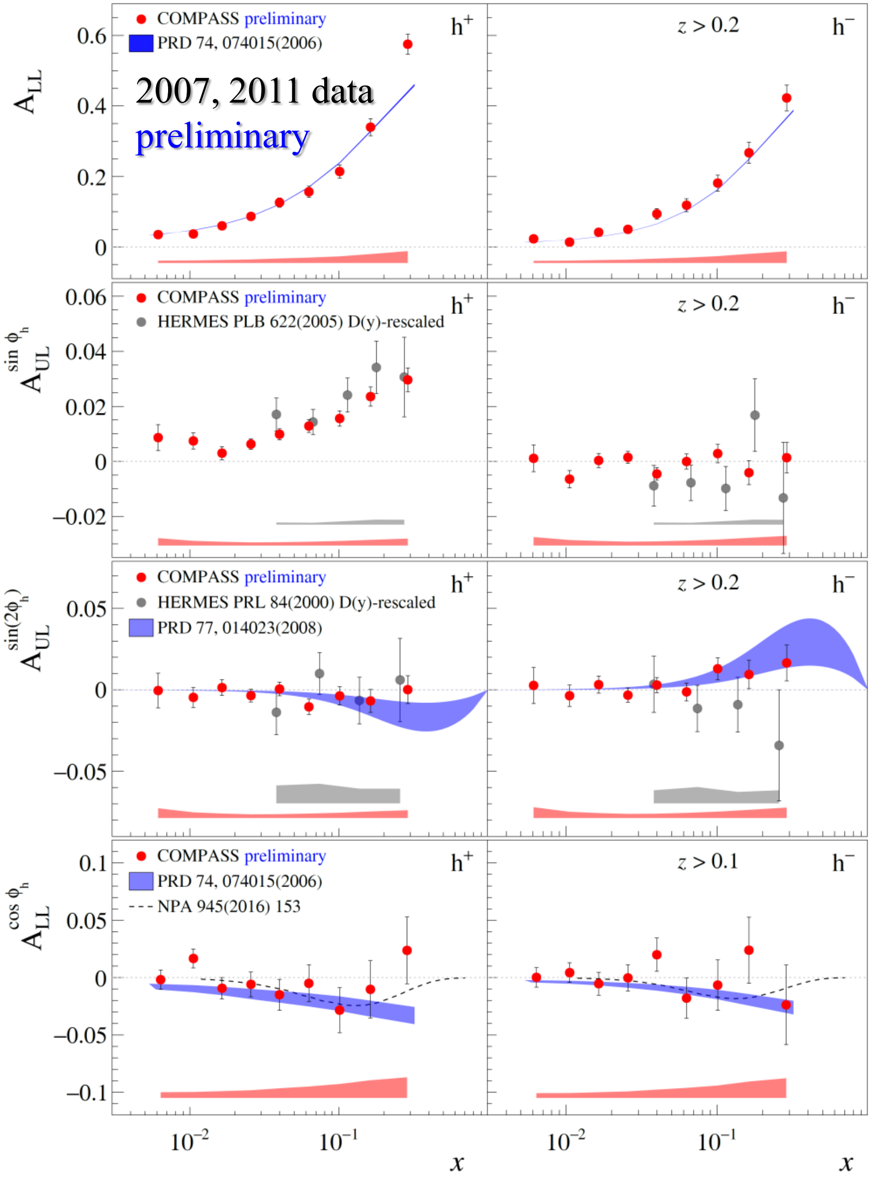
SIDIS: target longitudinal spin dependent asymmetries

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

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

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

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?

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

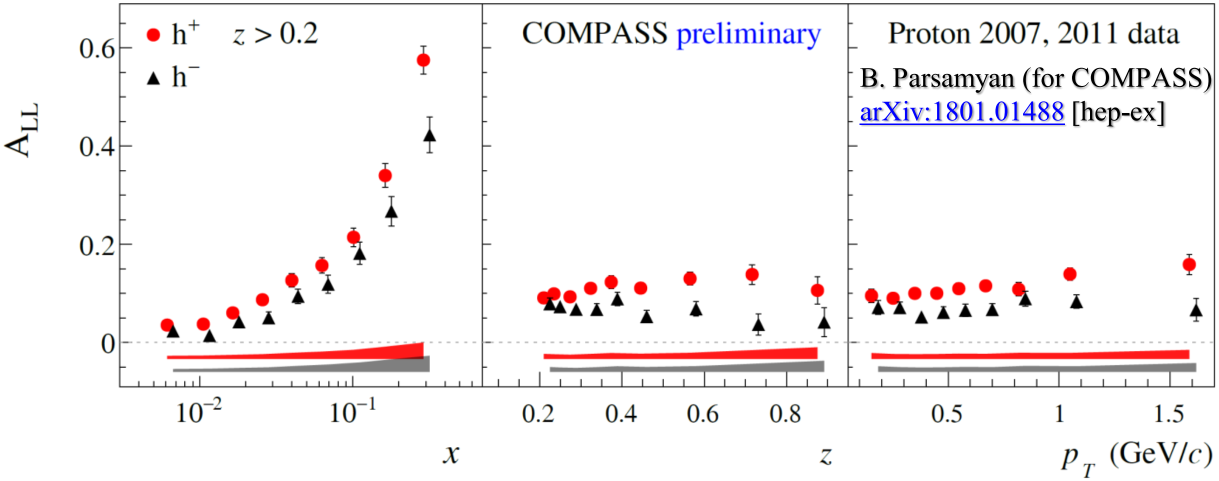
- Q-suppression, Various different “twist” ingredients
- Compatible with zero, in agreement with models

SIDIS: target longitudinal spin dependent asymmetries

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

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

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

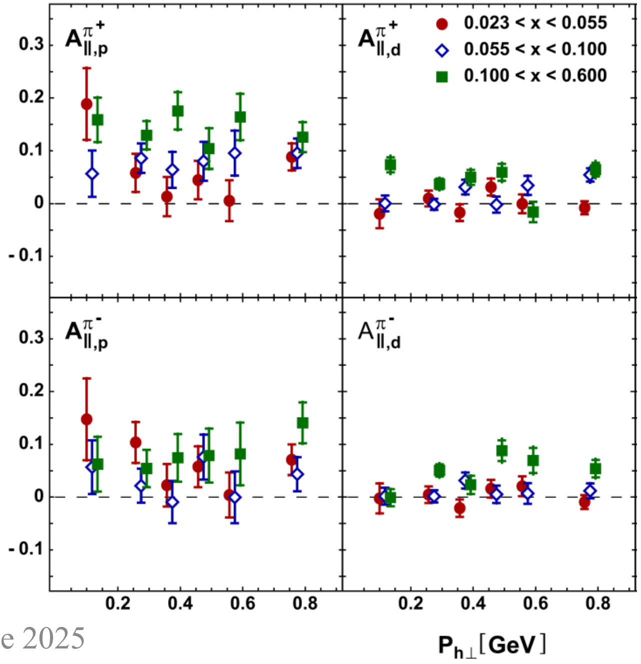


COMPASS preliminary

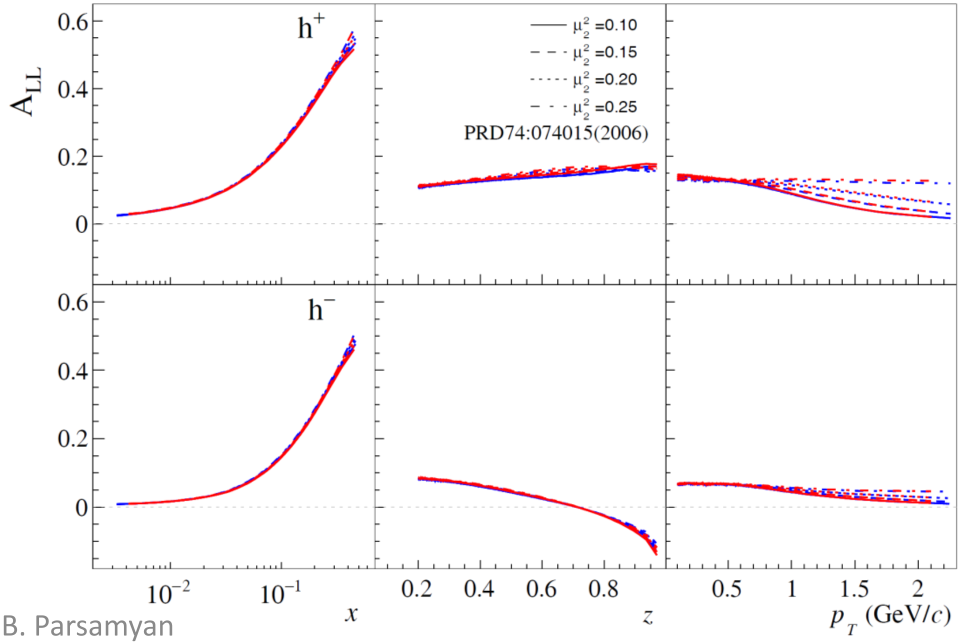
Proton 2007, 2011 data

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

HERMES: PRD 99, 112001 (2019)



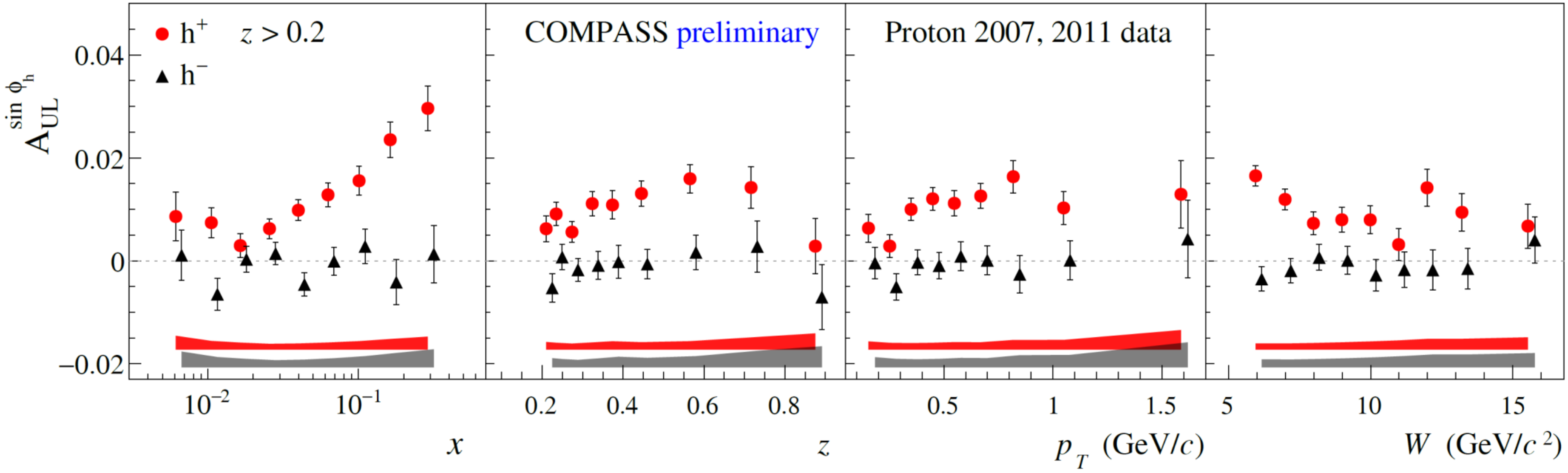
COMPASS Proton-2007, -2011 kinematics



SIDIS TSAs: subleading twist effects

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

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



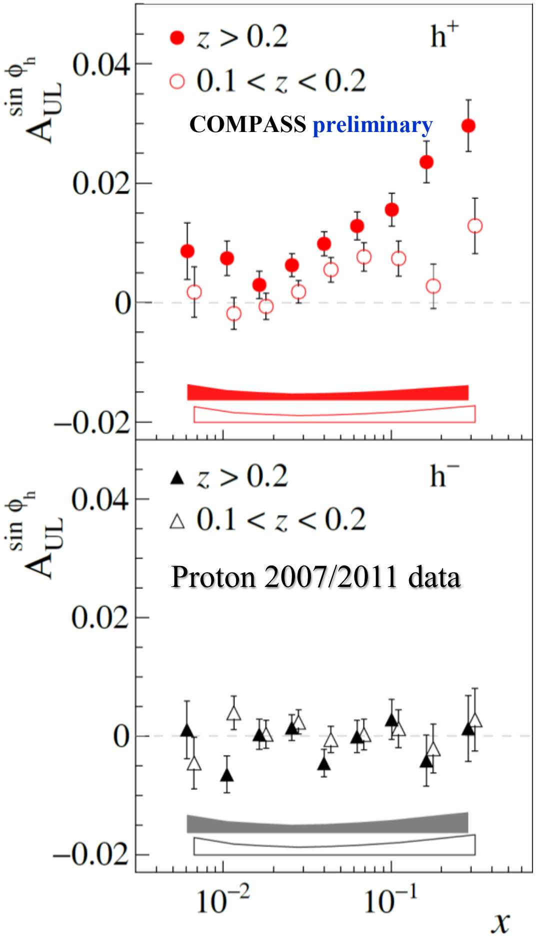
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- Non-zero trend for h^+, h^- compatible with zero

SIDIS TSAs: subleading twist effects

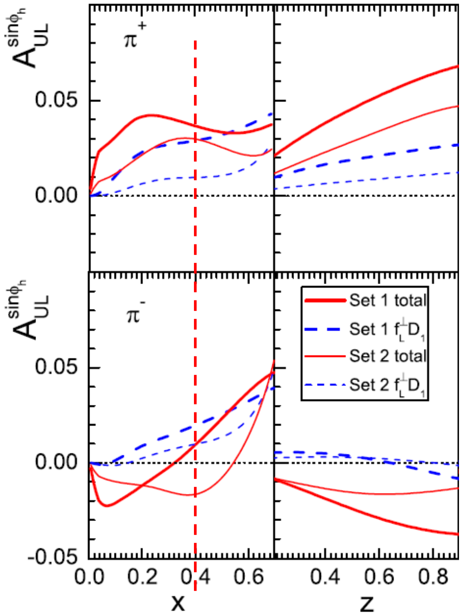
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_L\sqrt{2\varepsilon\left(1+\varepsilon\right)}A_{UL}^{\sin\phi_h}\sin\phi_h+\ldots\right\}$$

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

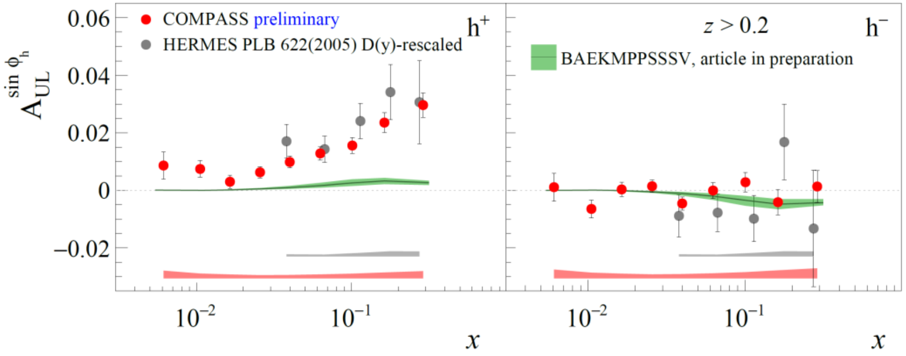
B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]



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



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



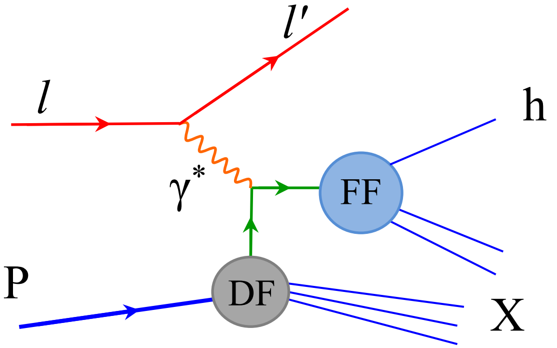
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h$^+$, h$^-$ compatible with zero, clear *z*-dependence

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

All measured by COMPASS

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

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



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

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

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

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

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

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

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

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

Twist-2

Twist-3

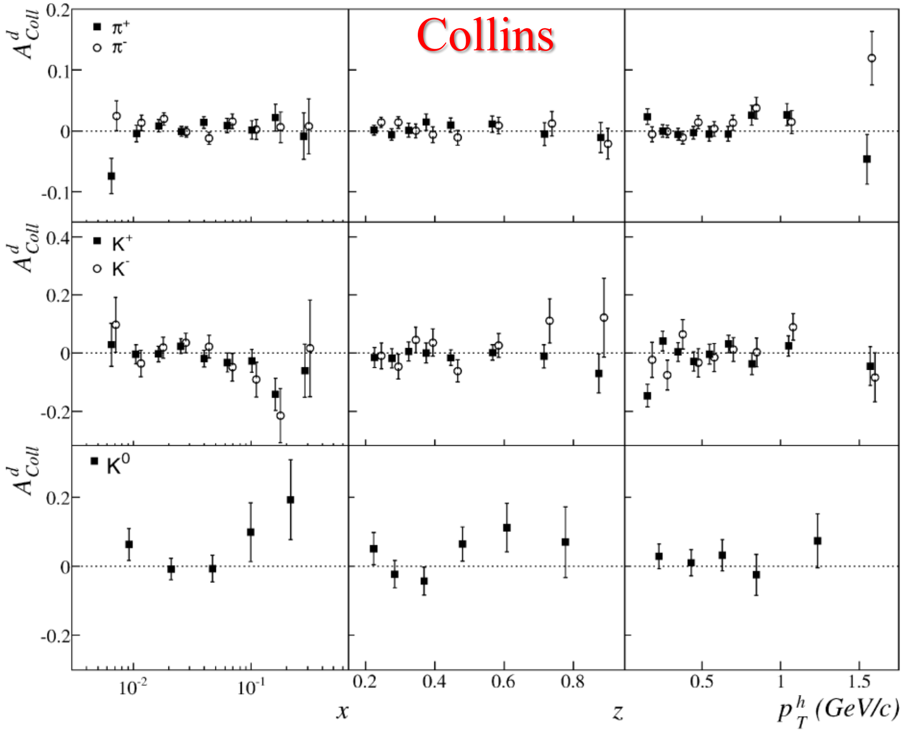
SIDIS TSAs: Collins and Sivers effects (deuteron)

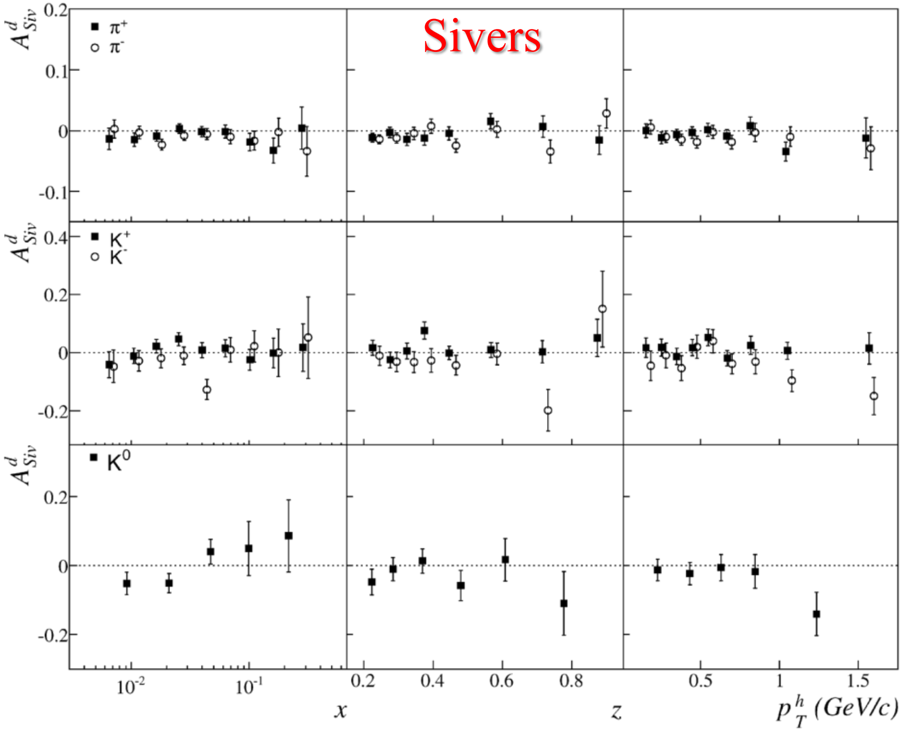
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_\mathrm{T}\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+S_\mathrm{T}\,\varepsilon\,A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)\ldots\right\}$$

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

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

COMPASS PLB 673 (2009) 127





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

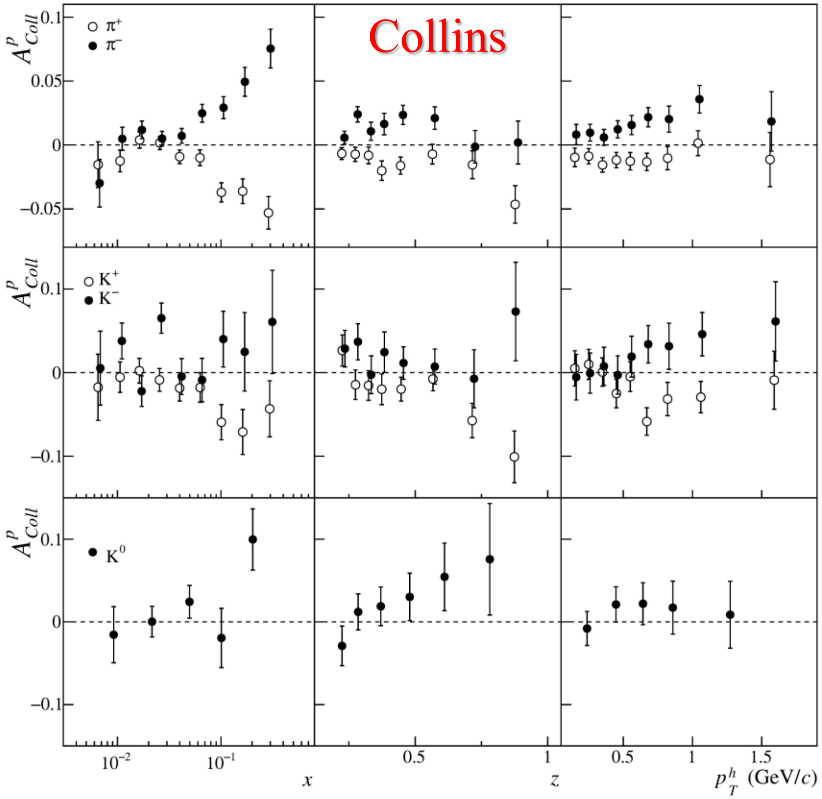
SIDIS TSAs: Collins and Sivers effects (proton)

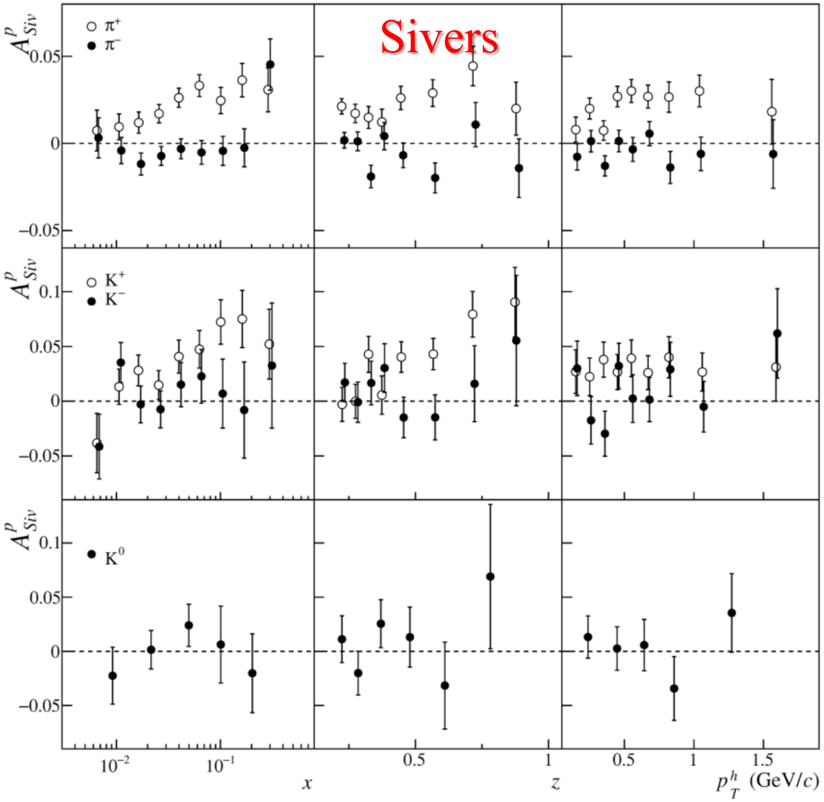
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_{\mathrm{T}}\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+S_{\mathrm{T}}\,\varepsilon\,A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)\ldots\right\}$$

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

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

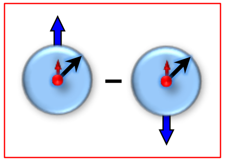
COMPASS PLB 744(2015)250





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

SIDIS TSAs: Collins effect and Transversity

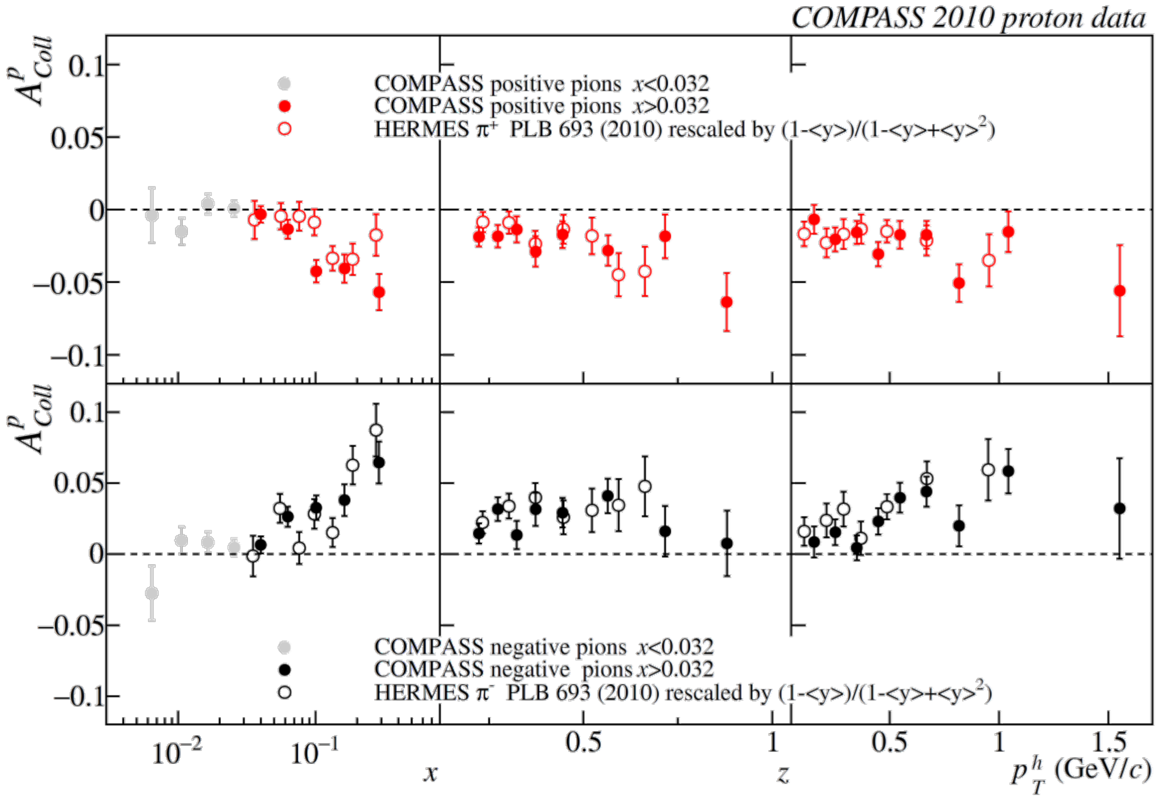


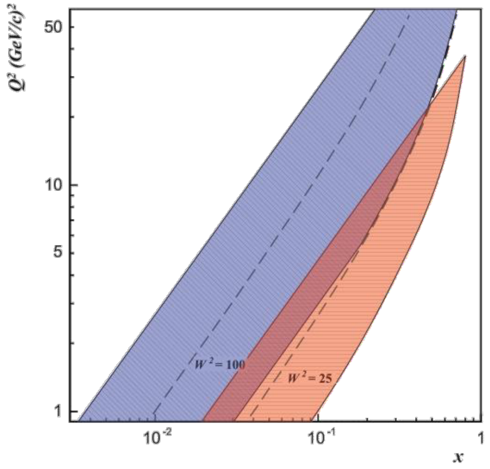
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_{\mathrm{T}}\,\varepsilon\, A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

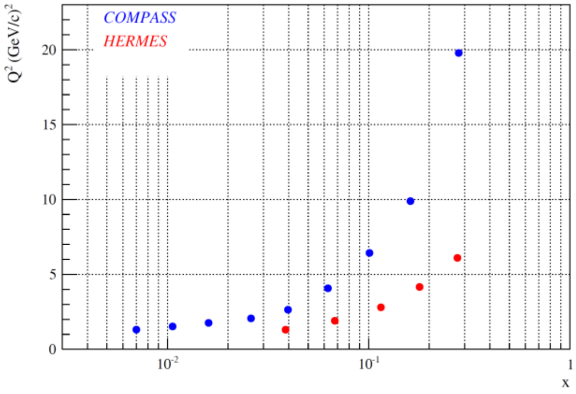
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

- 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

COMPASS PLB 744 (2015) 250



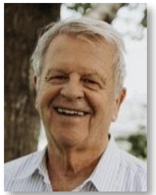




SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

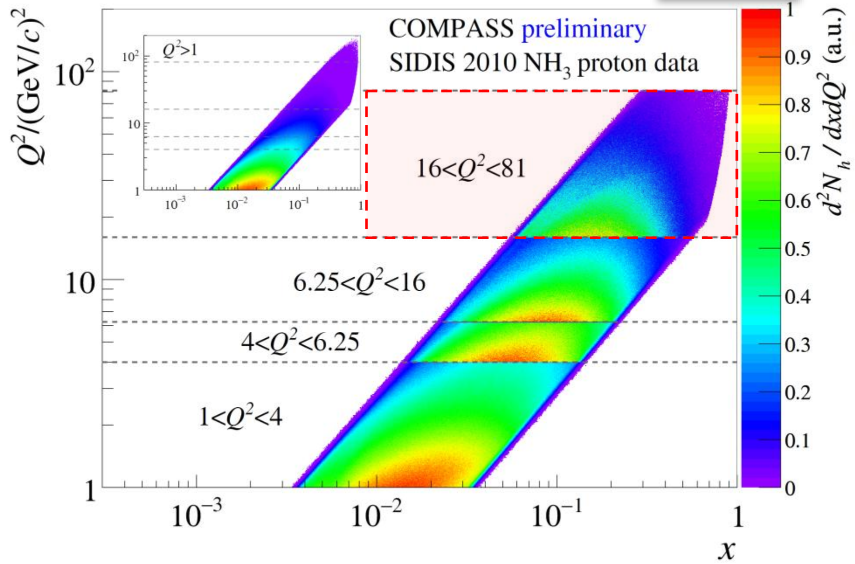
$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\; S_{\mathrm{T}}\, A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h-\phi_S\right)+\ldots\right\}$$

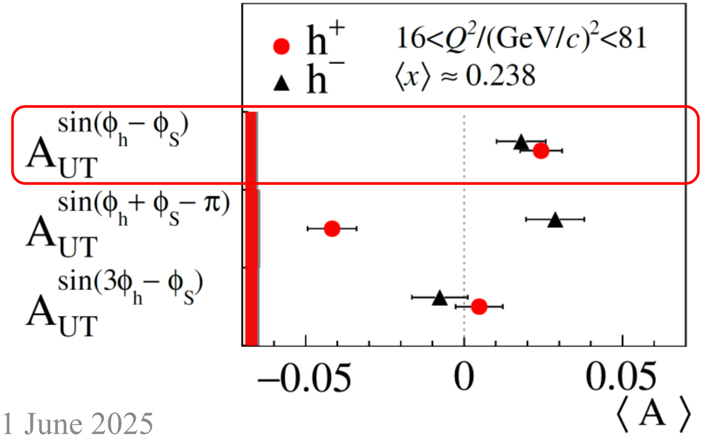
$$\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0}$$

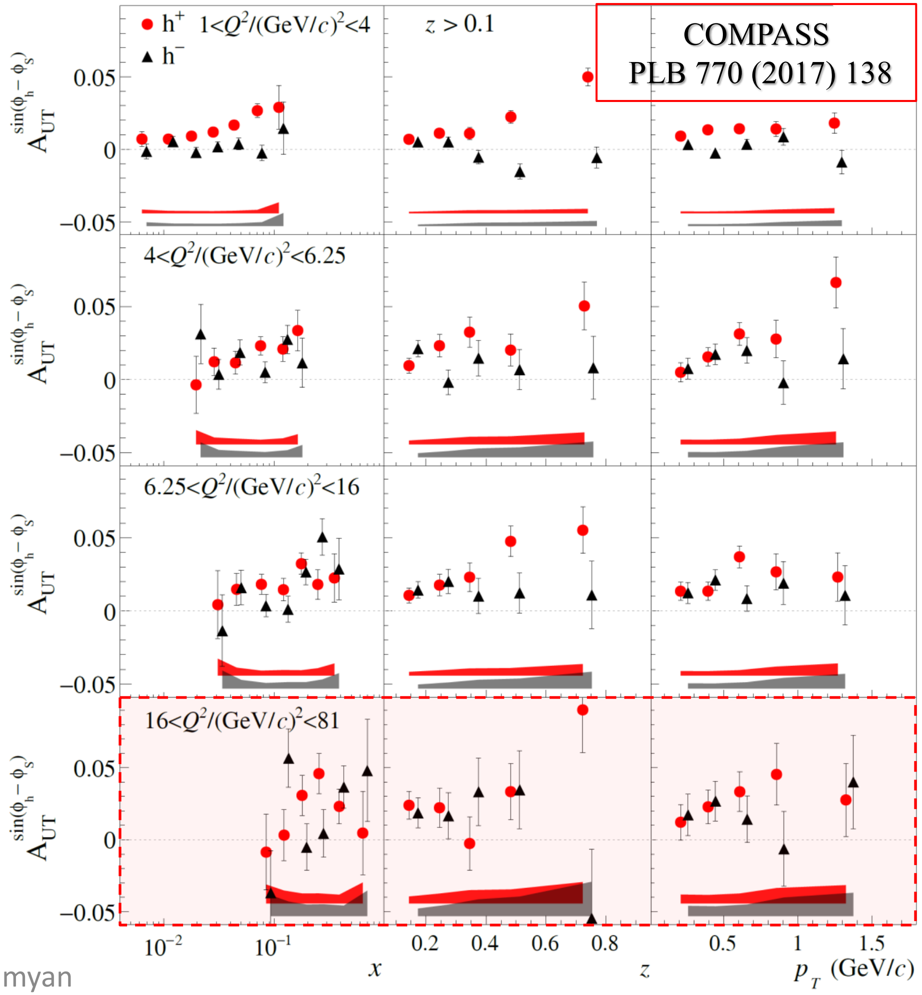


- COMPASS-HERMES discrepancy
- Q^2-evolution effect?

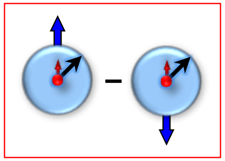
1st COMPASS multi-D fit done for all eight TSAs






COMPASS
PLB 770 (2017) 138

SIDIS TSAs: Collins effect and Transversity



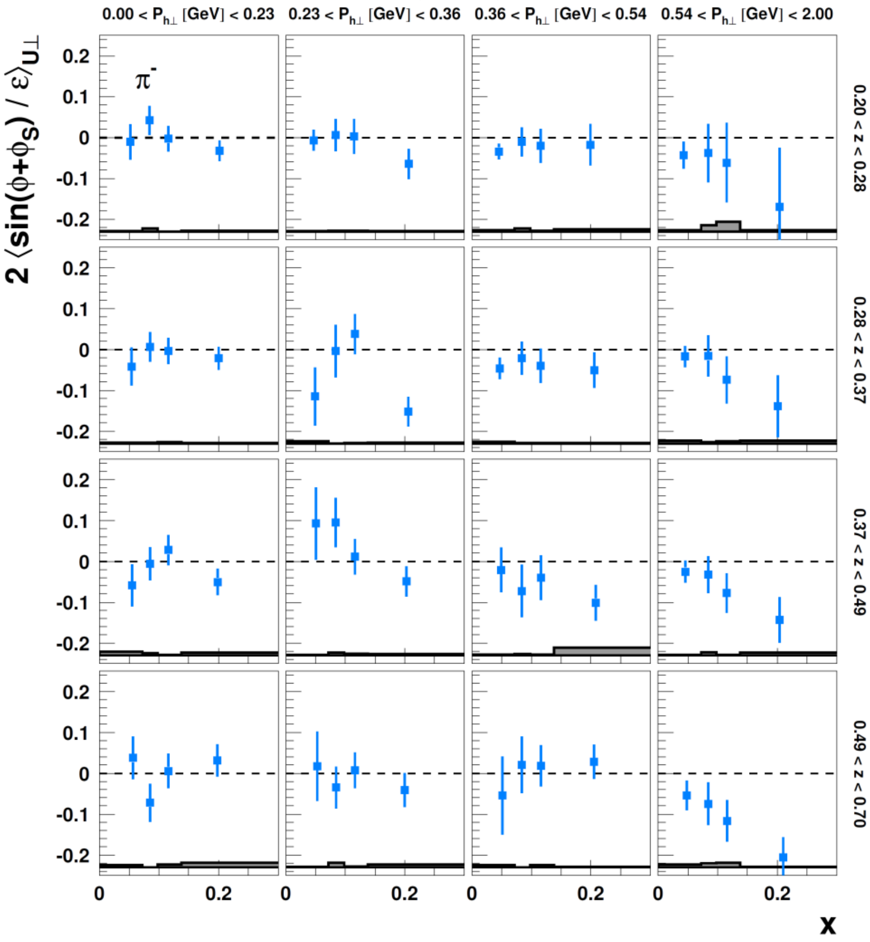
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_{\mathrm{T}}\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

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

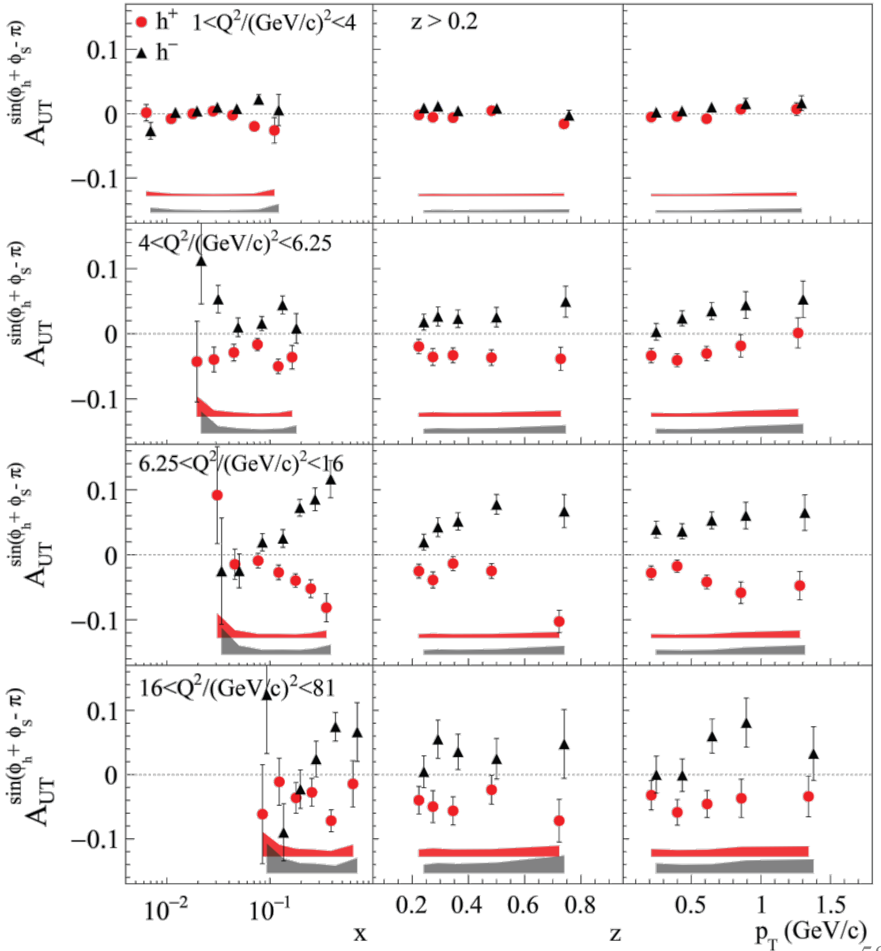
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

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

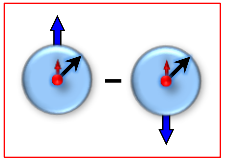
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



SIDIS TSAs: Collins effect and Transversity

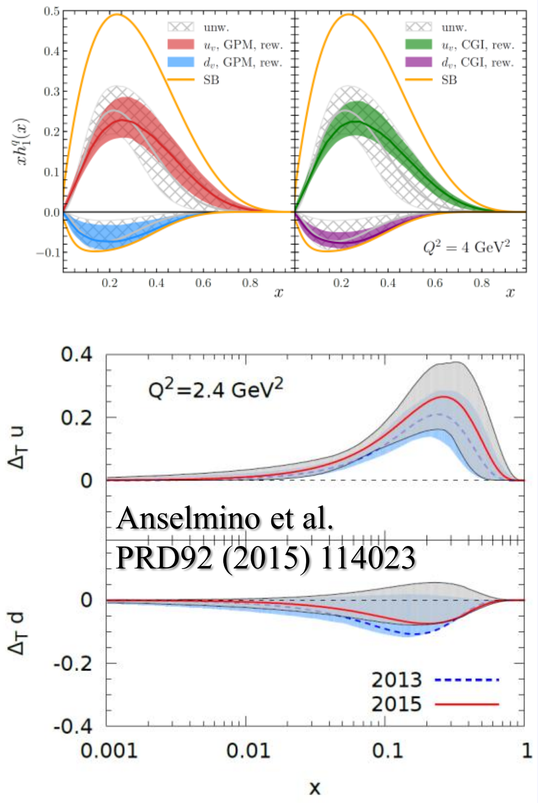


$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_{\mathrm{T}}\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

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

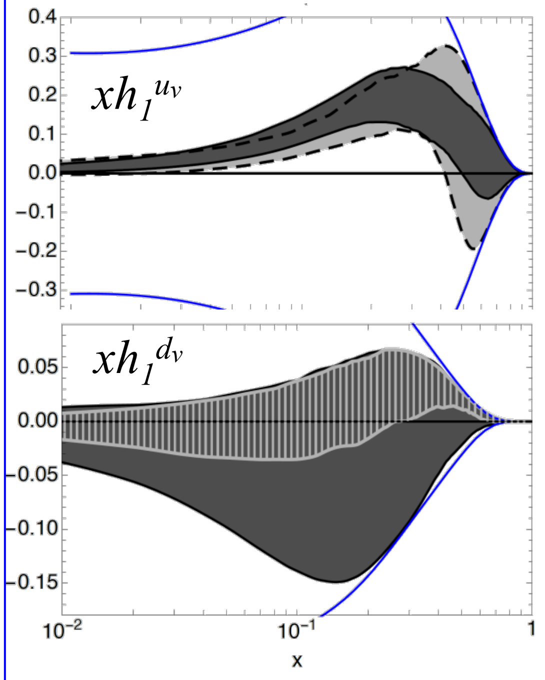
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution? Clear signal at STAR energies
- Extensive phenomenological studies and various global fits by different groups

Boglione et al. PLB 854 (2024) 138712

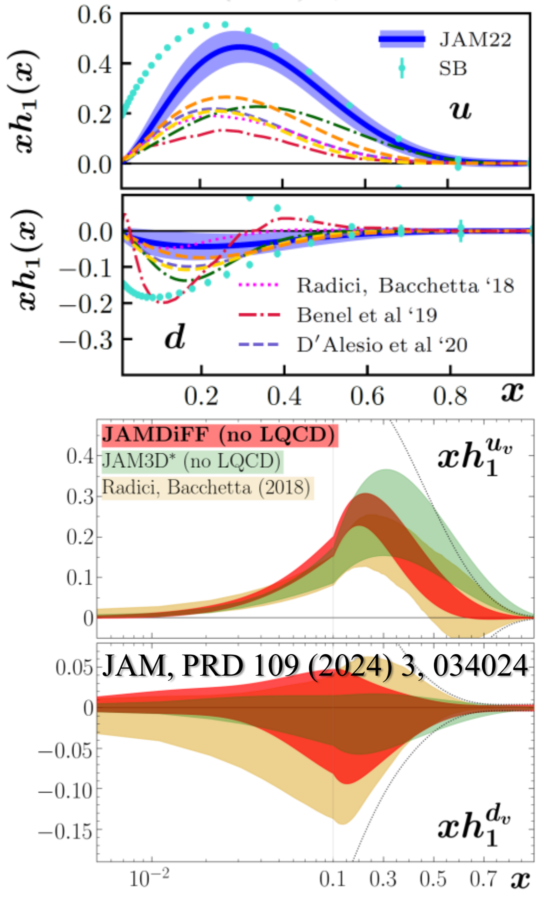


Anselmino et al. PRD92 (2015) 114023

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



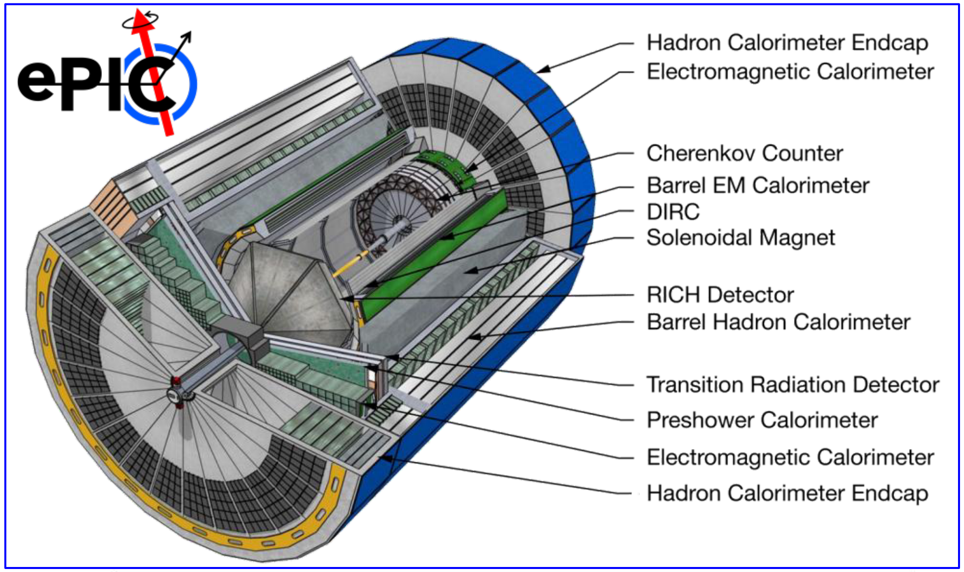
JAM PRD 106 (2022) 3, 034014

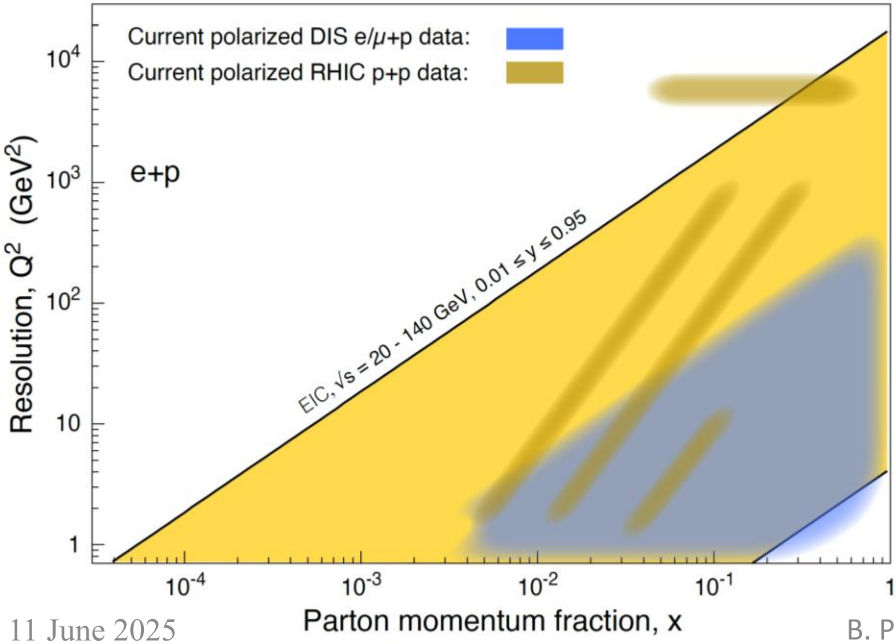


JAM, PRD 109 (2024) 3, 034024

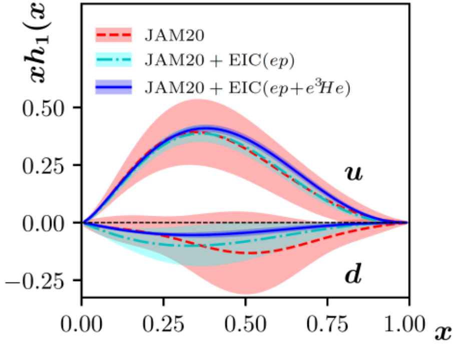
Electron Ion Collider(s): EIC

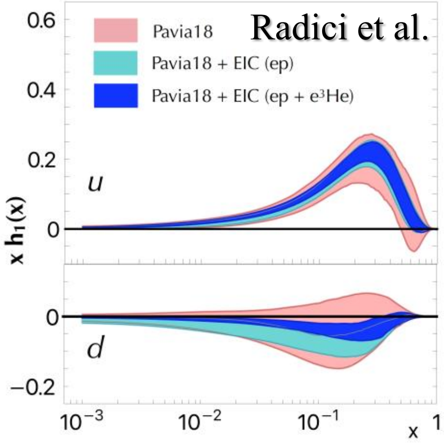
EIC WP, arXiv:1212.1701 [nucl-ex],
EIC YR, arXiv:2103.05419 [physics.ins-det]

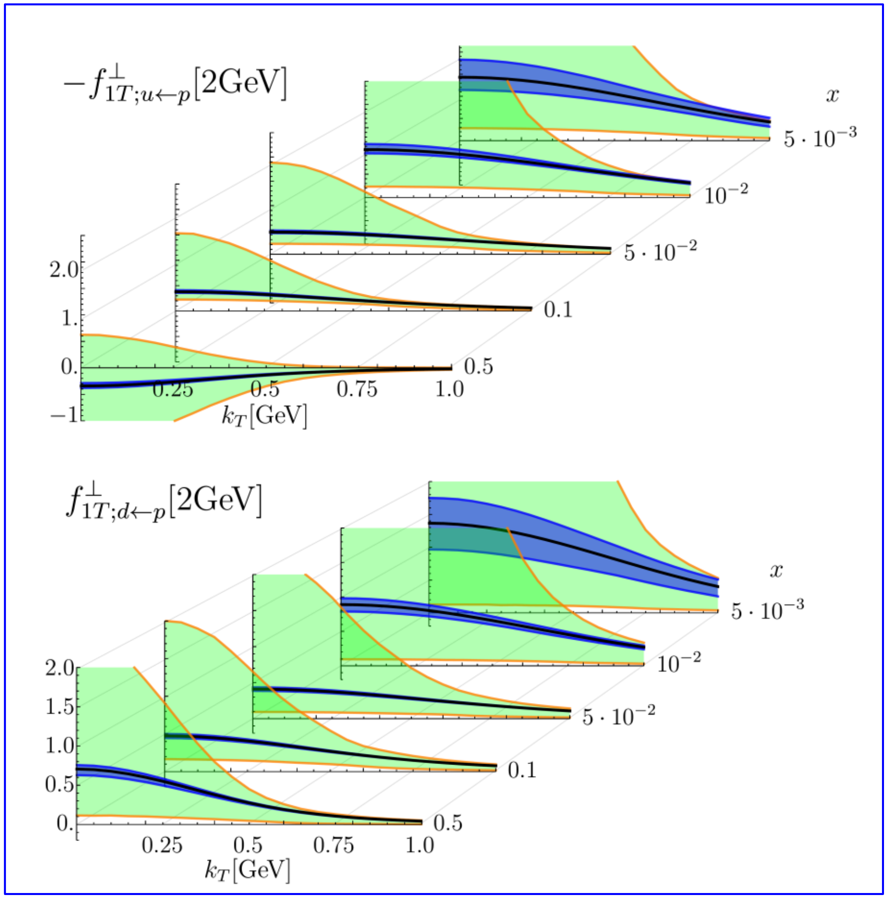




Gamberg et al. (JAM)
PLB 816 (2021) 136255

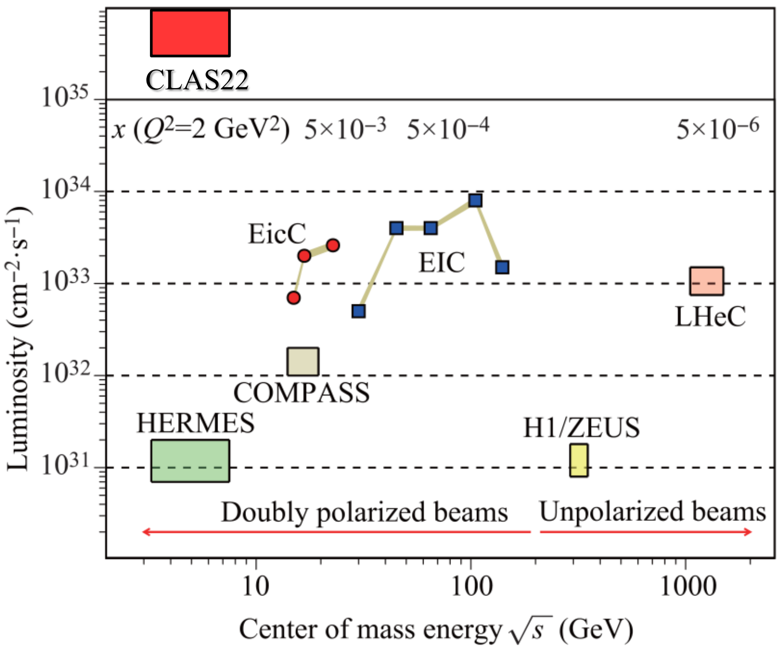


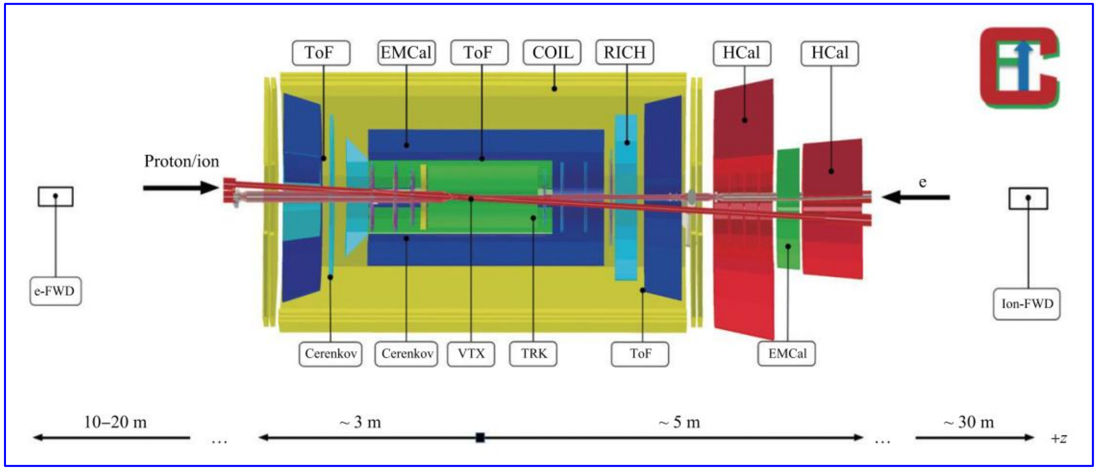


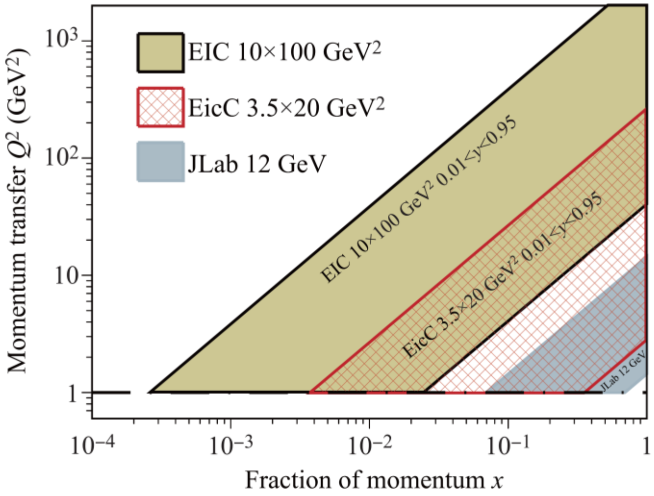


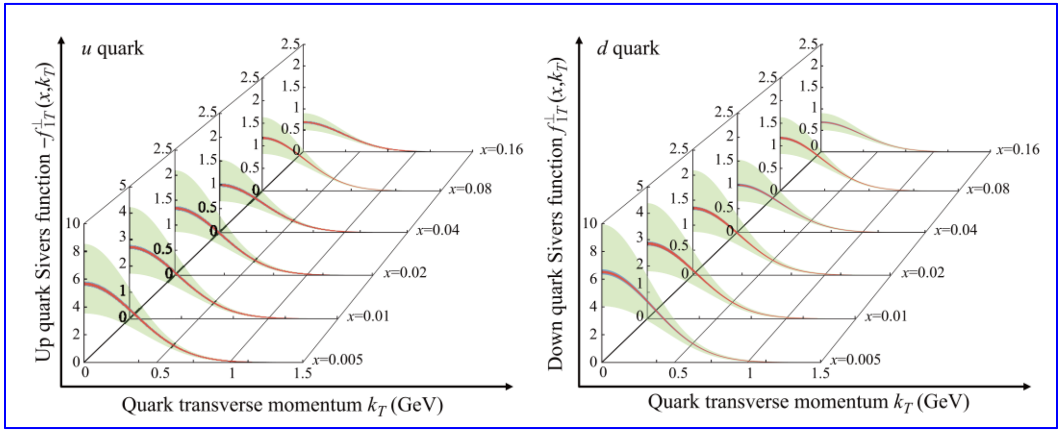
Electron Ion Collider(s): EICc

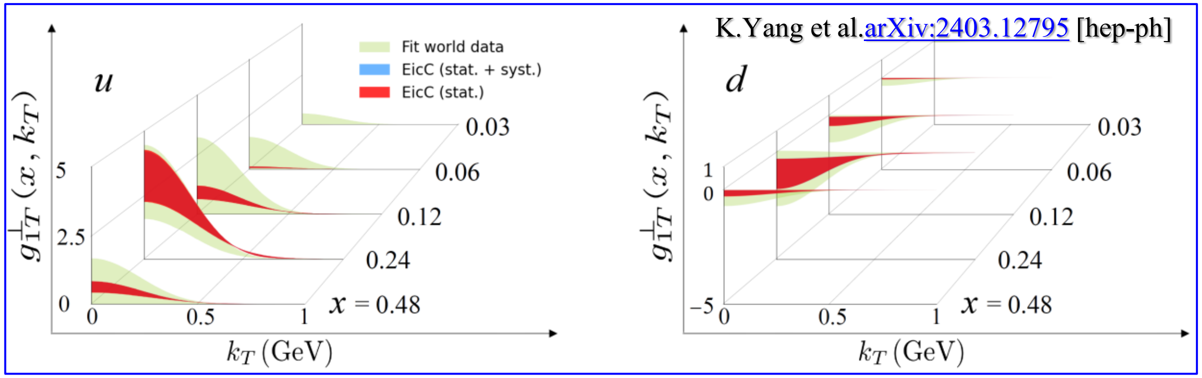
EICc, FP16(6), 64701 (2021), arXiv:2102.09222 [nucl-ex]





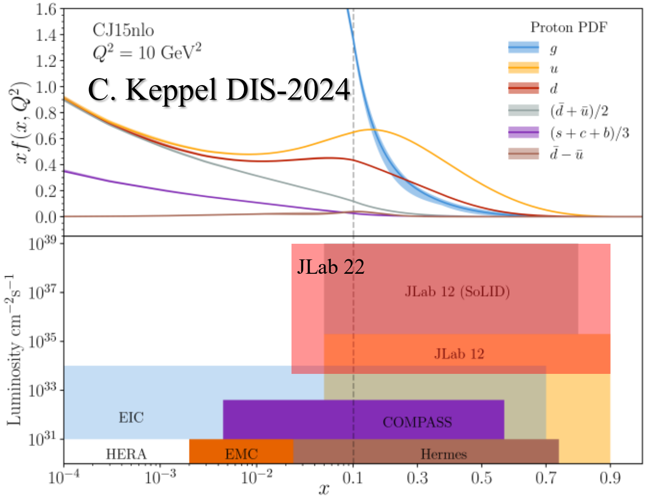




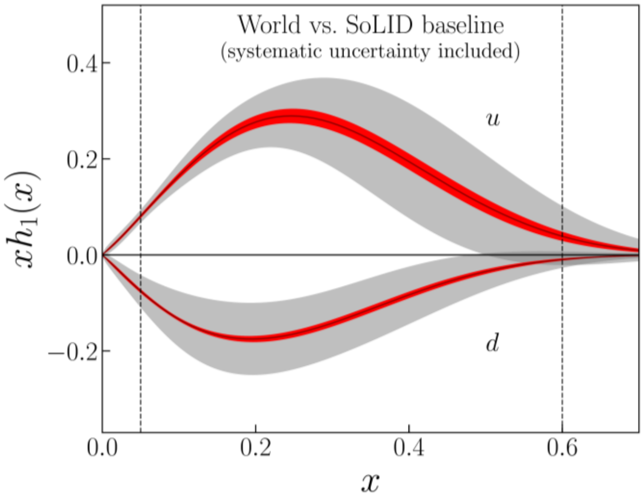


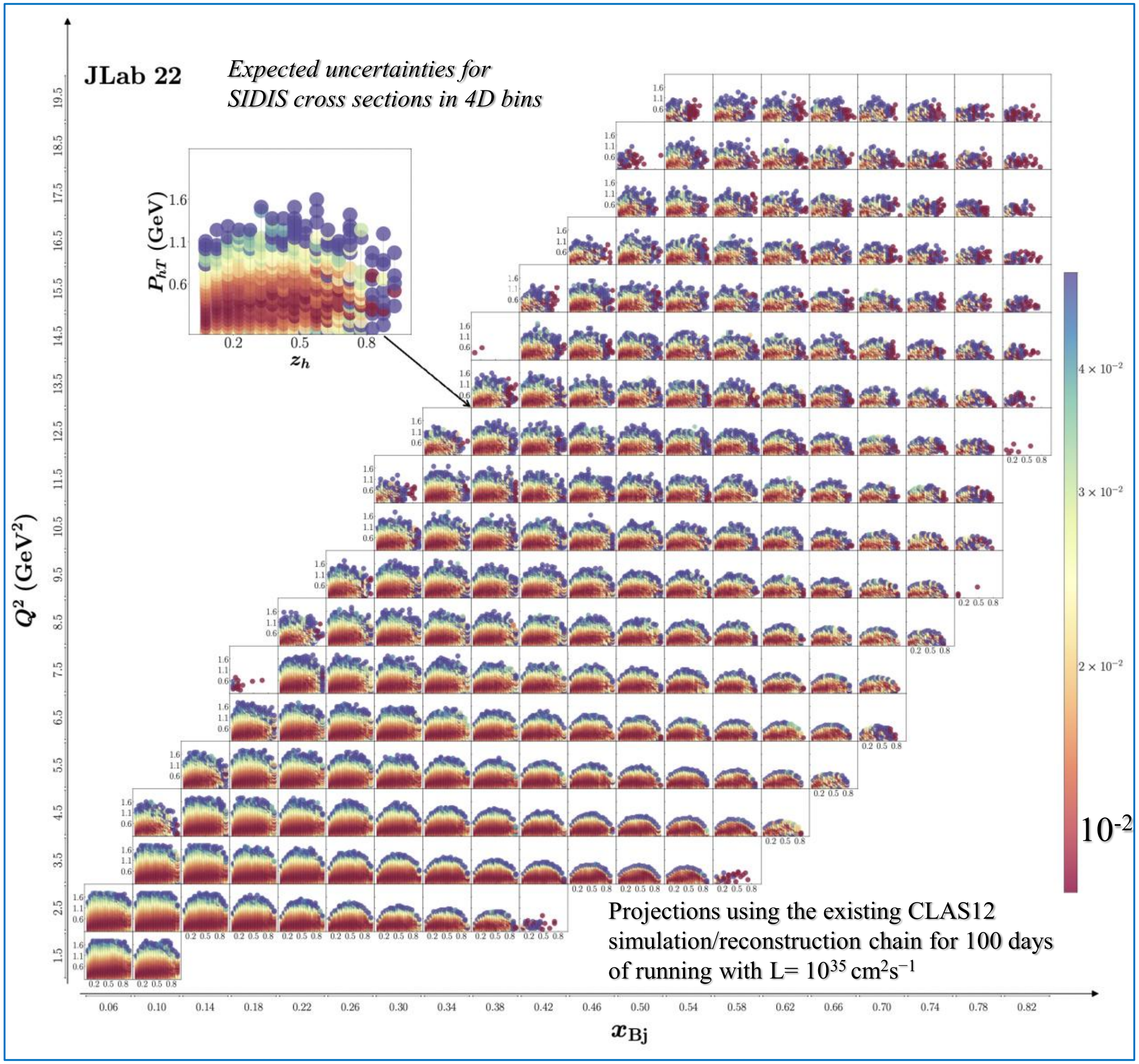
K.Yang et al.arXiv:2403.12795 [hep-ph]

JLab from 12 GeV, SoLID to 22 GeV



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

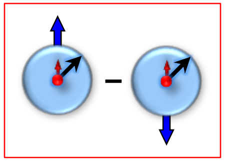




Projections using the existing CLAS12 simulation/reconstruction chain for 100 days of running with L= 10^{35} cm^{2}s^{-1}

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

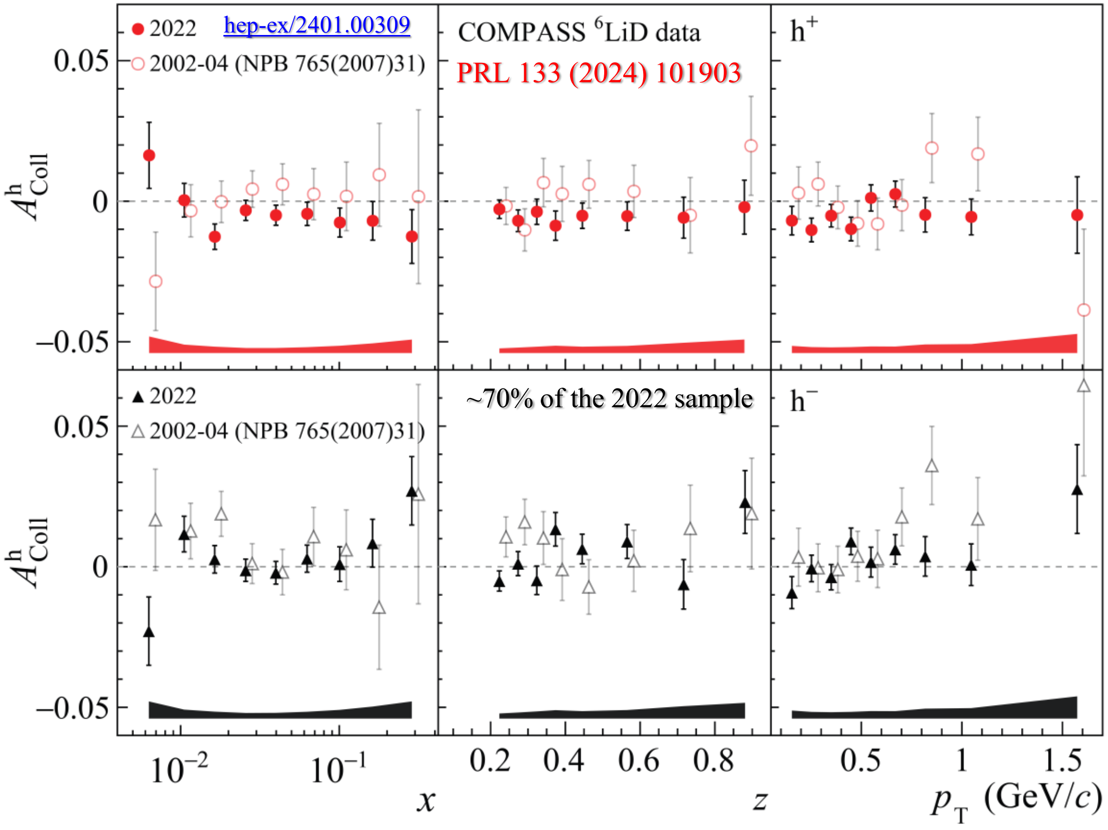
SIDIS TSAs: Collins effect and Transversity

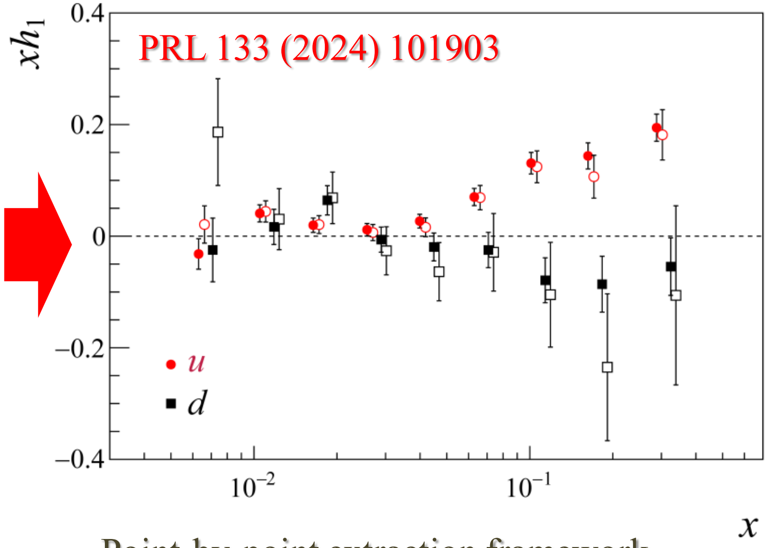


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_{\mathrm{T}}\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right)+\ldots\ \right\}$$

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

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



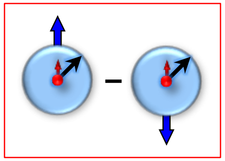


Point-by-point extraction framework
A. Martin et al. PRD **91**, 014034 (2015)
A. Martin et al. PRD **95**, 094024 (2017)

COMPASS 2022 run – highly successful data-taking!

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

SIDIS TSAs: Collins effect for K^0



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

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

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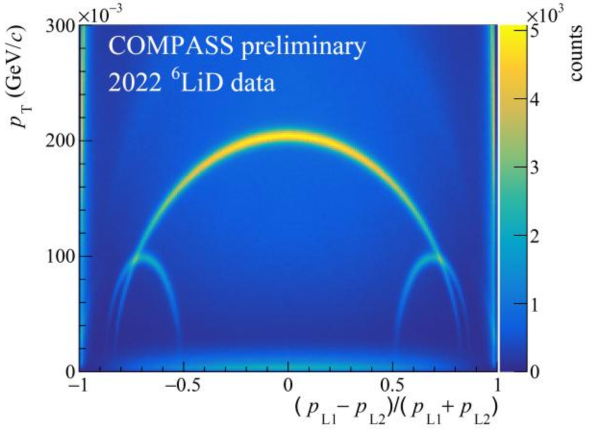
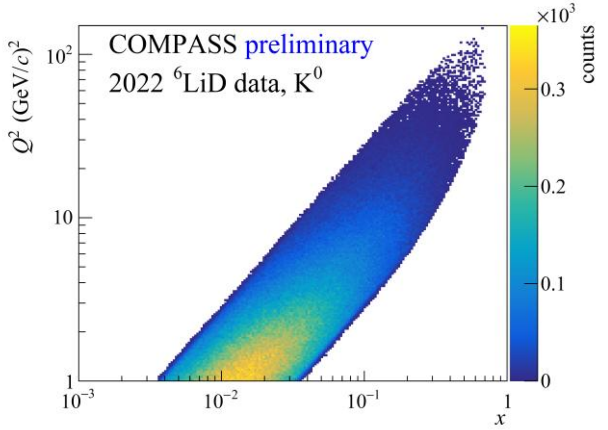
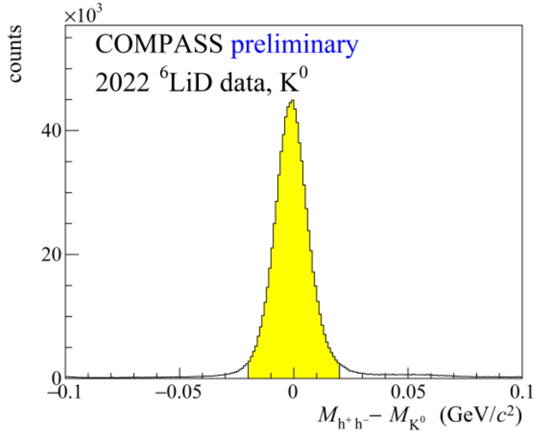
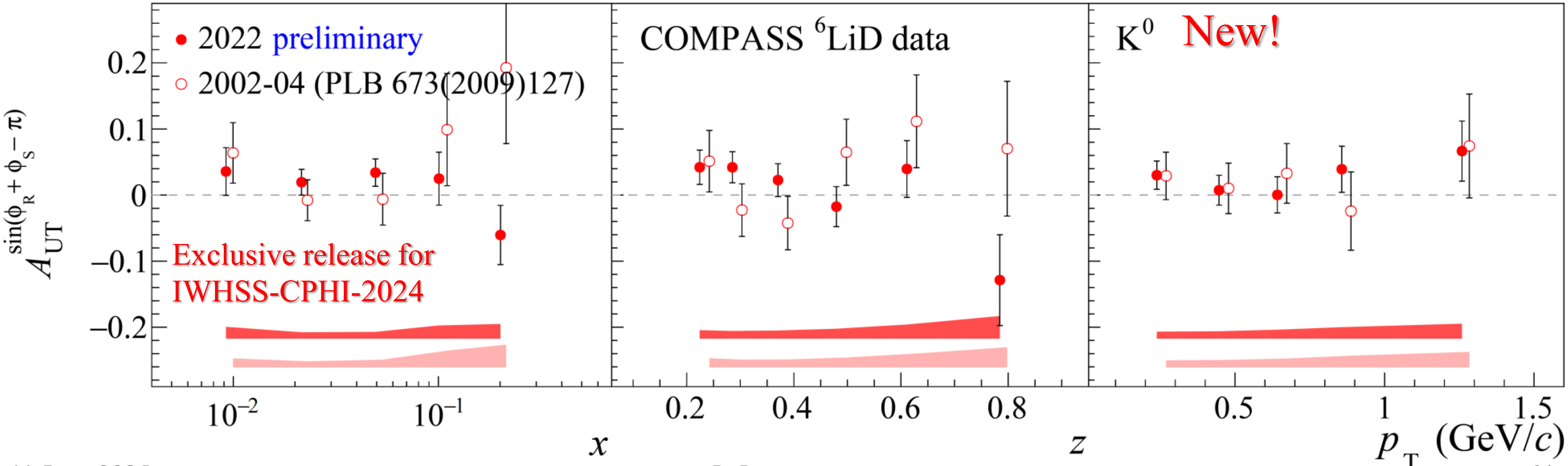




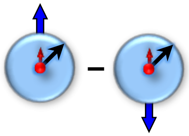




New!

Exclusive release for IWHSS-CPHI-2024

Dihadron Collins effect and Transversity

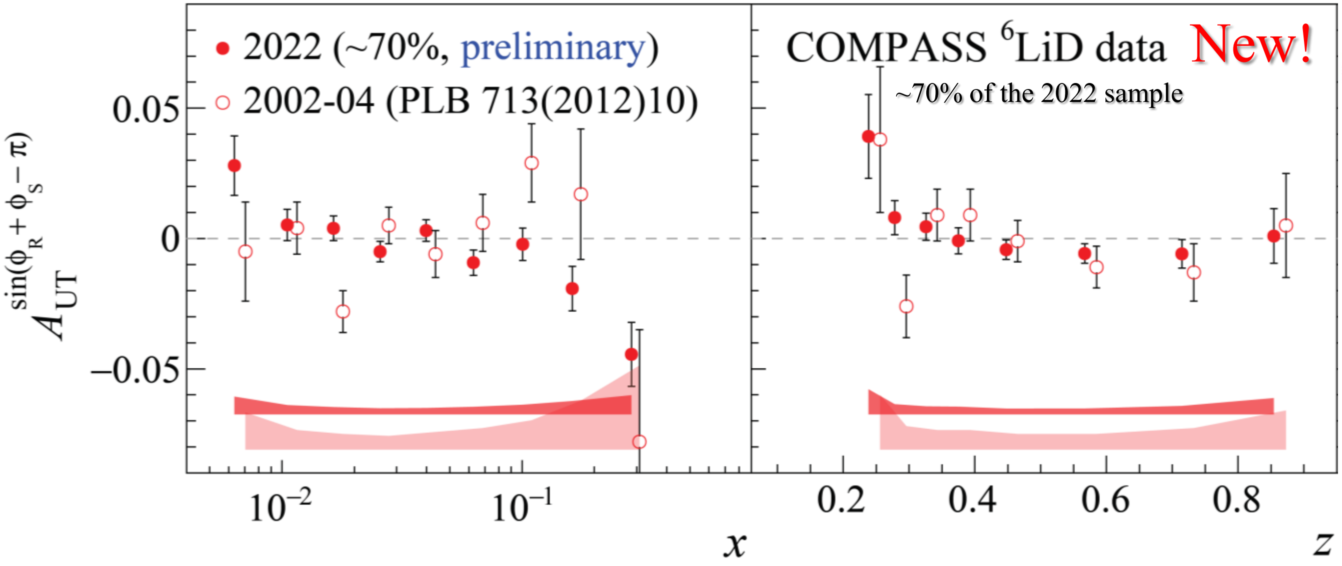


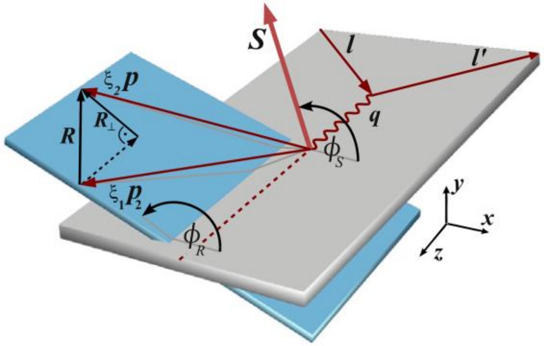
$$\frac{d^7\sigma}{d\cos\theta\, d M_{hh}\, d\phi_R\, d z\, d x\, d y\, d\phi_S} =$$

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

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

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

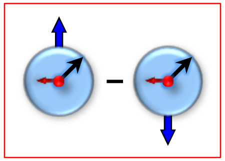




COMPASS 2022 run – highly successful data-taking!

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

SIDIS TSAs: Kotzinian-Mulders asymmetry

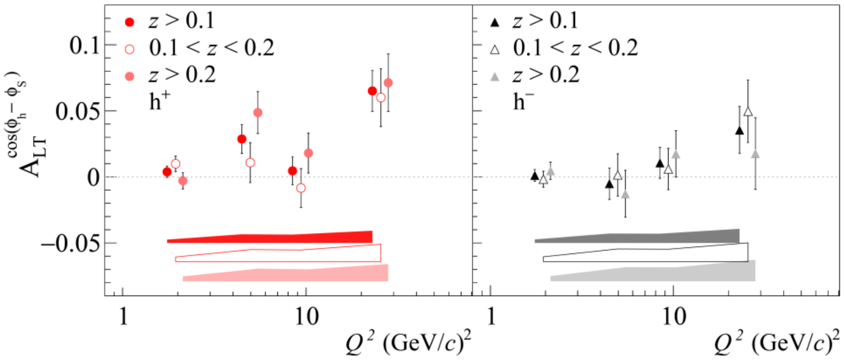


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + \lambda S_T \sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos\left(\phi_h - \phi_S\right) + \ldots\right\}$$

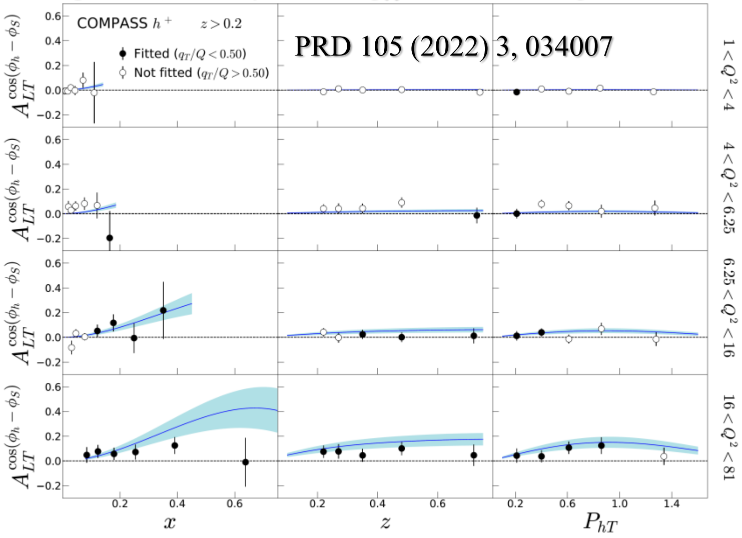
$$\boxed{F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{k_T}}{M} g_{1T}^q D_{1q}^h\right]}$$

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

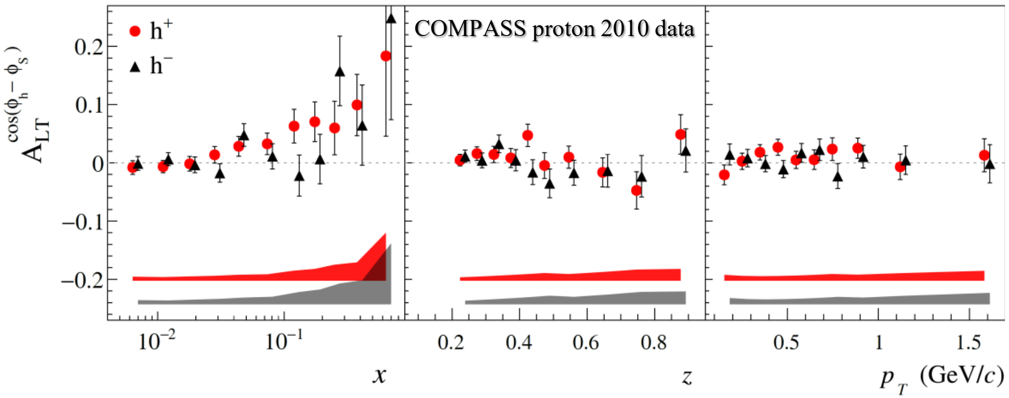


First global QCD analysis of the g_{1T} TMD PDF using SIDIS data

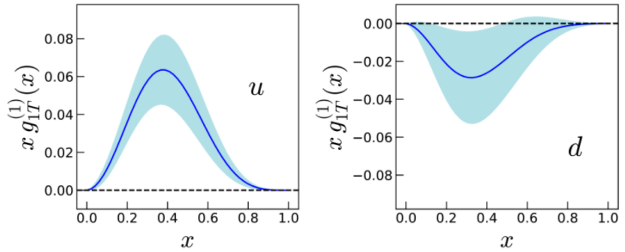


PRD 105 (2022) 3, 034007

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



COMPASS 2022 run: new unique deuteron data

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

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

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

Proton [NH₃]
COMPASS 2017
111 data points
*Adolph et al., P.L. **B770** (17) 138*

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

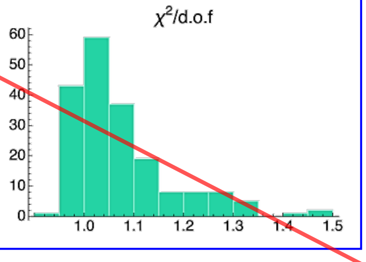
analysis of statistical error with replica method (200)
68% confidence level

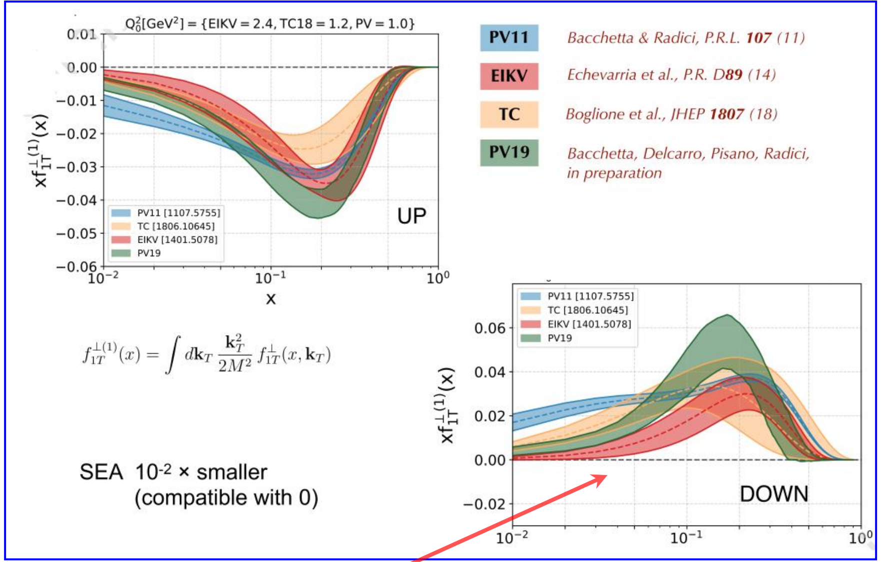
Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

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

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





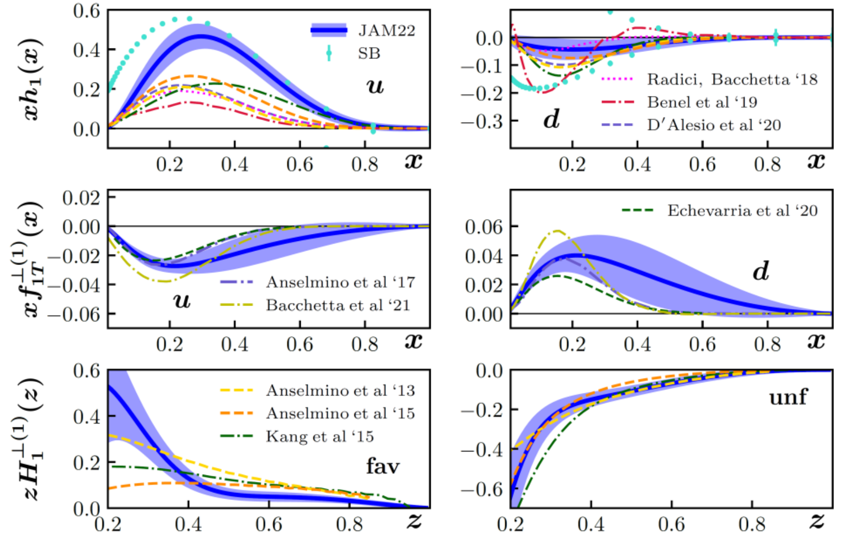
*Bacchetta & Radici, P.R.L. **107** (11)*
*Echevarria et al., P.R. D**89** (14)*
*Boglione et al., JHEP **1807** (18)*
Bacchetta, Delcarro, Pisano, Radici, in preparation

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

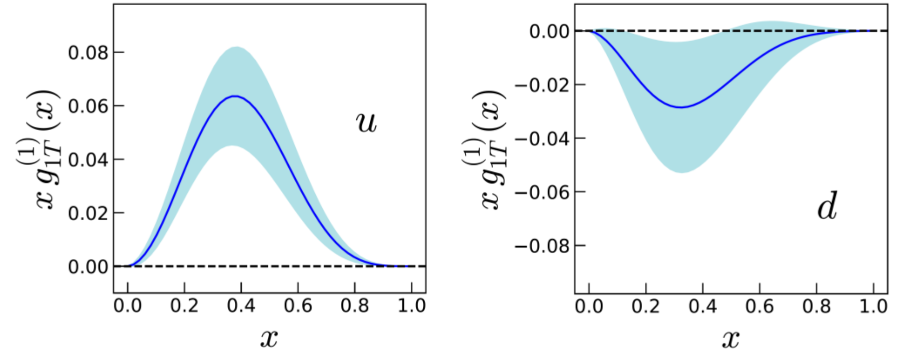
SEA 10^{-2} × smaller
(compatible with 0)

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…

- What about polarized Drell-Yan at AMBER?

N.B. These are informal, personal ideas not yet reviewed by the collaboration

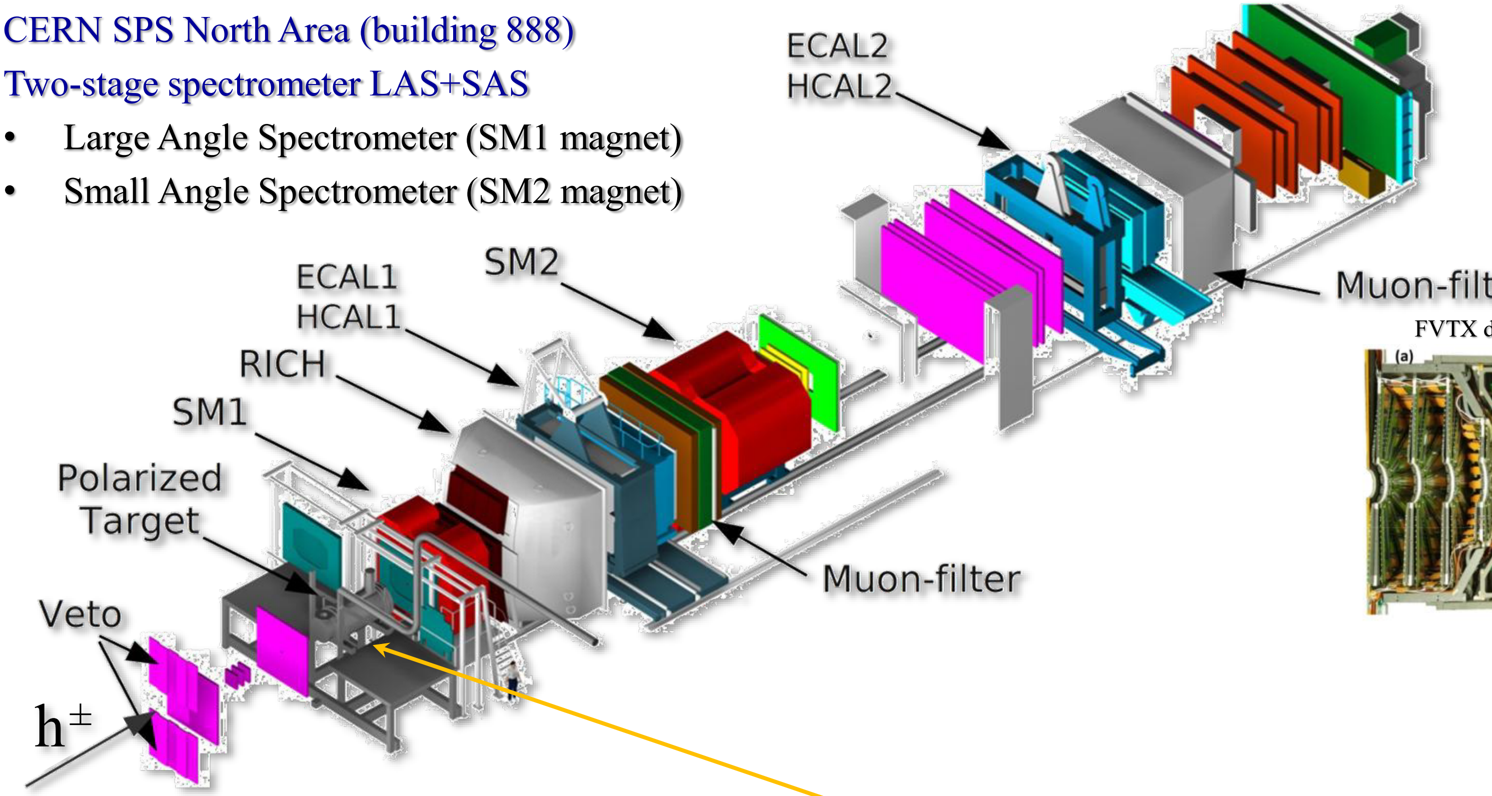
AMBER Phase I-II: DY program setup

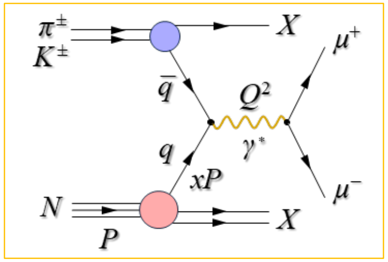
Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

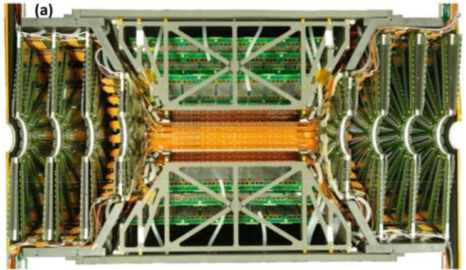
Two-stage spectrometer LAS+SAS

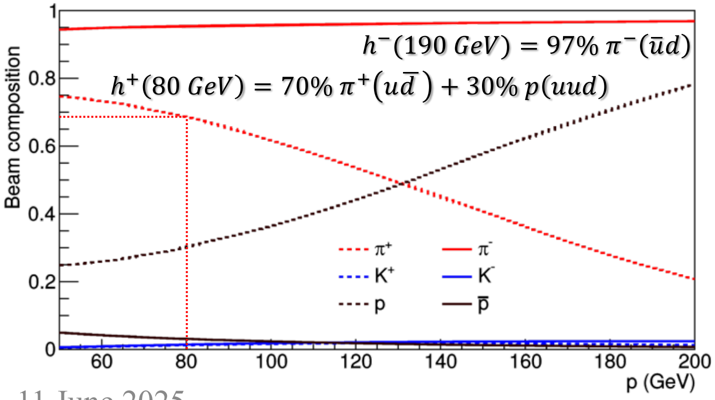
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)

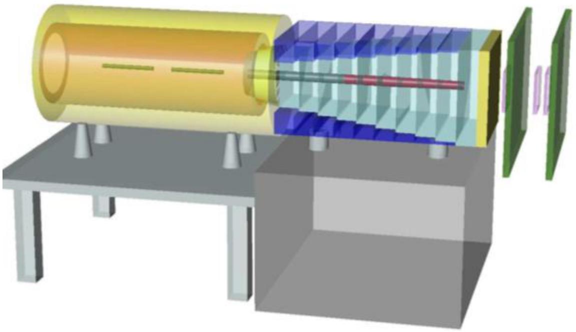




FVTX detector from PHENIX@RHIC

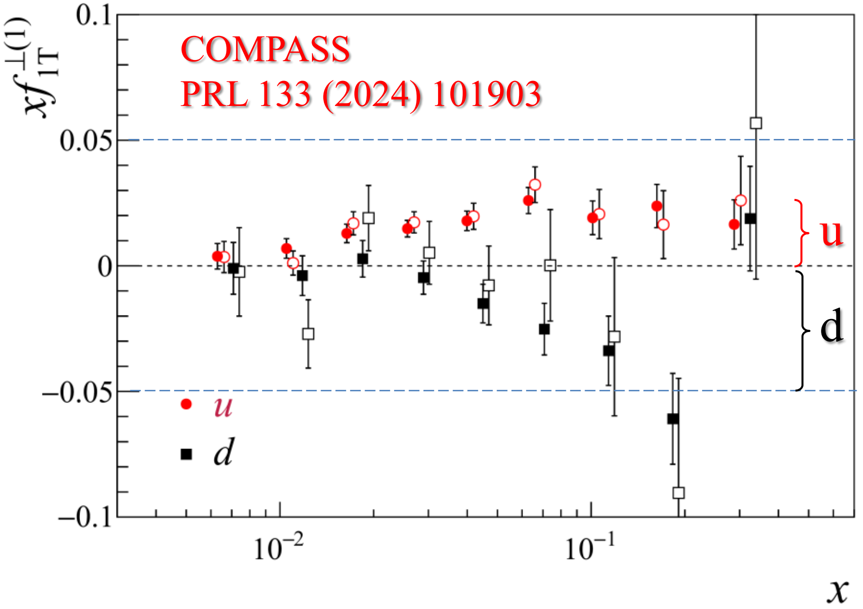




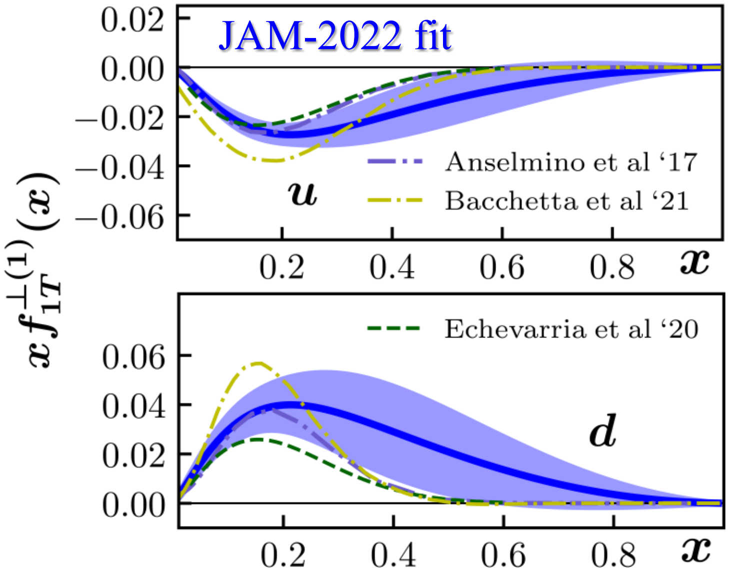


COMPASS 2022 –SIDIS and 2015/18 Drell-Yan data

Sivers asymmetry



PRD.106.034014



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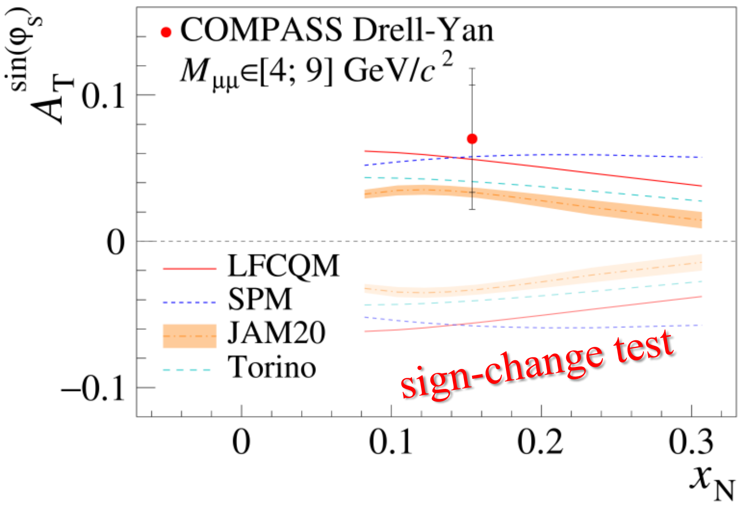
COMPASS: PRL 133 (2024) 071902



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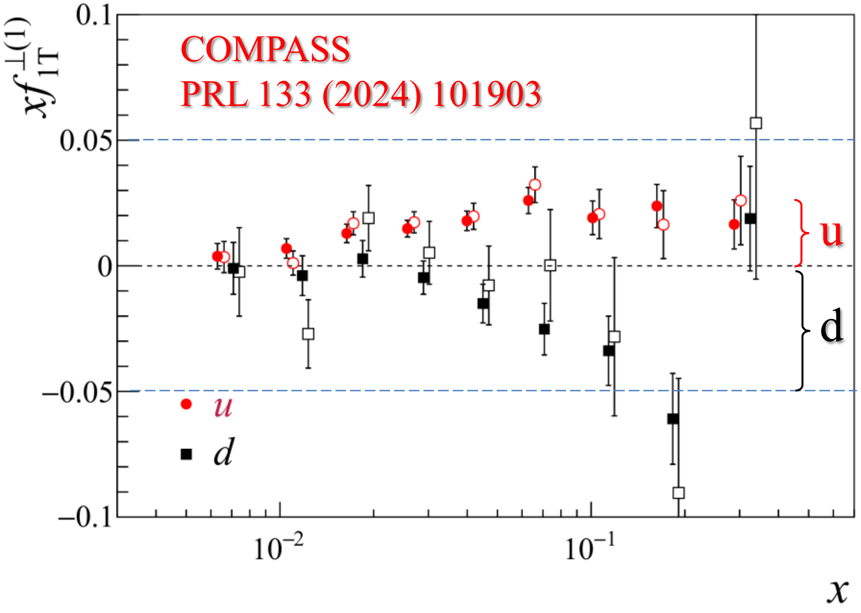
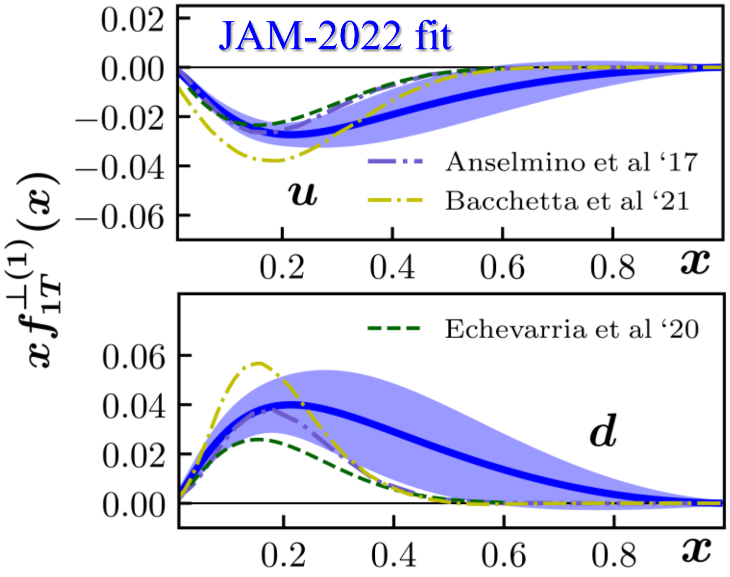

COMPASS
PRL 133 (2024) 101903

PRD.106.034014



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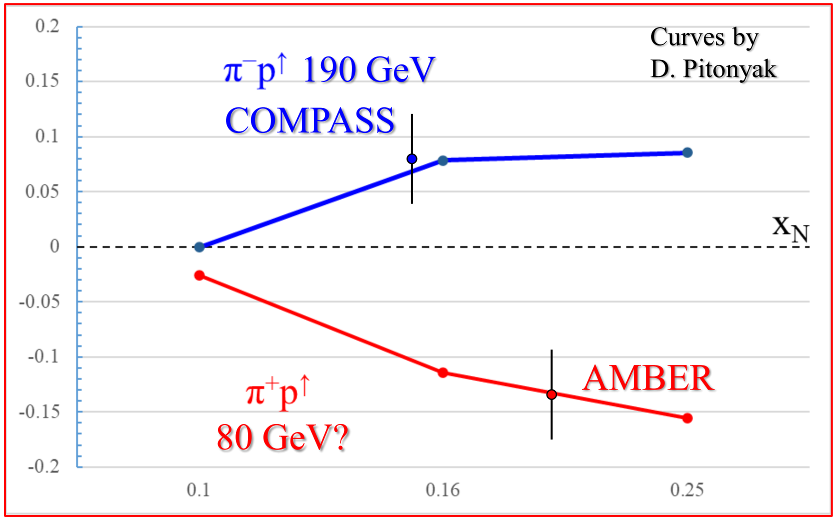
Curves by
D. Pitonyak

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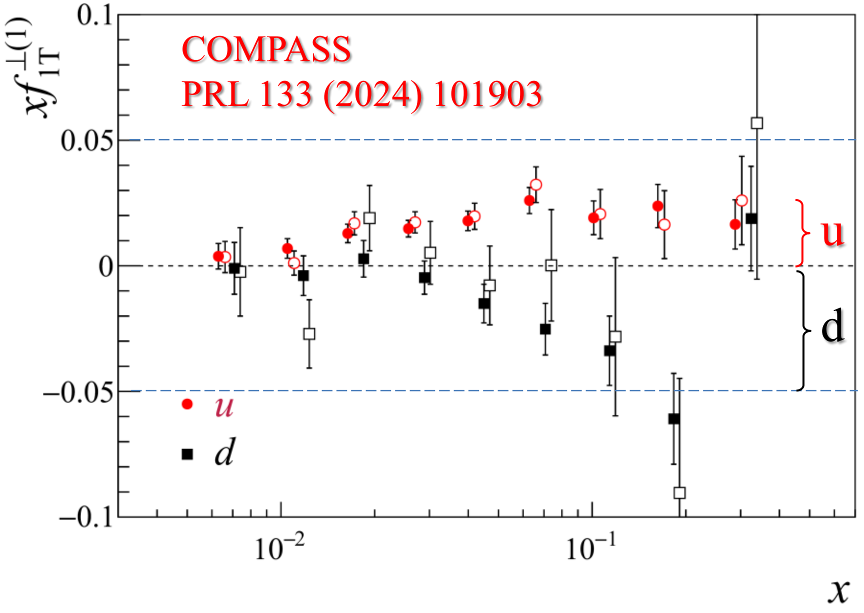
Sivers asymmetry



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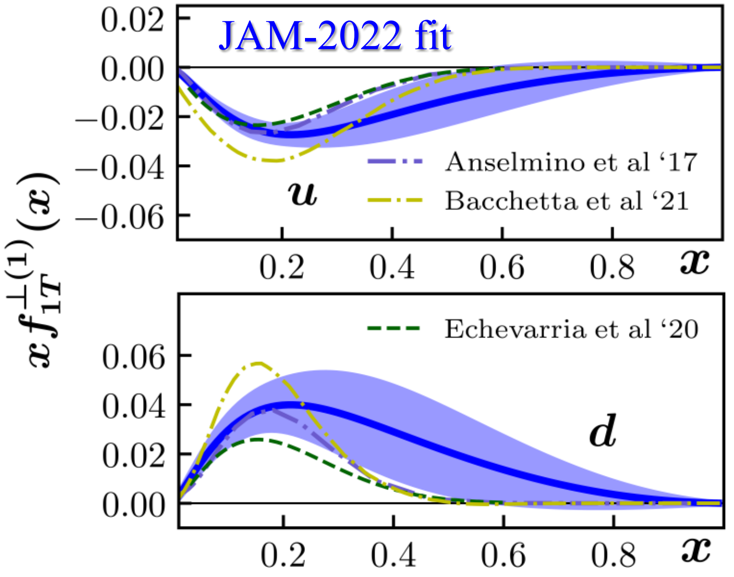

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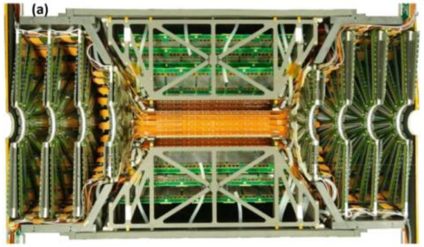

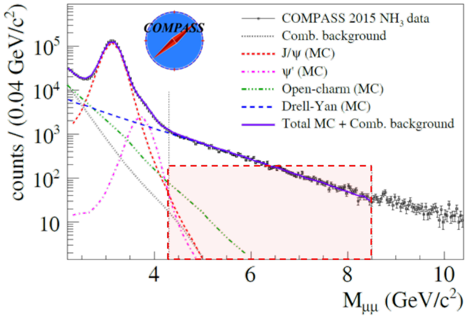

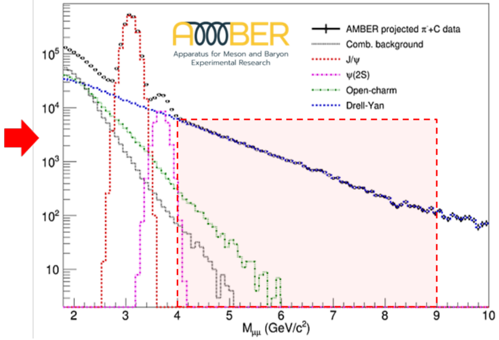

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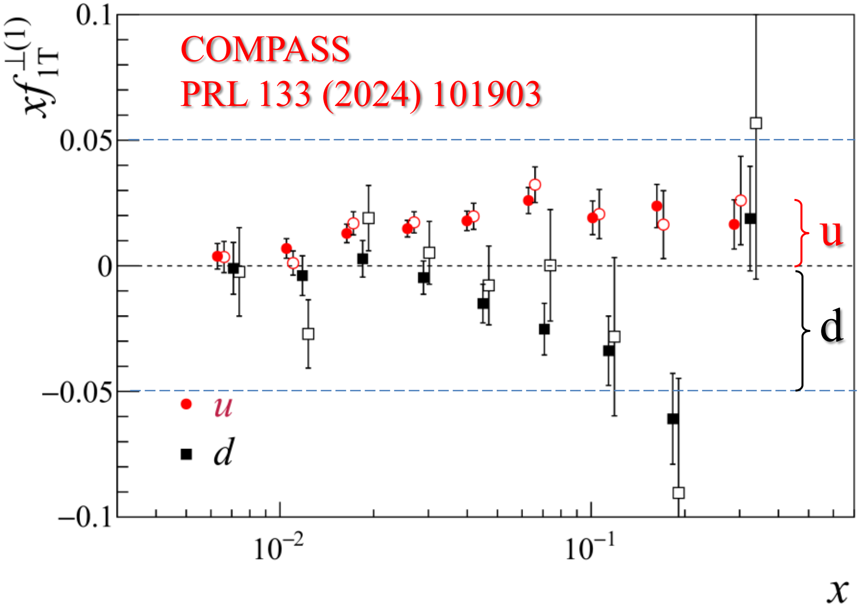

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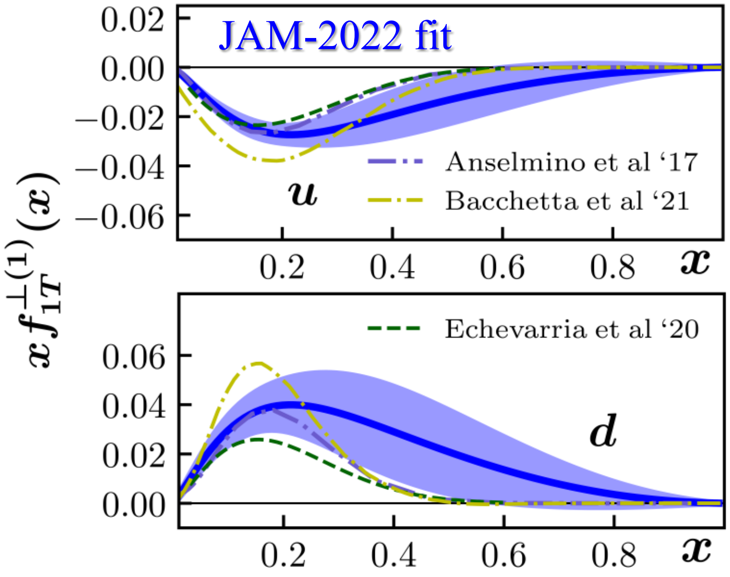

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Caveats:

- Proton contamination (~30%) → CEDARs
- Target readiness → interested groups
- Magnet readiness → CERN
- Shielding → larger bunker
- Setup revision needed
- Running time → after AMBER phase-1 DY

Generally positive feedback from the community
Will increase interest to AMBER
Potential for new groups otherwise not interested

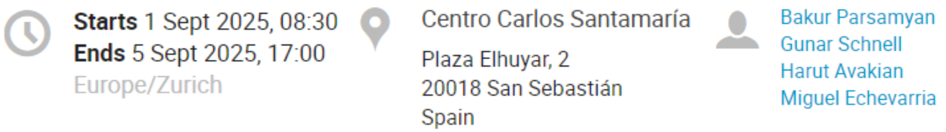
Conclusions

- COMPASS - longest-running CERN experiment (20 years of data-taking)
- 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
  - Highly successful SIDIS deuteron in 2022 run, promising preliminary results
- Since 2023 the experiment entered the Analysis Phase (4 new groups joined the Analysis Phase)
  - The spectrometer has been transferred to the AMBER collaboration
- AMBER took its first data in 2023-2024 (Antiproton production) and is preparing for the PRM run
- AMBER phase one comprises unique Drell-Yan measurements (after LS3)
- Long AMBER program is being developed: Phase-II proposal is being drafted
- LHCspin is a project for an FT experiment at LHCb operating with a polarized gas target
  - Successful data collection and proof of principle using SMOG2 unpolarized target
  - Important knowledge and wealth of data collected
  - R&D project in scope of small experiment in IR4 is planned to prepare the polarized target
  - LHCspin at LHCb to be operational during run 5.
- Altogether these FTs at CERN provide unique set of unprecedented measurements complementary to EIC, JLab22, NICA-SPD, etc.

Thank You!

IWHSS-QCD-N' 2025


Joint International Workshop on Hadron Structure and Spectroscopy (IWHSS 2025) and the QCD Structure of the Nucleon (QCD-N'25)

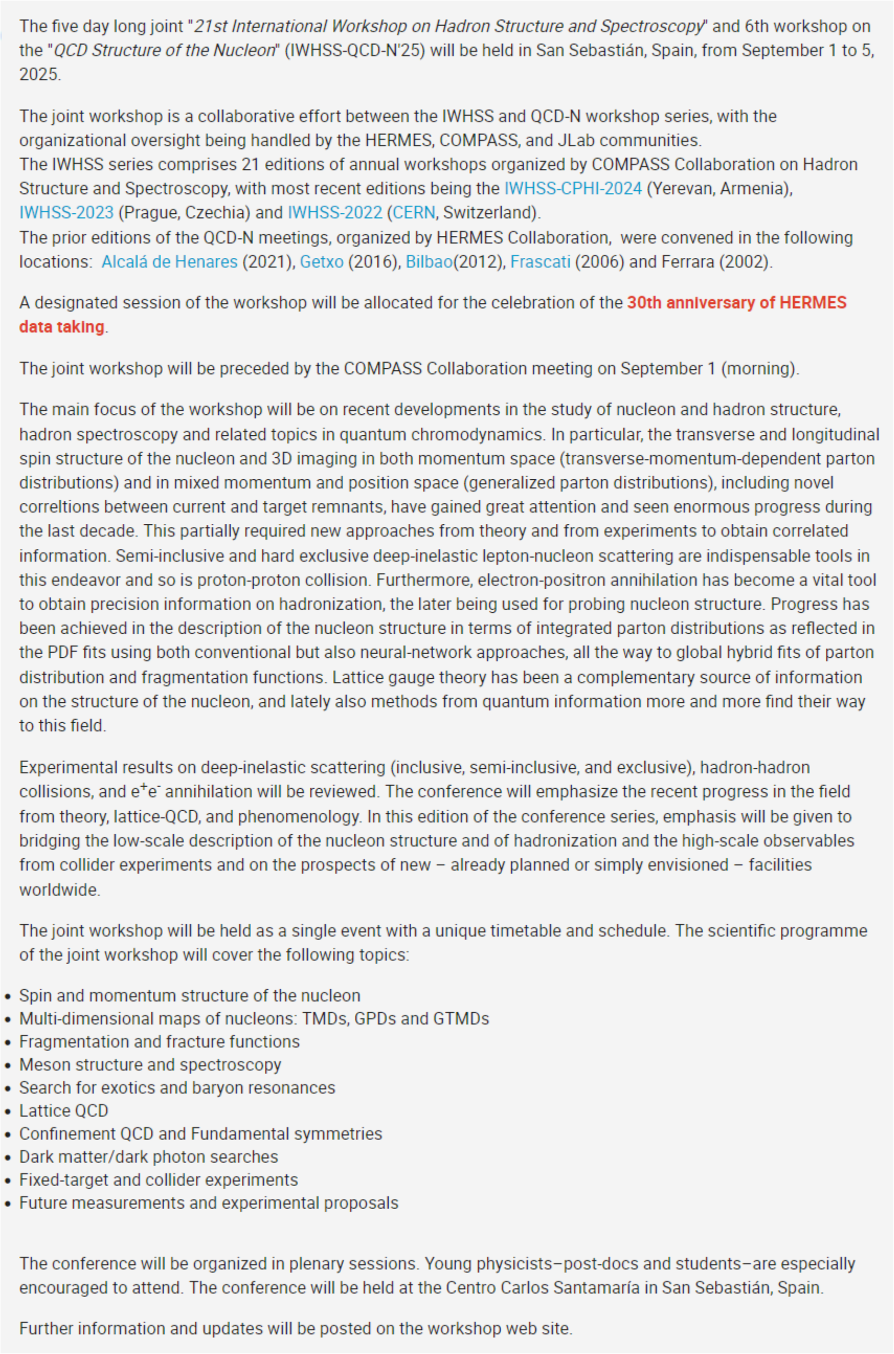

Starts 1 Sept 2025, 08:30
Ends 5 Sept 2025, 17:00
Europe/Zurich

Centro Carlos Santamaría
Plaza Elhuyar, 2
20018 San Sebastián
Spain

Bakur Parsamyan
Gunar Schnell
Harut Avakian
Miguel Echevarria

Joint HERMES-COMPASS-Jlab workshop
Indico: https://indico.cern.ch/e/IWHSS-QCDN-2025

Please pre-register and
Reserve your accommodation!


The five day long joint "*21st International Workshop on Hadron Structure and Spectroscopy*" and 6th workshop on the "*QCD Structure of the Nucleon*" (IWHSS-QCD-N'25) will be held in San Sebastián, Spain, from September 1 to 5, 2025.

The joint workshop is a collaborative effort between the IWHSS and QCD-N workshop series, with the organizational oversight being handled by the HERMES, COMPASS, and JLab communities.
The IWHSS series comprises 21 editions of annual workshops organized by COMPASS Collaboration on Hadron Structure and Spectroscopy, with most recent editions being the IWHSS-CPHI-2024 (Yerevan, Armenia), IWHSS-2023 (Prague, Czechia) and IWHSS-2022 (CERN, Switzerland).
The prior editions of the QCD-N meetings, organized by HERMES Collaboration, were convened in the following locations: Alcalá de Henares (2021), Getxo (2016), Bilbao(2012), Frascati (2006) and Ferrara (2002).

A designated session of the workshop will be allocated for the celebration of the **30th anniversary of HERMES data taking**.

The joint workshop will be preceded by the COMPASS Collaboration meeting on September 1 (morning).

The main focus of the workshop will be on recent developments in the study of nucleon and hadron structure, hadron spectroscopy and related topics in quantum chromodynamics. In particular, the transverse and longitudinal spin structure of the nucleon and 3D imaging in both momentum space (transverse-momentum-dependent parton distributions) and in mixed momentum and position space (generalized parton distributions), including novel correltions between current and target remnants, have gained great attention and seen enormous progress during the last decade. This partially required new approaches from theory and from experiments to obtain correlated information. Semi-inclusive and hard exclusive deep-inelastic lepton-nucleon scattering are indispensable tools in this endeavor and so is proton-proton collision. Furthermore, electron-positron annihilation has become a vital tool to obtain precision information on hadronization, the later being used for probing nucleon structure. Progress has been achieved in the description of the nucleon structure in terms of integrated parton distributions as reflected in the PDF fits using both conventional but also neural-network approaches, all the way to global hybrid fits of parton distribution and fragmentation functions. Lattice gauge theory has been a complementary source of information on the structure of the nucleon, and lately also methods from quantum information more and more find their way to this field.

Experimental results on deep-inelastic scattering (inclusive, semi-inclusive, and exclusive), hadron-hadron collisions, and e^+e^- annihilation will be reviewed. The conference will emphasize the recent progress in the field from theory, lattice-QCD, and phenomenology. In this edition of the conference series, emphasis will be given to bridging the low-scale description of the nucleon structure and of hadronization and the high-scale observables from collider experiments and on the prospects of new – already planned or simply envisioned – facilities worldwide.

The joint workshop will be held as a single event with a unique timetable and schedule. The scientific programme of the joint workshop will cover the following topics:

- Spin and momentum structure of the nucleon
- Multi-dimensional maps of nucleons: TMDs, GPDs and GTMDs
- Fragmentation and fracture functions
- Meson structure and spectroscopy
- Search for exotics and baryon resonances
- Lattice QCD
- Confinement QCD and Fundamental symmetries
- Dark matter/dark photon searches
- Fixed-target and collider experiments
- Future measurements and experimental proposals

The conference will be organized in plenary sessions. Young physicists–post-docs and students–are especially encouraged to attend. The conference will be held at the Centro Carlos Santamaría in San Sebastián, Spain.

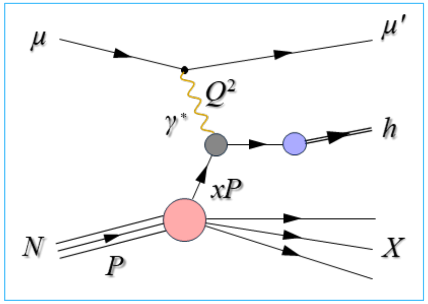
Further information and updates will be posted on the workshop web site.

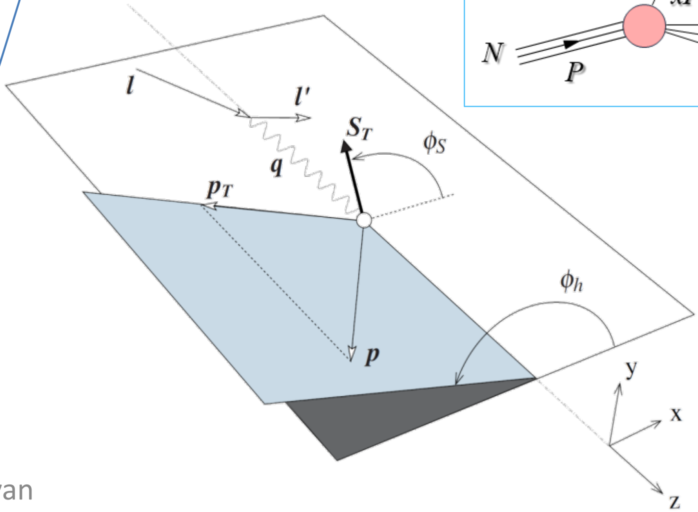
SIDIS x-section and TMDs at twist-2

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

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

		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





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

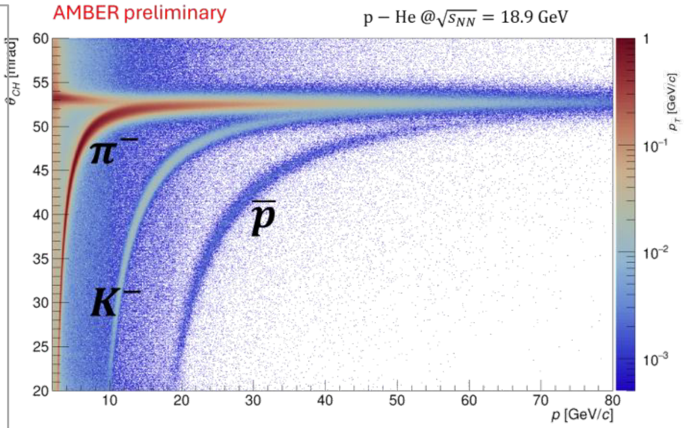
AMBER
Apparatus for Meson and Baryon
Experimental Research

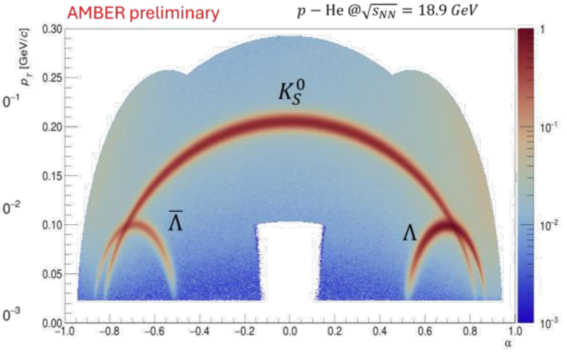
$\overline{p}$ production measurement

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

Understanding the $\overline{p}$ flux:

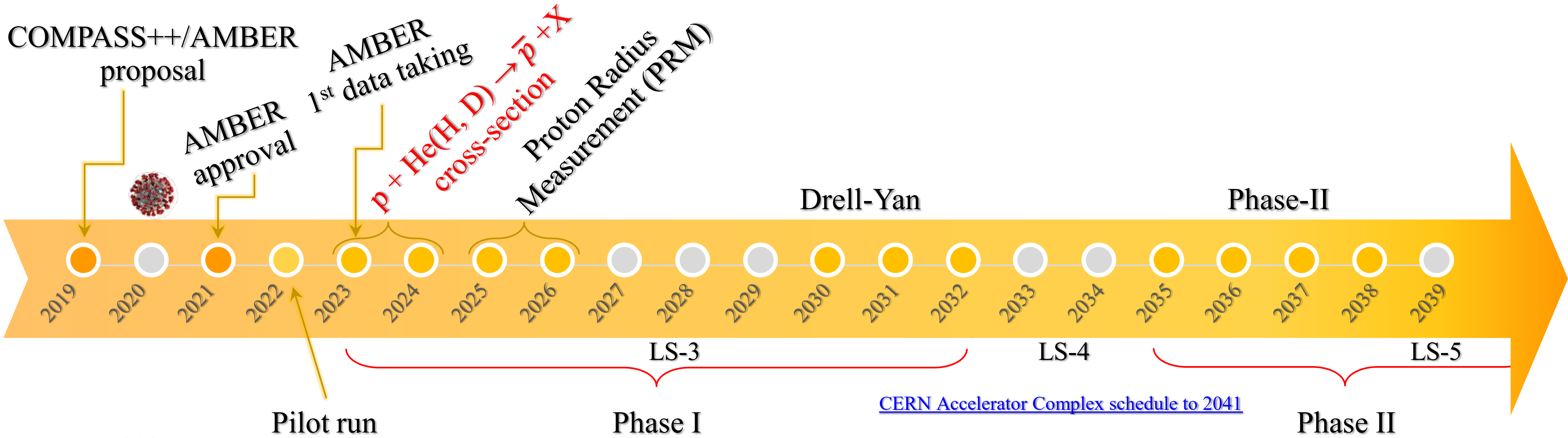
- Accurate determination of the CR-component
- Accuracy of the $\overline{p}$-production models is at ~20% level





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

Pilot run

LS-3

LS-4

LS-5

Phase I

Phase II

CERN Accelerator Complex schedule to 2041

AMBER measurements 2023-2024: proton charge radius

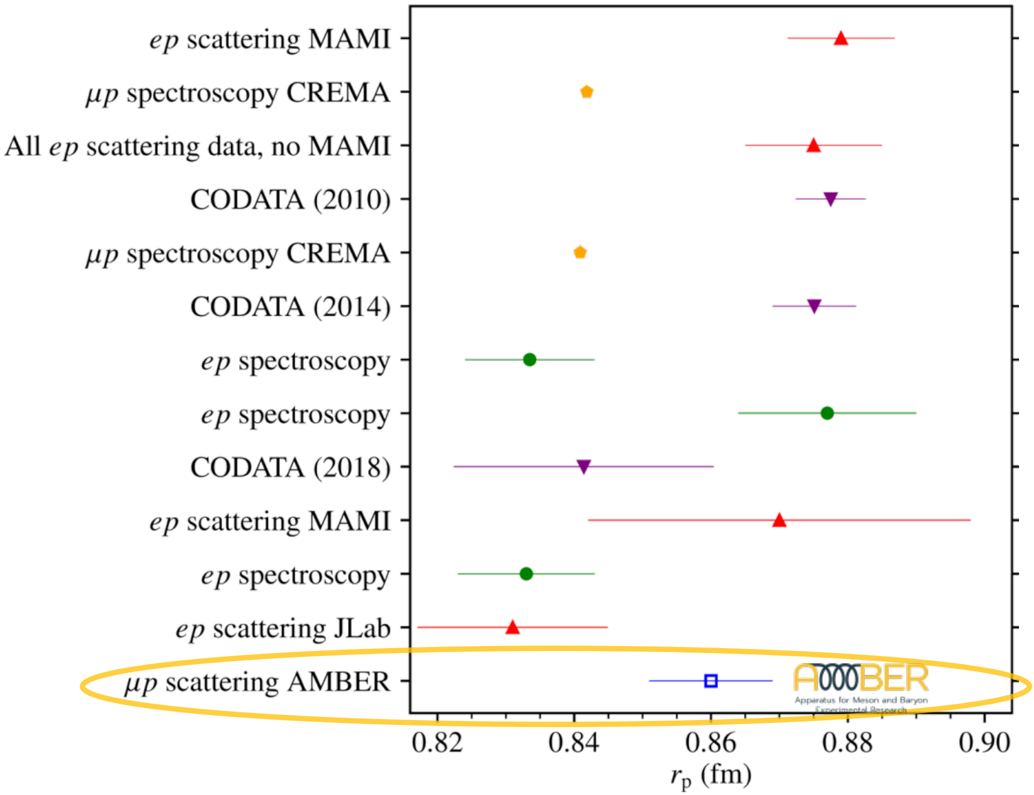
The proton-radius puzzle

- 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



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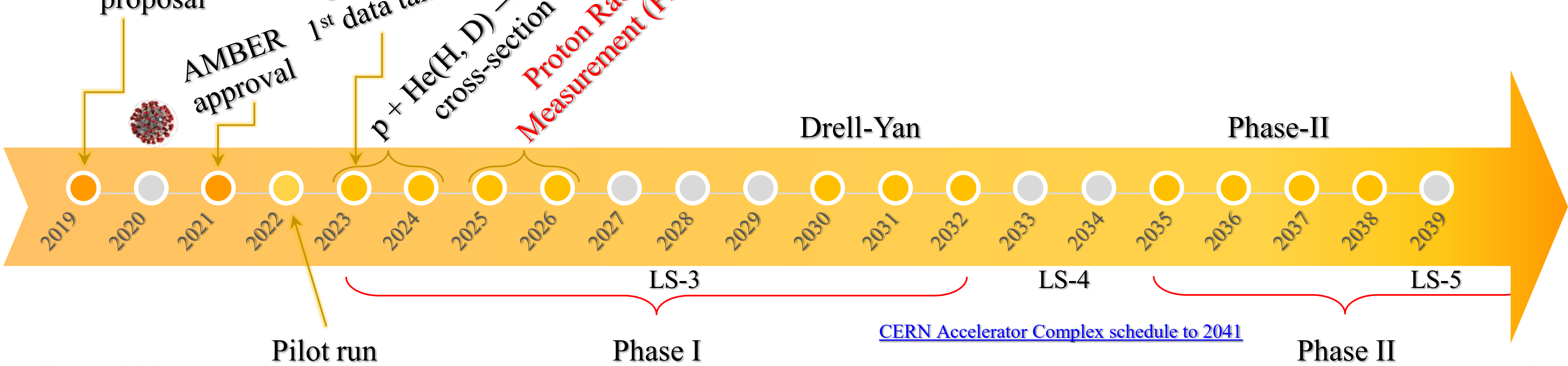
AMBER approval

Drell-Yan

Phase-II

LS-3

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LS-5

Pilot run

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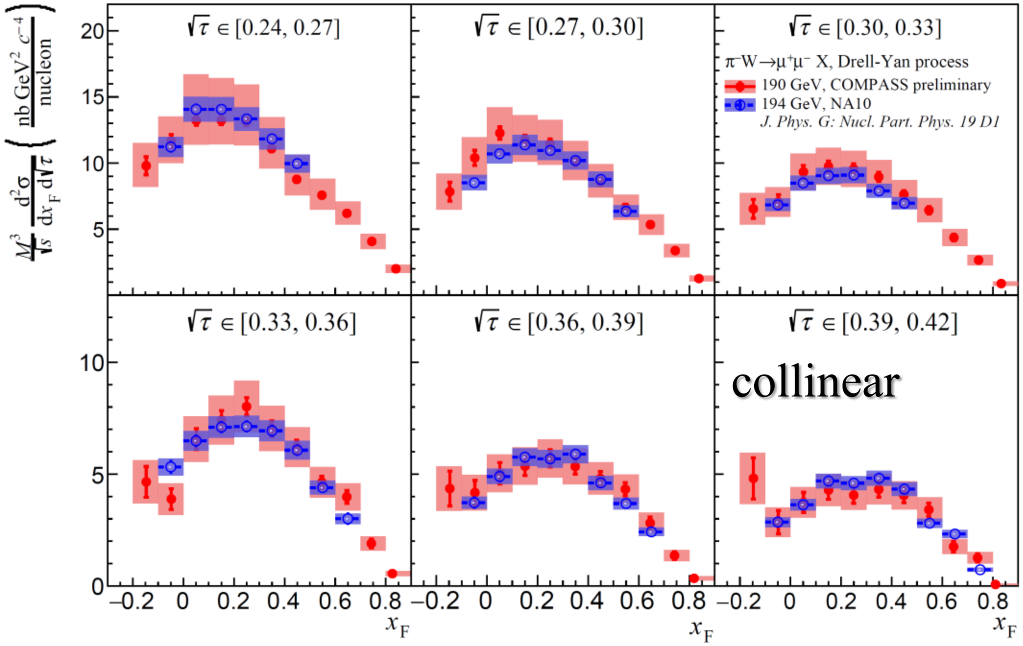
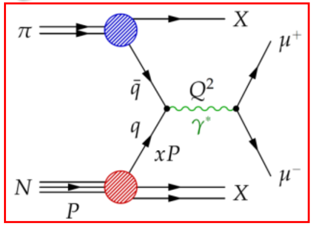
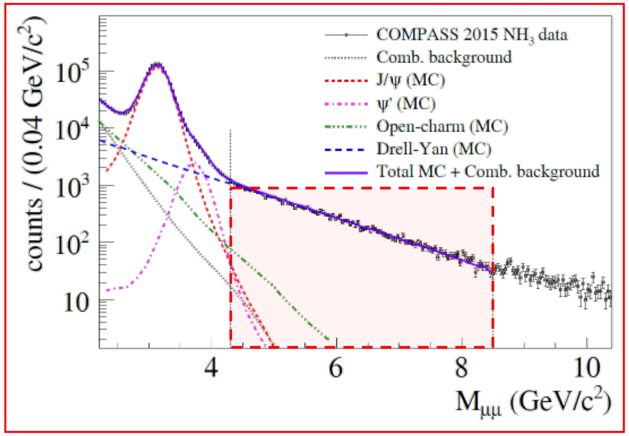
CERN Accelerator Complex schedule to 2041

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



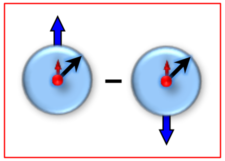




- First new results in 30 years!
- Data from light/heavy targets
    - NH_3-He, Al, W
    - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF

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

SIDIS TSAs: Collins effect and Transversity

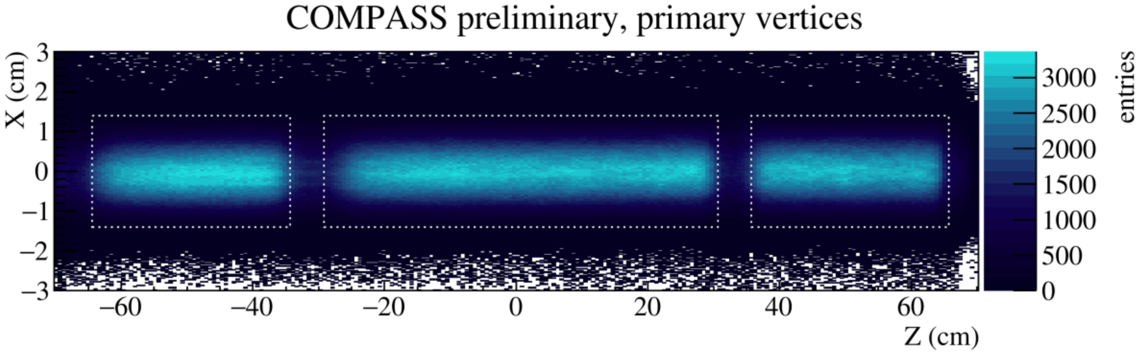


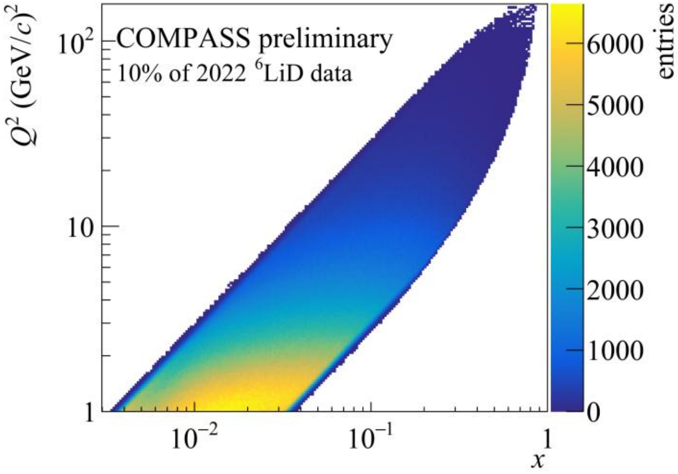
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_{\mathrm{T}}\,\varepsilon\, A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

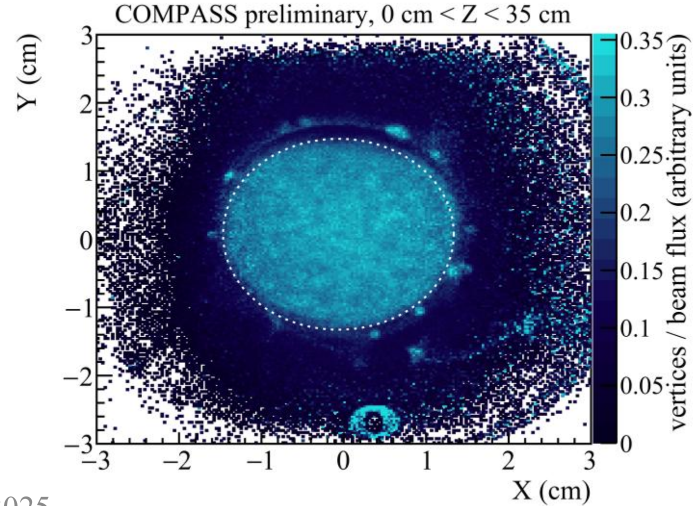
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

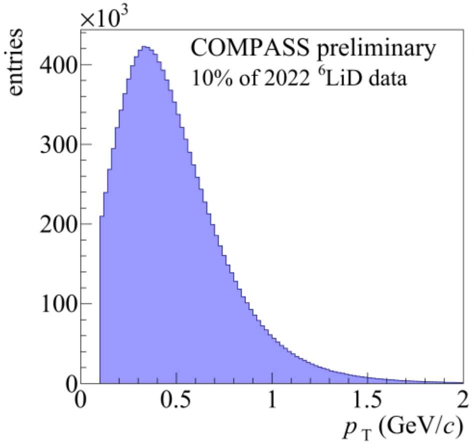
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS
  (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity

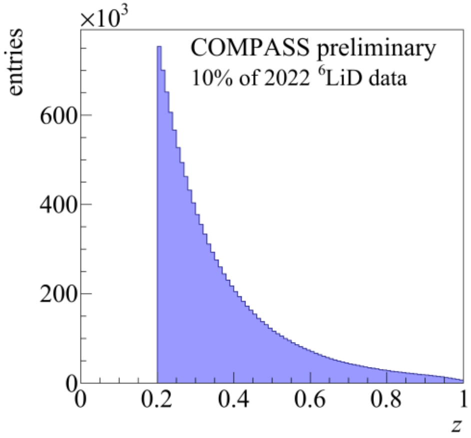
Highly successful
Run in 2022!





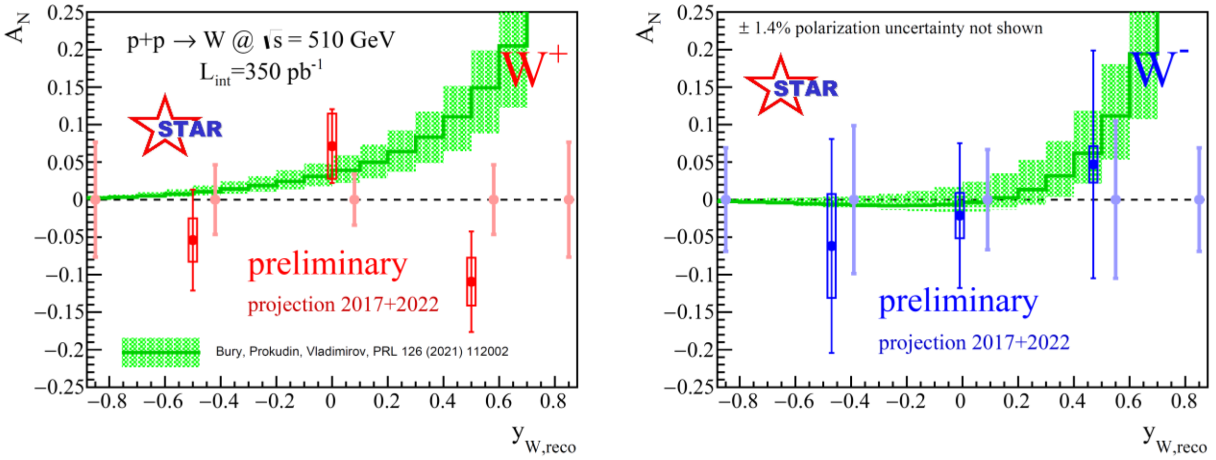




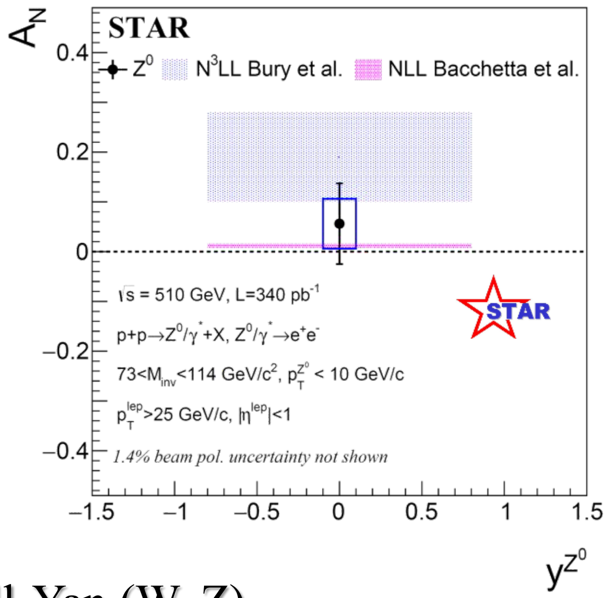


Sivers TMD PDF: sign change

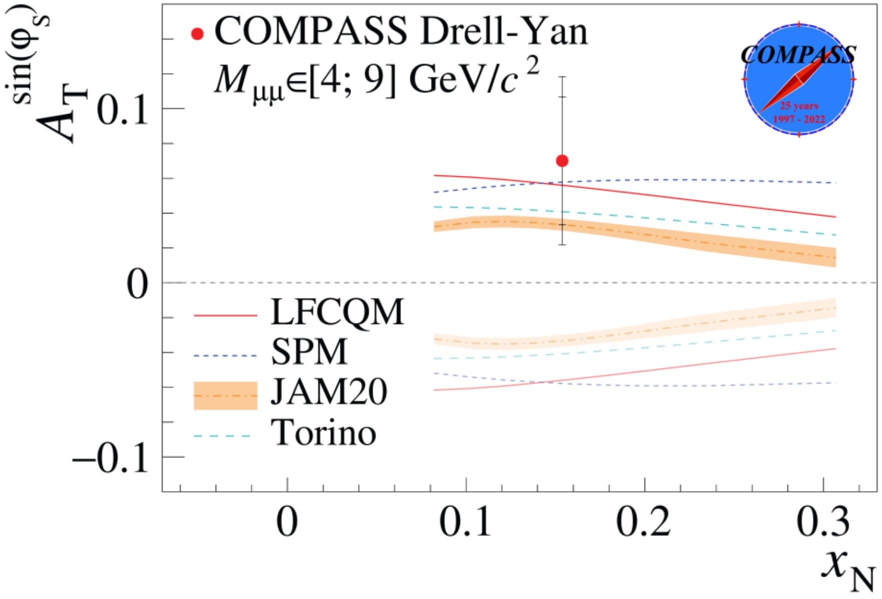
The RHIC Cold QCD program: arXiv:2302.00605 [nucl-ex]



STAR, arXiv:2308.15496 [hep-ex]



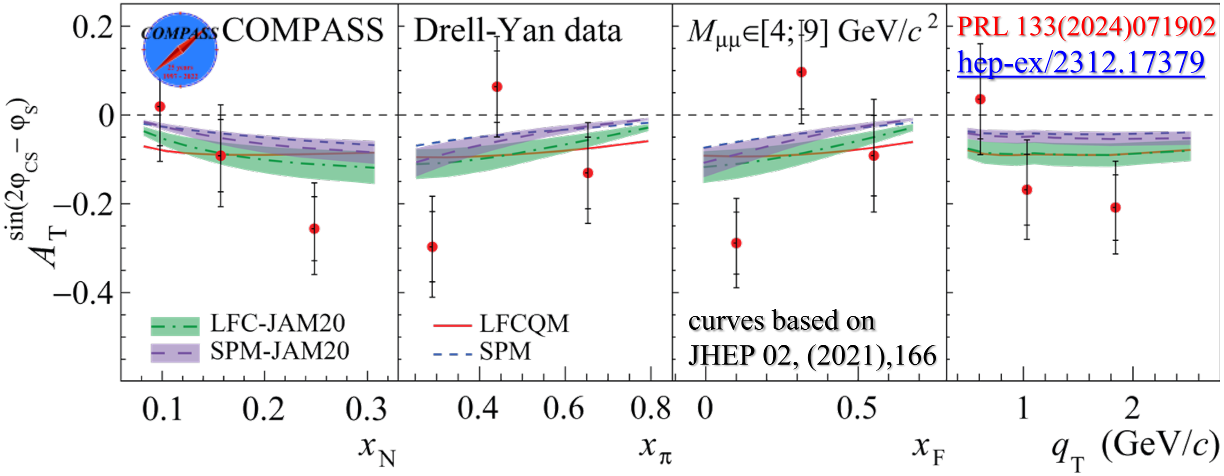
COMPASS, PRL 133 (2024) 071902



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

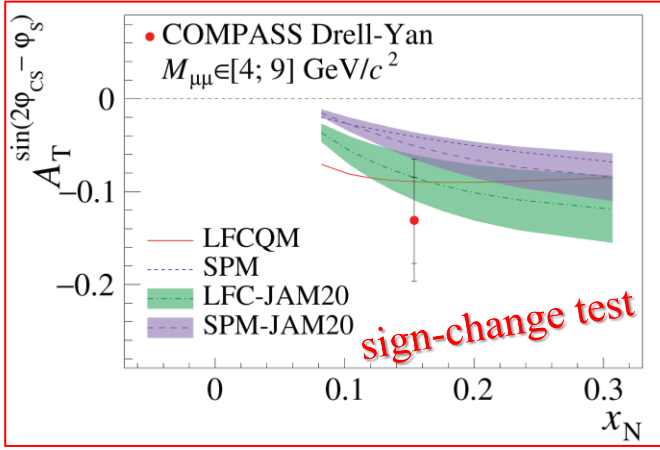
- Difficult measurement
  - Low x-section, background
- Sivers TMD PDF
- Pioneering measurements
  - COMPASS (Drell-Yan): 2015, 2018
  - STAR (W, Z): 2011, 2017, 2022
- COMPASS data favors the sign change
  - Useful input to constrain the fits

Boer-Mulders TMD PDF: sign change



PRL 133(2024)071902
hep-ex/2312.17379

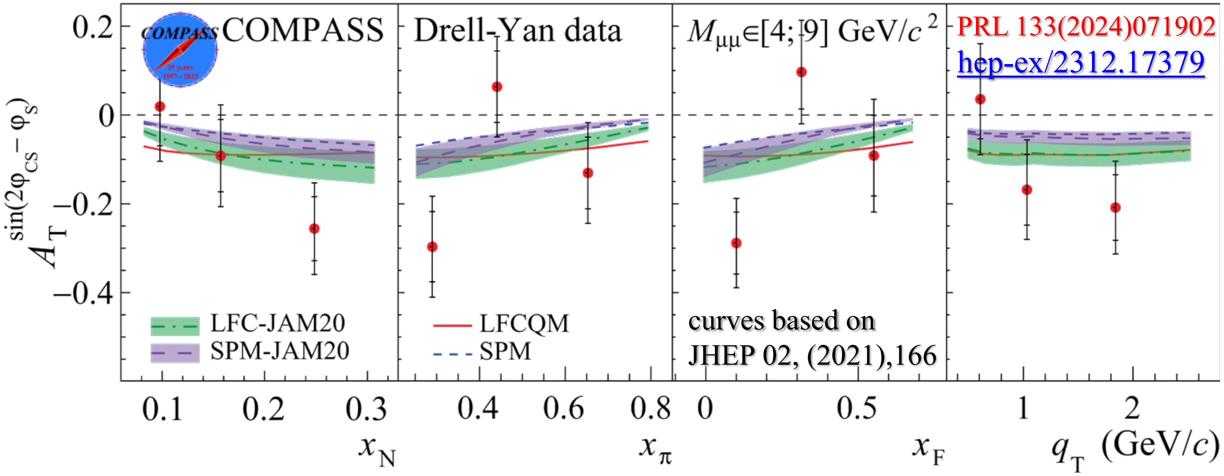
curves based on
JHEP 02, (2021),166

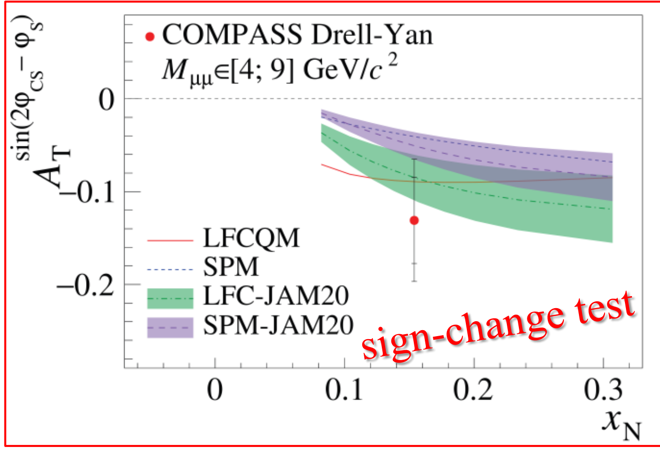


sign-change test

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





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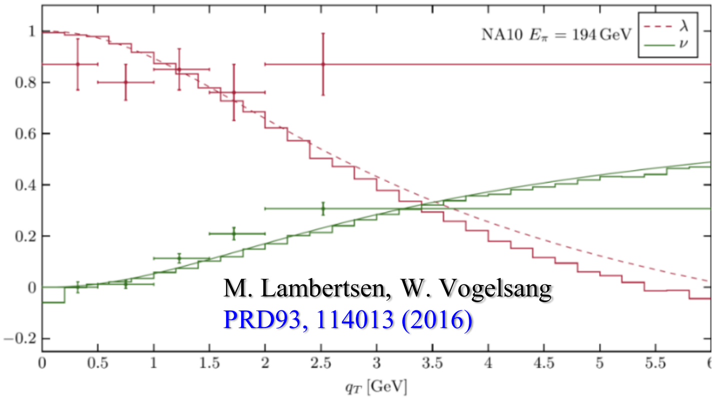
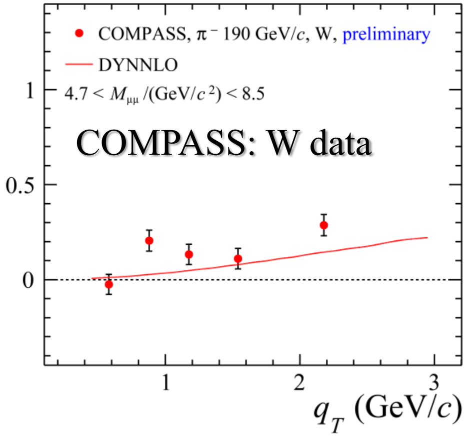
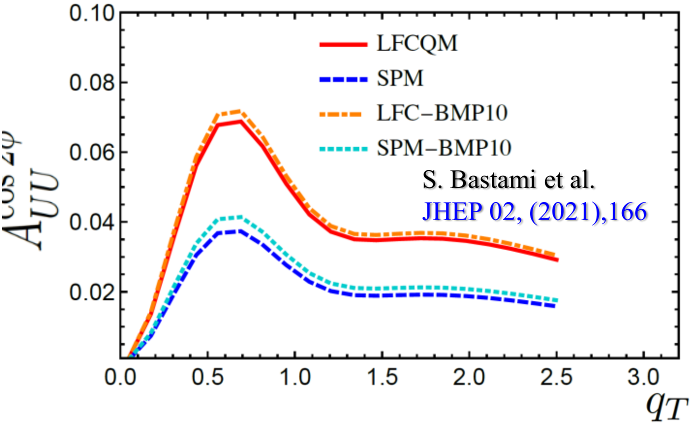


M. Lambertsen, W. Vogelsang
PRD93, 114013 (2016)



COMPASS: W data



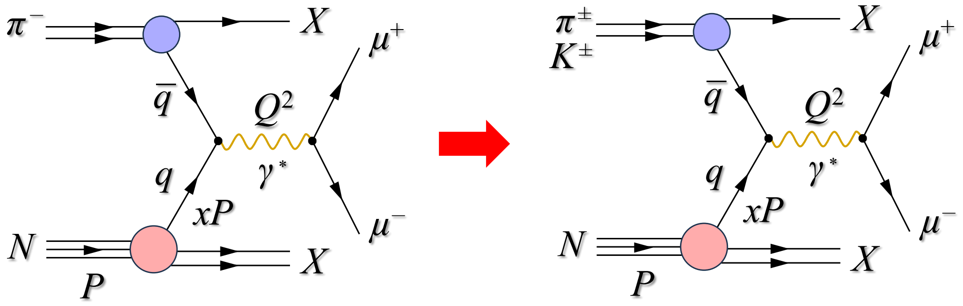
S. Bastami et al.
JHEP 02, (2021),166

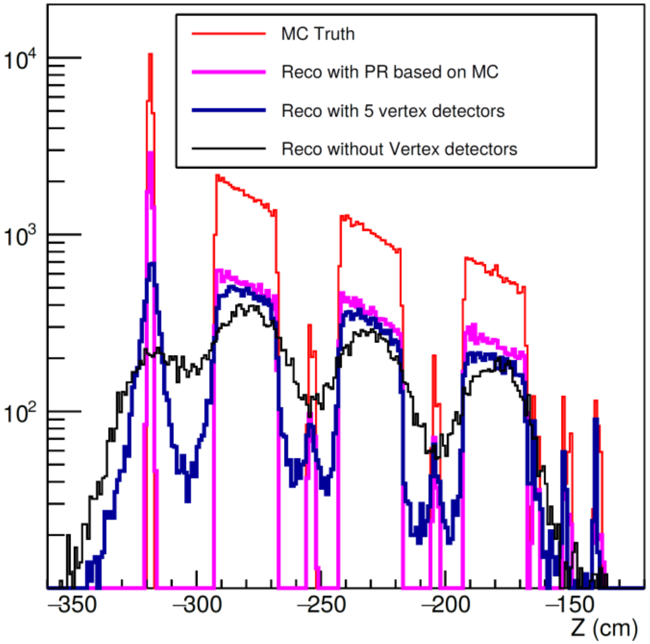
DY: $A_T^{\sin 2\varphi_{CS}} \propto \left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,p}^{\perp u}\right\} > 0 \Rightarrow h_{1,p}^{\perp u} > 0 \overset{\text{sign-change}}{\Leftrightarrow}$ SIDIS: $h_{1,p}^{\perp u} < 0$

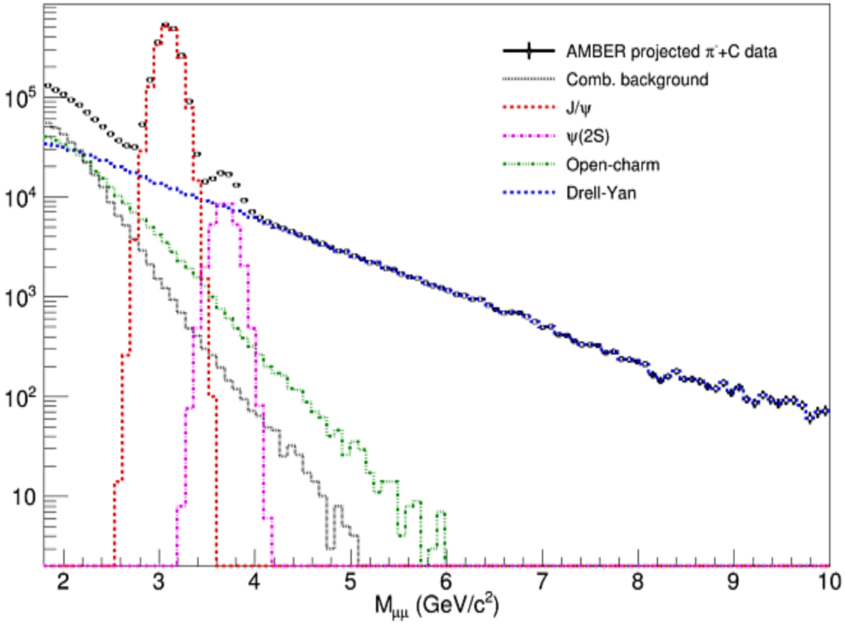
$h_{1,p}^{\perp u} < 0$ → SIDIS fits
V. Barone, et al.
PRD 82 (2010) 114025

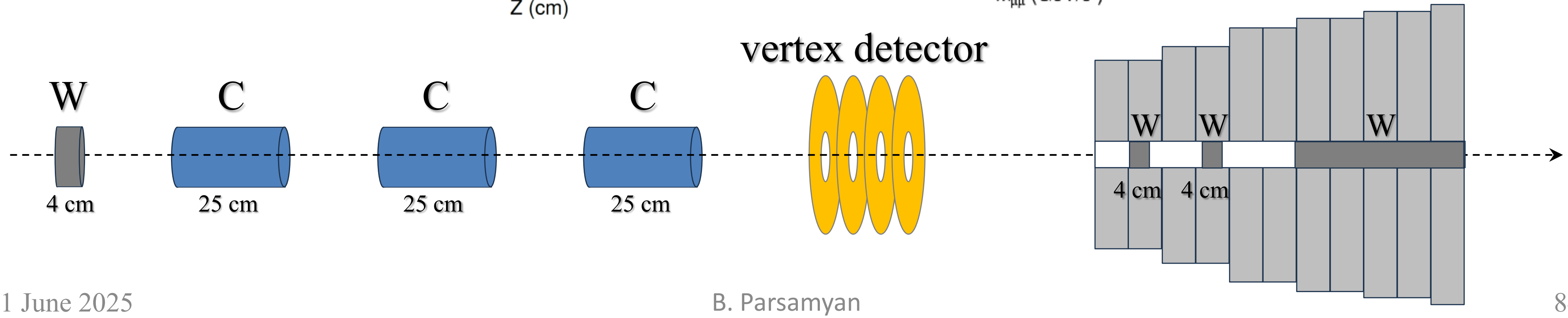
- COMPASS data favors proton Boer-Mulders TMD PDF sign-change

COMPASS→AMBER: Vertex detector improvements







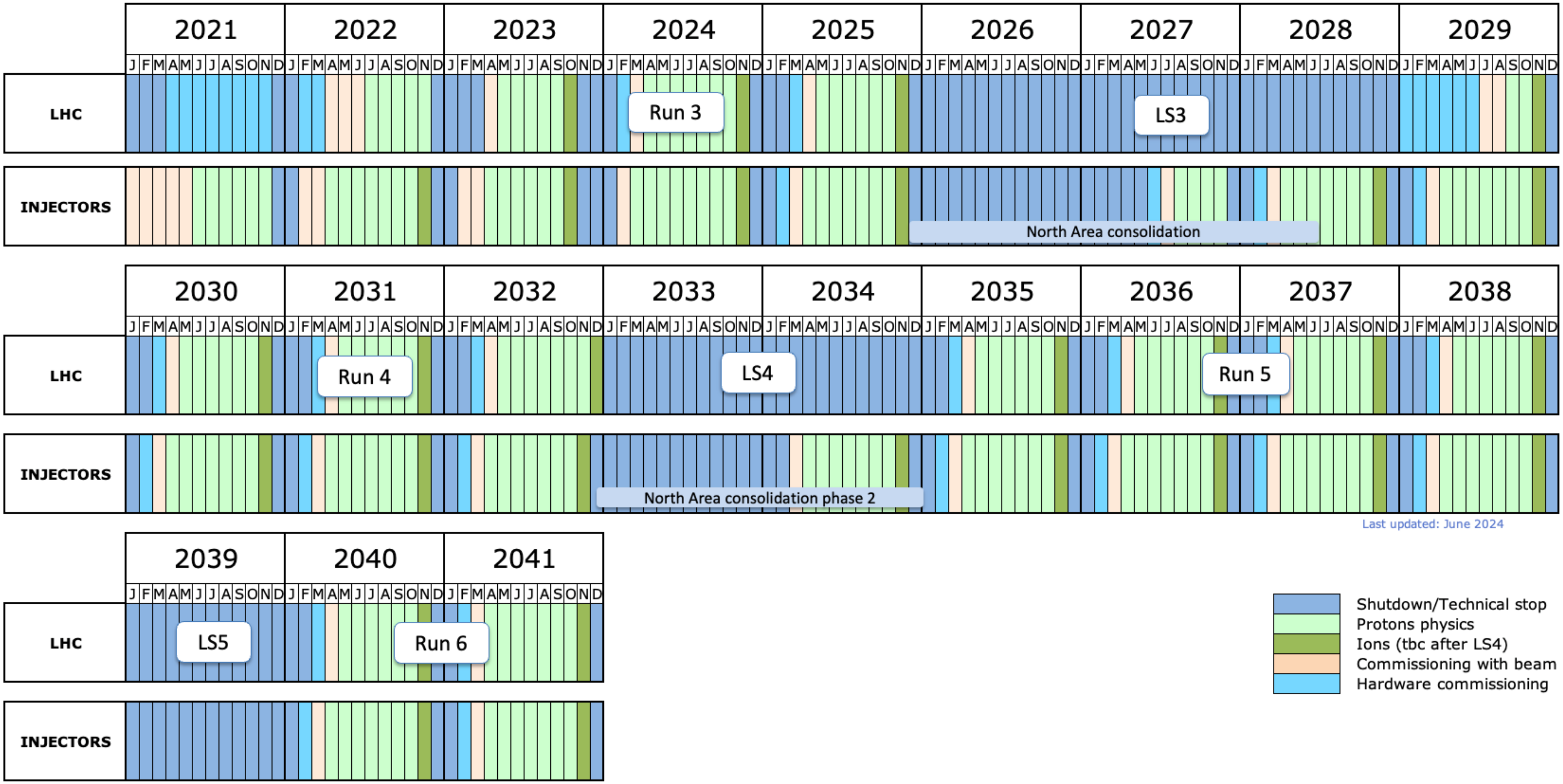


COMPASS data taking campaigns

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



Last updated: June 2024