Recent Highlights and Perspectives on Nucleon Spin and TMD Measurements from Fixed Target Experiments at CERN: COMPASS, AMBER and LHCspin

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Physics Opportunities at an Electron-Ion Collider
POETIC XI

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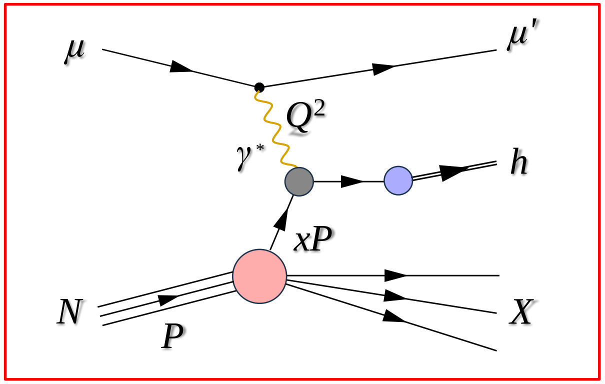
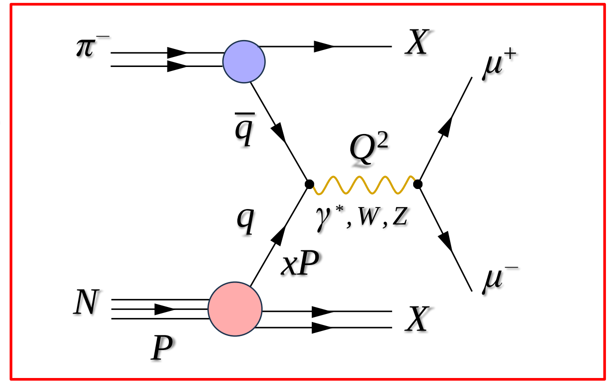
Florida International University
Miami, Florida, US

Main TMD tools – universality and synergies

Semi-inclusive DIS



Drell-Yan process



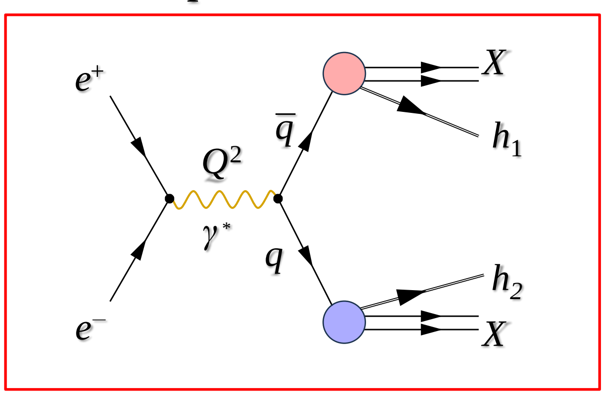
T-odd TMD PDFs

sign change

Fragmentation Functions

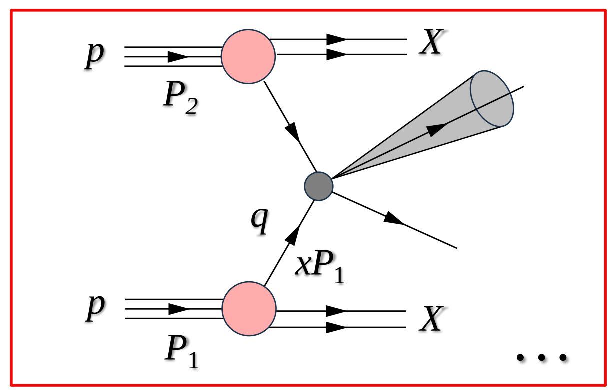
Parton Distribution Functions

Electron-positron annihilation



Cleanest access to hadronization/fragmentation

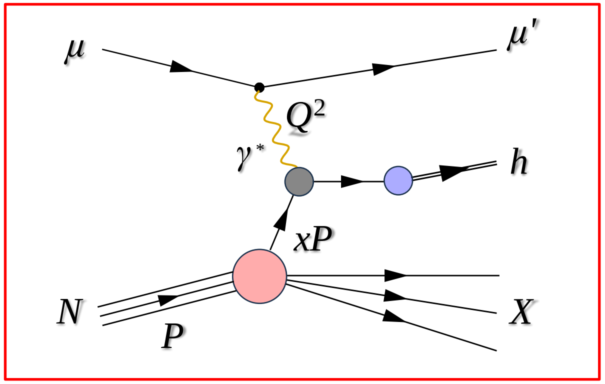
pp, pA-scattering, jet production, etc.



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

Main TMD tools – list of experiments (non exhaustive)

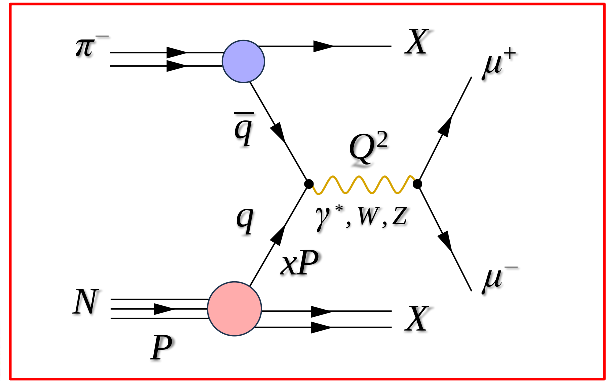
Semi-inclusive DIS



hermes DESY COMPASS CERN Jefferson Lab clas SoLID

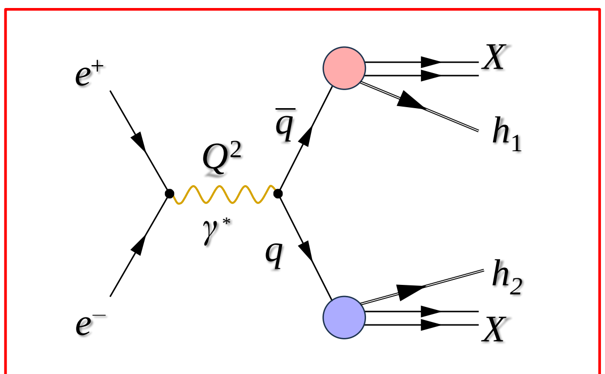
ePIC EIC Jefferson Lab @ 22 GeV

Drell-Yan process



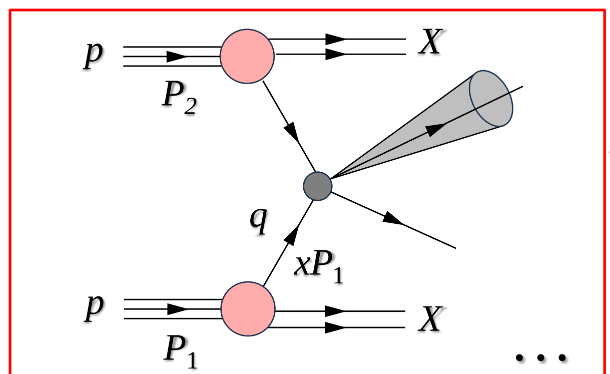
COMPASS CERN STAR SPIN QUEST Fermilab LHC spin AMBER Apparatus for Meson and Baryon Experimental Research

Electron-positron annihilation



Belle KEK BABAR SLAC NATIONAL ACCELERATOR LABORATORY BESIII

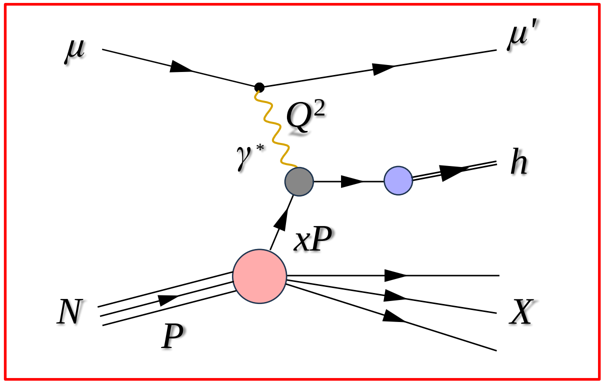
pp, pA-scattering, jet production, etc.



Brookhaven National Laboratory STAR PHENIX sPHENIX

Main TMD tools – list of experiments (non exhaustive)

Semi-inclusive DIS



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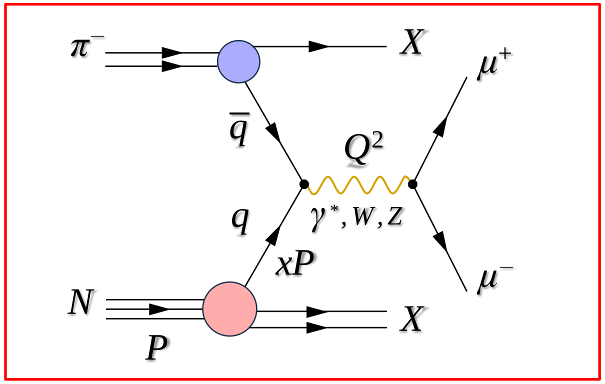
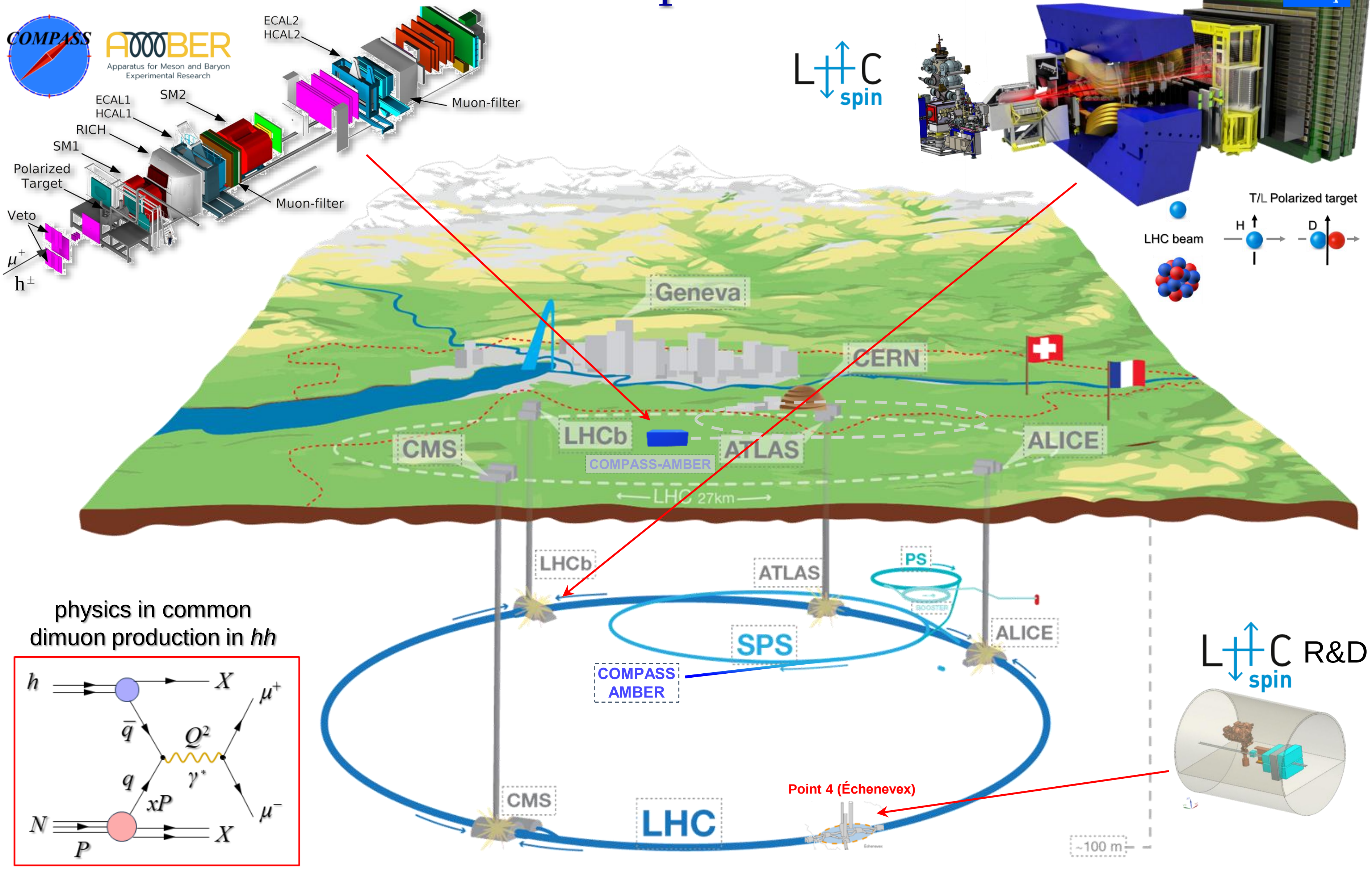


Electron-positron annihilation

pp, pA-scattering, jet production, etc.

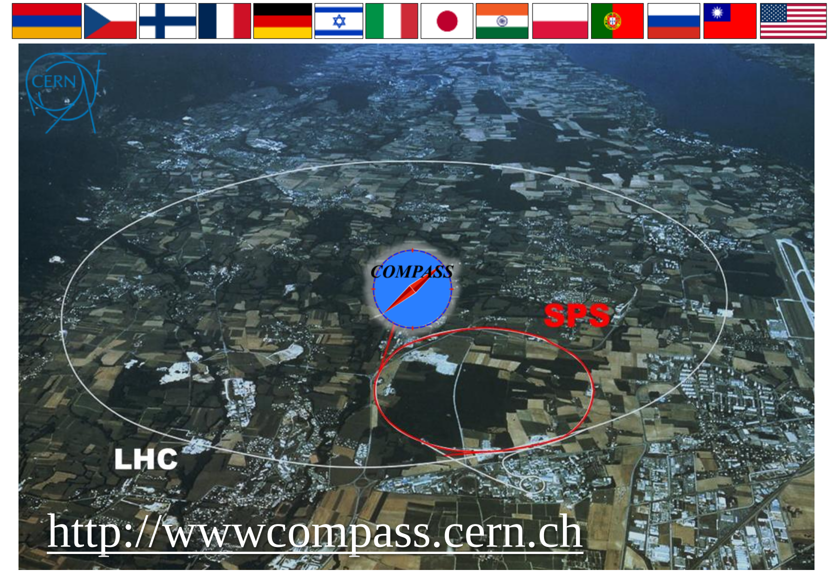
COMPASS-AMBER-LHCspin FTs at CERN



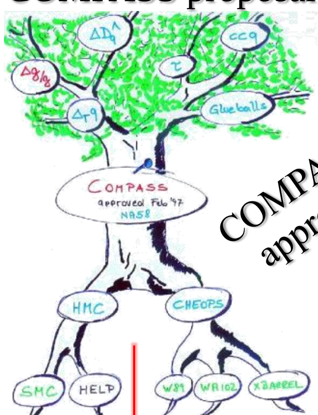
COMPASS timeline

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

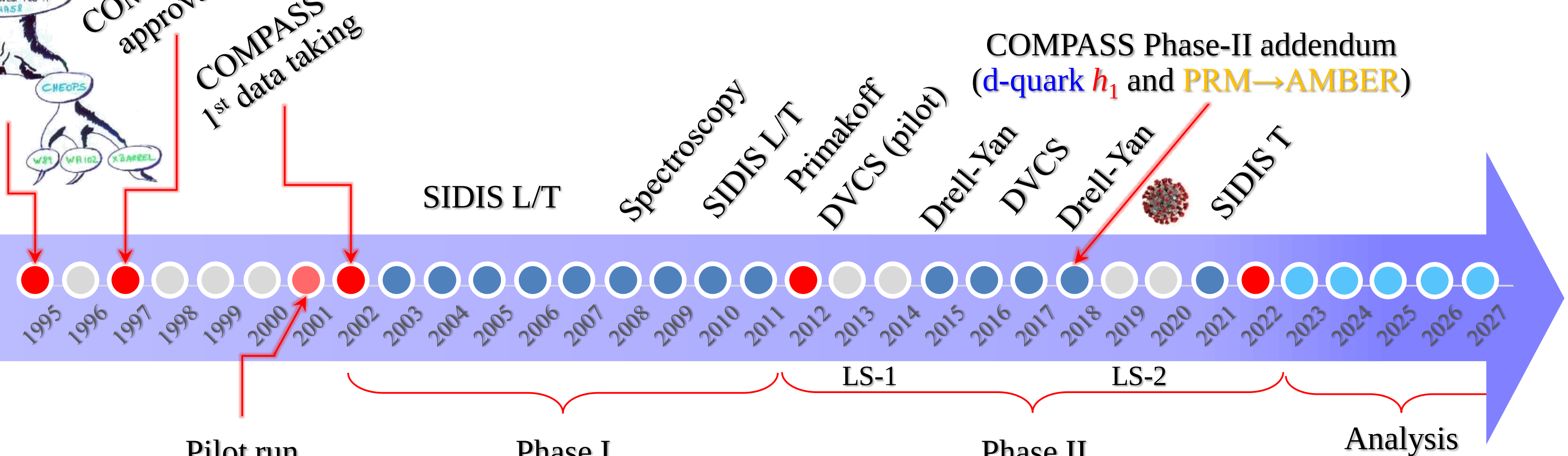
33 institutions from 15 countries: ~ 200 members



COMPASS proposal



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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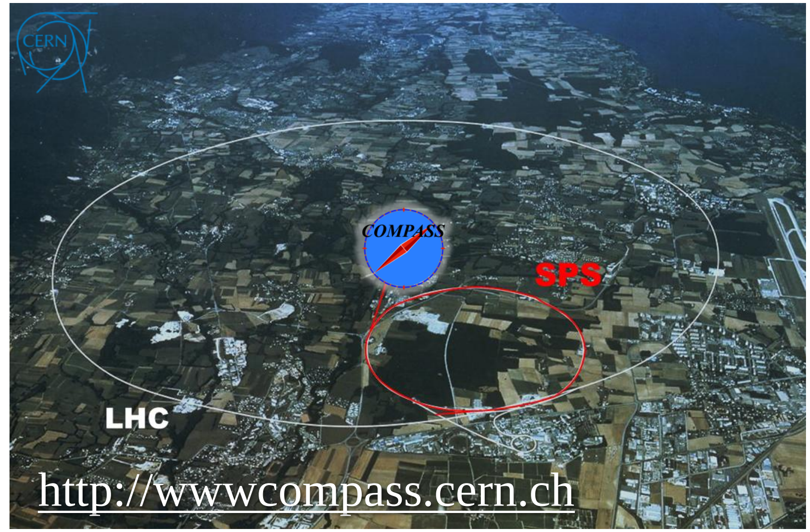
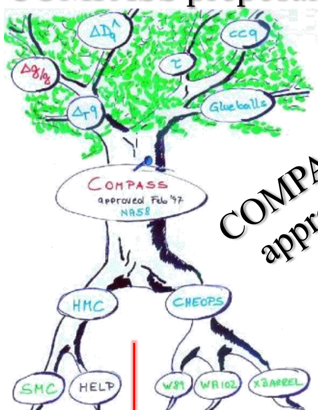
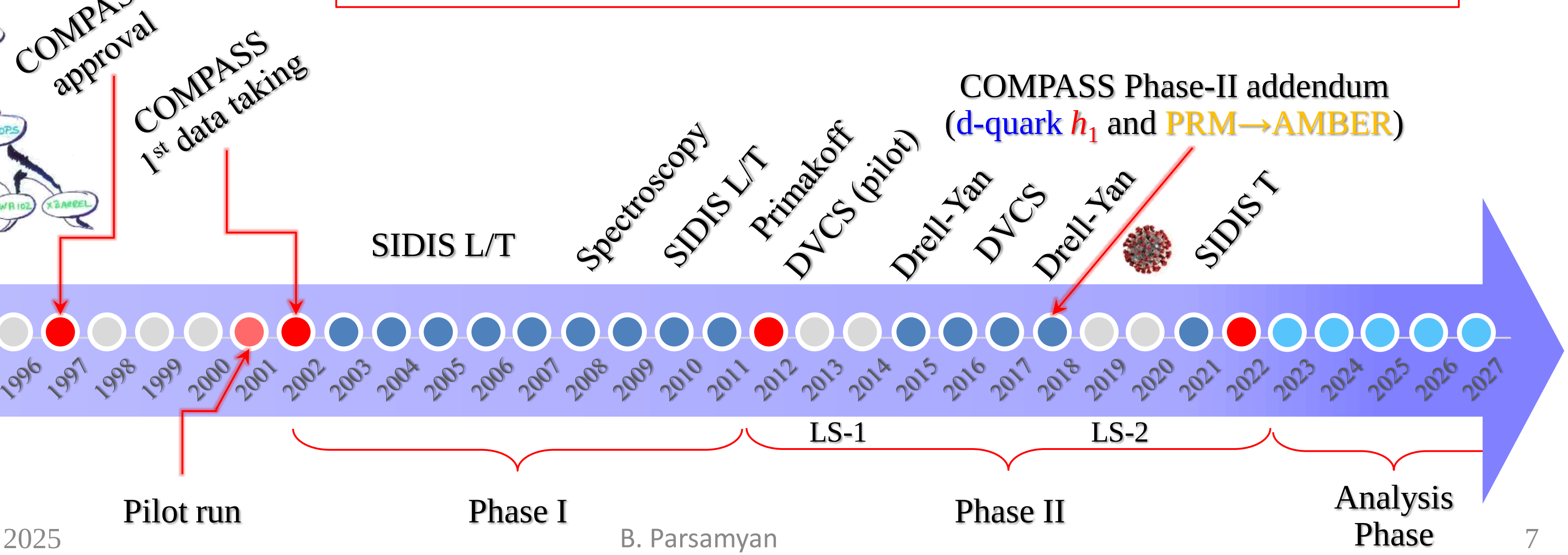


COMPASS proposal



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

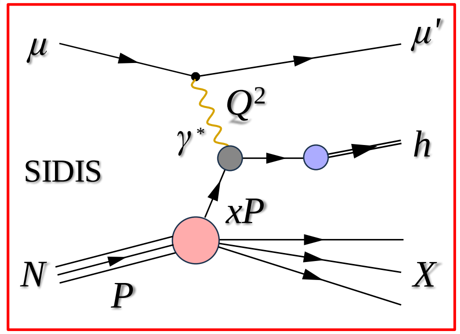


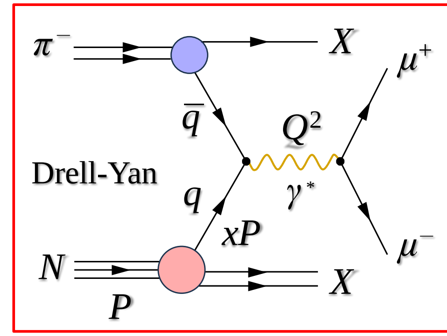
COMPASS Physics Program

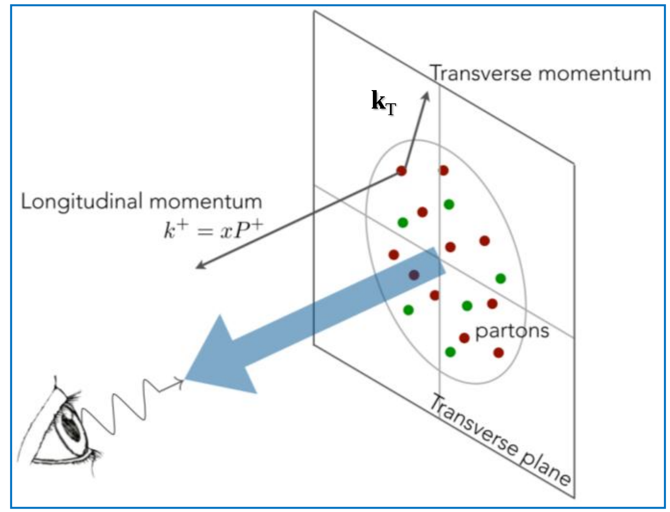
Nucleon structure

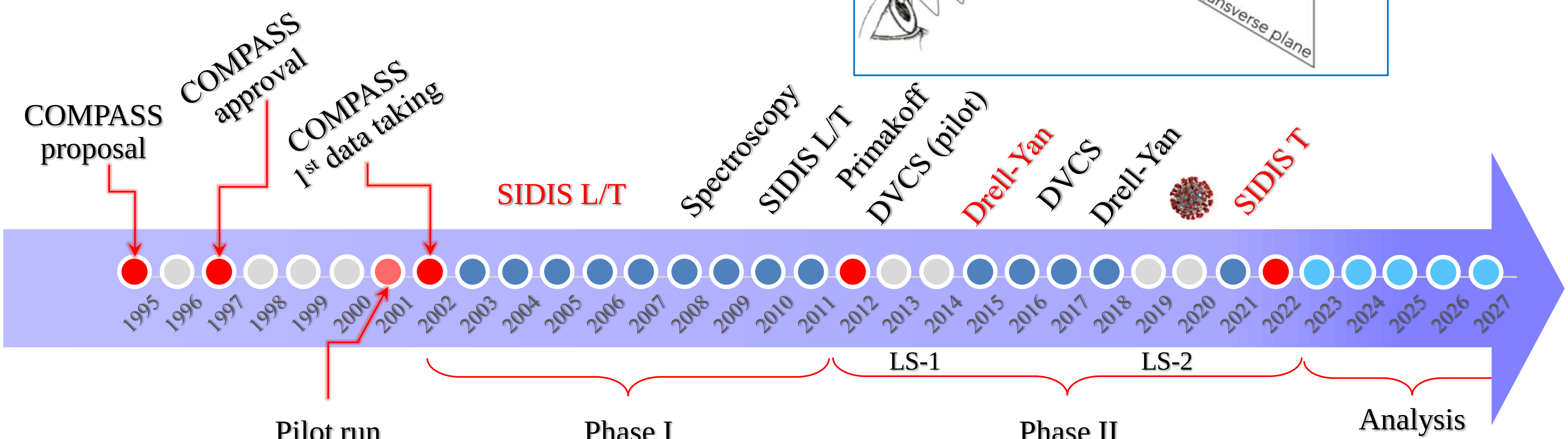
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Inclusive and Semi-Inclusive DIS
- Drell-Yan and J/ψ production
- Study of nucleon spin structure
  - Longitudinal and Transverse
- Collinear and TMD pictures
- Parton distribution functions and fragmentation functions
- Last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

This talk





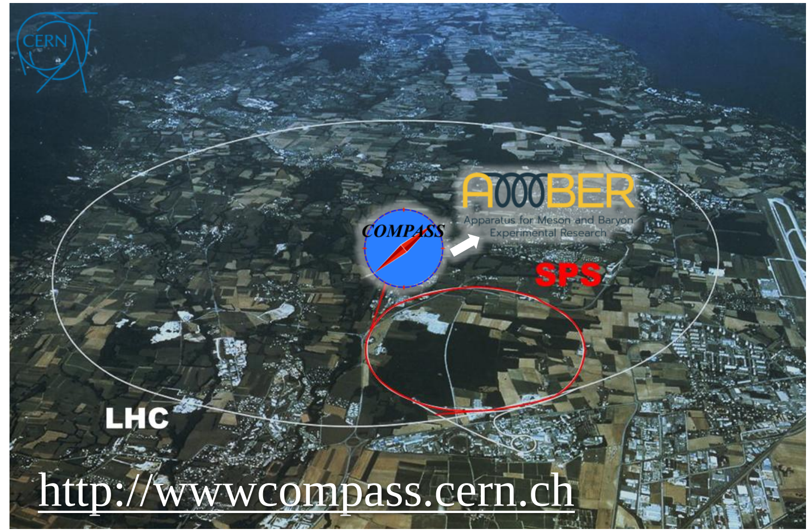




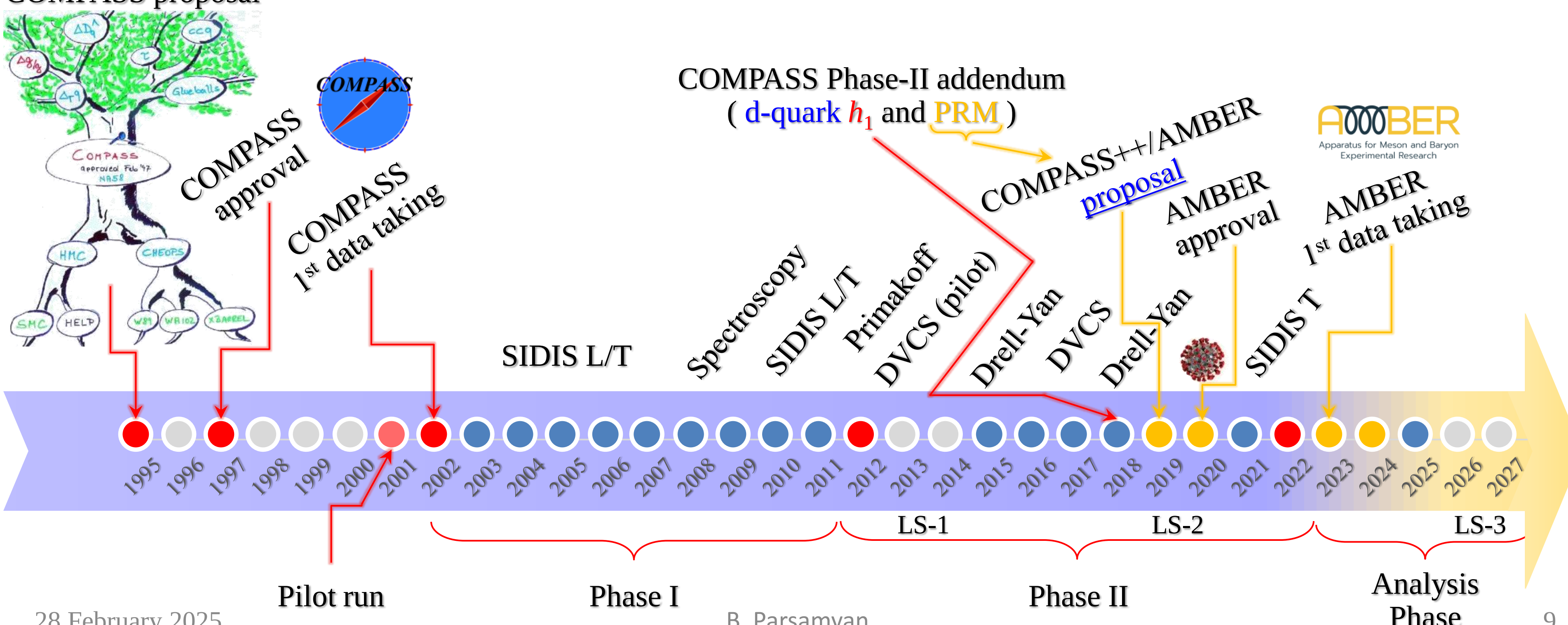
COMPASS-AMBER timeline

- 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 proposal



AMBER timeline

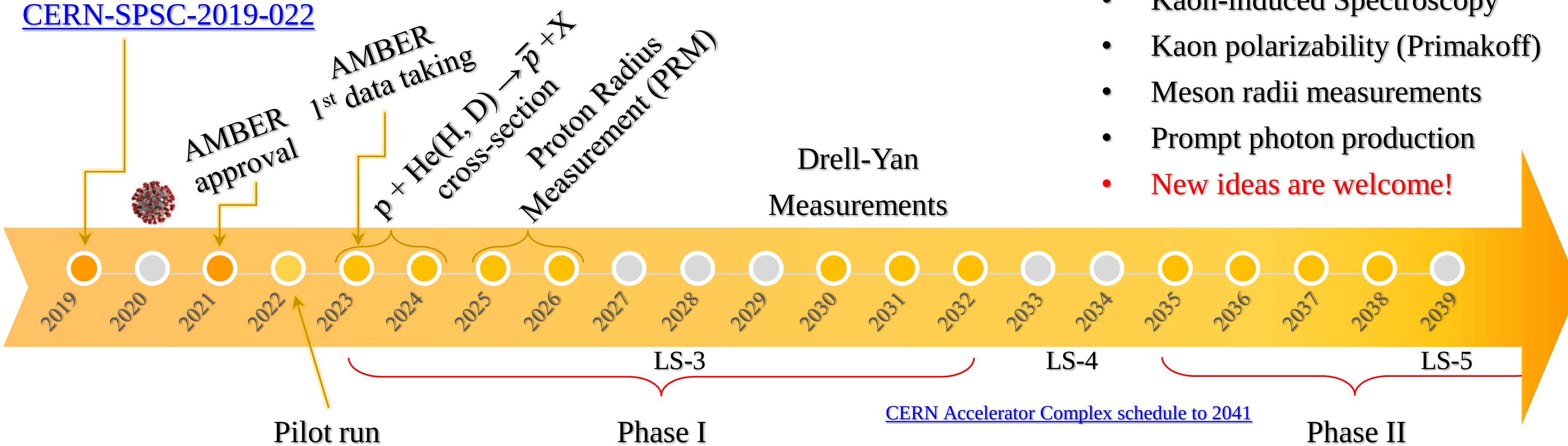
- CERN SPS north area – M2 beamline
- Successor of COMPASS
- Approved in 2019
- Taking data since 2023
- Phase-I is planned to continue after LS3

36 institutions from 14 countries: ~ 150 members

New collaborators are Welcome!

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

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

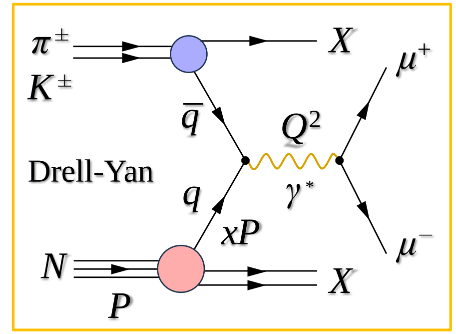


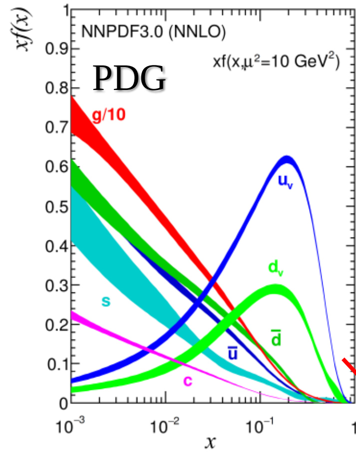
CERN Accelerator Complex schedule to 2041

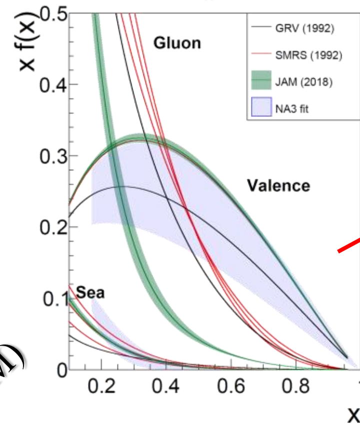
AMBER measurements 2023-2024: Drell-Yan

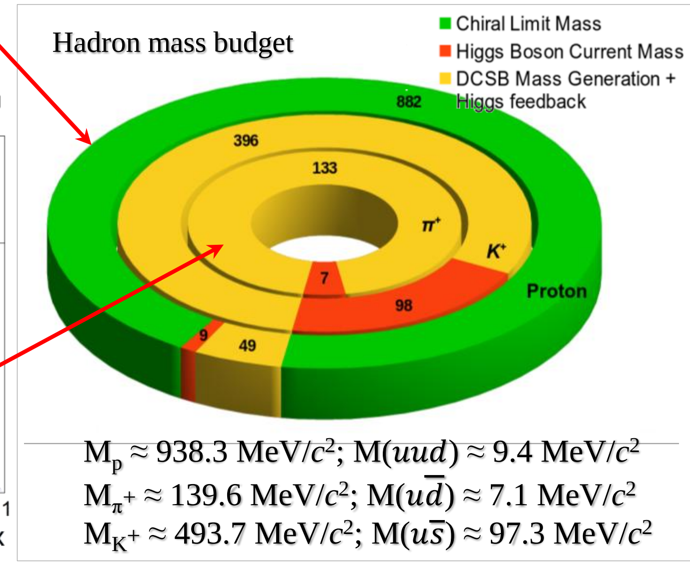
$\pi^{\pm}$, $K^{\pm}$ induced dimuon production: Drell-Yan, J/ψ (and ψ')

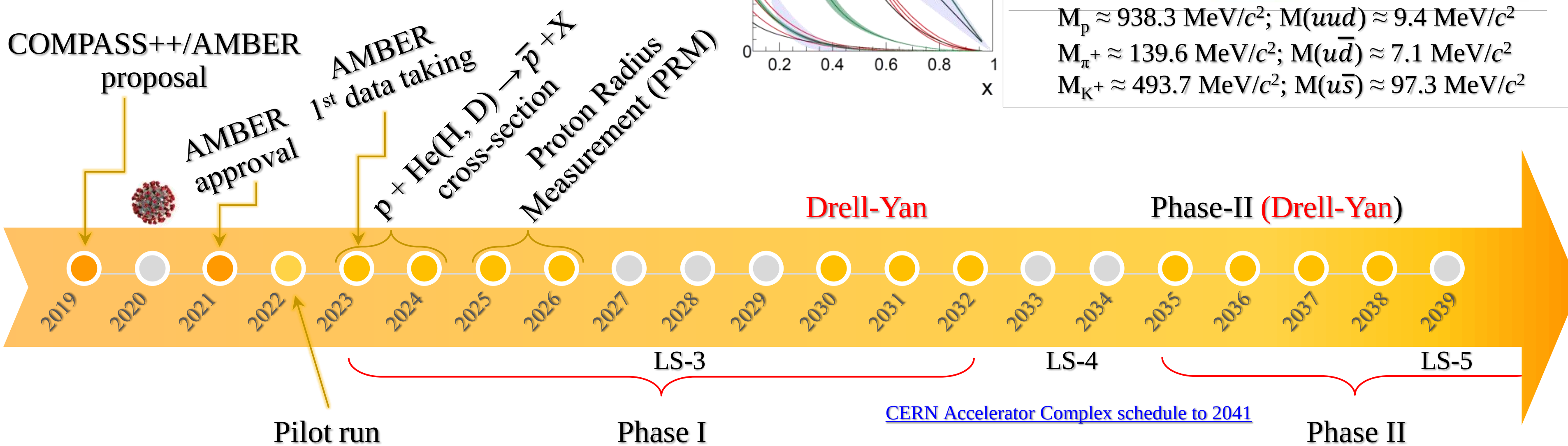
- Study of pion and kaon PDFs
  - Crucial input for the study of the Emergent Hadron Mass (EHM)
  - Possibility to collect unique balanced π^{+}/π^{-} induced DY data
- Measurement of λ, μ and ν (DY, J/ψ)
- J/ψ production mechanisms ($q\bar{q}, gg$)
- Carbon and tungsten targets
- Improved vertex/mass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











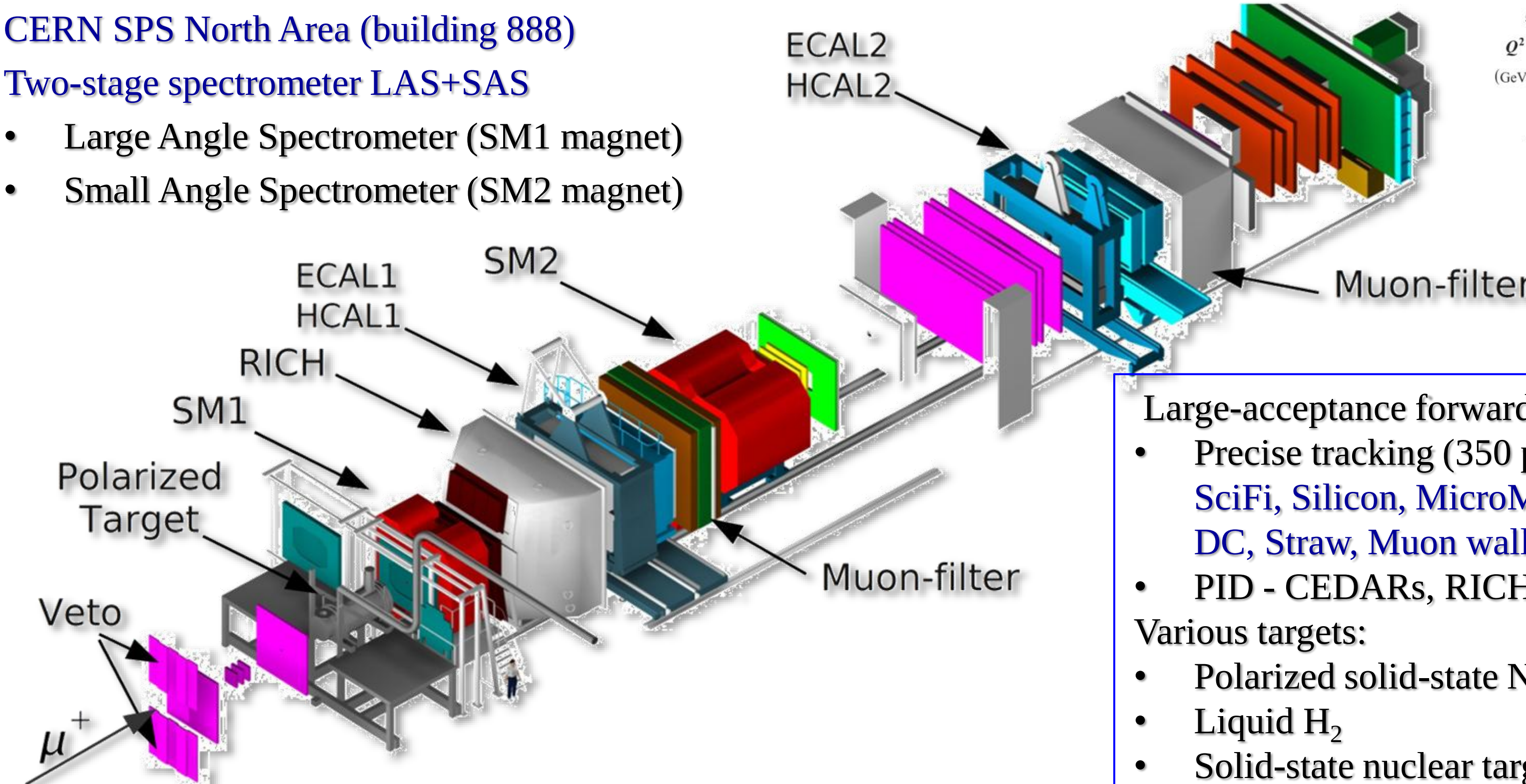
COMPASS experimental setup

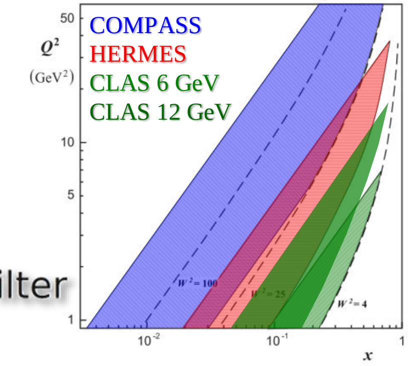
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





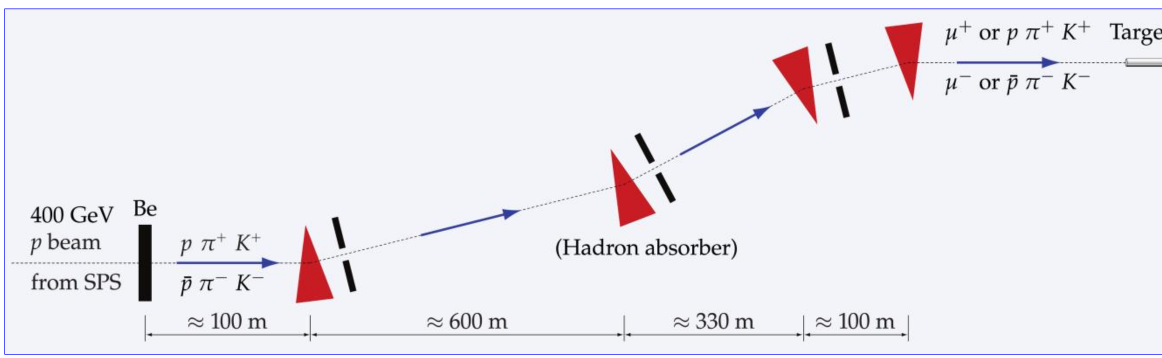
Large-acceptance forward spectrometer

- 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)
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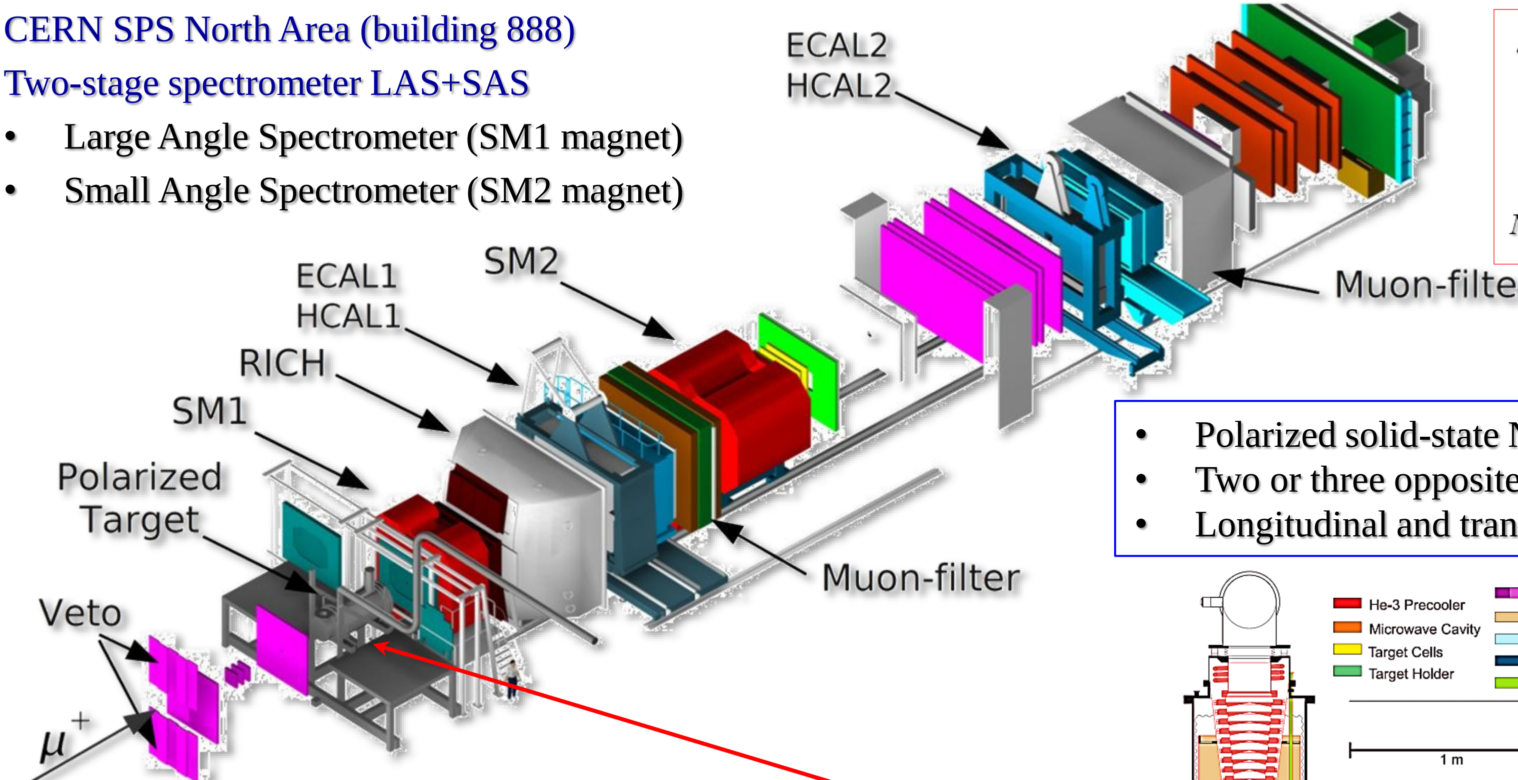
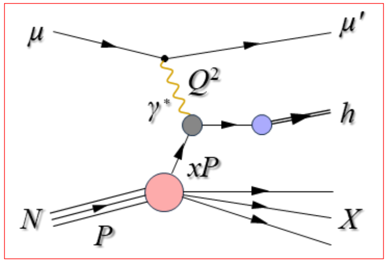
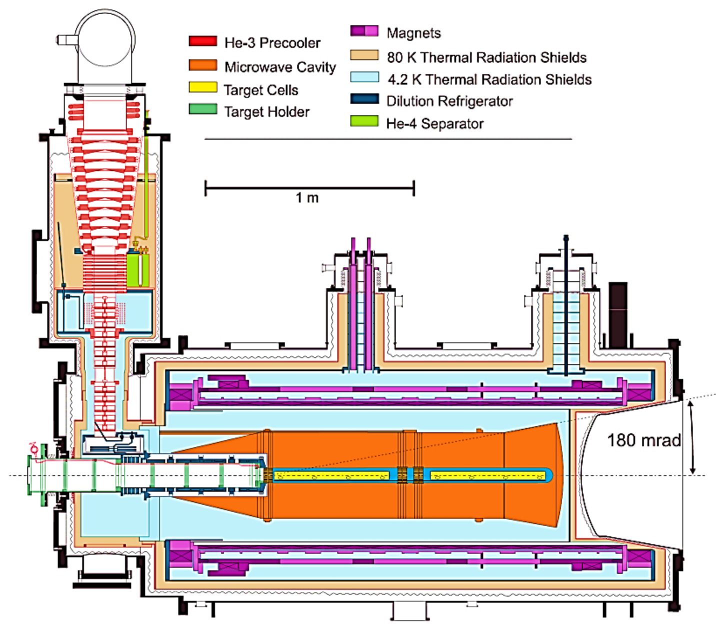




- Polarized solid-state NH_3 or ^6LiD
- Two or three oppositely polarized cells
- Longitudinal and transverse polarization



- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% $\bar{p}$
  - 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

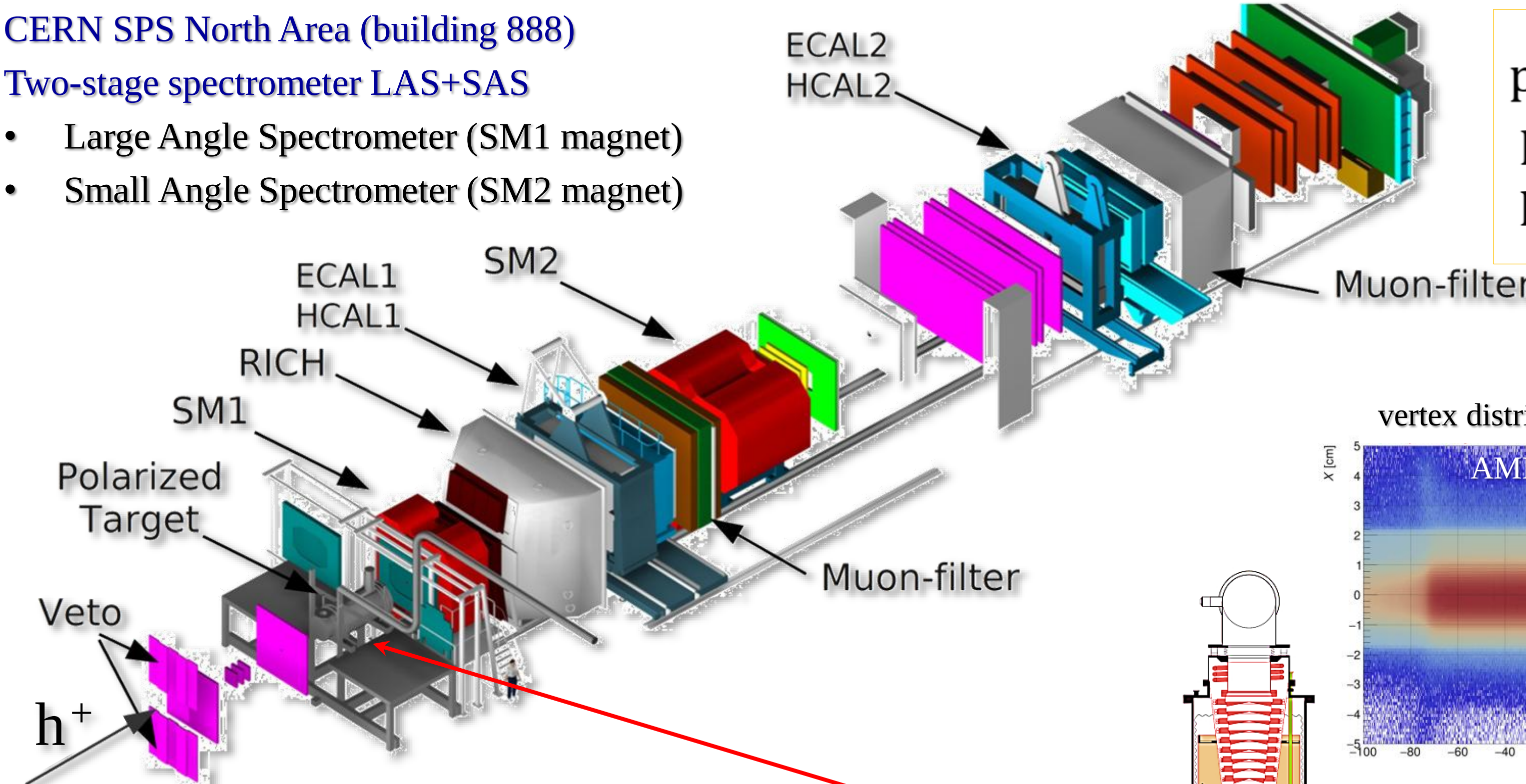
Apparatus for Meson and Baryon Experimental Research

CERN SPS North Area (building 888)

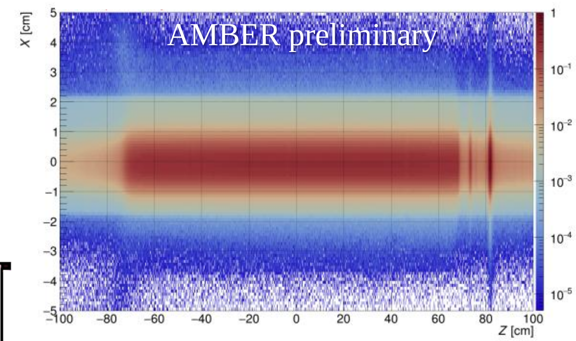
Two-stage spectrometer LAS+SAS

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

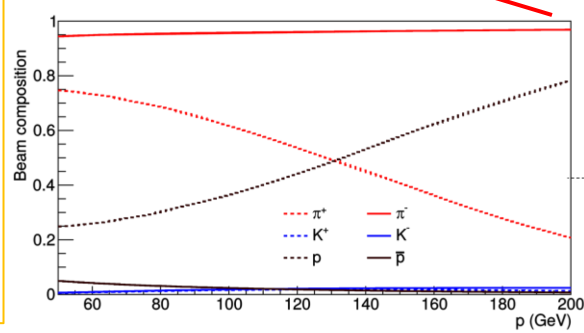
$$p + He \rightarrow \bar{p} + X$$
$$p + H \rightarrow \bar{p} + X$$
$$p + D \rightarrow \bar{p} + X$$

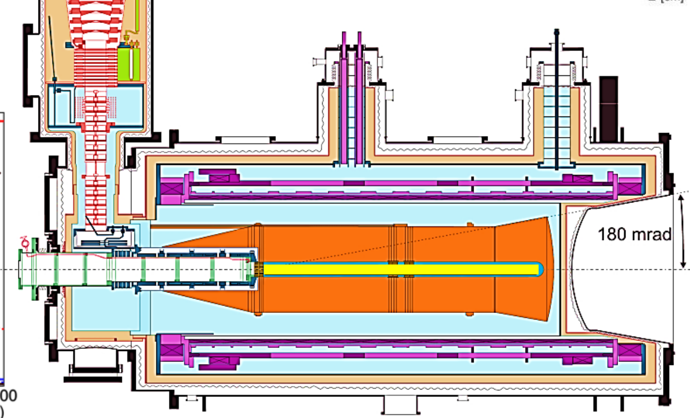


vertex distribution



- 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

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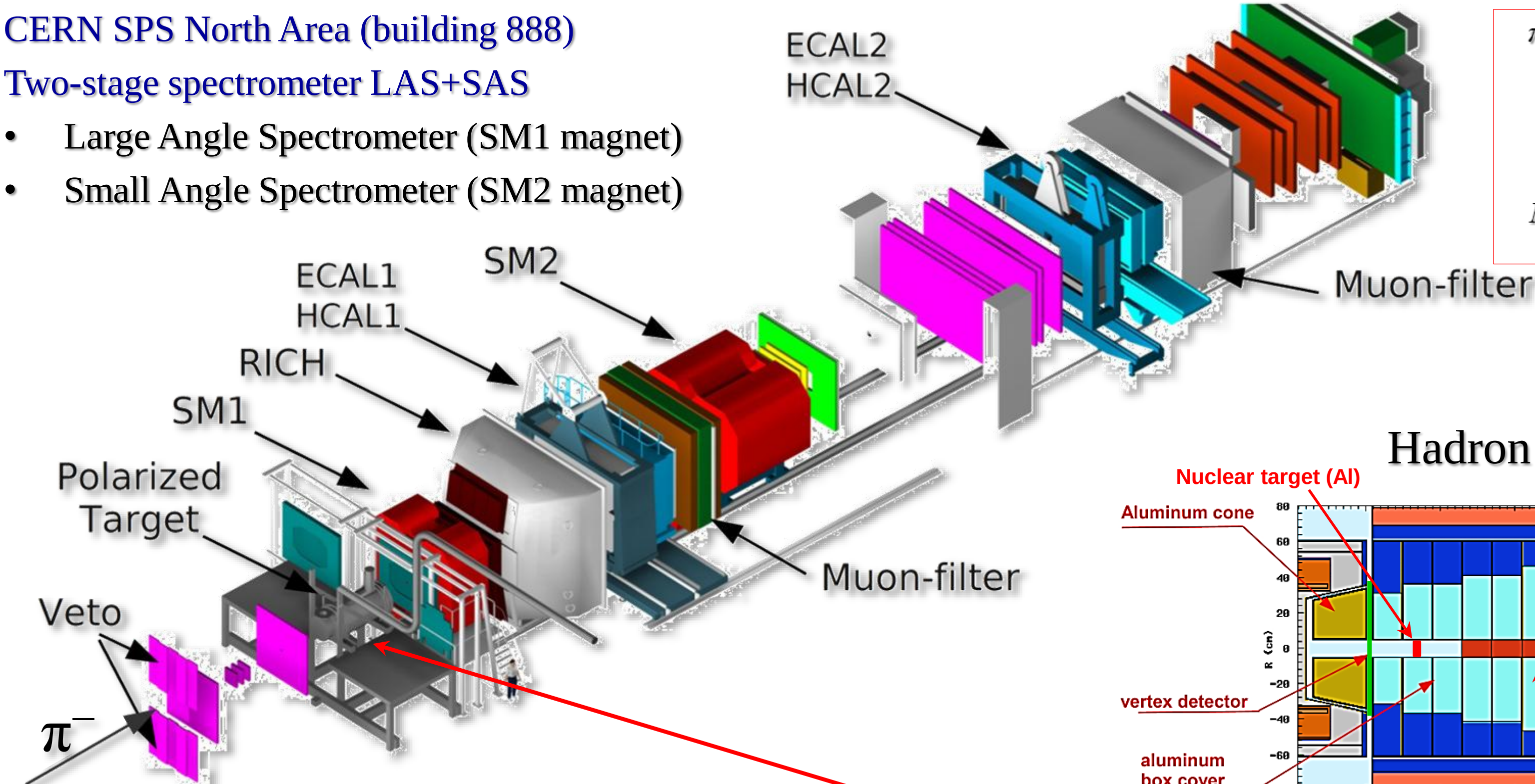
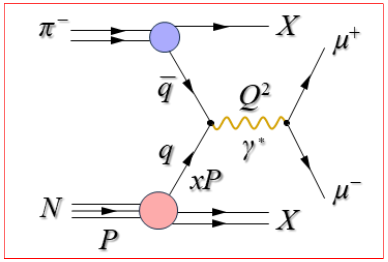
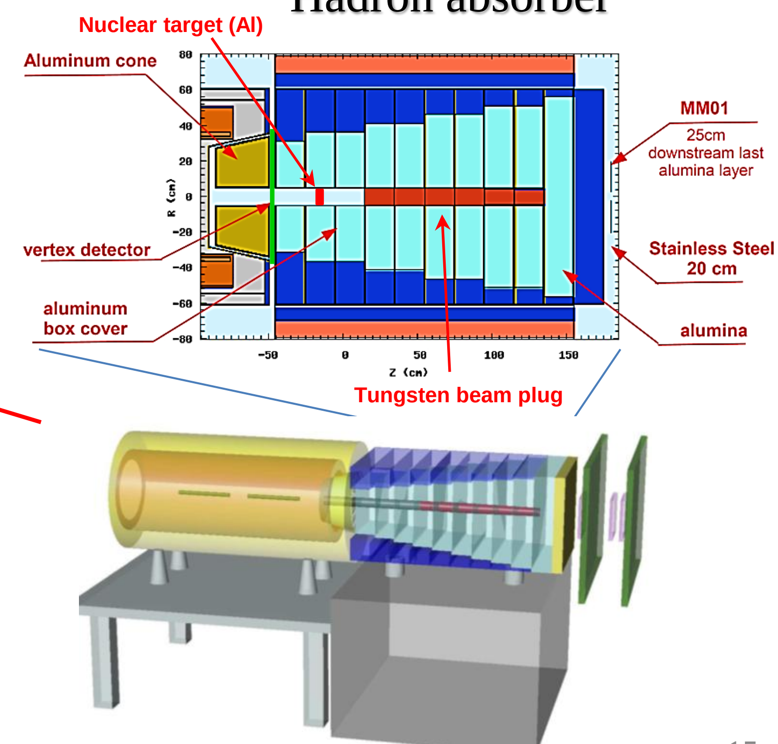




Hadron absorber



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- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
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  - $\mu^\pm$ longitudinally polarized

AMBER Phase I-II: DY program setup

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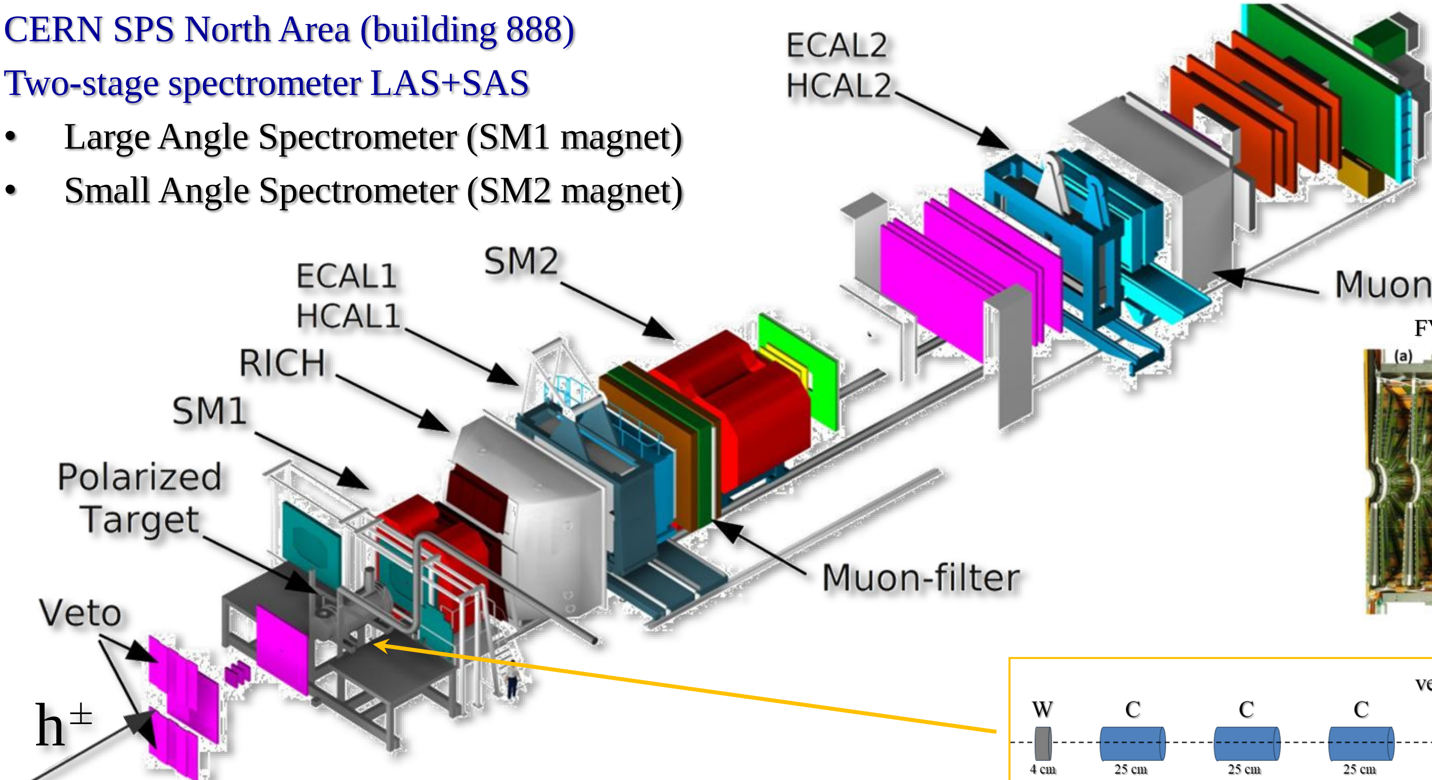
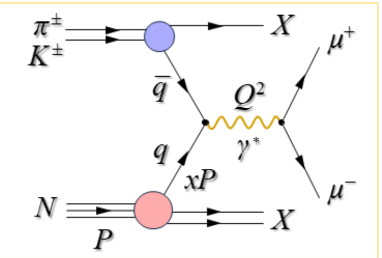
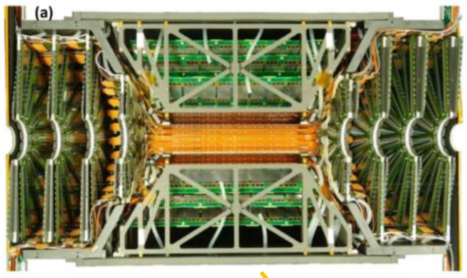
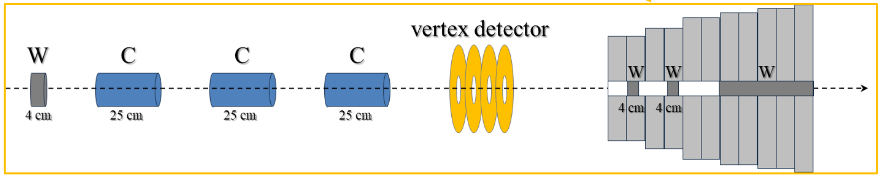
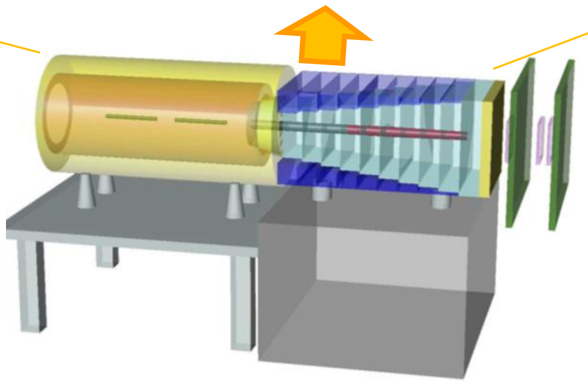




FVTX detector from PHENIX@RHIC



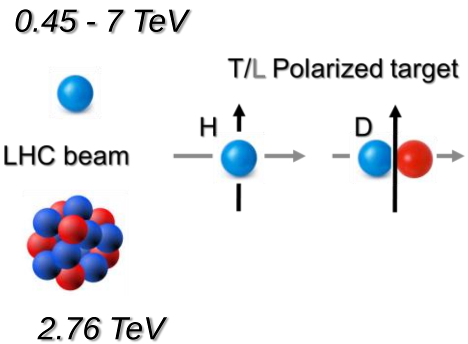




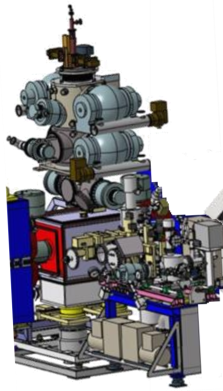
- Secondary h ± beam: $(\pi^{\pm}, K^{\pm}, p/\bar{p})$
- Improved beam PID (CEDARs)
  - enabling kaon physics
- Isoscalar target (C 3x25 cm) and W
- Vertex detector: improve Z and $M_{\mu\mu}$ resolution
- New trigger-less DAQ,
- Revised setup, new detectors

LHCspin experiment

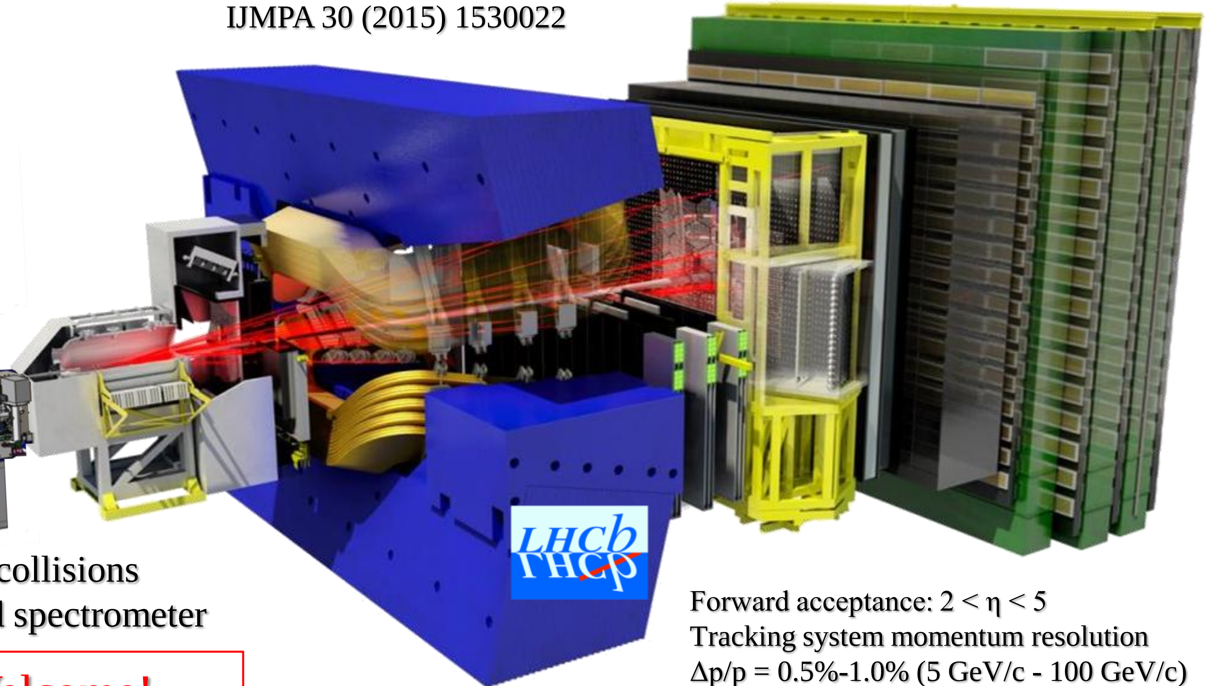
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



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



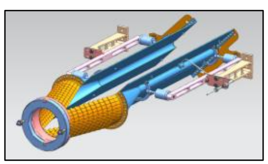
pp, Ap collisions
forward spectrometer



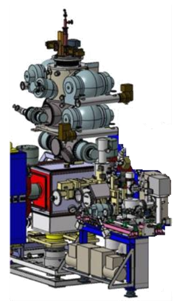
Forward acceptance: $2 < \eta < 5$
Tracking system momentum resolution
$\Delta p/p = 0.5\%\text{-}1.0\%$ (5 GeV/c - 100 GeV/c)

New collaborators are Welcome!

Timeline



SMOG2



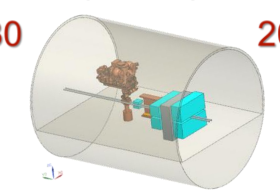
LHCspin R&D

As a group independent from LHCb collaboration

2024 2025 2026 2027 2030 2033 2035

LHC LS3
installation of the apparatus at the IR4

LHC Run4
data taking at the IR4

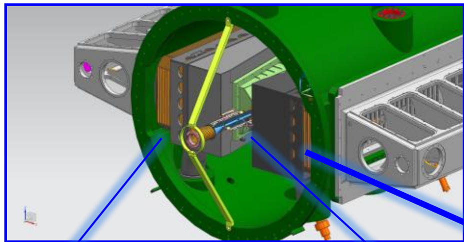


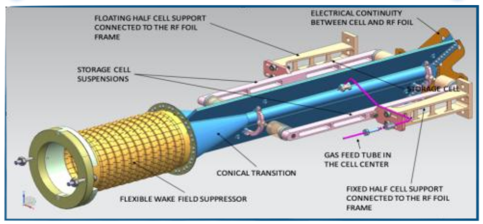
LHC LS4
installing the target at LHCb

LHCspin Run5+6
data taking at LHCb

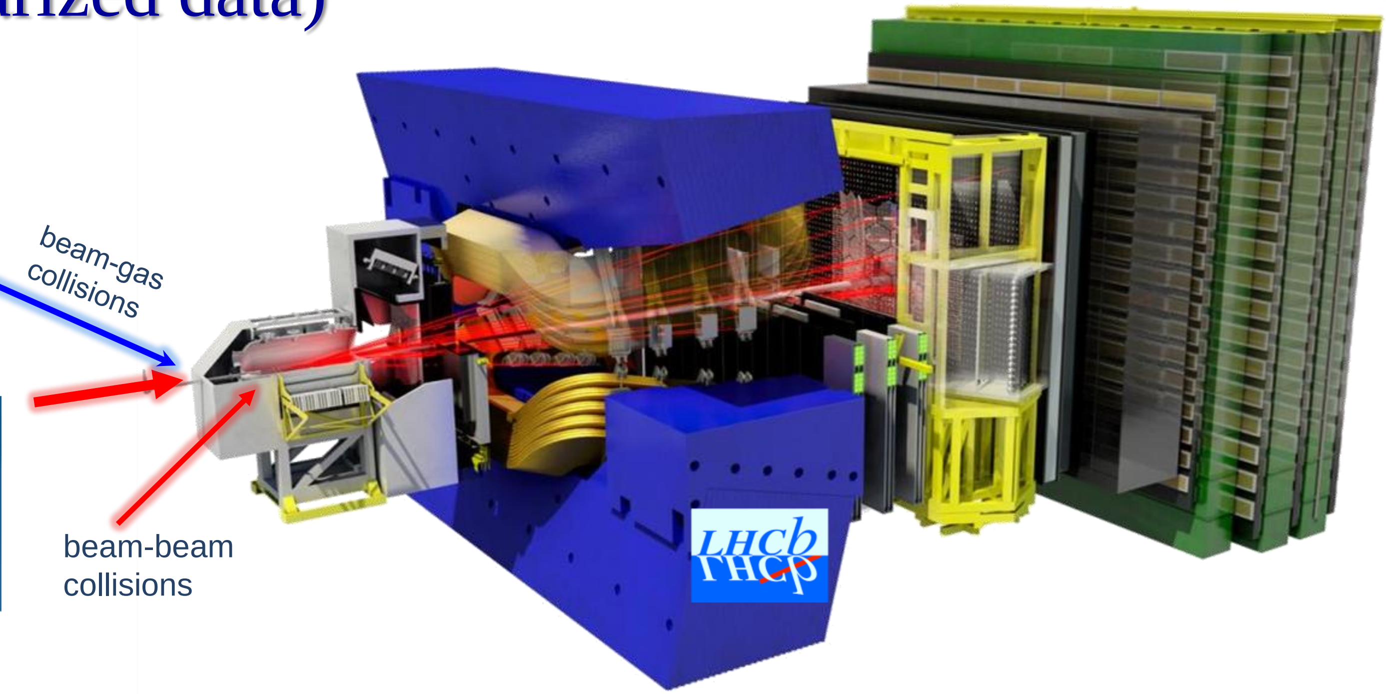
LHCspin

SMOG2 (unpolarized data)

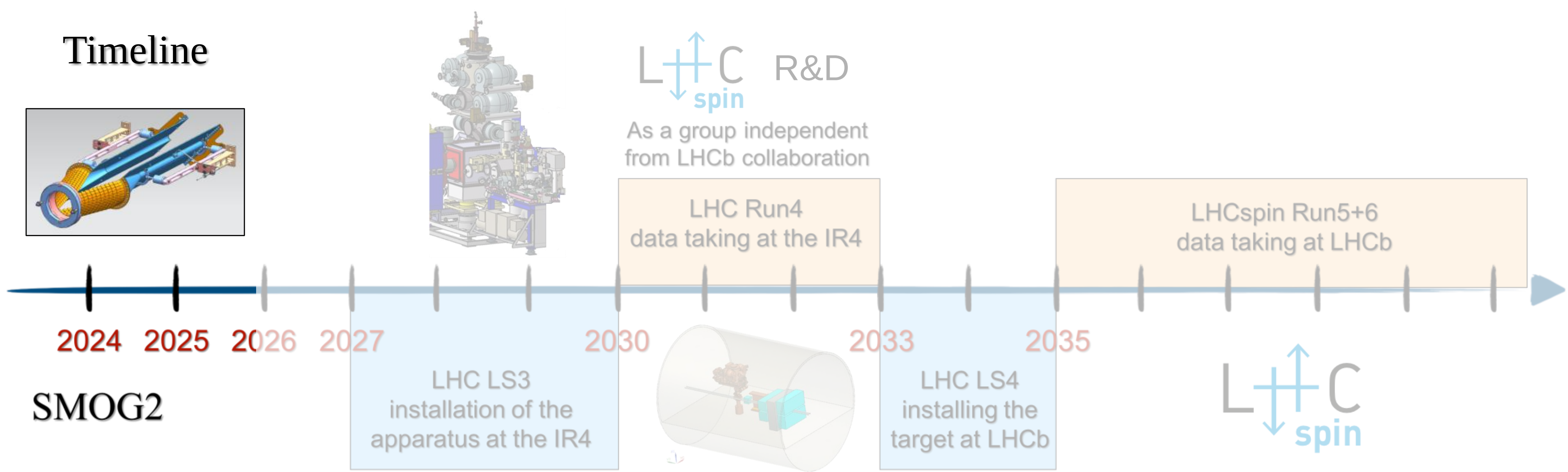




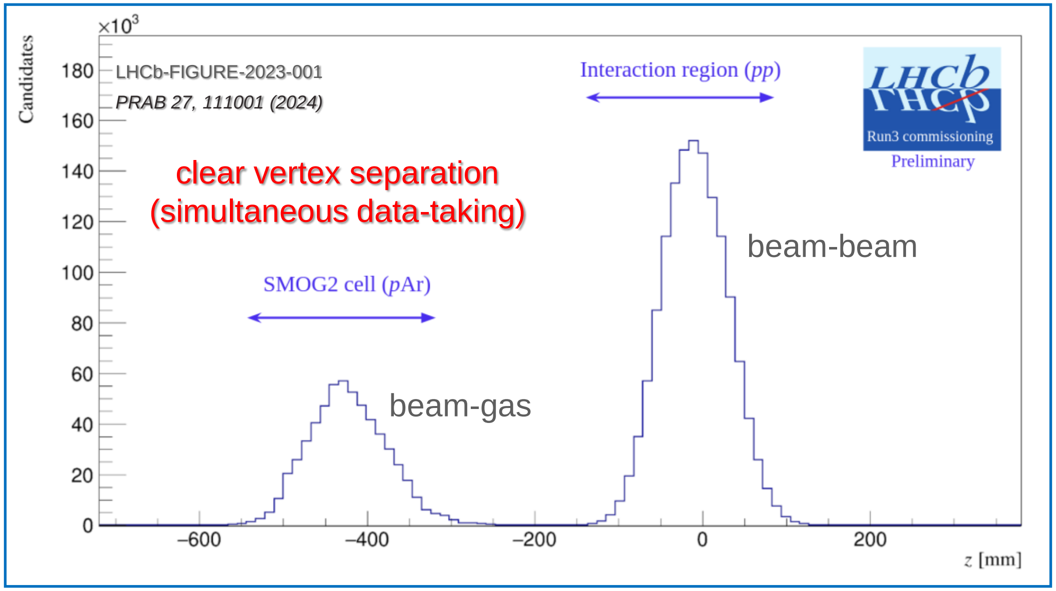
5 mm radius x 200 mm length

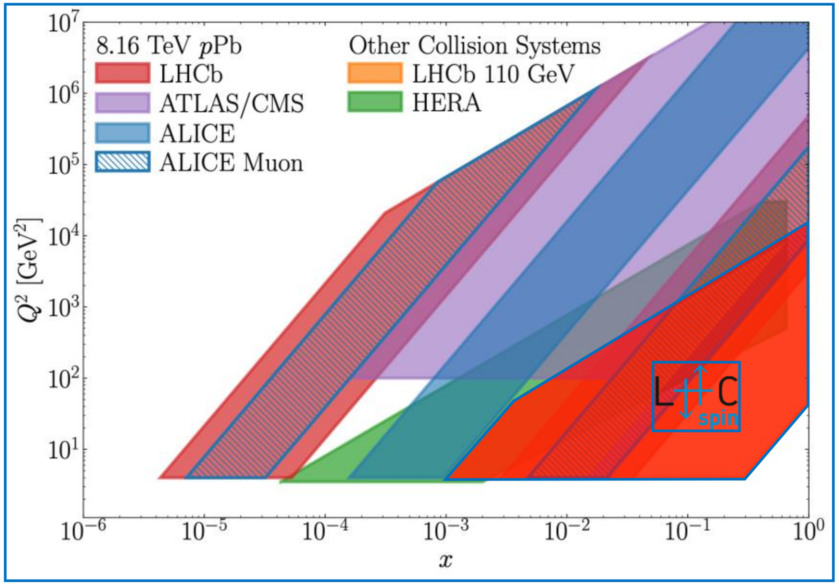


Timeline

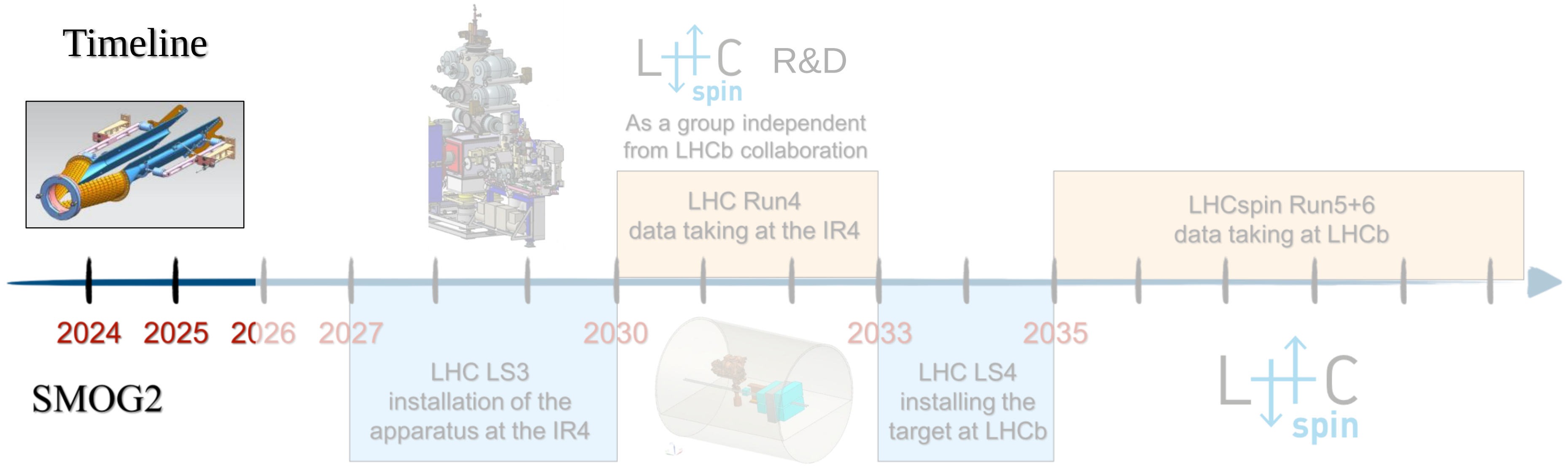


SMOG2 (unpolarized data) gas target: H_2, D_2, N_2, O_2, He, Ne, Ar, Kr, Xe





Negligible impact on the beam lifetime ($\tau^{p-H_2}_{beam-gas} \sim 2000$ days , $\tau^{Pb-Ar}_{beam-gas} \sim 500$ h)



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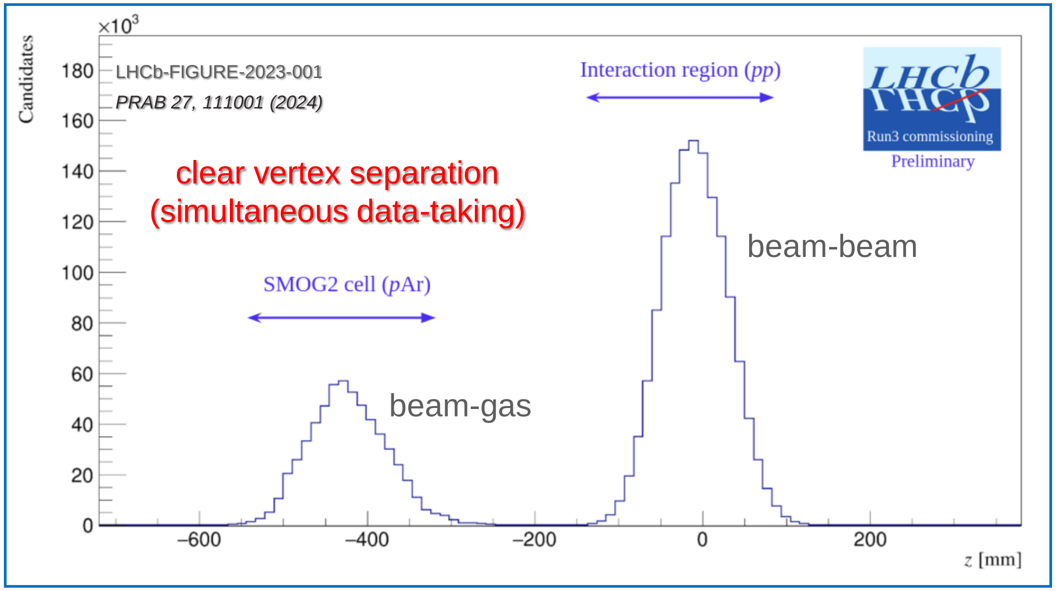
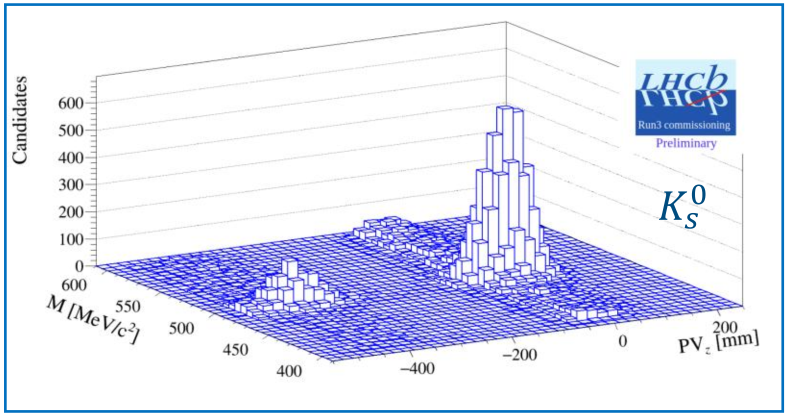
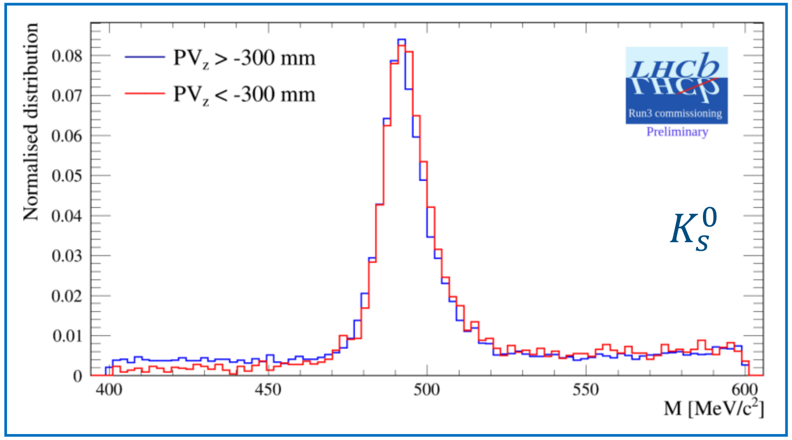
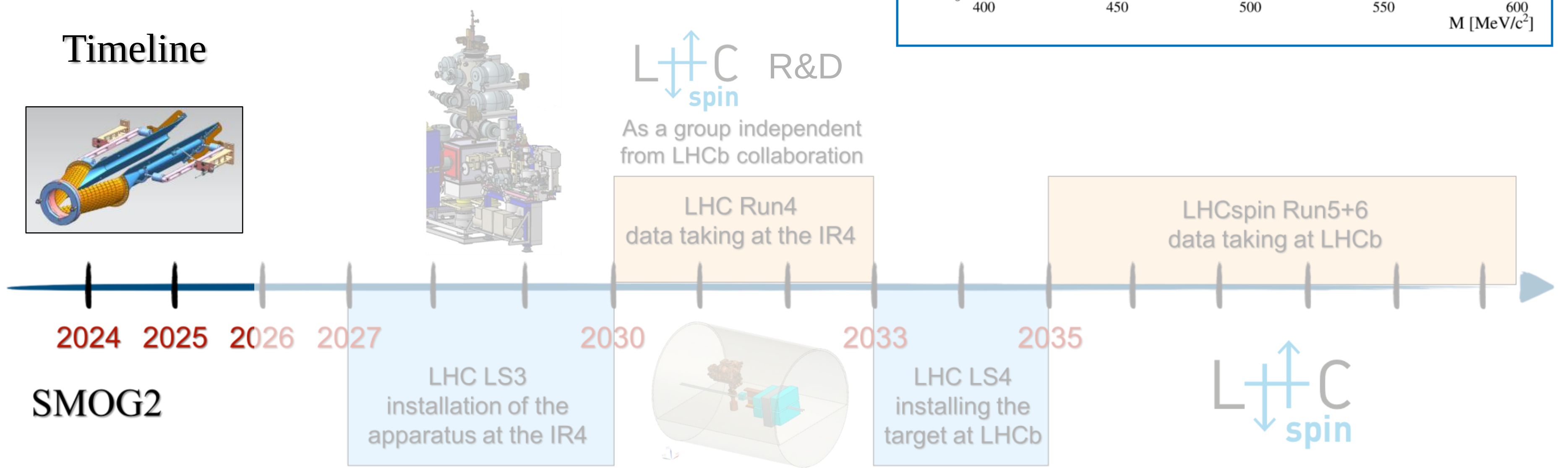


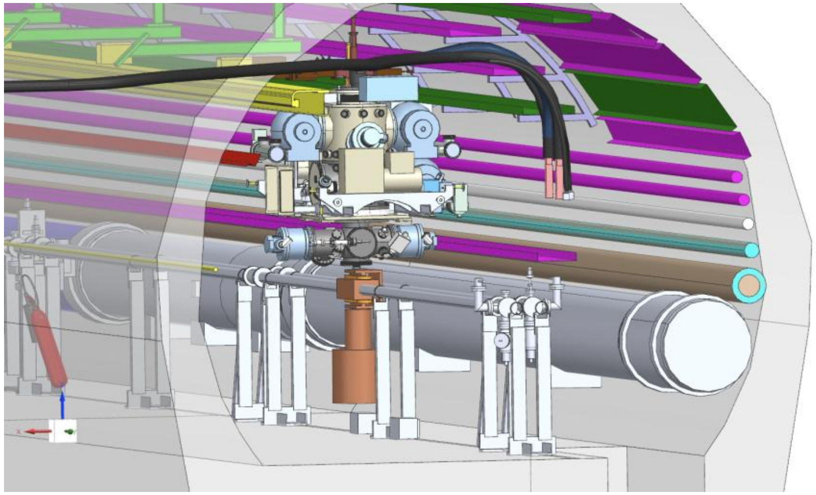


Negligible impact on the beam lifetime

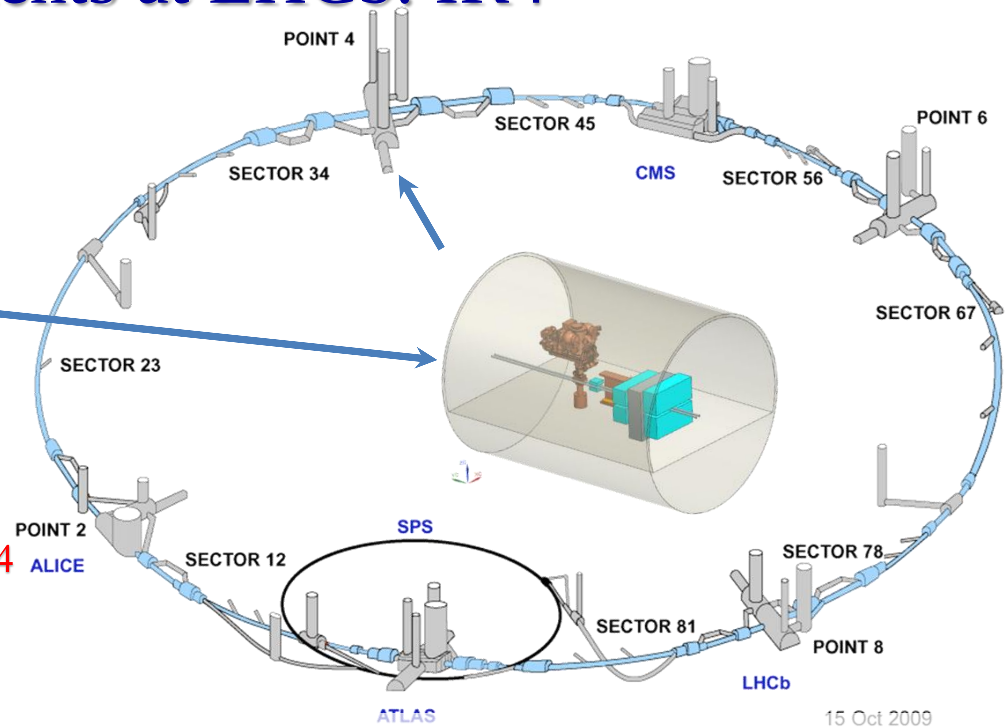




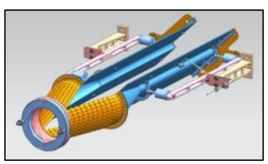
Towards polarized measurements at LHCb: IR4

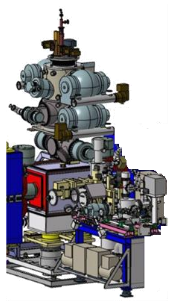


Install a compact "LHCb independent" apparatus in IR4
purpose: R&D to have a "plug & play" PGT for Run5
perform unique first ever physics measurements
perform service measurements related to LHC



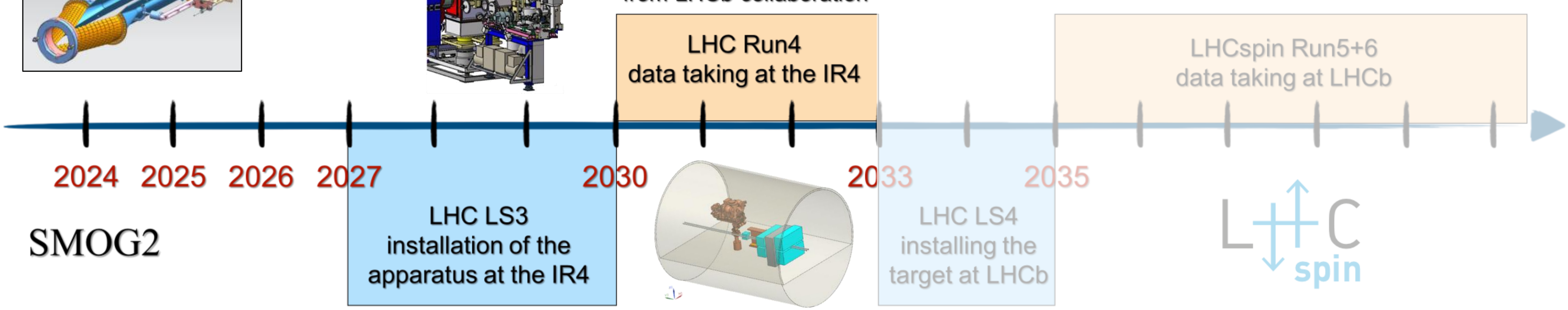
Timeline





LHCspin R&D

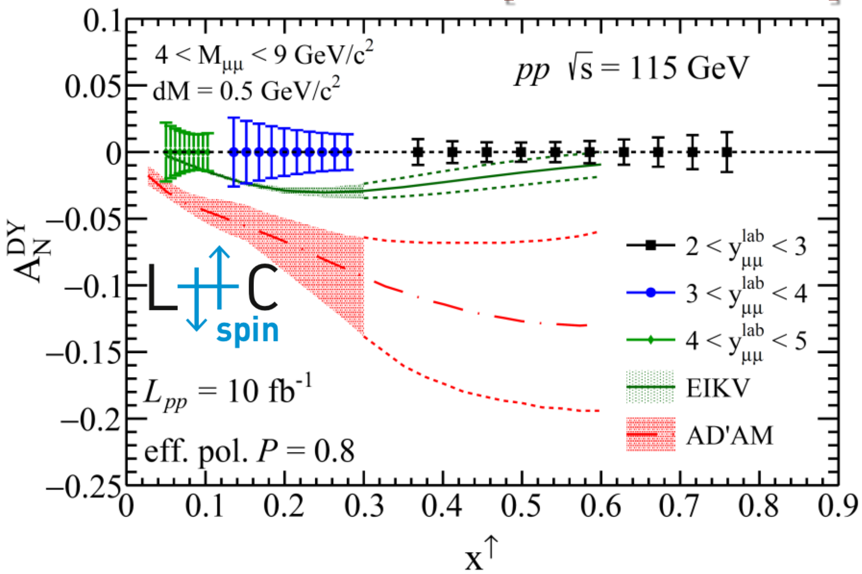
As a group independent from LHCb collaboration



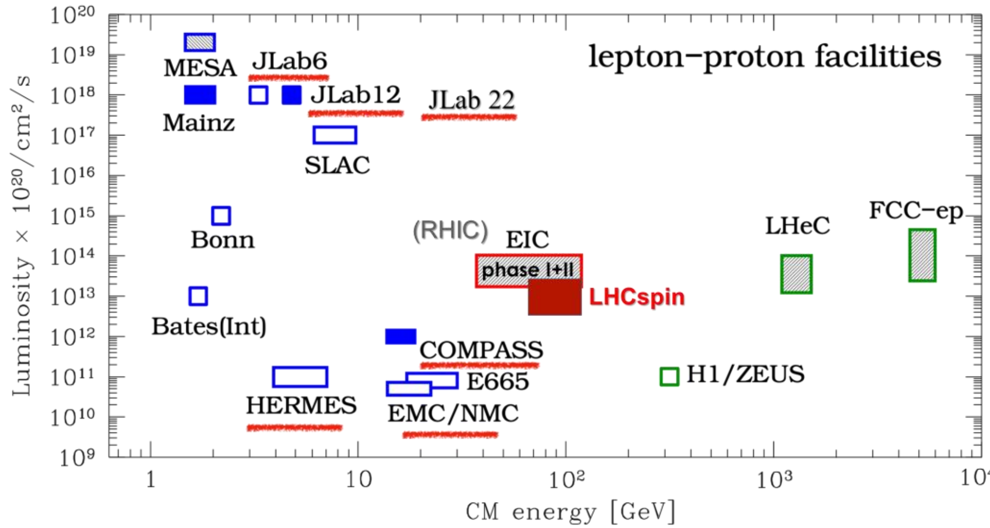
SMOG2

LHCspin experiment

[arXiv:1807.00603]

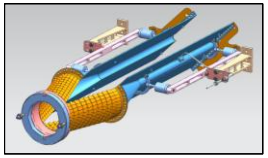


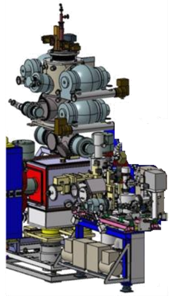
Channel	Events / week	Total yield
$J/\psi \to \mu^+\mu^-$	1.3×10^7 !!	1.5×10^9
$D^0 \to K^-\pi^+$	6.5×10^7	7.8×10^9
$\psi(2S) \to \mu^+\mu^-$	2.3×10^5	2.8×10^7
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	8.5	1.0×10^3
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	2.5×10^1	3.1×10^3
Drell Yan ($5 < M_{\mu\mu} < 9$ 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 effect / sign-change

Timeline





As a group independent from LHCb collaboration

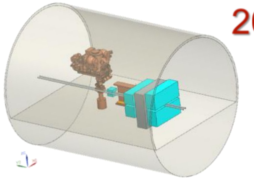
LHC Run4 data taking at the IR4

LHCspin Run5+6 data taking at LHCb

2024 2025 2026 2027 2030 2033 2035

SMOG2

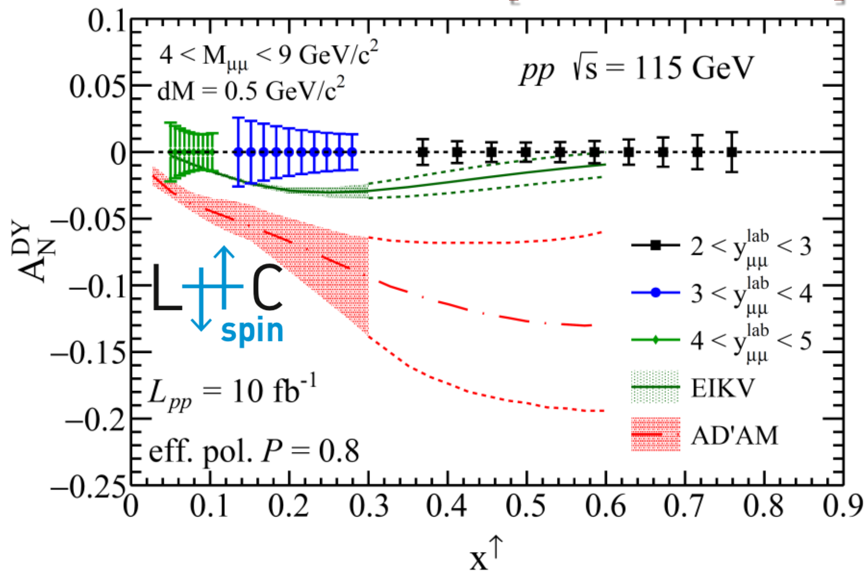
LHC LS3 installation of the apparatus at the IR4



LHC LS4 installing the target at LHCb

LHCspin experiment

[arXiv:1807.00603]



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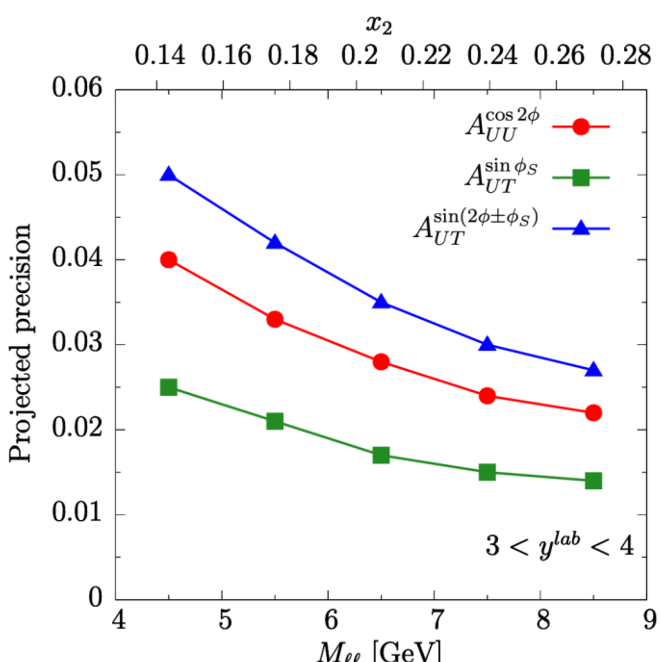
- Precise *spin asymmetry* on $J/\Psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ for $pH^\uparrow$ collisions in just few weeks
- Inclusive quarkonia production in (un)polarized pp interactions - ideal observable to access gTMDs
- Flavor separation using H/D, EMC effect
- Spin physics in heavy-ion collisions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



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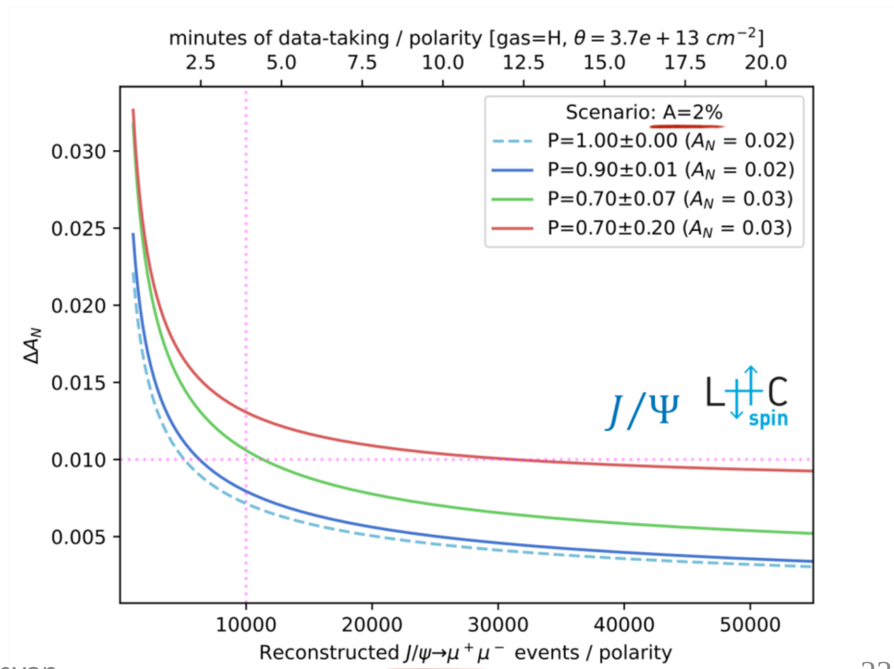
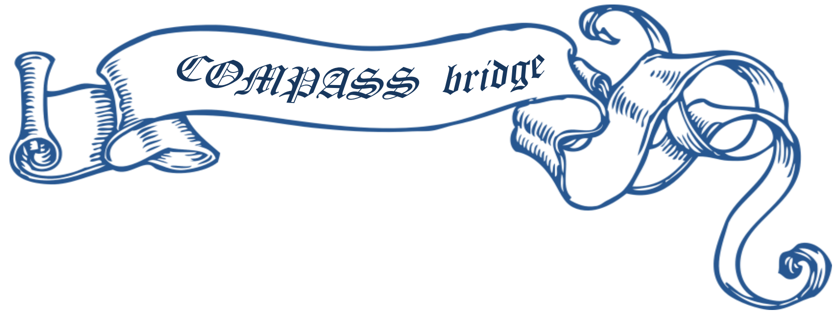
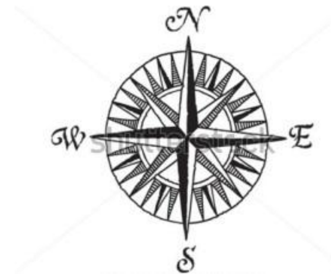
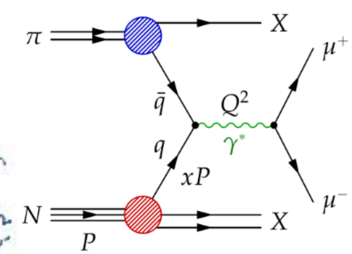
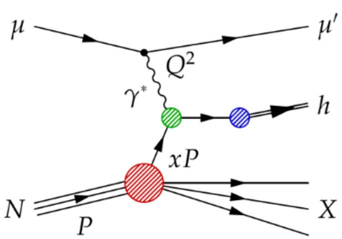






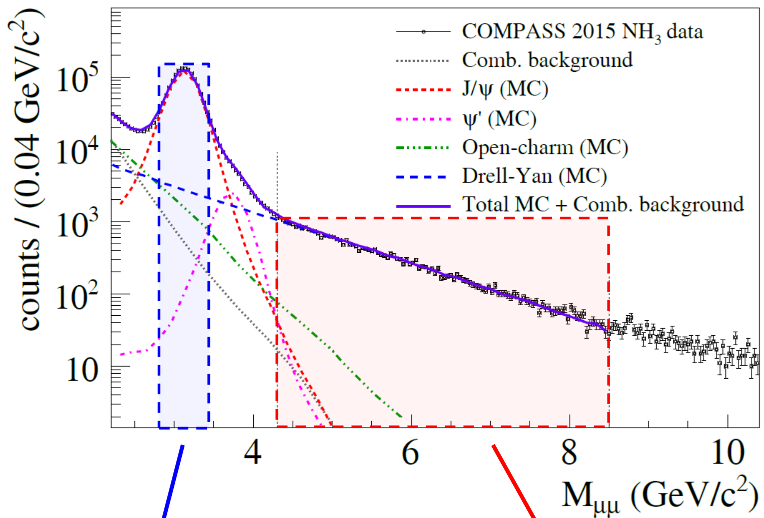


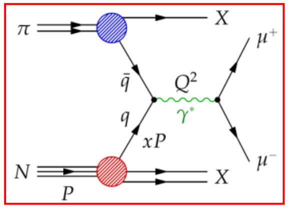
Drell-Yan



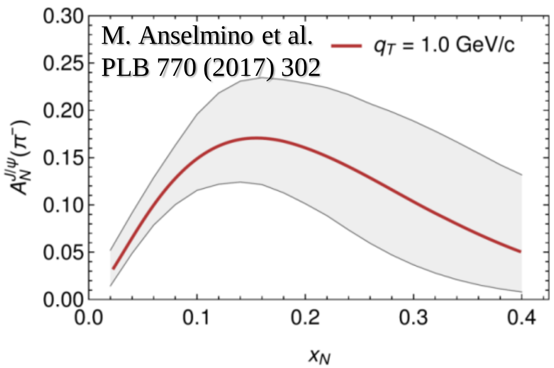
SIDIS

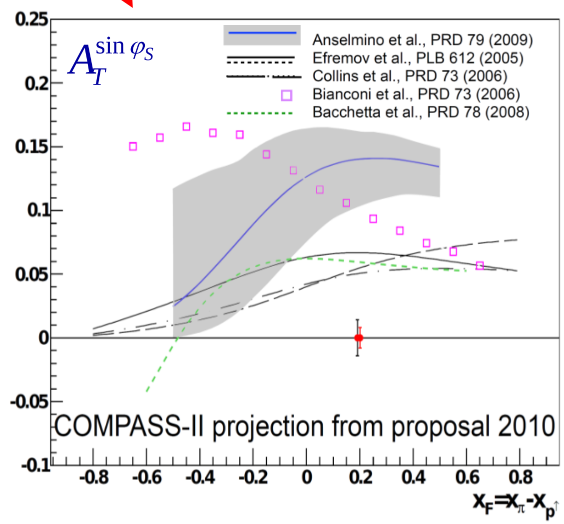
Single-polarized Drell-Yan cross-section at twist-2 (LO)





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





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

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

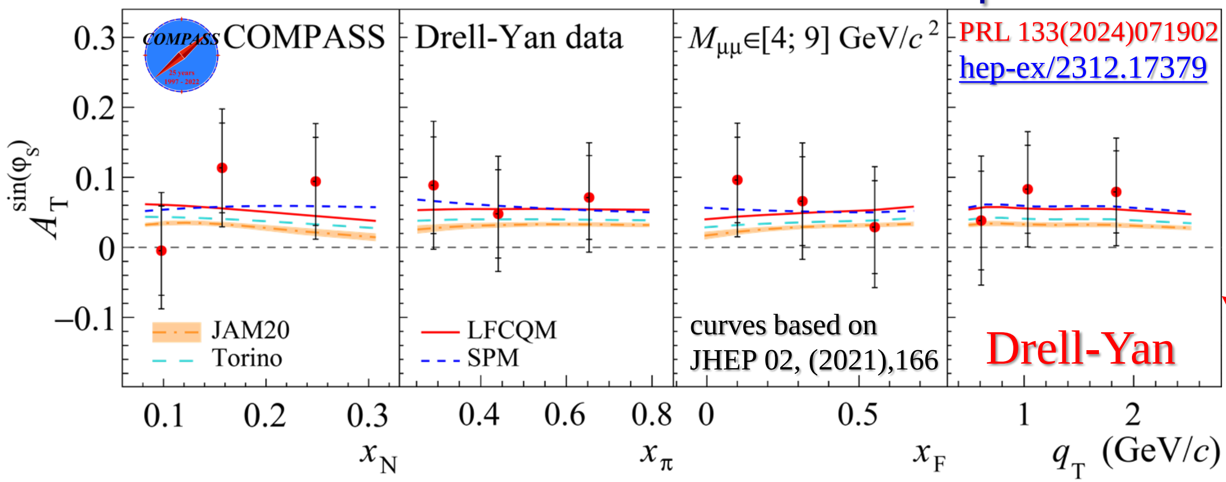
COMPASS phase-II proposal submitted in 2010 (Drell-Yan, DVCS,…)

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

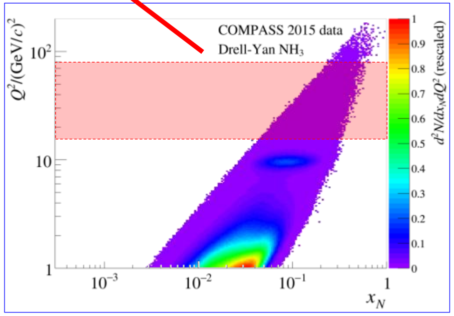
Sivers effect: Drell-Yan and J/ψ

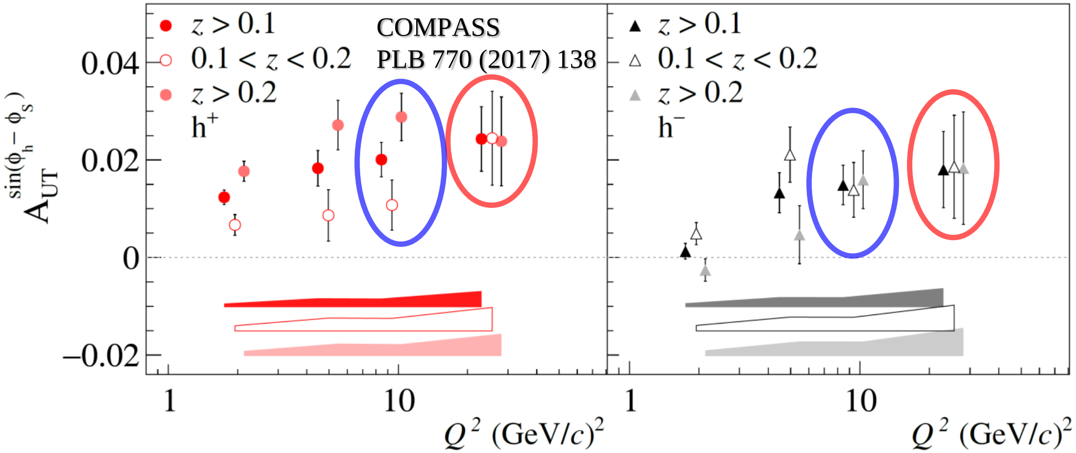
Sivers DY TSA

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



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





Sivers SIDIS TSA

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

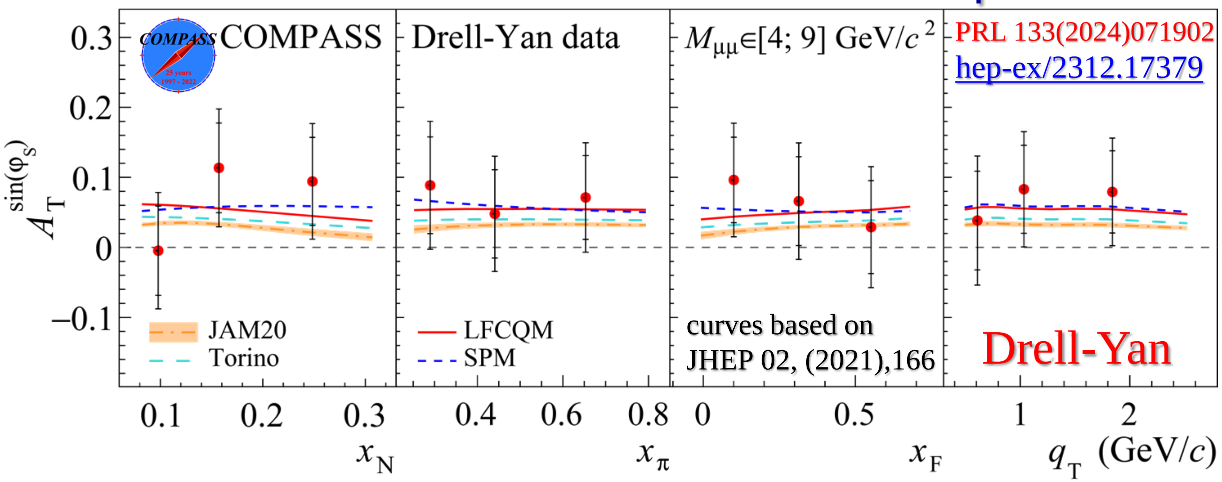
COMPASS proton Sivers measurements

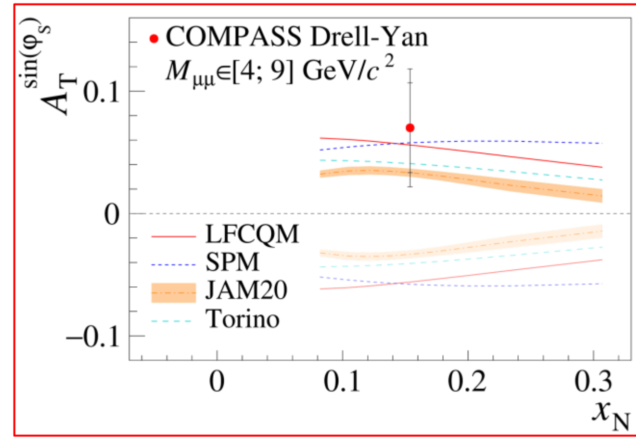
- Clear signal in the matching Q^2 ranges

Sivers effect: Drell-Yan and J/ψ

Sivers DY TSA

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





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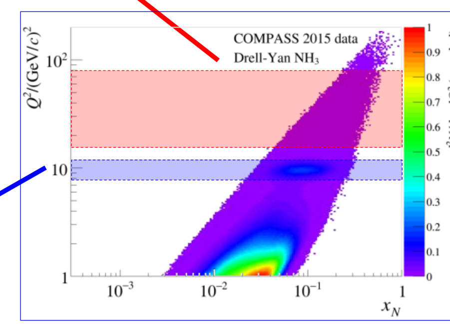
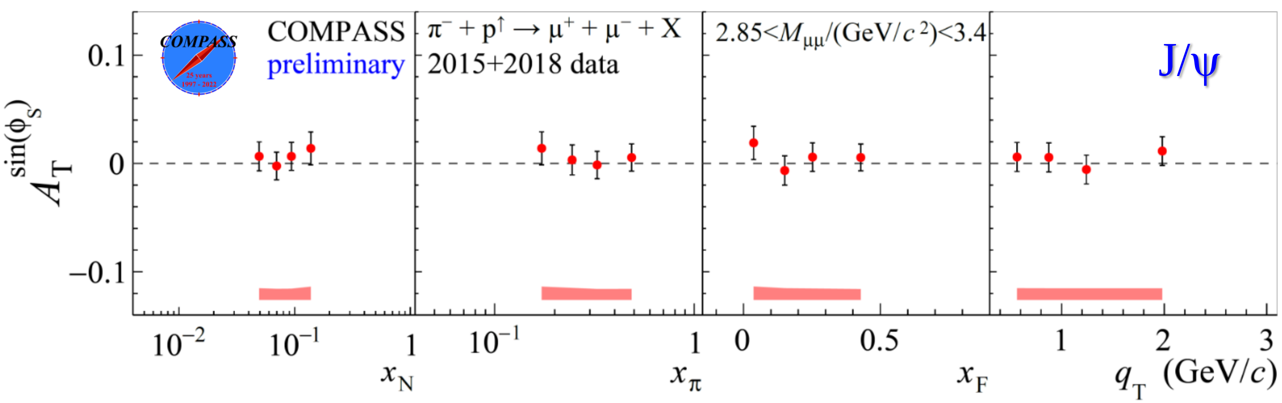
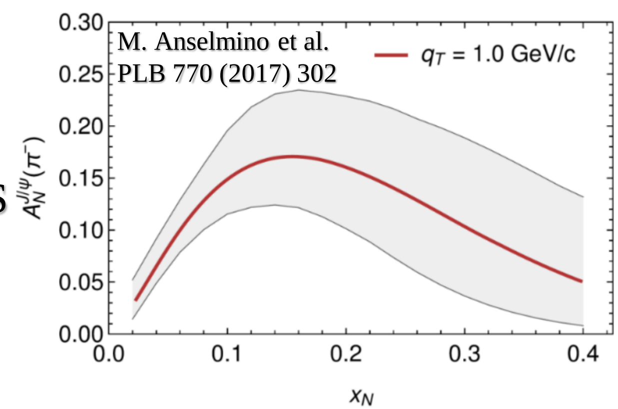




- J/ψ Sivers asymmetry is compatible with zero (within ~ 1%)
- Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS

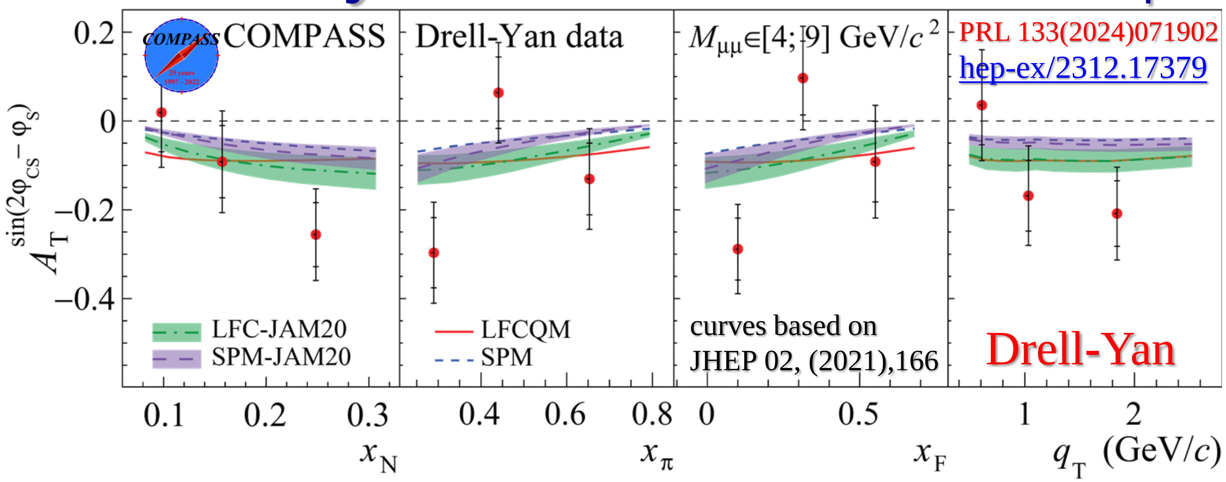


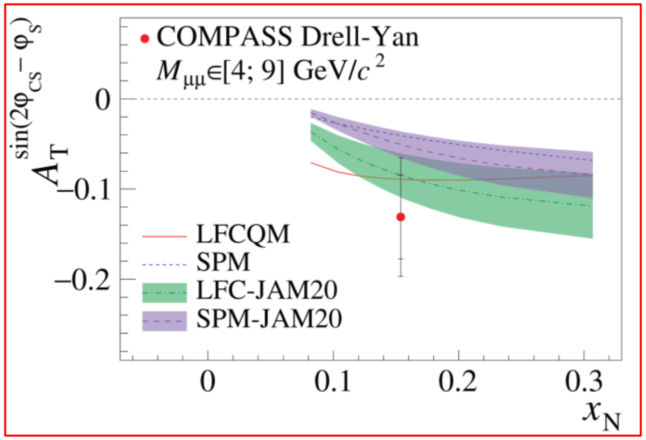
- Hint that J/ψ production might go via gg fusion in COMPASS?
- Access to small gluon TMDs?

Transversity TSA: Drell-Yan and J/ψ

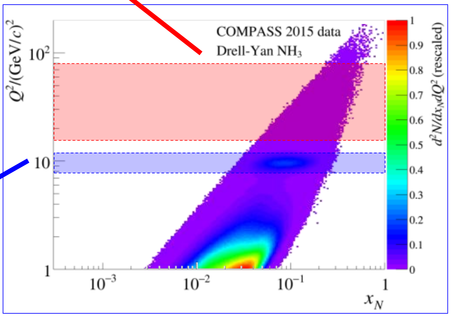
Transversity DY TSA

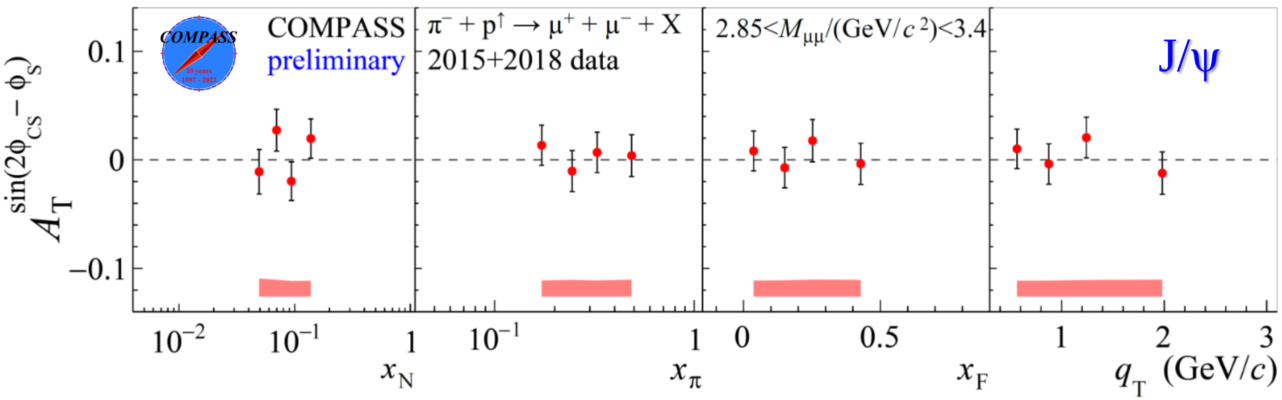
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$

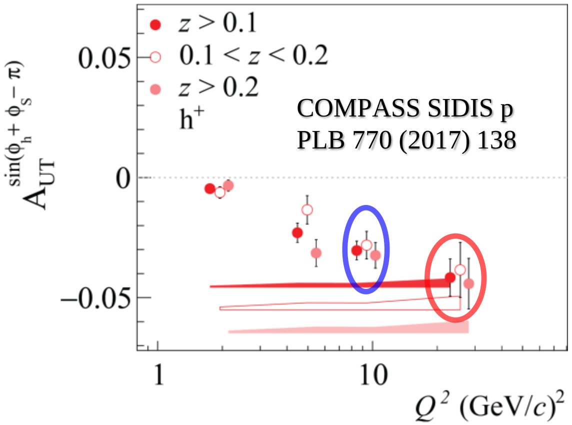




- The Drell-Yan Transversity asymmetry is negative (~2 s.d.)







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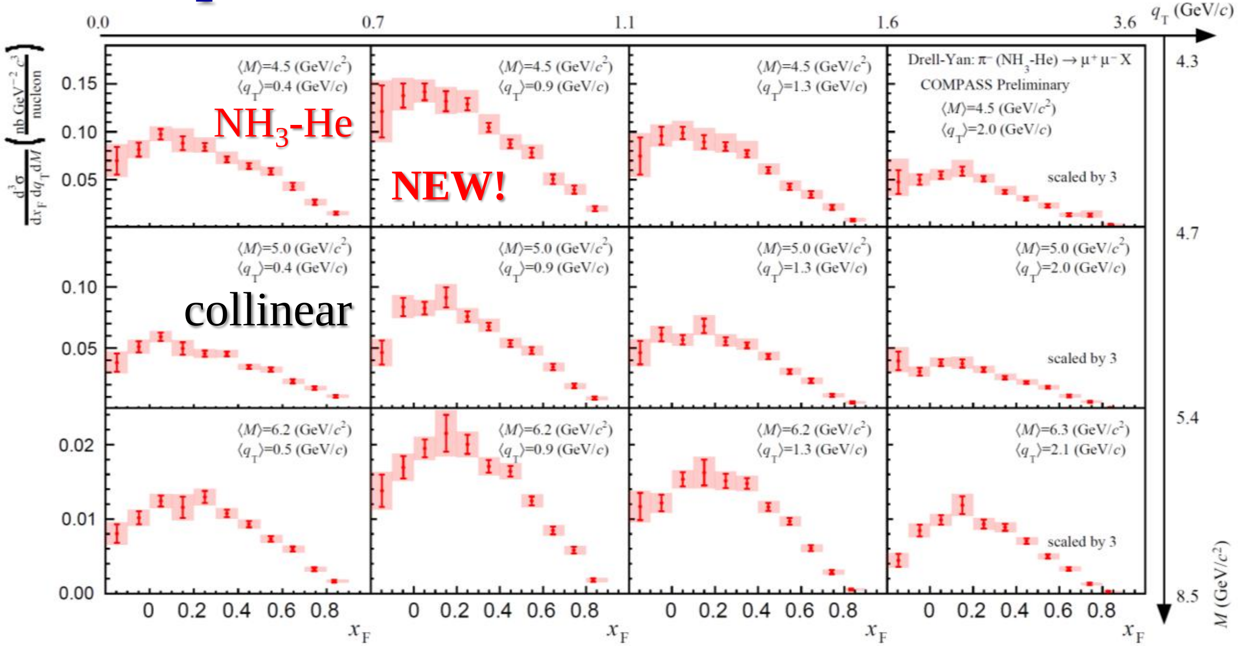
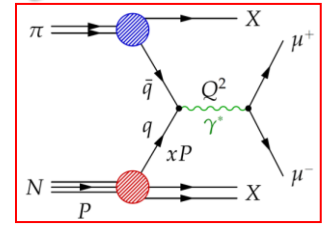
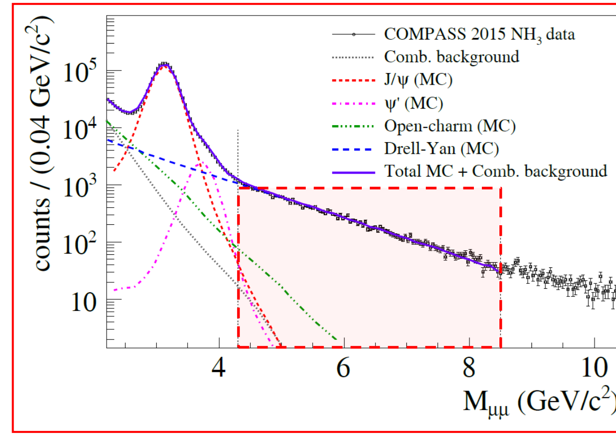
- Access to small gluon TMDs?

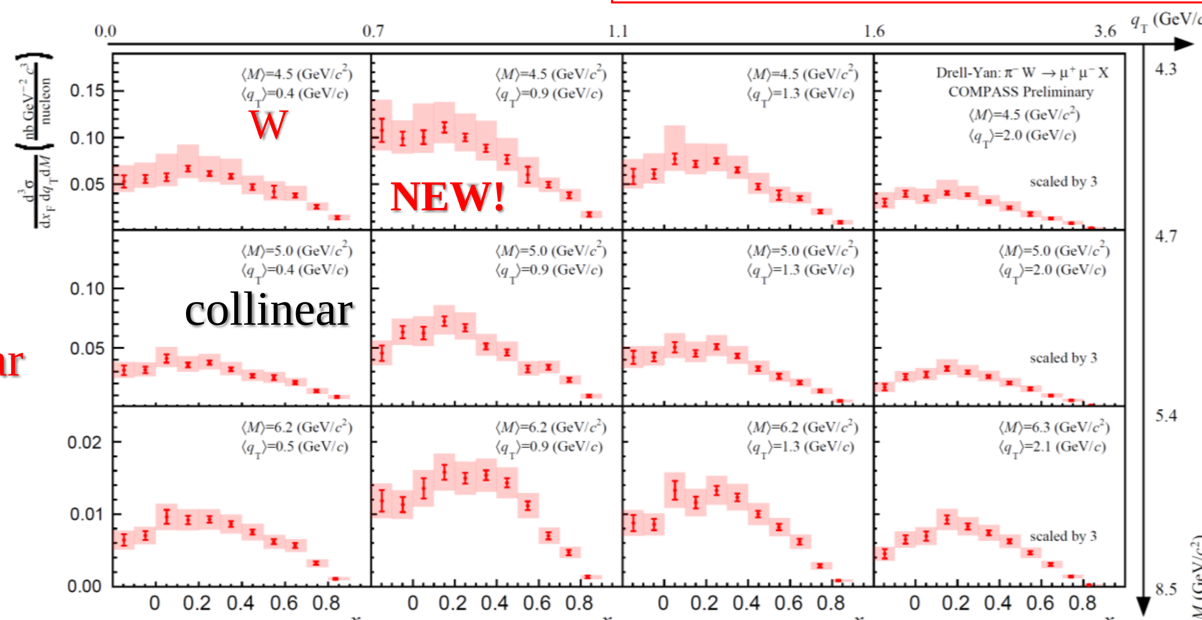
3D unpolarized Drell-Yan cross section on NH_3 and W







- 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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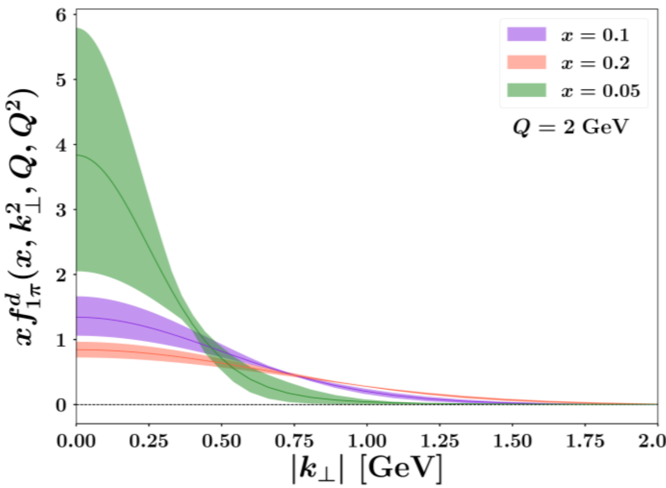
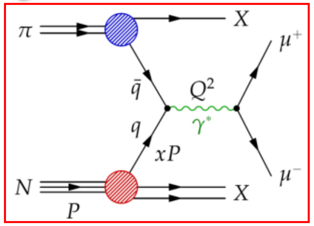
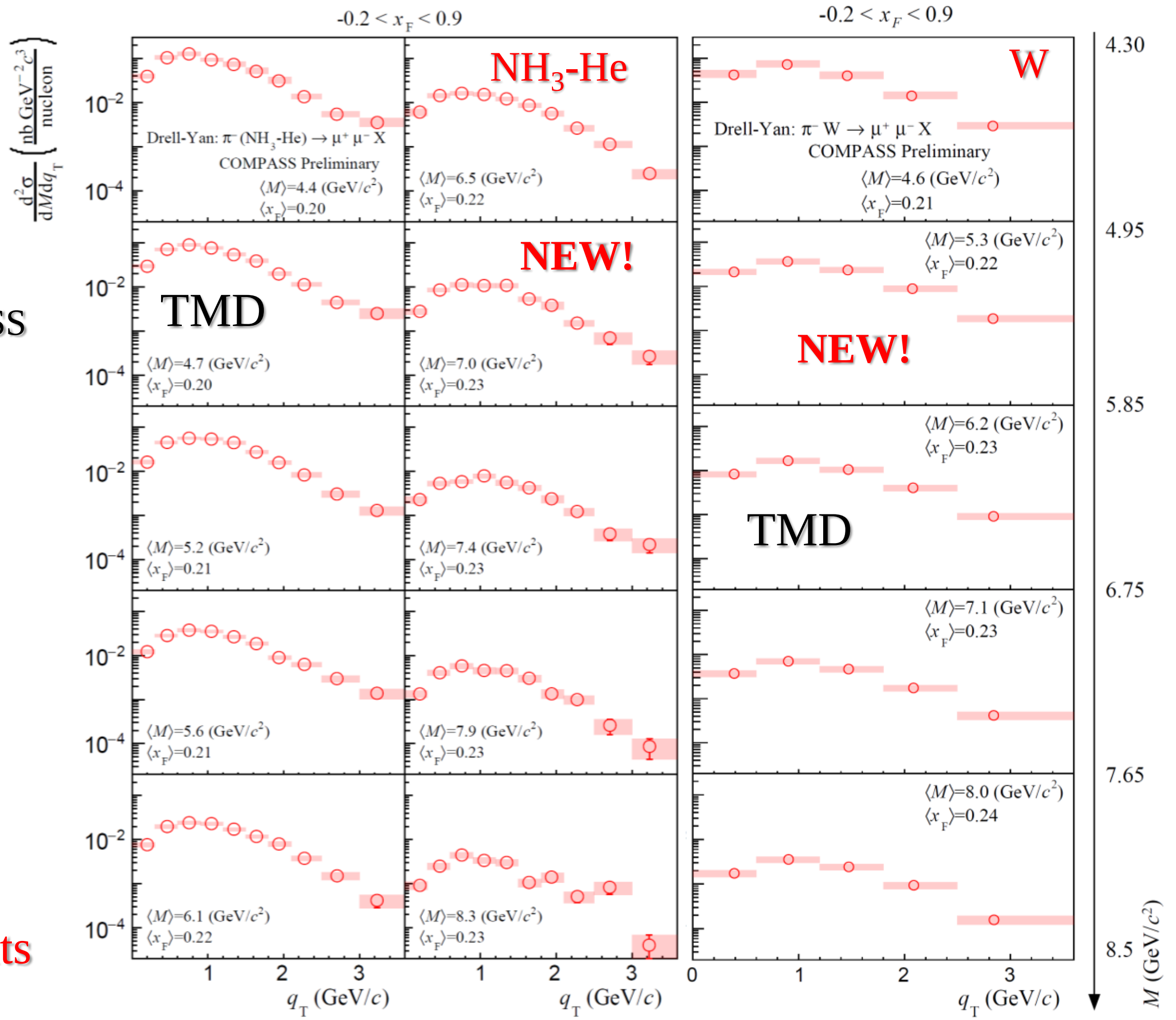


MAP collaboration
Phys. Rev. D. 107, 014014

recent global fit and projections for COMPASS





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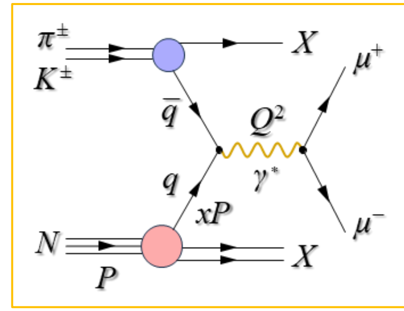
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF
- To be included in future global fits (MAP, JAM, etc.)

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

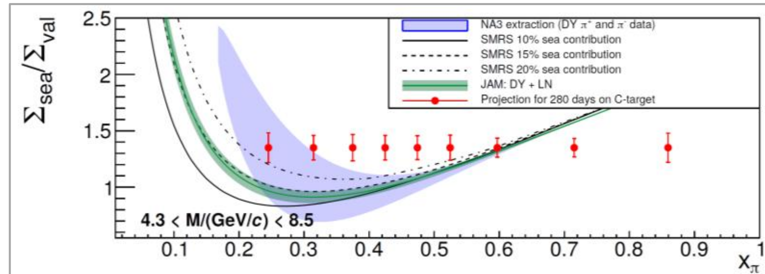
AMBER
Apparatus for Meson and Baryon Experimental Research

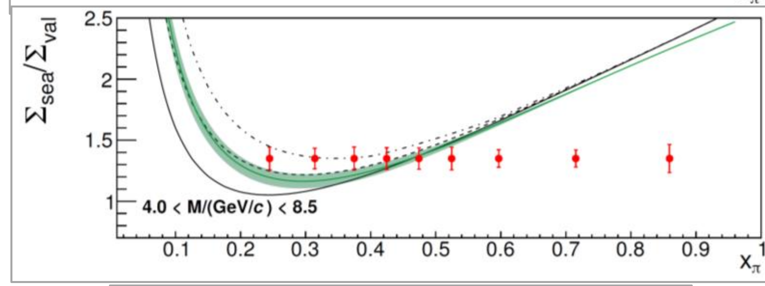
- Unique complementary measurements: $\pi^{\pm}$, $K^{\pm}$
  - Cross-sections, pion and kaon PDFs
    - Data for both collinear and TMD PDF studies
  - Drell-Yan, J/ψ and potentially ψ' channels
  - Study of nuclear effects with C and W



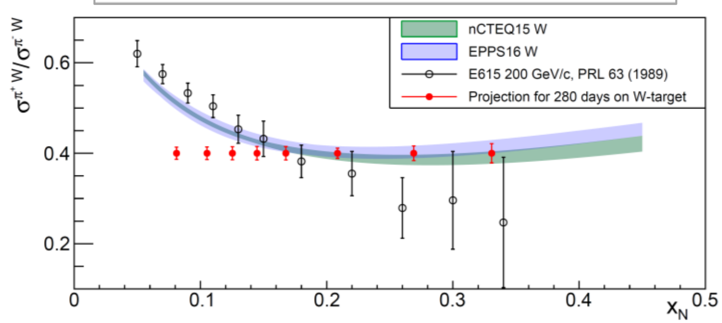
AMBER J/ψ events	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

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



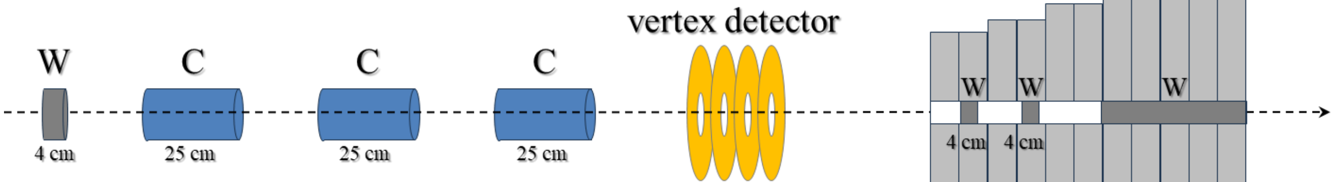


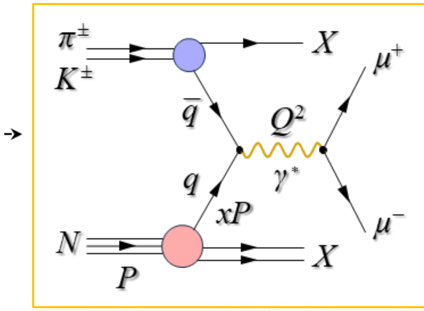
$\Sigma_{val} = \sigma^{\pi^- C} - \sigma^{\pi^+ C}$: only valence-valence
$\Sigma_{sea} = 4\sigma^{\pi^+ C} - \sigma^{\pi^- C}$: no valence-valence



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

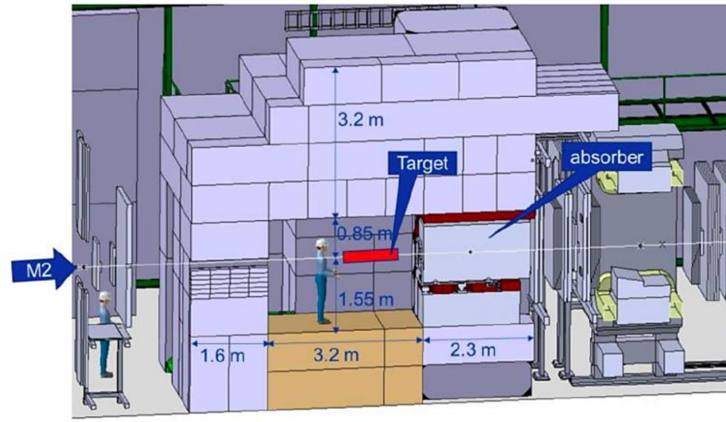
AMBER
Apparatus for Meson and Baryon Experimental Research

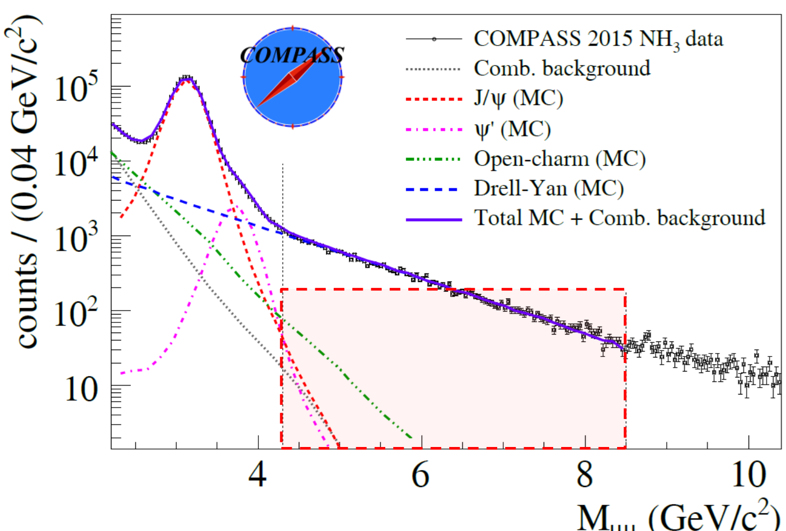


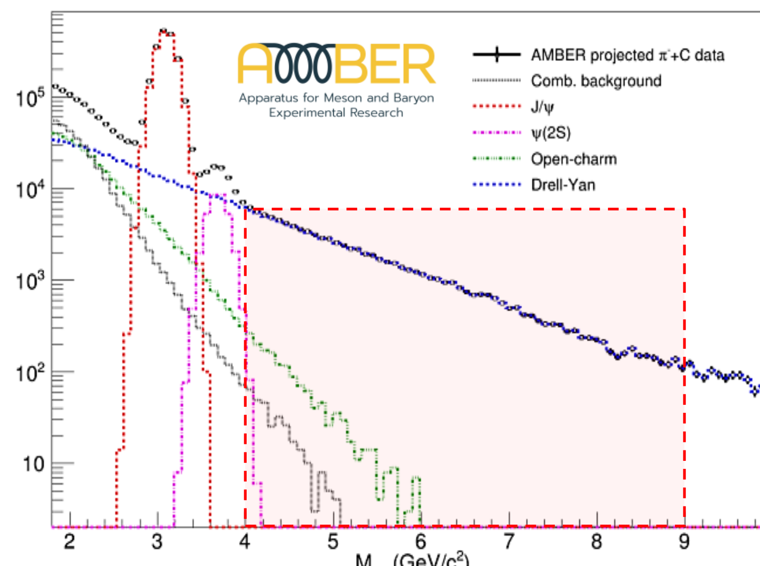


Compared to COMPASS

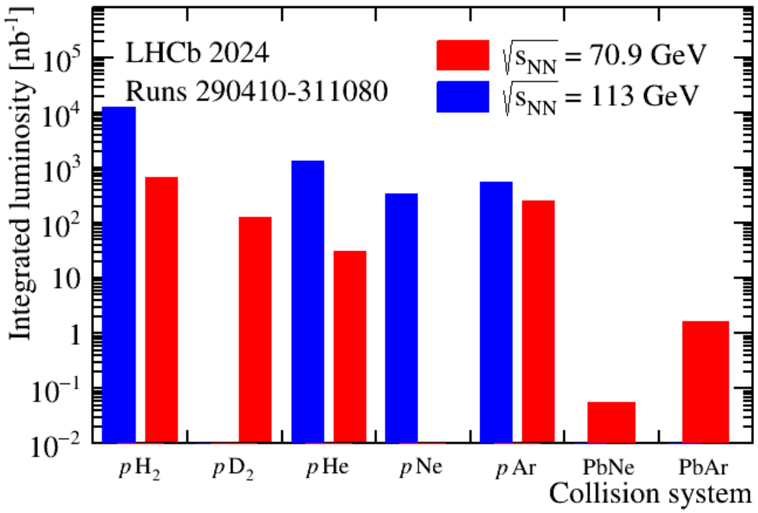
- Light isocalar target (carbon) instead of NH_3-He mix
- Improved mass resolution (~ 100 MeV/c^2)
  - Lower background → enlarge DY mass range
  - J/ψ and ψ(2S) studies
- Wider beam choice: $\pi^{\pm}$, $K^{\pm}$, p / $\bar{p}$, CEDARs (PID)
- Unique complementary measurements: $\pi^{\pm}$, $K^{\pm}$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



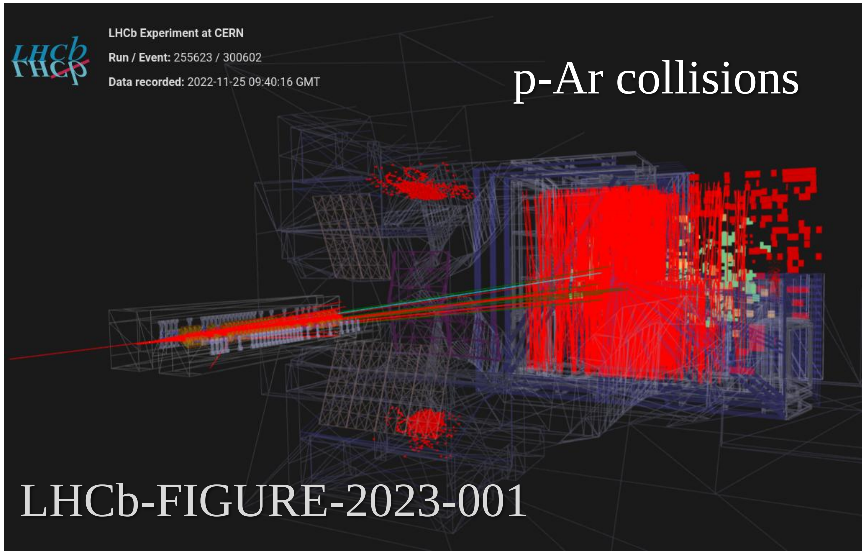




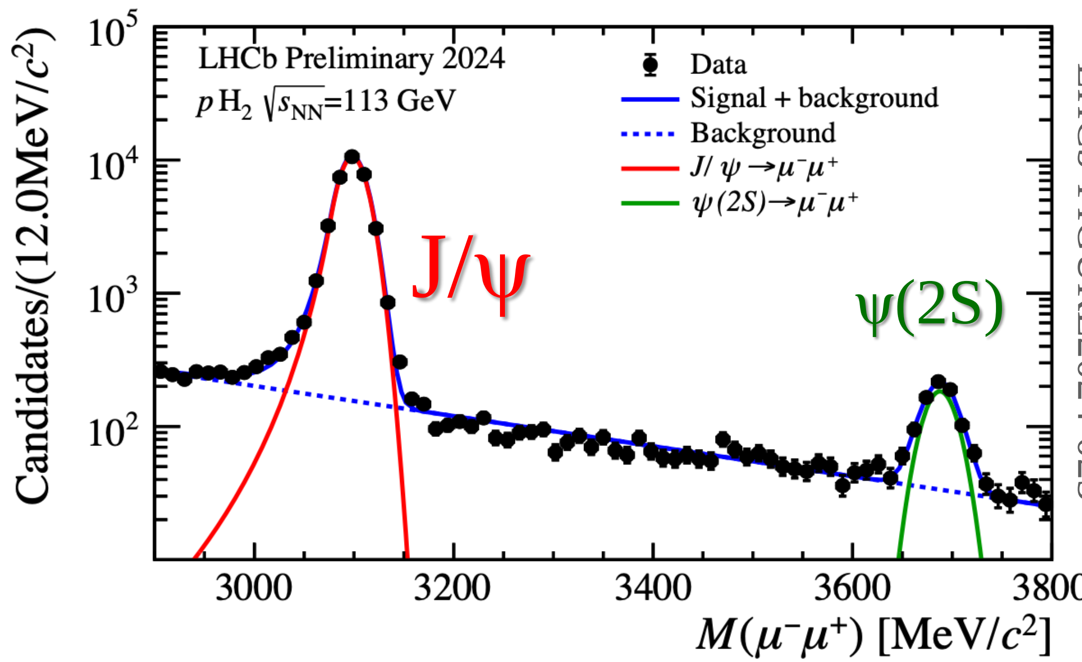
LHC – SMOG2 early data – fantastic precision



A wealth of unique data collected in 2024



tomography of the cell:
residual gas & secondary interactions



LHCb-FIGURE2024-023

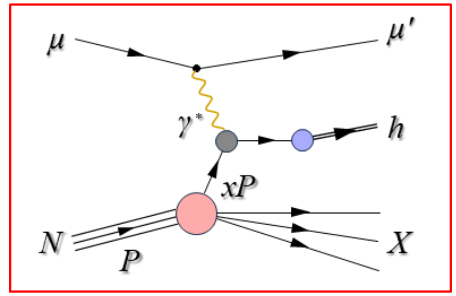
- Recent SIDIS highlights from COMPASS

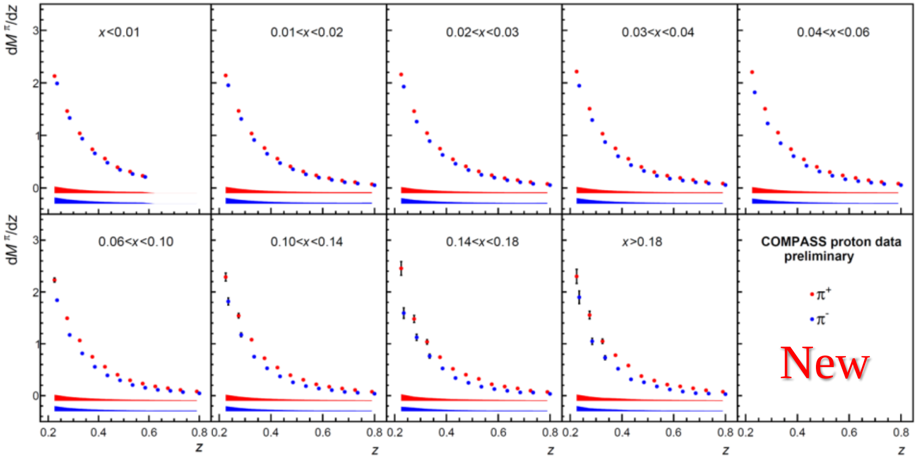
Hadron multiplicities; $h^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ (2016 data)

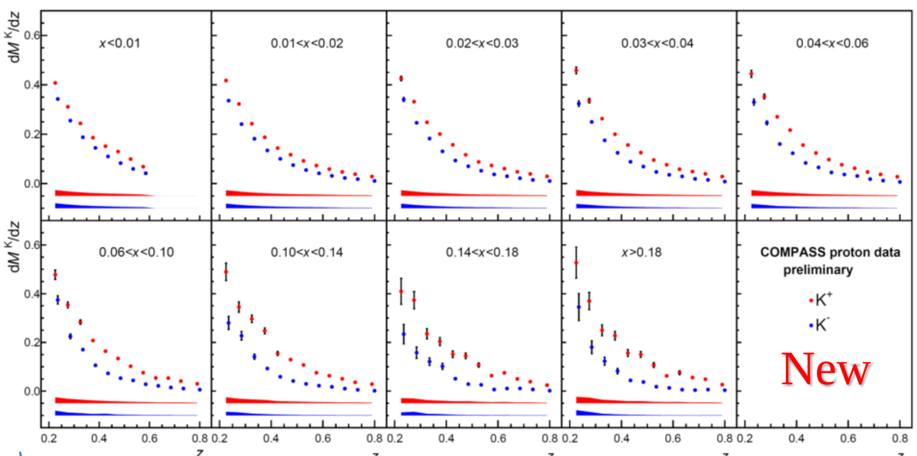
$f_1^q(x, \boldsymbol{k}_T^2)$
number density

collinear

A set of complex corrections:
- Acceptance, rad. corrections, PID, diffractive VMs, etc.



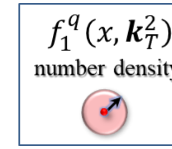




New radiative corrections (DJANGOH)

hep-ex/2410.12005 soon in PRD

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



collinear

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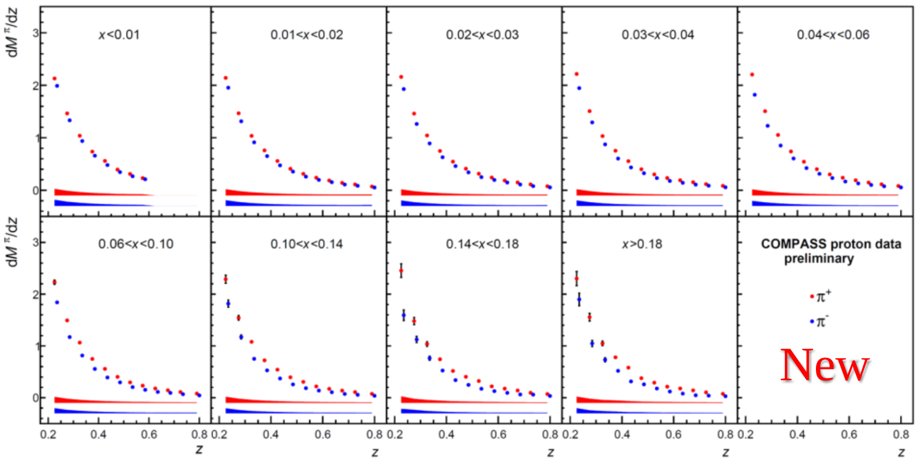

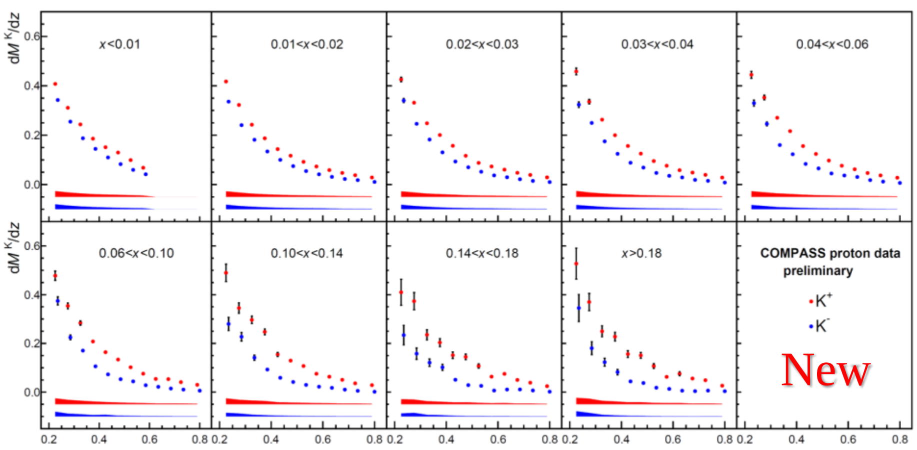

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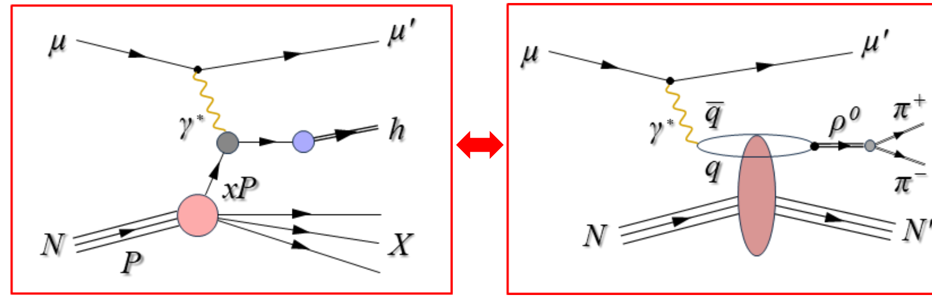


Diffractive VM production

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

SIDIS

- LEPTO 6.5 MC (diffractive contributions off)

Diffractive ρ^0 and ϕ mesons

- HEPGEN generator

Diffractive events enhance at low x and Q^2

- Pions from ρ^0 decay (at high z)

For pions maximum correction can reach even 50%

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

For kaons maximum correction ~24%

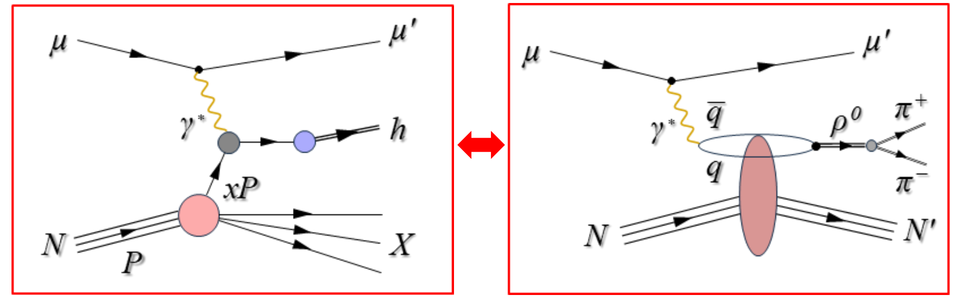
for ($z \approx 0.6$ and $Q^2 \approx 1$ (GeV/c)^2.

Cahn effect in SIDIS: Diffractive VMs contribution

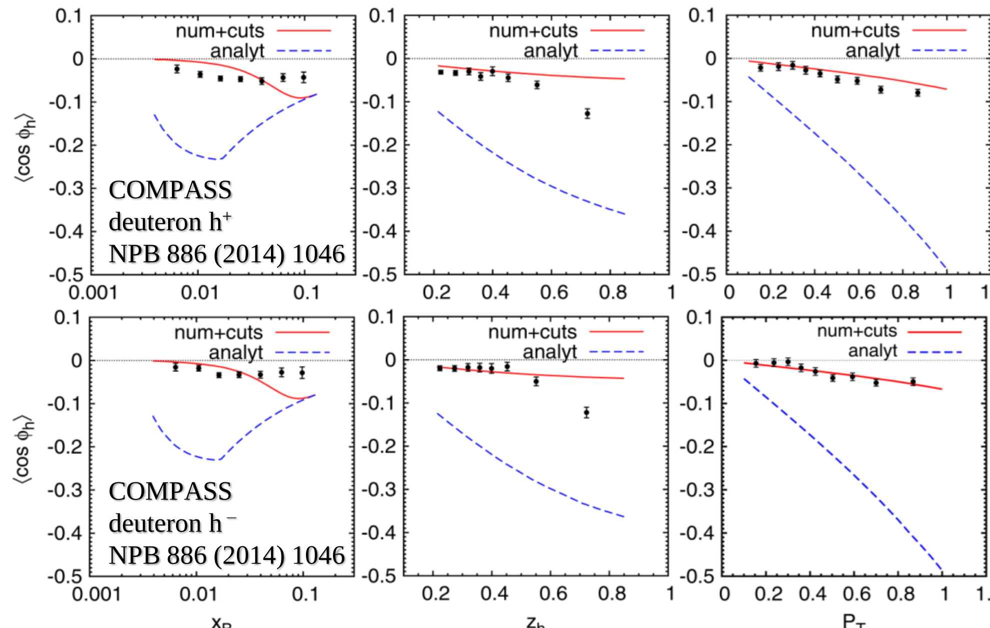
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$
$$\times\Big(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\ldots\Big)$$

Cahn effect

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



?



As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

- Measurements by different experiments

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

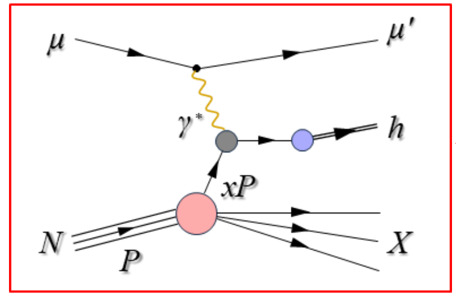
Cahn effect in SIDIS: Diffractive VMs contribution

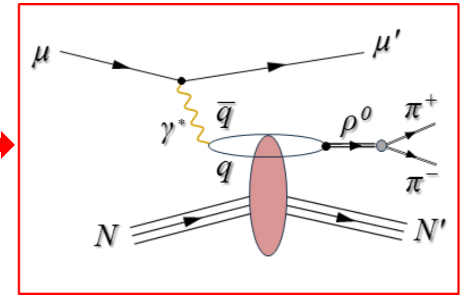
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

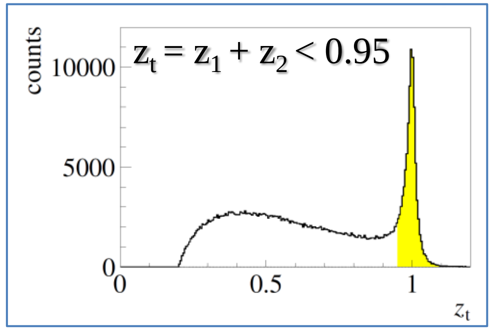
$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\ldots\right)$$

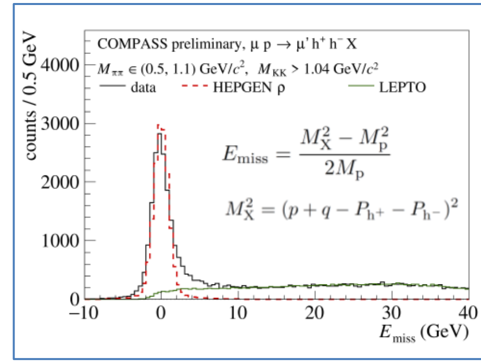
Cahn effect

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









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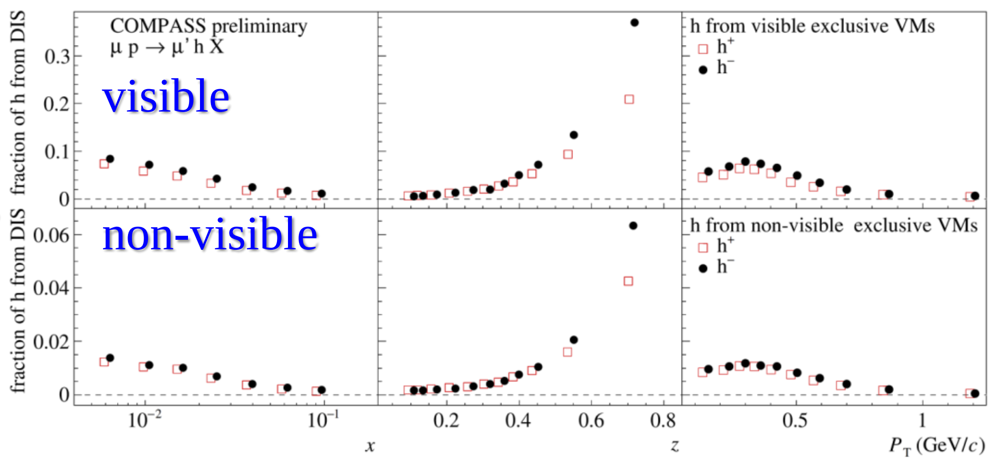
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.

VM fractions

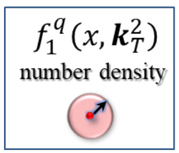


Cahn effect in SIDIS: DVMs

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

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

Cahn effect



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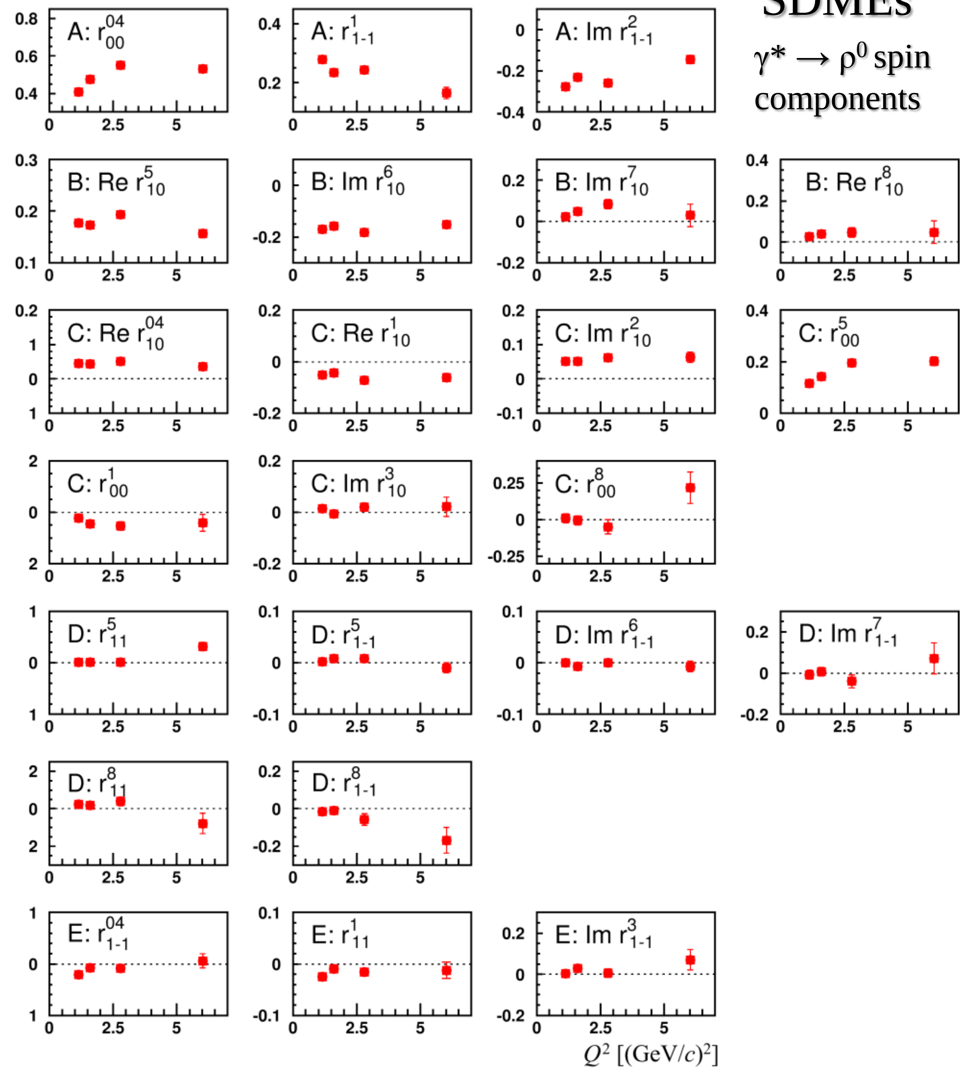
COMPASS, EPJC (2023) 83 924

SDMEs

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



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

Cahn effect in SIDIS: DVMs

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

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

Cahn effect

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

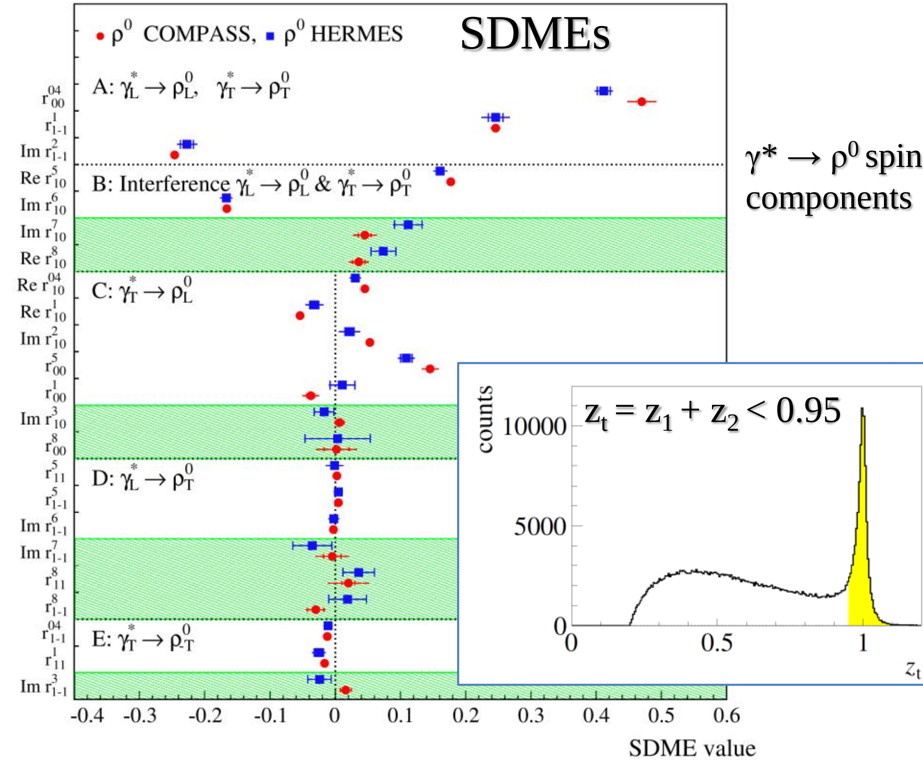
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

"Visible" hadron pairs

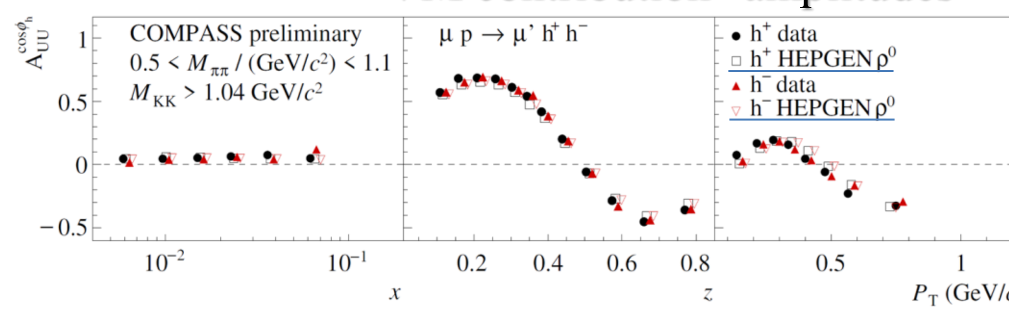
- Both hadrons reconstructed
- Removed by selecting: $z_t = z_{h+} + z_{h-} < 0.95$

COMPASS, EPJC (2023) 83 924



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

VM contribution "amplitudes"



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

Cahn effect in SIDIS: DVMs

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

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

Cahn effect

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

As of 1978 – simplistic kinematic effect:

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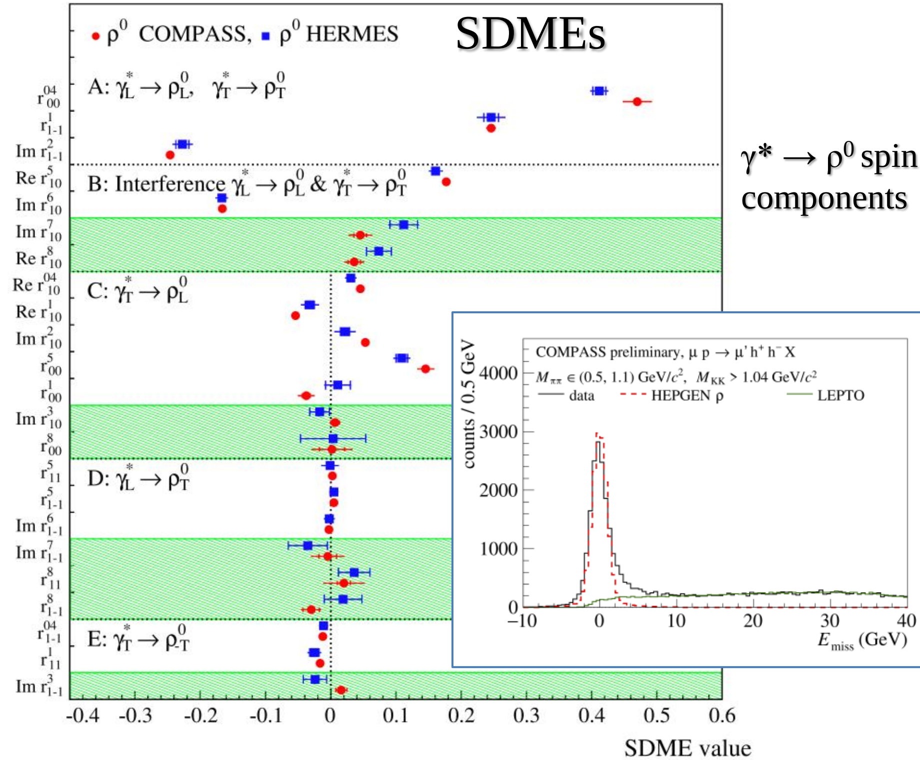
"Visible" hadron pairs

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

"Invisible" hadron pairs

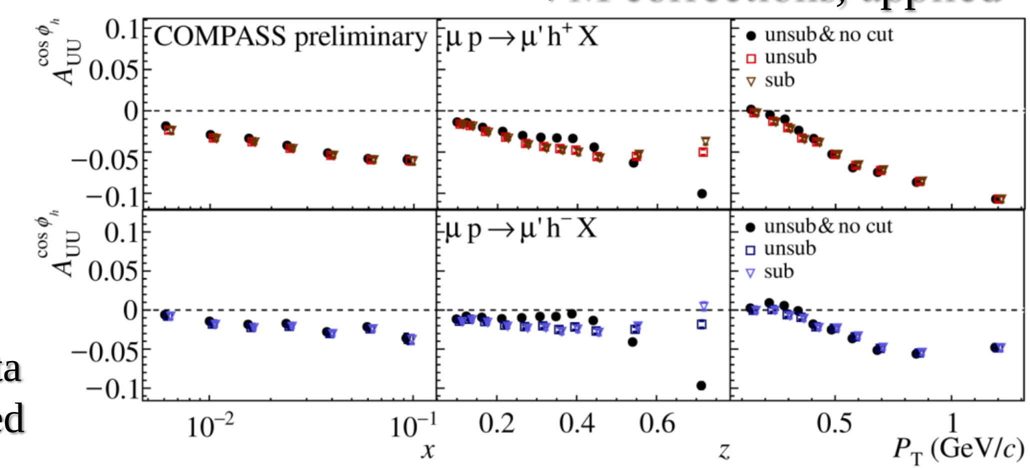
- Only one hadron out of two is reconstructed
- Subtraction done at the level of ϕ_h using simulated HEPGEN distribution for VMs
- HEPGEN and Lepto are normalized to the data using E_{miss} distribution, SIDIS tail is subtracted

COMPASS, EPJC (2023) 83 924



γ* → ρ⁰ spin components

VM corrections, applied

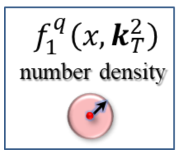


Cahn effect in SIDIS: DVMs and RCs

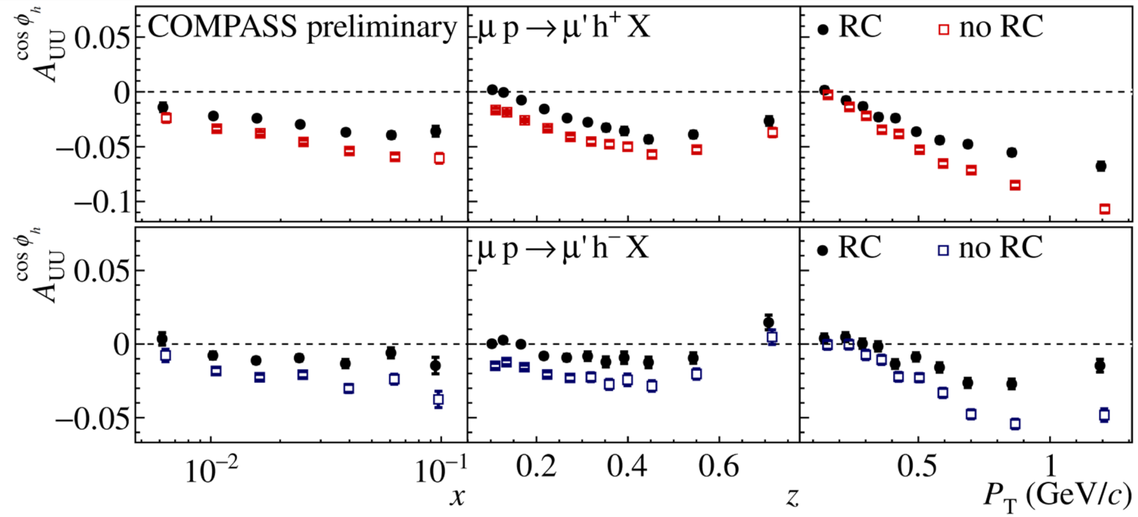
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

Cahn effect



RC corrections, applied



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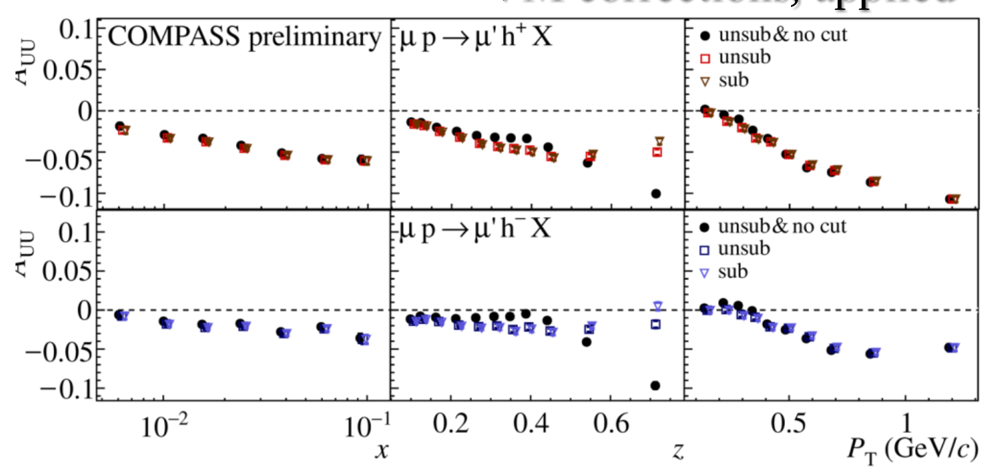
As of 2023 – complex SF (twist-2/3 functions)

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

VM corrections, applied

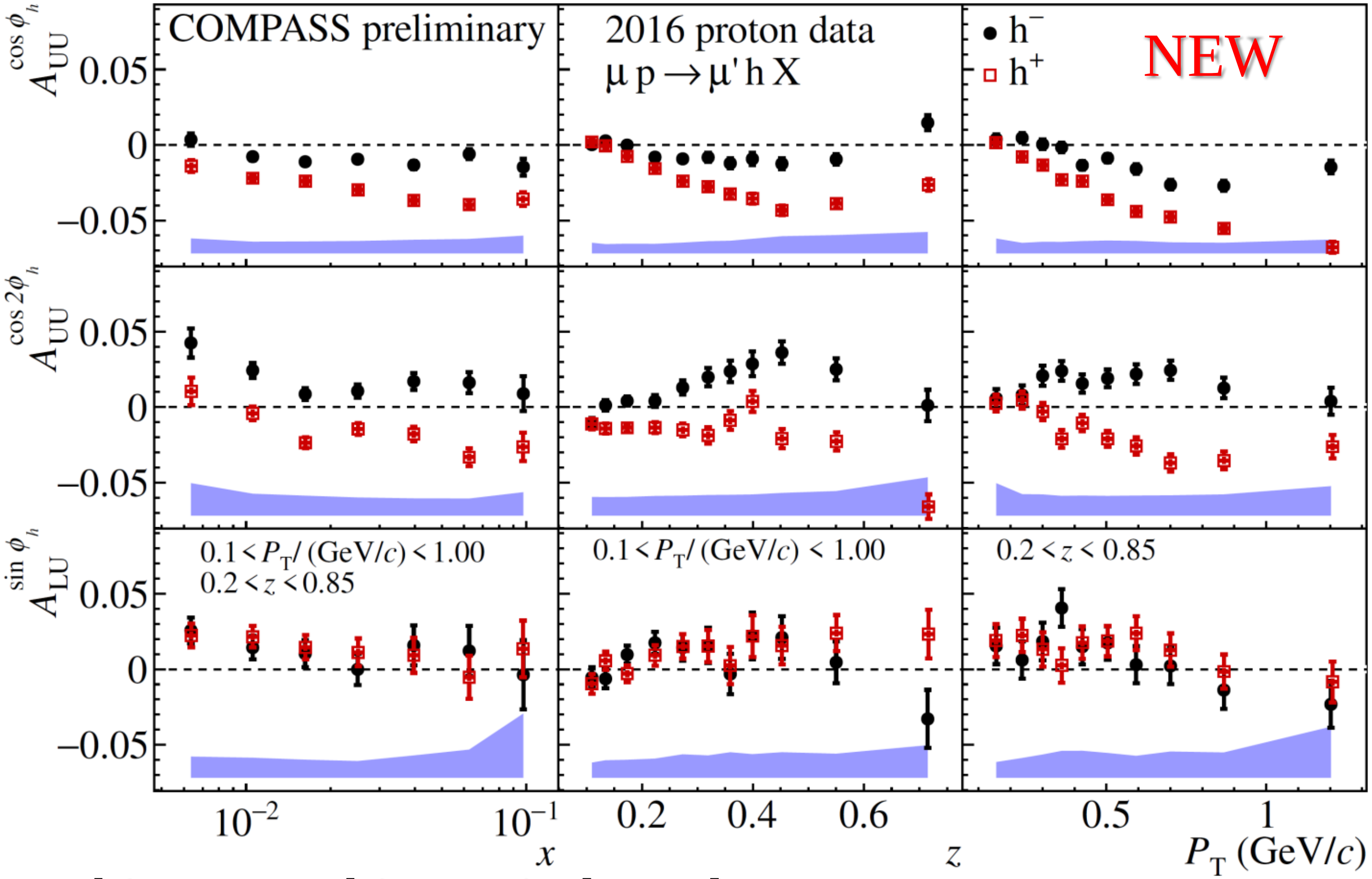


Azimuthal effects in unpolarized SIDIS

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

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

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



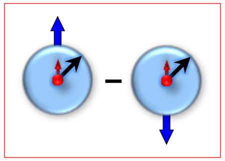
Cahn effect
Different for h+, h⁻
Non-trivial Q^2 dependence

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

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

Working on 3D kinematic dependences

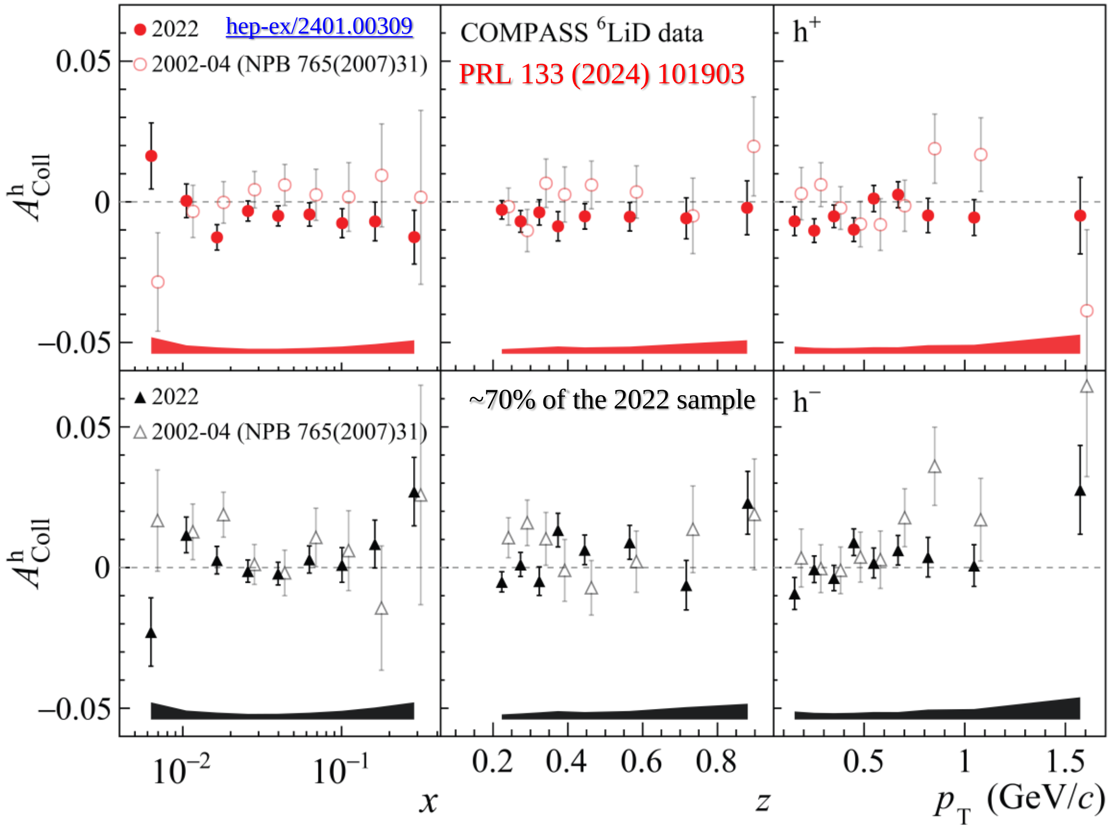
SIDIS TSAs: Collins effect and Transversity

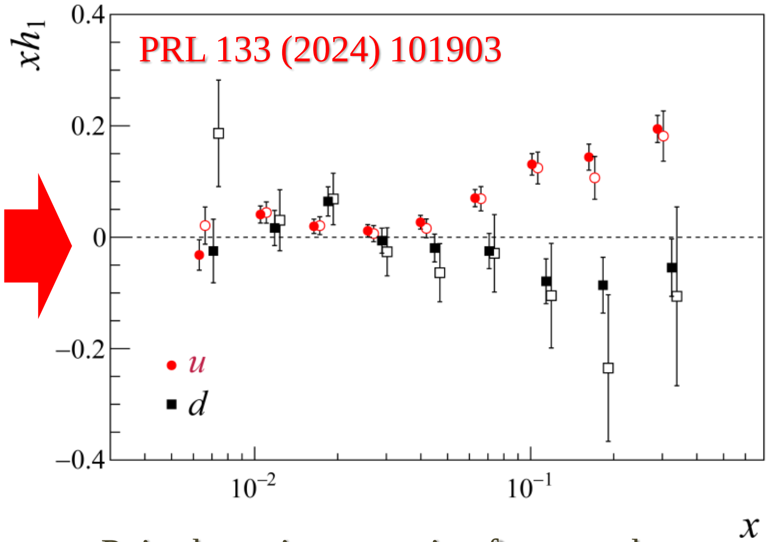


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \ldots\right\}$$

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

- 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



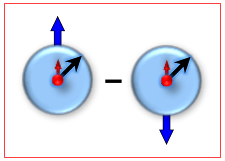


Point-by-point extraction framework
A. Martin et al. PRD **91**, 014034 (2015)
A. Martin et al. PRD **95**, 094024 (2017)

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



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

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

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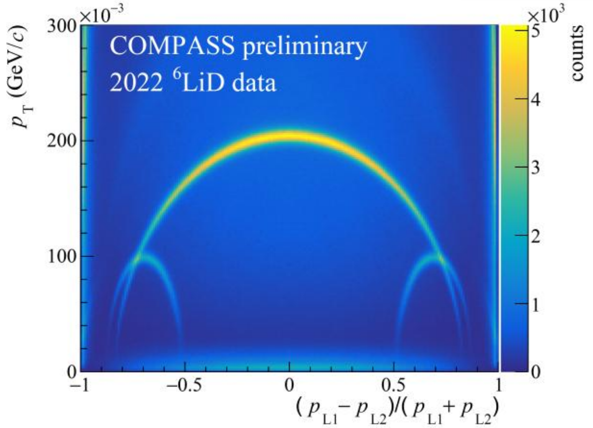
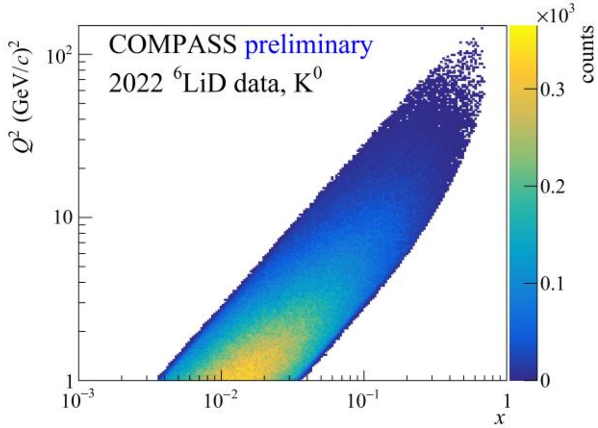
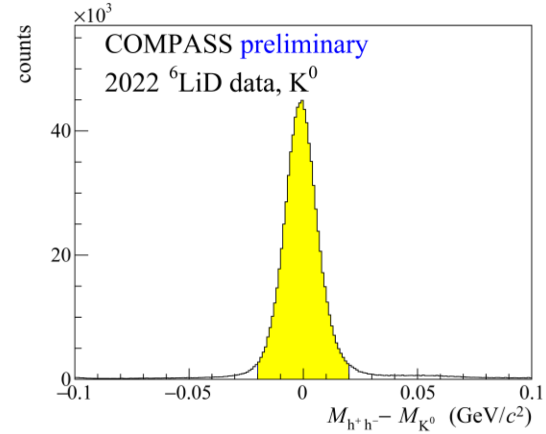
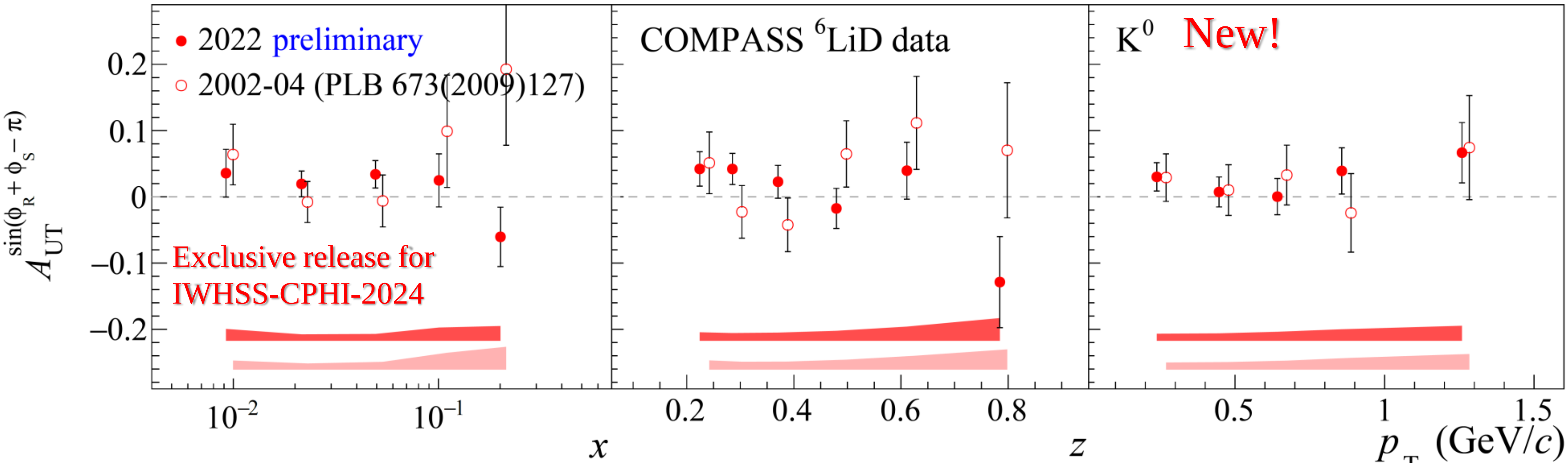
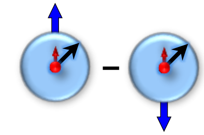






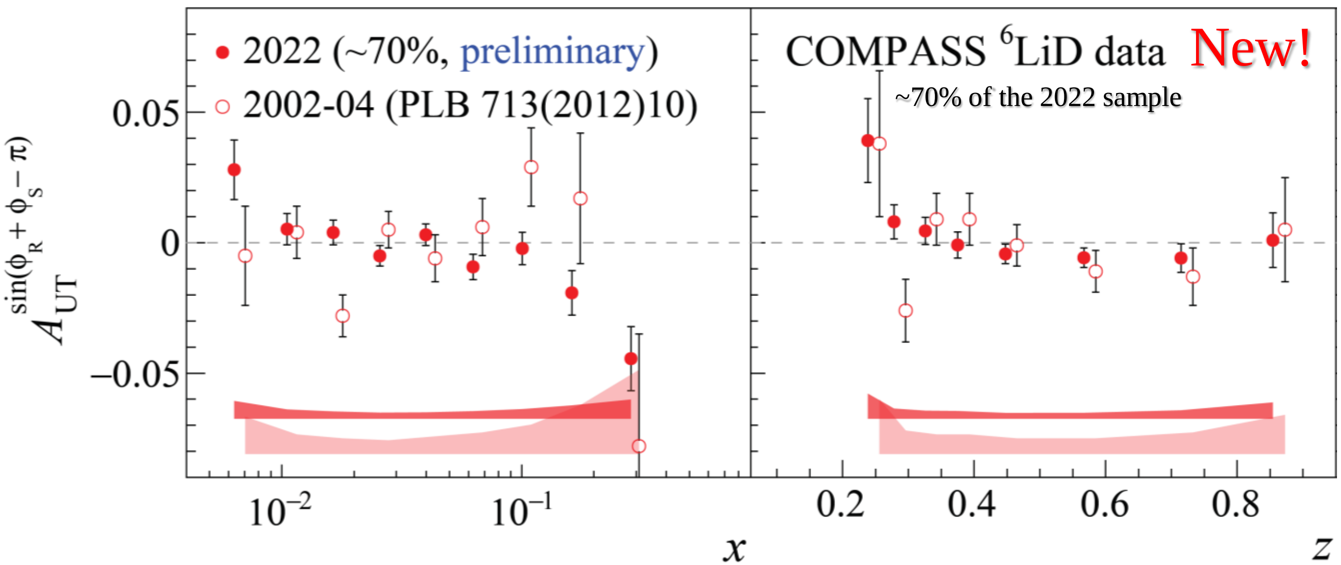


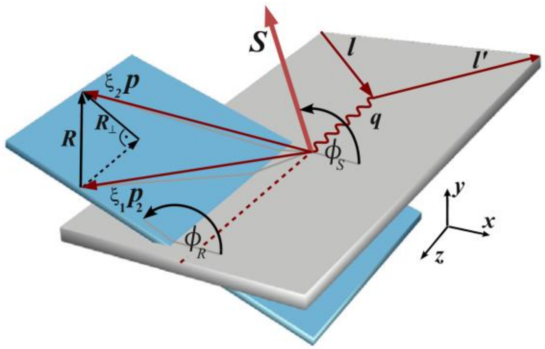
Dihadron Collins effect and Transversity



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

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





COMPASS 2022 run – highly successful data-taking!

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

COMPASS 2022 run: new unique deuteron data

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

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

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

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

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

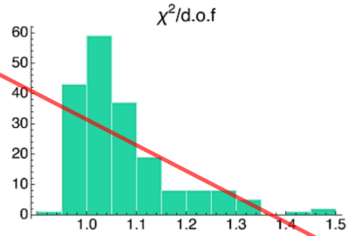
analysis of statistical error with replica method (200)
68% confidence level

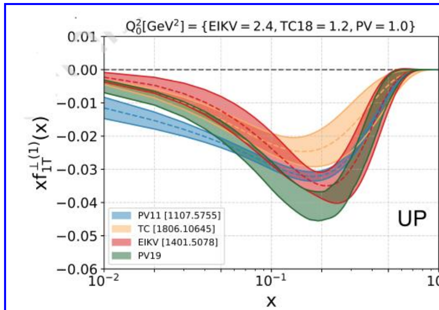
Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

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

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

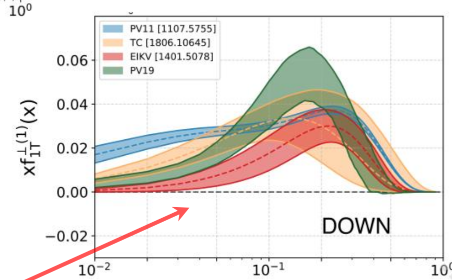




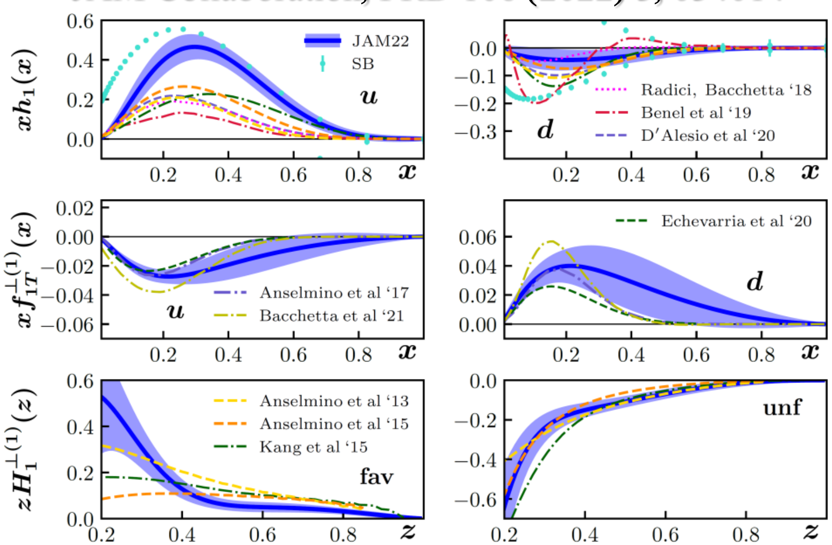
PV11	*Bacchetta & Radici, P.R.L.* ***107*** *(11)*
EIKV	*Echevarria et al., P.R. D**89** (14)*
TC	*Boglione et al., JHEP* ***1807*** *(18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

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

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

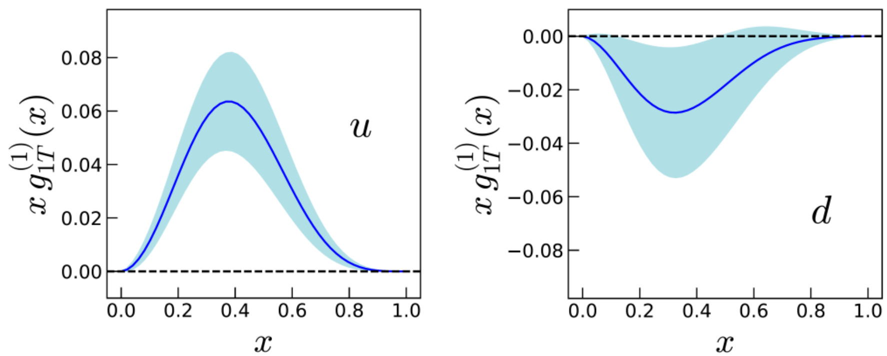


JAM Collaboration, PRD 106 (2022) 3, 034014



COMPASS 2022 deuteron run

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



More news soon…

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, etc.

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

Thank You!

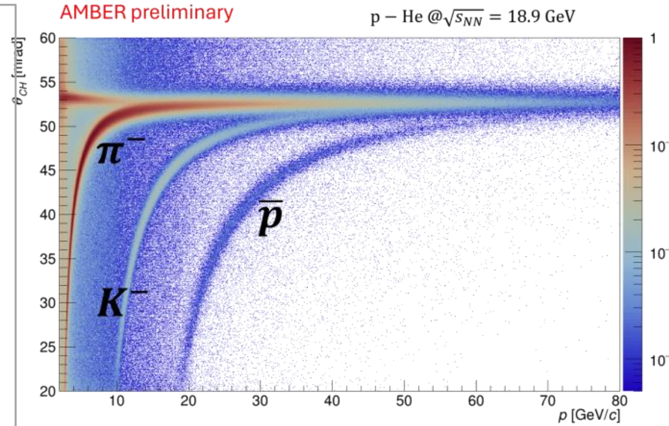
AMBER measurements 2023-2024: $\overline{p}$ production cross-section

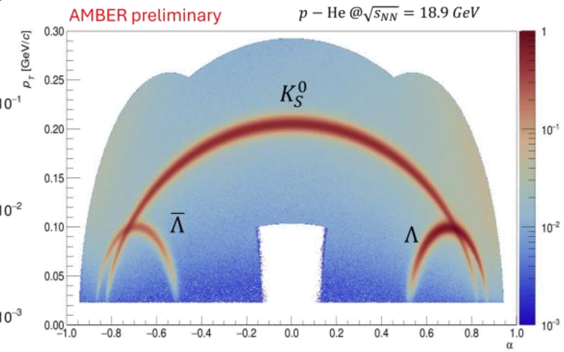
$\overline{p}$ production measurement

- $\overline{p}$ 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

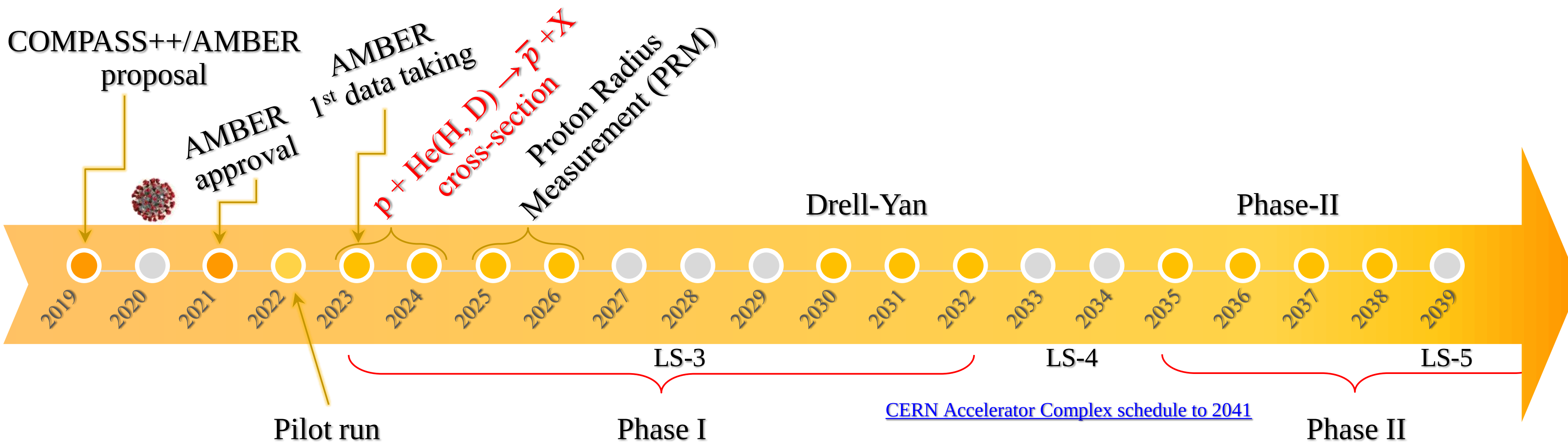




Motivation for AMBER 2023-2024 runs

New measurements needed to determine the

$\overline{p}$ -production from cosmic-ray collisions accurately



CERN Accelerator Complex schedule to 2041

AMBER measurements 2023-2024: proton charge radius

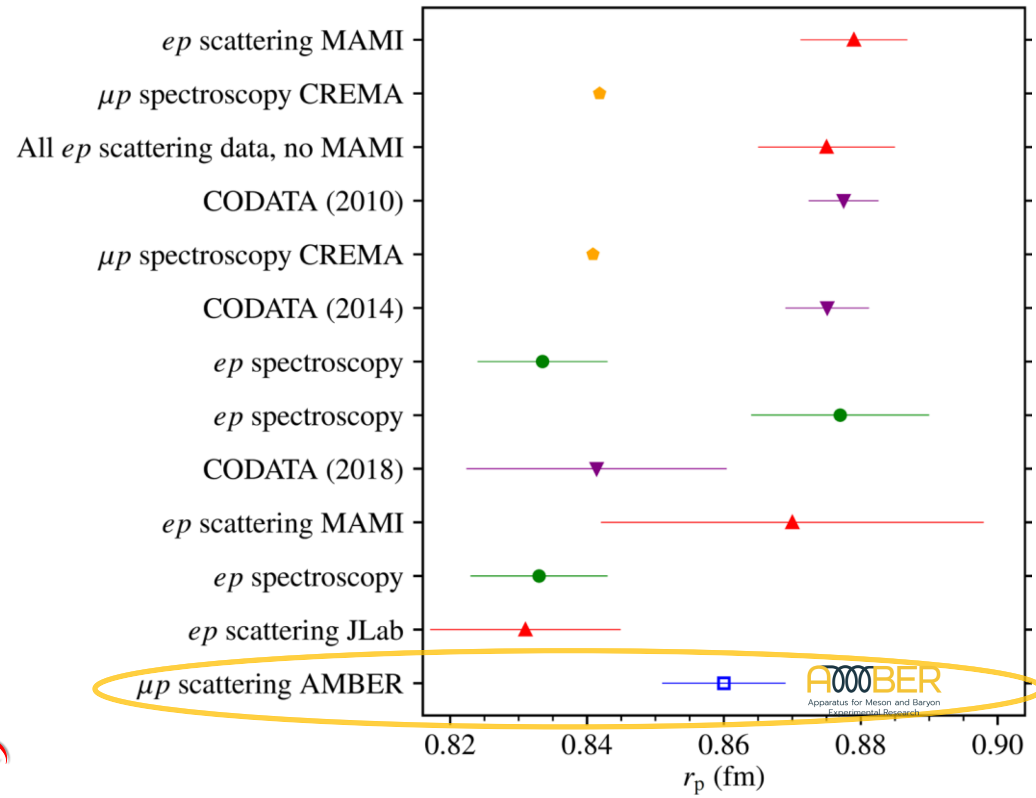
The proton-radius puzzle

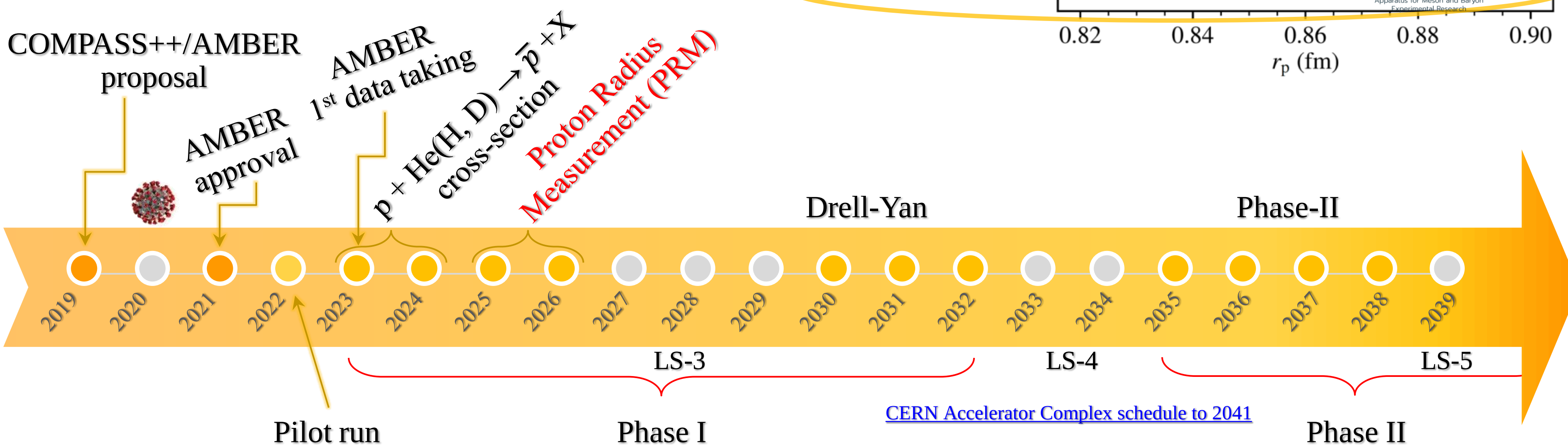
- Discrepancies between the charge-radius of the proton extracted from:
  - Electron-proton scattering
  - Hydrogen spectroscopy
  - Muonic-hydrogen spectroscopy

AMBER PRM

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

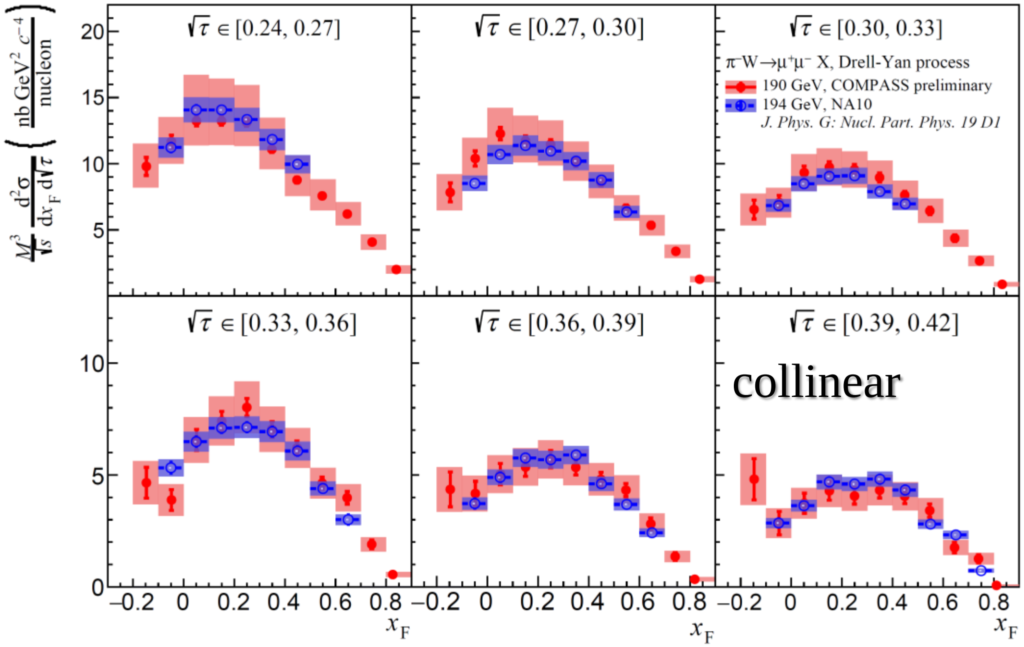
Ch. Dreisbach – CERN-THESIS-2022-286

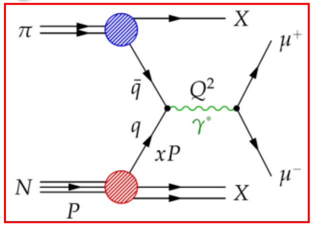


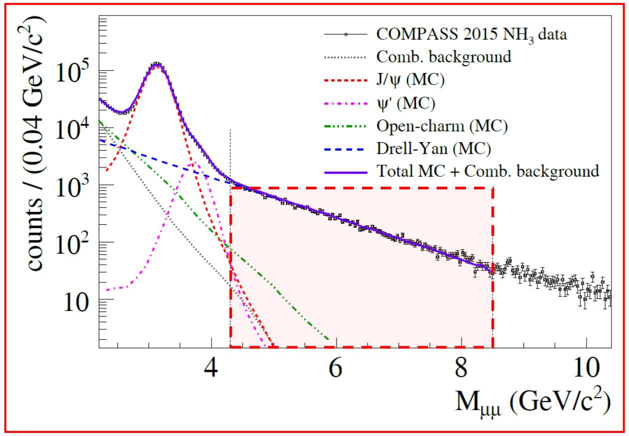


CERN Accelerator Complex schedule to 2041

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



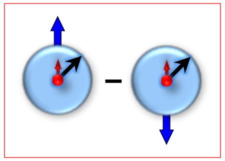




- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF

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

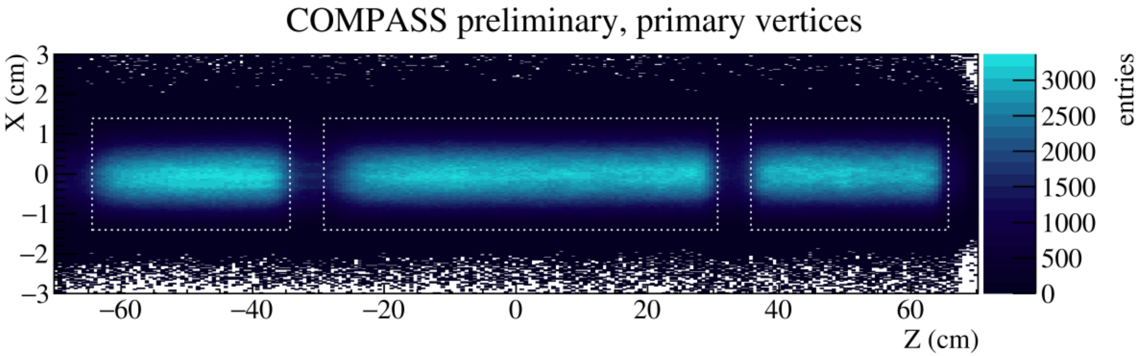


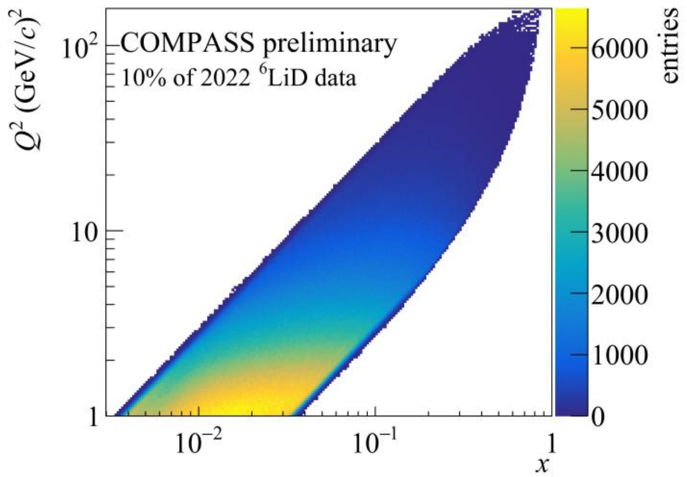
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \ldots\right\}$$

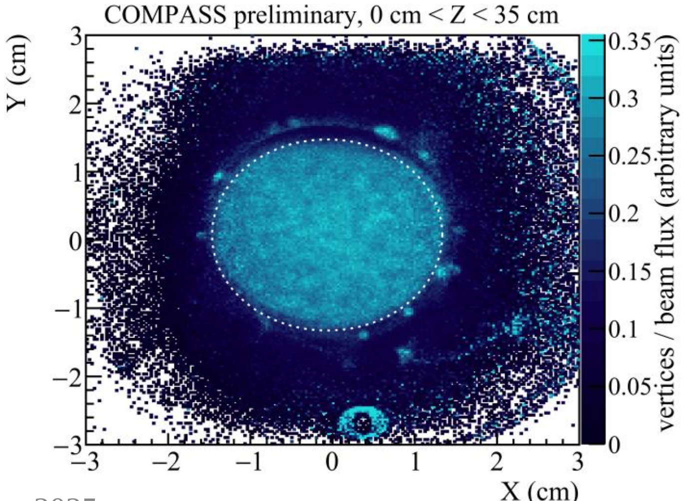
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

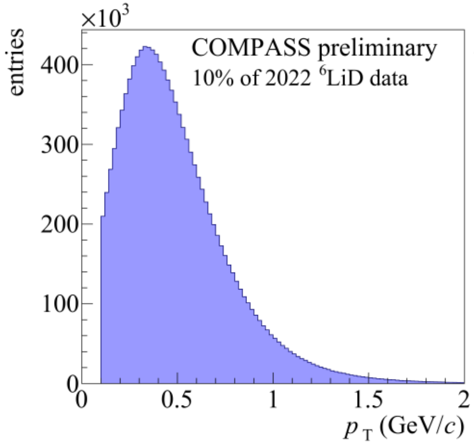
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity

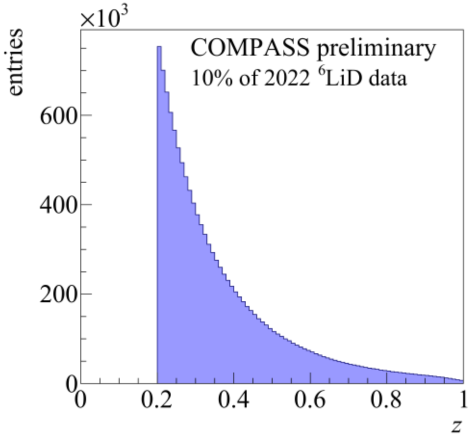
Highly successful Run in 2022!





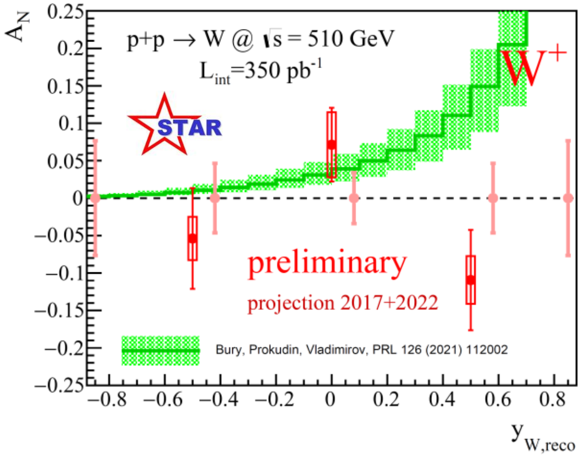


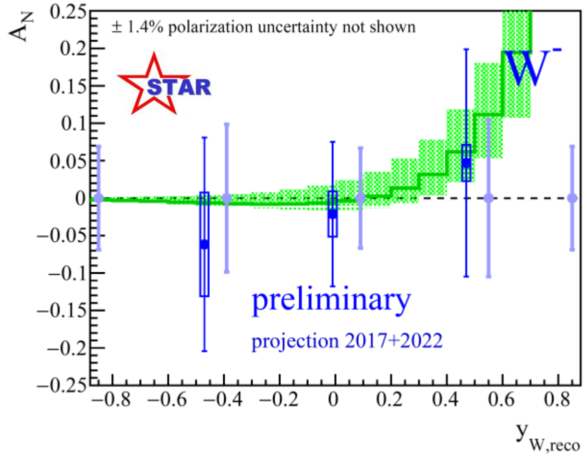




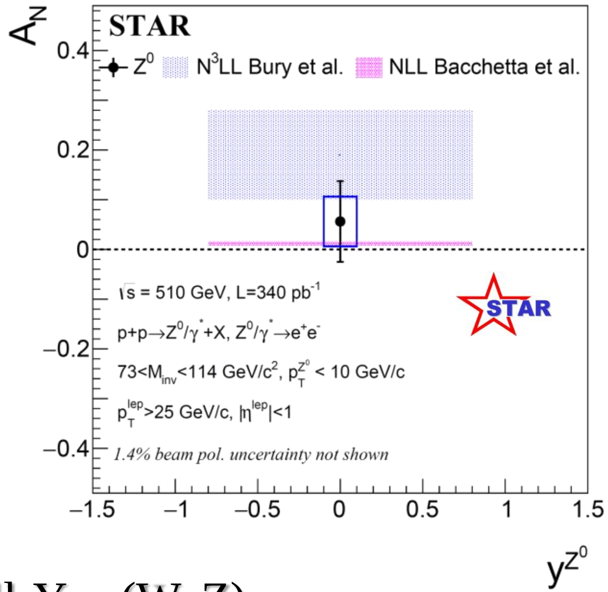
Sivers TMD PDF: sign change

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

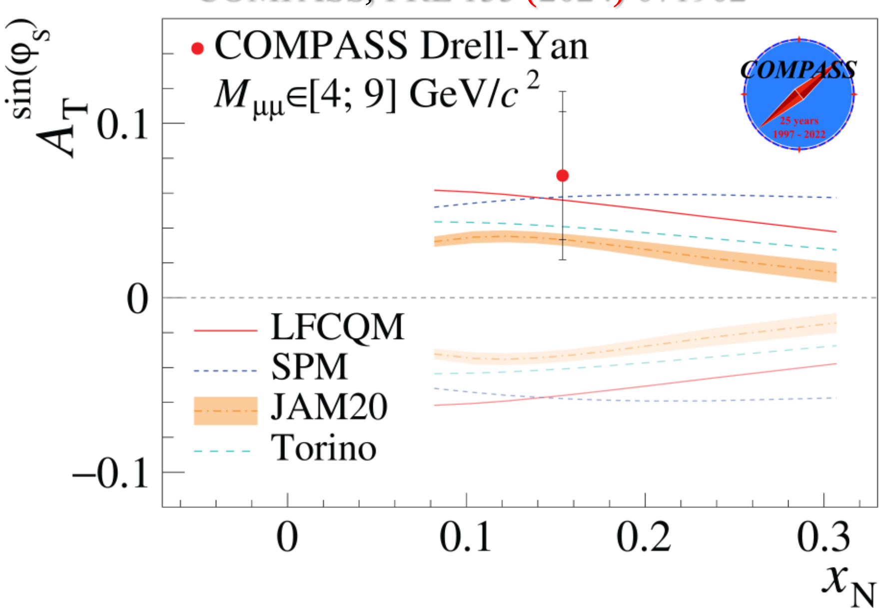




STAR, arXiv:2308.15496 [hep-ex]



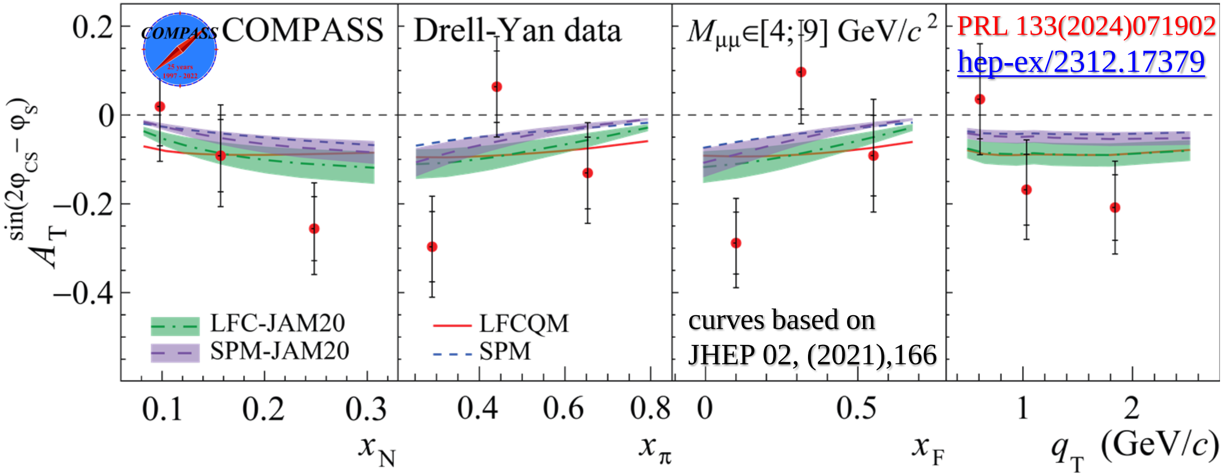
COMPASS, PRL 133 (2024) 071902

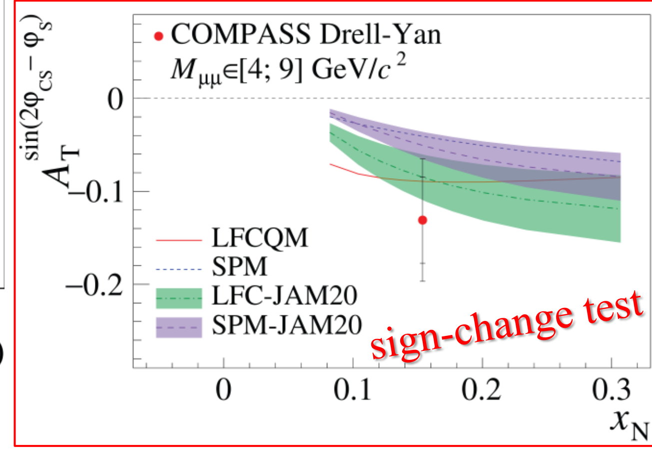


SIDIS↔Drell-Yan (W, Z)
sign change of T-odd TMD PDFs

- 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

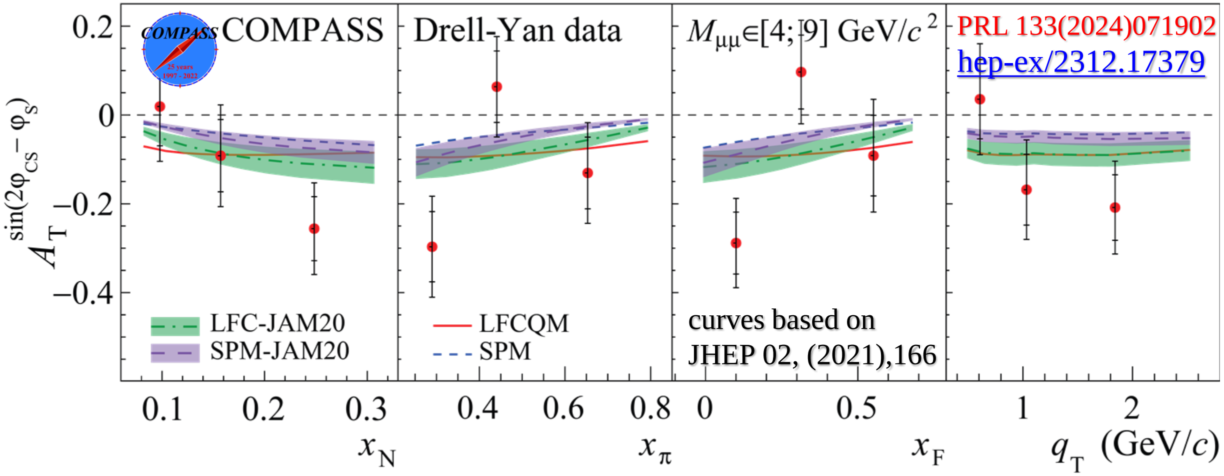
Boer-Mulders TMD PDF: sign change

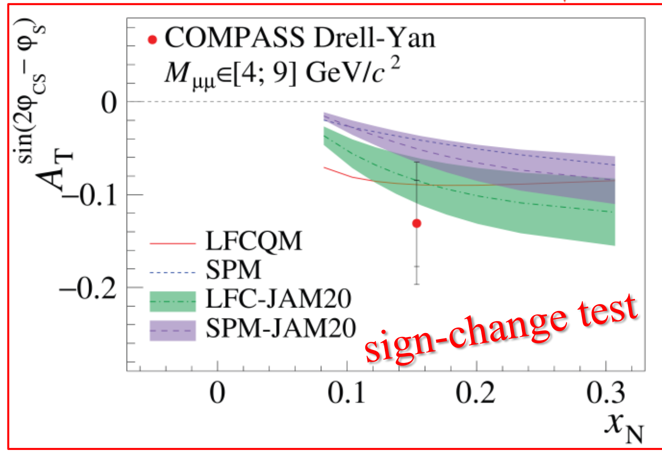




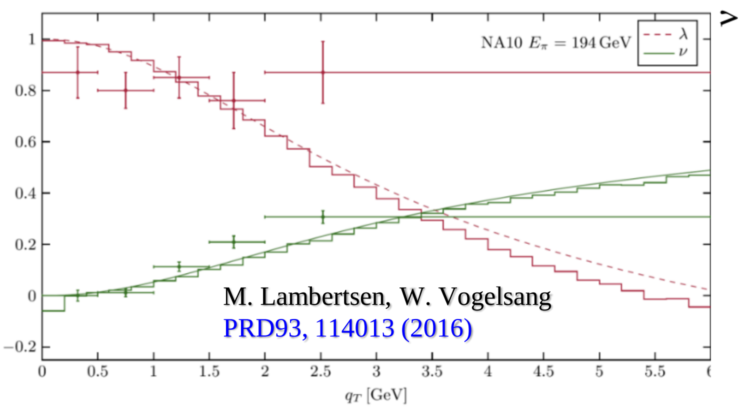
DY: $A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto -\left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,p}^{u}\right\} < 0 \Rightarrow h_{1,\pi^-}^{\perp\bar{u}} > 0$

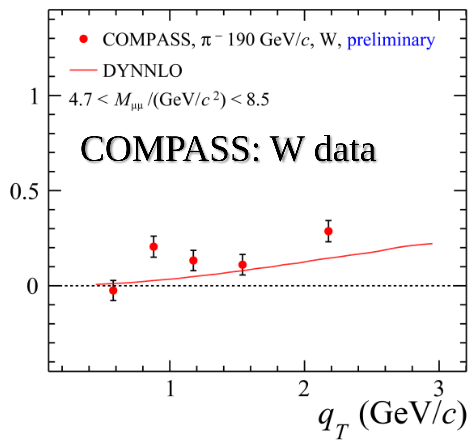
Boer-Mulders TMD PDF: sign change

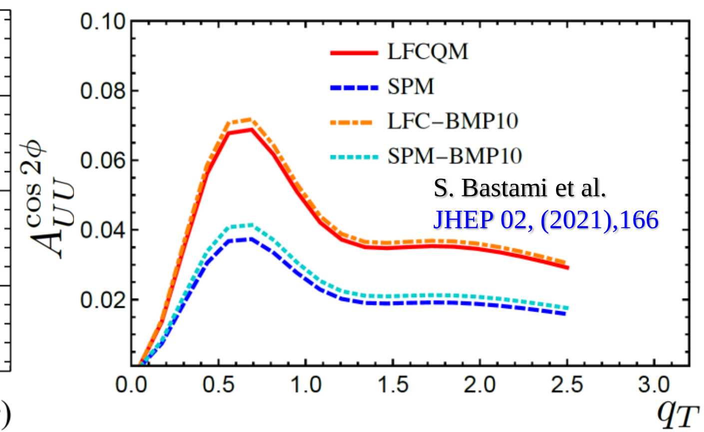




DY: $A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto -\left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,p}^{u}\right\} < 0 \Rightarrow h_{1,\pi^-}^{\perp\bar{u}} > 0$





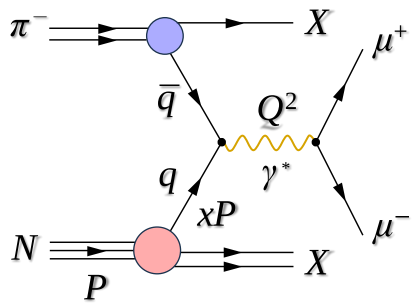


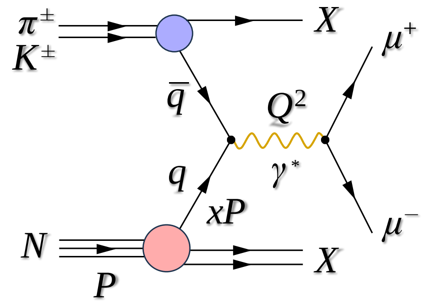
DY: $A_T^{\sin 2\varphi_{CS}} \propto \left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,p}^{\perp u}\right\} > 0 \Rightarrow h_{1,p}^{\perp u} > 0 \overset{\text{sign-change}}{\Leftrightarrow}$ SIDIS: $h_{1,p}^{\perp u} < 0$

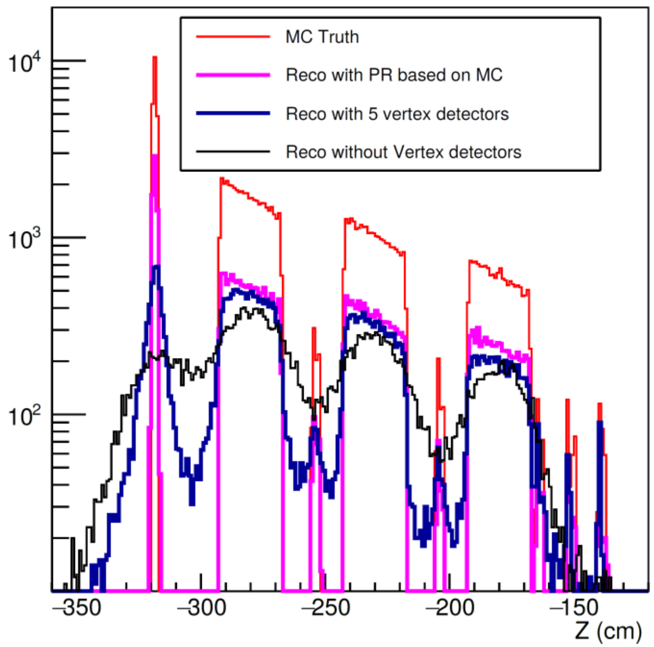
$h_{1,p}^{\perp u} < 0 \rightarrow$ SIDIS fits
V. Barone, et al.
PRD 82 (2010) 114025

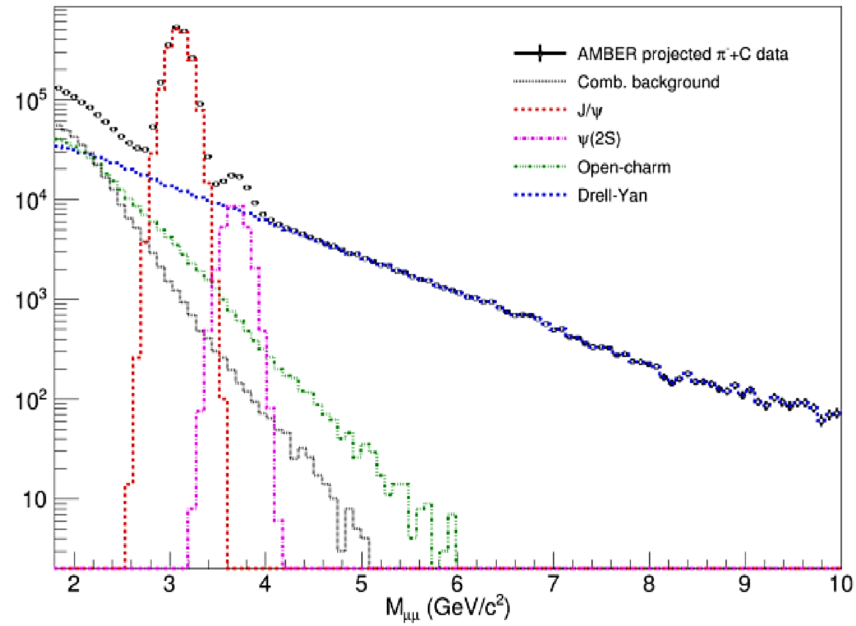
- COMPASS data favors proton Boer-Mulders TMD PDF sign-change

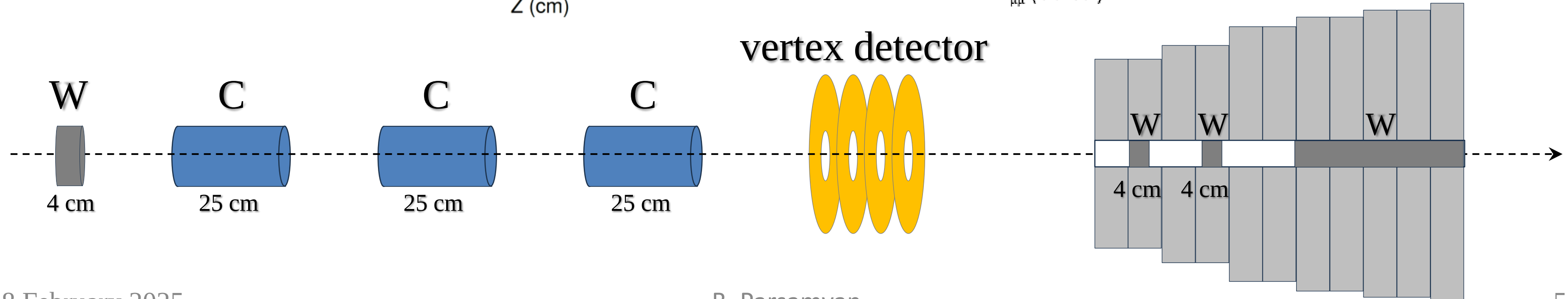
COMPASS→AMBER: Vertex detector improvements











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]