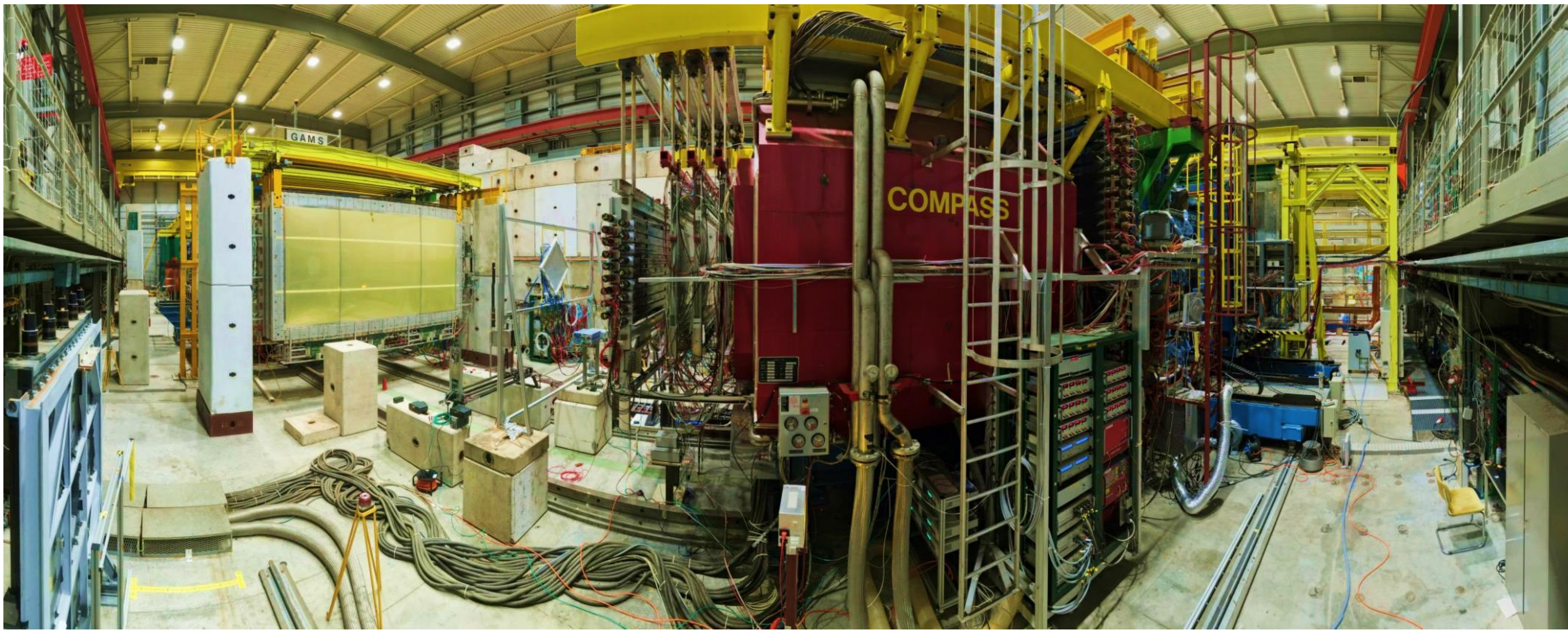
Status and plans of the COMPASS (NA58) Experiment

Bakur Parsamyan

(AANL, INFN section of Turin and CERN)

for the COMPASS collaboration



151st Meeting of the SPSC

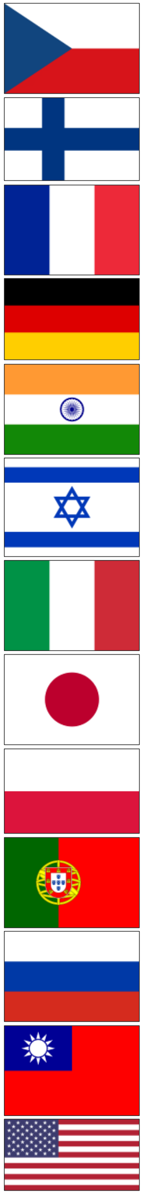
November 14th, 2023, CERN

Based on the COMPASS Status Report

CERN-SPSC-2023-035; SPSC-SR-338;

COMPASS collaboration

Co**m**mon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



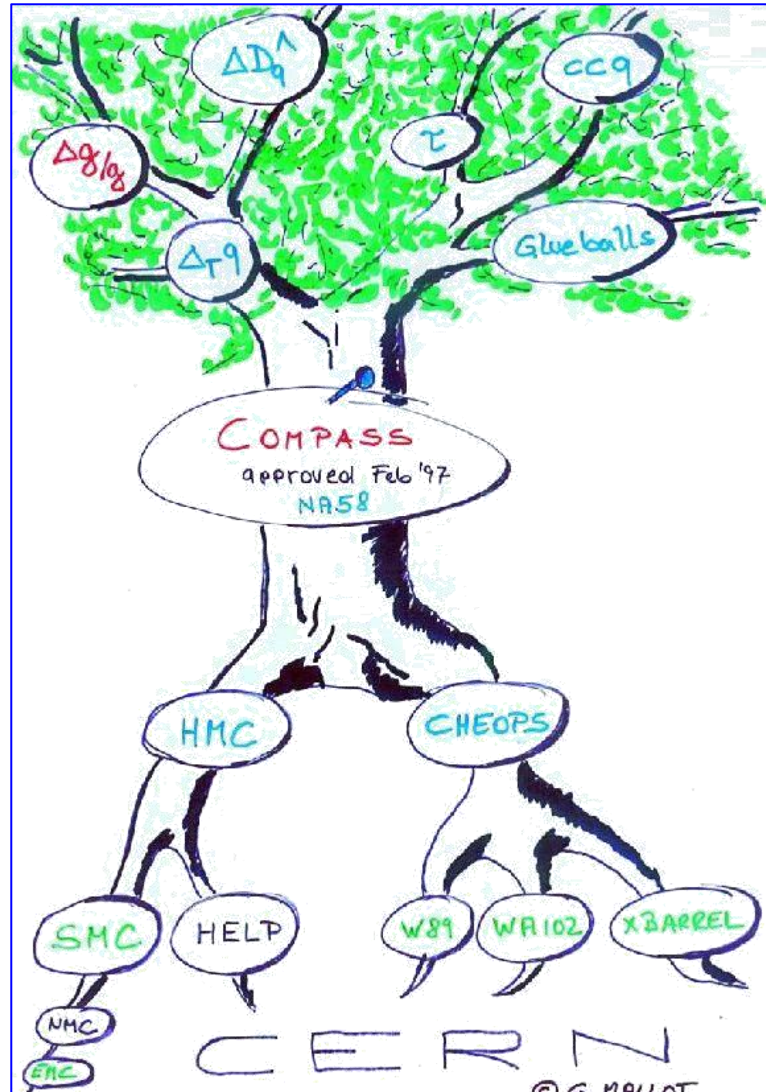
25 institutions from 13 countries
– nearly 200 physicists (in 2022)

- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

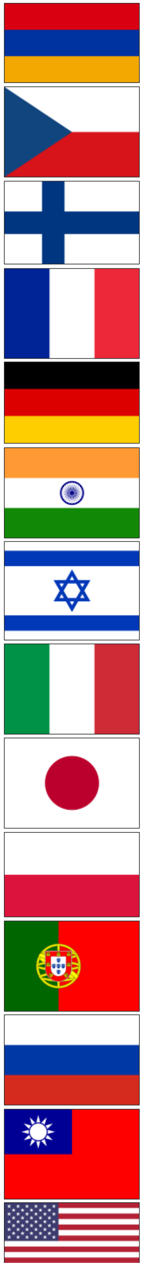
International Workshop on Hadron Structure and Spectroscopy

IWHSS-2022 workshop (anniversary edition)

https://indico.cern.ch/e/IWHSS-2022



COMPASS collaboration



Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

28 institutions from 14 countries
– nearly 215 physicists (in 2023: start of the Analysis Phase)

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

- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

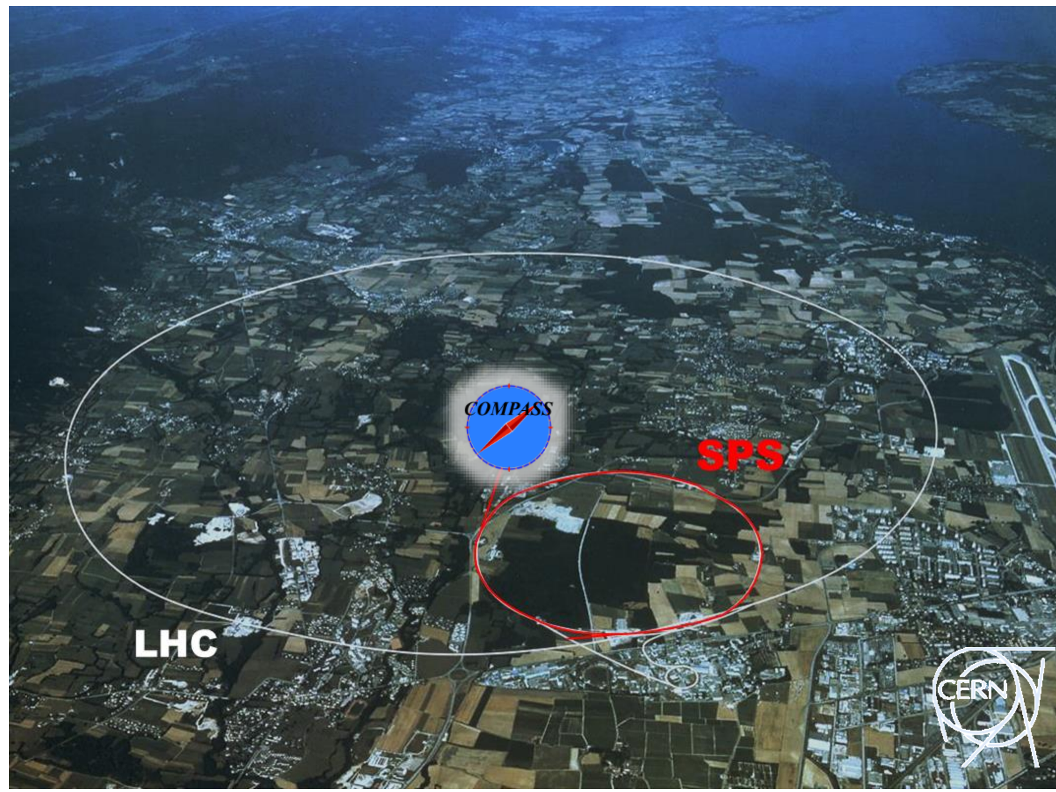
Wide physics program

COMPASS-I

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

COMPASS-II

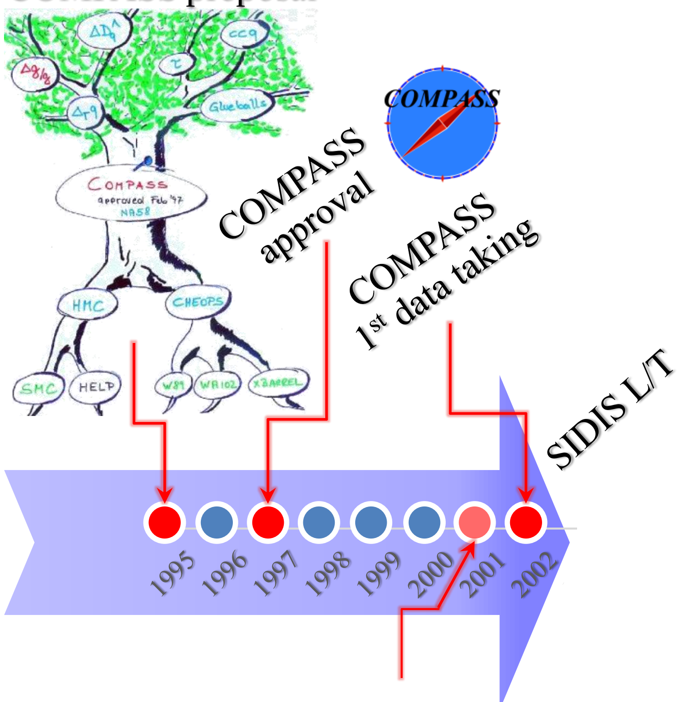
- **Data taking 2012-2022**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
- **Polarized Drell-Yan**
- **Transverse deuteron SIDIS 2022**



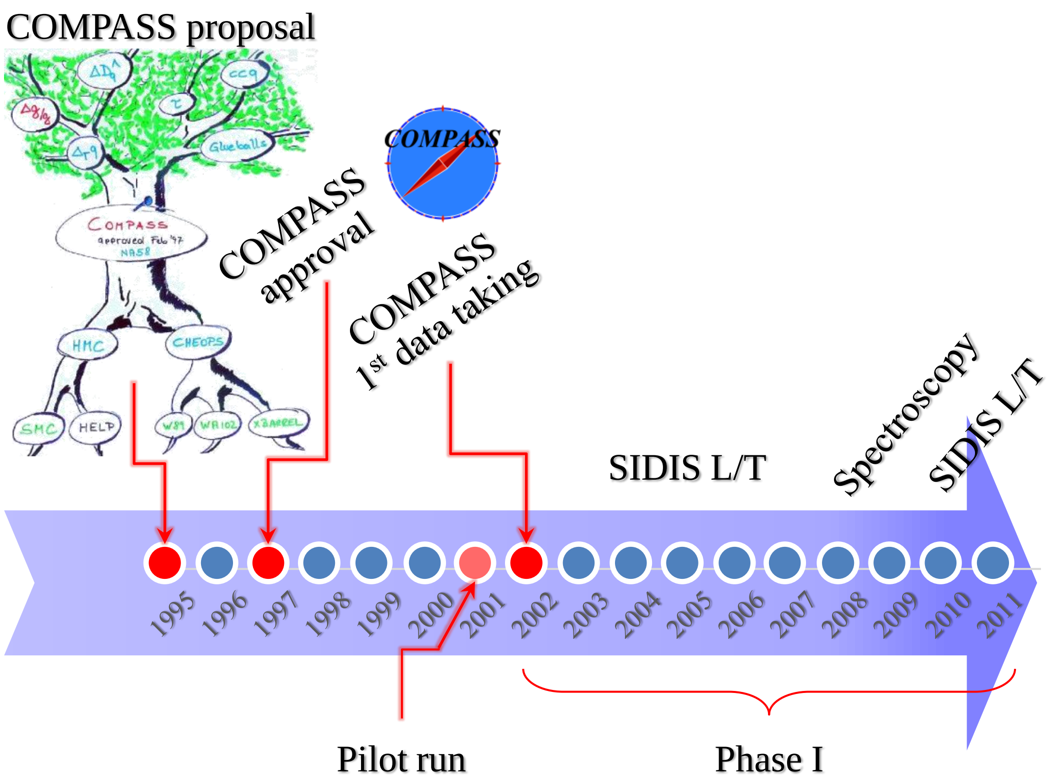
COMPASS web page: http://wwwcompass.cern.ch

COMPASS timeline

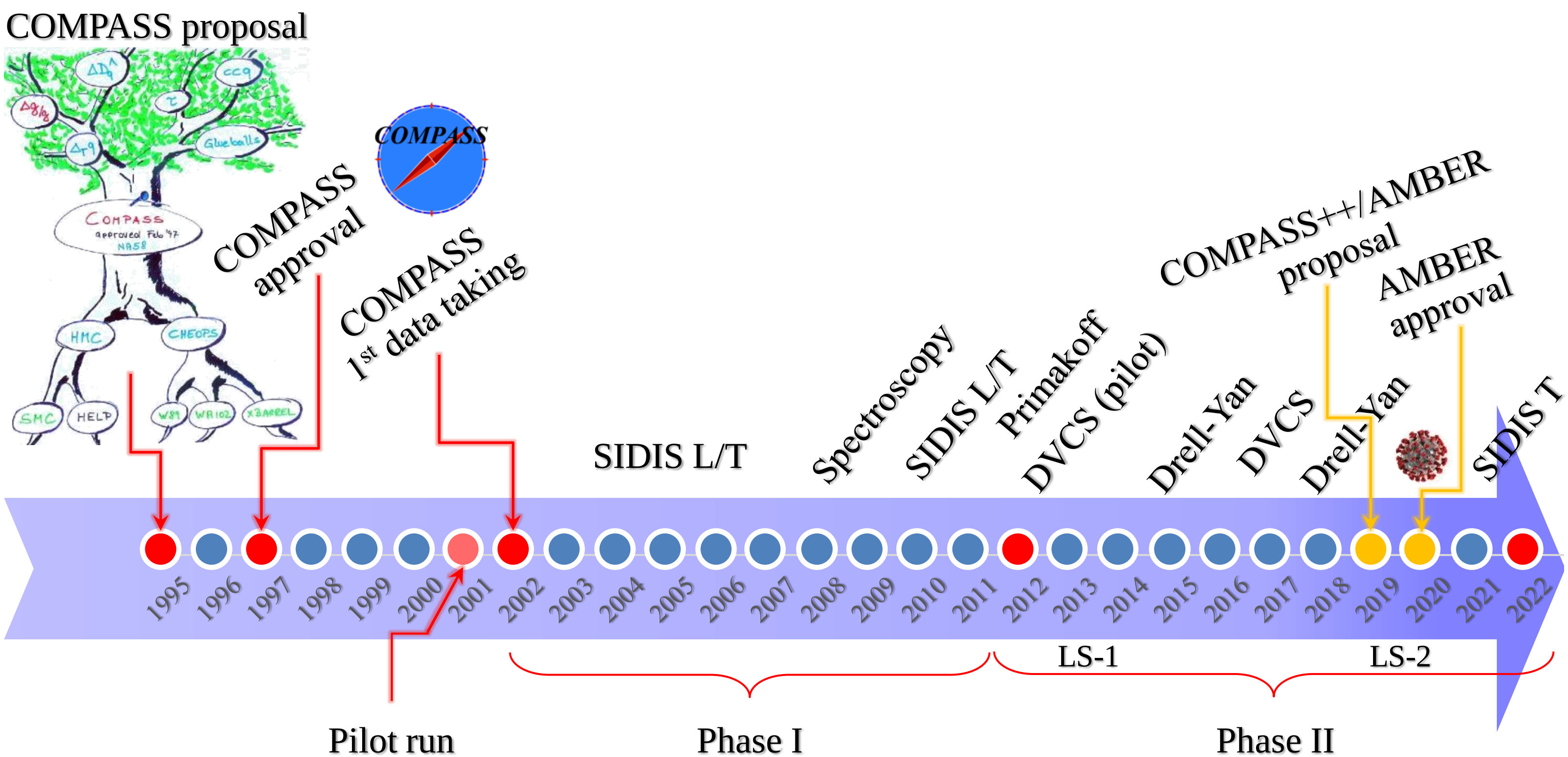
COMPASS proposal



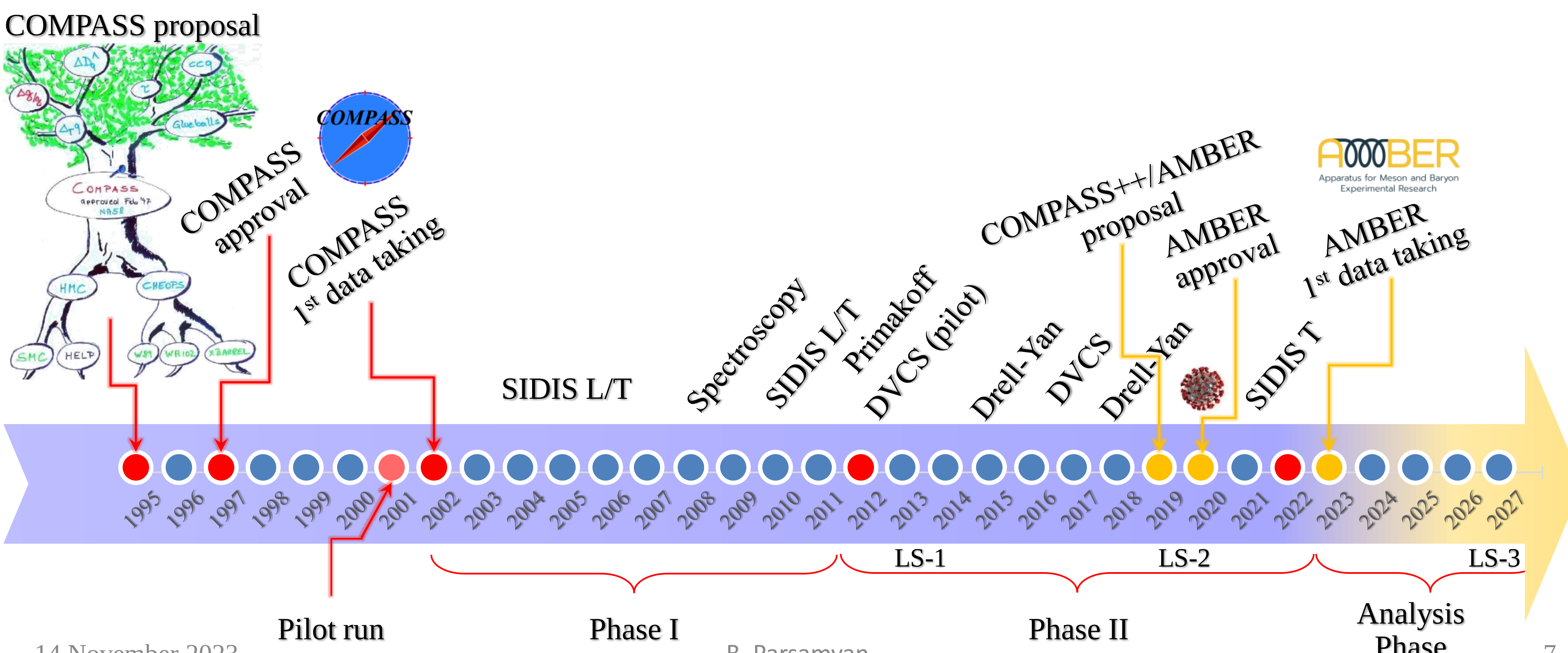
COMPASS timeline



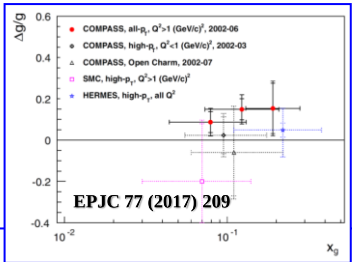
COMPASS timeline

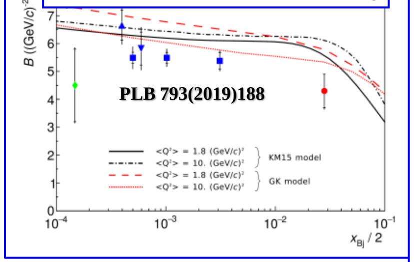


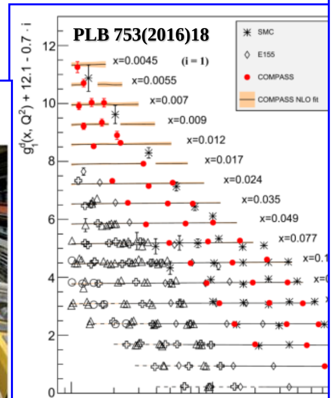
COMPASS → AMBER timeline

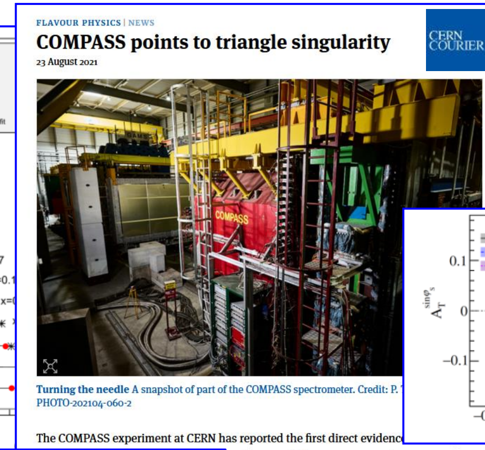


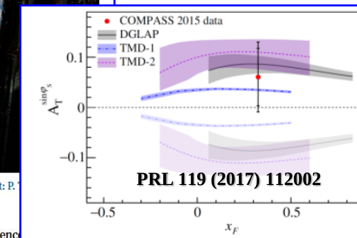
COMPASS Legacy

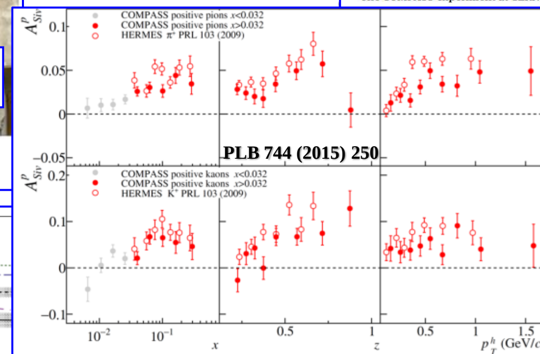


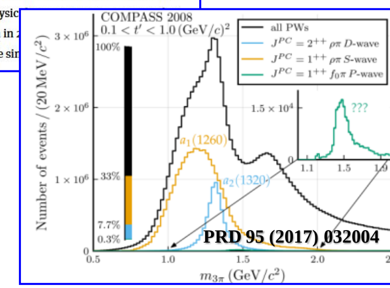


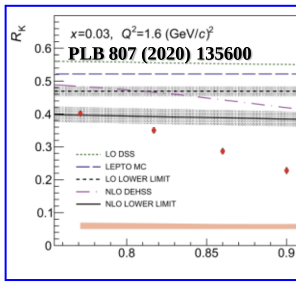




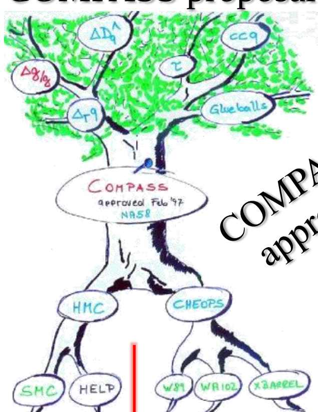


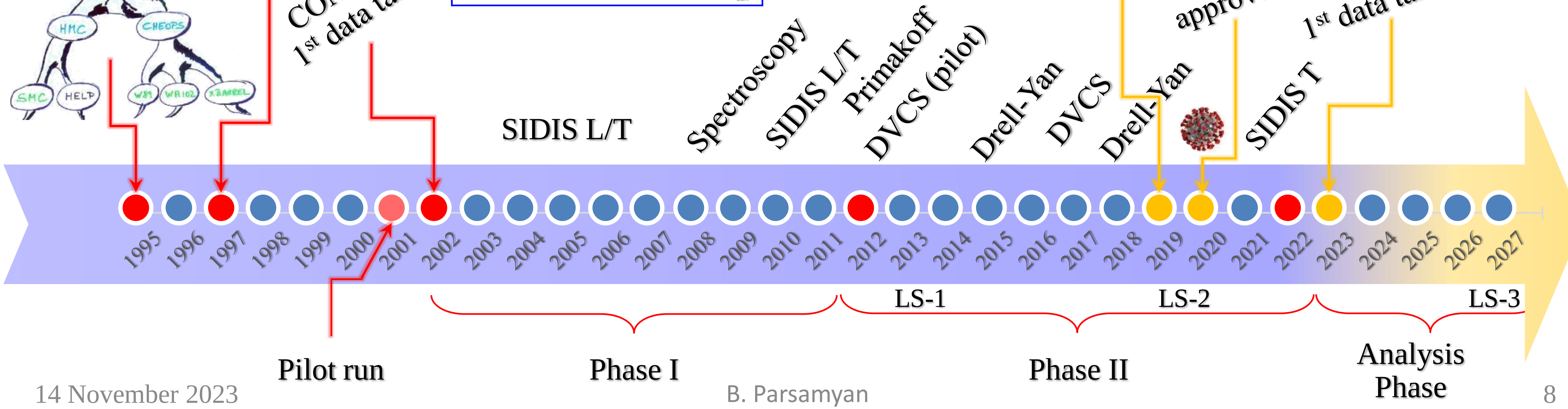






COMPASS proposal





COMPASS data taking campaigns

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

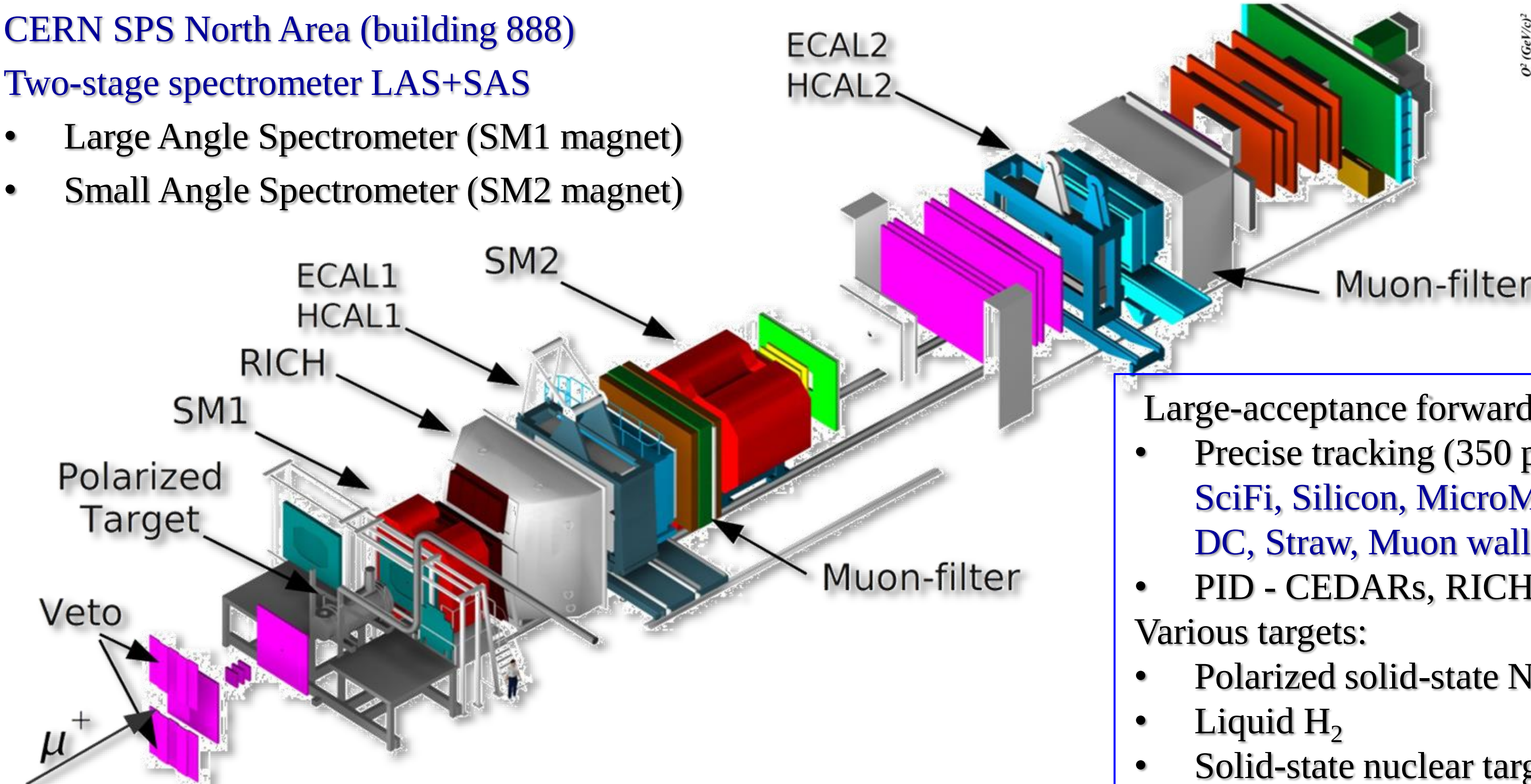
COMPASS experimental setup

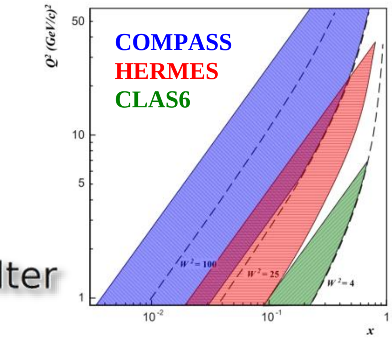
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





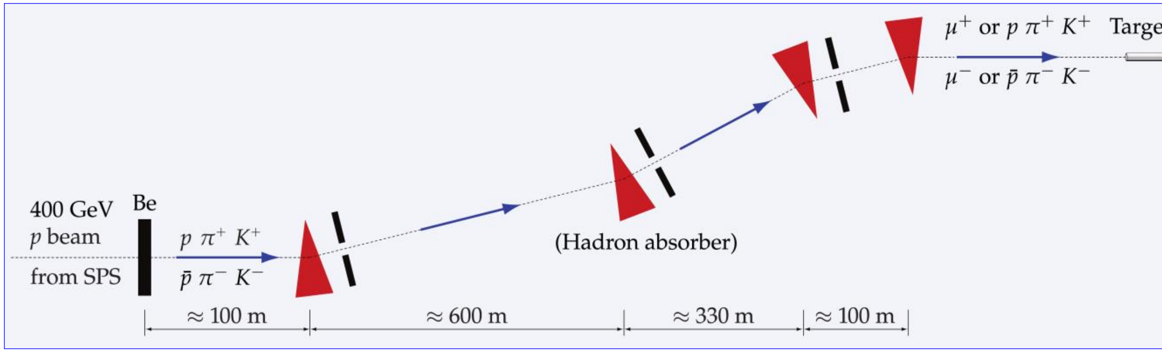
Large-acceptance forward spectrometer

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

Various targets:

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

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



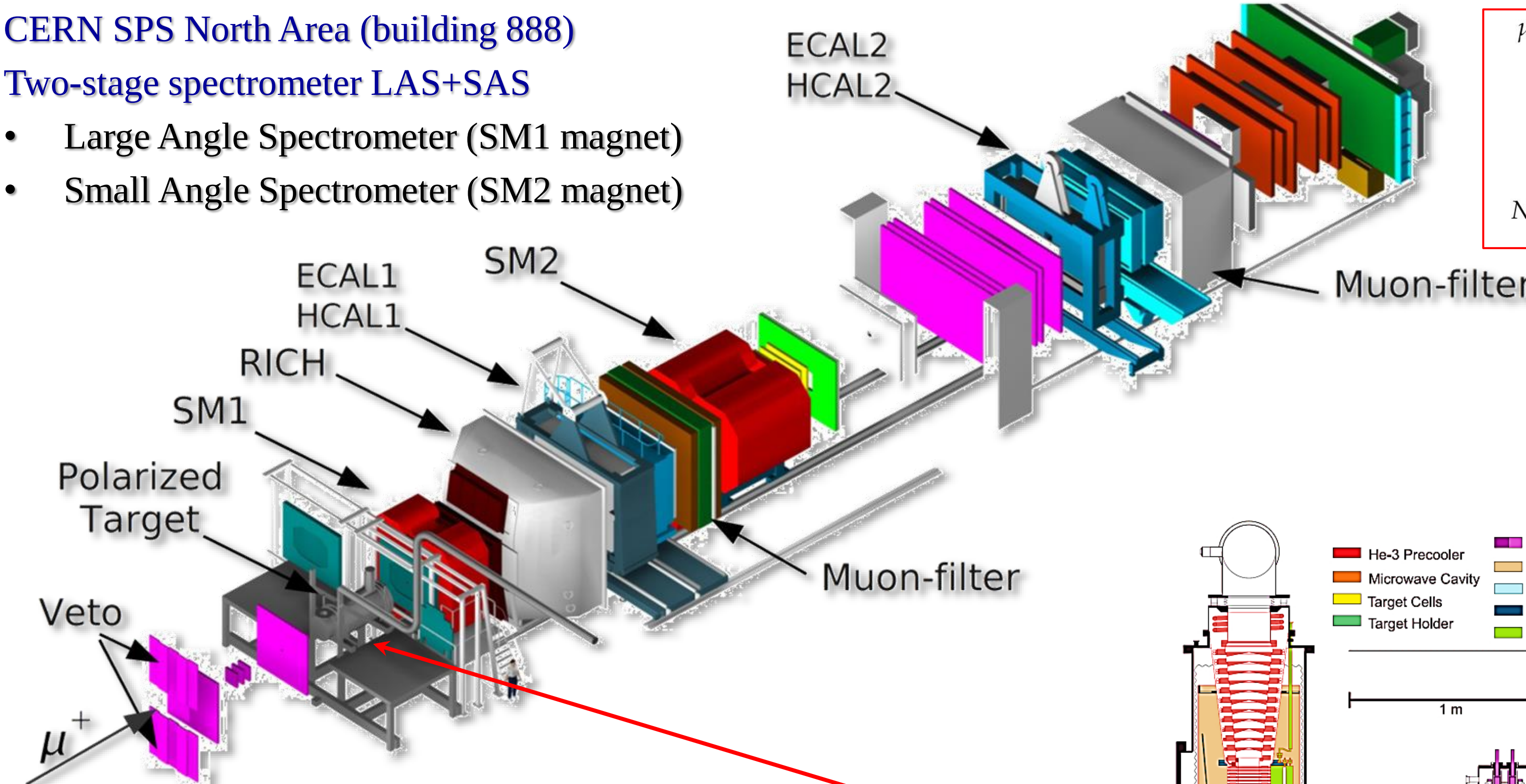
COMPASS experimental setup: Phase II (SIDIS programme)

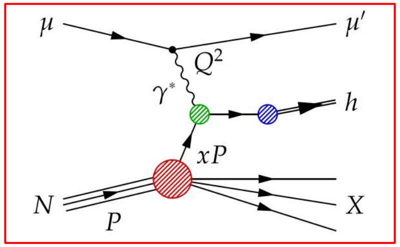
COmmon Muon Proton Apparatus for Structure and Spectroscopy

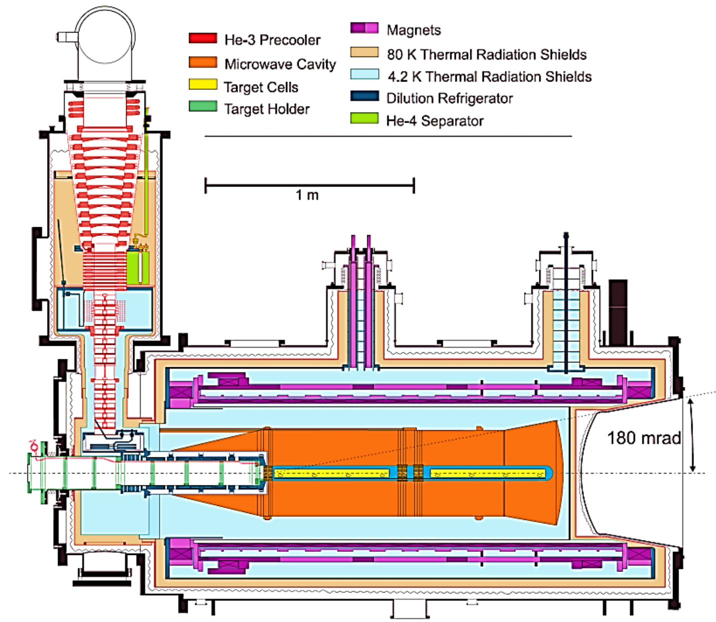
CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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







- 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

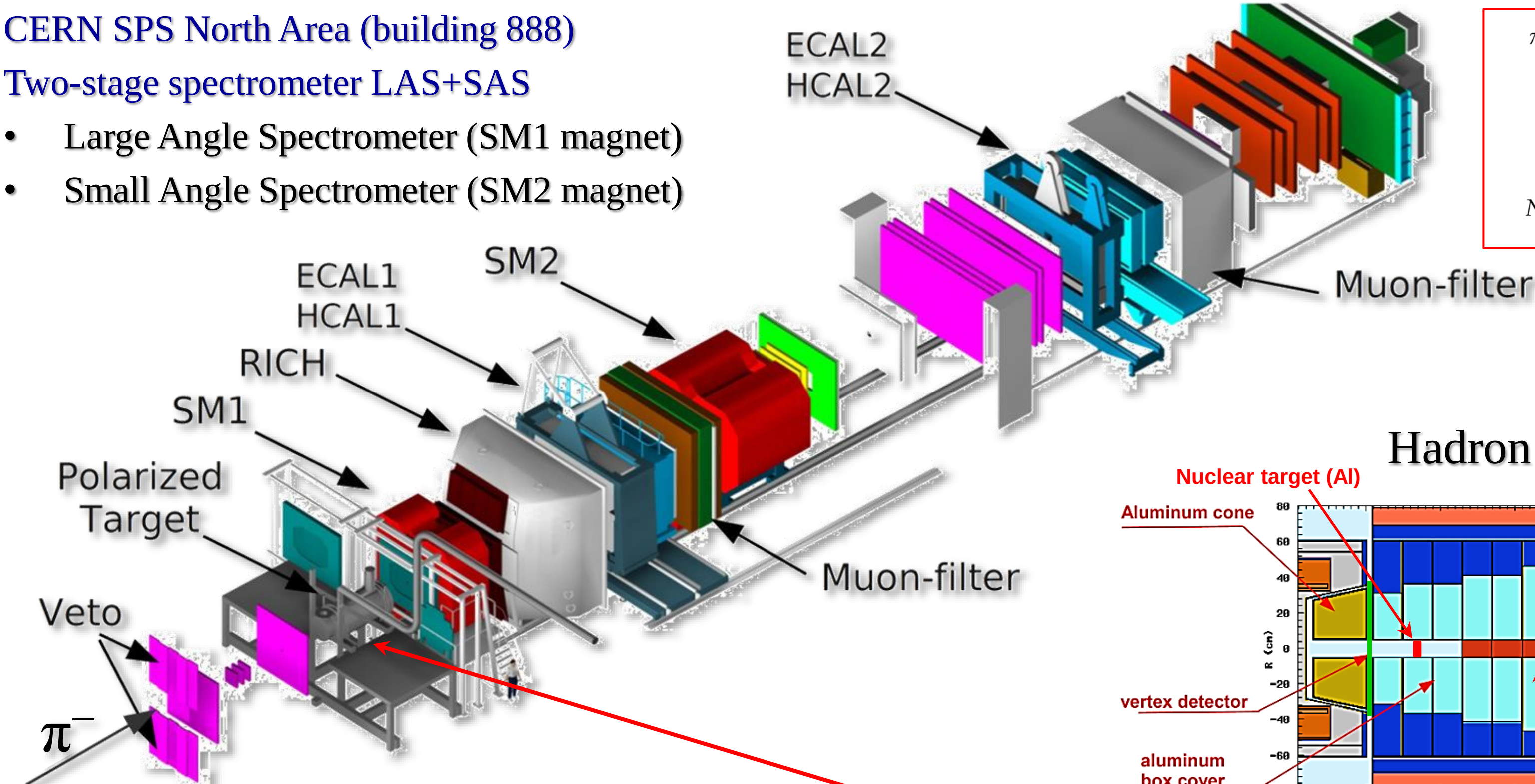
COMPASS experimental setup: Phase II (DY programme)

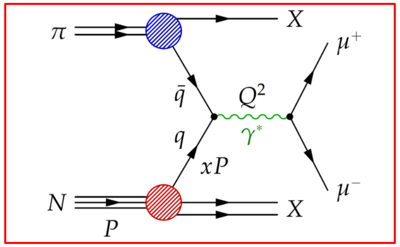
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

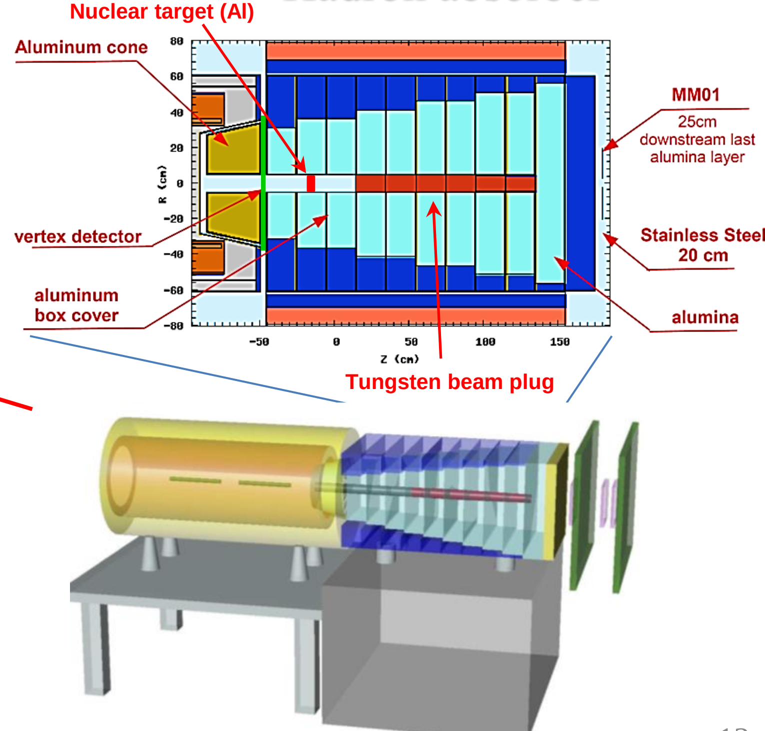
Two-stage spectrometer LAS+SAS

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





Hadron absorber



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

COMPASS experimental setup: Phase II (DVCS programme)

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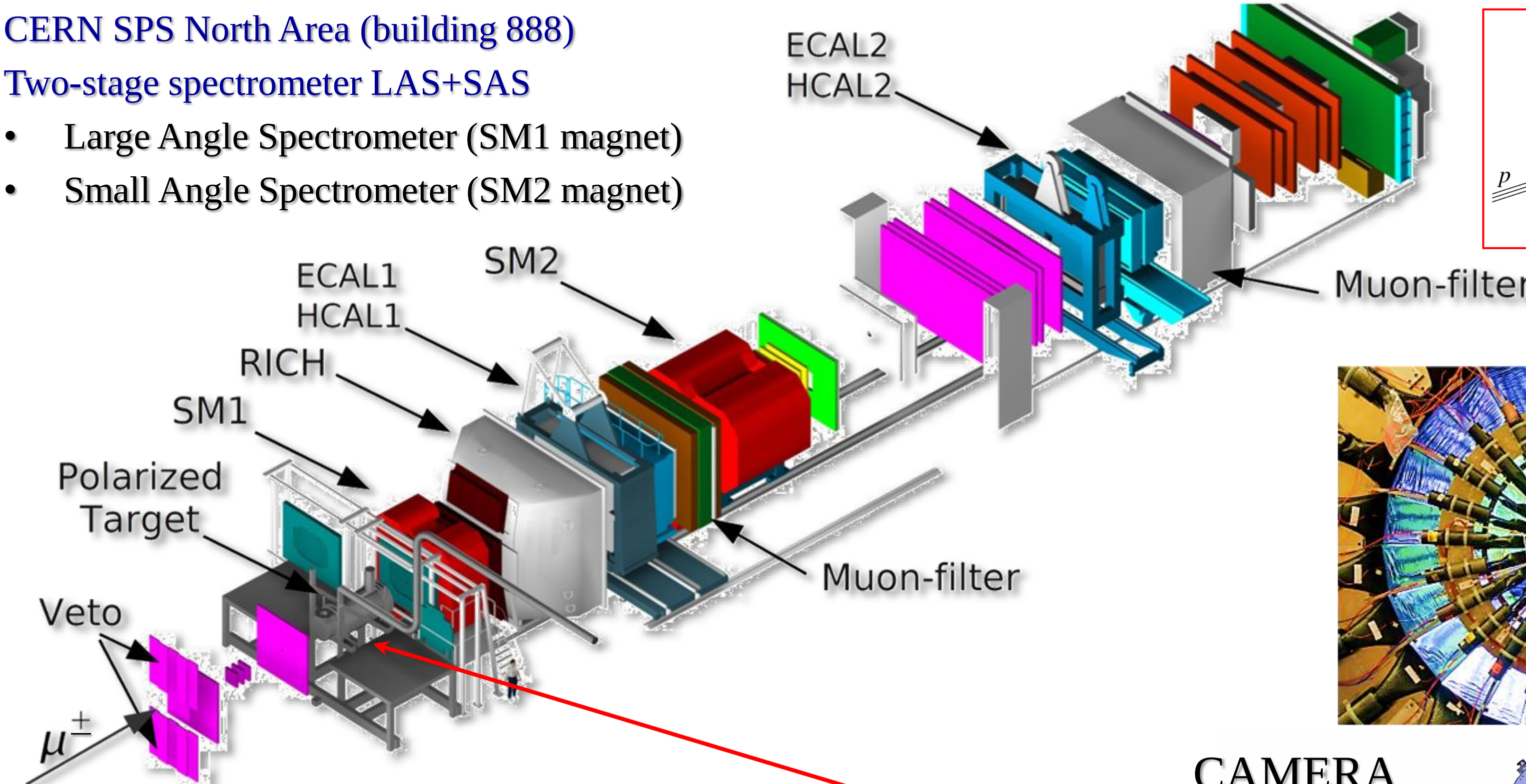
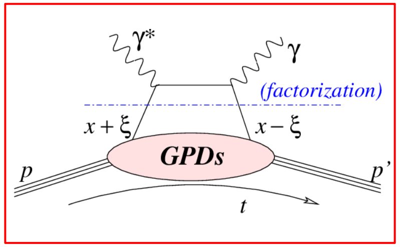
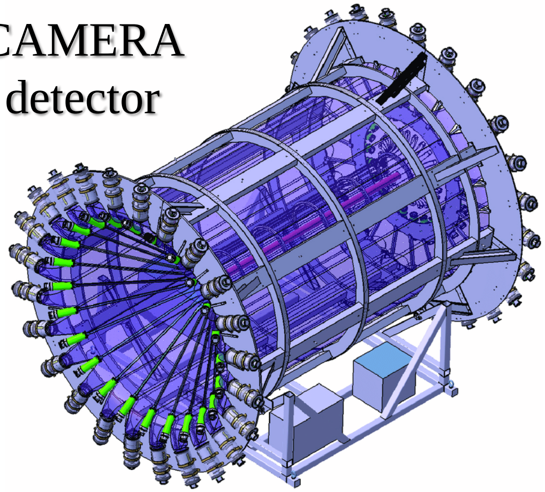




CAMERA detector



- Primary beam - 400 GeV p from SPS
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- 160 GeV tertiary muon beams
  - $\mu^{\pm}$ longitudinally polarized

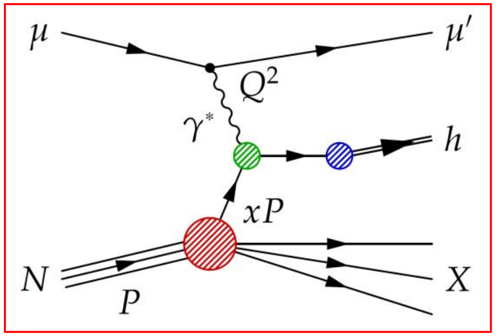
The COMPASS Experiment at the CERN SPS

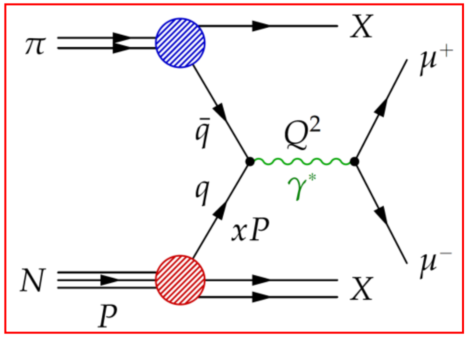
Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

Nucleon structure

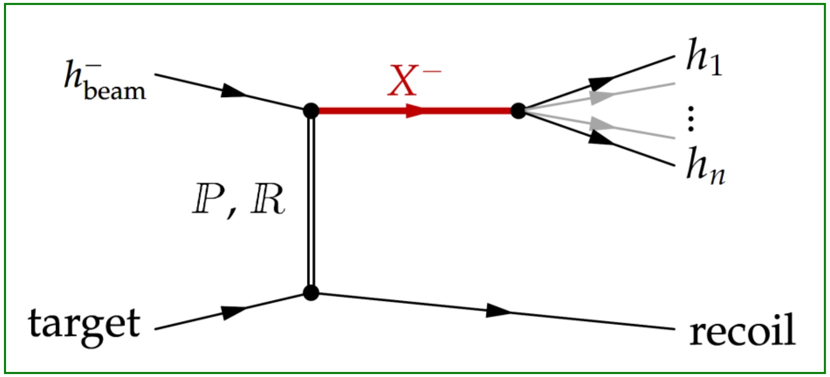
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions





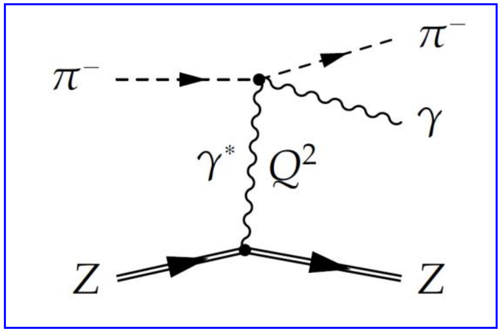
Hadron spectroscopy

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



Chiral dynamics

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



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Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

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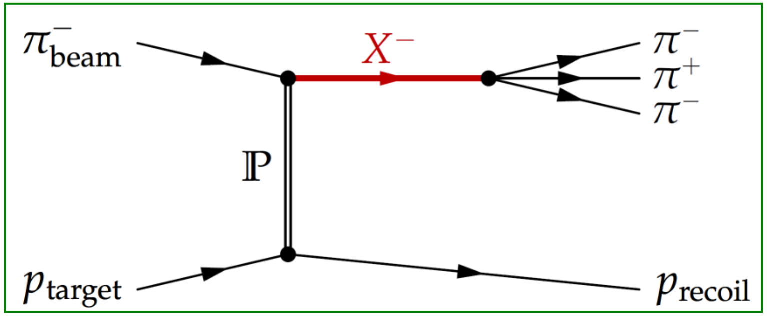

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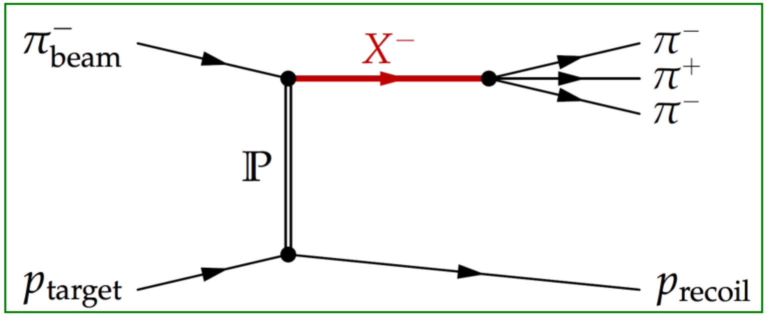
2022-2023 analyses/activities

Study of π_1 states $\pi^- p \rightarrow b_1(1235)\pi)^- p$ $\pi^- p \rightarrow f_1(1285)\pi^- p$	ongoing study improved event selection
Study of π_1 states $\pi^- p \rightarrow \pi^- \eta^{(\prime)} p$	ongoing study improved event selection
Excited kaons in: $K^- p \rightarrow K^- \pi^- \pi^+ p$	finalized (11 strange mesons) paper drafting
Chiral anomaly and radiative width of $\rho(770)$ $\pi^- \gamma \rightarrow \pi^- \pi^0$	systematic studies background subtraction
Excited kaons in: $K^- p \rightarrow \pi^- K_S^0 p$ $K^- p \rightarrow \Lambda\, p\, p$	ongoing study improved event selection
Isovector resonances in: $\pi^- p \rightarrow K^- K_S^0 K_S^0 p$	event selection finalized starting the PWA
Study ambiguities in PWA Novel methods for PWA	New: PWA continuity and regularization (information-field theory); Mathematical ambiguities – PWA
Technical MC advances $3\pi\gamma\gamma$ final state & beyond	New: Improved calorimetry simulations and calibrations

The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)



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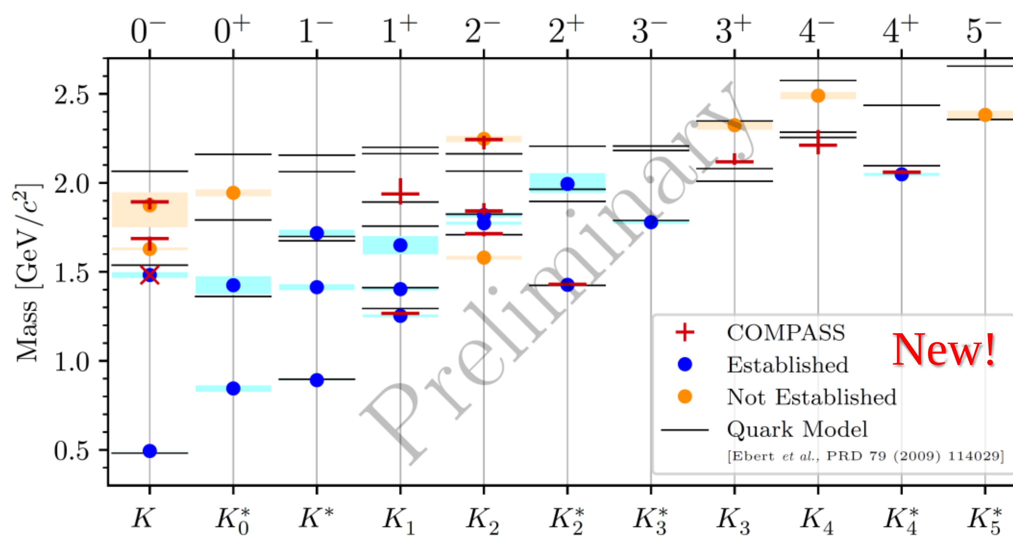

The Strange-Meson Spectrum at COMPASS

- The world's largest data sample on $K^-\pi^-\pi^+$
- 11 states extracted from the COMPASS data
- Possible exotic strange meson
- (a supernumerary state in $J^P = 0^-$)

The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

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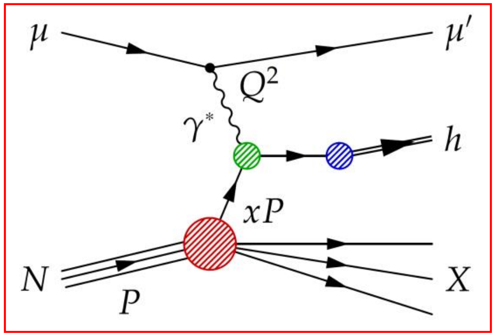
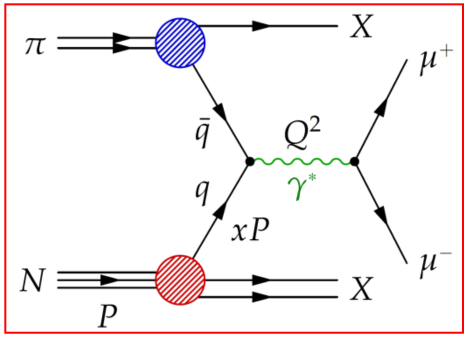
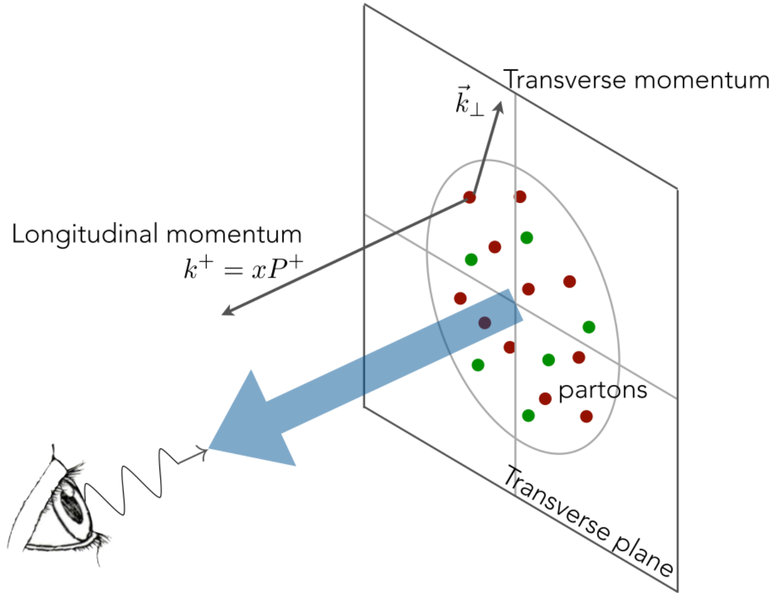
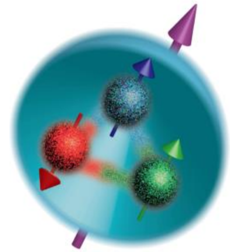


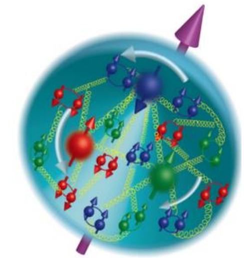




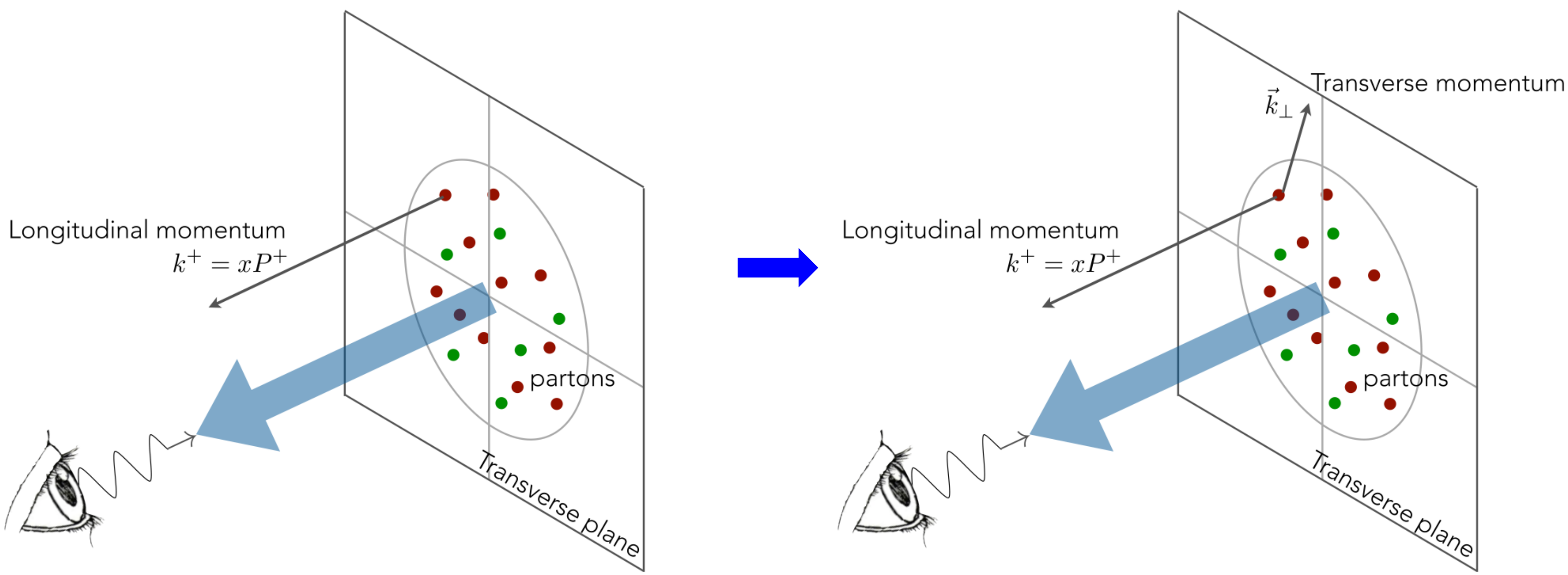
Nucleon spin structure



- 1964 Quark model 
- 1969 Parton model 
- 1973 asymptotic freedom and QCD 

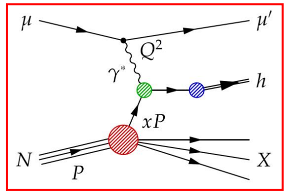


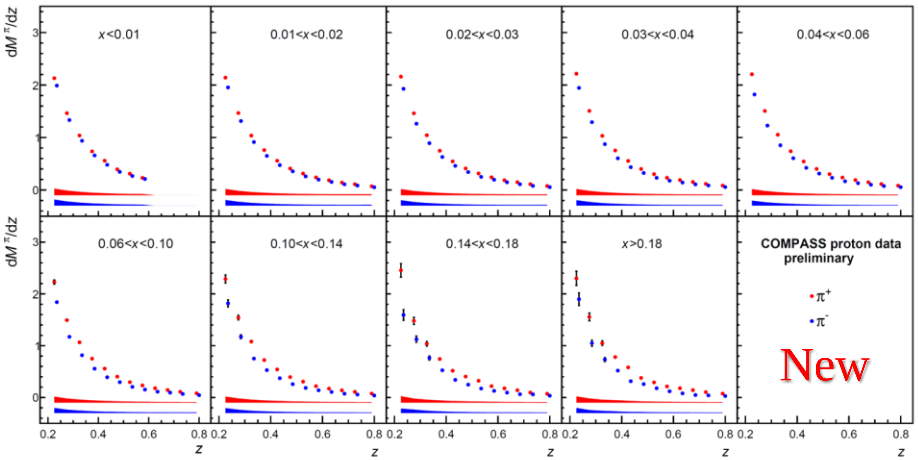
- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries 

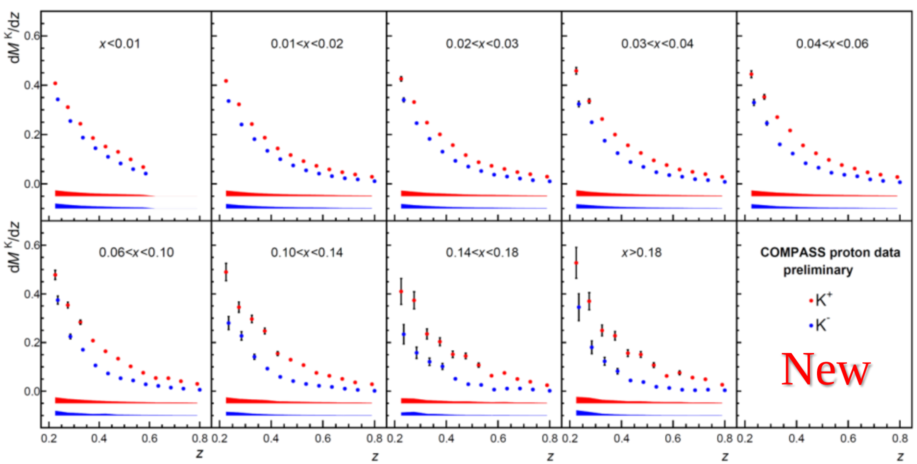


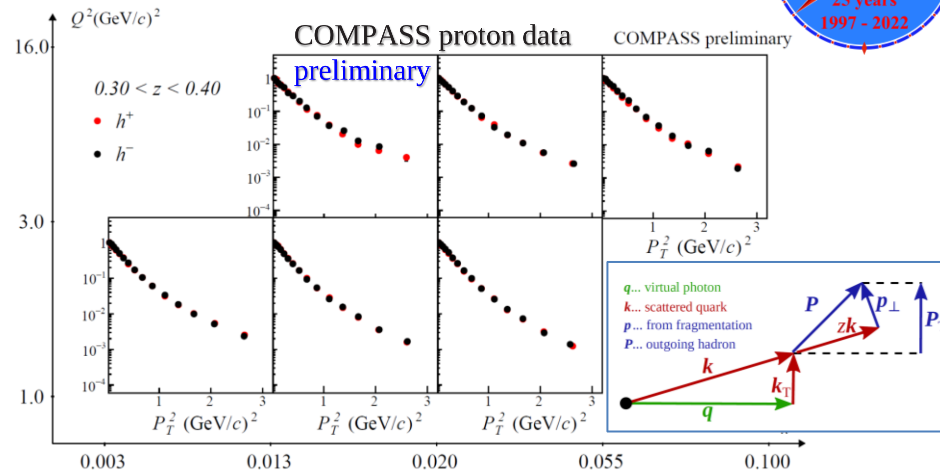
Hadron multiplicities; $h^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ (2016 data)

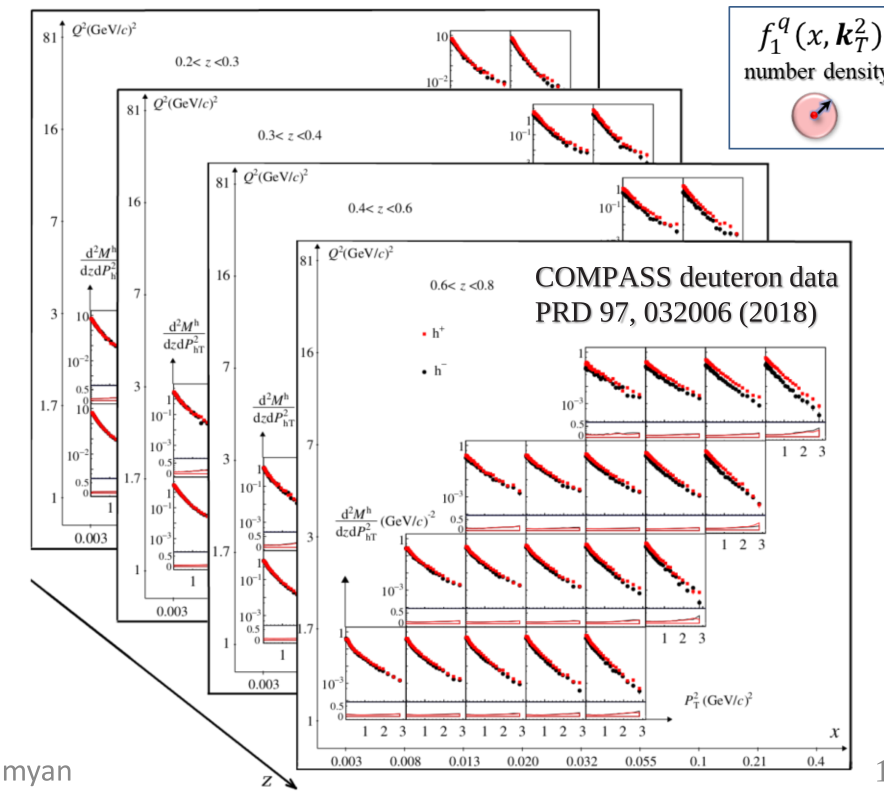
A set of complex corrections:
- Acceptance, diffractive VMs, radiative corrections, PID, etc.







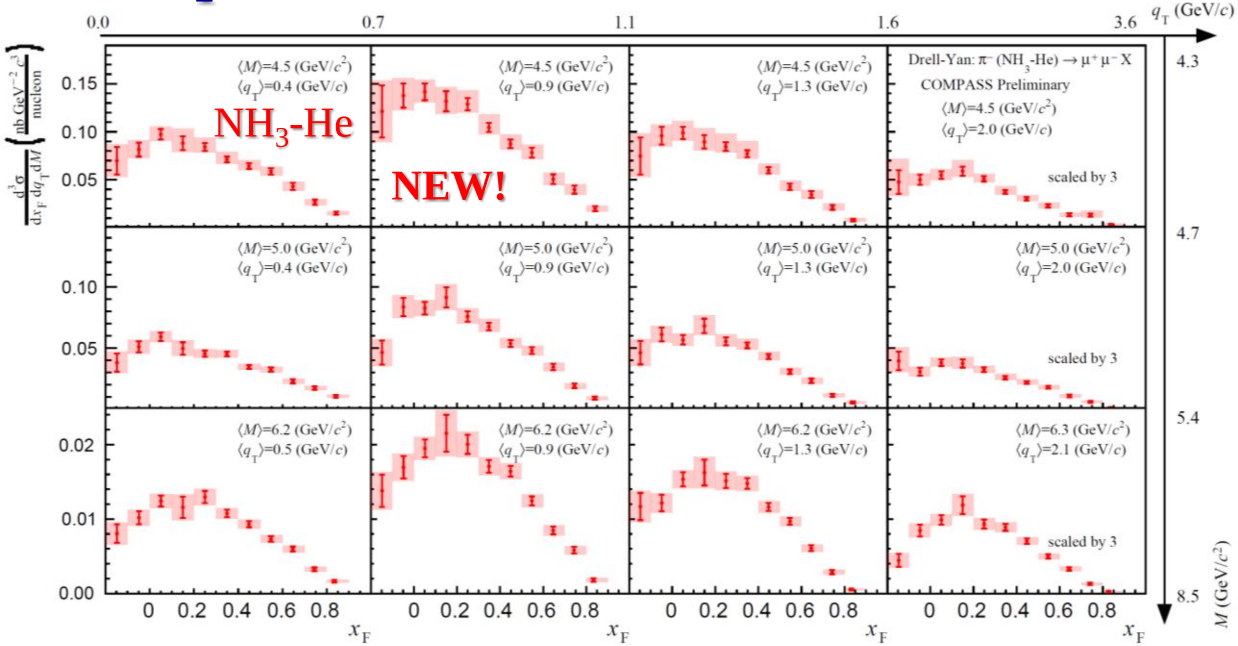


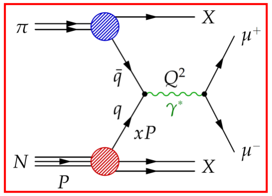


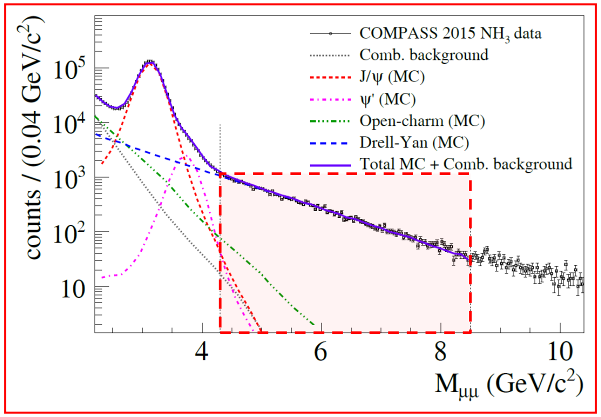
New radiative corrections

The corresponding article is being drafted

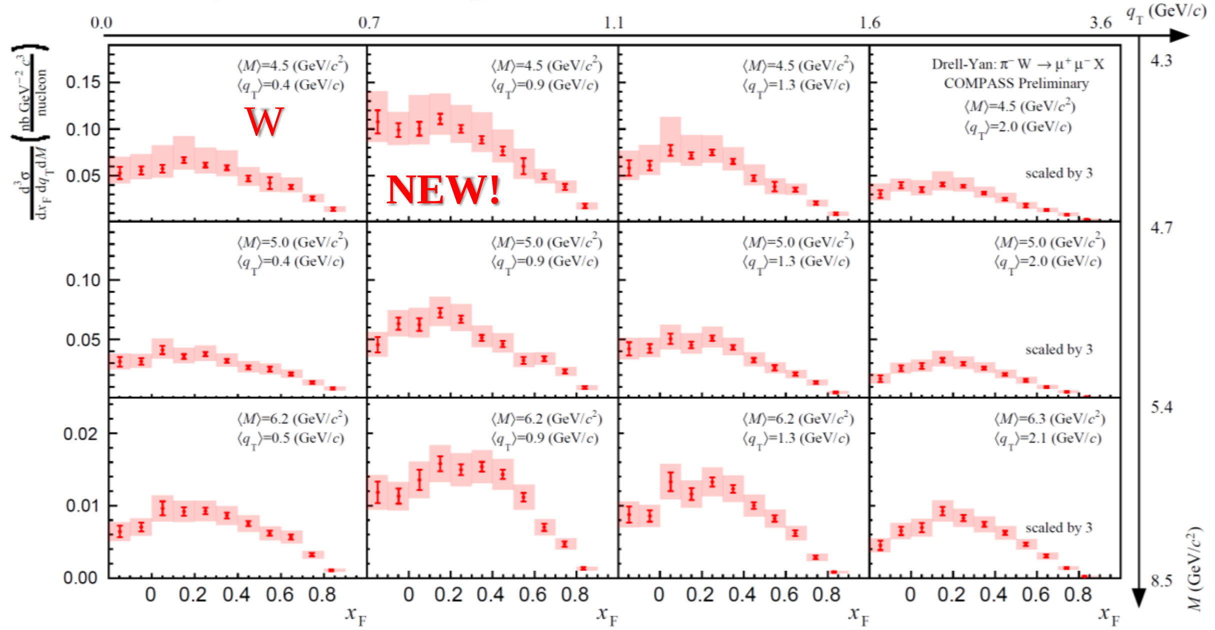
3D unpolarized Drell-Yan cross section on NH_3 and W







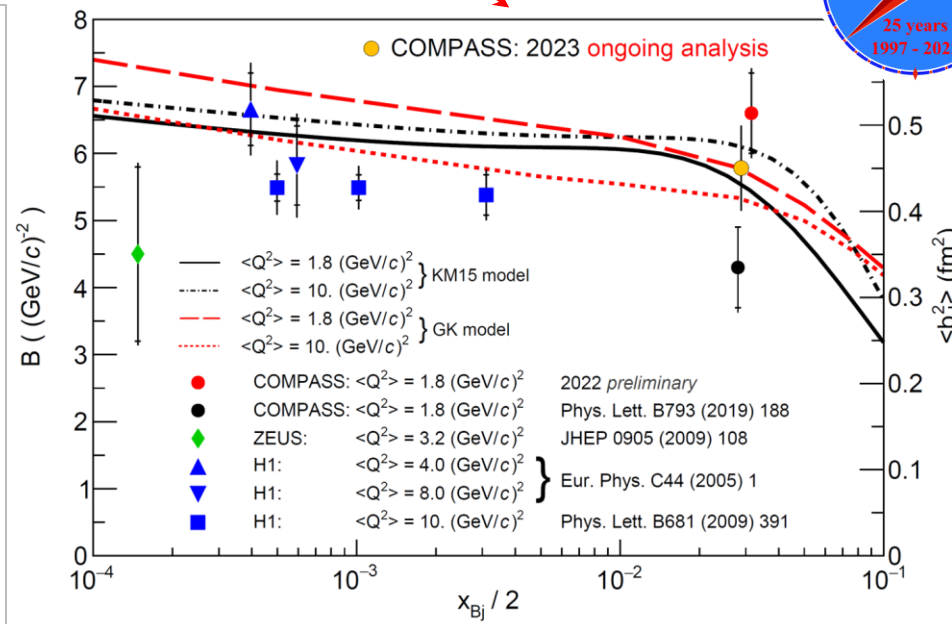
- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access pion TMD PDF

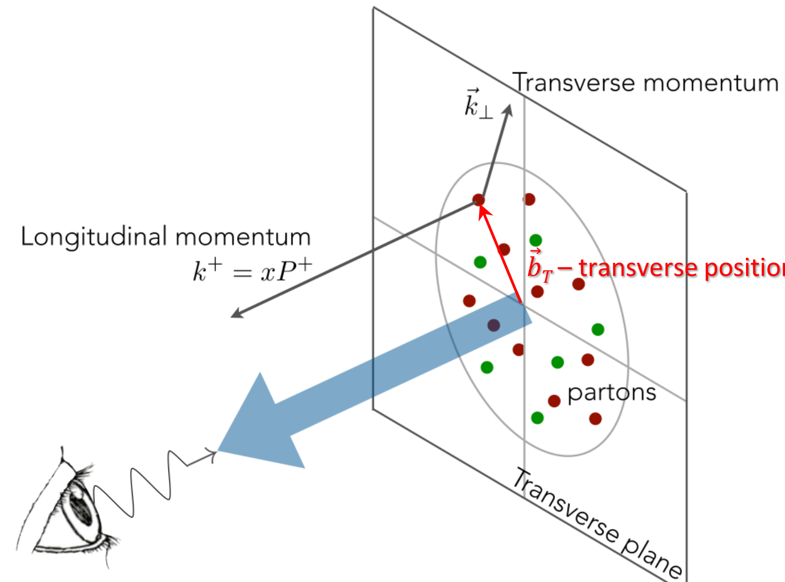


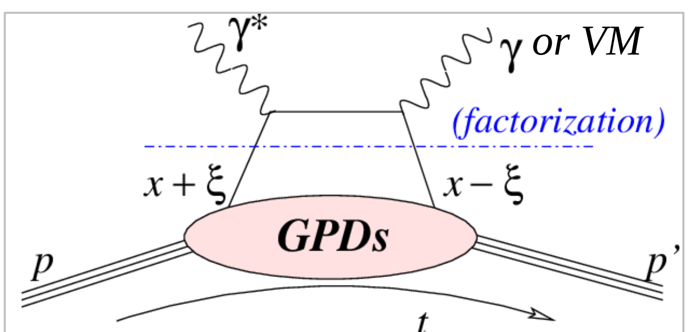
Nucleon 3D structure: GPDs

- Transverse position $\vec{b}_T$ of partons
  - Correlation between $\vec{b}_T$ and x
  - Complementary to TMD PDFs
- 8 generalized parton distribution functions (GPDs)
  - Contain information about parton orbital angular momentum
  - Mostly unknown
- COMPASS exclusive process measurements:
  - Deeply virtual Compton scattering (DVCS): $\mu + N \rightarrow \mu + \gamma + N$
  - Hard exclusive meson production (HEMP): $\mu + N \rightarrow \mu + VM + N$ with VM = π^0, $\rho(770)$, $\omega(782)$,..

COMPASS 2016 data (2/3)







Nucleon 3D structure: GPDs

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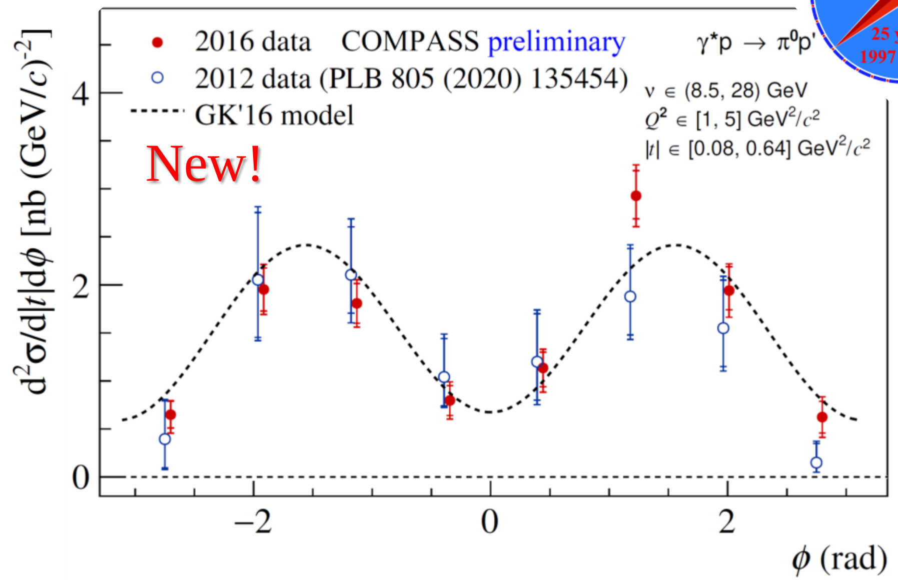
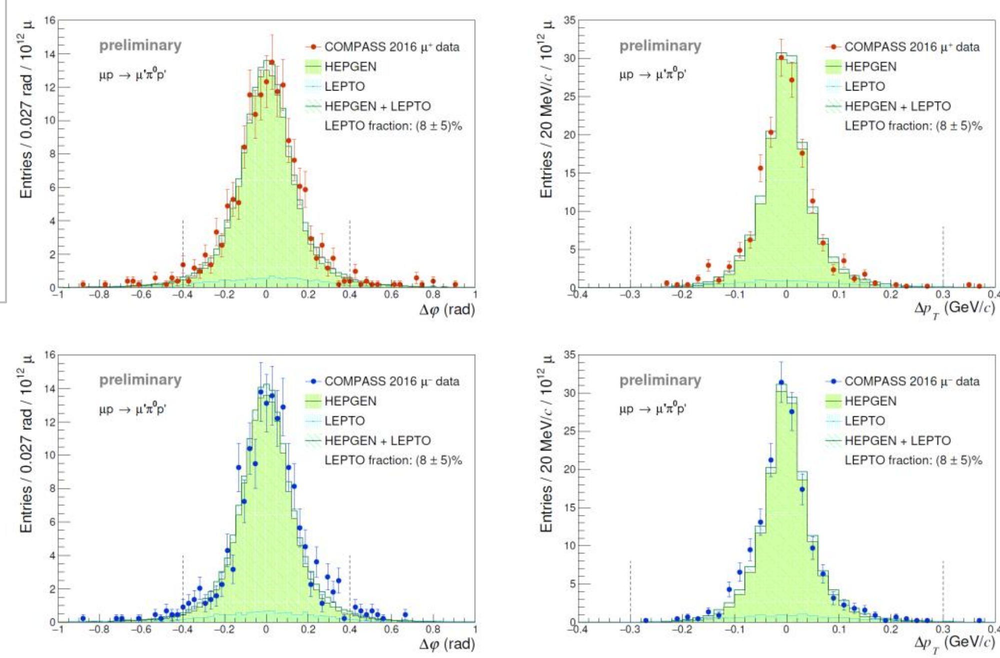
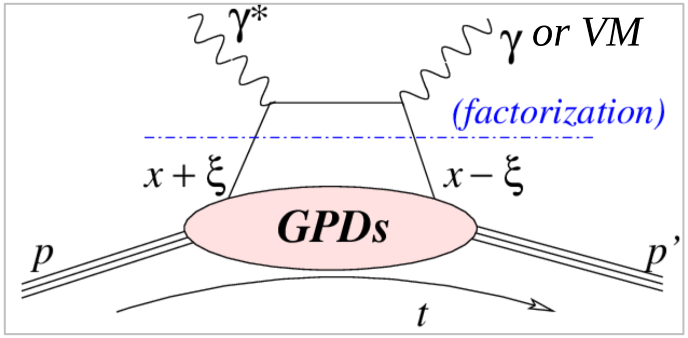






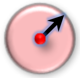
Cahn effect in SIDIS

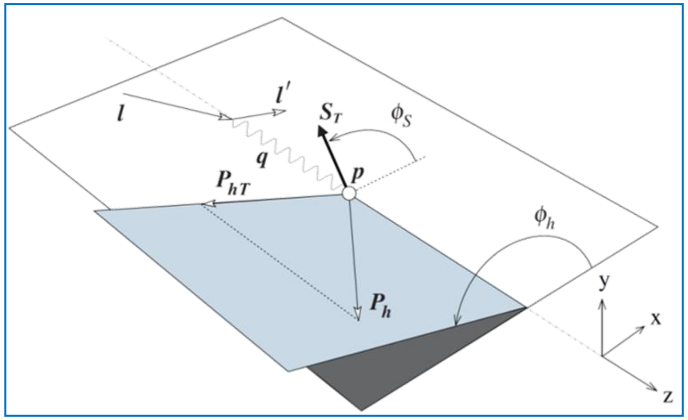
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} =$$

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

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

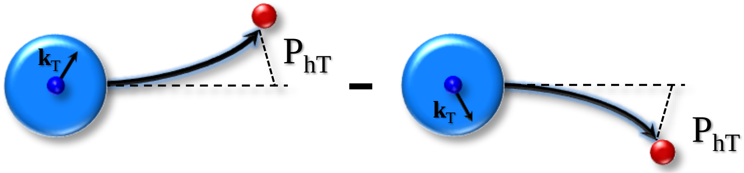
$f_1^q(x,\boldsymbol{k}_T^2)$
number density



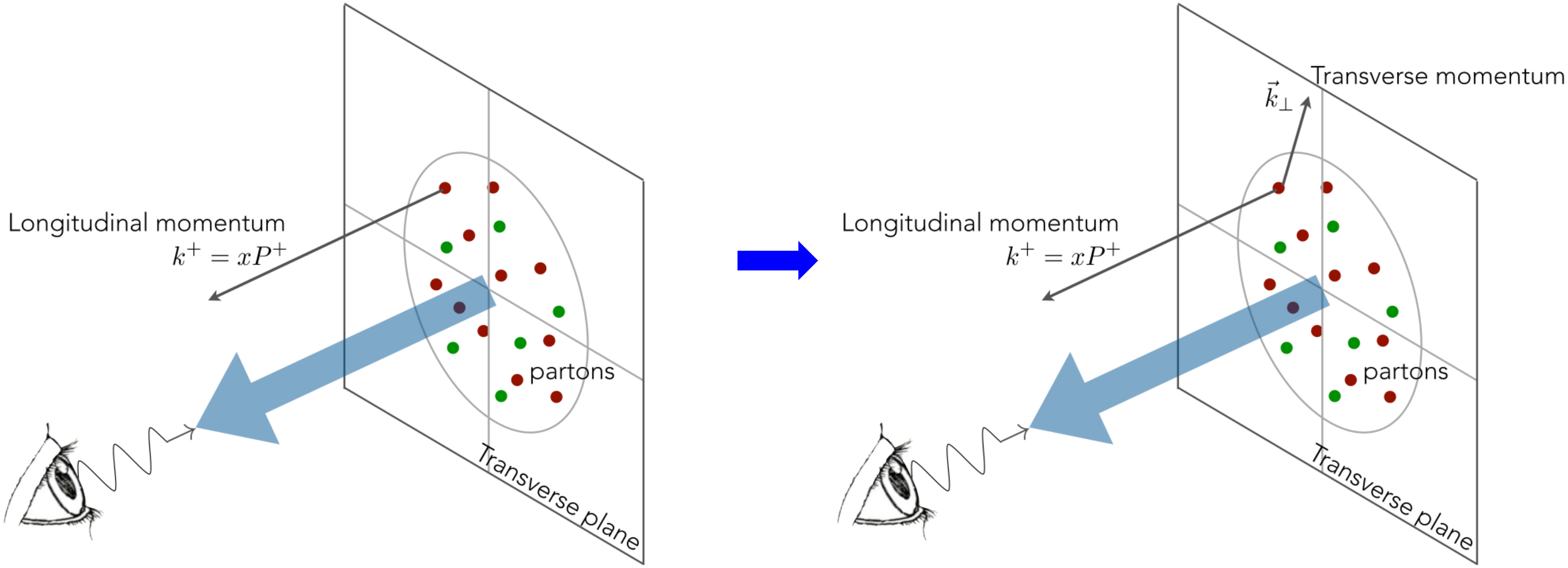


Cahn effect - R. N. Cahn, PLB 78 (1978)

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



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



Cahn effect in SIDIS

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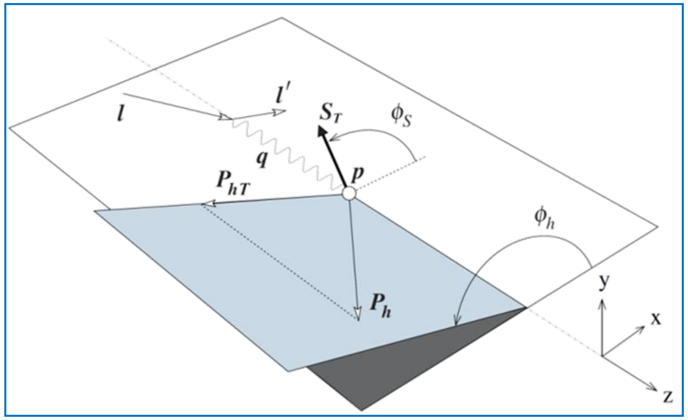
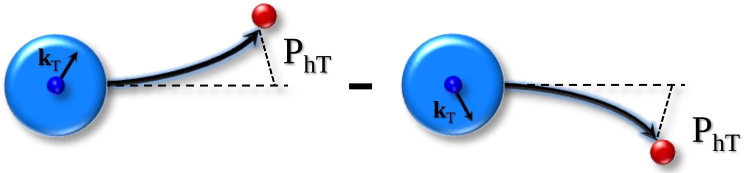
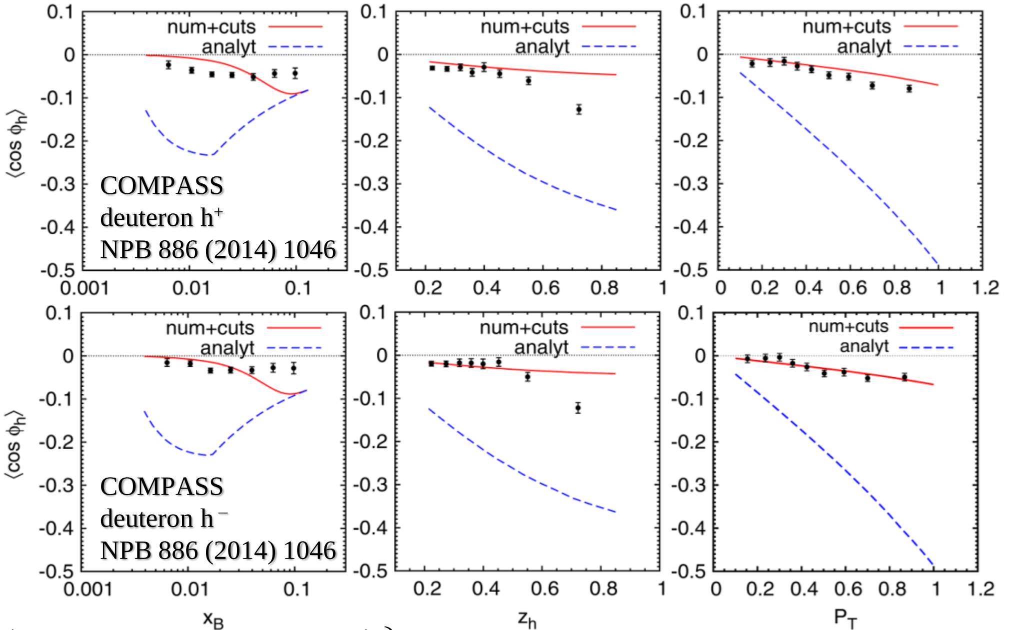
$$\times\left(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\ldots\right)$$

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

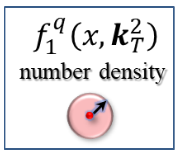
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q} C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

Cahn effect in SIDIS

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

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

Cahn effect



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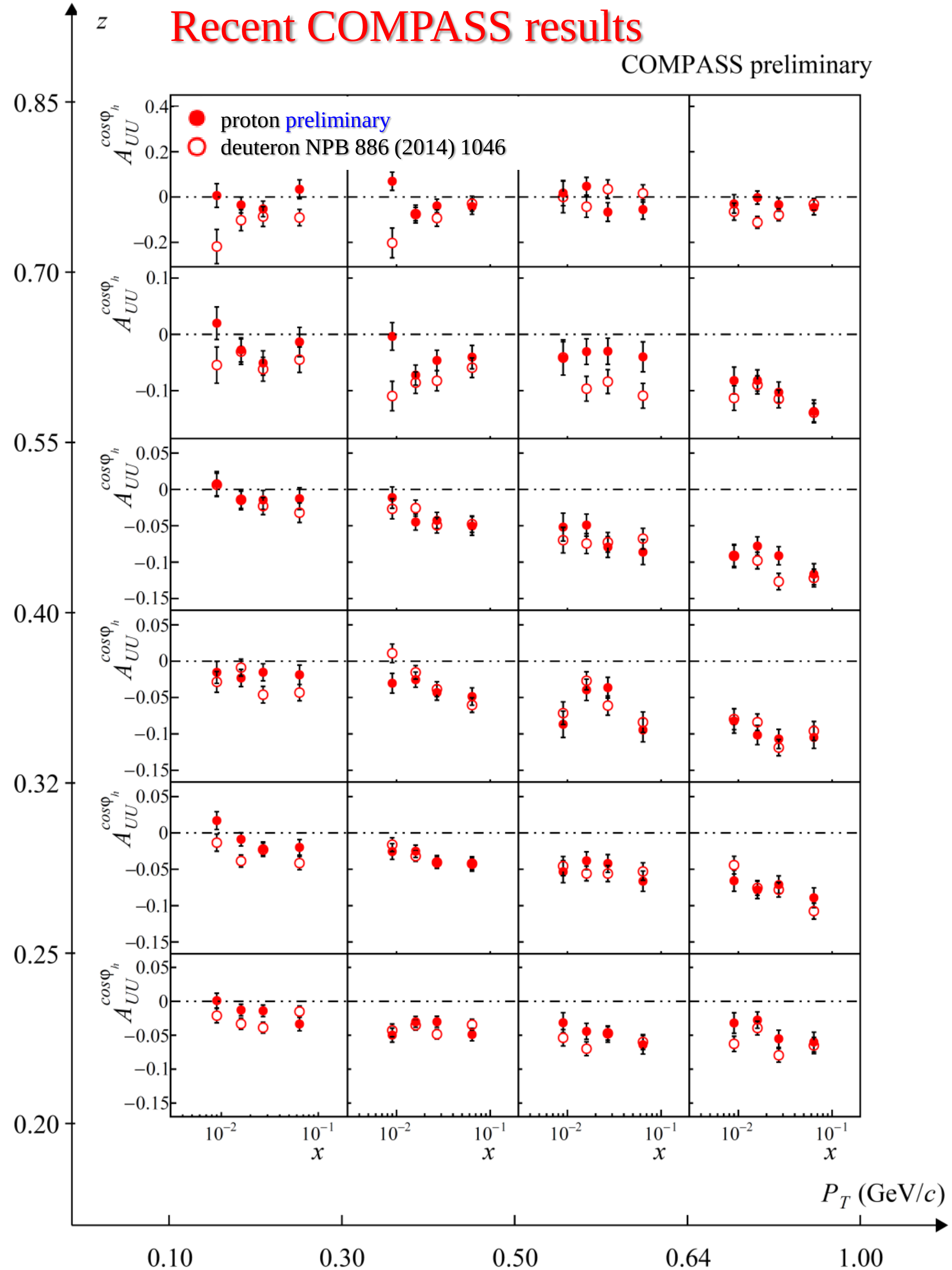
As of 2023 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation

Recent COMPASS results

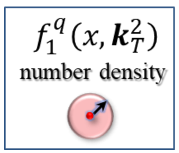


Cahn effect in SIDIS

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

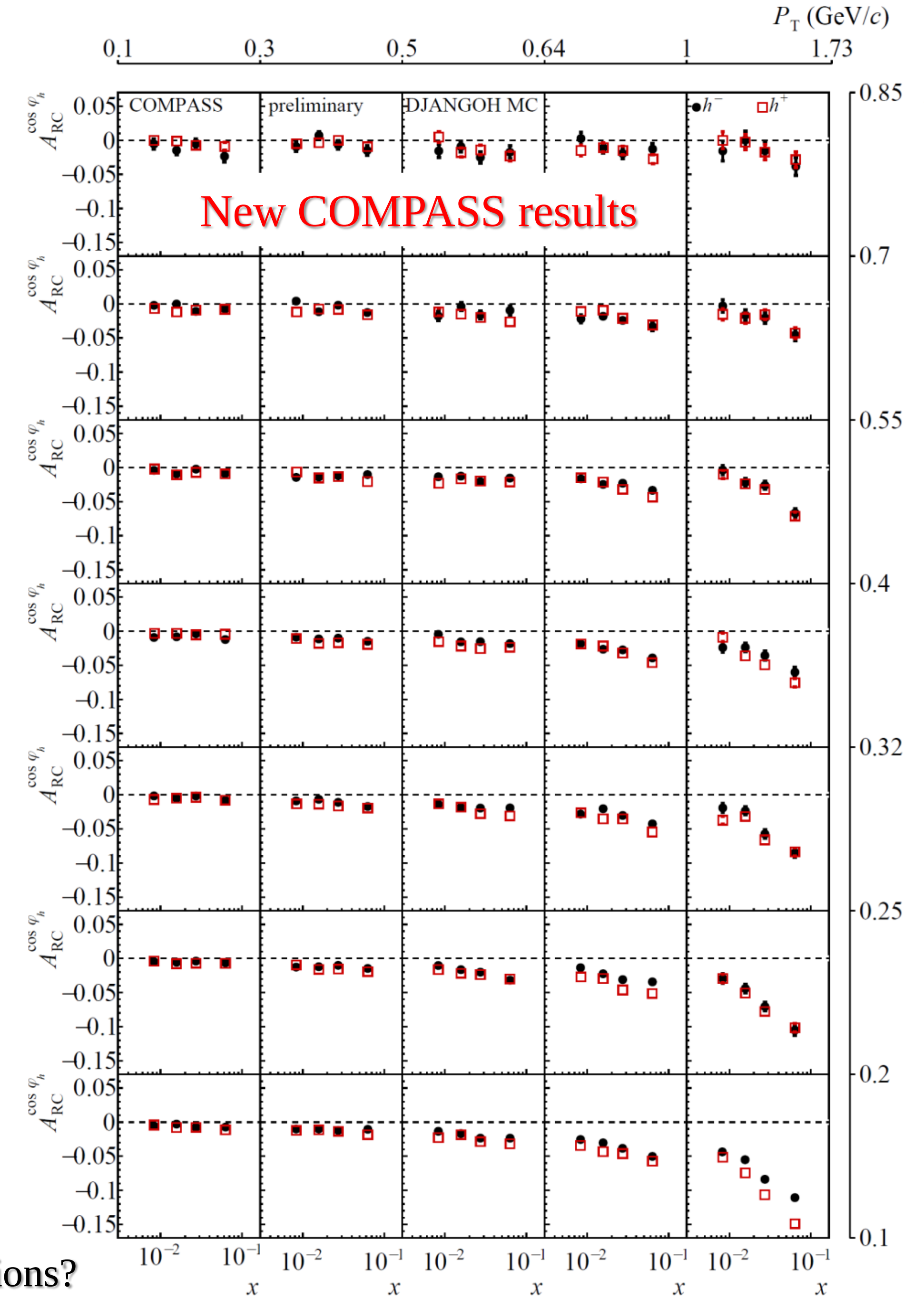
$$\times\left(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\ldots\right)$$

Cahn effect



As of 1978 – simplistic kinematic effect:
- non-zero k_T induces an azimuthal modulation

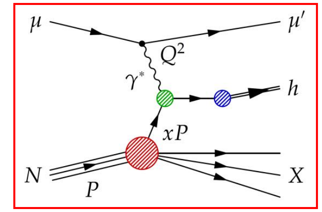
As of 2023 – complex SF (twist-2/3 functions)
- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
- Strong Q^2 dependence – unexplained
  - Do not seem to come from RCs
  - Transition between TMD ↔ collinear regions?



cosϕ$_h$ amplitude of the radiative corrections

SIDIS cross-section (TMD PDFs)

All measured by COMPASS



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

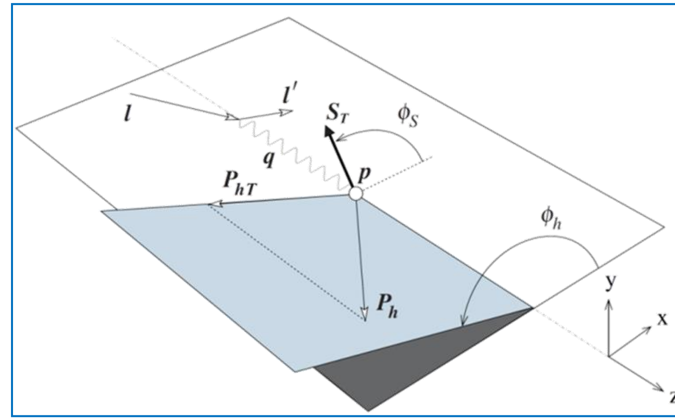
$$\times \Bigg\{ 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

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

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

$$+ S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array}\right]$$

$$+ S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right]\Bigg\}$$



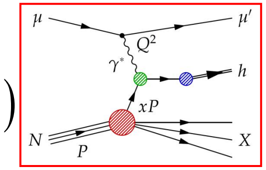
Nucleon \ Quark	U	L	T
U	number density		T-odd Boer-Mulders
L		Helicity	(worm-gear L)
T	T-odd Sivers	Kotzinian-Mulders (worm-gear T)	Transversity Pretzelosity

spin of the nucleon, spin of the quark, k_T

SIDIS and Drell-Yan cross-sections (TMD PDFs)

All measured by COMPASS

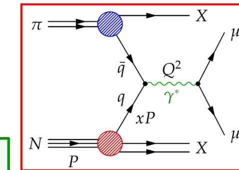
SIDIS



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

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

Drell-Yan



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

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

Quark / Nucleon	U	L	T
U	number density		T-odd Boer-Mulders
L		Helicity	(worm-gear L)
T	T-odd Sivers	Kotzinian-Mulders (worm-gear T)	Transversity Pretzelosity

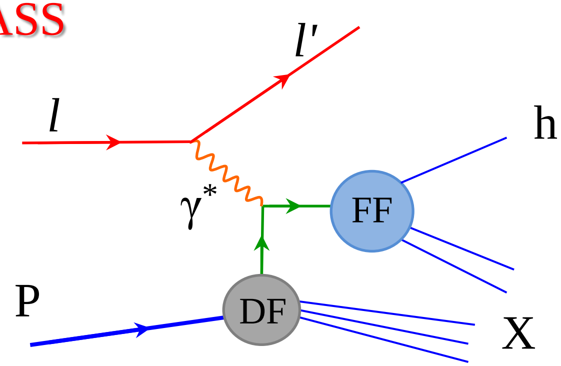
spin of the nucleon, spin of the quark, k_T

SIDIS cross-section (TMD PDFs): TSAs

All measured by COMPASS

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

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



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

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

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

Twist-2

Twist-3

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

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

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

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

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

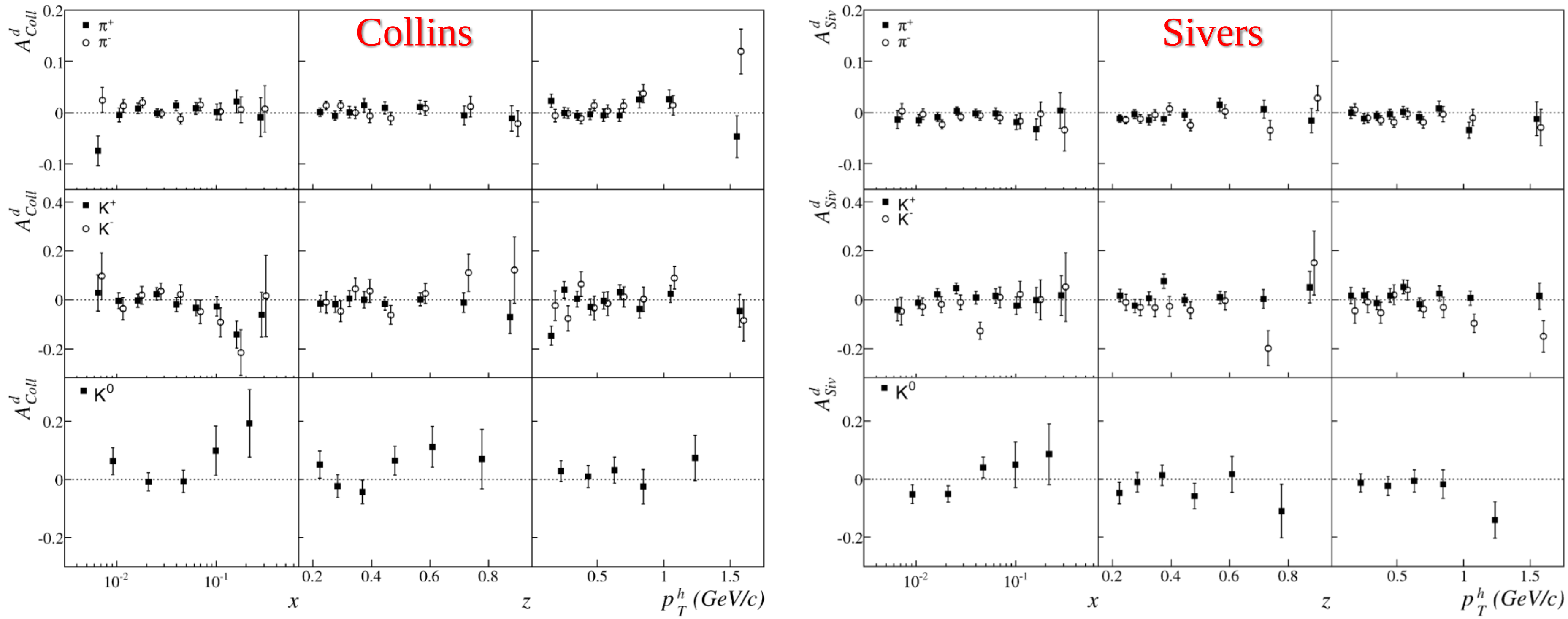
SIDIS TSAs: Collins and Sivers effects (deuteron)

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

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

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

COMPASS PLB 673 (2009) 127



- 1^{st} COMPASS deuteron measurements 2002-2004
- Collins and Sivers asymmetries compatible with zero within uncertainties.

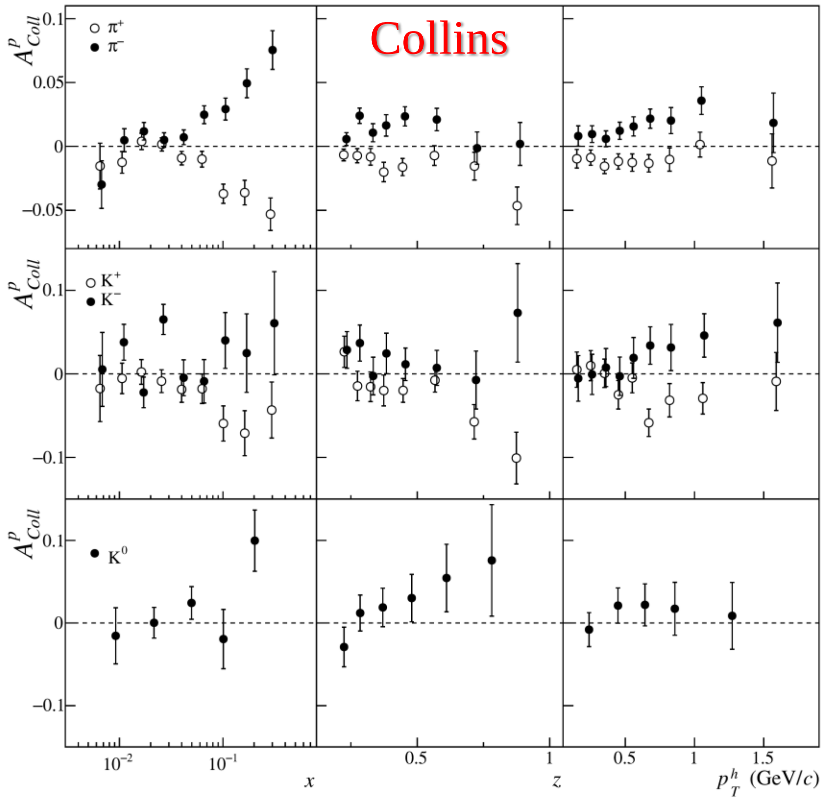
SIDIS TSAs: Collins and Sivers effects (proton)

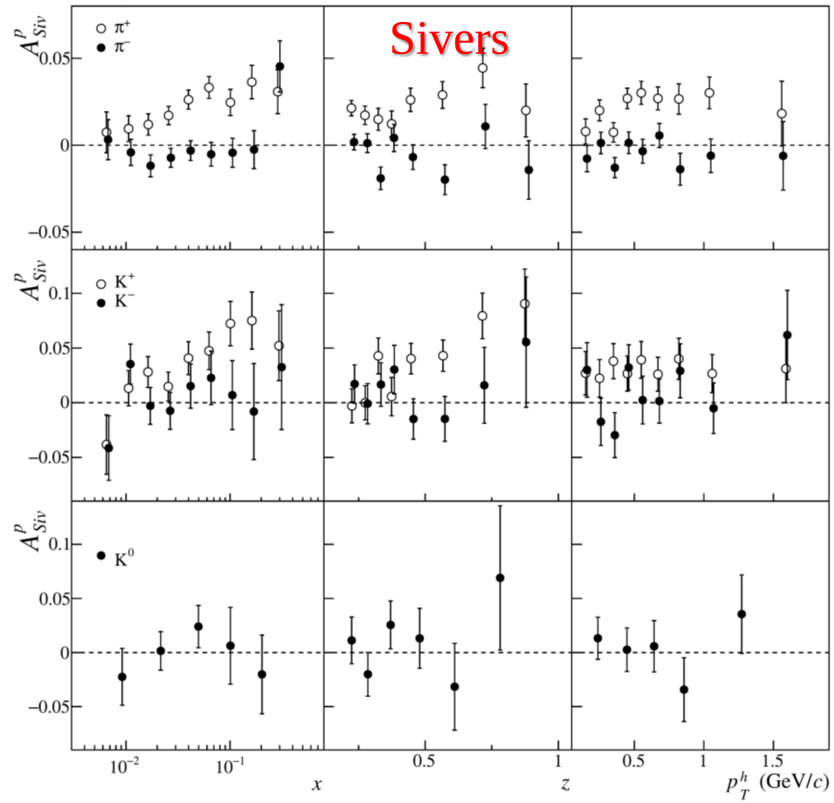
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) \ldots \right\}$$

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

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

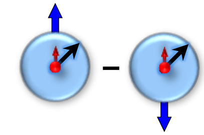
COMPASS PLB 744(2015)250





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

SIDIS TSAs: Collins effect and Transversity



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

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

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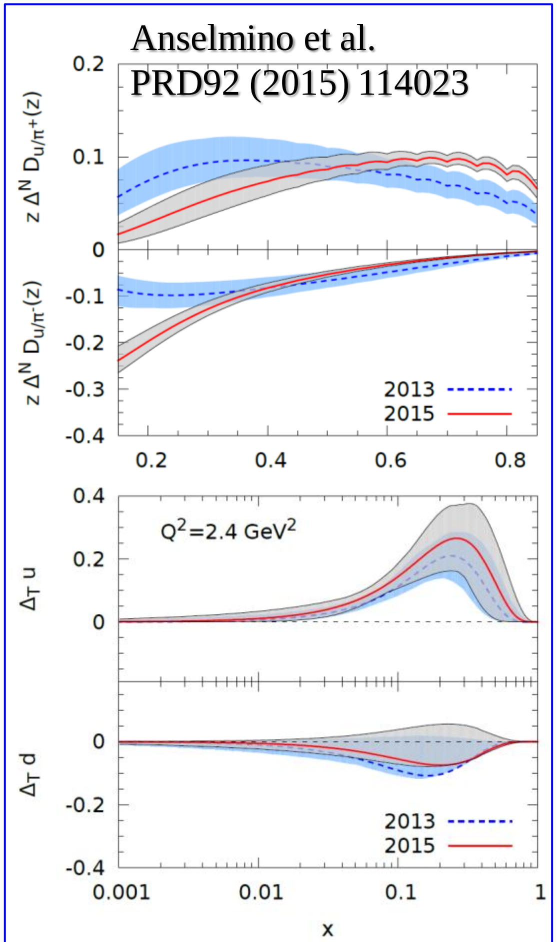
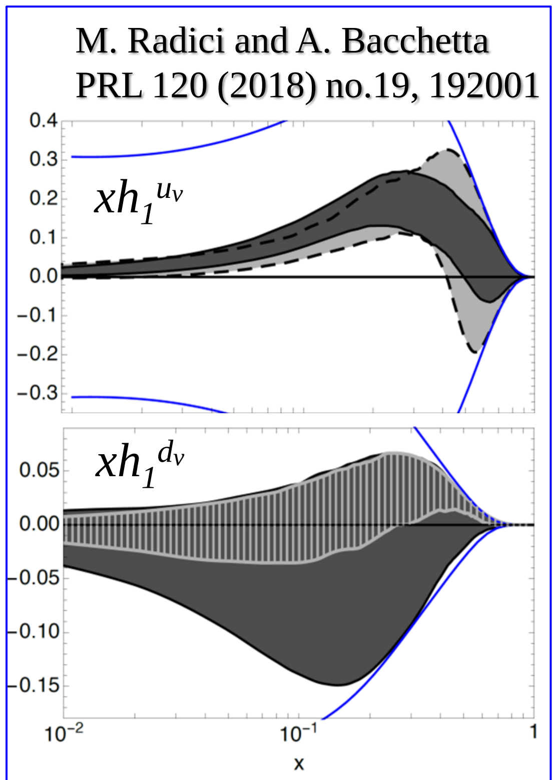
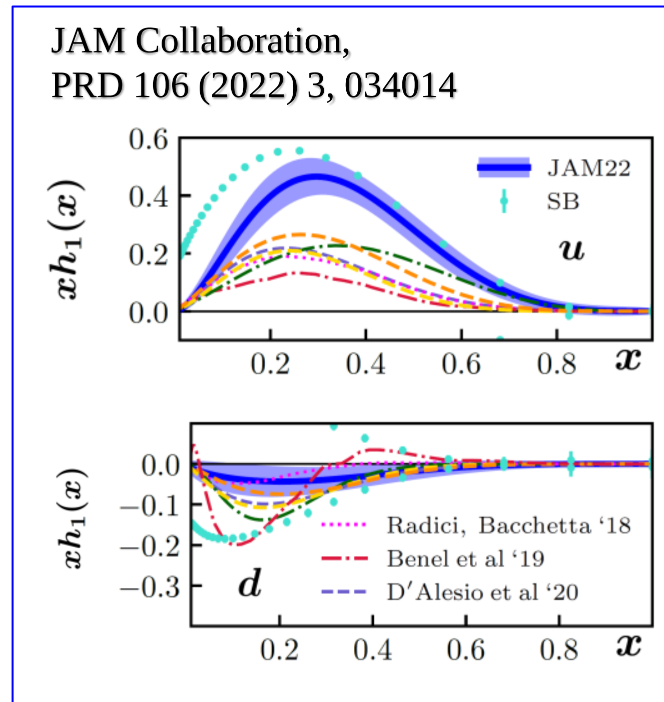
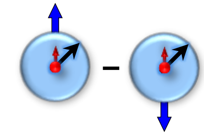






SIDIS TSAs: Collins effect and Transversity



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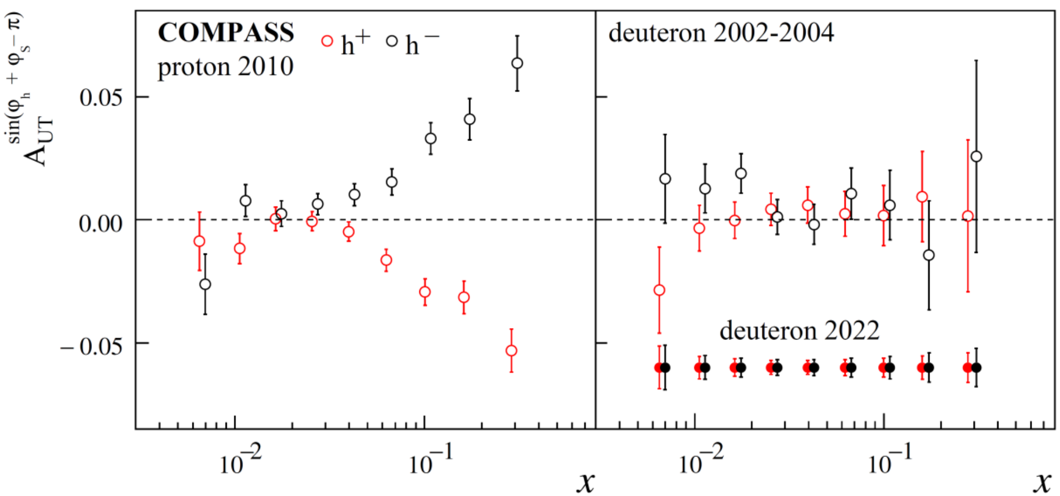
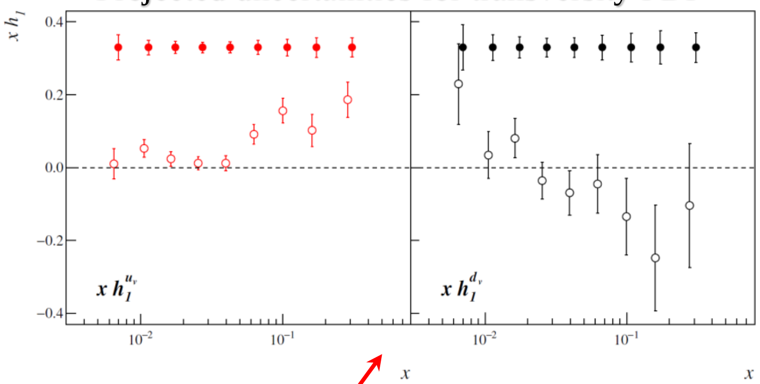
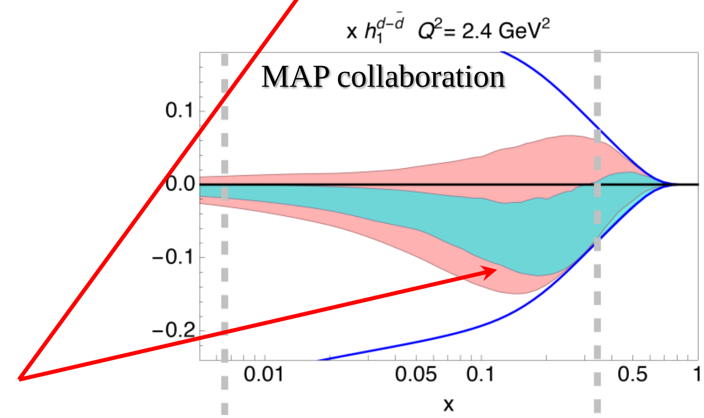
[Addendum to the COMPASS-II Proposal]
Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF



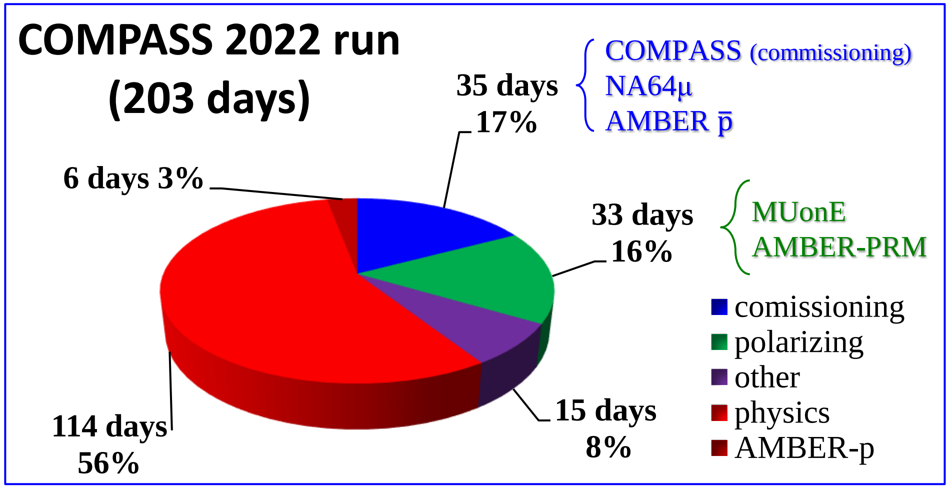


COMPASS-II (2022)

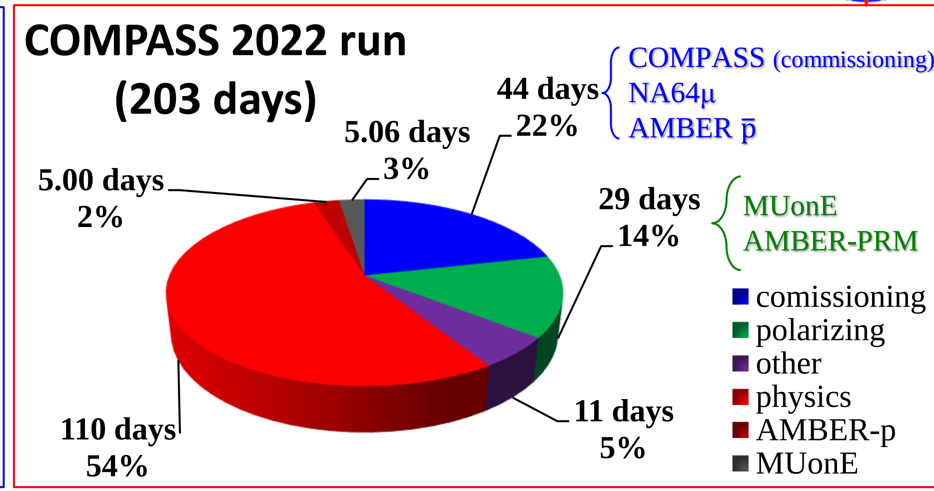
- 2^{nd} COMPASS deuteron measurements performed
- Crucial to constrain the transversity TMD PDF for the d-quark

COMPASS 2022 run

COMPASS proposal



final configuration



146th Meeting of the SPSC – minutes:

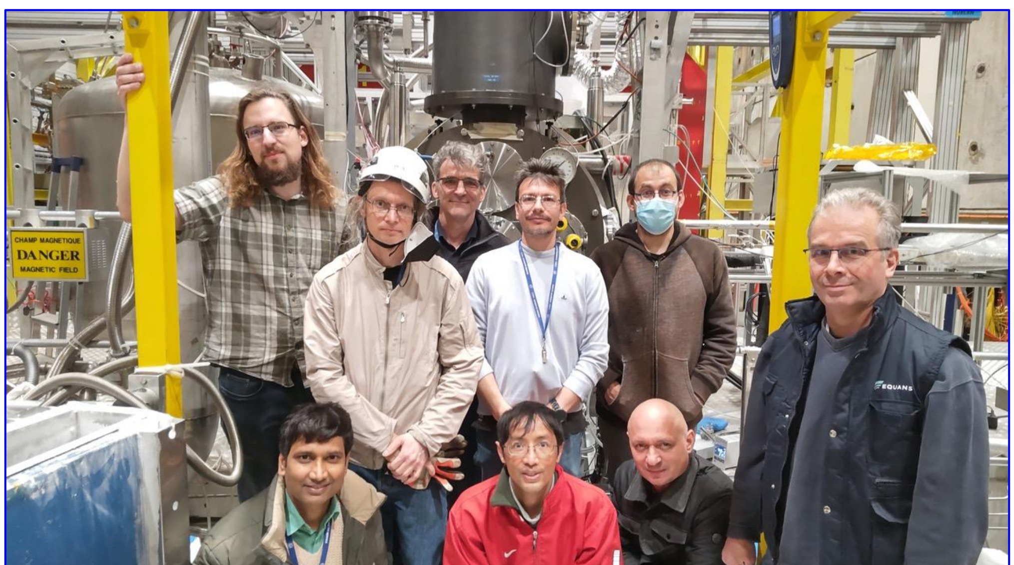
- SPSC is pleased by the synergistic approach in making optimal use of the beamline and commends COMPASS for taking the lead in this.
- The Committee notes with pleasure the readiness to take physics data, looks forward to a successful completion of the data collection for the transversity measurement, and supports the priority given to COMPASS during 2022 to complete its physics goals.

147th Meeting of the SPSC – draft minutes:

- The Committee acknowledges the efforts of COMPASS and of the other M2 beam line collaborations for the constructive and accommodating cooperation during the 2022 run.
- The committee congratulates COMPASS on the completion of a successful twenty years long data-taking program, resulting in important contributions to nuclear and particle physics.

COMPASS 2022 data-taking

- Overall very good performance of all detector systems and DAQ
  - No critical problems on the spectrometer side; high data collection efficiency
  - Increased DAQ capacities thanks to the optimizations carried out during the run
  - New monitoring tools to guarantee fast detection of detector problems
- After disastrous 2021… Quite smooth/good performance of all Polarized Target systems
  - Excellent performance of Gunn diodes
    (first tested in 2021, two more diodes purchased for 2022 run)
  - Average polarization is about 40-42%
    - smaller than the average ~50% polarization obtained when the material was last used in 2006 (i.e. 16 years ago)
  - Great support of CERN cryo division and PT magnet experts



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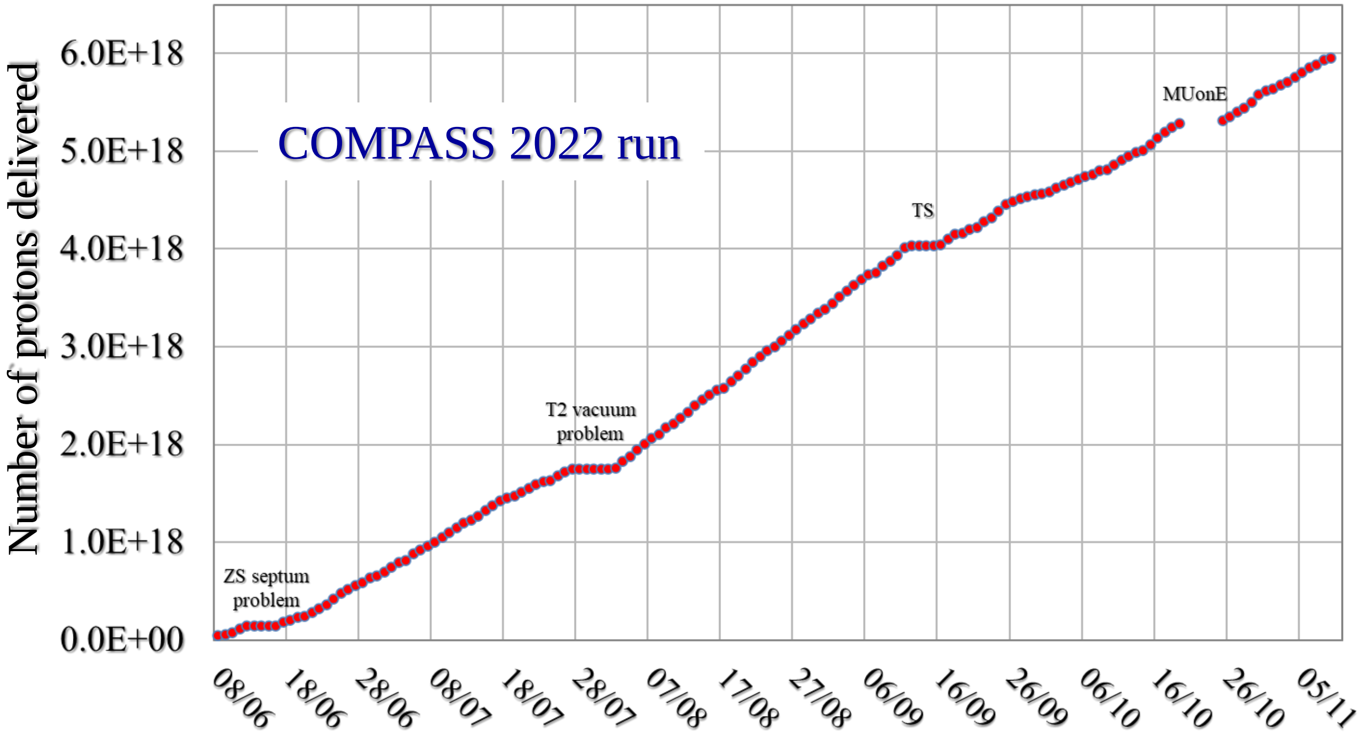
    - smaller than the average ~50% polarization obtained when the material was last used in 2006 (i.e. 16 years ago)
  - Great support of CERN cryo division and PT magnet experts
- SPS proton delivery to T6 excellently matched our request
  - Some unfortunate incidents causing down-times (e.g. PS POPS issues after the TS)
  - Despite very crowded injector schedule, a lot of tests and different operation-modes on accelerator side, the SPS efficiency was good enough (~73%, 82% in 2010)
  - Stable M2 beamline operation, no major incidents or problems
    - Tireless help and assistance from our beam physicists and BE department

Thanks to CERN for being such a great host laboratory
for COMPASS for so many years!

COMPASS 2022 data-taking

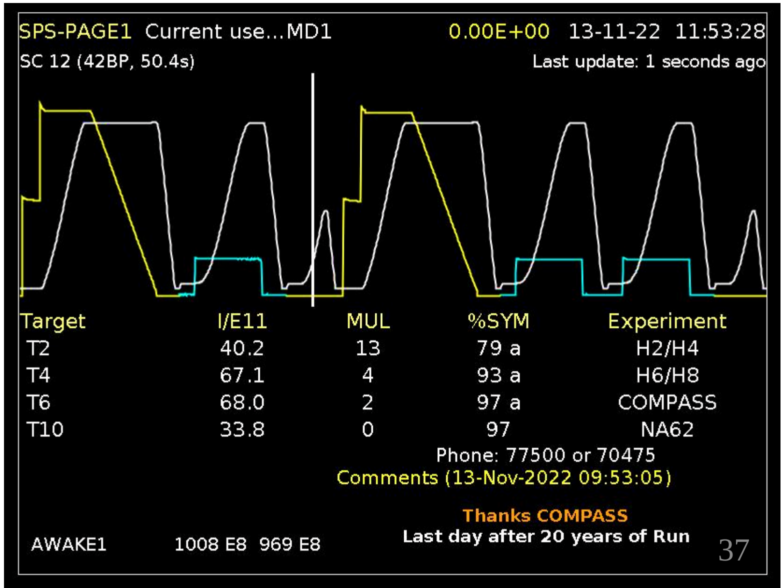


SPS efficiency: ~ 73%
Spectrometer efficiency: ~ 90%
Physics data collection efficiency: ~ 75%

Highly successful Run in 2022!

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

Thanks to CERN for being for so many years a great host laboratory for COMPASS!



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*

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

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

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

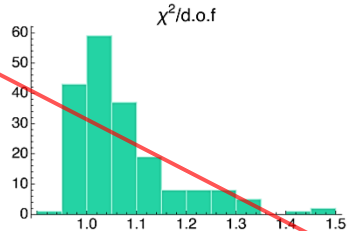
analysis of statistical error with replica method (200)
68% confidence level

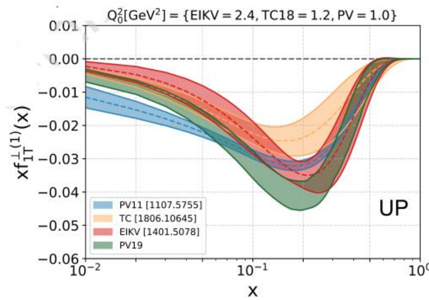
Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

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

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

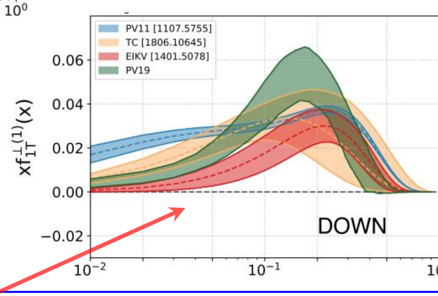




PV11	*Bacchetta & Radici, P.R.L. **107** (11)*
EIKV	*Echevarria et al., P.R. D**89** (14)*
TC	*Boglione et al., JHEP **1807** (18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

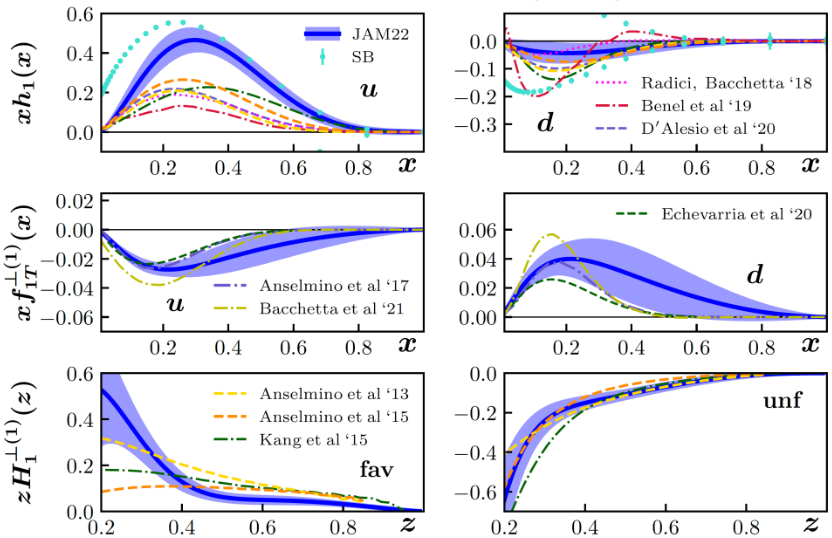
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \, \frac{\mathbf{k}_T^2}{2M^2} \, f_{1T}^{\perp}(x, \mathbf{k}_T)$$

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

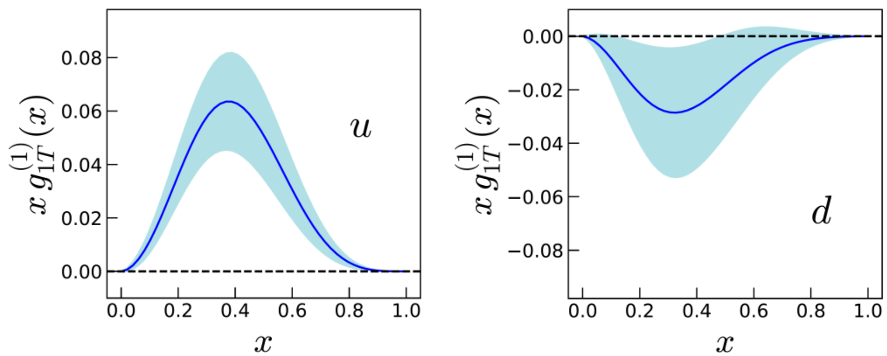


COMPASS 2022 deuteron run

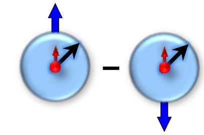
JAM Collaboration, PRD 106 (2022) 3, 034014



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



SIDIS TSAs: Collins effect and Transversity



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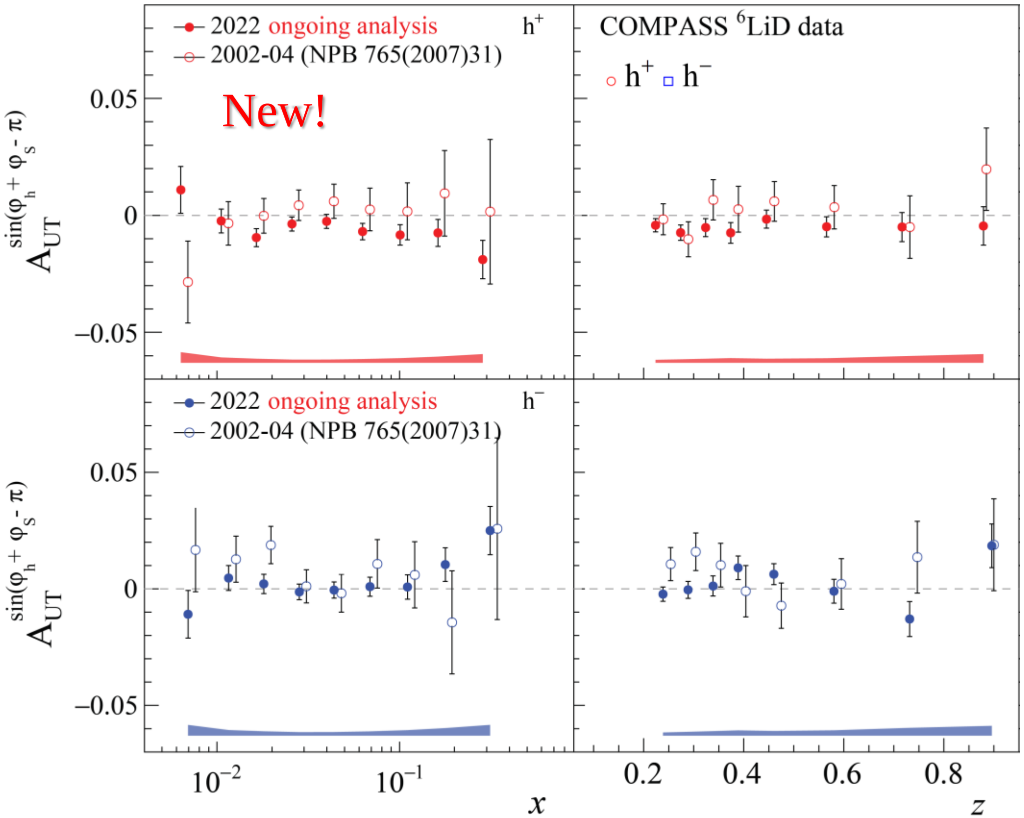
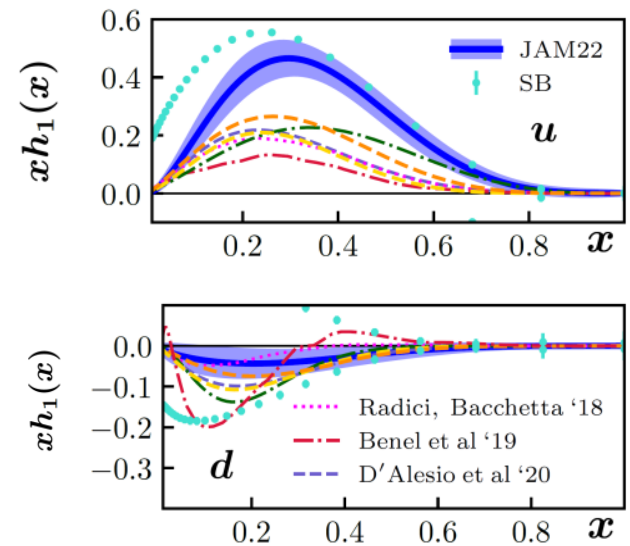


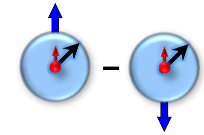
JAM Collaboration,
PRD 106 (2022) 3, 034014



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 and Transversity



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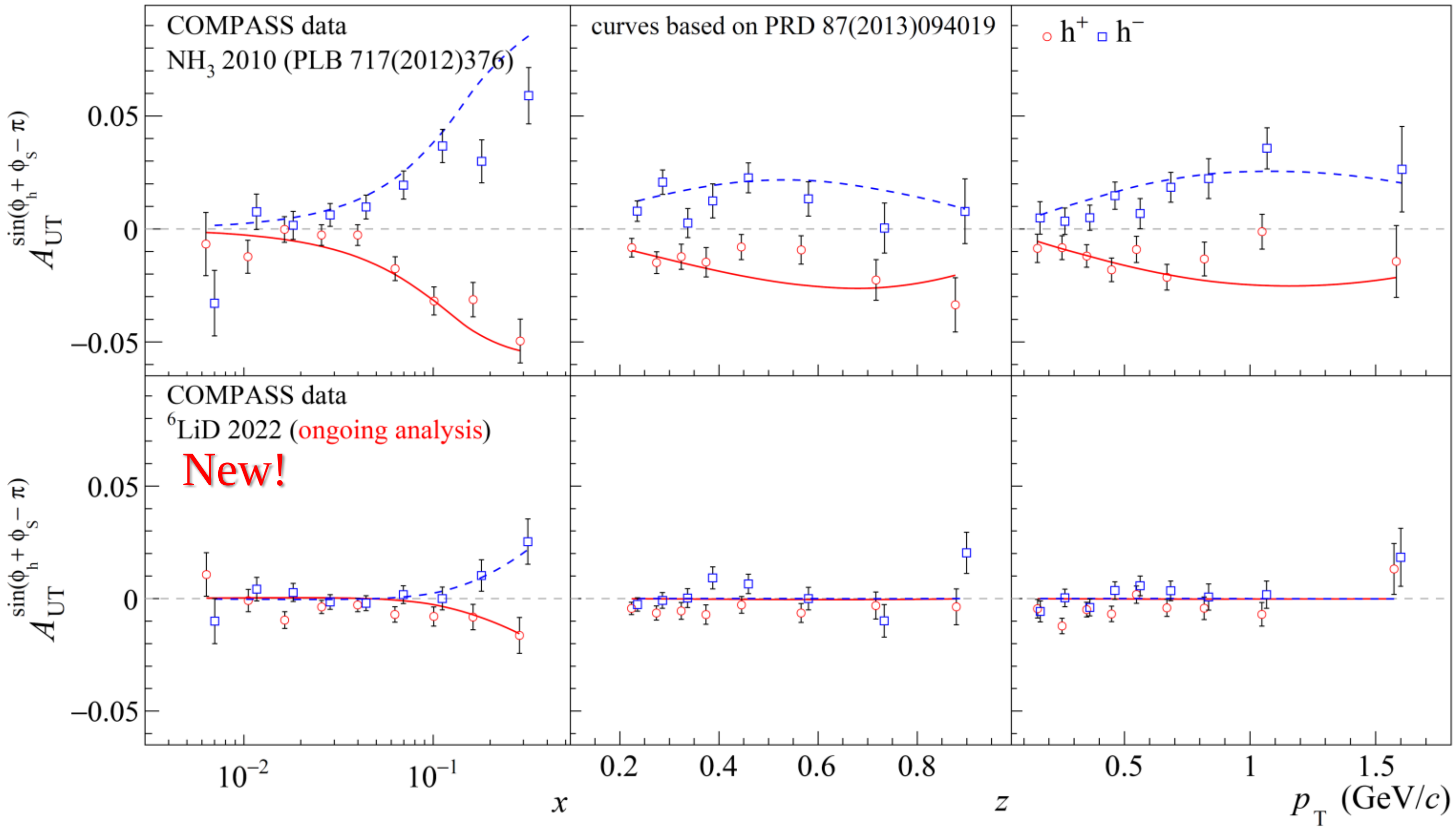

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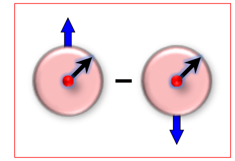
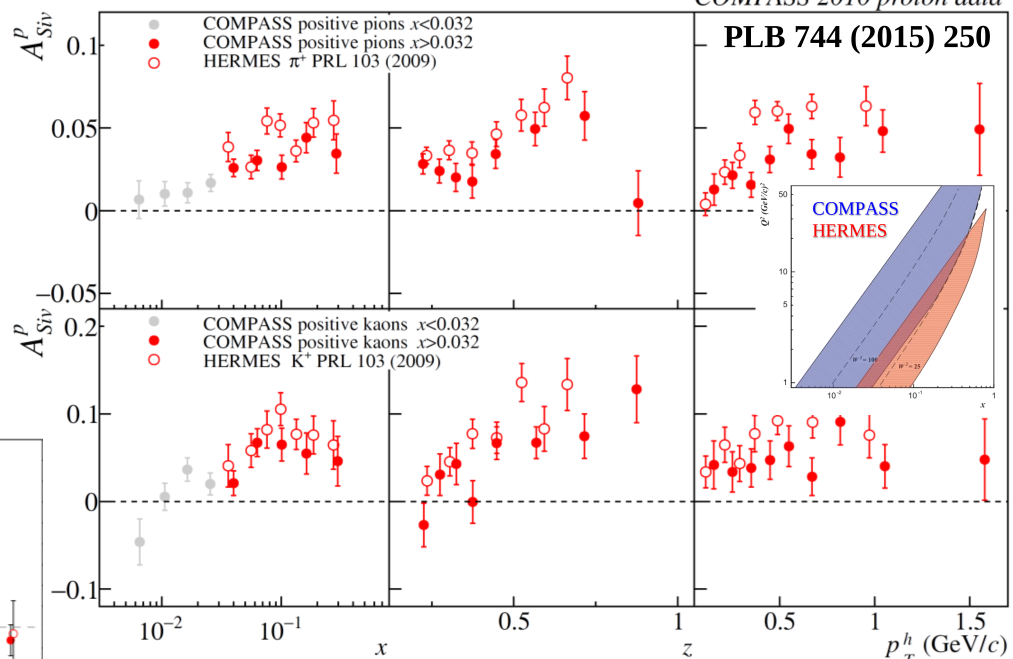
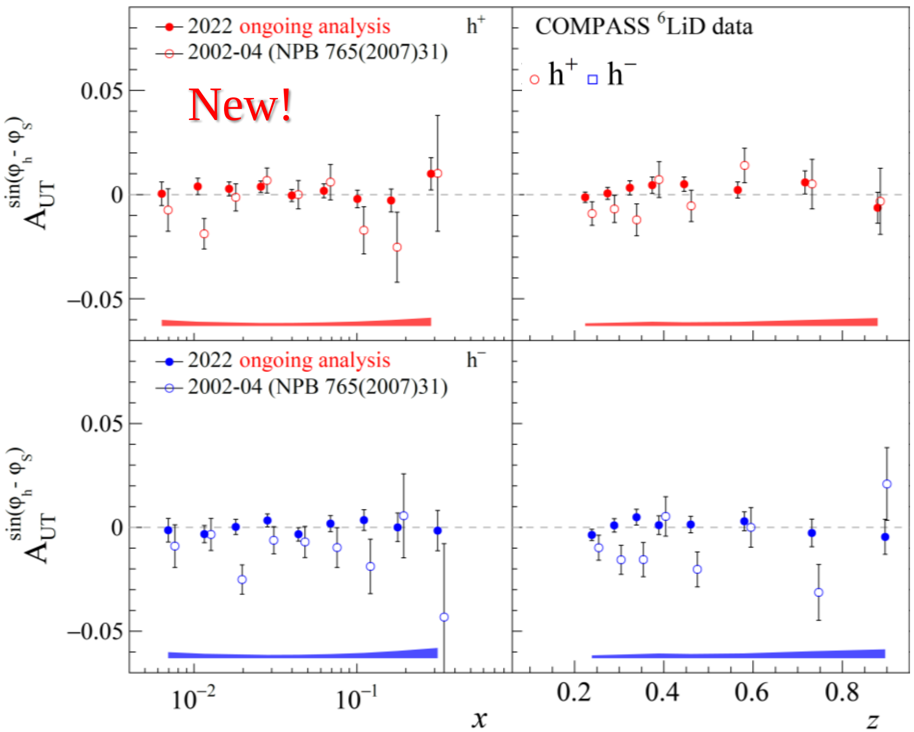


$$F_{UT,T}^{\sin(\phi_h - \phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h - \phi_S)} = 0$$

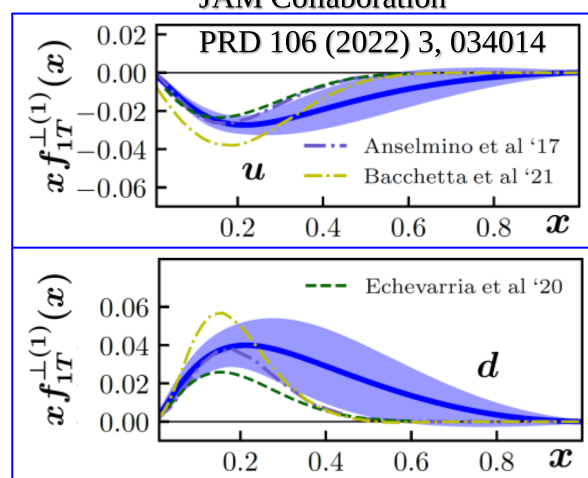
- COMPASS-HERMES discrepancy
- T-oddness: sign-change (SIDIS ↔ Drell-Yan)
  - Explored by COMPASS
- New precise deuteron data from COMPASS
  - Unique input to constrain Sivers PDF

COMPASS 2010 proton data

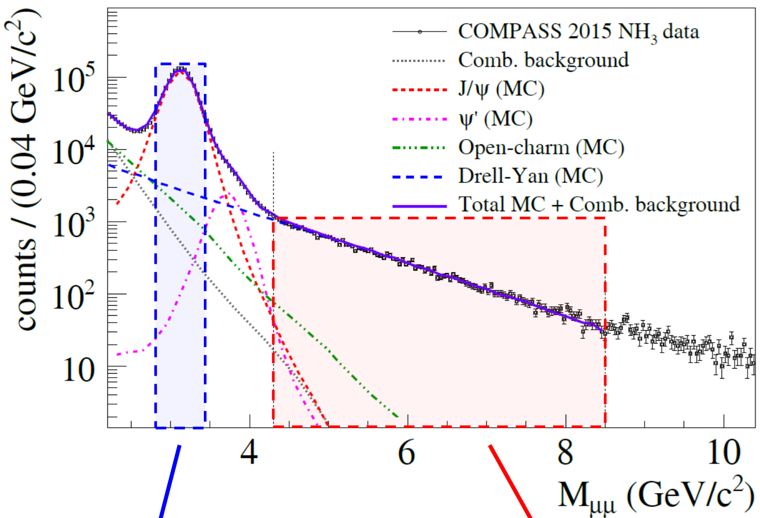


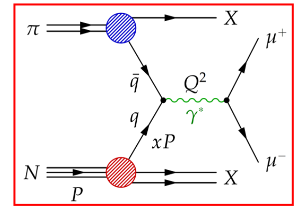


JAM Collaboration

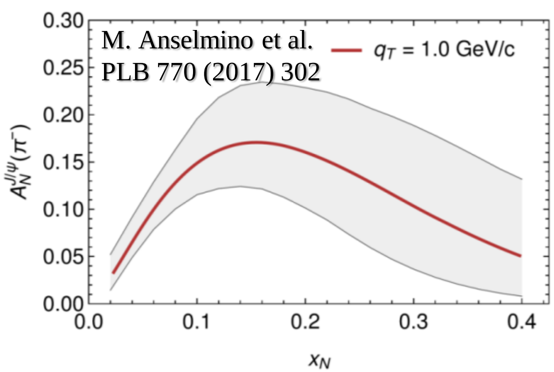


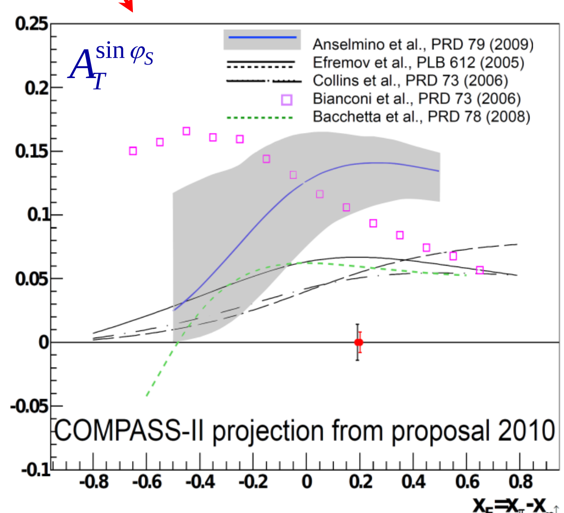
Single-polarized Drell-Yan cross-section at twist-2 (LO)





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





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

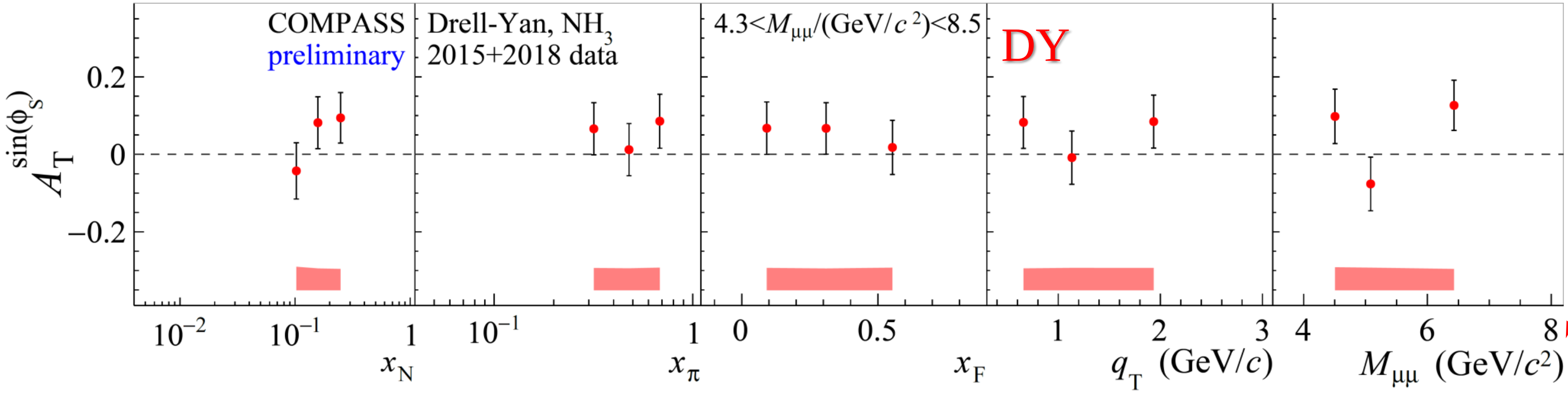
Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS → sign change test

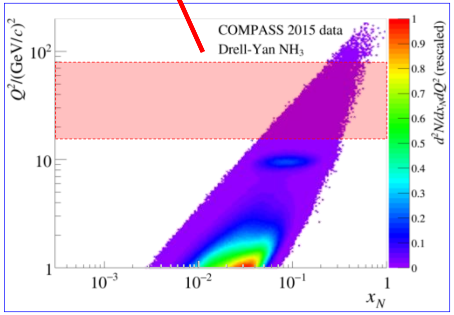
Drell-Yan TSAs – Sivers effect

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + \ldots \right]$$

Sivers DY TSA

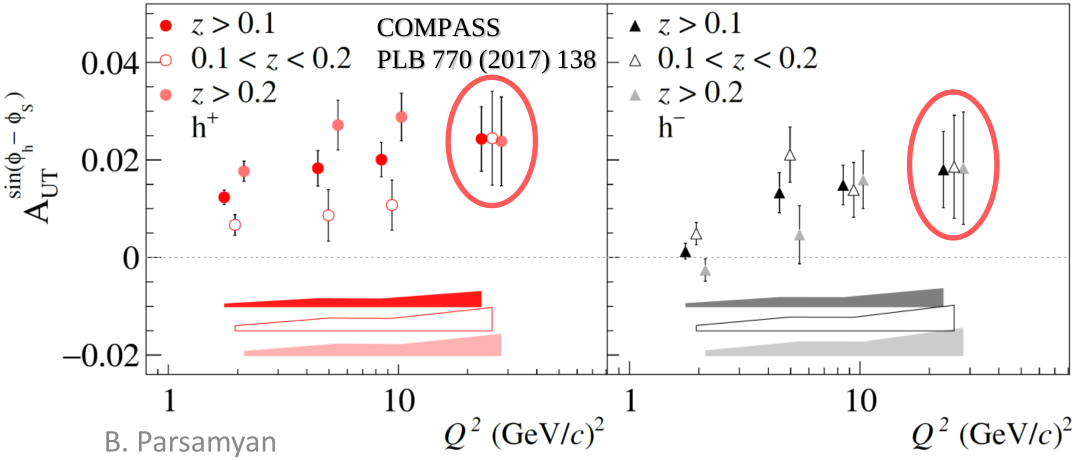
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$





Sivers SIDIS TSA

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



COMPASS proton Sivers measurements

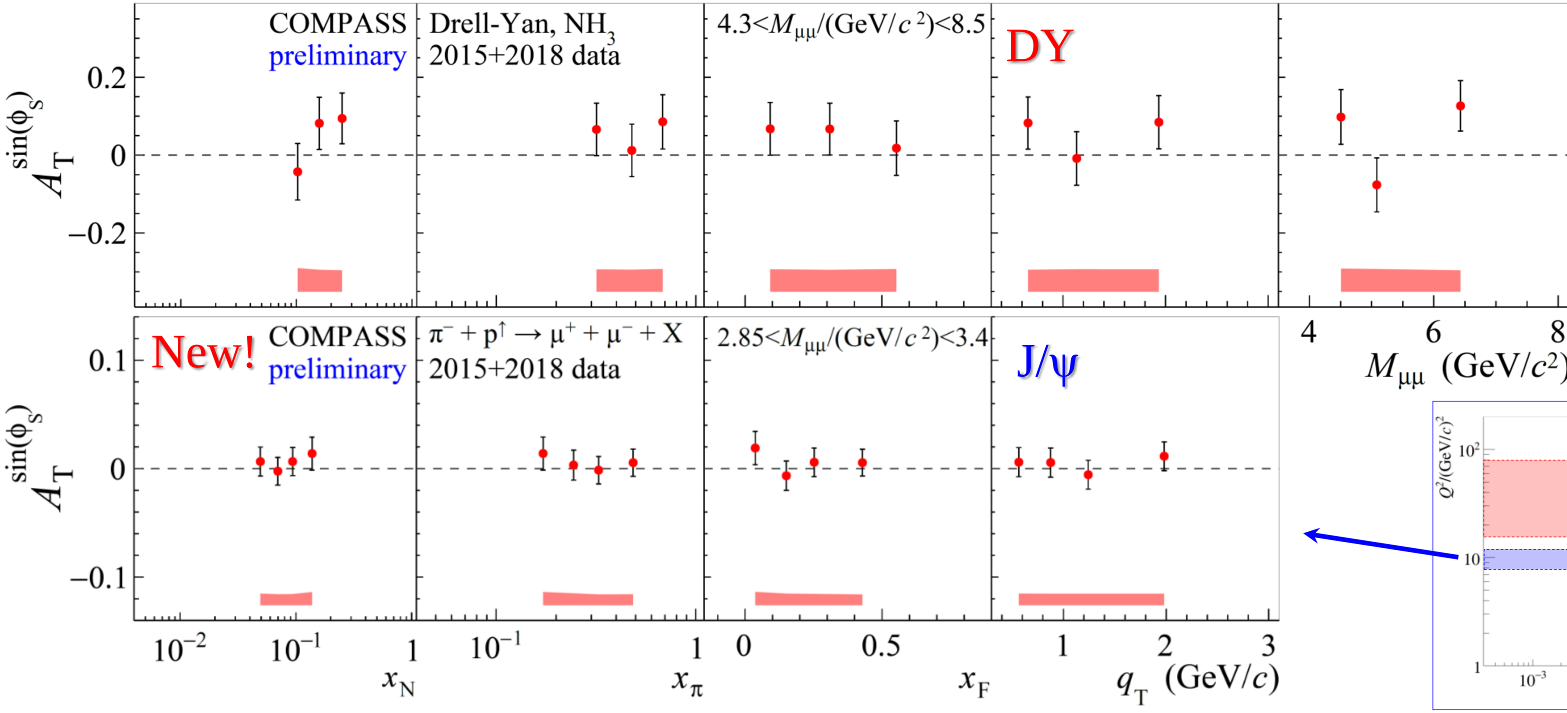
- Clear signal in the matching Q^2 ranges

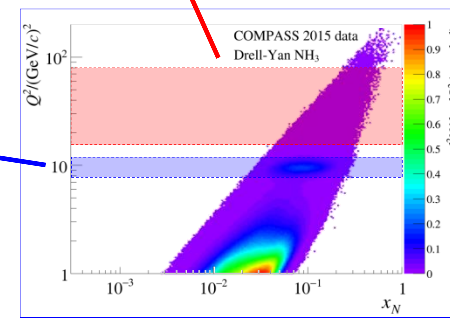
Drell-Yan TSAs – Sivers effect

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + \ldots \right]$$

Sivers DY TSA

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





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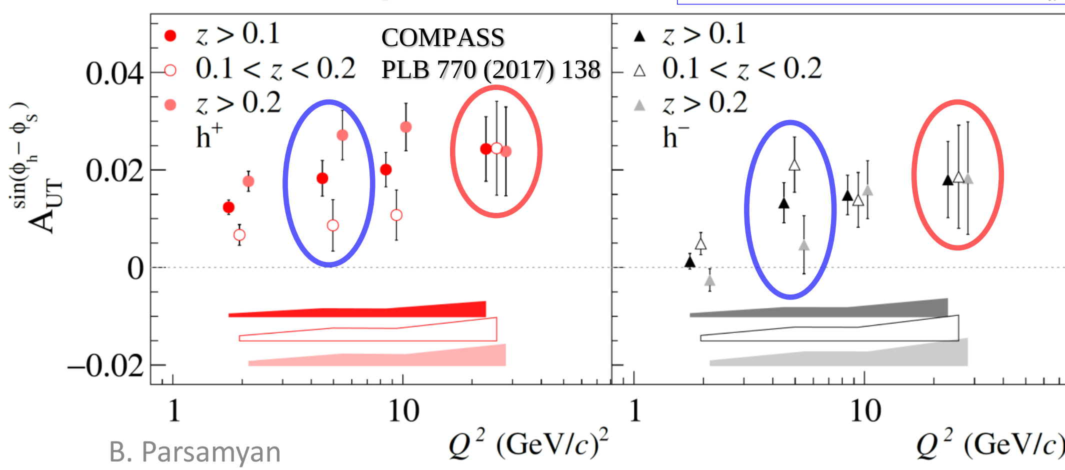
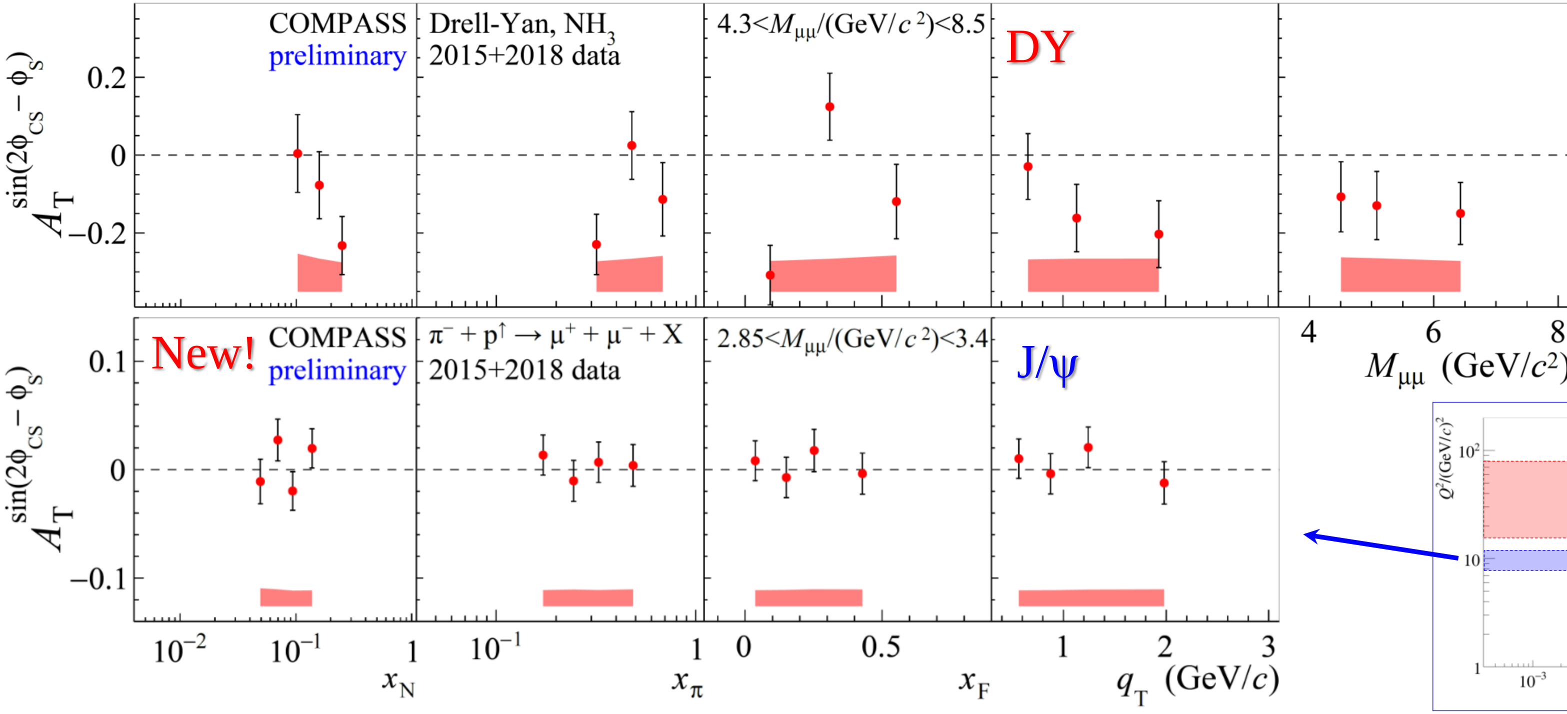


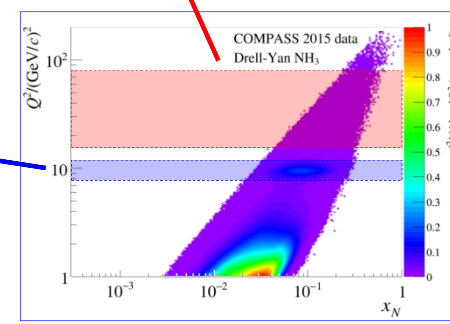
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

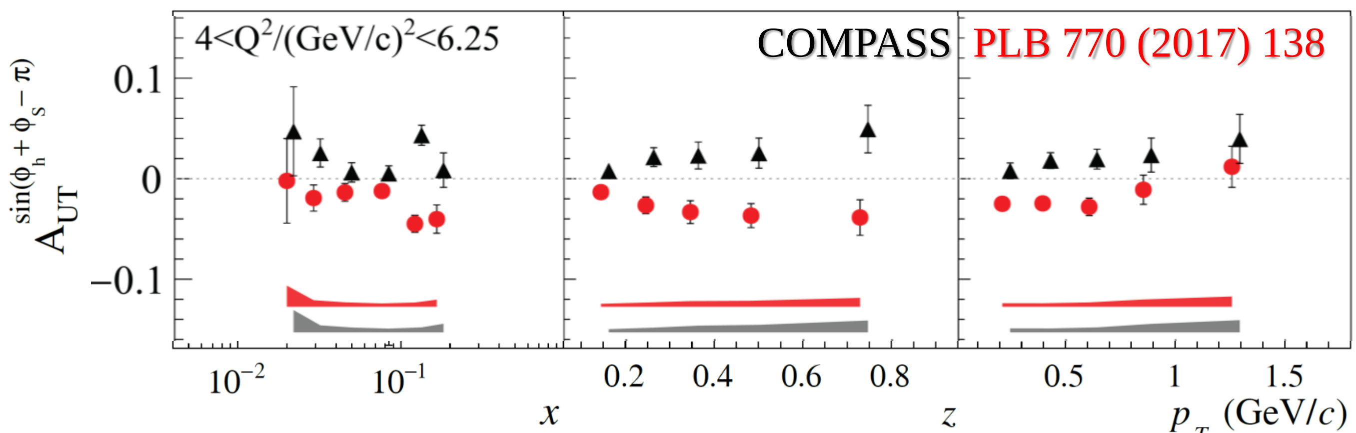
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$





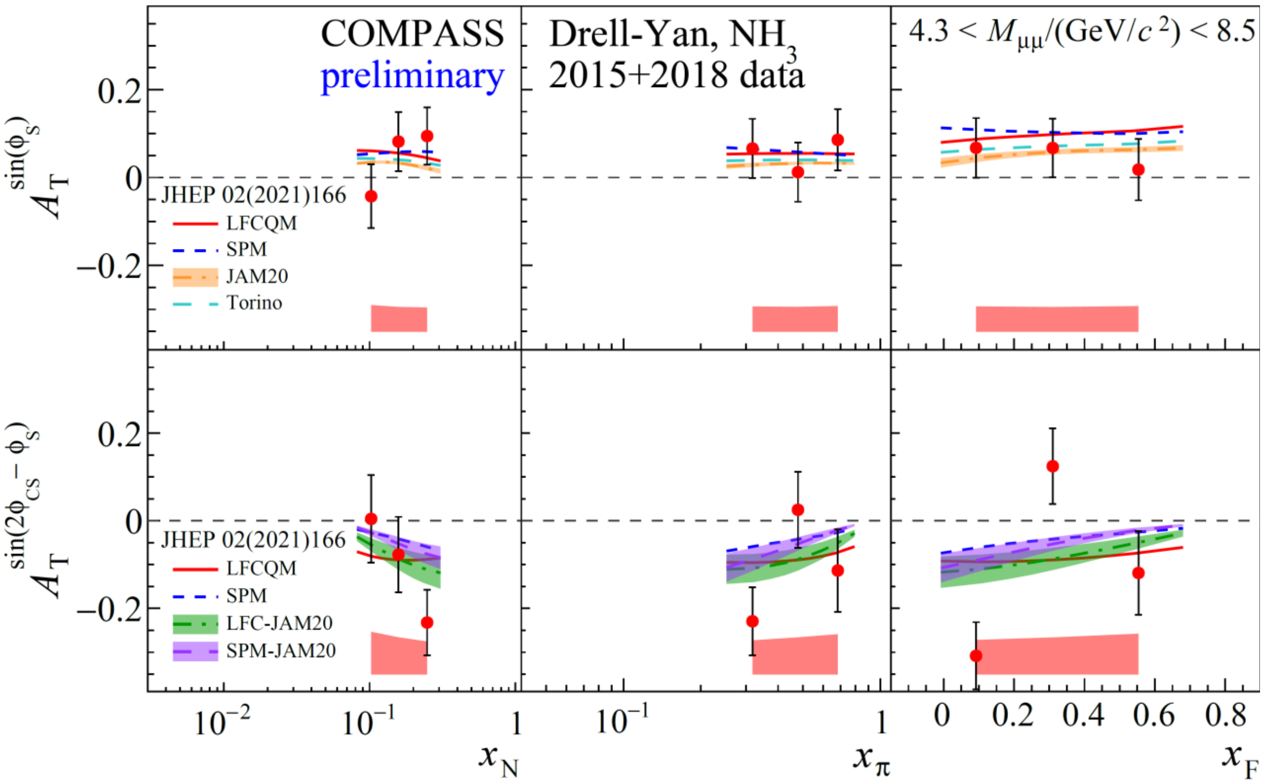
Collins SIDIS TSA

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

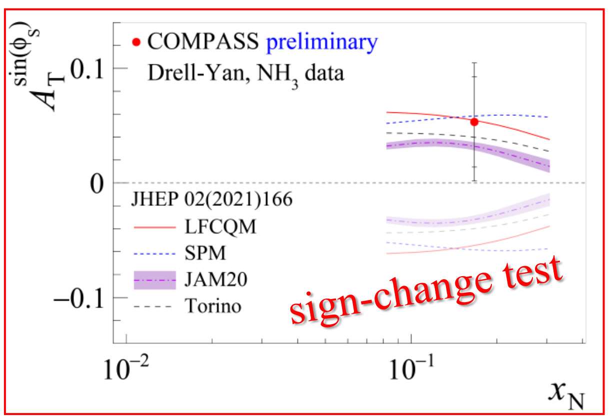


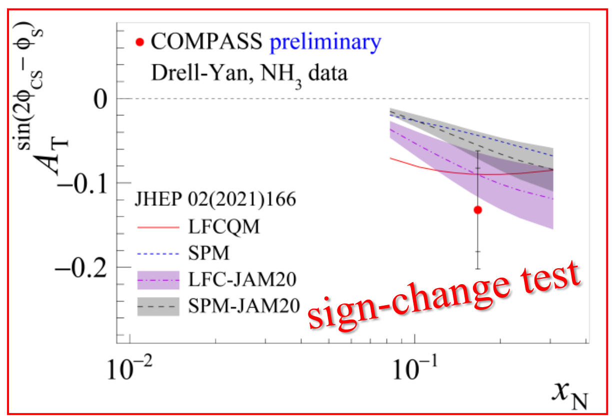
DY TSAs at COMPASS (high-mass range)

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



- General agreement with available theory/model predictions
- COMPASS data favors sign-change hypothesis for the Sivers TMD PDF
- COMPASS data also seem to favor pion Boer-Mulders TMD PDF sign-change (model-based)





Conclusions

COMPASS
25 years
1997 - 2022

- COMPASS holds the record for the longest-running CERN experiment (20 years of data-taking)
- Series of successful and important measurements addressing nucleon spin-structure
    - Inclusive measurements, unpolarized and polarized SIDIS (longitudinal/transverse)
    - First-ever polarized Drell-Yan measurements
- A wealth of (SI)DIS, Drell-Yan, DVCS, HEMP data collected across the years
    - Petabytes of data available for analysis
- Wide and unique kinematic domain accessing low x and large Q^2
    - Will remain unique for at least another decade
- World-unique SIDIS deuteron data collected in 2022
    - Highly successful run, promising preliminary results, analysis in full swing!
- Since 2023 the experiment entered the Analysis Phase
    - The spectrometer has been transferred to the COMPASS successor in the M2 beamline – the AMBER collaboration
    - 3 new groups (+1 under discussion) joined COMPASS Analysis Phase in 2023
- United COMPASS - AMBER community
    - Pool of experts, shared software, similar measurements ↔ analysis know-how, etc.
- Building connections with theorists and experiments
    - LHCb, LHC-FT, Spin-Quest, JLab 12/24 GeV, EIC, etc.

Thank You!

Joint XX-th International Workshop on Hadron Structure and Spectroscopy

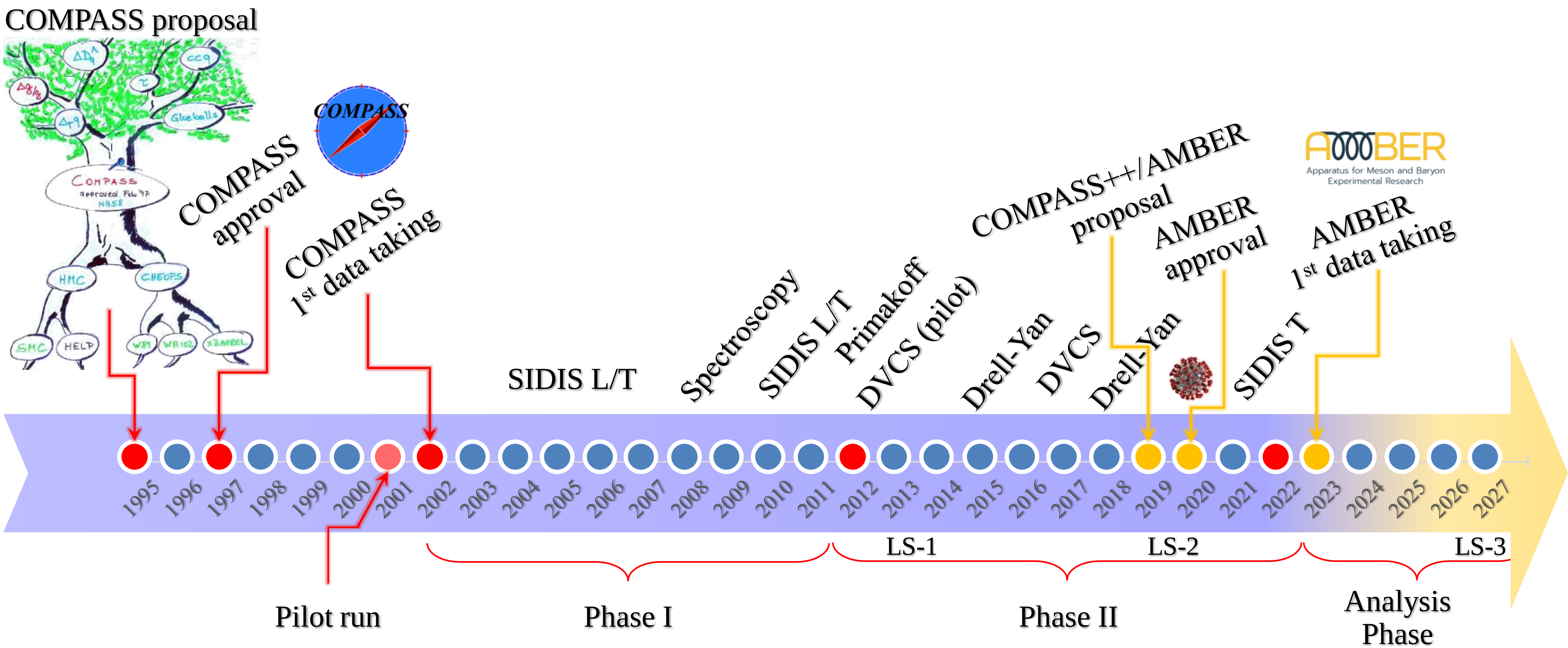
COMPASS
25 years
1997 - 2022

and 5-th Workshop on Correlations in Partonic and Hadronic Interactions

Yerevan, Armenia
30 September – 4 October, 2024

Spare slides

COMPASS→AMBER timeline

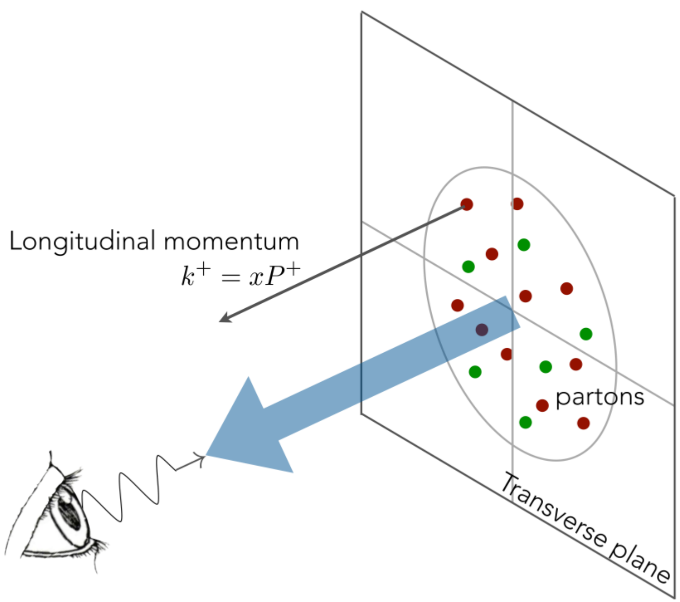


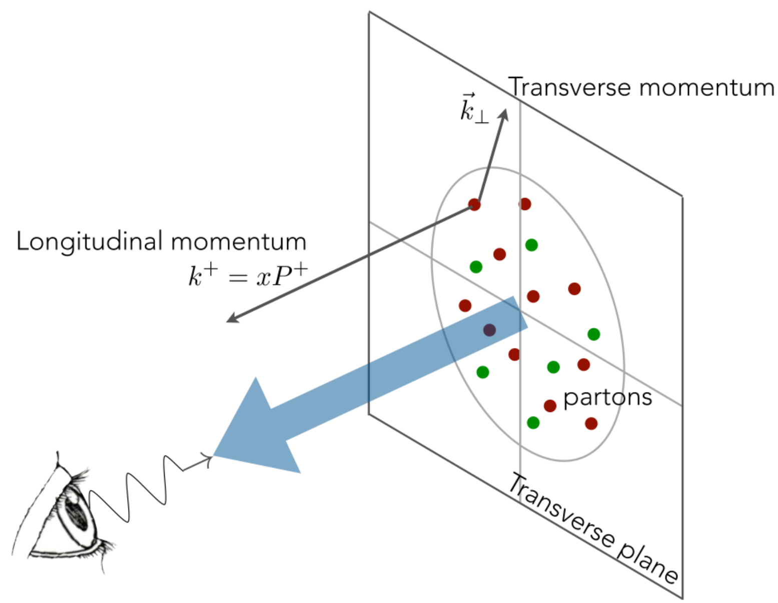
Nucleon spin structure: collinear approach ↔TMDs

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

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

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





Cahn effect in SIDIS

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

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

Cahn effect

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

number density

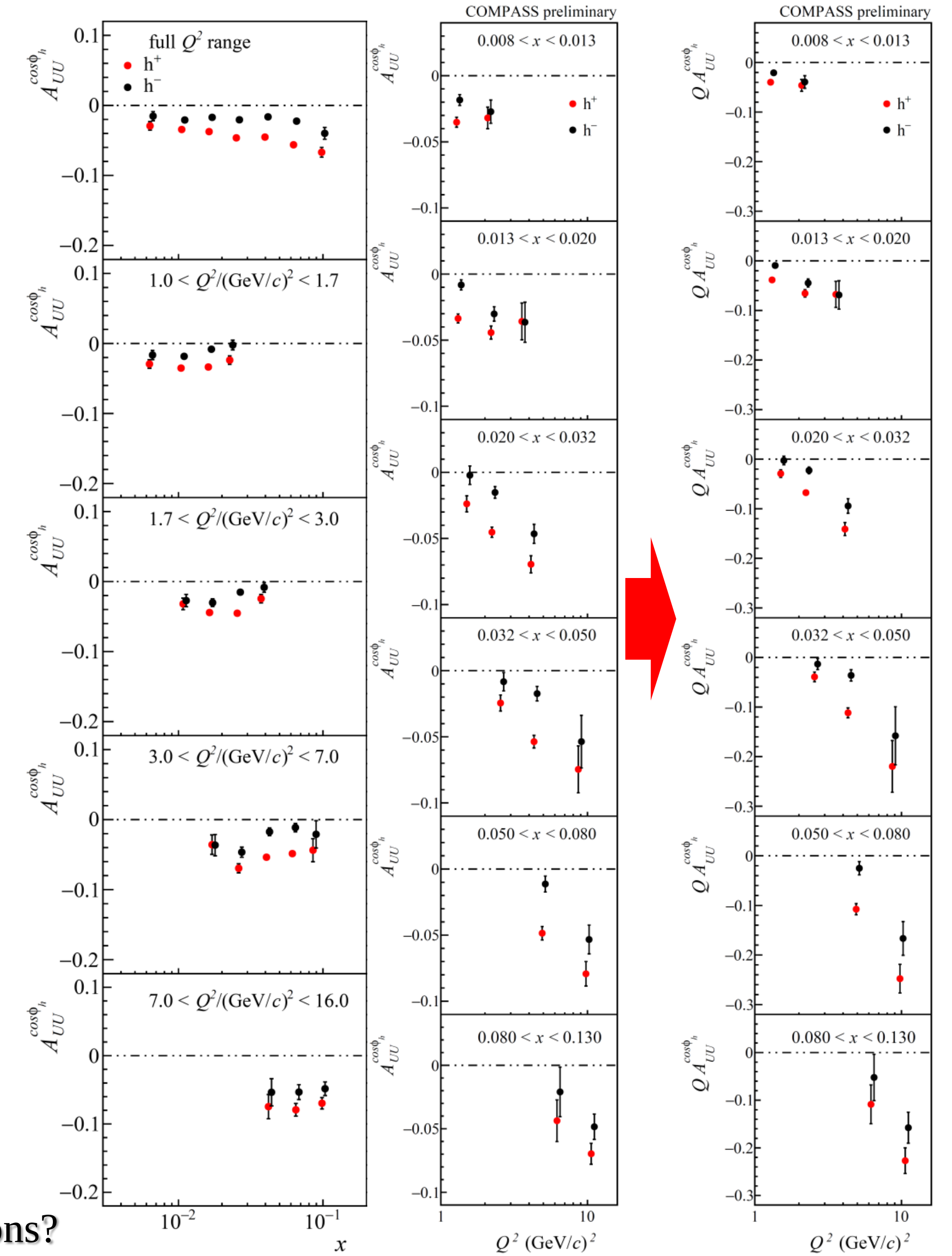
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

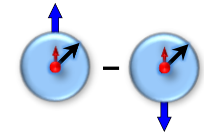
As of 2023 – complex SF (twist-2/3 functions)

- 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 between TMD ↔ collinear regions?

Recent COMPASS results



SIDIS TSAs: Collins effect and Transversity

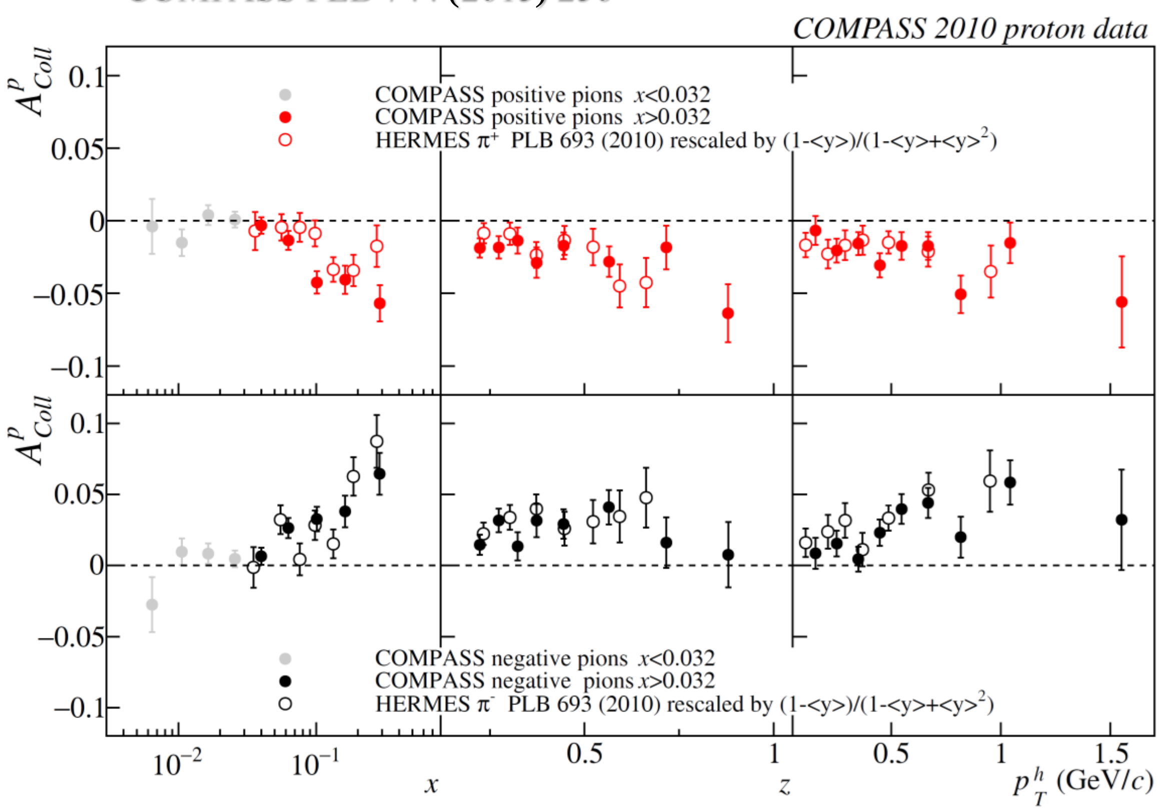


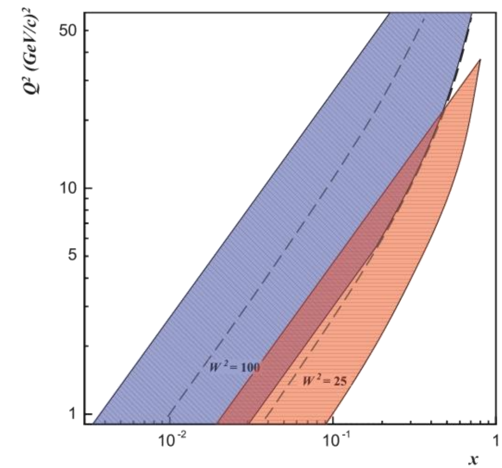
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) + \ldots\right\}$$

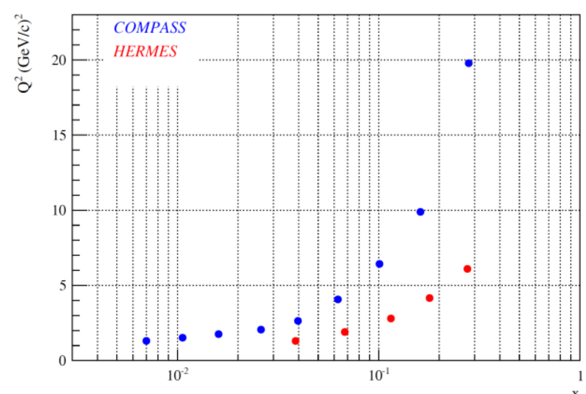
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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

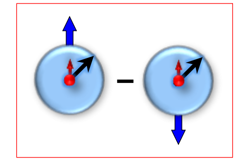
COMPASS PLB 744 (2015) 250







SIDIS TSAs: Collins effect and Transversity

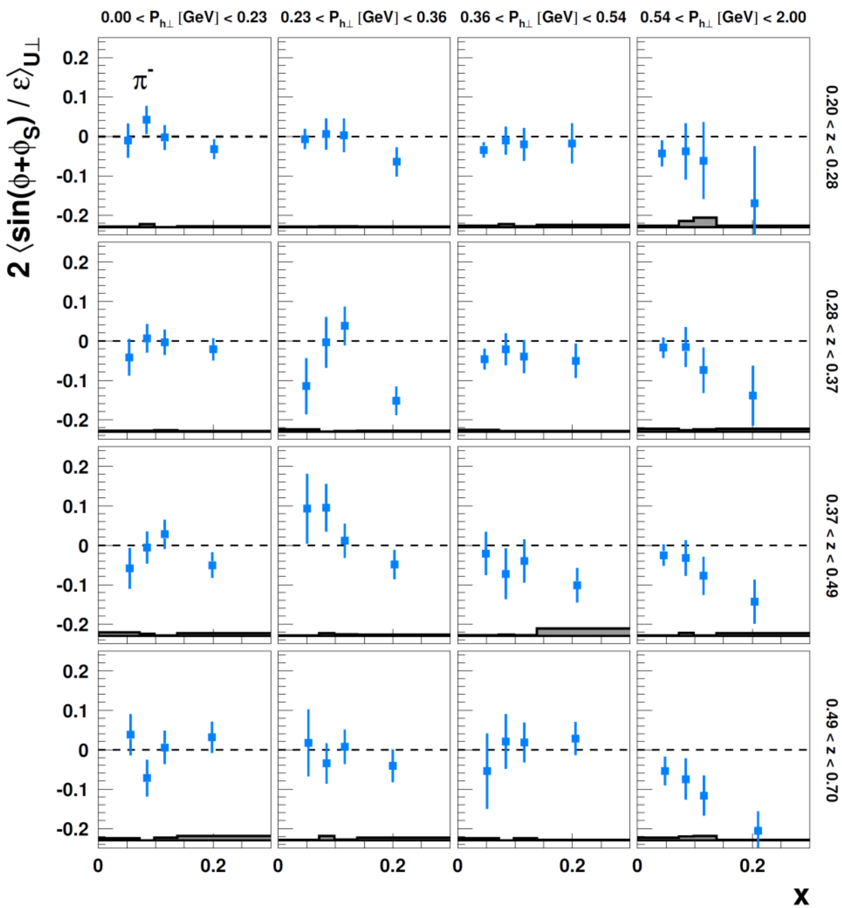


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \ldots\right\}$$

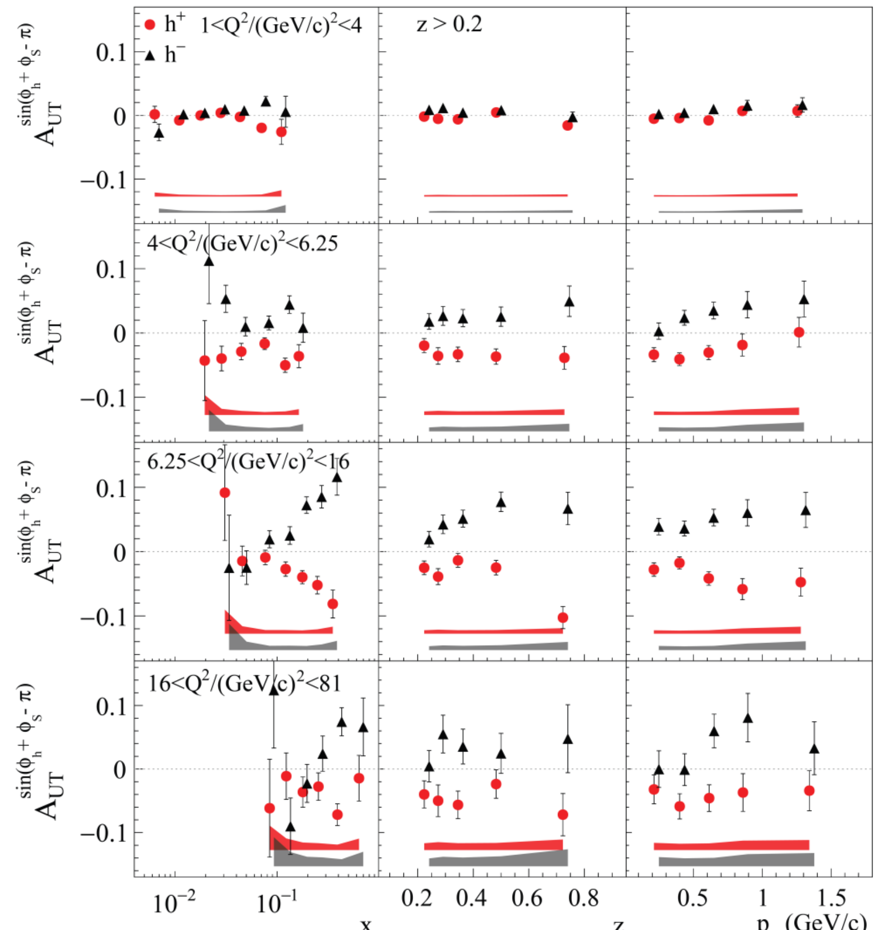
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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

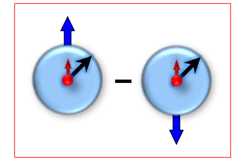
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



SIDIS TSAs: Collins effect and Transversity

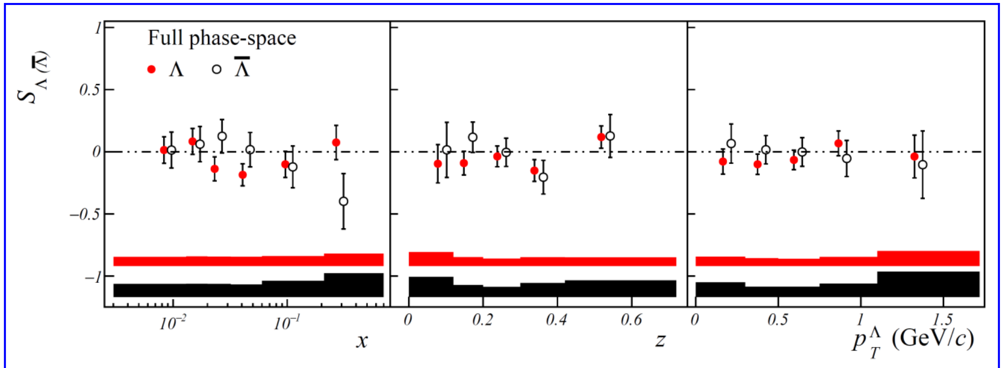


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

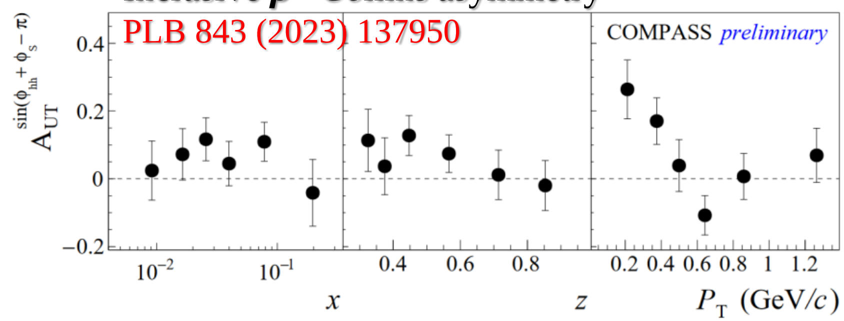
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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

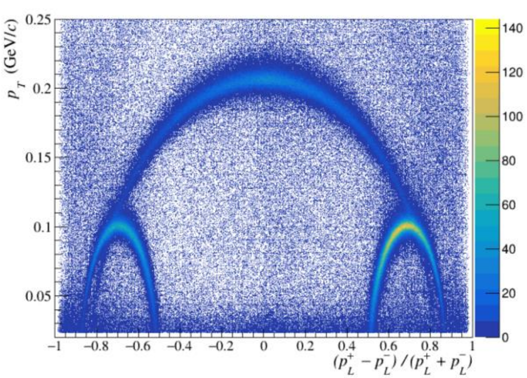
PLB 824 (2022) 136834

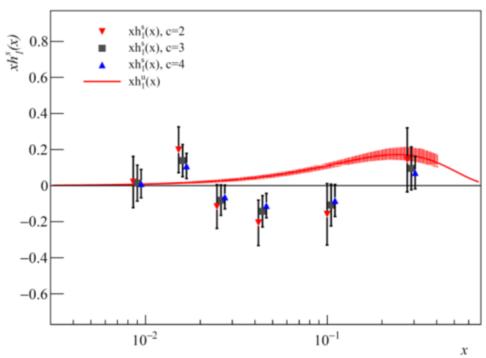


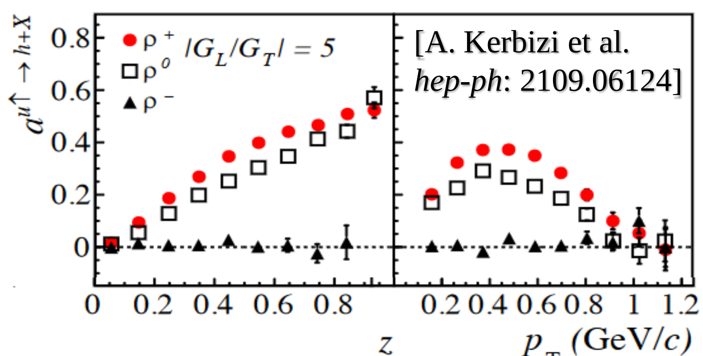
Inclusive ρ^0 Collins asymmetry



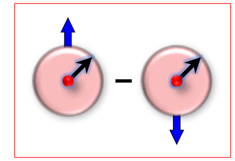
- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T







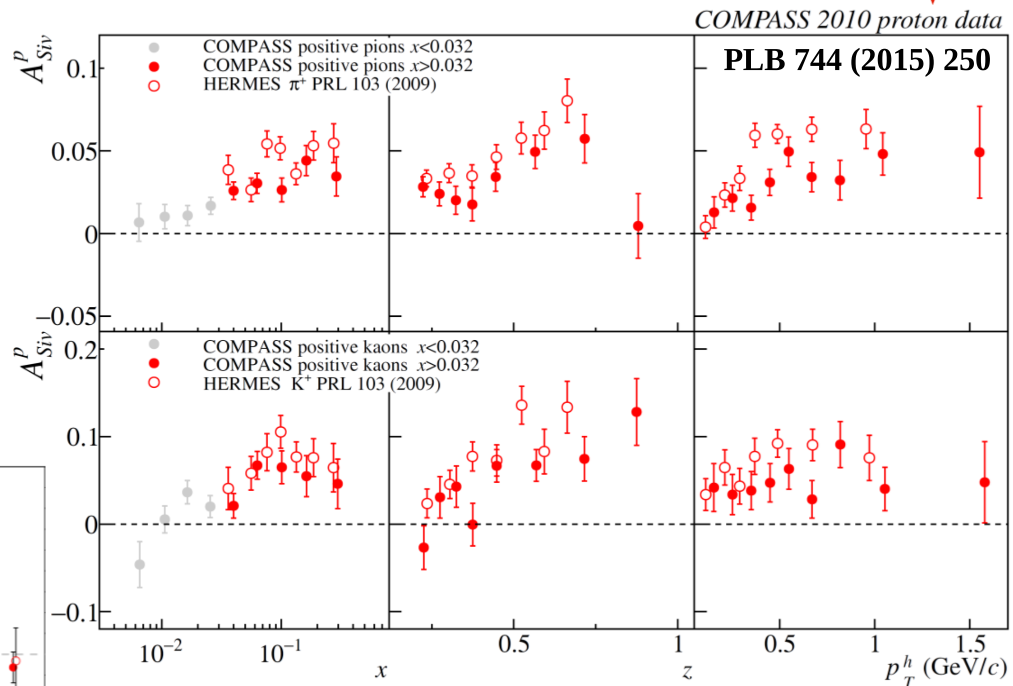
SIDIS TSAs: Sivers effect

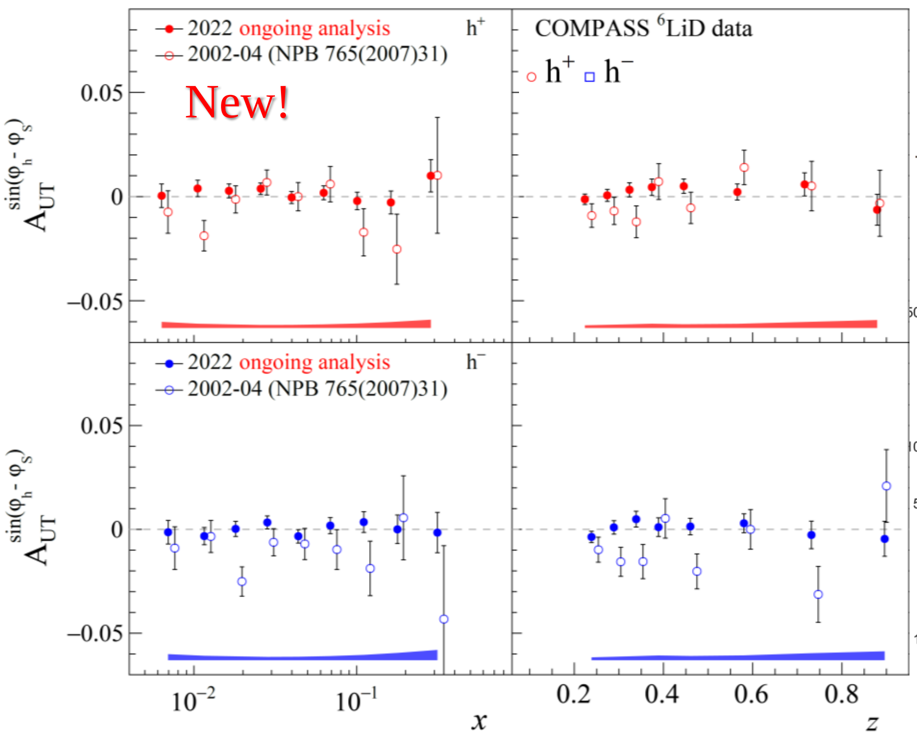


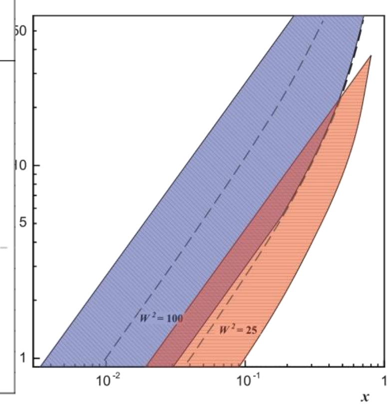
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

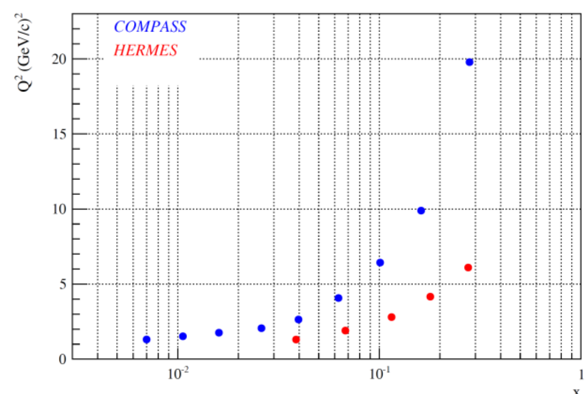
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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





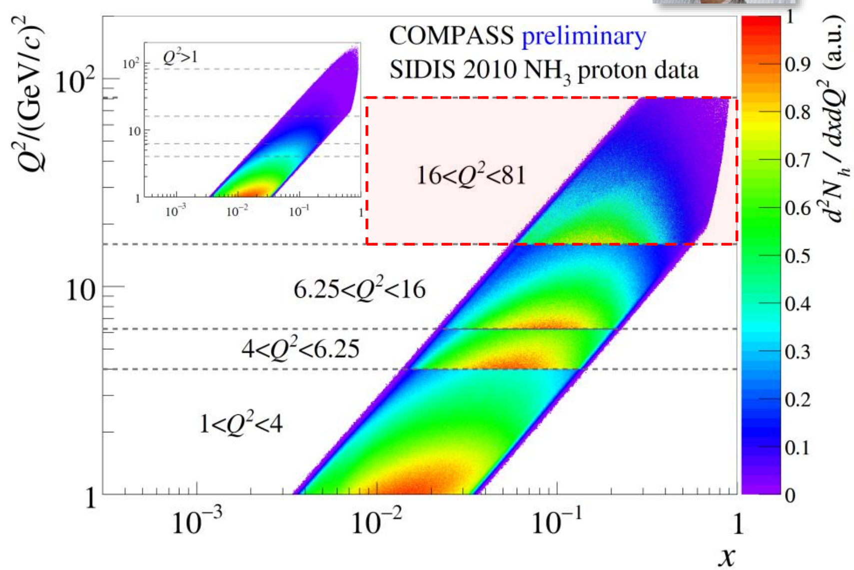


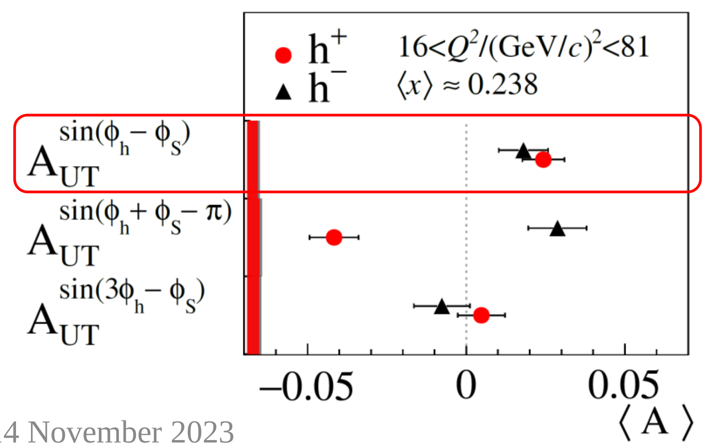


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

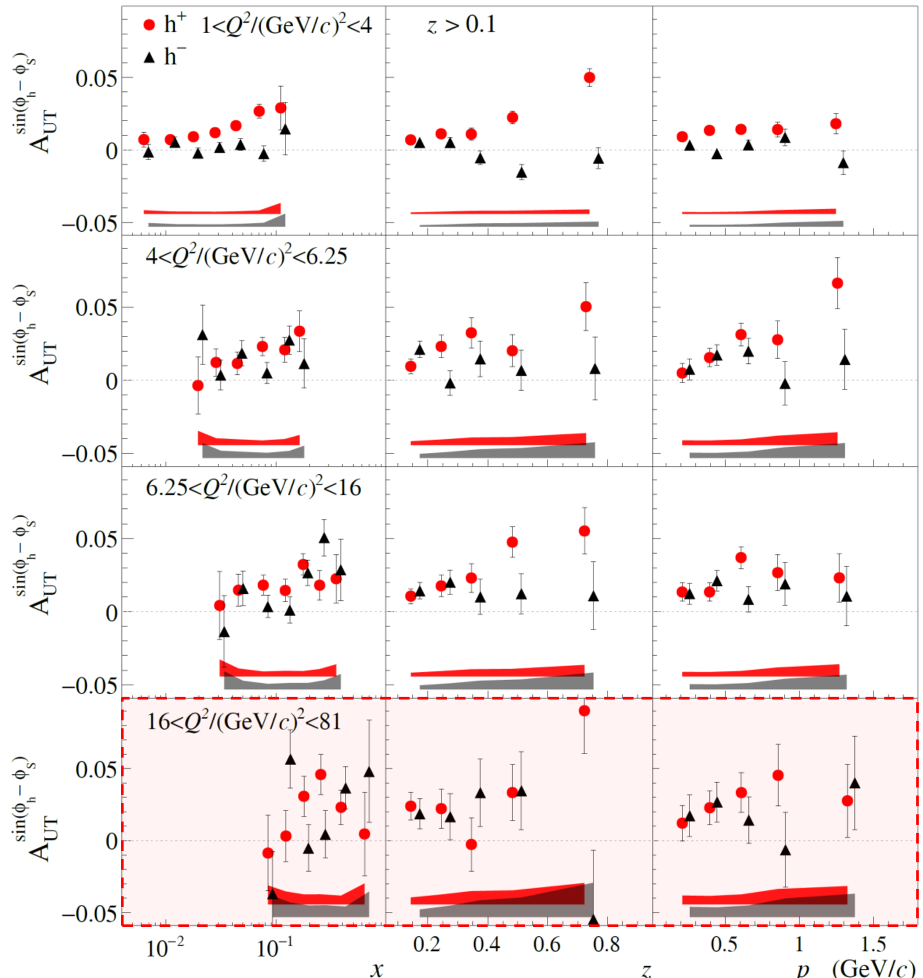
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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





COMPASS PLB 770 (2017) 138



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

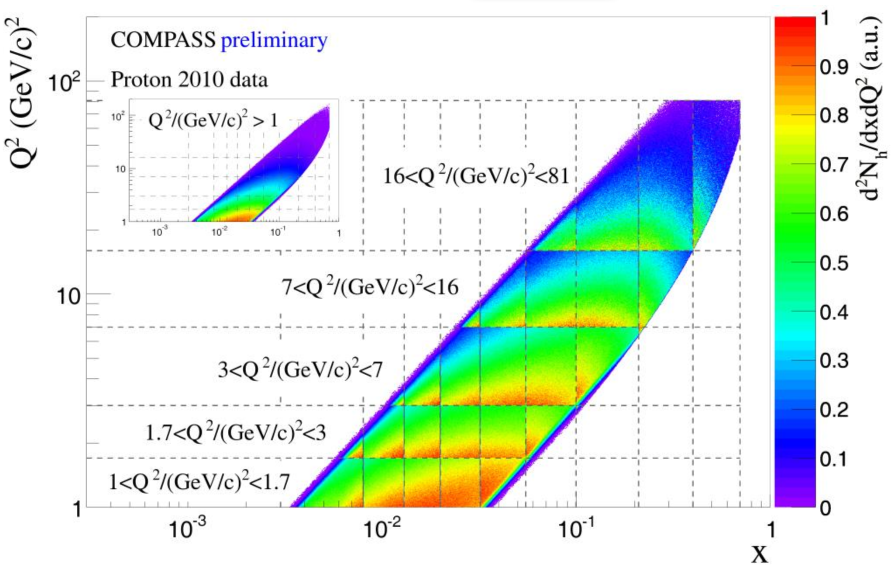
COMPASS Multi-D TSA analyses

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

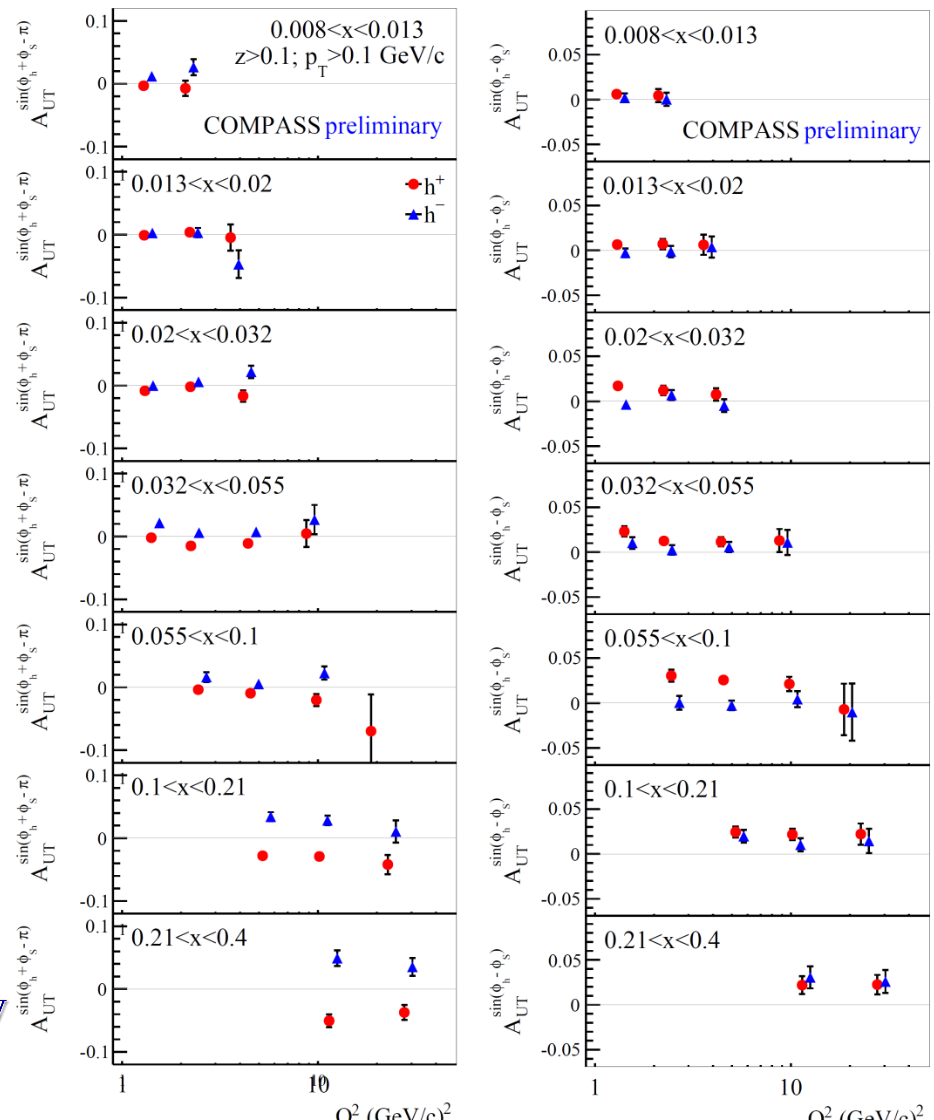
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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

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

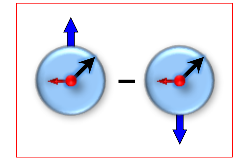


3D $x:Q^2:z$ or $x:Q^2:p_T$ $x:z:p_T$



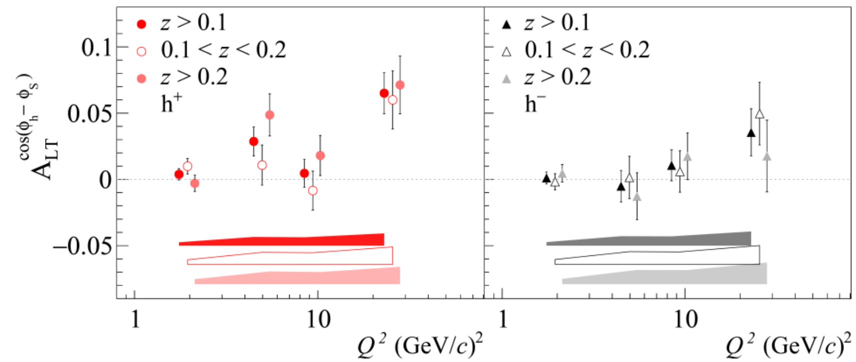
- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

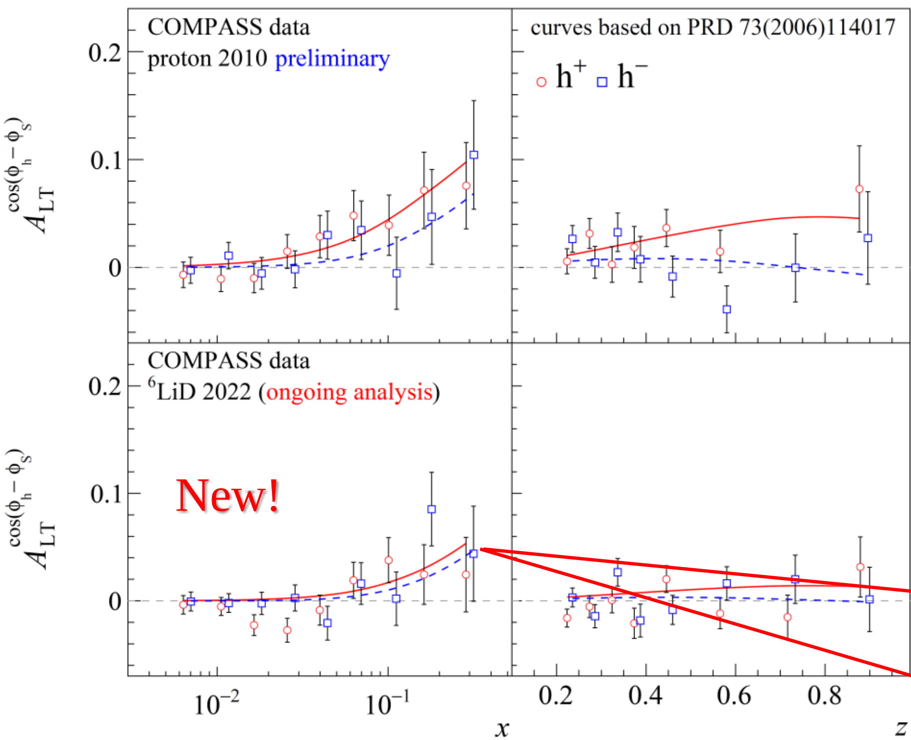
SIDIS TSAs: Kotzinian-Mulders asymmetry



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

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

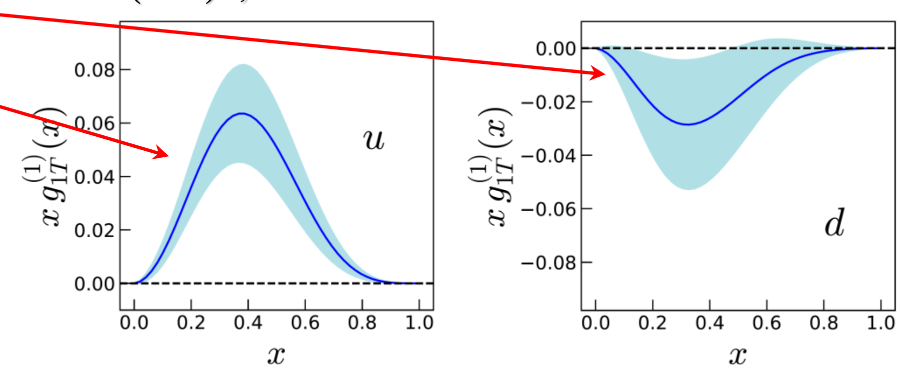




$A_{LT}^{\cos(\phi_h-\phi_S)}$ TSA - COMPASS/HERMES results

- Only "twist-2" ingredients
- Proton - sizable non-zero effect for h$^+$!
  - Similar effect at HERMES

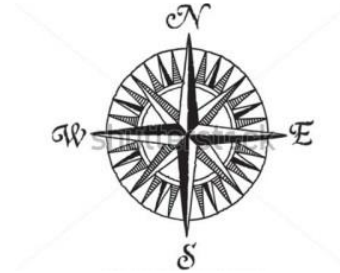
S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D.Pitonyak
PRD 105 (2022) 3, 034007

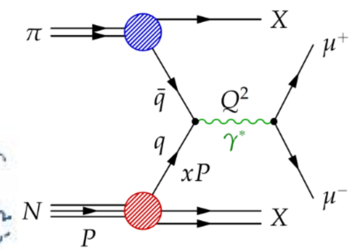


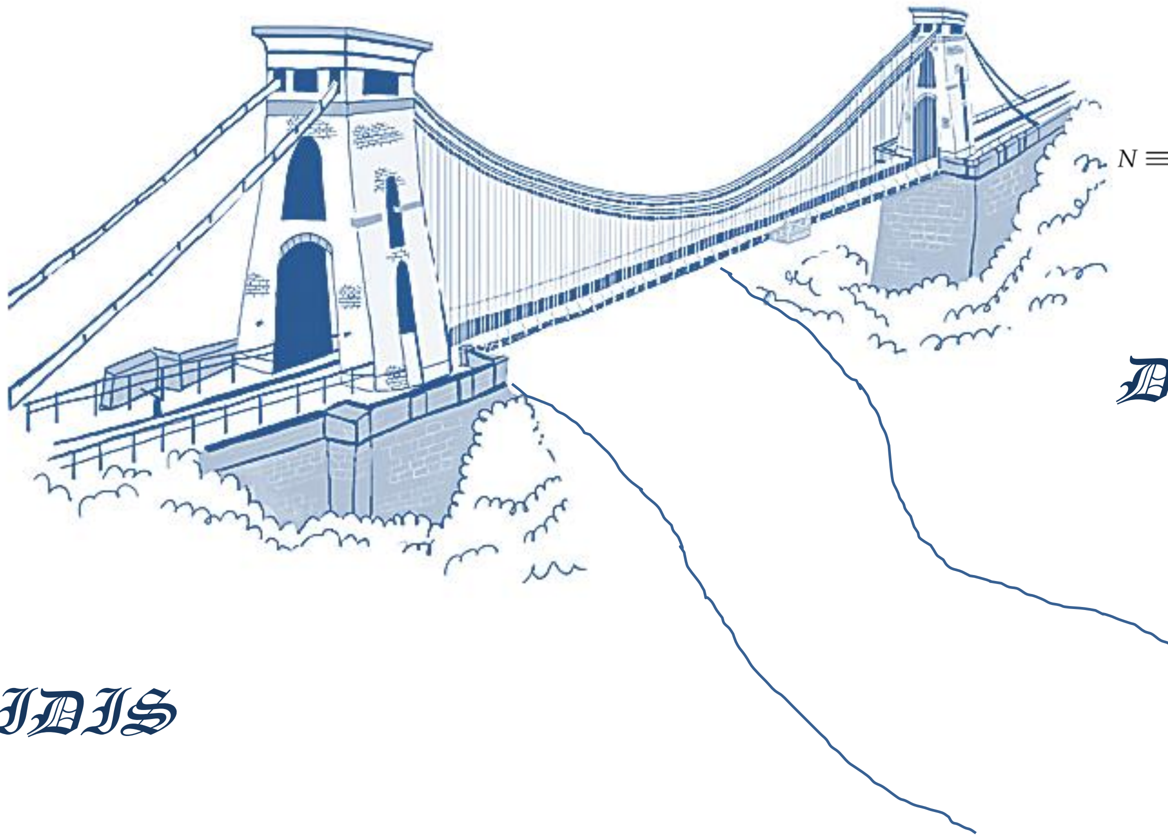
COMPASS 2022 run – data

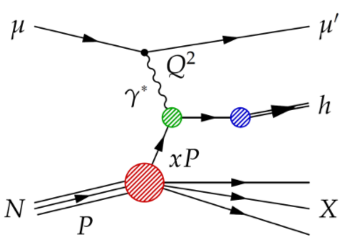
- Crucial to constrain *d*-quark TMD PDFs

COMPASS bridge









Drell-Yan

SIDIS

SIDIS and single-polarized DY x-sections at twist-2 (LO)

SIDIS

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

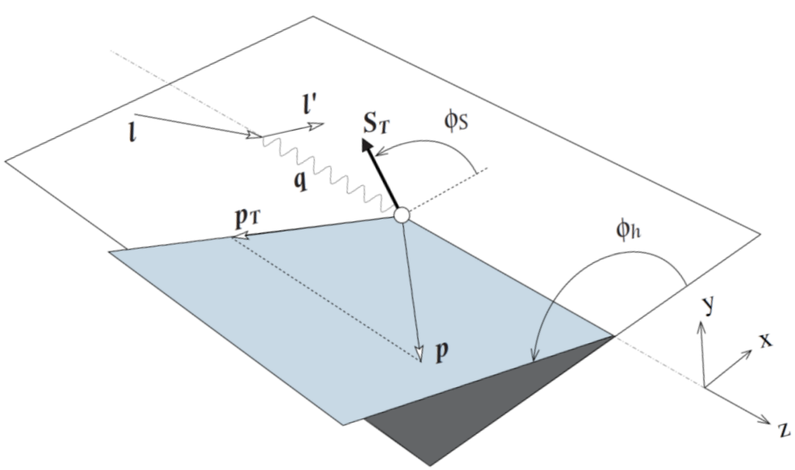
$$\times \begin{cases} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} \\ + S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h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

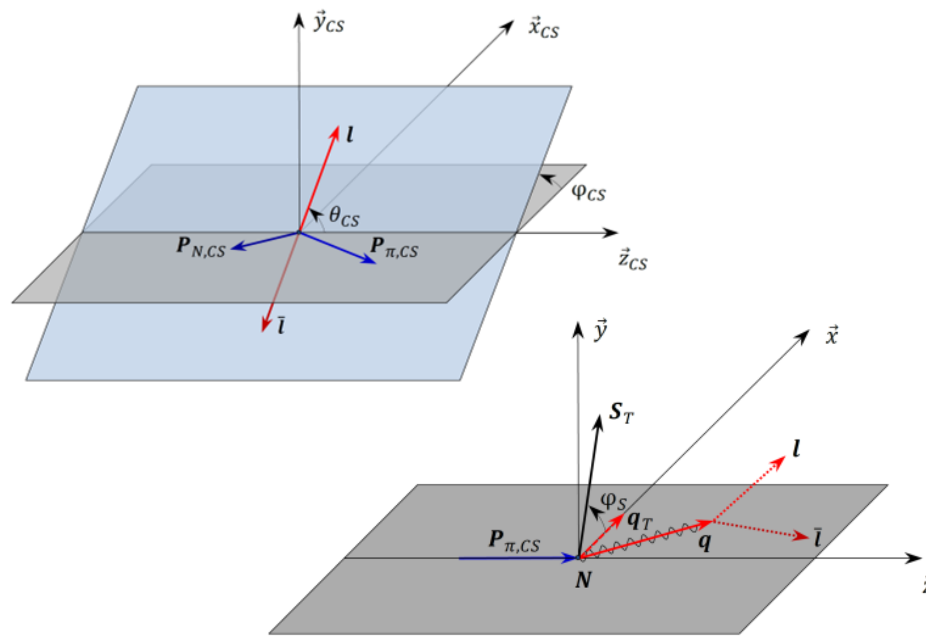
DY

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

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

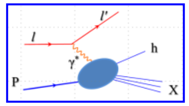
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$





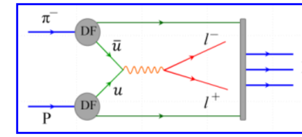
SIDIS and single-polarized DY x-sections at twist-2 (LO)

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



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

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



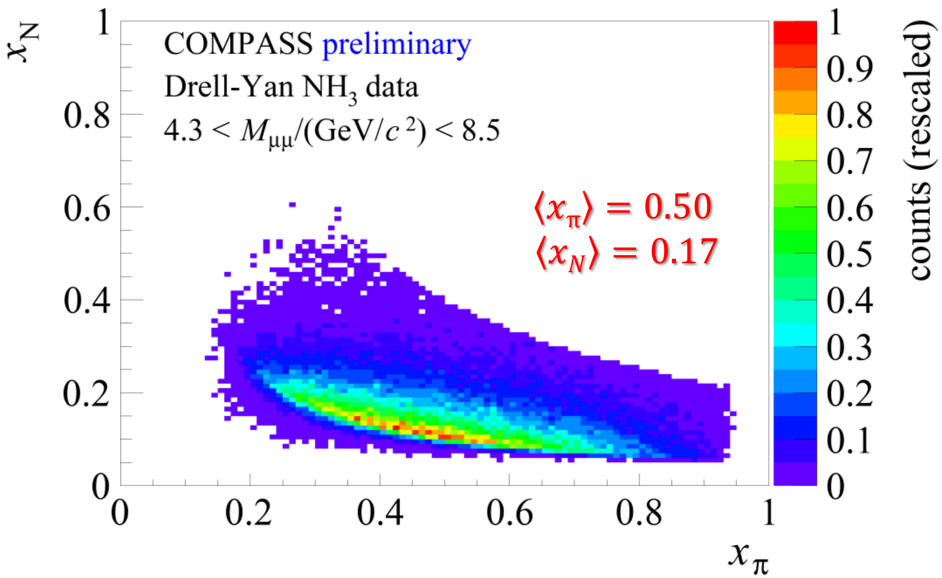
$$\times\left\{\begin{array}{l} 1+D_{[\sin^2\theta_{CS}]}A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} \\ +\ S_L\sin^2\theta_{CS}A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS} \\ +\ S_T\left[\begin{array}{l} A_T^{\sin\varphi_S}\sin\varphi_S \\ +D_{[\sin^2\theta_{CS}]}\left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S)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

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

SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q}\otimes H_{1q}^{\perp h} + \ldots$	Boer-Mulders	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q}\otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q}\otimes D_{1q}^{h}$	Sivers	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q}\otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^{q}\otimes H_{1q}^{\perp h}$	Transversity	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q}\otimes h_{1,p}^{q}$
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$	Pretzelosity	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q}\otimes h_{1T,p}^{\perp q}$

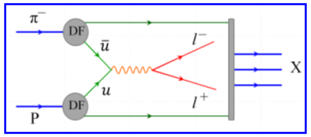
- Sign-change of T-odd Sivers and Boer-Mulders TMD PDFs;
- Multiple access to Collins FF $H_{1q}^{\perp h}$ and pion Boer-Mulders PDF $h_{1,\pi}^{\perp q}$

Single-polarized DY measurements at COMPASS



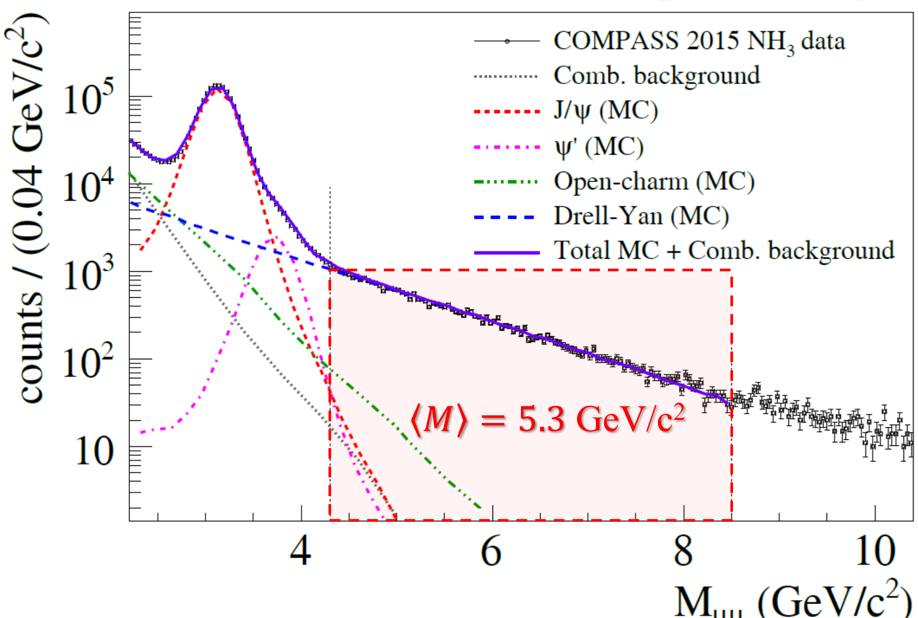
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right)$$

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



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

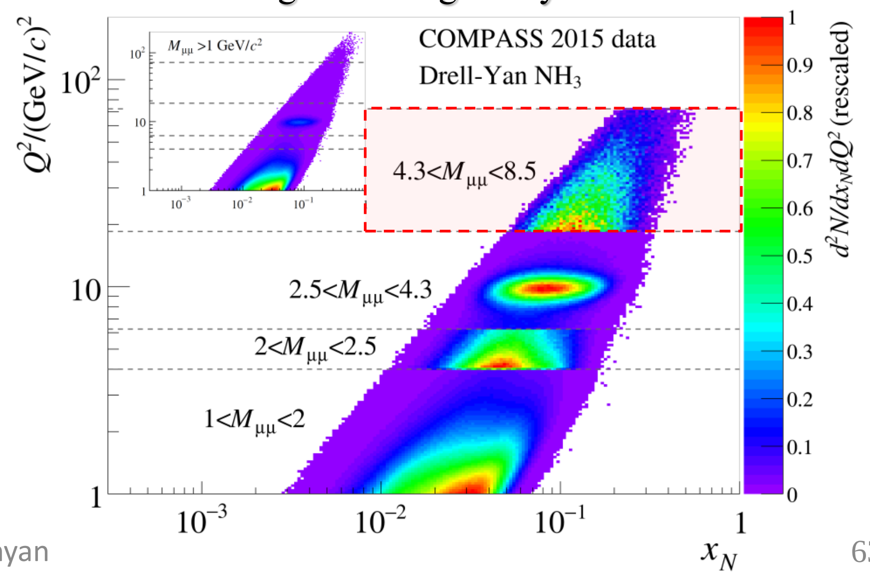
HM events are in the valence quark range



4.3 < M /(GeV/c^2) < 8.5 "High mass" range

Beyond charmonium region, background < 3%

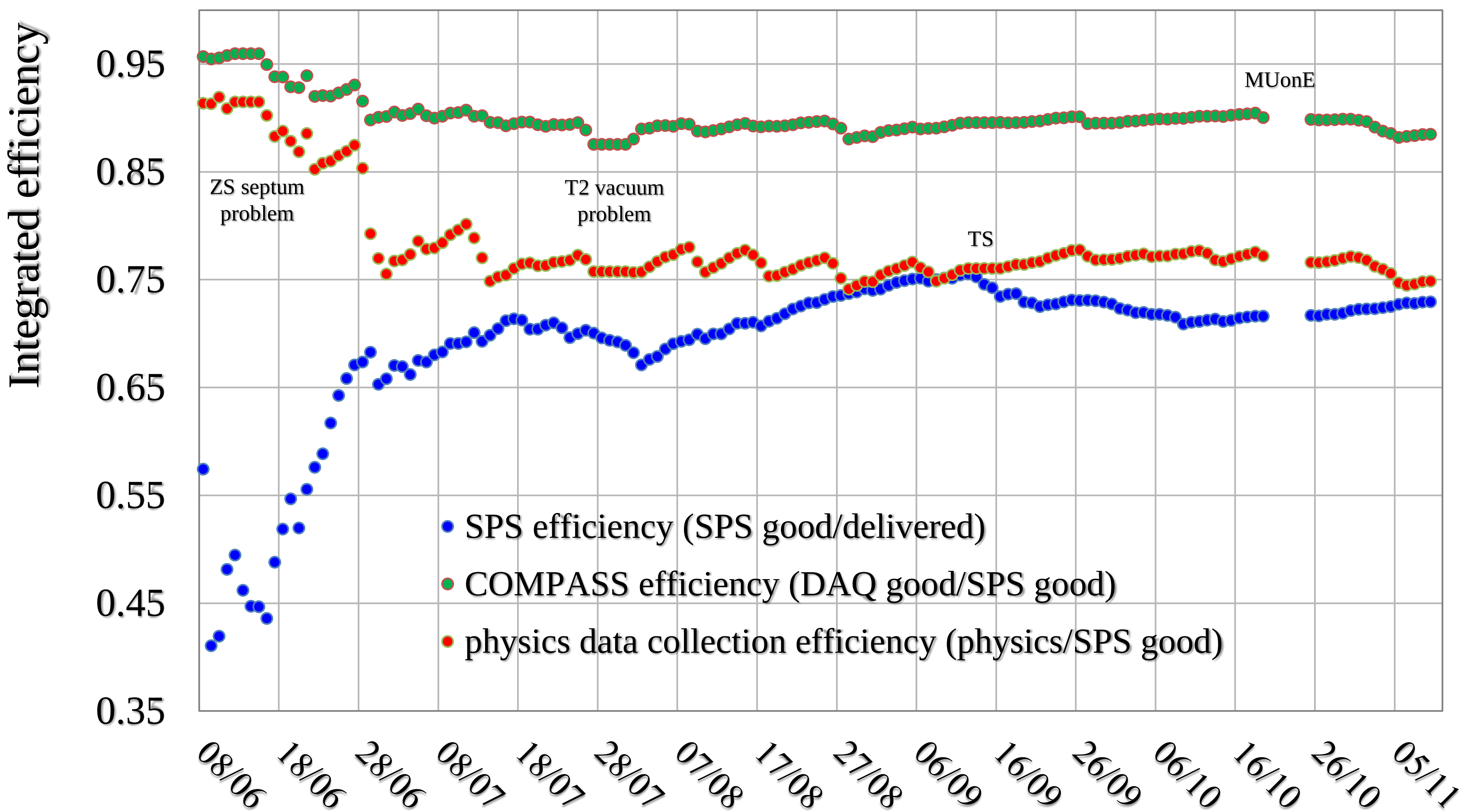
Valence region → largest asymmetries



COMPASS 2022 run: SPS/COMPASS efficiencies

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

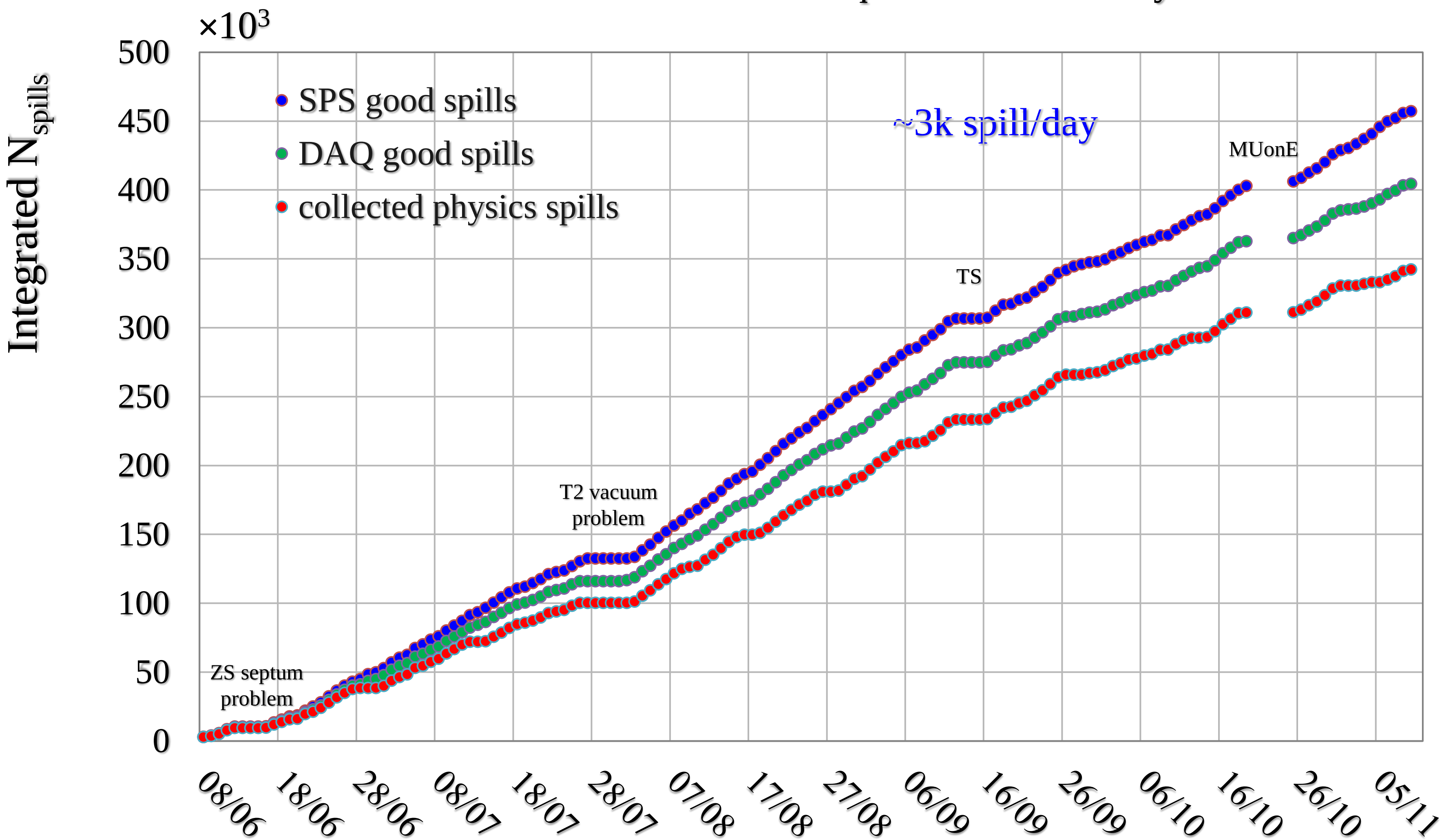
- SPS efficiency: ~73% (82% in 2010)



COMPASS 2022 run: delivered/collected spills

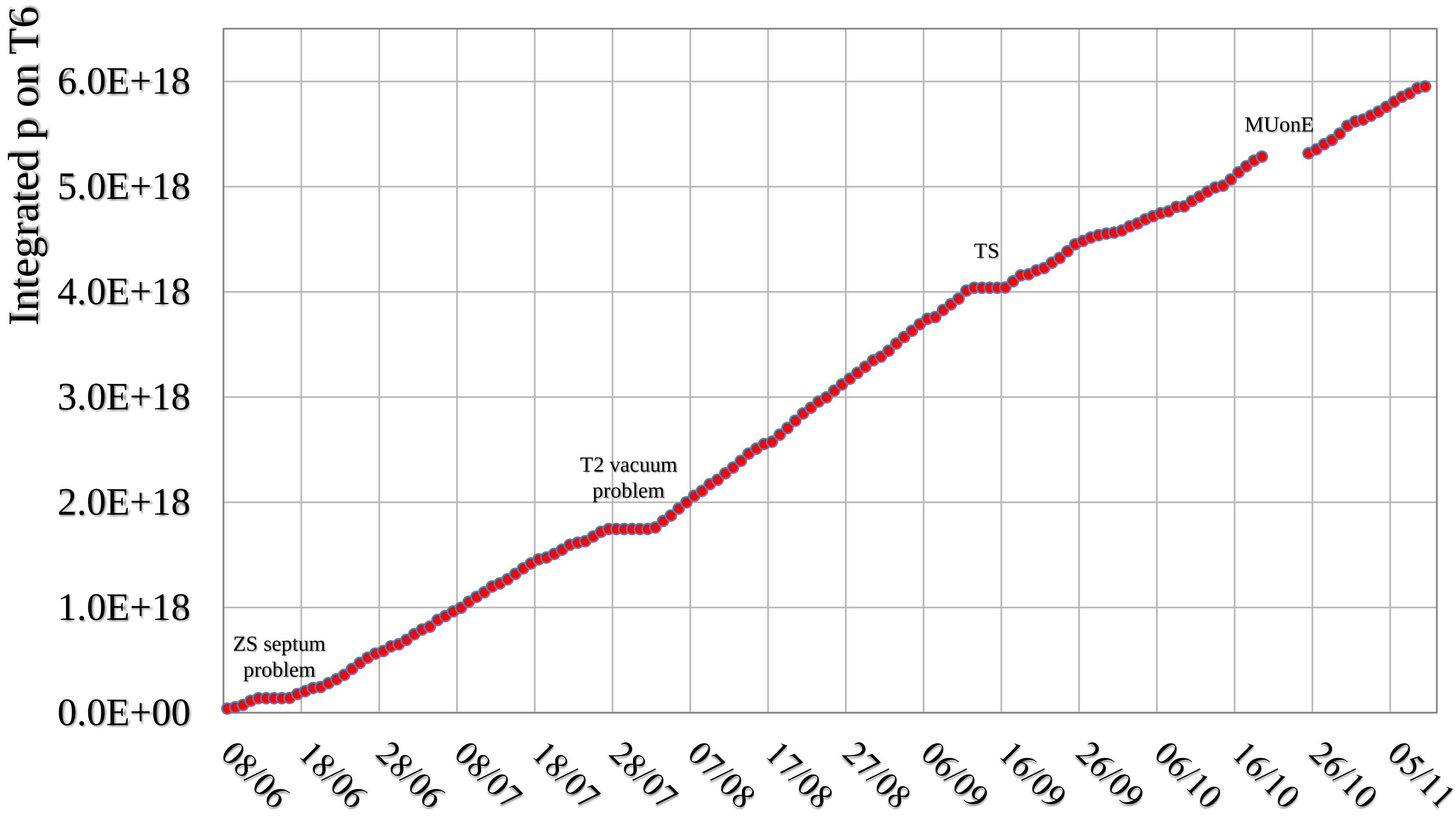
SPS efficiency: ~ 73%
Spectrometer efficiency: ~ 90%
Physics data collection efficiency: ~ 75%

- SPS efficiency: ~73% (82% in 2010)
- SPS beam delivery: ~3k good spills per day
- Overall quite stable intensity conditions on T6



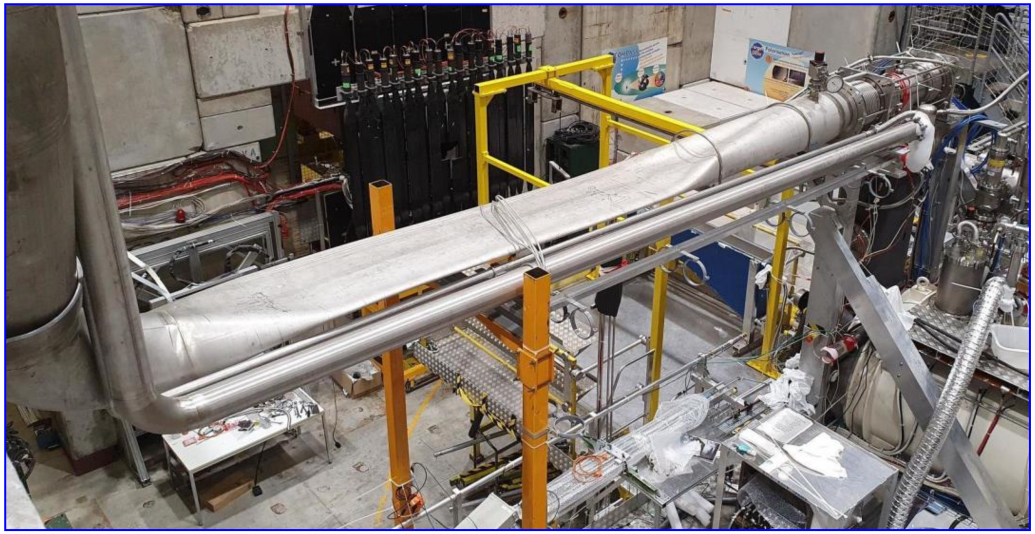
COMPASS 2022 run: protons delivered by SPS

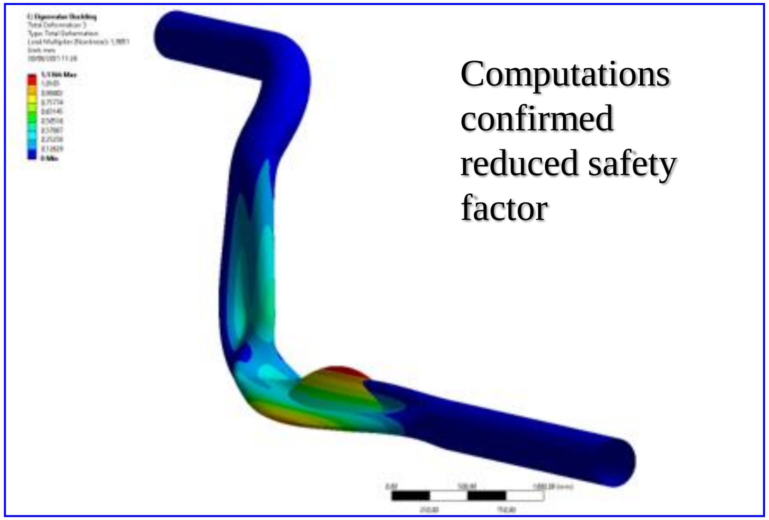
- COMPASS request in the approved proposal: 6.1×10^{18}
- Total number of protons delivered on T6: $\sim5.95\times10^{18}$ (98%) in about 150 days
- To be compared to $\sim5.1\times10^{18}$ in about 162 days in 2010



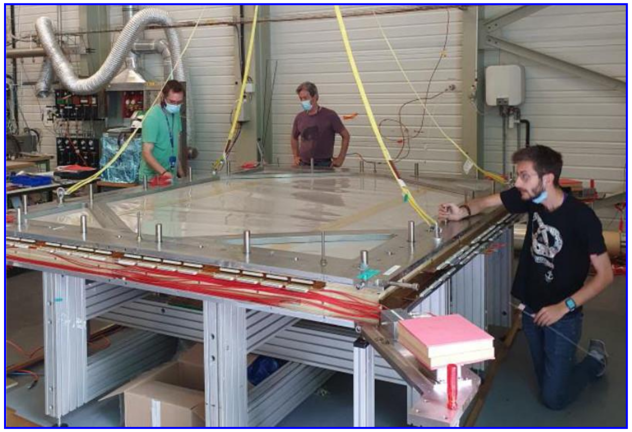
COMPASS 2022 data-taking

- Overall very good performance of all detector systems and DAQ
    - No critical problems on the spectrometer side; high data collection efficiency
    - Increased DAQ capacities thanks to the optimizations carried out during the run
    - New monitoring tools to guarantee fast detection of detector problems
- After disastrous 2021…





Highlights on the 2022-Run preparations



DC04 (Saclay)

- Broken wire blocking the operation of Y-plane
- Repaired within just two weeks
- Noise on some of the planes (grounding issue)
- Further investigated during Year-End Technical Stop (YETS)

DC05 (Illinois)

- Similar broken wire problem blocking one of the views
- Repaired during YETS
- Repaired within just two weeks

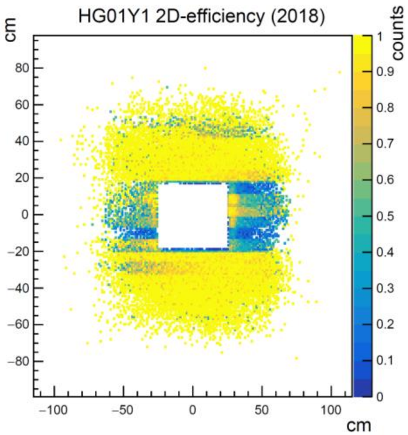
MWPCs (Torino)

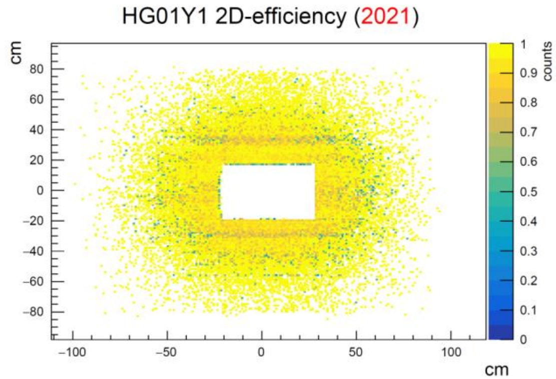
- In general, fully operational
- Some noise problems:
  - aging of Al-Mylar windows (bad electrical connection)
  - PB05 station refurbished during YETS
- New iFTDC-based FE (Compatible with streaming readout)
- Installed/tested on one plane during 2021 run
- One station (PA05) fully equipped for 2022 run
- Spared 'old' FE cards used for the other stations in 2022

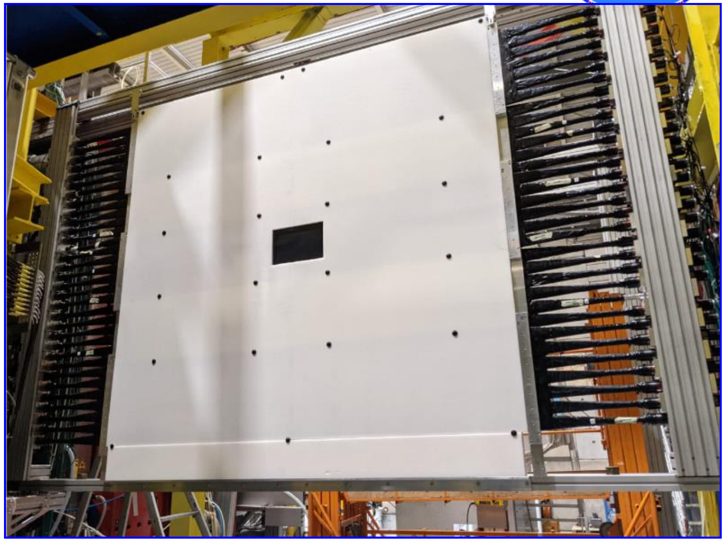
RICH-wall (Torino)

- Fully refurbished, installed and commissioned in June-2021
- Various frontend problems fixed: operated during 2021 run
- Further adjustments during YETS and comissioning-2022

Trigger hodoscopes: 2021-2022 repairs





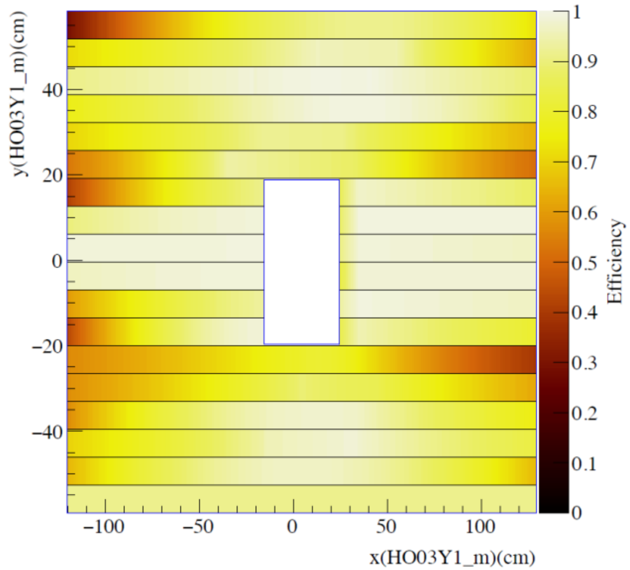


LAST trigger (H01)

- Inefficient central slabs in 2015-2018
  - New central slabs: scintillators, air light guides, discriminators
  - All slabs checked and repaired if necessary
  - Positive impact with online monitoring; to be verified in the analysis stage

Outer trigger (HO3-HO4)

- Inefficient slabs in 2015-2018
  - New PMTs were delivered with a huge delay
  - Part of the PMTs installed during commissioning
  - Remaining PMTs were installed during the run
  - Clear improvements seen with online monitoring



COMPASS 2022 data-taking

- Overall very good performance of all detector systems and DAQ
  - No critical problems on the spectrometer side; high data collection efficiency
  - Increased DAQ capacities thanks to the optimizations carried out during the run
  - New monitoring tools to guarantee fast detection of detector problems