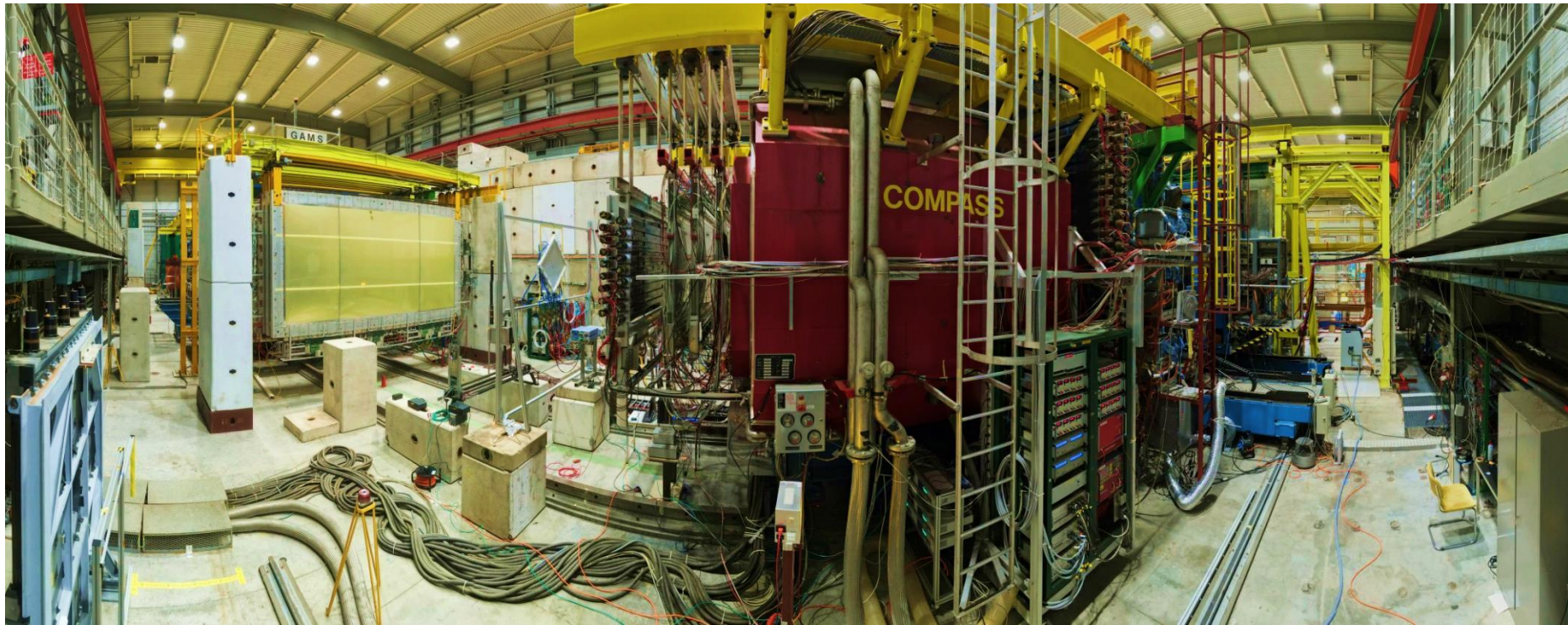


Spin physics overview at COMPASS: recent results and highlights



BAKUR PARSAMYAN

AANL, INFN section of Turin and CERN
on behalf of the COMPASS Collaboration



“Fixed target experiments at LHC”: STRONG – 2020 workshop
5-7 January 2022 Aussois, Vanoise Massif, France



COMPASS collaboration



Common Muon and Proton Apparatus for Structure and Spectroscopy



25 institutions from 13 countries
 – nearly 200 physicists

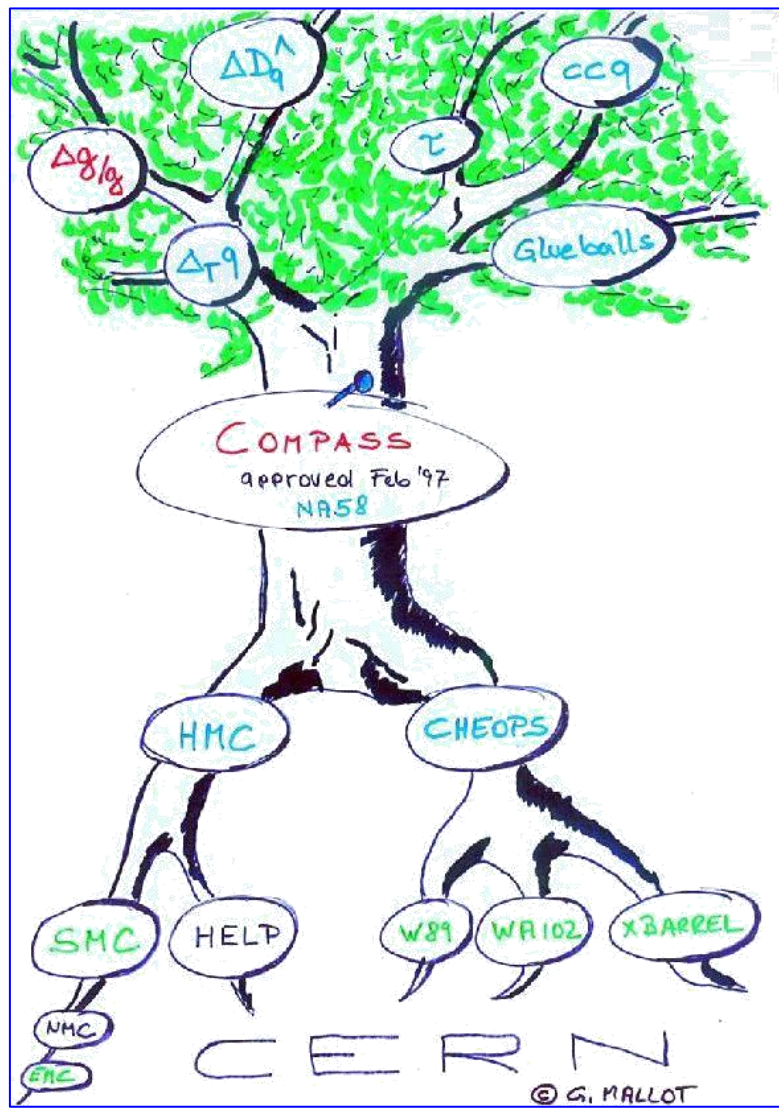
- CERN SPS north area
- Fixed target experiment
- Approved in 1997 (25 years)
- Taking data since 2002 (20 years)

International Workshop on Hadron Structure and Spectroscopy
 IWHSS-2022 workshop (anniversary edition)

CERN Globe, August 29-31, 2022



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



COMPASS collaboration

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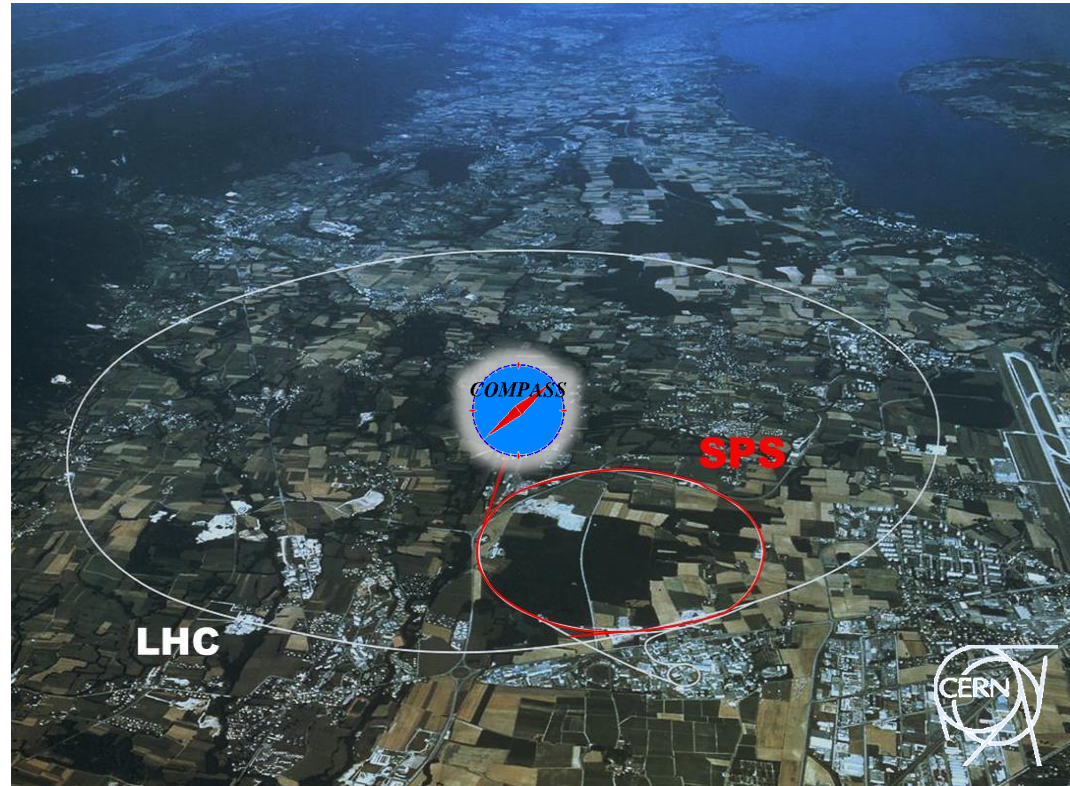
Wide physics program

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>

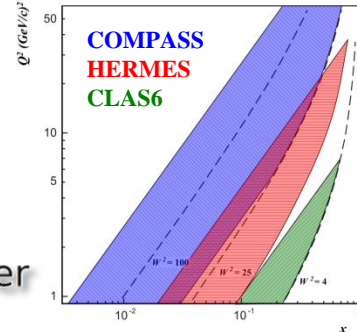
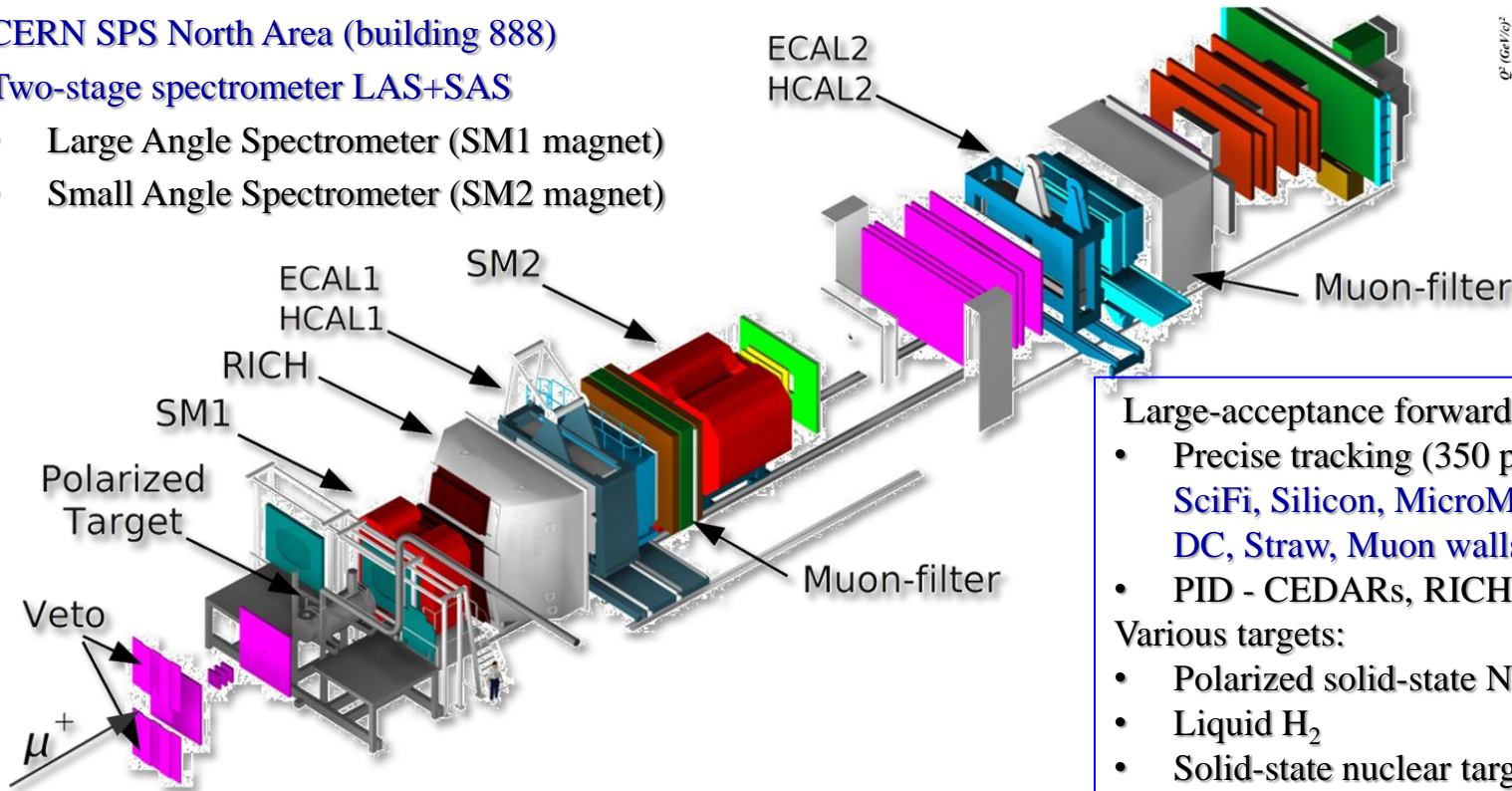
COMPASS experimental setup

COmmon MUon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

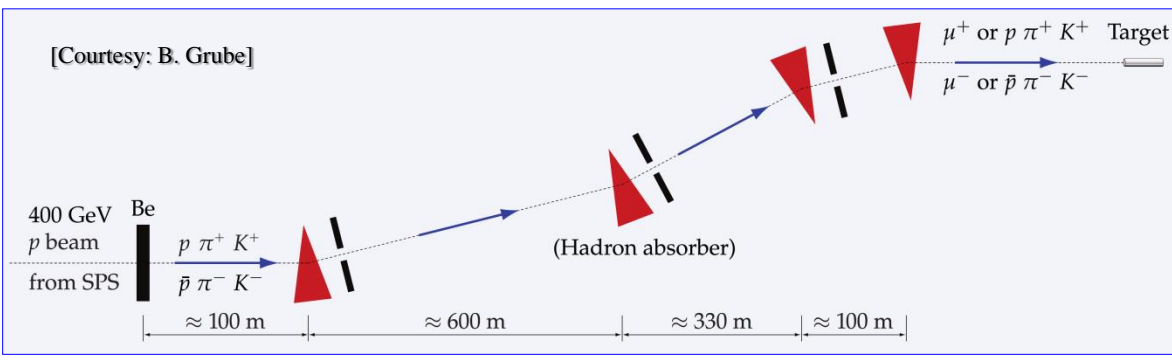
Two-stage spectrometer LAS+SAS

- 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 NH₃ or ⁶LiD
 - Liquid H₂
 - 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% *p*, 24% π⁺, 1% K⁺
- 160 GeV tertiary muon beams
 - μ[±] longitudinally polarized



COMPASS experimental setup: Phase II (SIDIS programme)

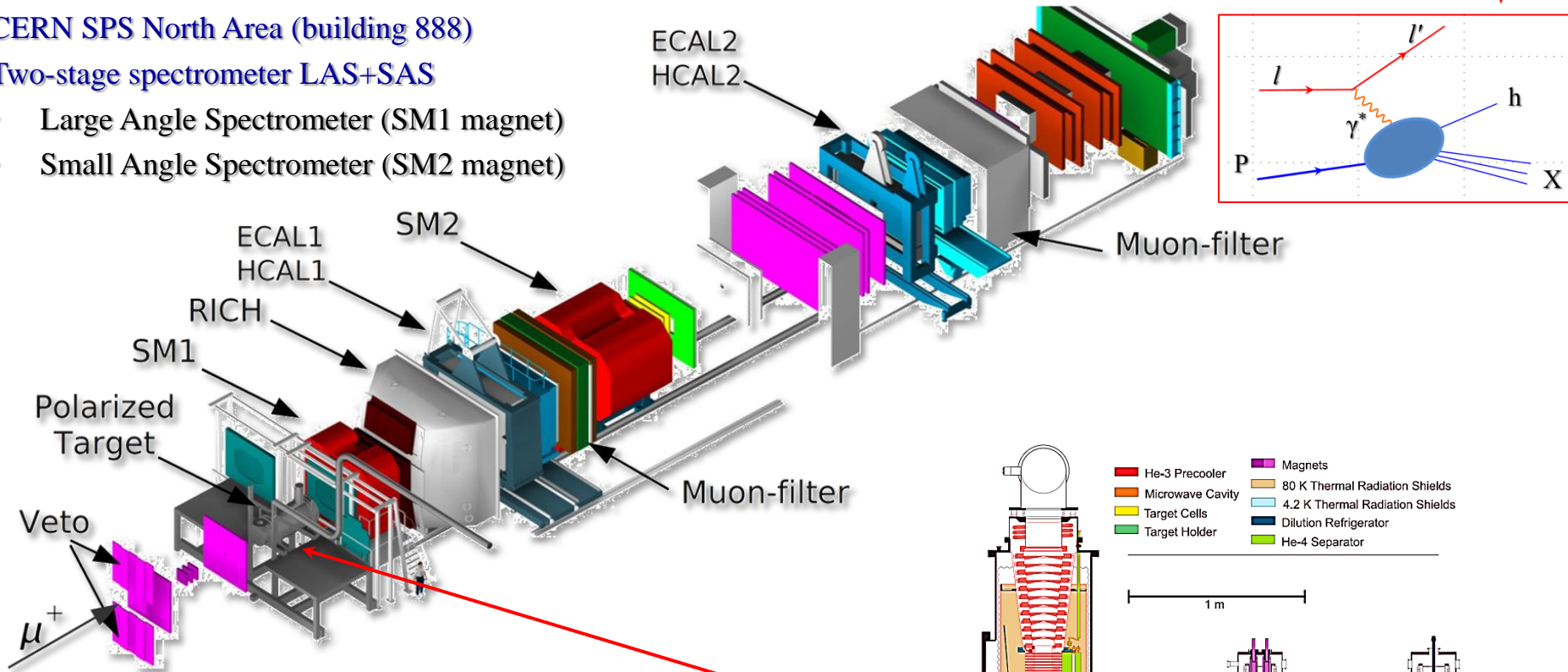


Common Muon Proton Apparatus for Structure and Spectroscopy

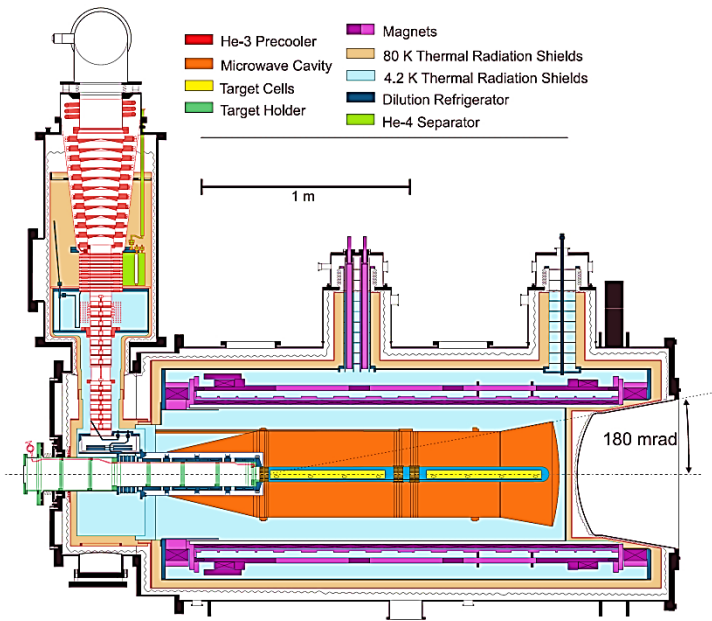
CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
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- Primary beam - 400 GeV p from SPS
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- 190 GeV secondary hadron beams
 - h^- beam: 97% π^- , 2% K^- , 1% p
 - h^+ beam: 75% p , 24% π^+ , 1% K^+
- 160 GeV tertiary muon beams
 - μ^+ longitudinally polarized



COMPASS experimental setup: Phase II (DY programme)

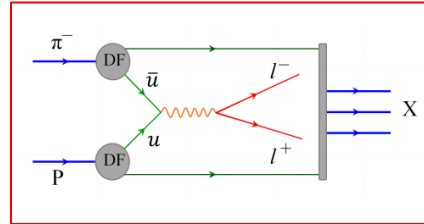
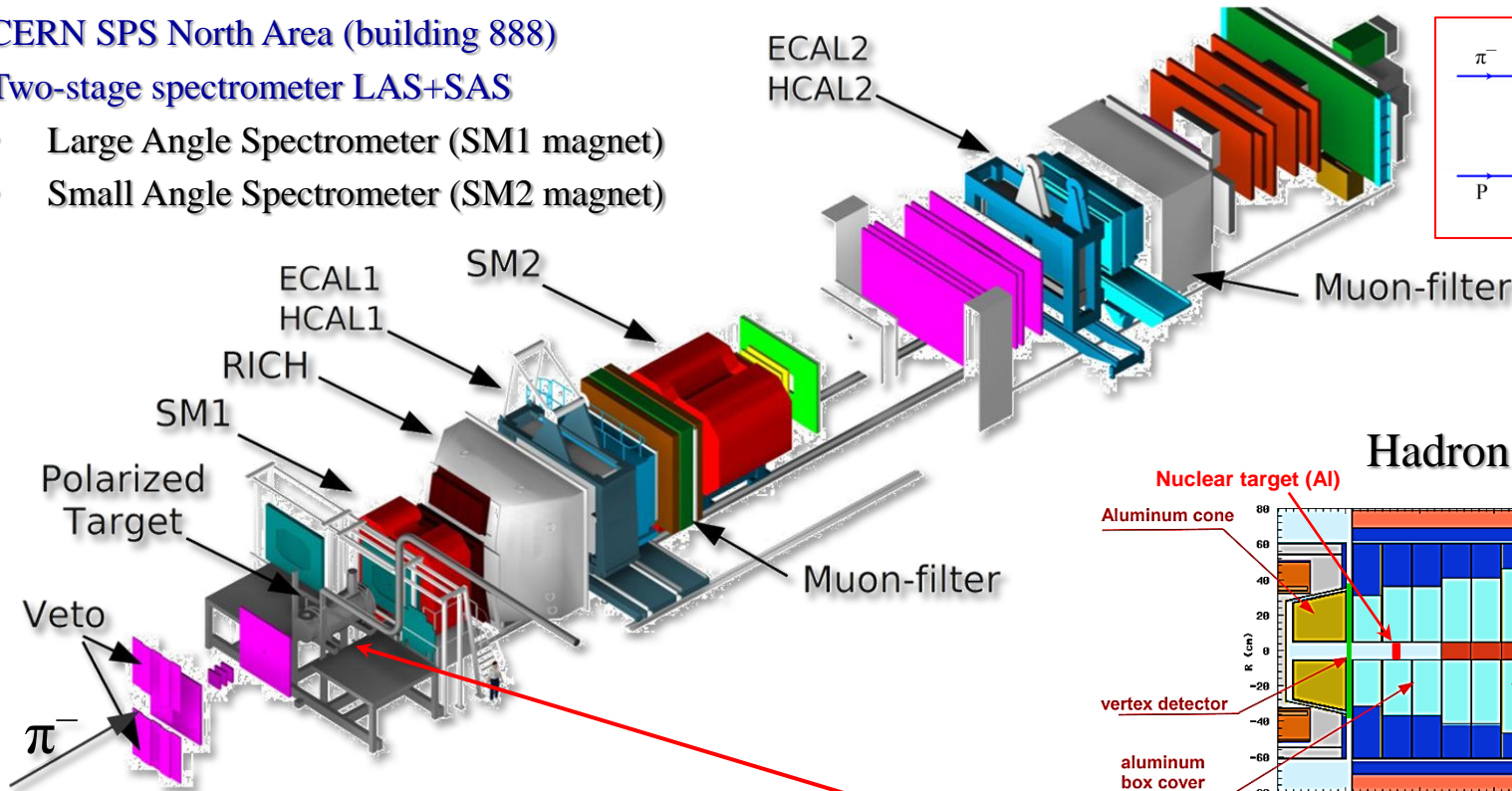


COmmon MUon Proton Apparatus for Structure and Spectroscopy

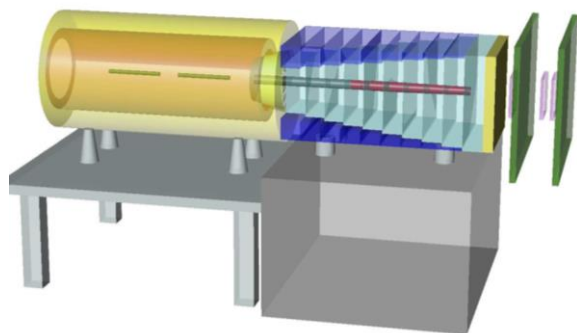
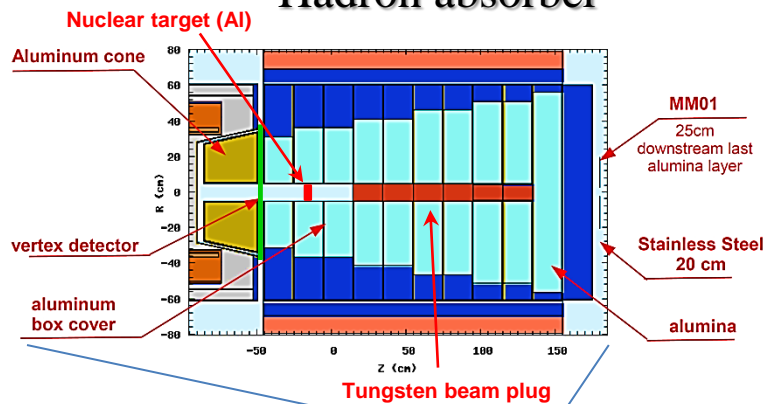
CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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



Hadron absorber



- 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% p , 24% π^+ , 1% K^+
- 160 GeV tertiary muon beams
 - μ^\pm longitudinally polarized



COMPASS data taking campaigns

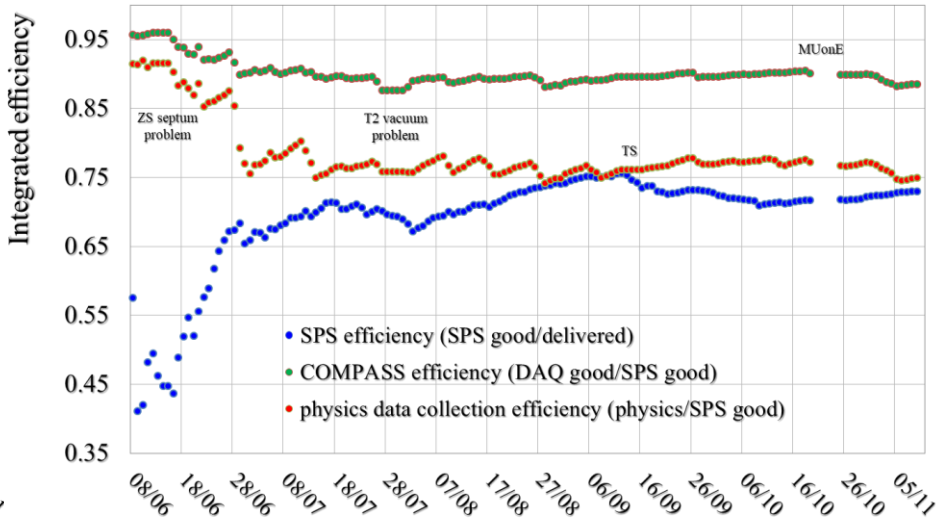
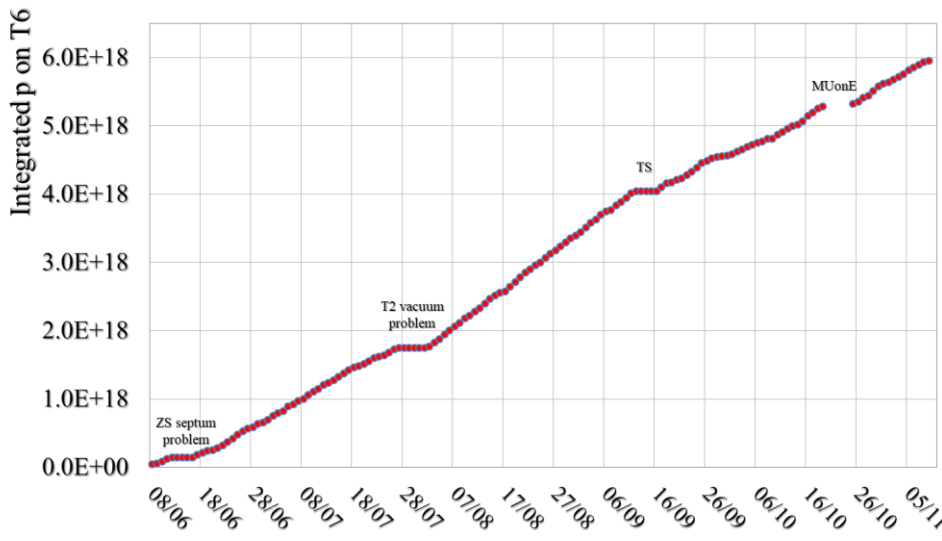
Beam	Target	year	Physics programme
μ^+	Polarized deuteron (${}^6\text{LiD}$)	2002 2003 2004	80% Longitudinal 20% Transverse SIDIS
		2006	Longitudinal SIDIS
	Polarized proton (NH_3)	2007	50% Longitudinal 50% Transverse SIDIS
π K p	LH_2 , Ni, Pb, W	2008 2009	Spectroscopy
μ^+	Polarized proton (NH_3)	2010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

COMPASS data taking campaigns

Beam	Target	year	Physics programme
μ^+	Polarized deuteron (^6LiD)	2002	80% Longitudinal 20% Transverse SIDIS
		2003	
		2004	

- Total number of protons delivered on T6:
 $\sim 5.95 \times 10^{18}$ (98%) in about 150 days

SPS efficiency: $\sim 73\%$
 Spectrometer efficiency: $\sim 90\%$
 Physics data collection efficiency: $\sim 75\%$



μ^+	Polarized deuteron (^6LiD)	2021 2022	Transverse SIDIS
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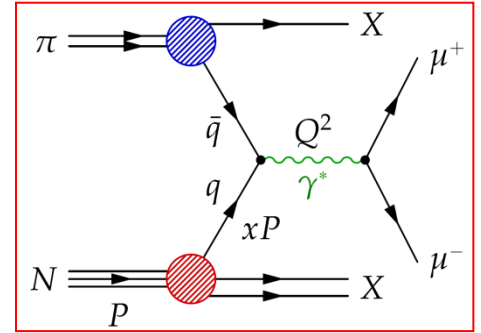
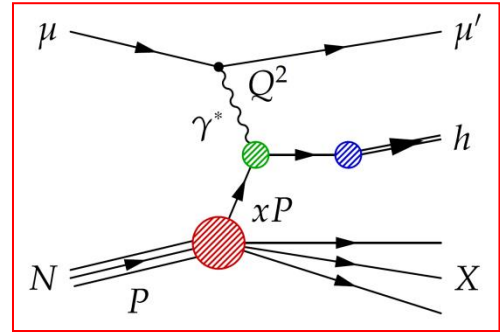
The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale
(momentum transfer)

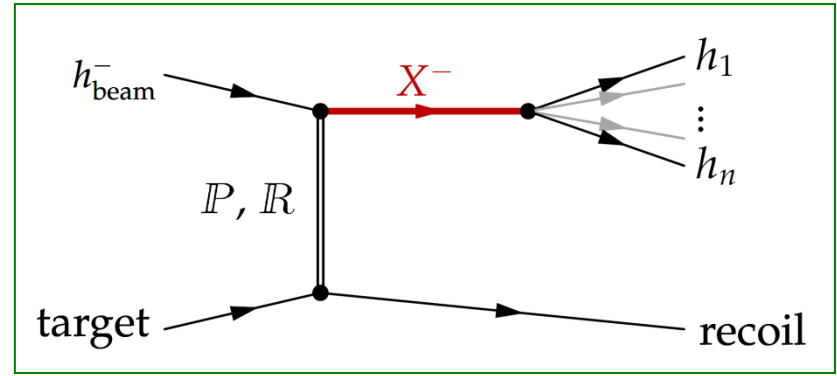
Nucleon structure

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



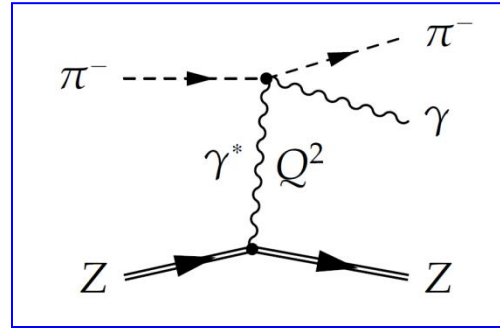
Hadron spectroscopy

- 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
- π^\pm and K^\pm polarizabilities
- Chiral anomaly $F_{3\pi}$



The COMPASS Experiment at the CERN SPS

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Nucleon structure

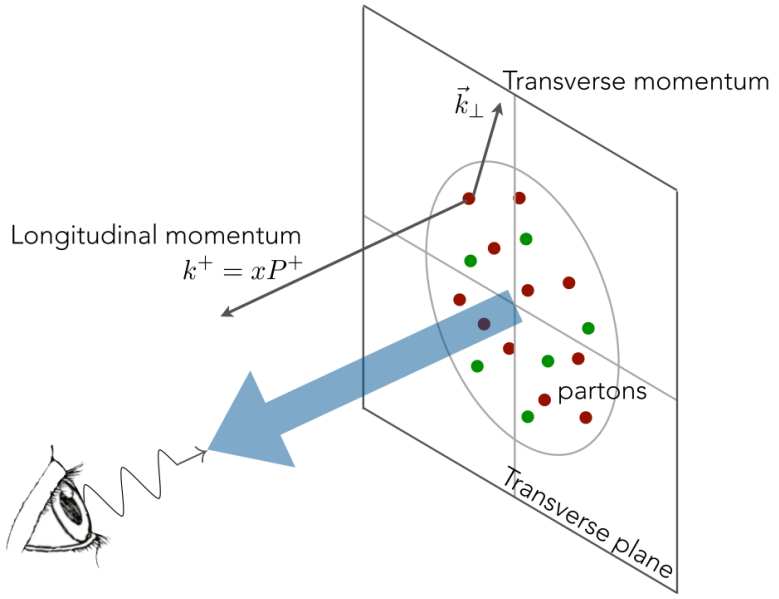
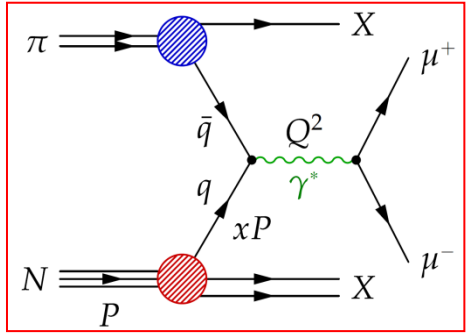
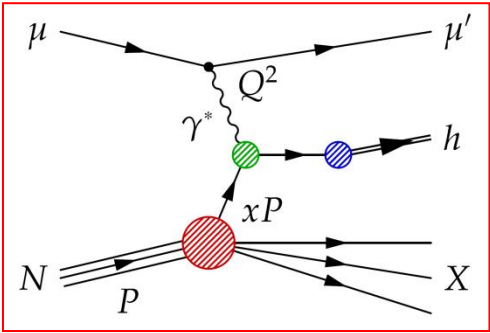
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Hadron spectroscopy

- Diffractive $\pi(K)$ dissociation reaction with proton target
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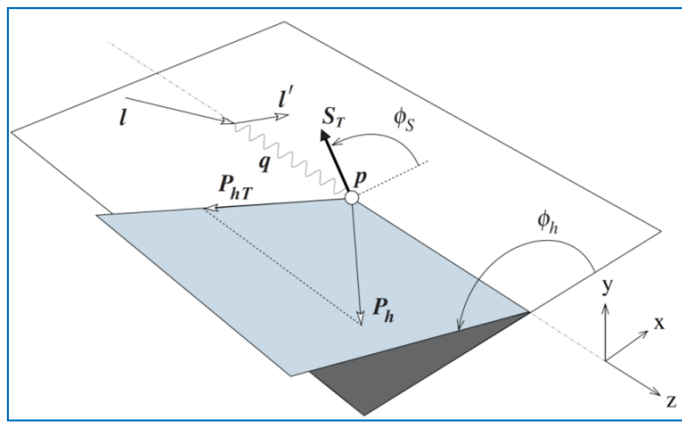
Chiral dynamics

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



Cahn effect in SIDIS

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



Cahn effect

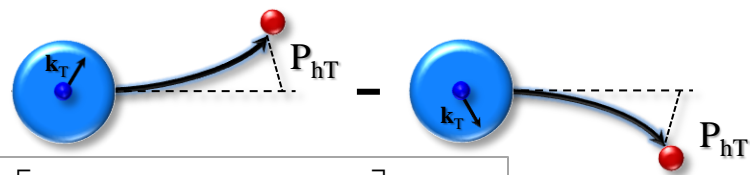
R.N. Cahn, **PLB 78 (1978)**



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;

$$k_T \rightarrow \cos\phi_q \rightarrow \cos\phi_h$$

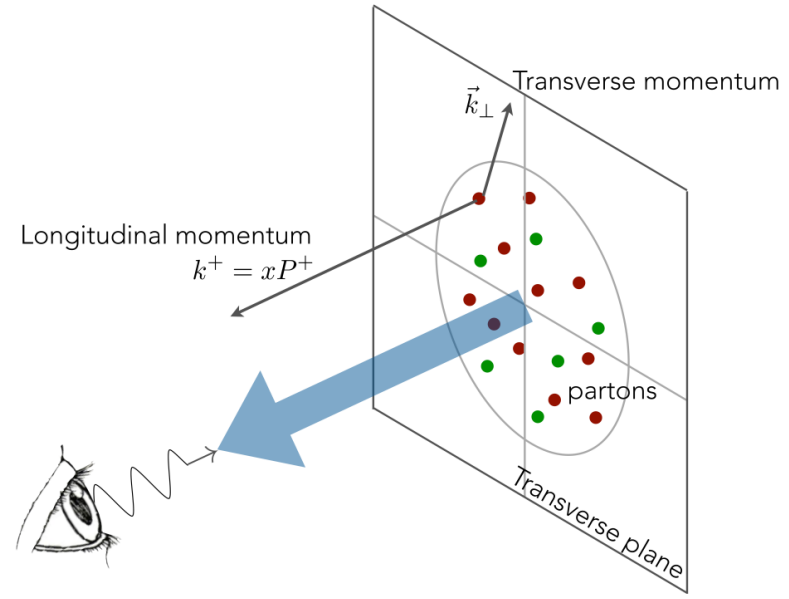


$$\hat{s} \approx xs \left[1 - 2\sqrt{1-y} \frac{k_T}{Q} \cdot \cos\phi_q \right]$$

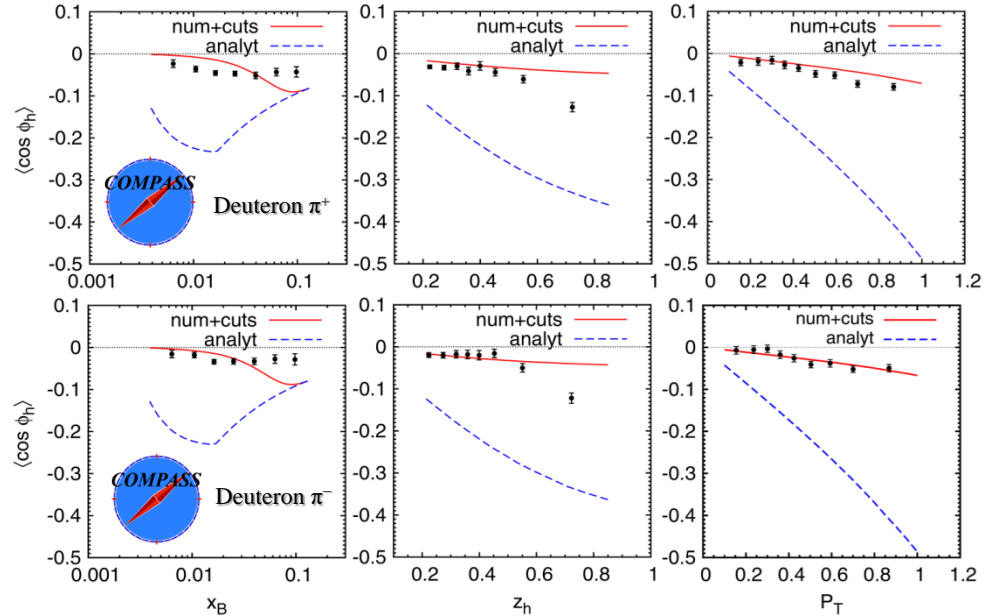
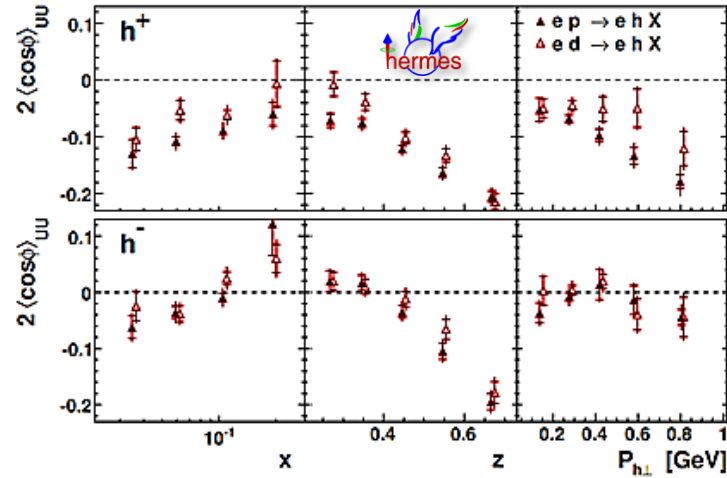
$$\hat{u} \approx -xs(1-y) \left[1 - \frac{2k_T}{Q\sqrt{1-y}} \cdot \cos\phi_q \right]$$

$$\hat{t} = -Q^2 = -xys, \quad \text{where } s = (l + P)^2$$

$$d\sigma^{lp \rightarrow l' hX} \propto d\sigma^{lq \rightarrow lq} \propto \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$$



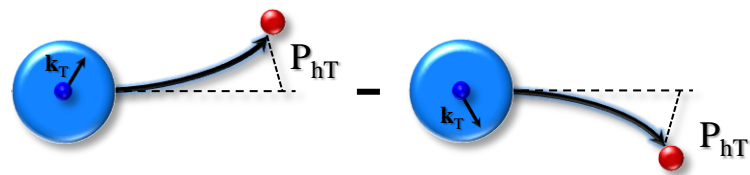
Significant non-zero effect observed by a number of experiments



Cahn effect in SIDIS

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

Quark	U
Nucleon	$f_1^q(x, k_T^2)$ number density
U	



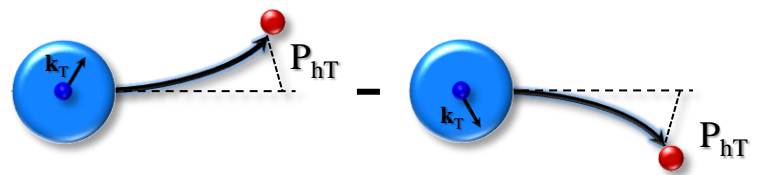
- As of 1978 – simplistic kinematic effect:
- non-zero k_T induces an azimuthal modulation
- As of 2022 – complex SF (twist-2/3 functions)
- Measurements by different experiments

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

Cahn effect in SIDIS

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

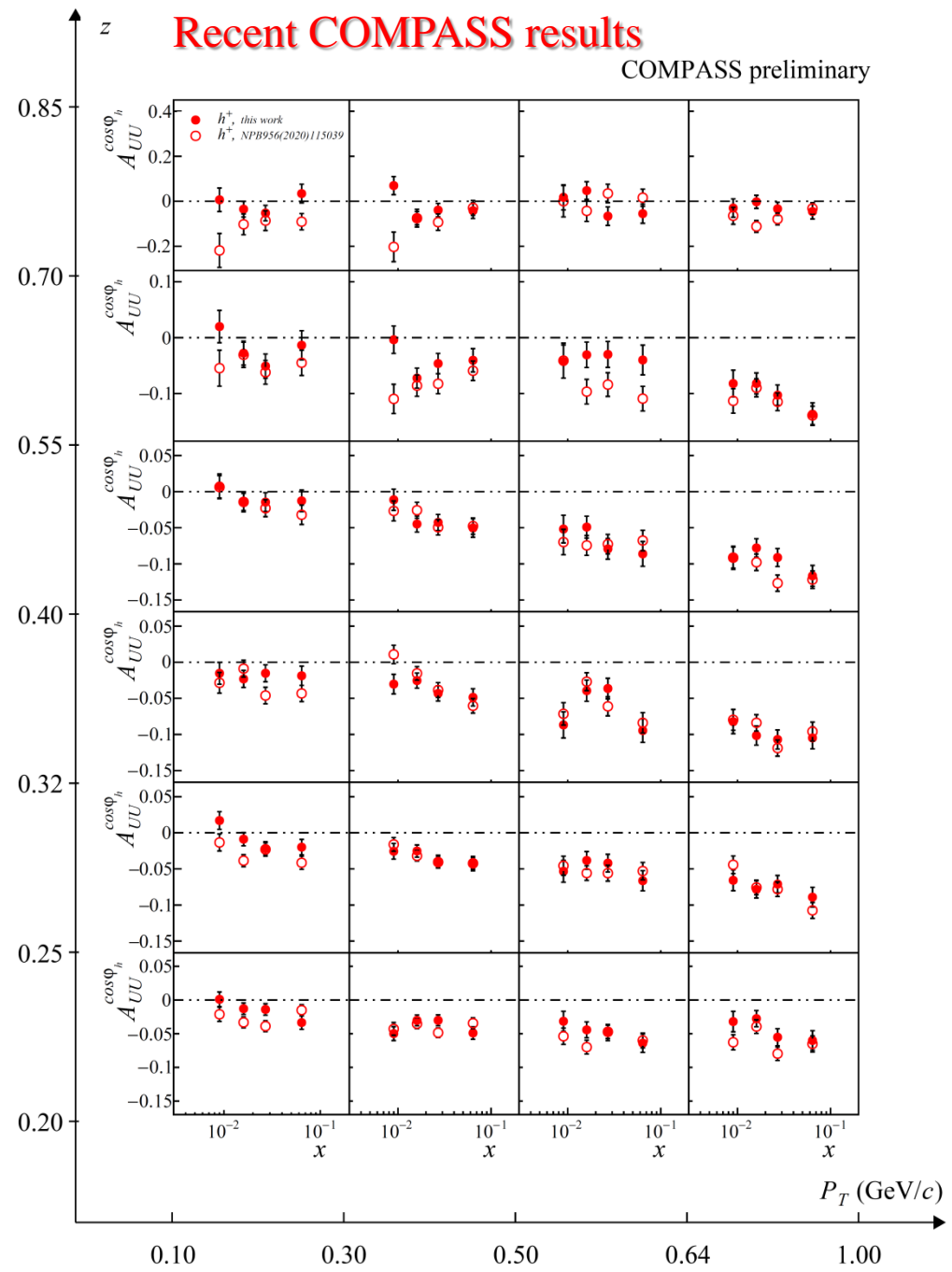
Quark	U
Nucleon	$f_1^q(x, k_T^2)$ number density



- As of 1978 – simplistic kinematic effect:
- non-zero k_T induces an azimuthal modulation
- As of 2022 – complex SF (twist-2/3 functions)
- Measurements by different experiments
 - Complex multi-D kinematic dependences
 - So far, no clear interpretation

Recent COMPASS results

COMPASS preliminary

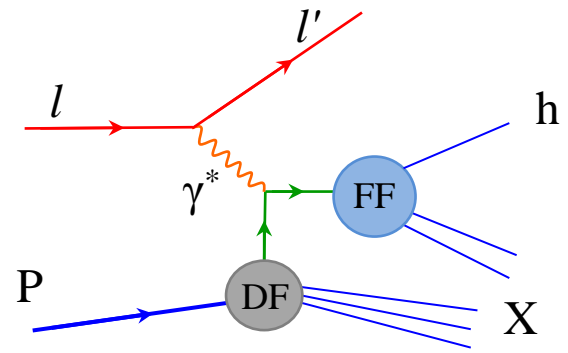


SIDIS x-section and TMDs at twist-2

All measured by COMPASS

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} =$$

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



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

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

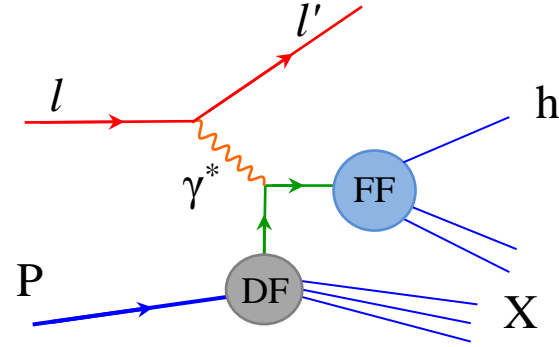
spin of the nucleon
 spin of the quark
 k_T

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_s} =$$

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



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

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

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

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

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

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

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

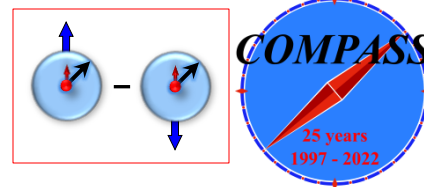
$$A_{LT}^{\cos(\phi_s)} \overset{WW}{\propto} Q^{-1} \left(g_{1T}^q \otimes D_{1q}^h + \dots \right)$$

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

Twist-2

Twist-3

SIDIS TSAs: Collins effect and Transversity



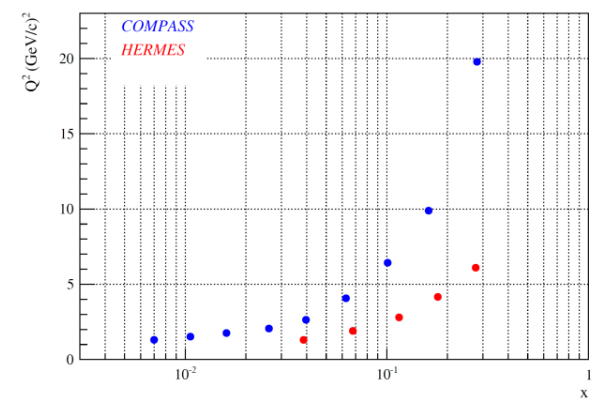
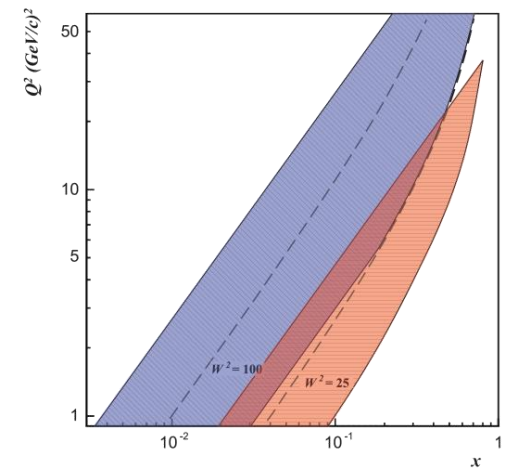
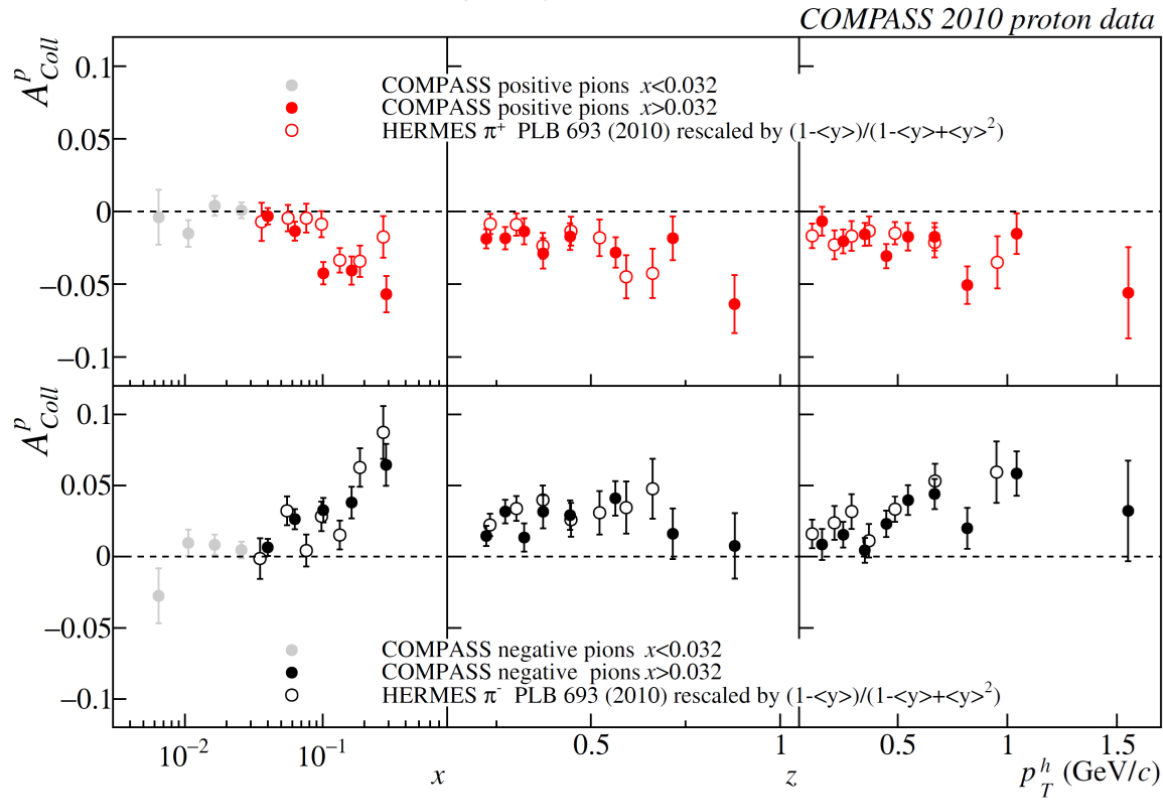
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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

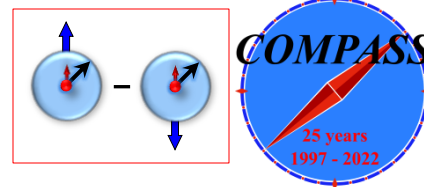


- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q² is different by a factor of ~2-3)
- No impact from Q²-evolution?

COMPASS PLB 744 (2015) 250



SIDIS TSAs: Collins effect and Transversity



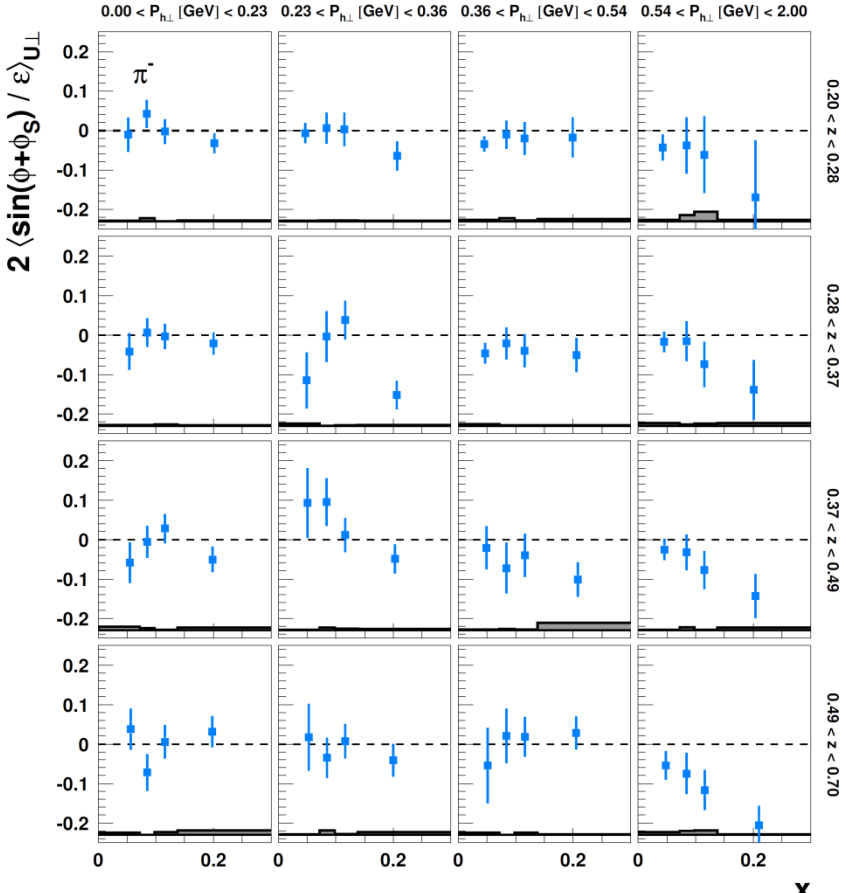
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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

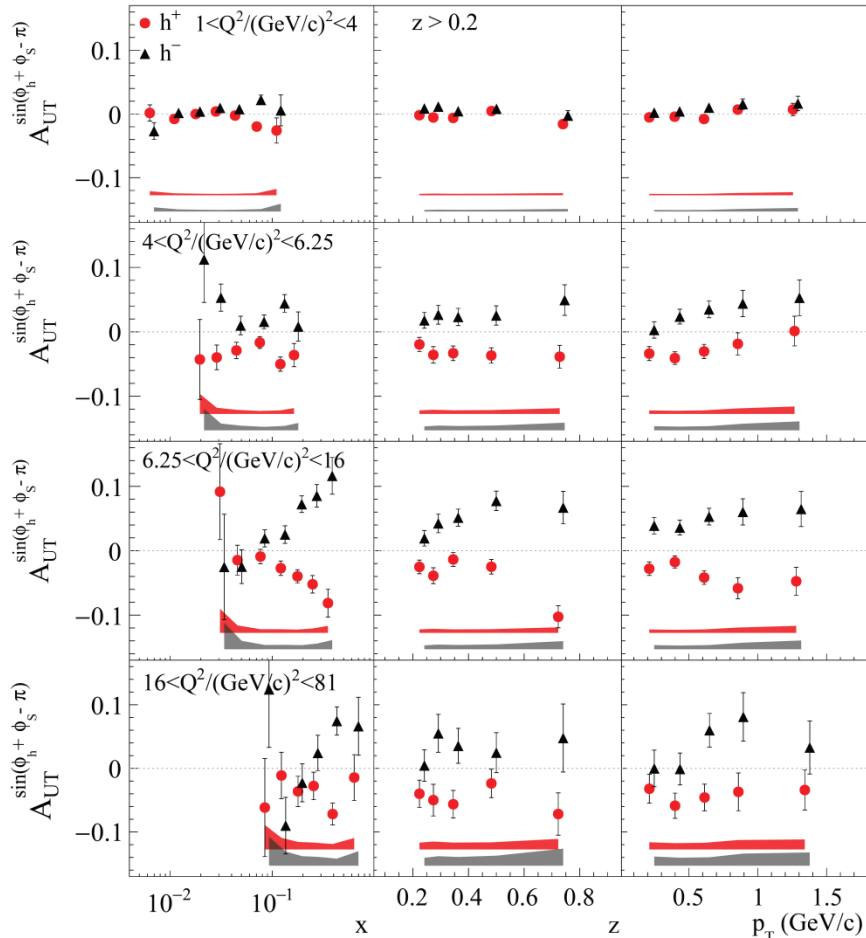


- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q² is different by a factor of ~2-3)
- No impact from Q²-evolution?

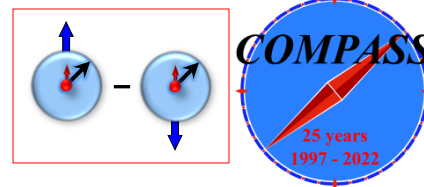
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



SIDIS TSAs: Collins effect and Transversity



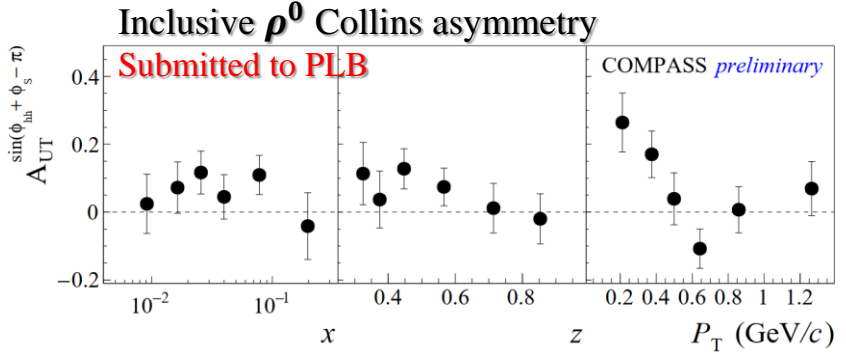
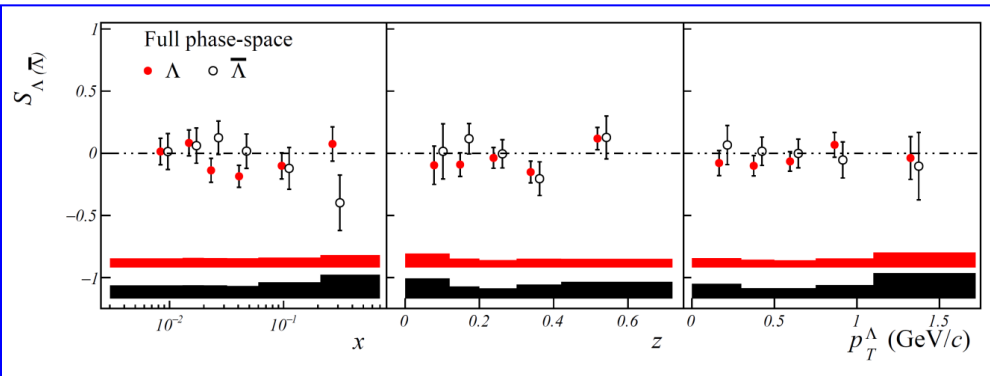
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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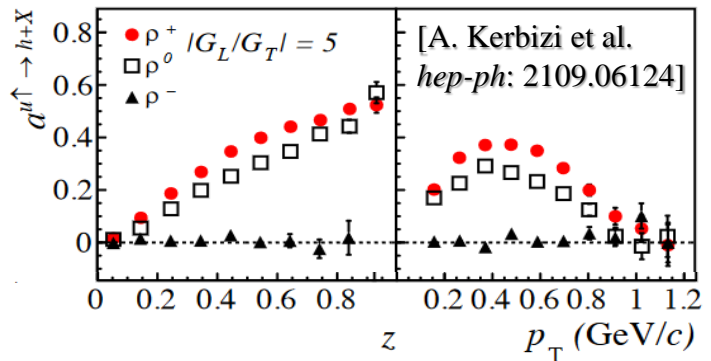
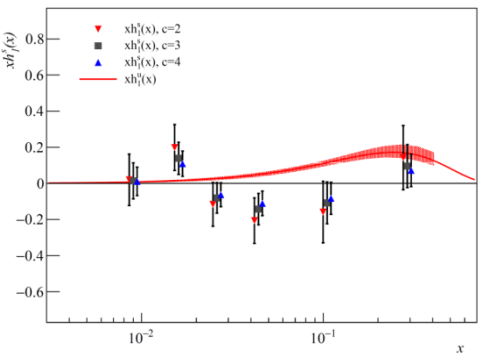
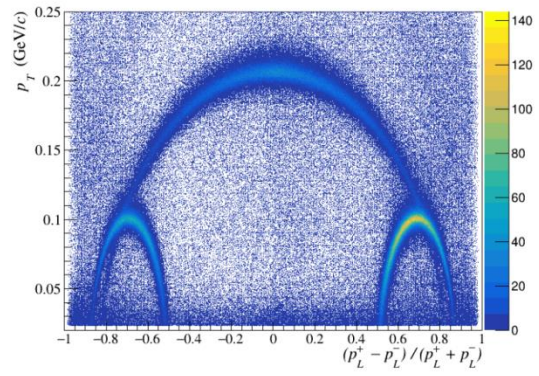


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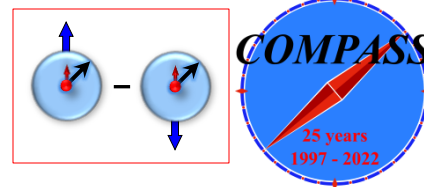
PLB 824 (2022) 136834 - NEW



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



SIDIS TSAs: Collins effect and Transversity



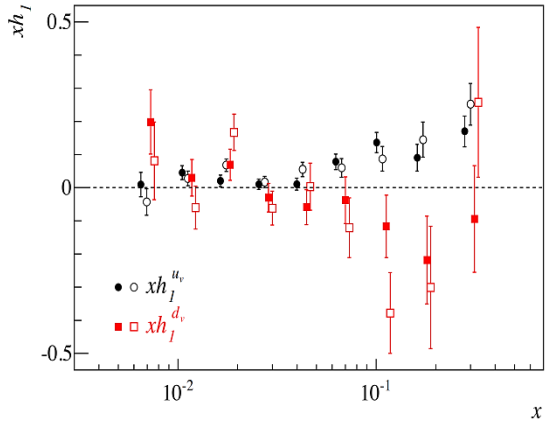
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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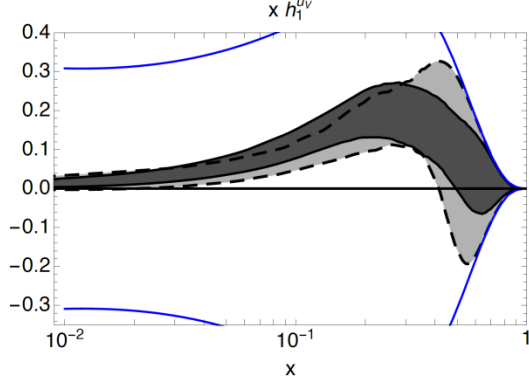


- Measured on P/D in SIDIS and in dihadron SIDIS
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- **No impact from Q²-evolution?**
- Extensive phenomenological studies and various global fits by different groups

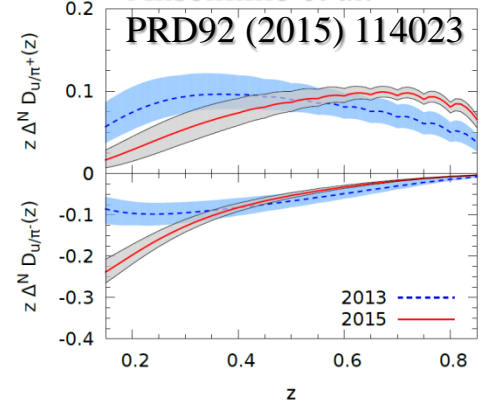
A. Martin, F. Bradamante, V. Barone
PRD91 (2015) no.1, 014034



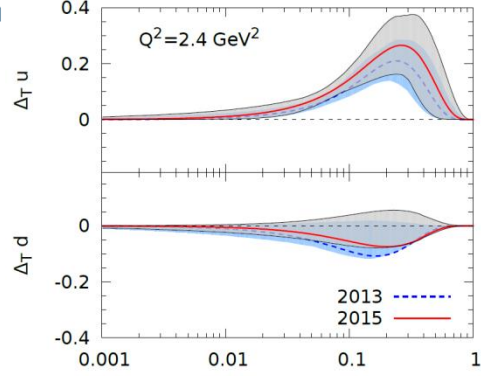
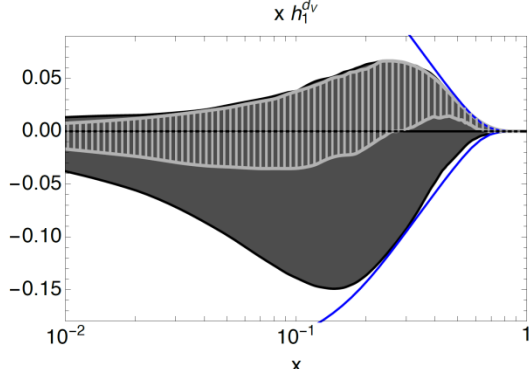
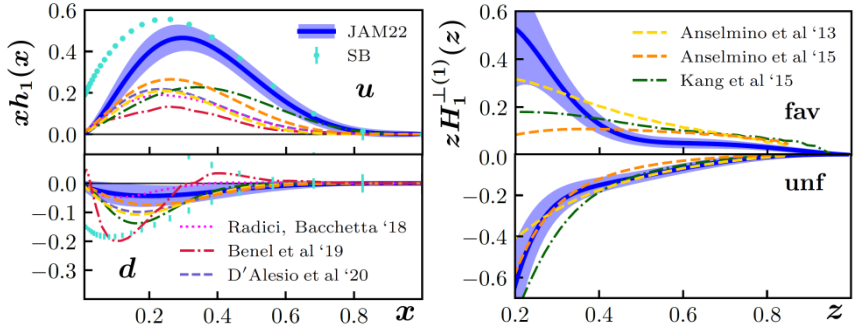
M. Radici and A. Bacchetta
PRL 120 (2018) no.19, 192001



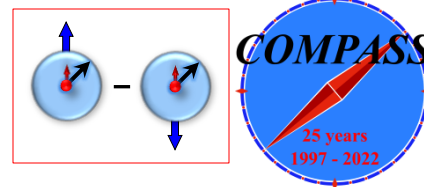
Anselmino et al.
PRD92 (2015) 114023



JAM Collaboration, [hep-ph arXiv:2205.00999](https://arxiv.org/abs/2205.00999)



SIDIS TSAs: Collins effect and Transversity



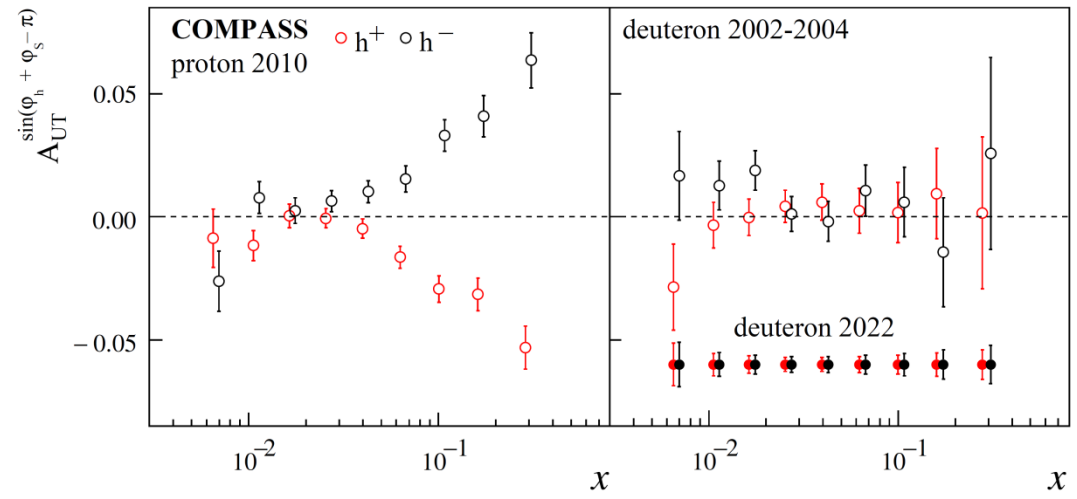
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \dots \right\}$$

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

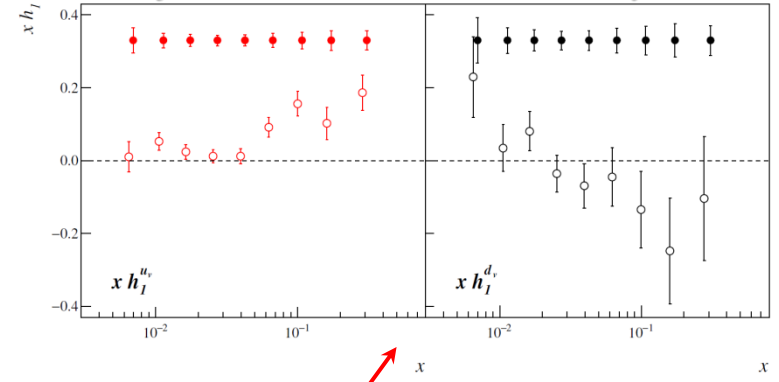


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[Addendum to the COMPASS-II Proposal]
Projected uncertainties for Collins asymmetry

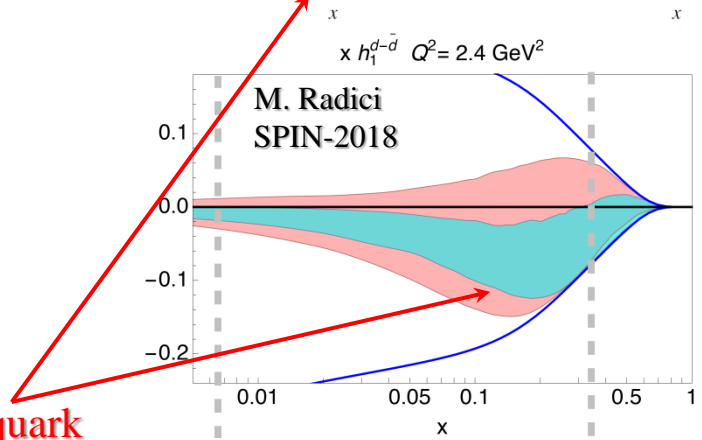


Projected uncertainties for transversity PDF



COMPASS-II (2022)

- Deuteron measurement being repeated
- Will be crucial to constrain the transversity TMD PDF for the d-quark



SIDIS TSAs: Sivers effect

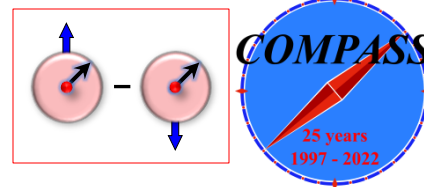
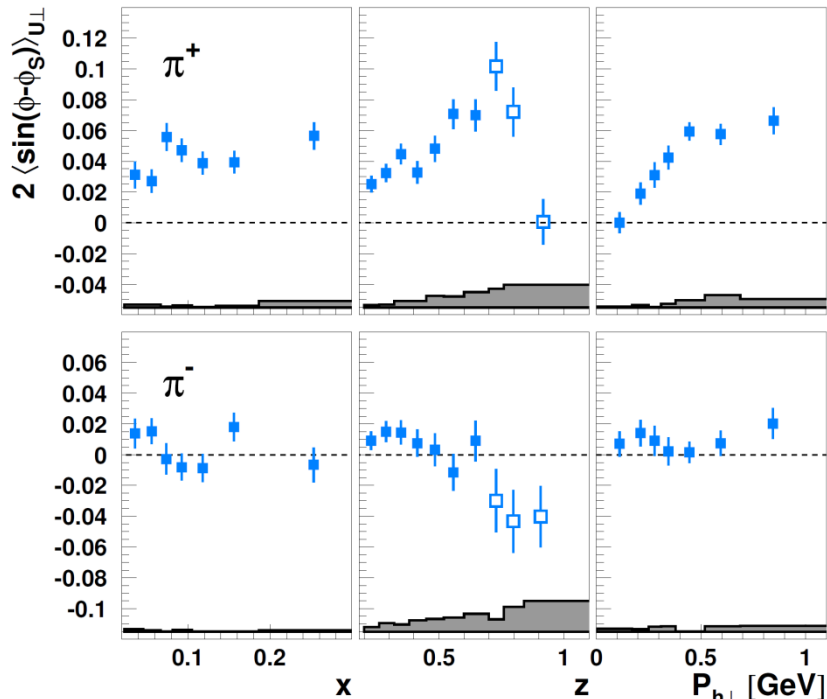
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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

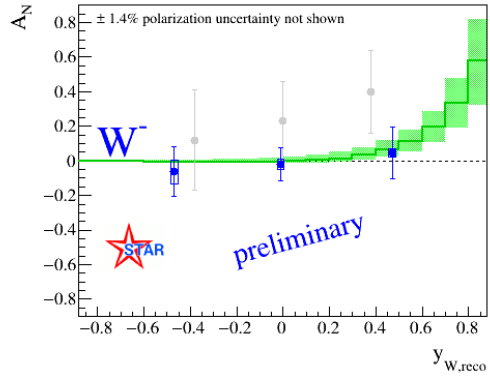
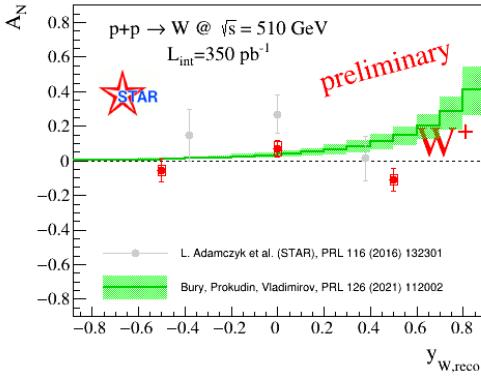
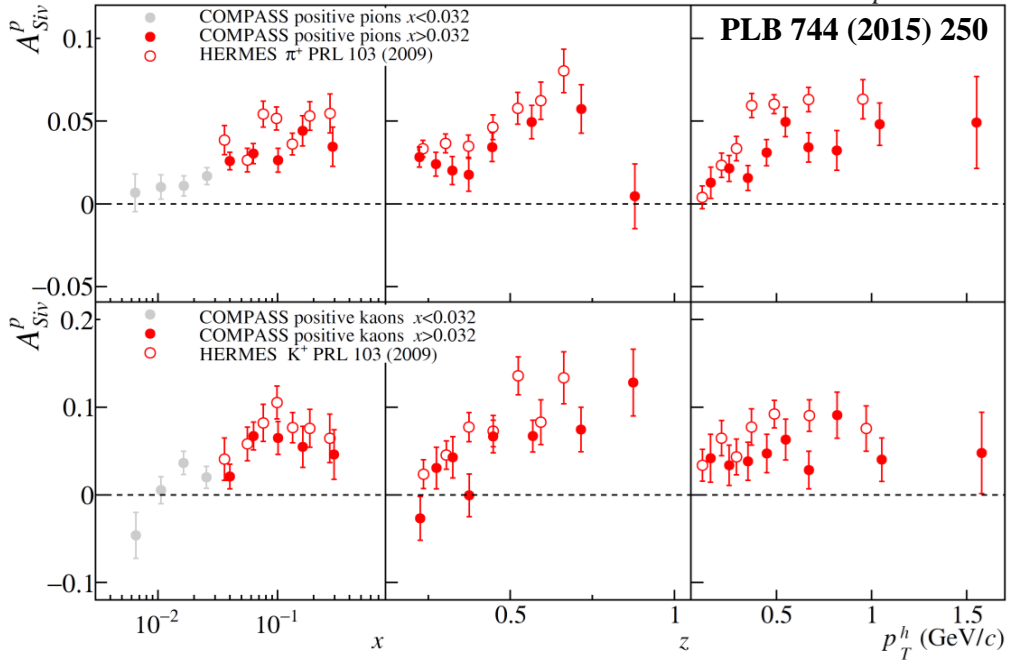


- Measured on proton and deuteron
- Expected to change sign between SIDIS and Drell-Yan

HERMES, JHEP 12 (2020) 010



COMPASS 2010 proton data



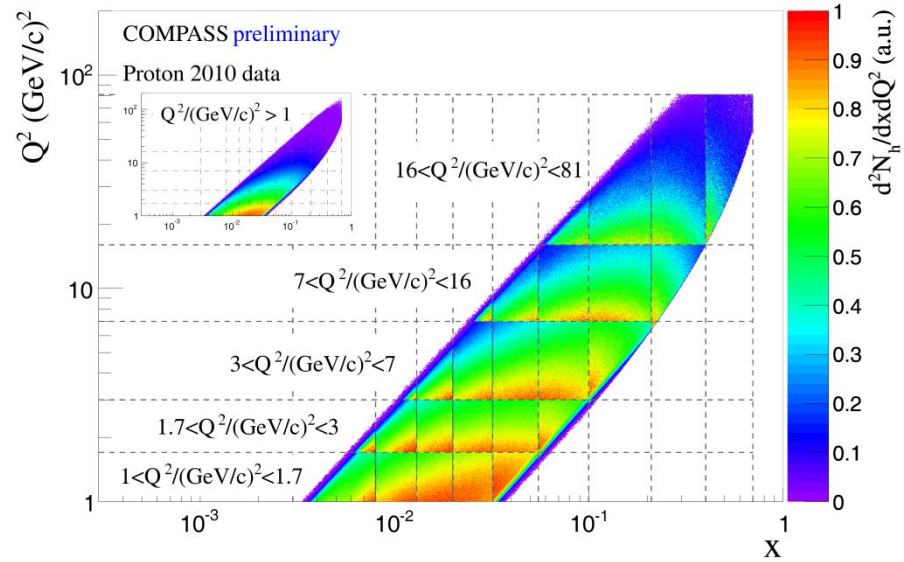
COMPASS Multi-D TSA analyses

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

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



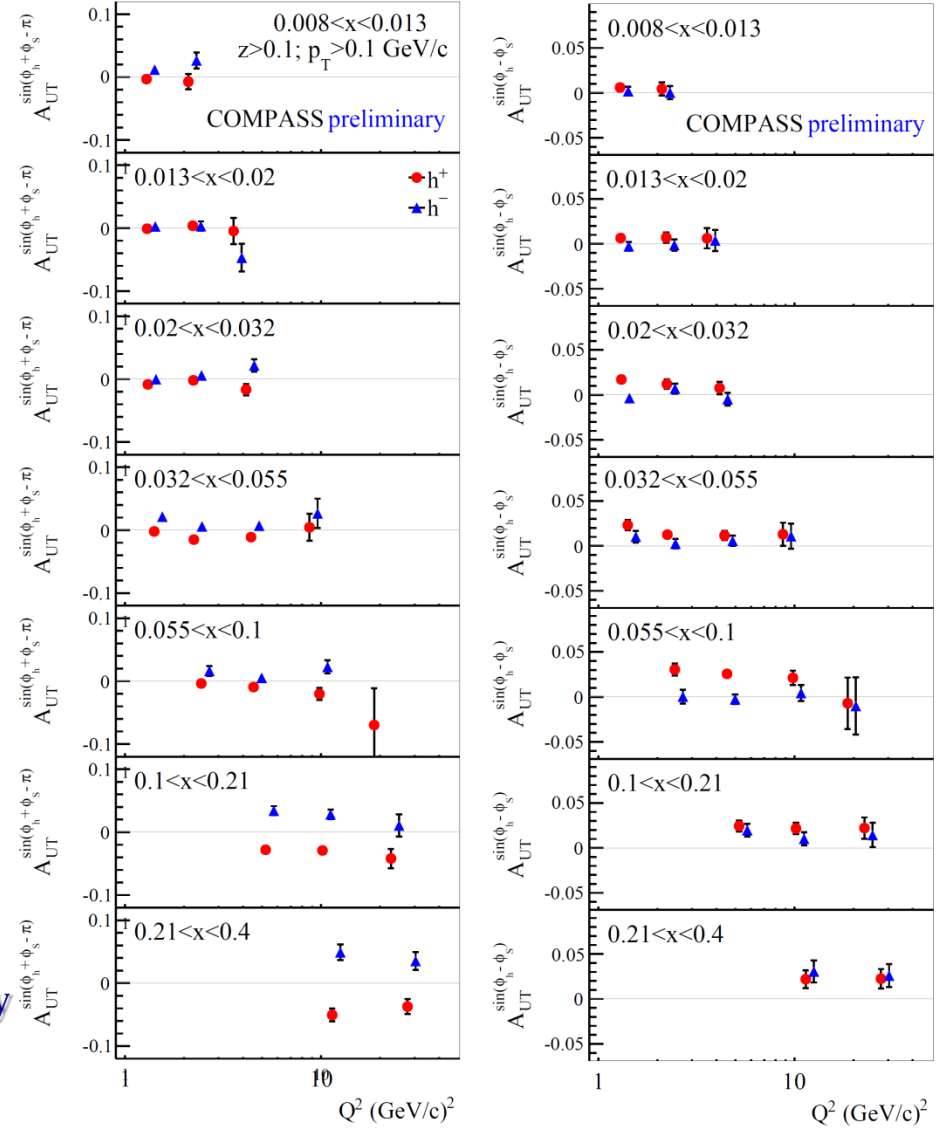
$$F_{UT}^{\sin(\phi_h + \phi_S)} = C \left[-\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} h_1^q H_{1q}^{\perp h} \right]$$



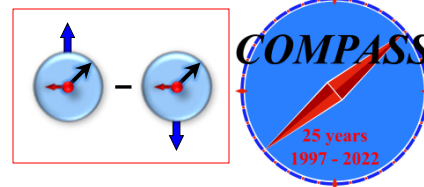
3D $x:Q^2:z$ or $x:Q^2:p_T$ $x:z:p_T$

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

B. Parsamyan (for COMPASS) [arXiv:1504.01599](https://arxiv.org/abs/1504.01599) [hep-ex] (SPIN-2014)

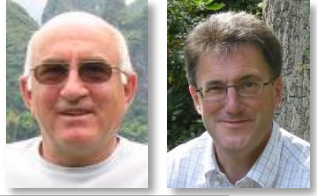


SIDIS TSAs: Kotzinian-Mulders asymmetry

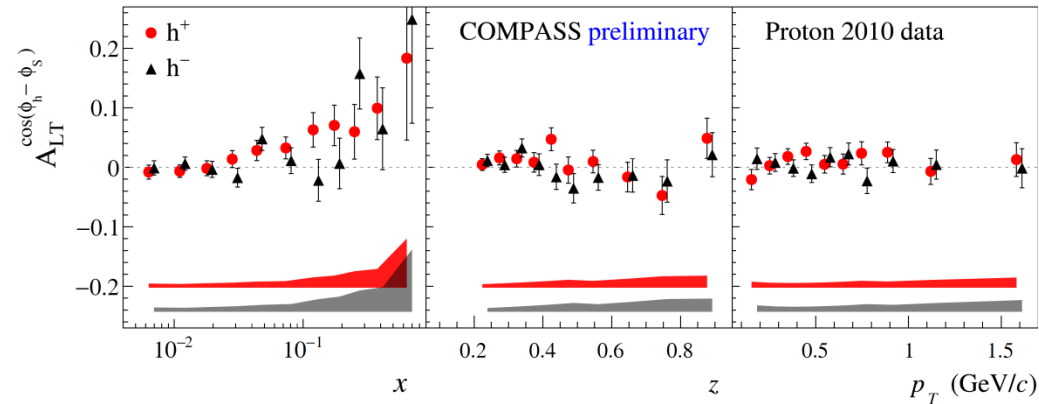


$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + \lambda S_T \sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + \dots \right\}$$

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



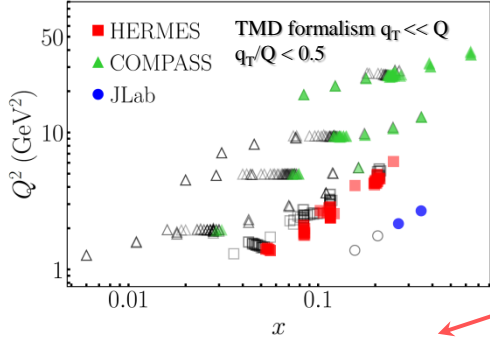
COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



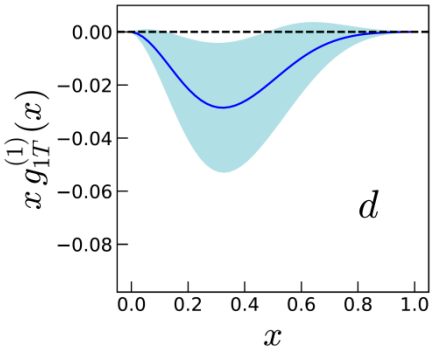
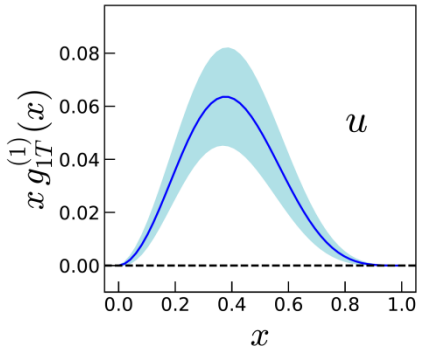
COMPASS/HERMES/CLAS6 results

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

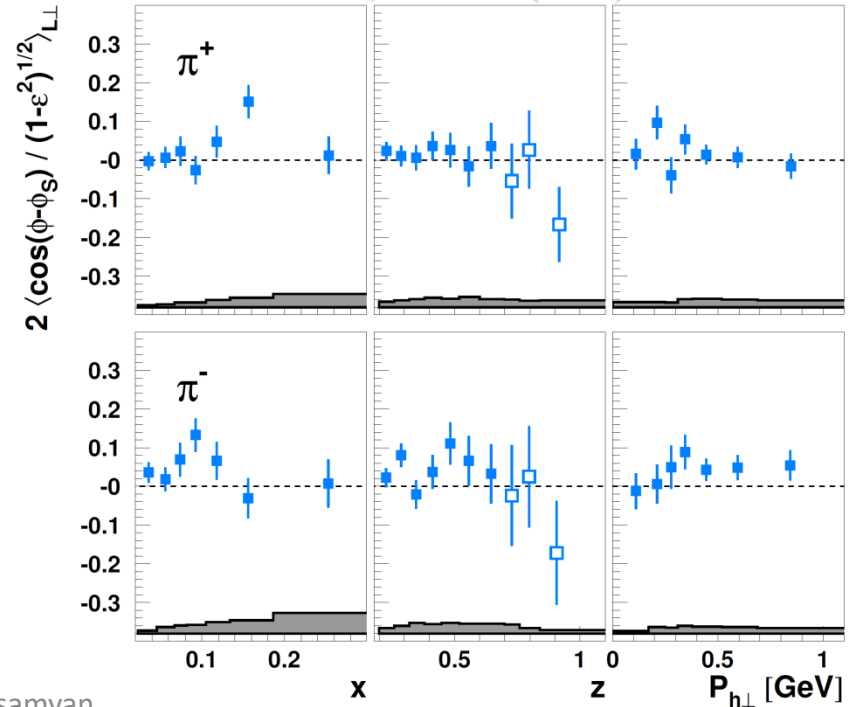
- Only “twist-2” ingredients
- **Sizable non-zero effect for h⁺ !**
- **Similar effect at HERMES**



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



HERMES, JHEP 12 (2020) 010



COMPASS 2022 run: new unique deuteron data to come



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

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

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

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

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

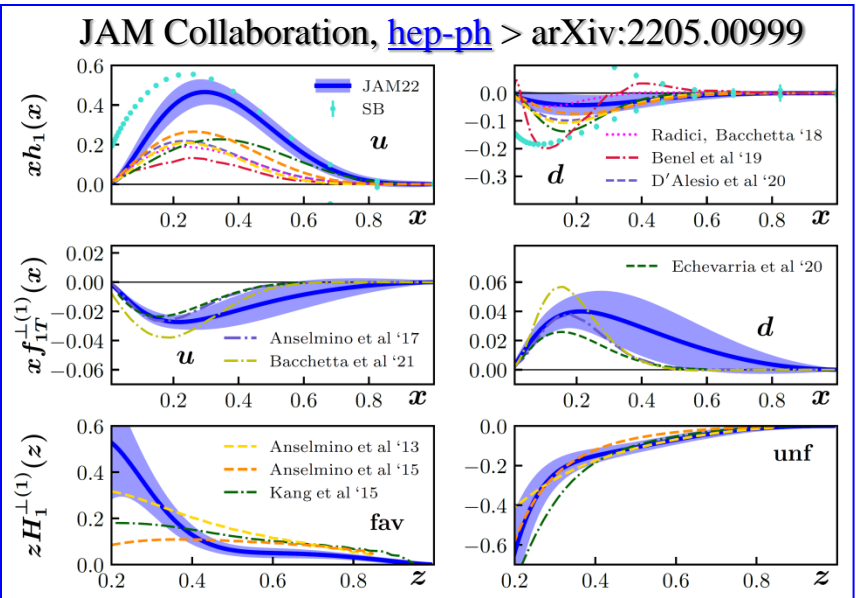
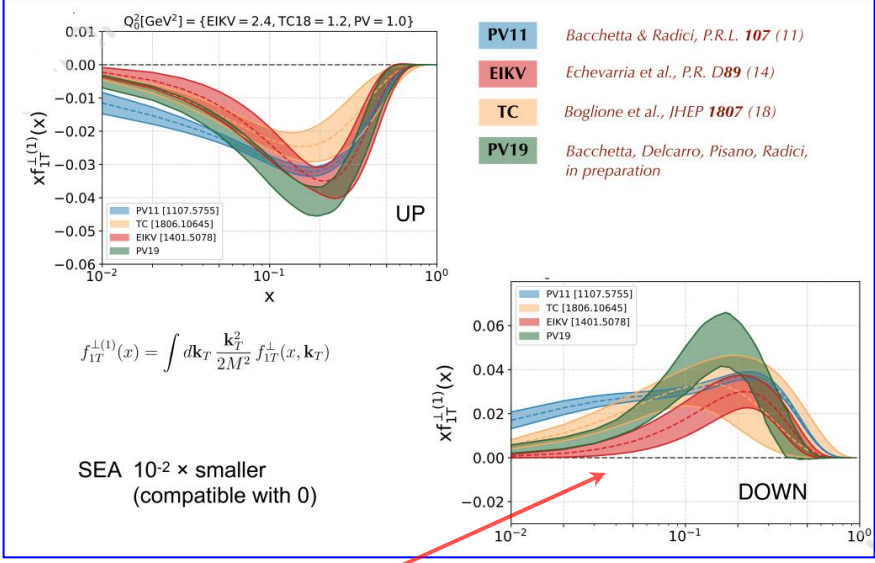
analysis of statistical error with replica method (200)
68% confidence level

Same kinematic cuts applied to unpolarized x, z, P_{LT} data projections

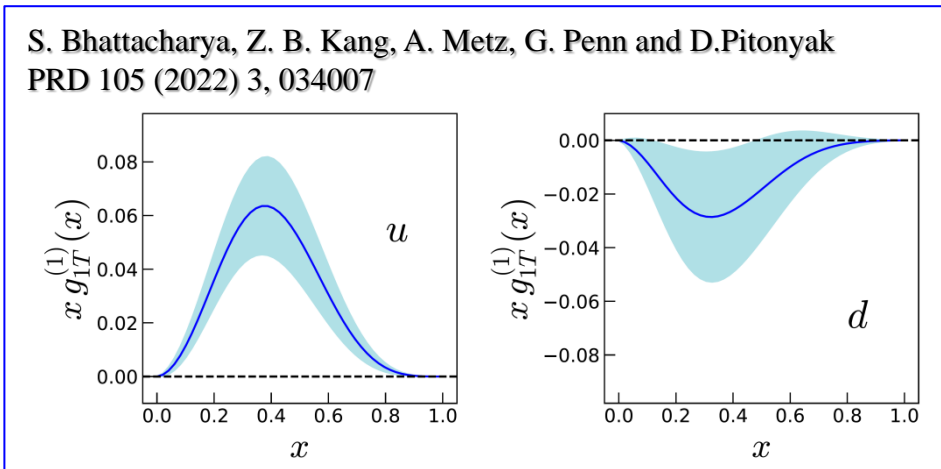
$Q^2 \geq 1.4 \text{ GeV}^2$ $0.2 \leq z \leq 0.7$
 $P_{HT} < \min[0.2Q, 0.7Qz] + 0.5 \text{ GeV}$

300 data points → **118 data fitted**
14 free parameters
 $\chi^2/\text{d.o.f.} = 1.06 \pm 0.10$

$\chi^2/\text{d.o.f.}$



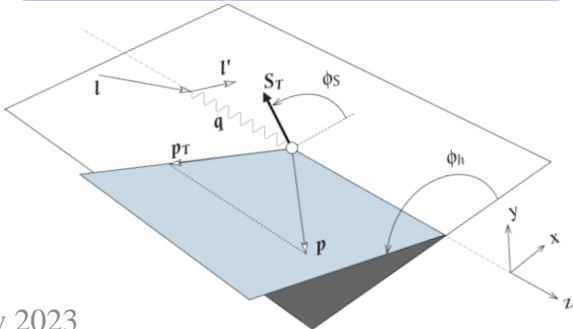
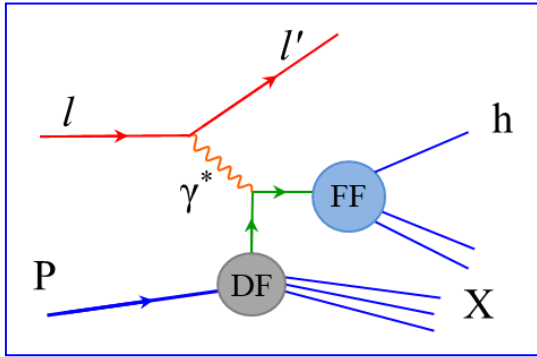
COMPASS 2022 deuteron run



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

$$\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \quad \text{SIDIS}$$

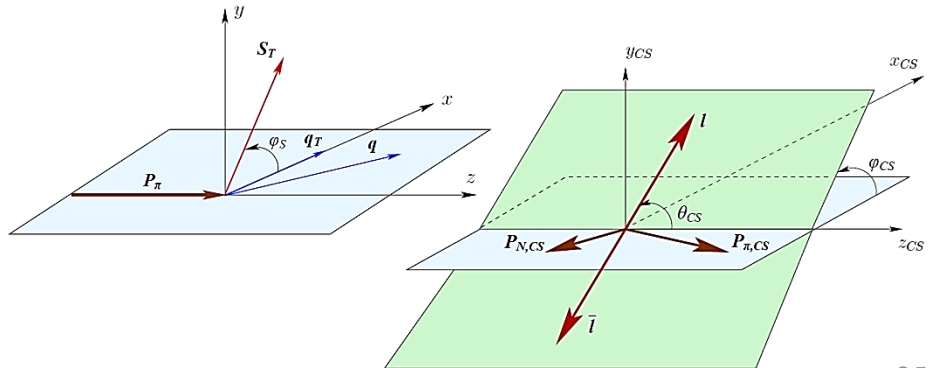
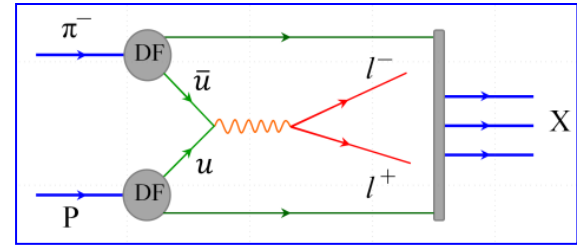
$$\left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \right\} \times \left\{ \begin{array}{l} + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h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



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

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

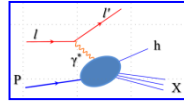
where $D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$



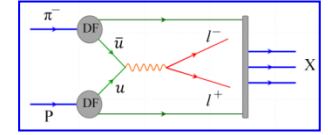
SIDIS and single-polarized DY x-sections at twist-2 (LO)



$$\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_s} \propto (F_{UU,T} + \varepsilon F_{UU,L})$$



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



$$\left\{ \begin{aligned} & 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ & + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} \\ & + S_T \begin{bmatrix} A_{UT}^{\sin(\phi_h - \phi_s)} \sin(\phi_h - \phi_s) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_s)} \sin(\phi_h + \phi_s) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_s)} \sin(3\phi_h - \phi_s) \end{bmatrix} \\ & + S_T \lambda \left[\sqrt{(1 - \varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_s)} \cos(\phi_h - \phi_s) \right] \end{aligned} \right\} \times \left\{ \begin{aligned} & 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ & + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ & + S_T \begin{bmatrix} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \\ \left. + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \end{bmatrix} \end{aligned} \right\}$$

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



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

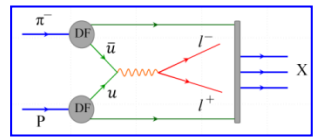
Complementary information from two different channels :

- SIDIS-DY bridging of nucleon TMD PDFs; Universality studies;
- **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

- $1.0 < M/(\text{GeV}/c^2) < 2.0$ “Low mass”
 - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π , K decays
- $2.0 < M/(\text{GeV}/c^2) < 2.5$ “Intermediate mass”
 - High DY-cross section
 - Still low DY-signal/background ratio
- $2.5 < M/(\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 - Strong J/ψ -signal \rightarrow study of J/ψ physics
 - Good signal/background
- $4.3 < M/(\text{GeV}/c^2) < 8.5$ “High mass”
 - Low DY cross-section
 - Beyond charmonium region, background $< 3\%$
 - Valence region \rightarrow largest asymmetries

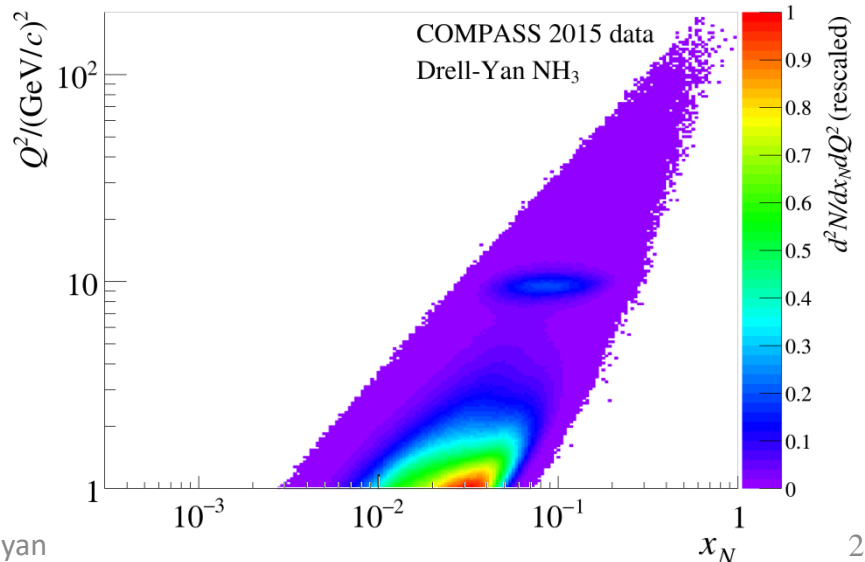
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$



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

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

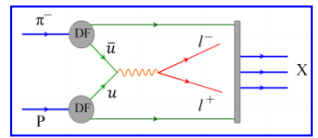
COMPASS x:Q² phase space



Single-polarized DY measurements at COMPASS

- $2.5 < M/(\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 - Strong J/ψ -signal \rightarrow study of J/ψ physics
 - Good signal/background
- $4.3 < M/(\text{GeV}/c^2) < 8.5$ “High mass”
 - Low DY cross-section
 - Beyond charmonium region, background $< 3\%$
 - Valence region \rightarrow largest asymmetries

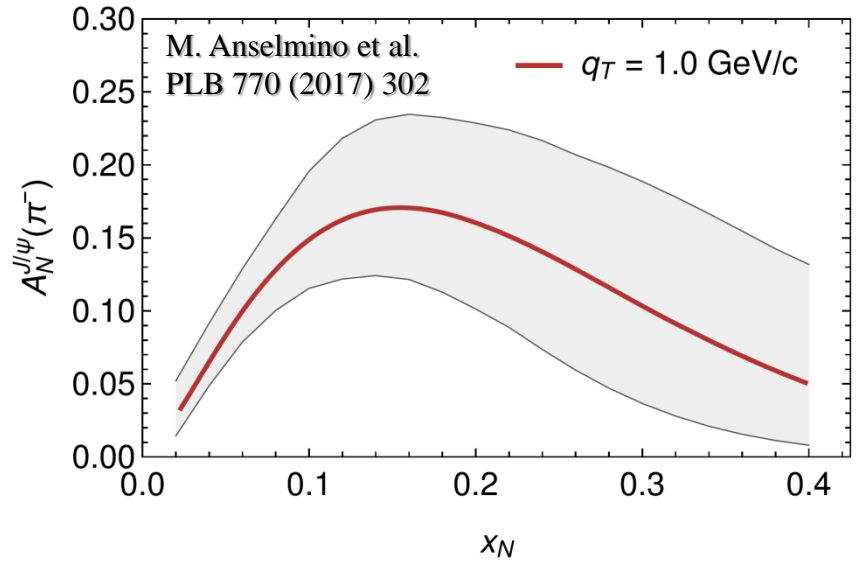
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$



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

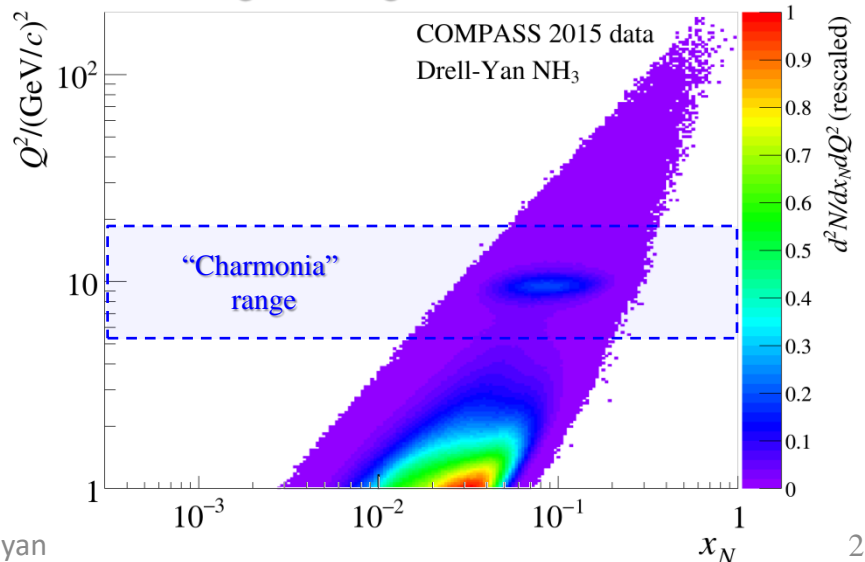
$$D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$$

$\langle x_{\pi^-} \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1 \text{ GeV}/c$



- Assuming $q\bar{q}$ -annihilation as dominant channel for J/ψ production at COMPASS
- Neglecting gluon fusion contribution and the role of feed-down J/ψ mesons

$2.5 < M/(\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 Strong J/ψ -signal \rightarrow study of J/ψ physics
 Good signal/background



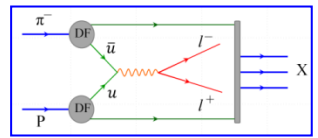
Single-polarized DY measurements at COMPASS

- $2.5 < M/(\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 - Strong J/ψ -signal \rightarrow study of J/ψ physics
 - Good signal/background
- $4.3 < M/(\text{GeV}/c^2) < 8.5$ “High mass”
 - Low DY cross-section
 - Beyond charmonium region, background $< 3\%$
 - Valence region \rightarrow largest asymmetries

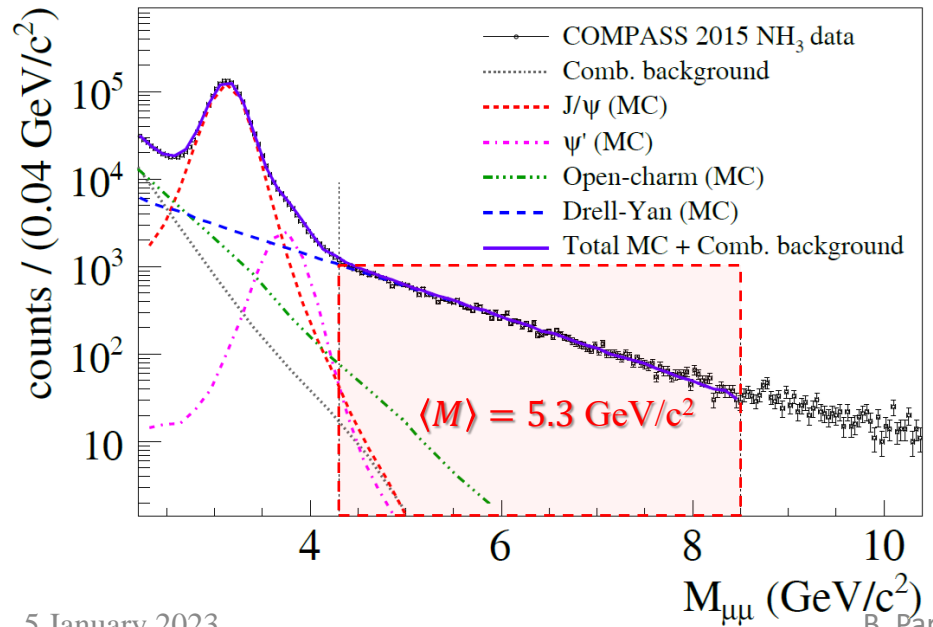
$\langle x_\pi \rangle = 0.50, \langle x_N \rangle = 0.17, \langle x_F \rangle = 0.33, \langle q_T \rangle = 1.2 \text{ GeV}/c$

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

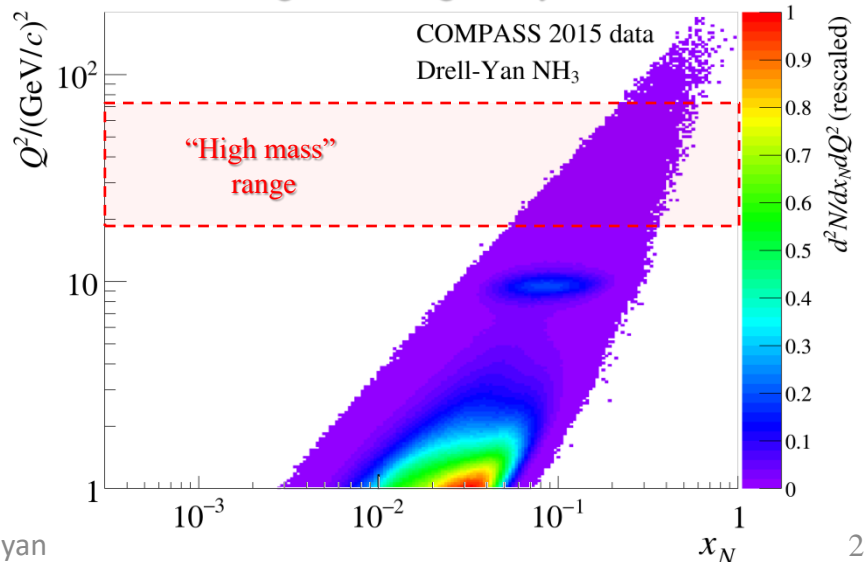
$$\left\{ 1 + \underbrace{D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}}_{\text{green box}} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \right\} \times \left\{ \underbrace{S_T}_{\text{red box}} \left[A_T^{\sin \varphi_S} \sin \varphi_S + D_{[\sin^2 \theta_{CS}]}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



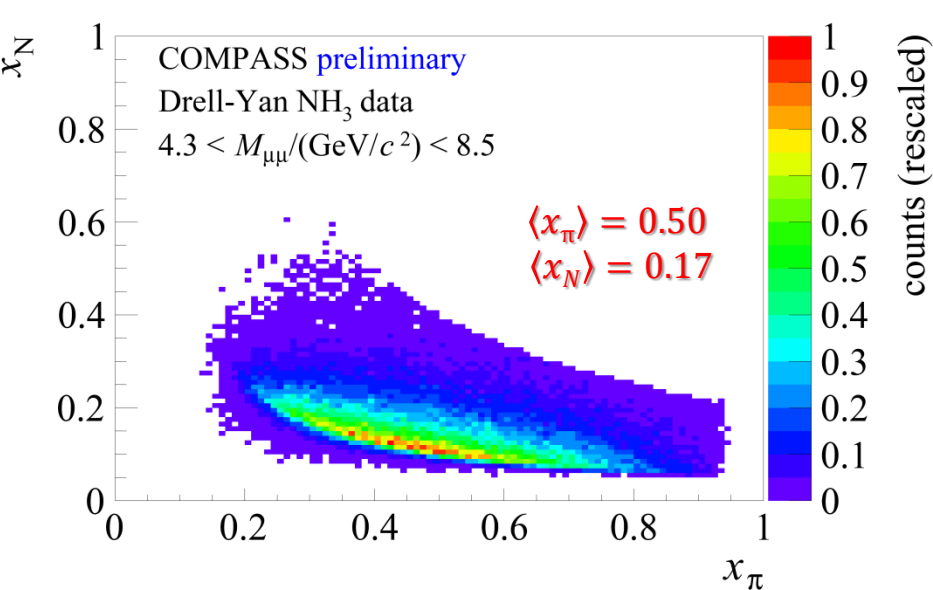
$$D_{[\sin^2 \theta_{CS}]} = \sin^2 \theta_{CS} / (1 + \cos^2 \theta_{CS})$$



$4.3 < M/(\text{GeV}/c^2) < 8.5$ “High mass” range
 Beyond charmonium region, background $< 3\%$
 Valence region \rightarrow largest asymmetries



Single-polarized DY measurements at COMPASS

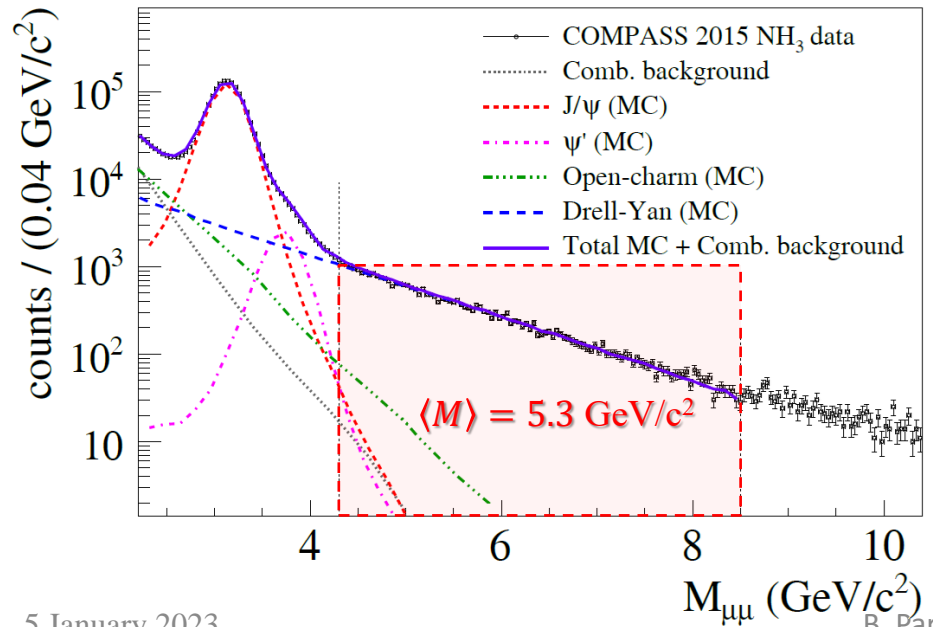


$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

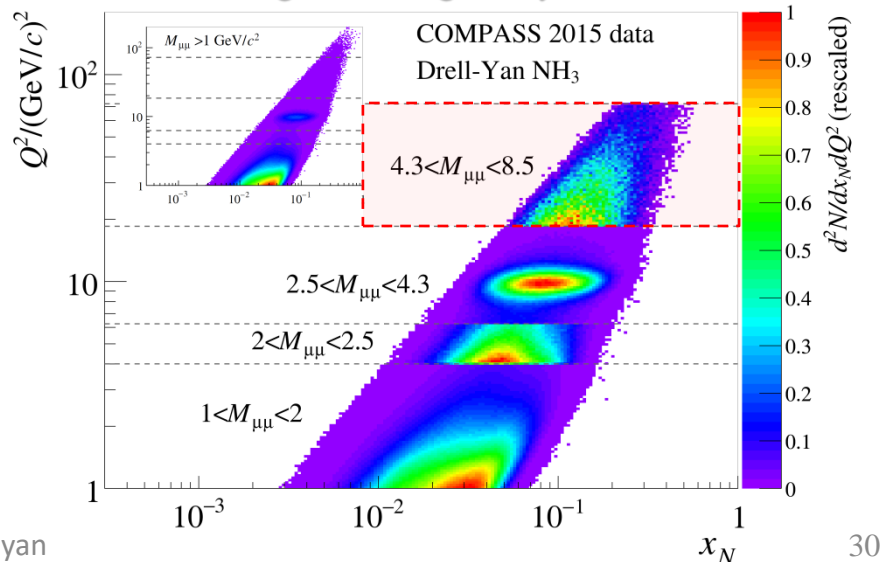
$$\left\{ 1 + \underbrace{D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}}_{\text{green box}} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \right\} \times \left\{ \underbrace{S_T}_{\text{pink box}} \left[A_T^{\sin \varphi_S} \sin \varphi_S + D_{[\sin^2 \theta_{CS}]}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

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

HM events are in the valence quark range



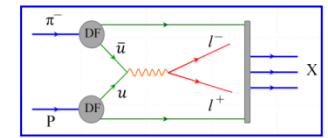
$4.3 < M/(\text{GeV}/c^2) < 8.5$ “High mass” range
Beyond charmonium region, background < 3%
Valence region → largest asymmetries



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

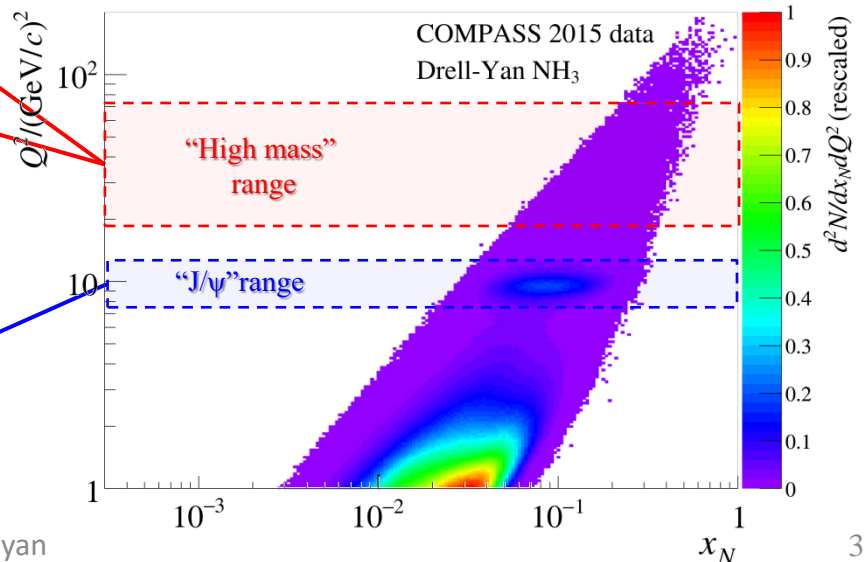
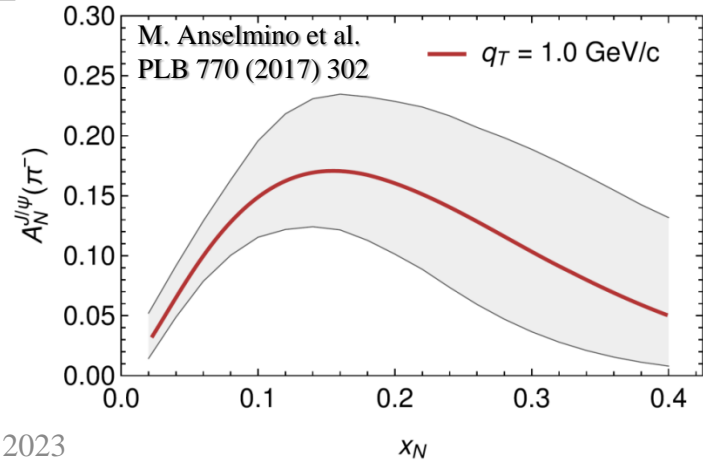
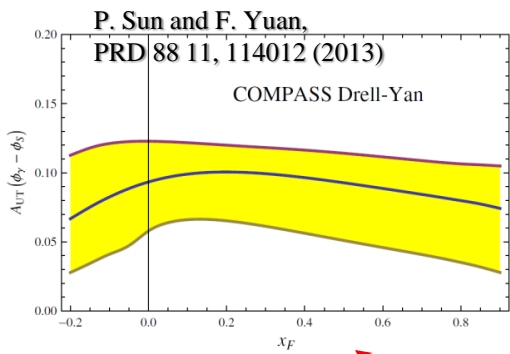
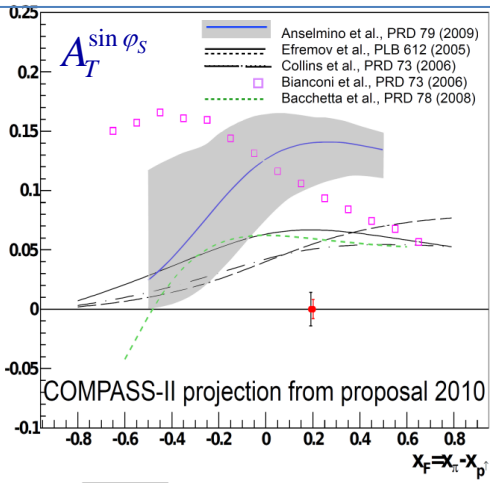
- $2.5 < M/(\text{GeV}/c^2) < 4.3$ “Charmonia mass”
 - Strong J/ψ -signal \rightarrow study of J/ψ physics
 - Good signal/background
- $4.3 < M/(\text{GeV}/c^2) < 8.5$ “High mass”
 - Low DY cross-section
 - Beyond charmonium region, background $< 3\%$
 - Valence region \rightarrow largest asymmetries

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



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

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





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

SIDIS

$$\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L})$$

$$\left\{ 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \right.$$

$$\times \left\{ \begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right.$$

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

DY

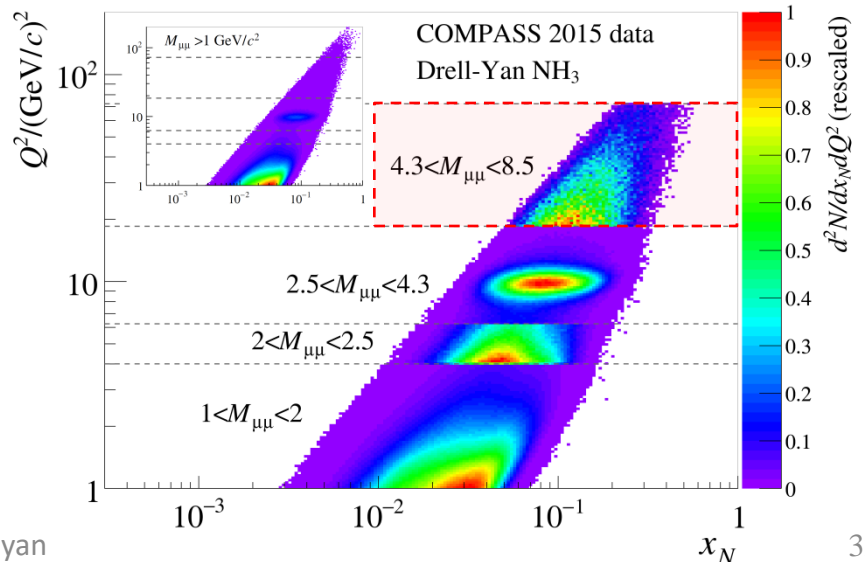
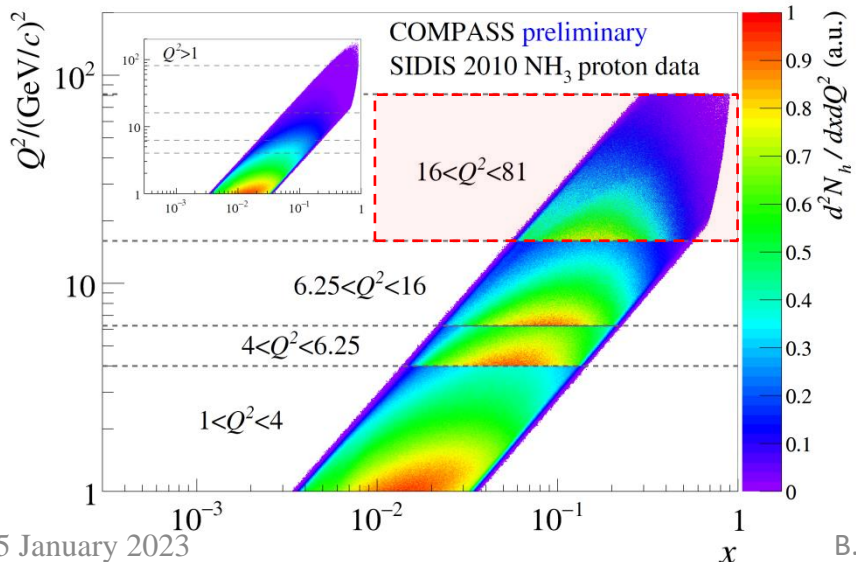
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$

$$\left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \right.$$

$$\times \left\{ \begin{array}{l} A_T^{\sin \varphi_S} \sin \varphi_S \\ + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right. \\ \left. + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \right) \end{array} \right.$$

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

Comparable x:Q² coverage – minimization of possible Q²-evolution effects

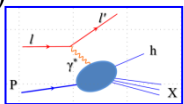


SIDIS and single-polarized DY x-sections at twist-2 (LO)

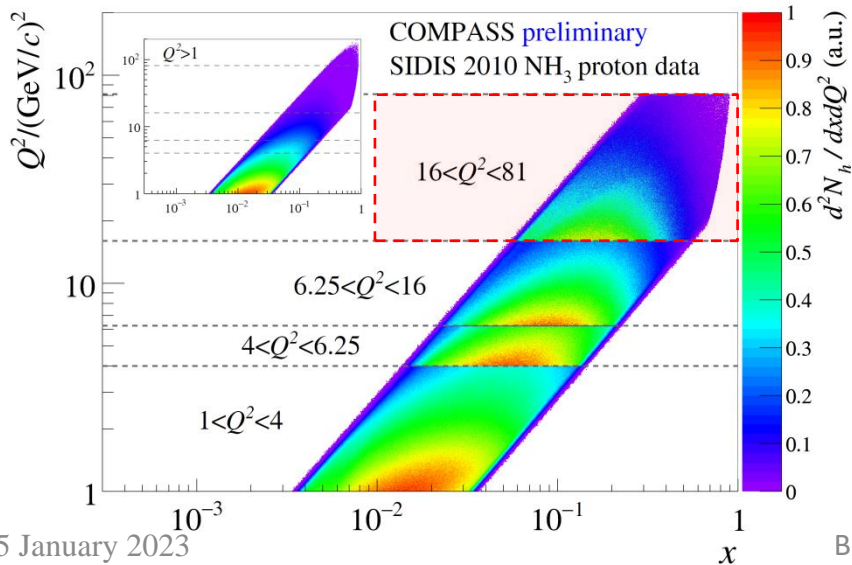


SIDIS

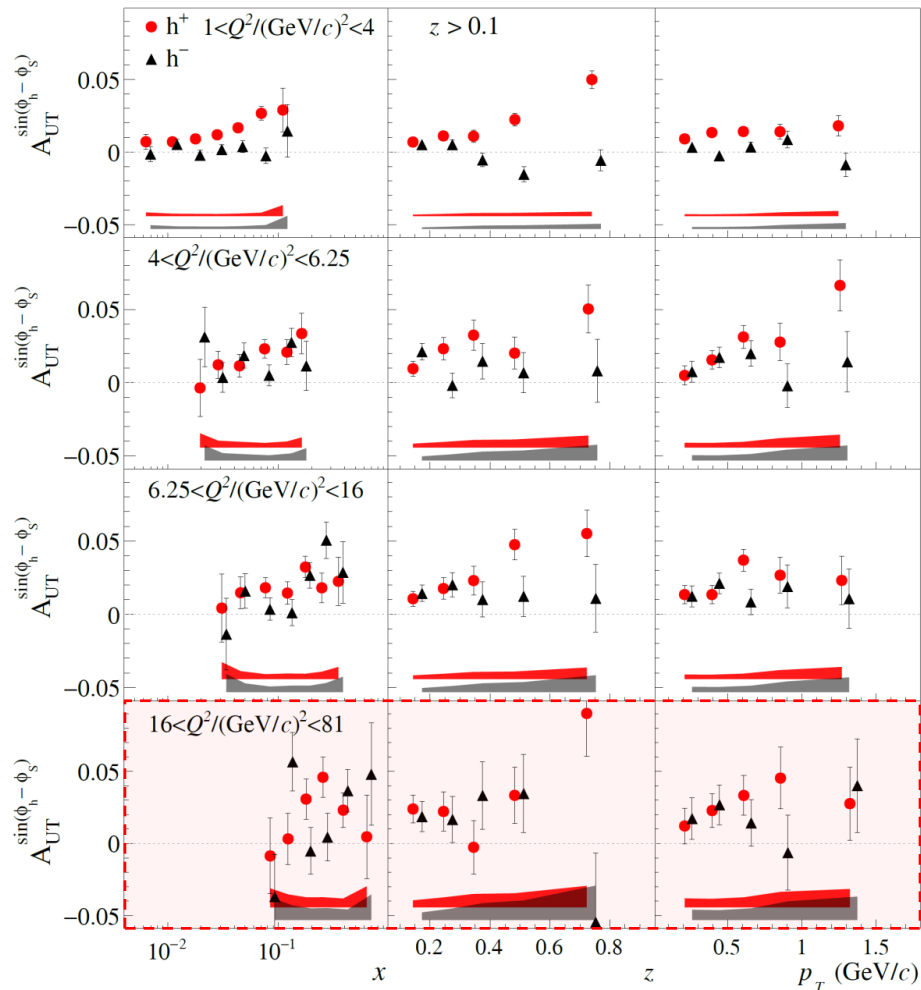
$$\frac{d\sigma^{LO}}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L})$$



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

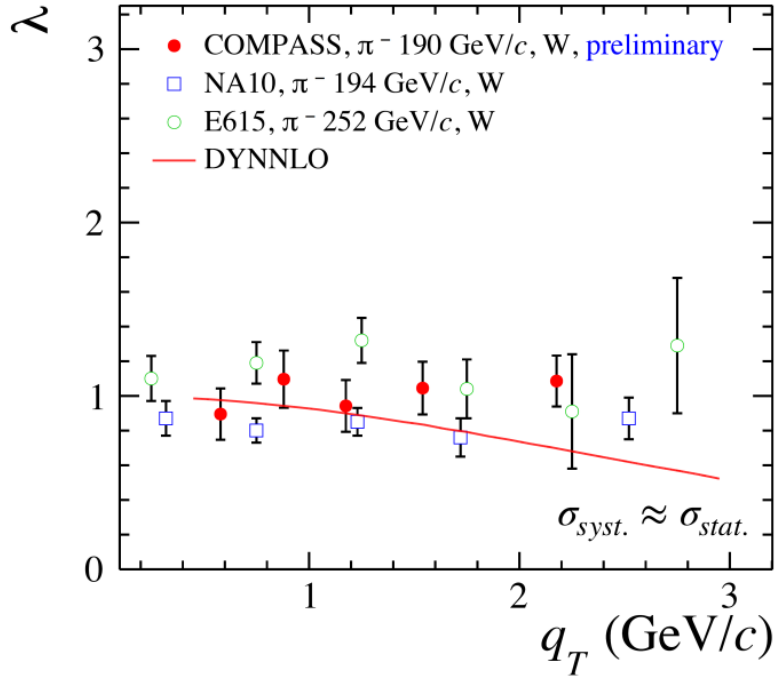


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1st COMPASS multi-D fit done for all eight TSAs

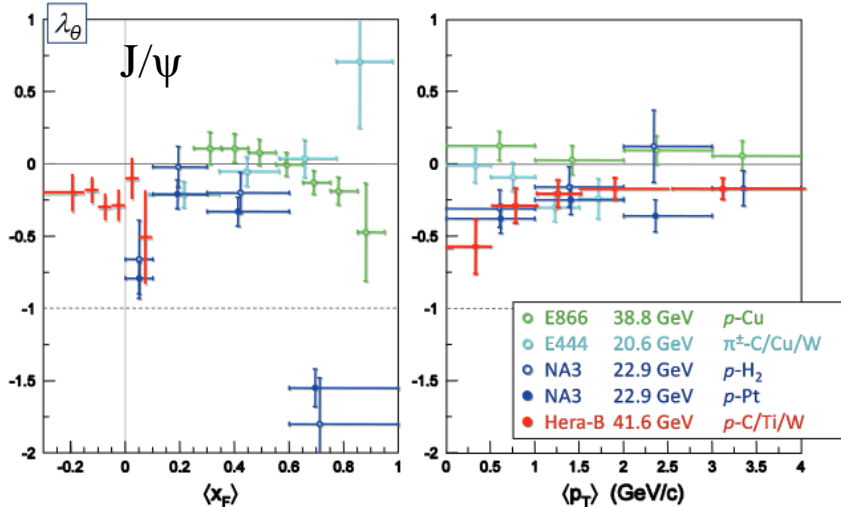
Single-polarized DY x-section: transverse part



$$\frac{d\sigma}{d\Omega} \propto (F_U^1 + F_U^2) (1 + A_U^1 \cos^2 \theta_{CS})$$

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

$$D_{[f(\theta_{CS})]} = f(\theta_{CS}) / (1 + A_U^1 \cos^2 \theta_{CS})$$



- All five Drell-Yan TSAs are extracted simultaneously using extended unbinned Maximum likelihood estimator.
- Depolarization factors are evaluated under assumption $A_U^1=1$ (DY) and $A_U^1=0$ (J/ψ)
- Possible impact of other scenarios leads to a normalization uncertainty of ~5%.

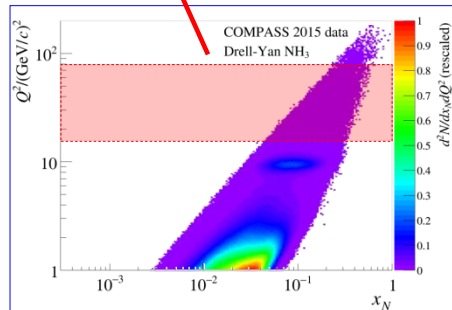
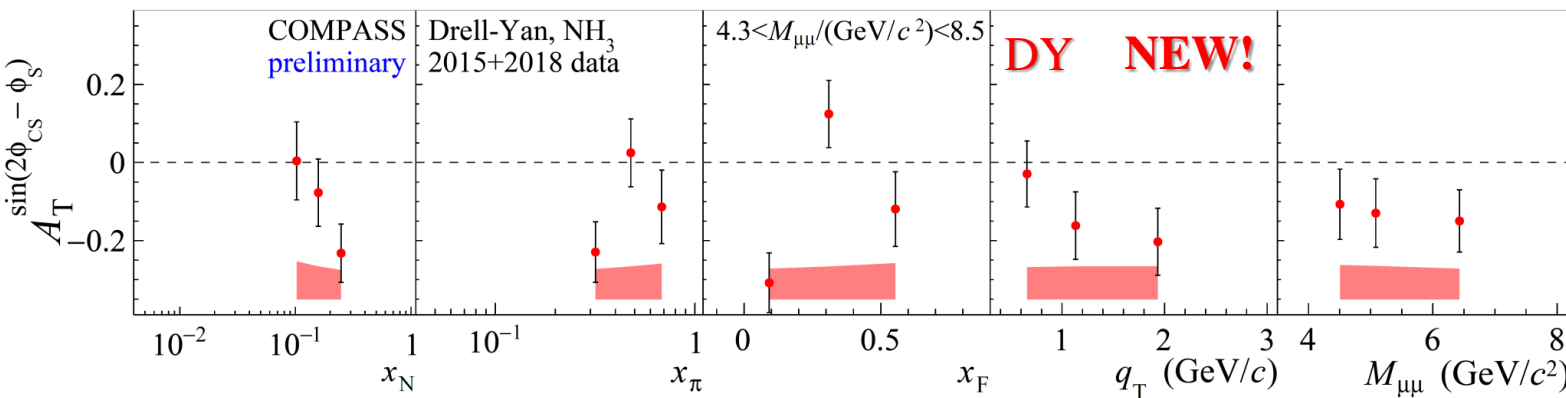
Drell-Yan TSAs – Transversity

Transversity DY TSA

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

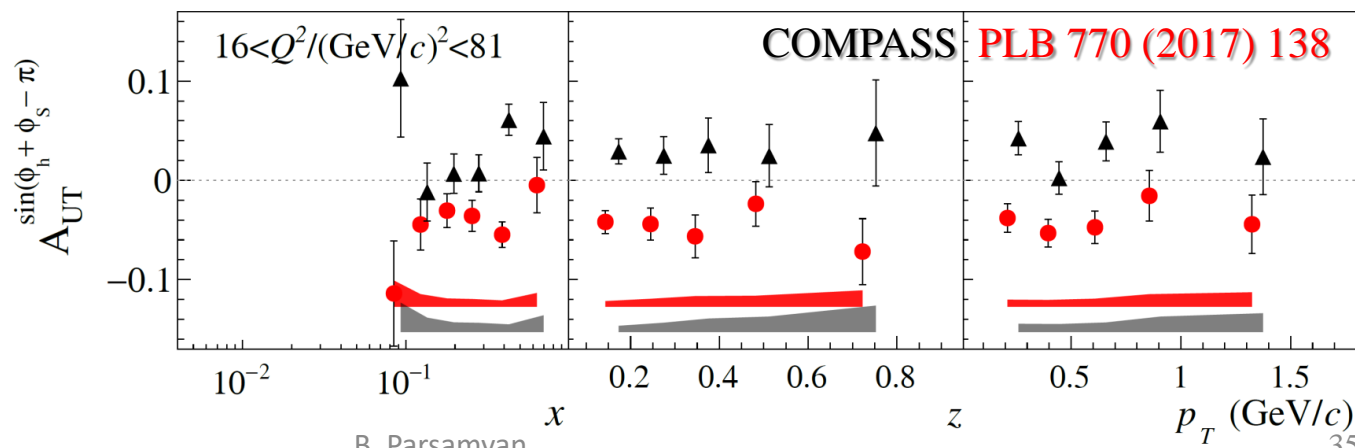


$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[D_{[\sin^2 \theta_{CS}]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS} - \varphi_S) + \dots \right]$$



Collins SIDIS TSA

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



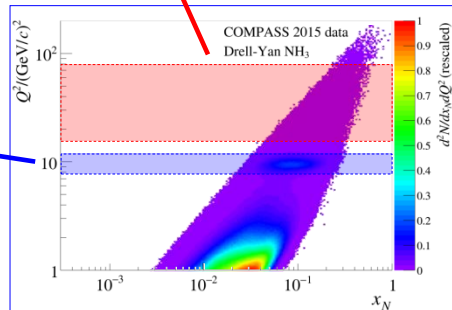
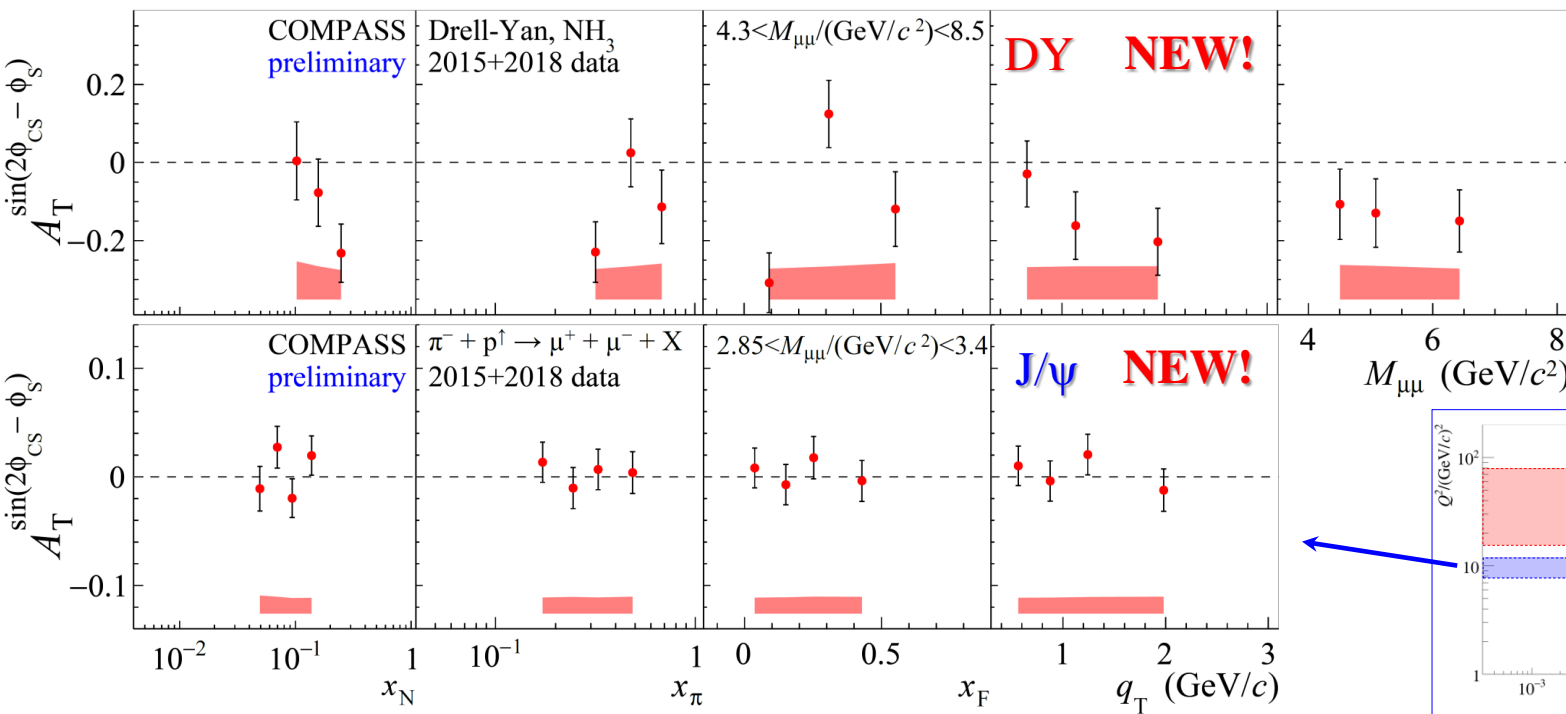
Drell-Yan TSAs – Transversity

Transversity DY TSA

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

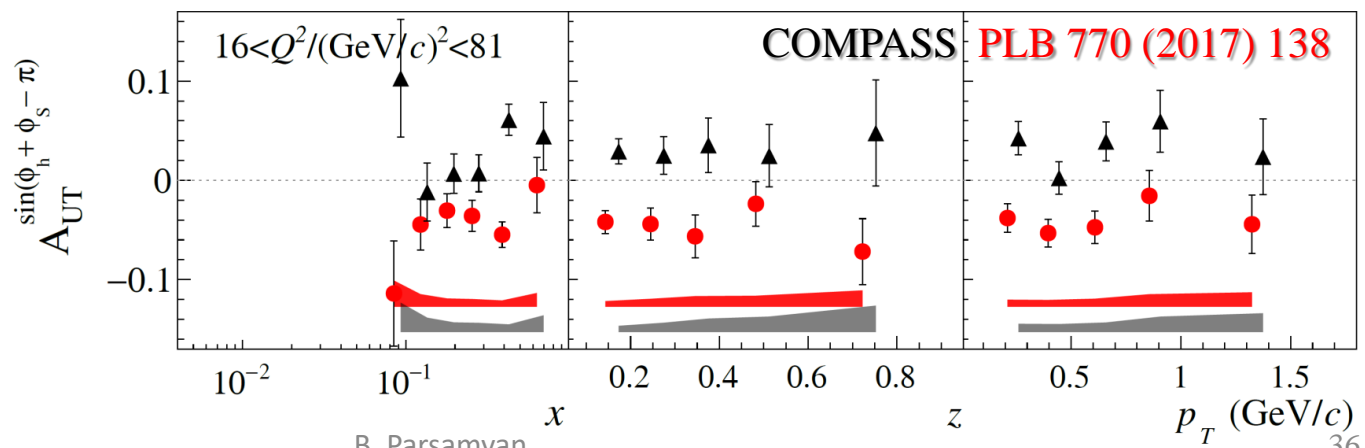


$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \dots + S_T \left[D_{[\sin^2\theta_{CS}]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) + \dots \right]$$



Collins SIDIS TSA

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

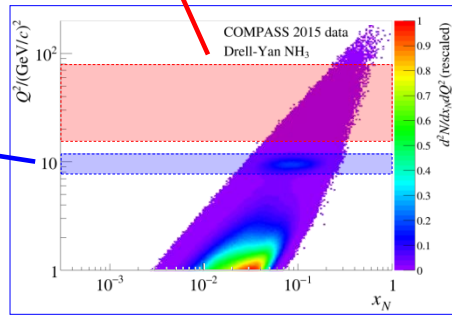
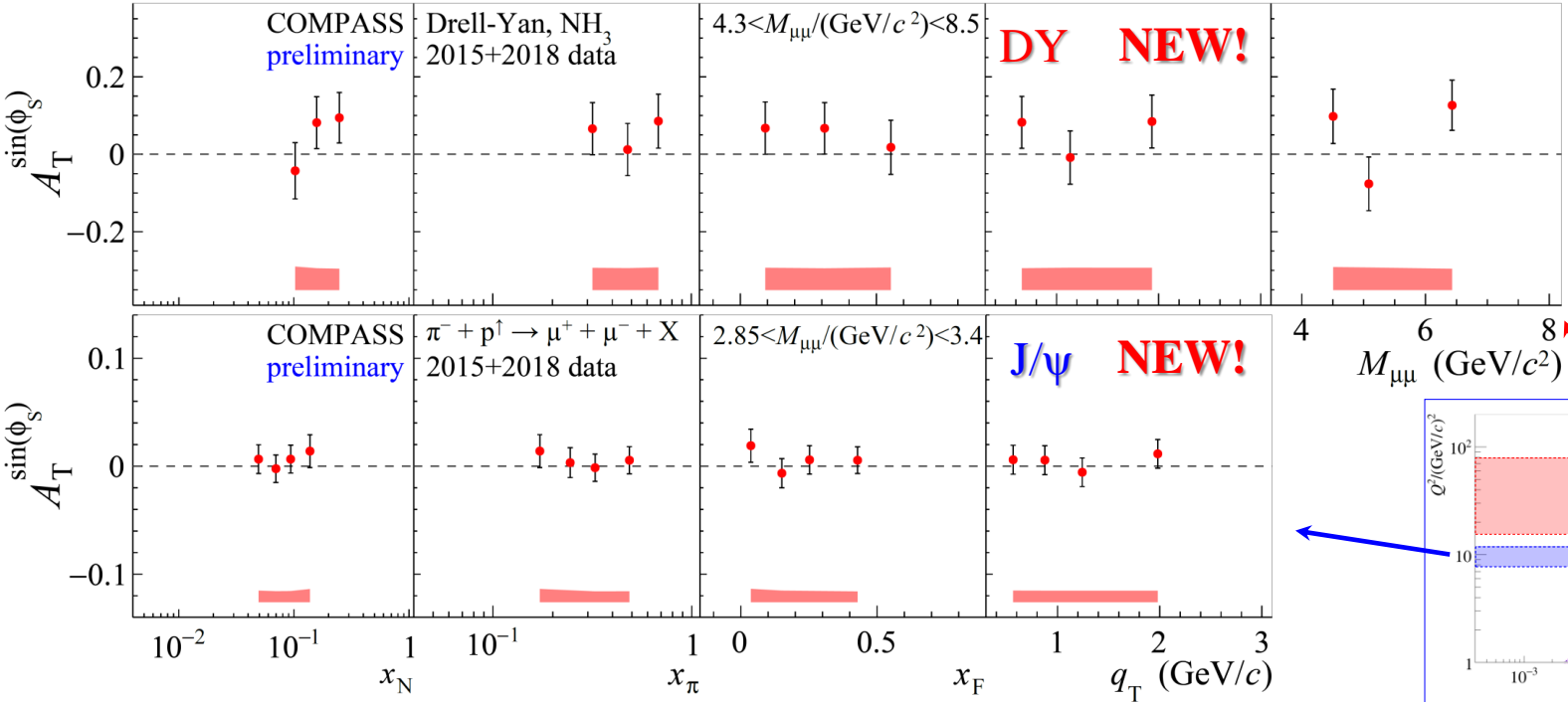


Drell-Yan TSAs – Sivers

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

Sivers DY TSA

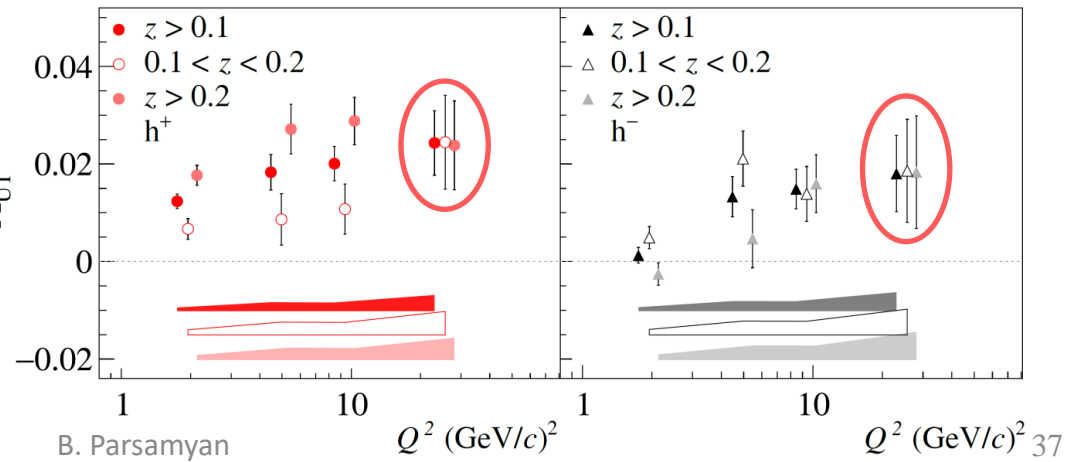
$$A_T^{\sin\phi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$



Sivers SIDIS TSA

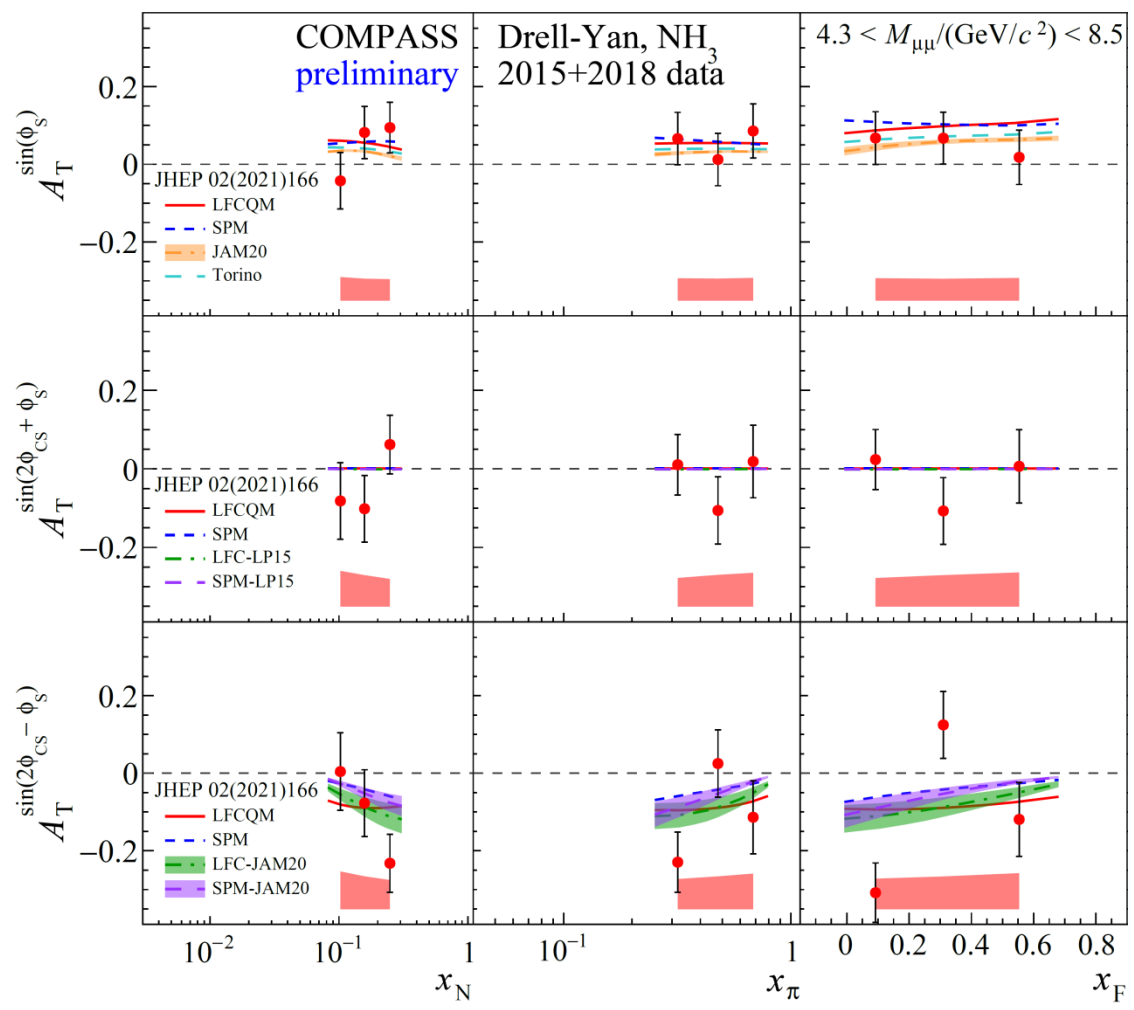
$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$$

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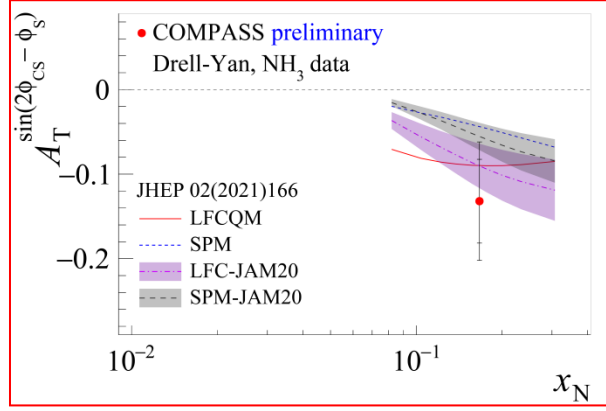
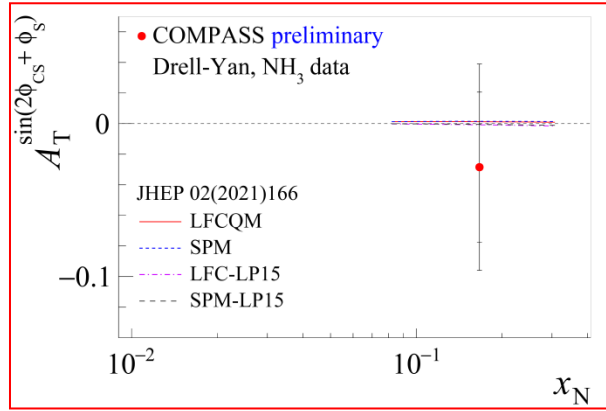
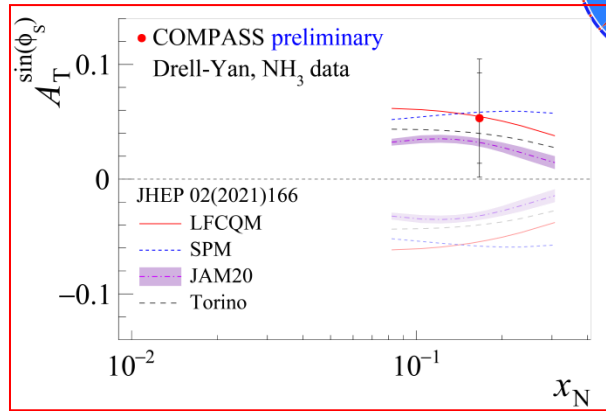


DY TSAs at COMPASS (high-mass range)

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



- General agreement with available theory predictions



Conclusions

- During phase I COMPASS has measured all SIDIS TSAs (P/D)
 - Deuteron TSAs are all compatible with zero
 - Non-zero Sivers and Collins asymmetries with proton target
 - Apart from Sivers and Collins effects non-zero signal was observed for *twist-2* $A_{LT}^{\cos(\phi_h - \phi_s)}$ and *subleading-twist* $A_{UT}^{\sin\phi_s}$ TSAs
 - First multi-D results for all TSAs - PLB 770 (2017) 138
 - No hints for significant Q^2 -dependences of Sivers and Collins TSAs
- SIDIS measurements with transversely polarized deuteron target in 2022
 - Unique input for d-quark transversity and many other studies
- During phase II COMPASS performed **first ever polarized DY measurements** PRL 119, 112002 (2017)
- Final results for combined 2015+2018 data sample have been presented in 2022 **the paper is in preparation**
 - COMPASS data favors the sign-change of Sivers TMD PDF in DY
 - All measured J/ψ TSAs are consistent with zero
- DY x-section and unpolarized asymmetry studies are ongoing

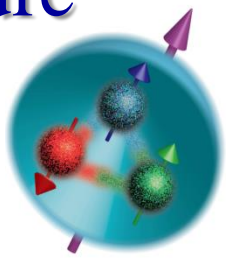
Thank you!



- Spare slides

Nucleon transverse structure

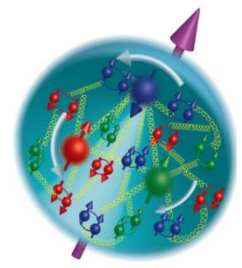
- 1964 Quark model



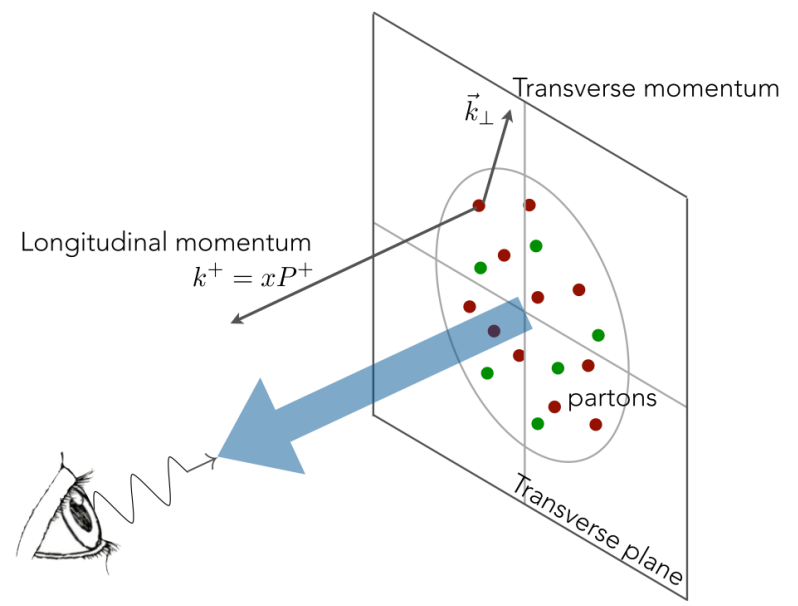
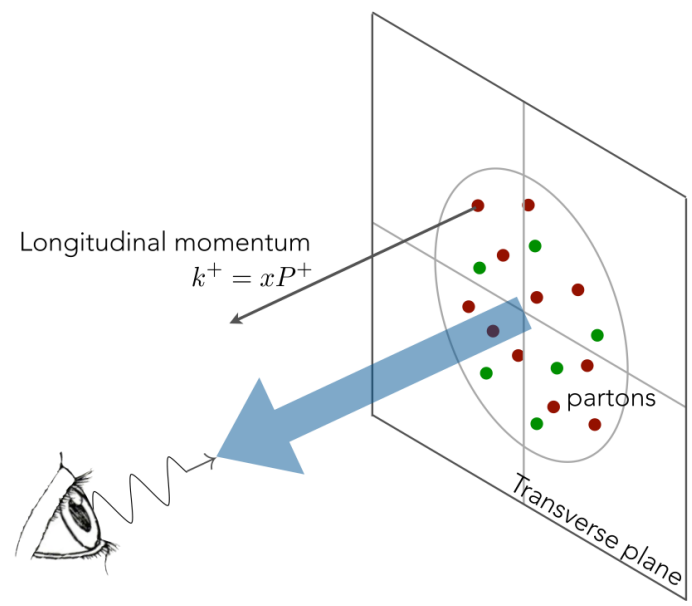
- 1969 Parton model



- 1973 asymptotic freedom and QCD





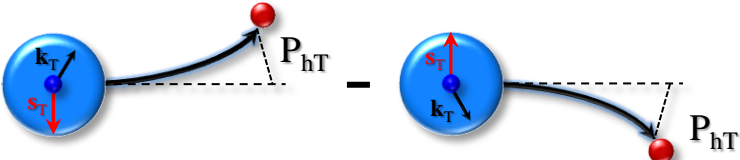
- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries



Boer-Mulders effect in SIDIS

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

Quark	U	T
Nucleon	U	T
U	$f_1^q(x, k_T^2)$ number density 	$h_1^{\perp q}(x, k_T^2)$ Boer-Mulders 

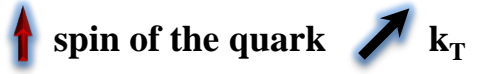
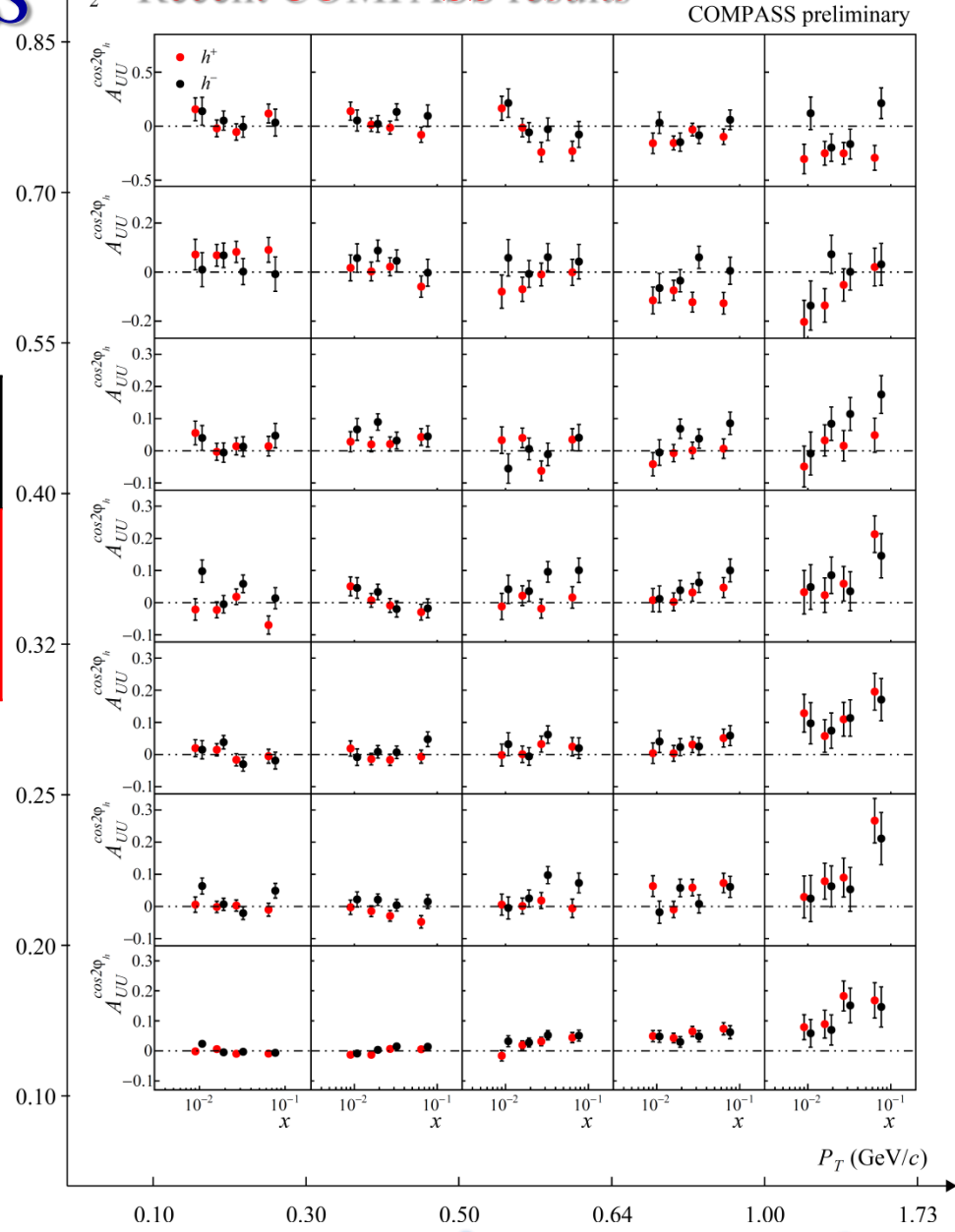


Arises due to the correlation between quark transverse spin and intrinsic transverse momentum






$$F_{UU}^{\cos 2\phi_h} = C \left\{ - \frac{2(\hat{h} \cdot p_T)(\hat{h} \cdot k_T) - p_T \cdot k_T}{MM_h} h_1^{\perp q} H_{1q}^{\perp h} \right\}$$

Recent COMPASS results

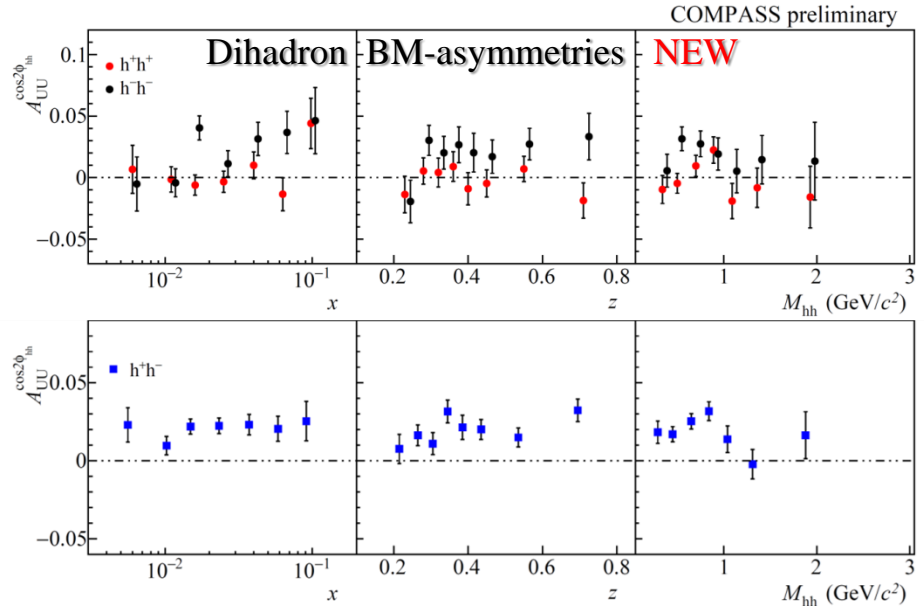
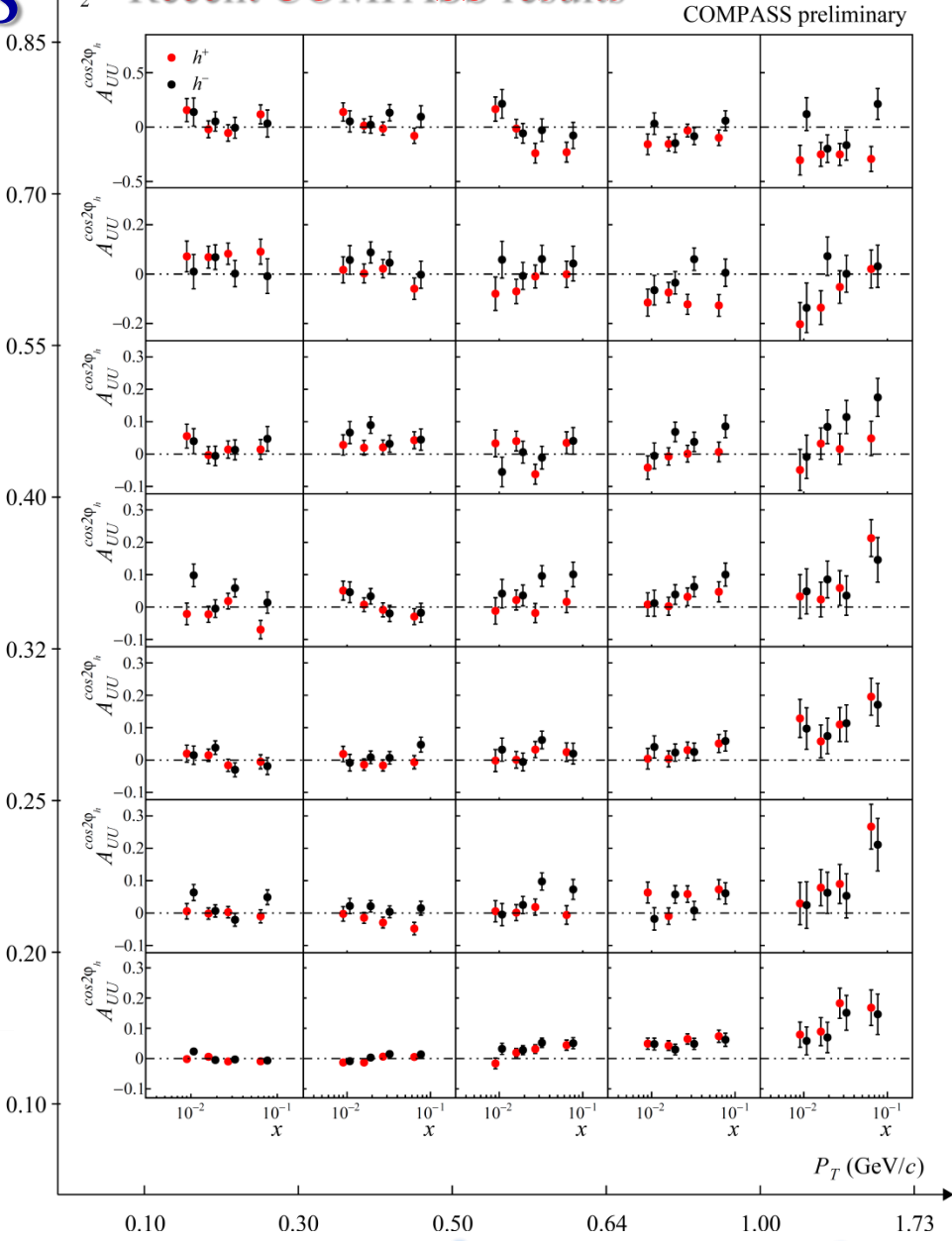


Boer-Mulders effect in SIDIS

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

Quark	U		T
Nucleon			
U	$f_1^q(x, k_T^2)$ number density 		$h_1^{\perp q}(x, k_T^2)$ Boer-Mulders  - 

Recent COMPASS results



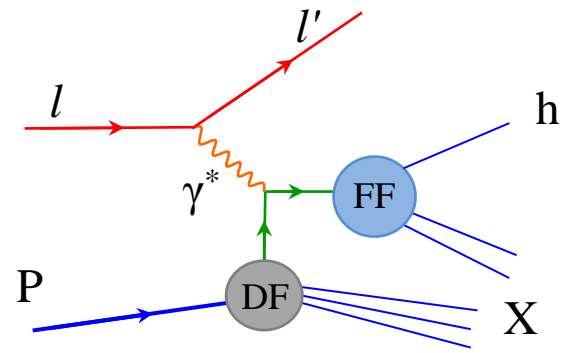
↑ spin of the quark ↗ k_T

SIDIS x-section and TMDs at twist-2

$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} = \text{All measured by COMPASS}$$

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

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



Quark \ Nucleon	U	L	T
U	number density		Boer-Mulders
L		helicity	worm-gear L

spin of the nucleon
 spin of the quark
 k_T

SIDIS: target longitudinal spin dependent asymmetries

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

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

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

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

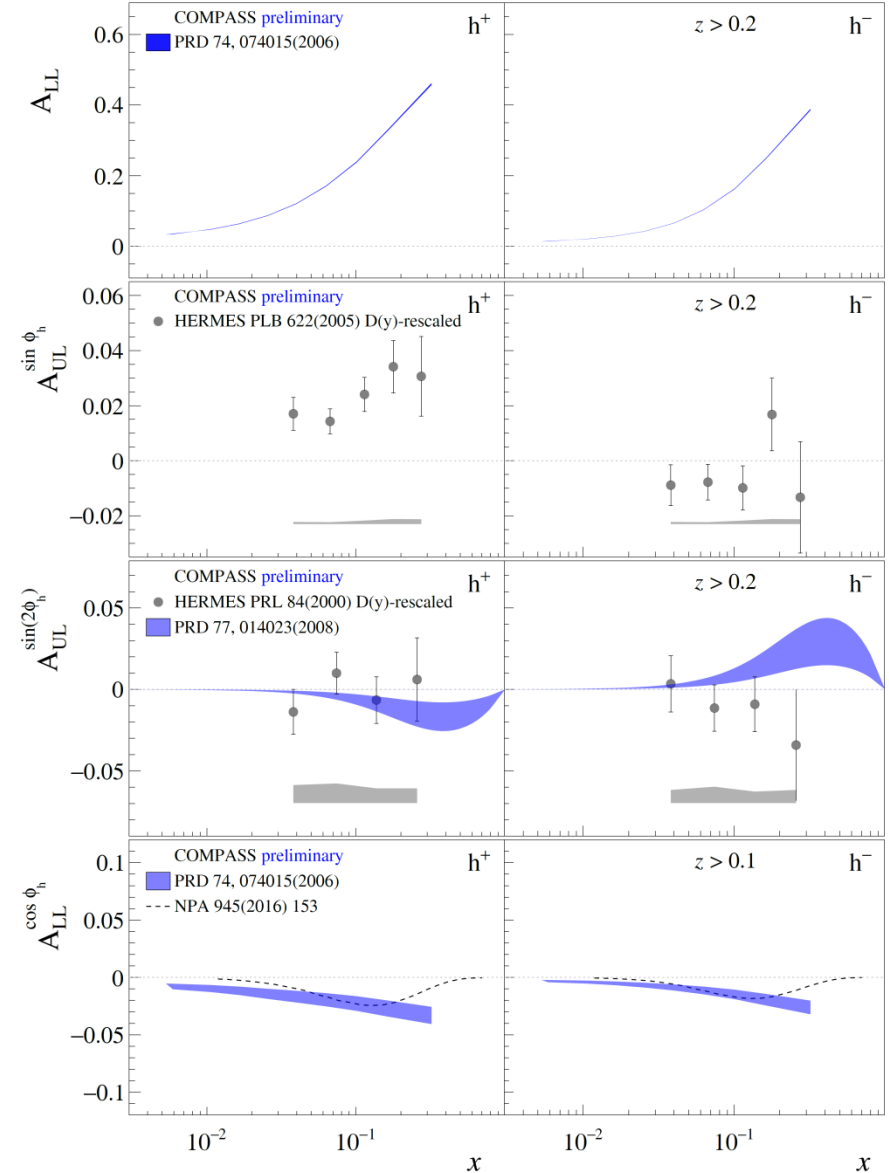
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} \left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) \right.$$

$$\left. + \frac{\hat{h} \cdot \mathbf{k}_T}{M} \left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z} \right) \right\}$$

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

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} \left(x e_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) \right.$$

$$\left. + \frac{\hat{h} \cdot \mathbf{k}_T}{M} \left(x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z} \right) \right\}$$



SIDIS: target longitudinal spin dependent asymmetries



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

$$\left. \begin{aligned} &+ S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ &+ S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \end{aligned} \right\}$$

COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

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

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

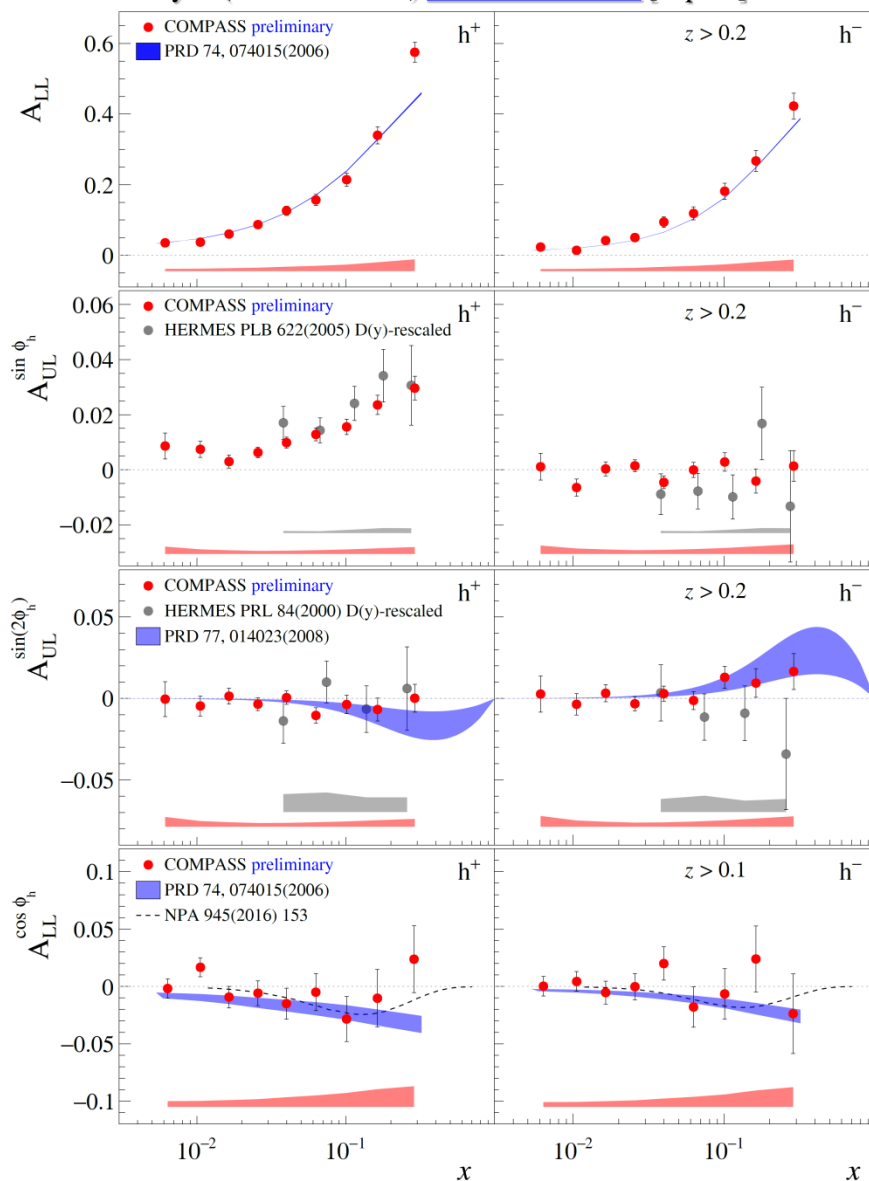
$A_{UL}^{\sin 2\phi_h}$

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

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

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

B. Parsamyan (for COMPASS) [arXiv:1801.01488](https://arxiv.org/abs/1801.01488) [hep-ex]



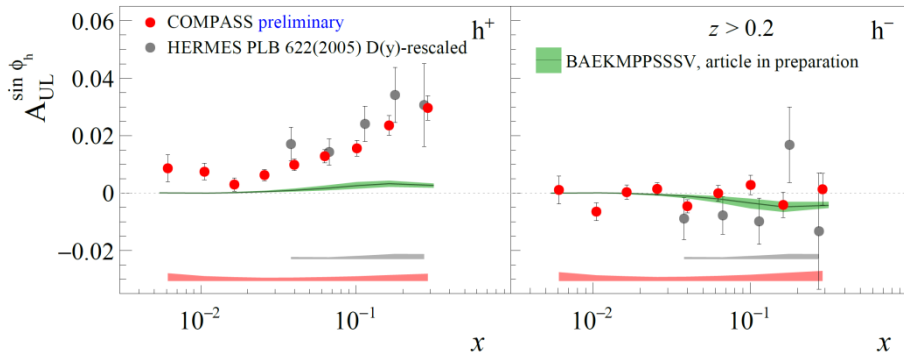
SIDIS: target longitudinal spin dependent asymmetries

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

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

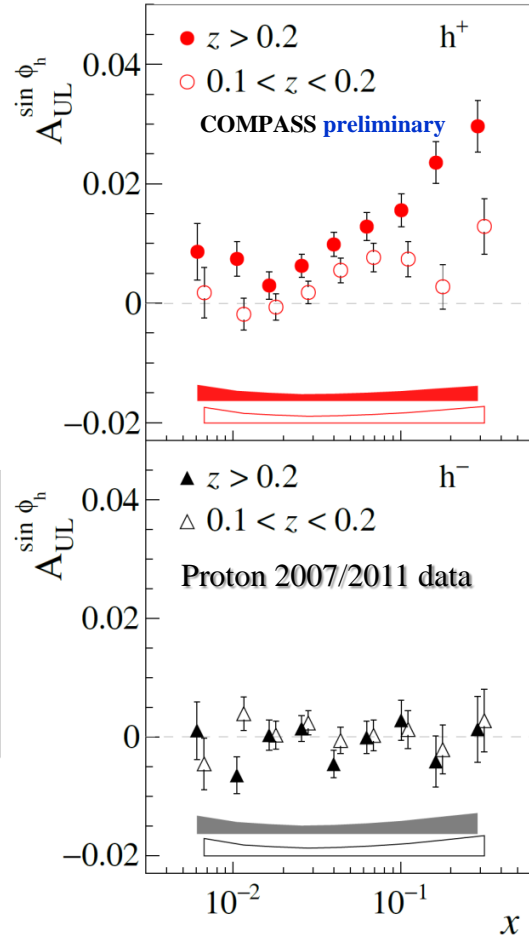
S. Bastami et al. JHEP 1906 (2019) 007:

“SIDIS in Wandzura-Wilczek-type approximation”



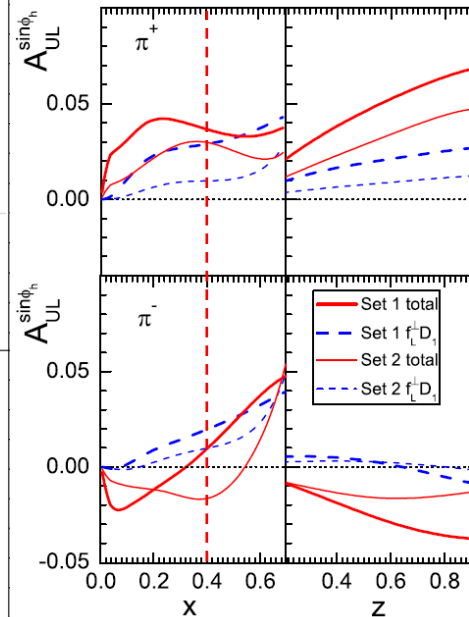
B. Parsamyan (for COMPASS)

[arXiv:1801.01488](https://arxiv.org/abs/1801.01488) [hep-ex]



Zhun Lu

Phys. Rev. D 90, 014037(2014)



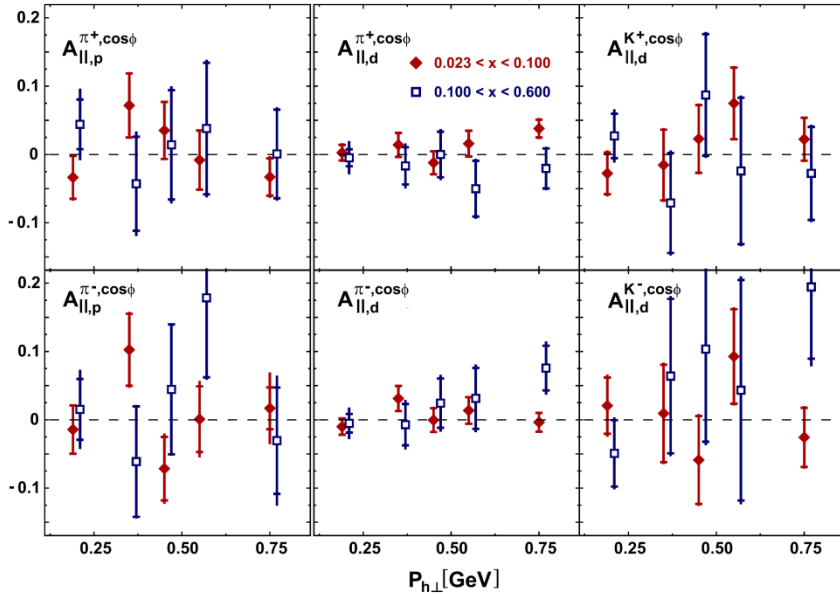
- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- **Strong non-zero effect for h^+ , h^- compatible with zero, clear z -dependence**

SIDIS: target longitudinal spin dependent asymmetries

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

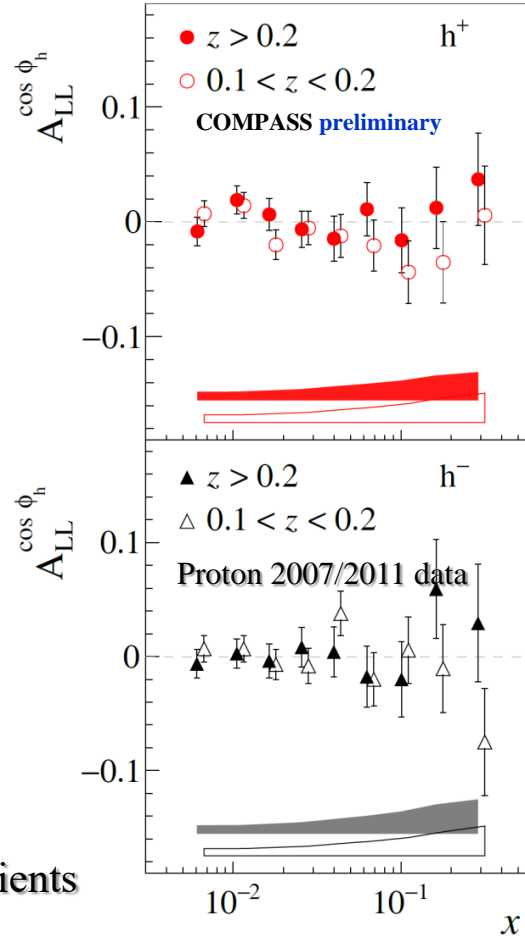
$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{h} \cdot \mathbf{p}_T}{M_h} \left(x e_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z} \right) + \frac{\hat{h} \cdot \mathbf{k}_T}{M} \left(x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z}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

HERMES: PRD 99, 112001 (2019) **NEW**



B. Parsamyan (for COMPASS)

[arXiv:1801.01488](https://arxiv.org/abs/1801.01488) [hep-ex]



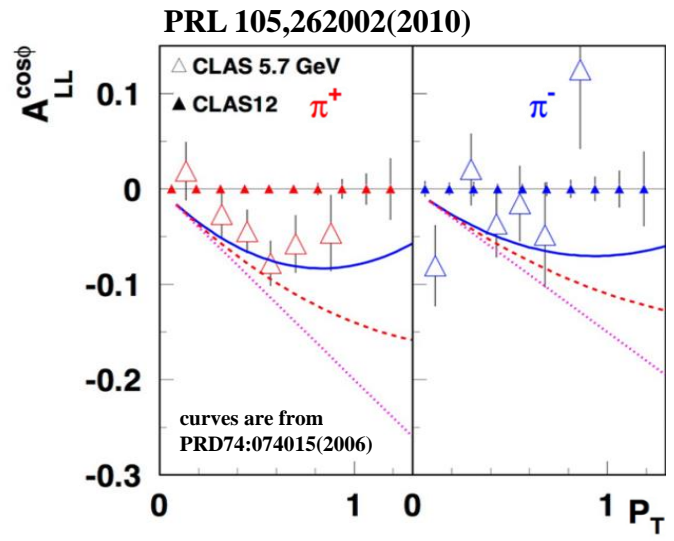
- Q-suppression, various different “twist” ingredients

- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

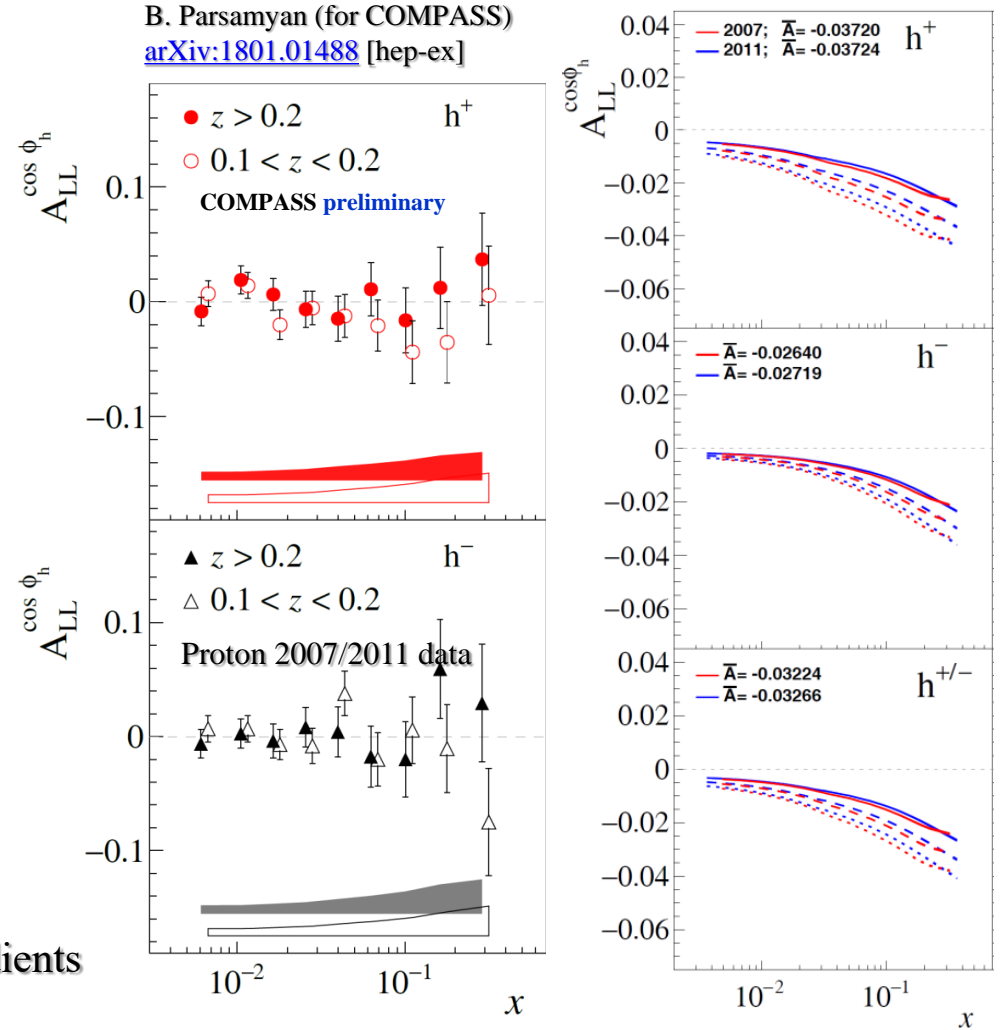
SIDIS: target longitudinal spin dependent asymmetries

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

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



B. Parsamyan (for COMPASS)
[arXiv:1801.01488](https://arxiv.org/abs/1801.01488) [hep-ex]



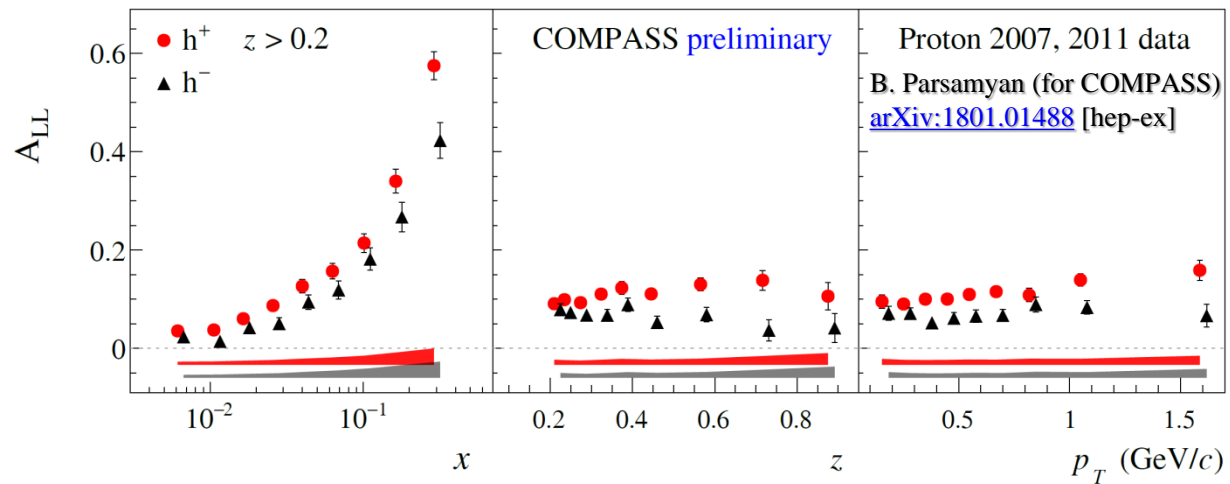
- Q-suppression, various different “twist” ingredients
- **Measured to be non zero at JLab**
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

SIDIS: target longitudinal spin dependent asymmetries

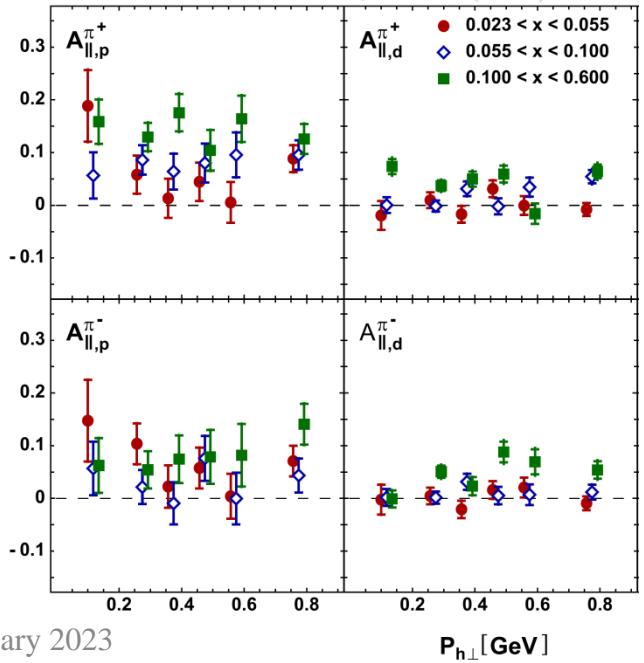
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_L \lambda \sqrt{1 - \varepsilon^2} A_{LL} + \dots \right\}$$

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

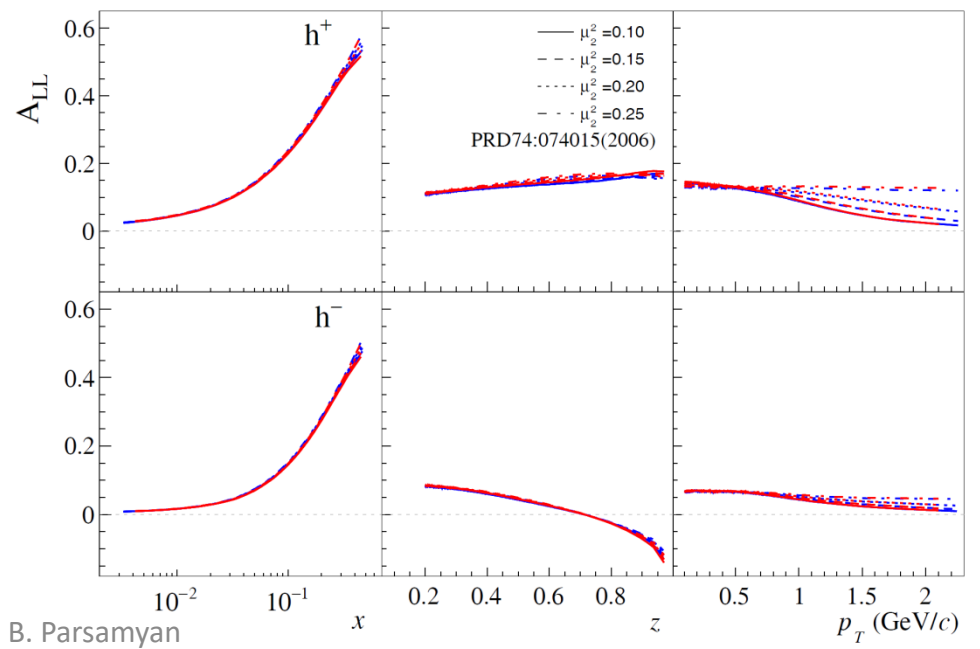
- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T -dependence observed



HERMES: PRD 99, 112001 (2019)



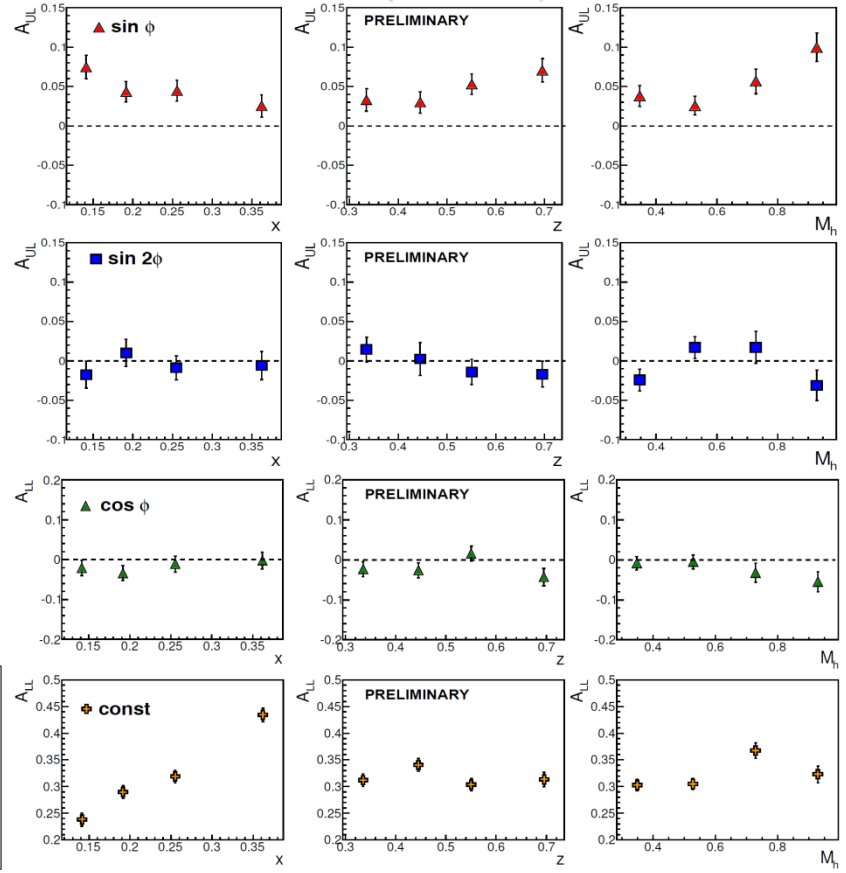
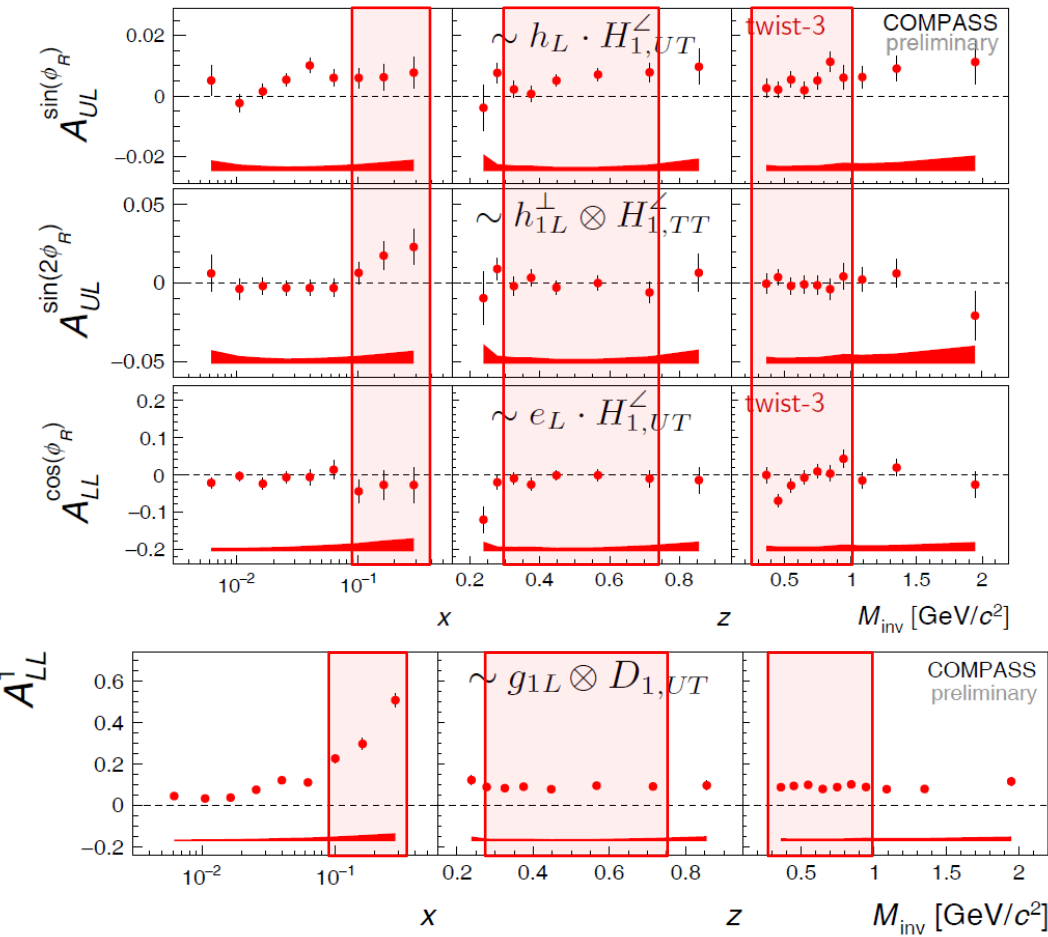
COMPASS Proton-2007, -2011 kinematics



Selected results for di-hadron asymmetries

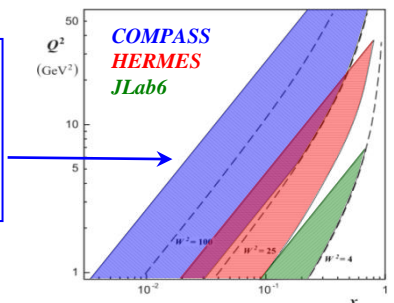
COMPASS (NH₃) 2007+2011 data

CLAS 6 GeV (NH₃)
S. A. Pereira: PoS (DIS 2014) 231



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

$Q^2 > 1 \text{ (GeV/c)}^2$
 $0.0025 < x < 0.7$
 $0.1 < y < 0.9$
 $W > 5 \text{ GeV/c}^2$



COMPASS Multi-D TSA analyses

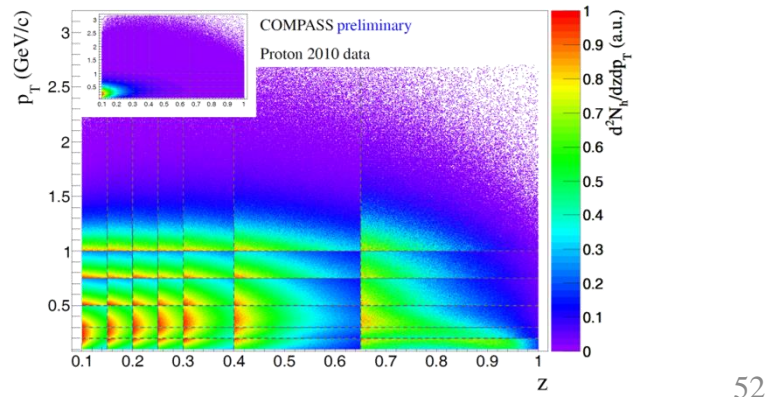
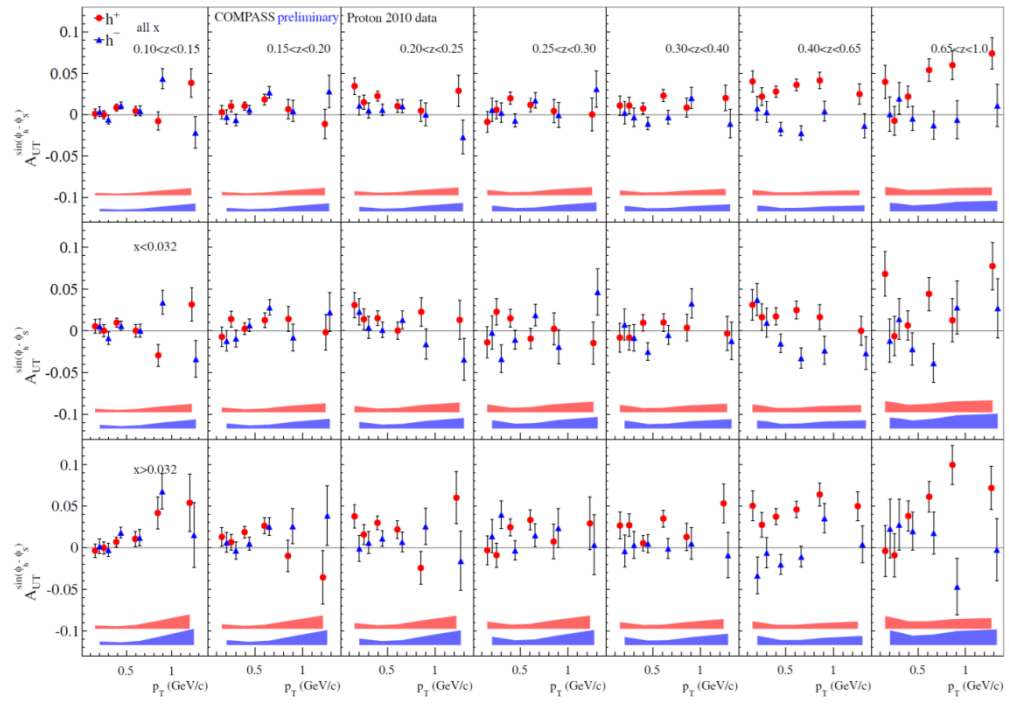
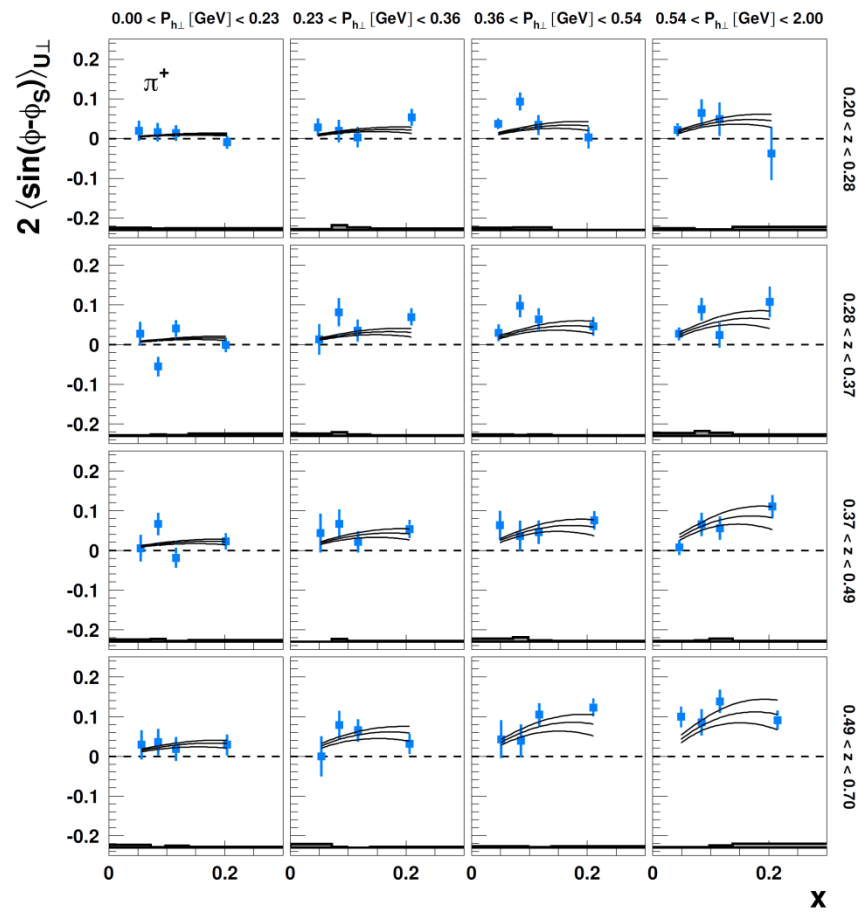
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi_h d\phi_S} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \left\{ 1 + \dots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + \dots \right\}$$

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



B. Parsamyan (for COMPASS) [arXiv:1504.01599](https://arxiv.org/abs/1504.01599) [hep-ex] (SPIN-2014)

HERMES, JHEP 12 (2020) 010

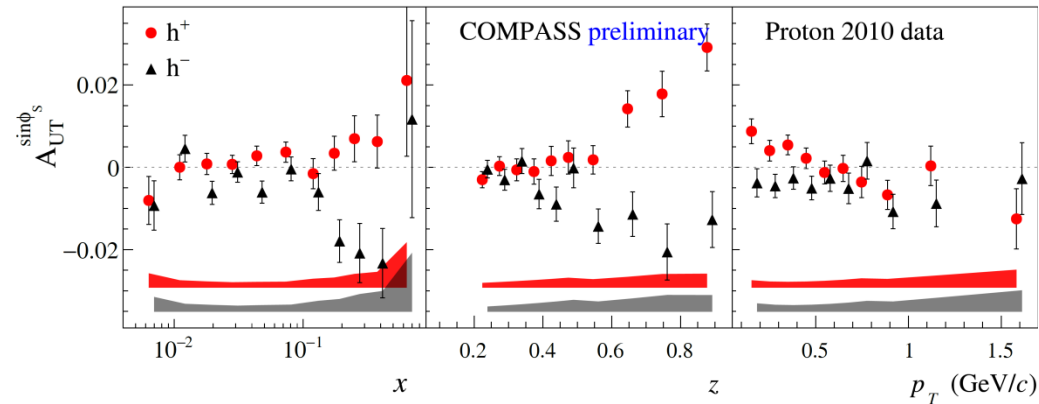


SIDIS TSAs: subleading twist effects

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

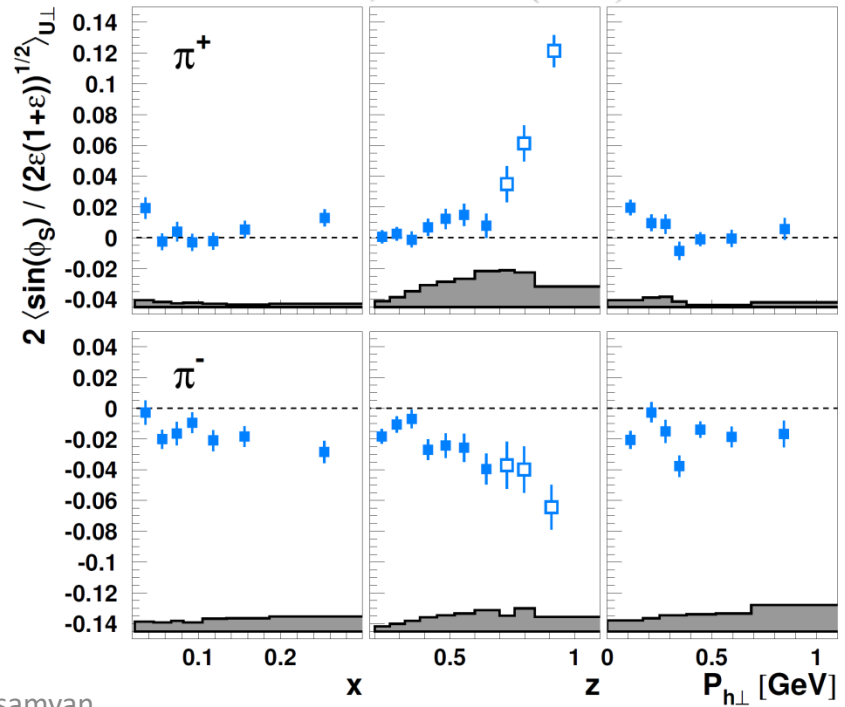
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C \left\{ \left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z} \right) - \frac{\mathbf{p}_T \cdot \mathbf{k}_T}{2MM_h} \left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z} \right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z} \right) \right] \right\}$$

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

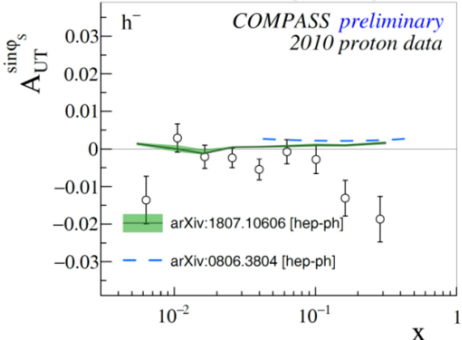


- COMPASS/HERMES results
- $A_{UT}^{\sin\phi_S}$
- Q-suppression
 - various “twist-2/3” ingredients
 - **non-zero signal for h^\pm at large z ?**

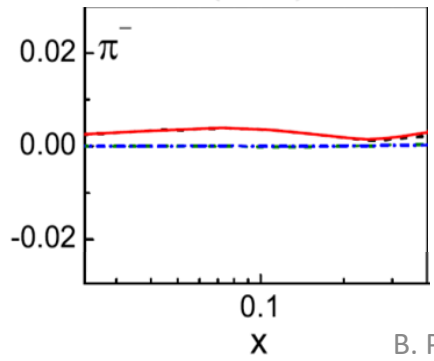
HERMES, JHEP 12 (2020) 010



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



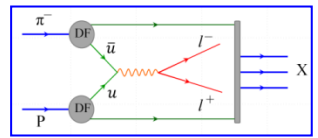
W. Mao et al.
PRD 90 (2014) 014048



Single-polarized DY measurements at COMPASS

- $2.5 < M/(GeV/c^2) < 4.3$ “Charmonia mass”
 - Strong J/ψ -signal \rightarrow study of J/ψ physics
 - Good signal/background
- $4.3 < M/(GeV/c^2) < 8.5$ “High mass”
 - Low DY cross-section
 - Beyond charmonium region, background $< 3\%$
 - Valence region \rightarrow largest asymmetries

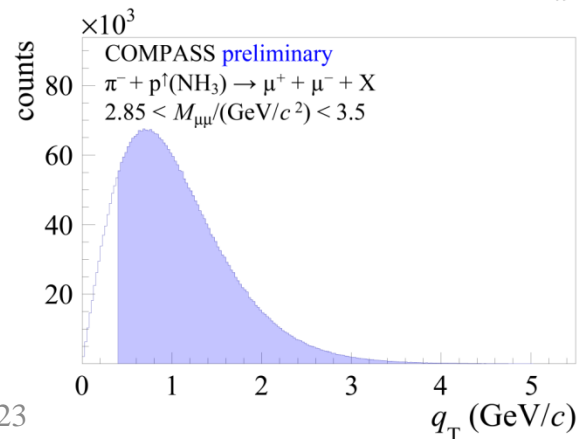
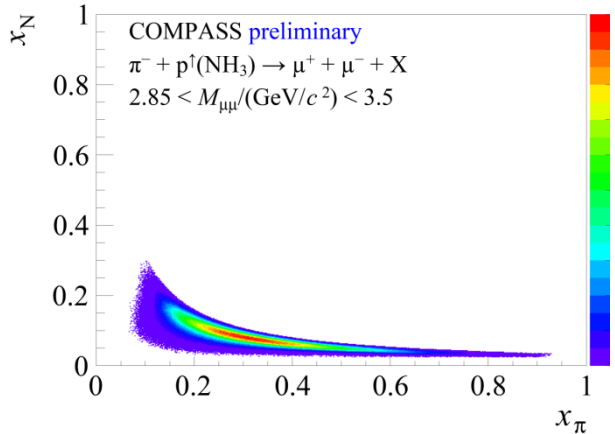
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 (1 + \cos^2 \theta_{CS})$$



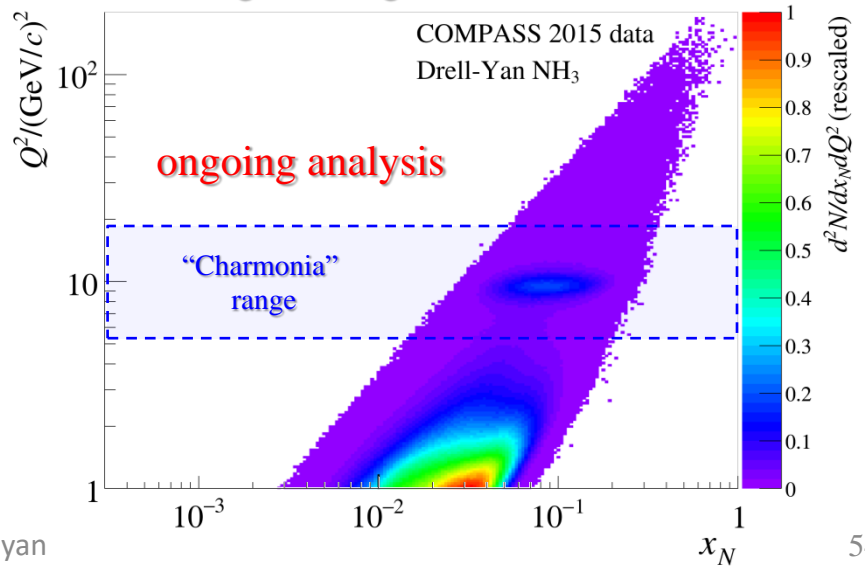
$$\left\{ 1 + D_{[\sin^2 \theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2 \theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \right\} \times \left\{ S_T \left[A_T^{\sin \varphi_S} \sin \varphi_S + D_{[\sin^2 \theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS}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

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

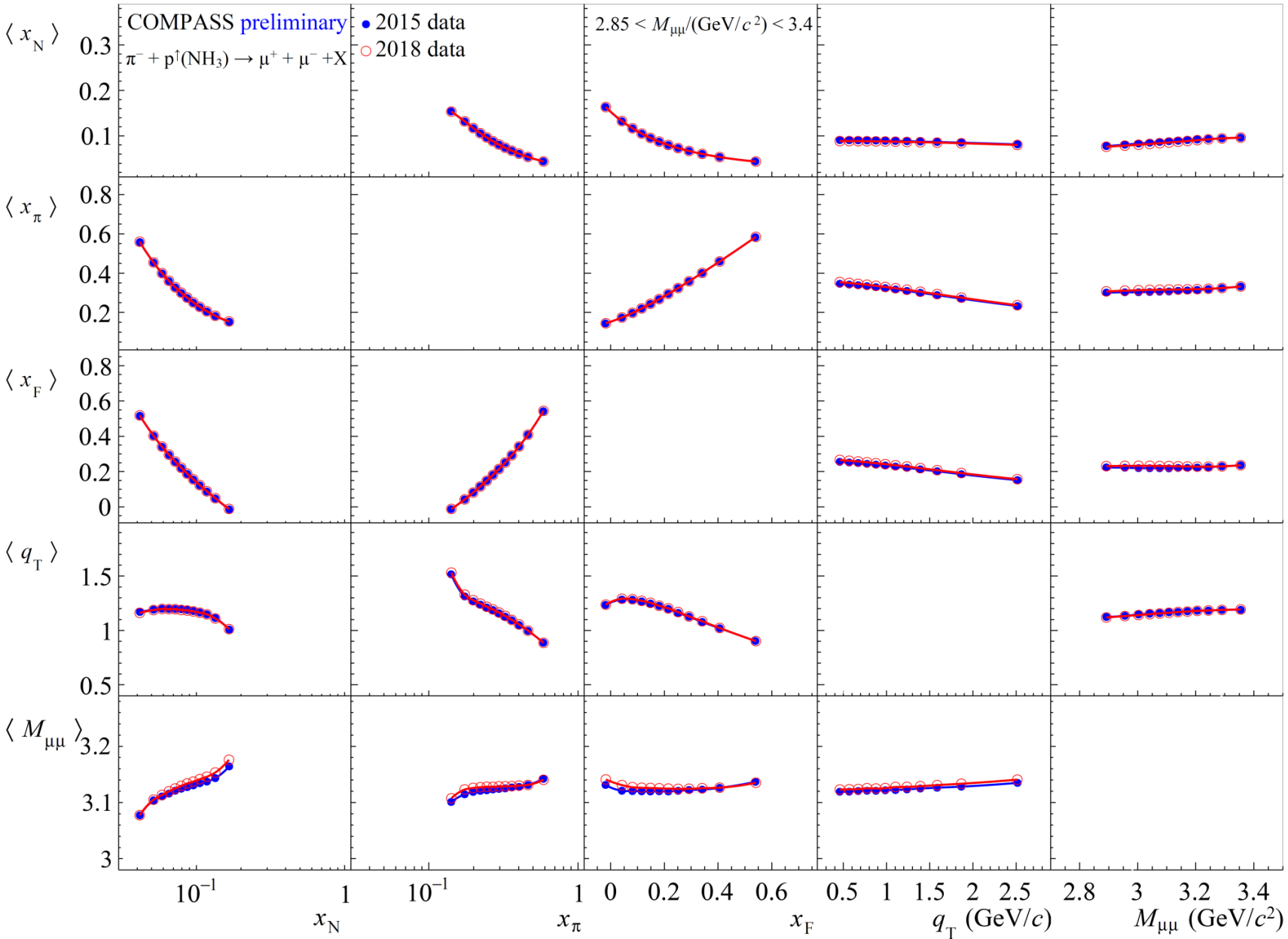
$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1 \text{ GeV}/c$



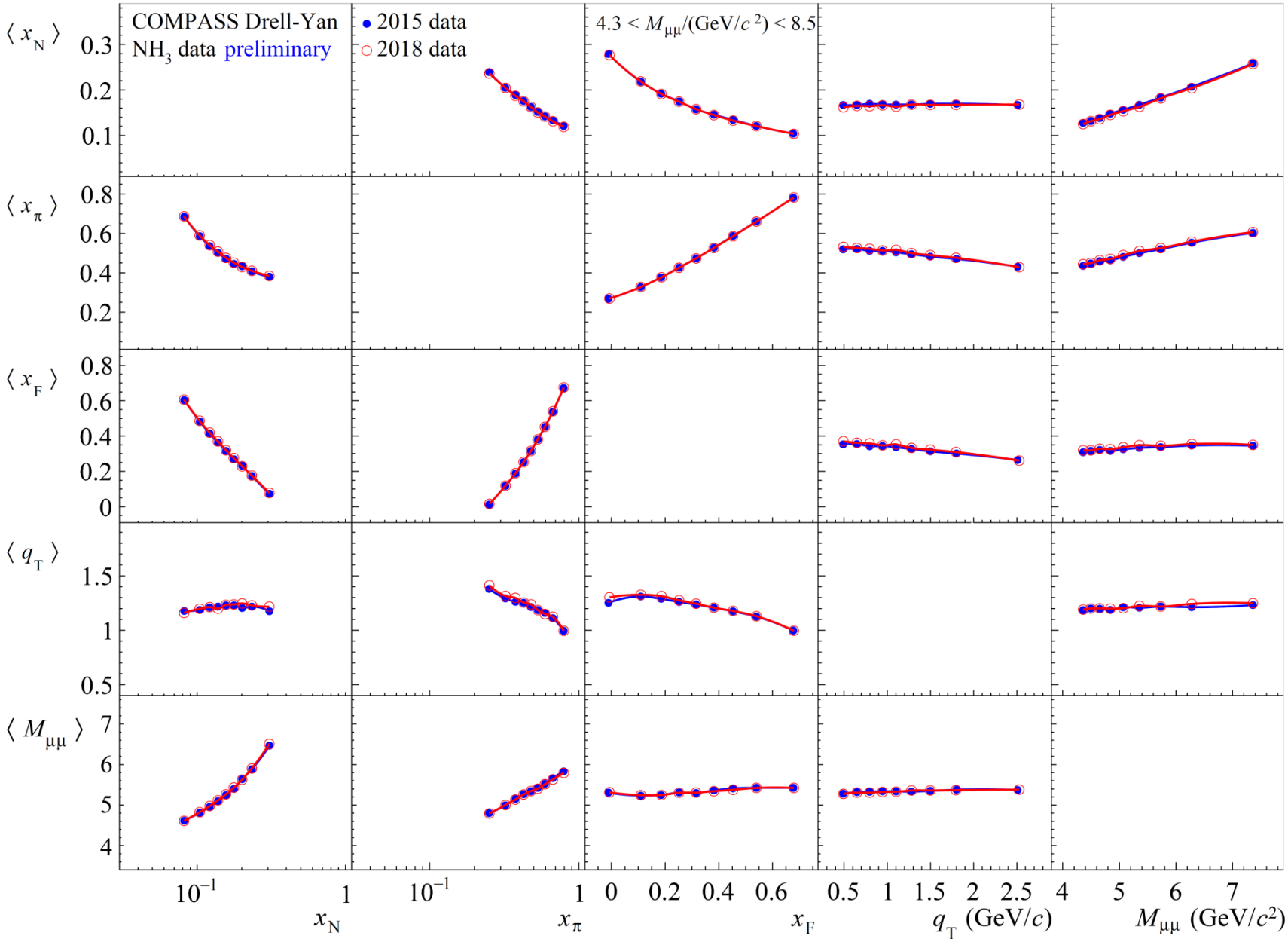
$2.5 < M/(GeV/c^2) < 4.3$ “Charmonia mass”
 Strong J/ψ -signal \rightarrow study of J/ψ physics
 Good signal/background



Kinematic map: J/ψ mass range



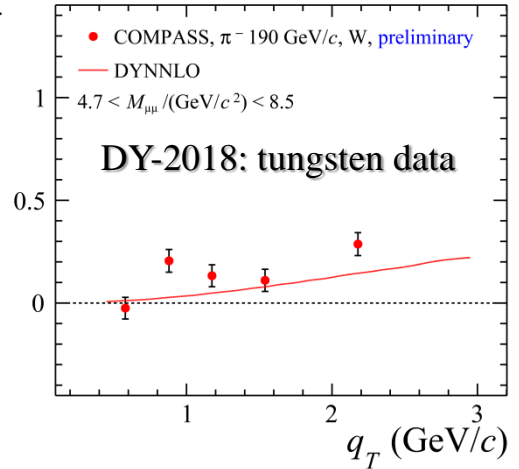
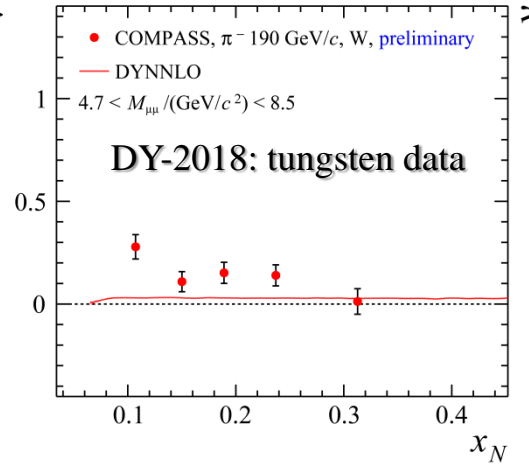
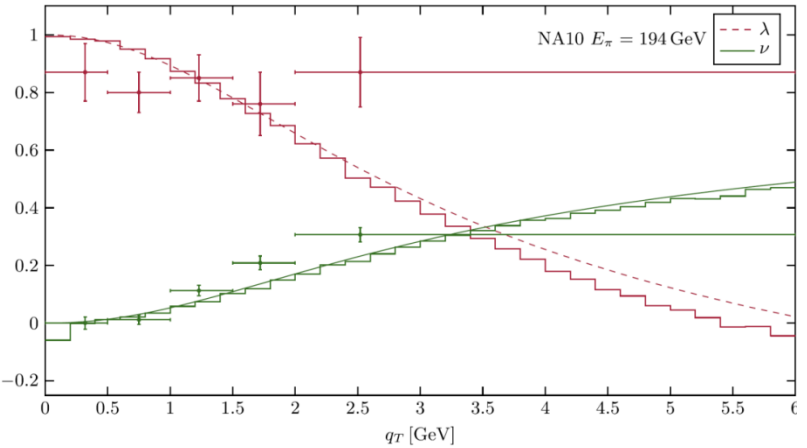
Kinematic map: DY - high mass range



Unpolarized Drell-Yan results (high-mass range)

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

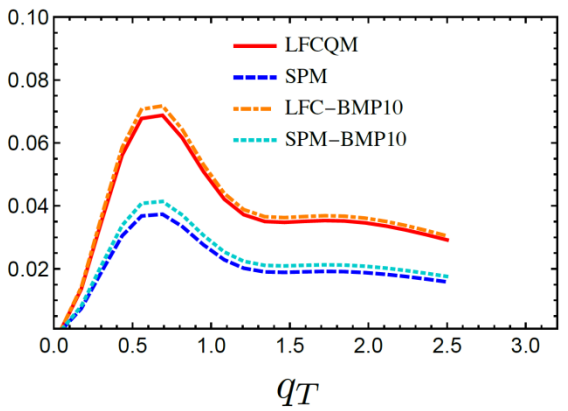
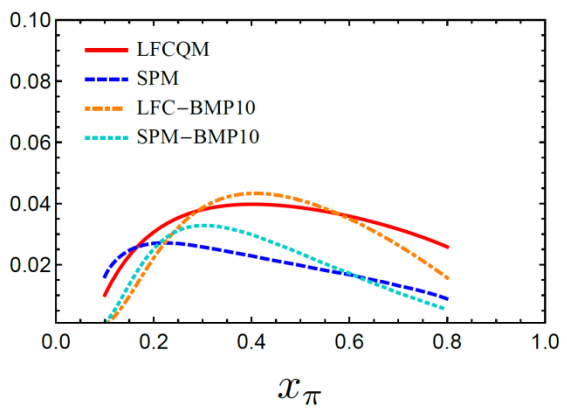
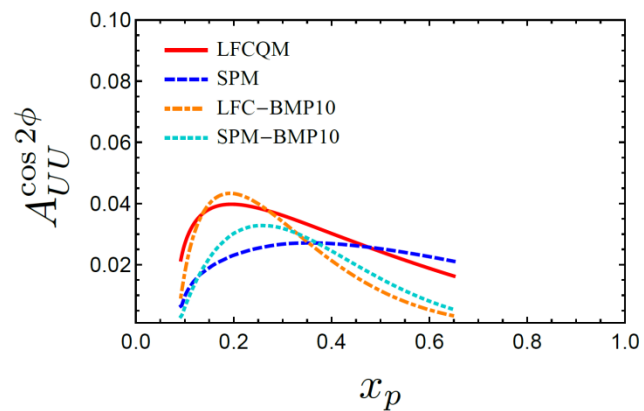
DIS-2021



NA10 data Z.Phys.C 37,545(1988)

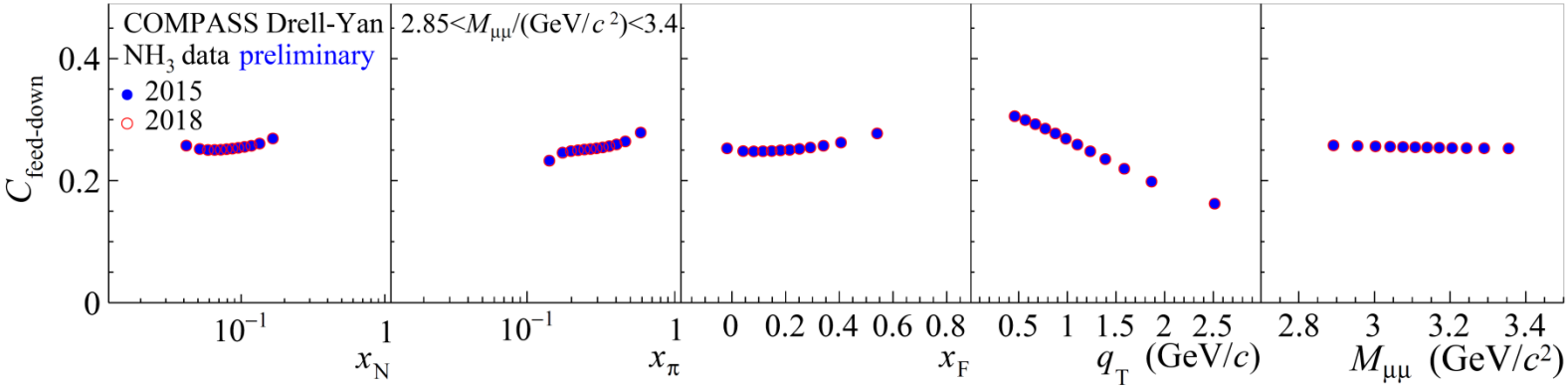
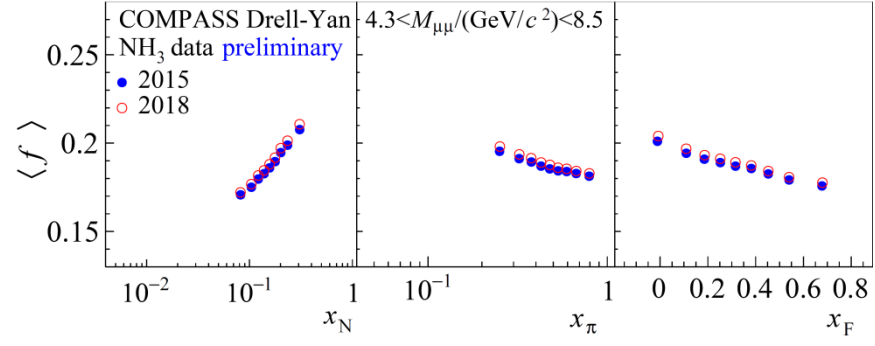
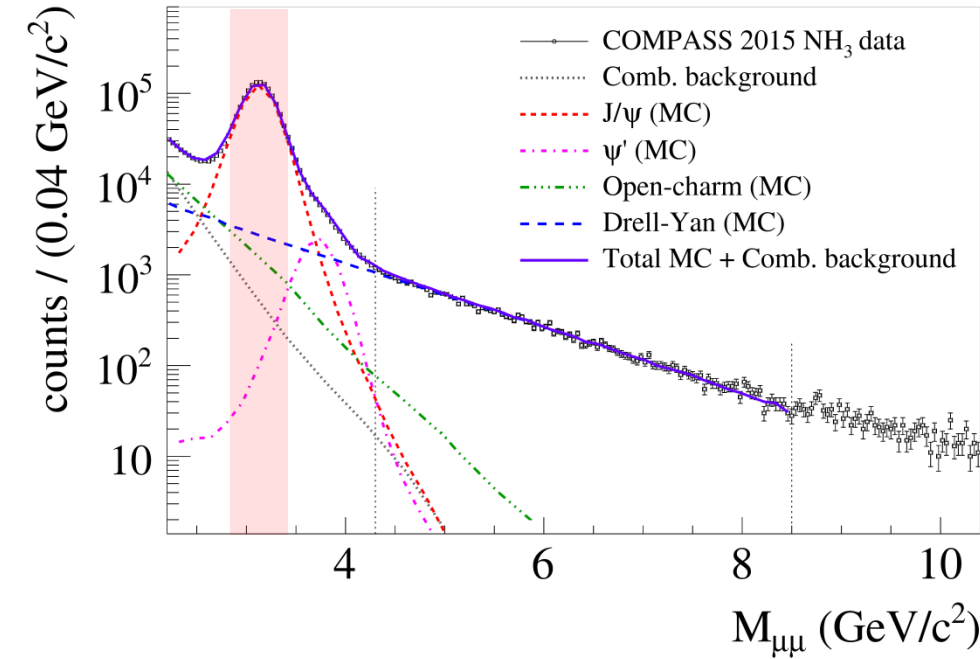
DY-2018 NH₃ data: ongoing analysis

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



Is there a room for BM at low (COMPASS) q_T?

Drell-Yan 2015-2018 TSAs: J/ψ mass range



- Dilution factor and feed down contribution**

Parton Reggeization approach
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