Nucleon spin structure studies at COMPASS: recent results and prospects

BAKUR PARSAMYAN

INFN section of Turin and CERN

on behalf of the COMPASS Collaboration

APCTP Focus Program in Nuclear Physics 2022:

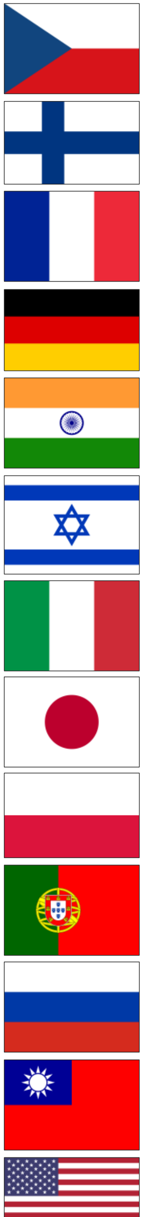
Hadron Physics Opportunities with JLab Energy and Luminosity Upgrade

APCTP, Pohang, Korea

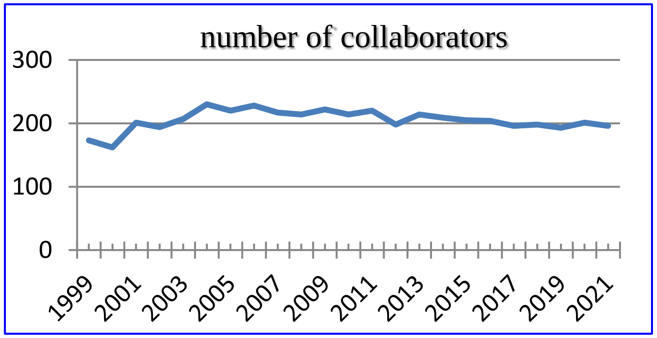
18-23 July, 2022

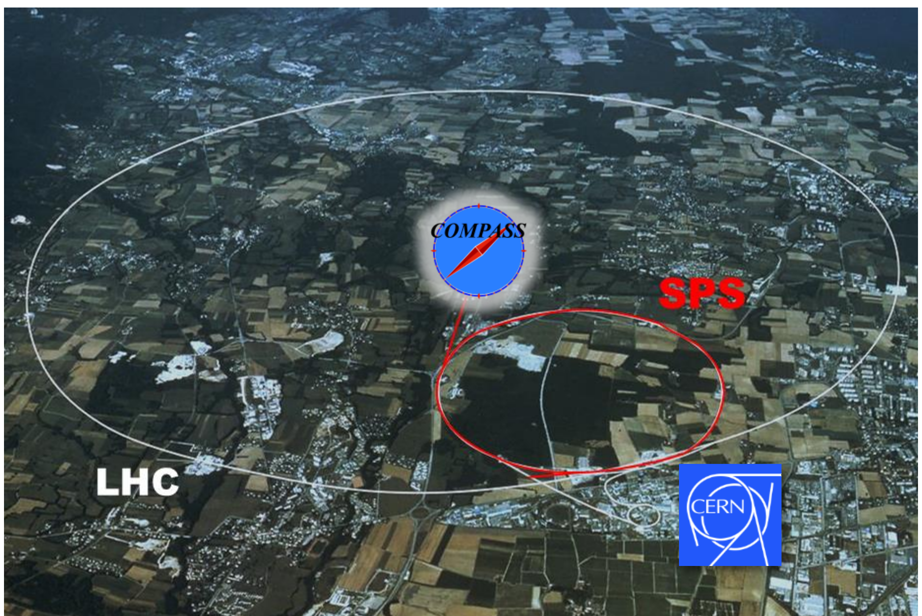
COMPASS collaboration

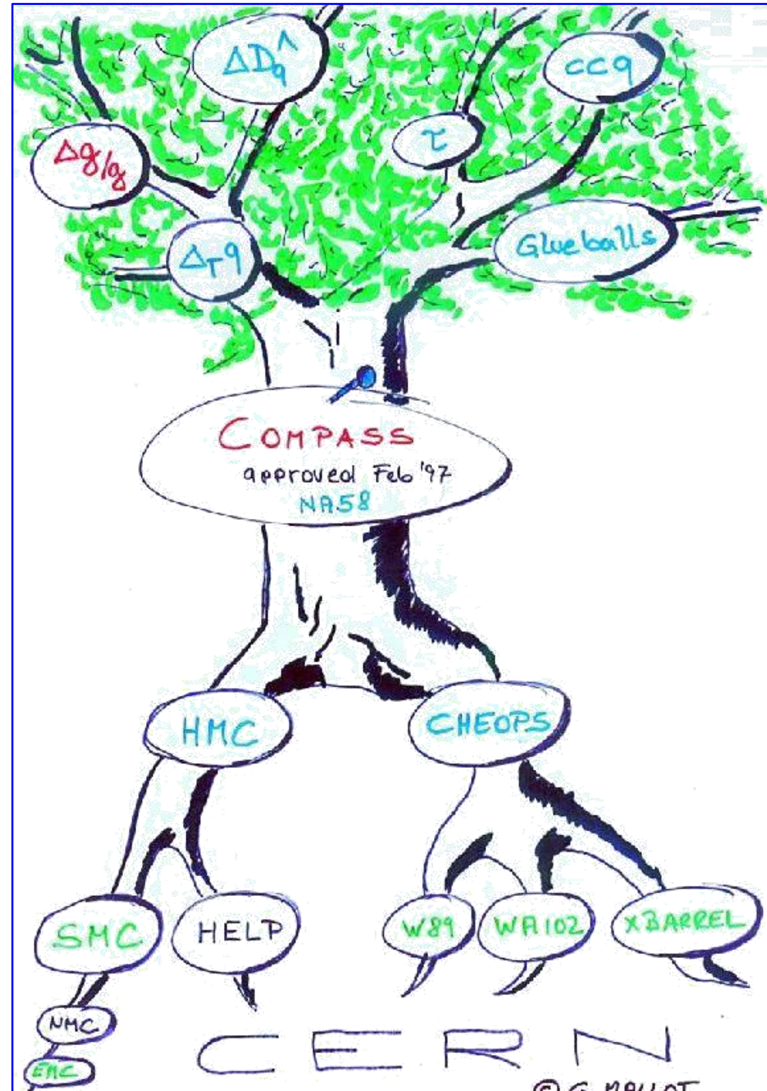
Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



25 institutions from 13 countries
– nearly 200 physicists







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

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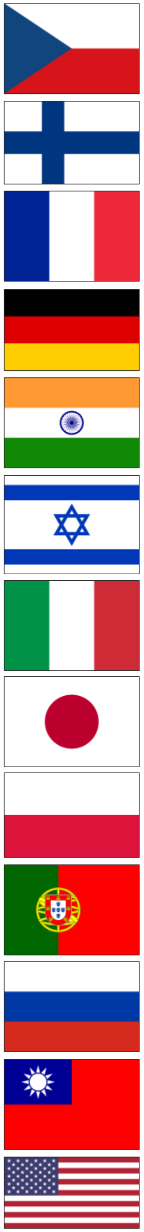

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- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

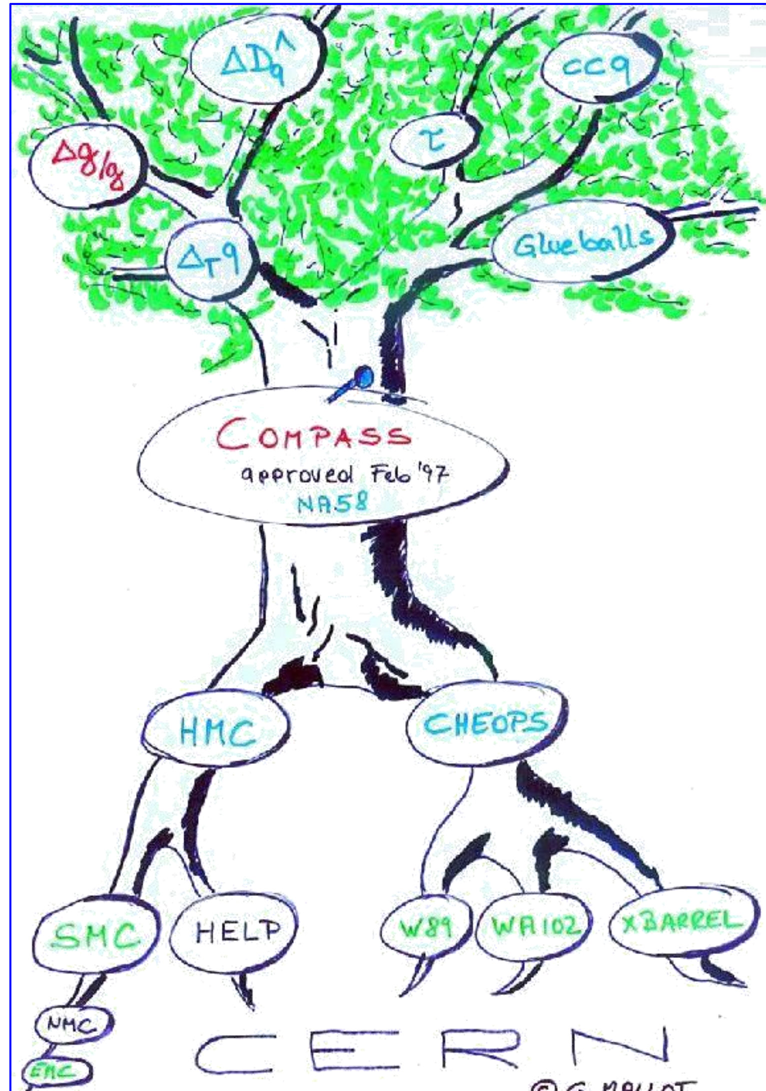
Wide physics program

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**



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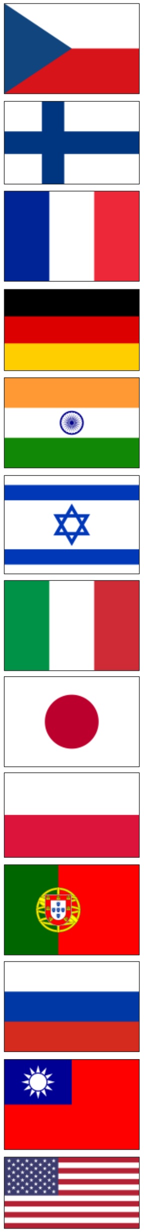

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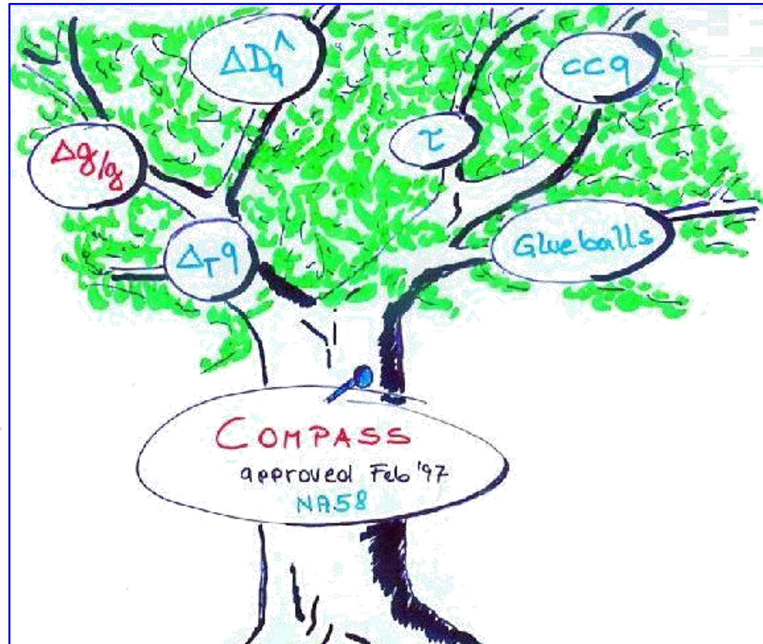
International Workshop on Hadron Structure and Spectroscopy

IWHSS-2022 workshop (anniversary edition)

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



COMPASS legacy overview

F. Bradamante S. Paul G. Mallot

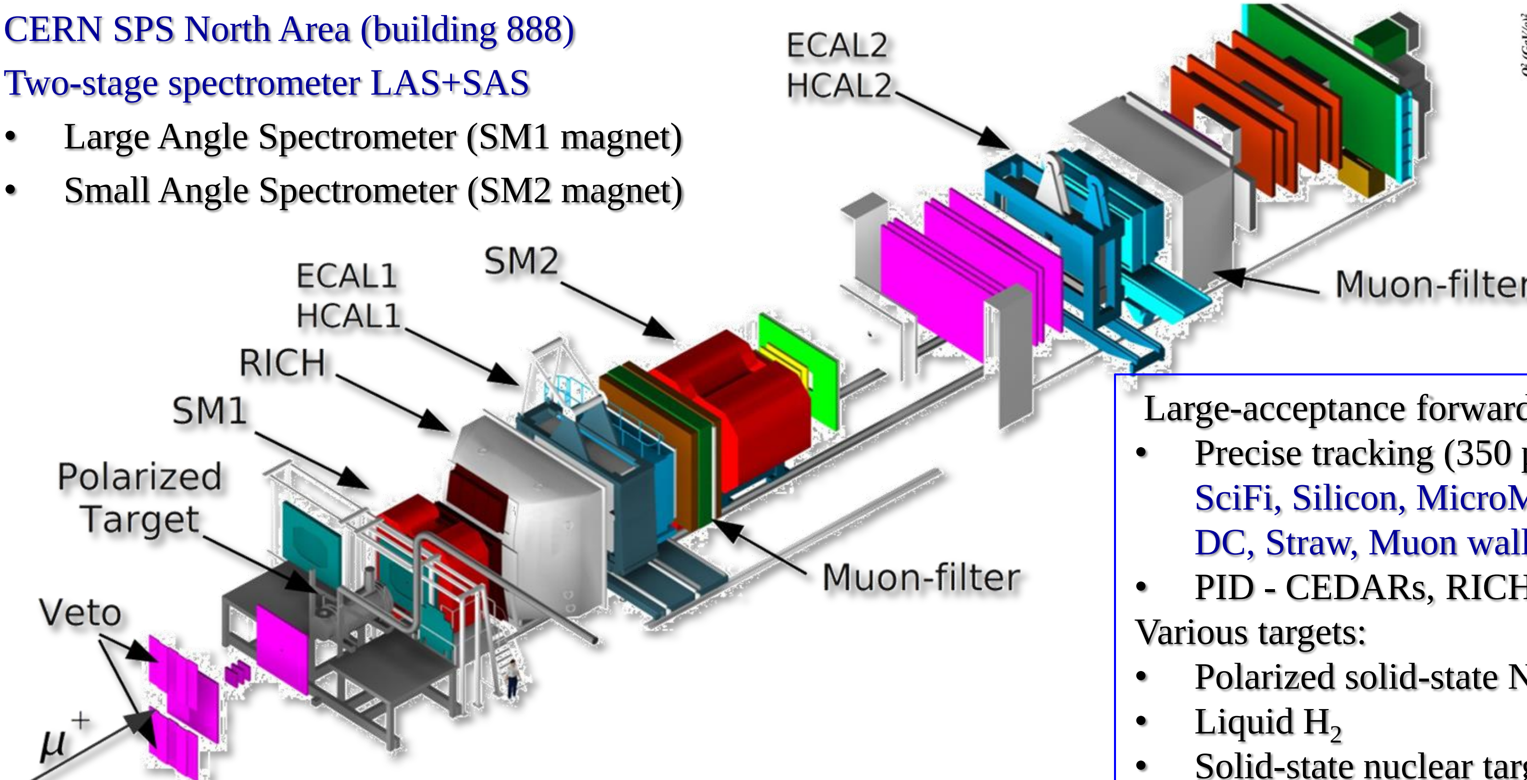
COMPASS experimental setup

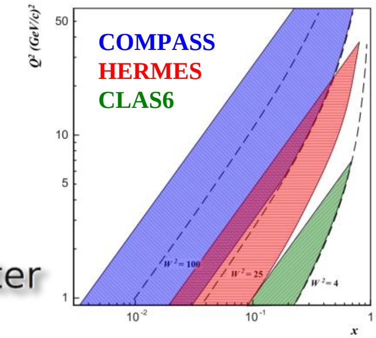
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





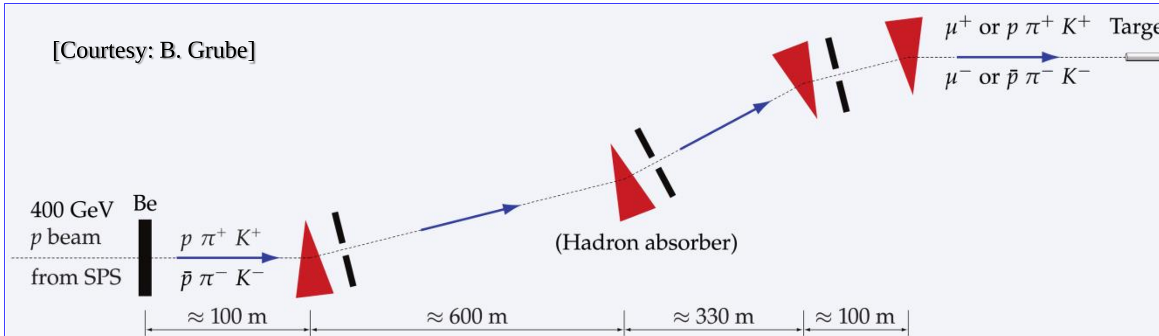
Large-acceptance forward spectrometer

- 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 ^6LiD
- 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% p, 24% π^+, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized



COMPASS experimental setup: Phase II (DVCS programme)

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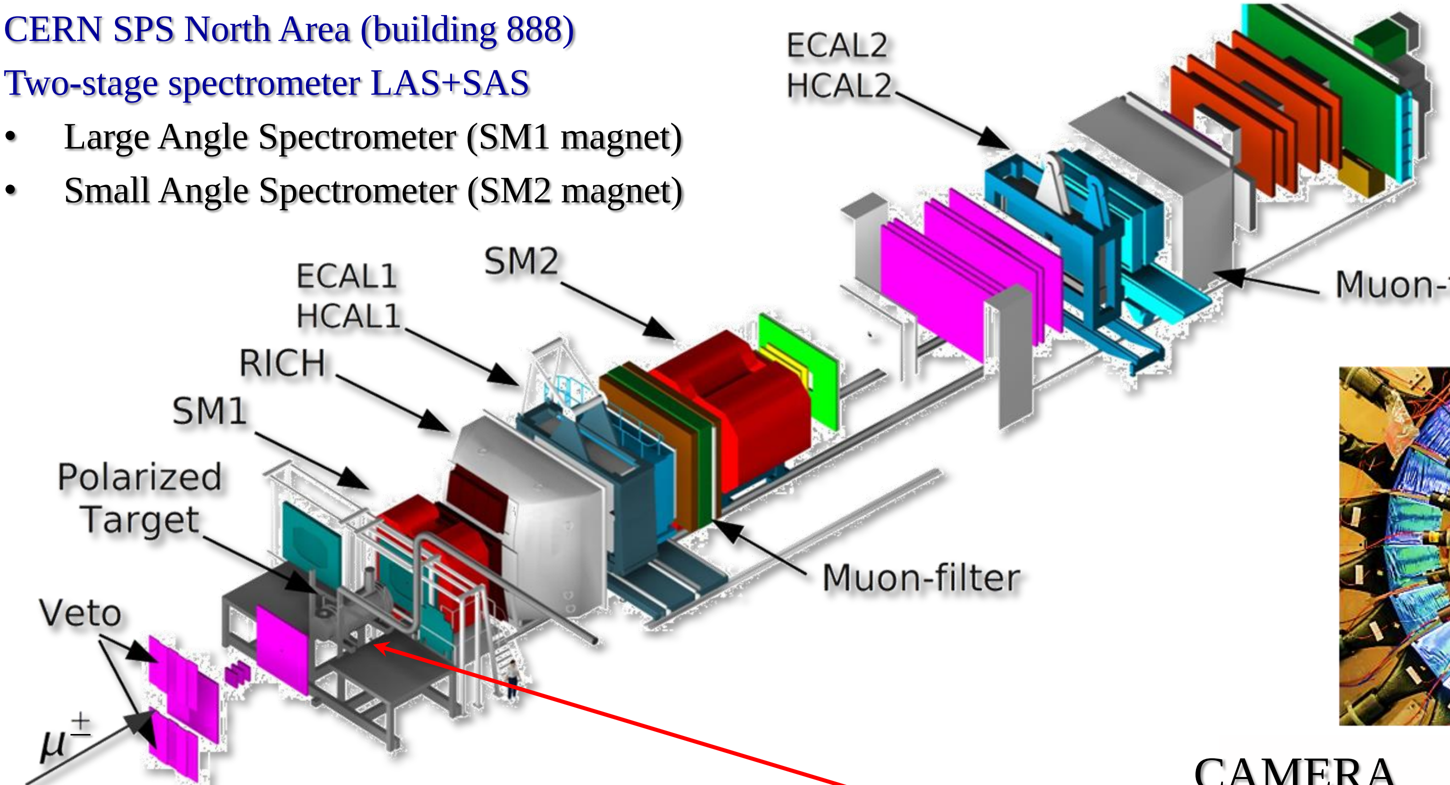

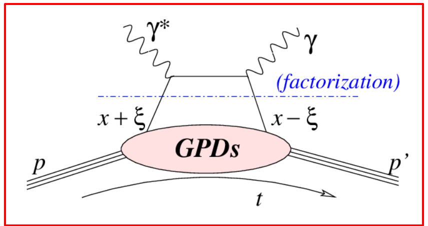

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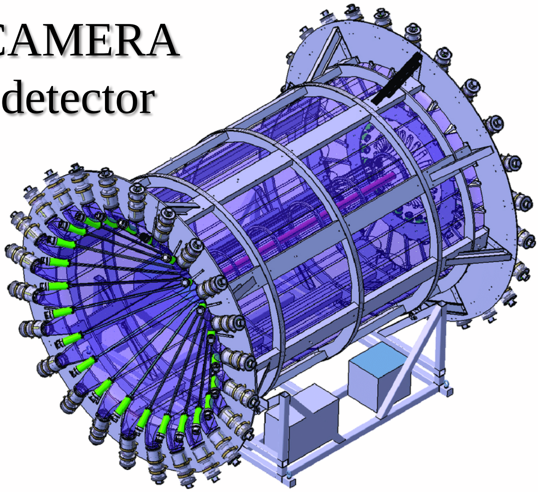
CAMERA detector



COMPASS experimental setup: Phase II (SIDIS programme)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

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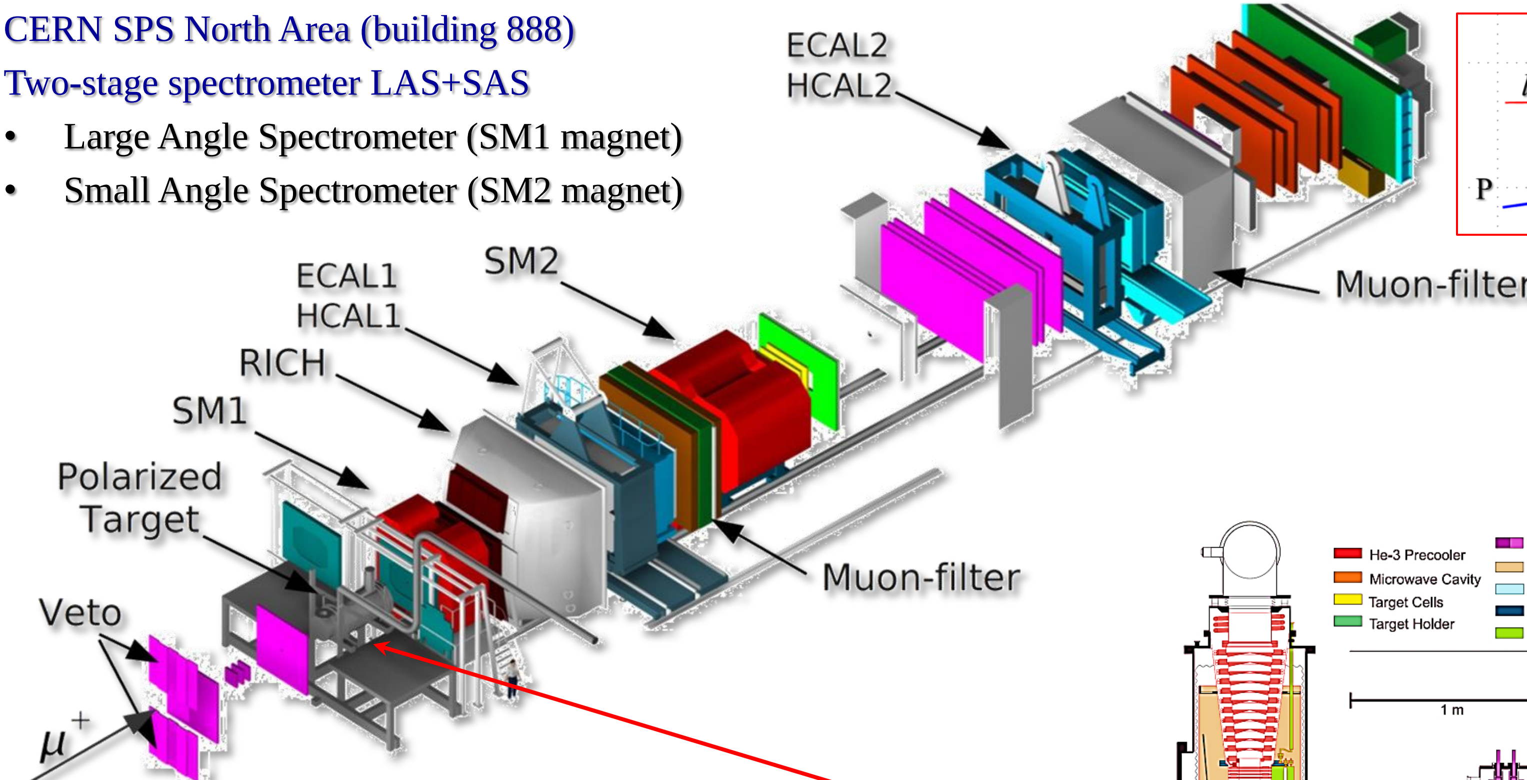

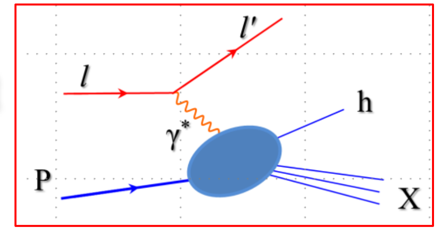

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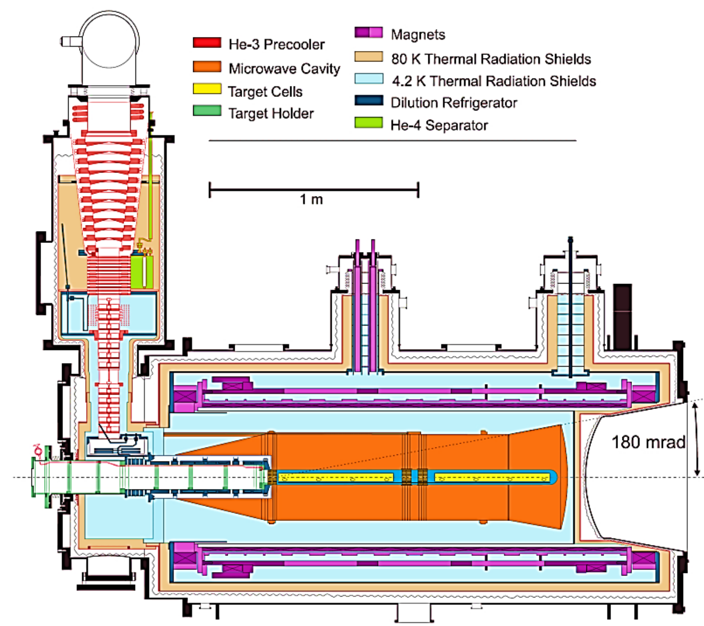
  - μ^+ longitudinally polarized



COMPASS experimental setup: Phase II (DY programme)

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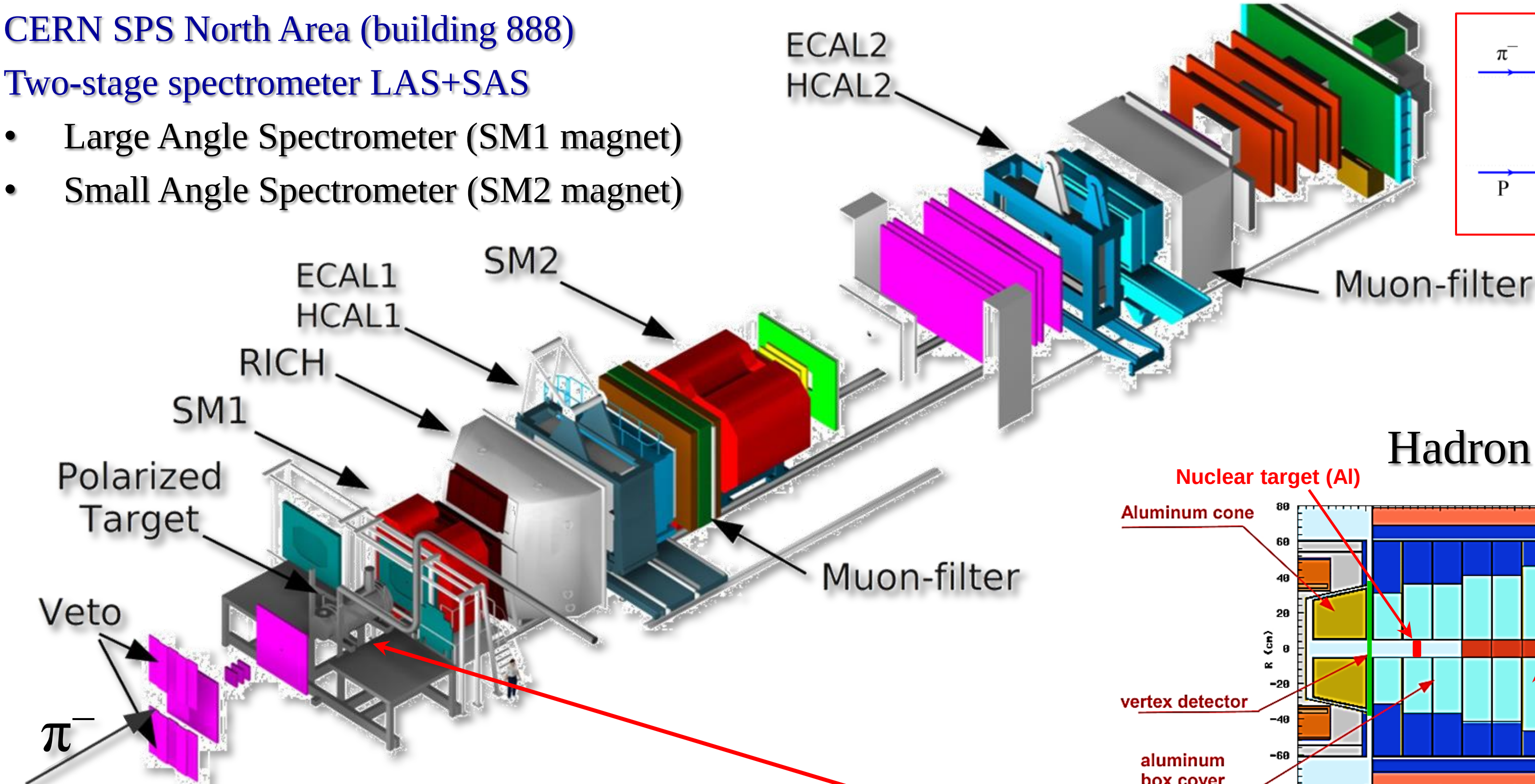
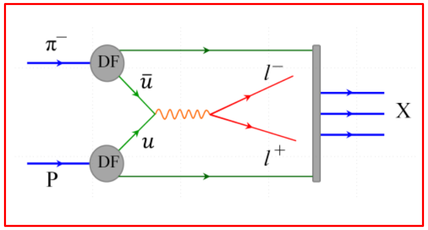
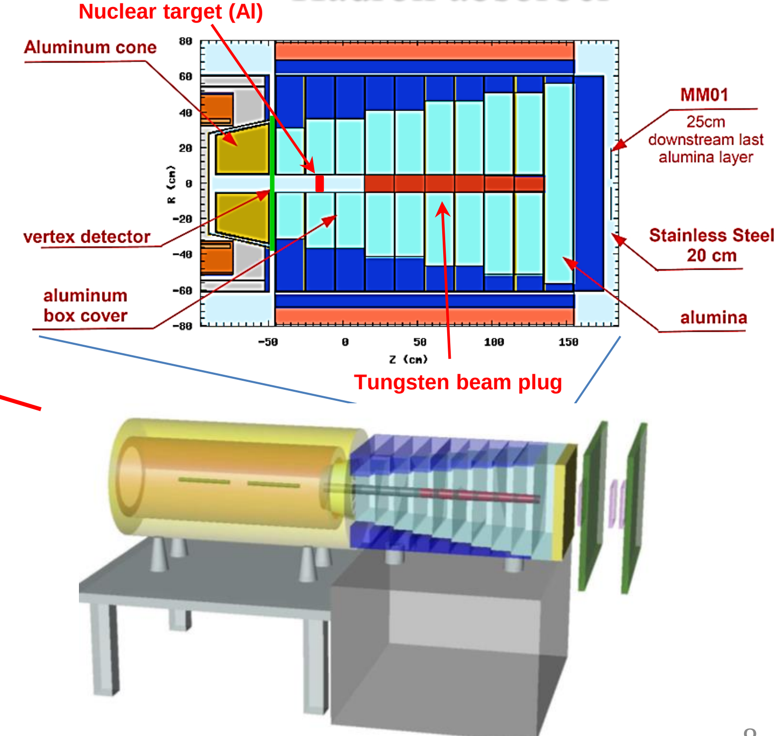




Hadron absorber



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  - $\mu^\pm$ 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

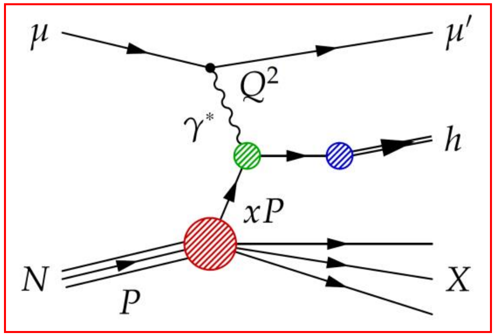
- Hard scattering of $\mu^\pm$ and π^- off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

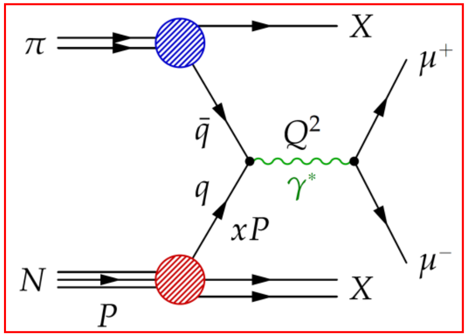
Hadron spectroscopy

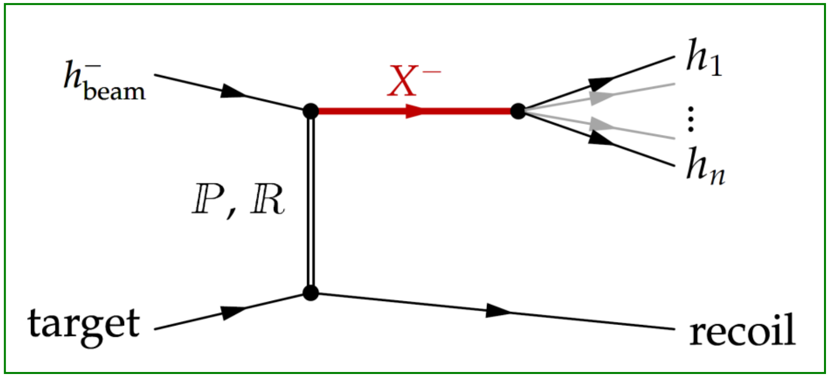
- Diffractive *π(K)* dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

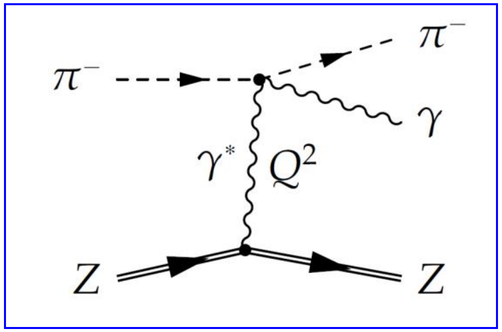
Chiral dynamics

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









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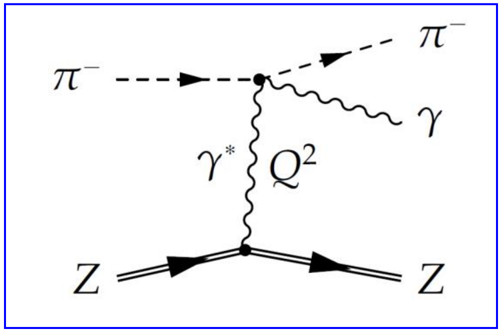


PRL **114,** 062002 (2015)

Measurement of the Charged-Pion Polarizability

(COMPASS Collaboration)

(Received 2 June 2014; revised manuscript received 24 December 2014; published 10 February 2015)

The COMPASS collaboration at CERN has investigated pion Compton scattering, $\pi^-\gamma \to \pi^-\gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^-\mathrm{Ni} \to \pi^-\gamma\mathrm{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasireal photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, $Q^2 < 0.0015\ (\mathrm{GeV}/c)^2$. From a sample of 63 000 events, the pion electric polarizability is determined to be $\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}\ \mathrm{fm}^3$ under the assumption $\alpha_\pi = -\beta_\pi$, which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong interaction that has been addressed since long by various methods with conflicting outcomes. While this result is in tension with previous dedicated measurements, it is found in agreement with the expectation from chiral perturbation theory. An additional measurement replacing pions by muons, for which the cross-section behavior is unambiguously known, was performed for an independent estimate of the systematic uncertainty.

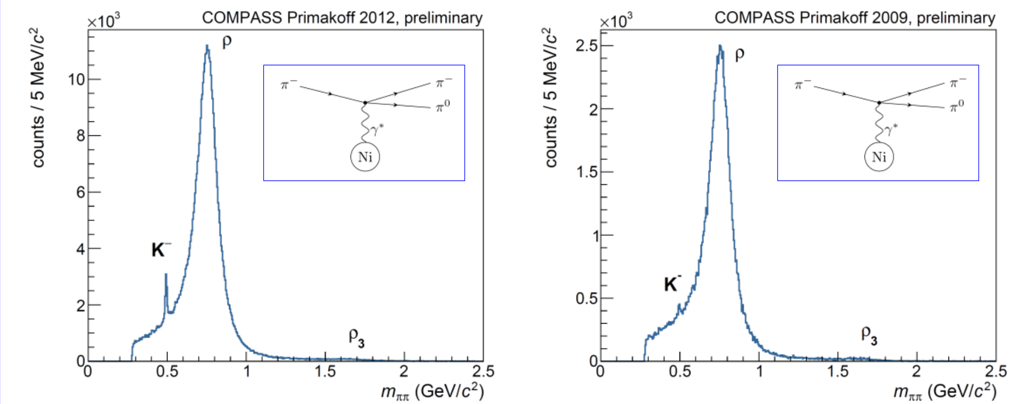
$$\alpha_\pi = (2.0 \pm 0.6_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}) \times 10^{-4}\ \mathrm{fm}^3$$

Chiral dynamics

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

ongoing analysis:

study of chiral anomaly in $\pi^-\gamma \to \pi^-\pi^0$



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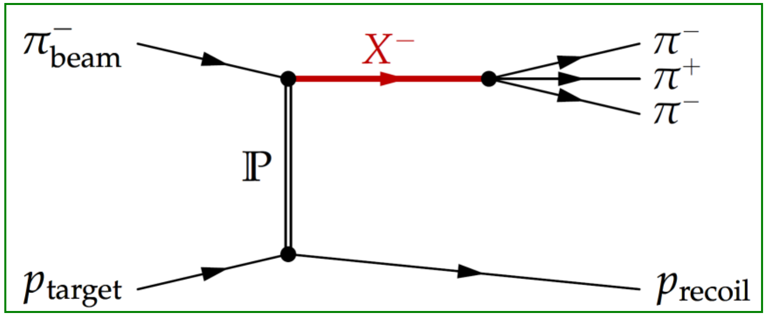

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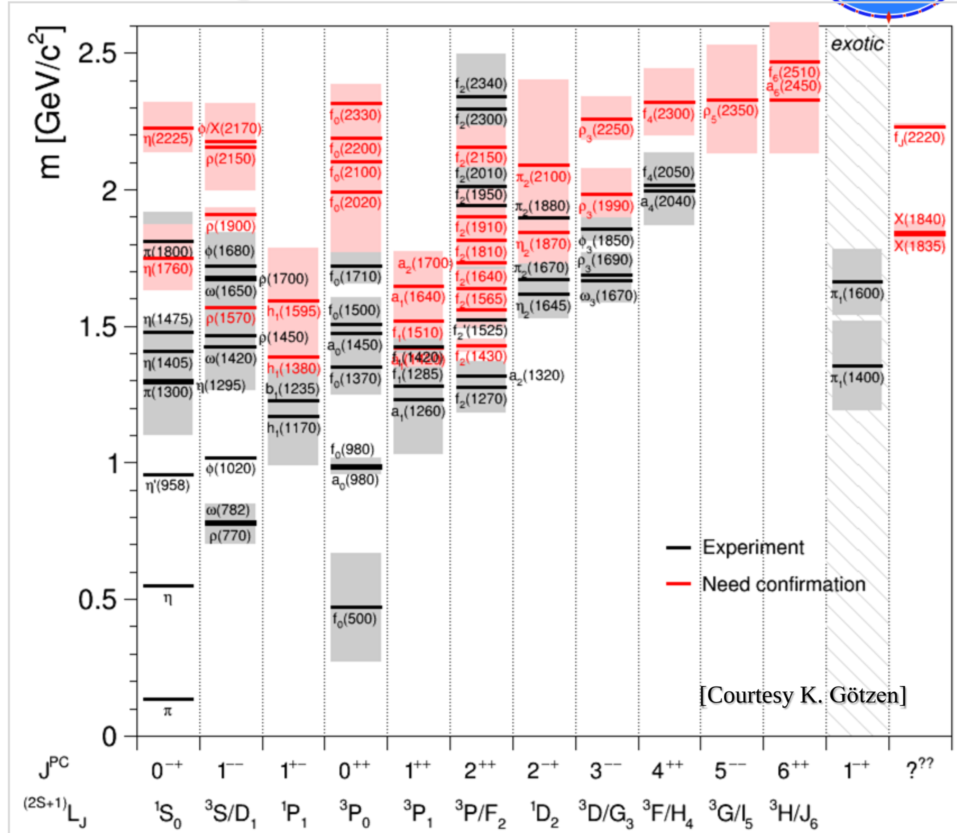

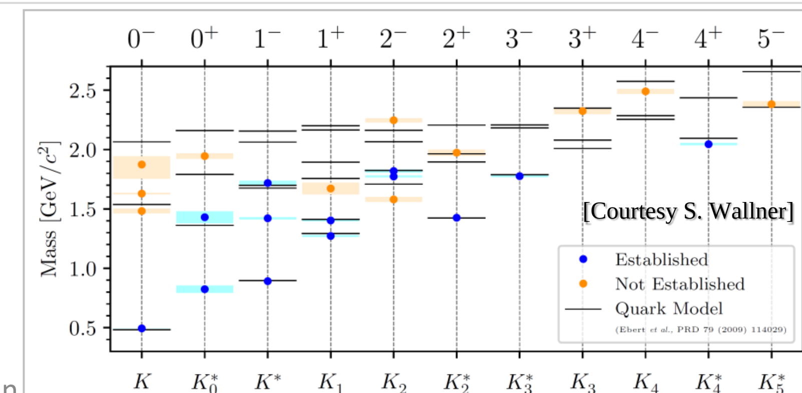

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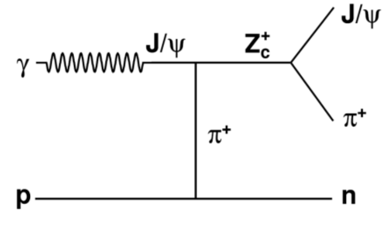
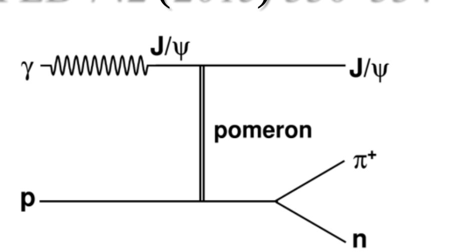
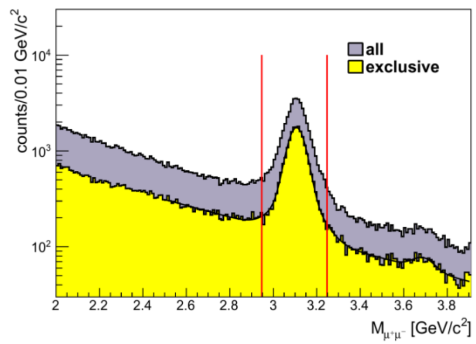
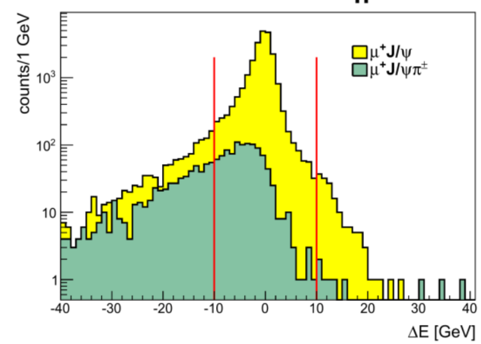
Search for exclusive photoproduction of $Z_c^{\pm}$ (3900)

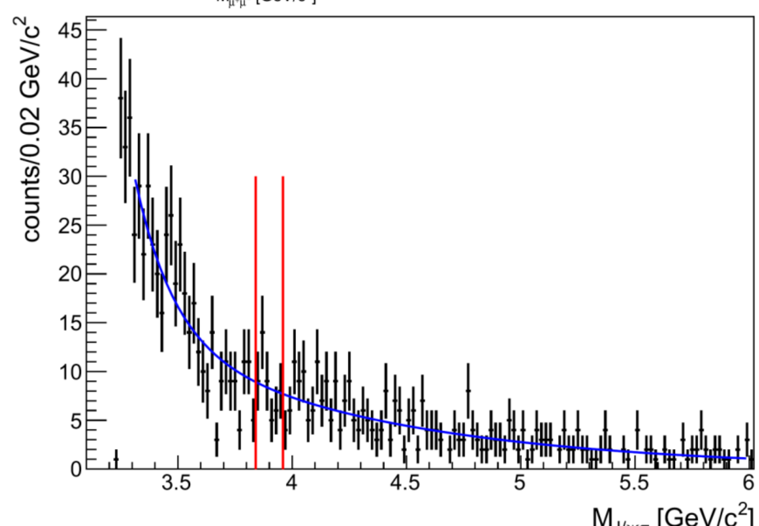
PLB 742 (2015) 330–334











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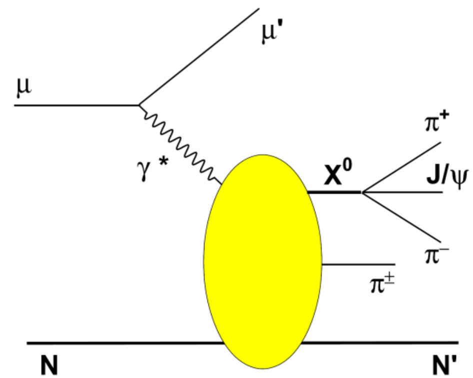
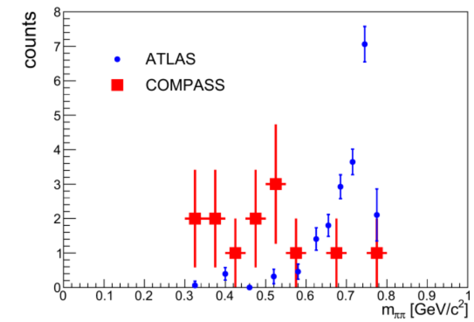
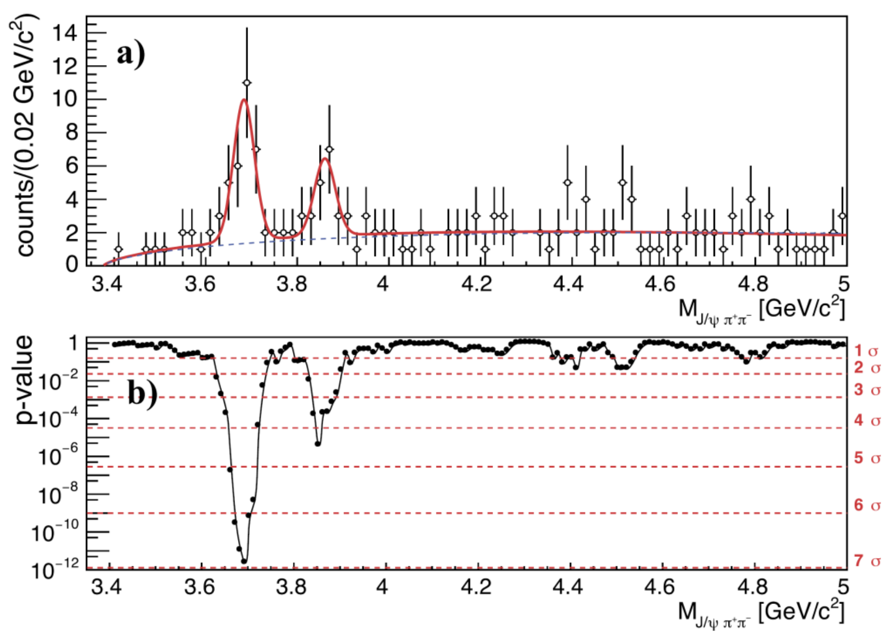
Search for exclusive muoproduction of $X(3872)$, observation of $\widetilde{X}(3872)$ PLB 783 (2018) 334–340







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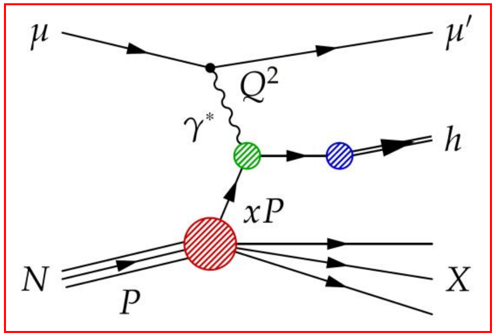
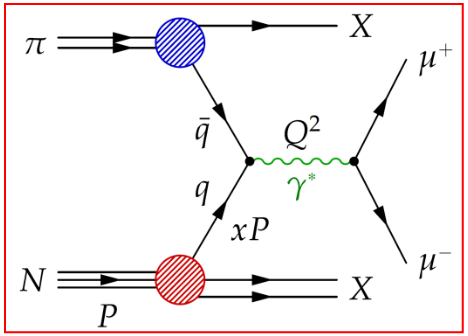
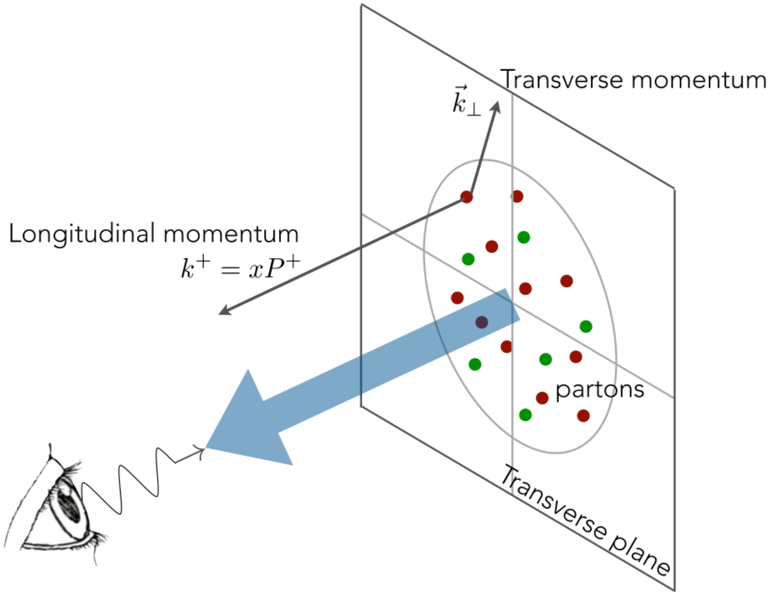


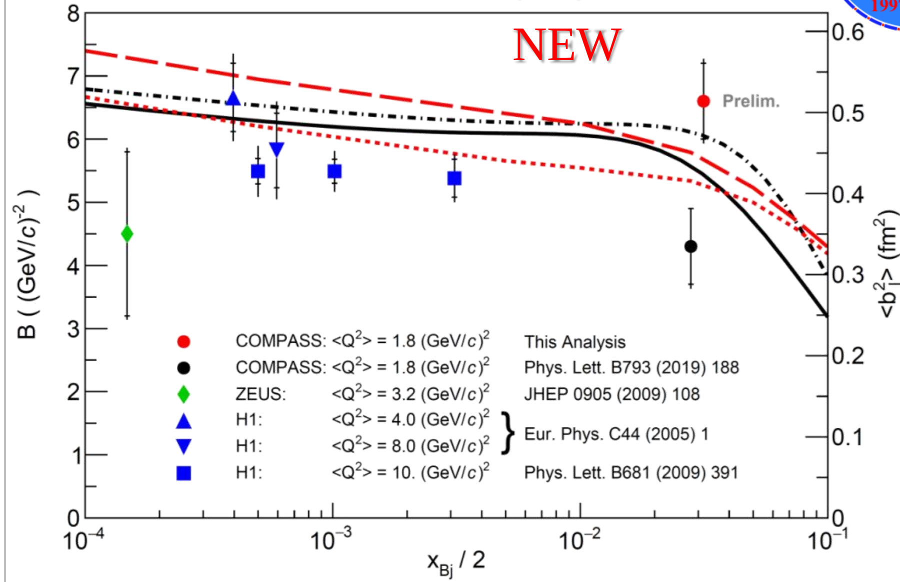


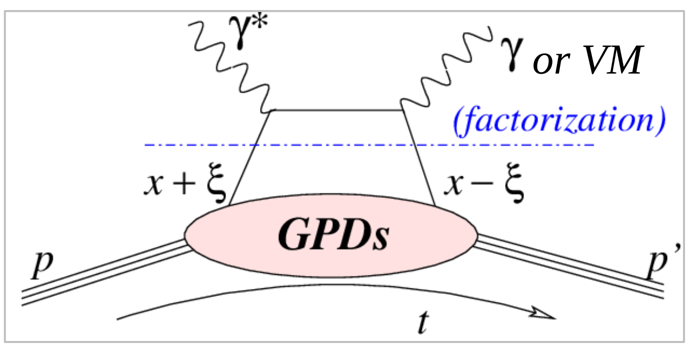


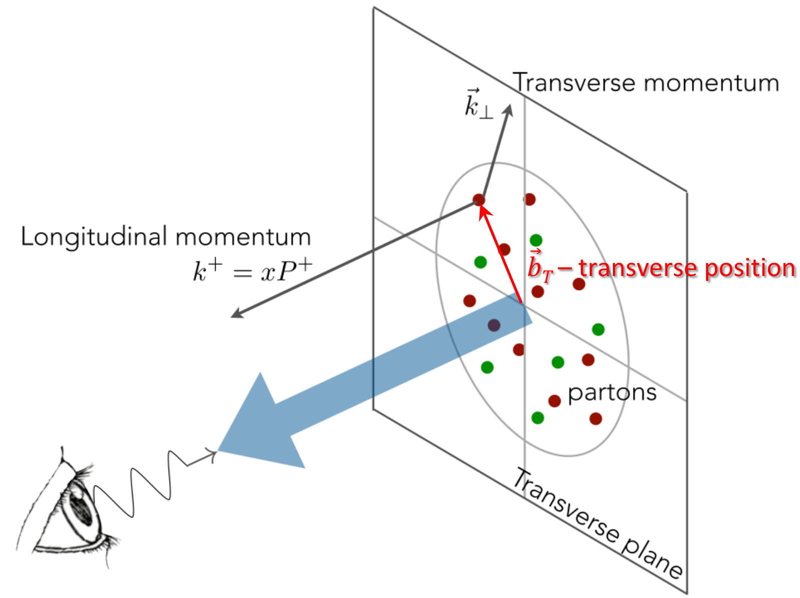
Nucleon transverse structure

- 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
- Measured in exclusive processes:
  - Deeply virtual Compton scattering (DVCS): $\mu + \mathrm{N} \rightarrow \mu + \gamma + \mathrm{N}$
  - Hard exclusive meson production (HEMP): $\mu + \mathrm{N} \rightarrow \mu + \mathrm{VM} + \mathrm{N}$ with VM = π^0, $\rho(770)$, $\omega(782)$,..

COMPASS 2016 data (2/3)

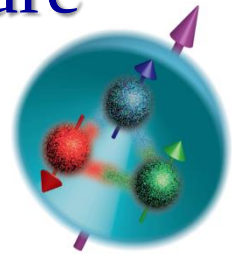






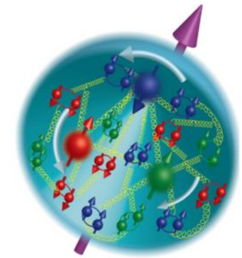
Nucleon transverse structure

- 1964 Quark model 

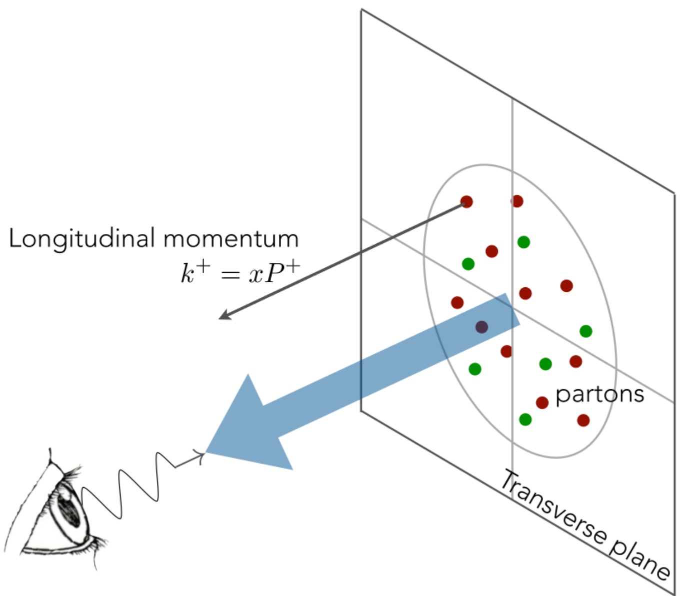


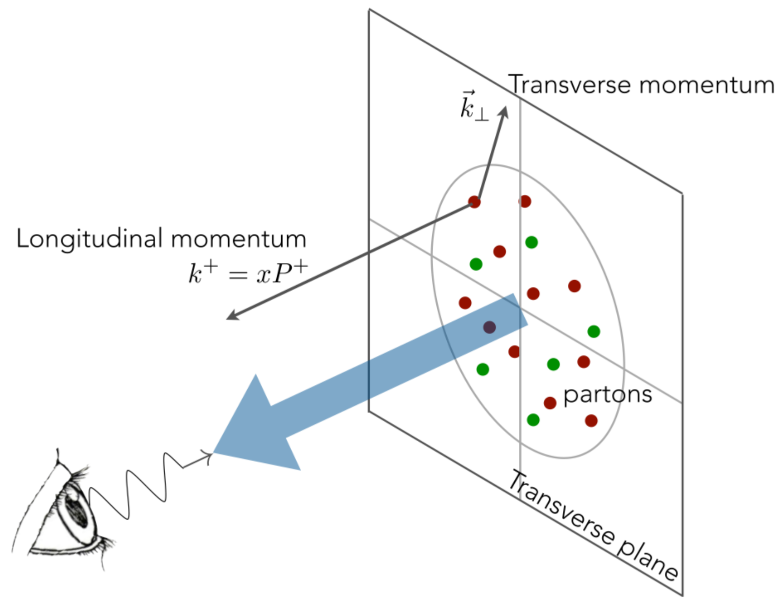
- 1969 Parton model 

- 1973 asymptotic freedom and QCD 



- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries 

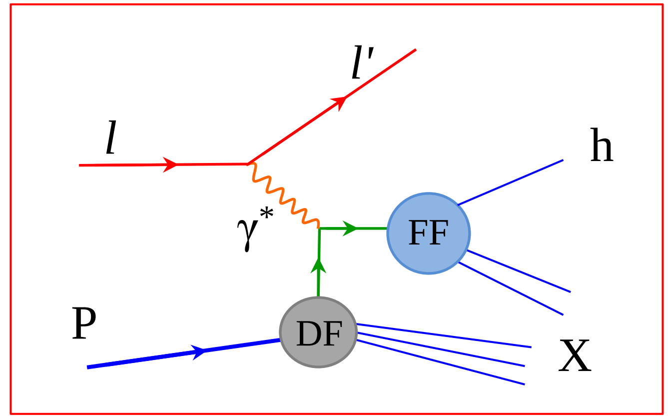




Cahn effect in SIDIS

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

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



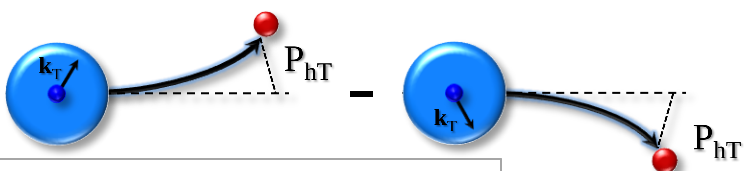
Cahn effect

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

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

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;

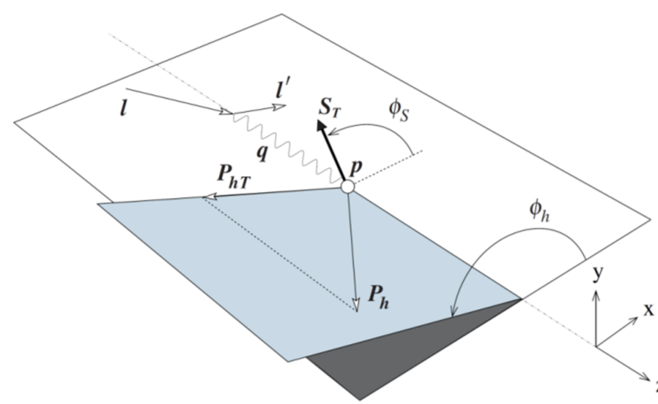


$$\hat{s} \simeq xs\left[1-2\sqrt{1-y}\,\frac{k_T}{Q}\cdot\cos\varphi_q\right]$$

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

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

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



Cahn effect in SIDIS

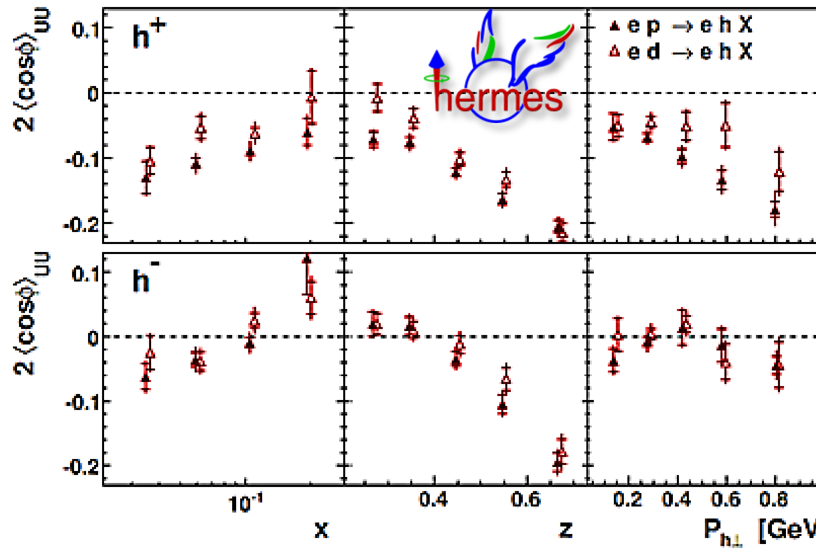
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

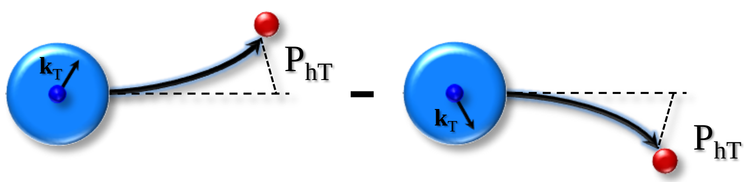
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

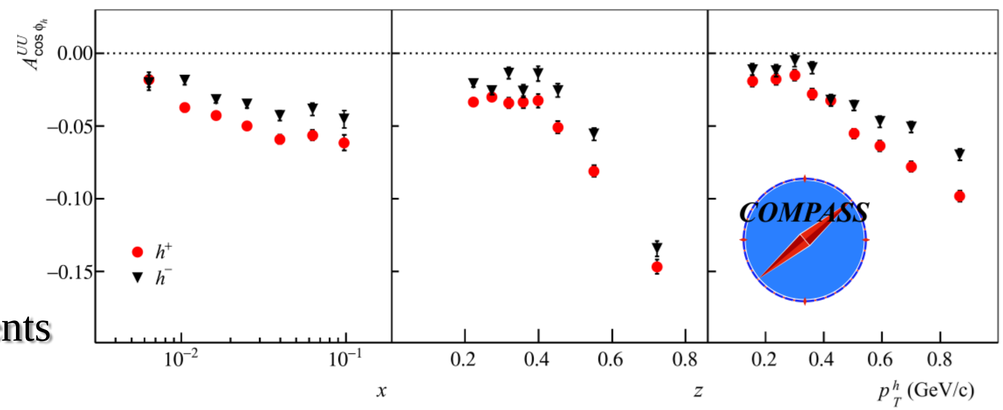
$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\right)$$

Quark / Nucleon	U
U	$f_1^q(x, \boldsymbol{k}_T^2)$ **number density**

Significant non-zero effect observed by a number of experiments







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

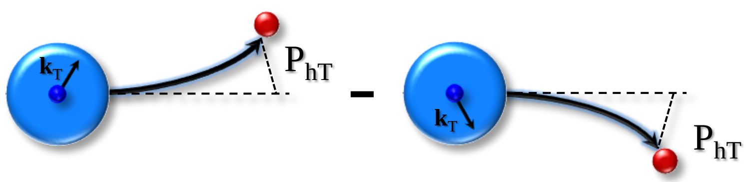
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

Cahn effect in SIDIS

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

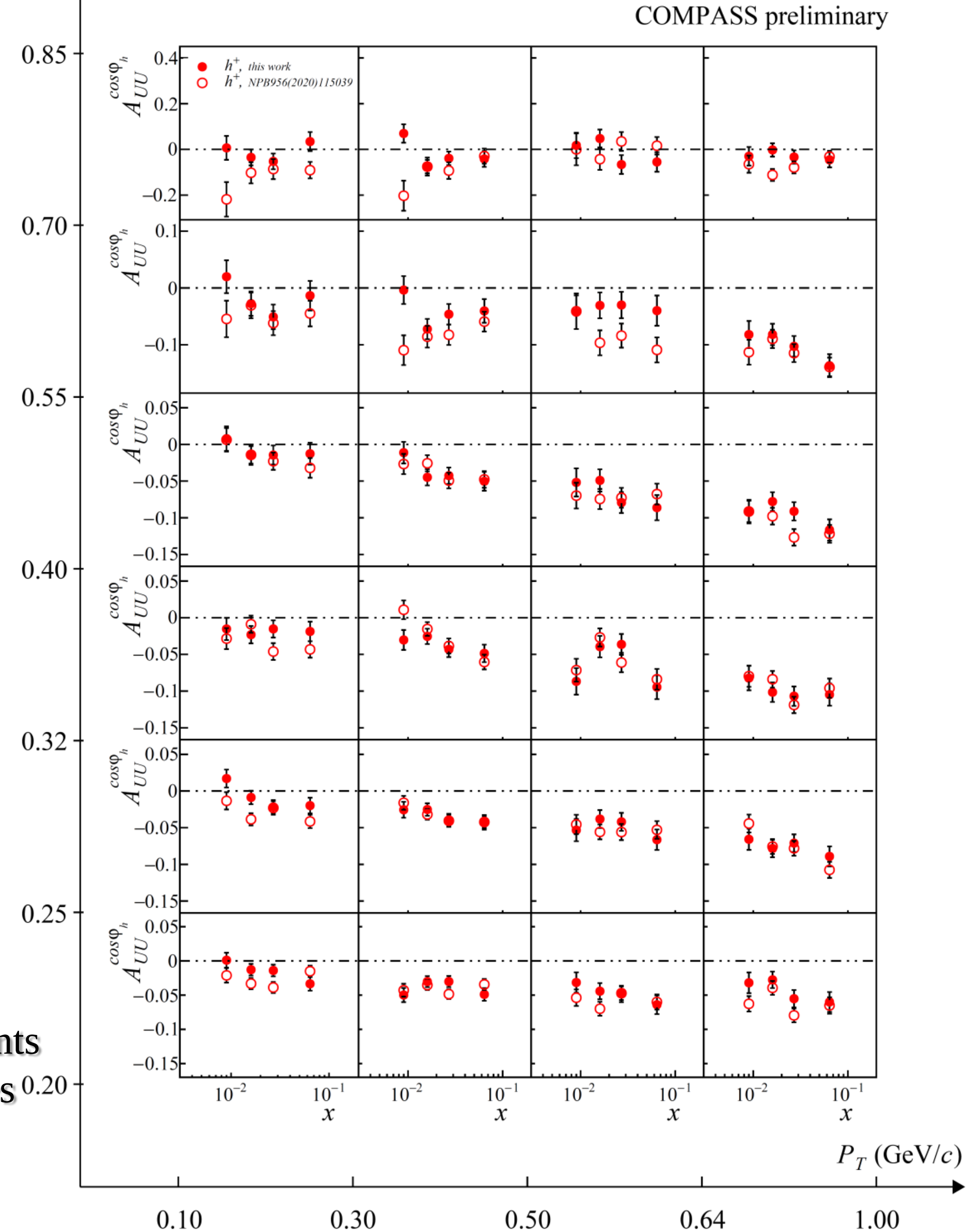
$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\right)$$

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



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

Recent COMPASS results



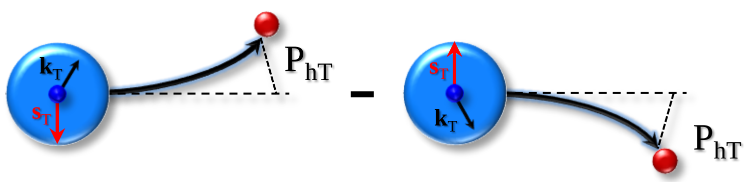
Boer-Mulders effect in SIDIS

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

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

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

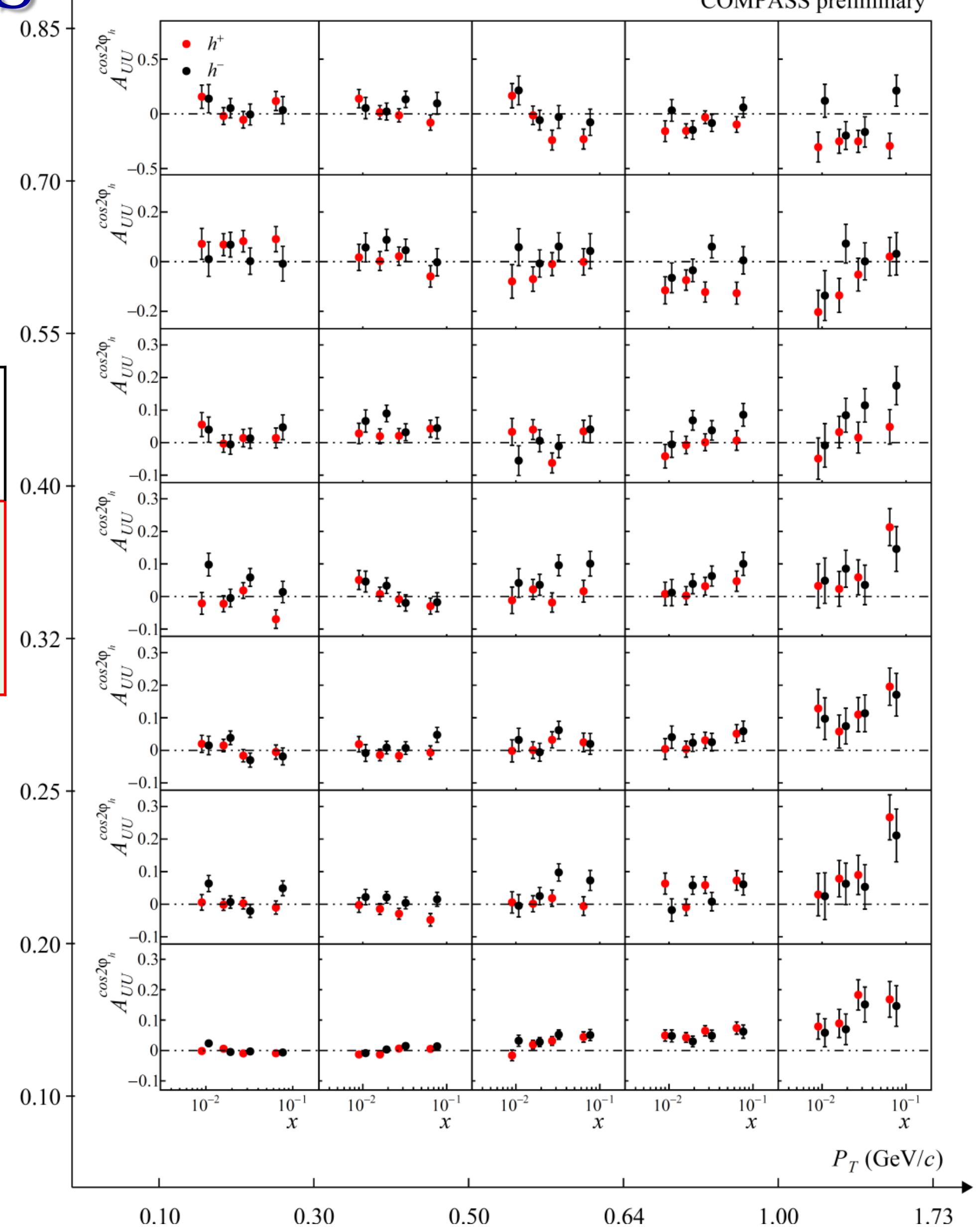
Quark / Nucleon	U		T
U	$f_1^q(x, \boldsymbol{k}_T^2)$ **number density**		$h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ **Boer-Mulders**



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

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

Recent COMPASS results



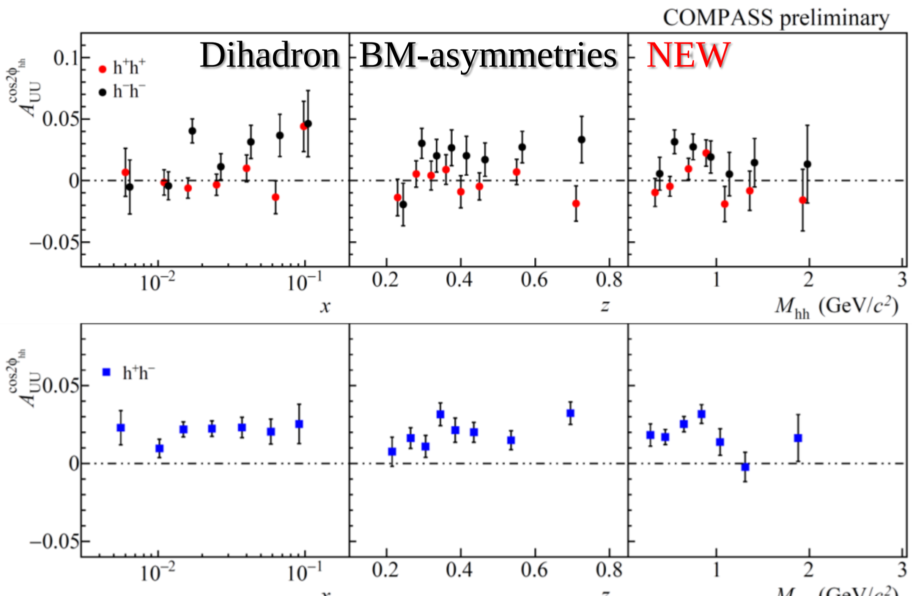
spin of the quark **k_T**

Boer-Mulders effect in SIDIS

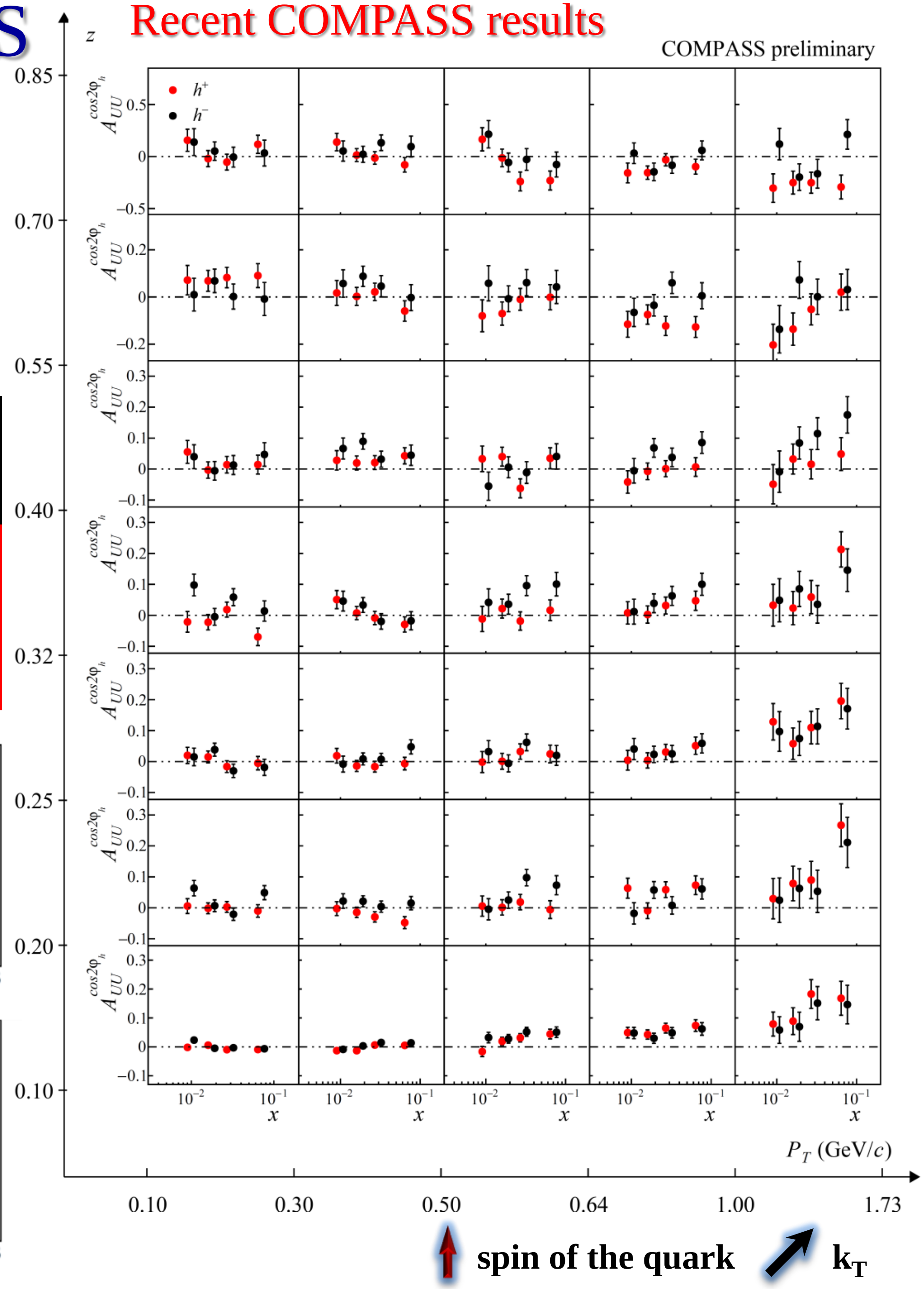
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

Quark / Nucleon	U		T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density** 		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders** 



Recent COMPASS results

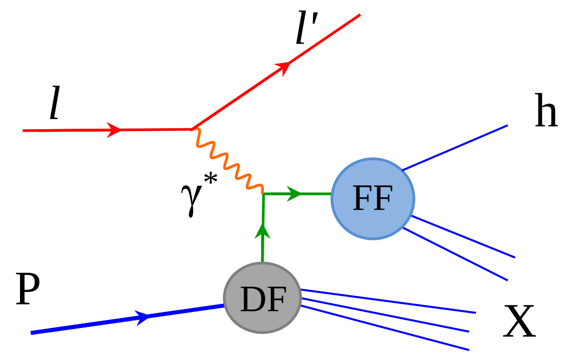


SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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

spin of the nucleon **spin of the quark** $\mathbf{k_T}$

SIDIS: target longitudinal spin dependent asymmetries

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

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

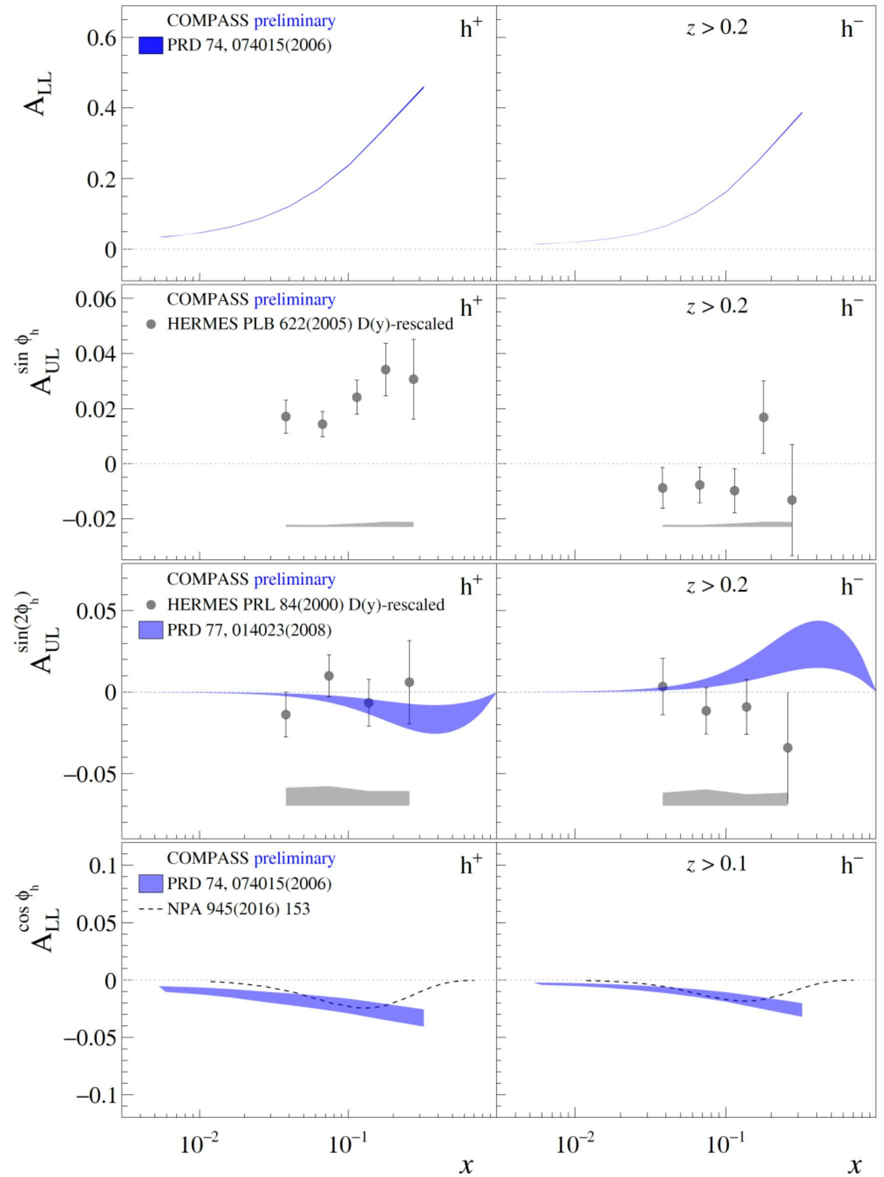
$$\left. + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \right\}$$

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

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

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

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



SIDIS: target longitudinal spin dependent asymmetries

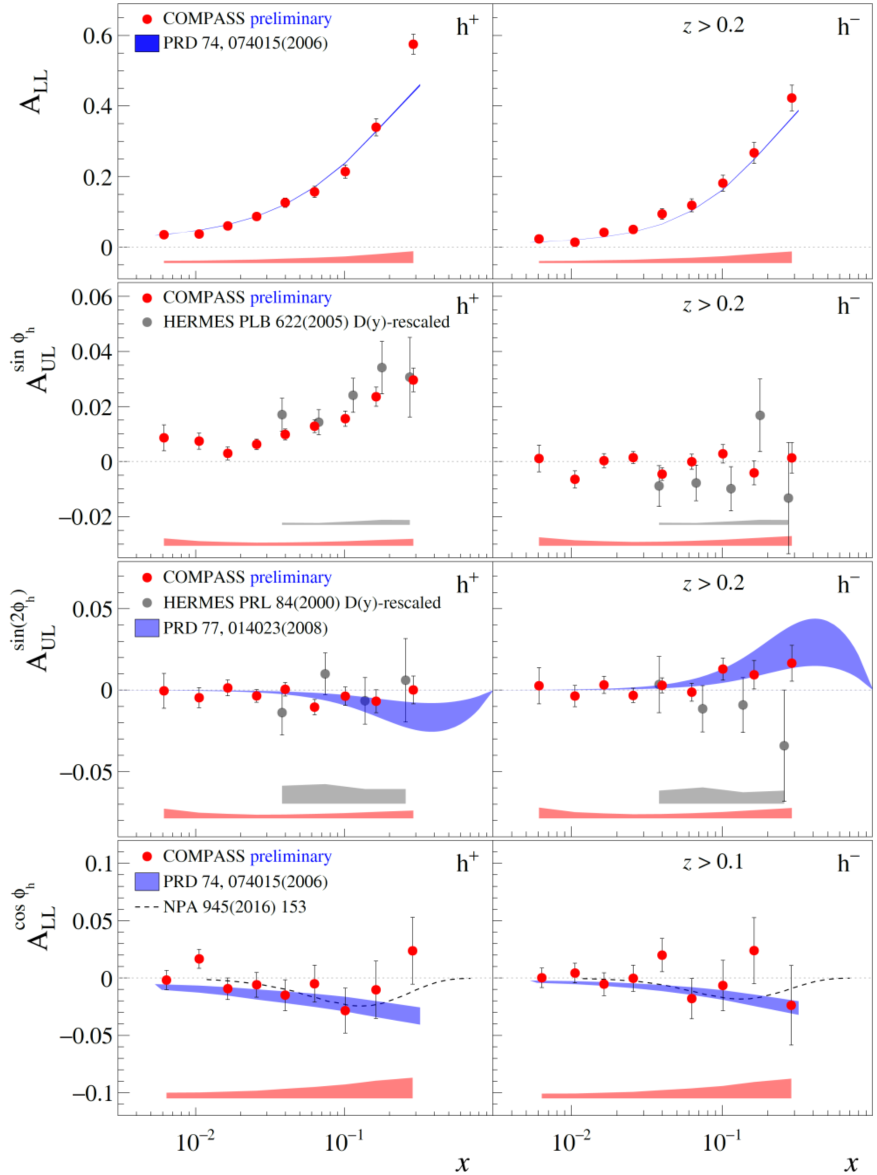
COMPASS 25 years 1997 - 2022

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

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

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

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



COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

$A_{UL}^{\sin\phi_h}$
- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- Significant h+ asymmetry, clear z-dependence
- h– compatible with zero

$A_{UL}^{\sin 2\phi_h}$
- Only "twist-2" ingredients
- Additional p_T-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

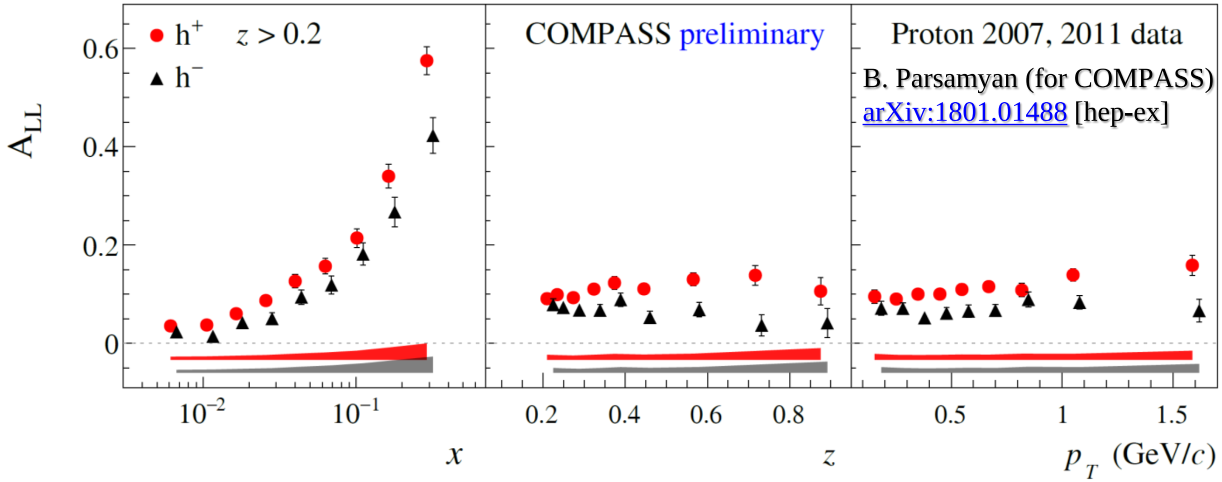
$A_{LL}^{\cos\phi_h}$
- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models

SIDIS: target longitudinal spin dependent asymmetries

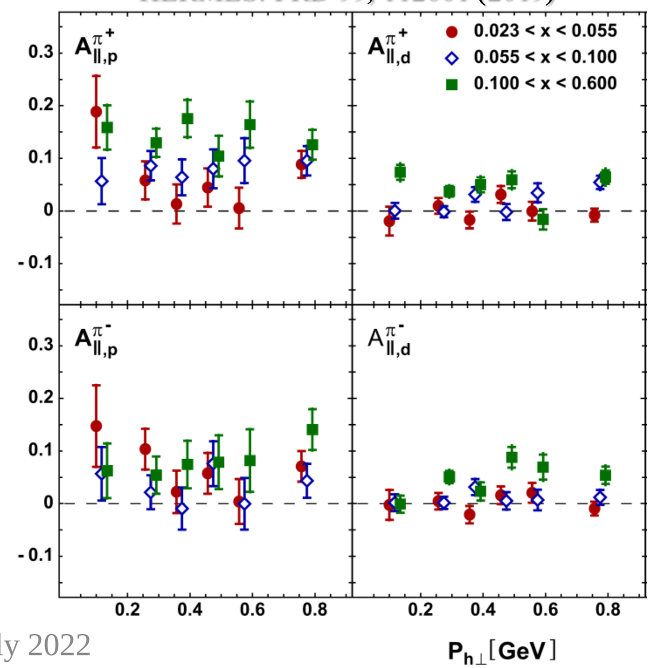
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} + \ldots \right\}$$

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

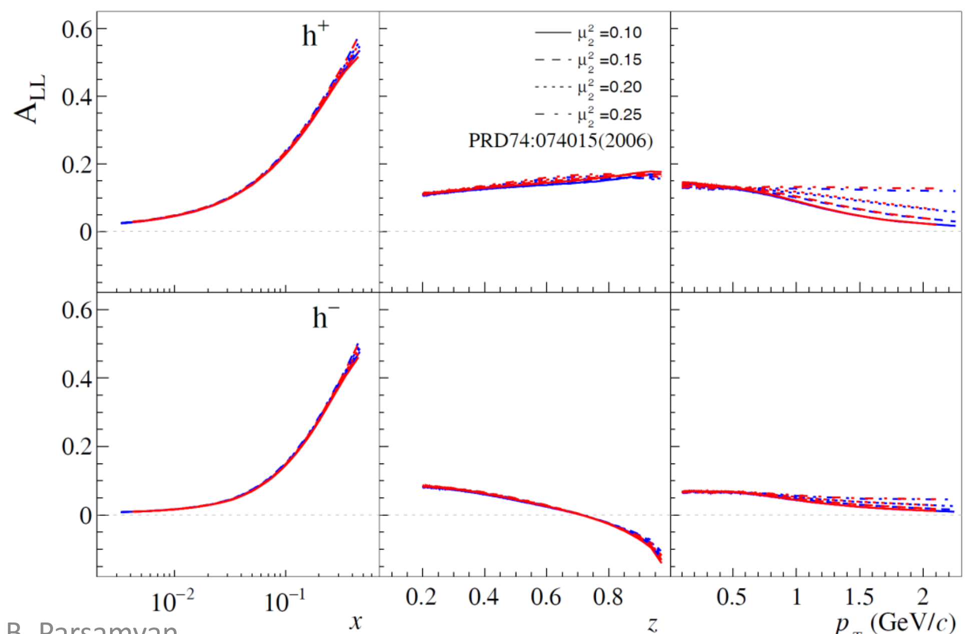
- Measurement of (semi-)inclusive A_1(A_{LL}) is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed



HERMES: PRD 99, 112001 (2019)

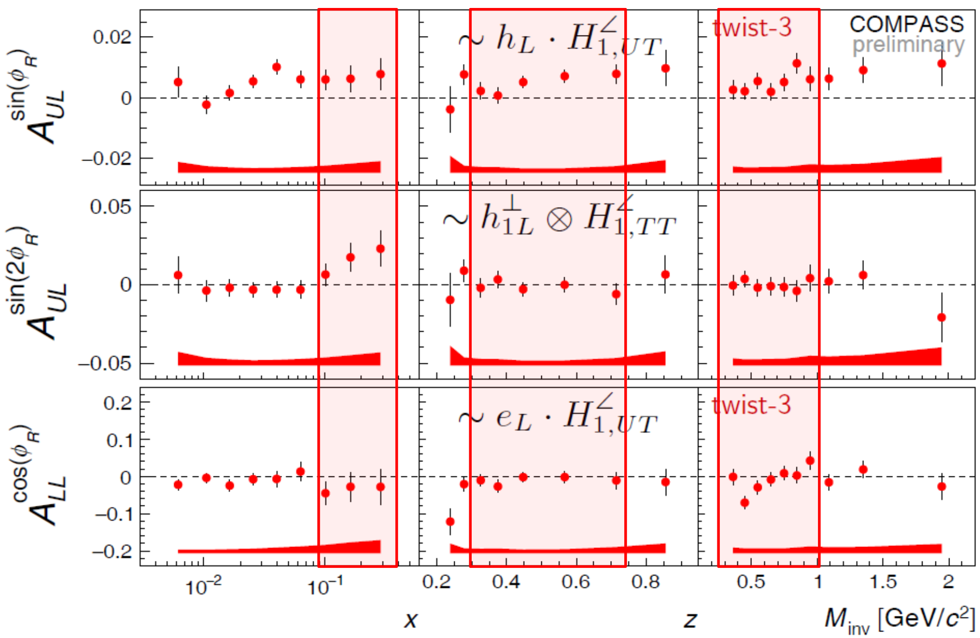


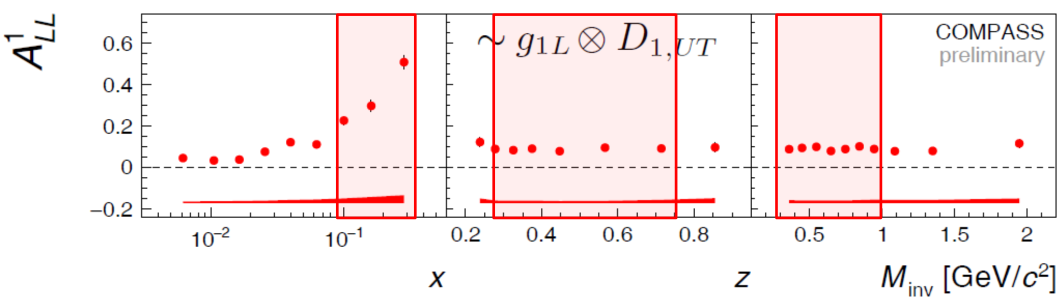
COMPASS Proton-2007, -2011 kinematics



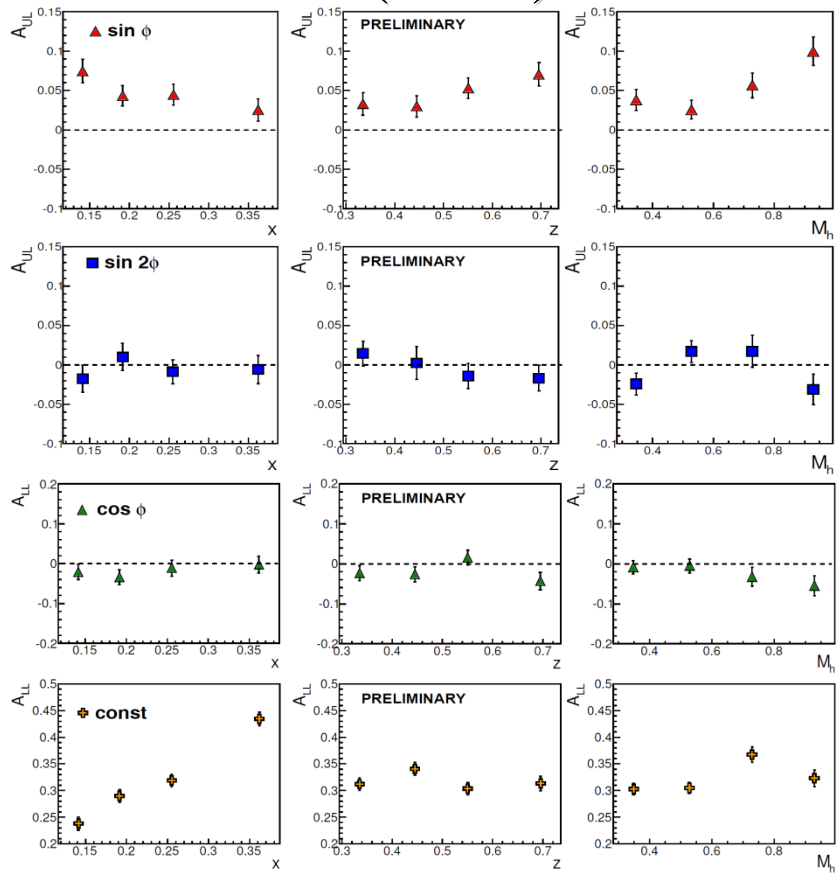
Selected results for di-hadron asymmetries

COMPASS (NH_3) 2007+2011 data

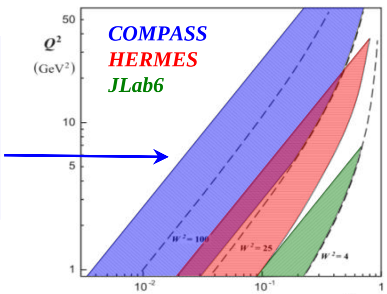




CLAS 6 GeV (NH_3)
S. A. Pereira: PoS (DIS 2014) 231



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



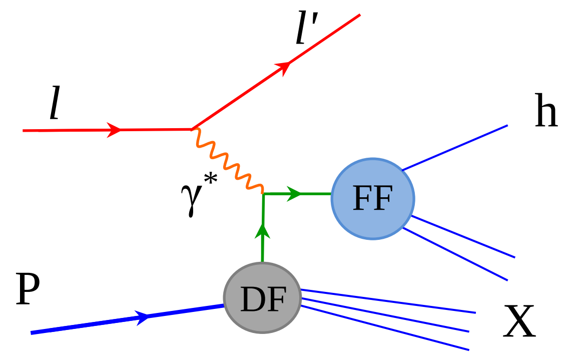
- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A^1_{LL}
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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

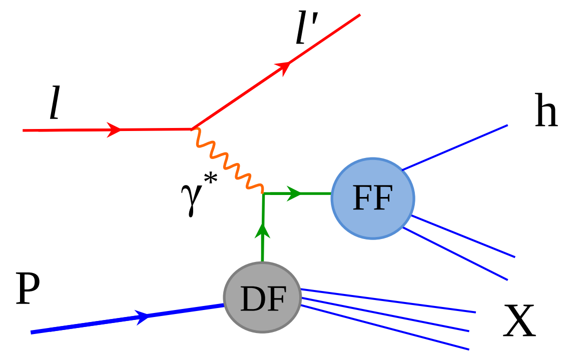
spin of the nucleon **spin of the quark** **k_T**

SIDIS x-section and TMDs at twist-2

All measured by COMPASS

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

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



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

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

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

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

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

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

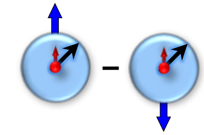
$$A_{LT}^{\cos(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^h+\ldots\right)$$

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

Twist-2

Twist-3

SIDIS TSAs: Collins effect and Transversity

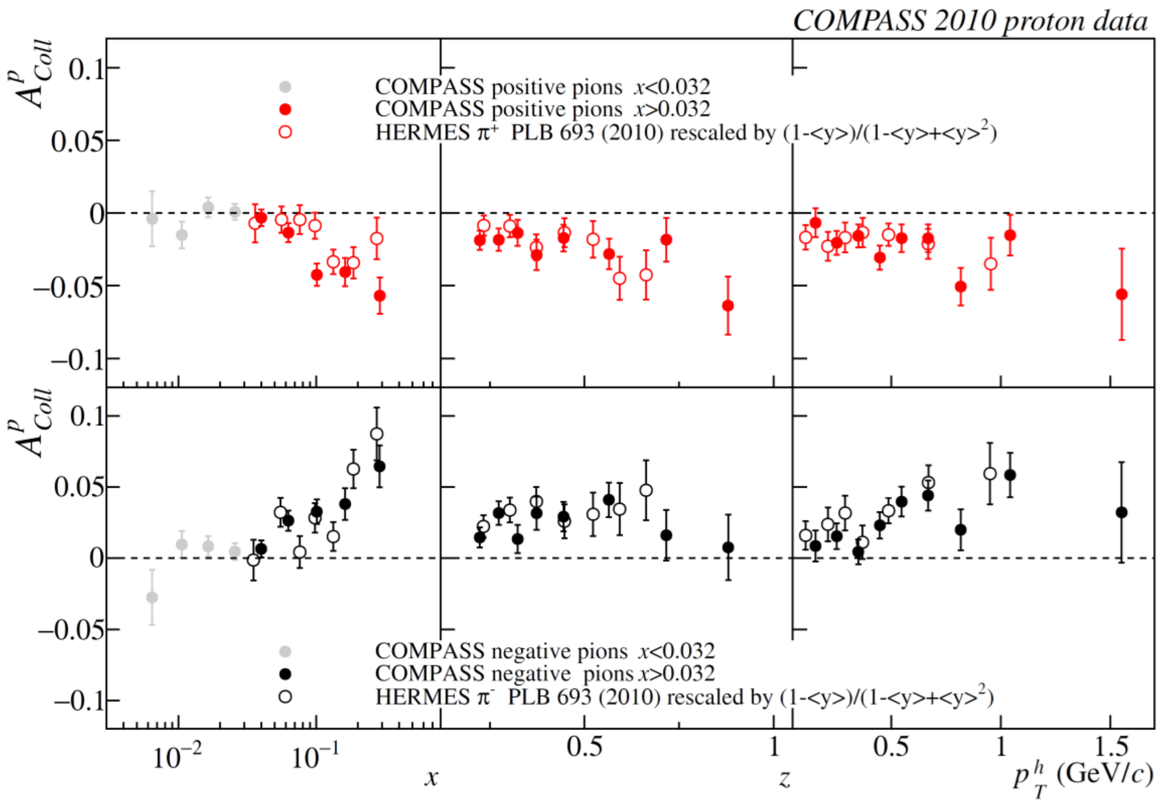


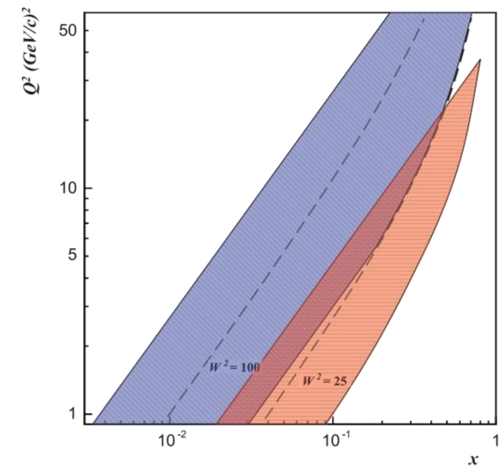
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) + \ldots\right\}$$

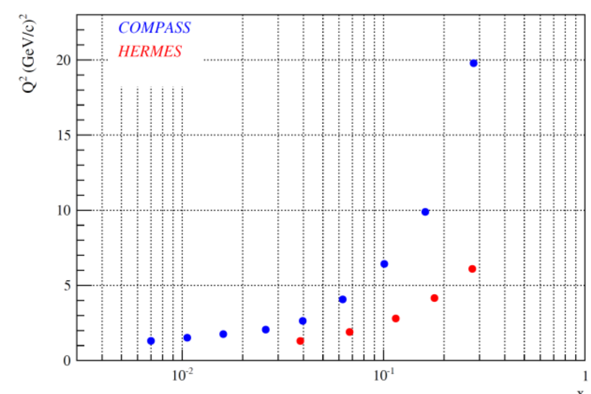
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

- 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

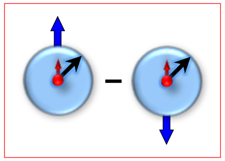






SIDIS TSAs: Collins effect and Transversity

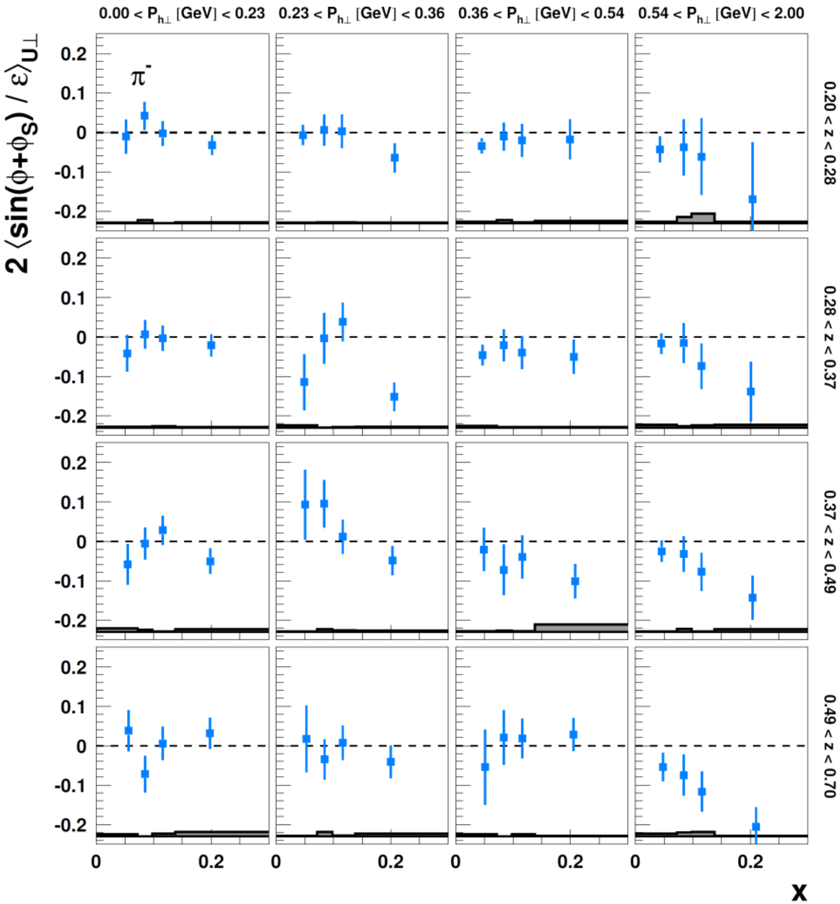
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$



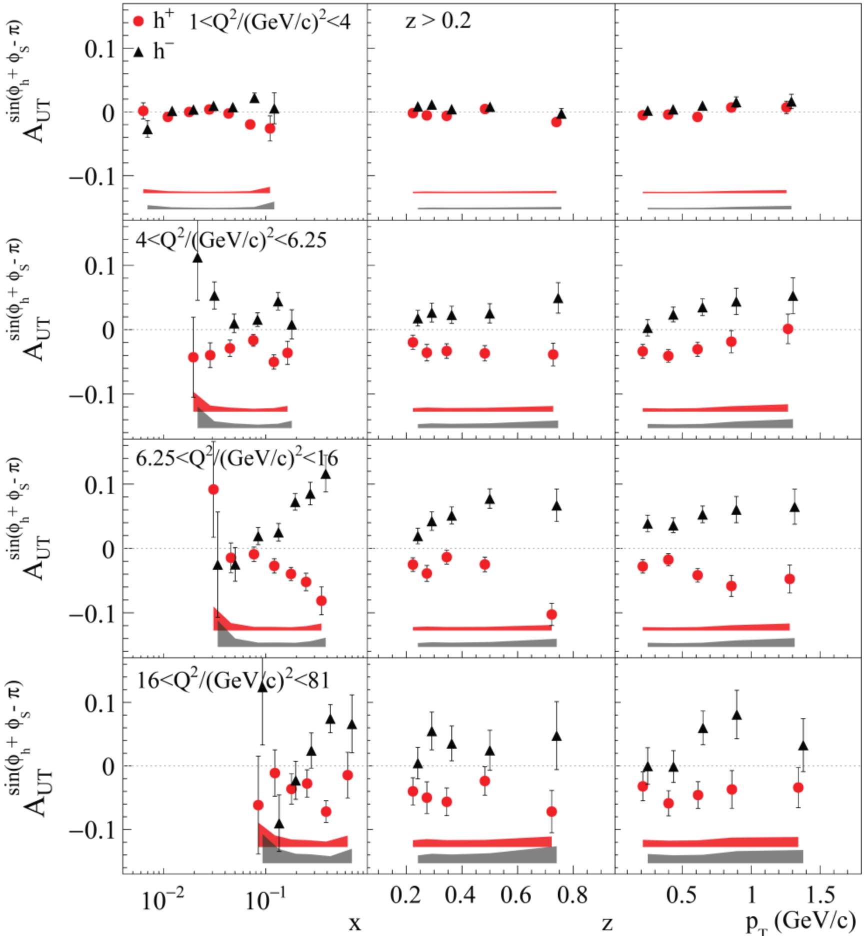
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

- 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?

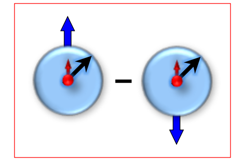
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



SIDIS TSAs: Collins effect and Transversity



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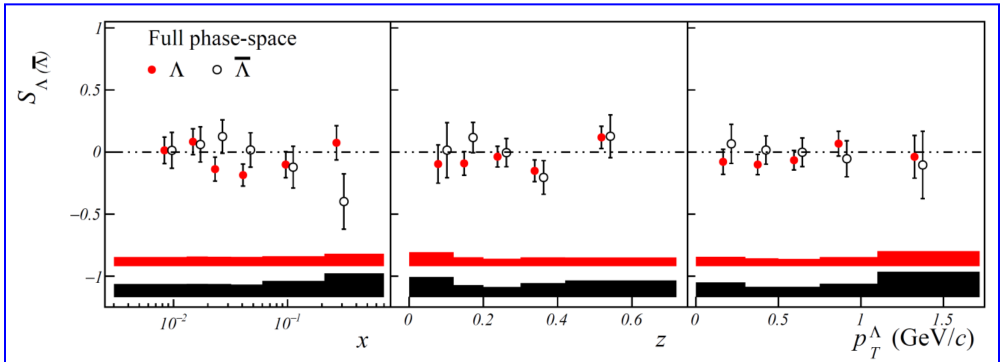
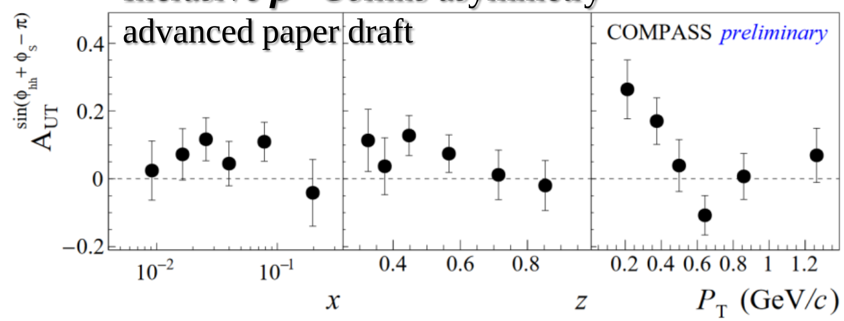
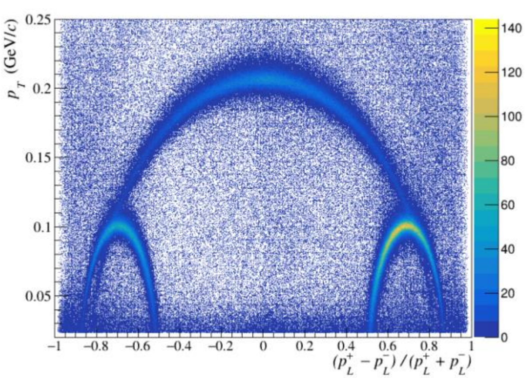
PLB 824 (2022) 136834 - NEW

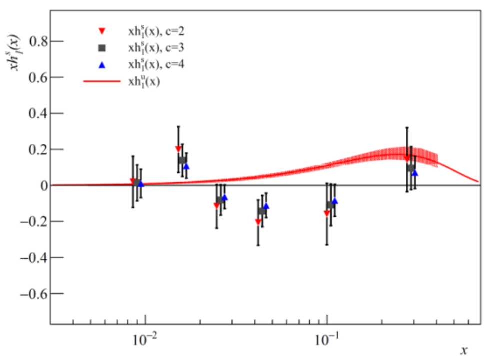


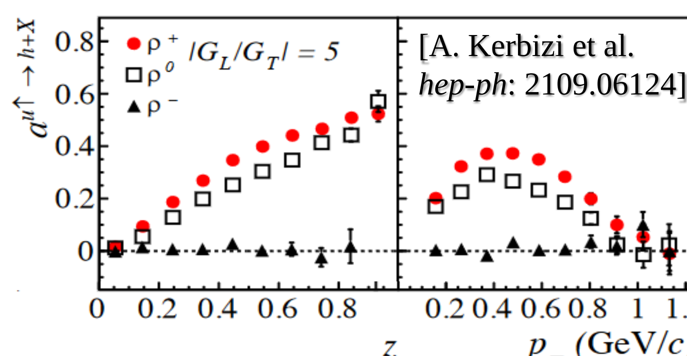
Inclusive ρ^0 Collins asymmetry



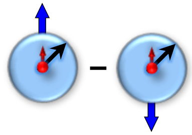
- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T







SIDIS TSAs: Collins effect and Transversity



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

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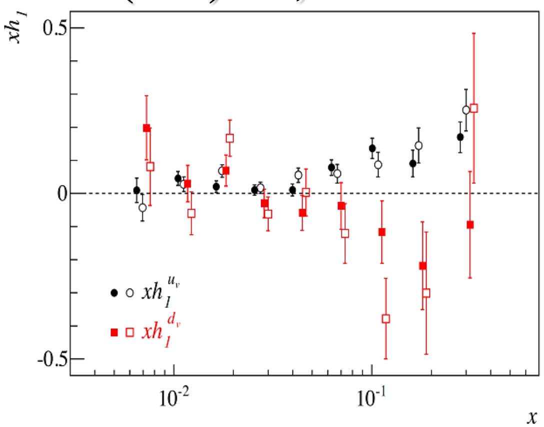
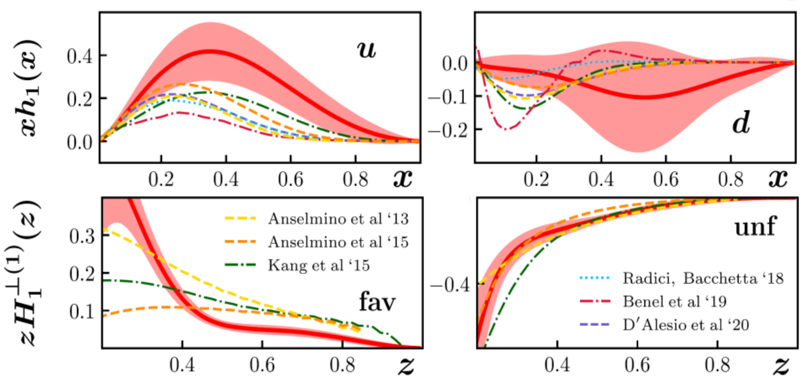
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

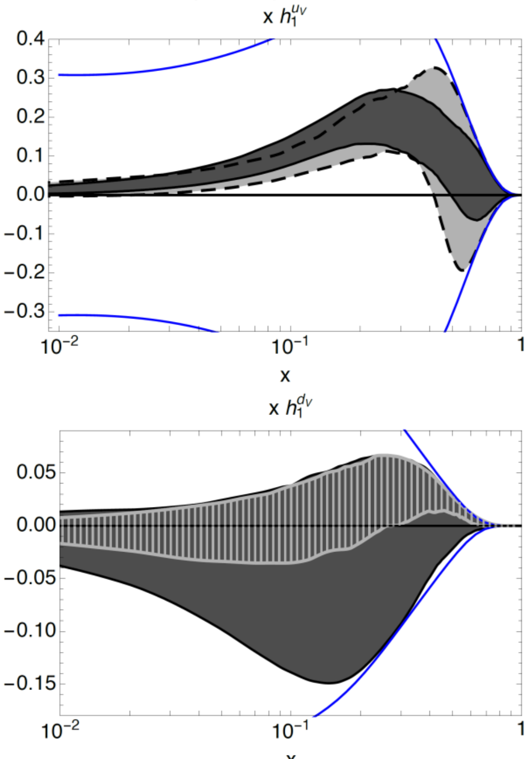
A. Martin, F. Bradamante, V. Barone
PRD91 (2015) no.1, 014034



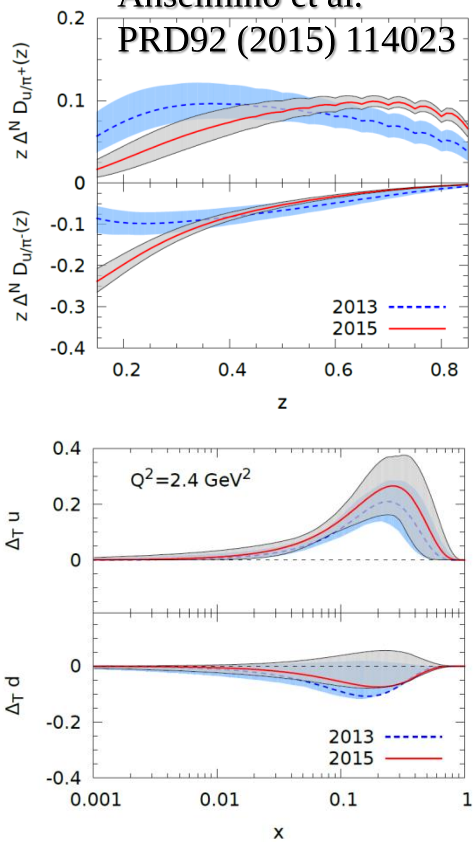
JAM Collaboration, PRD 102, 054002 (2020)]



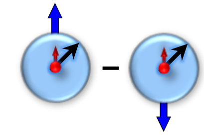
M. Radici and A. Bacchetta
PRL 120 (2018) no.19, 192001



Anselmino et al.
PRD92 (2015) 114023



SIDIS TSAs: Collins effect and Transversity



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

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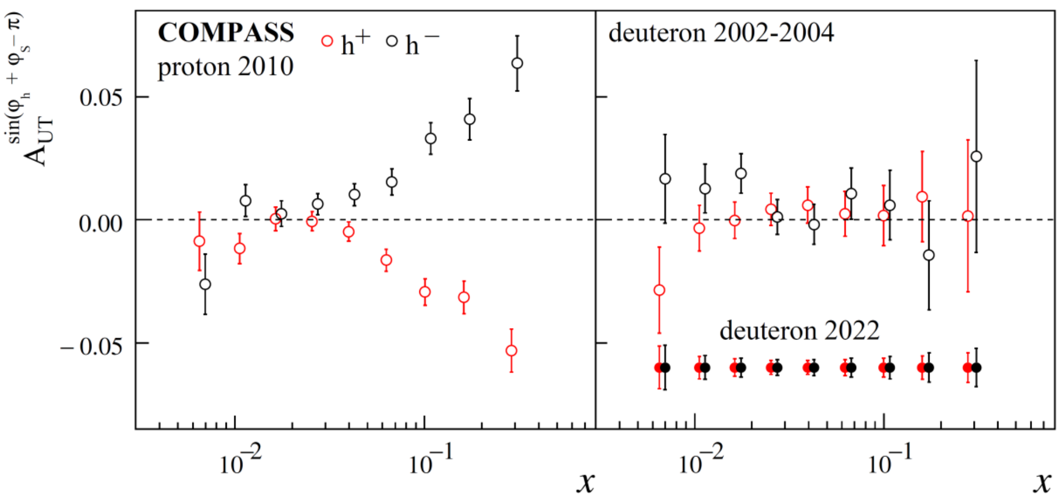
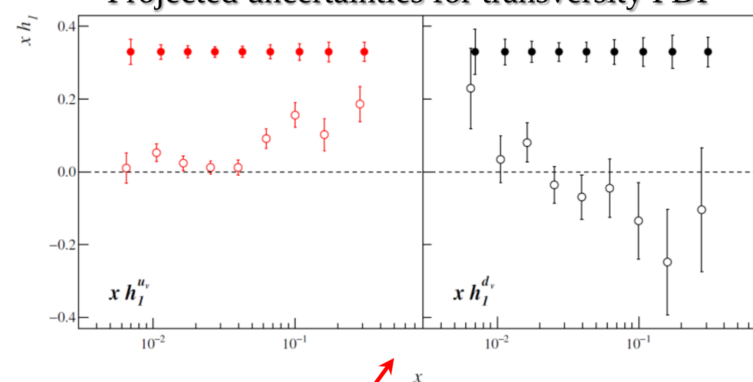
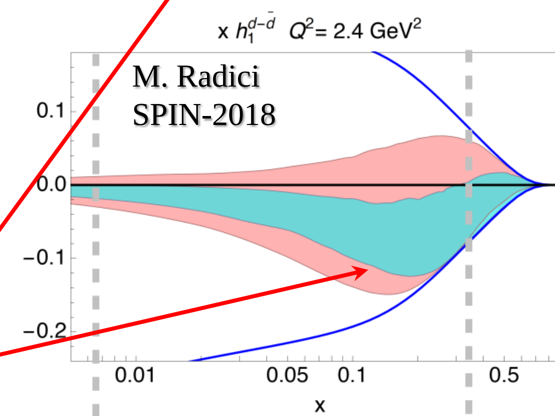
[Addendum to the COMPASS-II Proposal]
Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF

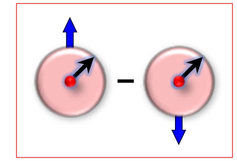




COMPASS-II (2022)

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

SIDIS TSAs: Sivers effect

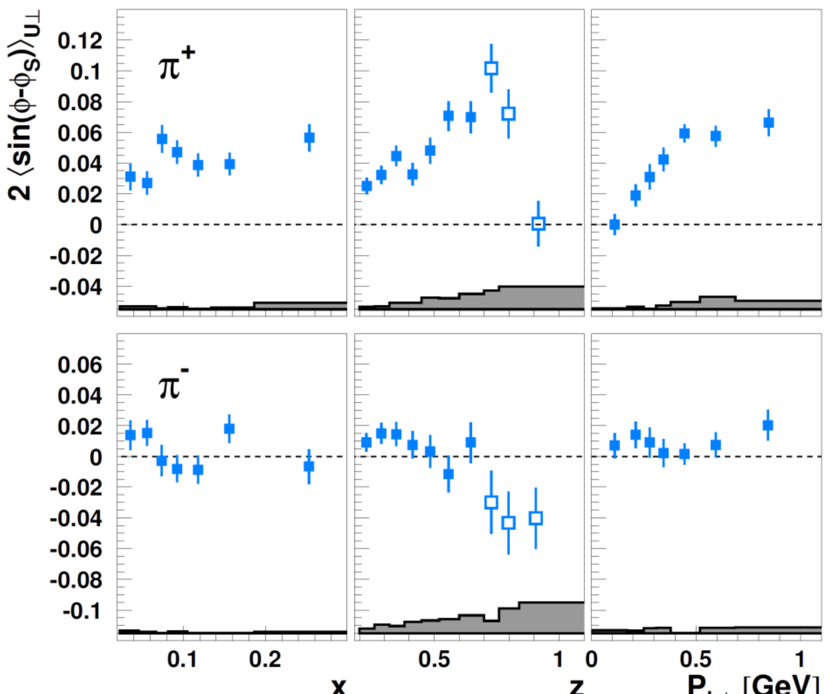


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

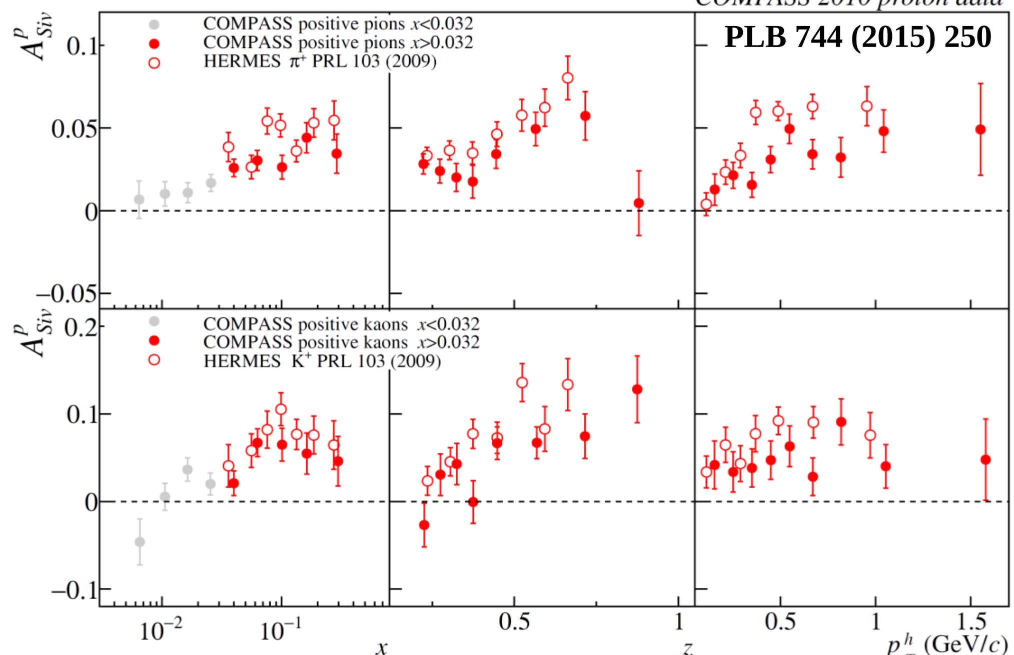
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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

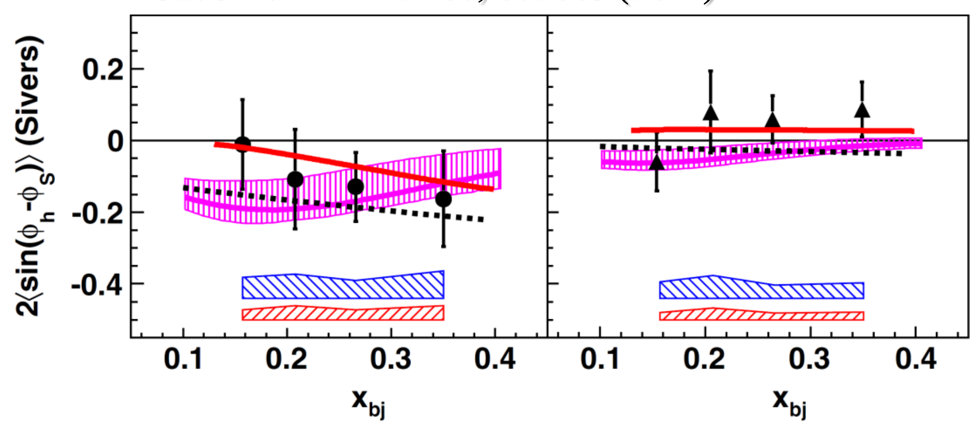
HERMES, JHEP 12 (2020) 010



COMPASS 2010 proton data



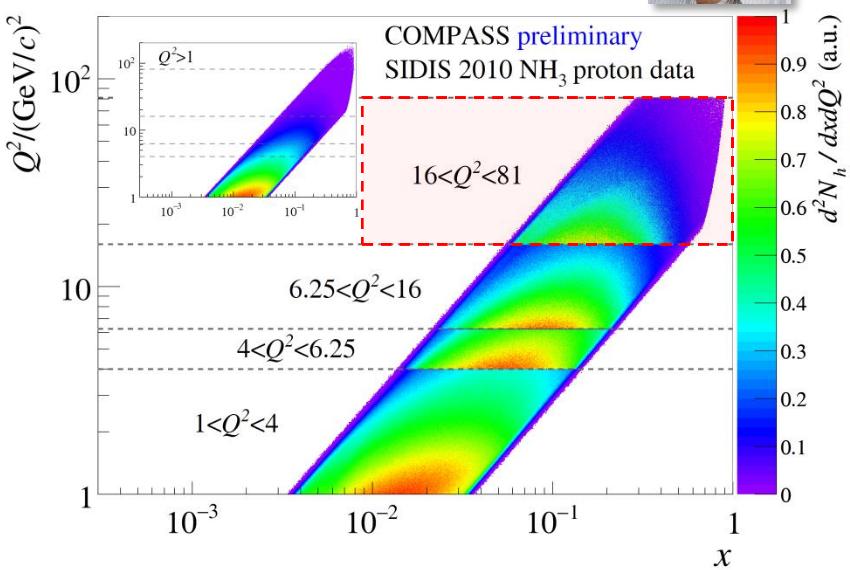
JLab Hall A PRL 107, 072003 (2011)

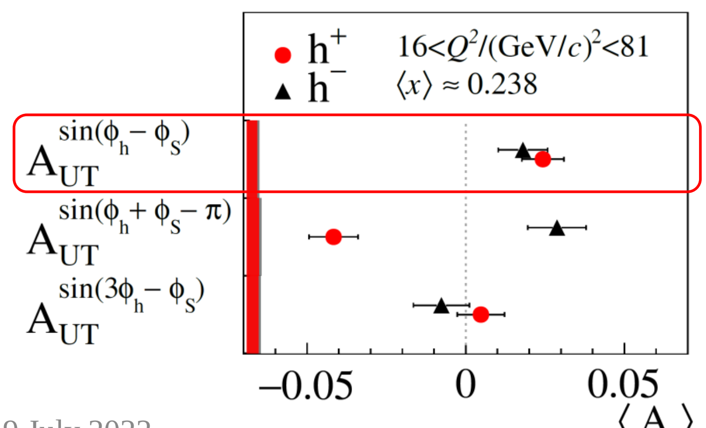


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

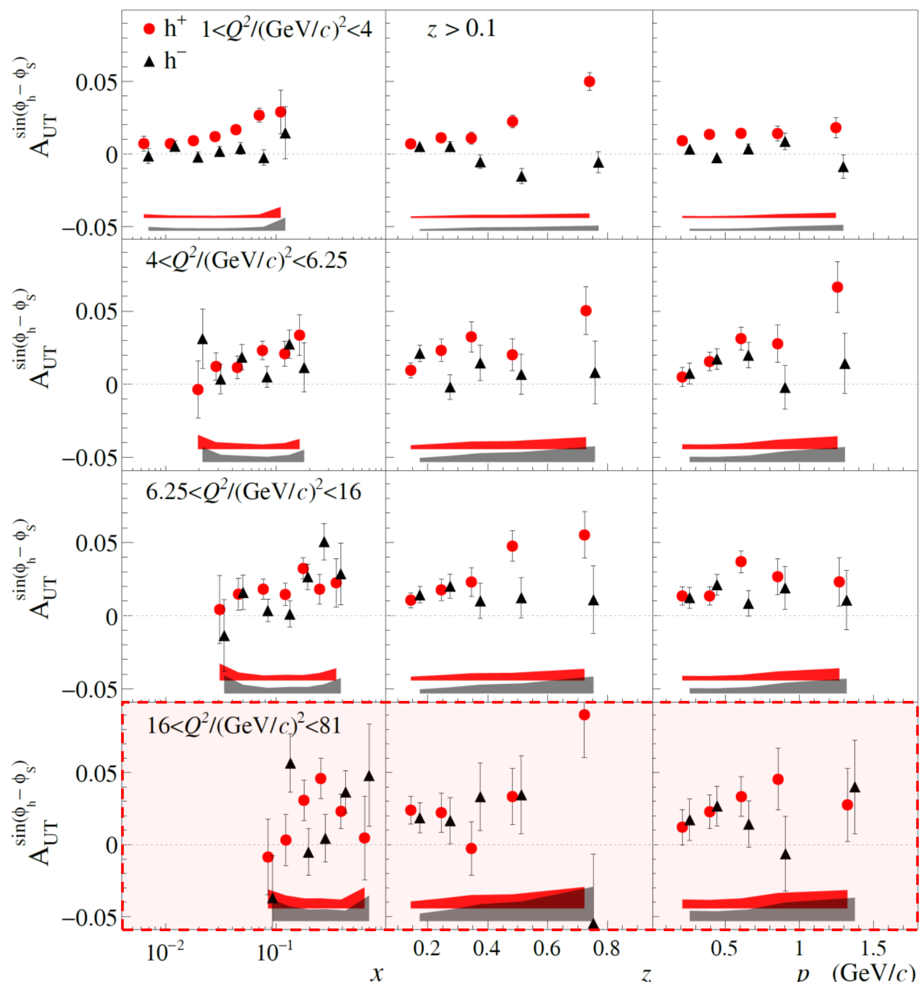
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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





COMPASS PLB 770 (2017) 138



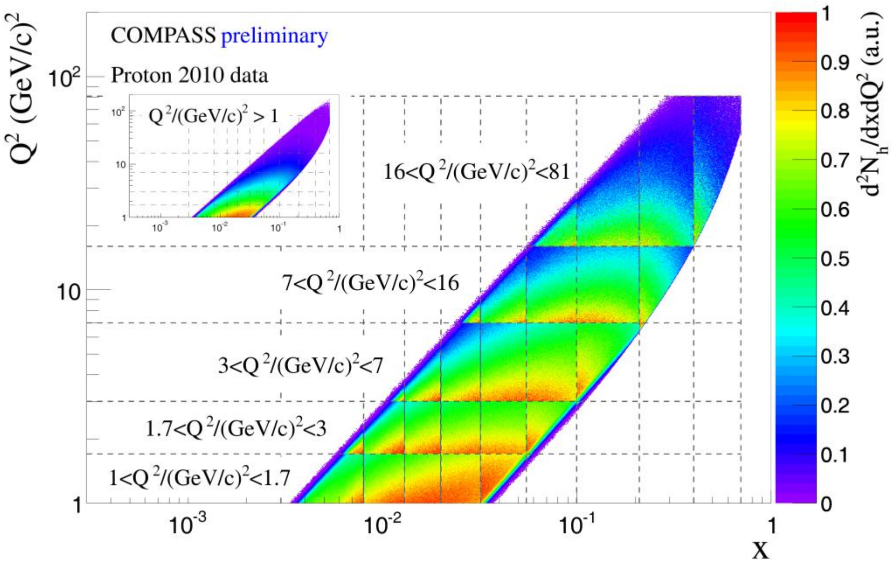
1st COMPASS multi-D fit done for all eight TSAs

COMPASS Multi-D TSA analyses

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

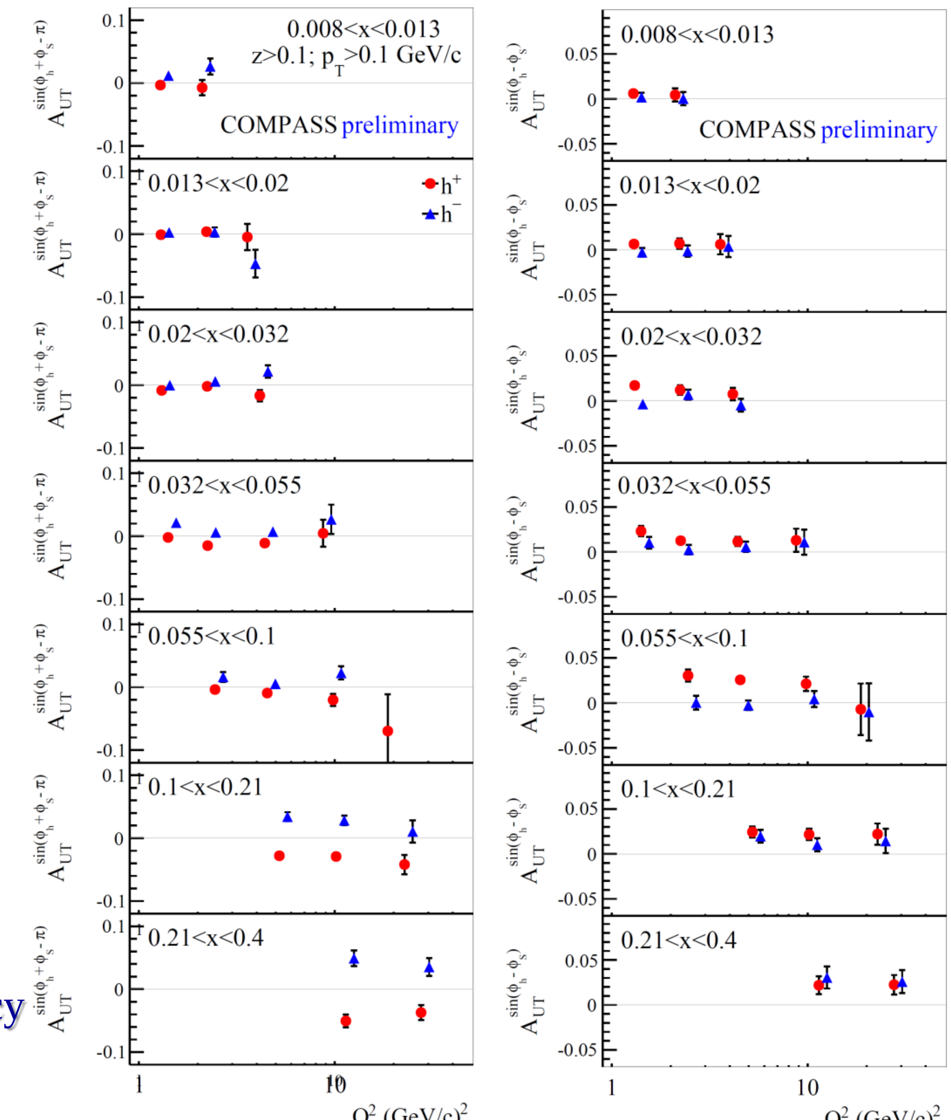
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{k_T}}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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



3D x:Q^2:z or x:Q^2:p$_T$ x:z:p$_T$

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



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

COMPASS Multi-D TSA analyses

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

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

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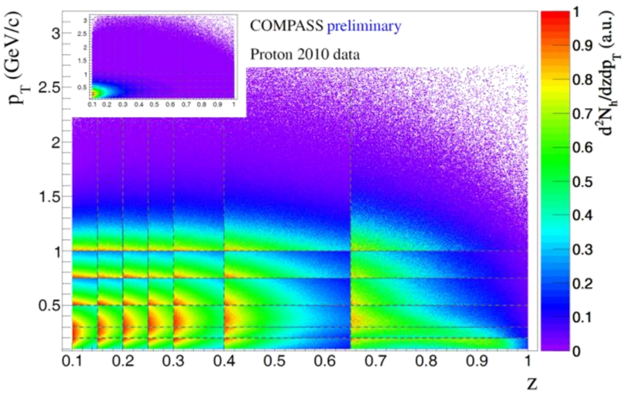
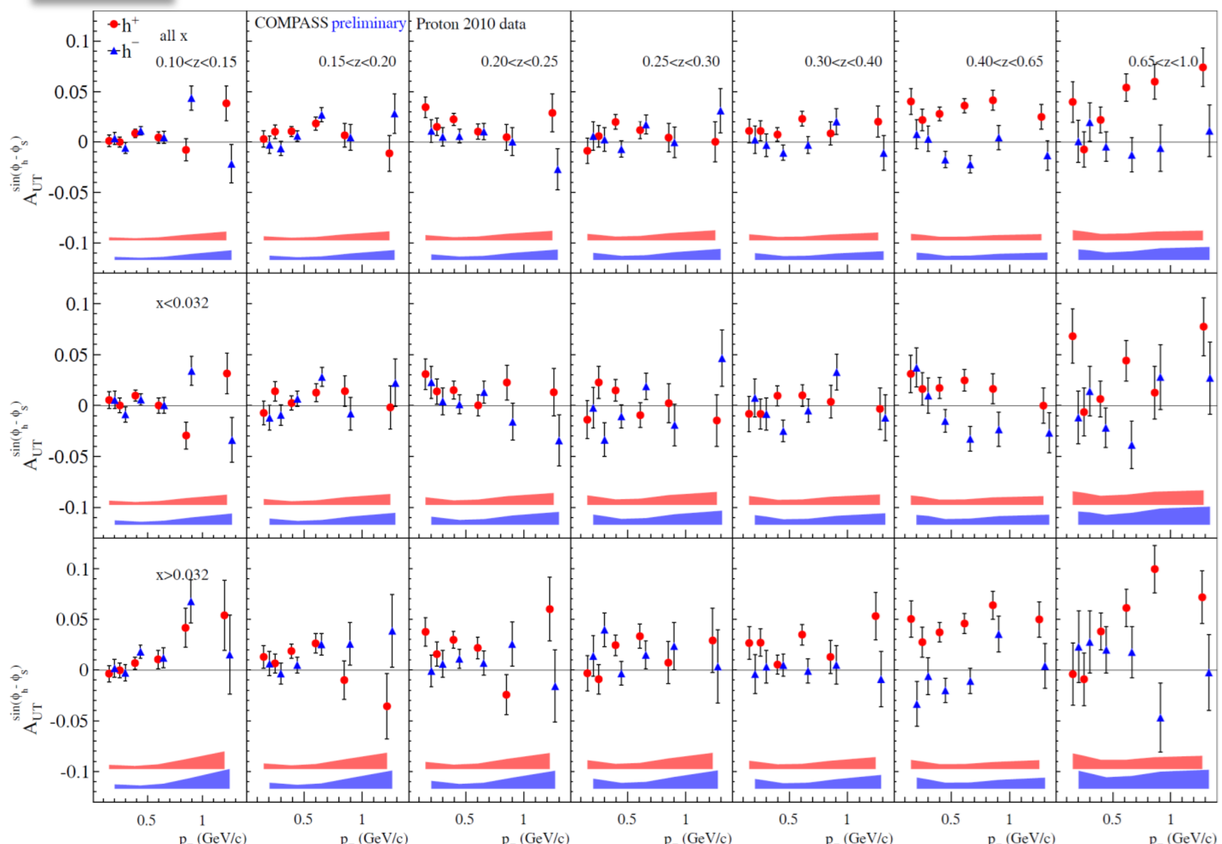




Multi-D extraction
3D $x{:}Q^2{:}z$ or $x{:}Q^2{:}p_T$ $x{:}z{:}p_T$

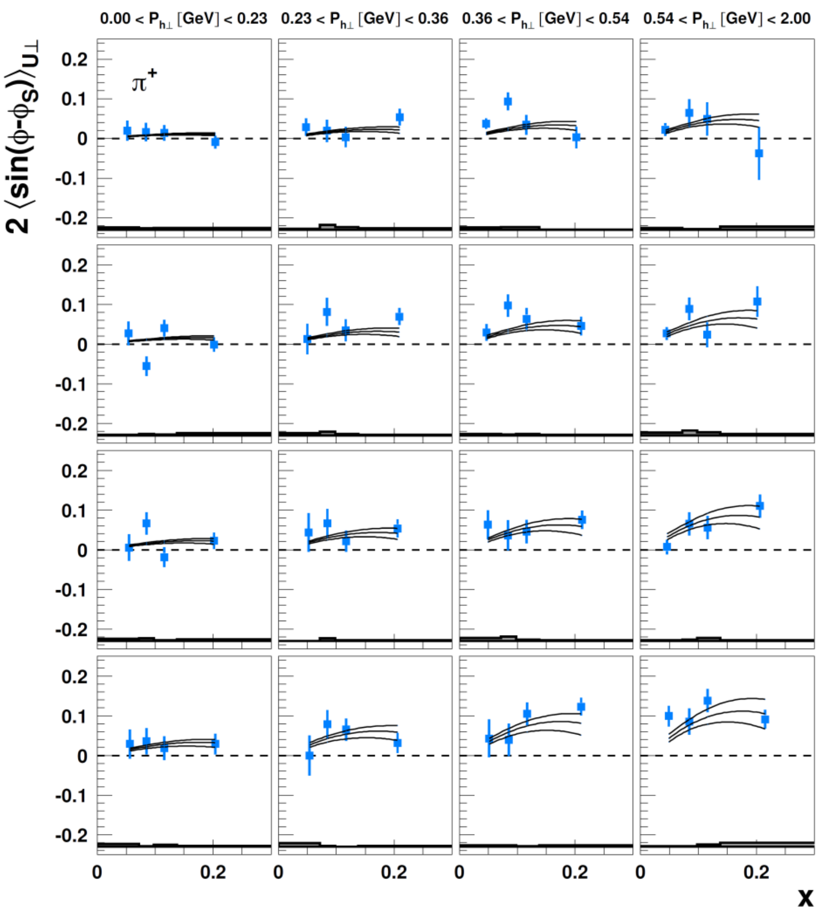
- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?
- Negative amplitude for h^- at large z?

COMPASS Multi-D TSA analyses

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

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

HERMES, JHEP 12 (2020) 010



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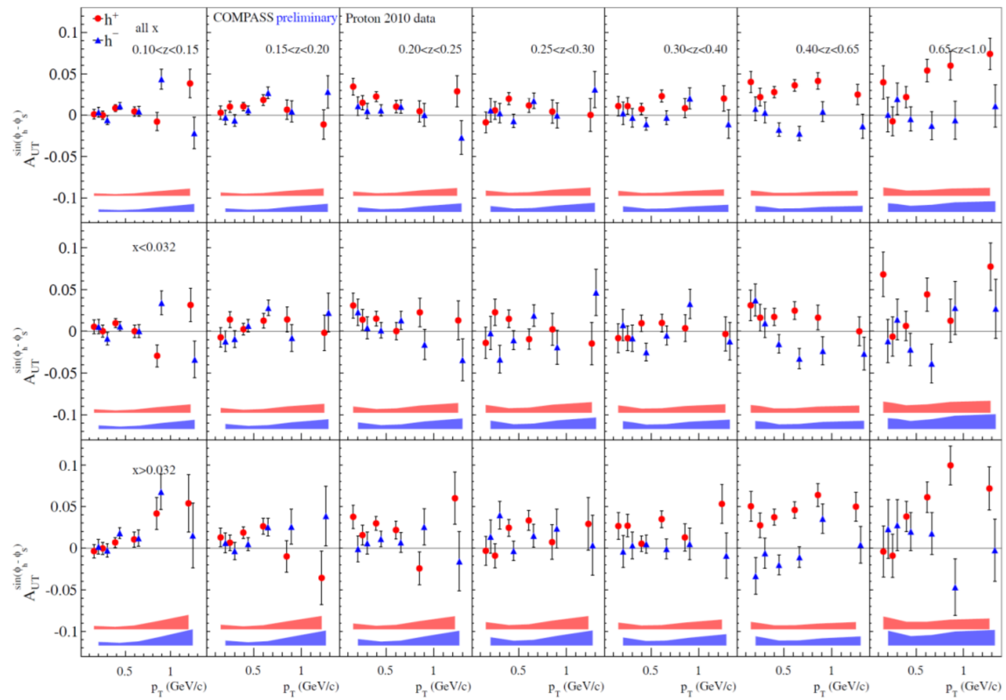
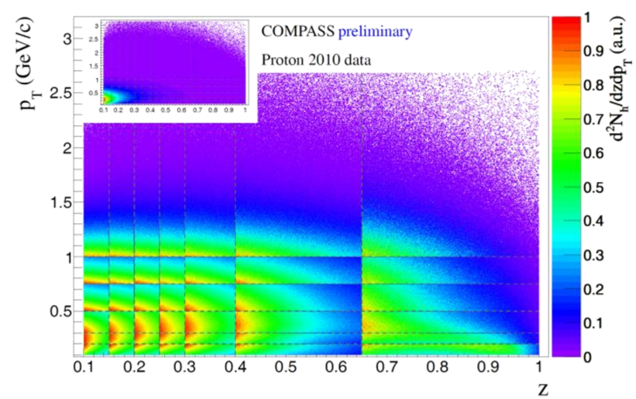
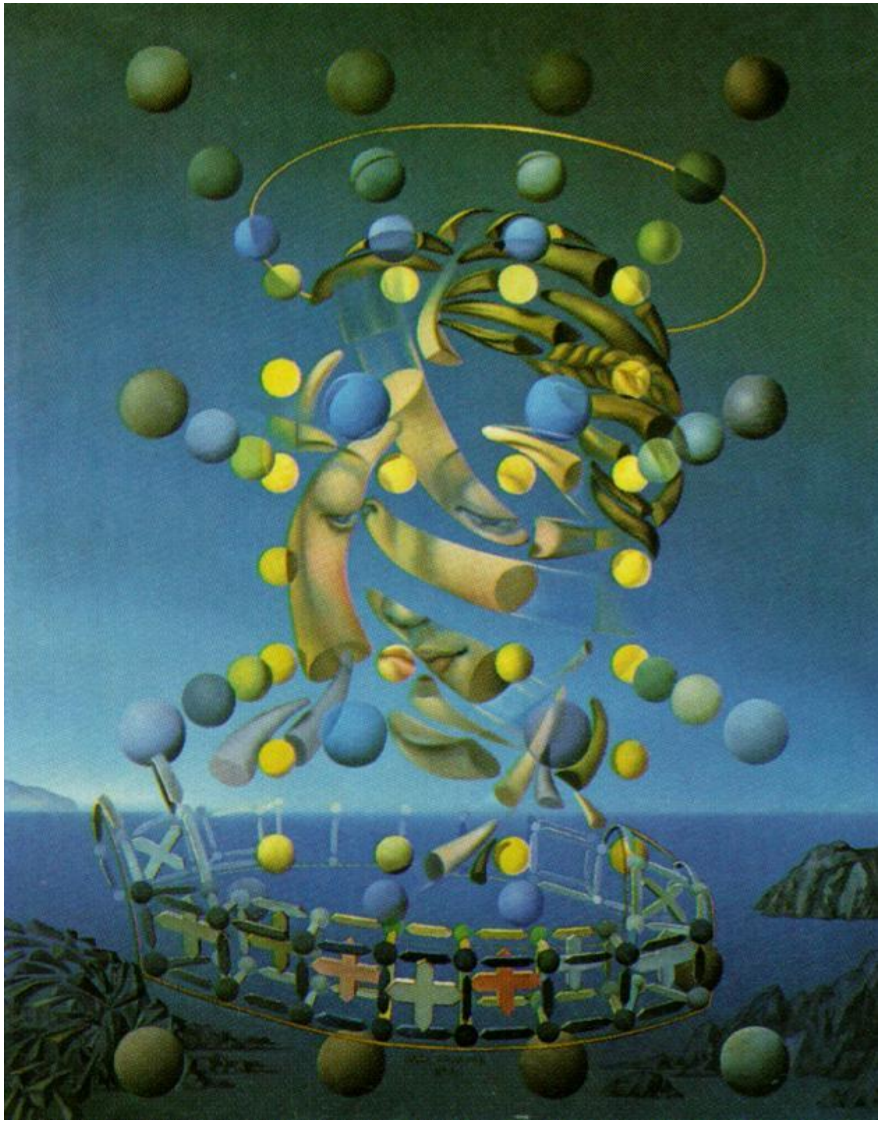




“Nature”

“1D”

Raphael “Madonna del Prato”



Salvador Dali “Maximum Speed of Raphael's Madonna”

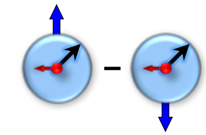
"Nature"

"multi-D" with available statistics

Raphael *"Madonna del Prato"*

Raphael *"Madonna del Prato"* *(poor resolution)*

SIDIS TSAs: Kotzinian-Mulders asymmetry



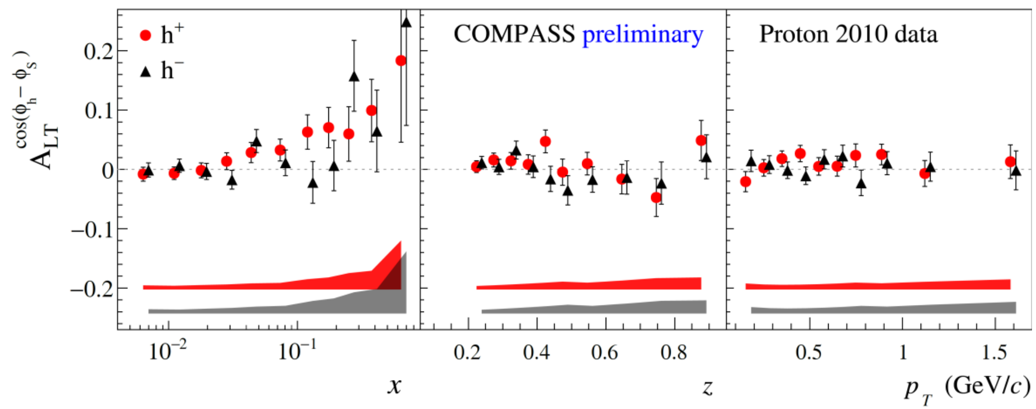
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + \lambda S_T \sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos\left(\phi_h - \phi_S\right) + \ldots\right\}$$

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

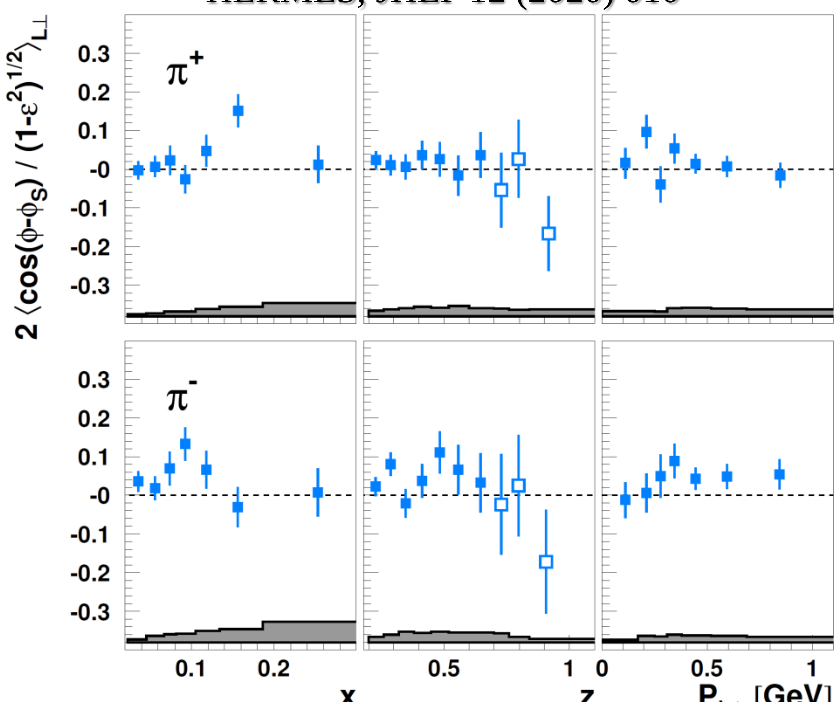
COMPASS/HERMES/CLAS6 results $A_{LT}^{\cos(\phi_h-\phi_S)}$

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

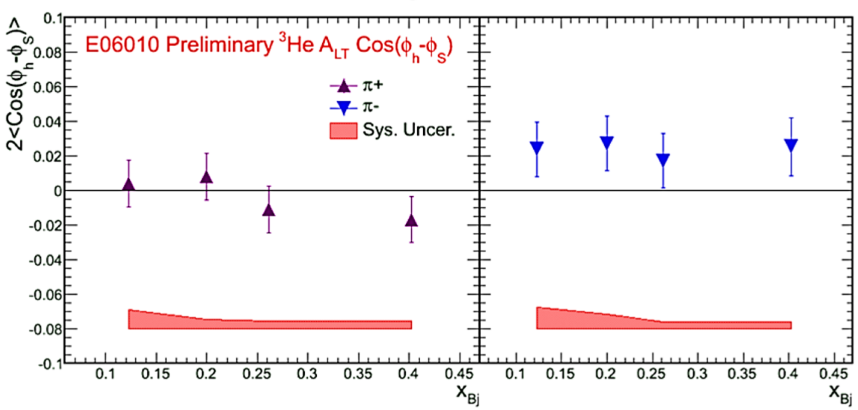
COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



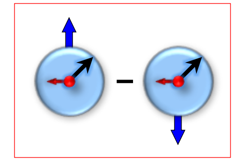
HERMES, JHEP 12 (2020) 010



CLAS6, neutron target



SIDIS TSAs: Kotzinian-Mulders asymmetry



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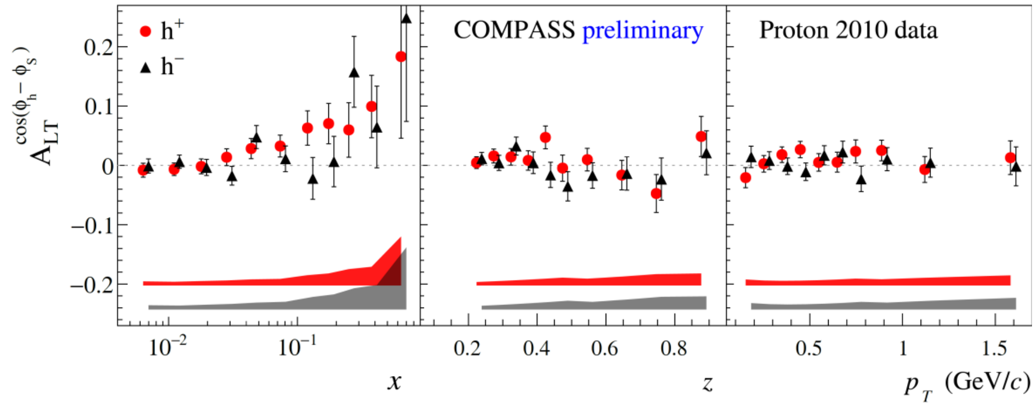
$$F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} g_{1T}^q D_{1q}^h\right]$$

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



COMPASS/HERMES/CLAS6 results $A_{LT}^{\cos(\phi_h-\phi_S)}$

- Only "twist-2" ingredients
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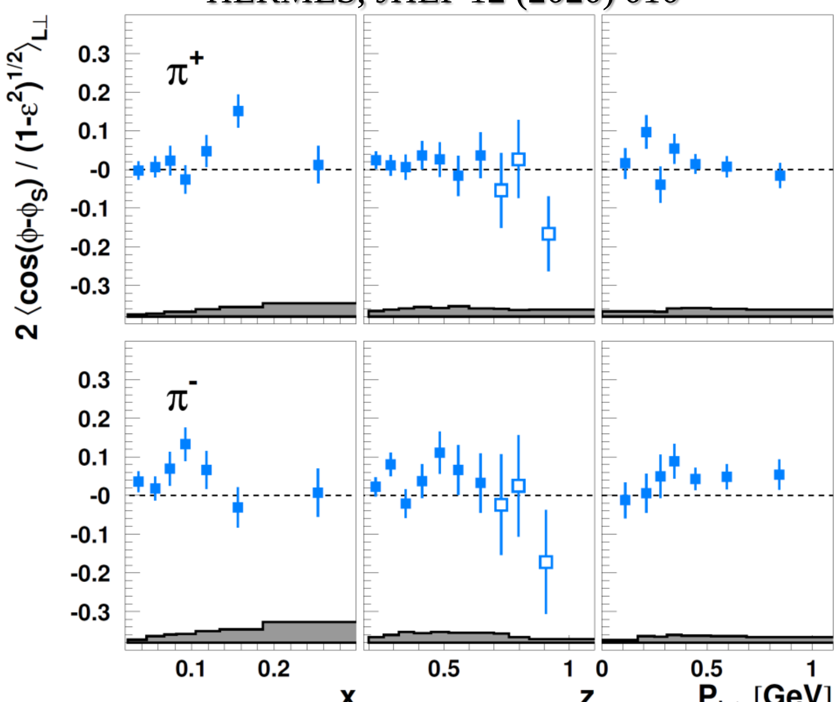
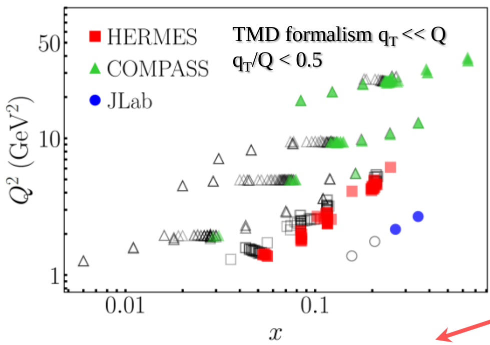
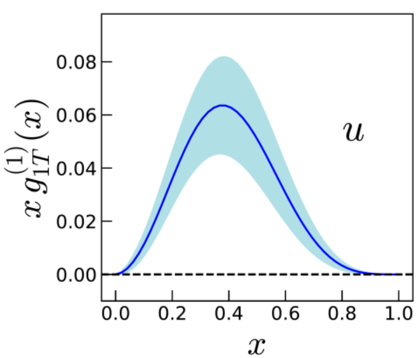
- Similar effect at HERMES

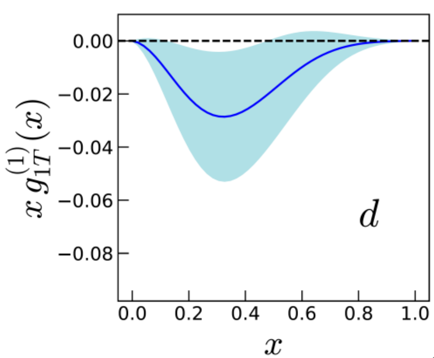
HERMES, JHEP 12 (2020) 010





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





SIDIS TSAs: subleading twist effects

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

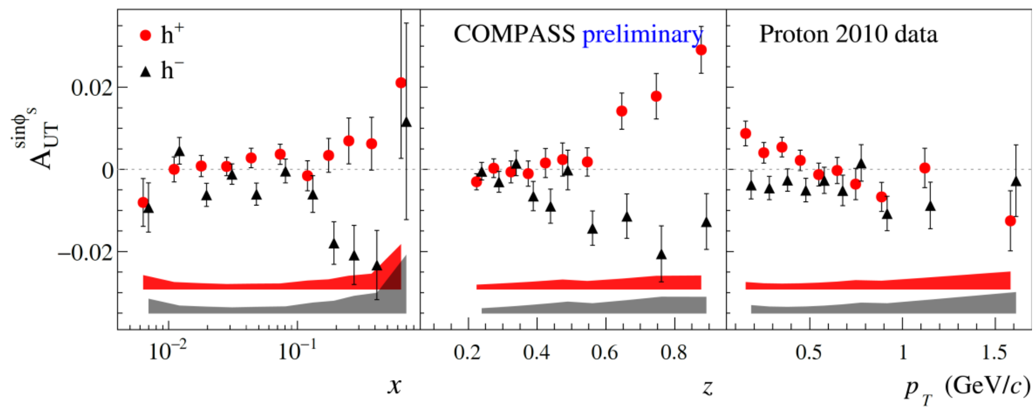
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C\left\{\left(xf_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(xh_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(xh_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

COMPASS/HERMES results

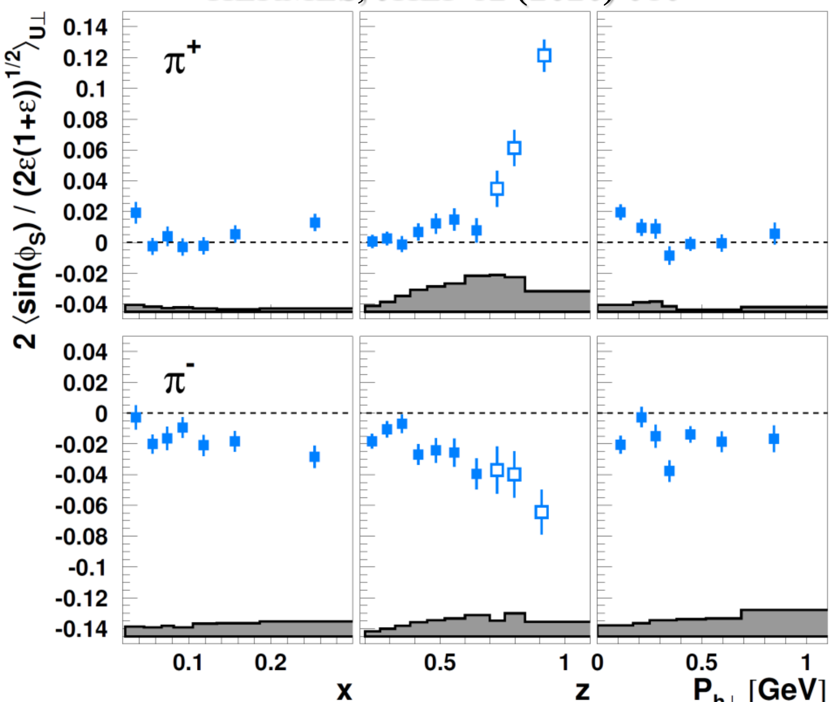
$A_{UT}^{\sin\phi_S}$

- Q-suppression
- various "twist-2/3" ingredients
- non-zero signal for $h^{\pm}$ at large z?

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



HERMES, JHEP 12 (2020) 010

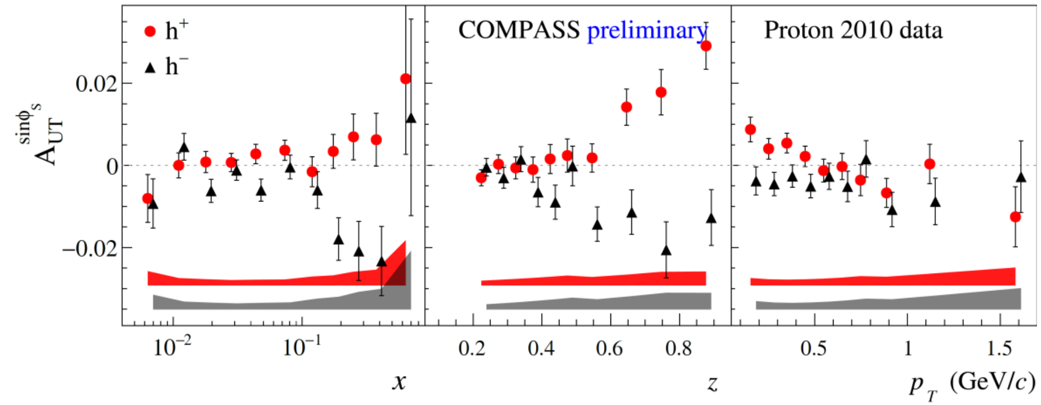


SIDIS TSAs: subleading twist effects

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

$$F_{UT}^{\sin\phi_S}=\frac{2M}{Q}C\left\{\left(xf_T^qD_{1q}^h-\frac{M_h}{M}h_1^q\frac{\tilde{H}_q^h}{z}\right)-\frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(xh_T^qH_{1q}^{\perp h}+\frac{M_h}{M}g_{1T}^q\frac{\tilde{G}_q^{\perp h}}{z}\right)-\left(xh_T^{\perp q}H_{1q}^{\perp h}-\frac{M_h}{M}f_{1T}^{\perp q}\frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

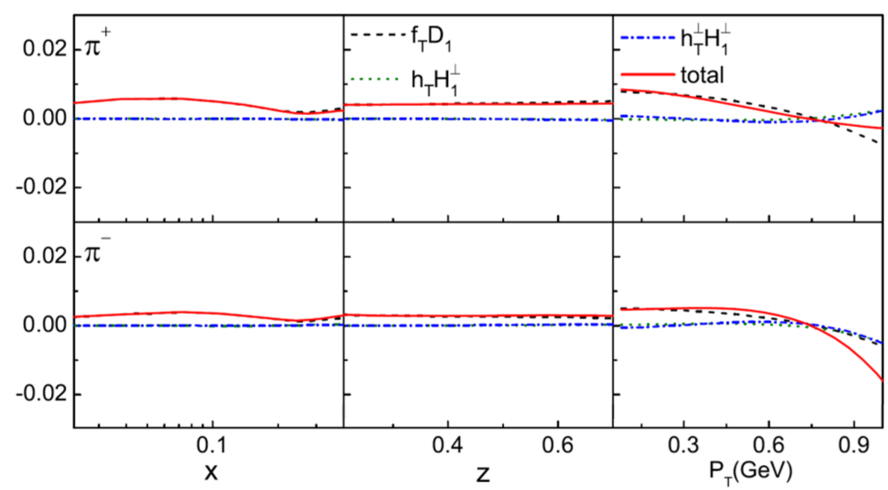
COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



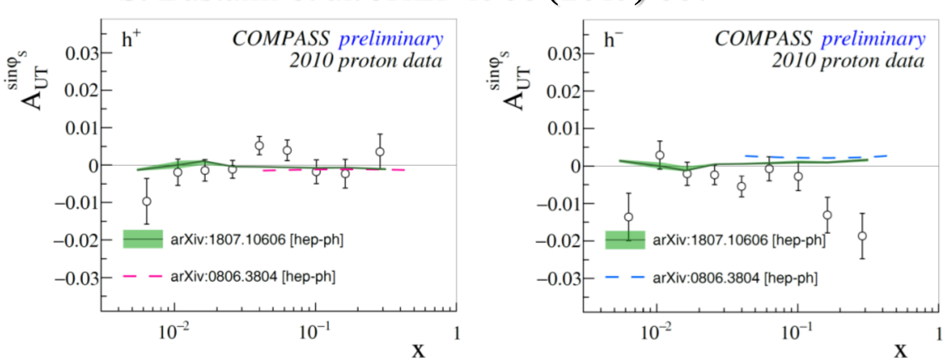
COMPASS/HERMES results $A_{UT}^{\sin\phi_S}$

- Q-suppression
- various “twist-2/3” ingredients
- non-zero signal for $h^{\pm}$ at large z?

W. Mao, Z. Lu and B.Q. Ma Phys.Rev. D 90 (2014) 014048



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



COMPASS 2022 run: new unique deuteron data to come

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

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

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

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

Same kinematic cuts applied to unpolarized

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

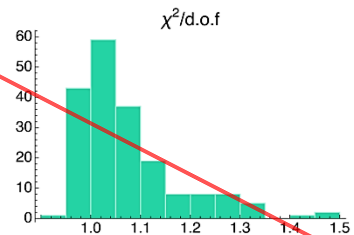
x, z, P_{hT} data projections

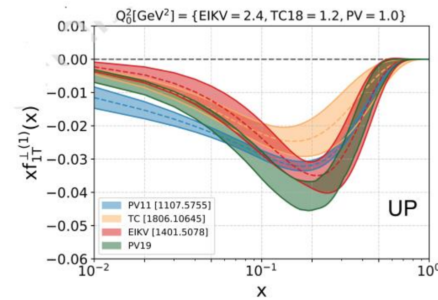
300 data points → **118** data fitted
14 free parameters
χ²/d.o.f. = 1.06 ± 0.10

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

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

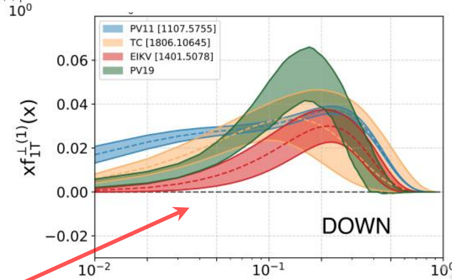




PV11	*Bacchetta & Radici, P.R.L. **107** (11)*
EIKV	*Echevarria et al., P.R. D**89** (14)*
TC	*Boglione et al., JHEP **1807** (18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

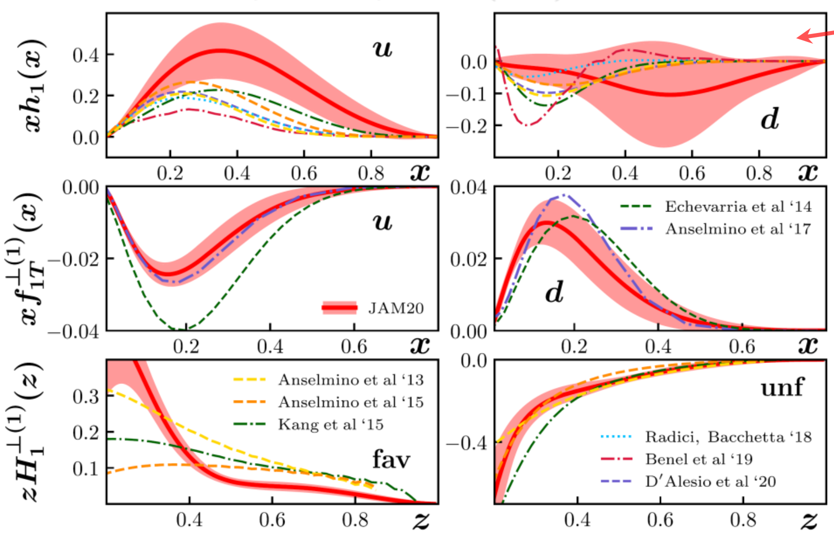
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \, \frac{\mathbf{k}_T^2}{2M^2} \, f_{1T}^{\perp}(x, \mathbf{k}_T)$$

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

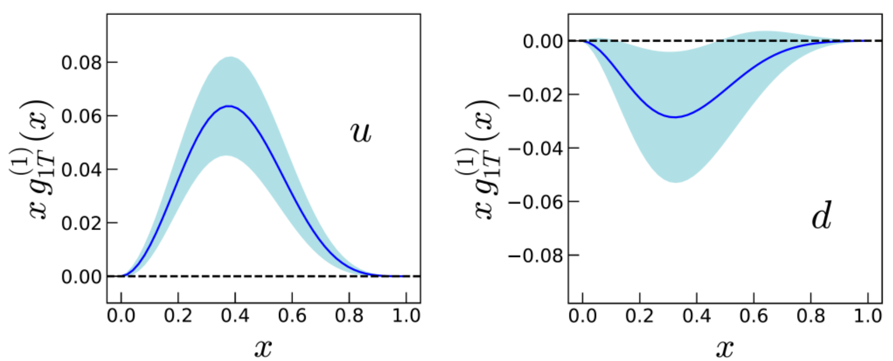


COMPASS 2022 deuteron run

JAM Collaboration, PRD 102, 054002 (2020)



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



Conclusions-SIDIS

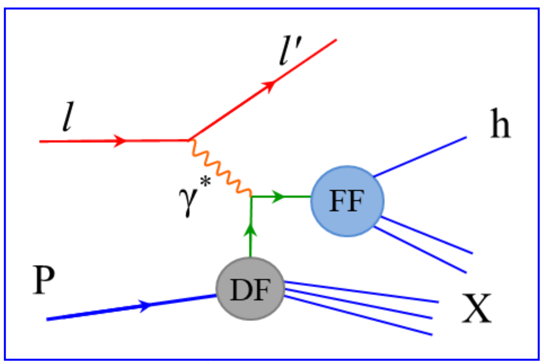
- During phase I COMPASS has measured all SIDIS TSAs (P/D)
  - Deuteron TSAs are all compatible with zero
  - Non-zero Sivers and Collins asymmetries with proton target
  - Apart from Sivers and Collins effects non-zero signal was observed for *twist-2* $A_{LT}^{cos(\phi_h-\phi_S)}$ and *subleading-twist* $A_{UT}^{\sin\phi_S}$ TSAs
  - First multi-D results for all TSAs - PLB 770 (2017) 138
    - No hints for significant Q^2-dependences of Sivers and Collins TSAs
- COMPASS has measured all SIDIS LSAs (P/D)
  - Deuteron azimuthal LSAs are compatible with zero
  - Interesting proton results, non-zero asymmetries
  - *twist-2* $A_{UL}^{\sin 2\phi_h}$ asymmetry seem to exhibit a Collins-like behavior
  - Significant effect was observed for *subleading-twist* $A_{UL}^{\sin\phi_h}$ LSA

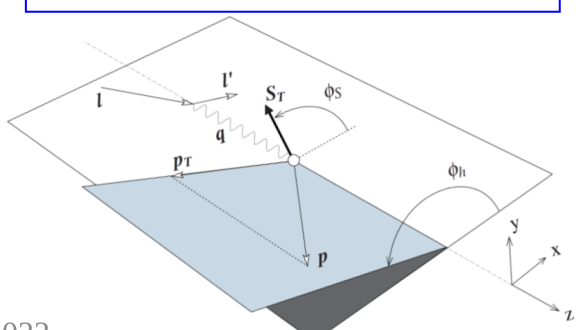
- SIDIS measurements with transversely polarized deuteron target in 2022
  - Unique input for d-quark transversity and many other studies

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

SIDIS

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

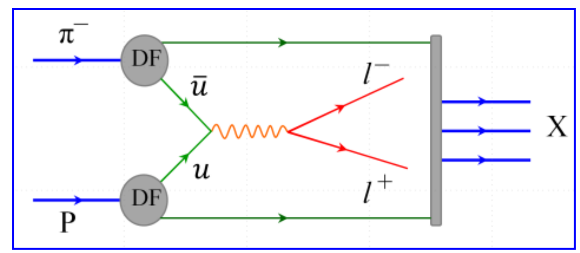


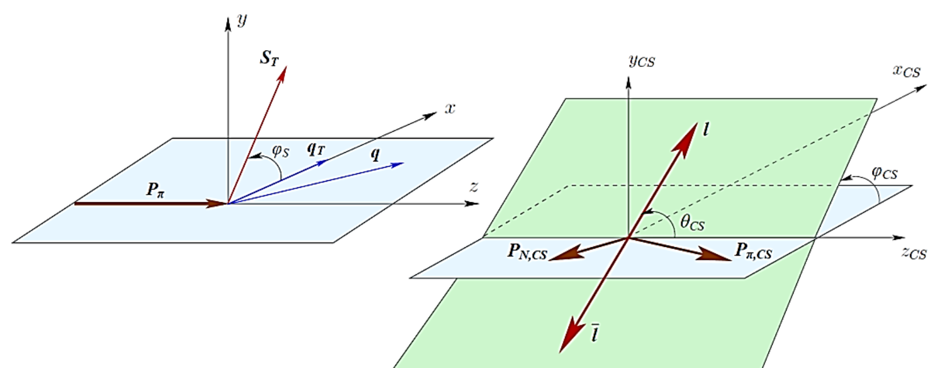


DY

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

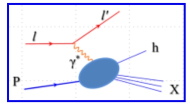
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$





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

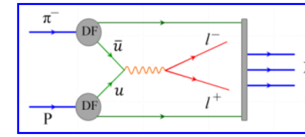
$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$



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

SIDIS-DY bridge

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



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

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

SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q}\otimes H_{1q}^{\perp h}+\dots$	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	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q}\otimes h_{1T,p}^{\perp q}$

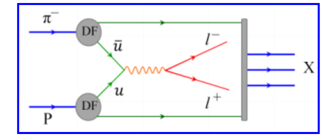
Complementary information from two different channels :

- 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

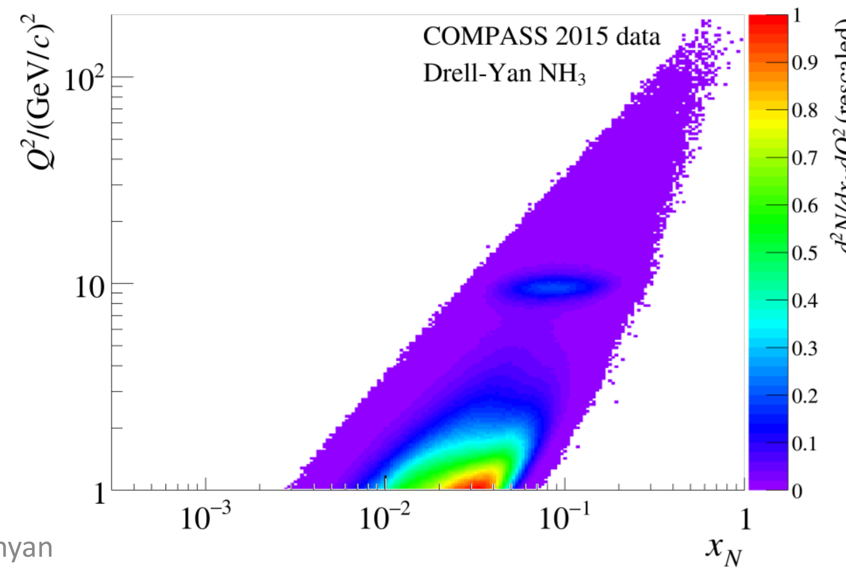
- $1.0 < M/(\mathrm{GeV}/c^2) < 2.0$ "Low mass"
  - Large background contamination, combinatorial, Open-charm (B) $D\bar{D}$, $B\bar{B}$, π, K decays
- $2.0 < M/(\mathrm{GeV}/c^2) < 2.5$ "Intermediate mass"
  - High DY-cross section
  - Still low DY-signal/background ratio
- $2.5 < M/(\mathrm{GeV}/c^2)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

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



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

COMPASS x:Q² phase space



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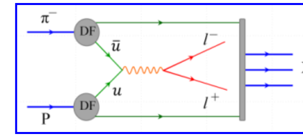
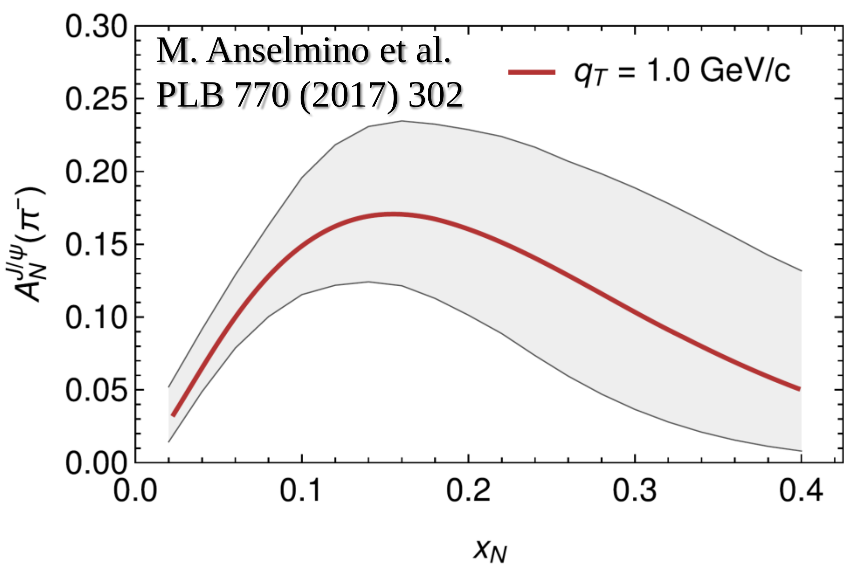
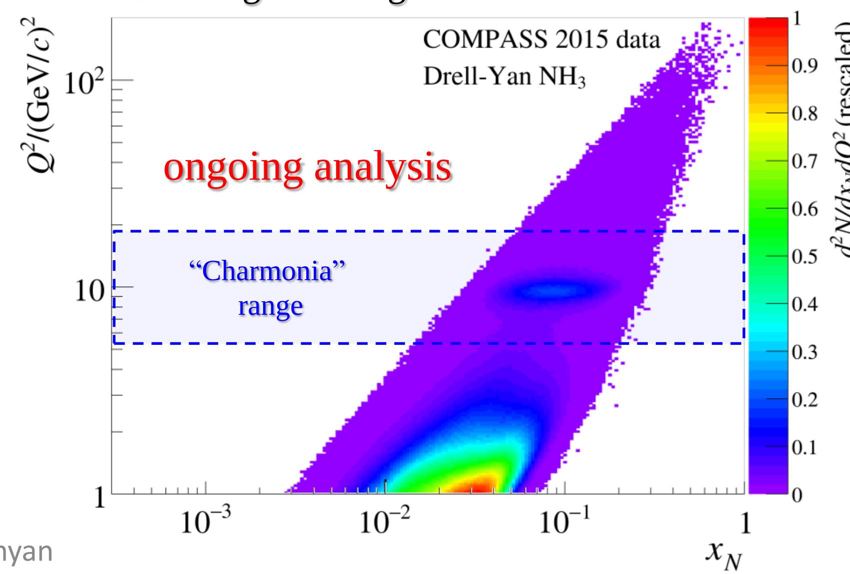


$$D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$$

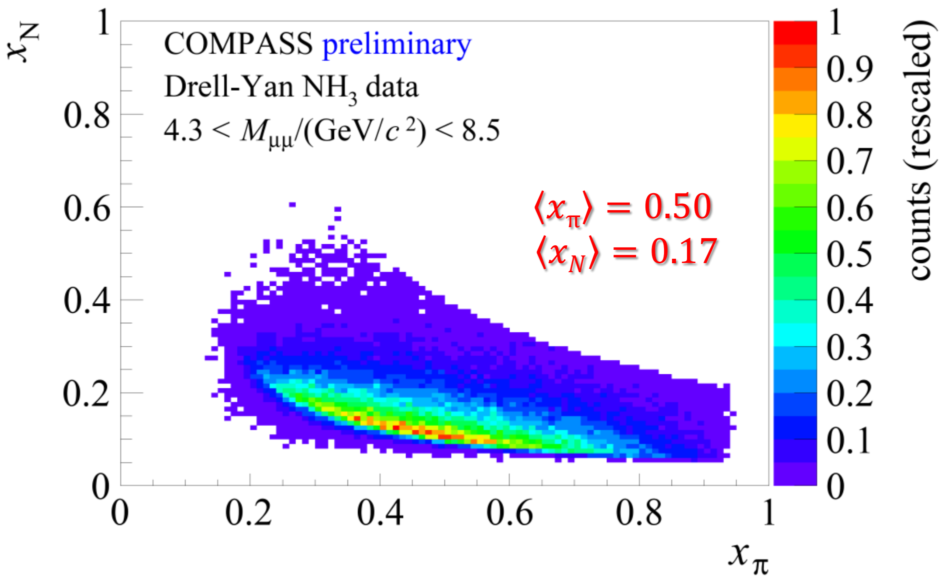
$\langle x_\pi \rangle = 0.31, \langle x_N \rangle = 0.09, \langle x_F \rangle = 0.22, \langle q_T \rangle = 1.1$ GeV/c



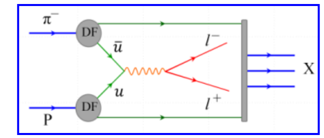
2.5 < M /(GeV/c2) < 4.3 "Charmonia mass"
Strong J/ψ-signal → study of J/ψ physics
Good signal/background



Single-polarized DY measurements at COMPASS

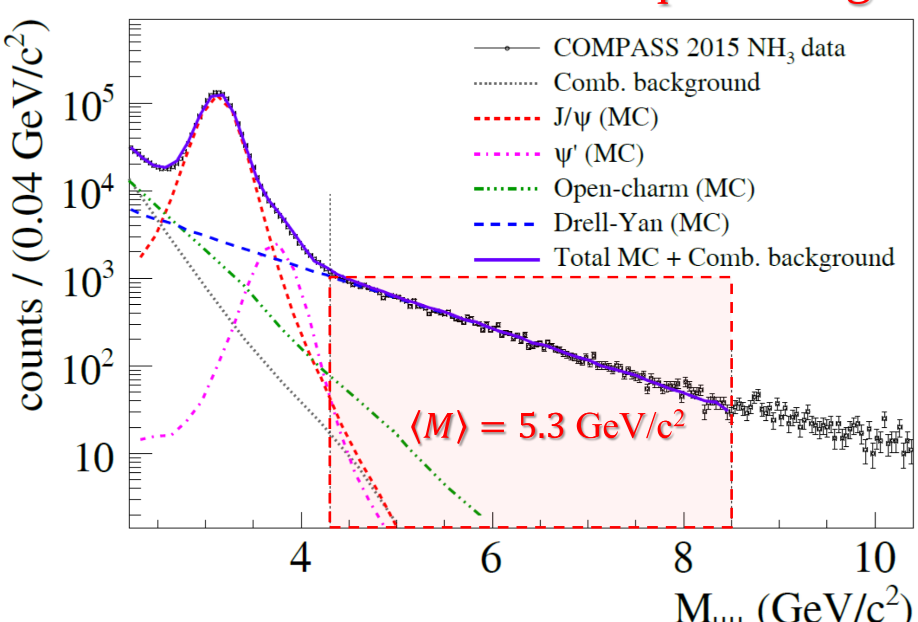


$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta_{CS}]}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



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

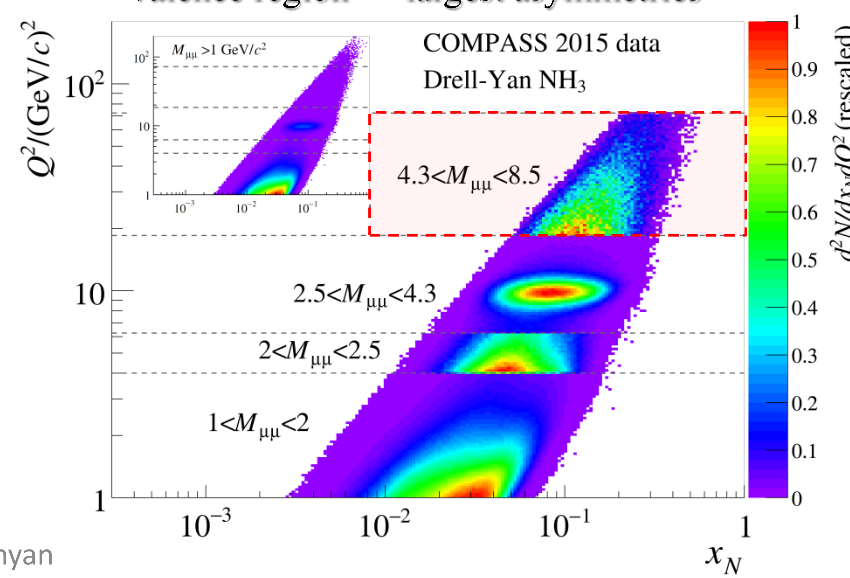
HM events are in the valence quark range



$4.3 < M/(\mathrm{GeV}/c^2) < 8.5$ "High mass" range

Beyond charmonium region, background < 3%

Valence region → largest asymmetries

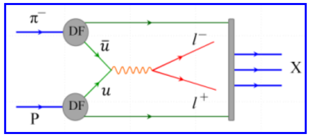


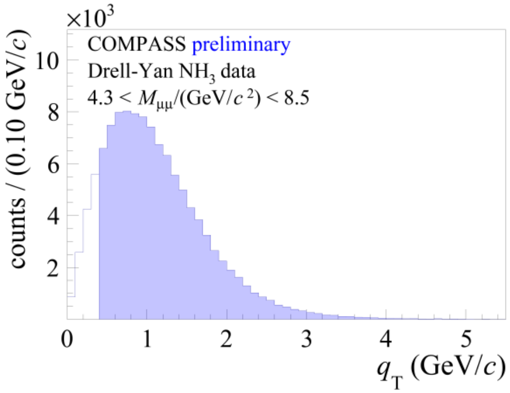
Single-polarized DY measurements at COMPASS

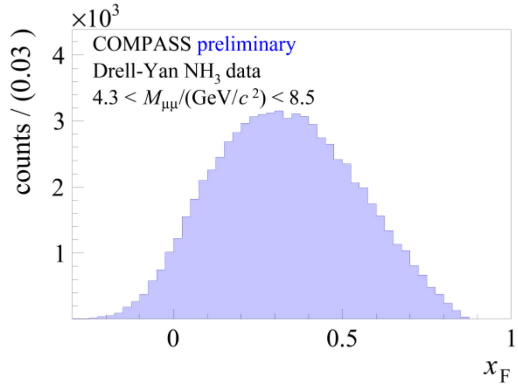
Dimuon transverse momentum $q_T > 0.4$ GeV/c
$\langle x_F \rangle = 0.33, \ \langle q_T \rangle = 1.2$ GeV/c

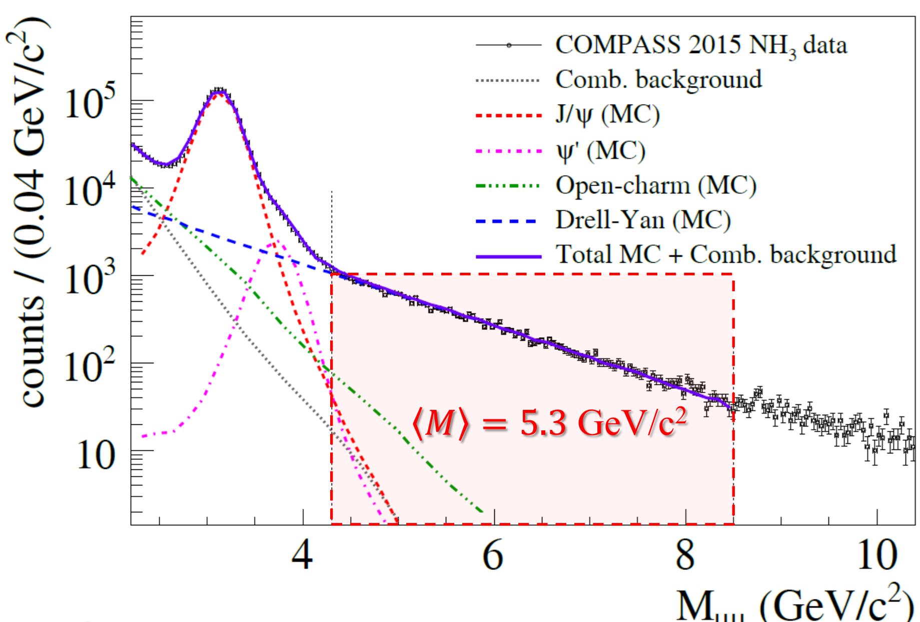
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta_{CS}]}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

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

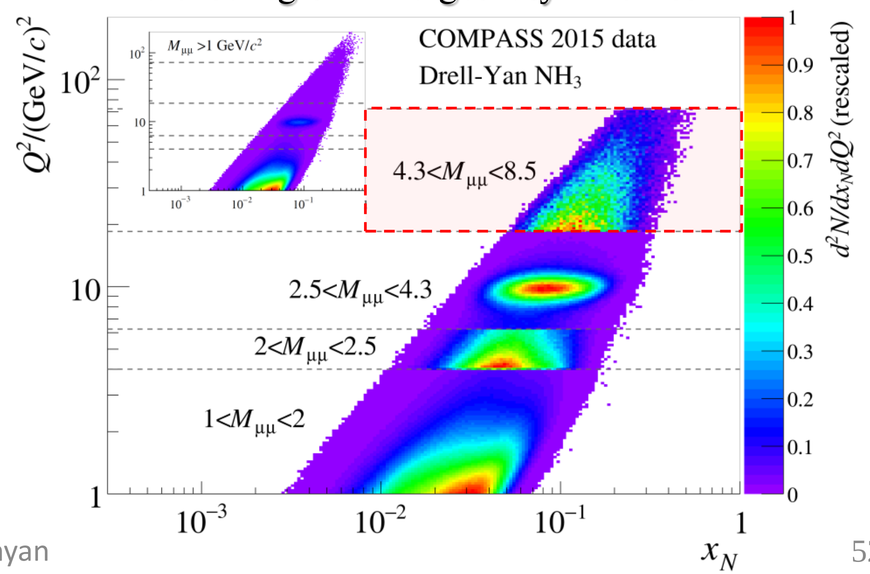




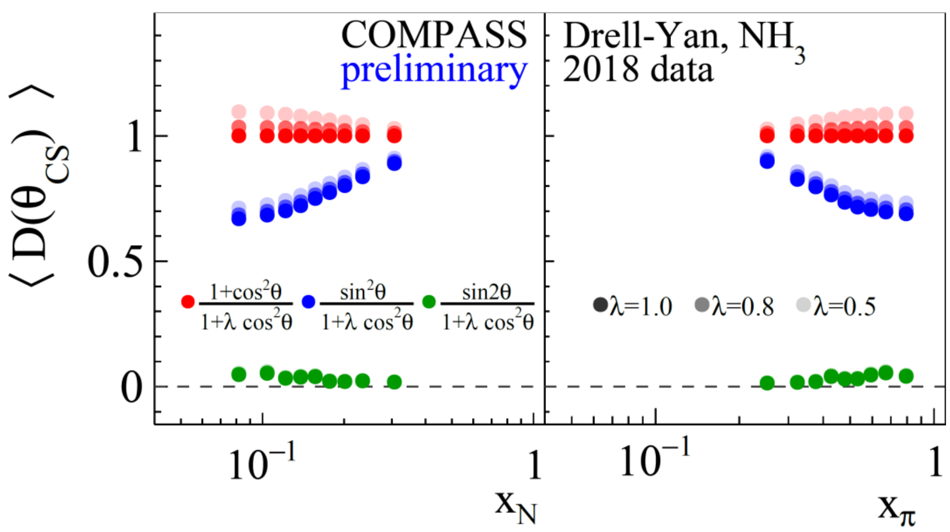




4.3 < M /(GeV/c²) < 8.5 "High mass" range
Beyond charmonium region, background < 3%
Valence region → largest asymmetries



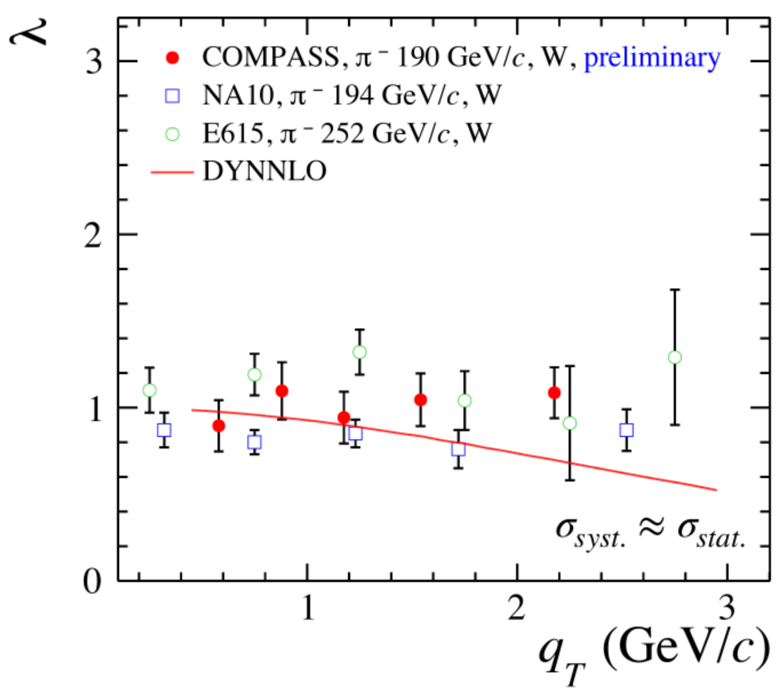
Single-polarized DY x-section: transverse part



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

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

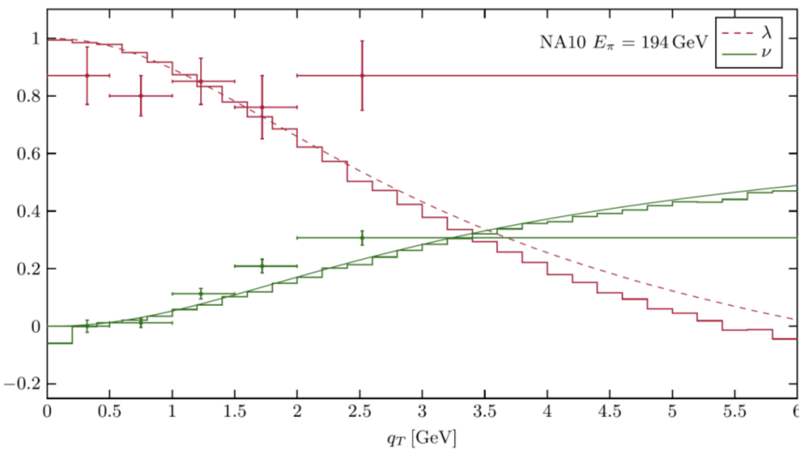
$$D_{[f(\theta_{CS})]} = f(\theta_{CS}) / \left(1+A_U^1\cos^2\theta_{CS}\right)$$



- All five Drell-Yan TSAs are extracted simultaneously using extended unbinned Maximum likelihood estimator.
- Depolarization factors are evaluated under assumption $A_U^1=1$
- Possible impact of $A_U^1 \neq 1$ scenarios lead to a normalization uncertainty of at most −5%.

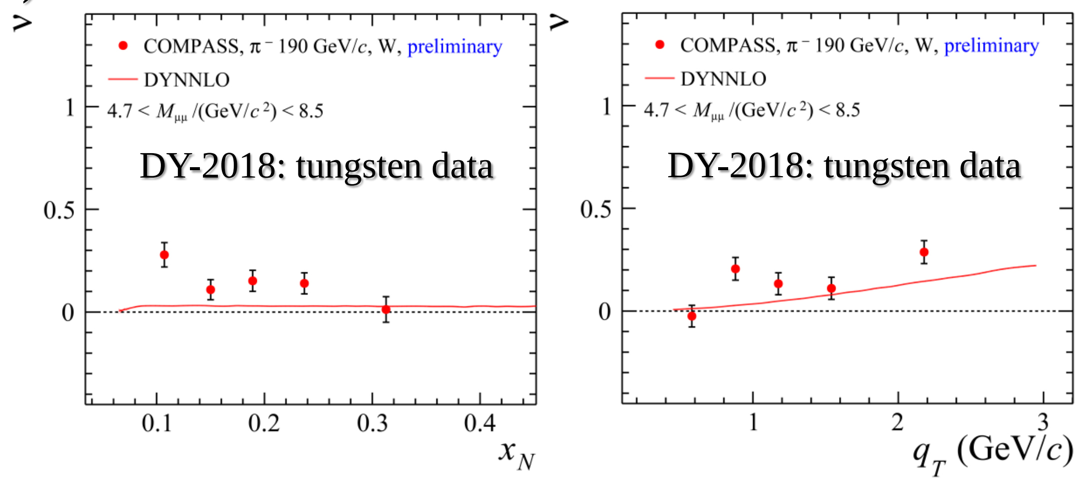
Unpolarized Drell-Yan results (high-mass range)

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



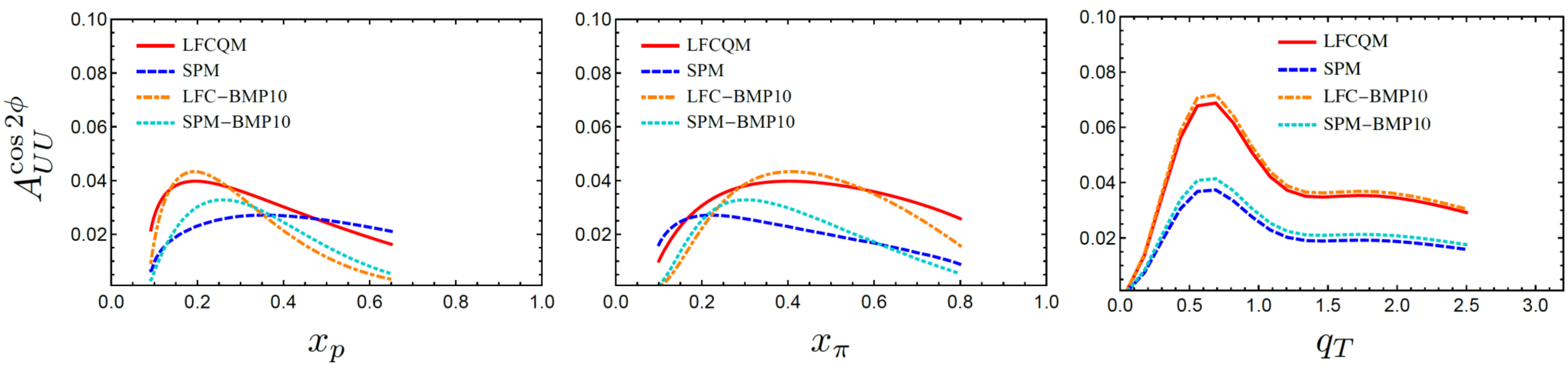
NA10 data **Z.Phys.C 37,545(1988)**

DIS-2021



DY-2018 NH_3 data: ongoing analysis

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



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

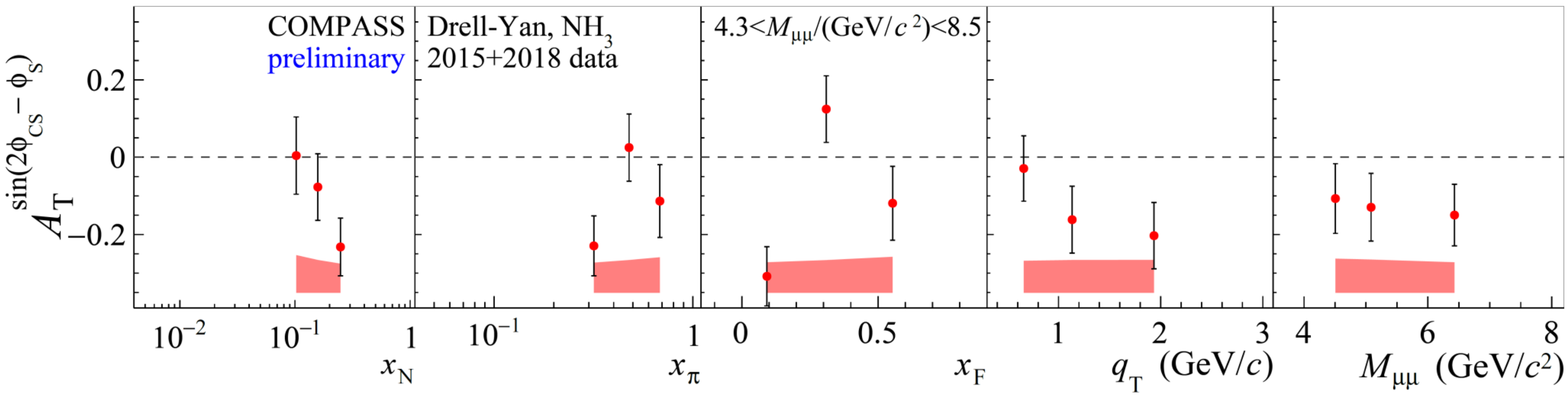
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

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

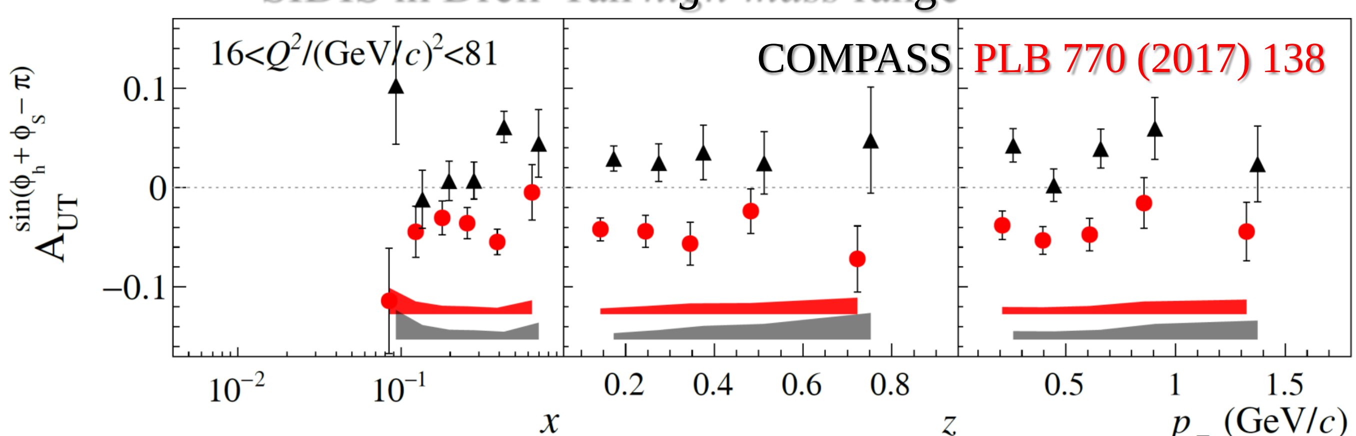
COMPASS 2015 + 2018 data **NEW!**



SIDIS in Drell-Yan *high-mass* range

Collins SIDIS TSA

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



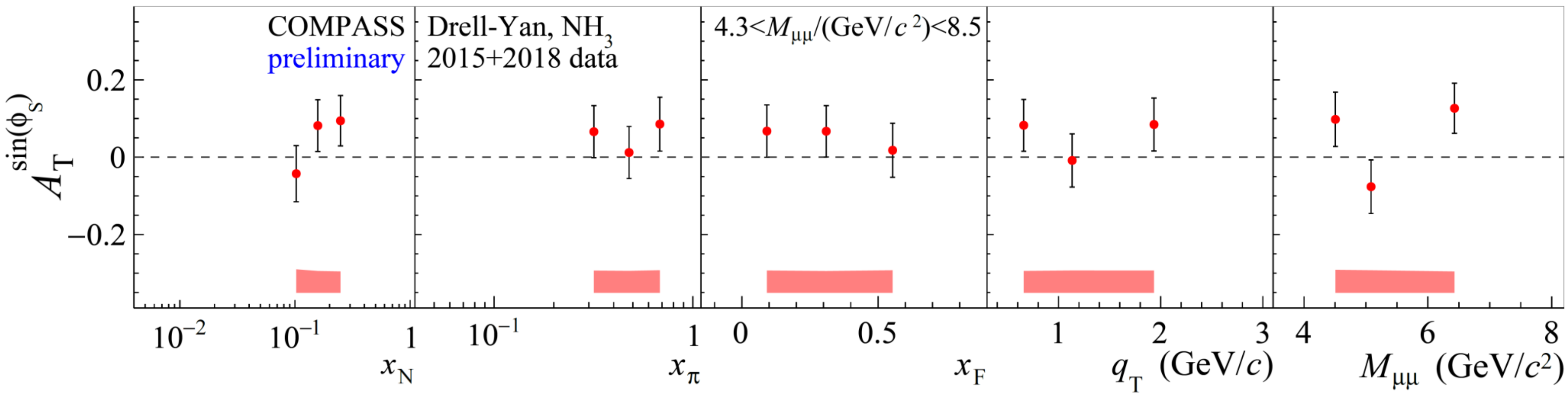
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

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

COMPASS 2015 + 2018 data **NEW!**

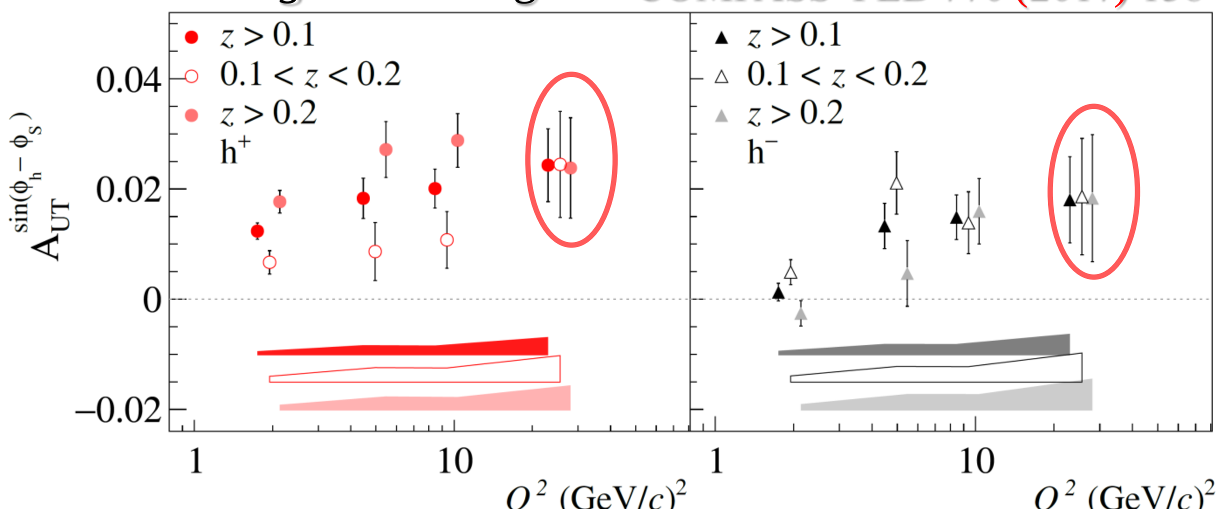


SIDIS in Drell-Yan *high-mass* range

COMPASS PLB 770 (2017) 138

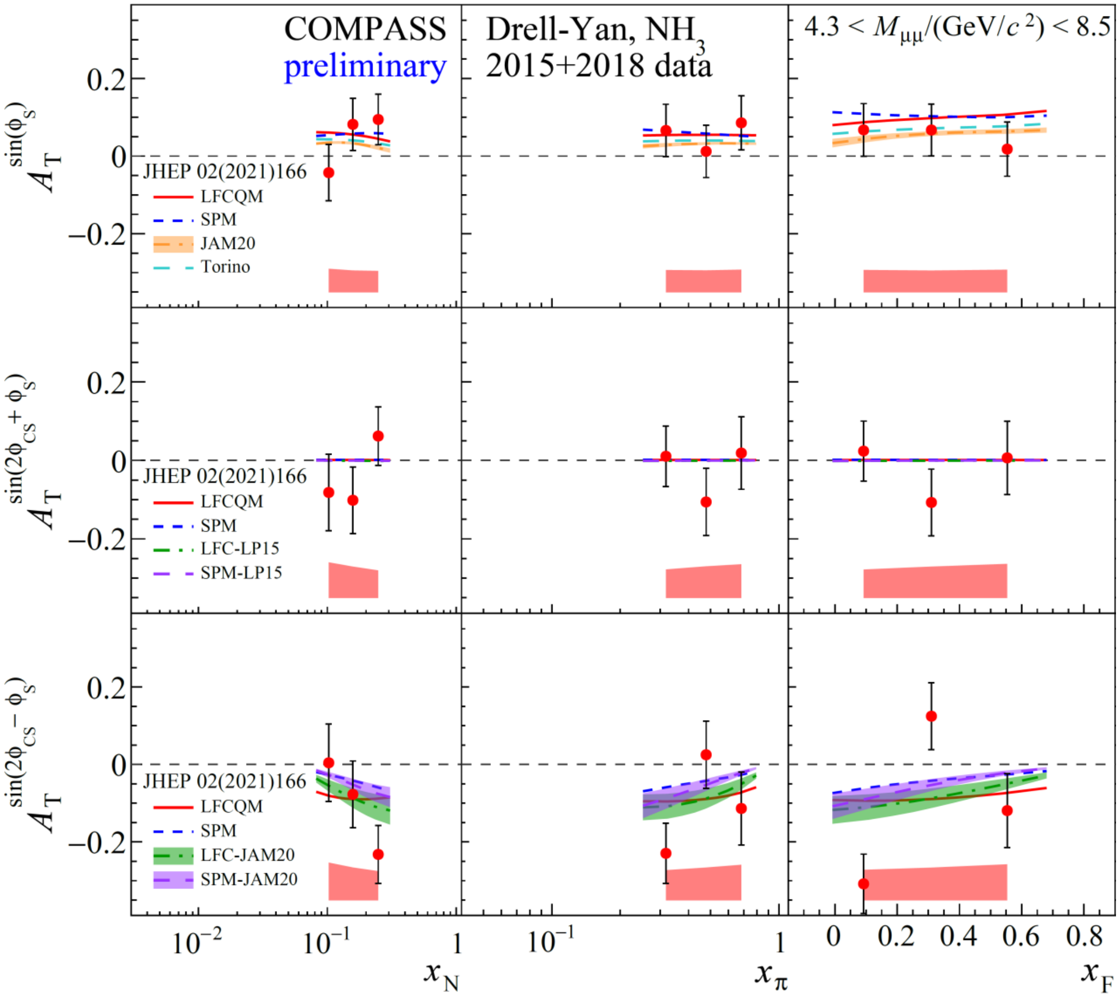
Sivers SIDIS TSA

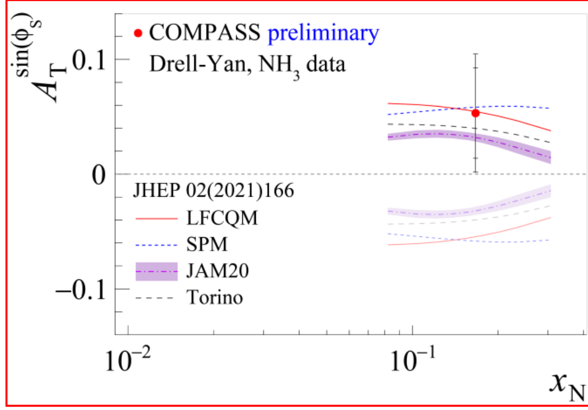
$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$

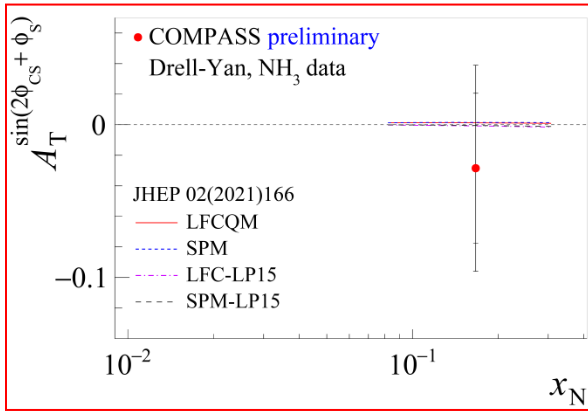


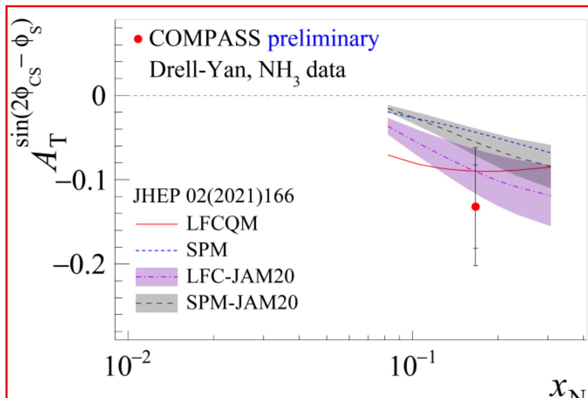
DY TSAs at COMPASS (high-mass range)

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





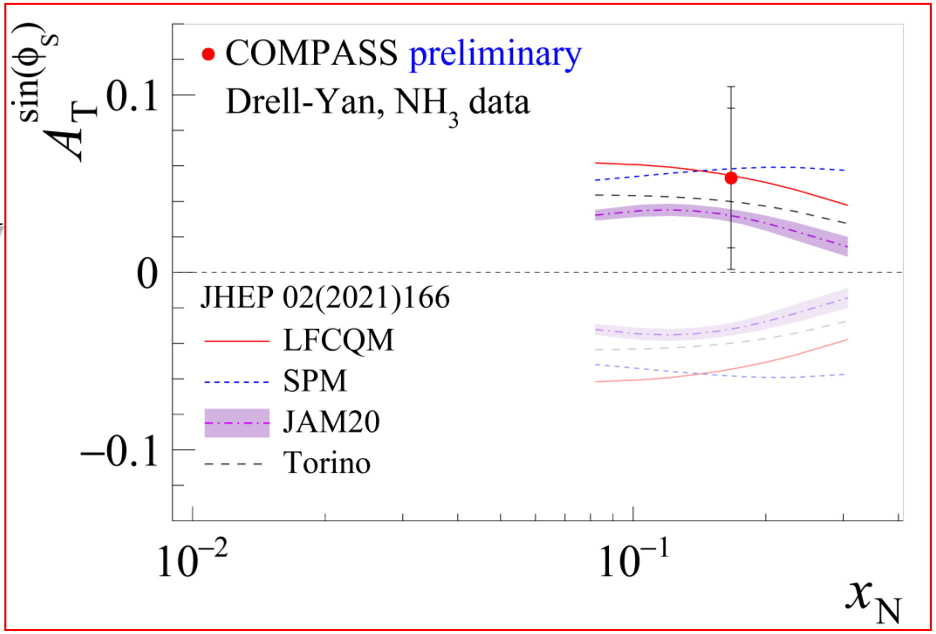




- General agreement with available theory predictions

Conclusions - DY TSAs at COMPASS

- During phase I COMPASS has measured all possible SIDIS TSAs.
    - Non-zero Sivers and Collins SIDIS-TSAs in the Drell-Yan "high-mass range": PLB 770 (2017) 138
- In 2017 COMPASS has published the results for the first polarized DY measurements: PRL 119, 112002 (2017)
- The second year of polarized DY data-taking was performed in 2018
- Re-production and re-analysis of both 2015 2018 data is over
- Final results have been presented at DIS-2022 and other conferences: the paper is in preparation
- COMPASS data favors the sign-change of Sivers TMD PDF
- DY x-section and unpolarized asymmetry studies are ongoing
- The x-sections and asymmetries in J/ψ mass range are being actively studied



Thank you!