TMD effects in polarized processes
Experiment overview
(non-comprehensive)

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7th International Workshop on "Transverse phenomena in hard processes"
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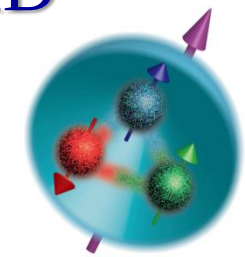
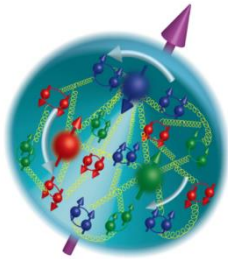
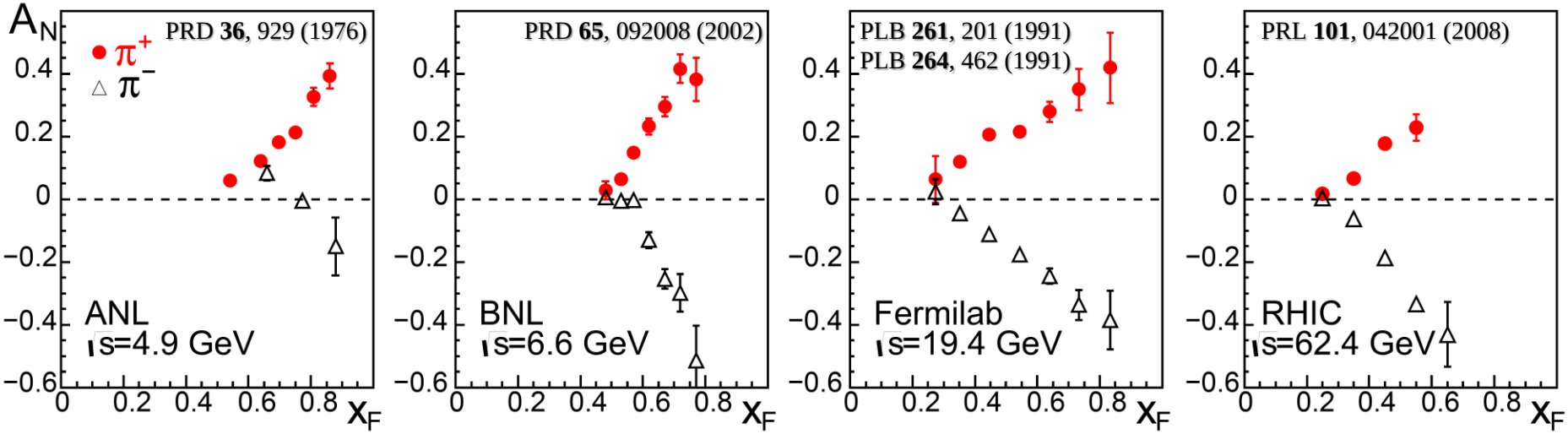
Nucleon spin structure: TMD

- 1964 Quark model 
- 1969 Parton model 
- 1973 asymptotic freedom and QCD 
- 1976 large transverse single spin asymmetry in forward $\pi^{\pm}$ production







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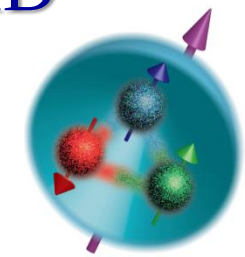
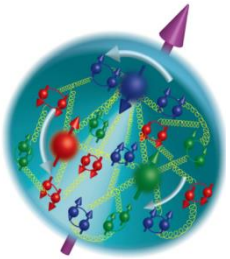
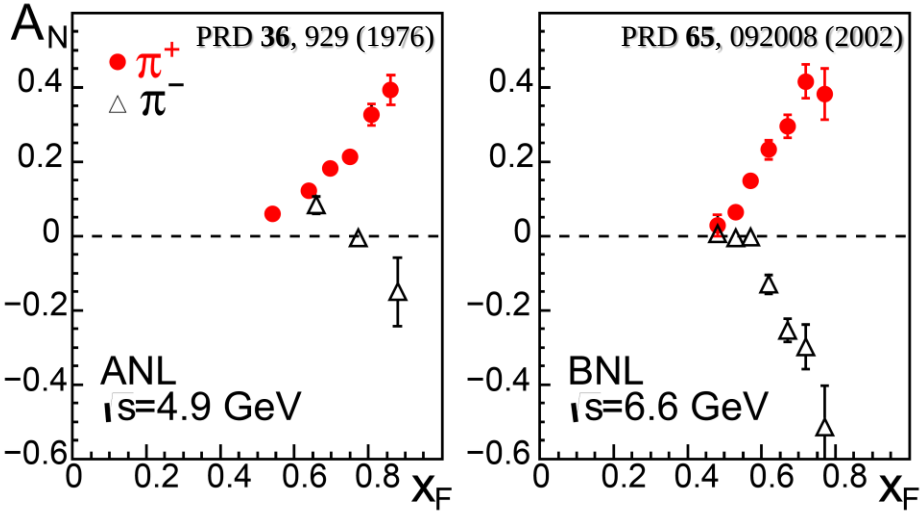
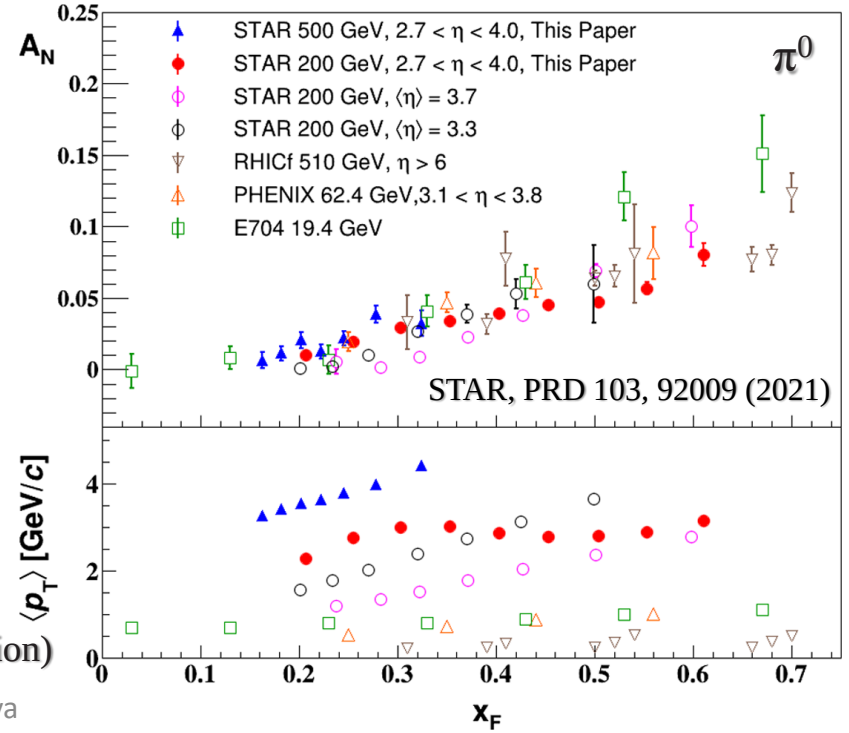


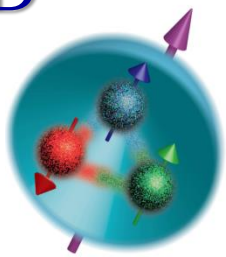






- TMD Sivers and Collins or
- Twist-3 Sivers (Efremov-Teryaev-Qui-Sterman (ETQS) function)

Nucleon spin structure: TMD



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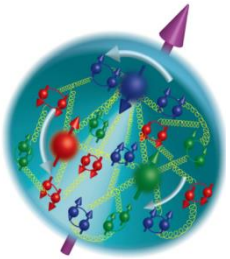

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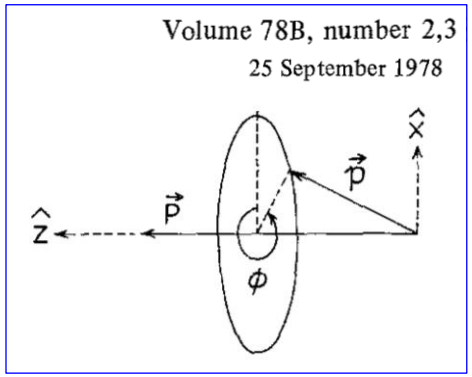
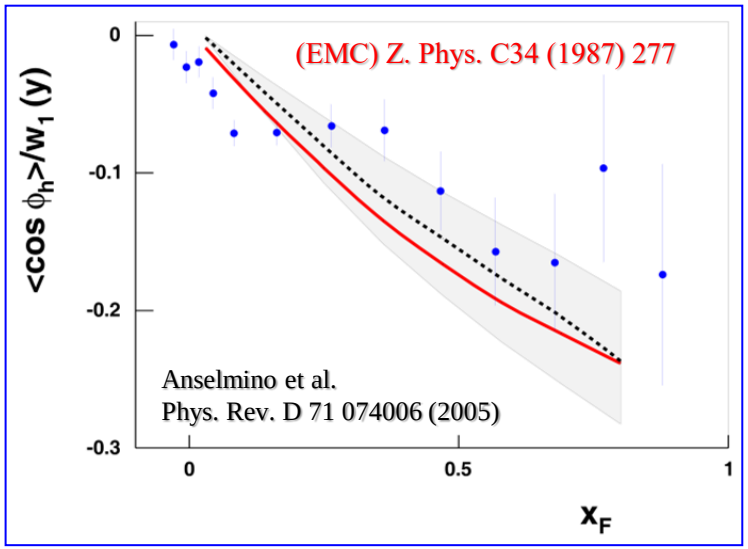
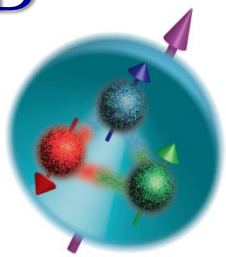




(SLAC) Phys. Rev. Lett. 31, 786 (1973)
(EMC) Phys. Lett. B 130 (1983) 118,
(EMC) Z. Phys. C34 (1987) 277
(EMC) Z. Phys. C52, 361 (1991).
(E665) Phys. Rev. D48 (1993) 5057
(ZEUS) Eur. Phys. J. C11, 251 (1999)
(ZEUS) Phys. Lett. B 481, 199 (2000)
(H1) Phys. Lett. B654, 148 (2007)

Nucleon spin structure: TMD



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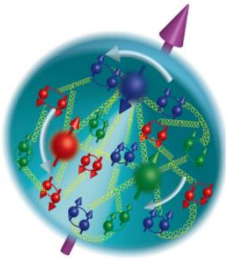

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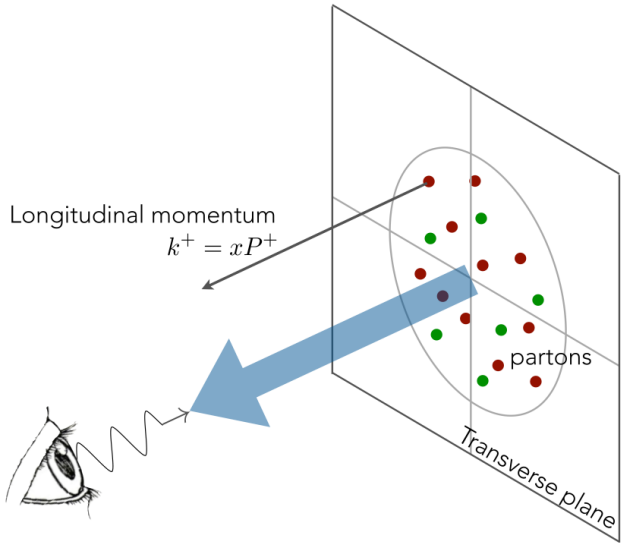
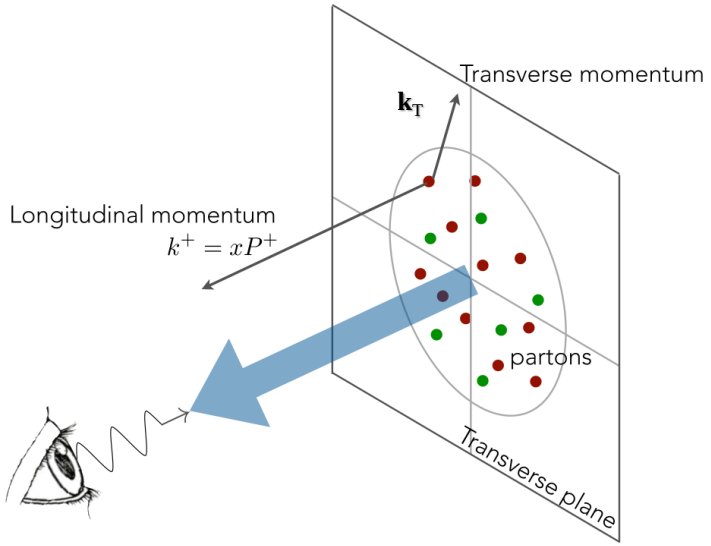




Nucleon spin structure (twist-2): collinear approach ↔TMDs

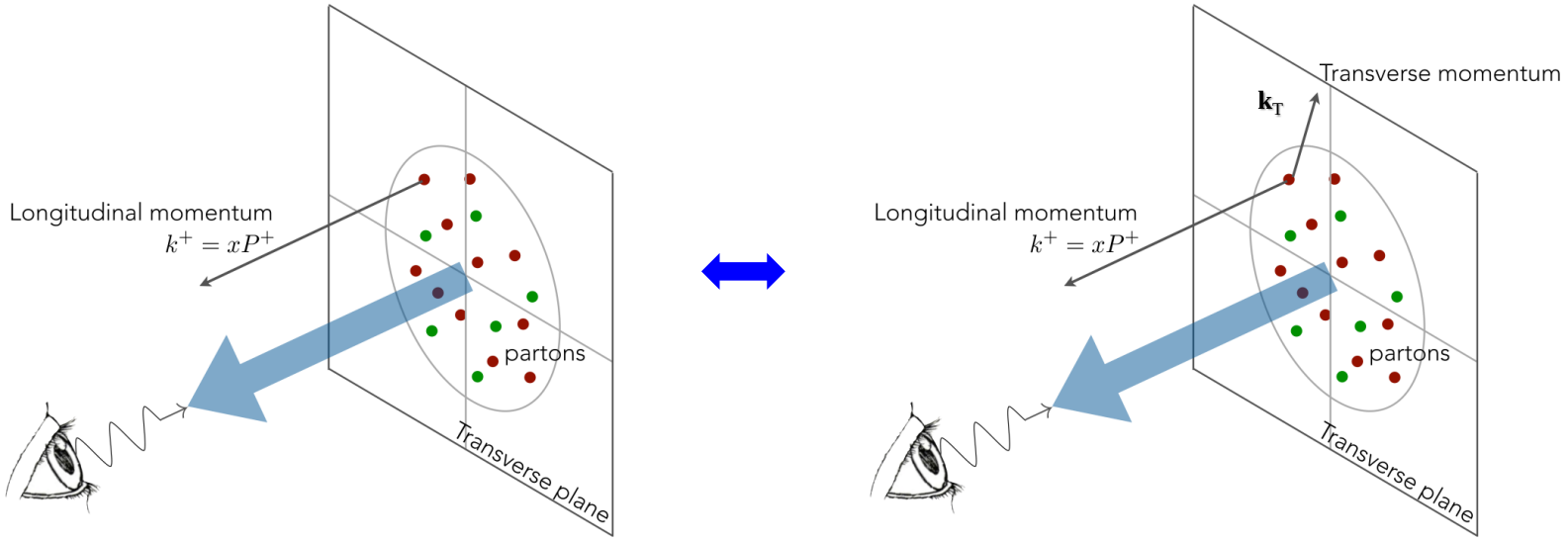
quark

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

quark

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

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



Nucleon spin structure (twist-2): TMDs

quark

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

quark

nucleon	U	L	T
U	$f_1^q(x, \boldsymbol{k}_T^2)$ number density		chiral-odd $h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ Boer-Mulders T-odd
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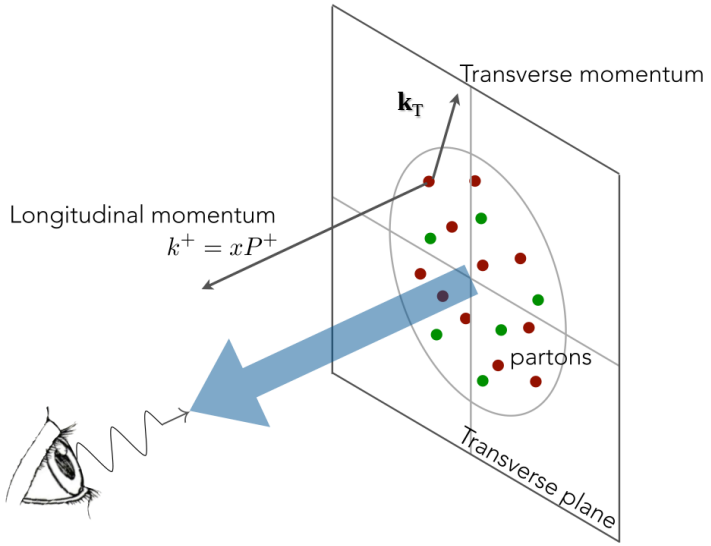
- spin of the nucleon; - spin of the quark - k_T



See Francesco Murgia's talk

SIDIS x-section and TMDs at twist-2

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

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

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

quark

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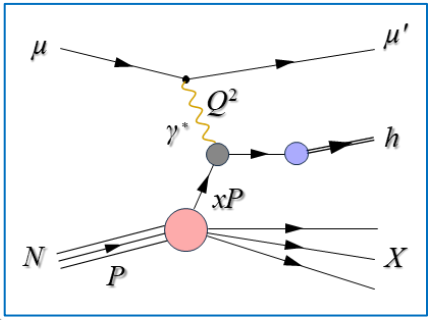

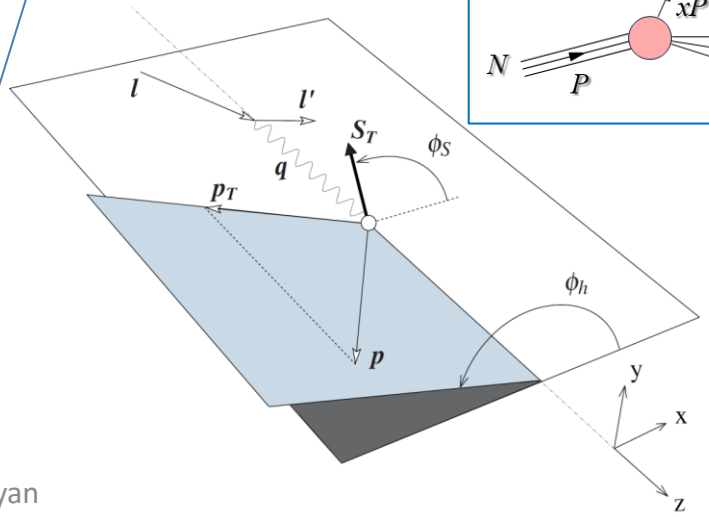

SIDIS x-section and TMDs at twist-2

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

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

quark

nucleon	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ Boer-Mulders T-odd
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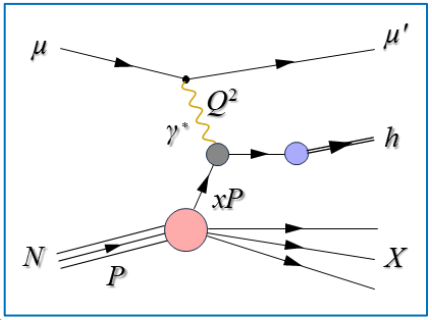
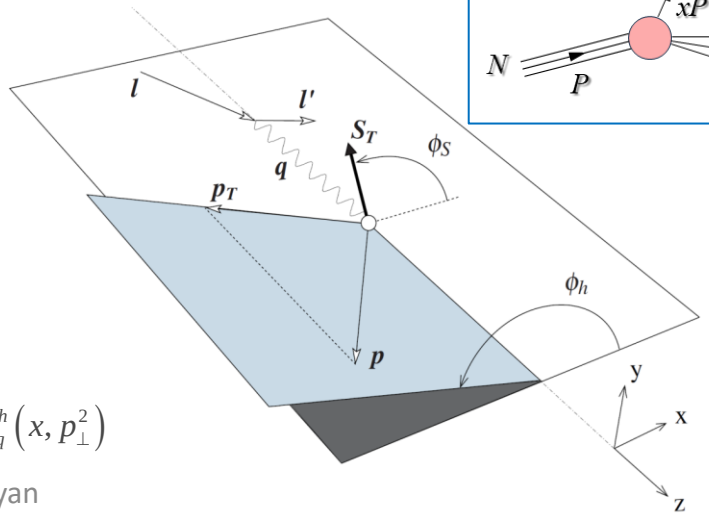
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$	Boer-Mulders (T-odd)
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers (T-odd)
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transversity
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretzelosity





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

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

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

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

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

quark

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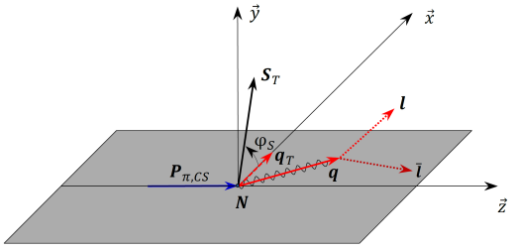
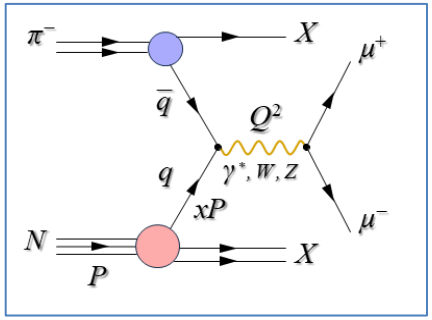
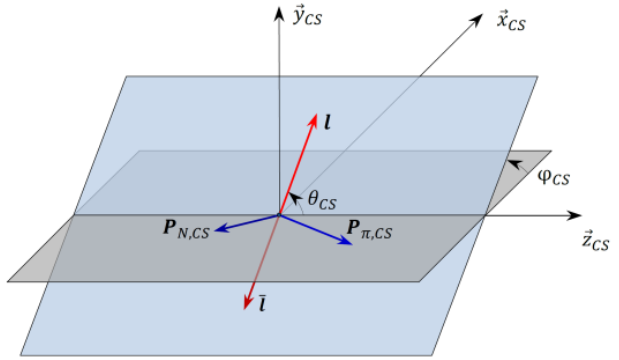
$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$	Boer-Mulders (T-odd)
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	Sivers (T-odd)
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$	Transversity
$A_T^{\sin(2\varphi_{CS}+\varphi_S)}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

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

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

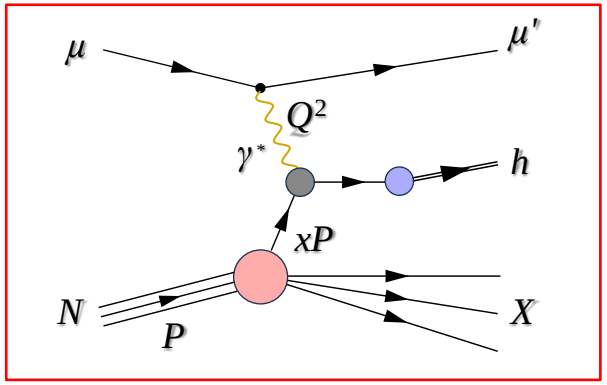






Polarized SIDIS and Drell-Yan: universality

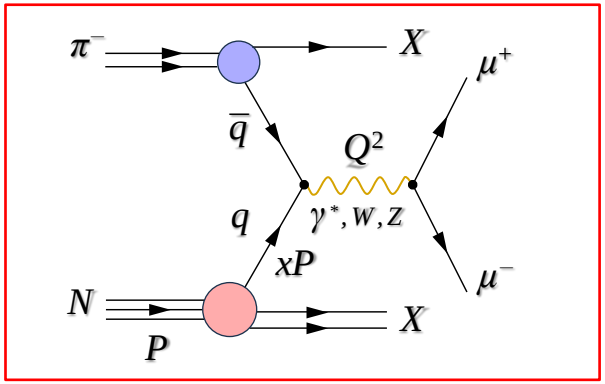
Semi-inclusive DIS



T-odd TMD PDFs

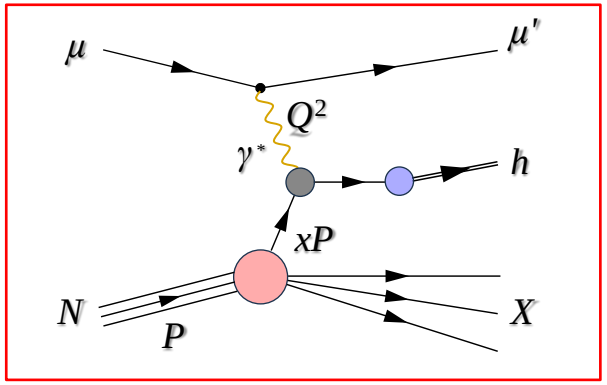
sign change

Drell-Yan process



Polarized SIDIS and DY – factorization and kinematic regions

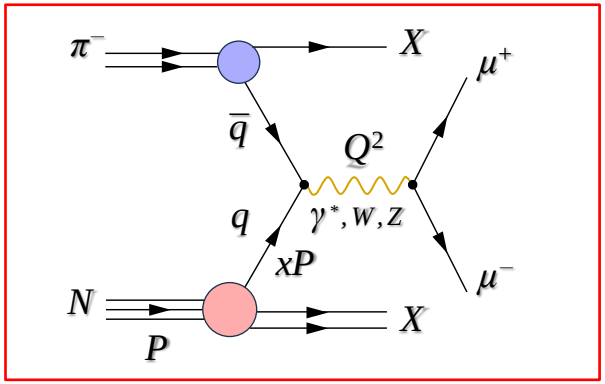
Semi-inclusive DIS



T-odd TMD PDFs

sign change

Drell-Yan process



High q_T – Collinear factorization
Low q_T – TMD factorization

$q_T \geq Q$

Current fragmentation
Collinear factorization

High x_F – Current fragmentation
Low x_F – Target fragmentation

Target fragmentation
TMD factorization
Fracture Functions

Soft region

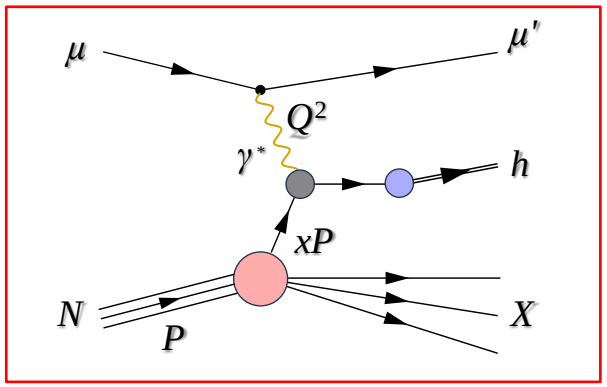
Current fragmentation
TMD factorization
PDFs, FFs

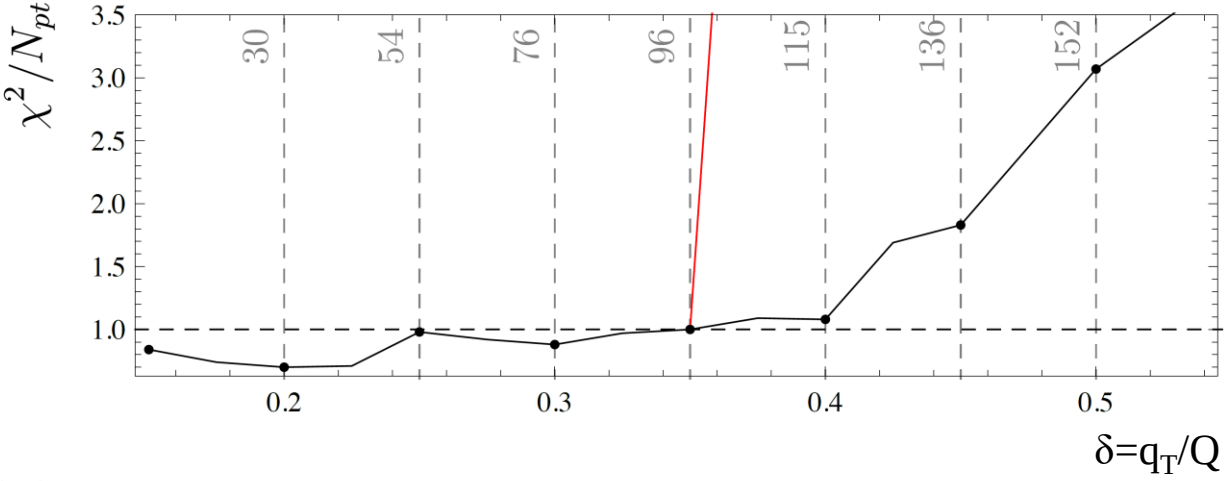
$q_T << Q$

x_F

Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS





M. Bury, A. Prokudin and A. Vladimirov
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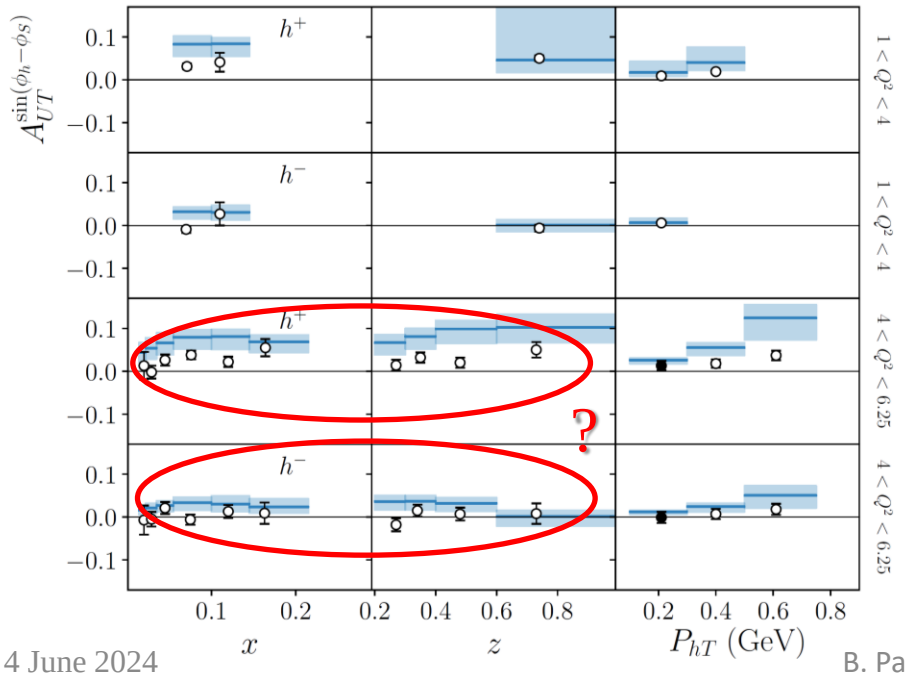
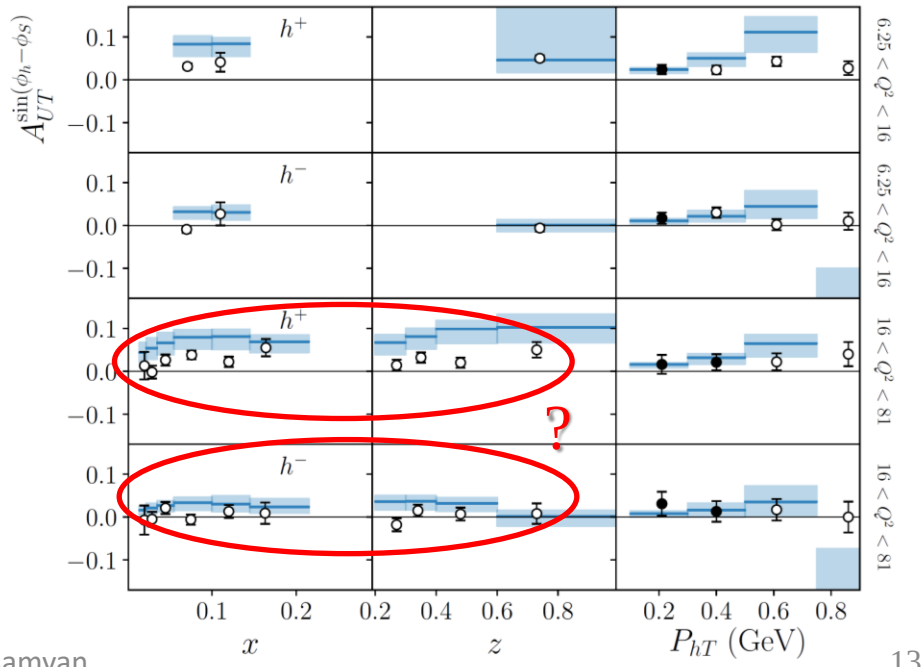
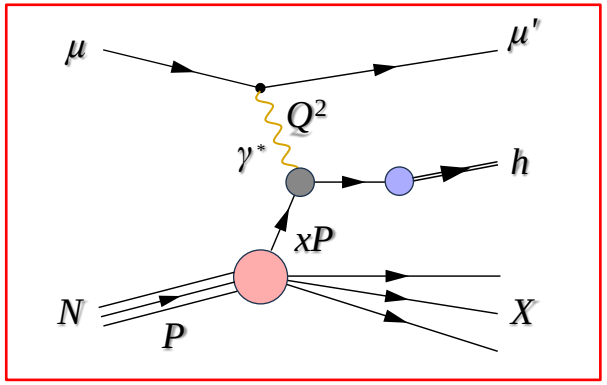
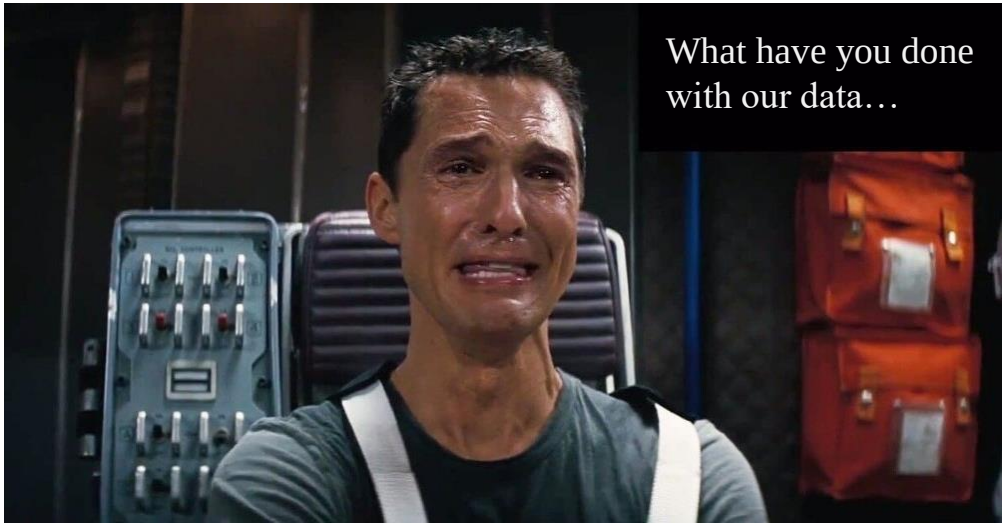




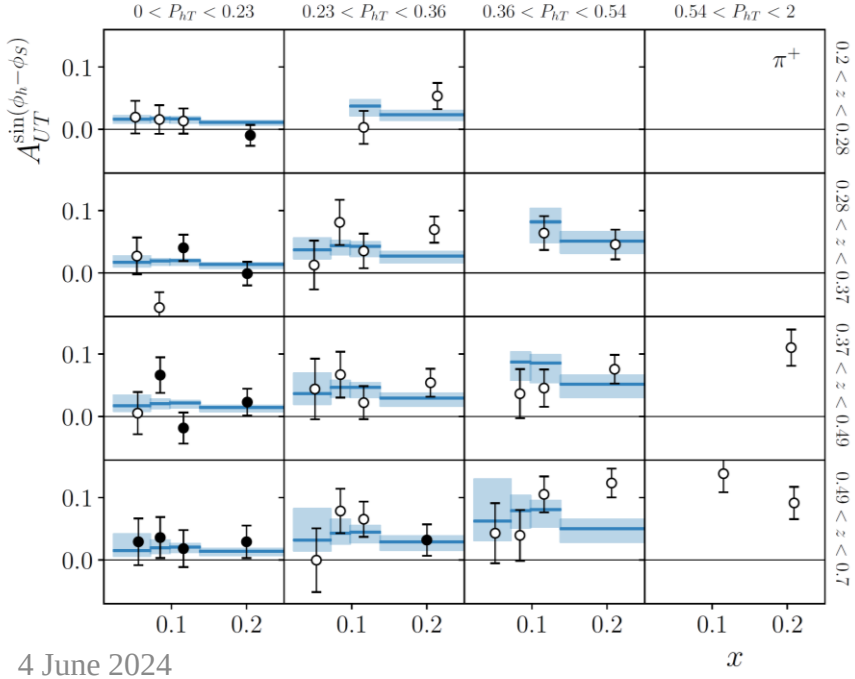
Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS



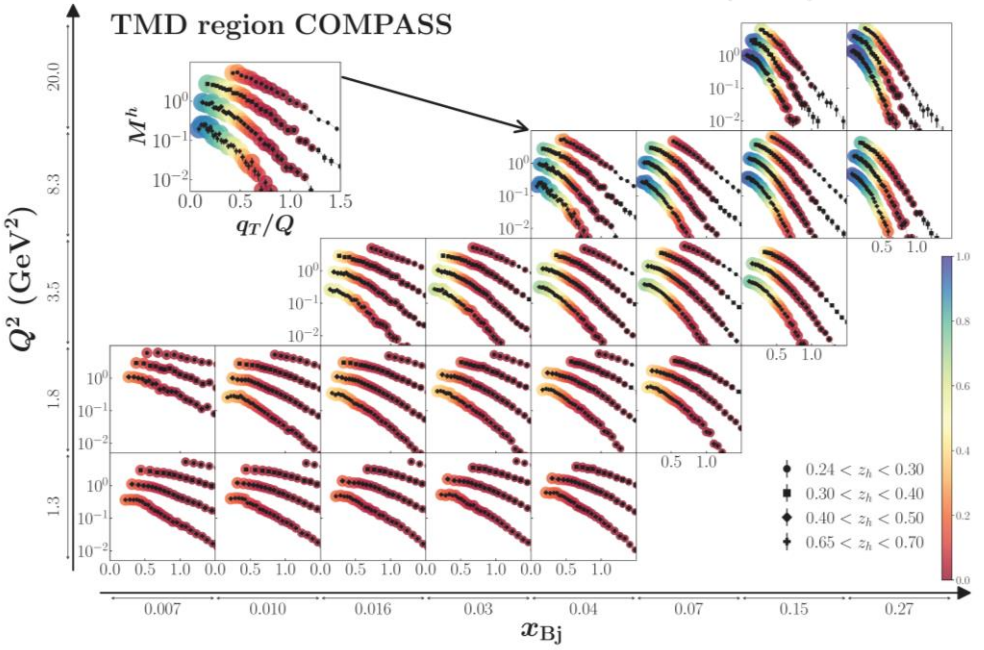


M. Bury, A. Prokudin and A. Vladimirov
JHEP 05 (2021) 151



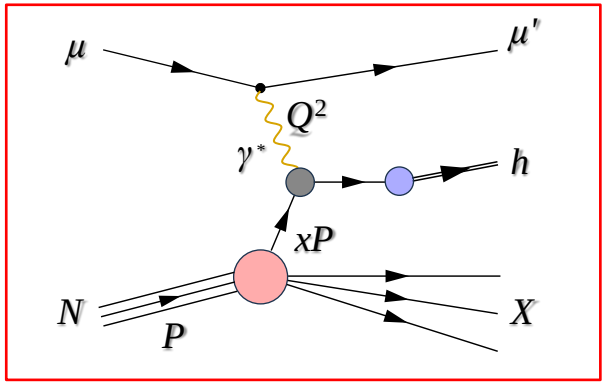
One persons ‘complication’ is another person's signal…
A. Vossen

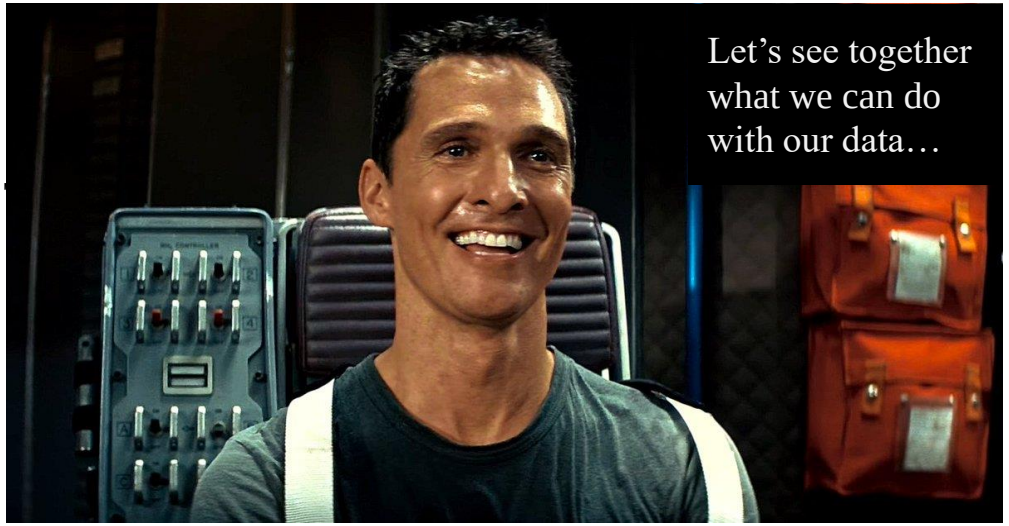
JAM, JHEP 04 (2022) 084

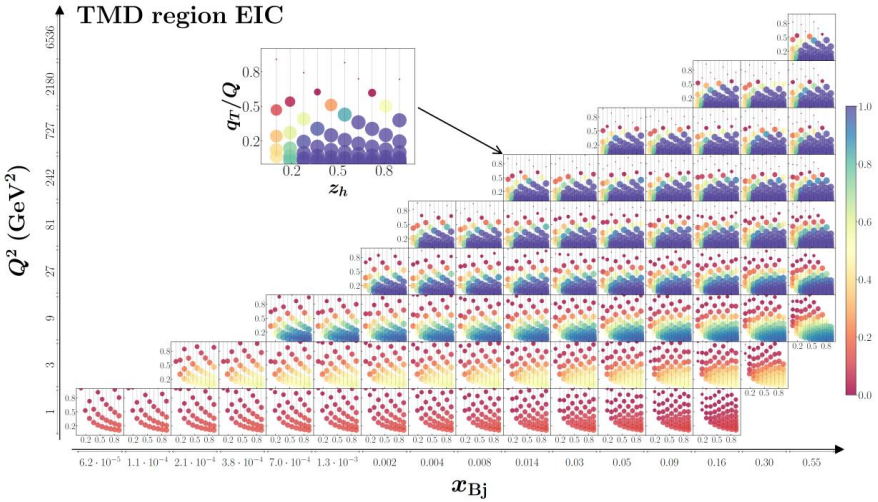


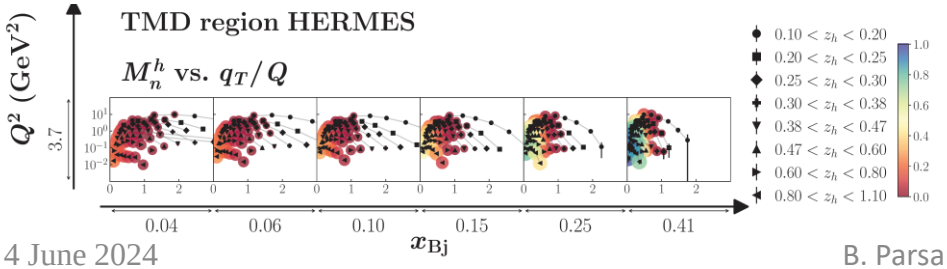
Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS

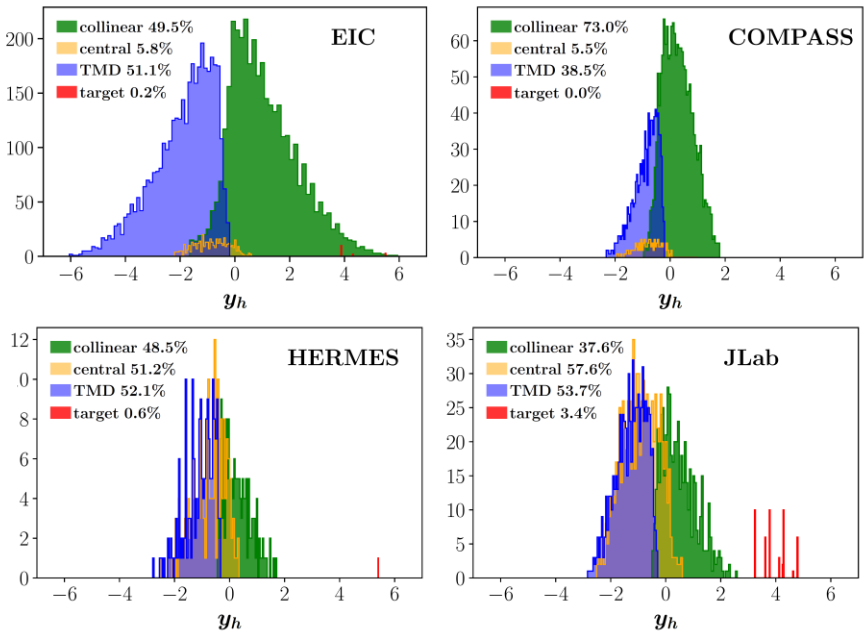






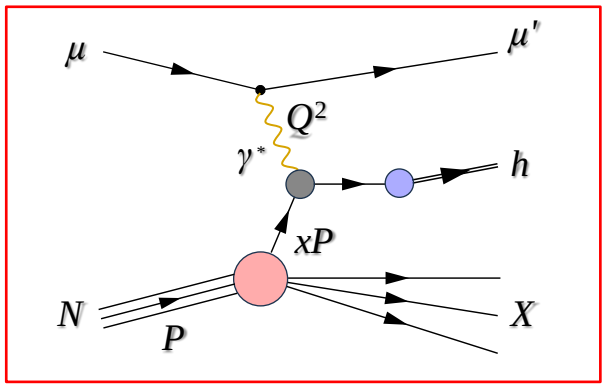


JAM, JHEP 04 (2022) 084



Main polarized SIDIS (Drell-Yan) inputs 1995-2022

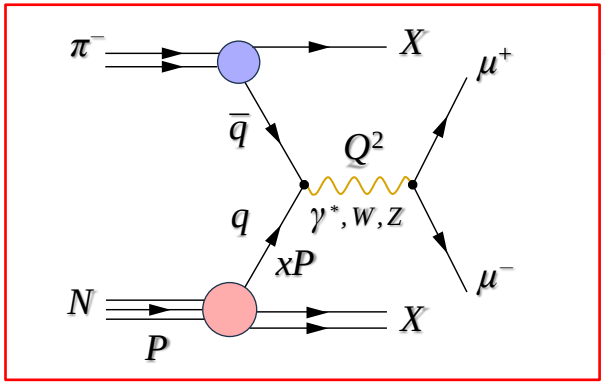
Semi-inclusive DIS

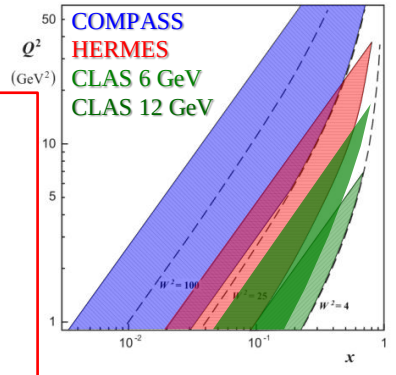


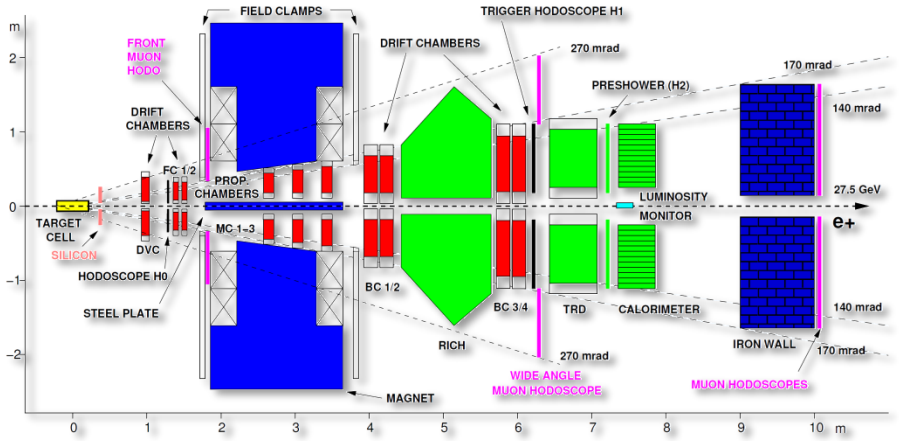
T-odd TMD PDFs

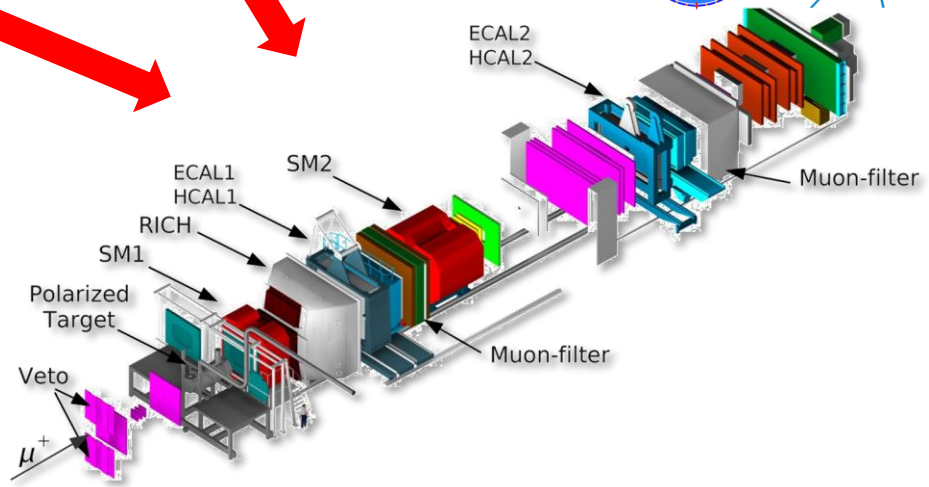
sign change

Drell-Yan process







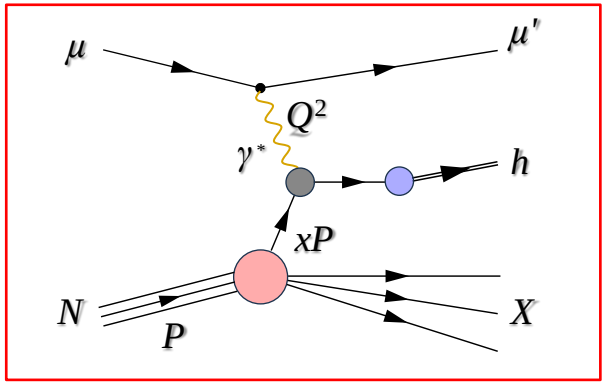


HERMES (data taking: 1995-2007)
Beam: e^+, e^- 27.6 GeV/c
L- and T- polarized proton target

COMPASS (data taking: 2002-2022)
Beam: μ^+, 160 GeV/c
L- and T- polarized NH3, 6LiD targets

Main TMD tools – universality and synergies

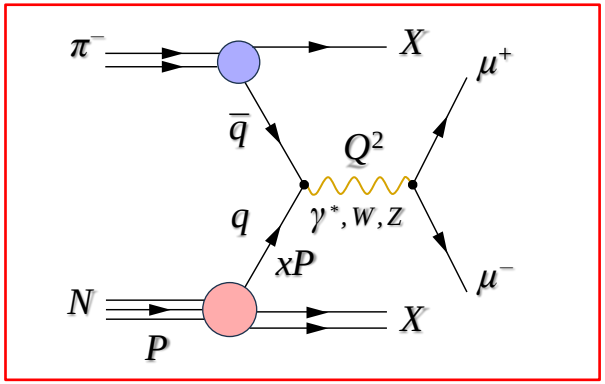
Semi-inclusive DIS



T-odd TMD PDFs

sign change

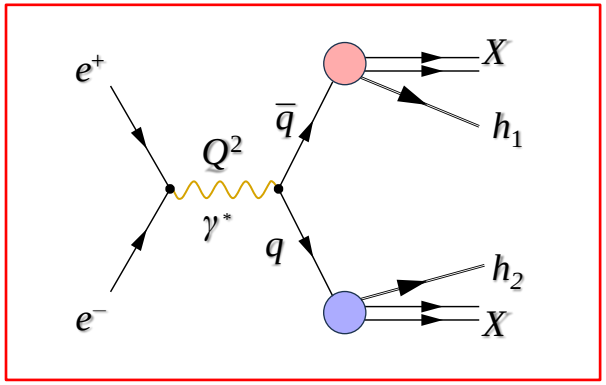
Drell-Yan process



Fragmentation Functions

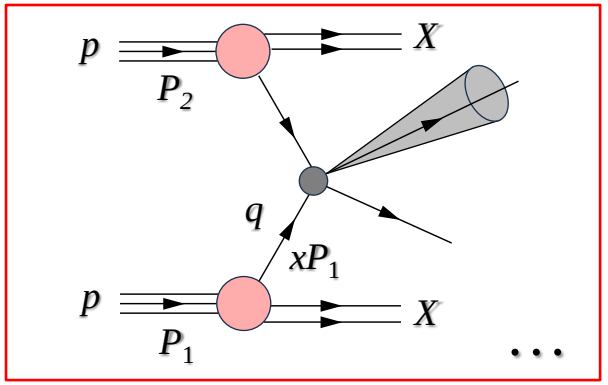
Parton Distribution Functions

Electron-positron annihilation



Cleanest access to hadronization/fragmentation

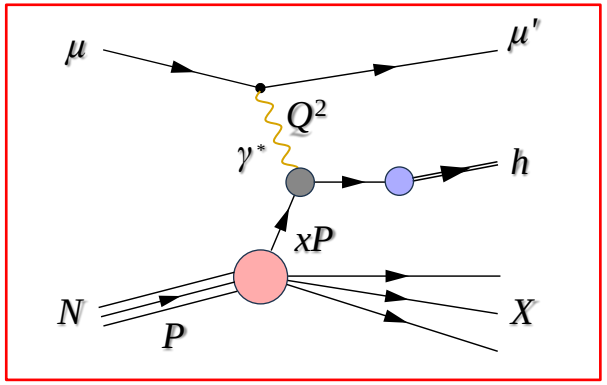
pp, pA-scattering, jet production, etc.



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

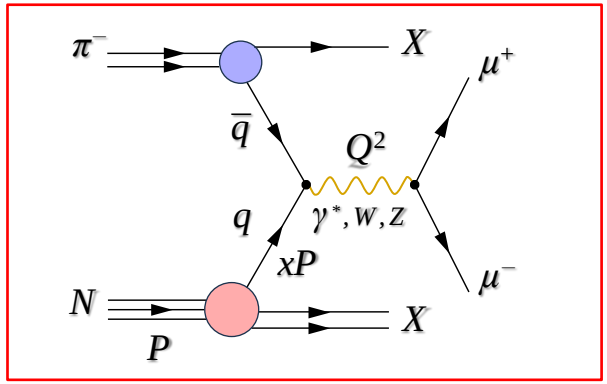
Main TMD tools – list of experiments (non exhaustive)

Semi-inclusive DIS



hermes, DESY., COMPASS 25 years 1997 - 2022, CERN, Jefferson Lab, CLAS, SoLID

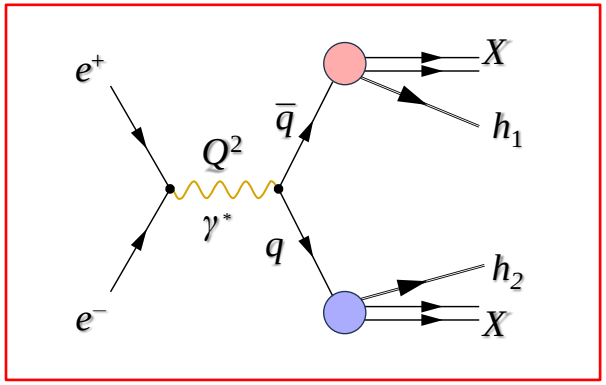
Drell-Yan process



COMPASS 25 years 1997 - 2022, CERN, STAR, SPIN QUEST, Fermilab, LHC spin

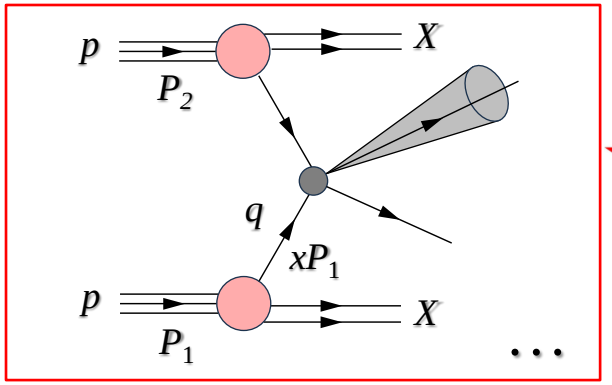
ePIC, Jefferson Lab @ 22 GeV

Electron-positron annihilation



Belle, KEK, BABAR, SLAC NATIONAL ACCELERATOR LABORATORY, BESIII

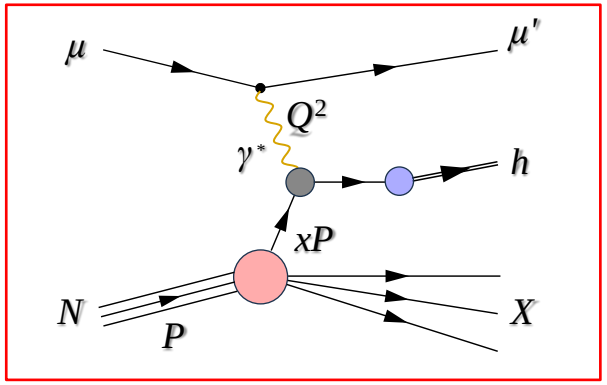
pp, pA-scattering, jet production, etc.



Brookhaven National Laboratory, STAR, PHENIX, sPHENIX

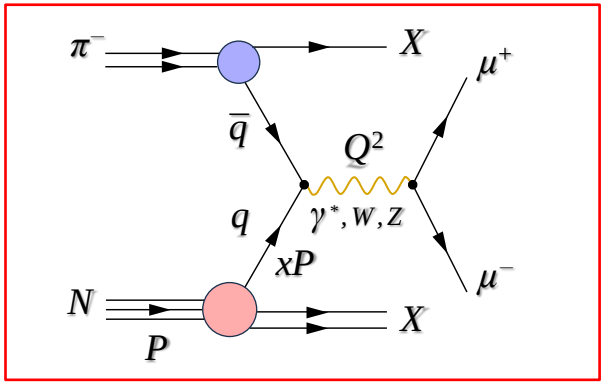
Main TMD tools – experiment overviews

Semi-inclusive DIS



hermes, DESY., COMPASS, CERN, Jefferson Lab, clas, SoLID

Drell-Yan process



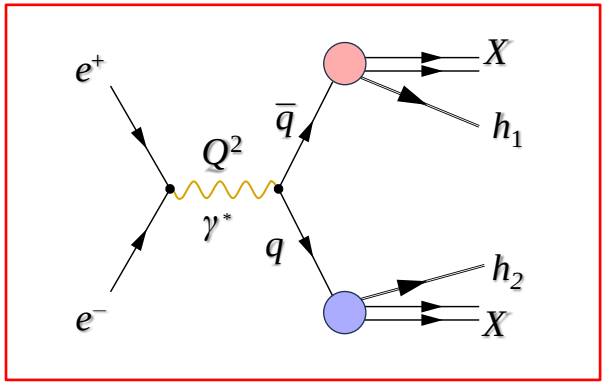
COMPASS, CERN, STAR, SPIN QUEST, Fermilab, LHC spin

Catarina Quintans, Oleg Eyser, Charlotte Van Hulse

ePIC, Jefferson Lab @ 22 GeV

Harut Avagyan, Elke-Caroline Aschenauer, Yuxiang Zhao, Stefan Diehl, Haiyan Gao, Athira Vijayakumar, Andrea Bressan

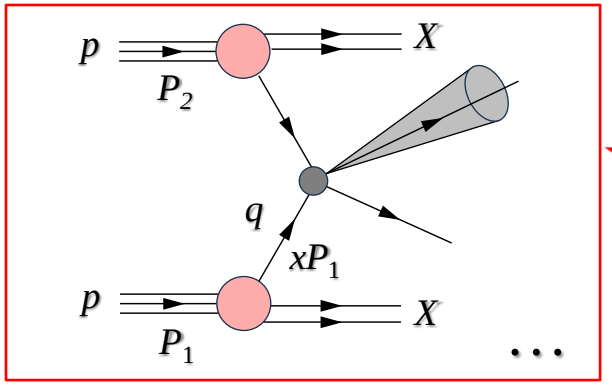
Electron-positron annihilation



Belle, KEK, BABAR, SLAC NATIONAL ACCELERATOR LABORATORY, BESIII

Anselm Vossen, Bernd Surrow, Gunar Schnell

pp, pA-scattering, jet production, etc.



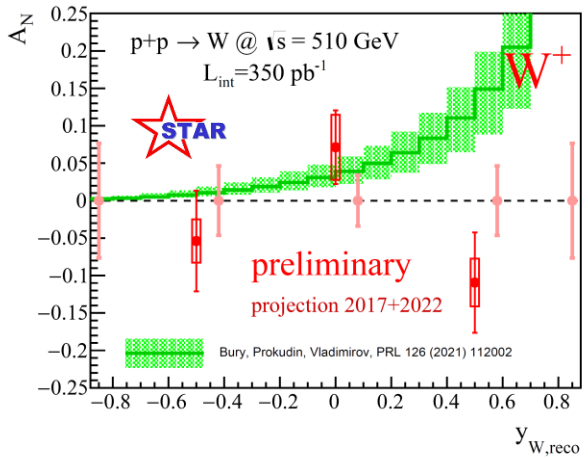
Brookhaven National Laboratory, STAR, PHENIX, sPHENIX

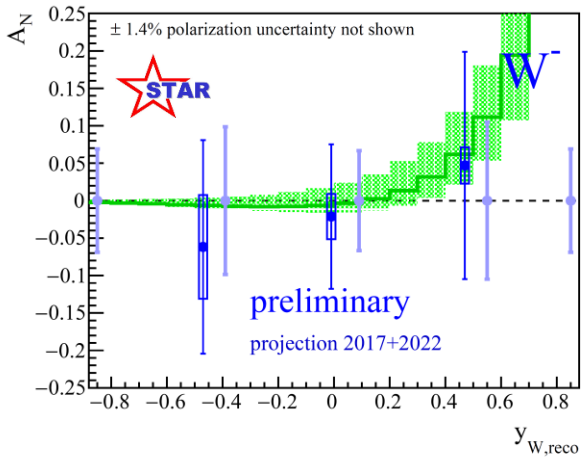
Oleg Eyser, Bassam Aboona, Bok Jeongsu

- Universality (sign changes)

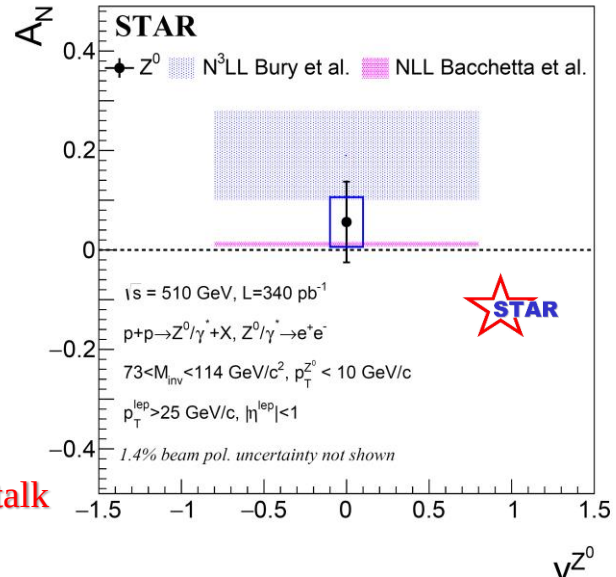
Sivers TMD PDF: sign change

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



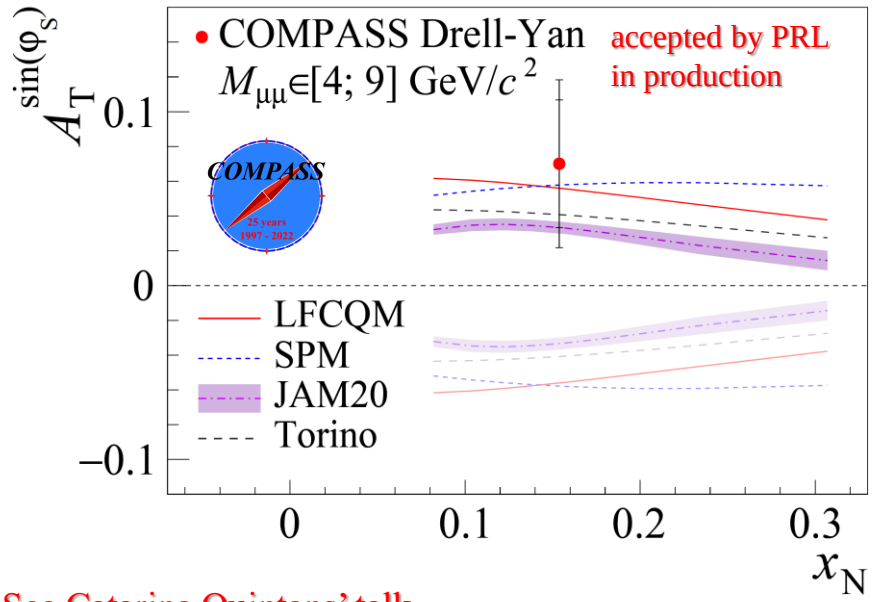


STAR, arXiv:2308.15496 [hep-ex]



See Oleg Eyser's talk

COMPASS, arXiv:2312.17379 [hep-ex]



See Catarina Quintans' talk

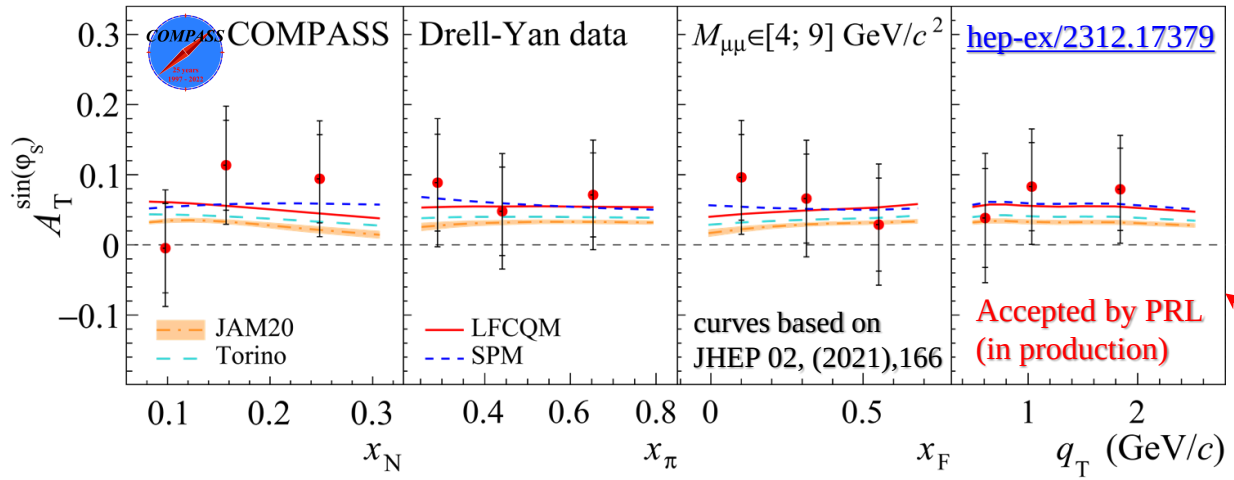
SIDIS↔Drell-Yan (W, Z)
sign change of T-odd TMD PDFs

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

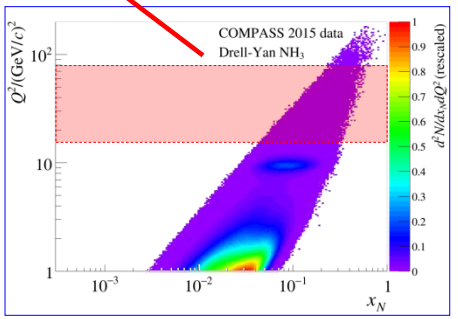
Sivers effect: Drell-Yan and J/ψ

Sivers DY TSA

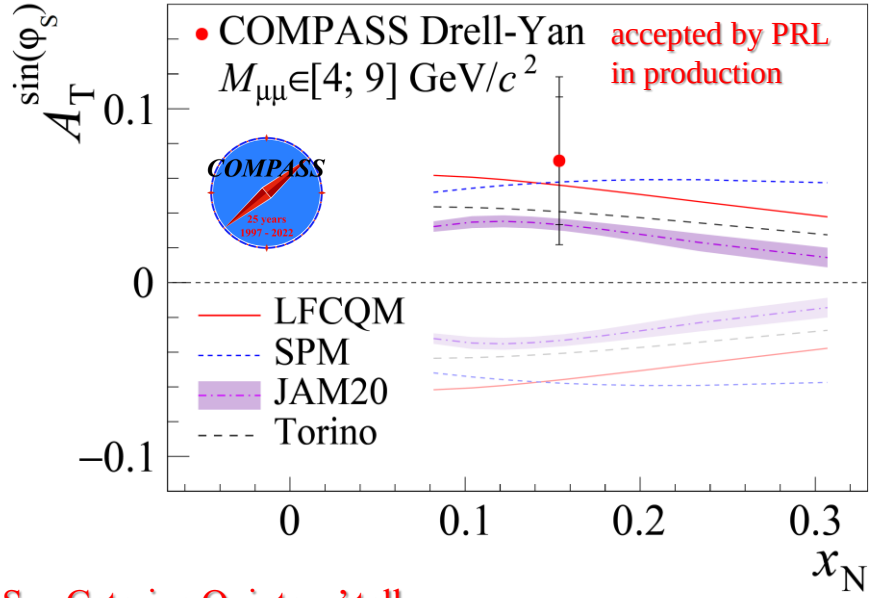
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$$



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



COMPASS, arXiv:2312.17379 [hep-ex]



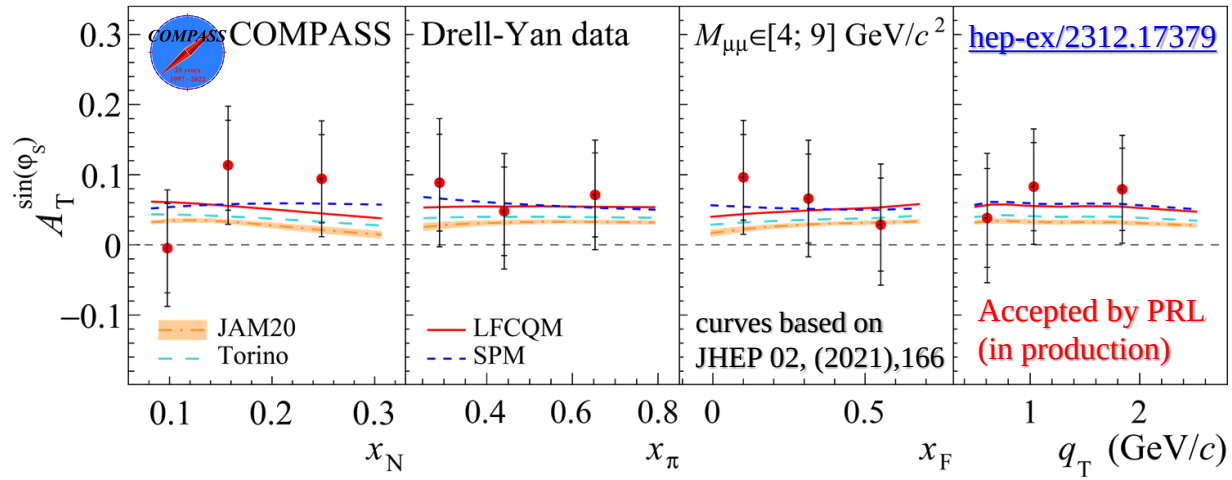
See Catarina Quintans' talk

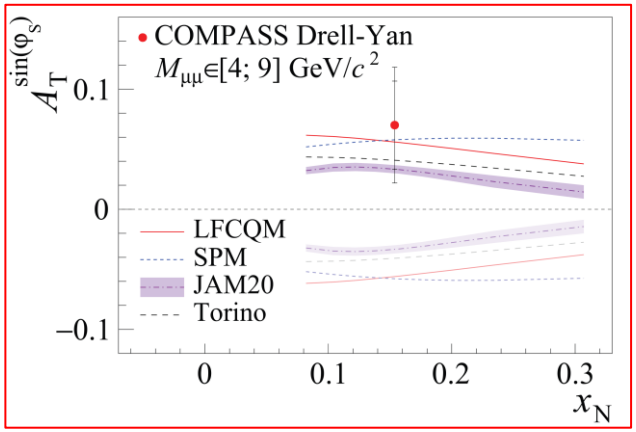
- COMPASS data favors the sign change
  - Useful input to constrain the fits
  - None of the models can be preferred

Sivers effect: Drell-Yan and J/ψ

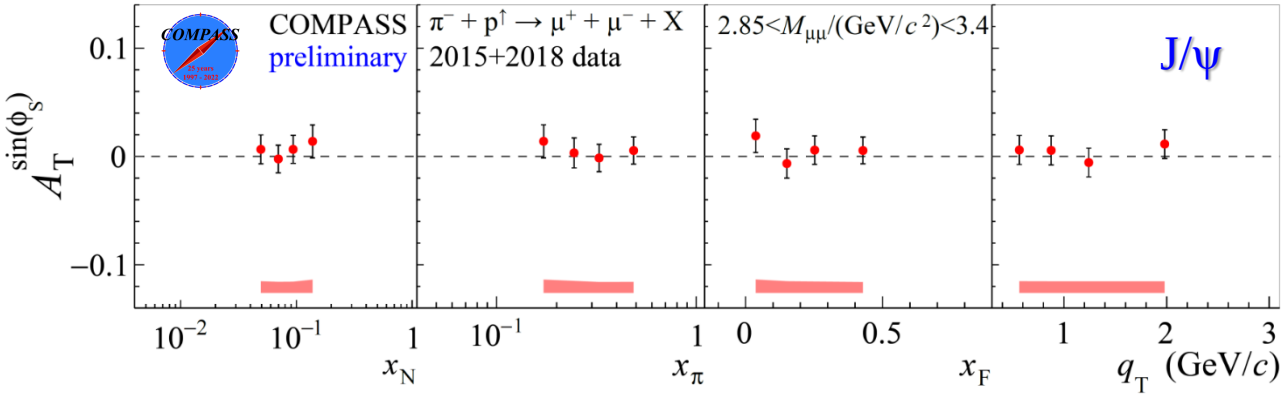
Sivers DY TSA

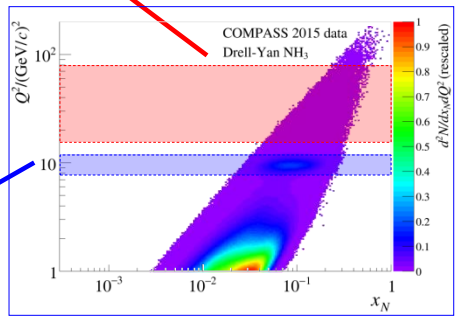
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

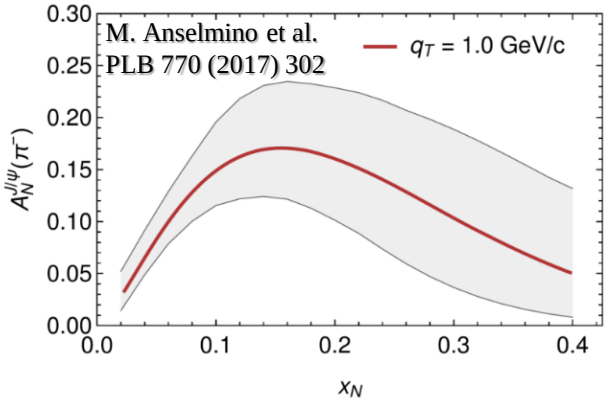




- The Drell-Yan Sivers asymmetry tends to be positive (~1.5 s.d.)



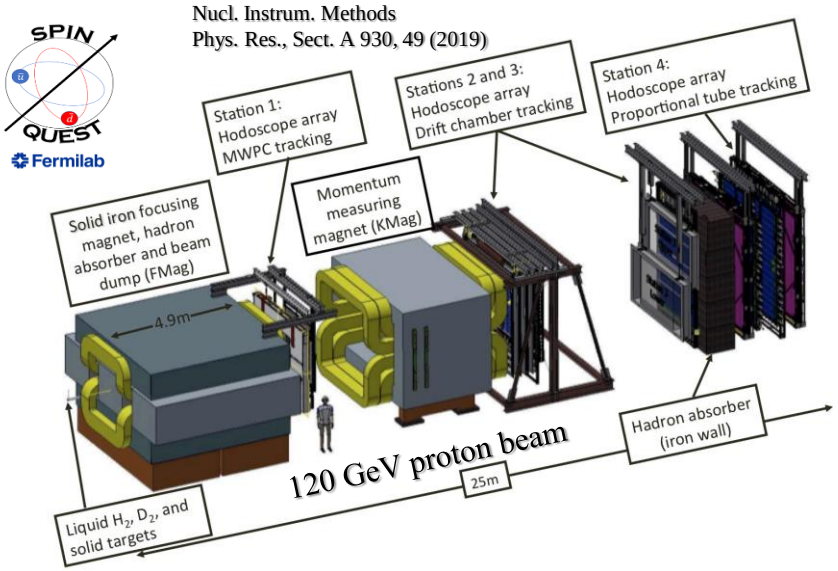


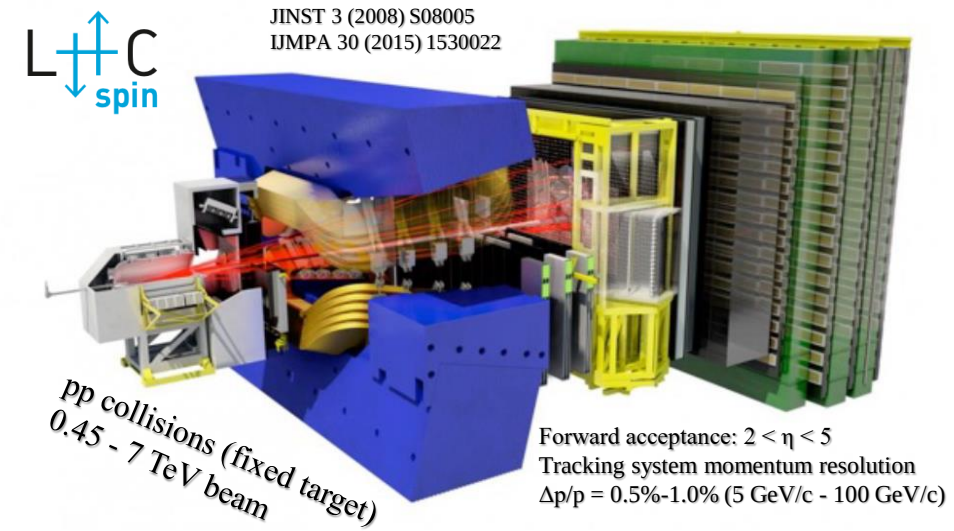


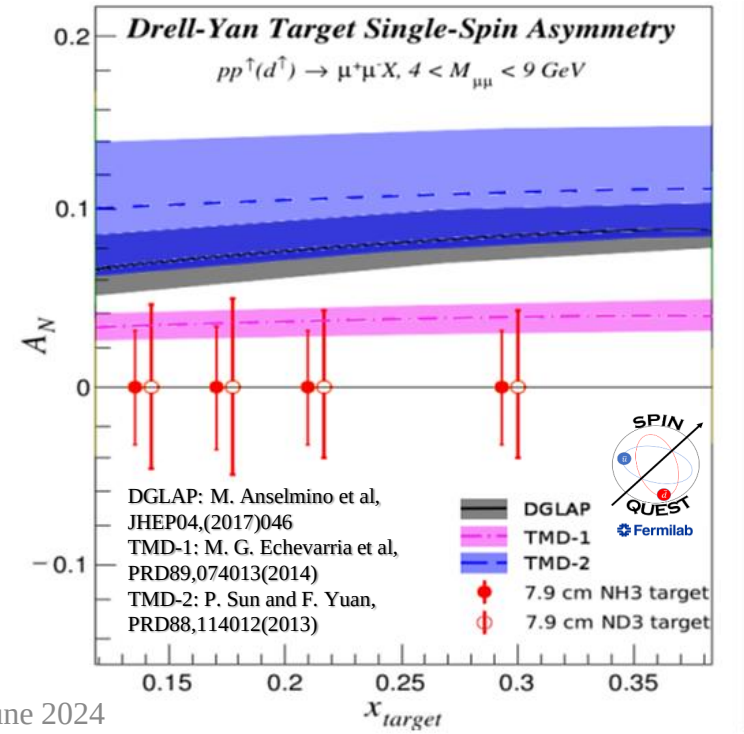
- J/ψ Sivers asymmetry is compatible with zero (within ~ 1%)
- Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS
- Hint that J/ψ production might go via gg fusion in COMPASS?
- Access to small gluon TMDs?

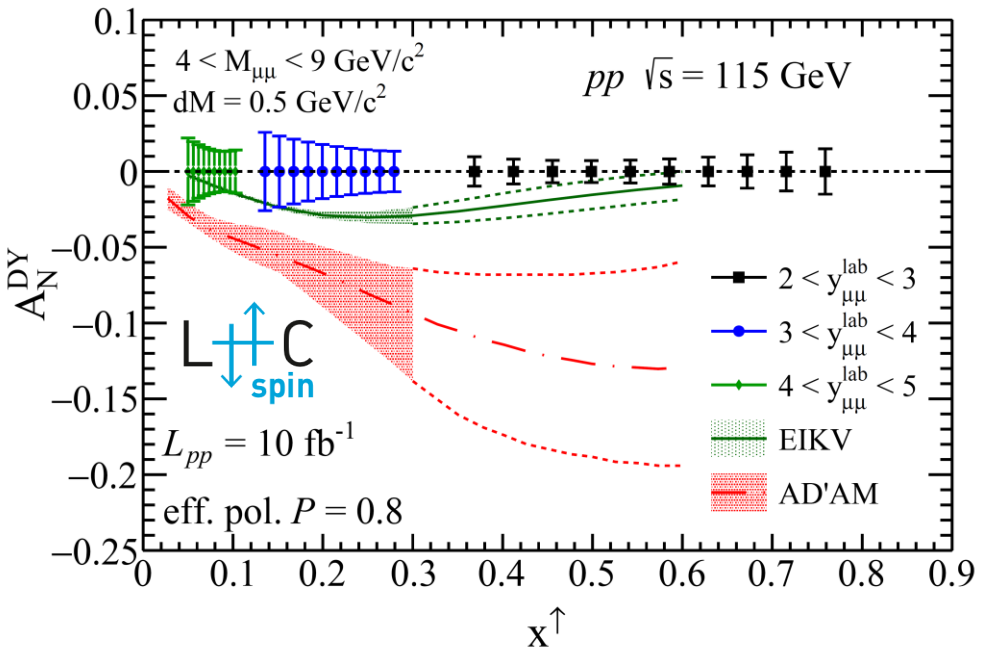
See Catarina Quintans' talk

Sivers TMD PDF: sign change - future



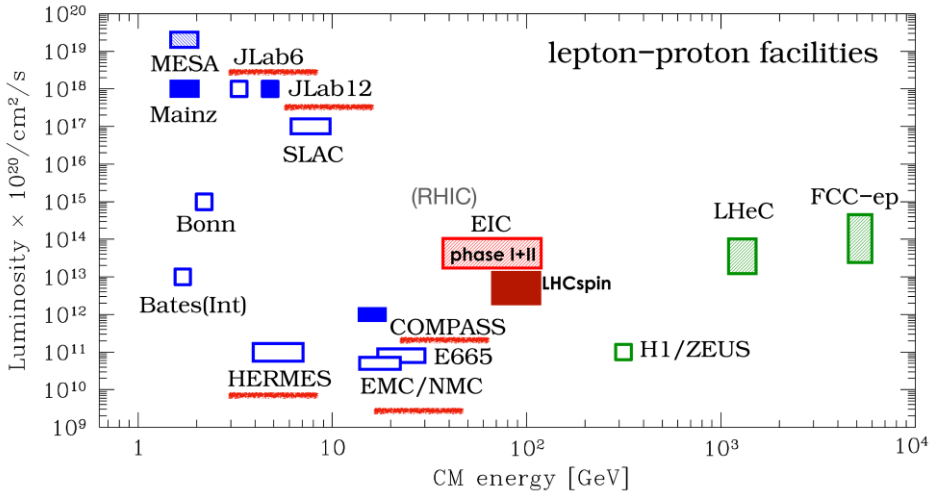


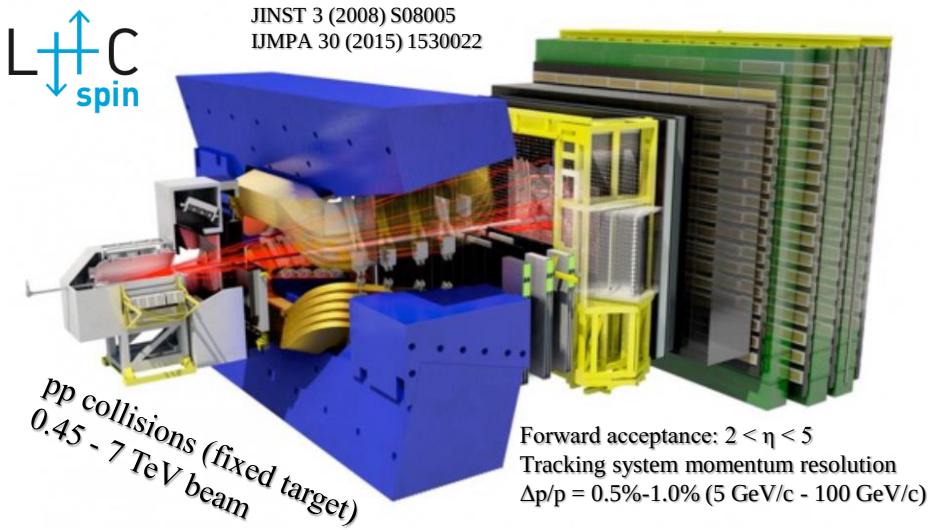


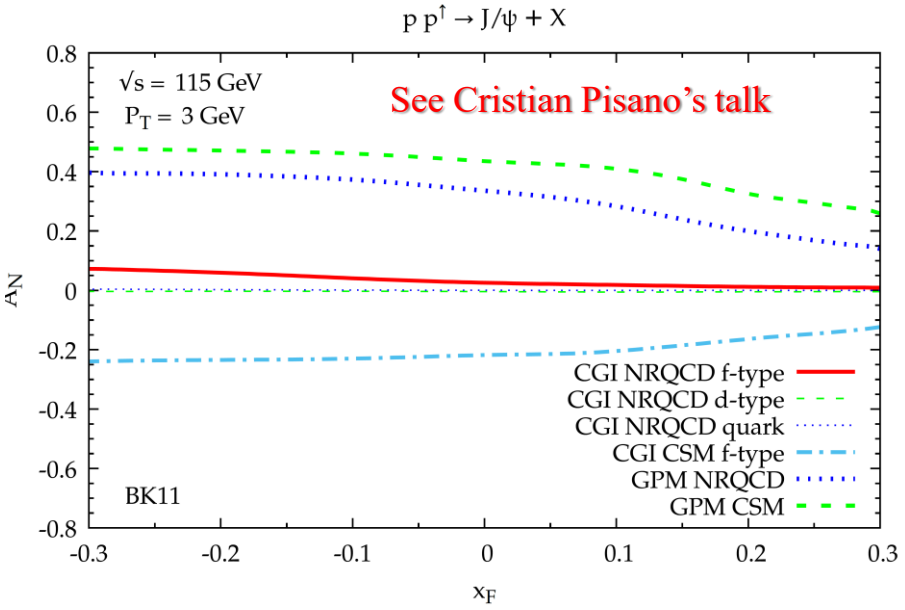


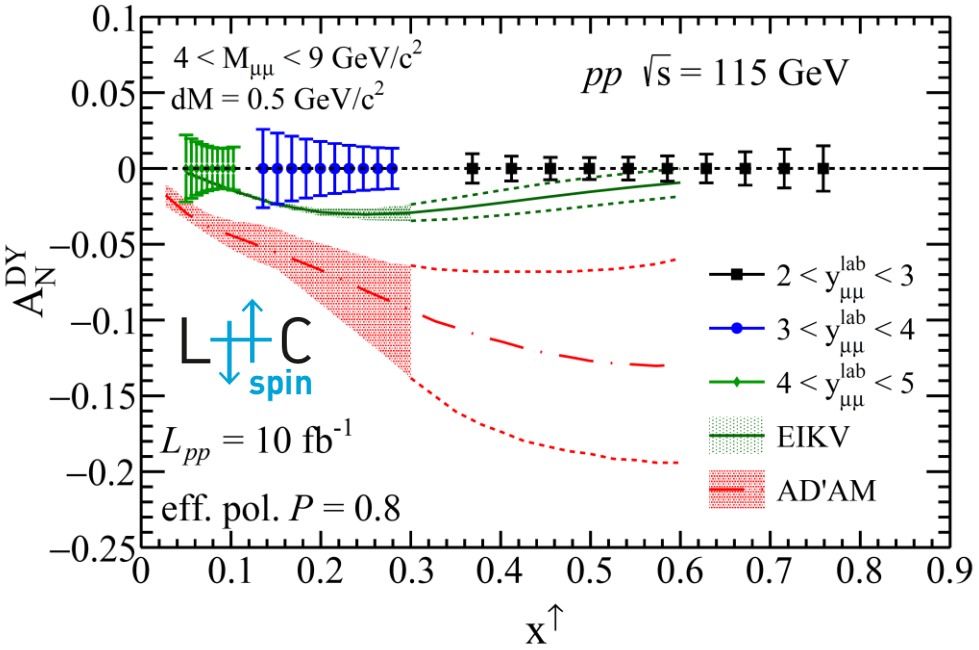
See Charlotte Van Hulse's talk

Sivers TMD PDF: sign change - future



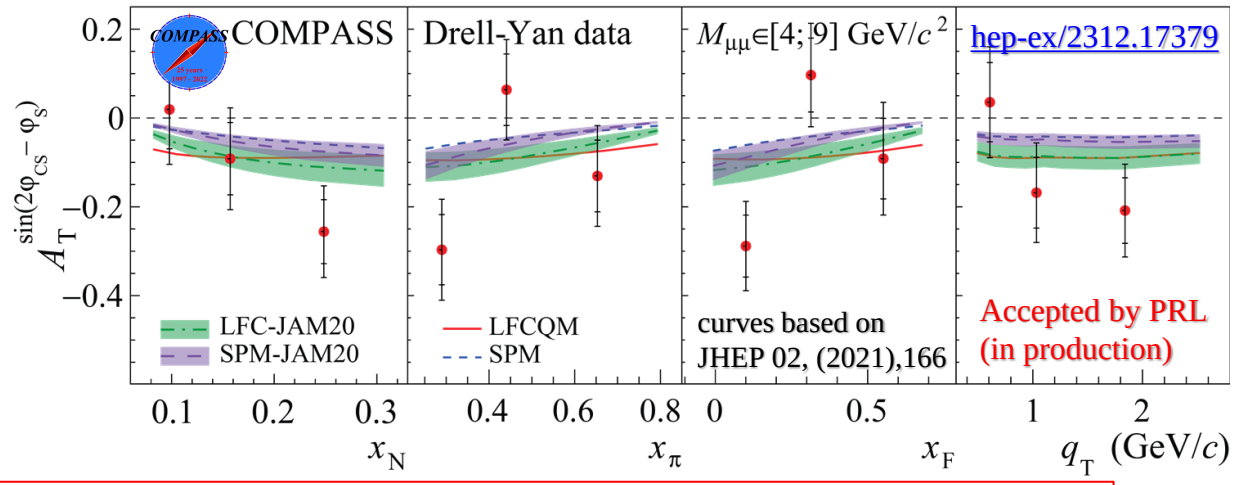


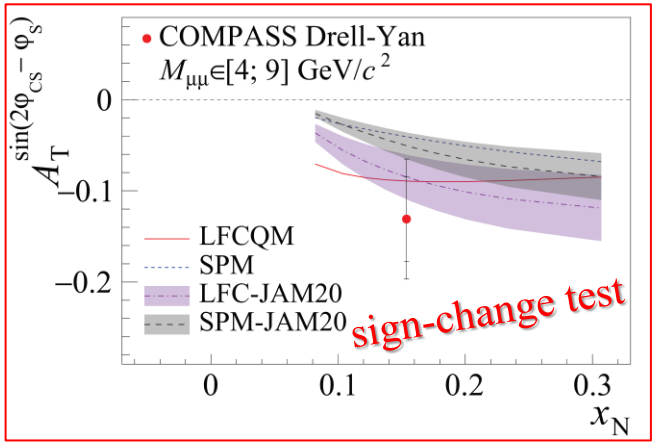




See Charlotte Van Hulse's talk

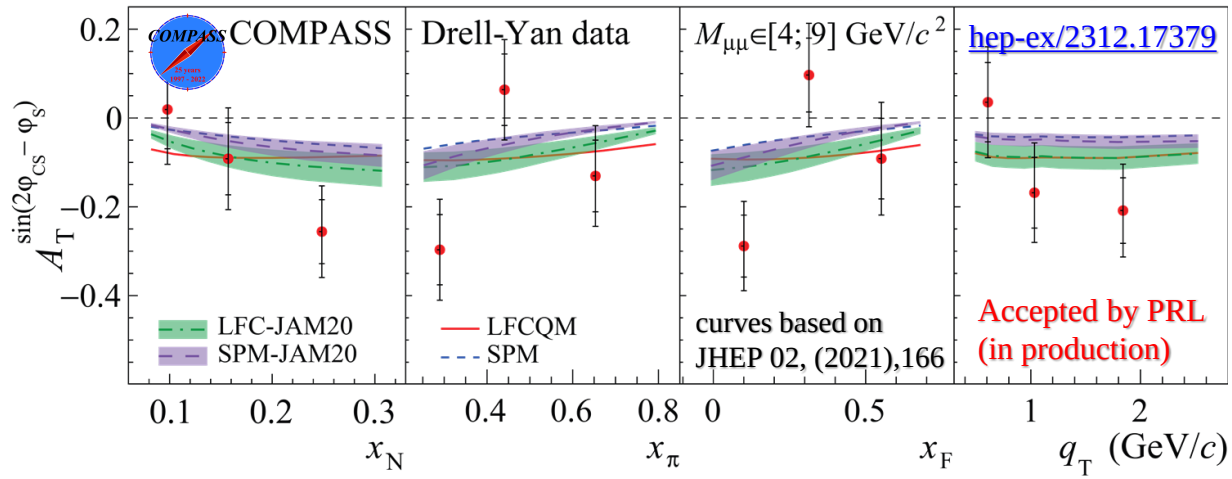
Boer-Mulders TMD PDF: sign change

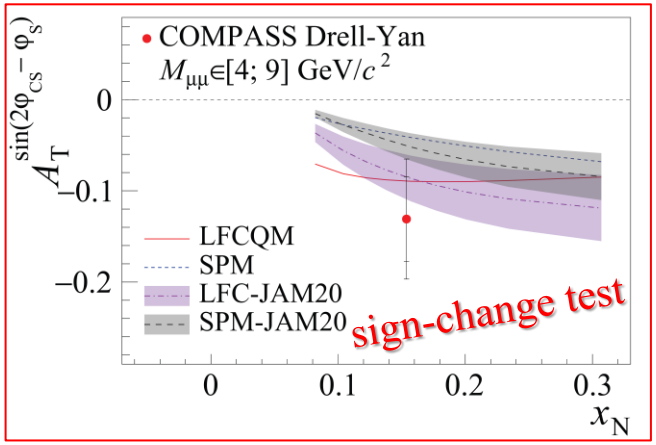




DY: $A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto -\left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,p}^{u}\right\} < 0 \Rightarrow h_{1,\pi^-}^{\perp\bar{u}} > 0$

Boer-Mulders TMD PDF: sign change





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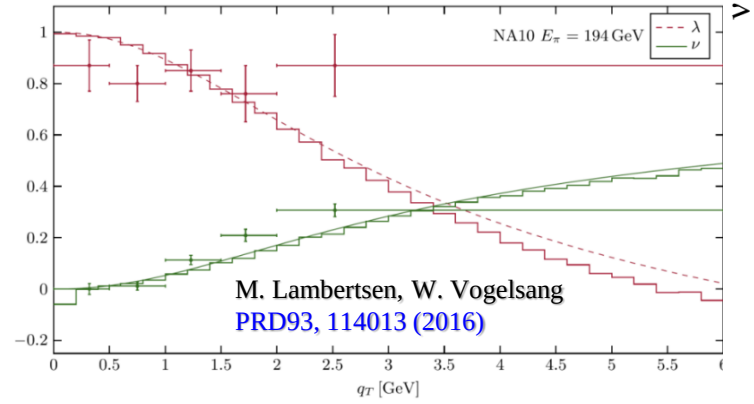

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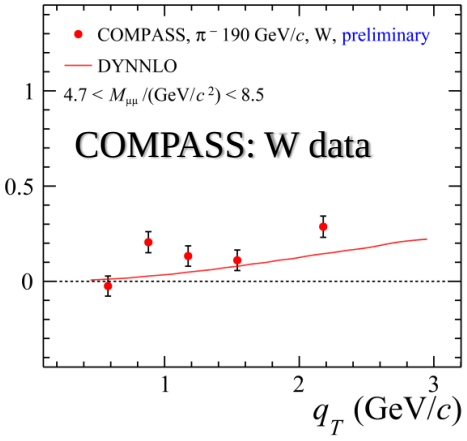
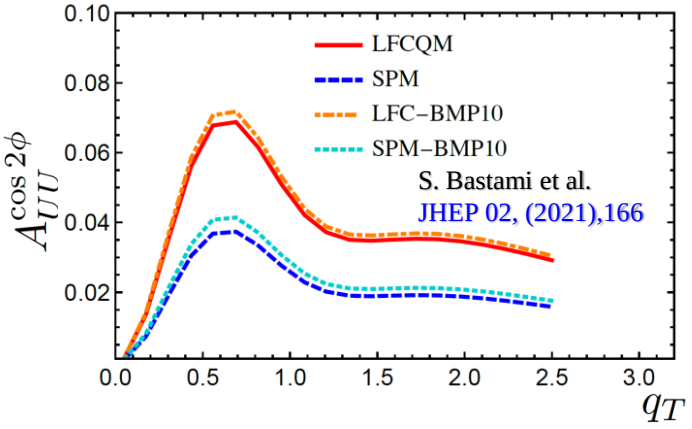




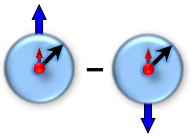
DY: $A_T^{\sin 2\varphi_{CS}} \propto \left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,p}^{\perp u}\right\} > 0 \Rightarrow h_{1,p}^{\perp u} > 0 \overset{\text{sign-change}}{\Leftrightarrow}$ SIDIS: $h_{1,p}^{\perp u} < 0$

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

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

- Collins and Sivers effects

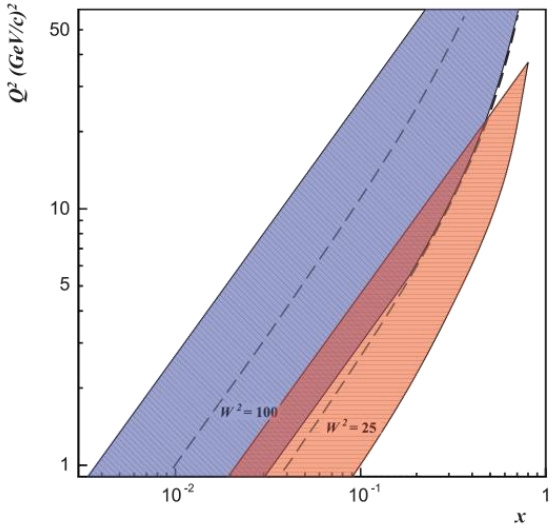
SIDIS TSAs: Collins effect and Transversity



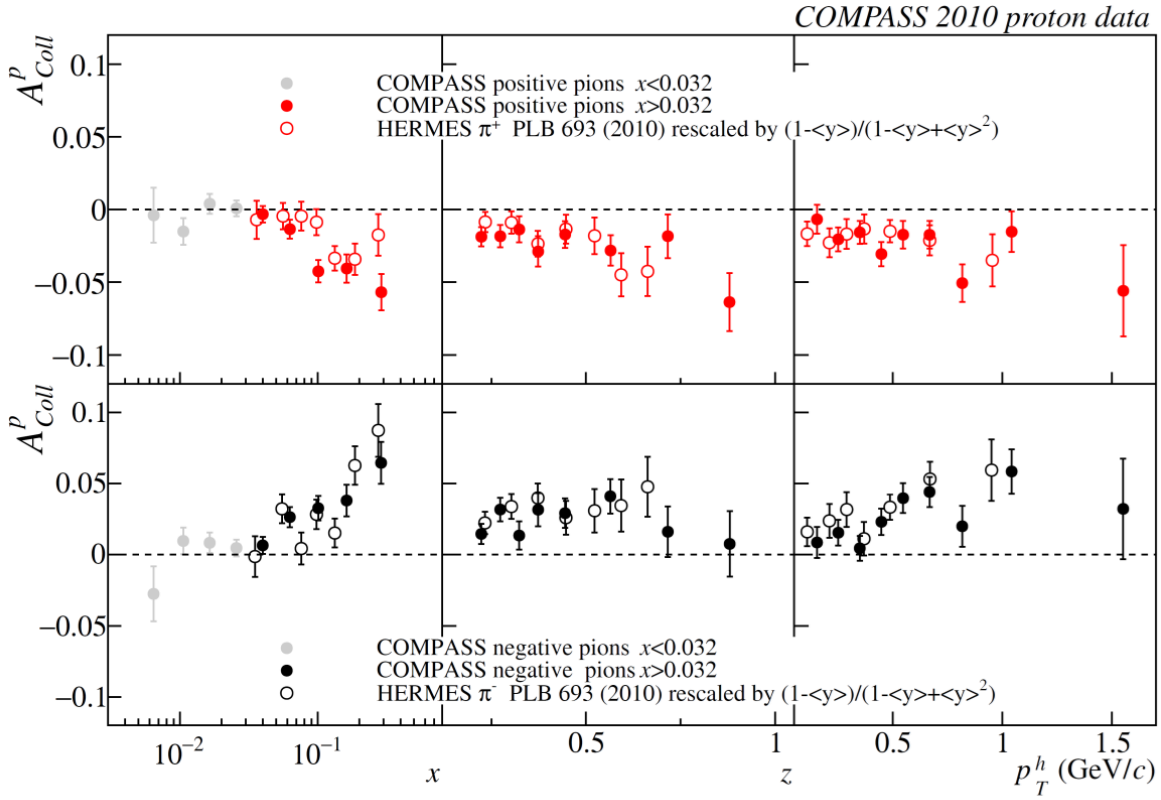
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon\, A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\right\}$$

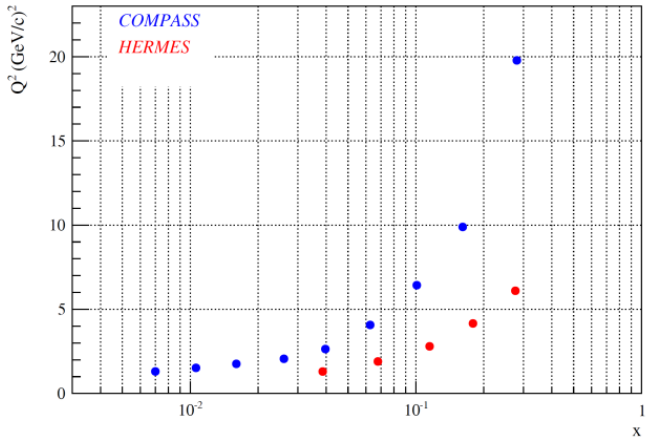
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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



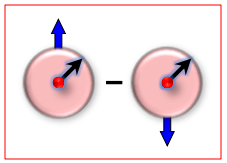
COMPASS PLB 744 (2015) 250





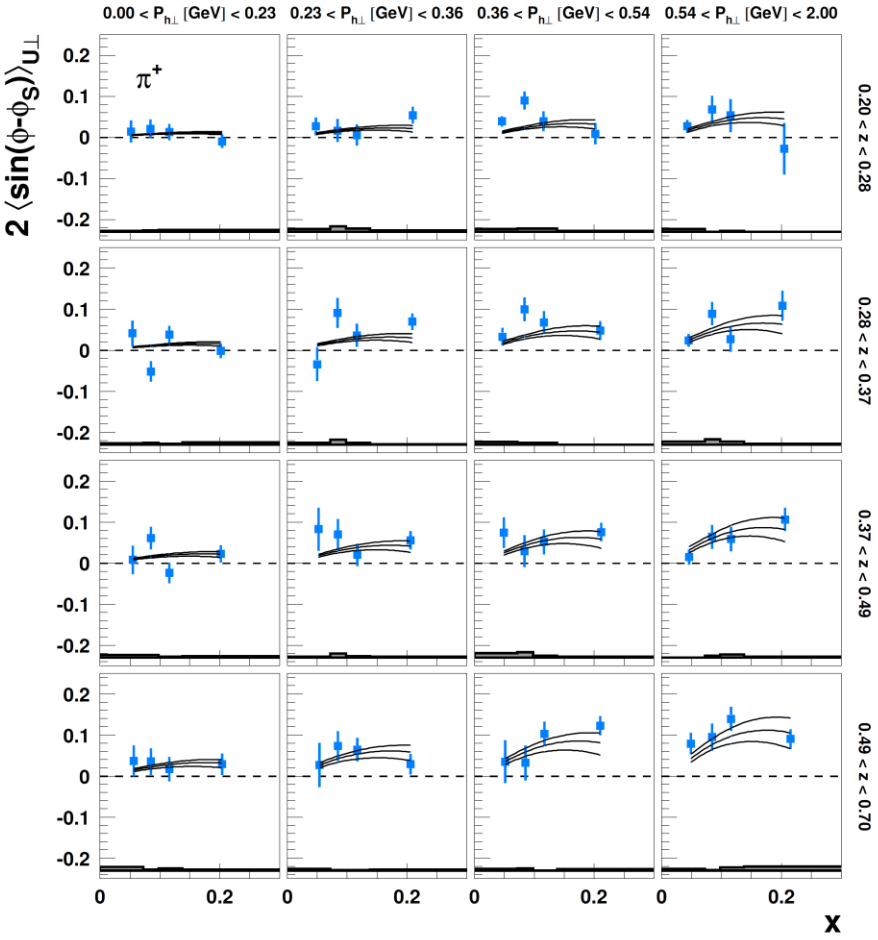
SIDIS TSAs: Sivers effect

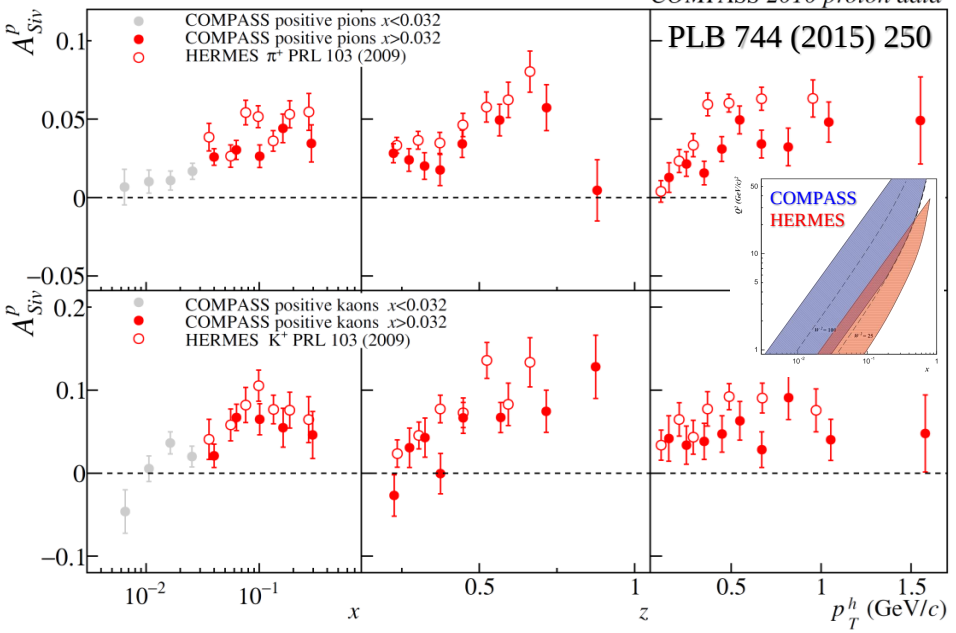
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h - \phi_S\right) + \ldots\right\}$$

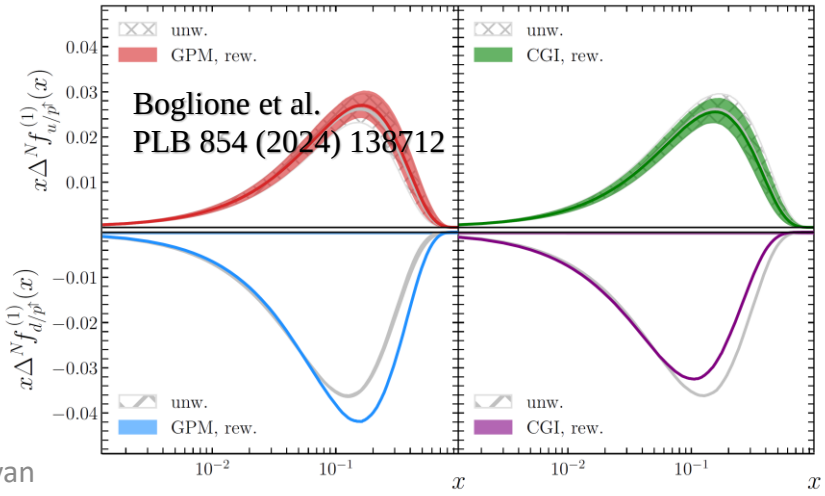


$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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







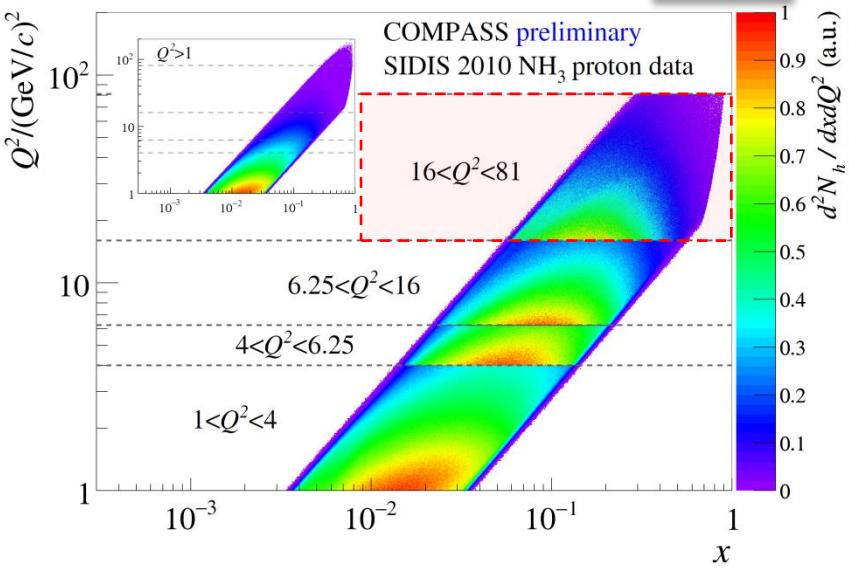
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

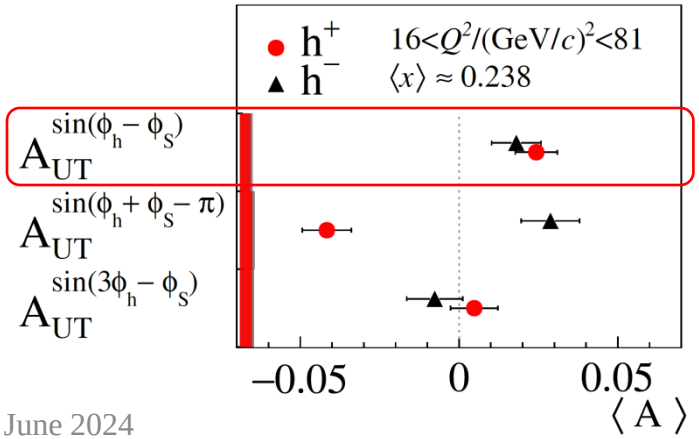
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h - \phi_S\right) + \ldots\right\}$$

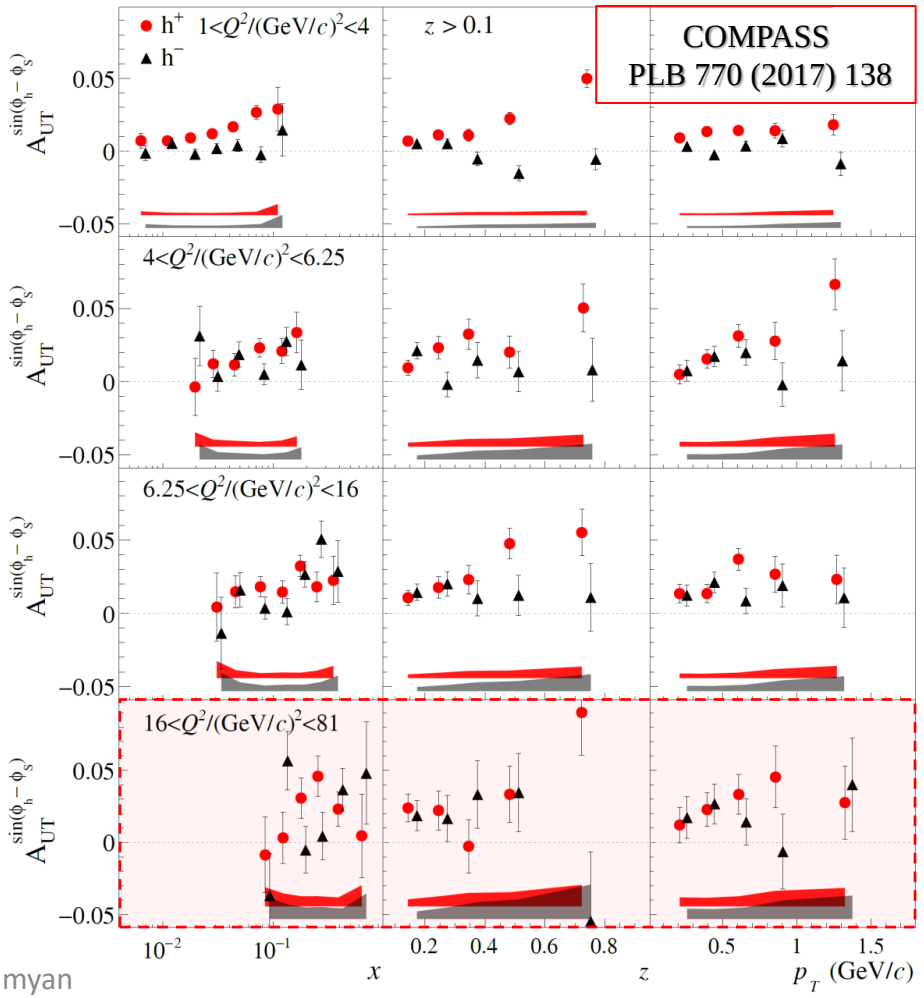
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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

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







SIDIS TSAs: Collins effect and Transversity

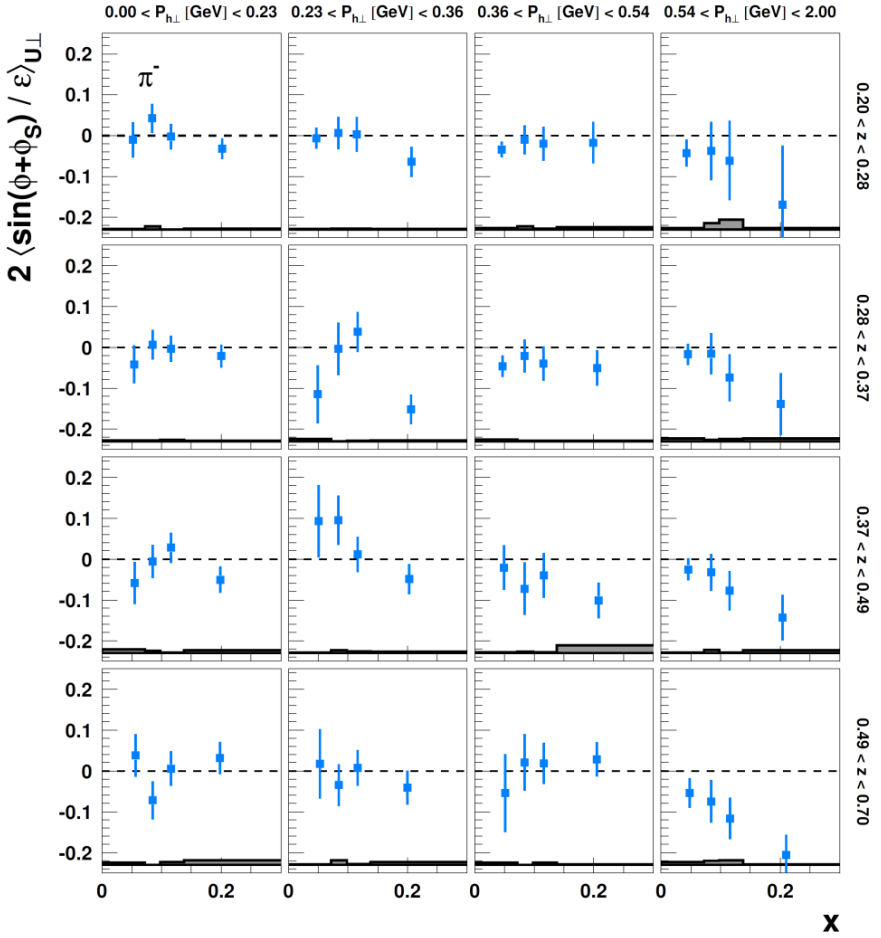
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + ... + S_T\, \varepsilon\, A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + ...\right\}$$

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

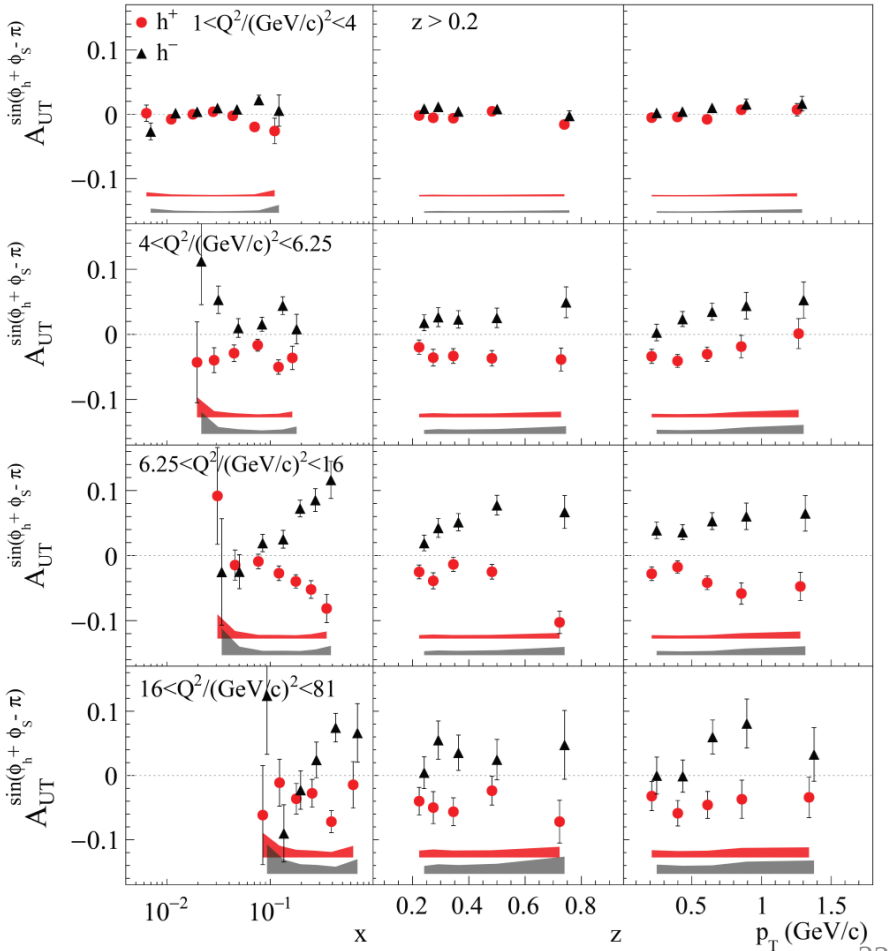
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

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

HERMES, JHEP 12 (2020) 010

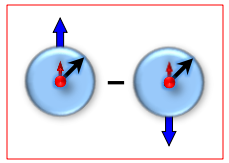


COMPASS, PBL 770 (2017) 138



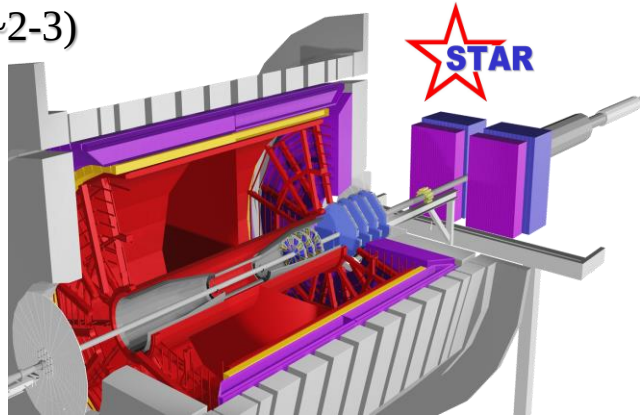
SIDIS TSAs: Collins effect and Transversity

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

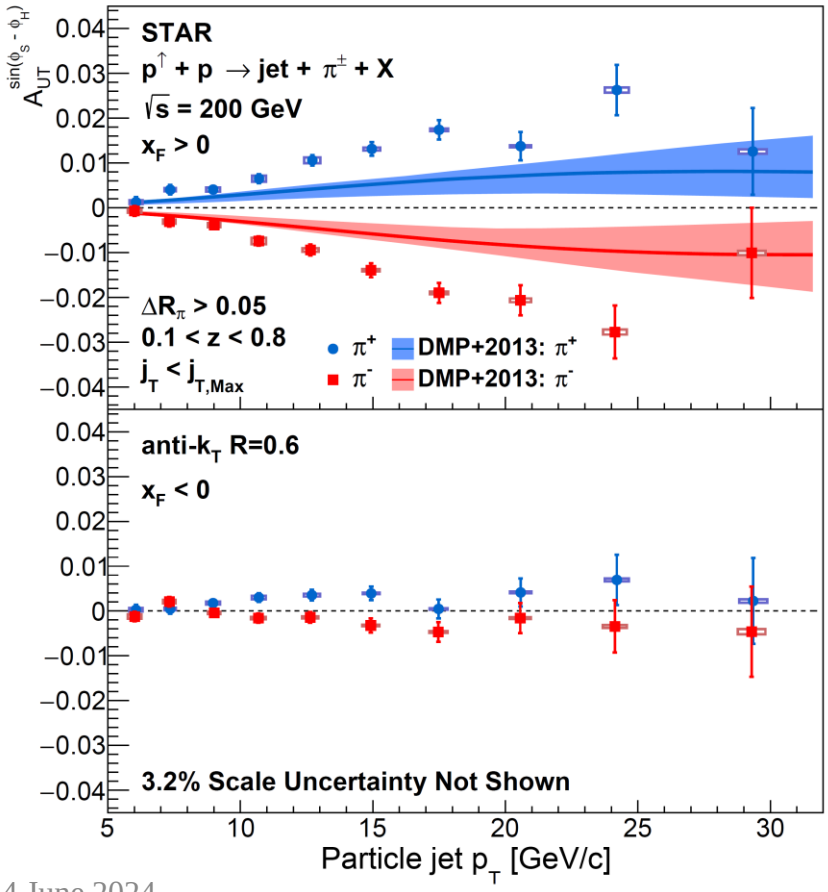


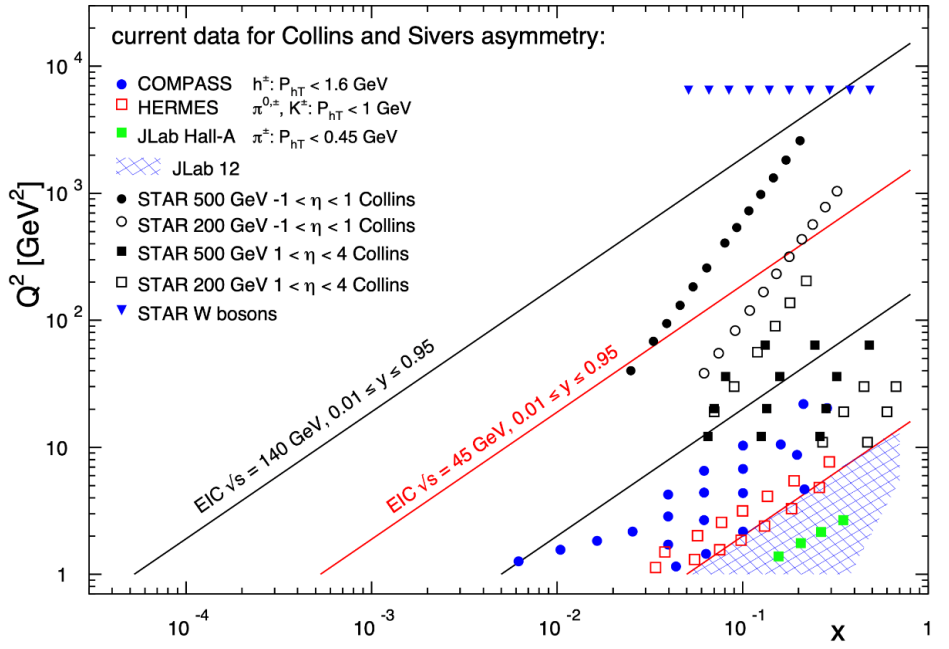
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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



STAR, PRD 106, 072010



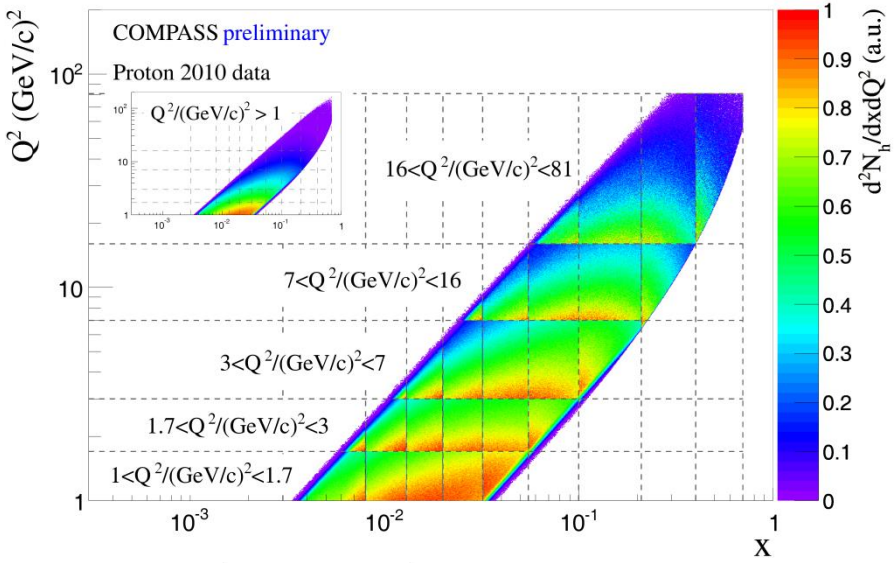


COMPASS Multi-D TSA analyses

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

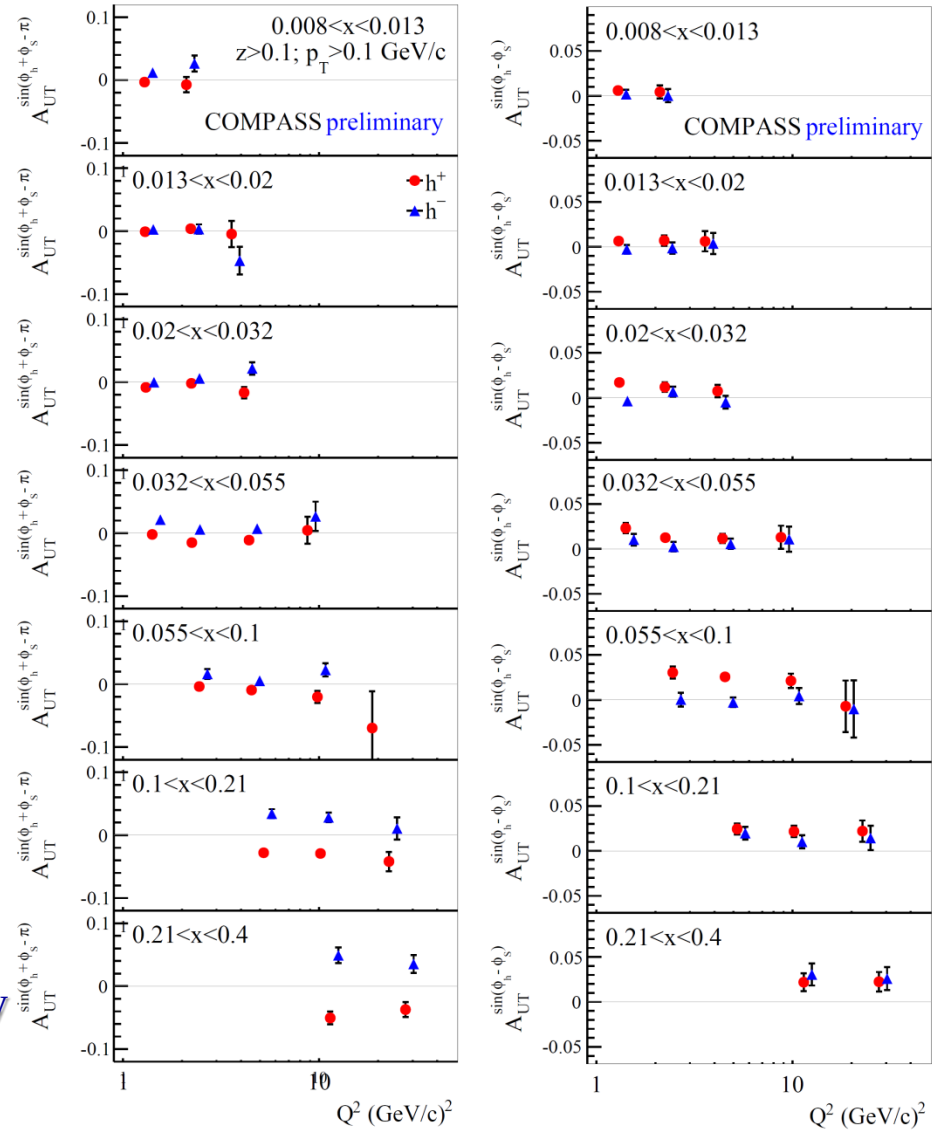
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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



3D x:Q²:z or x:Q²:p_T x:z:p_T

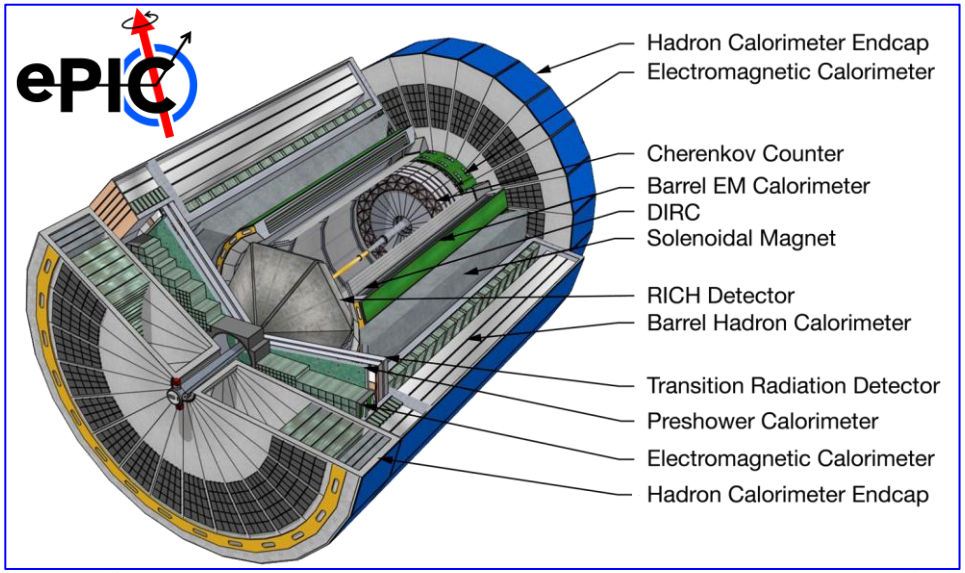
B.Parsamyan (for COMPASS) arXiv:1504.01599 [hep-ex] (SPIN-2014)



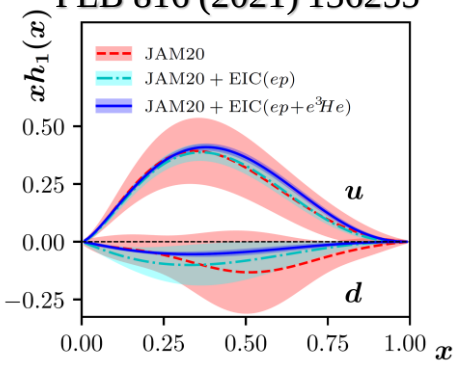
- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

Electron Ion Collider(s): EIC

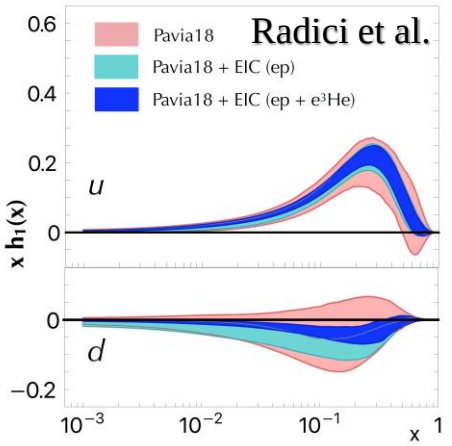
EIC WP, arXiv:1212.1701 [nucl-ex],
EIC YR, arXiv:2103.05419 [physics.ins-det]

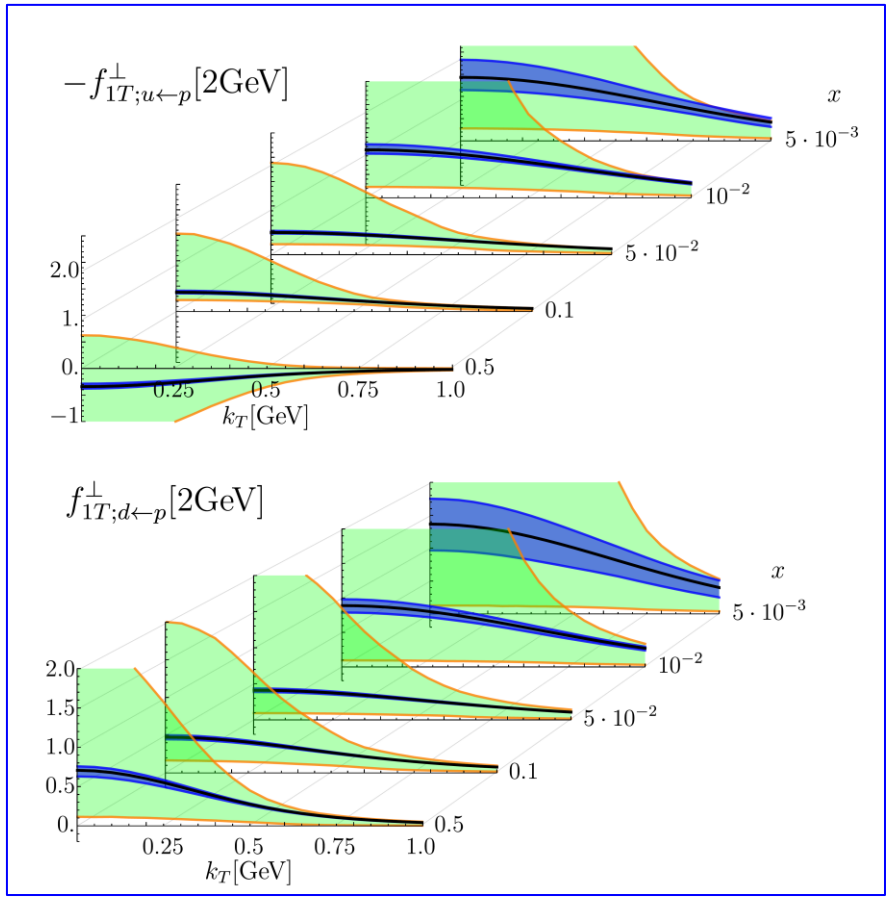


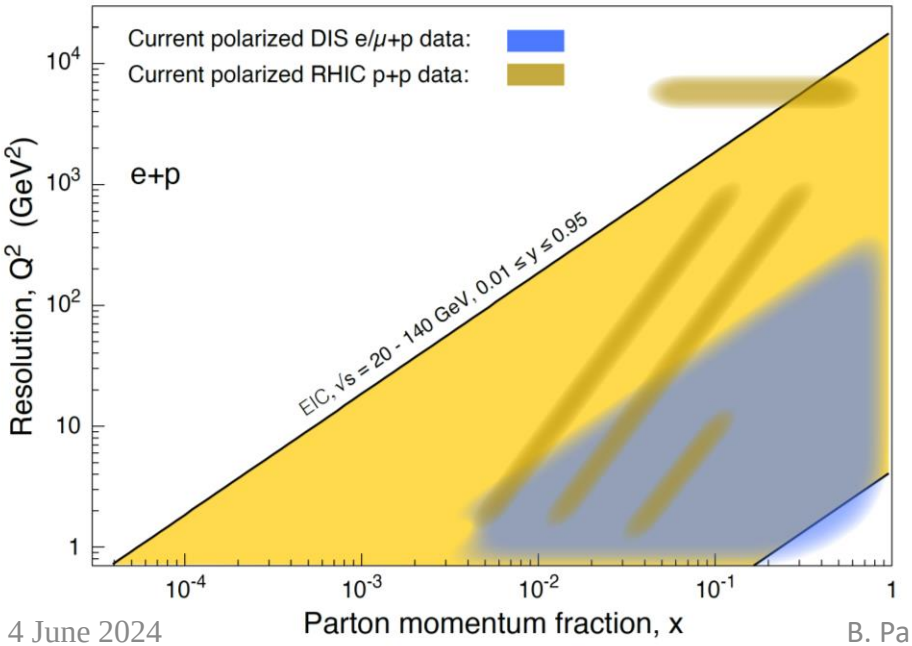
Gamberg et al. (JAM)
PLB 816 (2021) 136255



Radici et al.



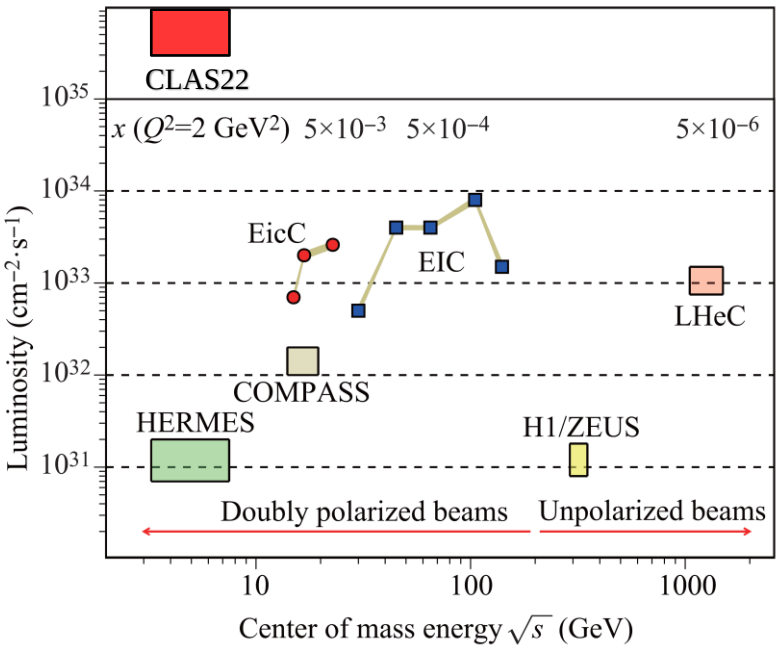


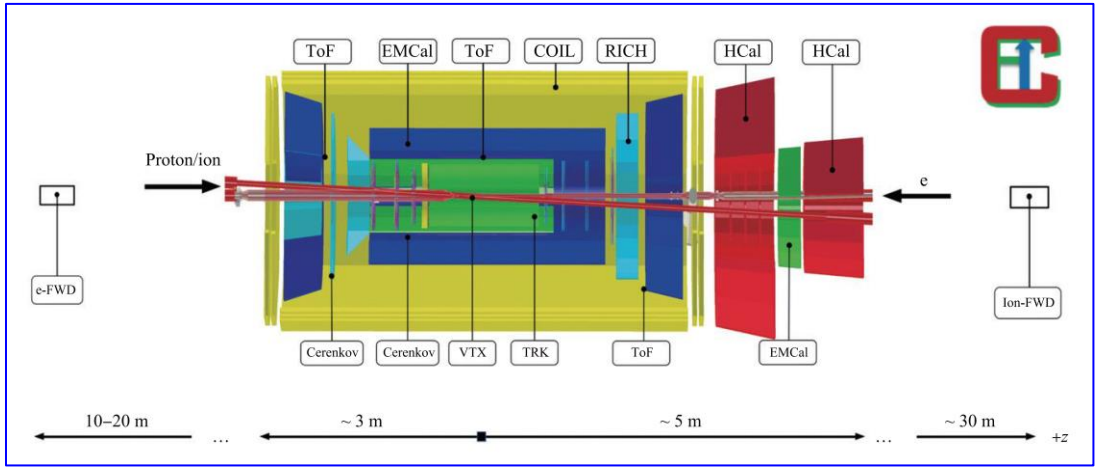


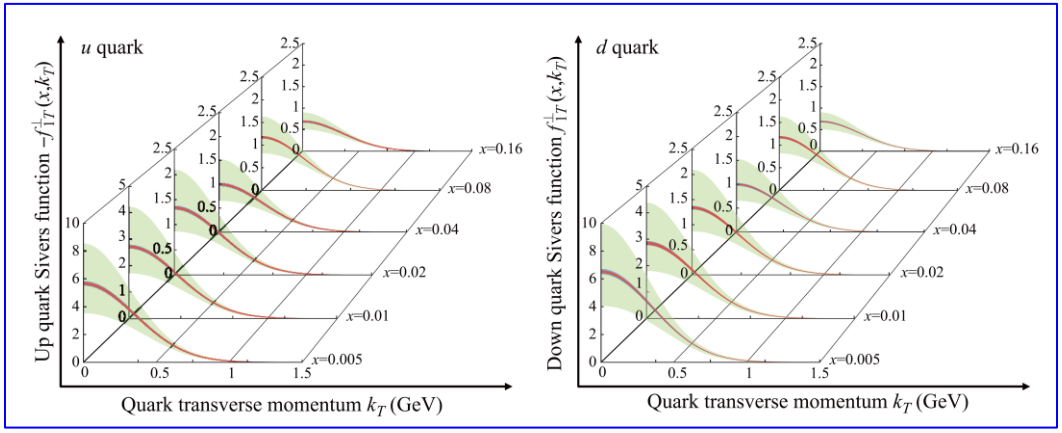
See Elke Aschenauer's talk

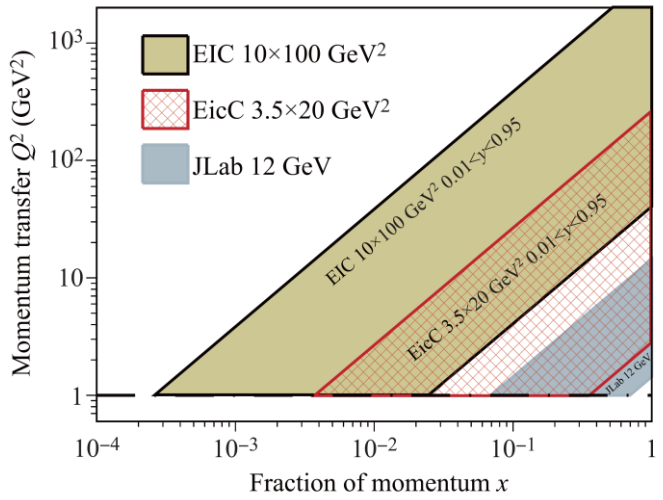
Electron Ion Collider(s): EICc

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



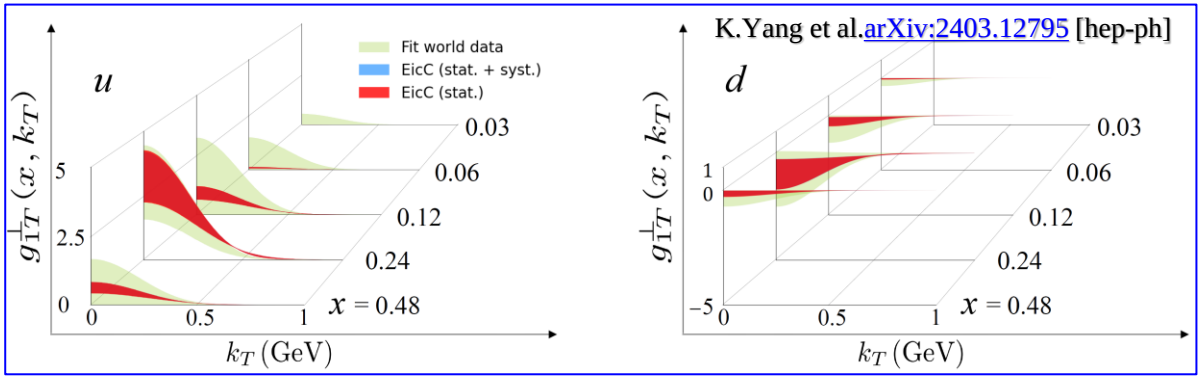




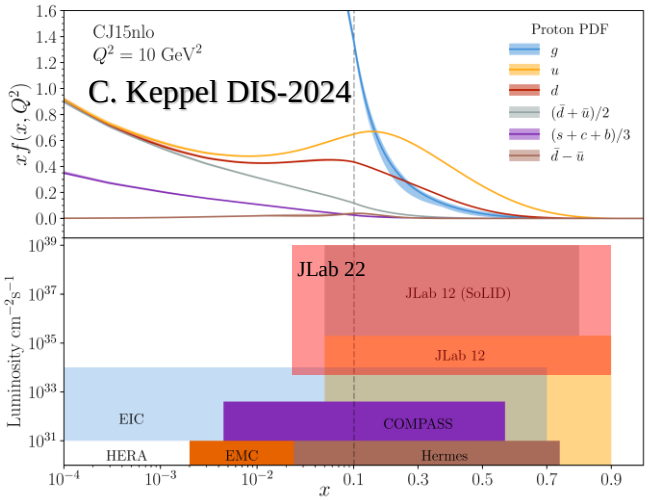


See Yuxiang Zhao's talk

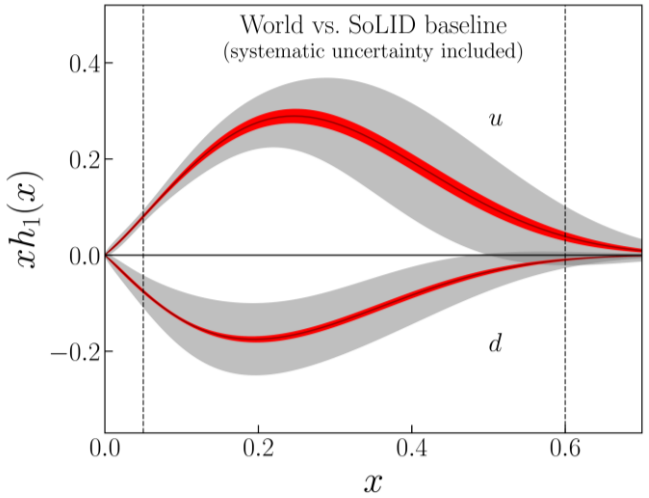
K.Yang et al.arXiv:2403.12795 [hep-ph]

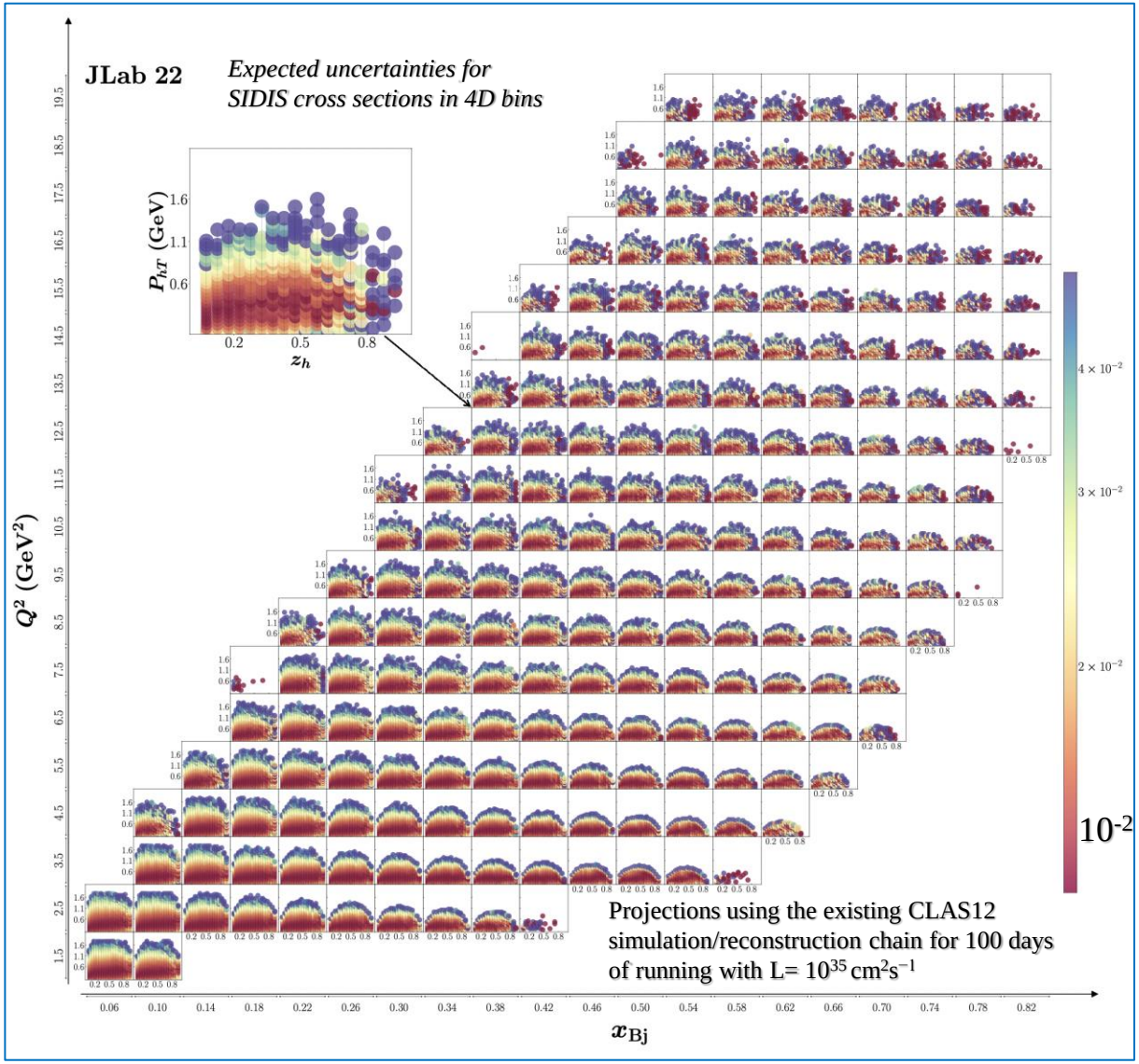


JLab from 12 GeV, SoLID to 22 GeV



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

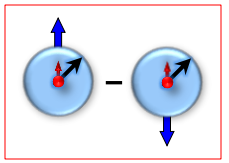




- High luminosity, complementary kinematic coverages, evolution studies, all TMDs, etc.
- Together with EIC/EICc - complete picture!

SIDIS TSAs: Collins effect and Transversity

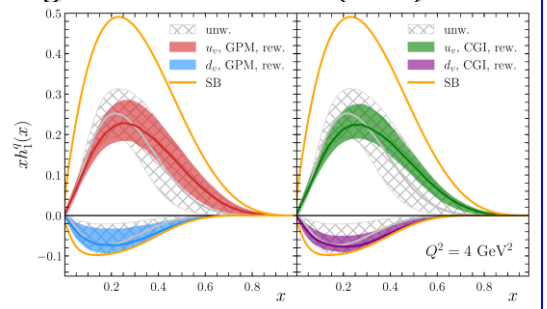
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + ... + S_T\, \varepsilon\, A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + ...\right\}$$



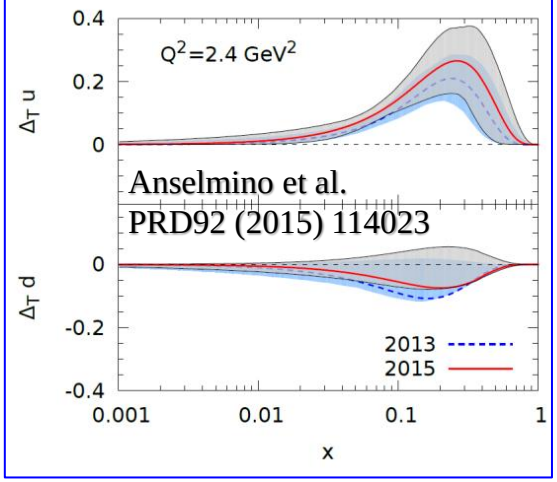
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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

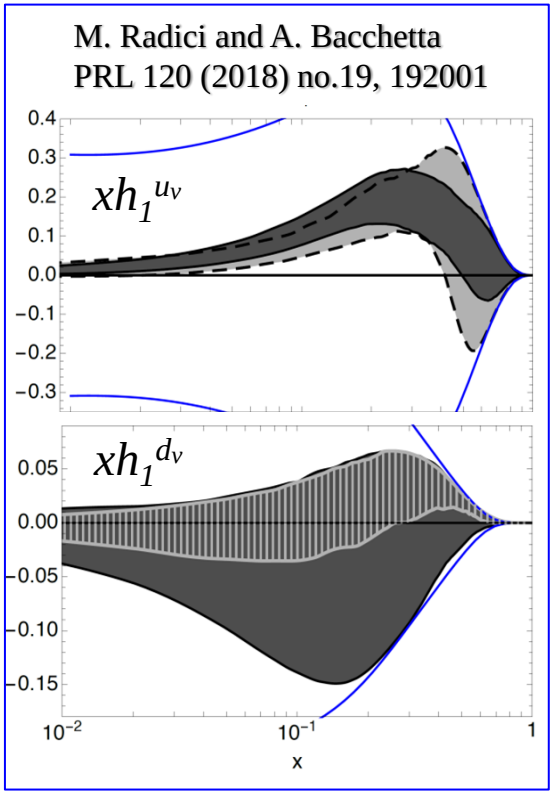
Boglione et al. PLB 854 (2024) 138712



See Carlo Flore's talk

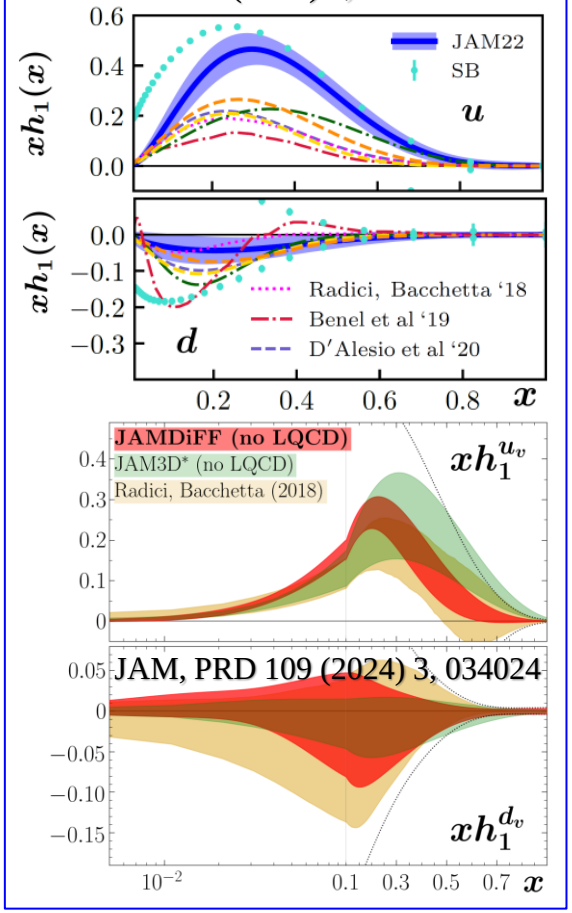


M. Radici and A. Bacchetta
PRL 120 (2018) no.19, 192001



See Marco Radici's talk

JAM PRD 106 (2022) 3, 034014



SIDIS TSAs: Collins effect and Transversity

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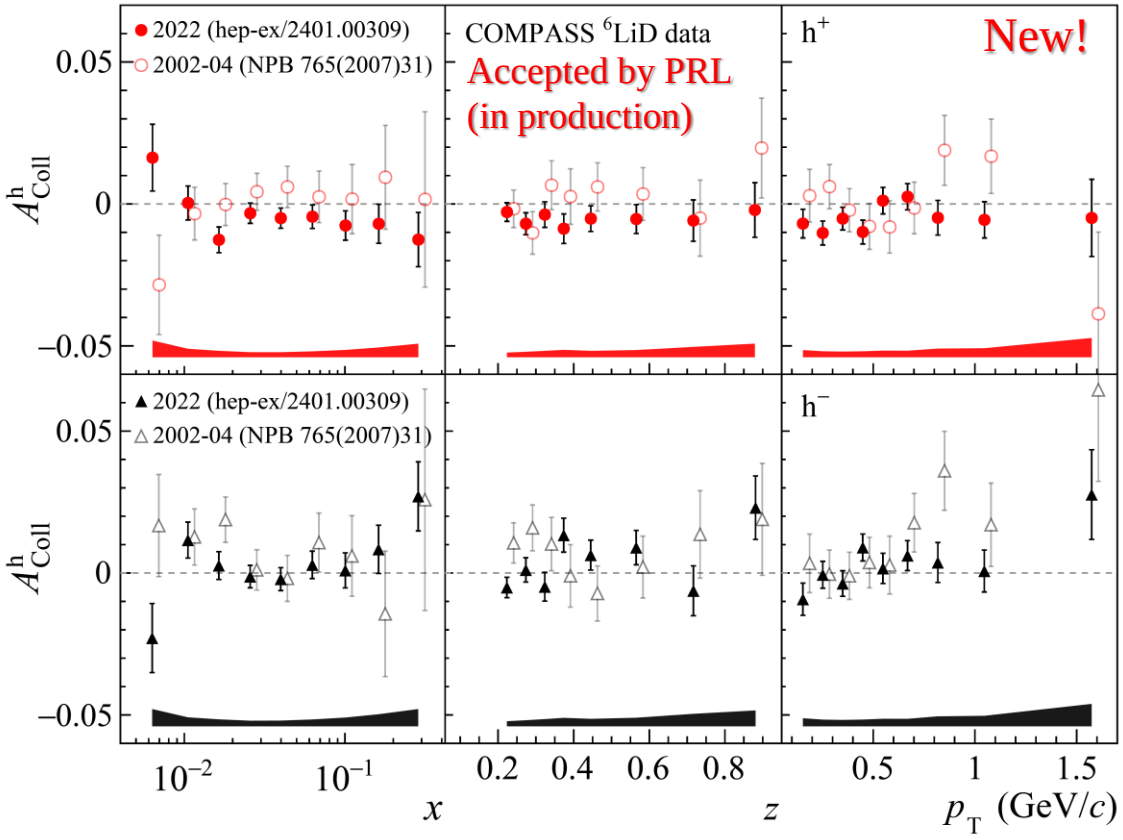
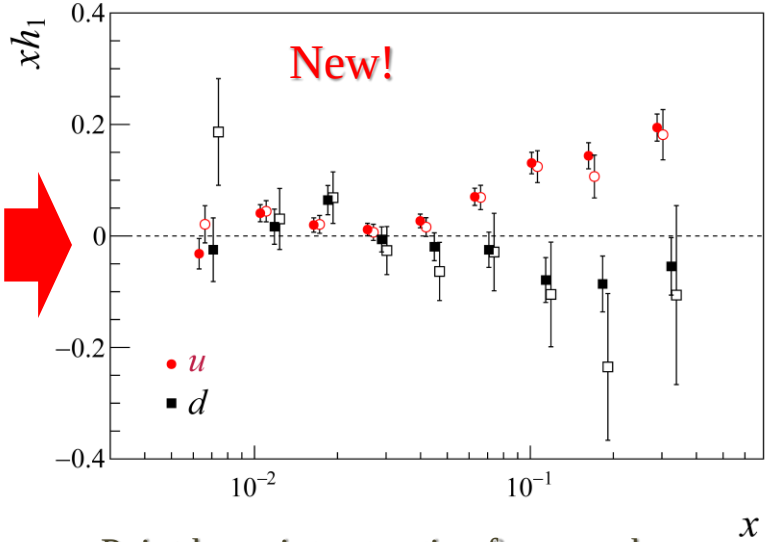
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity



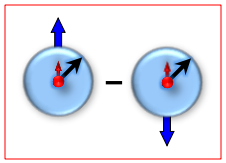


Point-by-point extraction framework
A. Martin et al. PRD **91**, 014034 (2015)
A. Martin et al. PRD **95**, 094024 (2017)

COMPASS 2022 run – highly successful data-taking!

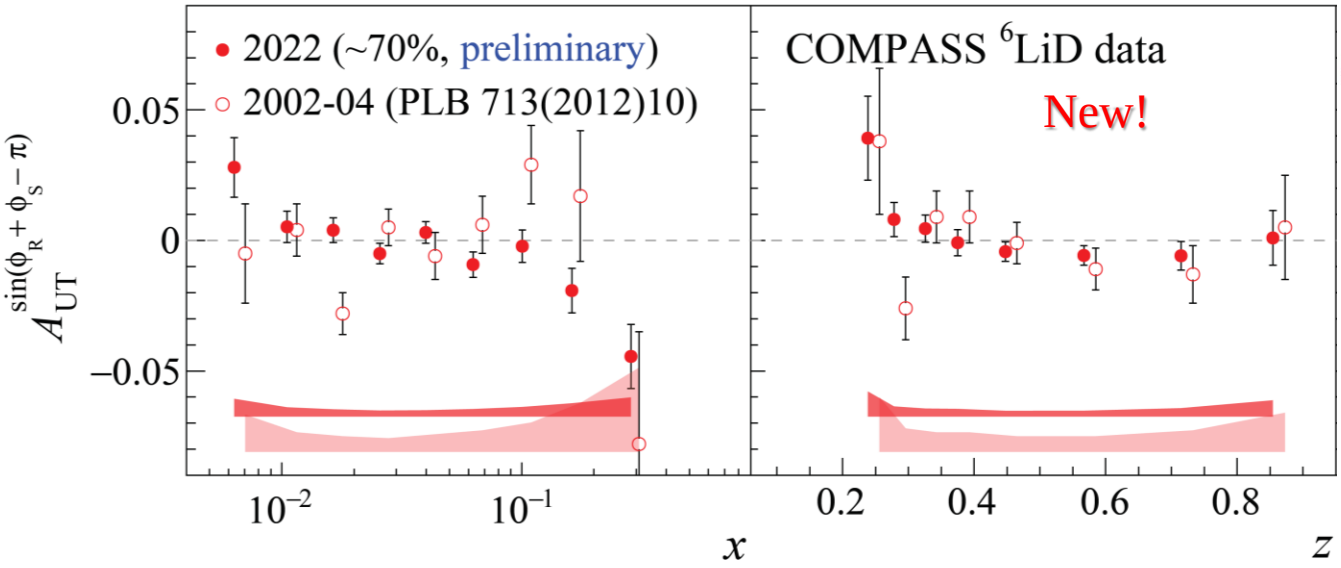
- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades

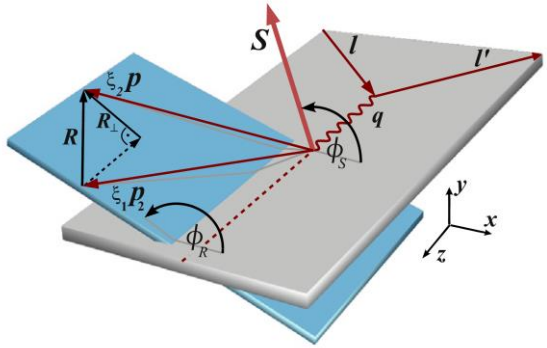
Dihadron Collins effect and Transversity



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

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





COMPASS 2022 run – highly successful data-taking!

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

See Athira Vijayakumar's talk

COMPASS 2022 run: new unique deuteron data

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

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

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

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

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

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

Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

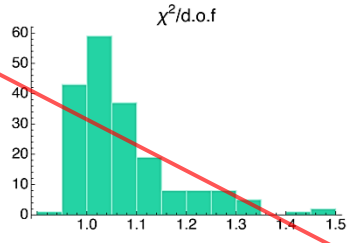
$Q^2 \geq 1.4$ GeV^2 $\quad 0.2 \leq z \leq 0.7$

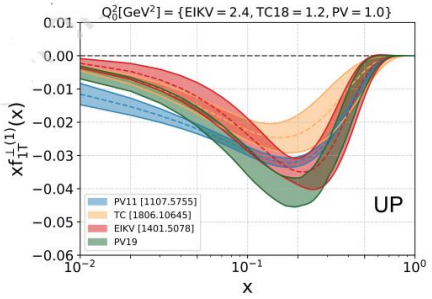
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

300 data points → **118** data fitted

14 free parameters

χ^2/d.o.f. = 1.06 ± 0.10





PV11 — Bacchetta & Radici, P.R.L. **107** (11)

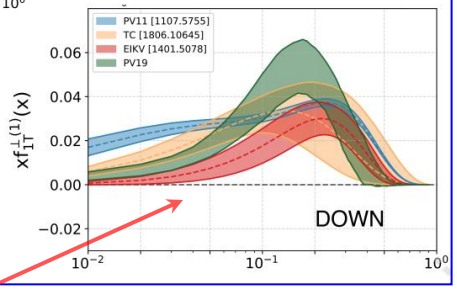
EIKV — Echevarria et al., P.R. D**89** (14)

TC — Boglione et al., JHEP **1807** (18)

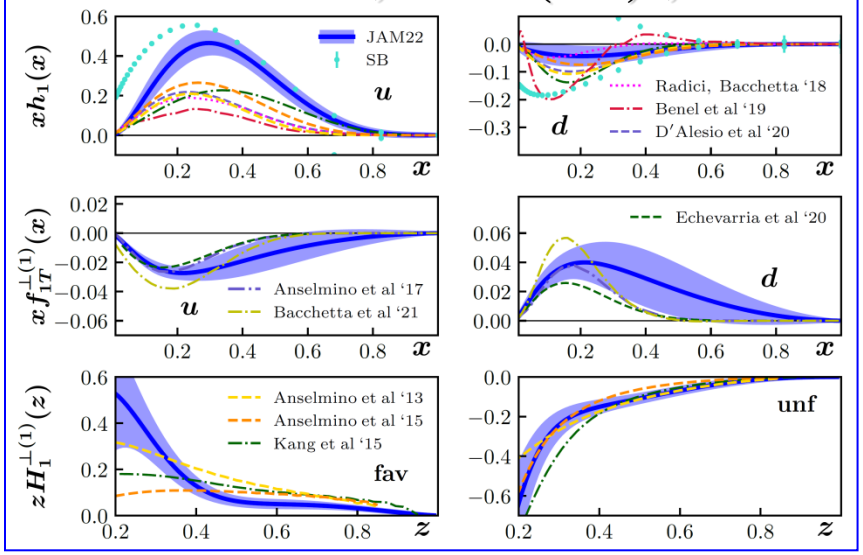
PV19 — Bacchetta, Delcarro, Pisano, Radici, in preparation

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

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

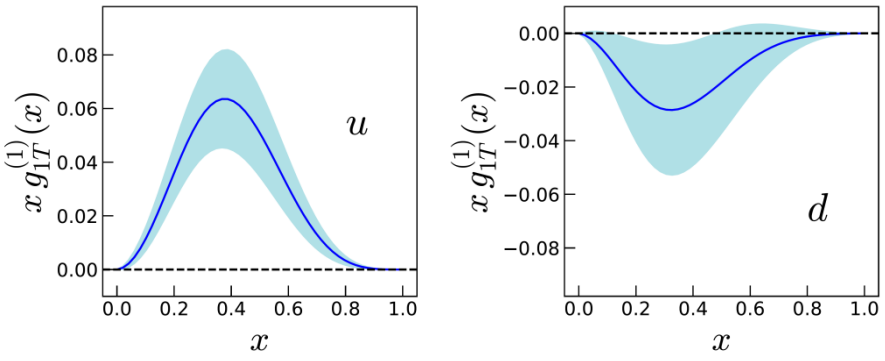


JAM Collaboration, PRD 106 (2022) 3, 034014



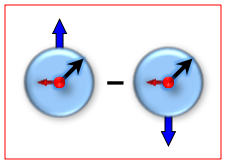
COMPASS 2022 deuteron run

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



SIDIS TSAs: Kotzinian-Mulders asymmetry

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



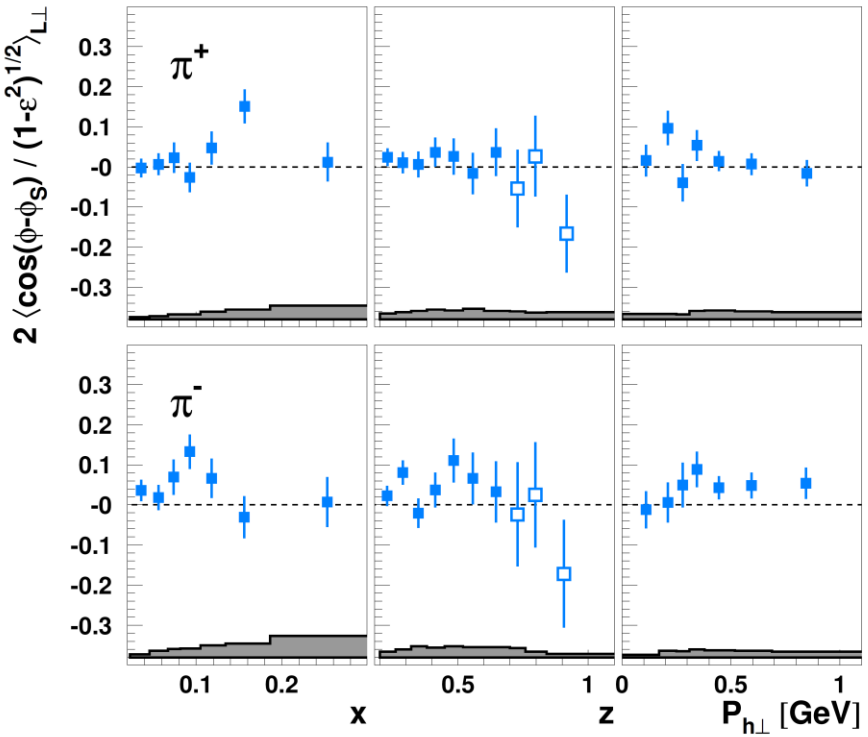
$$F_{LT}^{\cos(\phi_h - \phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} g_{1T}^q D_{1q}^h\right]$$

COMPASS/HERMES/CLAS6 results

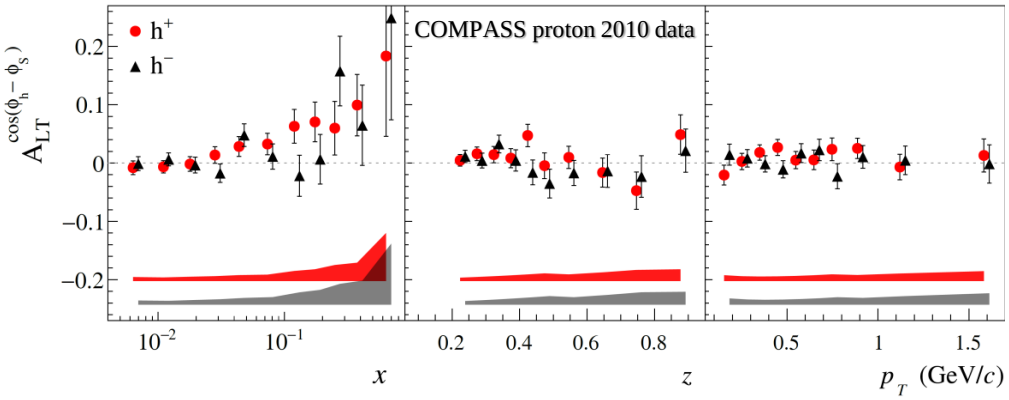
$A_{LT}^{\cos(\phi_h - \phi_S)}$

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

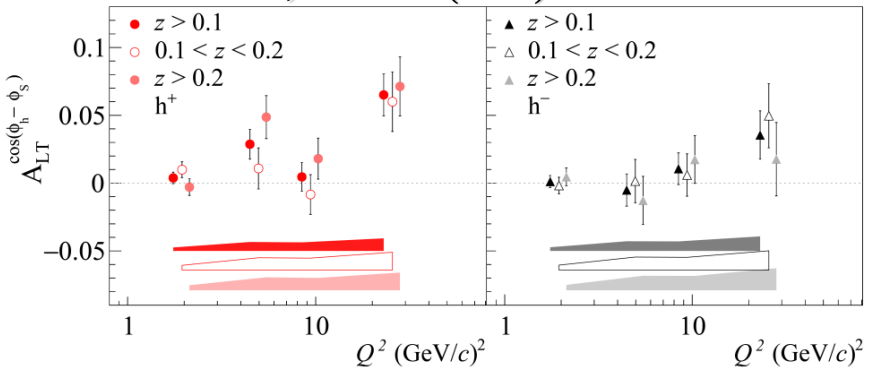
HERMES, JHEP 12 (2020) 010



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



COMPASS, PBL 770 (2017) 138



See also, PRD 107, (2023) 034016 – global fit by:
M. Horstmann, A. Schafer and A. Vladimirov

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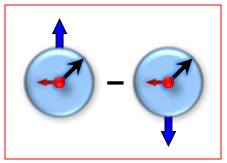

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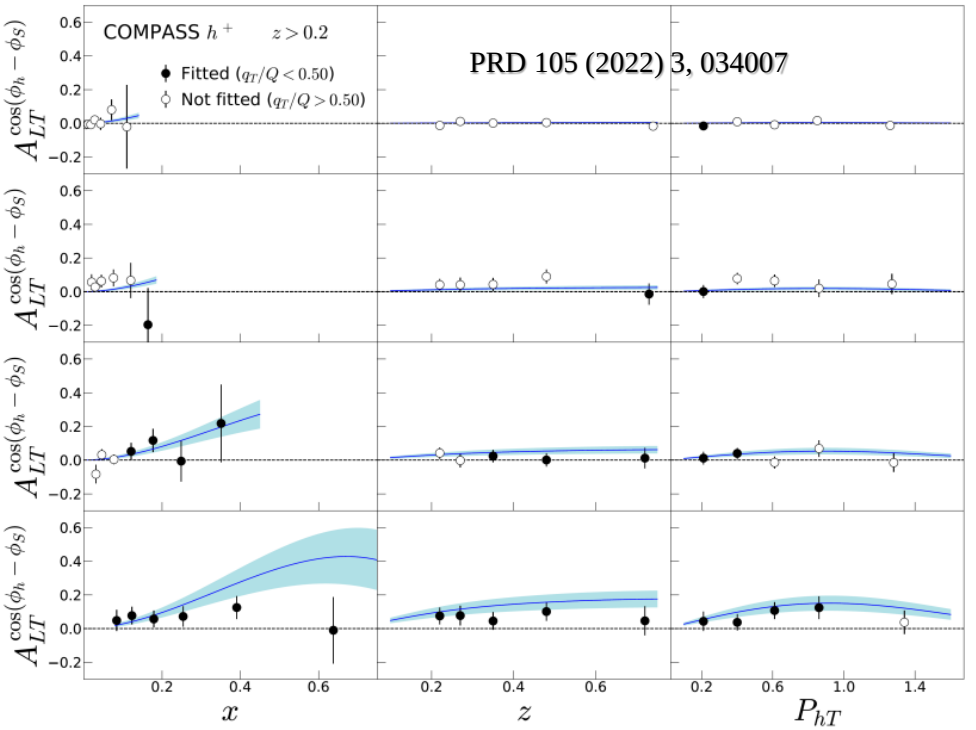
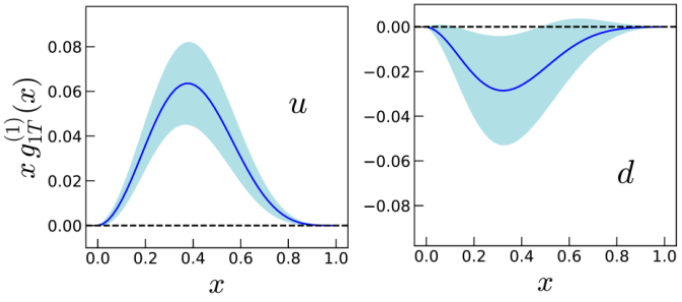
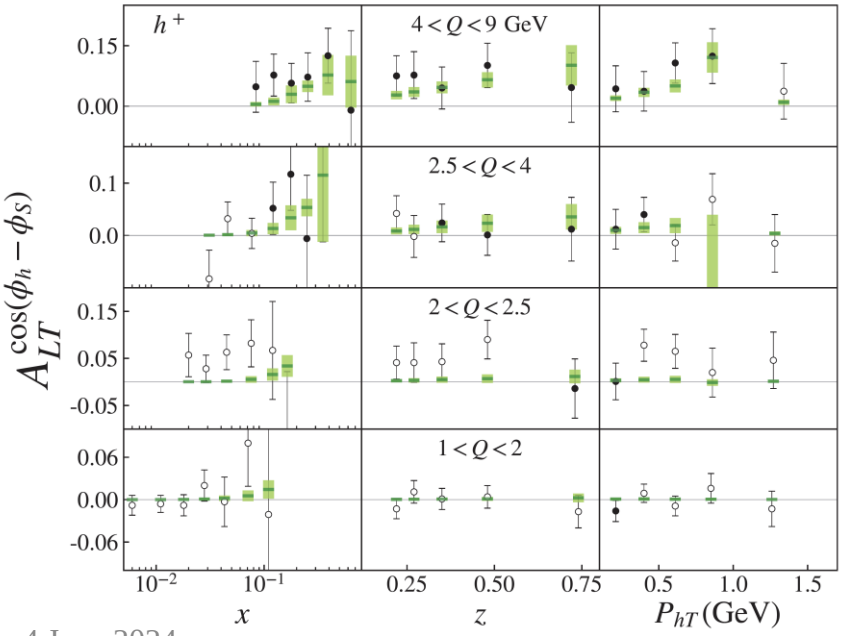
First global QCD analysis of the g_{1T} TMD PDF using SIDIS data





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



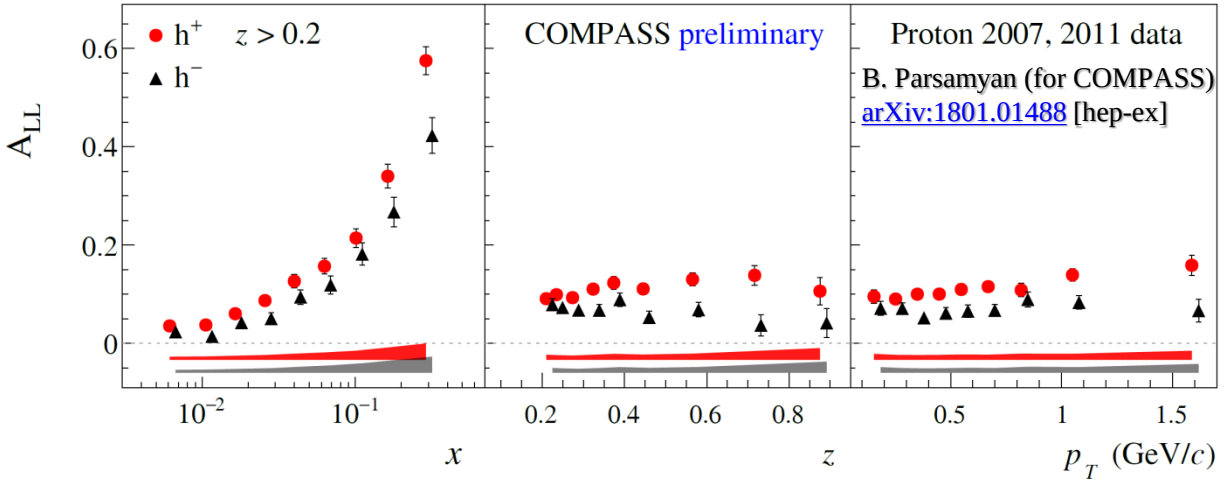
See also, PRD 107, (2023) 034016 – global fit by: M. Horstmann, A. Schafer and A. Vladimirov

SIDIS: target longitudinal spin dependent asymmetries

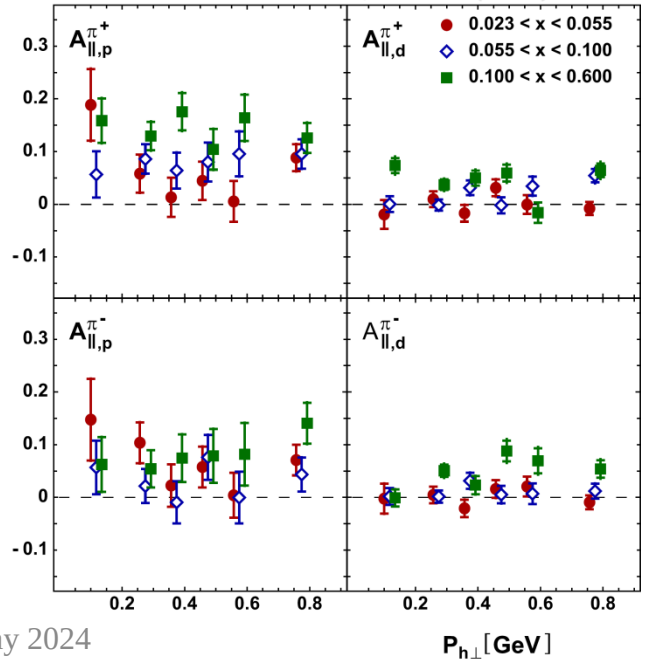
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2}\, A_{LL} + \ldots\right\}$$

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

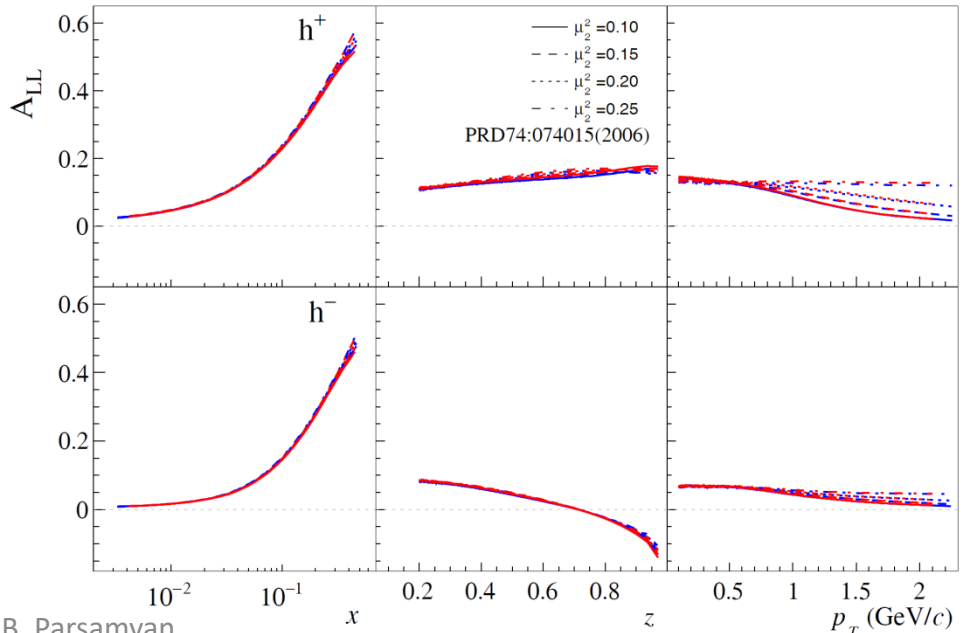
- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed



HERMES: PRD 99, 112001 (2019)



COMPASS Proton-2007, -2011 kinematics



- The role of vector mesons

Cahn effect in SIDIS

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

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

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

Cahn effect

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

As of 1978 – simplistic kinematic effect:

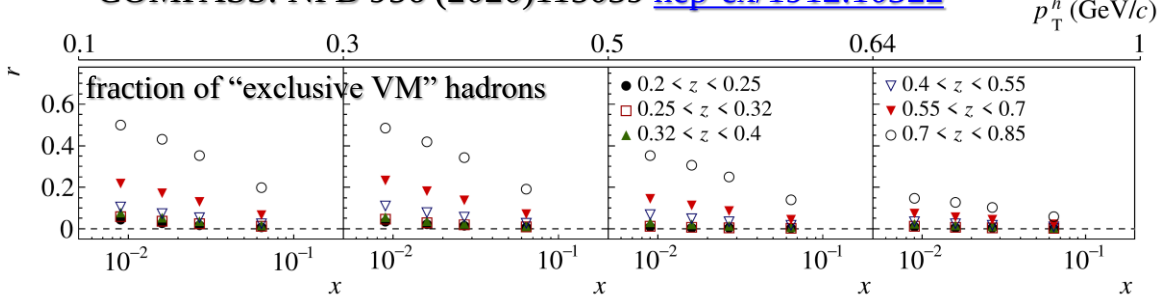
- non-zero k_T induces an azimuthal modulation

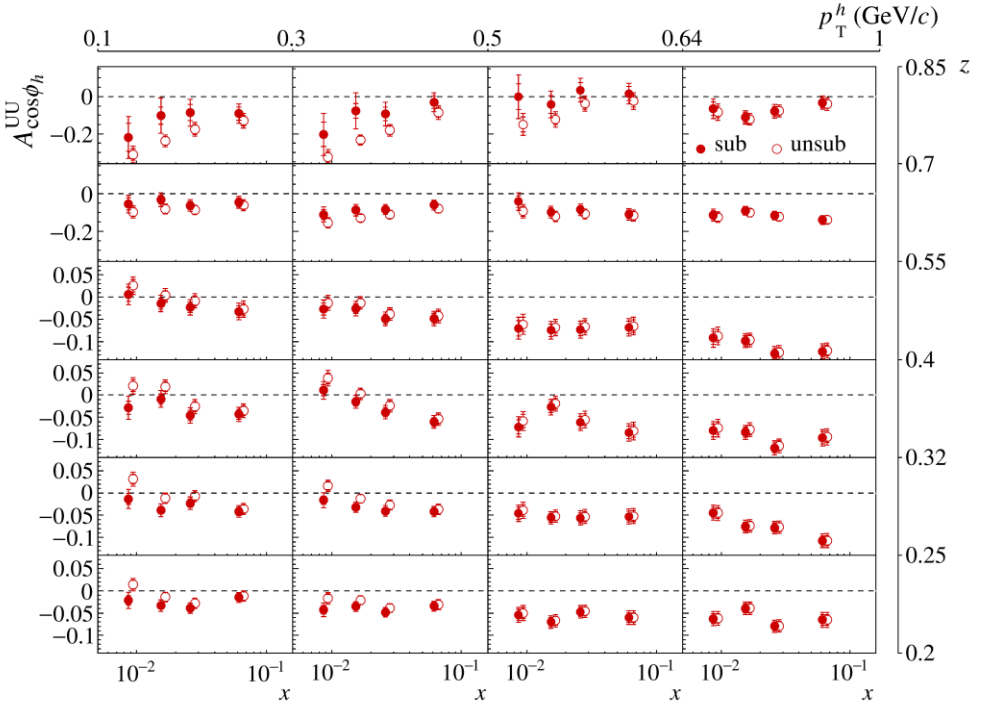
As of 2023 – complex SF (twist-2/3 functions)

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

Contribution of exclusive diffractive processes to the measured azimuthal asymmetries in SIDIS

COMPASS: NPB 956 (2020)115039 hep-ex/1912.10322





See Jan Matousek's talk

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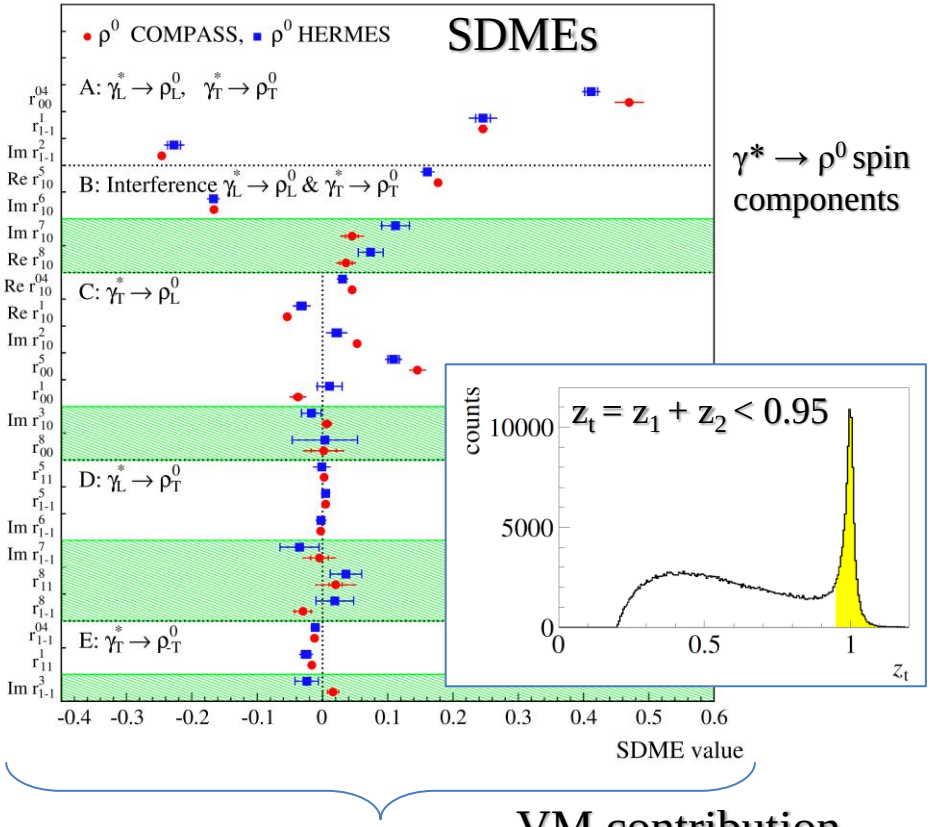
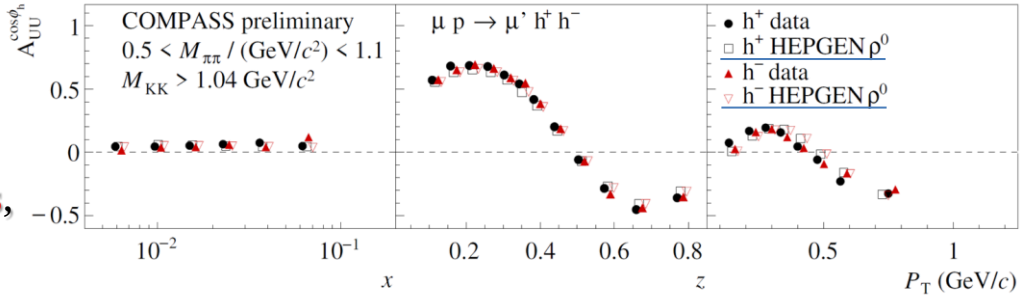
COMPASS, EPJC (2023) 83 924



γ* → ρ⁰ spin components

VM contribution



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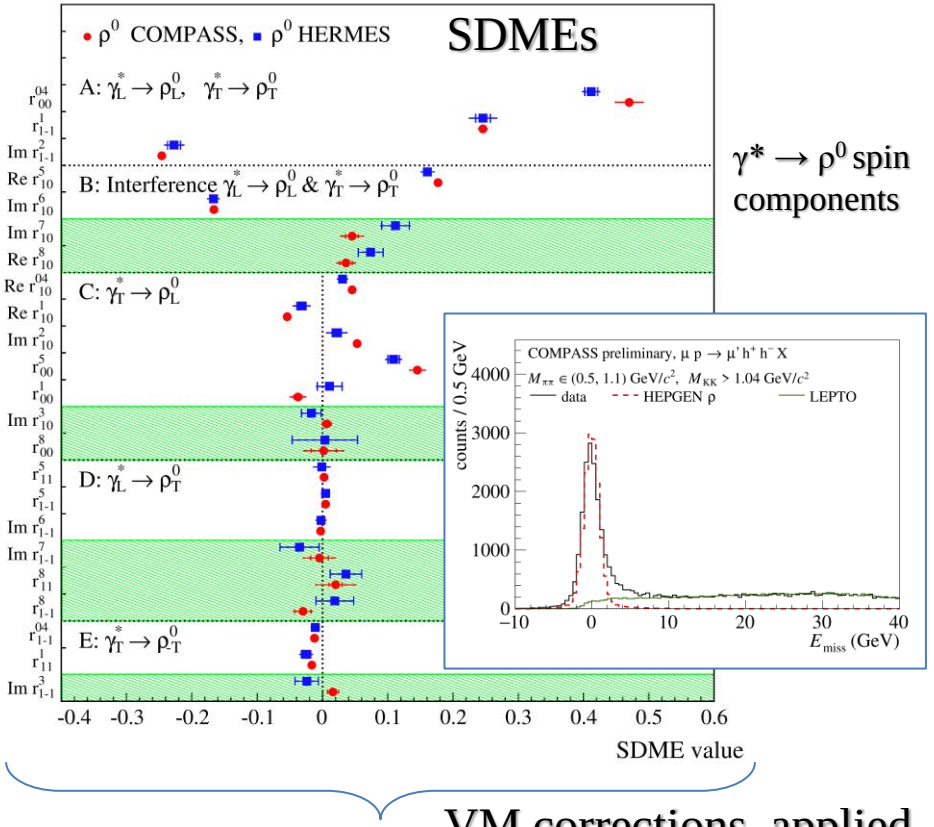
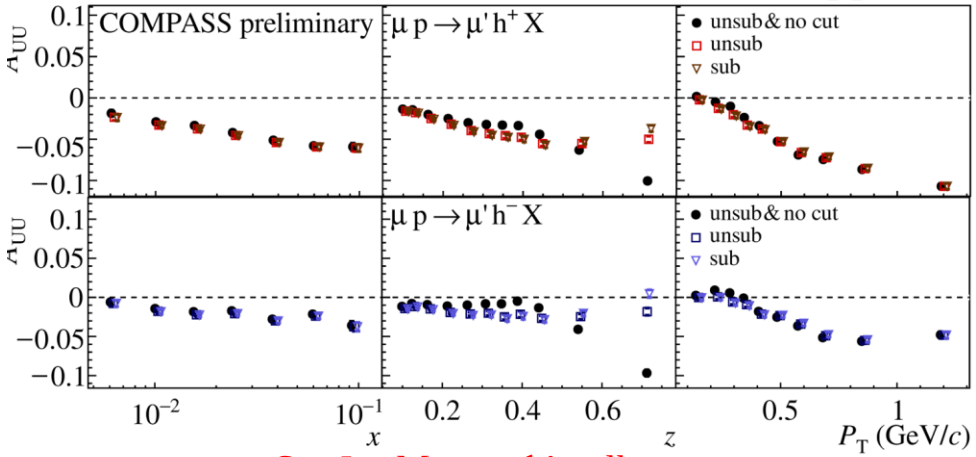
COMPASS, EPJC (2023) 83 924



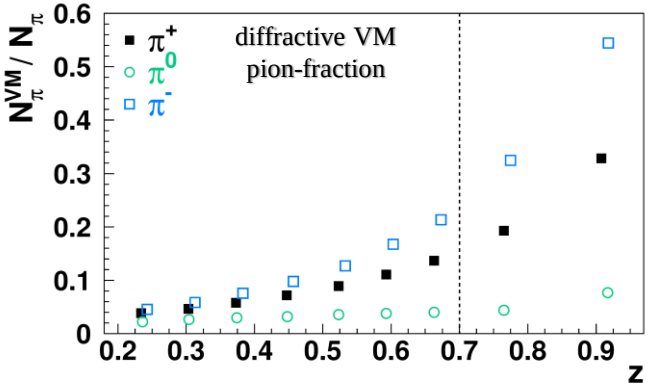
VM corrections, applied



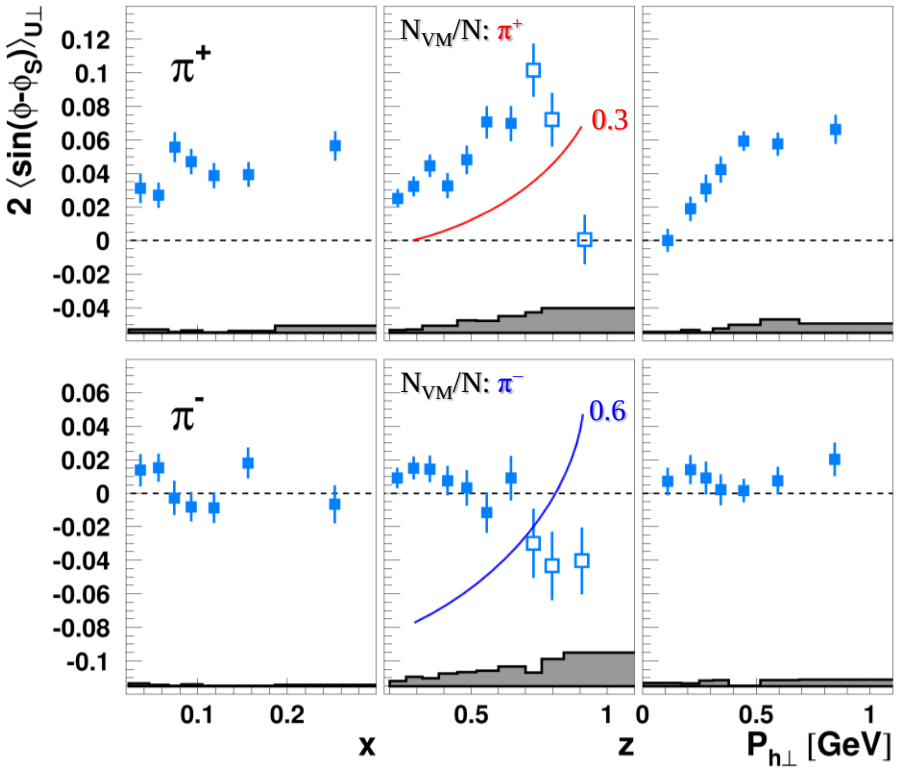
See Jan Matousek's talk

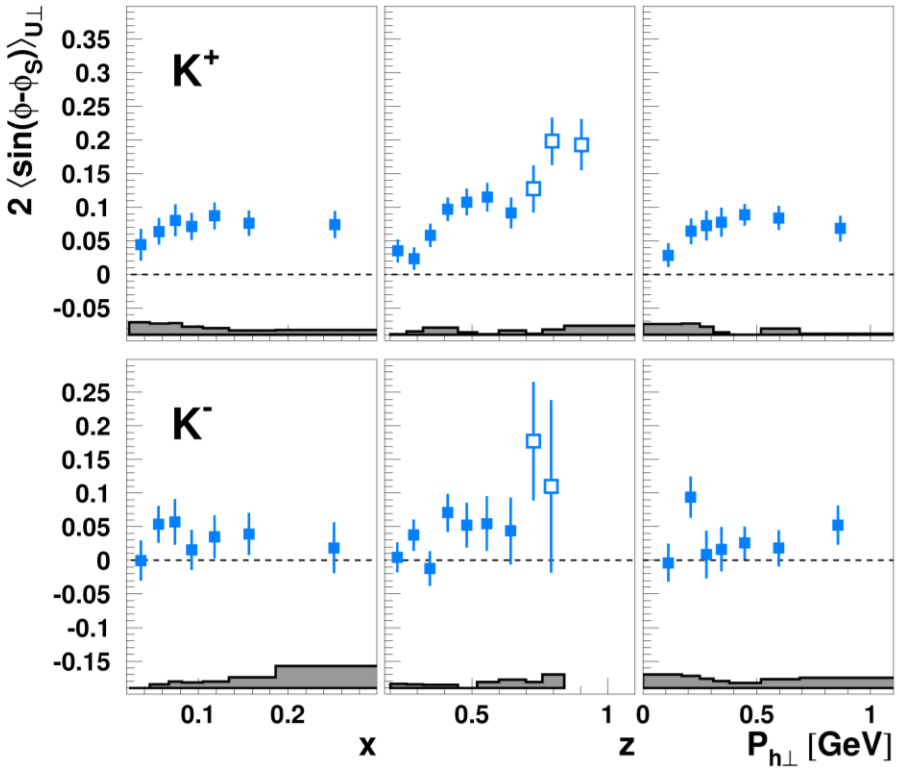
HERMES: Sivers effect and diffractive VMs

- The asymmetry drops at large z for pion
  - Not the case for kaons
- Can it be caused by exclusive diffractive VMs?
- The contamination indeed grows with *z* for pions
  - At the level of 10% for kaons



HERMES: JHEP 12(2020)010 hep-ex/2007.07755





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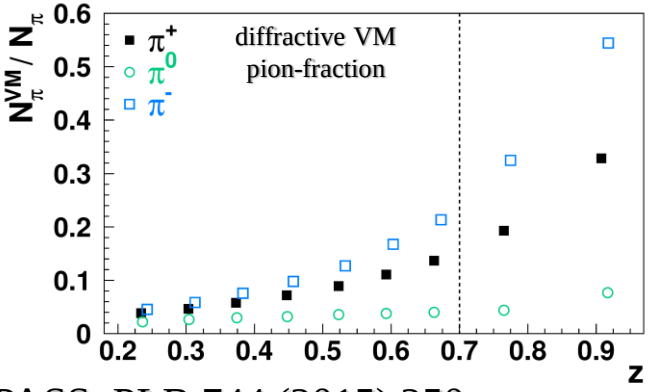
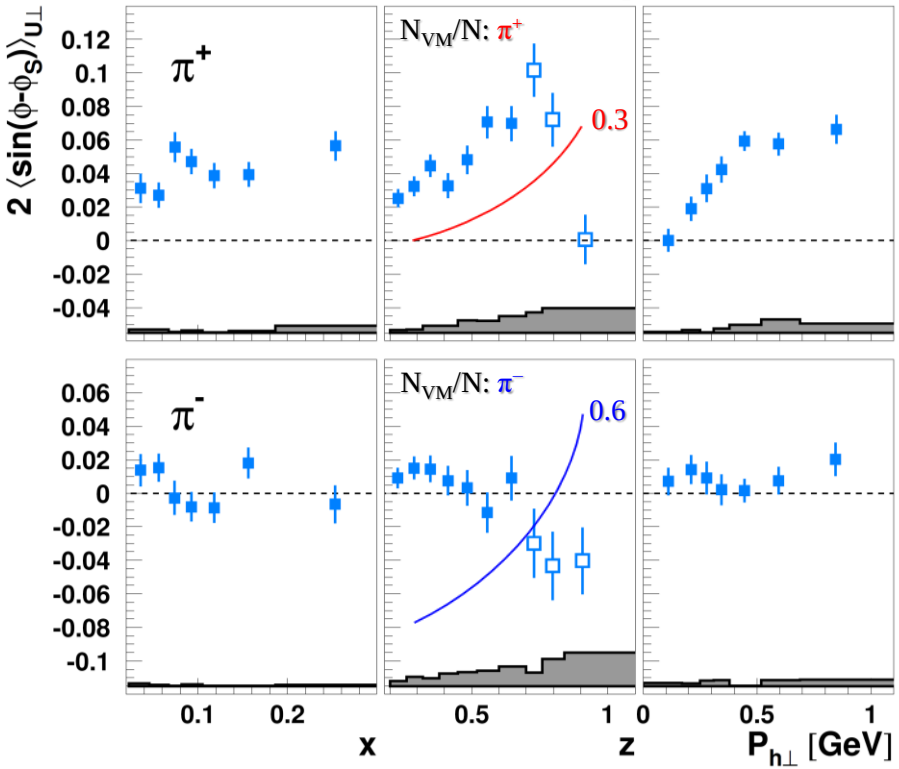
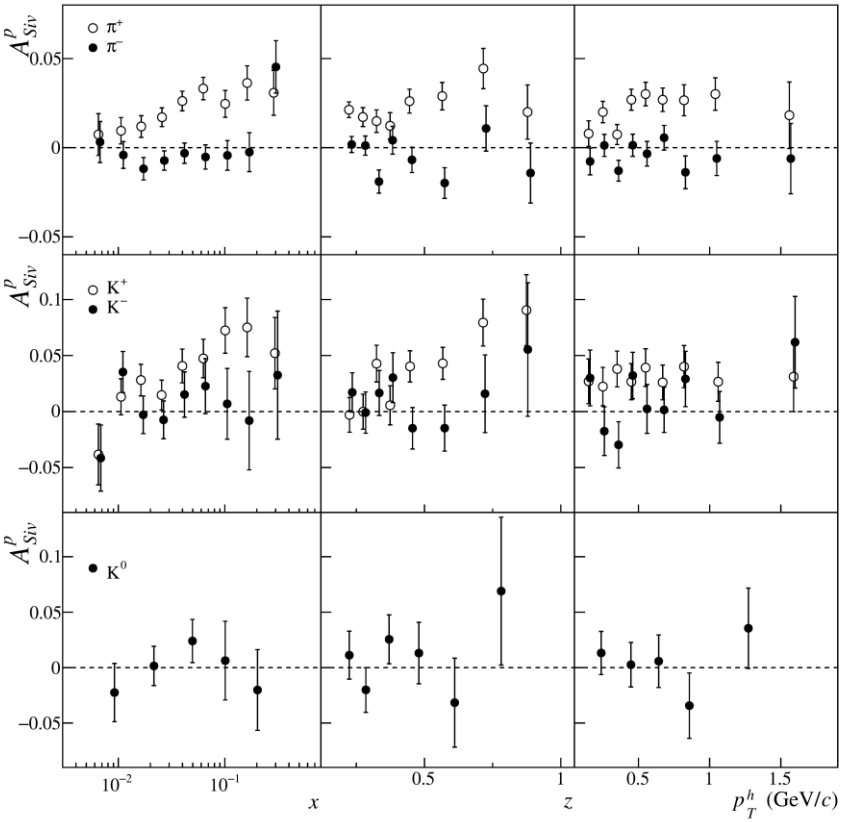


HERMES: JHEP 12(2020)010 hep-ex/2007.07755



COMPASS: PLB 744 (2015) 250



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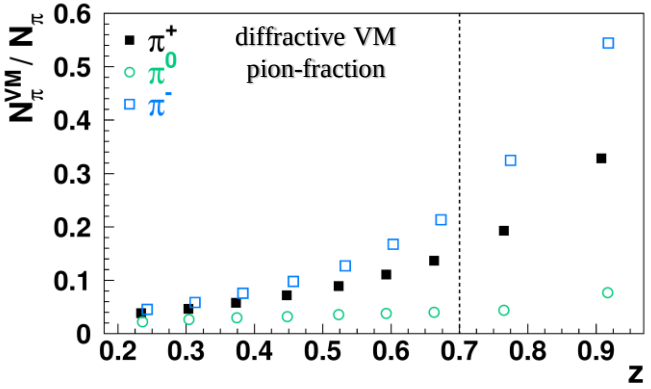
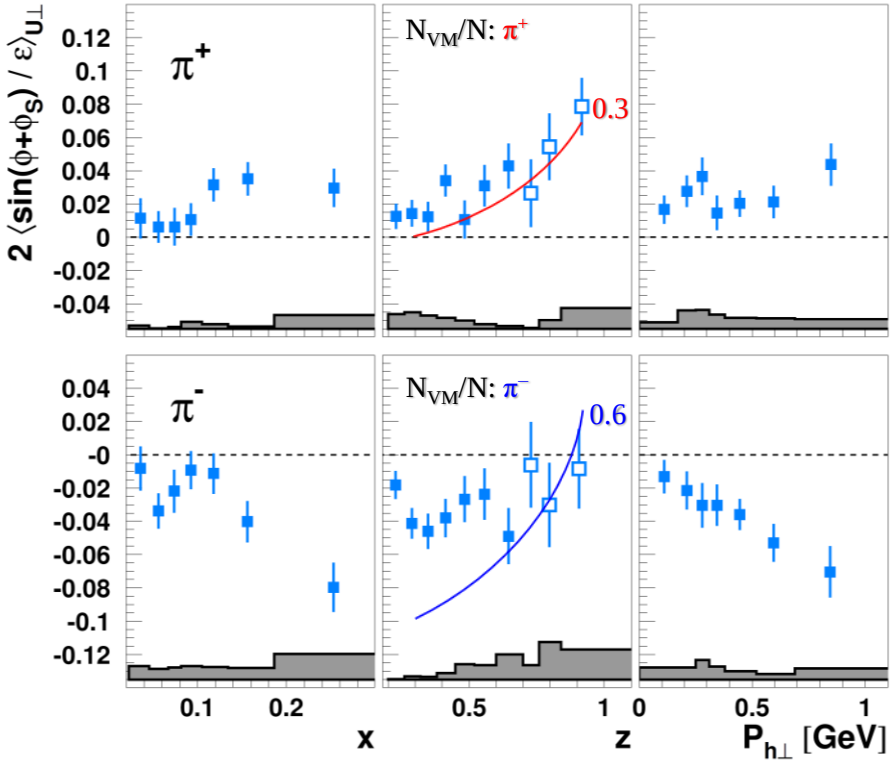
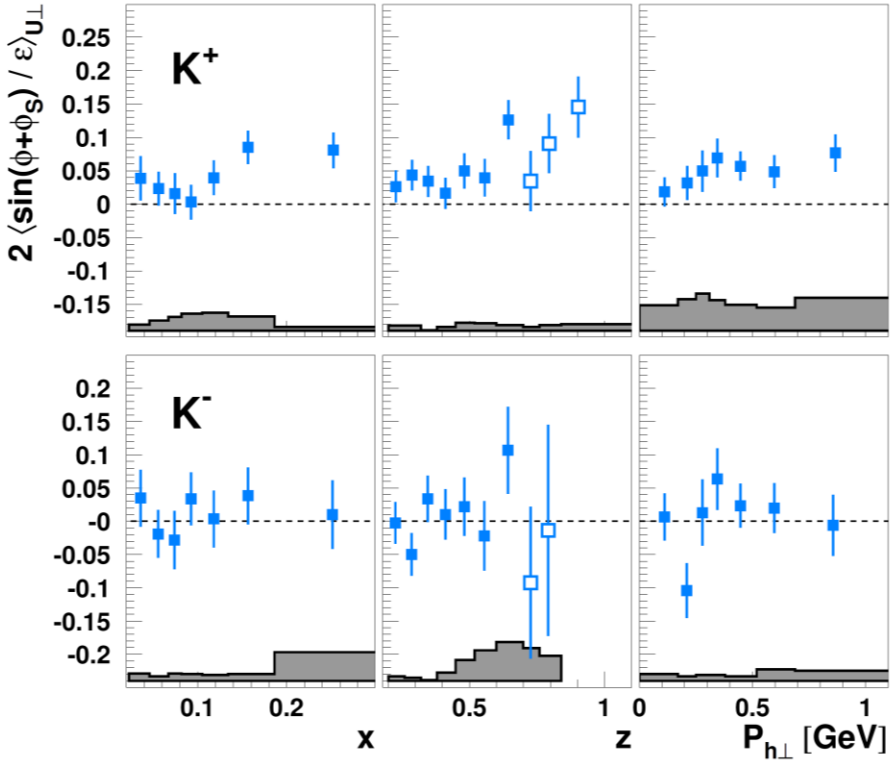
- Not clear with Collins







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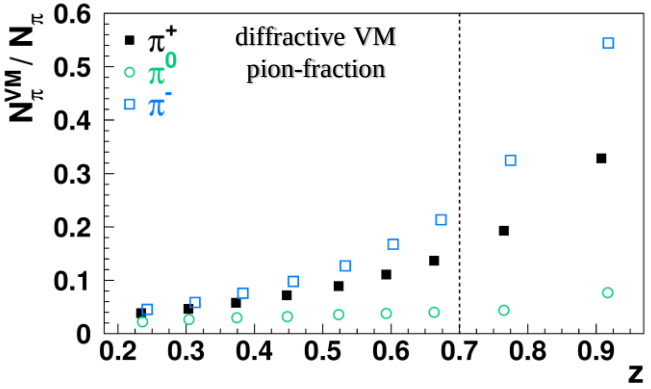
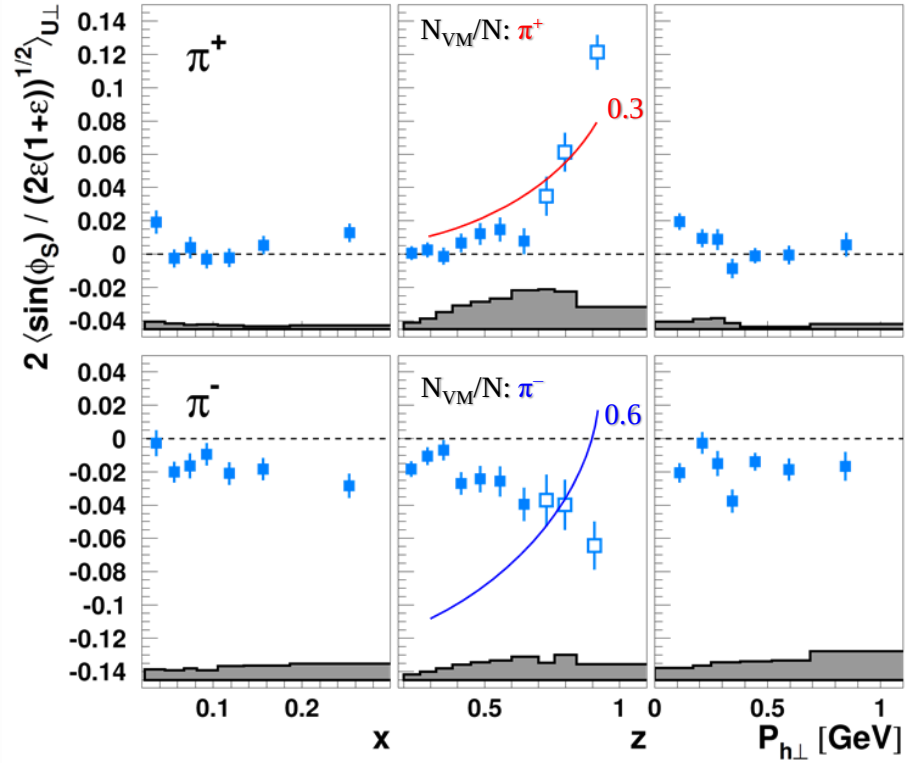
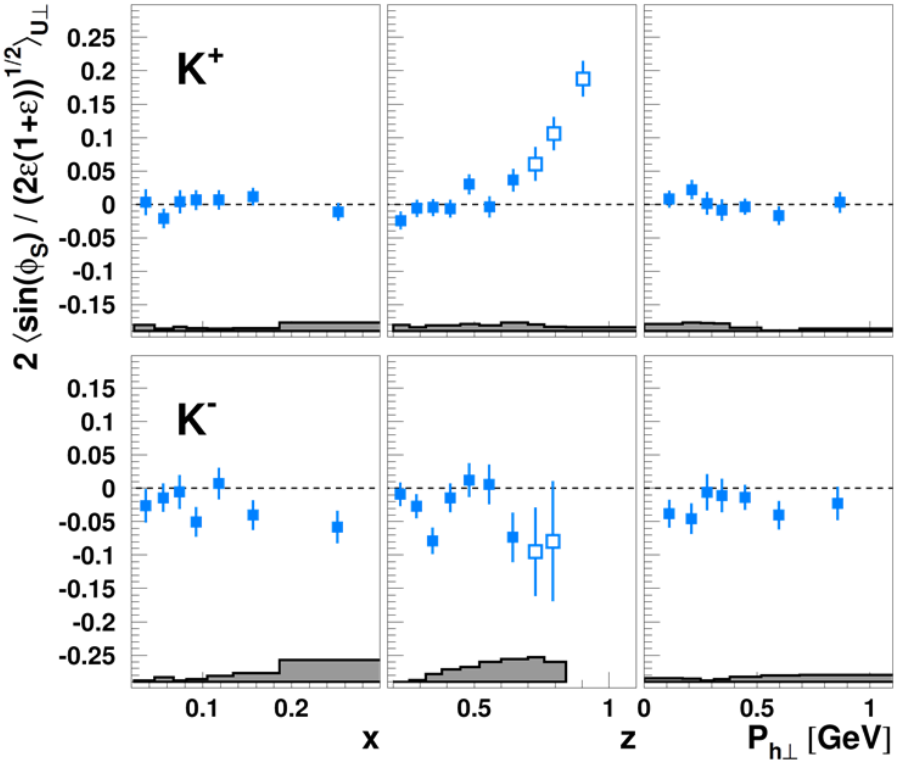
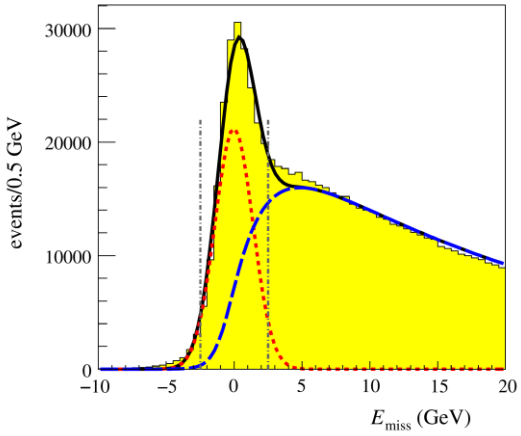


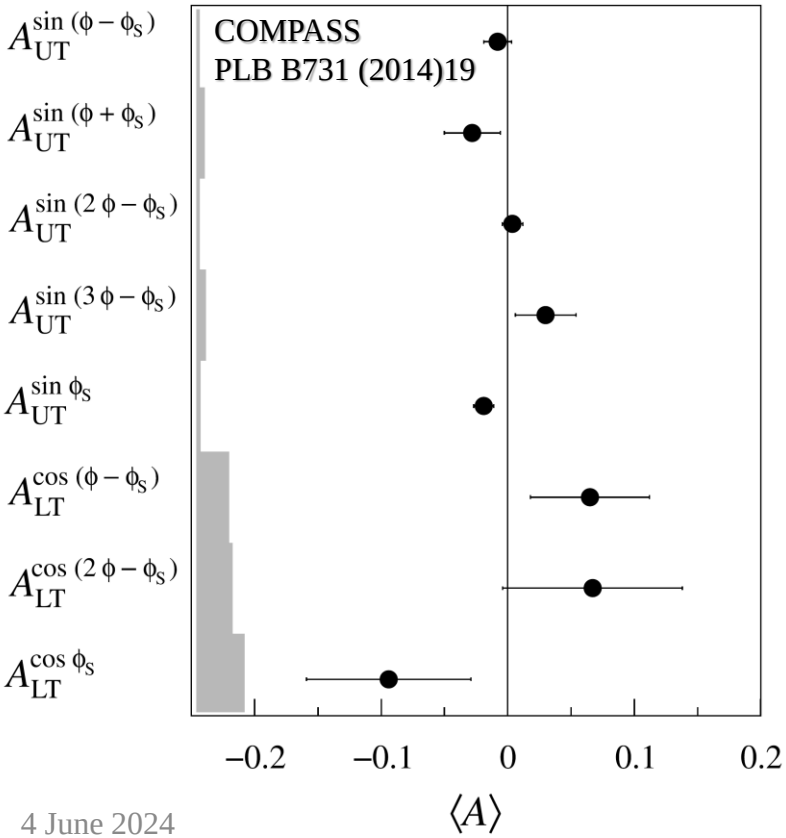




COMPASS: Exclusive ρ^0 TSAs

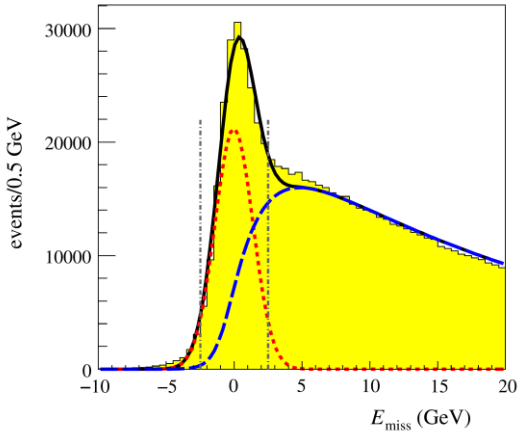


exclusive

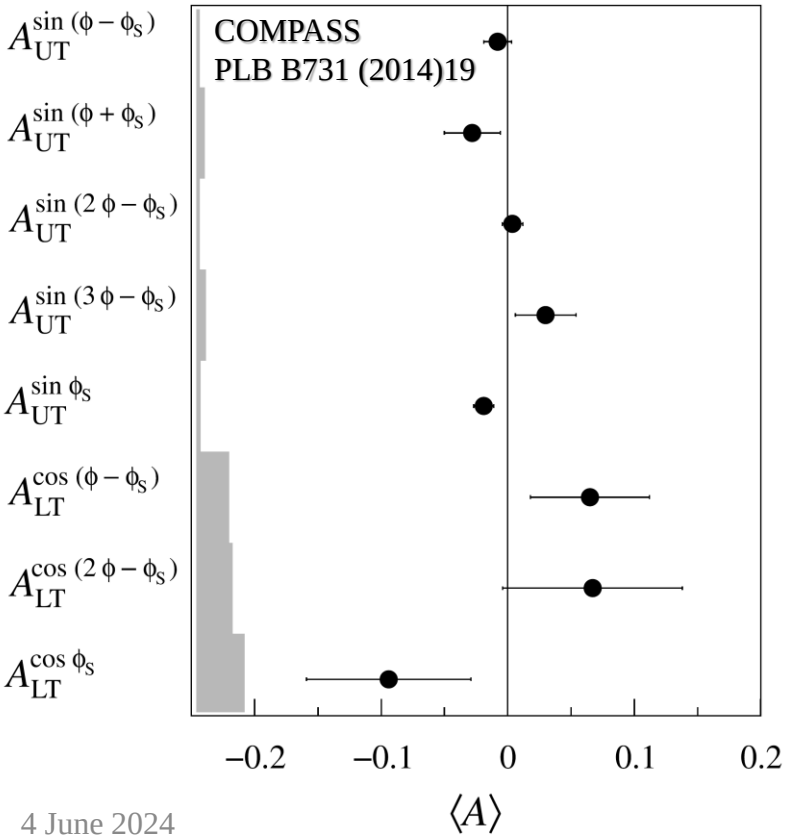


- Both Collins and Sivers TSAs are small an compatible with zero
  - $\sin(\varphi_S)$ is small, but possibly non zero
  - Can VM pion asymmetries still be large?

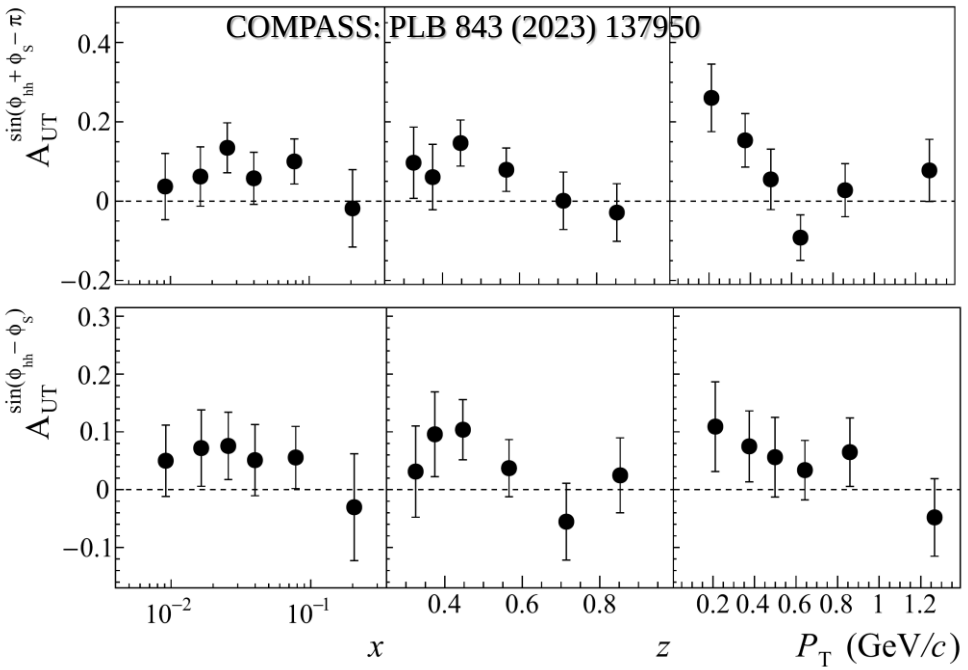
COMPASS: Exclusive ρ^0 TSAs



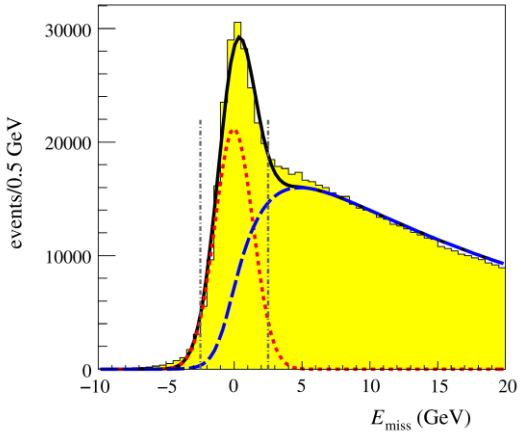
exclusive



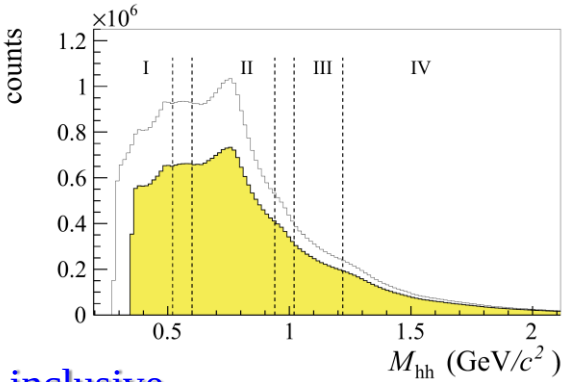
- Both Collins and Sivers TSAs are small an compatible with zero
  - $\sin(\varphi_S)$ is small, but possibly non zero
  - Can VM pion asymmetries still be large?
- COMPASS has checked also the inclusive ρ^0 Collins and Sivers asymmetries
  - Both tend to be positive
  - The fraction of inclusive ρ^0 in the selected dihedron sample is below 20%
  - Further checks needed, StringSpinner?



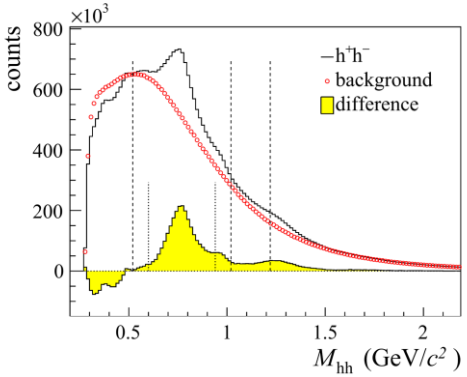
COMPASS: Exclusive and Inclusive ρ^0 TSAs

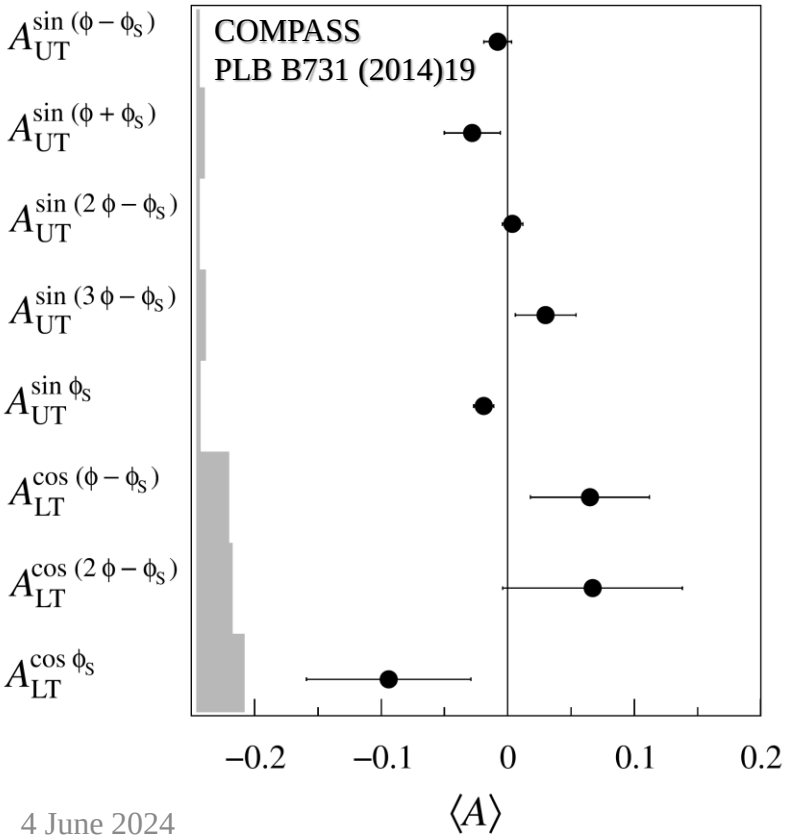


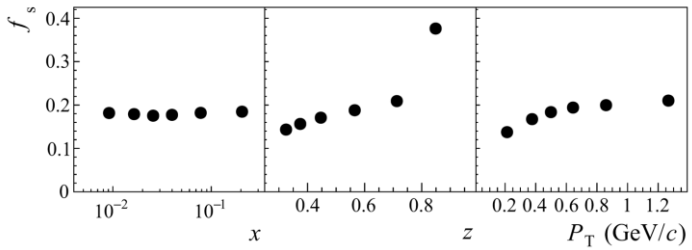
exclusive

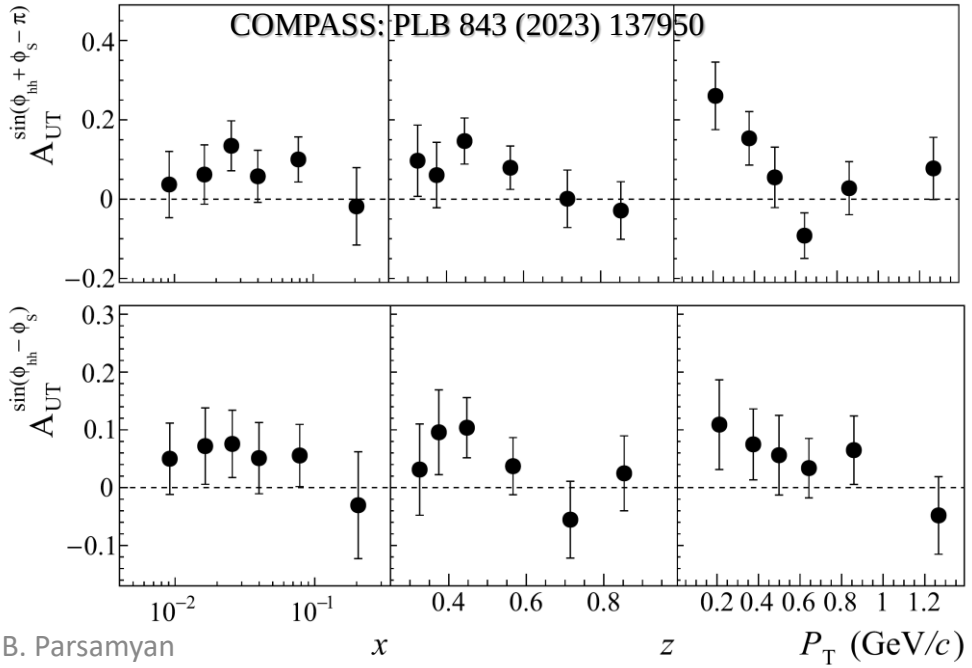


inclusive







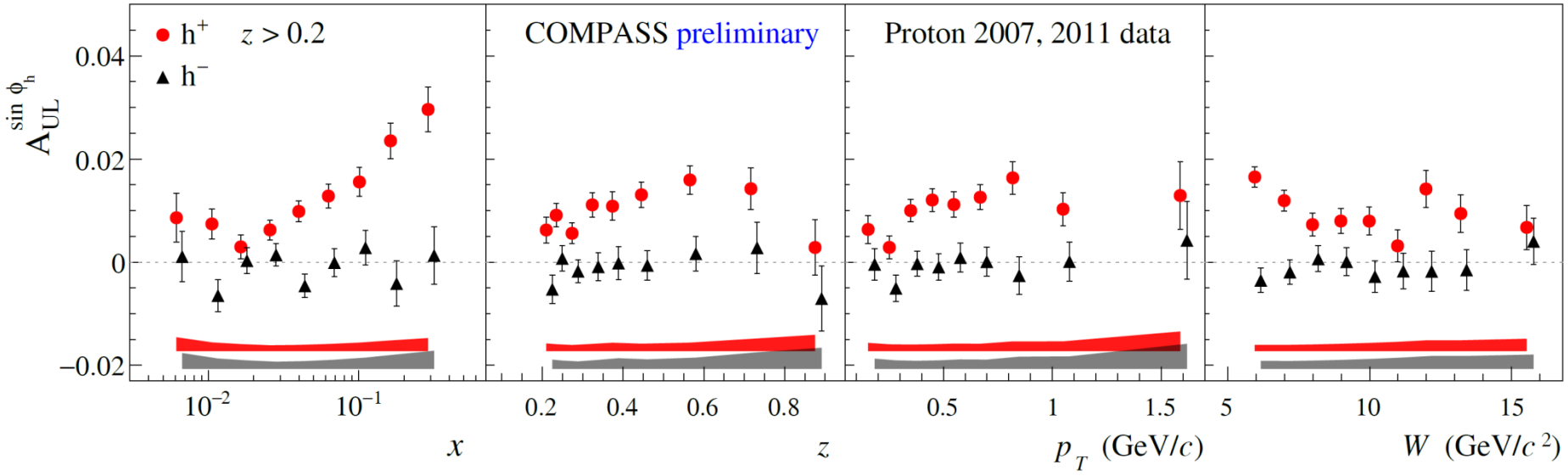


- Interesting twist-3 asymmetries

SIDIS TSAs: subleading twist effects

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

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



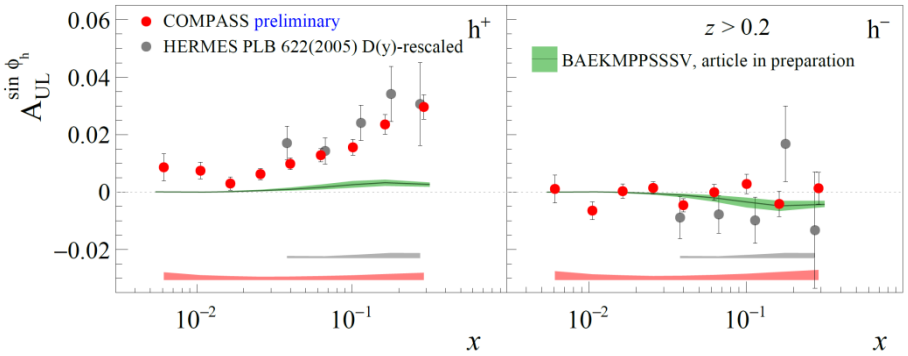
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h^+, h^- compatible with zero

SIDIS TSAs: subleading twist effects

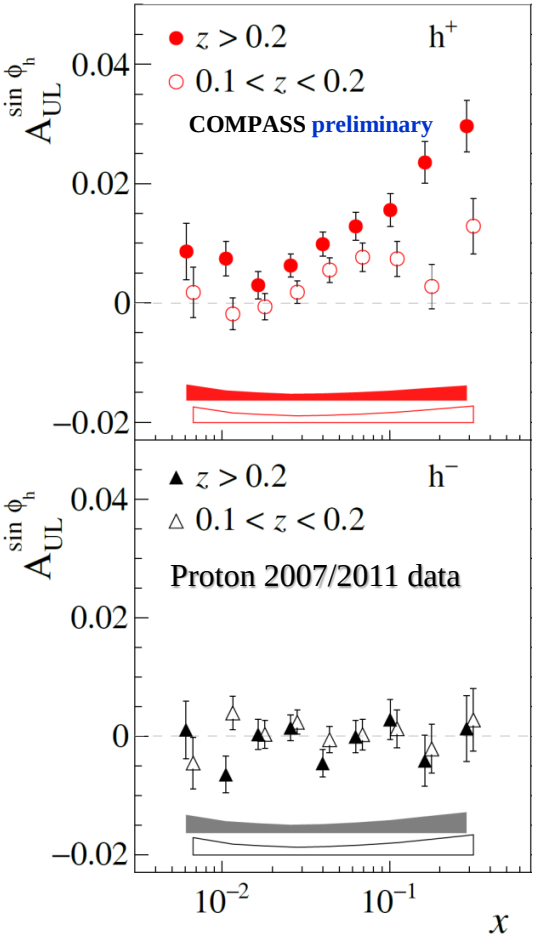
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)}\, A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

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

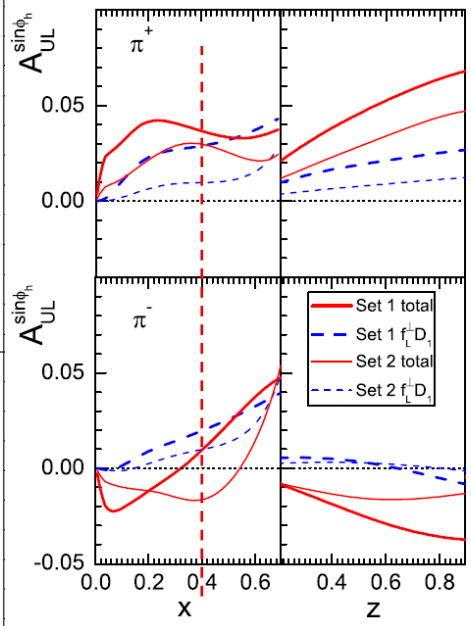
S. Bastami et al. JHEP 1906 (2019) 007:
"SIDIS in Wandzura-Wilczek-type approximation"



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



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



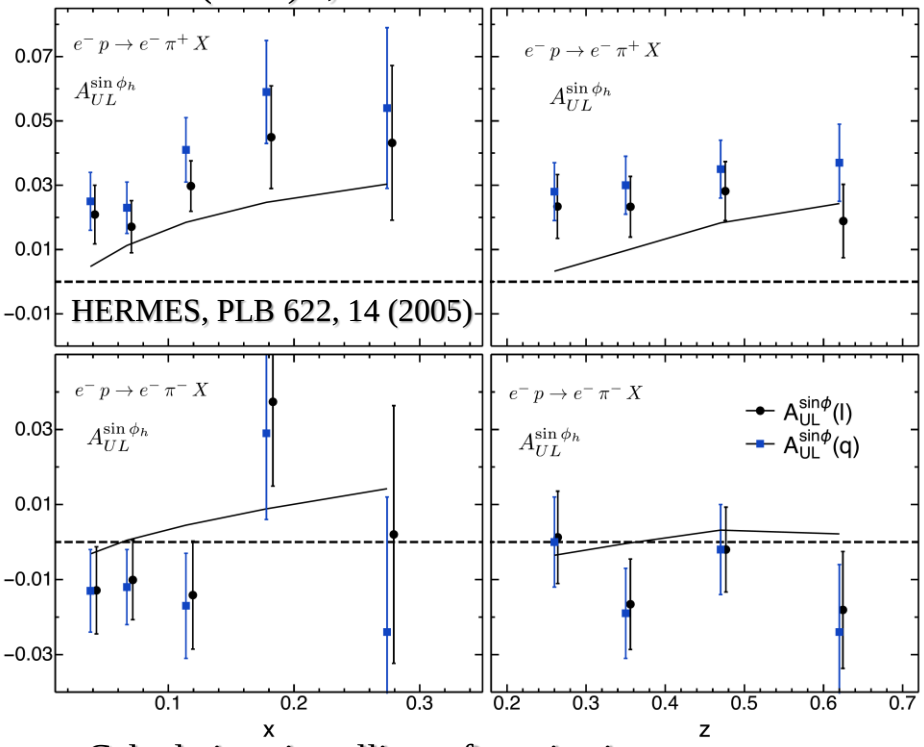
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h^+, h^- compatible with zero, clear z-dependence

SIDIS TSAs: subleading twist effects

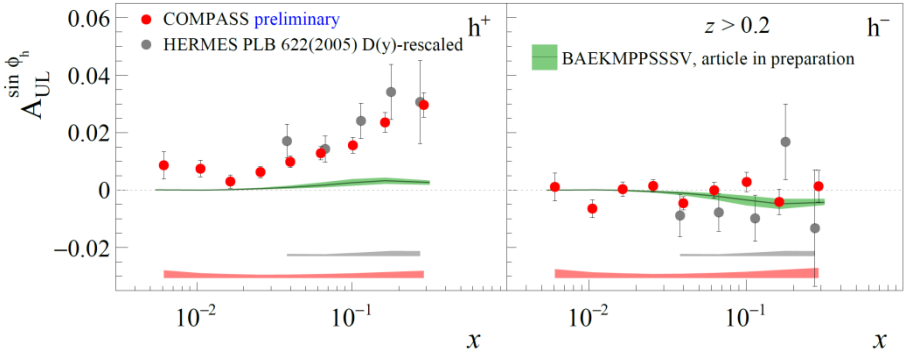
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \sqrt{2\varepsilon(1+\varepsilon)}\, A_{UL}^{\sin\phi_h} \sin\phi_h + \ldots\right\}$$

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

M.Abele, M.Aicher, F.Piacenza, A.Schäfer, W.Vogelsang
PRD 106 (2022) 1, 014020



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



- Calculations in collinear factorization (lowest order of pQCD)
  - T-odd effect for photon exchange
  - Contributions from QCD loop effects
  - Related to proton helicity
- To be compared to predictions within TMD formalism

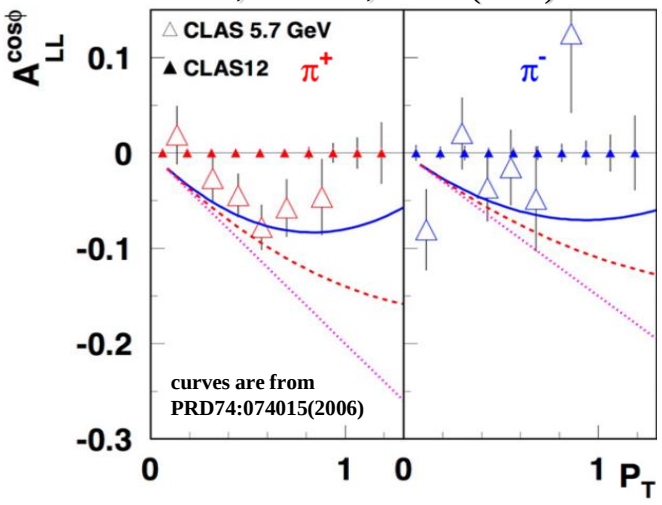
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h^+, h^- compatible with zero, clear *z*-dependence

SIDIS TSAs: subleading twist effects

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

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

CLAS, PRL 105,262002(2010)



B. Parsamyan (for COMPASS)
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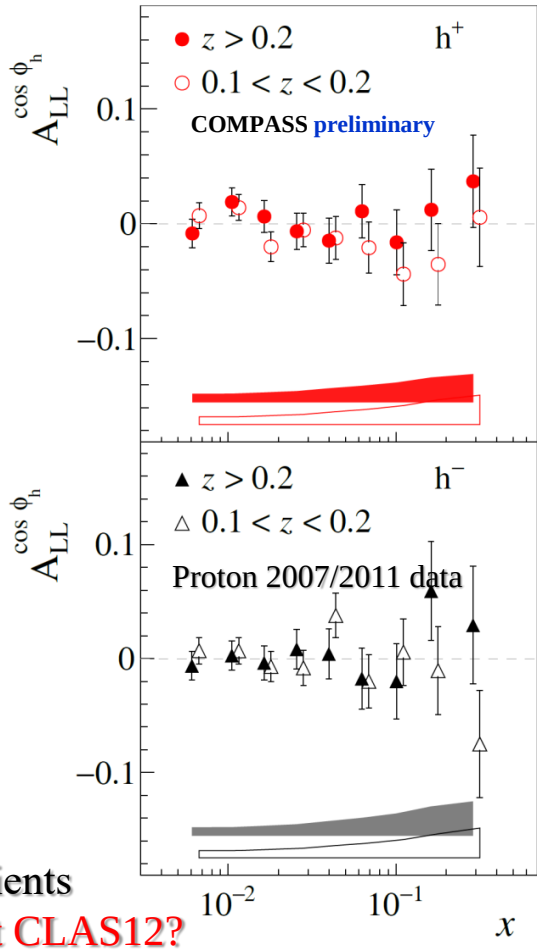
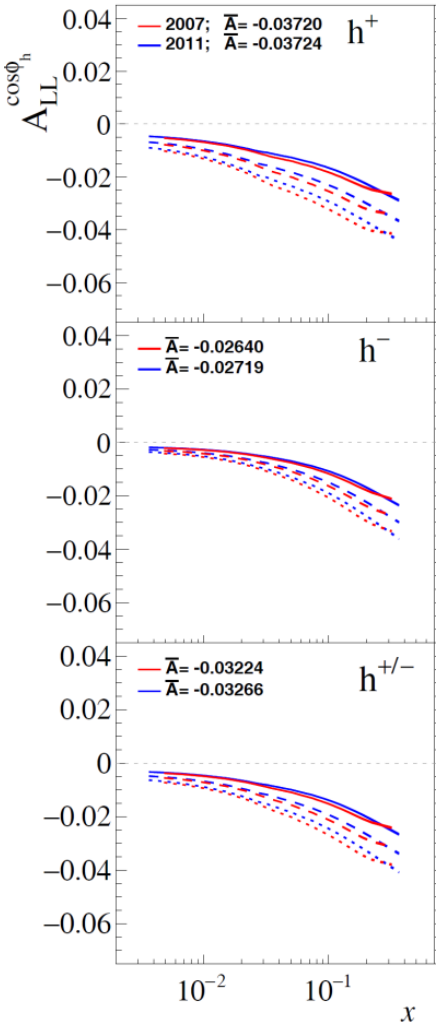




- Q-suppression, various different "twist" ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

SIDIS TSAs: subleading twist effects

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

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

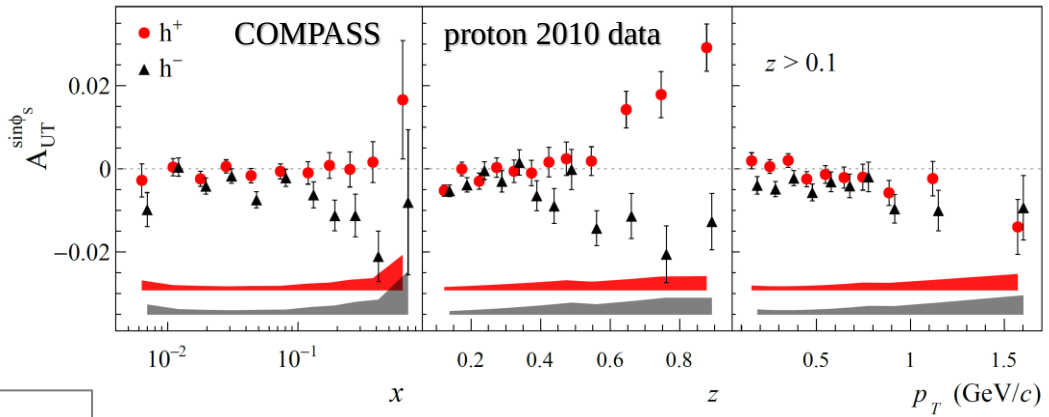
COMPASS/HERMES results

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

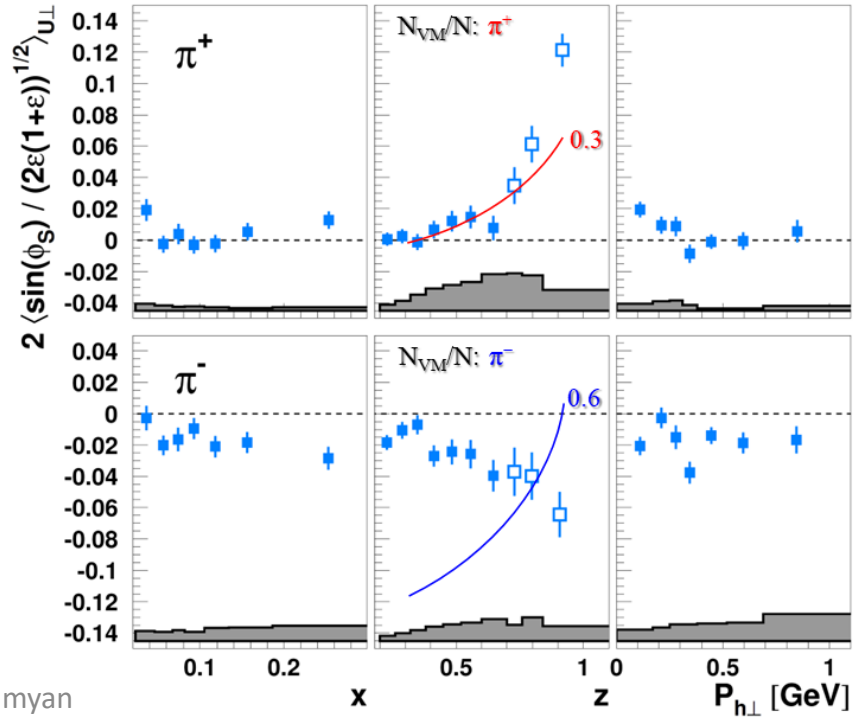
- Q-suppression
- various "twist-2/3" ingredients
- non-zero signal for $h^{\pm}$ at large z?
- Survives integration of hadron p_T
  - gives access to transversity PDF (without involving convolution over k_T)

See Daniel Pitonyak's talk

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



HERMES, JHEP 12 (2020) 010



SIDIS TSAs: subleading twist effects

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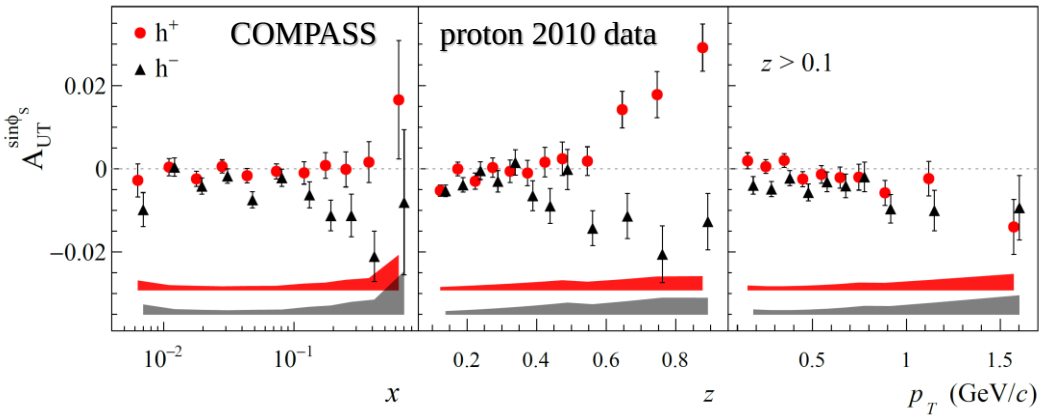
$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C\left\{\left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(x h_T^{\perp q} H_{1q}^{\perp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

COMPASS/HERMES results

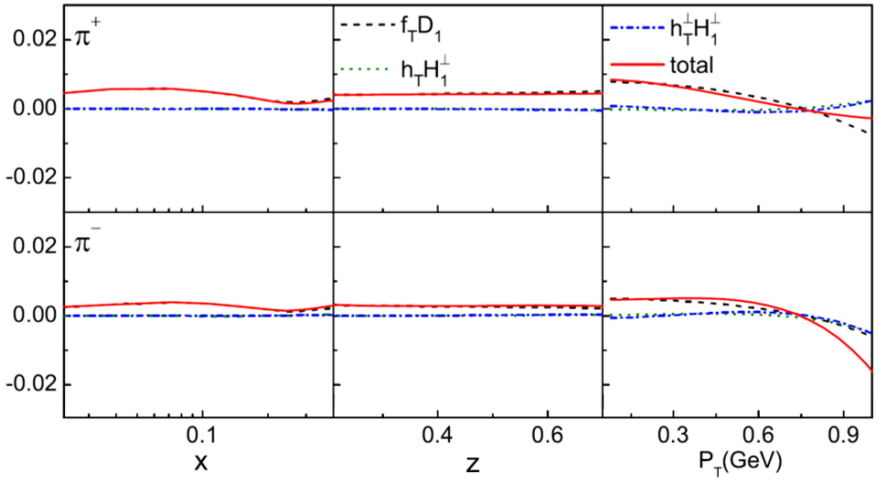
$A_{UT}^{\sin\phi_S}$

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

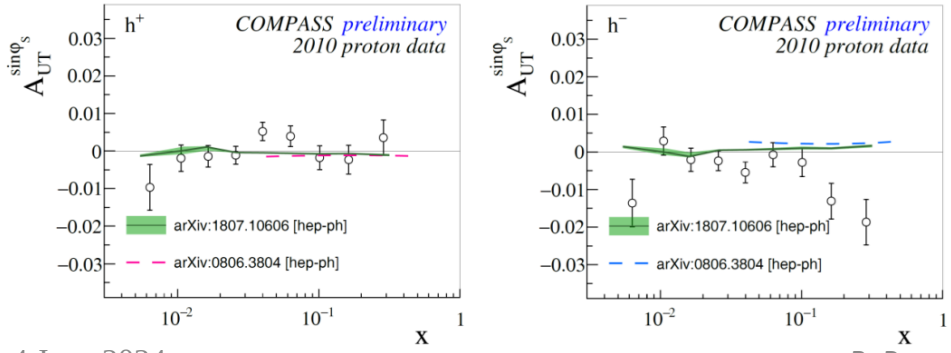
COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



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



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



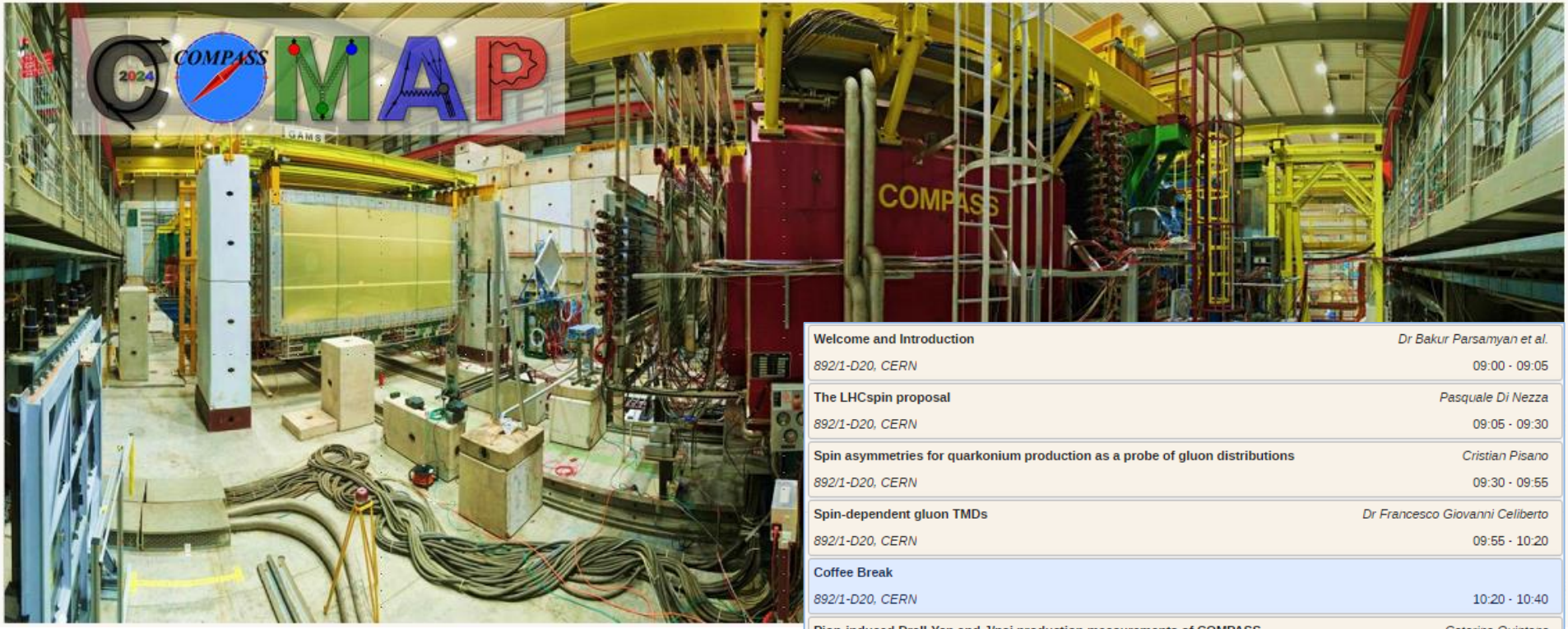
- Closing remarks

Moving towards Open Data and Data Preservation

- There is an increasing interest in making experimental data Open
- Becoming more relevant for CERN
- Important for CERN to be play a leading role in Open Science
  - Recent Open Science policy released by CERN
- The latest European Strategy report encouraged the development of internal policies on Open Data and Data preservation
- The policy has been broken down into the 4 levels of data as defined in the
- DHEP study on data preservation:
  - Level 1 – Scientific publications, and associated additional data
  - Level 2 – Data useful for Education and Outreach
  - Level 3 – Reconstruction level data useful for general physics analysis
  - Level 4 – RAW data
- All large-LHC experiments already release data for L1 and L2 in broadly similar ways
  - L4 is not practically useful
  - The discussion focused on the policy for L3 data
- Any rules relating to publicly releasing L3 data need to be approved by each experiment's Collaboration Board
- General effort to find a good balance between:
  - Making data openly available
  - Preserving the data
  - Protecting the collaborations

Conclusions

- Importance of careful understanding and confrontation of experimental data from different experiments
  - Different kinematic domains and phase-space limitations
  - Experiments employ complex analysis techniques, Monte-Carlo simulations, and sophisticated corrections (acceptance, VMs, radiative corrections)
- Close collaboration between different experiments → general benefit for the field
  - Knowledge transfer, comparison of the analysis techniques, tools, and methodology, cross-analyses between different experiments
- Close collaboration between experiment and phenomenology/theory
  - Flexibility in adapting on the analysis side to the choice of the observables, phase-space selections, etc. (before publishing the data)
  - Different possibilities for common paper projects, external membership
- Possibility to organize effective and fruitful collaborative work



The 8th edition of COMAP mini-workshop dedicated to synergies between COMPASS, LHCspin and AMBER projects

22 May 2024, CERN, Switzerland
for registration/info see:
https://indico.cern.ch/e/COMAP-LHCspin-AMBER

Organizers: Bakur Parsamyan, Pasquale Di Nezza, Fulvio Tessarotto, Jan Matousek, Luciano Libero Pappalardo, Marco Santimaria, Thomas Poschl

Welcome and Introduction	*Dr Bakur Parsamyan et al.*	
892/1-D20, CERN	09:00 - 09:05	
The LHCspin proposal	*Pasquale Di Nezza*	
892/1-D20, CERN	09:05 - 09:30	
Spin asymmetries for quarkonium production as a probe of gluon distributions	*Cristian Pisano*	
892/1-D20, CERN	09:30 - 09:55	
Spin-dependent gluon TMDs	*Dr Francesco Giovanni Celiberto*	
892/1-D20, CERN	09:55 - 10:20	
Coffee Break		
892/1-D20, CERN	10:20 - 10:40	
Pion-induced Drell-Yan and J/psi production measurements of COMPASS	*Catarina Quintans*	
892/1-D20, CERN	10:40 - 11:05	
Quarkonium Polarization Measurements: Challenges and Opportunities	*Ilse Kraetschmer*	
892/1-D20, CERN	11:05 - 11:30	
LHCspin UPC physycis opportunities		
892/1-D20, CERN	11:30 - 11:55	
The physics case of LHCspin	*Luciano Libero Pappalardo*	
892/1-D20, CERN	14:00 - 14:25	
LHCspin simulations	*Marco Santimaria*	
892/1-D20, CERN	14:25 - 14:50	
Pion and kaon PDFs confronted by fixed-target charmonium production	*Jen-Chieh Peng*	
892/1-D20, CERN	14:50 - 15:15	
Drell-Yan and J/psi measurements programm at AMBER		
892/1-D20, CERN	15:15 - 15:40	
Round table		
892/1-D20, CERN	15:40 - 16:20	

Possible topics for next COMAPs

- Vector mesons
- Kinematic cuts and binning for TSAs (TMD/collinear regimes)
- Radiative corrections

…

Joint XX-th International Workshop on Hadron Structure and Spectroscopy and 5-th Workshop on Correlations in Partonic and Hadronic Interactions

2024 30/09 - 04/10

IWHSS

Yerevan Armenia

COMPASS 25 years 1997 - 2022

Yerevan, Armenia

30 September – 4 October, 2024

https://indico.cern.ch/e/IWHSS-CPHI-2024

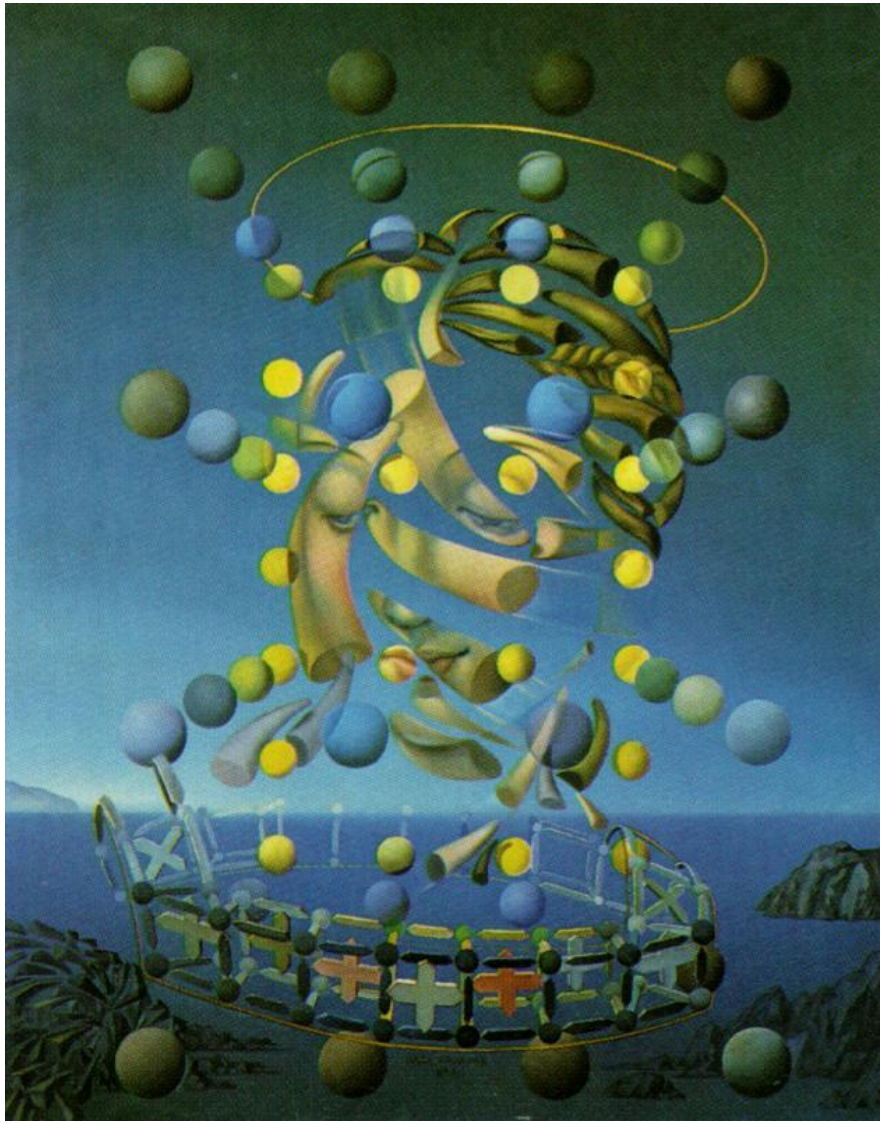
Confirmed speakers

Abhay Deshpande	Dennis Sivers	Leonard Gamberg	Stefan Diehl
Albi Kerbizi	Eric Voutier	Liliet Diaz	Stephane Peigné
Alessandro Bacchetta	Gregory Matousek	Marco Radici	Holly Szumila-Vance
Alessandro Pilloni	Giulio Mezzadri	Misak Sargsian	Timothy Hayward
Alexander Ilyichev	Gunar Schnell	Nobuo Sato	Valery Kubarovsky
Alexey Prokudin	Igor Denisenko	Oleg Eyser	Valerio Bertone
Alexey Vladimirov	Ishara Fernando	Pasquale Di Nezza	Xuan Tong
Asmita Mukherjee	Jen-Chieh Peng	Patrizia Rossi	Whitney Armstrong
Audrey Francisco	Jinlong Zhang	Paweł Sznajder	Xiao-Rui Lyu
Charlotte Van Hulse	Lamiaa El Fassi	Shohini Bhattacharya	Yuri Kovchegov
Cristian Pisano	Latifa Elouadrhiri	Silvia Niccolai	Zein-Eddine Meziani

“Nature”

“1D”

Raphael “Madonna del Prato”

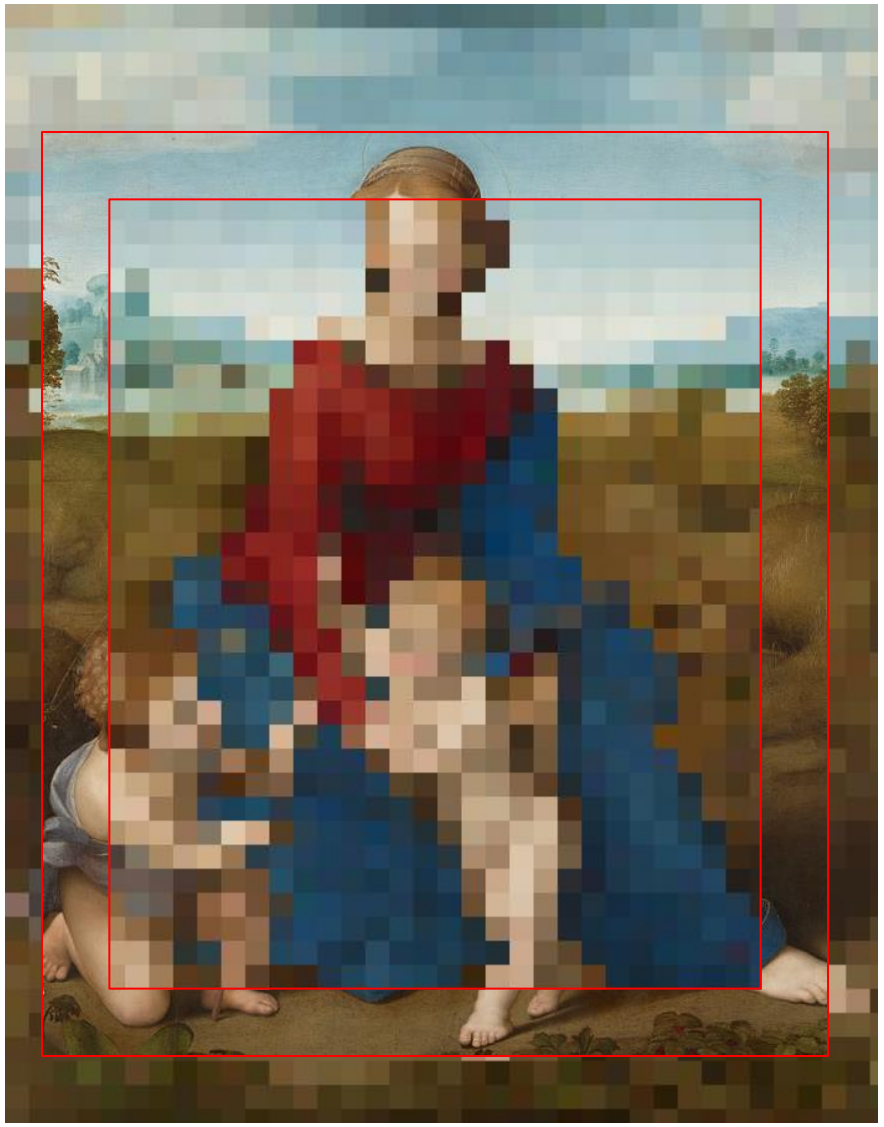


Salvador Dali “Maximum Speed of Raphael's Madonna”

"Nature"

"multi-D" with available statistics

Raphael "Madonna del Prato"

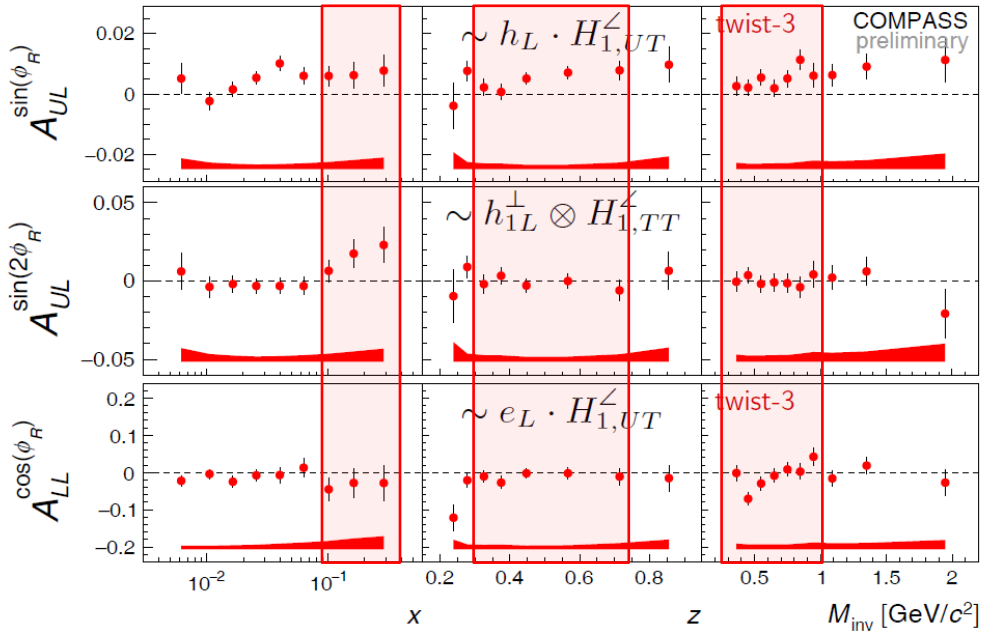


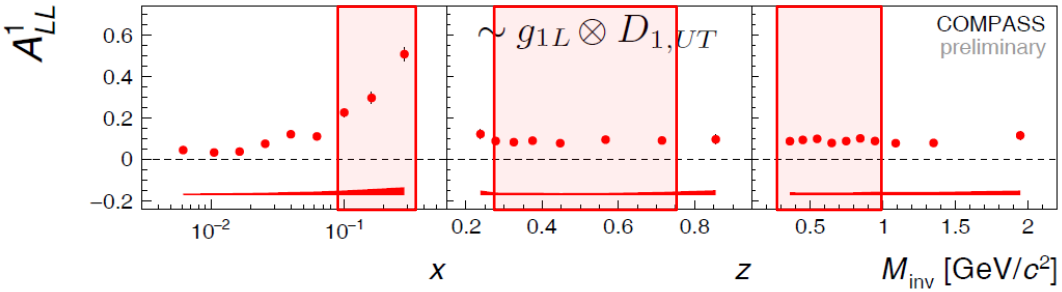
Raphael "Madonna del Prato" (poor resolution)

- Spare slides

Selected results for di-hadron LSAs

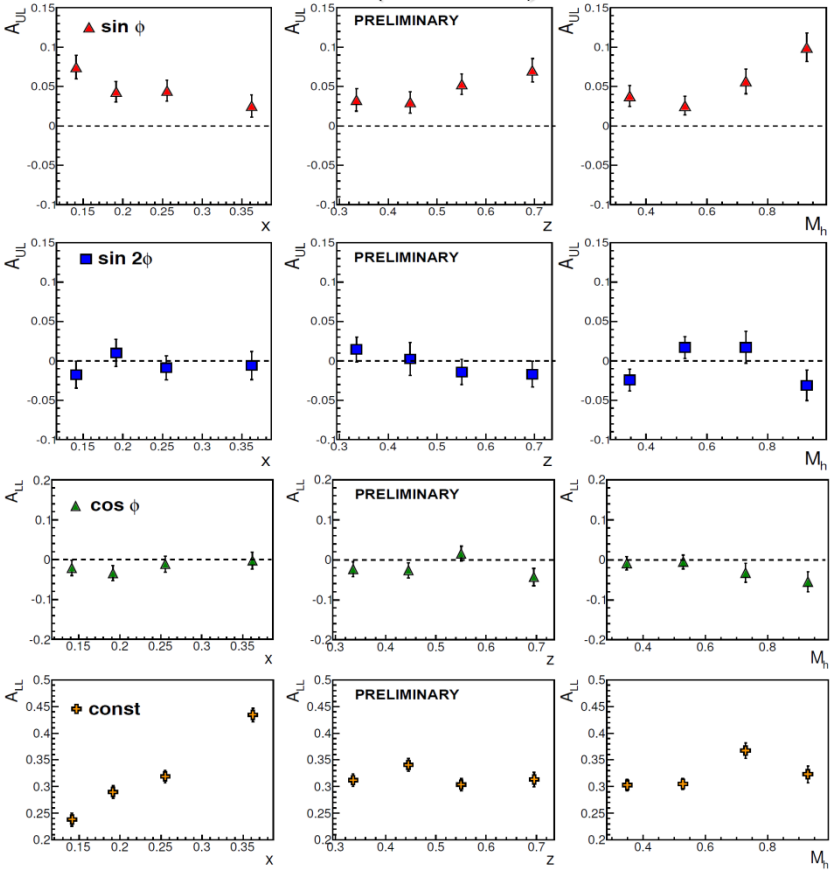
COMPASS (NH_3) 2007+2011 data: preliminary



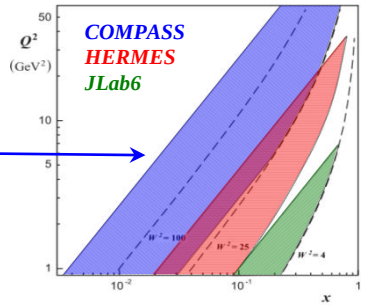


CLAS 6 GeV (NH_3)

S. A. Pereira: PoS (DIS 2014) 231

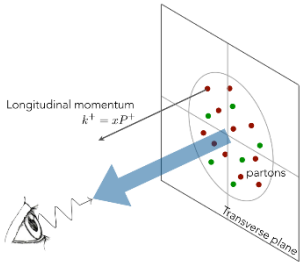


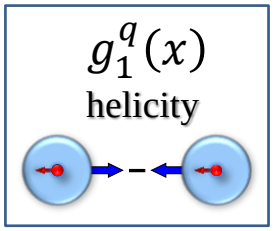
$Q^2 > 1\,(\mathrm{GeV/c})^2$
$0.0025 < x < 0.7$
$0.1 < y < 0.9$
$W > 5\,\mathrm{GeV/c}^2$



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

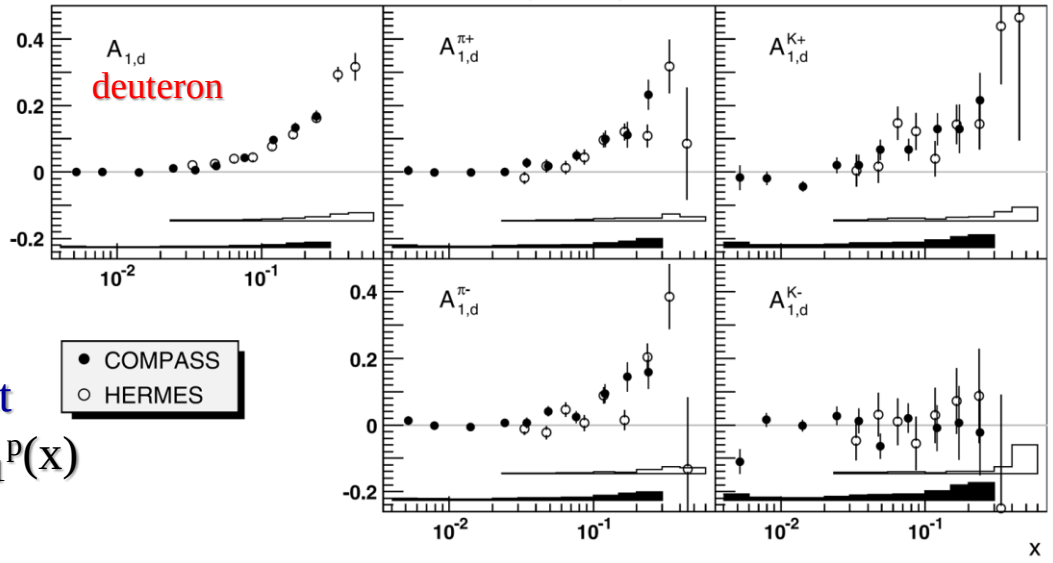
Nucleon spin structure: helicity $g^q_{1,d(p)}(x)$



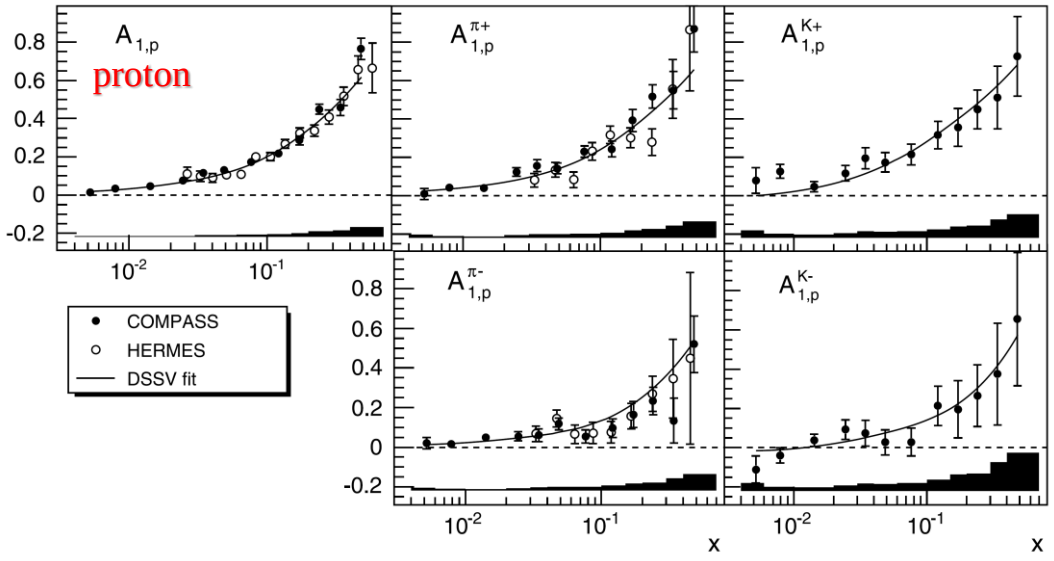


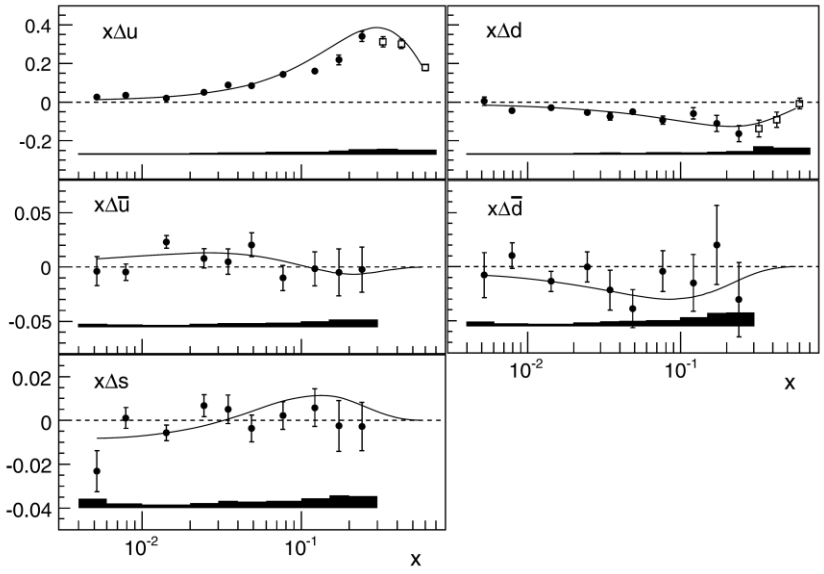
- COMPASS contribution: lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$
- Both inclusive and semi-inclusive measurements – access to flavor

COMPASS PLB 680 (2009) 217



COMPASS PLB 693 (2010) 227





SIDIS: target longitudinal spin dependent asymmetries

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

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

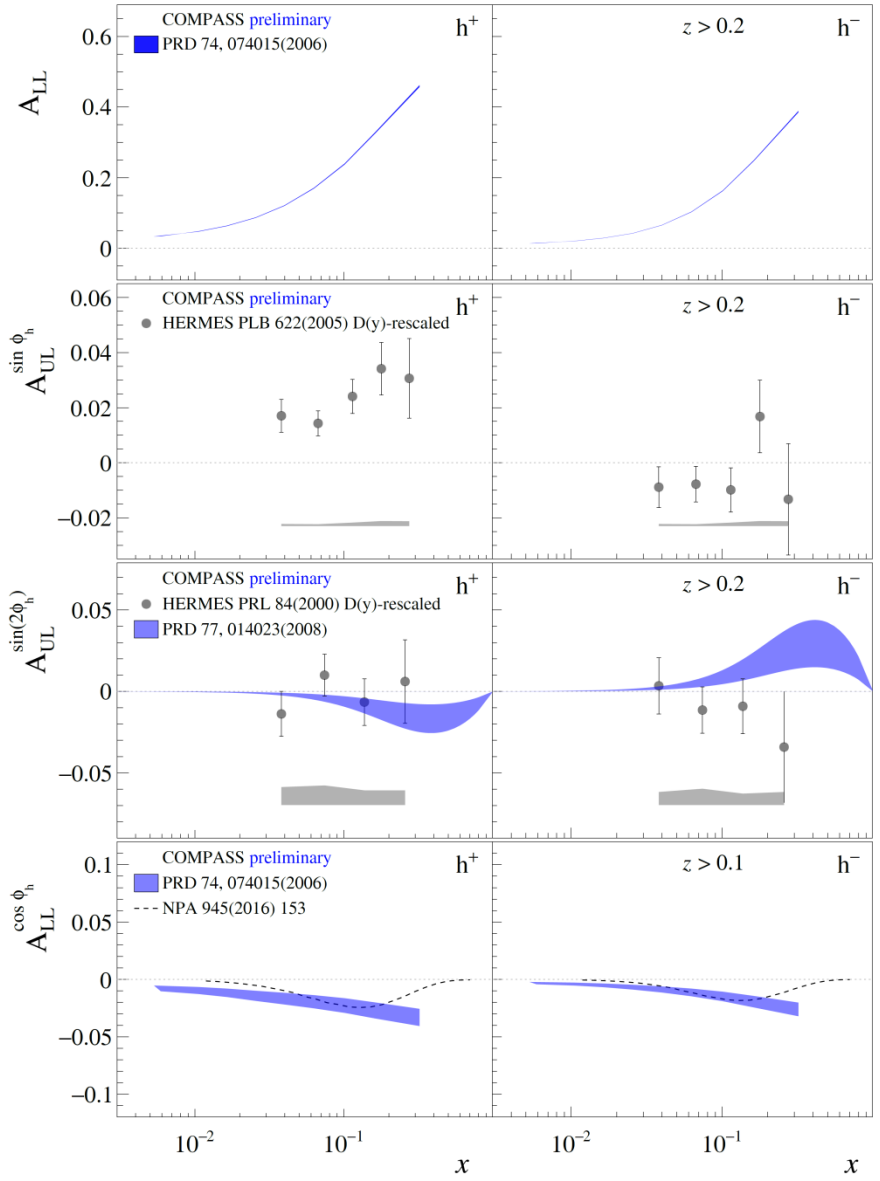
$$+ S_L \lambda \left[\sqrt{1-\varepsilon^2}\, A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\, A_{LL}^{\cos\phi_h} \cos\phi_h\right]\Big\}$$

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

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

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

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



SIDIS: target longitudinal spin dependent asymmetries

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

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

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

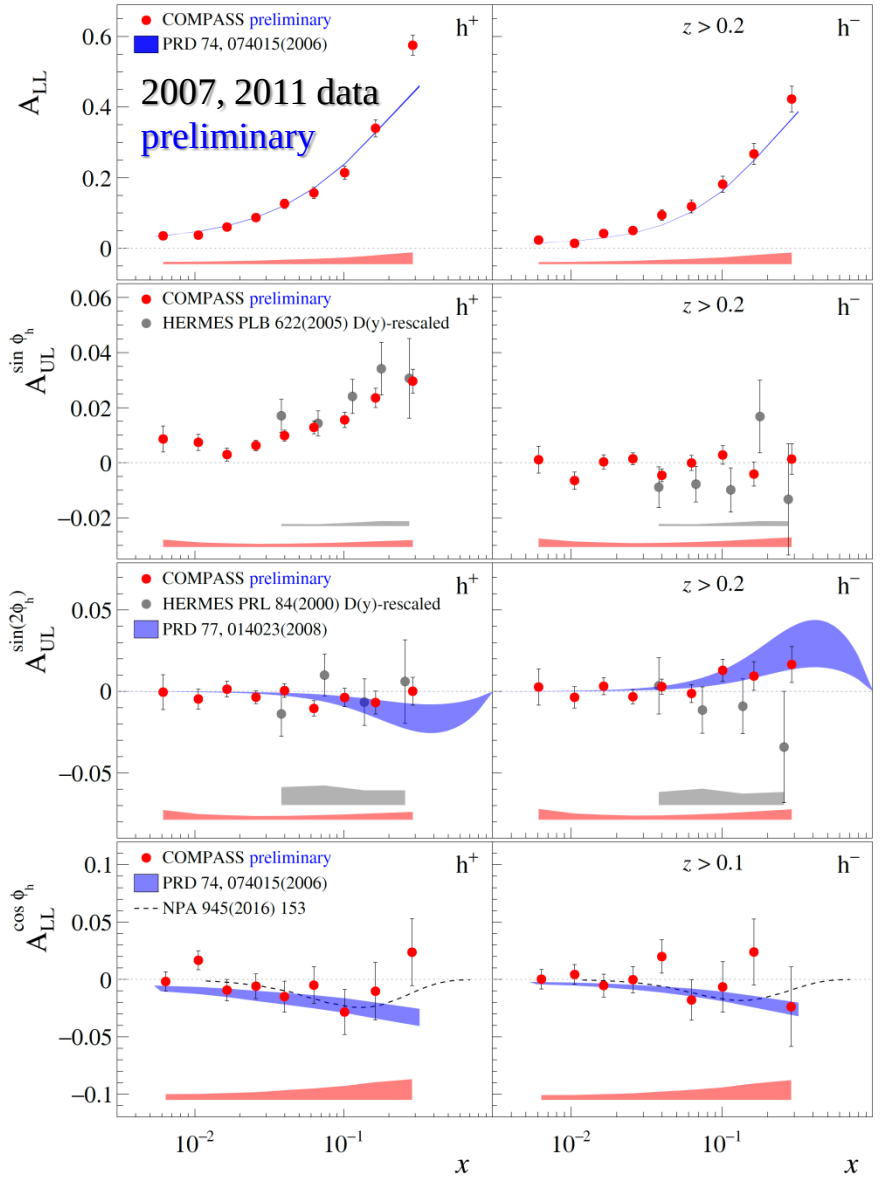
$A_{UL}^{\sin 2\phi_h}$

- 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 [hep-ex]



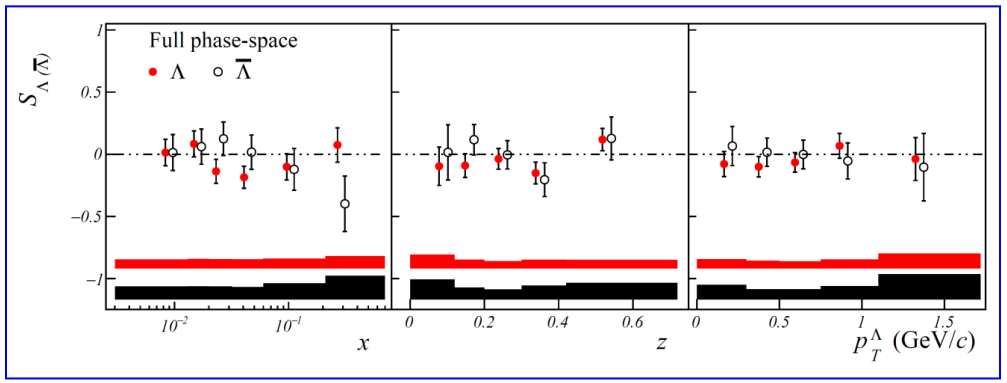
SIDIS TSAs: Collins effect and Transversity

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

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

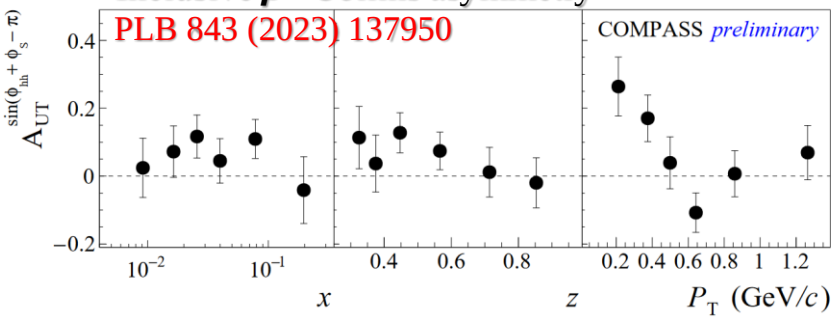
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

PLB 824 (2022) 136834

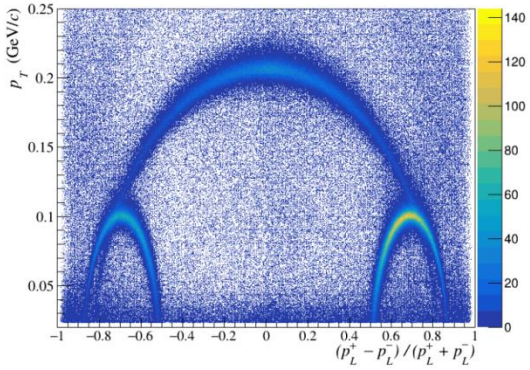


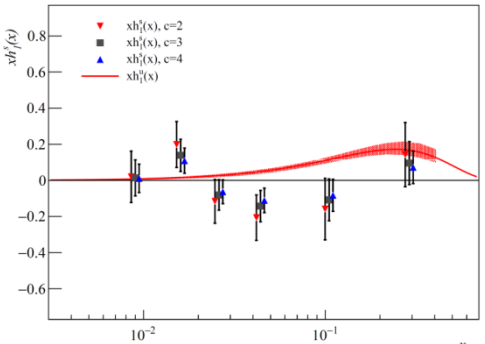
Inclusive $\boldsymbol{\rho^0}$ Collins asymmetry

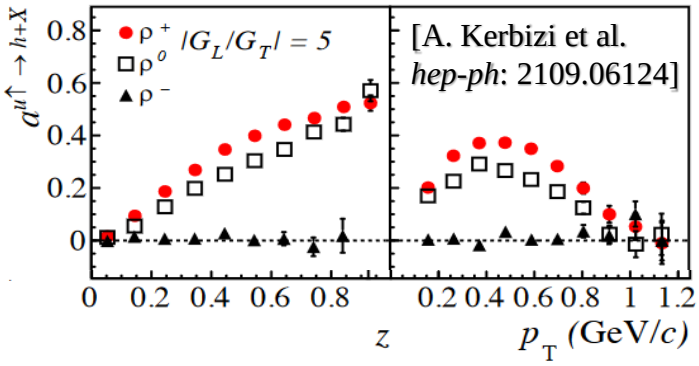
PLB 843 (2023) 137950



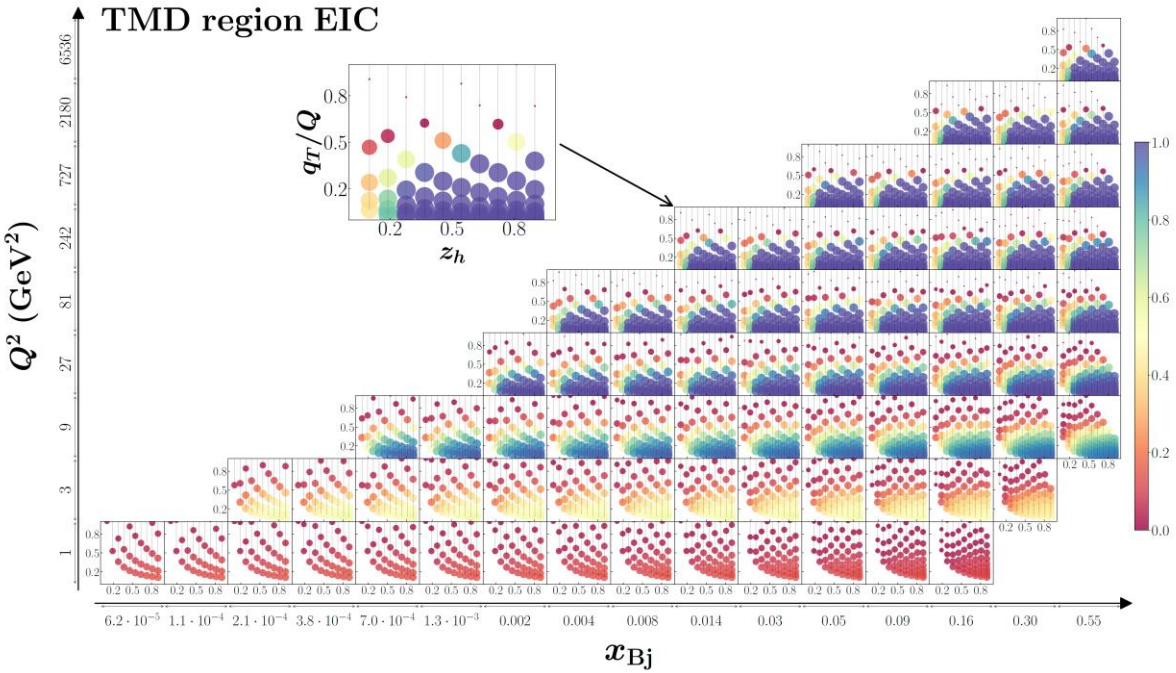
- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T



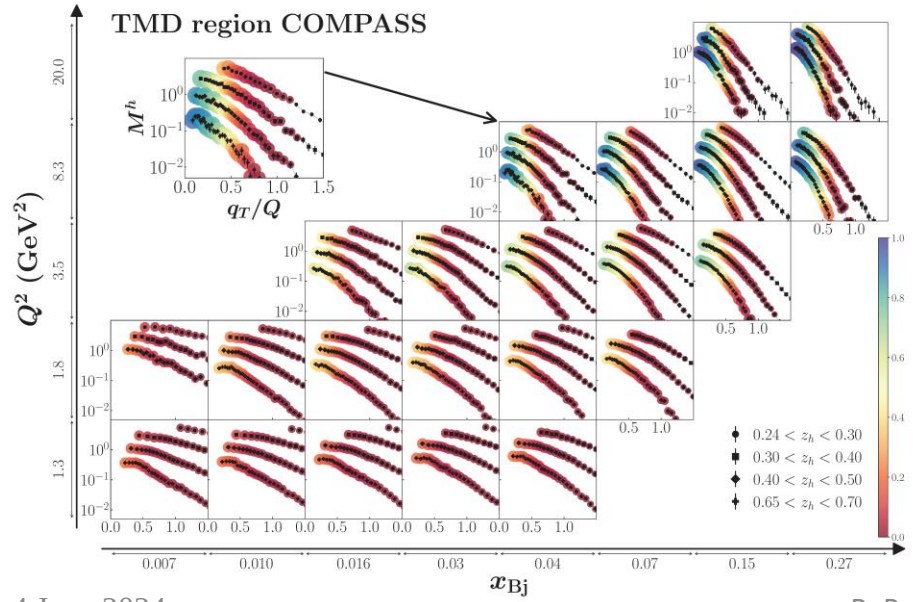


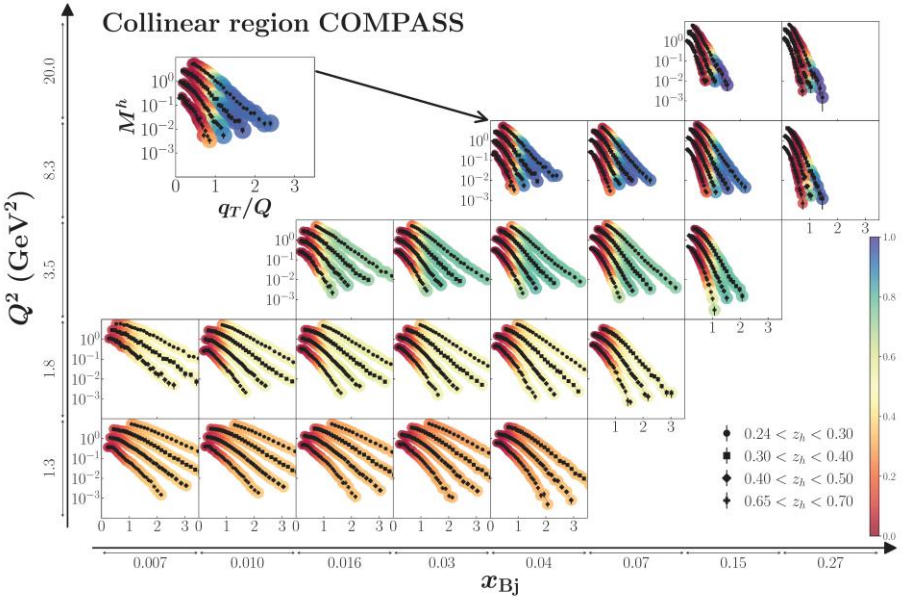


Polarized SIDIS and DY – factorization and kinematic regions

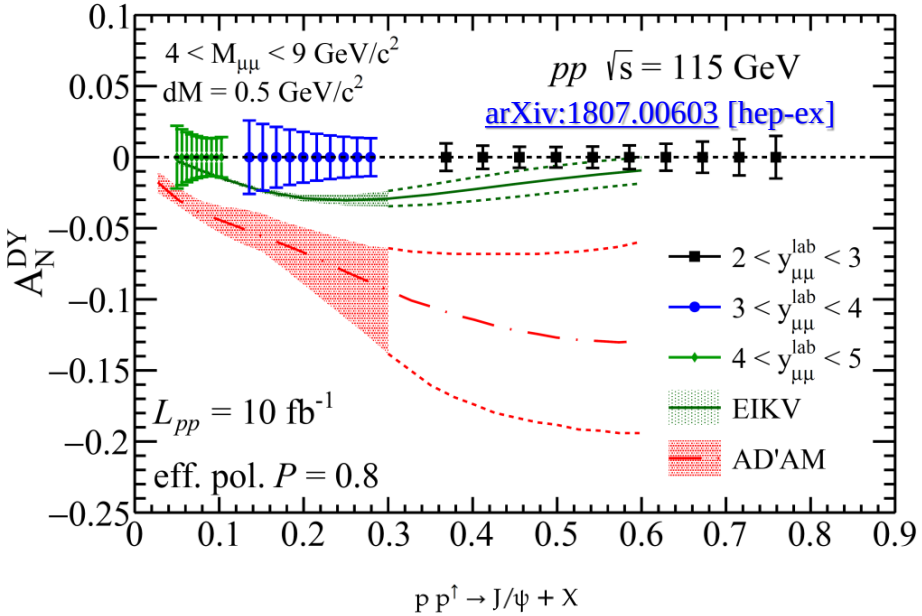


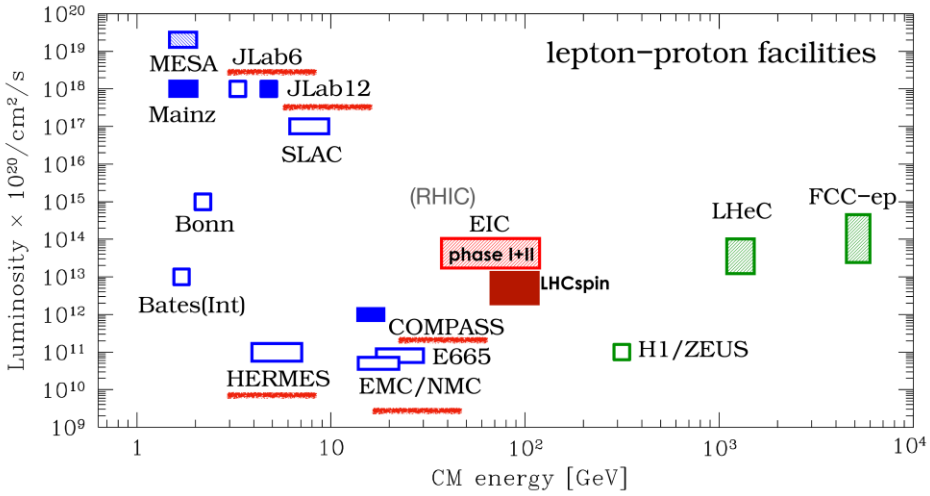
JAM, JHEP 04 (2022) 084

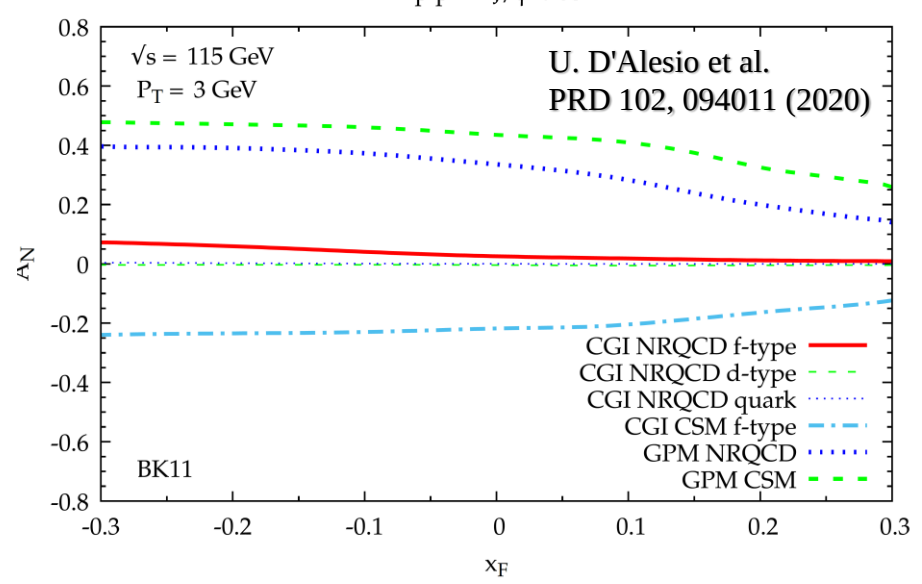


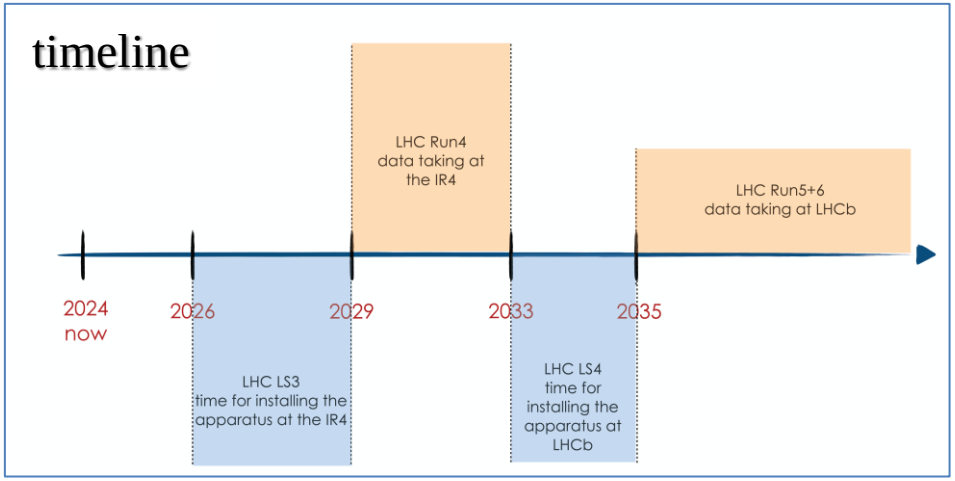


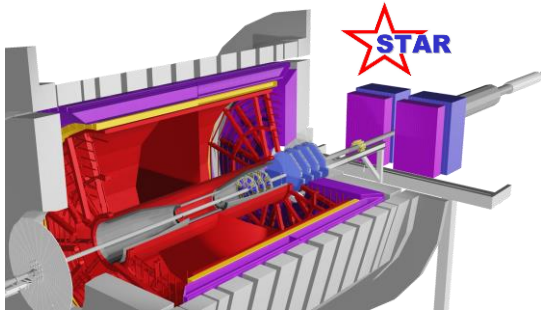
LHCspin

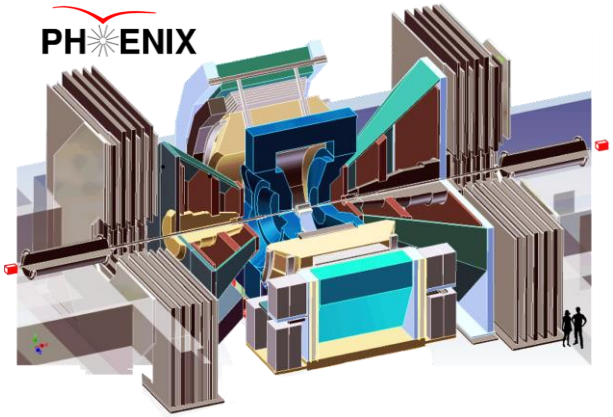

4 < M_μμ < 9 GeV/c²
dM = 0.5 GeV/c²
pp √s = 115 GeV
arXiv:1807.00603 [hep-ex]
L_pp = 10 fb⁻¹
eff. pol. P = 0.8
2 < y^lab_μμ < 3
3 < y^lab_μμ < 4
4 < y^lab_μμ < 5
EIKV
AD'AM
A_N^DY

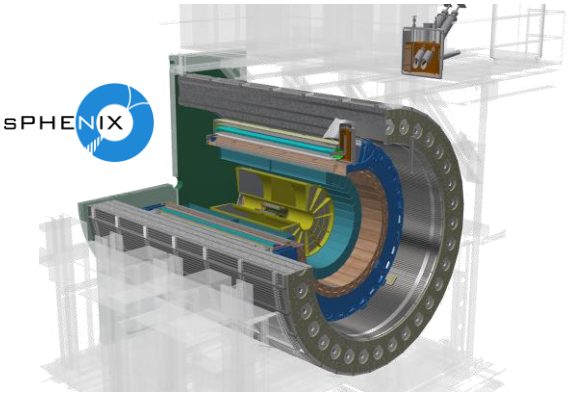

lepton−proton facilities
MESA
JLab6
JLab12
Mainz
SLAC
Bonn
(RHIC)
EIC
phase I+II
LHCspin
LHeC
FCC−ep
Bates(Int)
COMPASS
E665
HERMES
EMC/NMC
H1/ZEUS
Luminosity × 10³⁰/cm²/s
CM energy [GeV]


p p↑ → J/ψ + X
√s = 115 GeV
P_T = 3 GeV
U. D'Alesio et al.
PRD 102, 094011 (2020)
CGI NRQCD f-type
CGI NRQCD d-type
CGI NRQCD quark
CGI CSM f-type
GPM NRQCD
GPM CSM
BK11
A_N
x_F


timeline
LHC Run4
data taking at
the IR4
LHC Run5+6
data taking at LHCb
2024
now
2026
2029
2033
2035
LHC LS3
time for installing the
apparatus at the IR4
LHC LS4
time for
installing the
apparatus at
LHCb







RHIC / BNL

pp & pA (L- and T-polarized protons)

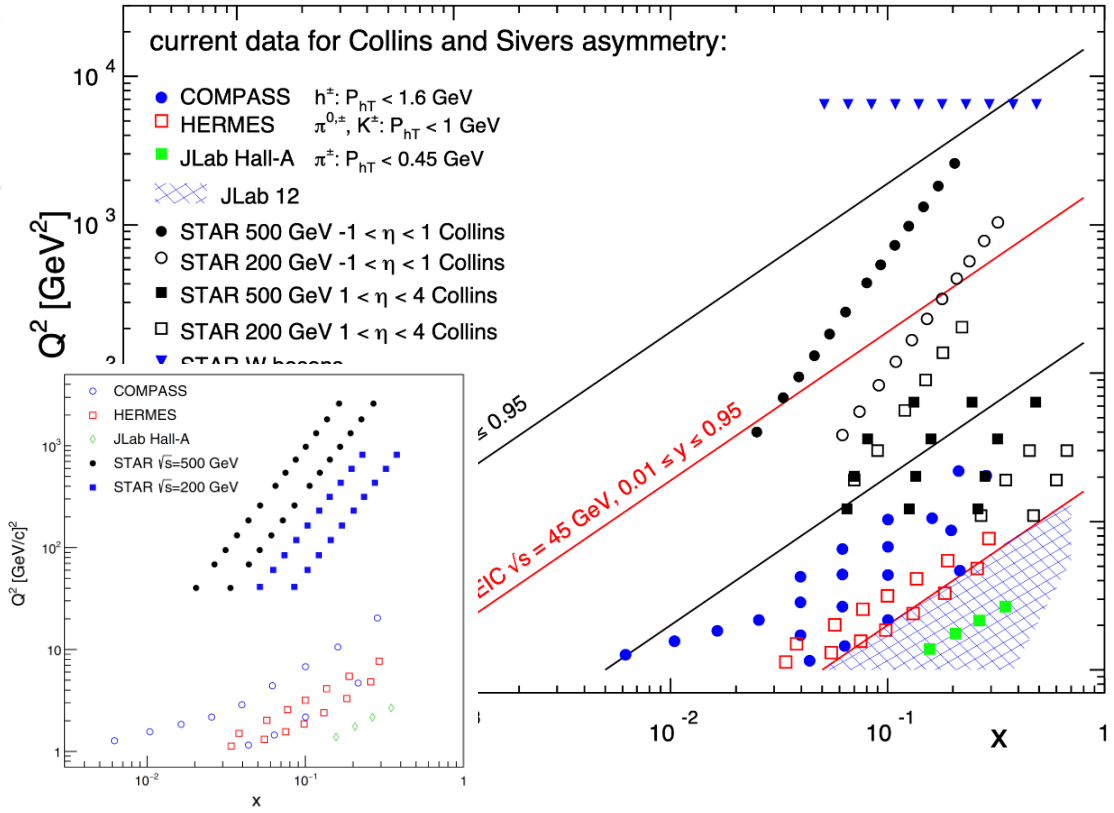
$\sqrt{s}$ = 200, 500/510 GeV

STAR (2000-2025)

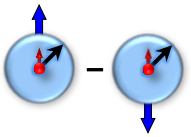
- Collins asymmetry at mid-rapidity (200 and 510 GeV *pp)*
- Similar *x*-coverage as in SIDIS experiments
- 1-2 order of magnitude larger Q^2
- Forward upgrade → x>0.5, intermediate Q^2
  (SIDIS – STAR mid-rapidity)

PHENIX (2000-2015)

sPHENIX starting 2024-2025



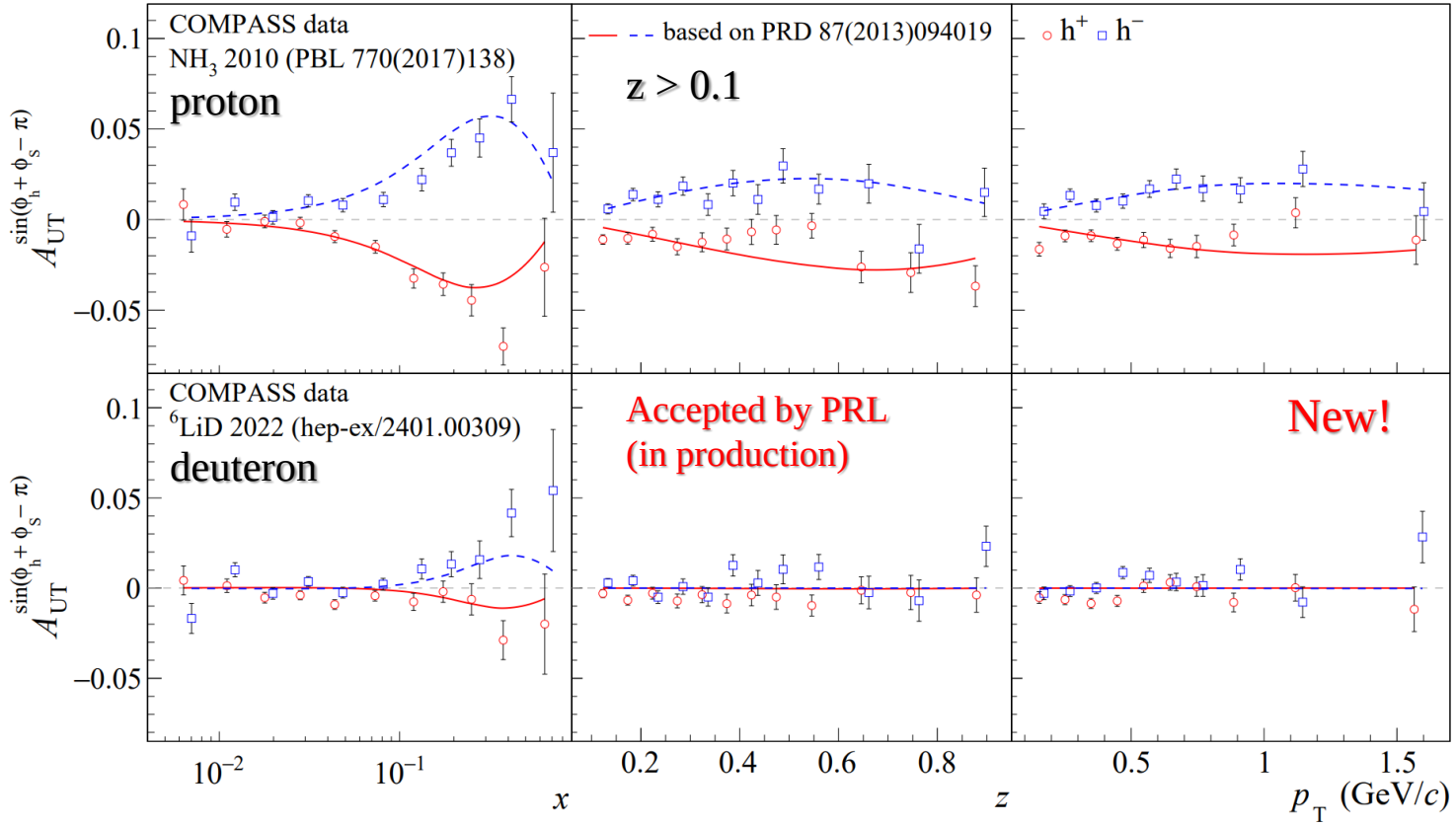
SIDIS TSAs: Collins effect and Transversity



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

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

- Measured on P/D in SIDIS and dihadron SIDIS
- Extensive phenomenological studies and various global fits by different groups
- New deuteron data crucial to constrain *d*-quark transversity

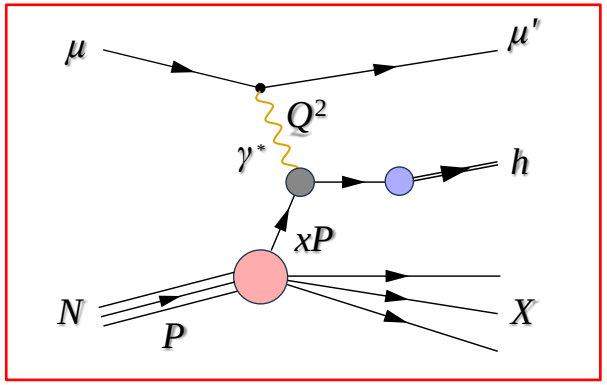


COMPASS 2022 run – highly successful data-taking!

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

Polarized SIDIS and DY – factorization and kinematic regions

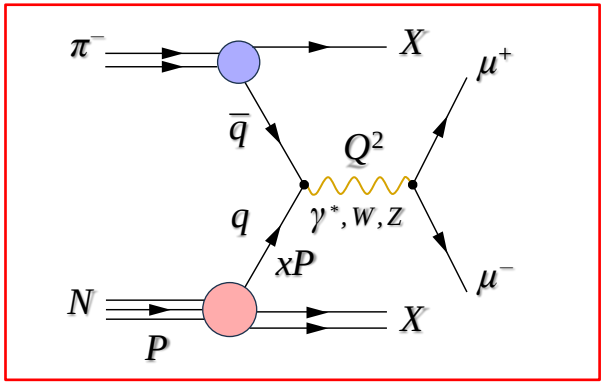
Semi-inclusive DIS



T-odd TMD PDFs

sign change

Drell-Yan process



High q_T – Collinear factorization
Low q_T – TMD factorization

$q_T \geq Q$

Current fragmentation
Collinear factorization

High x_F – Current fragmentation
Low x_F – Target fragmentation

Target fragmentation
TMD factorization
Fracture Functions

Soft region

Current fragmentation
TMD factorization
PDFs, FFs

$q_T << Q$

x_F