TMD effects in polarized processes Experiment overview

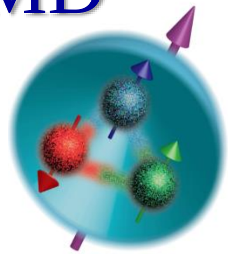
(non-comprehensive)

BAKUR PARSAMYAN

AANL, CERN, INFN (Turin) and
Yamagata University

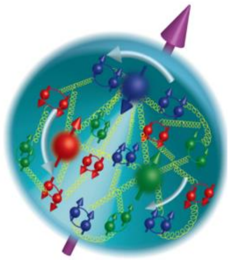
7th International Workshop on “Transverse phenomena in hard processes”
June 3-7, University of Trieste, Trieste, Italy

Nucleon spin structure: TMD



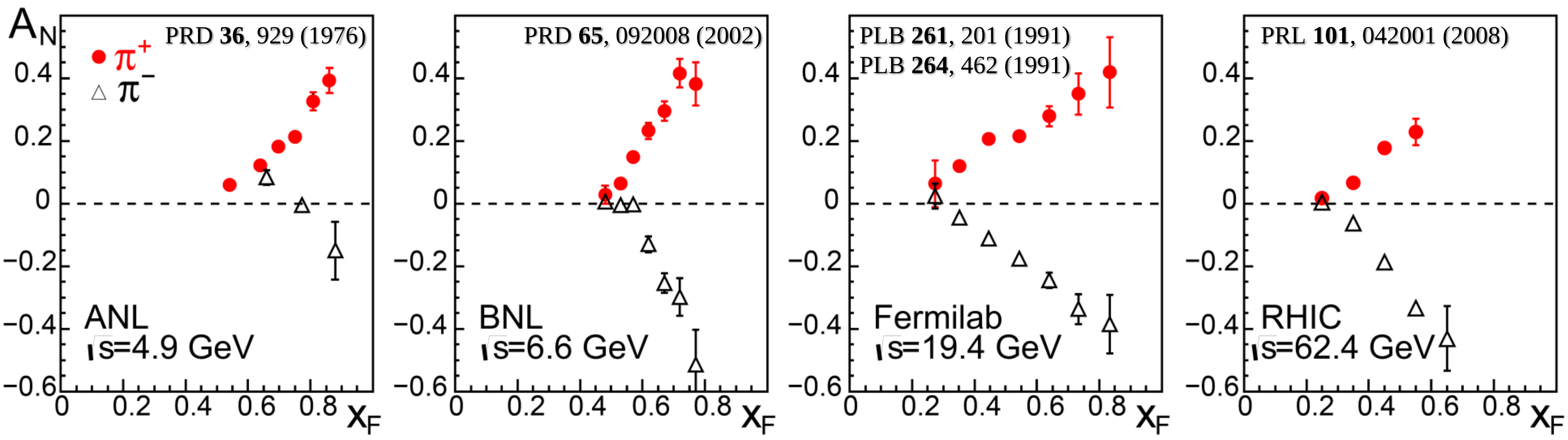
- 1964 Quark model

- 1969 Parton model



- 1973 asymptotic freedom and QCD

- 1976 large transverse single spin asymmetry in forward $\pi^{\pm}$ production



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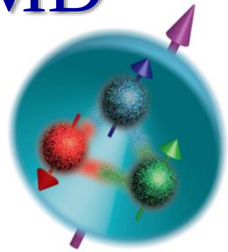

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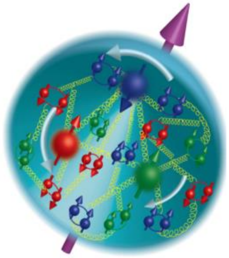

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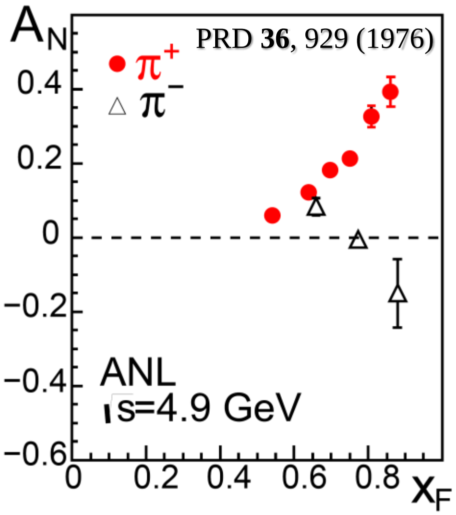
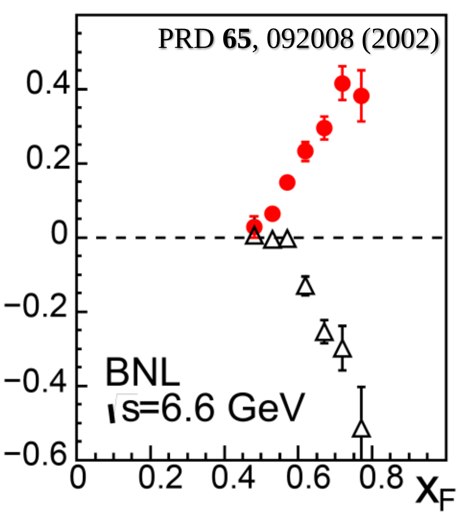
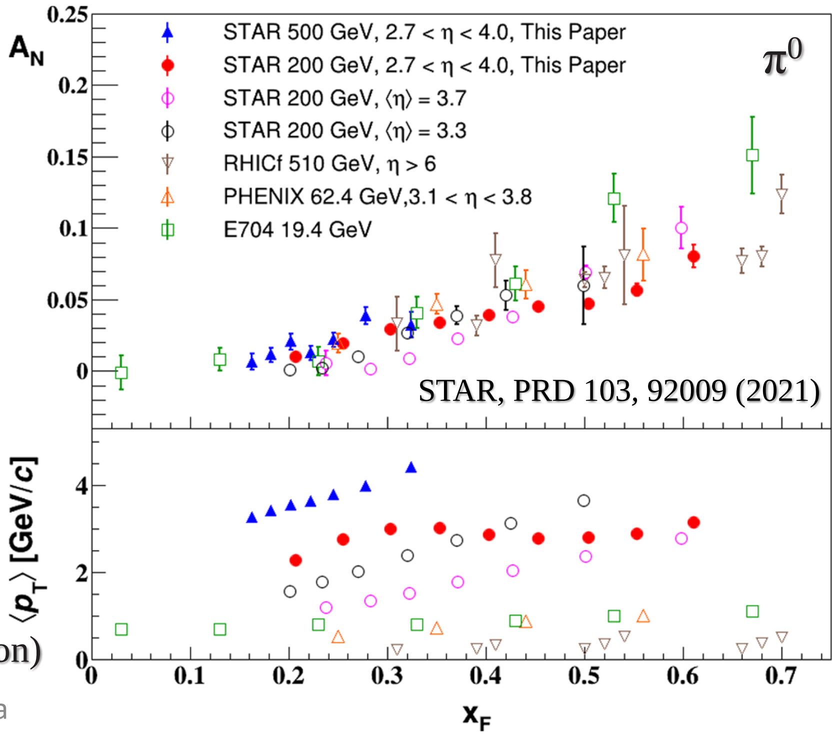
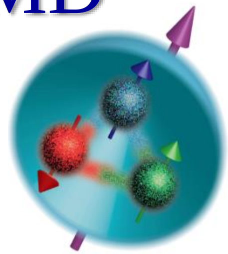






- TMD Sivers and Collins or
- Twist-3 Sivers (Efremov-Teryaev-Qui-Sterman (ETQS) function)

Nucleon spin structure: TMD



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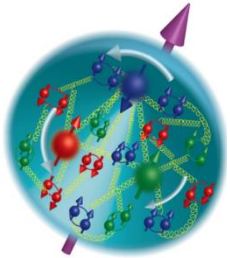

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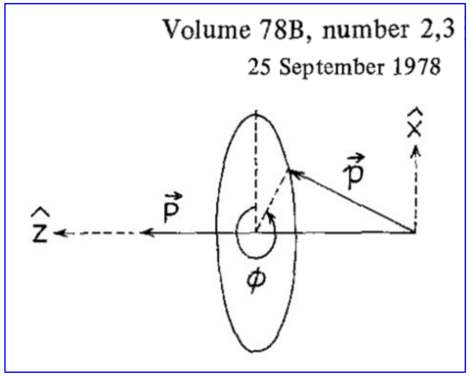

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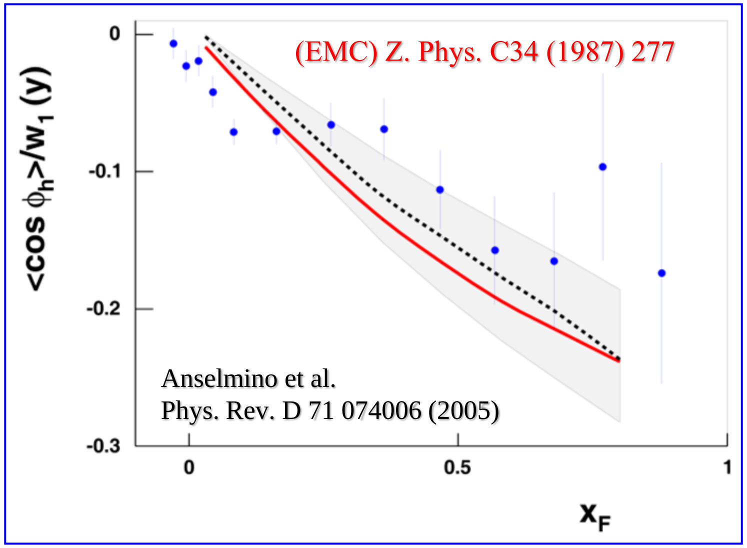
25 September 1978

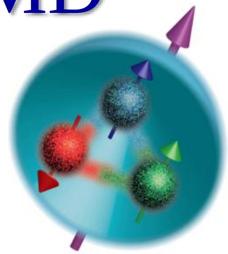


(EMC) Z. Phys. C34 (1987) 277

Anselmino et al.
Phys. Rev. D 71 074006 (2005)

(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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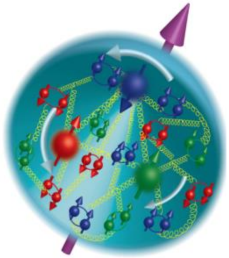

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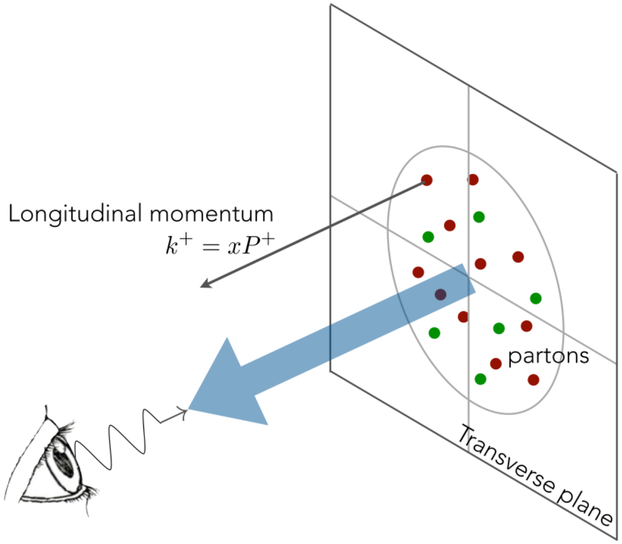
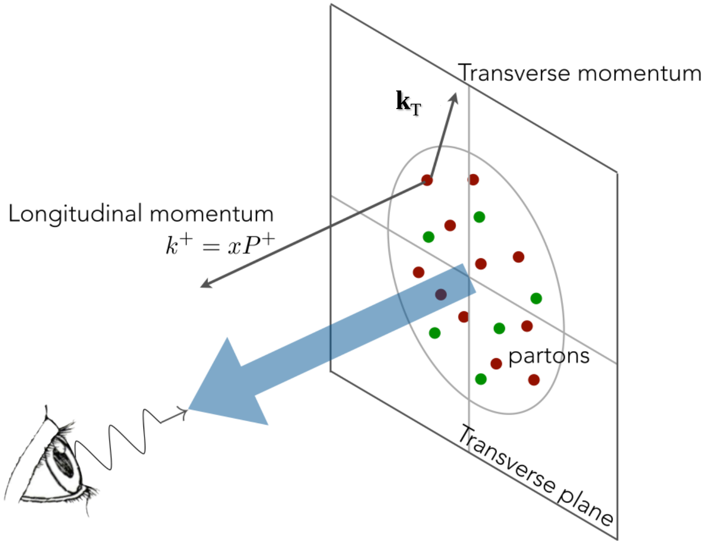




Nucleon spin structure (twist-2): collinear approach ↔TMDs

quark

nucleon

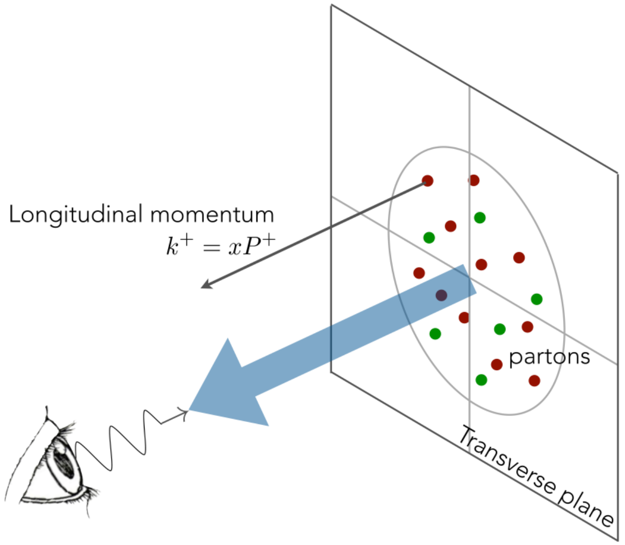
	U	**L**	**T**
U	$f_1^q(x)$ number density		
L		$g_1^q(x)$ helicity	
T			$h_1^q(x)$ transversity

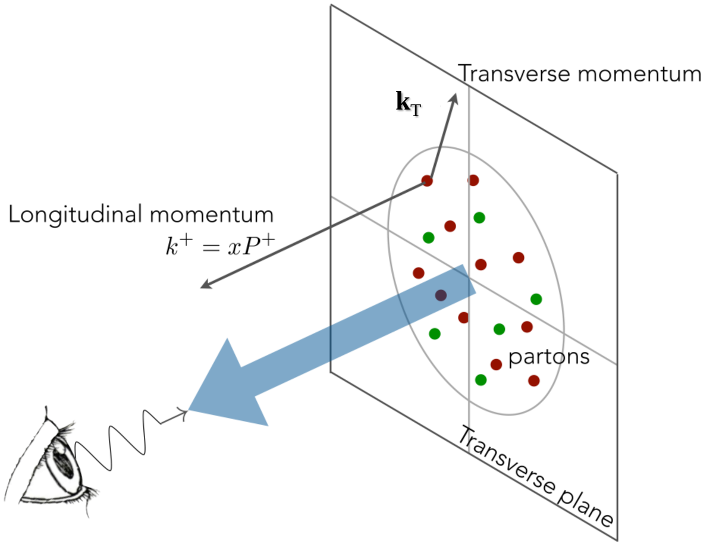
quark

nucleon

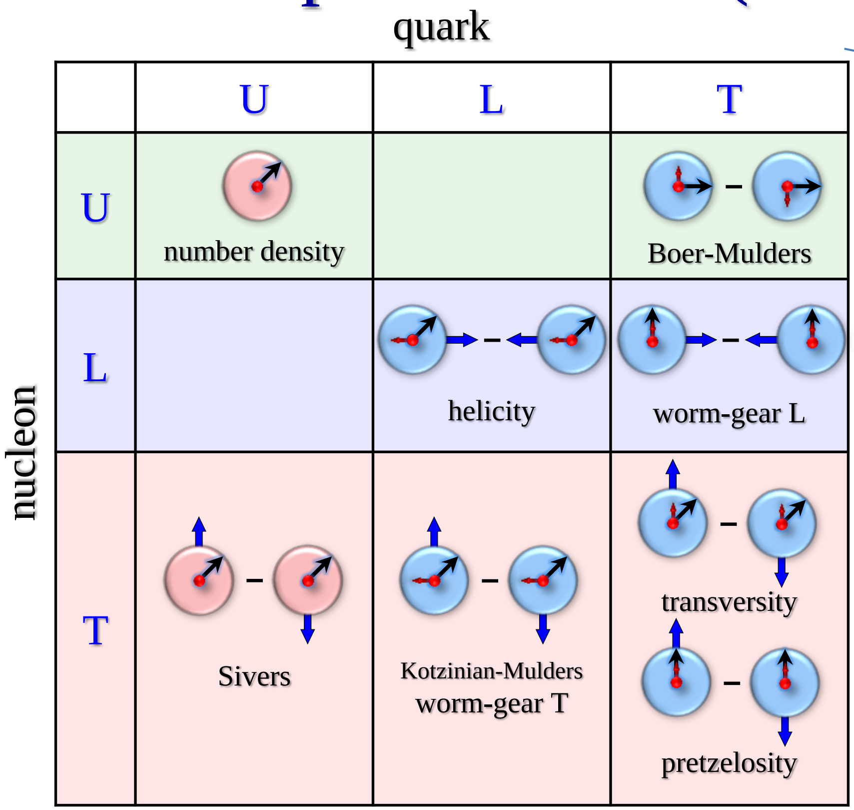
	U	**L**	**T**
U	$f_1^q(x, \boldsymbol{k}_T^2)$ number density		chiral-odd $h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ Boer-Mulders T-odd
L		$g_1^q(x, \boldsymbol{k}_T^2)$ Helicity	chiral-odd $h_{1L}^{\perp q}(x, \boldsymbol{k}_T^2)$ worm-gear L
T	$f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x,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

↑ - spin of the nucleon; ↑ - spin of the quark ↗ - k_T

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
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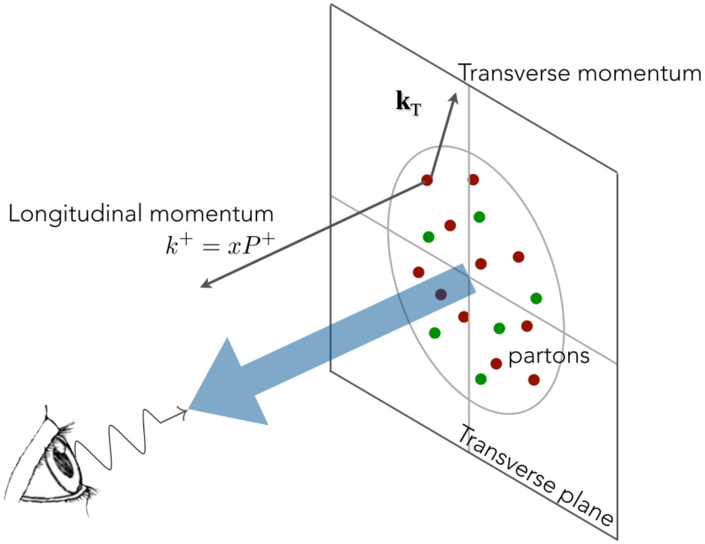


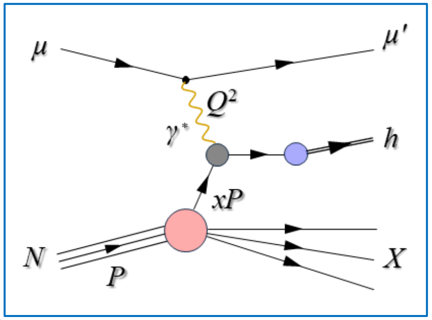
See Francesco Murgia's talk

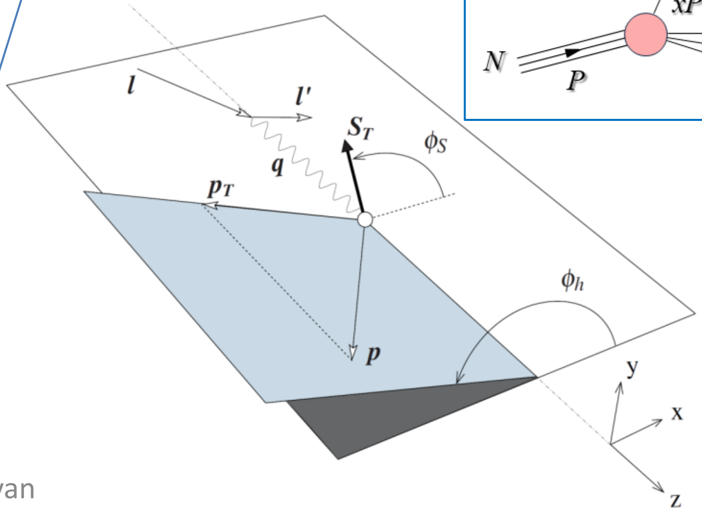
SIDIS x-section and TMDs at twist-2

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

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

		quark		
		U	**L**	**T**
nucleon	**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
	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	$h_1^q(x,\boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ pretzelosity





SIDIS x-section and TMDs at twist-2

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

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

		quark		
		U	**L**	**T**
nucleon	**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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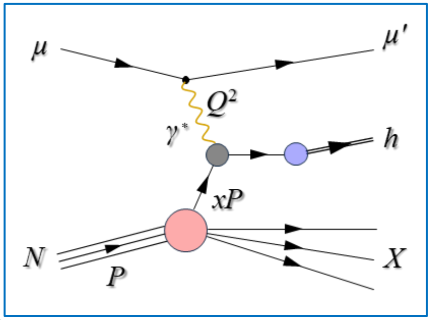
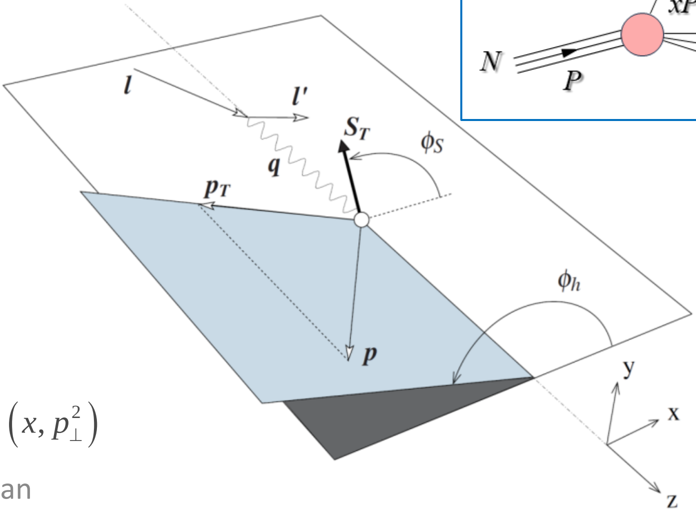
	T	$f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x, \boldsymbol{k}_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x, \boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ pretzelosity

$A_{UU}^{\cos 2\phi_h} \propto \underline{h_1^{\perp q}} \otimes \underline{H_{1q}^{\perp h}}$	Boer-Mulders (T-odd)
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto \underline{f_{1T}^{\perp q}} \otimes D_{1q}^h$	Sivers (T-odd)
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto \underline{h_1^q} \otimes \underline{H_{1q}^{\perp h}}$	Transversity
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto \underline{h_{1T}^{\perp q}} \otimes \underline{H_{1q}^{\perp h}}$	Pretzelosity





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

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

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

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

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

quark

nucleon

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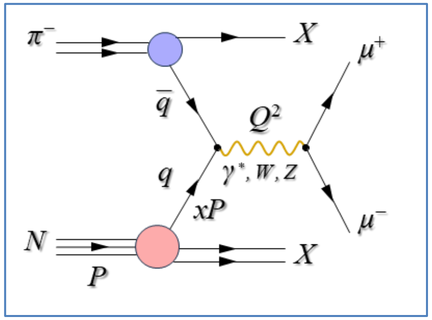
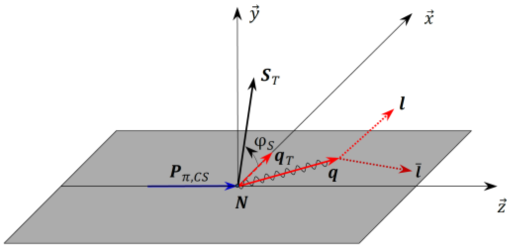
L		$g_1^q(x,\boldsymbol{k}_T^2)$ Helicity	$h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ worm-gear L
T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x,\boldsymbol{k}_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x,\boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ pretzelosity

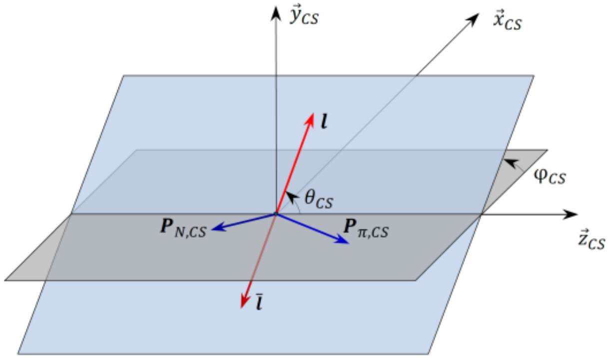
$A_U^{\cos 2\varphi_{CS}} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{\perp q}}$	Boer-Mulders (T-odd)
$A_T^{\sin\varphi_S} \propto \underline{f_{1,\pi}^{q}} \otimes \underline{f_{1T,p}^{\perp q}}$	Sivers (T-odd)
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto \underline{h_{1,\pi}^{\perp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

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

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

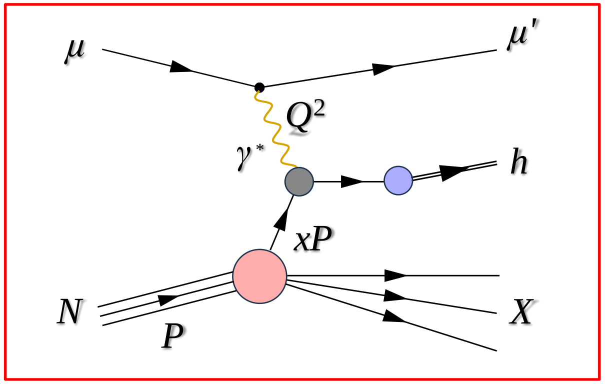






Polarized SIDIS and Drell-Yan: universality

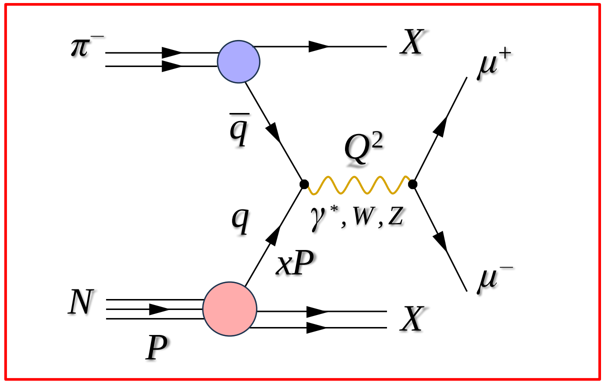
Semi-inclusive DIS



T-odd TMD PDFs

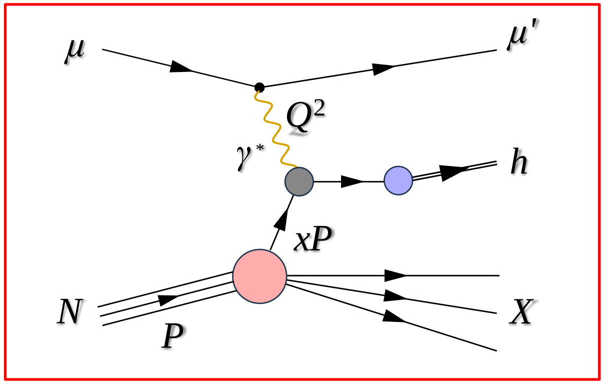
sign change

Drell-Yan process



Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS

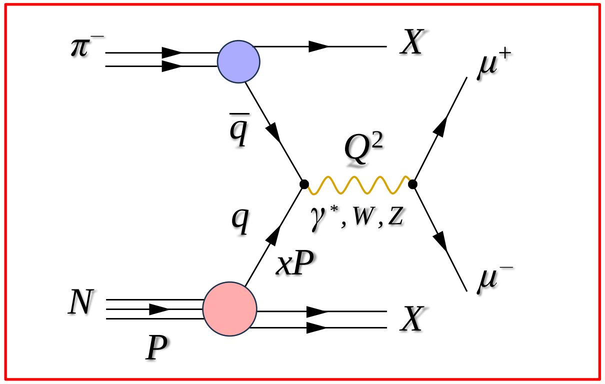


T-odd TMD PDFs

↔

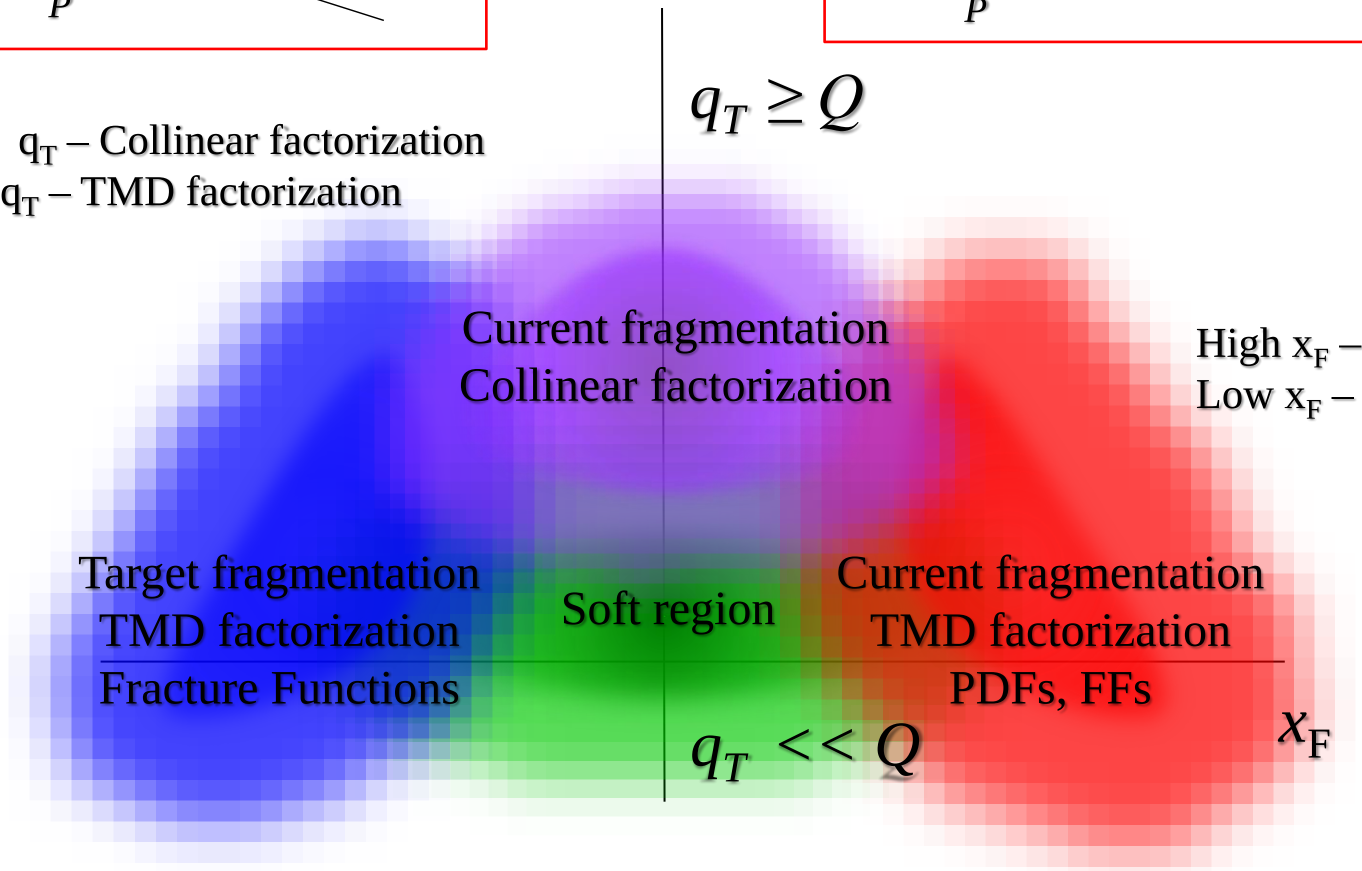
sign change

Drell-Yan process



High q_T – Collinear factorization
Low q_T – TMD factorization

High x_F – Current fragmentation
Low x_F – Target fragmentation



$q_T \geq Q$

Current fragmentation
Collinear factorization

Target fragmentation
TMD factorization
Fracture Functions

Soft region

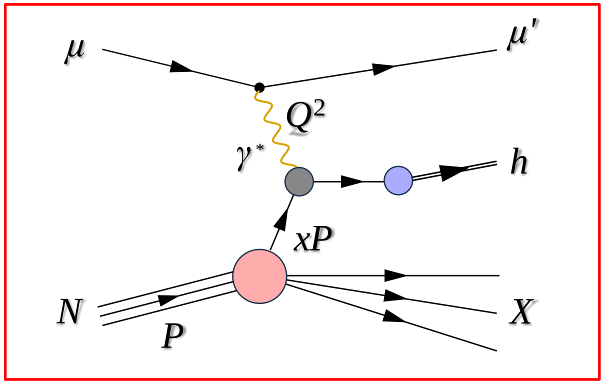
Current fragmentation
TMD factorization
PDFs, FFs

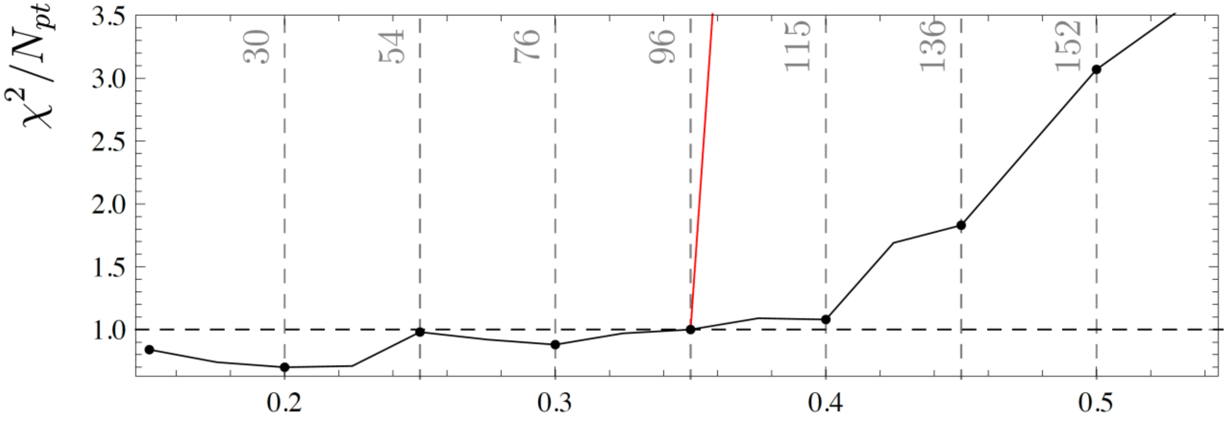
x_F

$q_T << Q$

Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS





δ=q_T/Q

M. Bury, A. Prokudin and A. Vladimirov
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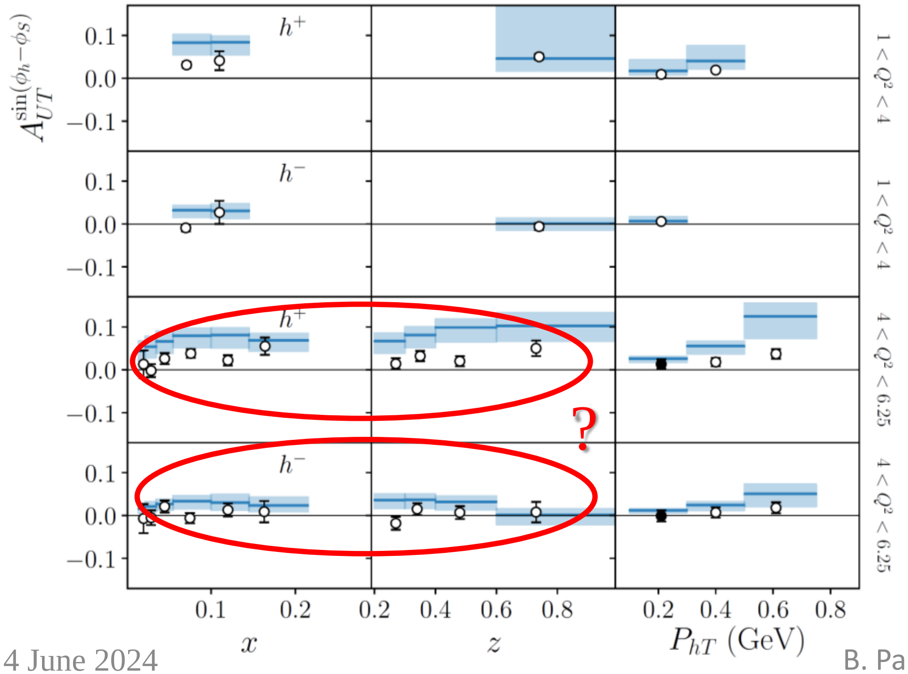
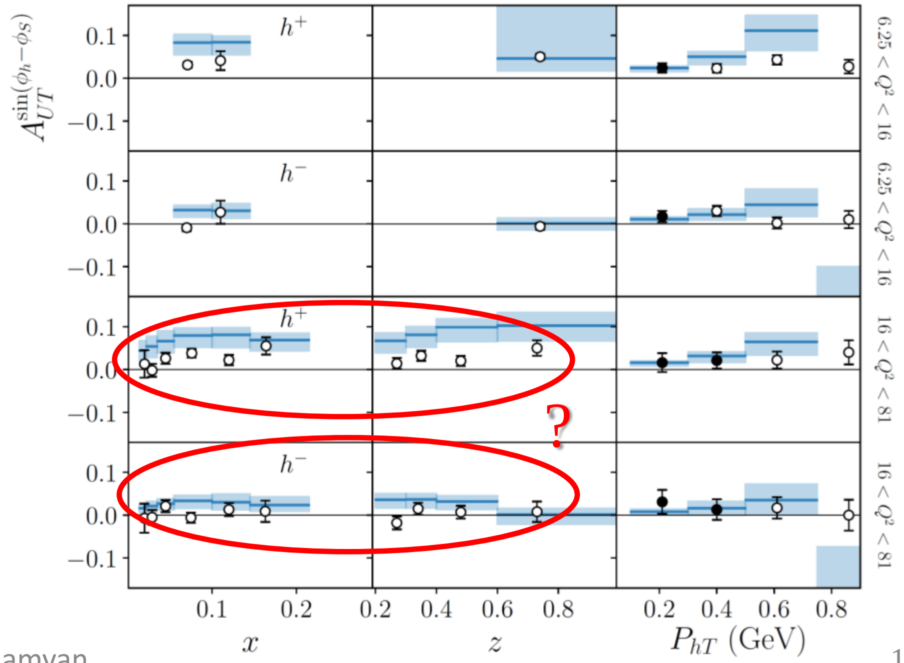
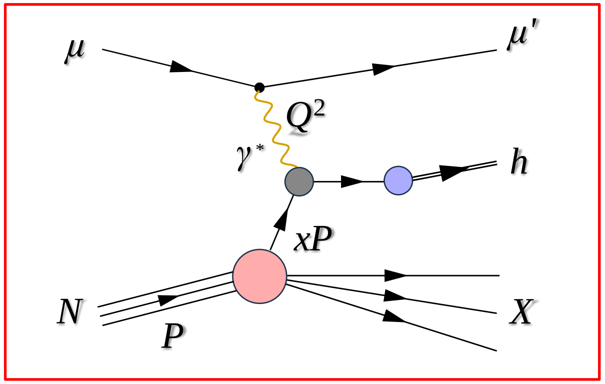
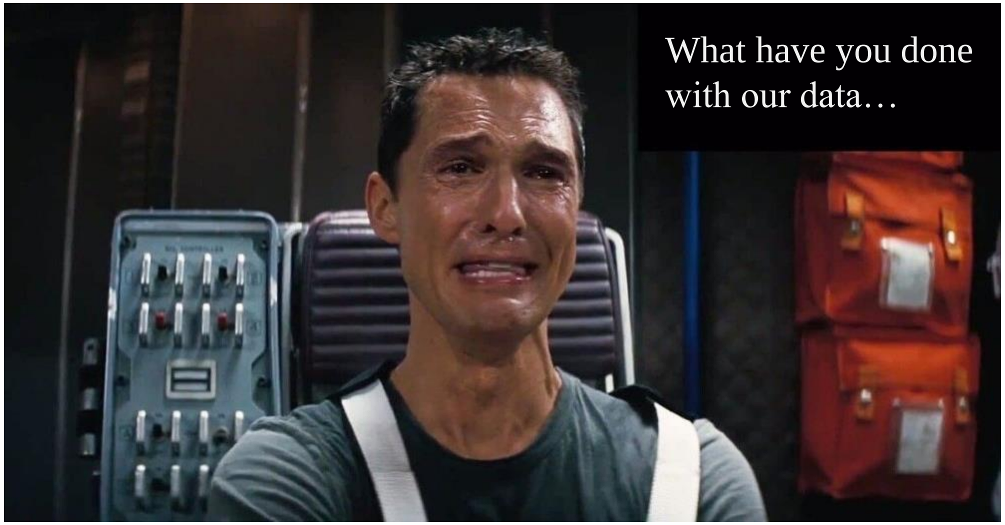




Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS





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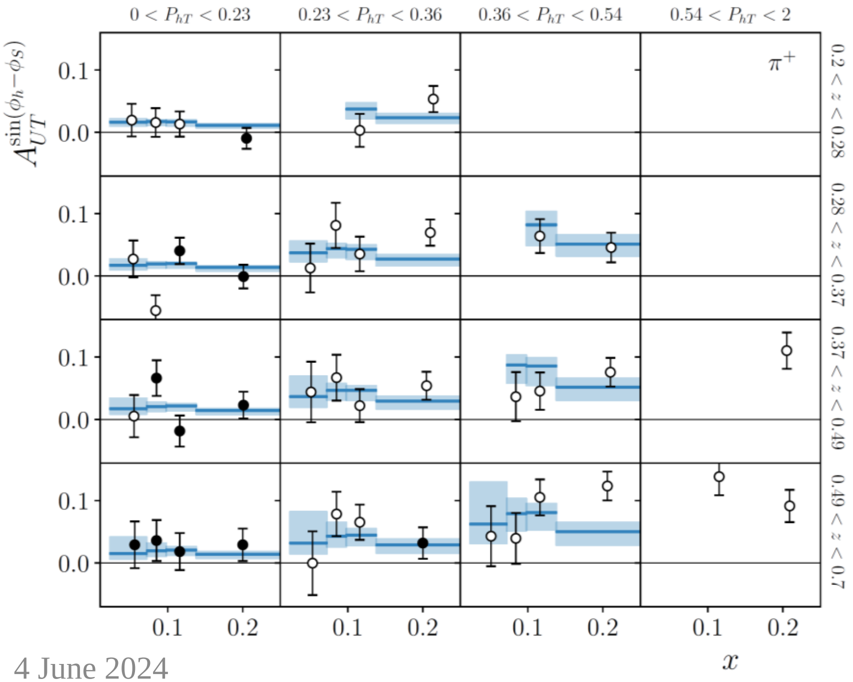
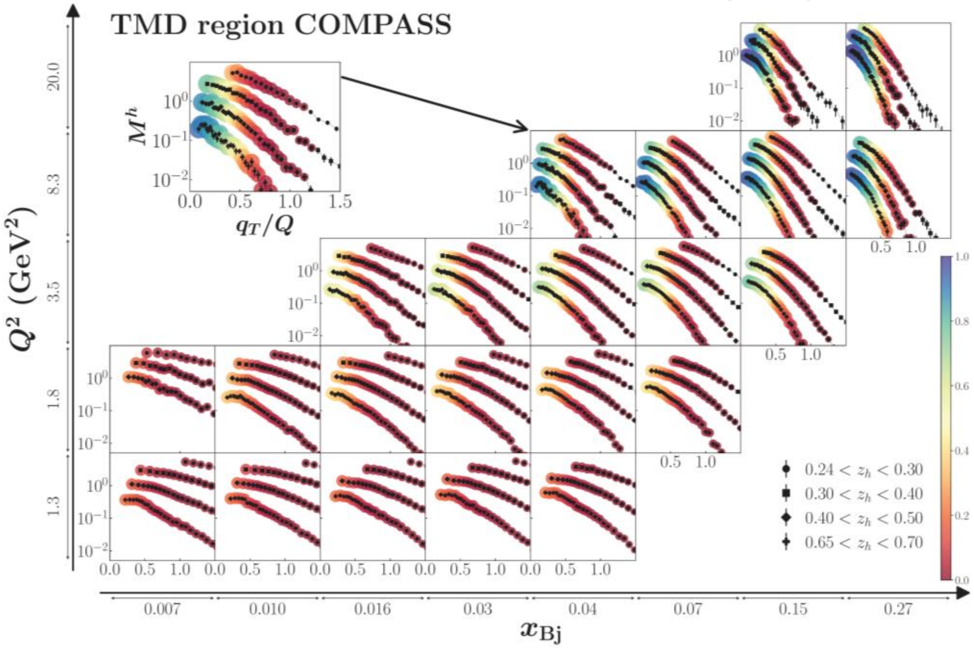
JHEP 05 (2021) 151



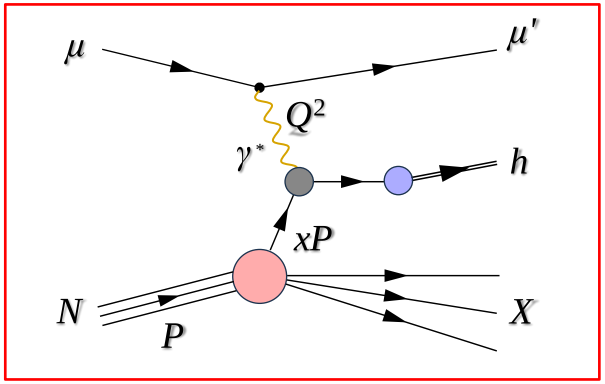
One persons ‘complication’ is another person's signal…
A. Vossen

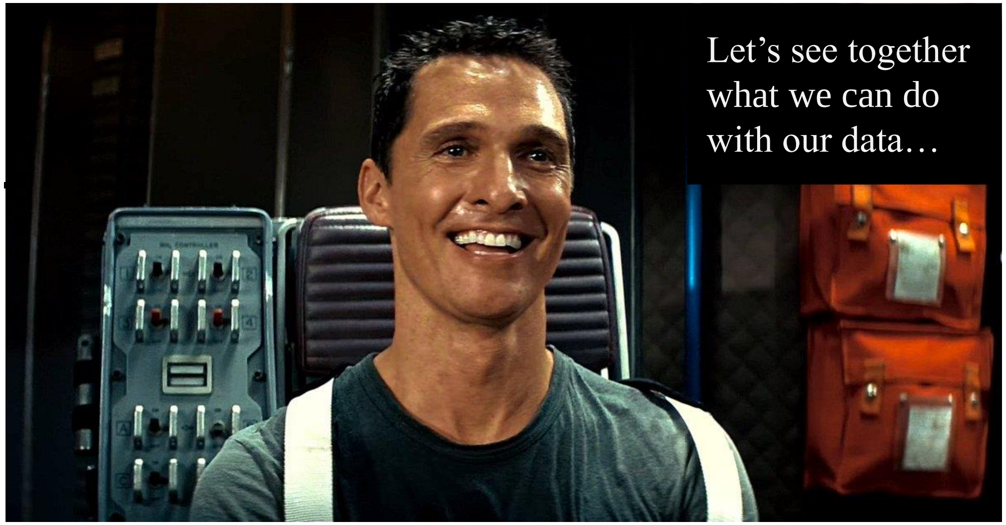
JAM, JHEP 04 (2022) 084

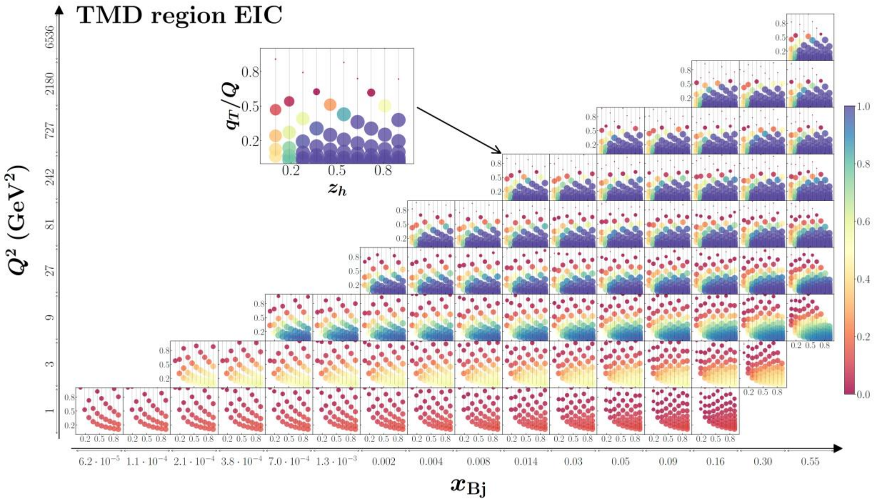


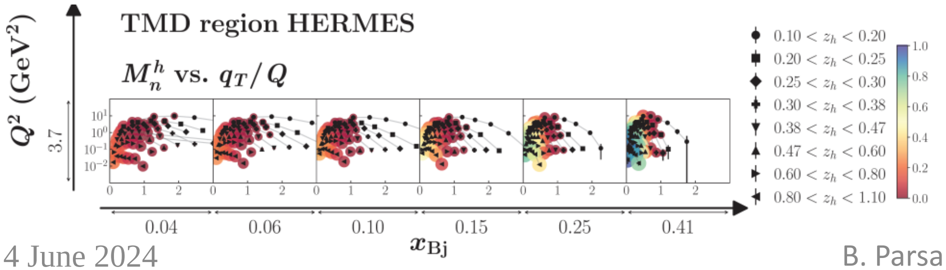
Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS

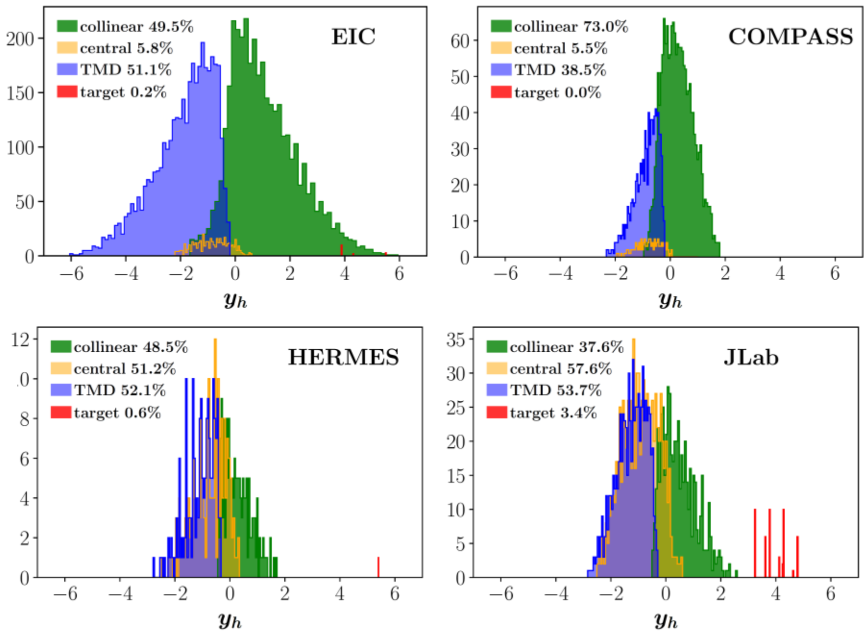



Let’s see together what we can do with our data…



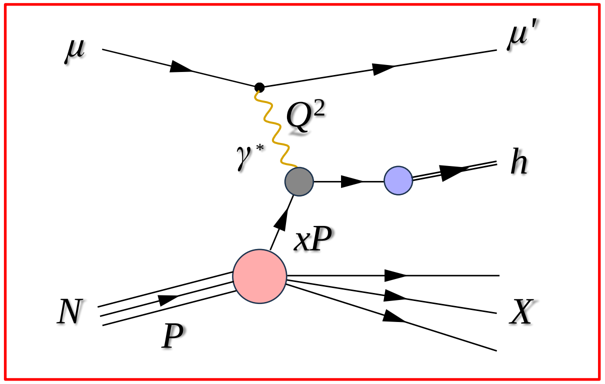


JAM, JHEP 04 (2022) 084

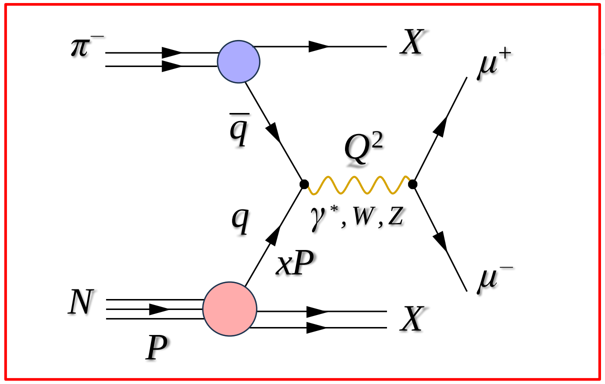


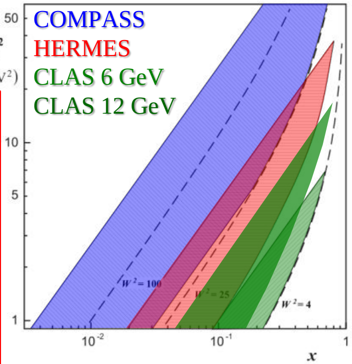
Main polarized SIDIS (Drell-Yan) inputs 1995-2022

Semi-inclusive DIS



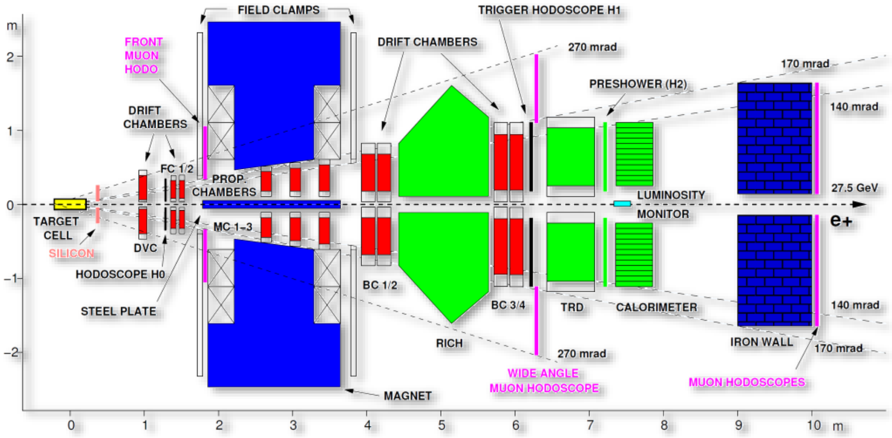
Drell-Yan process

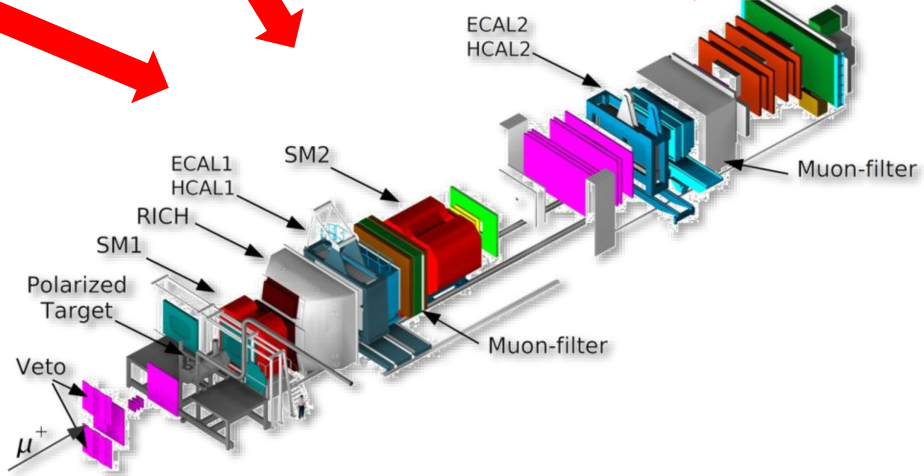




T-odd TMD PDFs

sign change



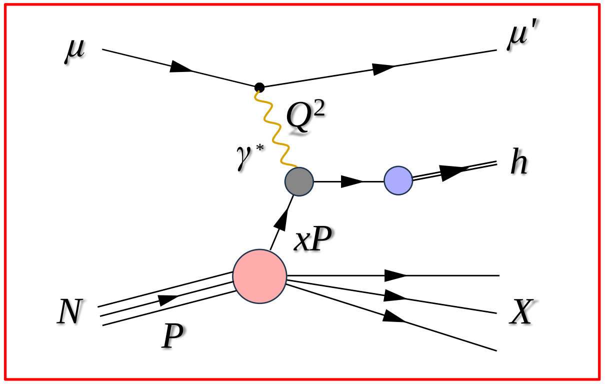


HERMES (data taking: 1995-2007)
Beam: e^+, e^- 27.6 GeV/c
L- and T- polarized proton target

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

Main TMD tools – universality and synergies

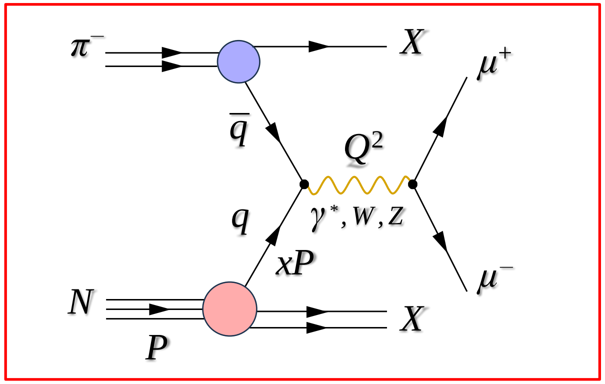
Semi-inclusive DIS



T-odd TMD PDFs

sign change

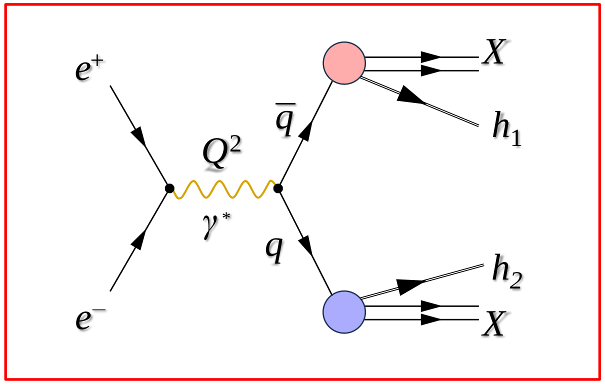
Drell-Yan process



Fragmentation Functions

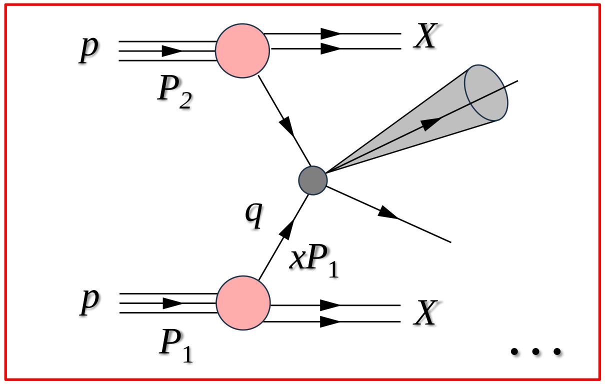
Parton Distribution Functions

Electron-positron annihilation



Cleanest access to hadronization/fragmentation

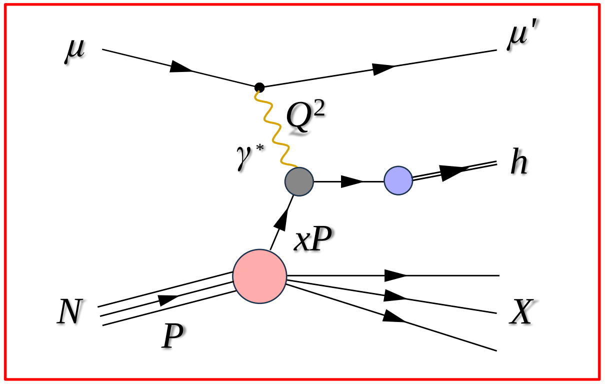
pp, pA-scattering, jet production, etc.



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

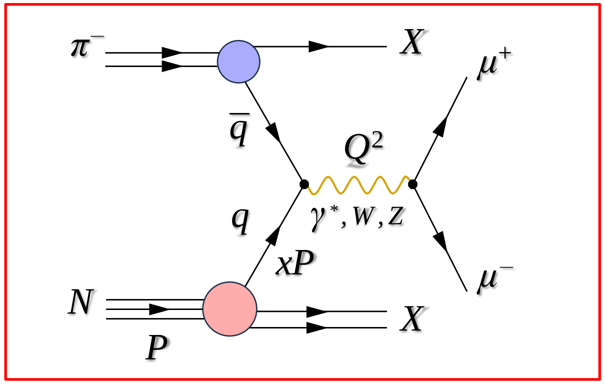


hermes
DESY.
COMPASS
CERN
Jefferson Lab
clas
SoLID

ePIC

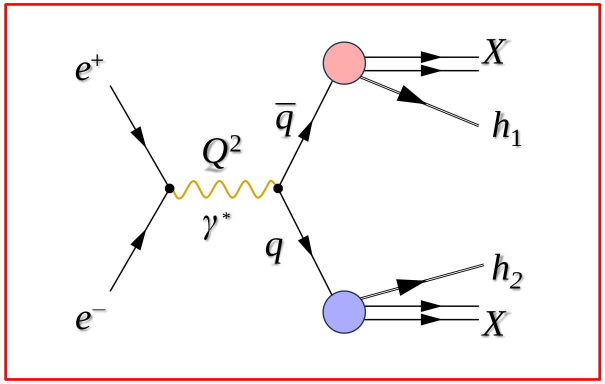
Jefferson Lab @ 22 GeV

Drell-Yan process



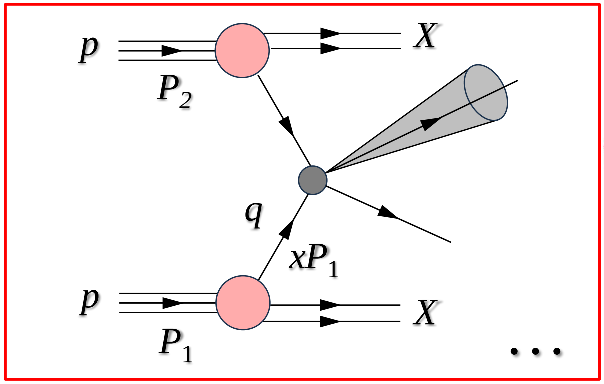
COMPASS
CERN
STAR
SPIN QUEST
LHC spin
Fermilab

Electron-positron annihilation



Belle
KEK
BABAR
SLAC
NATIONAL ACCELERATOR LABORATORY
BESIII

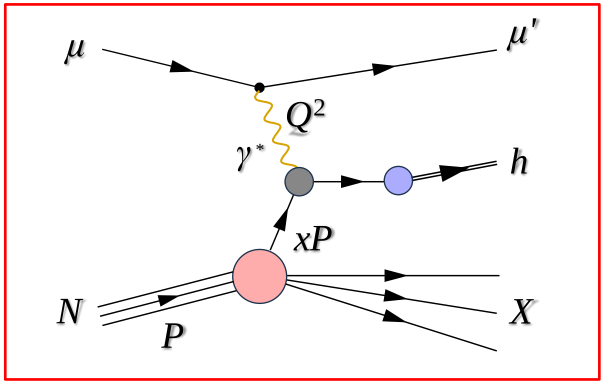
pp, pA-scattering, jet production, etc.



Brookhaven
National Laboratory
STAR
PHENIX
sPHENIX

Main TMD tools – experiment overviews

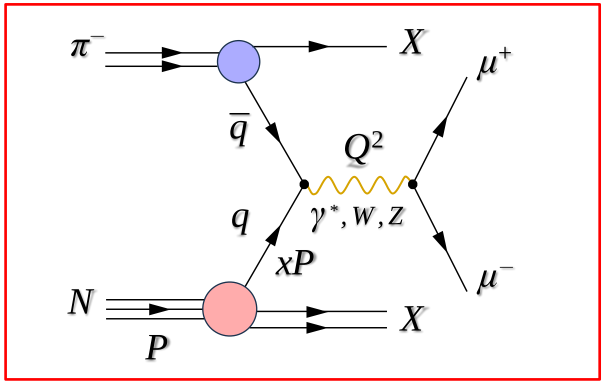
Semi-inclusive DIS



Jefferson Lab @ 22 GeV

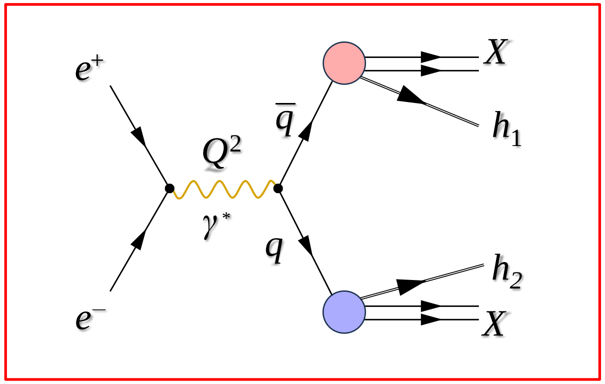
Harut Avagyan, Elke-Caroline Aschenauer, Yuxiang Zhao, Stefan Diehl,
Haiyan Gao, Athira Vijayakumar, Andrea Bressan

Drell-Yan process



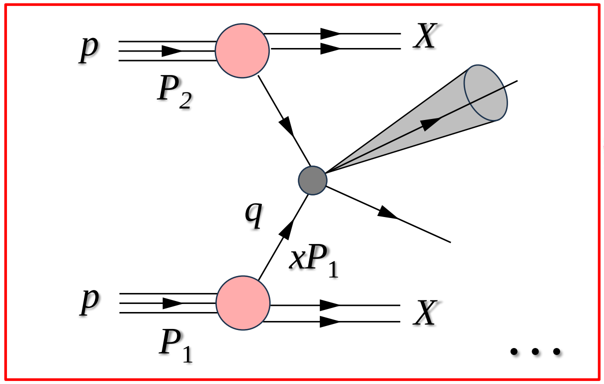
Catarina Quintans, Oleg Eyser, Charlotte Van Hulse

Electron-positron annihilation



Anselm Vossen, Bernd Surrow, Gunar Schnell

pp, pA-scattering, jet production, etc.

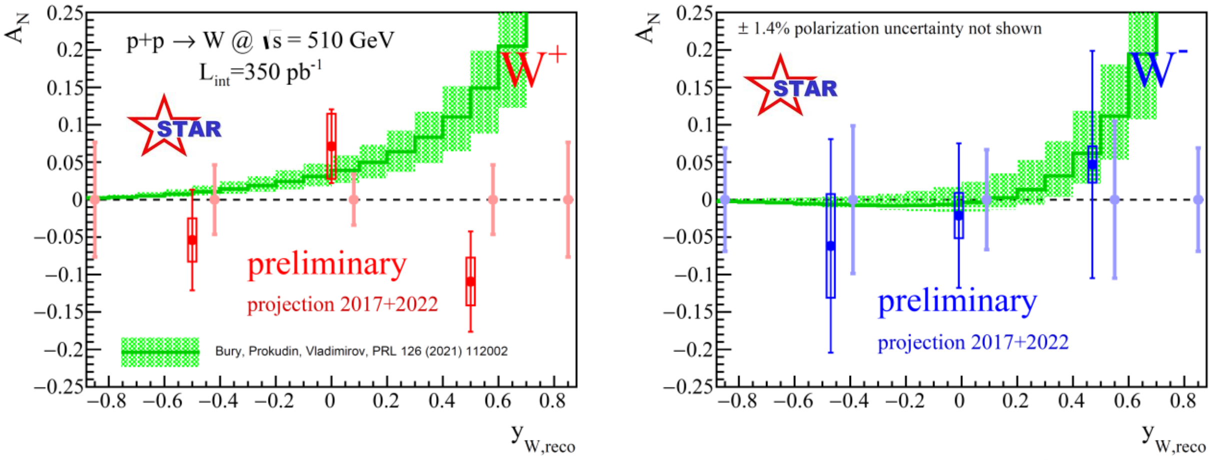


Oleg Eyser, Bassam Aboona, Bok Jeongsu

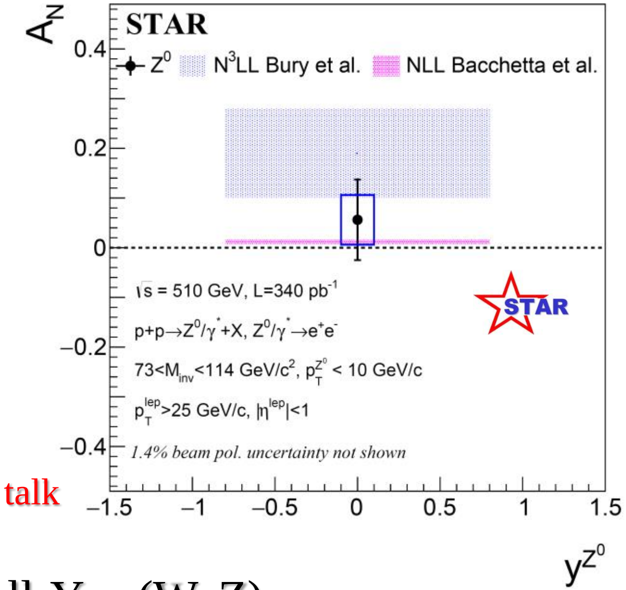
- Universality (sign changes)

Sivers TMD PDF: sign change

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

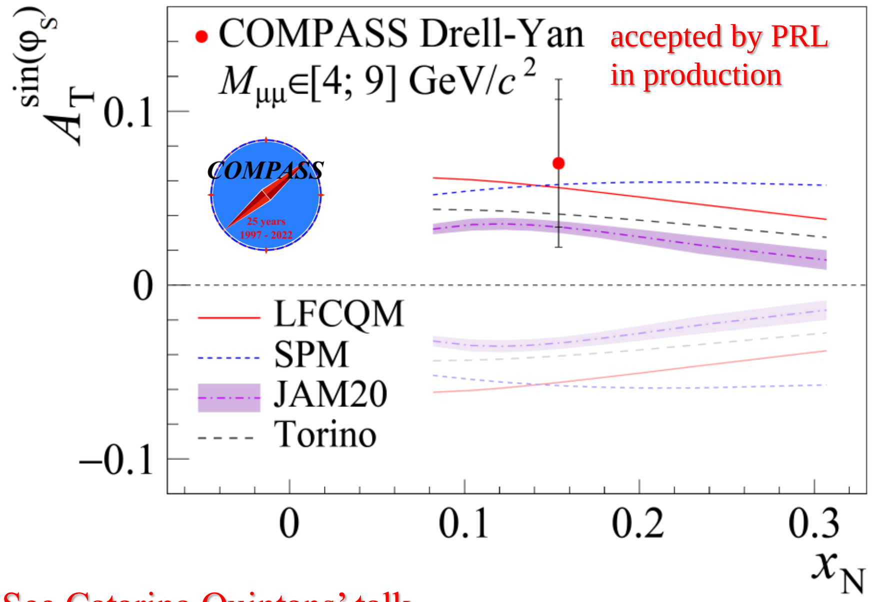


STAR, arXiv:2308.15496 [hep-ex]



See Oleg Eyser's talk

COMPASS, arXiv:2312.17379 [hep-ex]



See Catarina Quintans' talk

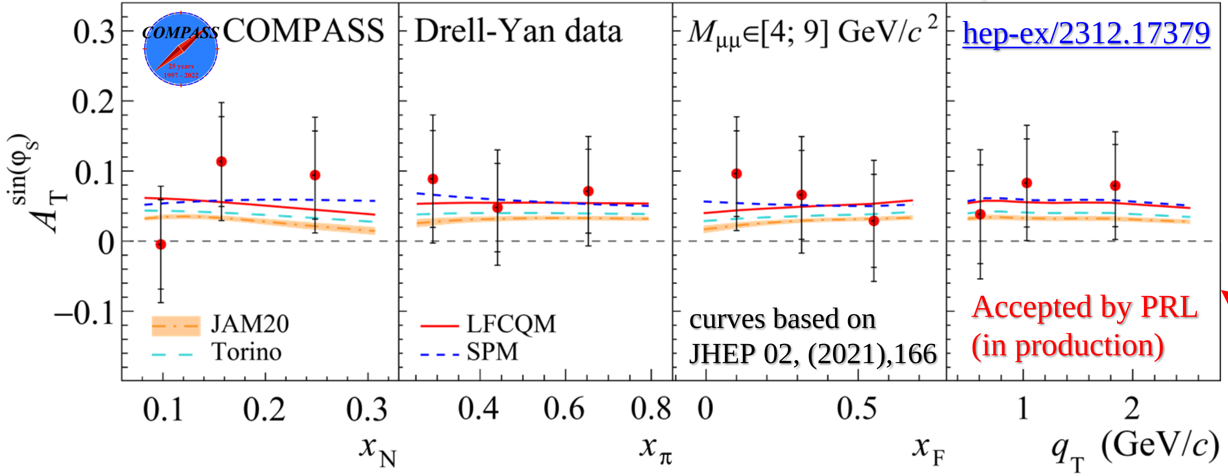
SIDIS↔Drell-Yan (W, Z)
sign change of T-odd TMD PDFs

- 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

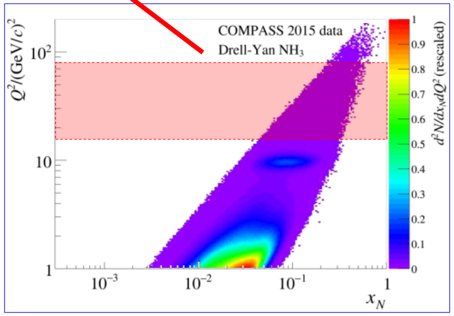
Sivers DY TSA

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



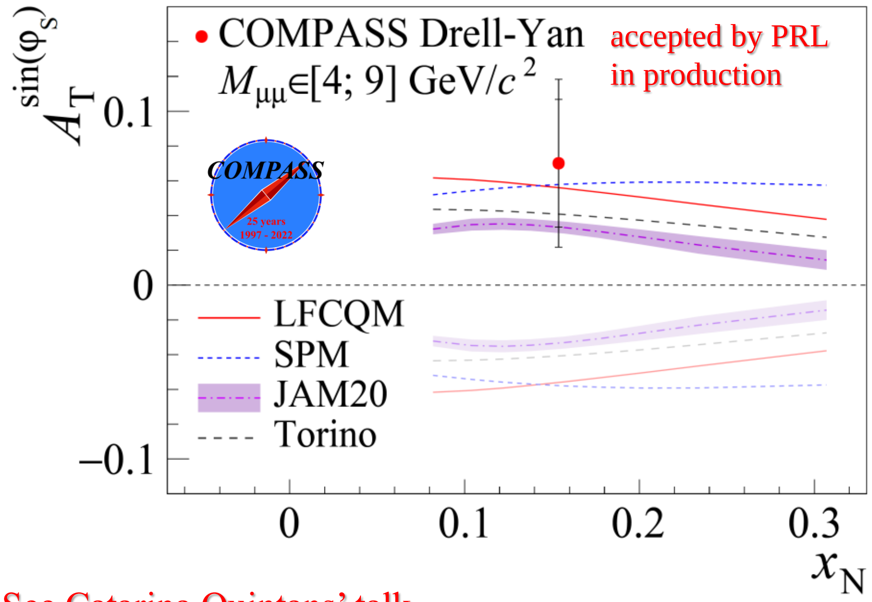
curves based on JHEP 02, (2021),166

Accepted by PRL (in production)



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

COMPASS, arXiv:2312.17379 [hep-ex]



accepted by PRL in production

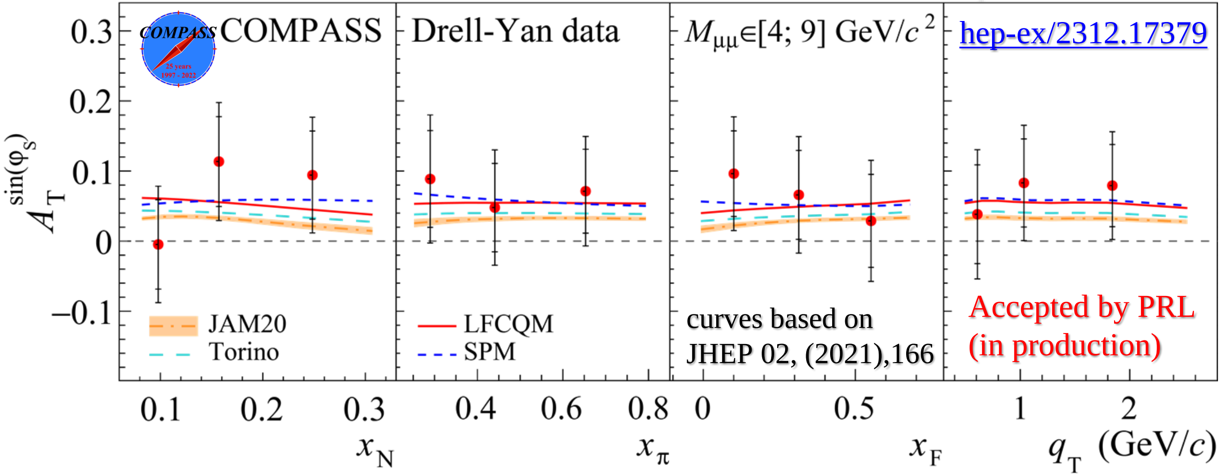
- COMPASS data favors the sign change
  - Useful input to constrain the fits
  - None of the models can be preferred

See Catarina Quintans' talk

Sivers effect: Drell-Yan and J/ψ

Sivers DY TSA

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



hep-ex/2312.17379

curves based on JHEP 02, (2021),166

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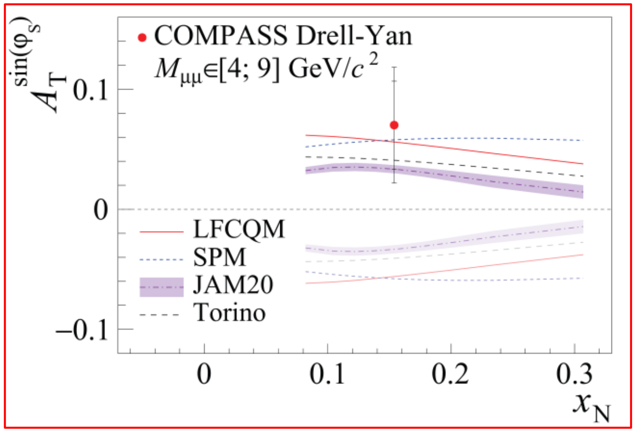

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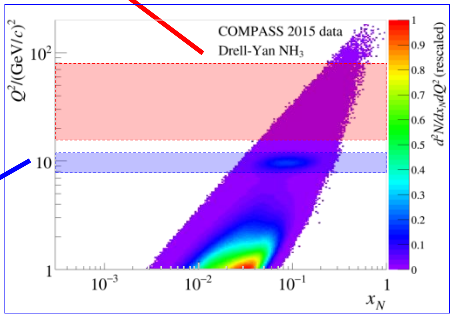
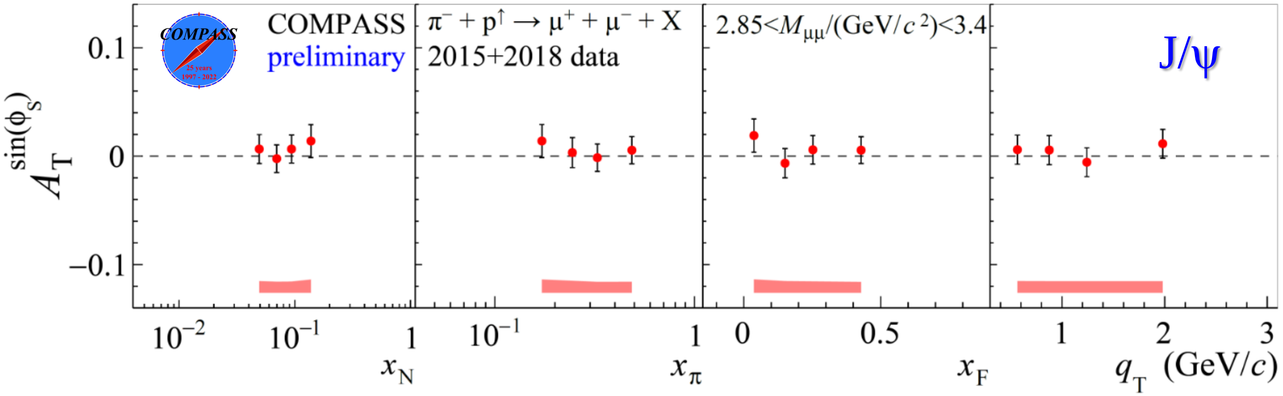
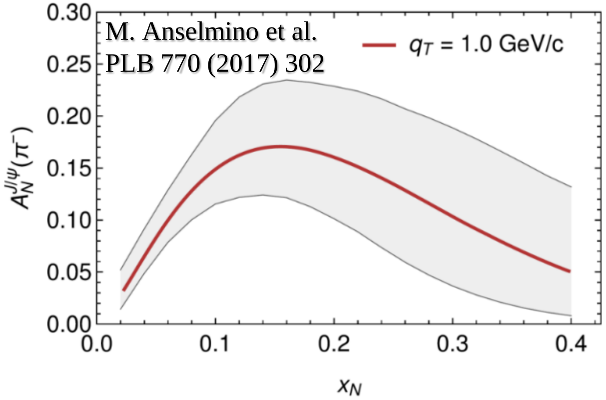




- J/ψ Sivers asymmetry is compatible with zero (within ~ 1%)
- Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS
- Hint that J/ψ production might go via gg fusion in COMPASS?
- Access to small gluon TMDs?

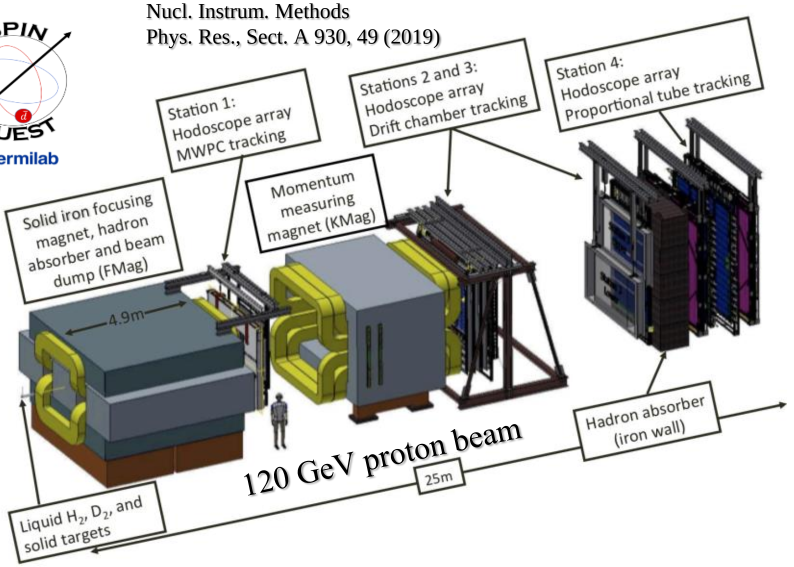


M. Anselmino et al. PLB 770 (2017) 302

See Catarina Quintans' talk

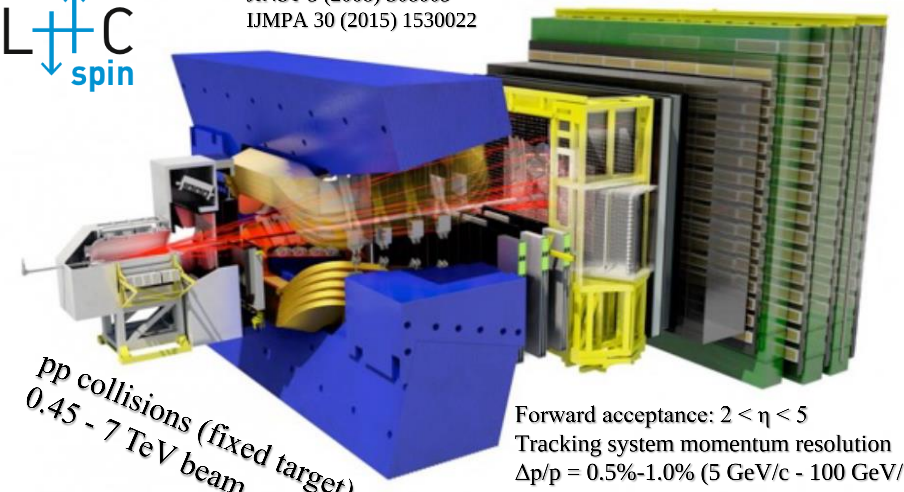
Sivers TMD PDF: sign change - future

Nucl. Instrum. Methods
Phys. Res., Sect. A 930, 49 (2019)



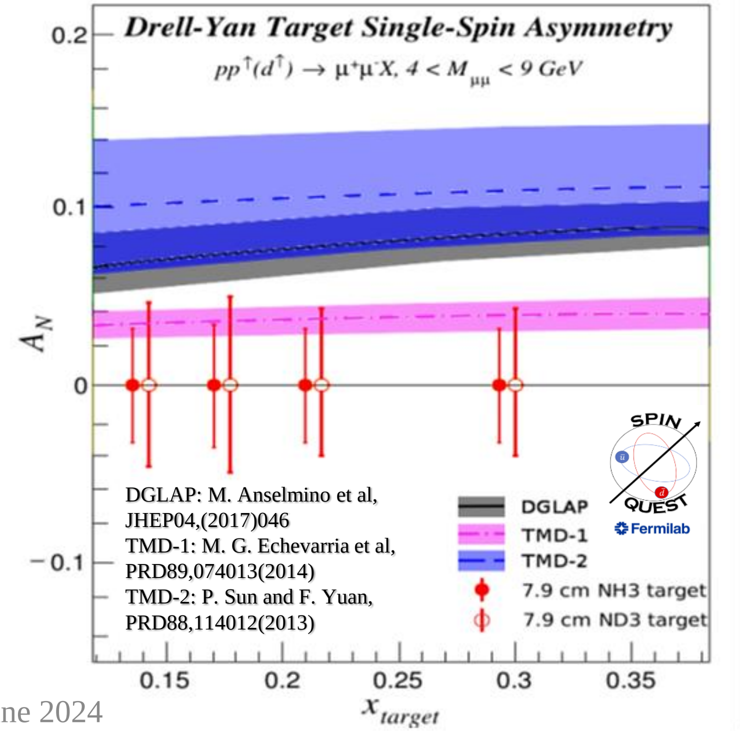
120 GeV proton beam

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

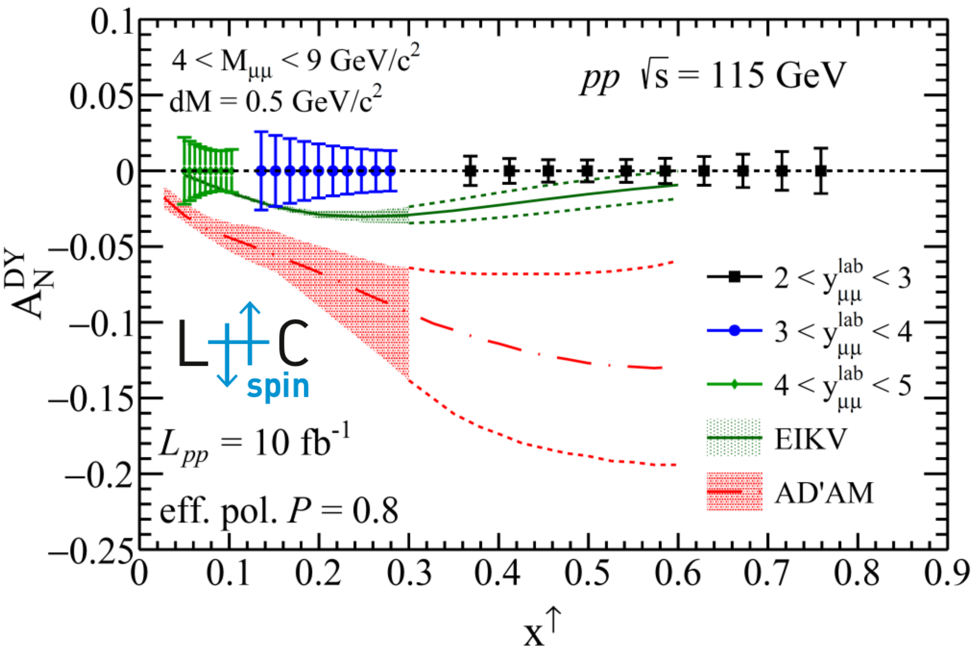


pp collisions (fixed target)
0.45 - 7 TeV beam

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

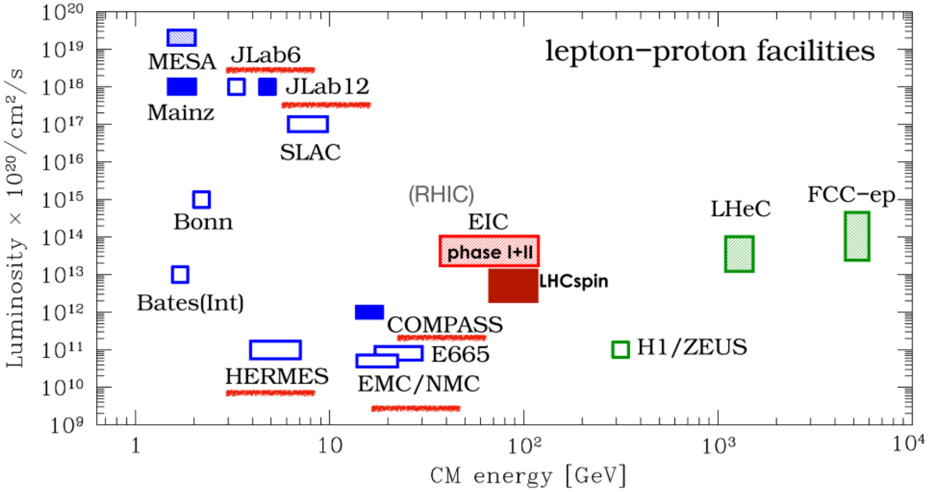


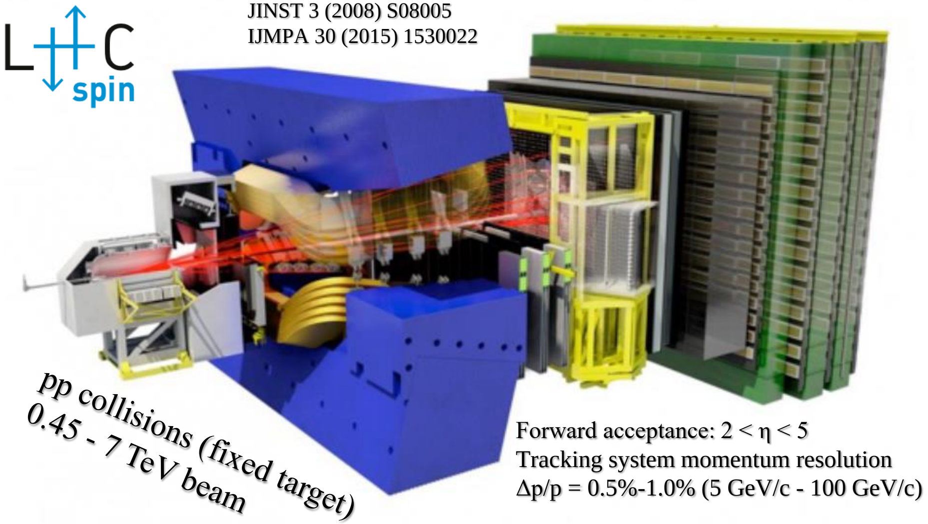
DGLAP: M. Anselmino et al, JHEP04,(2017)046
TMD-1: M. G. Echevarria et al, PRD89,074013(2014)
TMD-2: P. Sun and F. Yuan, PRD88,114012(2013)



See Charlotte Van Hulse's talk

Sivers TMD PDF: sign change - future





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

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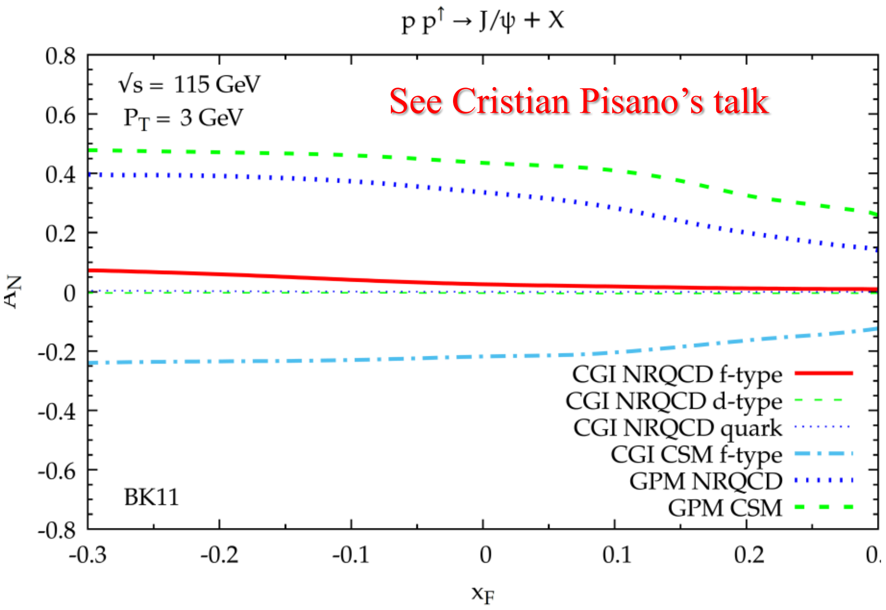
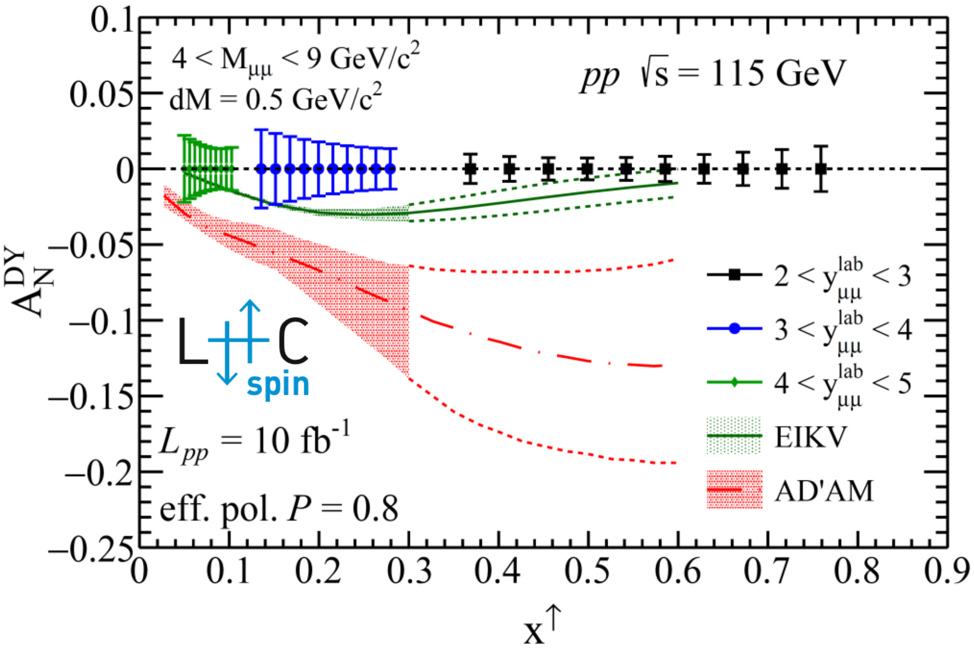
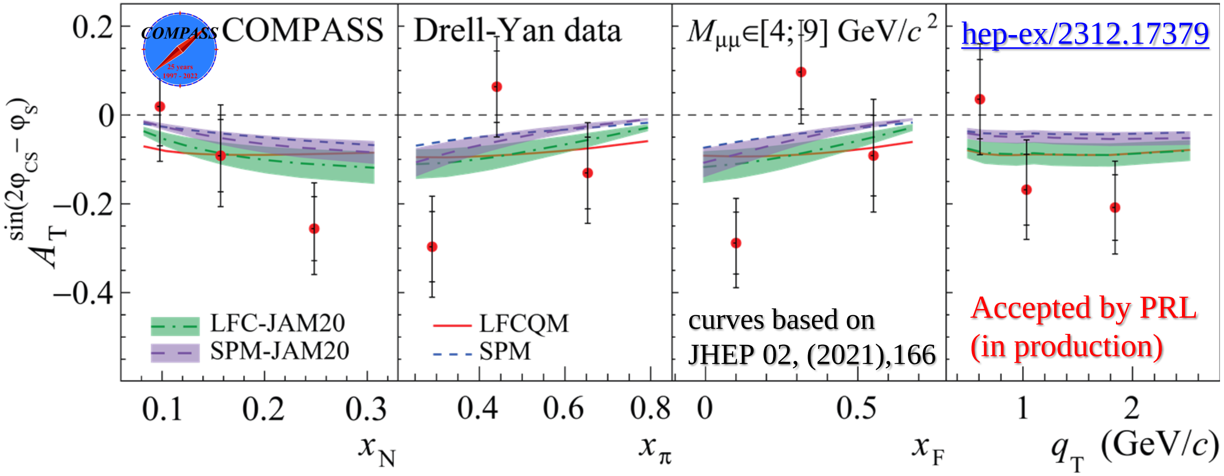


See Cristian Pisano’s talk



See Charlotte Van Hulse’s talk

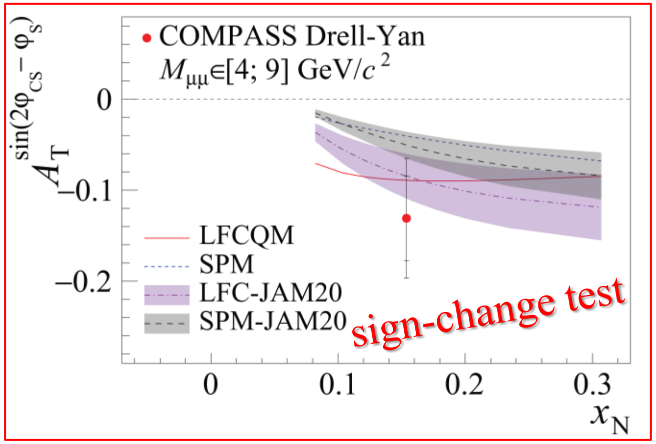
Boer-Mulders TMD PDF: sign change



hep-ex/2312.17379

curves based on JHEP 02, (2021),166

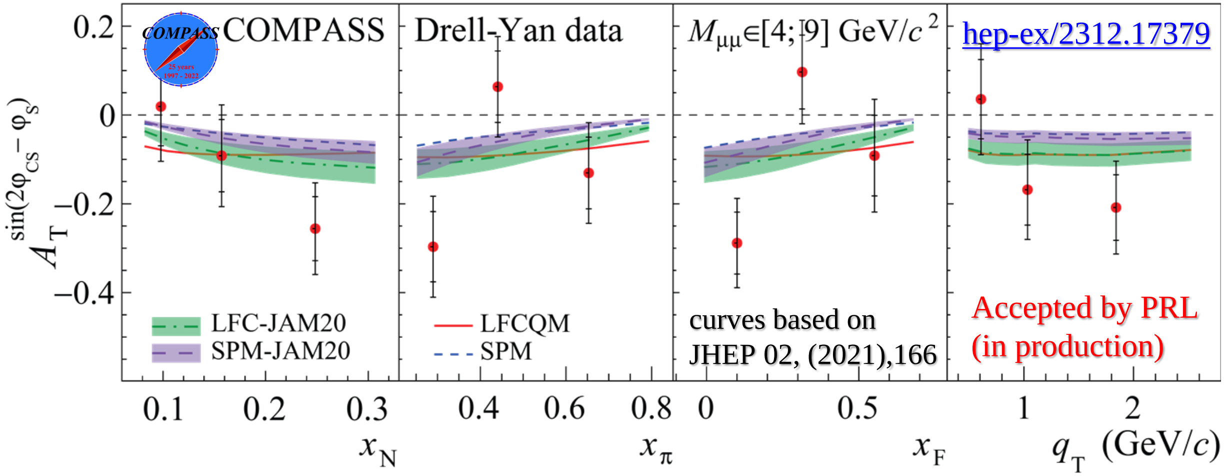
Accepted by PRL (in production)



sign-change test

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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curves based on JHEP 02, (2021),166

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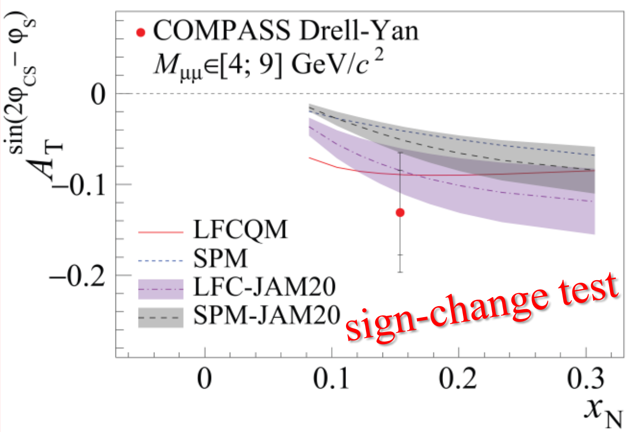

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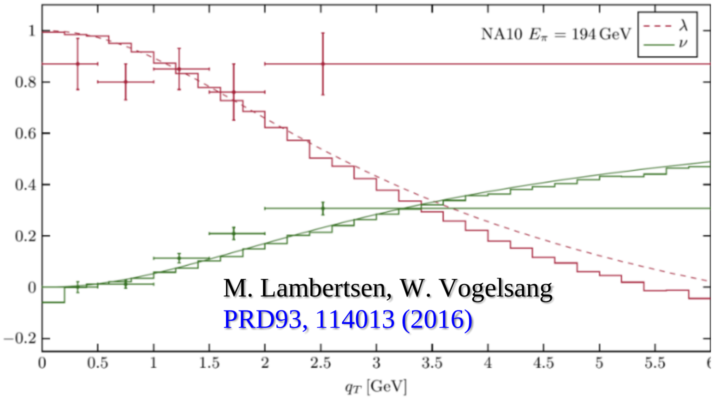
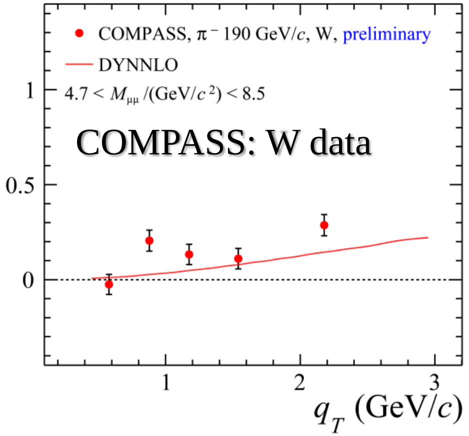
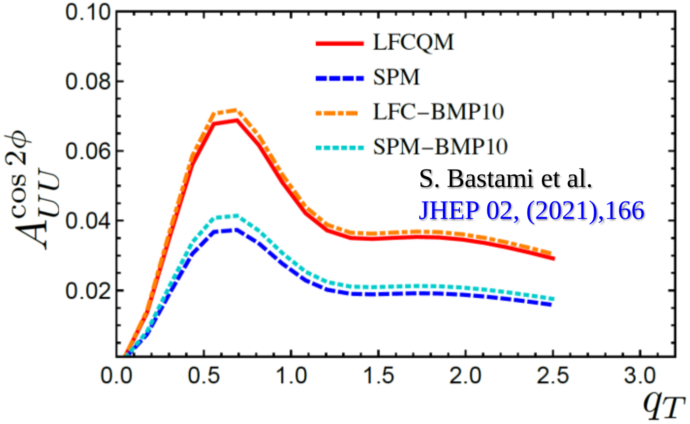


M. Lambertsen, W. Vogelsang
PRD93, 114013 (2016)



COMPASS: W data



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

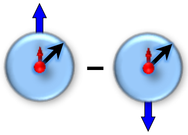
$$\text{DY: } A_T^{\sin 2\varphi_{CS}} \propto \left\{h_{1,\pi^-}^{\perp\bar{u}} \otimes h_{1,p}^{\perp u}\right\} > 0 \Rightarrow h_{1,p}^{\perp u} > 0 \overset{\text{sign-change}}{\Leftrightarrow} \text{SIDIS: } h_{1,p}^{\perp u} < 0$$

$h_{1,p}^{\perp u} < 0$ → 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

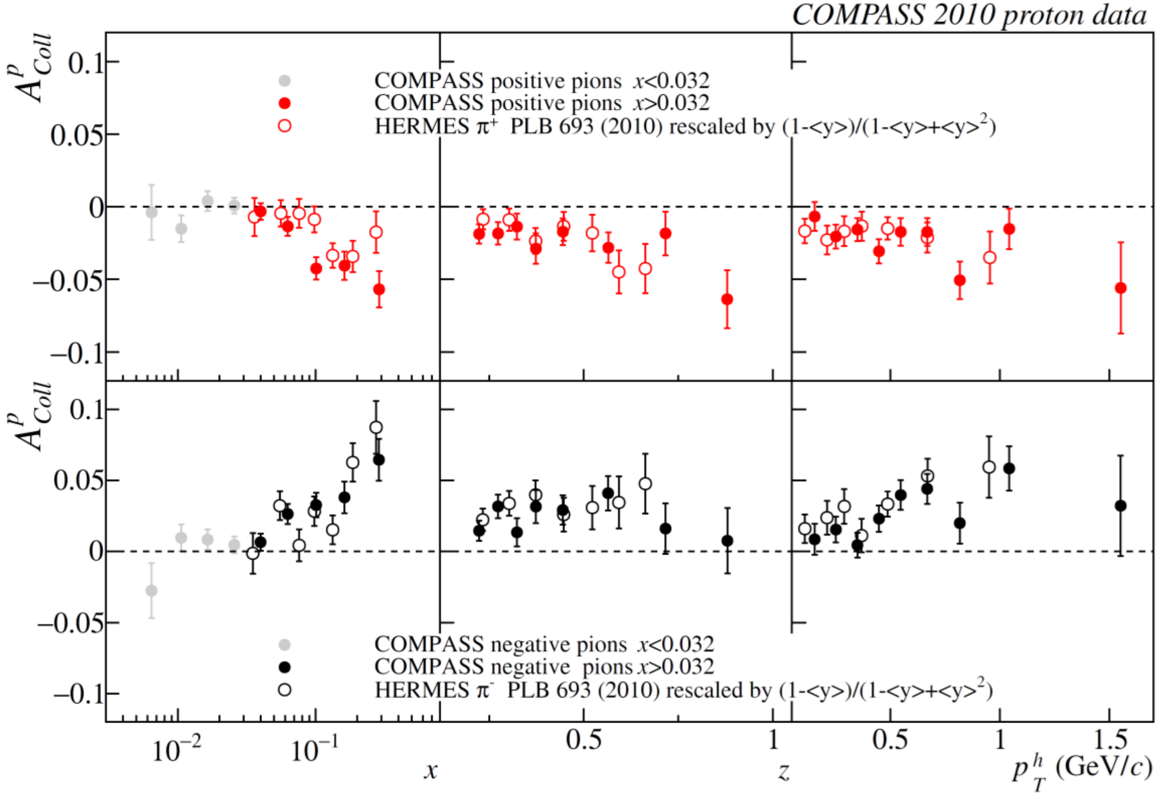


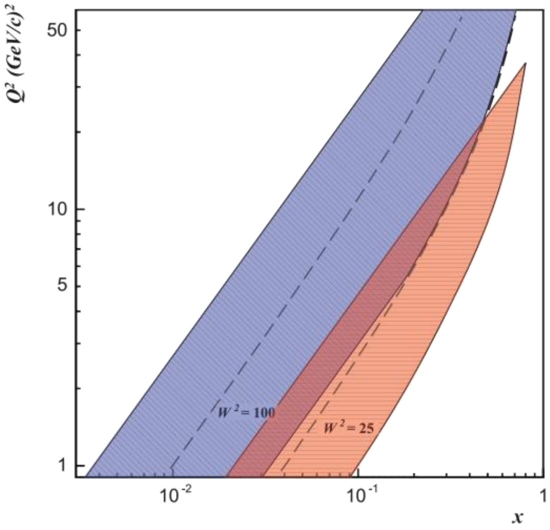
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

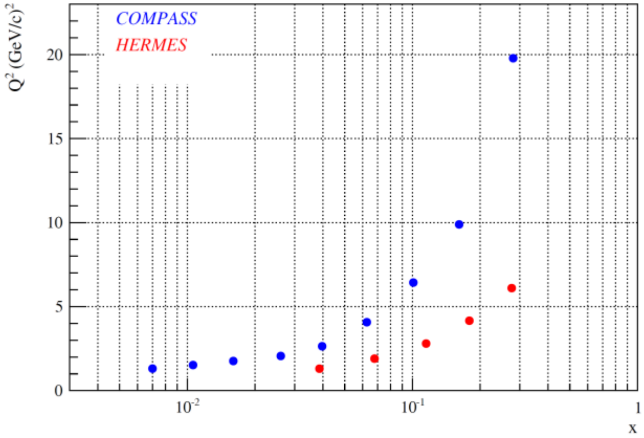
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{h}\cdot p_T}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

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

COMPASS PLB 744 (2015) 250

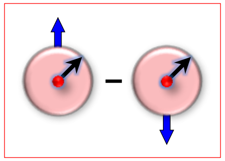






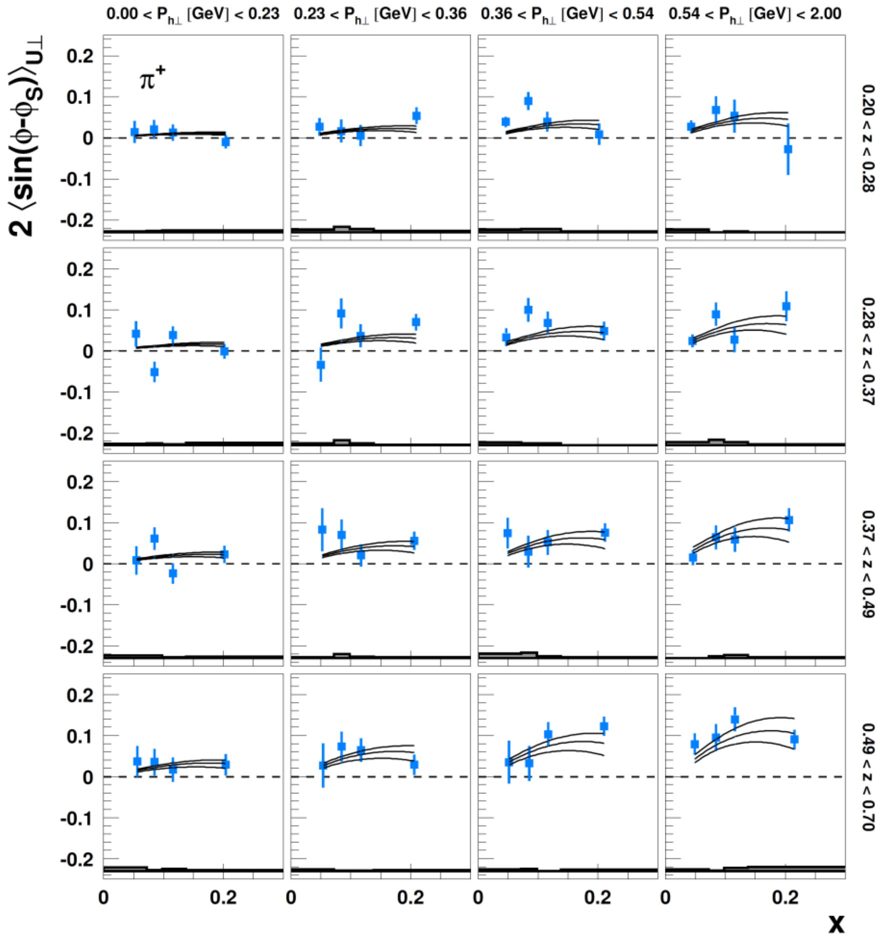
SIDIS TSAs: Sivers effect

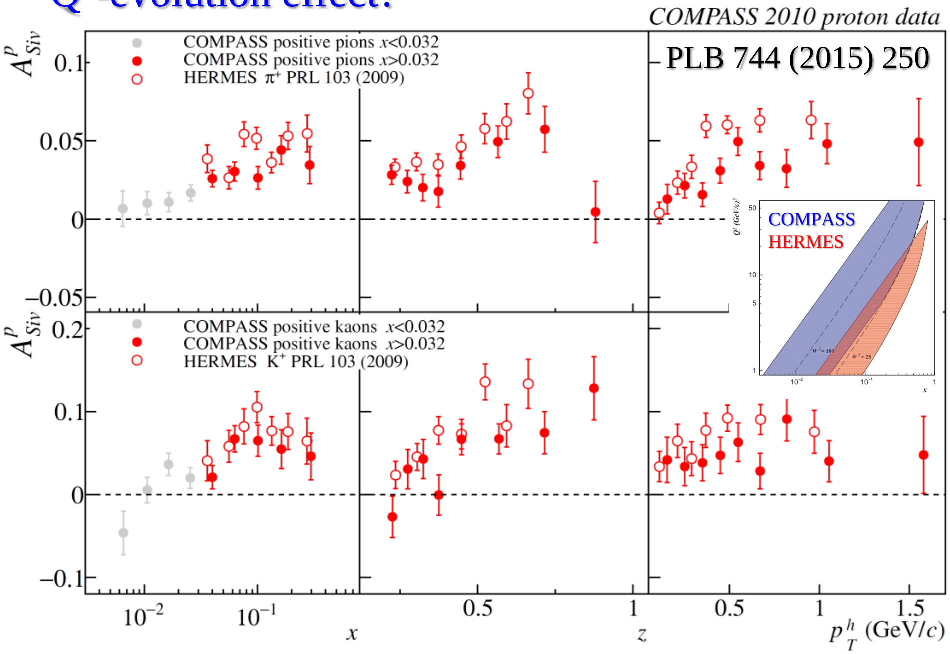
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\ A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+\ldots\right\}$$



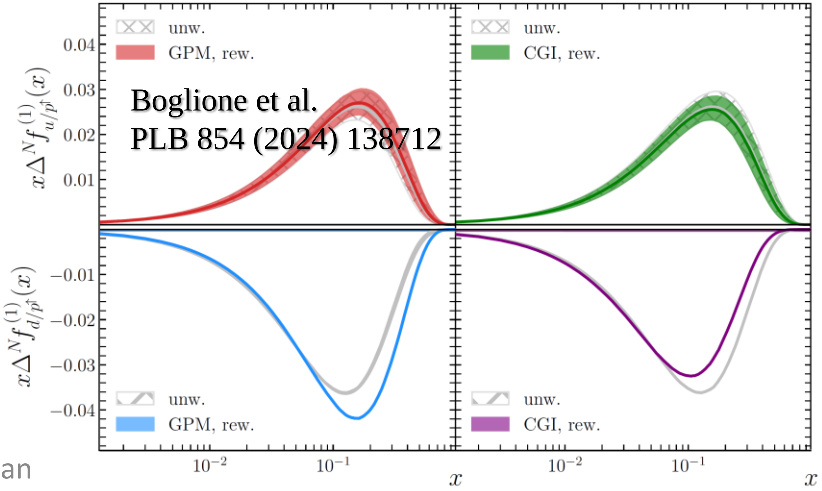
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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





PLB 744 (2015) 250



Boglione et al.
PLB 854 (2024) 138712

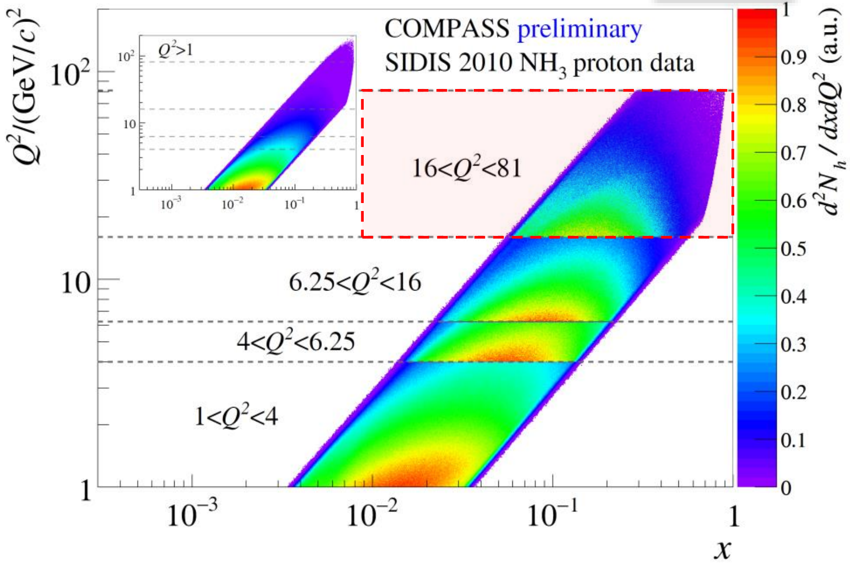
SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

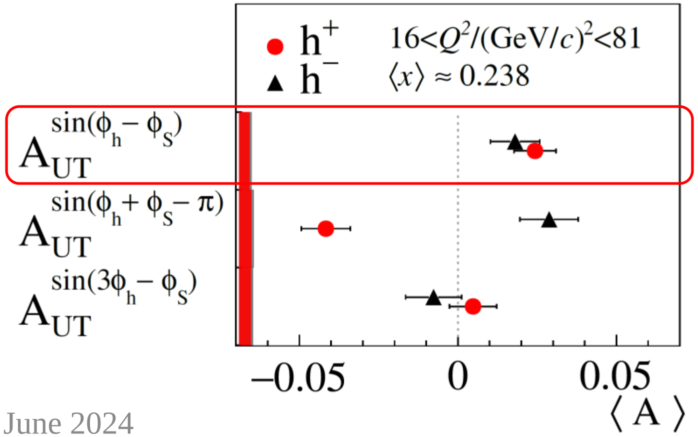
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+\ldots+ S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h-\phi_S\right)+\ldots\right\}$$

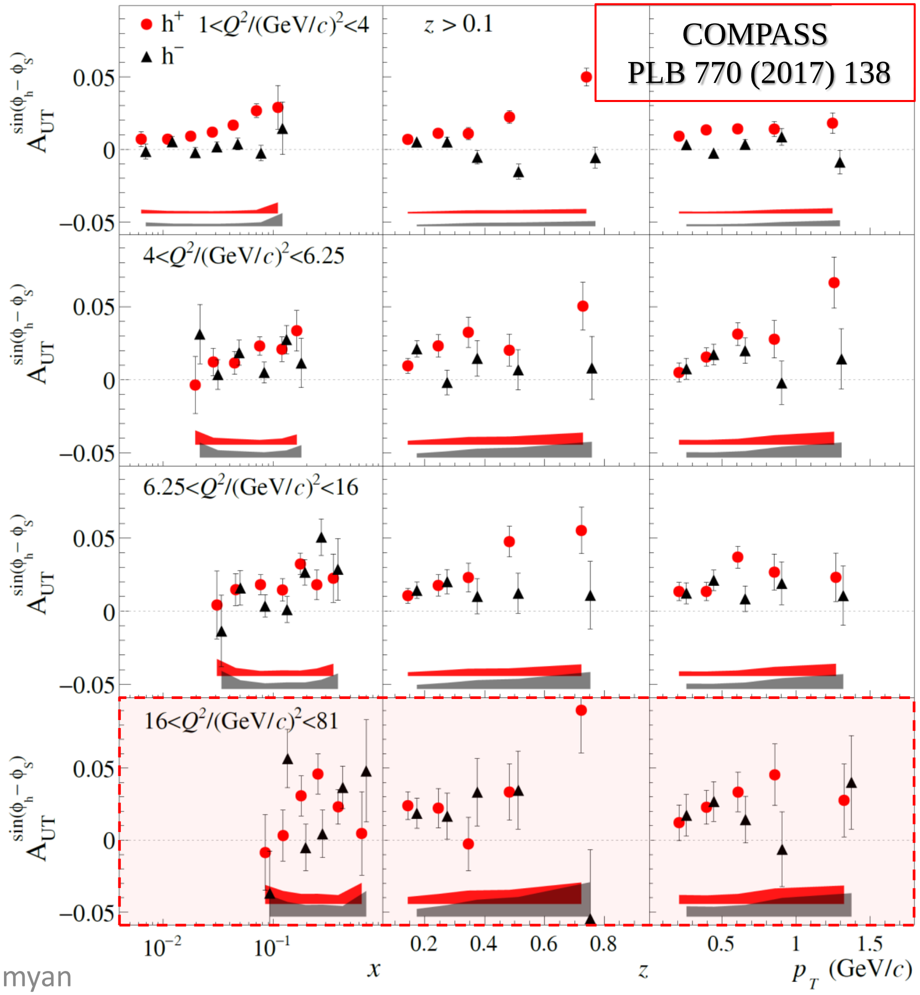
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{k_T}}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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

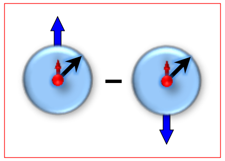
1st COMPASS multi-D fit done for all eight TSAs







SIDIS TSAs: Collins effect and Transversity



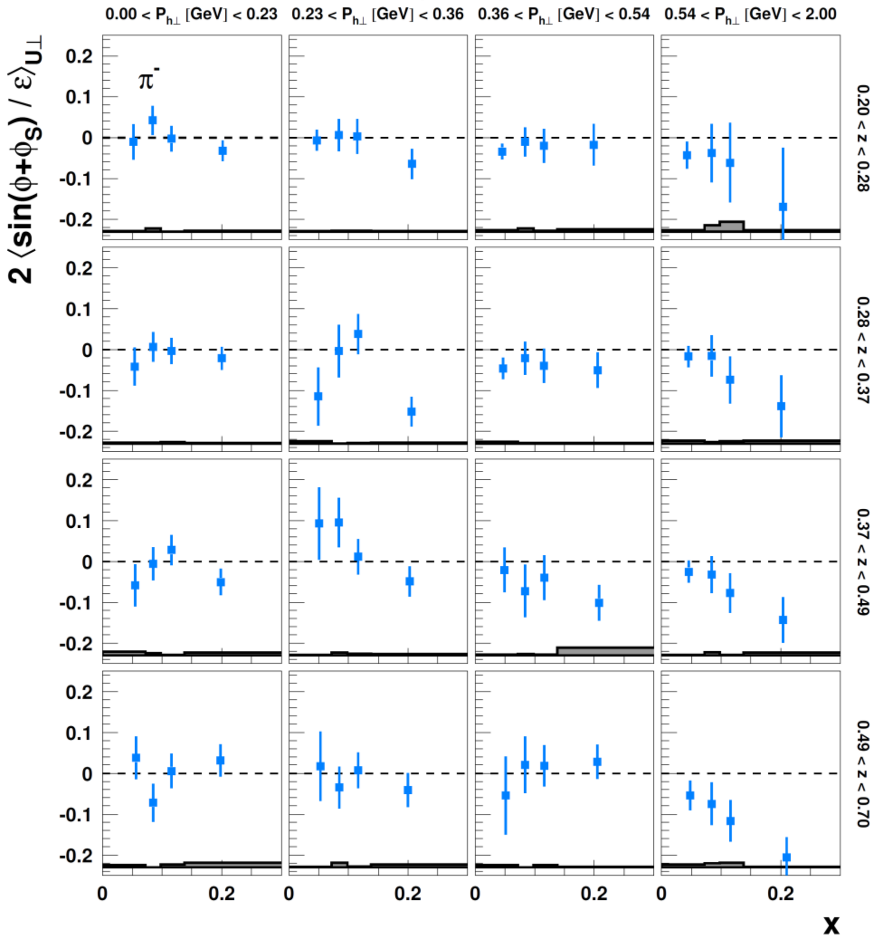
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

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

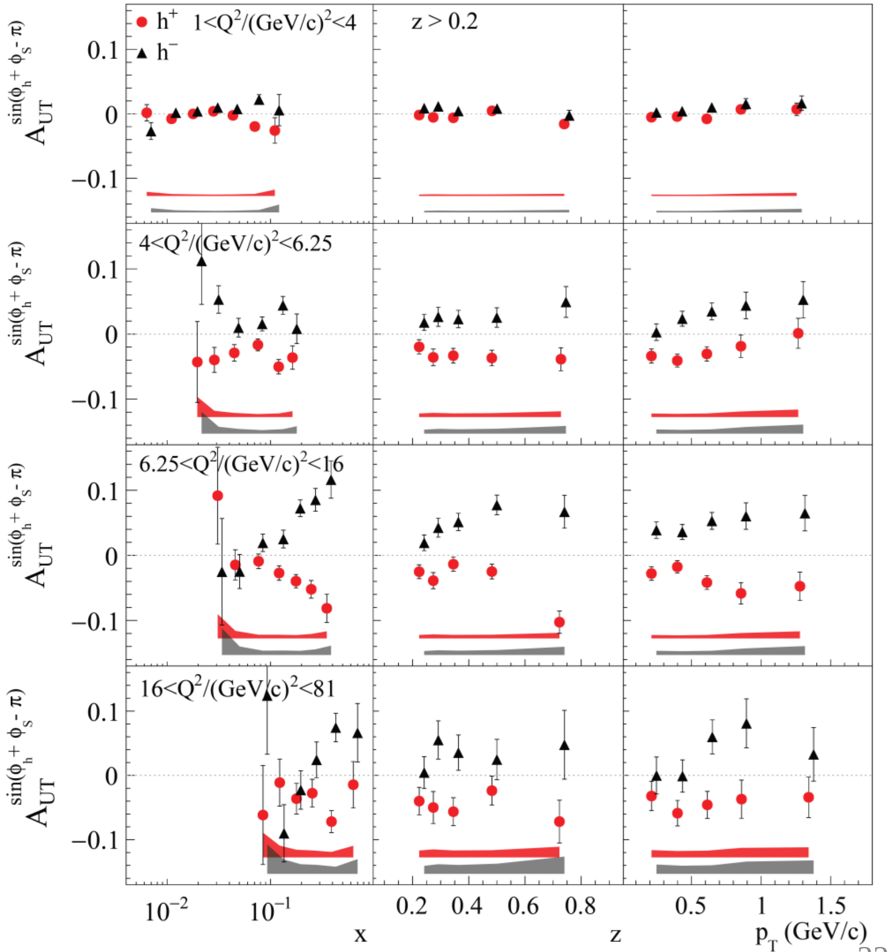
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

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

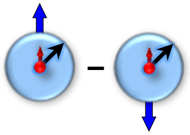
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



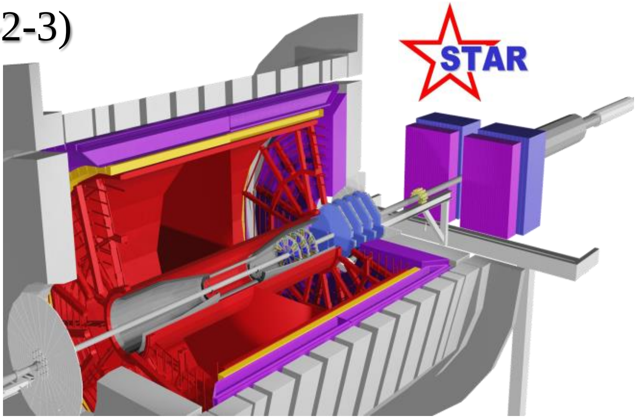
SIDIS TSAs: Collins effect and Transversity



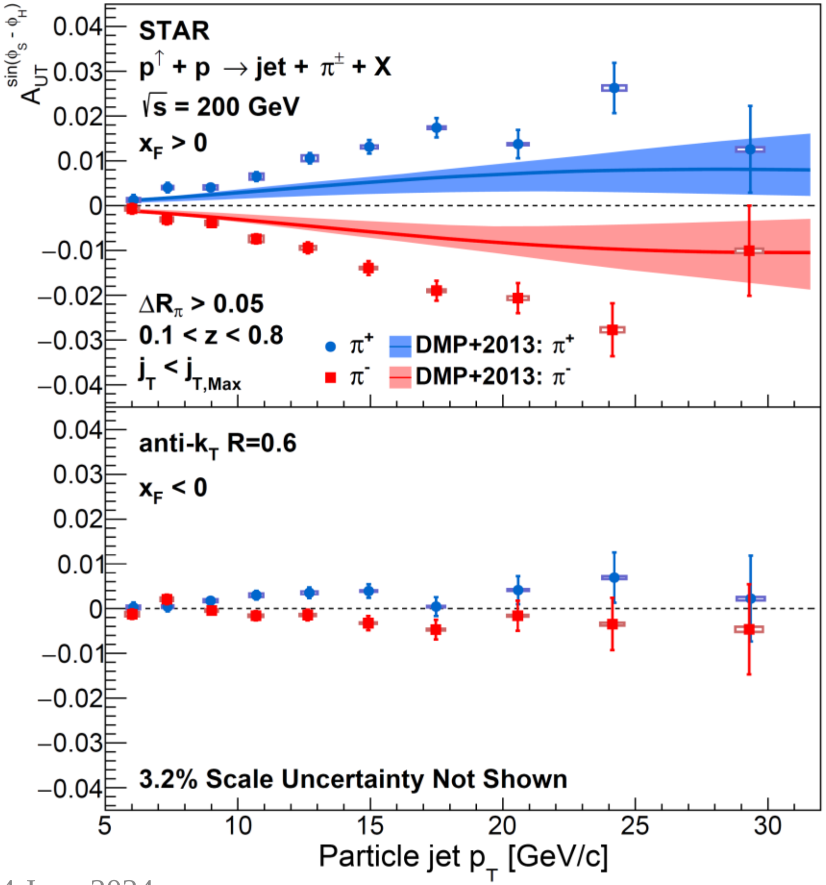
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+ S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

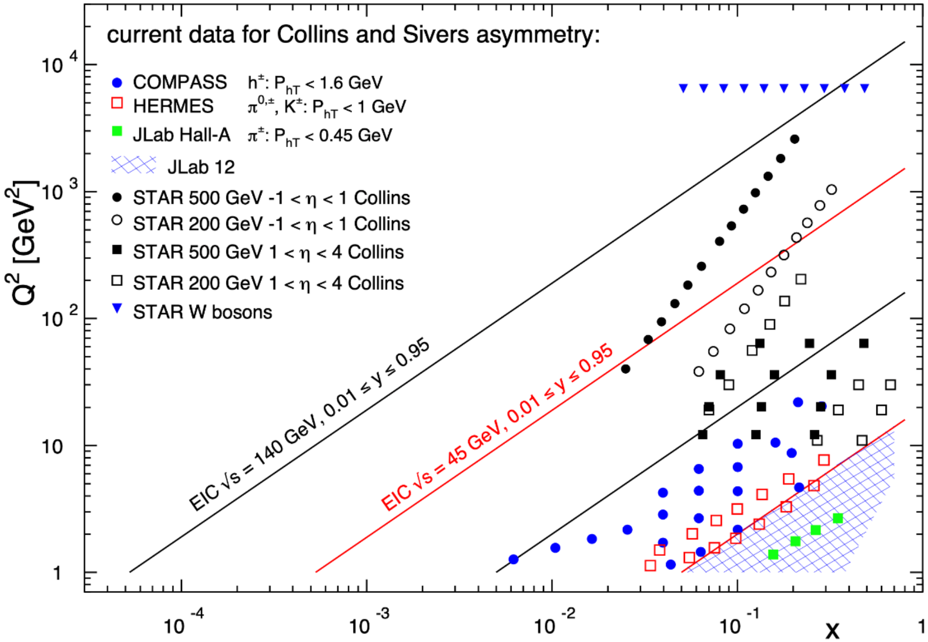
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

- 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





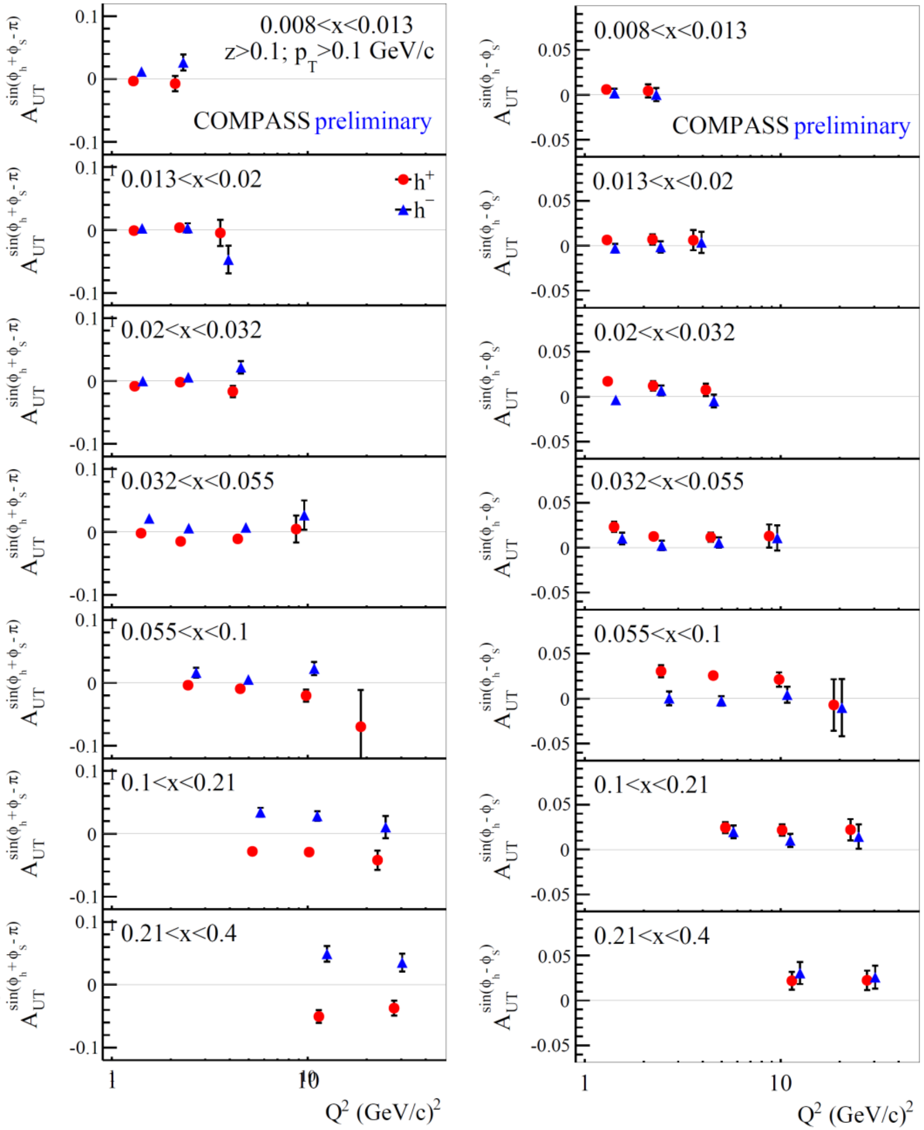
COMPASS Multi-D TSA analyses

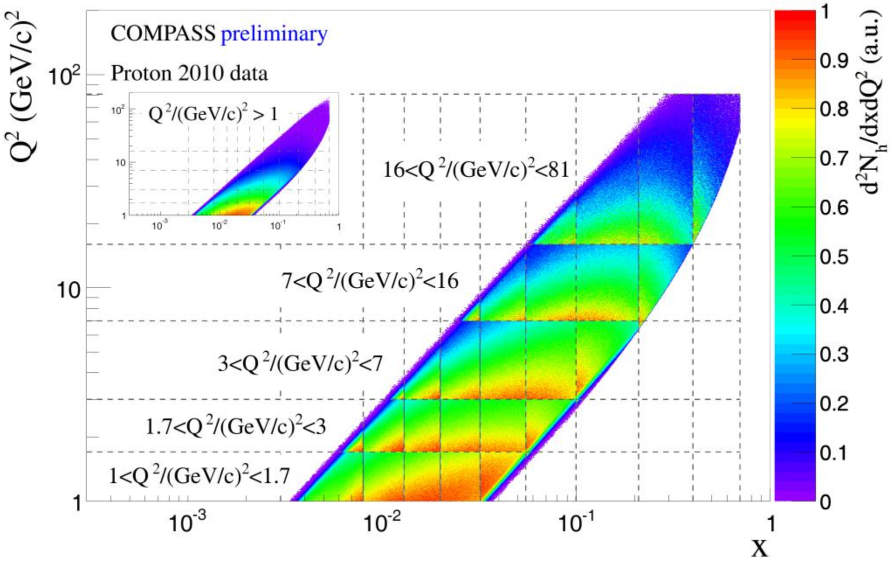
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_T\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)\ldots\right\}$$

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

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

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



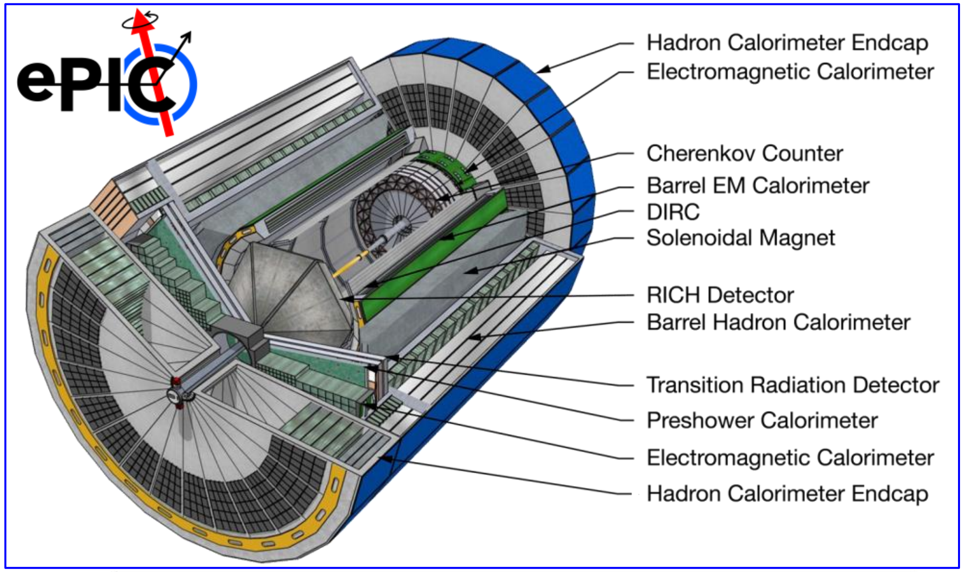


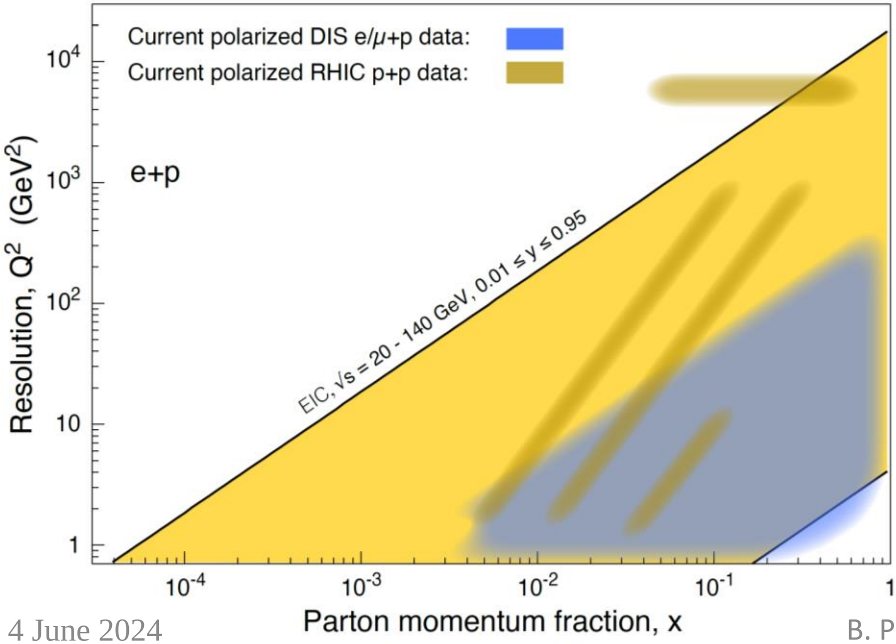
3D $x:Q^2:z$ or $x:Q^2:p_T$ $x:z:p_T$

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

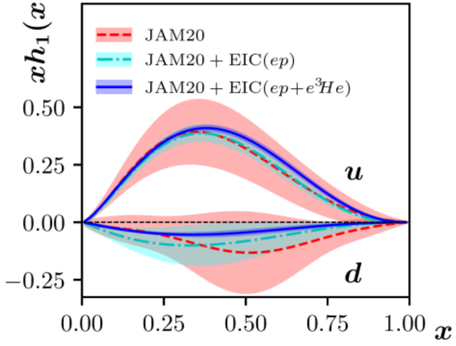
Electron Ion Collider(s): EIC

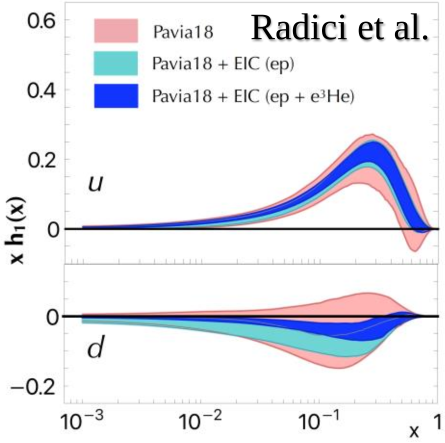
EIC WP, arXiv:1212.1701 [nucl-ex],
EIC YR, arXiv:2103.05419 [physics.ins-det]

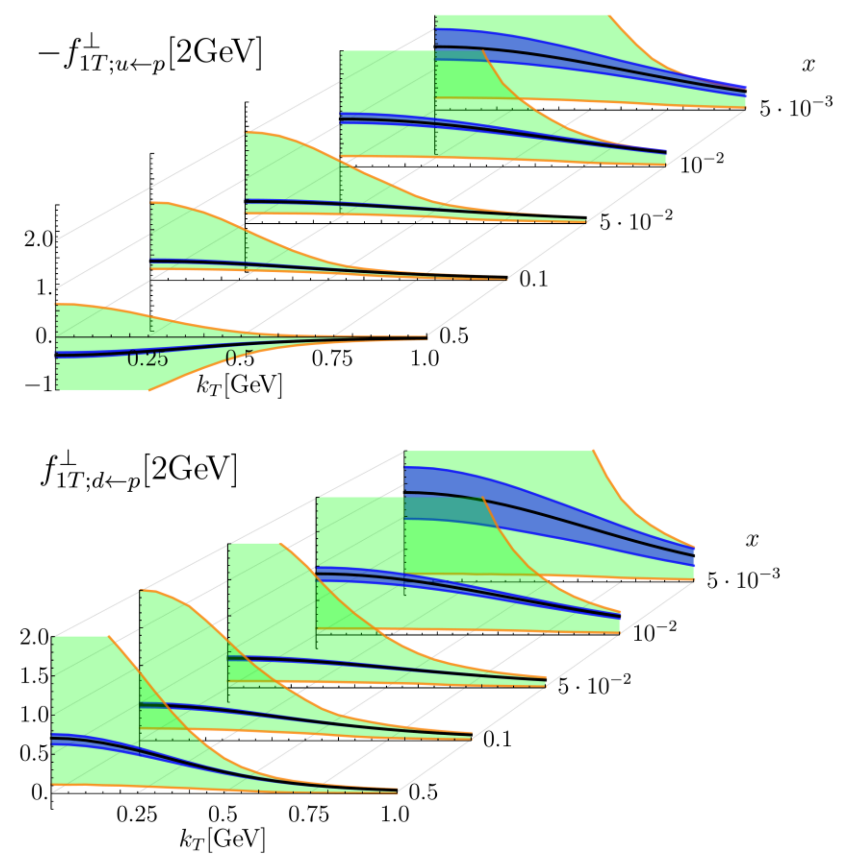




Gamberg et al. (JAM)
PLB 816 (2021) 136255



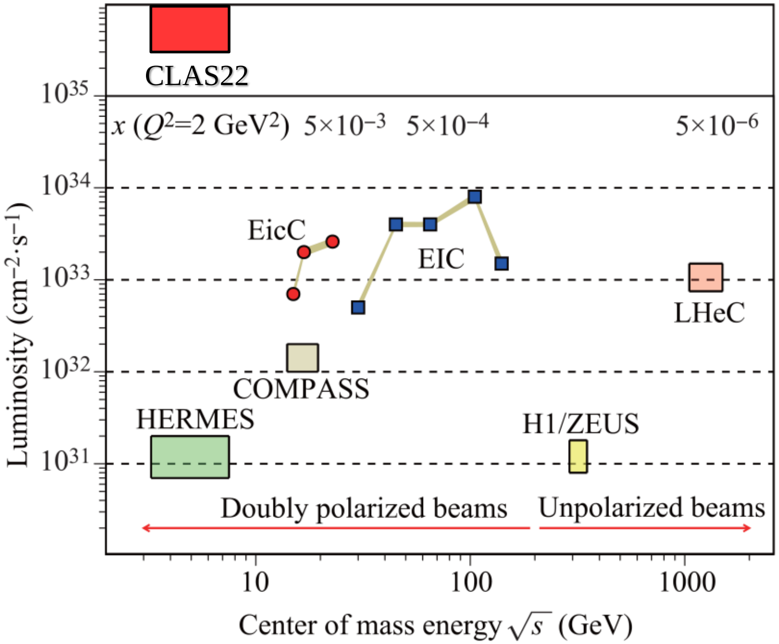


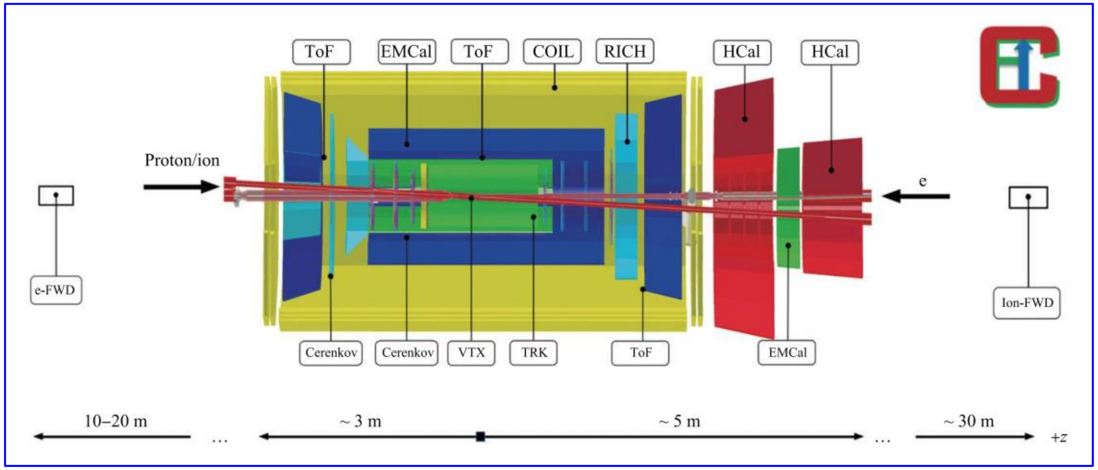


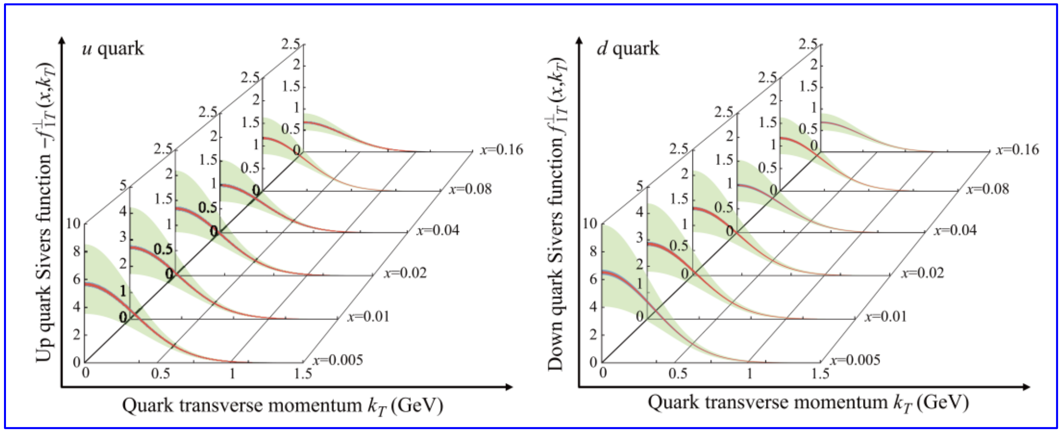
See Elke Aschenauer's talk

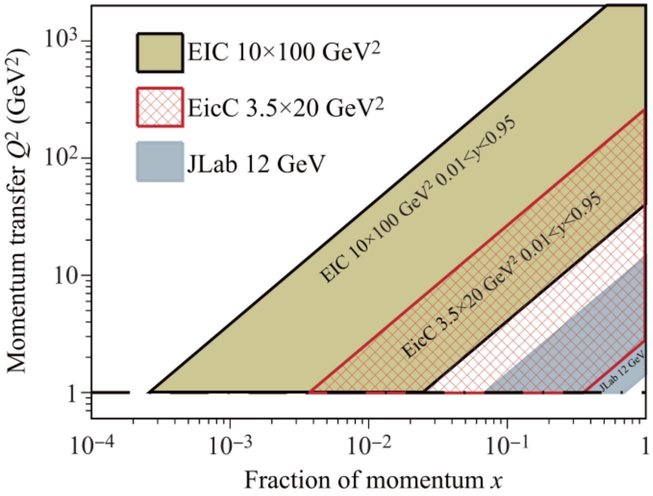
Electron Ion Collider(s): EICc

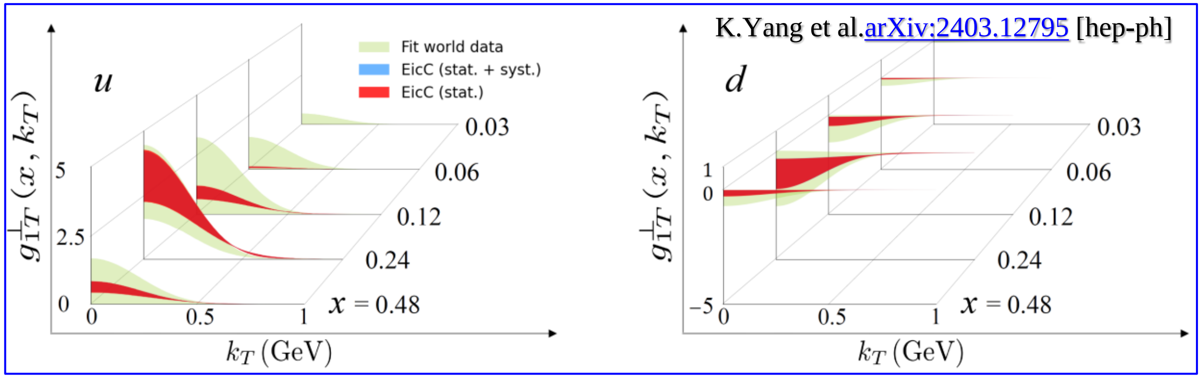
EICc, FP16(6), 64701 (2021), arXiv:2102.09222 [nucl-ex]







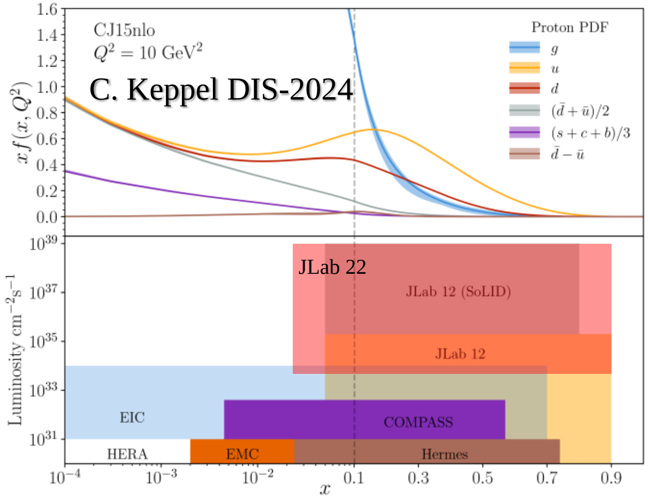




K.Yang et al.arXiv:2403.12795 [hep-ph]

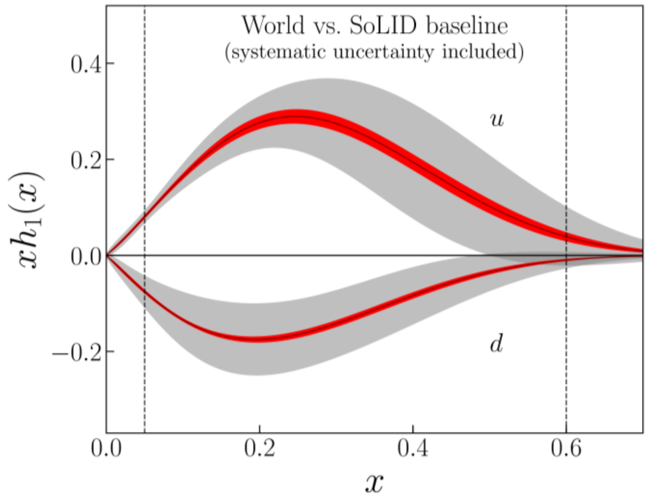
See Yuxiang Zhao’s talk

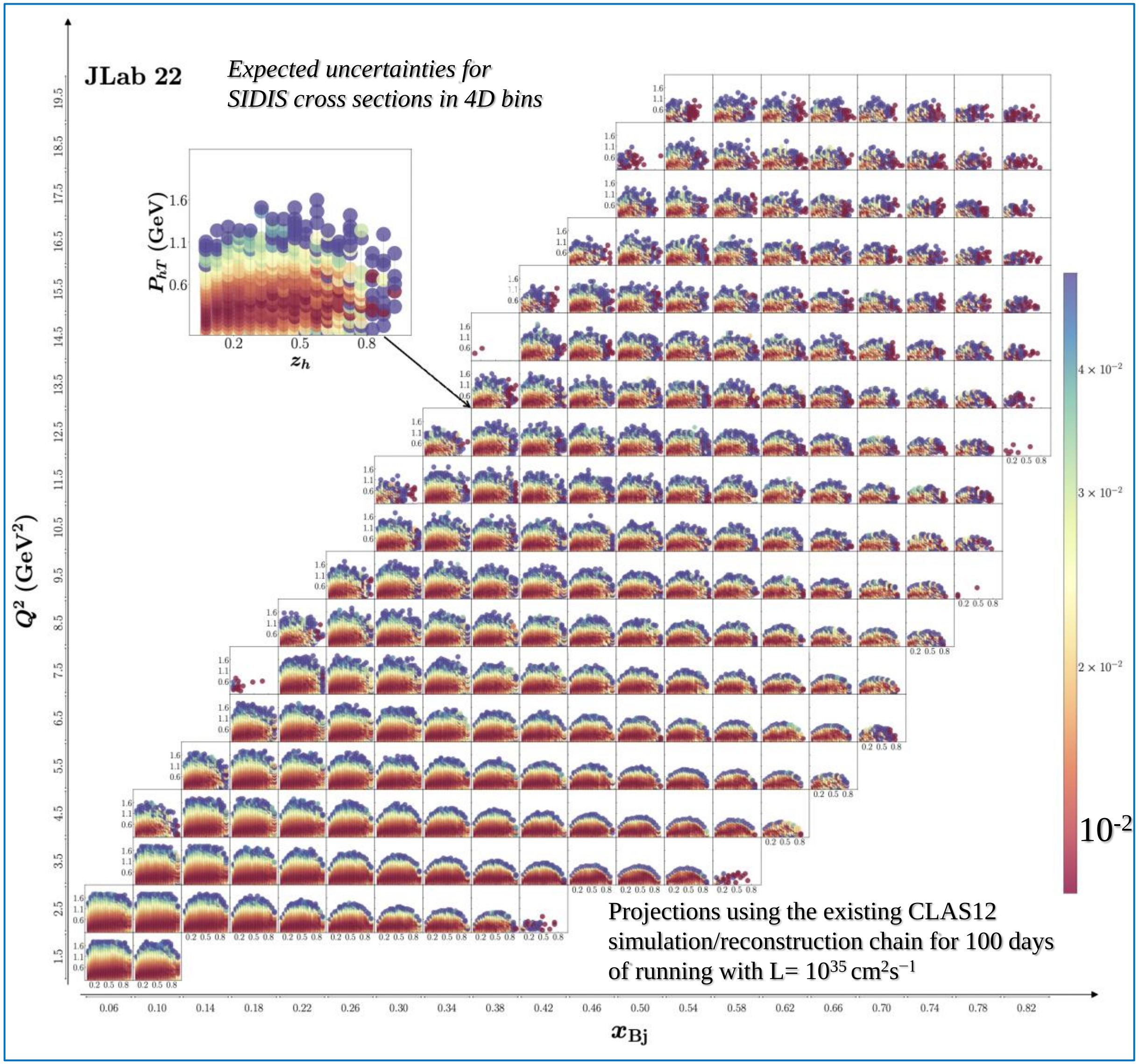
JLab from 12 GeV, SoLID to 22 GeV



C. Keppel DIS-2024

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





JLab 22

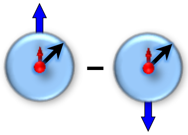
Expected uncertainties for SIDIS cross sections in 4D bins

Projections using the existing CLAS12 simulation/reconstruction chain for 100 days of running with L= 10^{35} cm^{2}s^{-1}

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

See Harut Avagyan's talk

SIDIS TSAs: Collins effect and Transversity

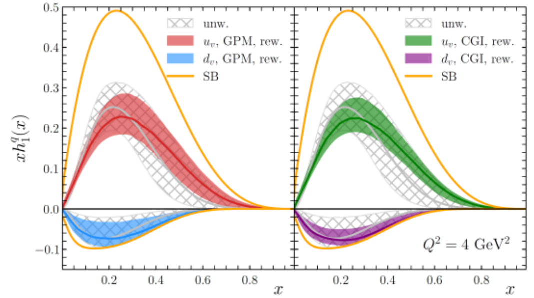


$$\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S}\propto\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

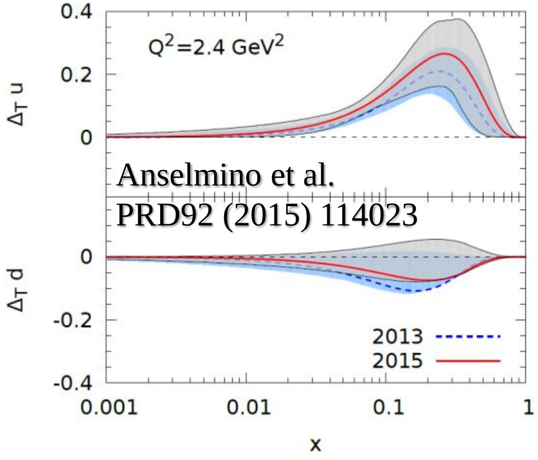
$$F_{UT}^{\sin(\phi_h+\phi_S)}=C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}h_1^qH_{1q}^{\perp h}\right]$$

- 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

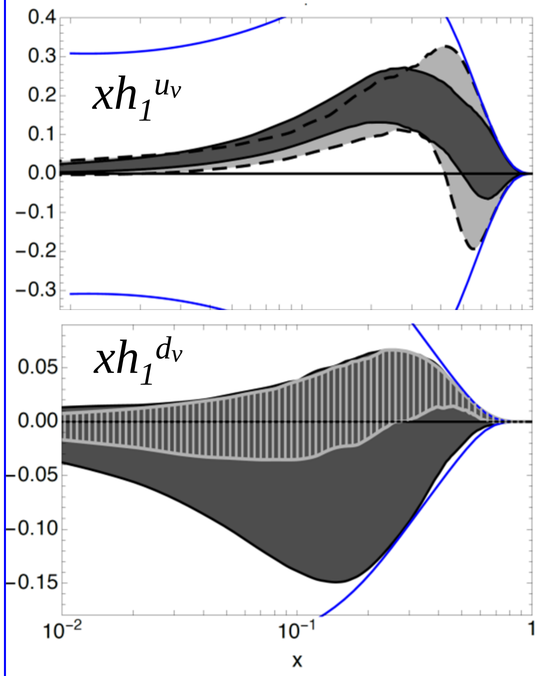


See Carlo Flore's talk

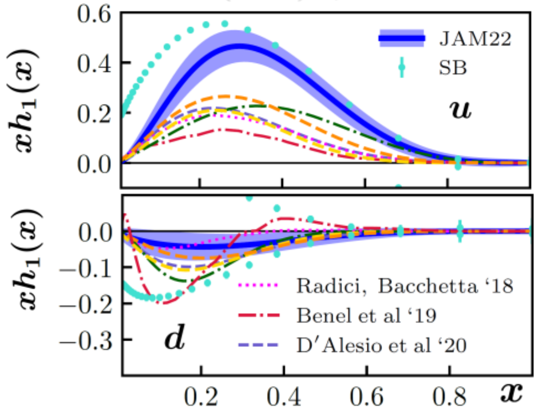


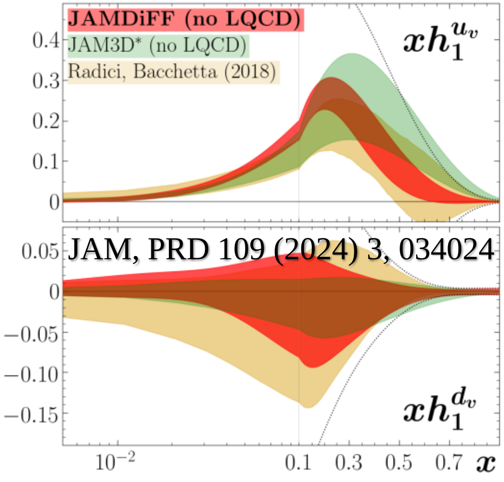
Anselmino et al. PRD92 (2015) 114023

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



JAM PRD 106 (2022) 3, 034014

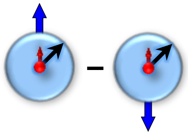




JAM, PRD 109 (2024) 3, 034024

See Marco Radici's talk

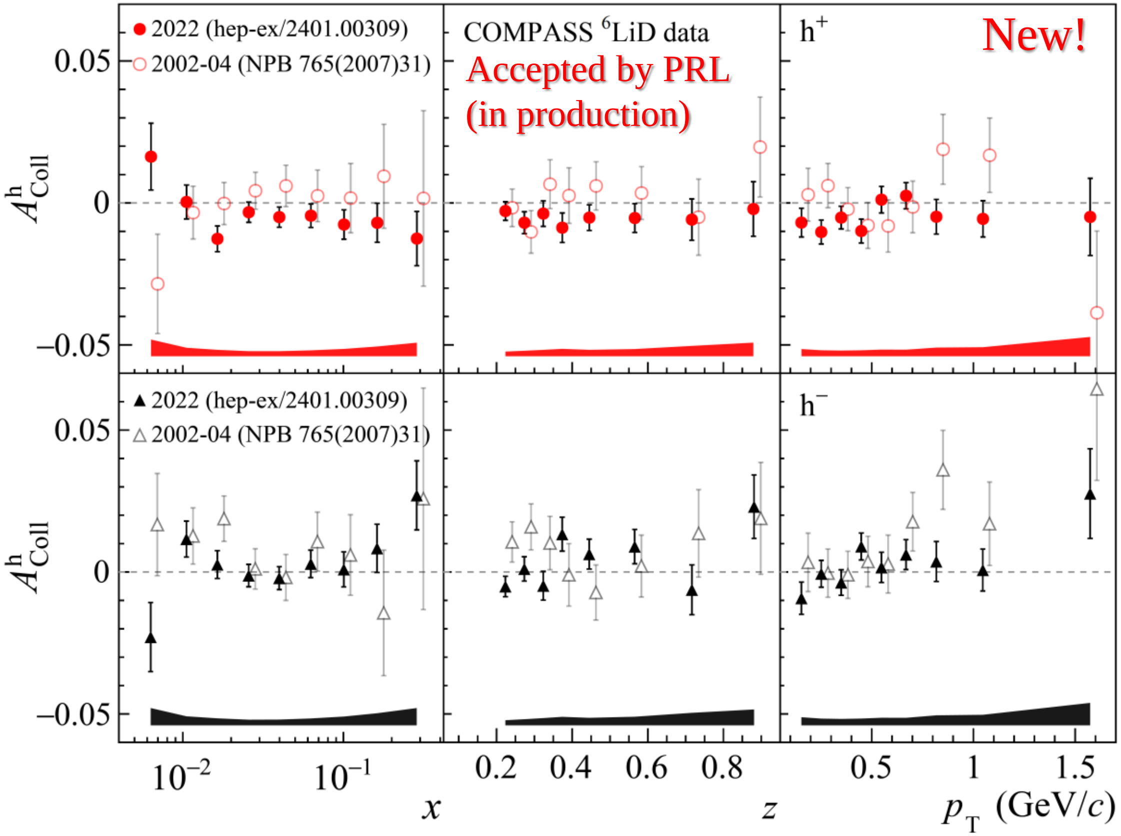
SIDIS TSAs: Collins effect and Transversity



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

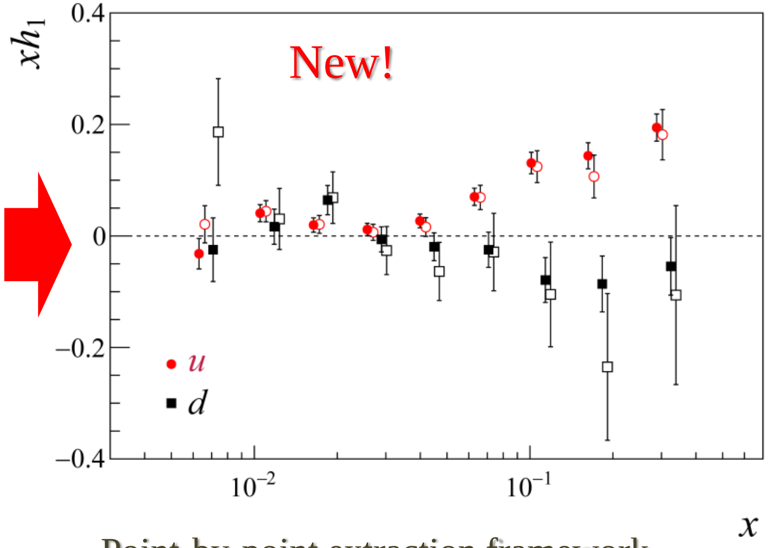
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

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



Accepted by PRL (in production)

New!



New!

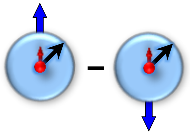
Point-by-point extraction framework
A. Martin et al. PRD **91**, 014034 (2015)
A. Martin et al. PRD **95**, 094024 (2017)

COMPASS 2022 run – highly successful data-taking!

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

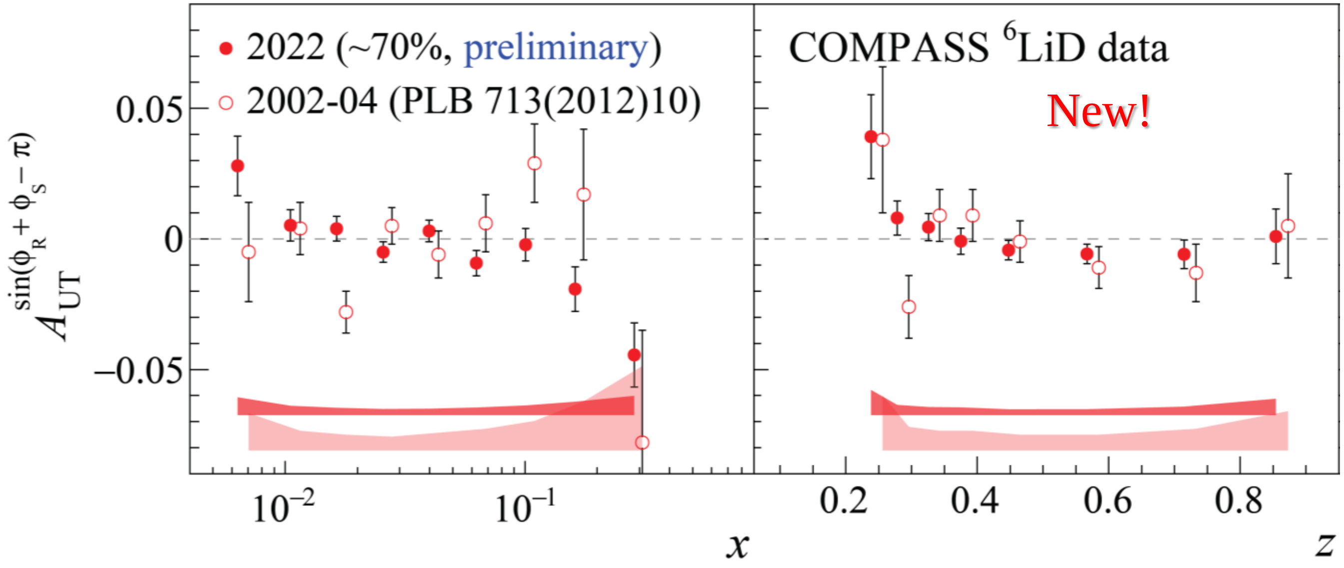
See Athira's and Franco's talks

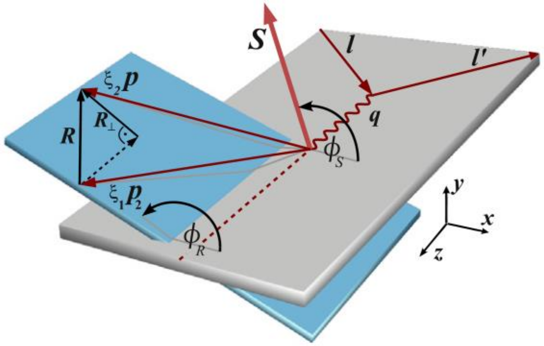
Dihadron Collins effect and Transversity



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

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





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

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

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

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

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

Pavia group fits

Bacchetta, Delcarro, Pisano, Radici, in preparation

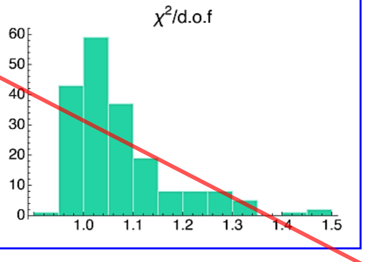
analysis of statistical error with replica method (200) 68% confidence level

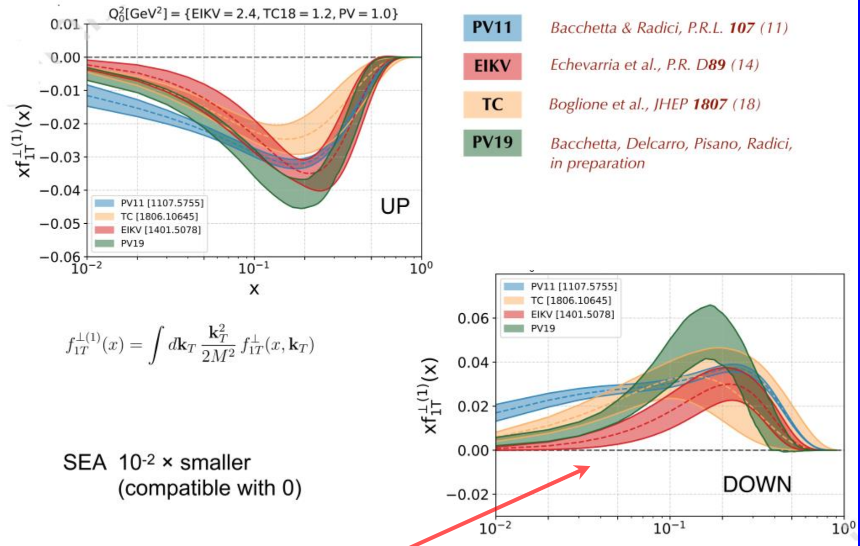
Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

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

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





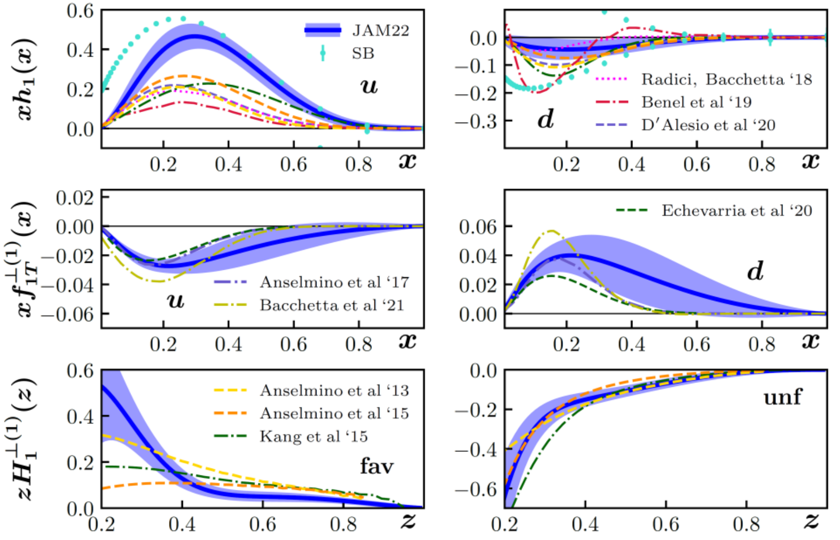
PV11 *Bacchetta & Radici, P.R.L. **107** (11)*
EIKV *Echevarria et al., P.R. D**89** (14)*
TC *Boglione et al., JHEP **1807** (18)*
PV19 *Bacchetta, Delcarro, Pisano, Radici, in preparation*

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

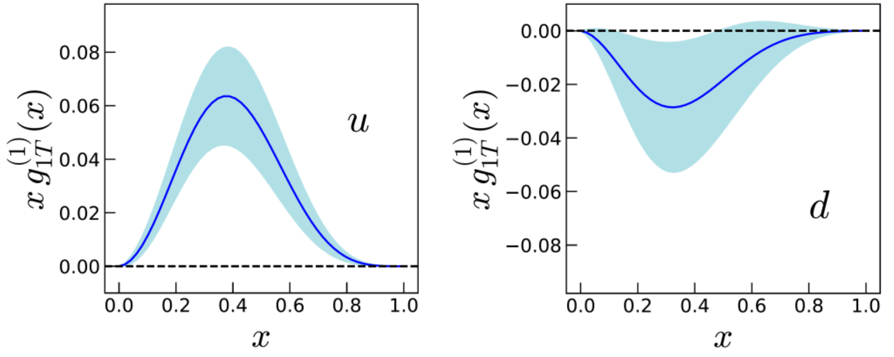
SEA 10^{-2} × smaller
(compatible with 0)

COMPASS 2022 deuteron run

JAM Collaboration, PRD 106 (2022) 3, 034014

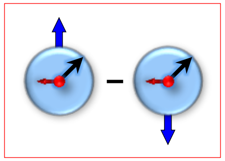


S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D.Pitonyak
PRD 105 (2022) 3, 034007



SIDIS TSAs: Kotzinian-Mulders asymmetry

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

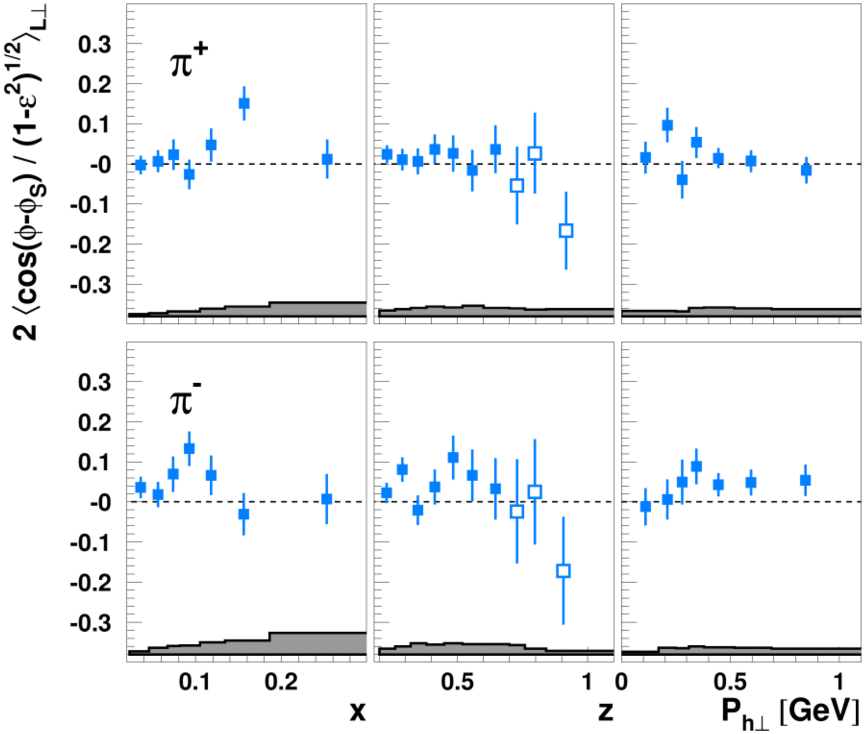


$$\boxed{F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\, g_{1T}^q D_{1q}^h\right]}$$

COMPASS/HERMES/CLAS6 results

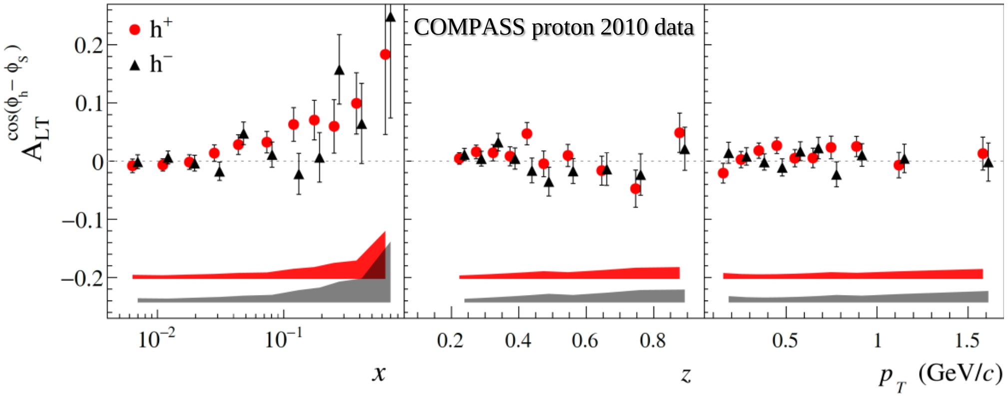
$A_{LT}^{\cos(\phi_h-\phi_S)}$

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

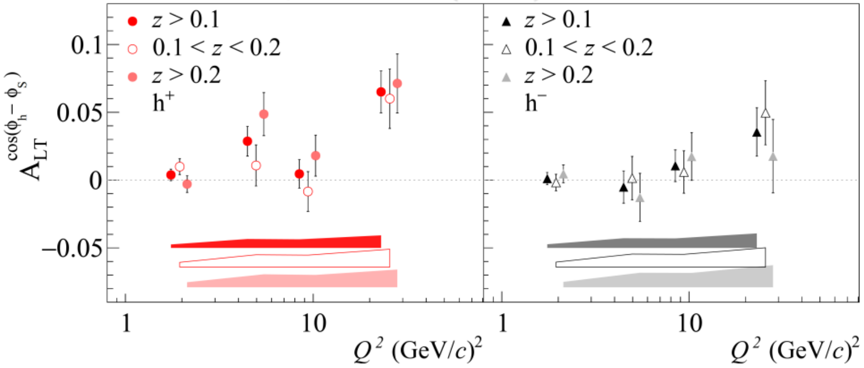


HERMES, JHEP 12 (2020) 010

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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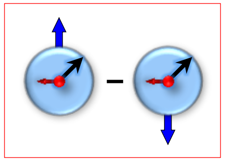

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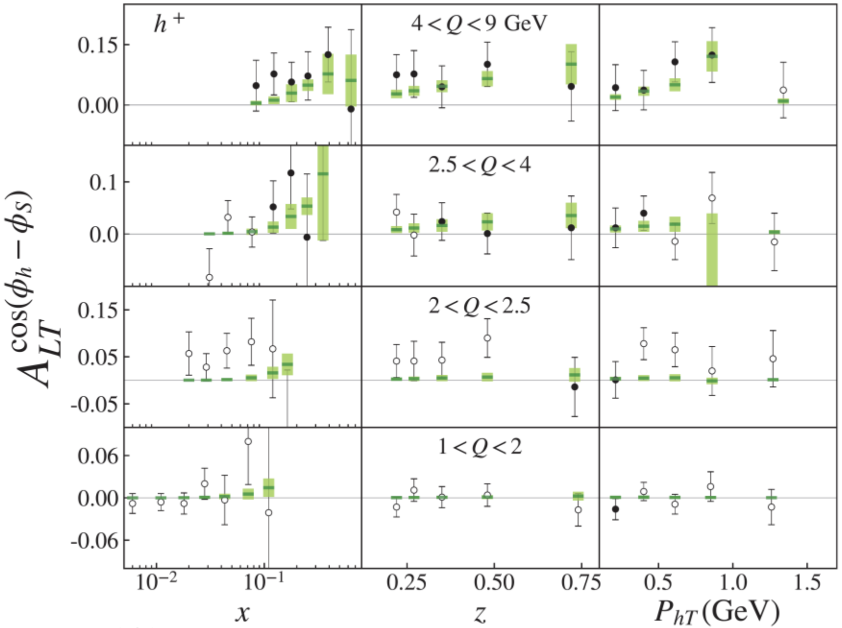
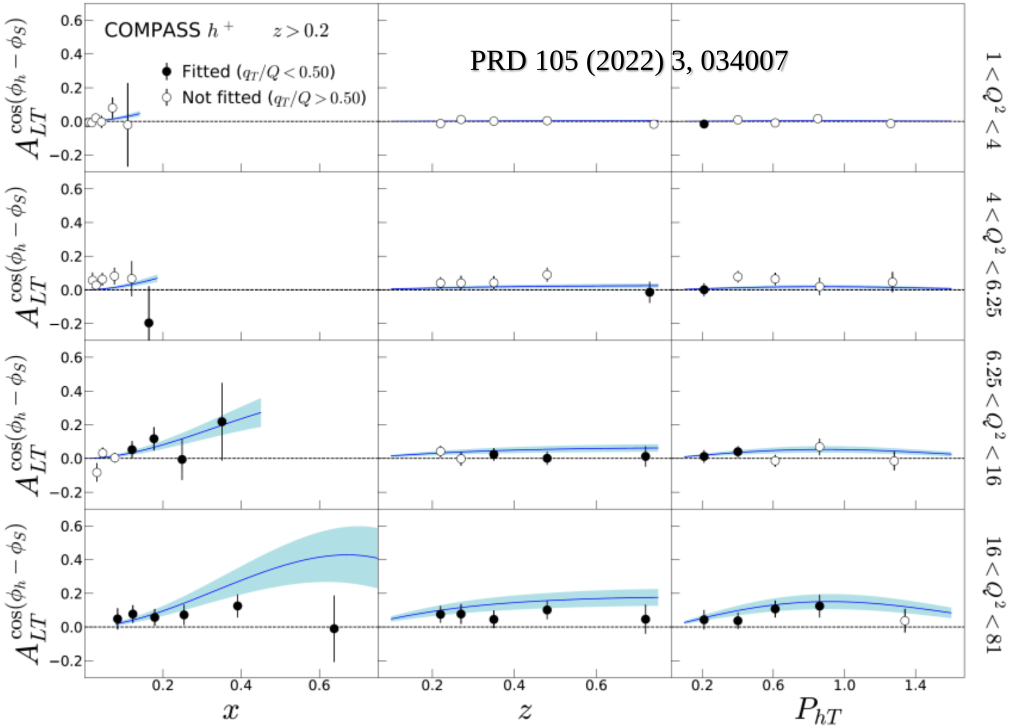
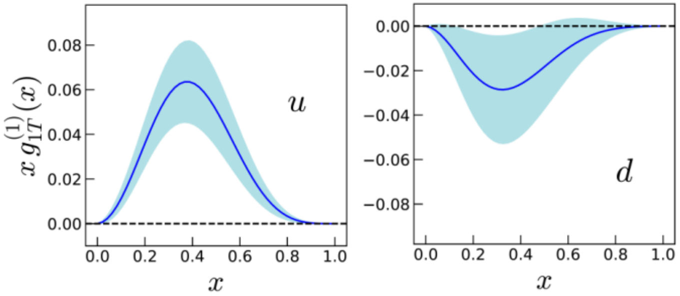
K.Yang et al.arXiv:2403.12795 [hep-ph]



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





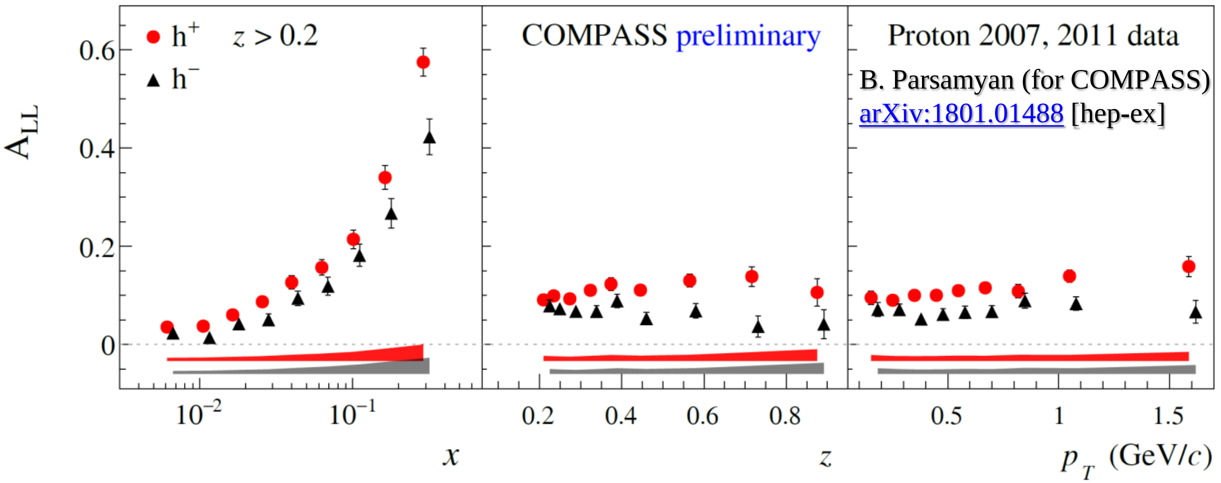
See also, PRD 107, (2023) 034016 – global fit by: M. Horstmann, A. Schafer and A. Vladimirov

SIDIS: target longitudinal spin dependent asymmetries

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

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

- 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

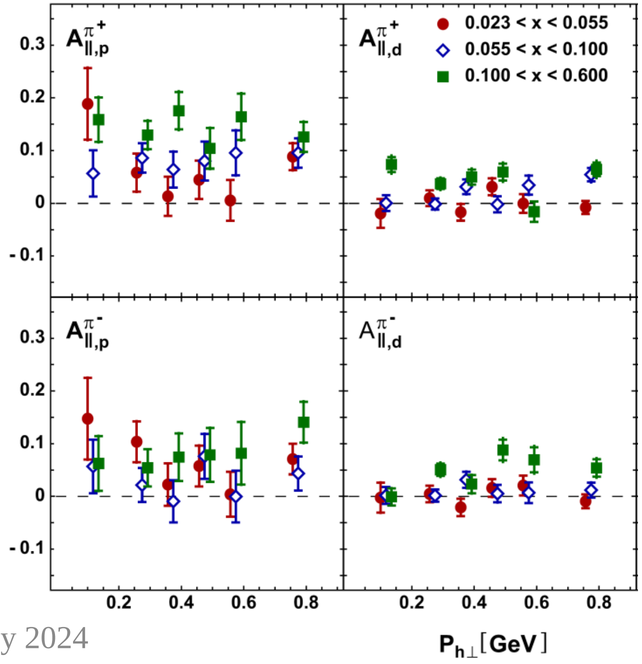


COMPASS preliminary

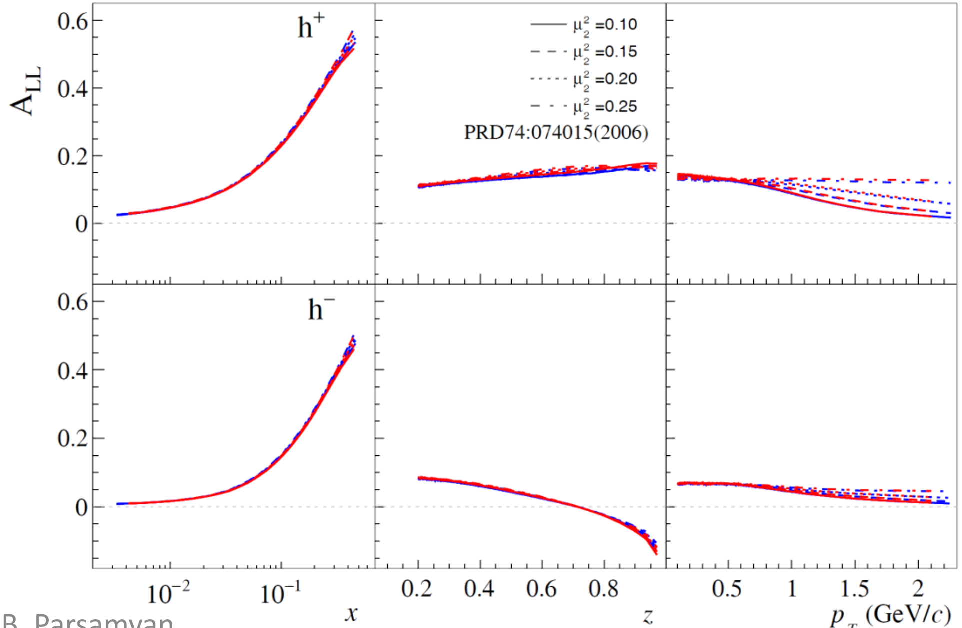
Proton 2007, 2011 data

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

HERMES: PRD 99, 112001 (2019)



COMPASS Proton-2007, -2011 kinematics

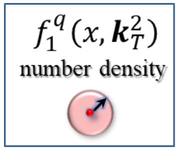


- The role of vector mesons

Cahn effect in SIDIS

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

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



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

number density

As of 1978 – simplistic kinematic effect:

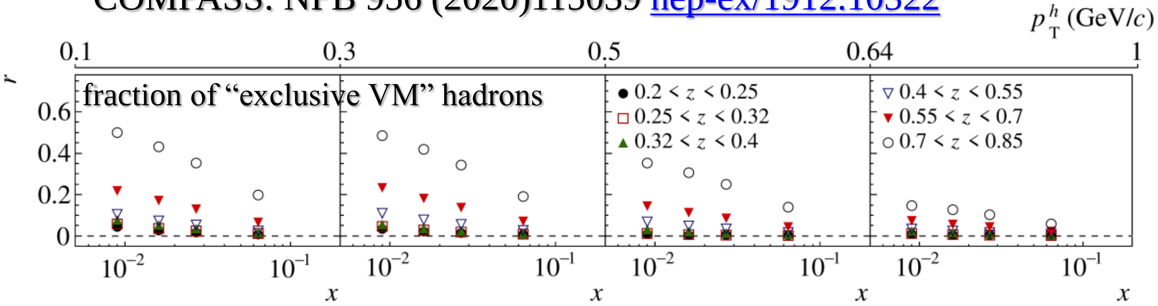
- non-zero k_T induces an azimuthal modulation

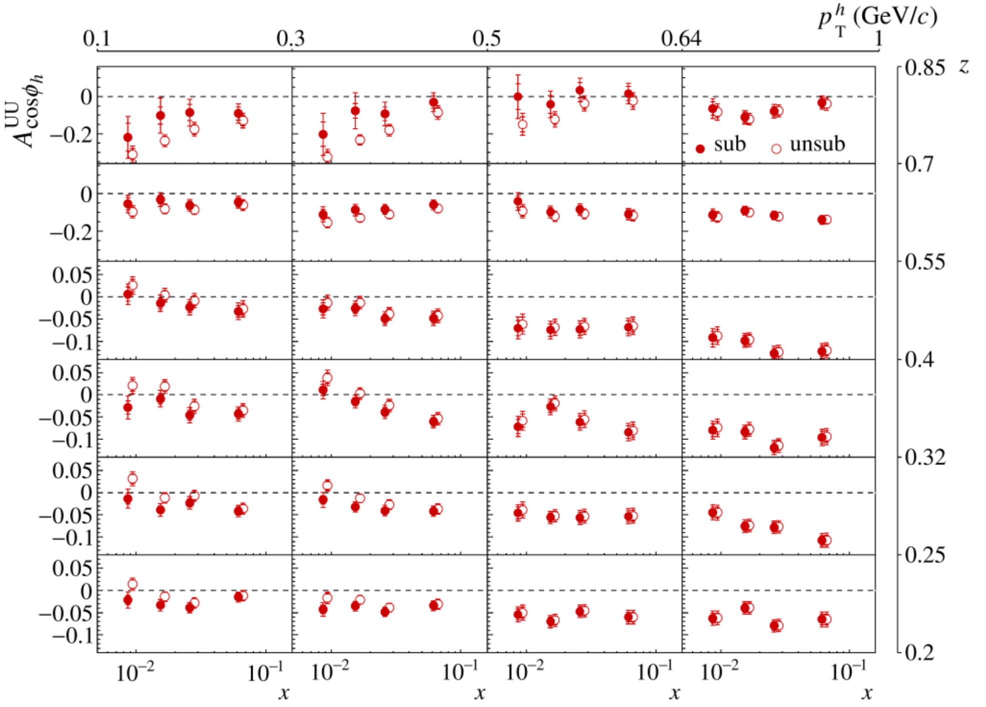
As of 2023 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
    - So far, no comprehensive interpretation
- A set of complex corrections:
    - Acceptance, diffractively produced VM 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

Cahn effect in SIDIS

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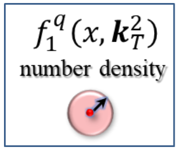

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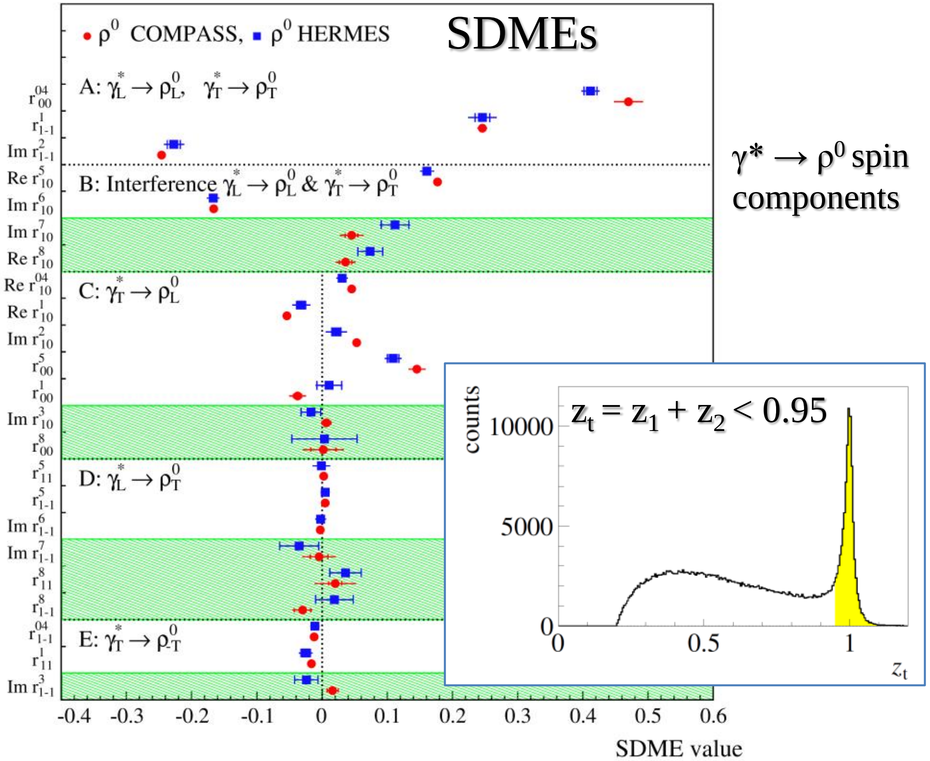
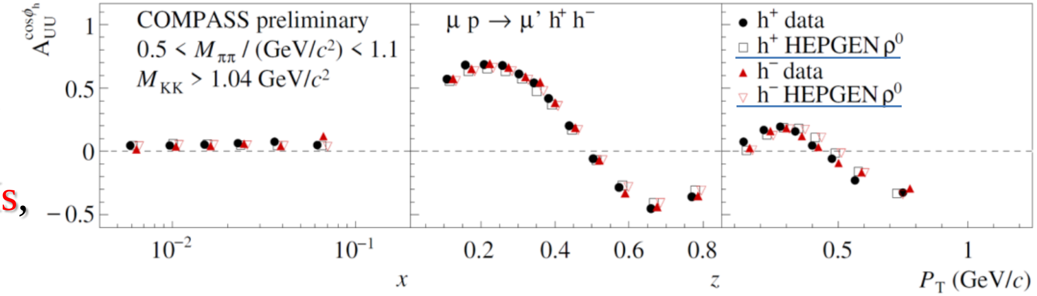
COMPASS, EPJC (2023) 83 924



γ* → ρ^0 spin components

VM contribution



See Jan Matousek's talk

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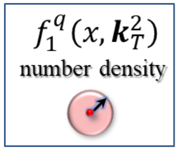

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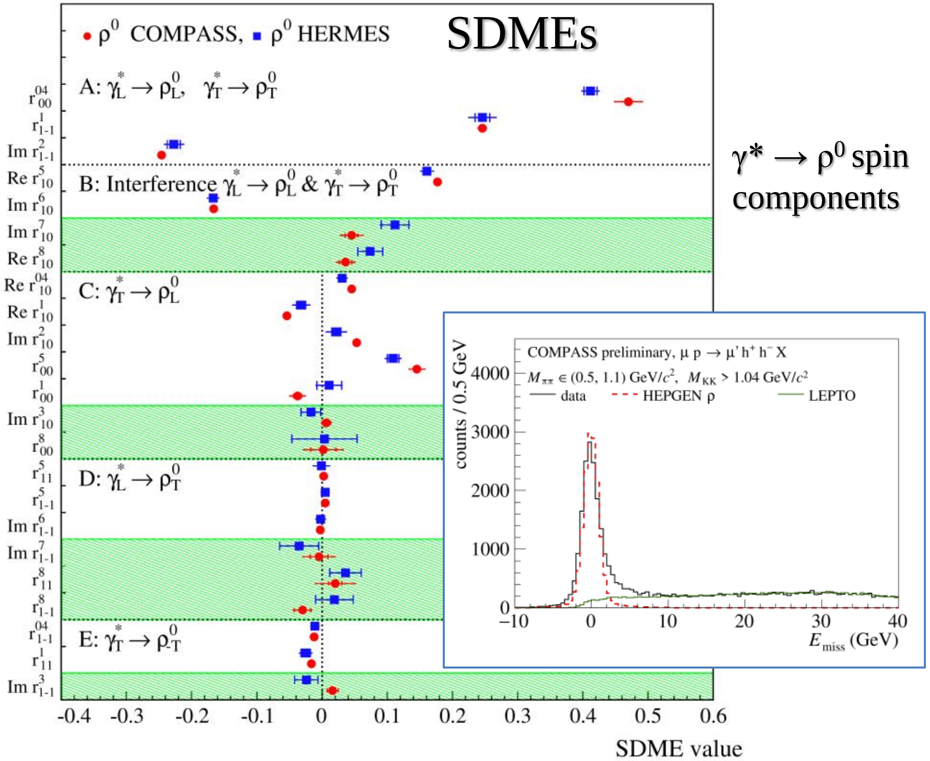
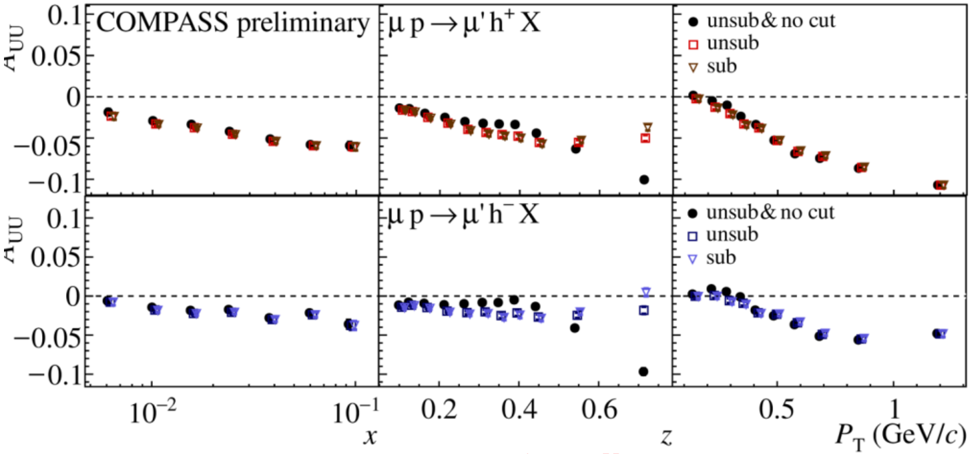
COMPASS, EPJC (2023) 83 924



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

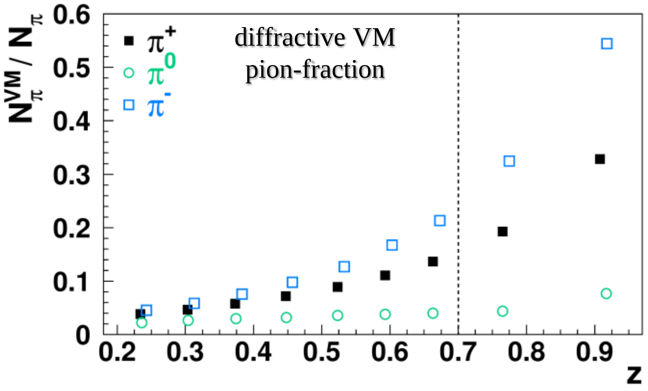
VM corrections, applied



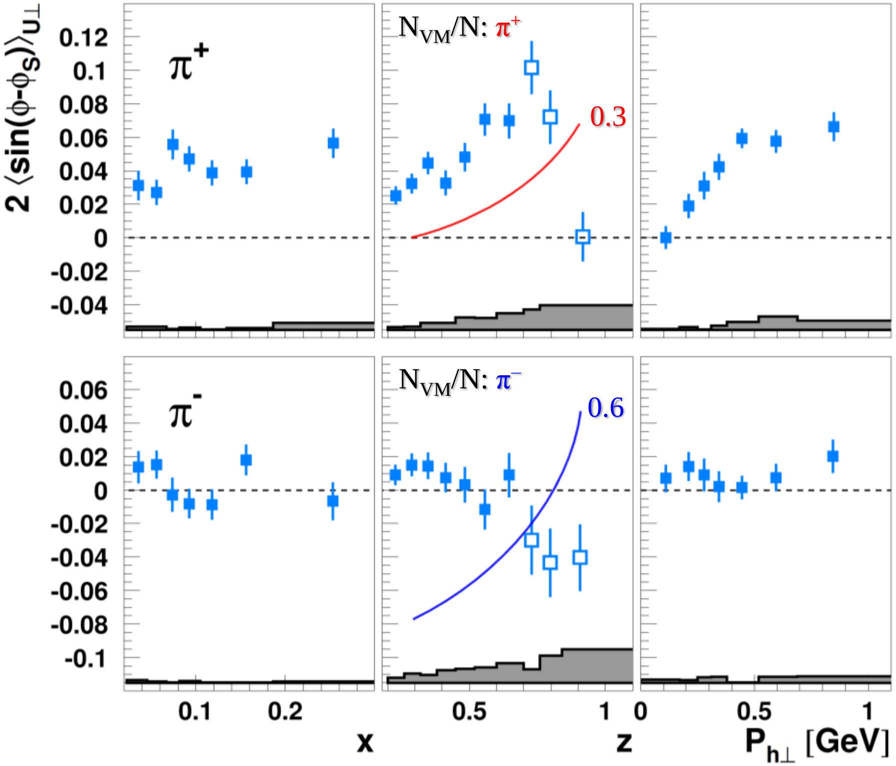
See Jan Matousek's talk

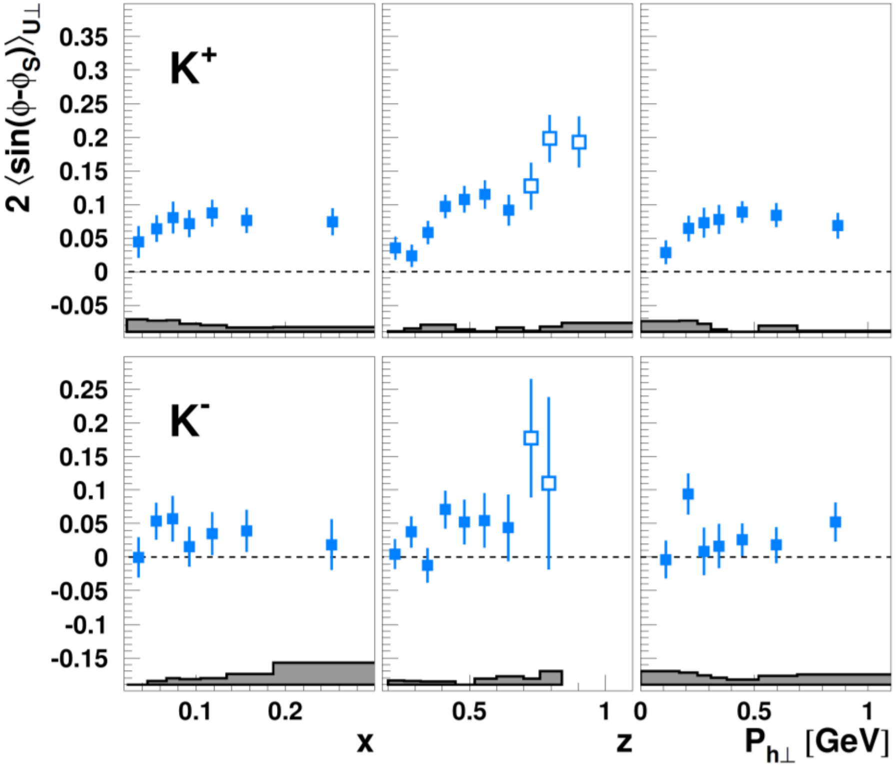
HERMES: Sivers effect and diffractive VMs

- 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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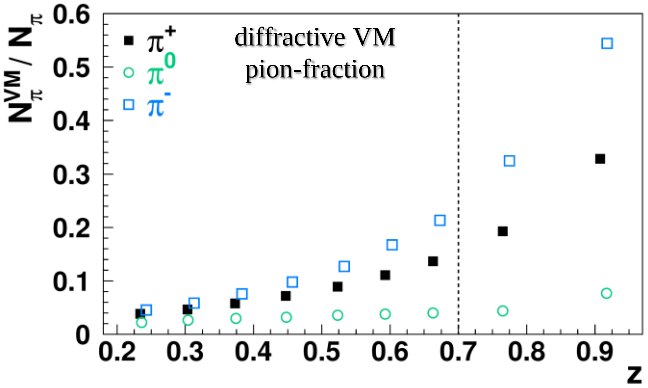

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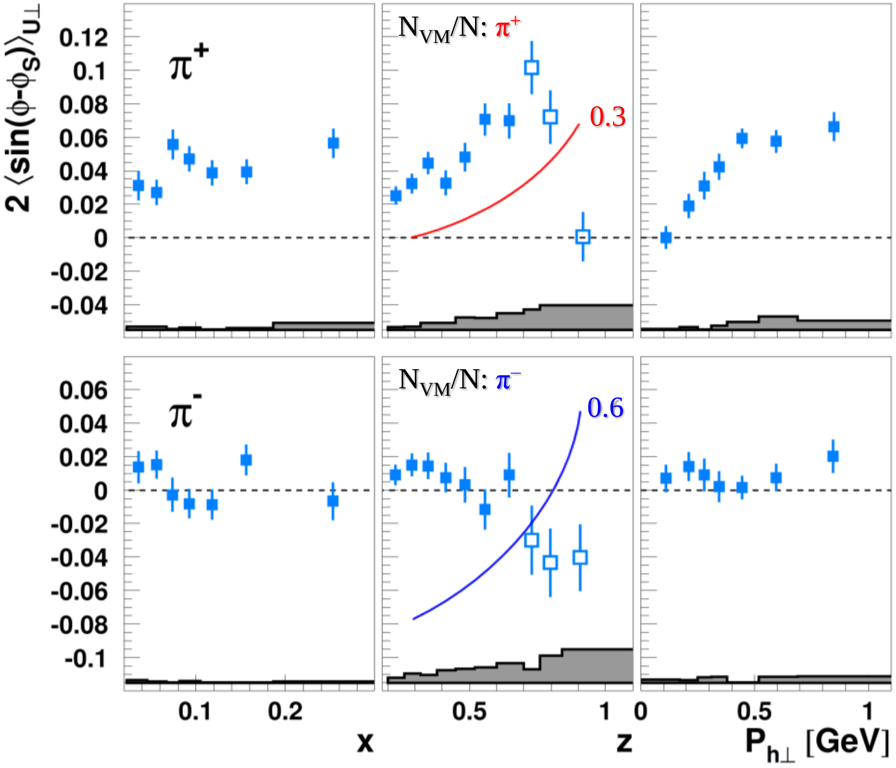
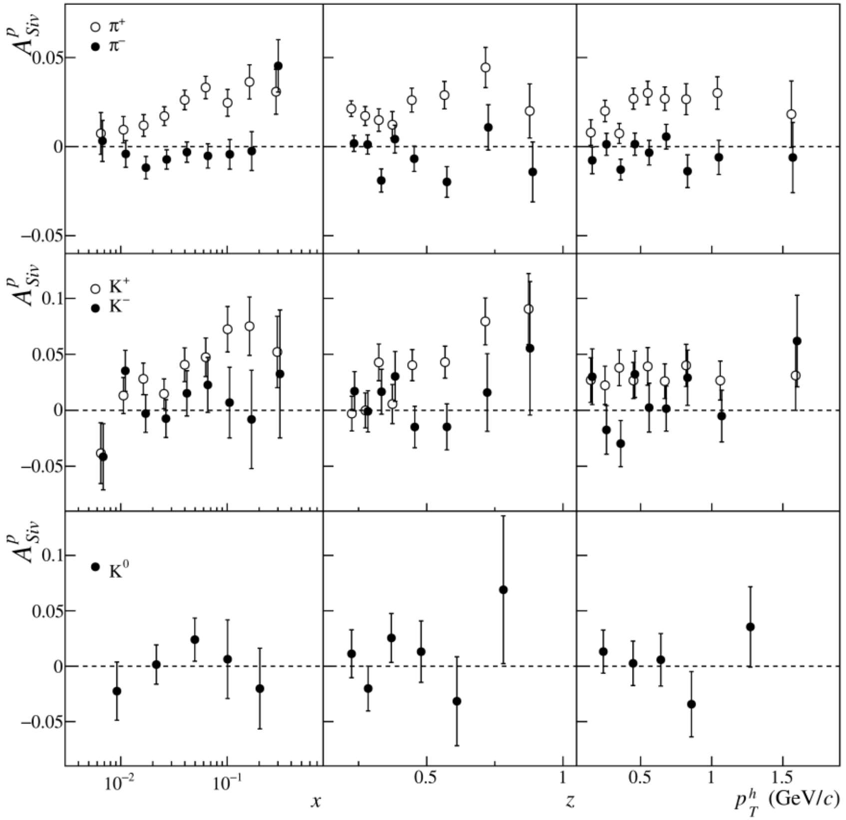


COMPASS: PLB 744 (2015) 250



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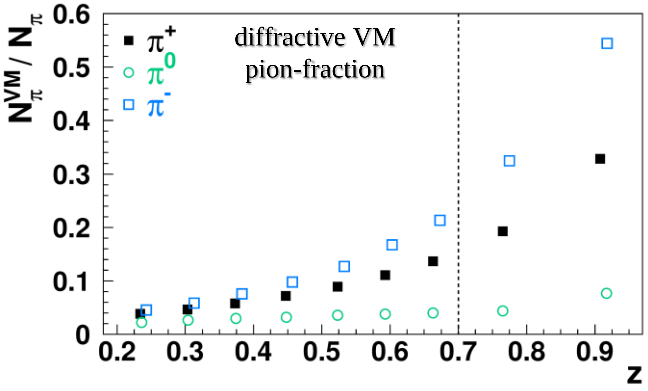
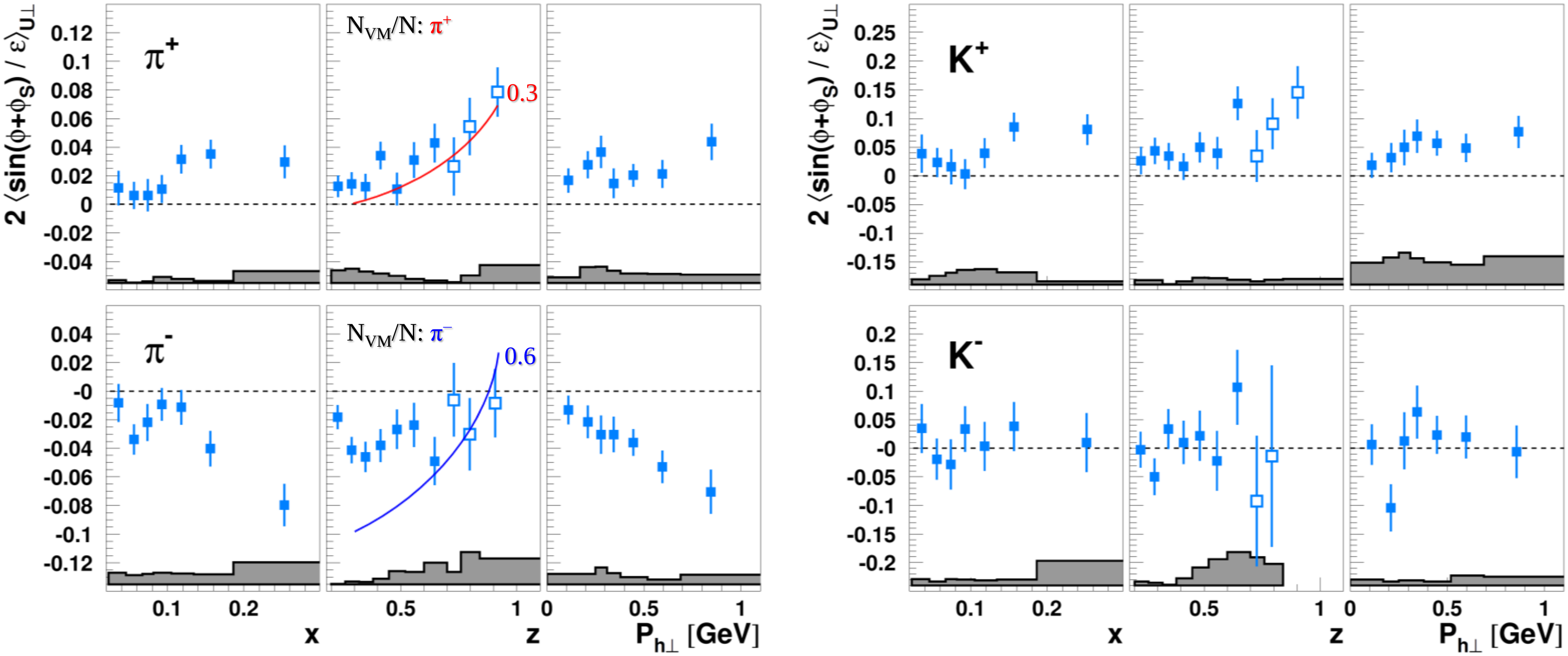
- Similar effect in COMPASS?
- Not clear with Collins





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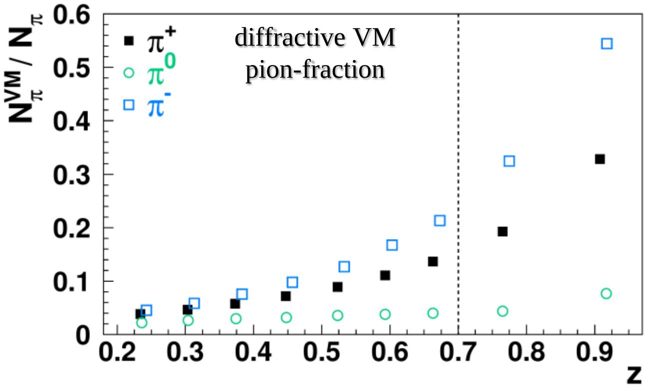
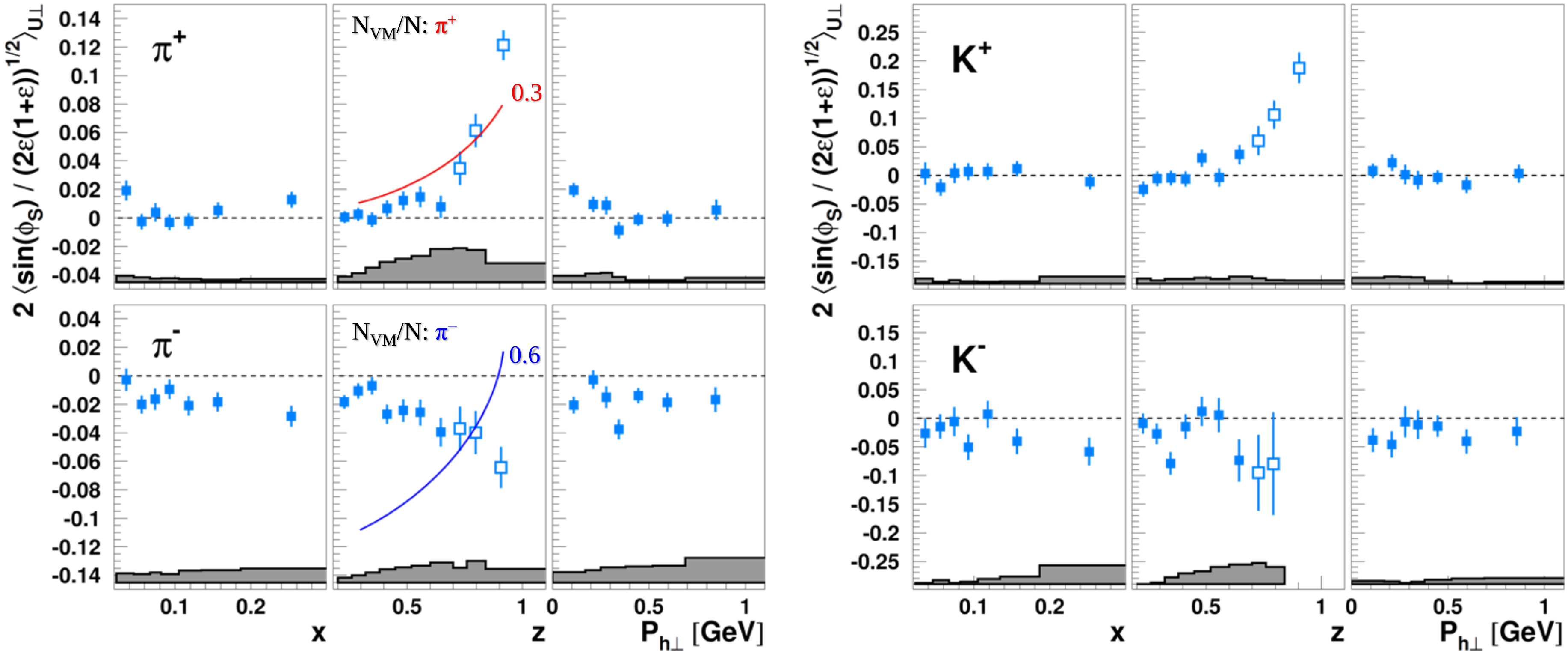
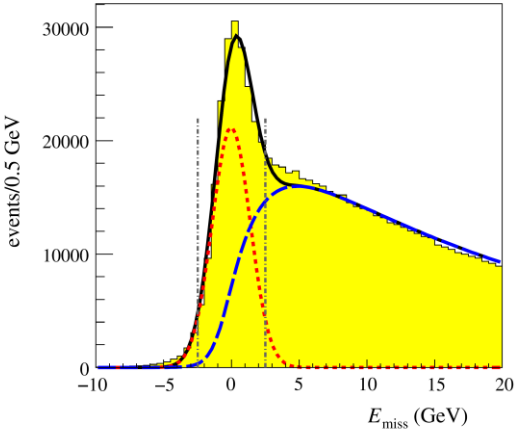
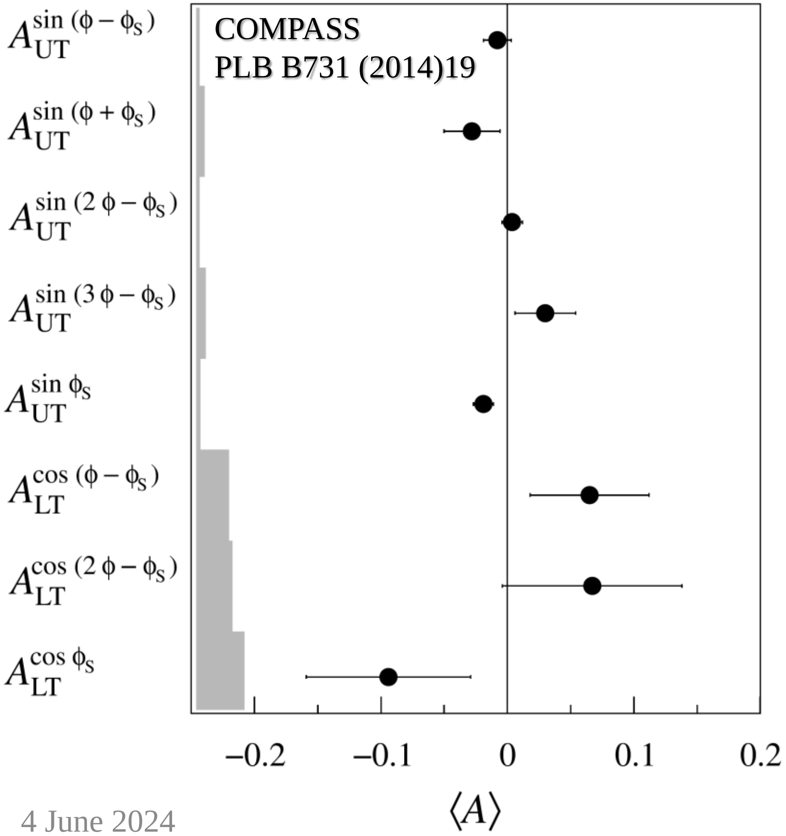




COMPASS: Exclusive ρ^0 TSAs



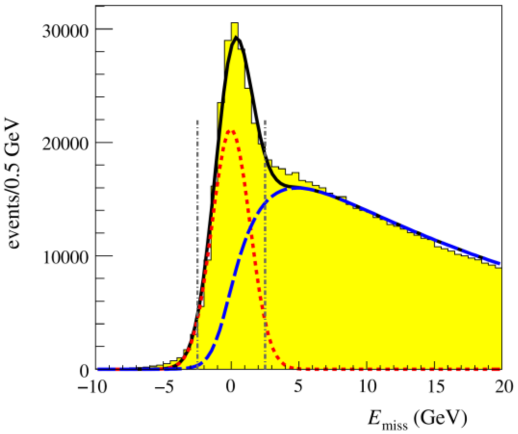
exclusive



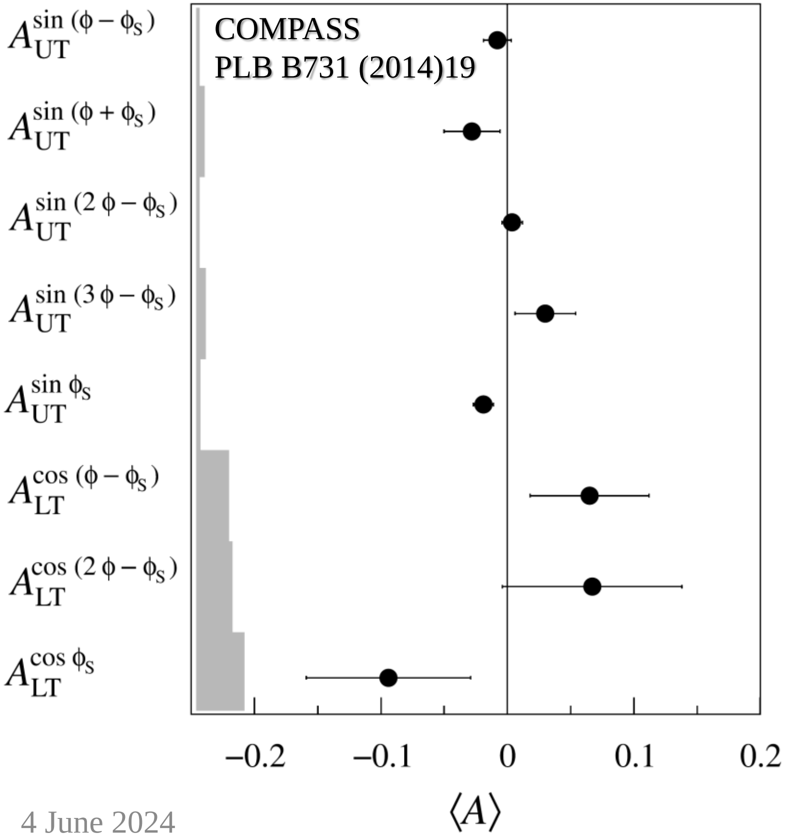
COMPASS
PLB B731 (2014)19

- 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?

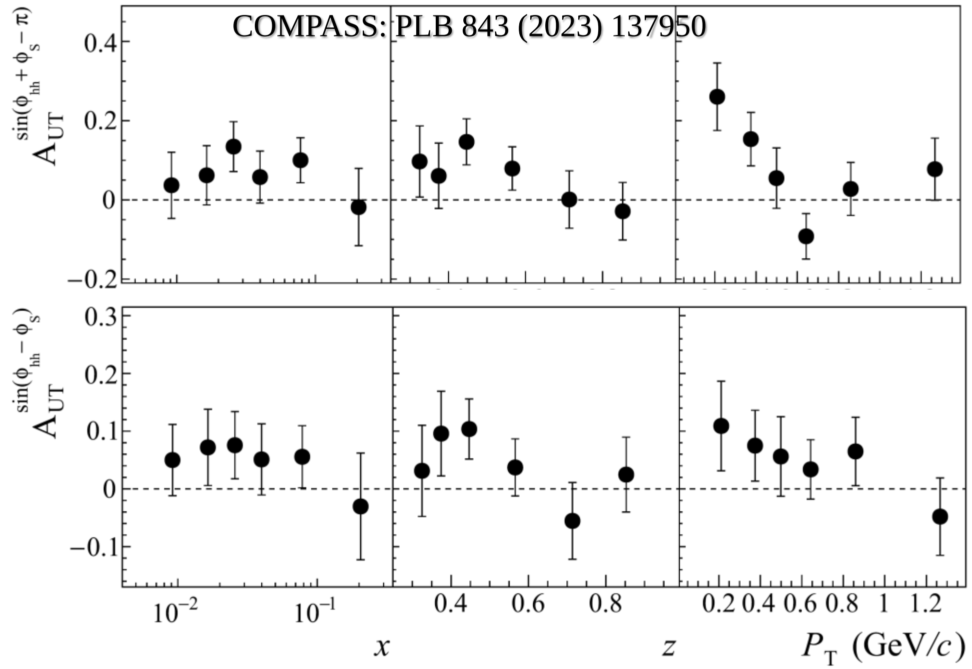
COMPASS: Exclusive ρ^0 TSAs



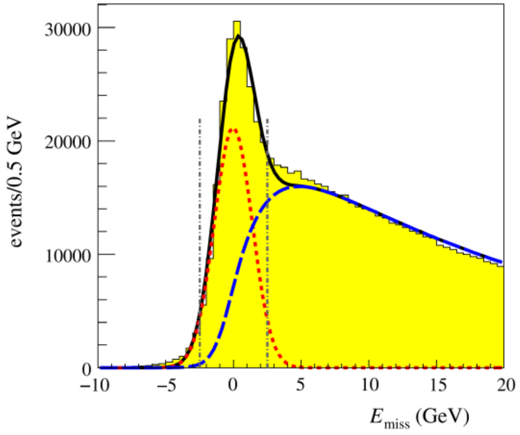
exclusive



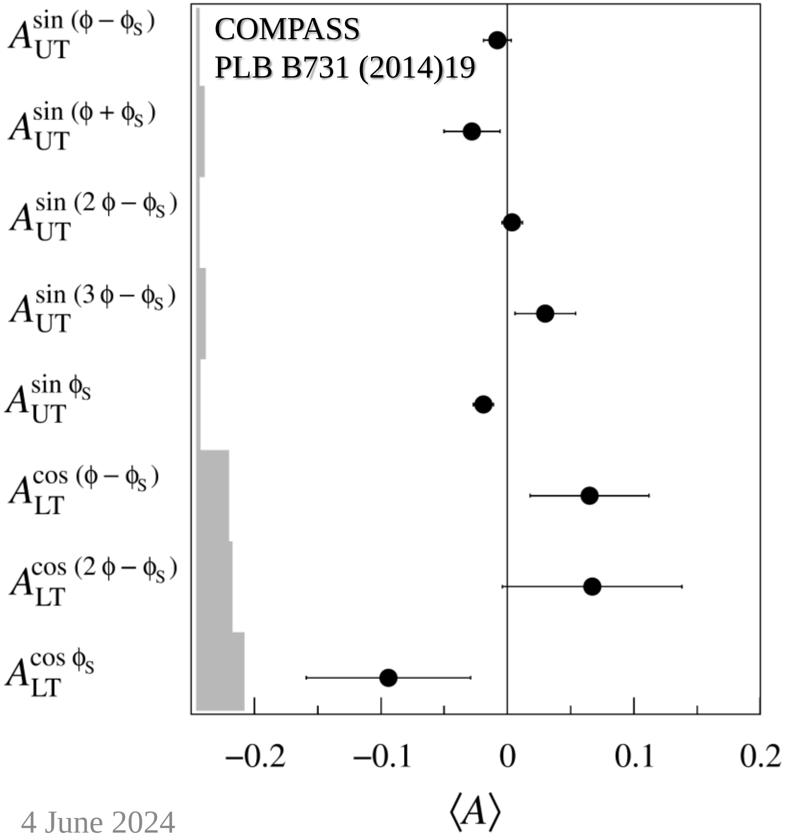
- Both Collins and Sivers TSAs are small an compatible with zero
  - $\sin(\varphi_S)$ is small, but possibly non zero
  - Can VM pion asymmetries still be large?
- COMPASS has checked also the inclusive ρ^0 Collins and Sivers asymmetries
  - Both tend to be positive
  - The fraction of inclusive ρ^0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



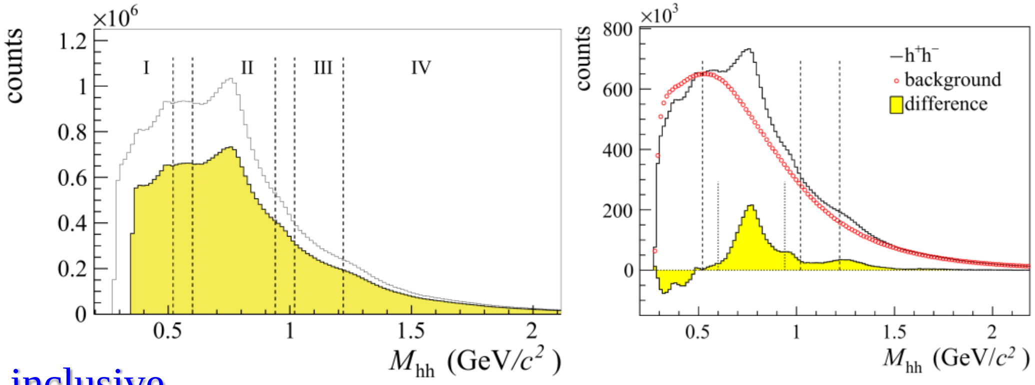
COMPASS: Exclusive and Inclusive ρ^0 TSAs

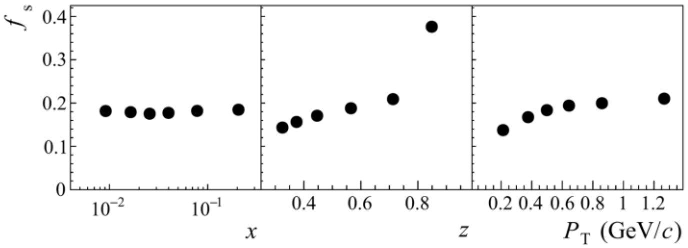


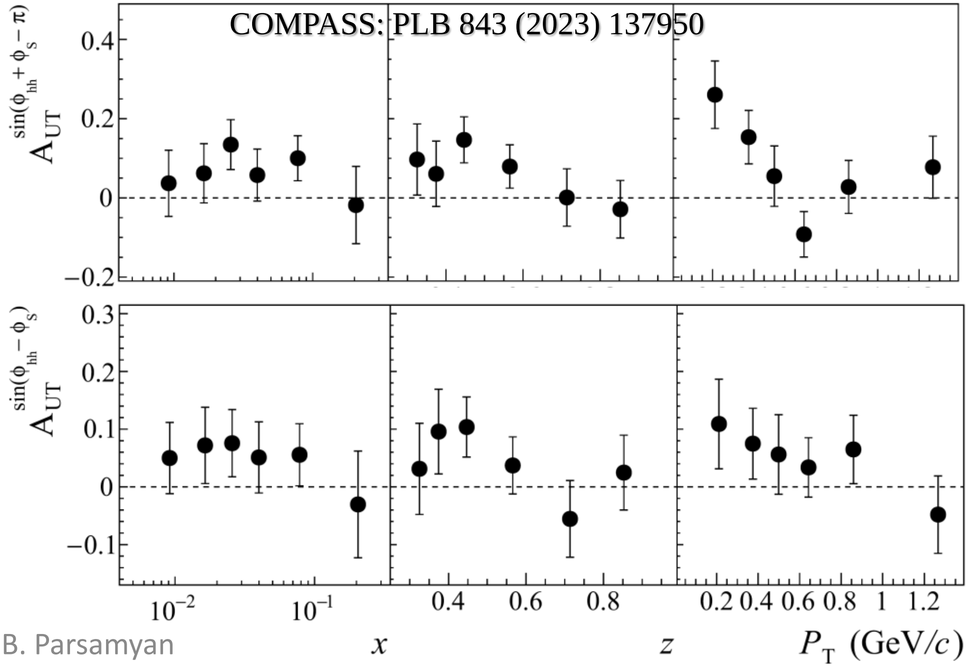
exclusive



inclusive





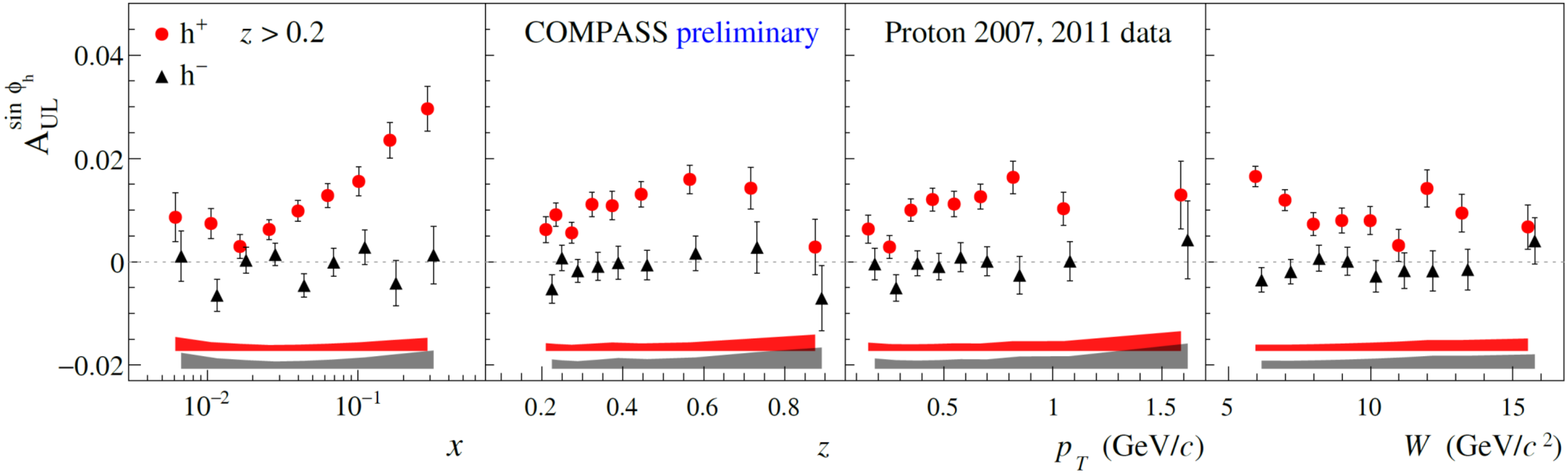


- Interesting twist-3 asymmetries

SIDIS TSAs: subleading twist effects

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

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



- Q-suppression, TSA-mixing
- Various different “twist” ingredients
- Non-zero trend for h⁺, h⁻ compatible with zero

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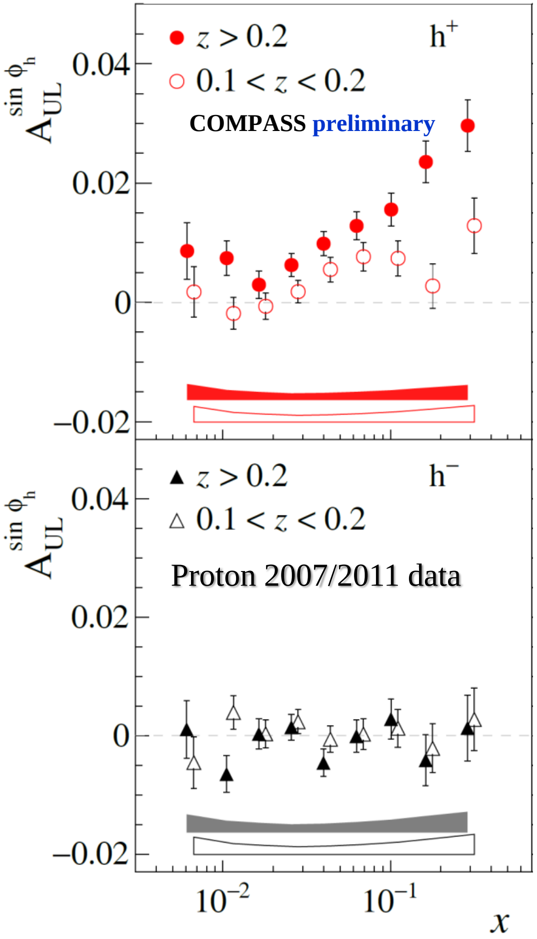
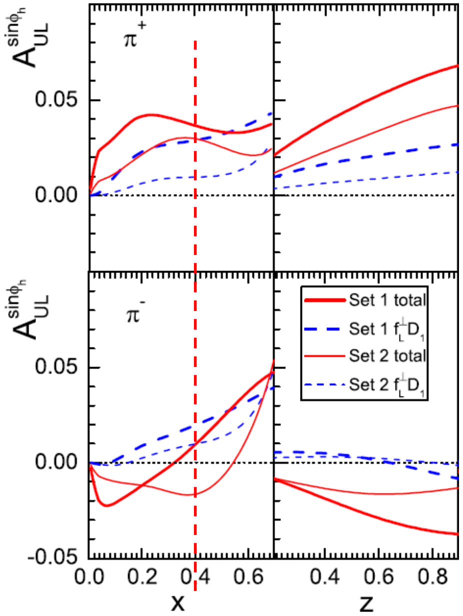
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_L\ \sqrt{2\varepsilon\left(1+\varepsilon\right)}A_{UL}^{\sin\phi_h}\sin\phi_h+\ldots\right\}$$

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

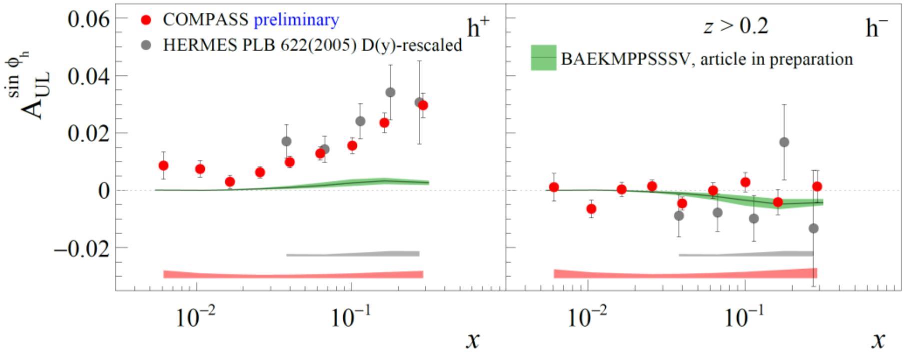
B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]



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



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



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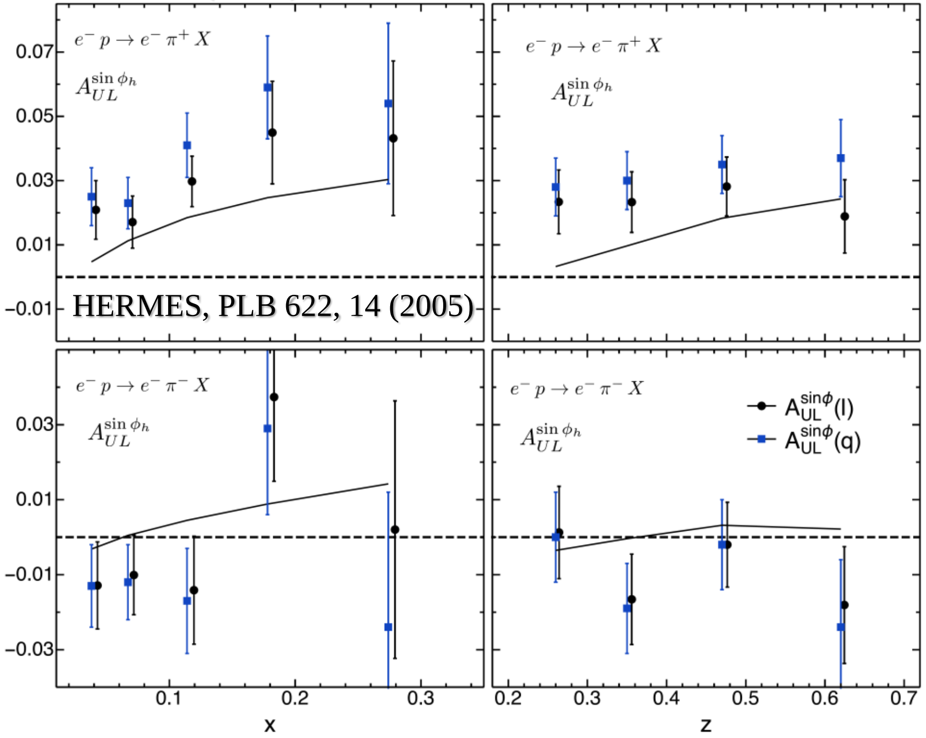
- Various different "twist" ingredients
- Non-zero trend for h$^+$, h$^-$ compatible with zero, clear *z*-dependence

SIDIS TSAs: subleading twist effects

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

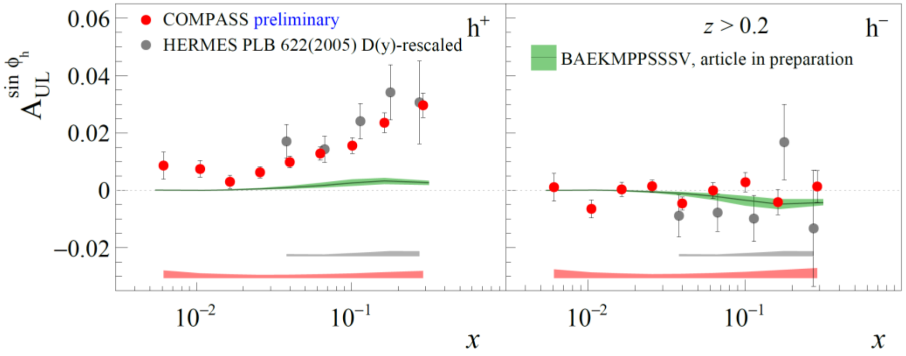
$$\boxed{\begin{aligned} F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\Bigg\{ & -\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^q H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{G}_q^{\perp h}}{z}\right) \\ & +\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp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

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



- 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

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



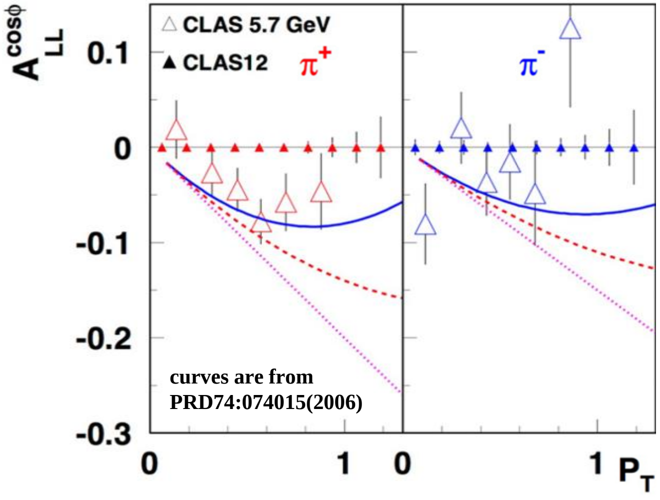
- Q-suppression, TSA-mixing
- Various different "twist" ingredients
- Non-zero trend for h^+, h^- compatible with zero, clear z-dependence

SIDIS TSAs: subleading twist effects

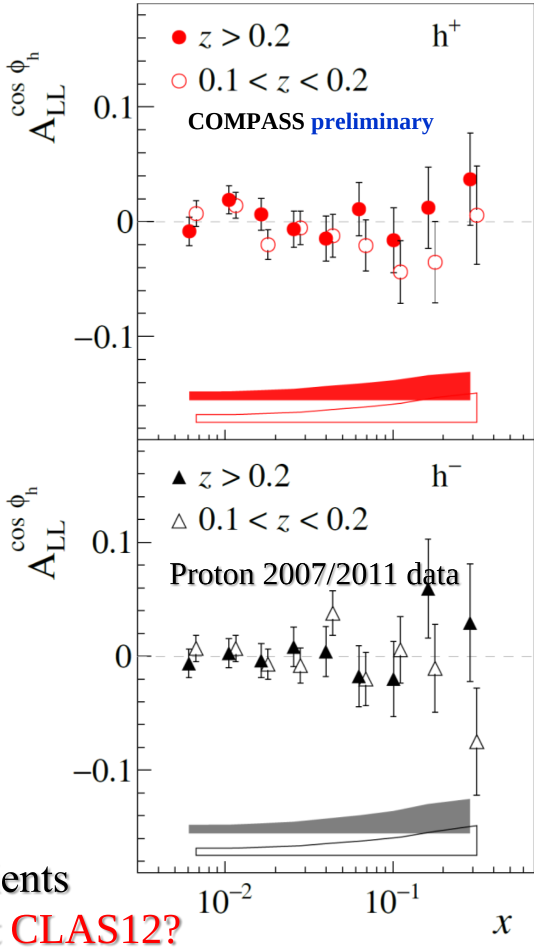
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \ldots\right\}$$

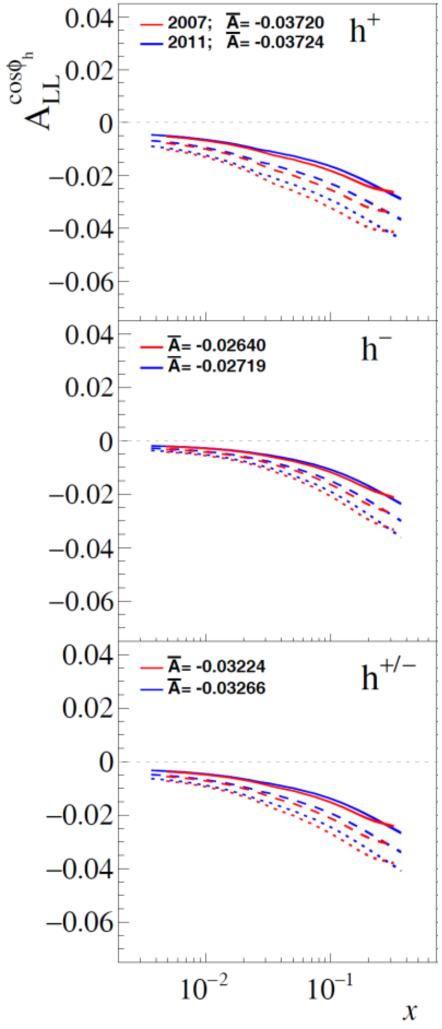
$$\boxed{F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xg_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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

CLAS, PRL 105,262002(2010)



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





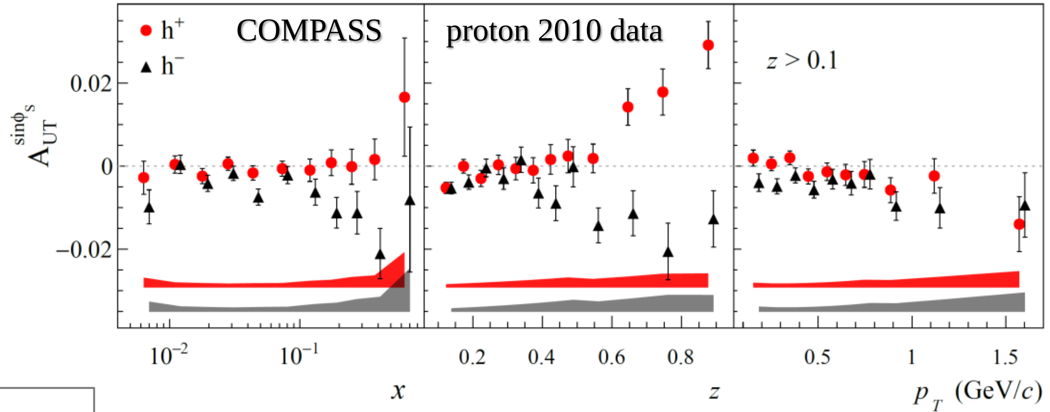
- Q-suppression, various different "twist" ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

SIDIS TSAs: subleading twist effects

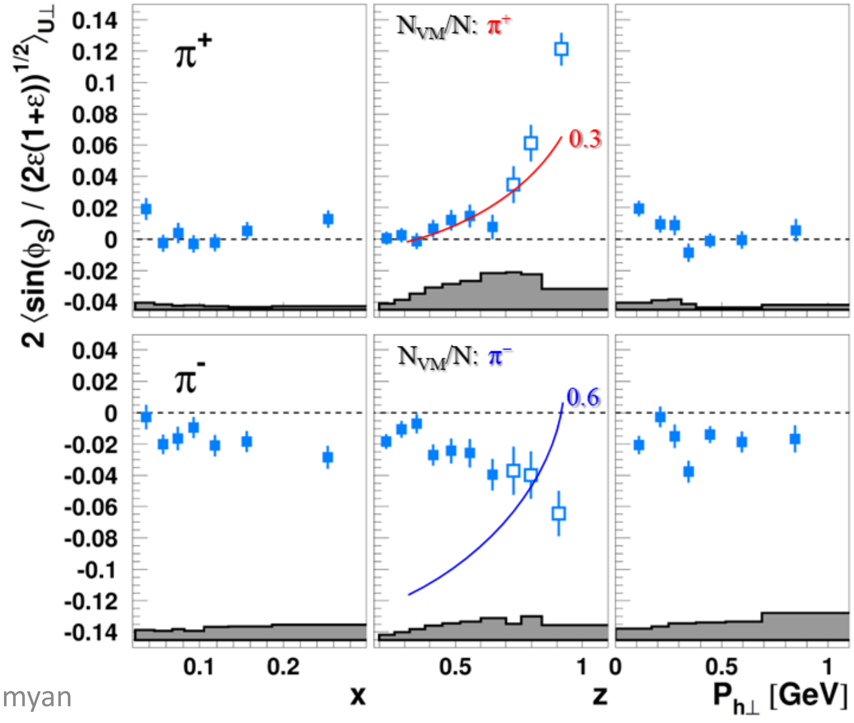
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\;S_T\sqrt{2\varepsilon\left(1+\varepsilon\right)}A_{UT}^{\sin\phi_S}\,\sin\phi_S+\ldots\right\}$$

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

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



HERMES, JHEP 12 (2020) 010



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$_T$)

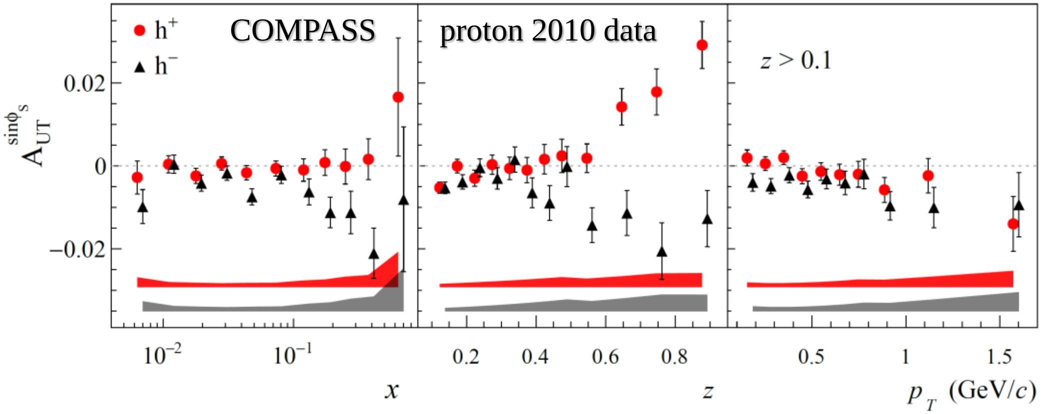
See Daniel Pitonjak’s talk

SIDIS TSAs: subleading twist effects

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

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

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

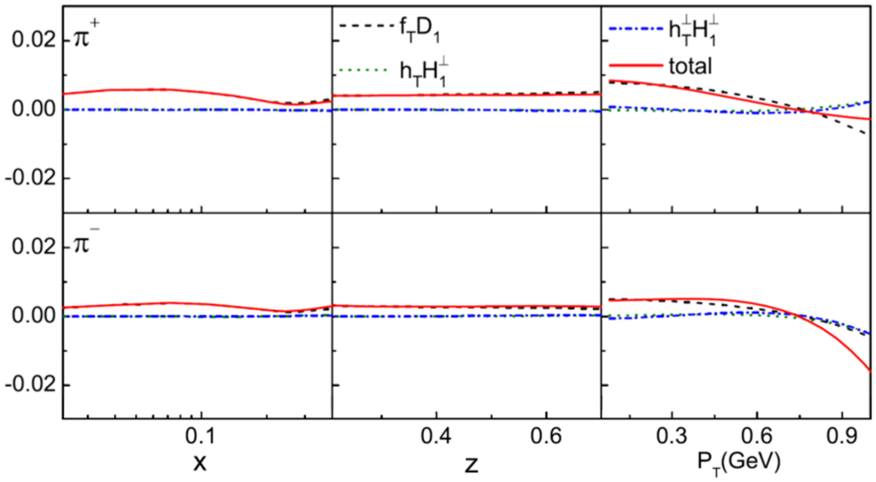


COMPASS/HERMES results

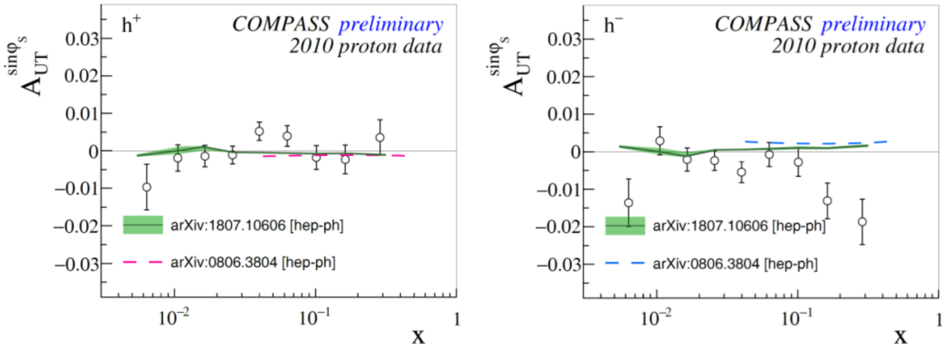
$A_{UT}^{\sin\phi_S}$

- Q-suppression
- various “twist-2/3” ingredients
- non-zero signal for h± at large z?

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



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



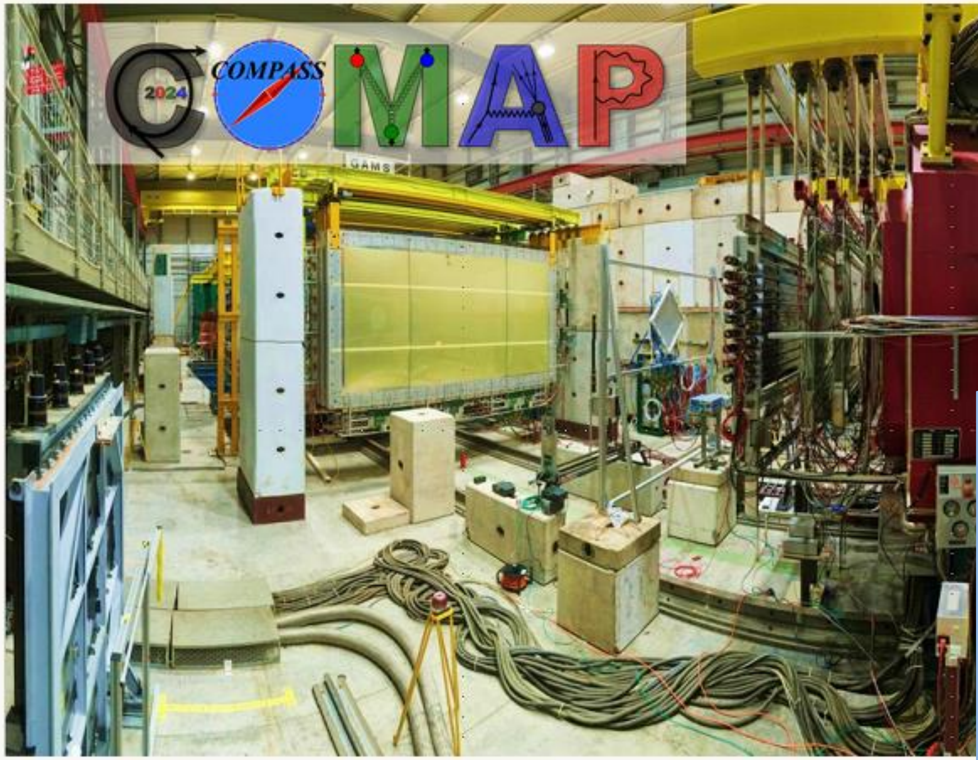
- Closing remarks

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



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

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

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

Yerevan, Armenia

30 September – 4 October, 2024

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

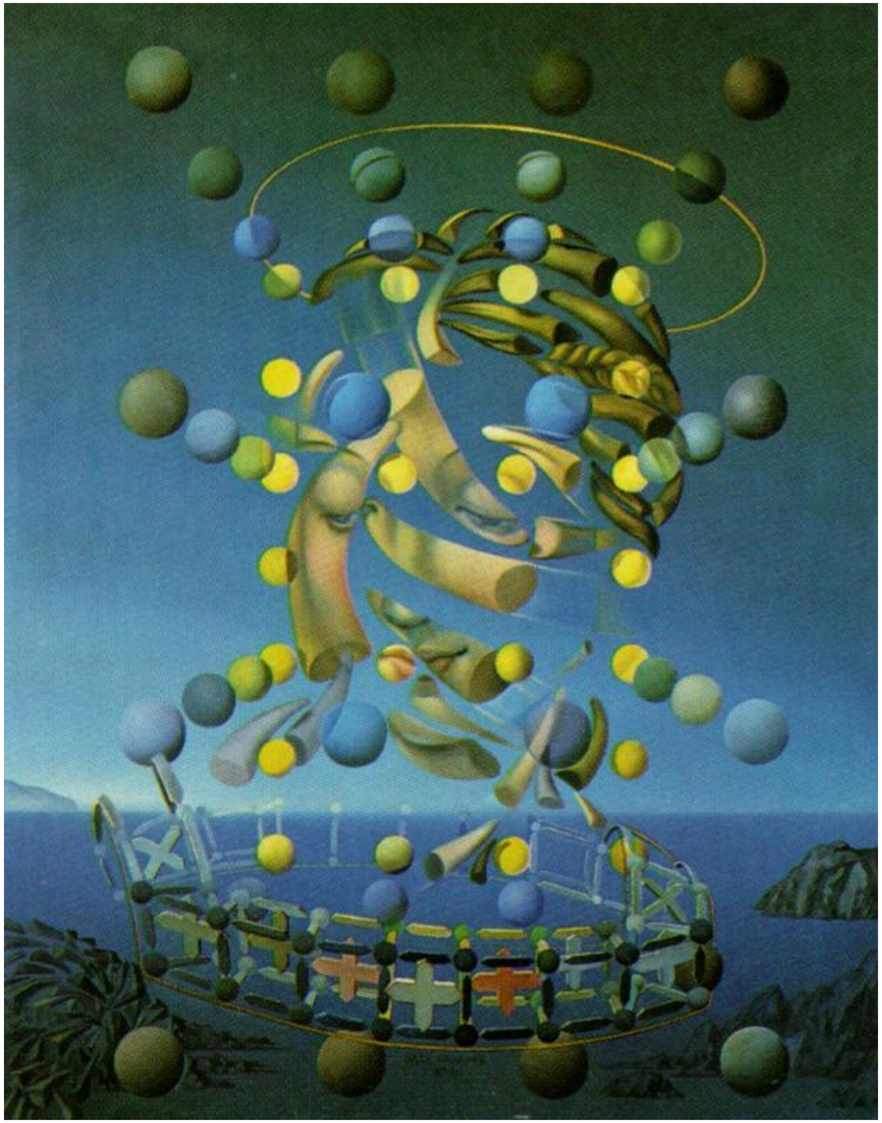
Confirmed speakers

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

“Nature”

“1D”

Raphael “Madonna del Prato”

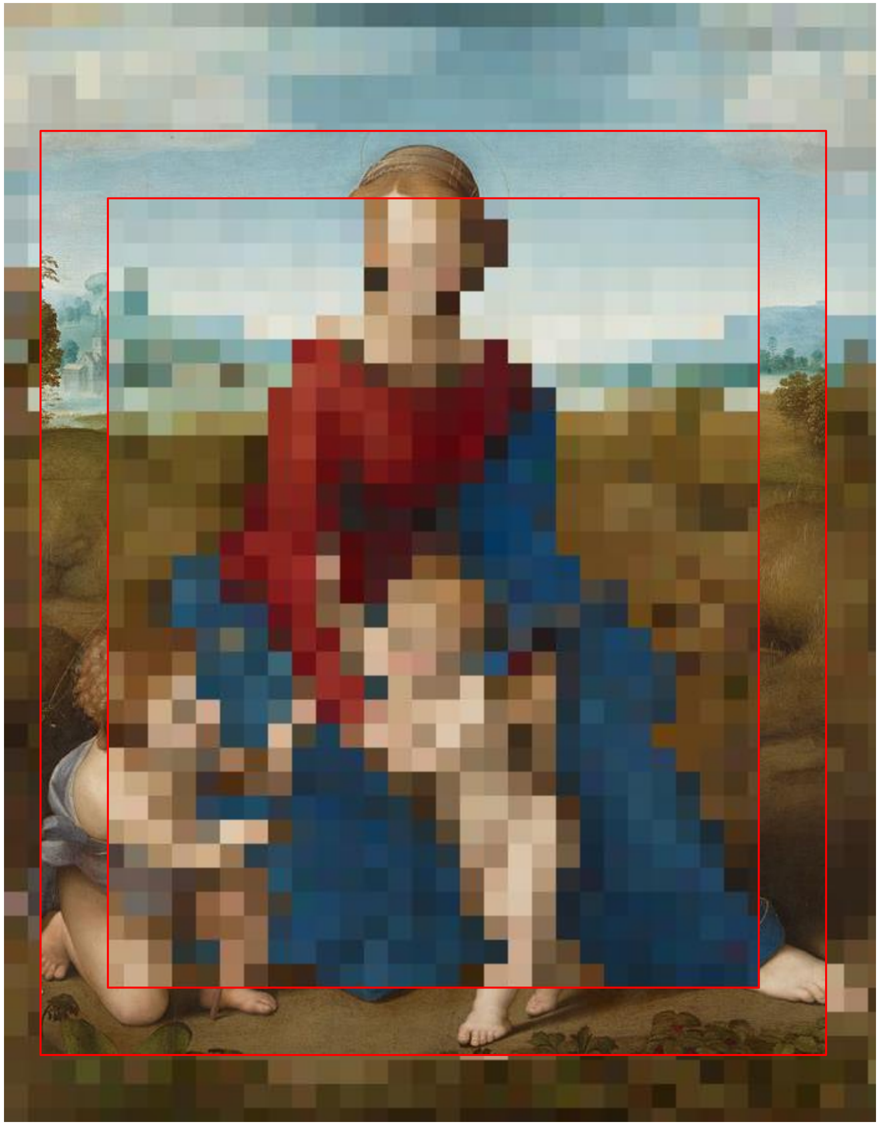


Salvador Dali “Maximum Speed of Raphael's Madonna”

“Nature”

“multi-D” with available statistics

Raphael “Madonna del Prato”

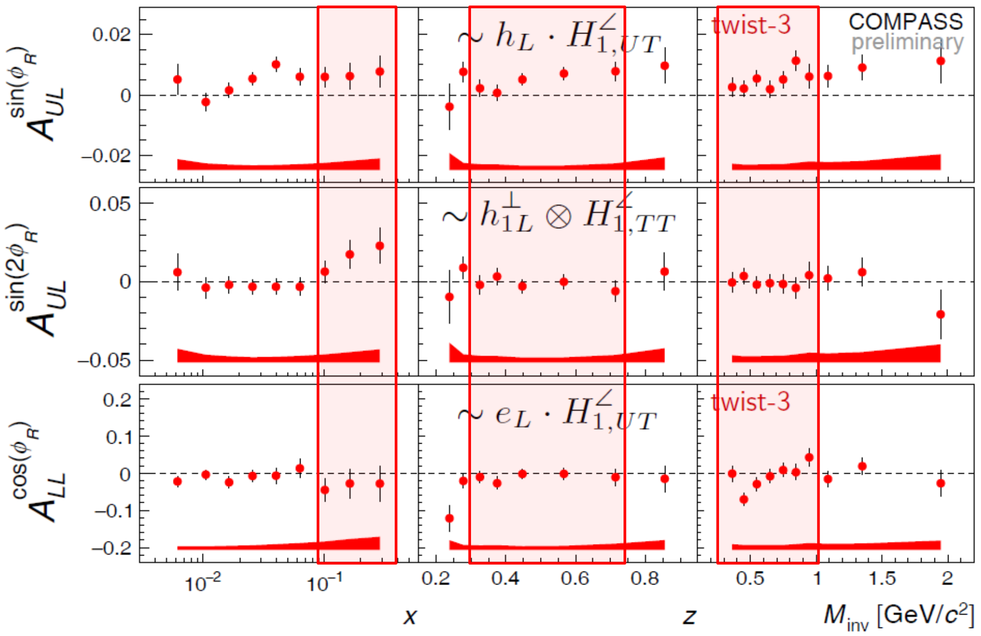


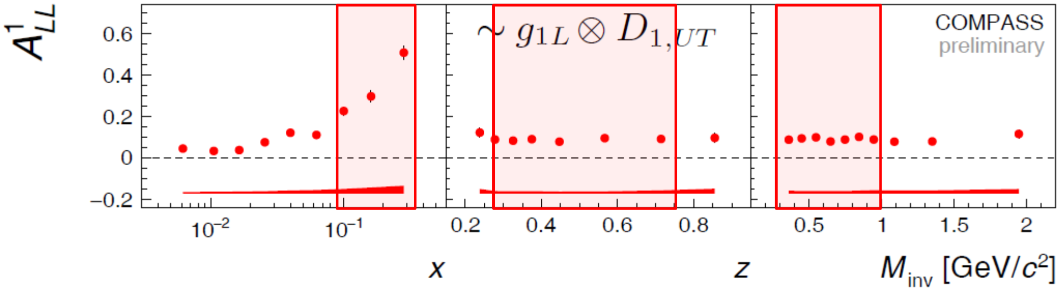
Raphael “Madonna del Prato” (poor resolution)

- Spare slides

Selected results for di-hadron LSAs

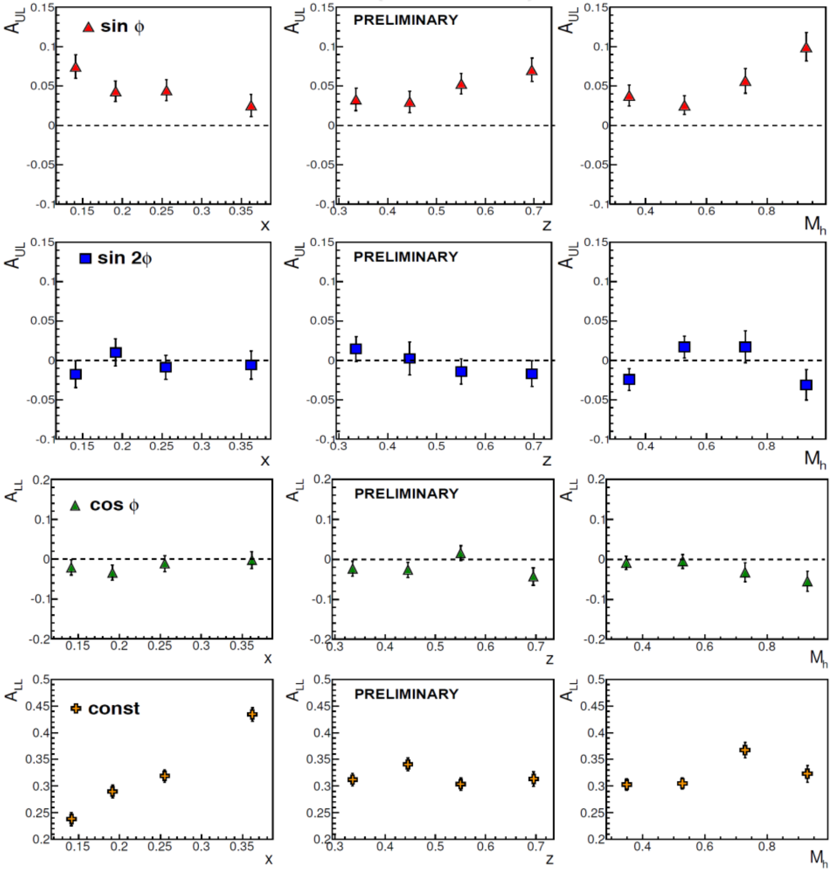
COMPASS (NH_3) 2007+2011 data: preliminary





CLAS 6 GeV (NH_3)

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

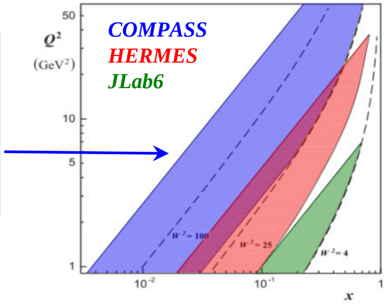


$Q^2 > 1\,(\mathrm{GeV}/c)^2$

$0.0025 < x < 0.7$

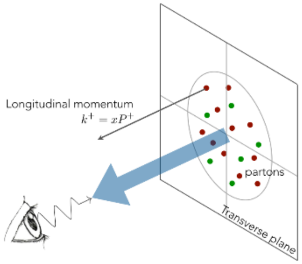
$0.1 < y < 0.9$

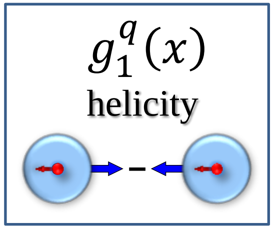
$W > 5\,\mathrm{GeV}/c^2$



- 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 $A_{UL}^{\sin2\phi_R}$ at large x?

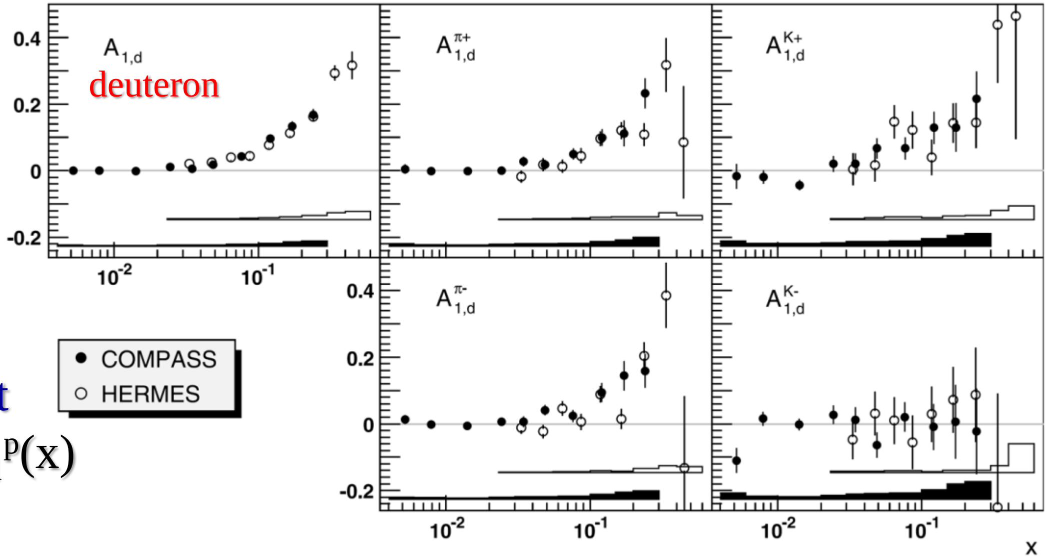
Nucleon spin structure: helicity $g^{q}_{1,d(p)}(x)$

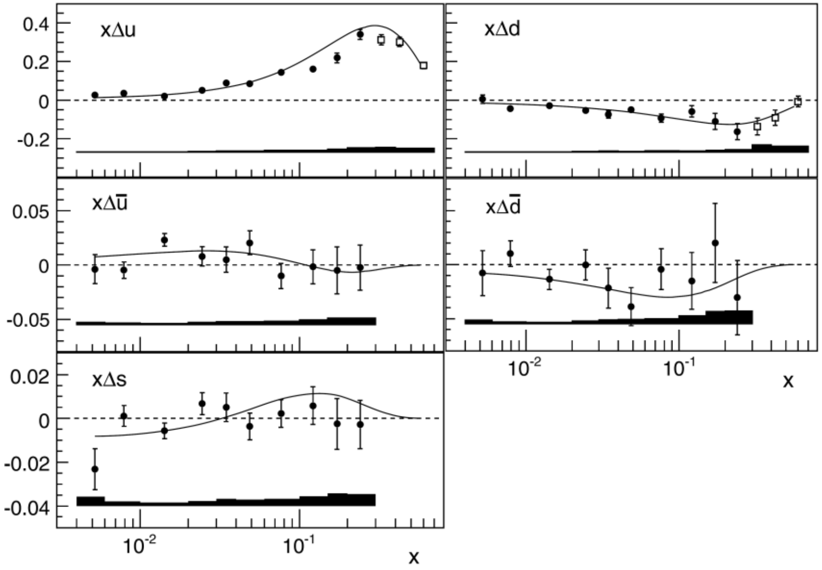




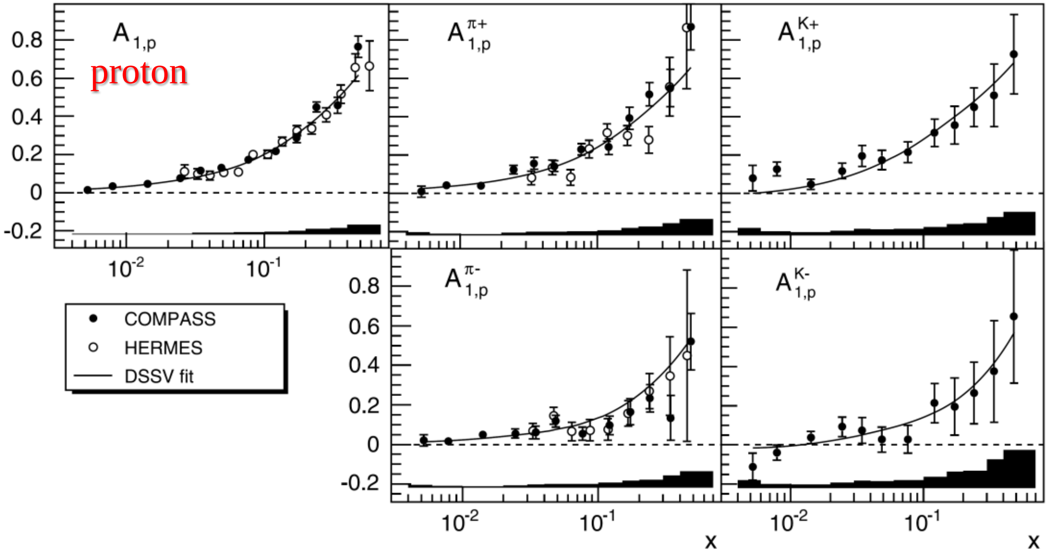
- COMPASS contribution: lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$
- Both inclusive and semi-inclusive measurements – access to flavor

COMPASS PLB 680 (2009) 217





COMPASS PLB 693 (2010) 227



SIDIS: target longitudinal spin dependent asymmetries

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

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

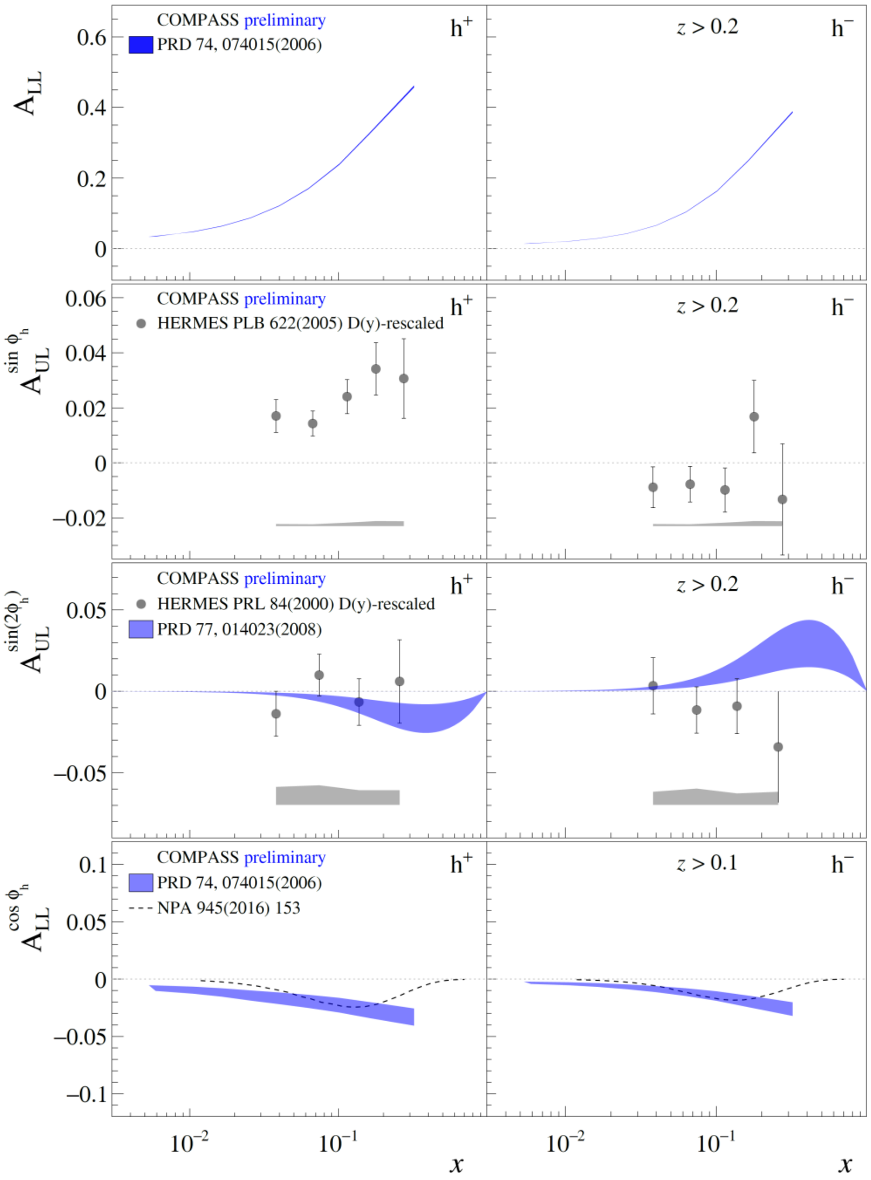
$$+\,S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL}+\sqrt{2\varepsilon\left(1-\varepsilon\right)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]\Bigg\}$$

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

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

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

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



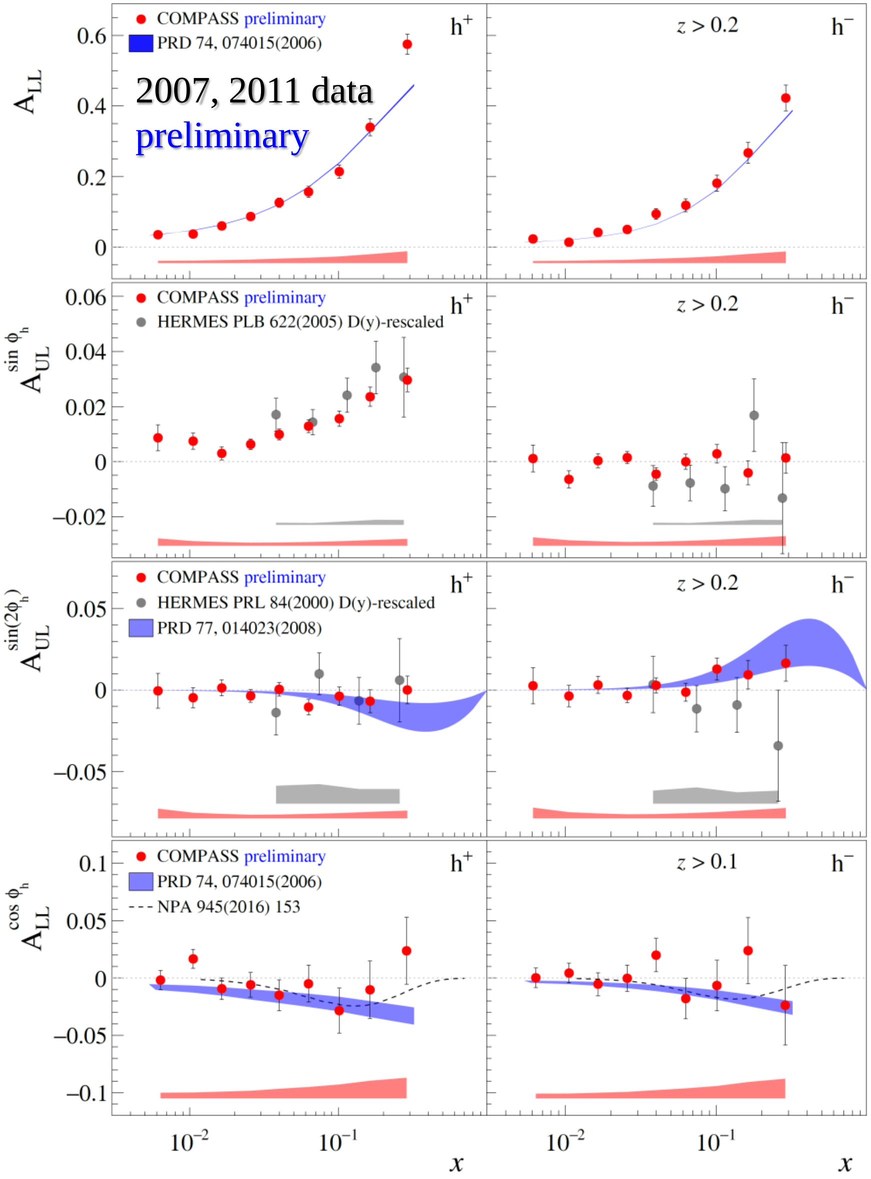
SIDIS: target longitudinal spin dependent asymmetries

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

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

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

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



COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

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

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

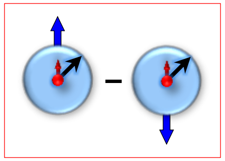
$A_{UL}^{\sin 2\phi_h}$

- Only "twist-2" ingredients
- Additional p$_T$-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

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

- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models

SIDIS TSAs: Collins effect and Transversity

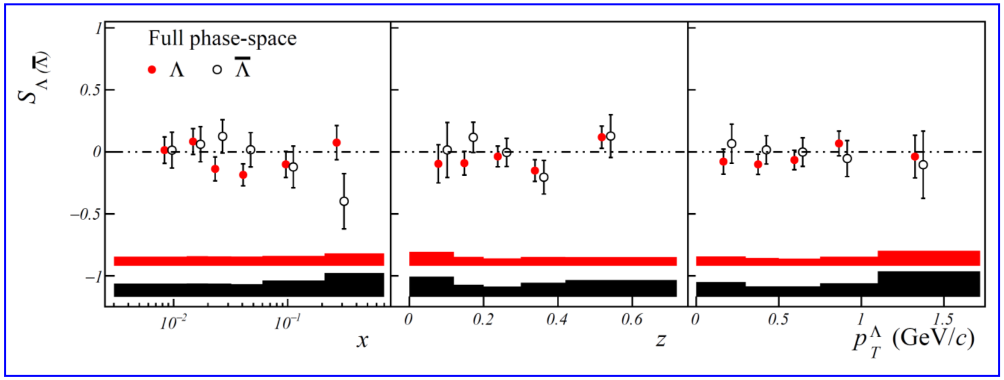


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + \ S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\ \right\}$$

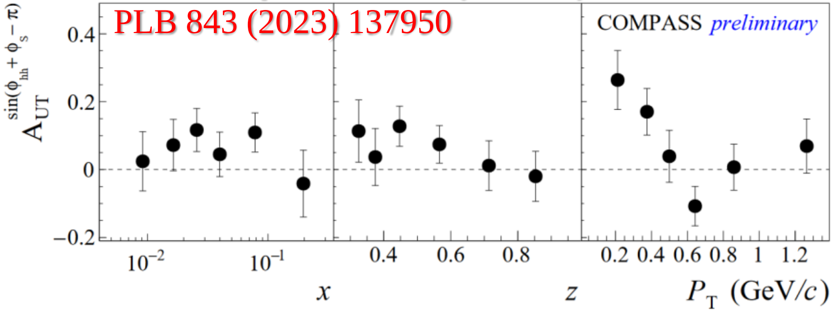
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

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

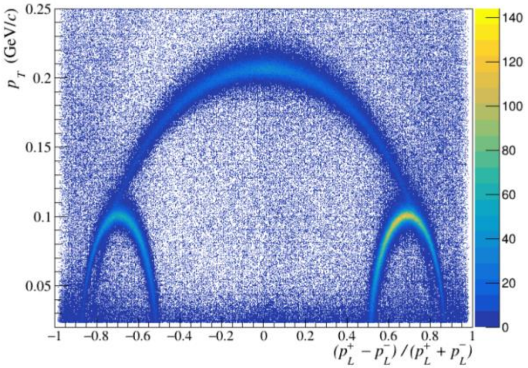
PLB 824 (2022) 136834

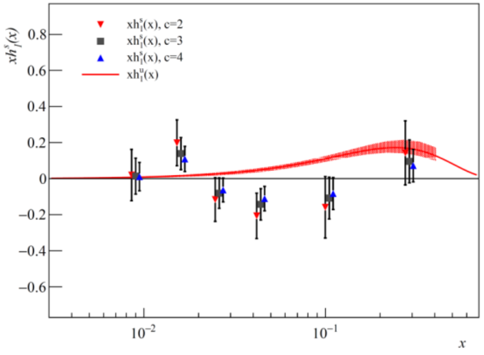


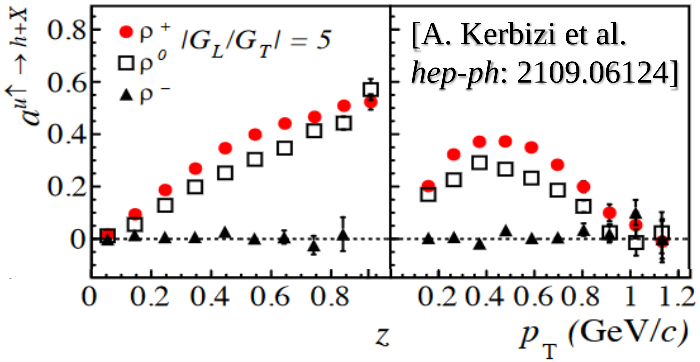
Inclusive $\boldsymbol{\rho^0}$ Collins asymmetry


PLB 843 (2023) 137950

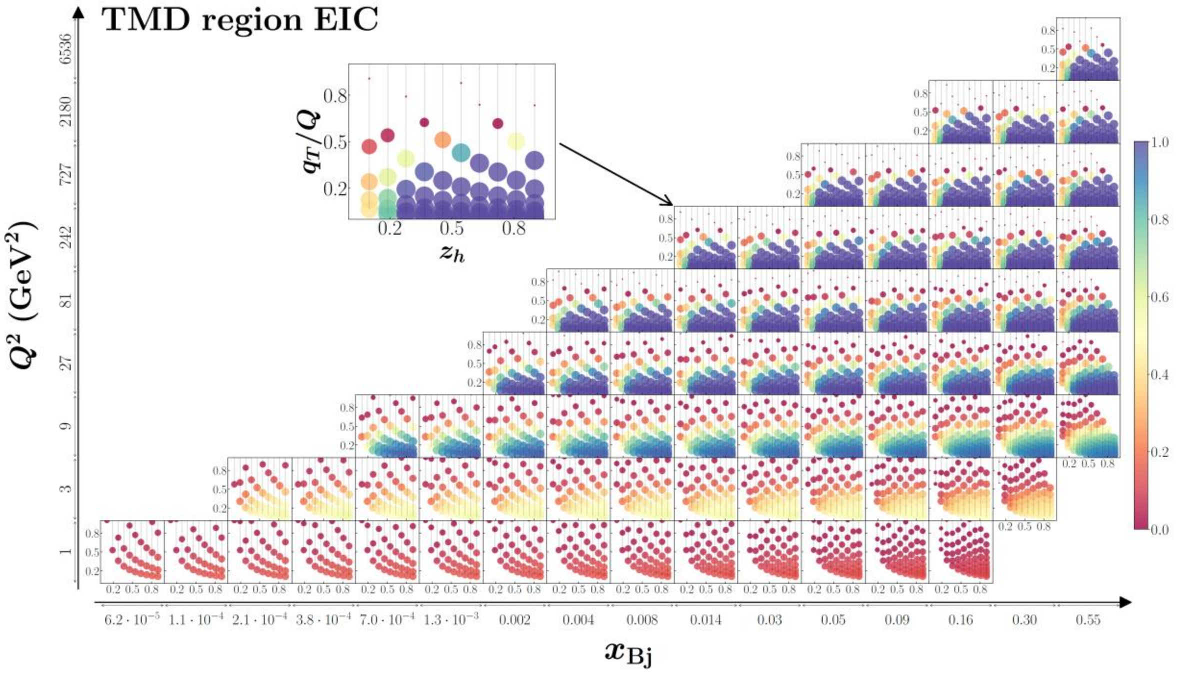
- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T



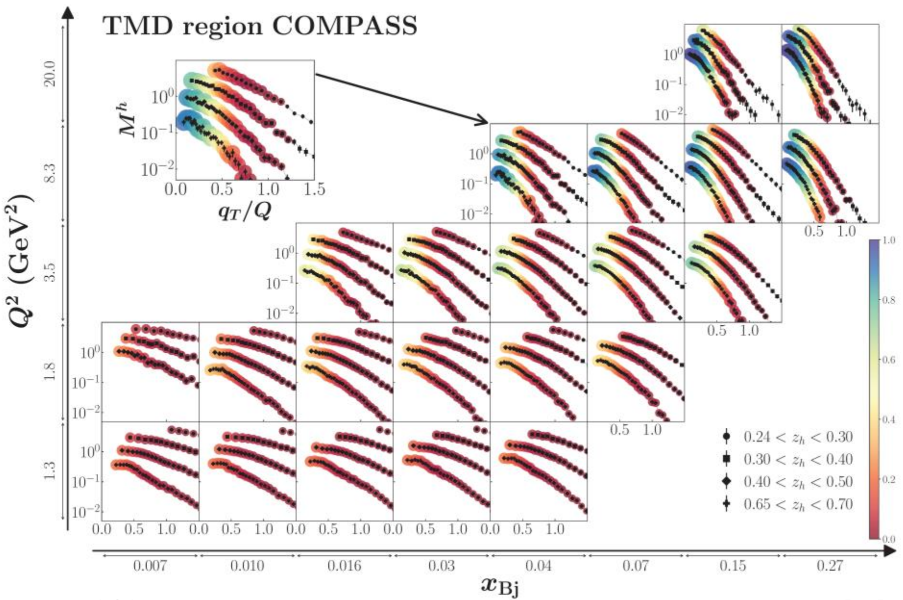


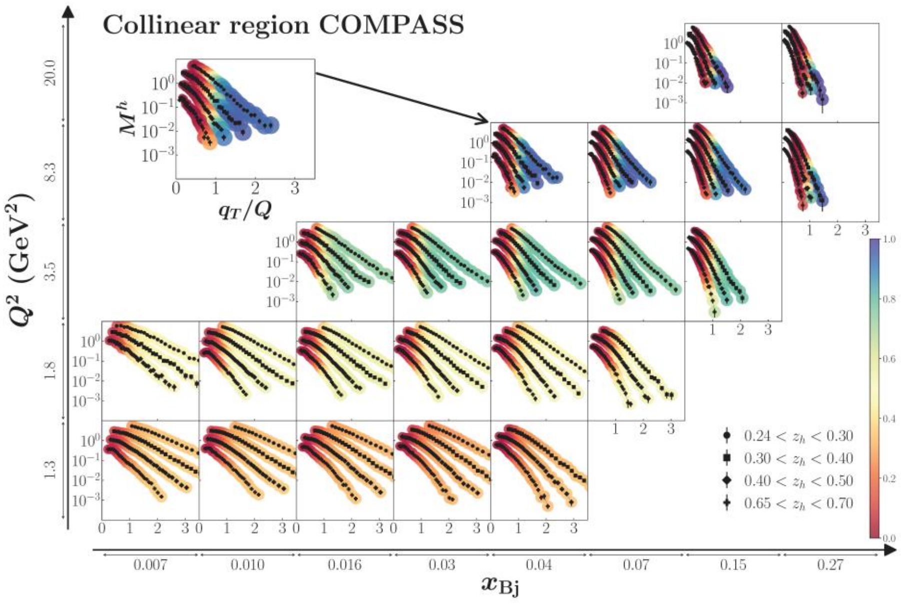

[A. Kerbizi et al. *hep-ph*: 2109.06124]

Polarized SIDIS and DY – factorization and kinematic regions

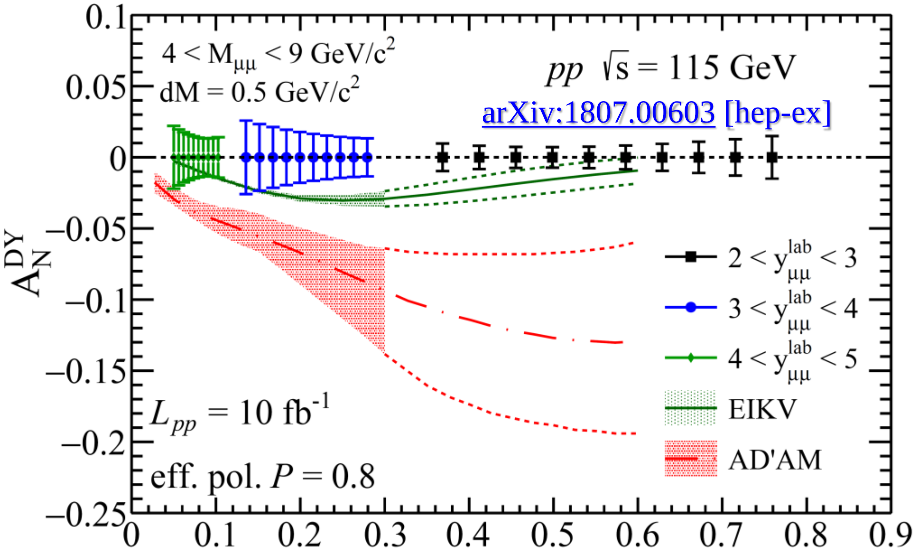


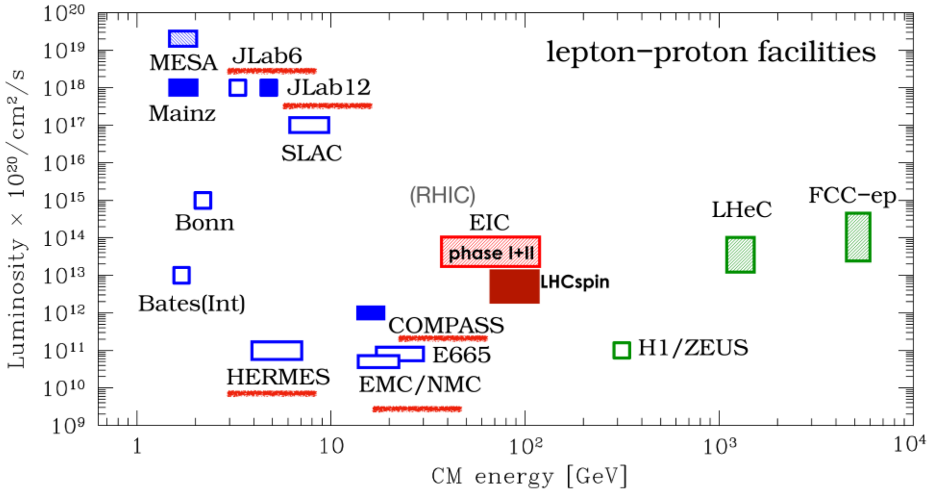
JAM, JHEP 04 (2022) 084

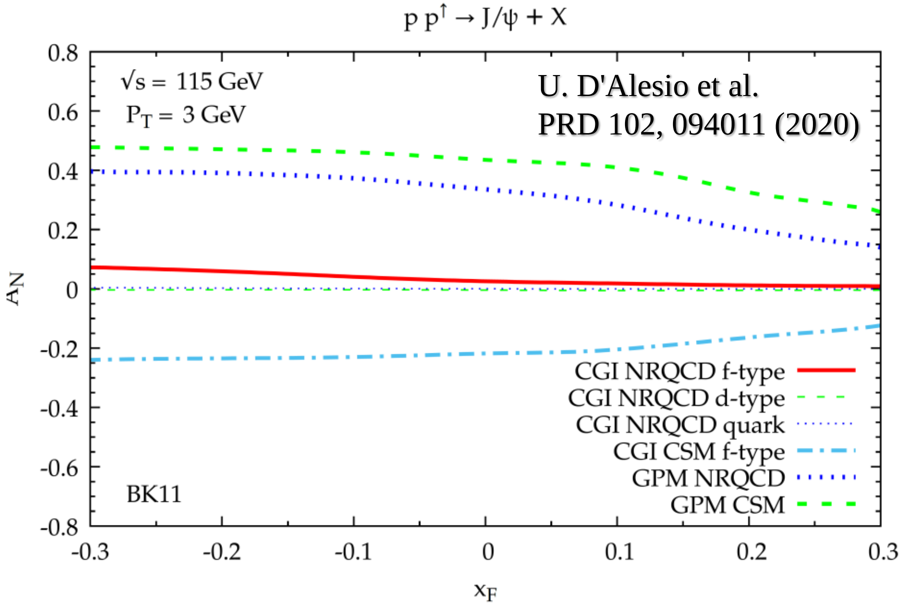


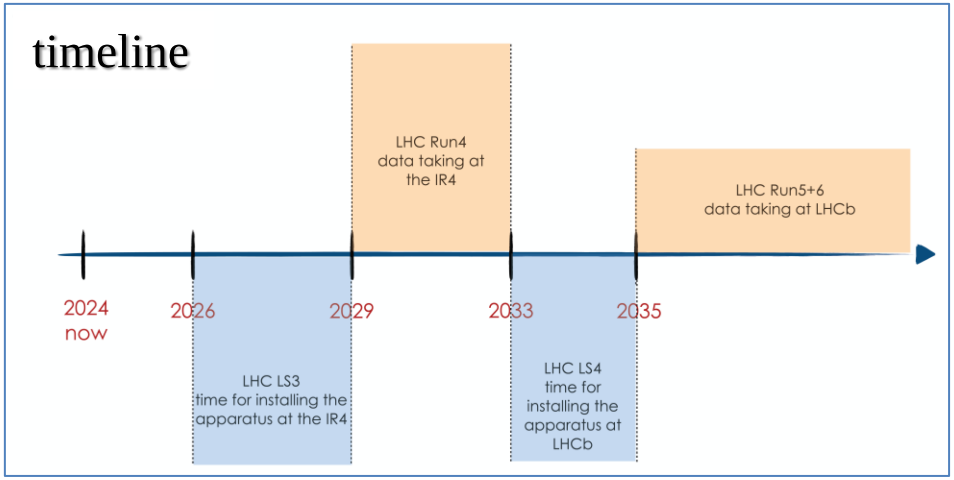


LHCspin








timeline

LHC Run4 data taking at the IR4

LHC Run5+6 data taking at LHCb

2024 now

2026

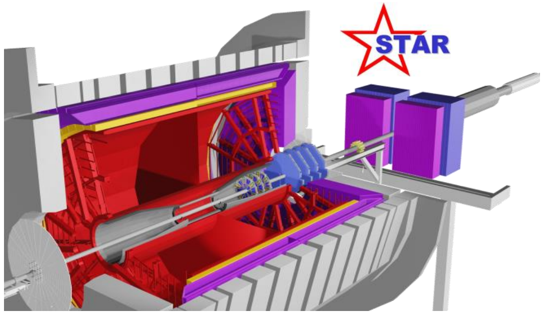
2029

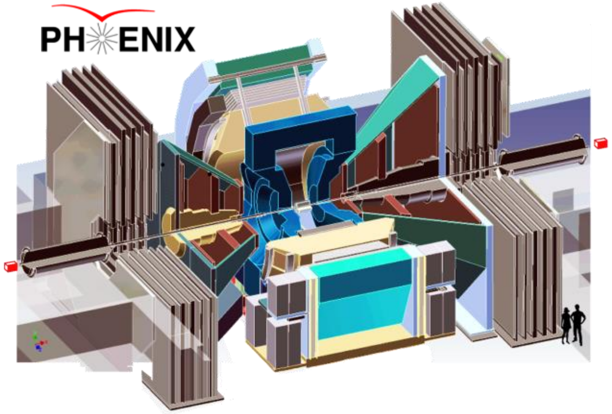
2033

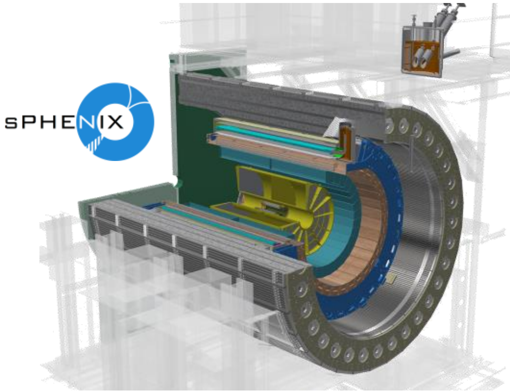
2035

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)

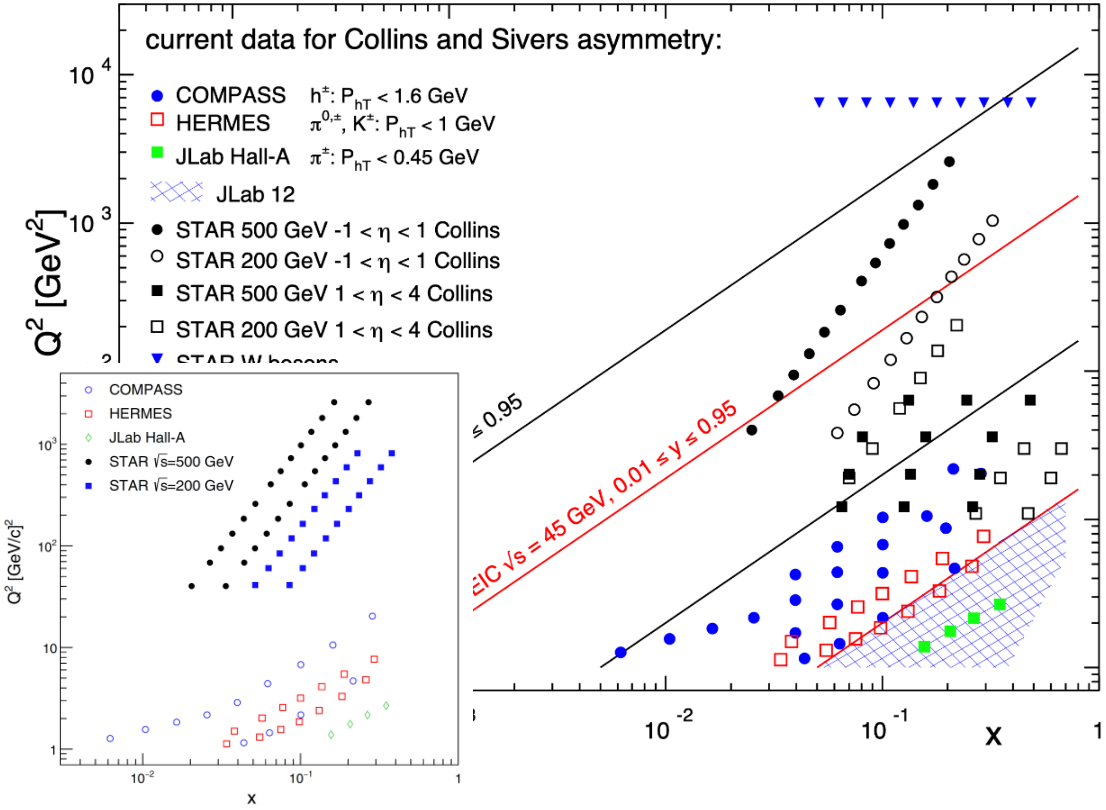
$\sqrt{s}$ = 200, 500/510 GeV

STAR (2000-2025)

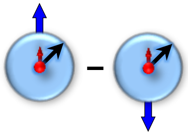
- Collins asymmetry at mid-rapidity (200 and 510 GeV *pp)*
- Similar *x*-coverage as in SIDIS experiments
- 1-2 order of magnitude larger Q^2
- Forward upgrade → x>0.5, intermediate Q^2 (SIDIS – STAR mid-rapidity)

PHENIX (2000-2015)

sPHENIX starting 2024-2025



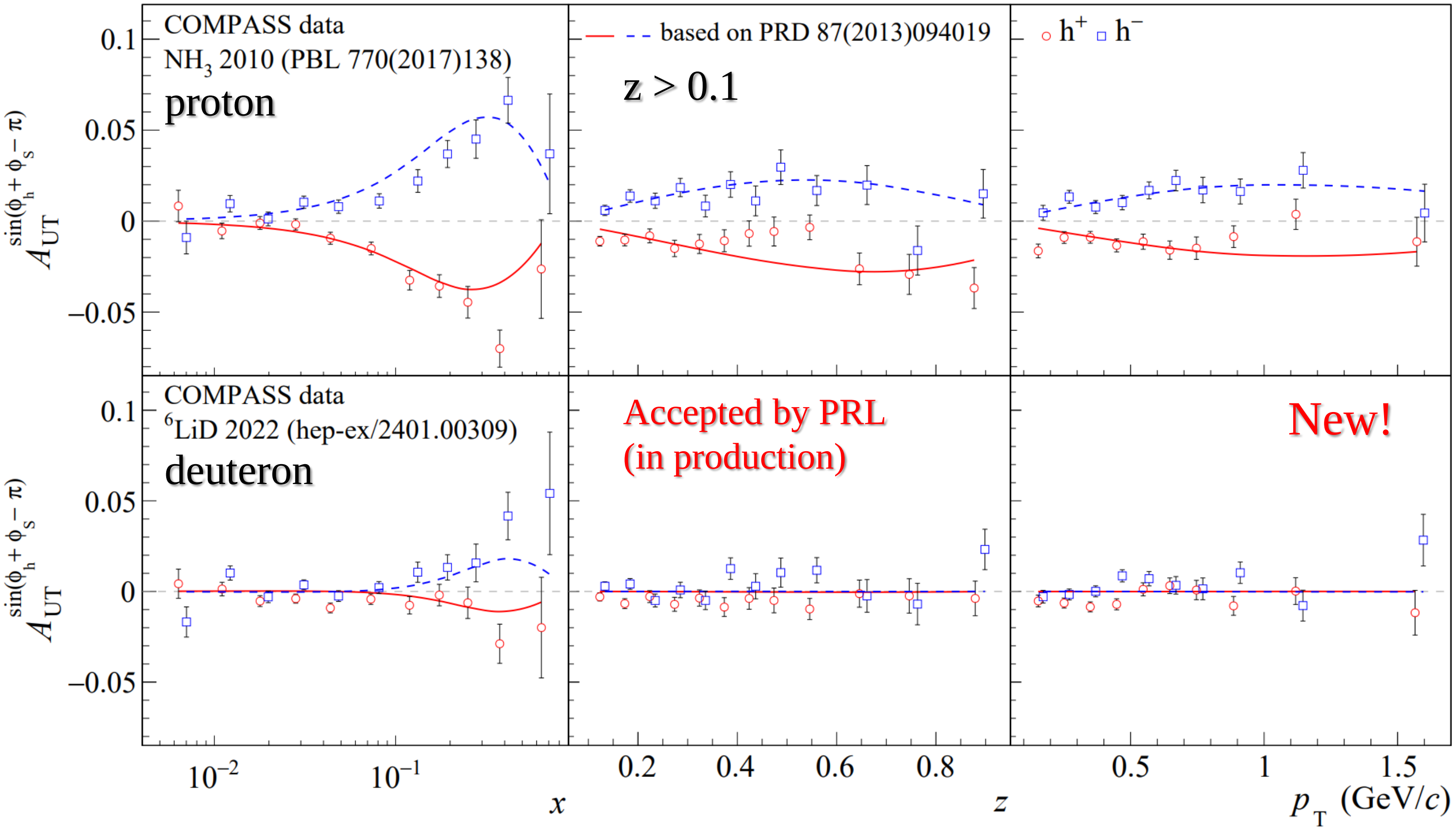
SIDIS TSAs: Collins effect and Transversity



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

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

- 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