The role of multi-D approach in TMD studies: COMPASS experience

Bakur Parsamyan

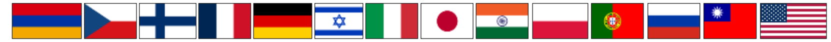
AANL, CERN and Yamagata University

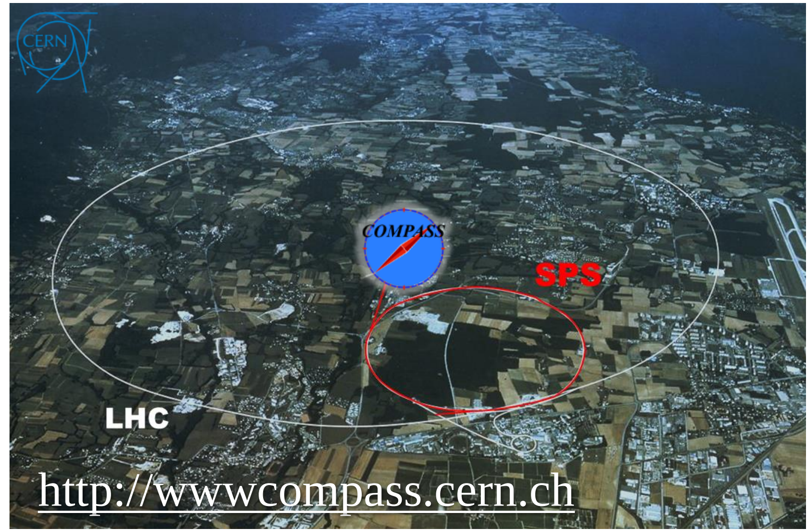
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV
December 9 – 13, INFN, Laboratori Nazionali di Frascati, Italy

COMPASS timeline

- CERN SPS north area – M2 beamline
- Fixed target experiment
- Approved in 1997
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

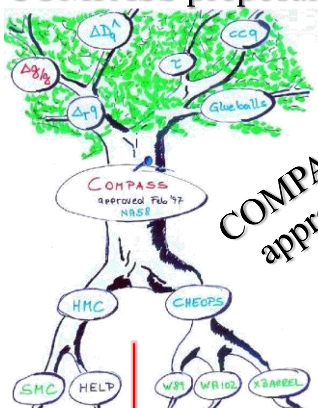
33 institutions from 15 countries: ~ 200 members

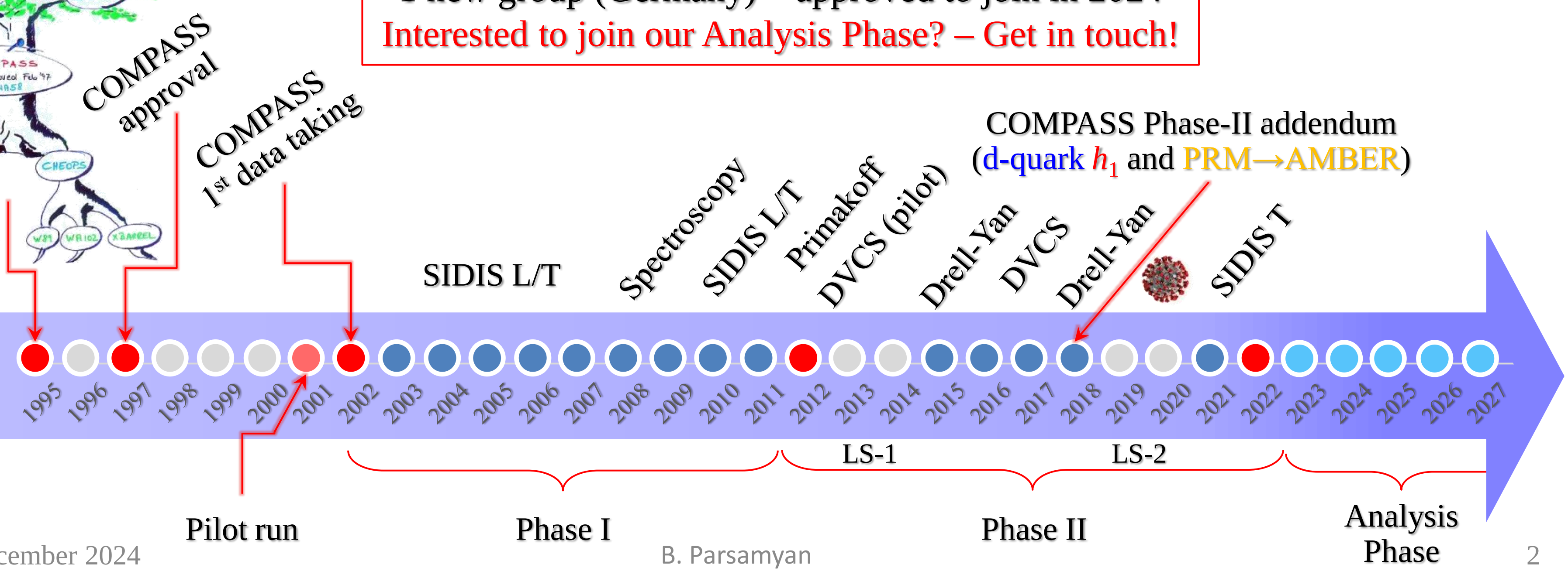




3 new groups joined COMPASS in 2023
UCon (US), AANL (Armenia), NCU (Taiwan)
1 new group (Germany) – approved to join in 2024
Interested to join our Analysis Phase? – Get in touch!

COMPASS proposal

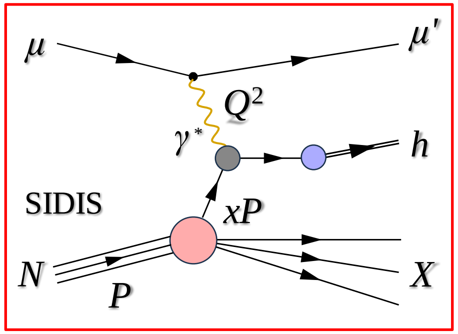


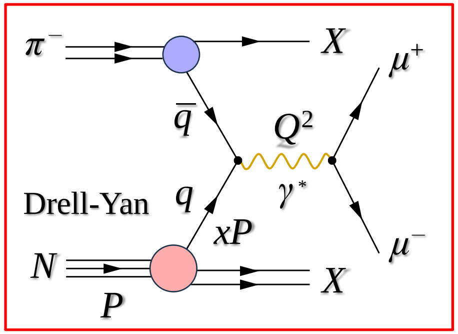


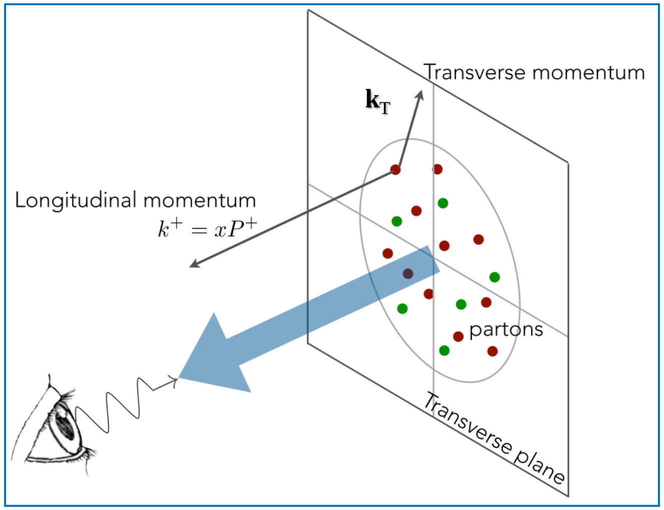
COMPASS Physics Program

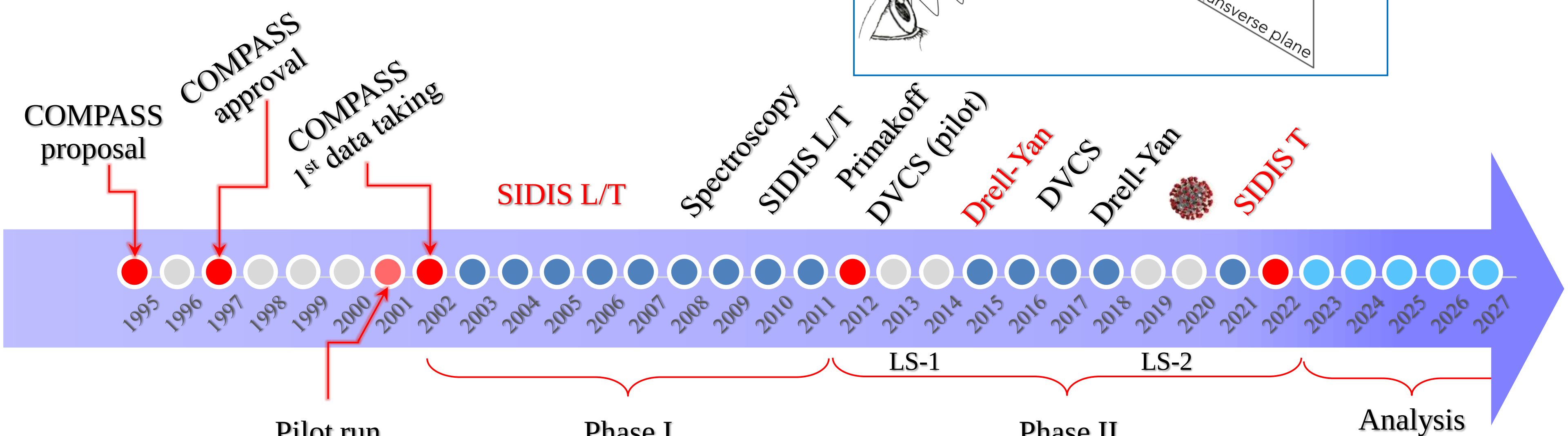
Nucleon structure

- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Inclusive and Semi-Inclusive DIS
- Drell-Yan and J/ψ production
- Study of nucleon spin structure
  - Longitudinal and Transverse
- Collinear and TMD pictures
- Parton distribution functions and fragmentation functions
- Last COMPASS measurement: 2022 run – transverse SIDIS









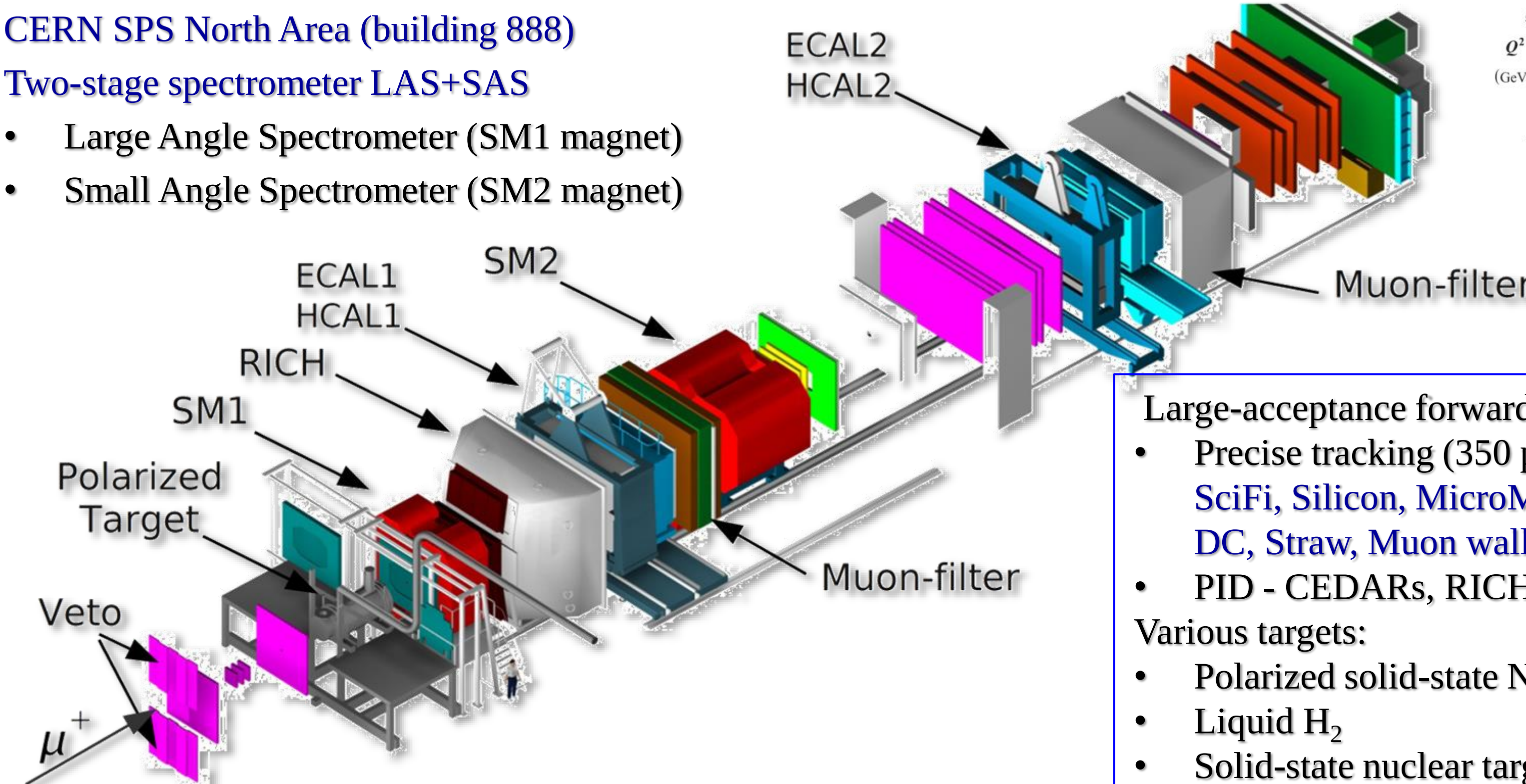
COMPASS experimental setup

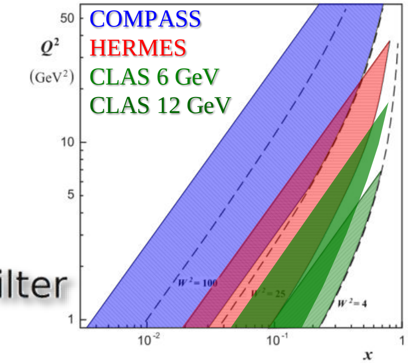
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





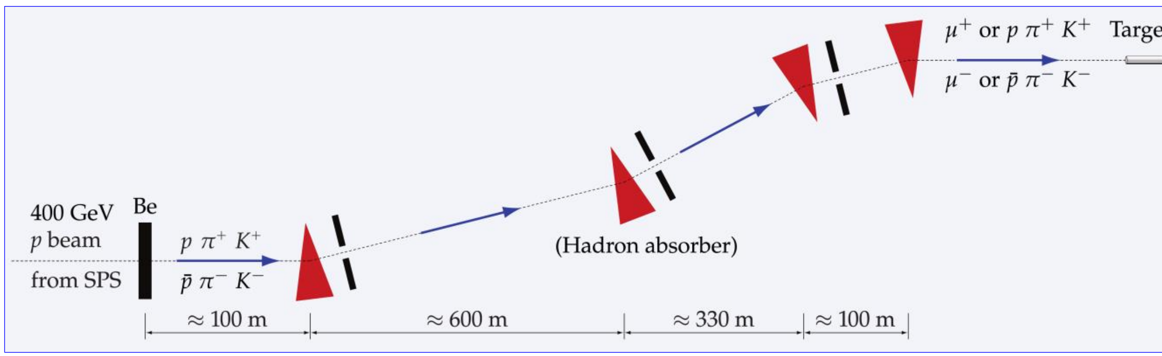
Large-acceptance forward spectrometer

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

Various targets:

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

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



COMPASS experimental setup: Phase II (SIDIS program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
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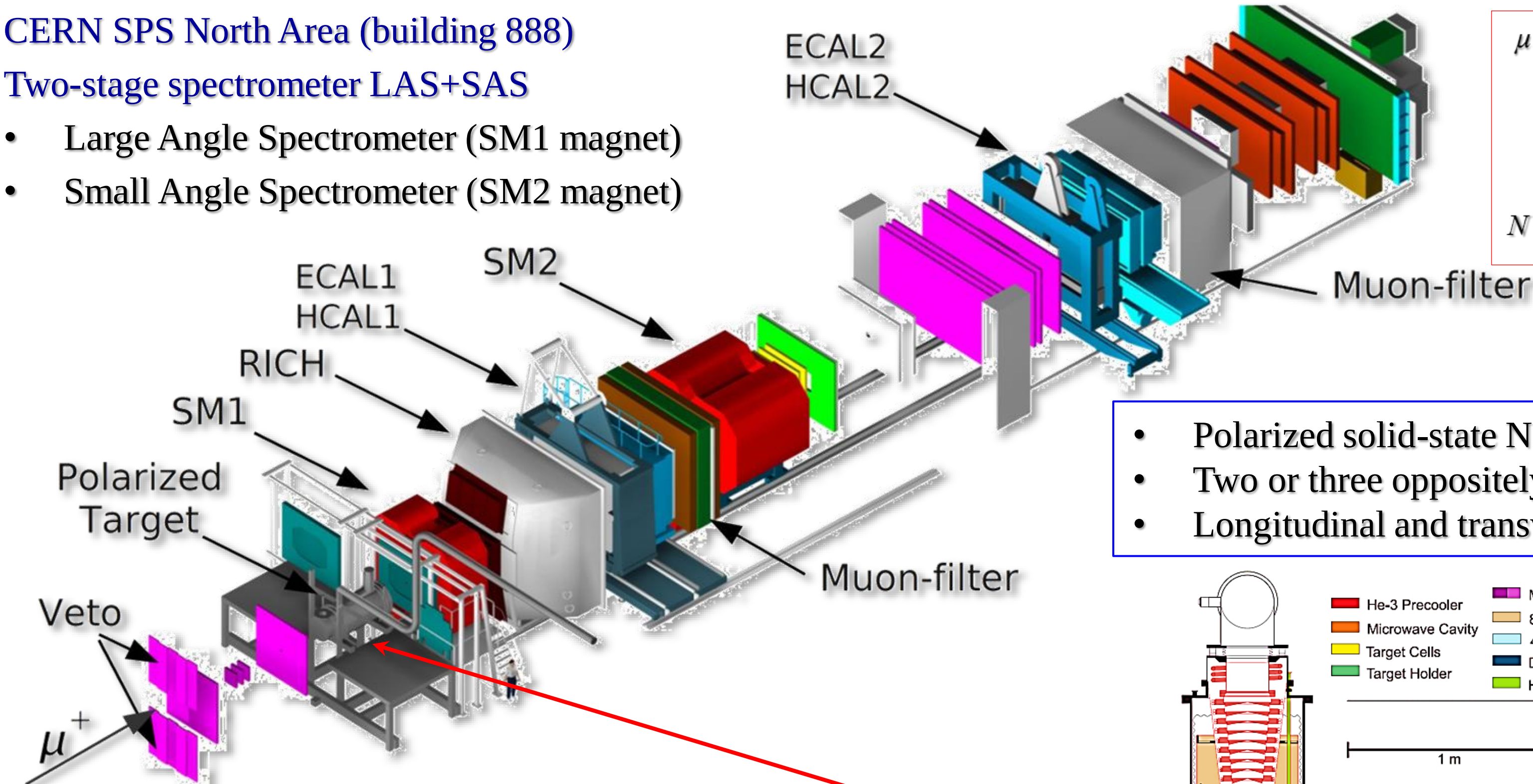
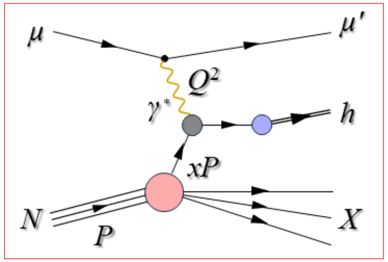
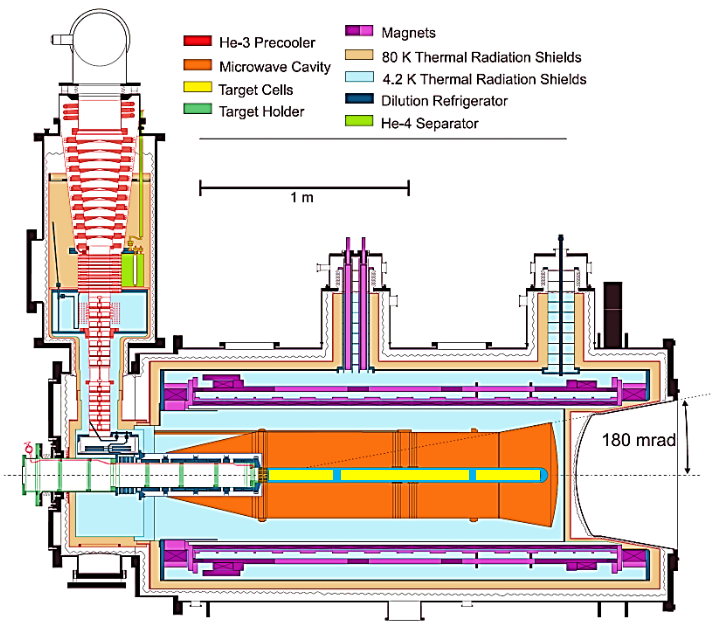




- Polarized solid-state NH_3 or ^{6}LiD
- Two or three oppositely polarized cells
- Longitudinal and transverse polarization

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



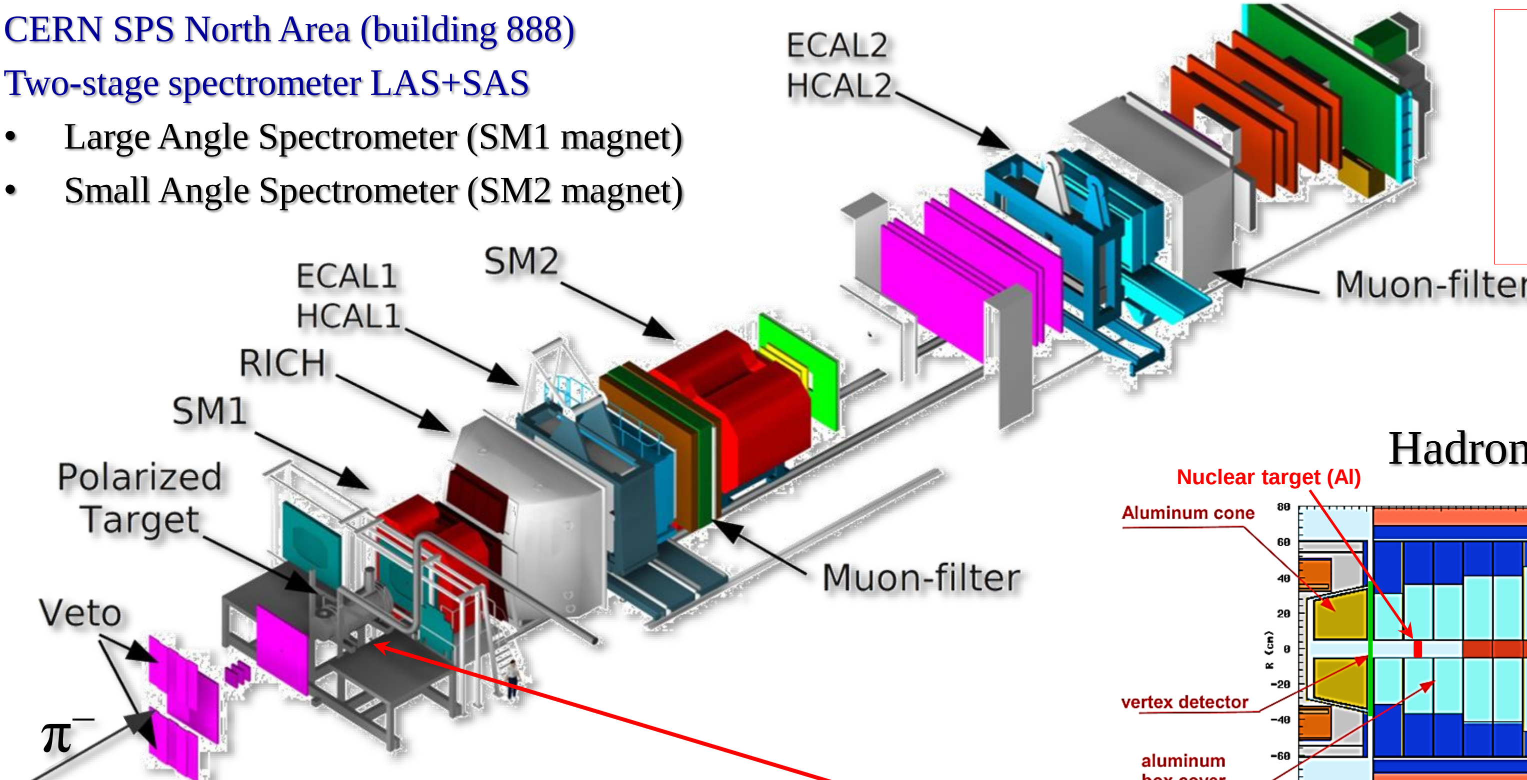
COMPASS experimental setup: Phase II (DY program)

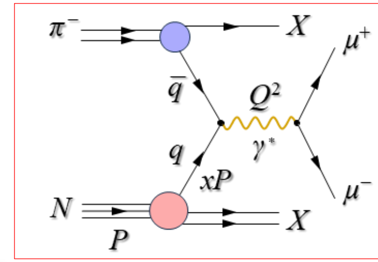
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

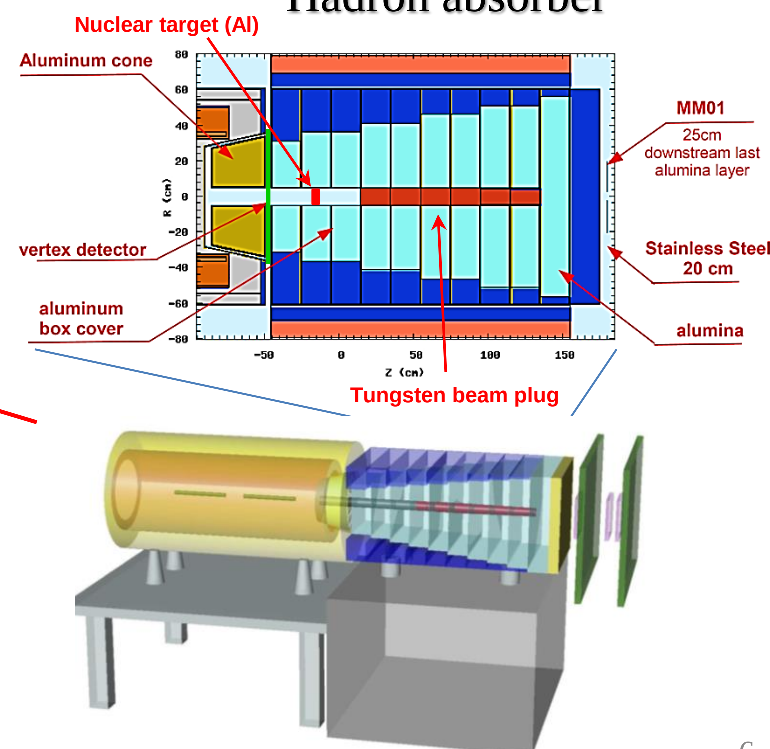
Two-stage spectrometer LAS+SAS

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





Hadron absorber



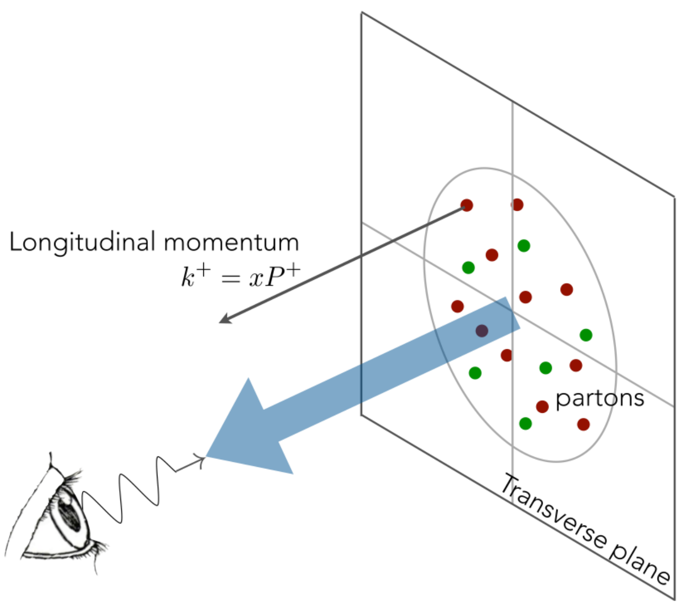
- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h⁻ beam: 97% π^-, 2% K^-, 1% p
  - h⁺ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

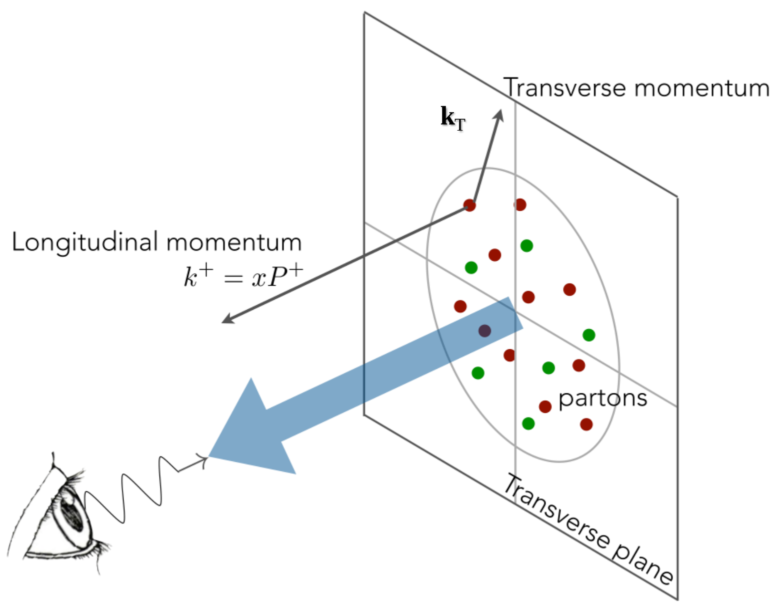
Nucleon spin structure (twist-2): collinear approach ↔TMDs

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

nucleon \ quark	U	L	T
U	$f_1^q(x, \boldsymbol{k}_T^2)$ number density		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



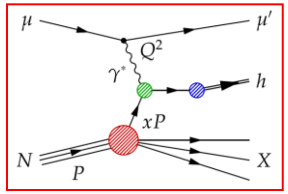


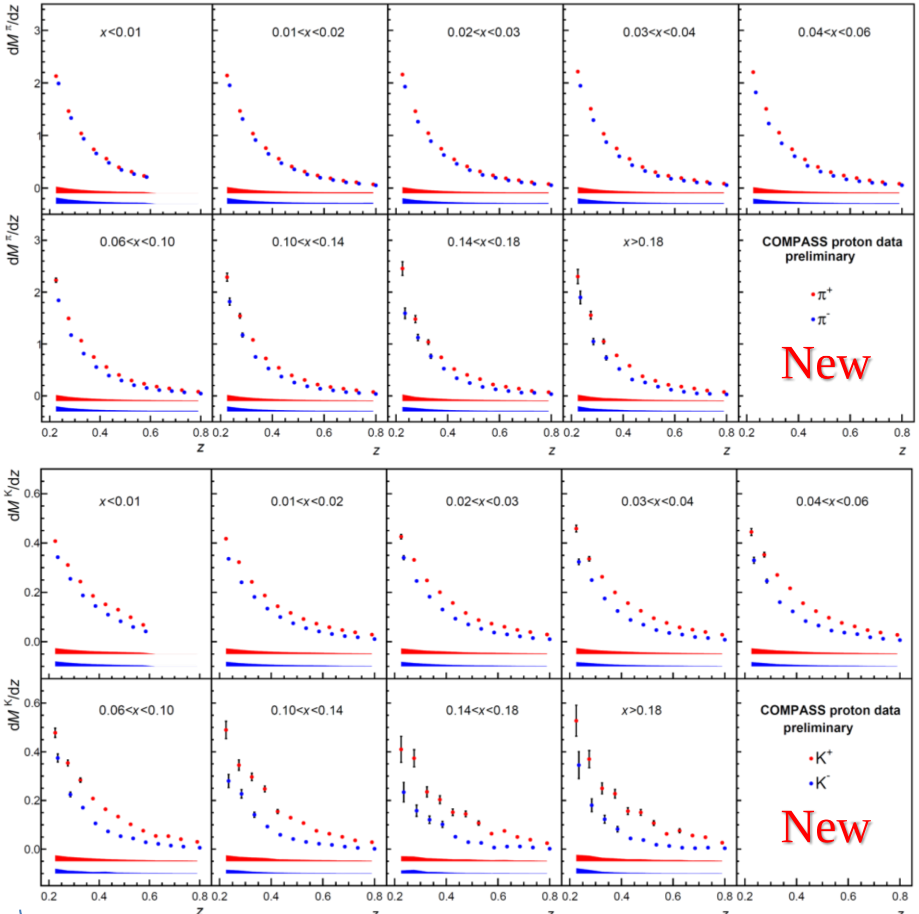
Hadron multiplicities; $h^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ (2016 data)

collinear

A set of complex corrections:

- Acceptance, rad. corrections, PID, diffractive VMs, etc.

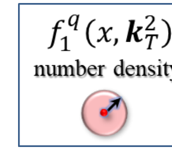


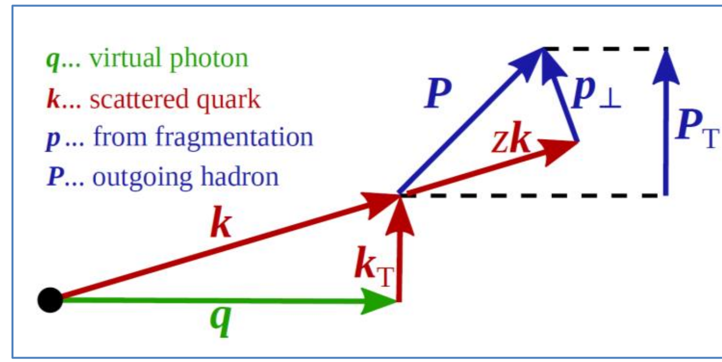


New radiative corrections (DJANGOH)

hep-ex/2410.12005 submitted to PRD

TMD





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

collinear

A set of complex corrections:

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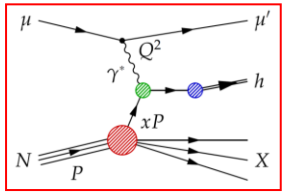
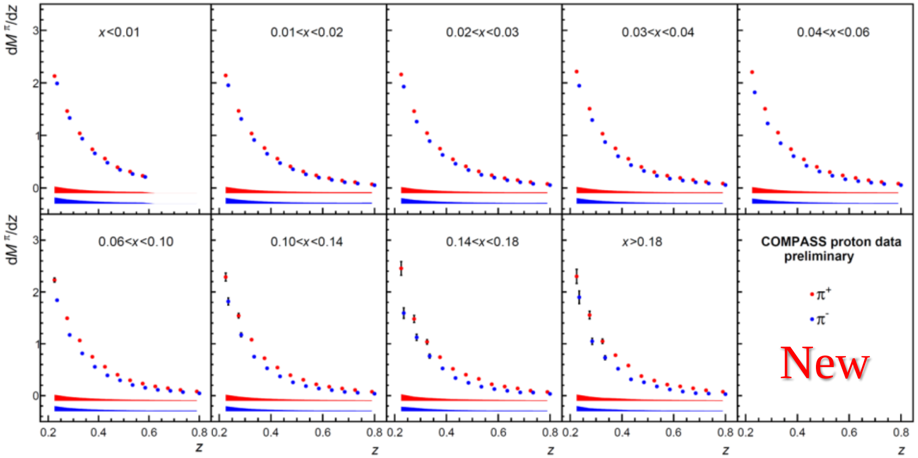
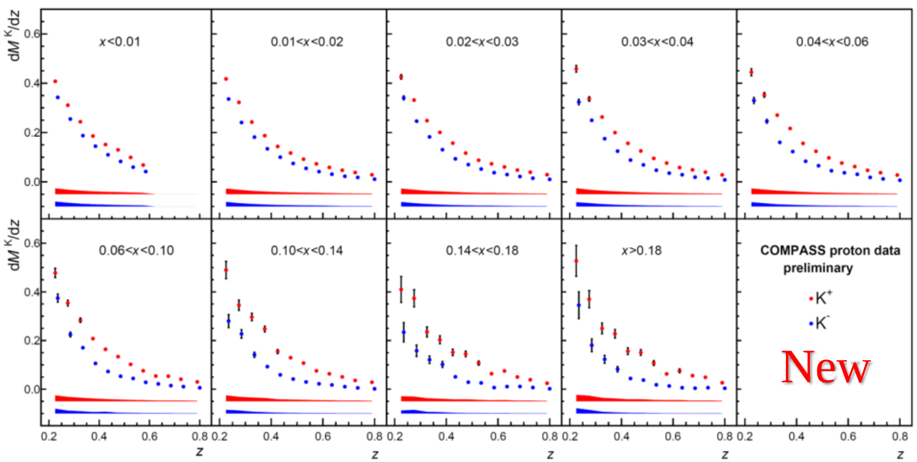
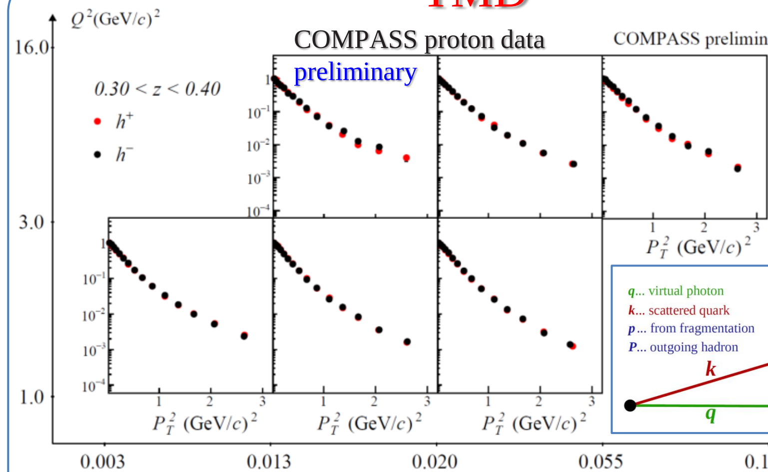
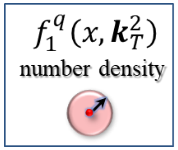


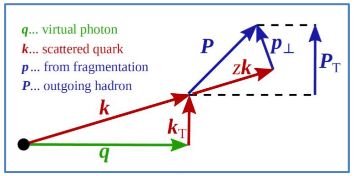


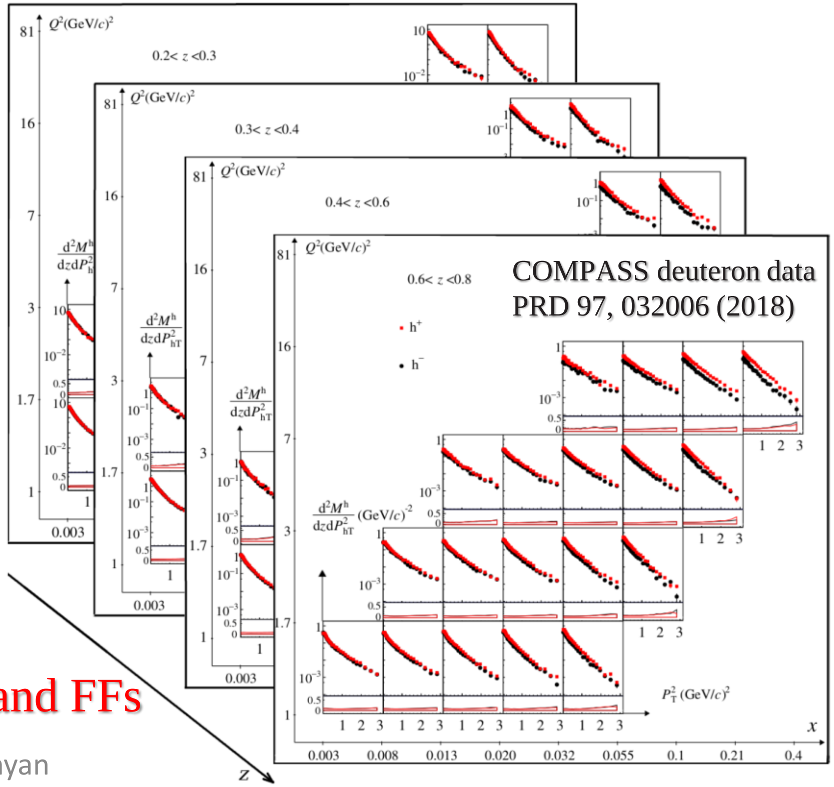


TMD





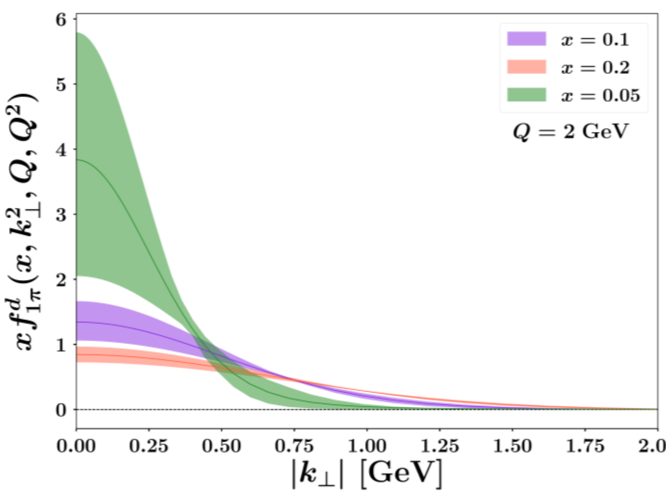




New radiative corrections being applied

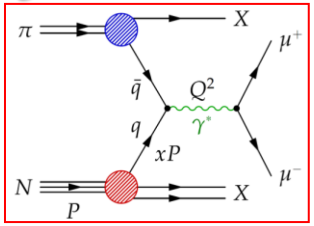
Multi-D is crucial to explore all features of PDFs and FFs

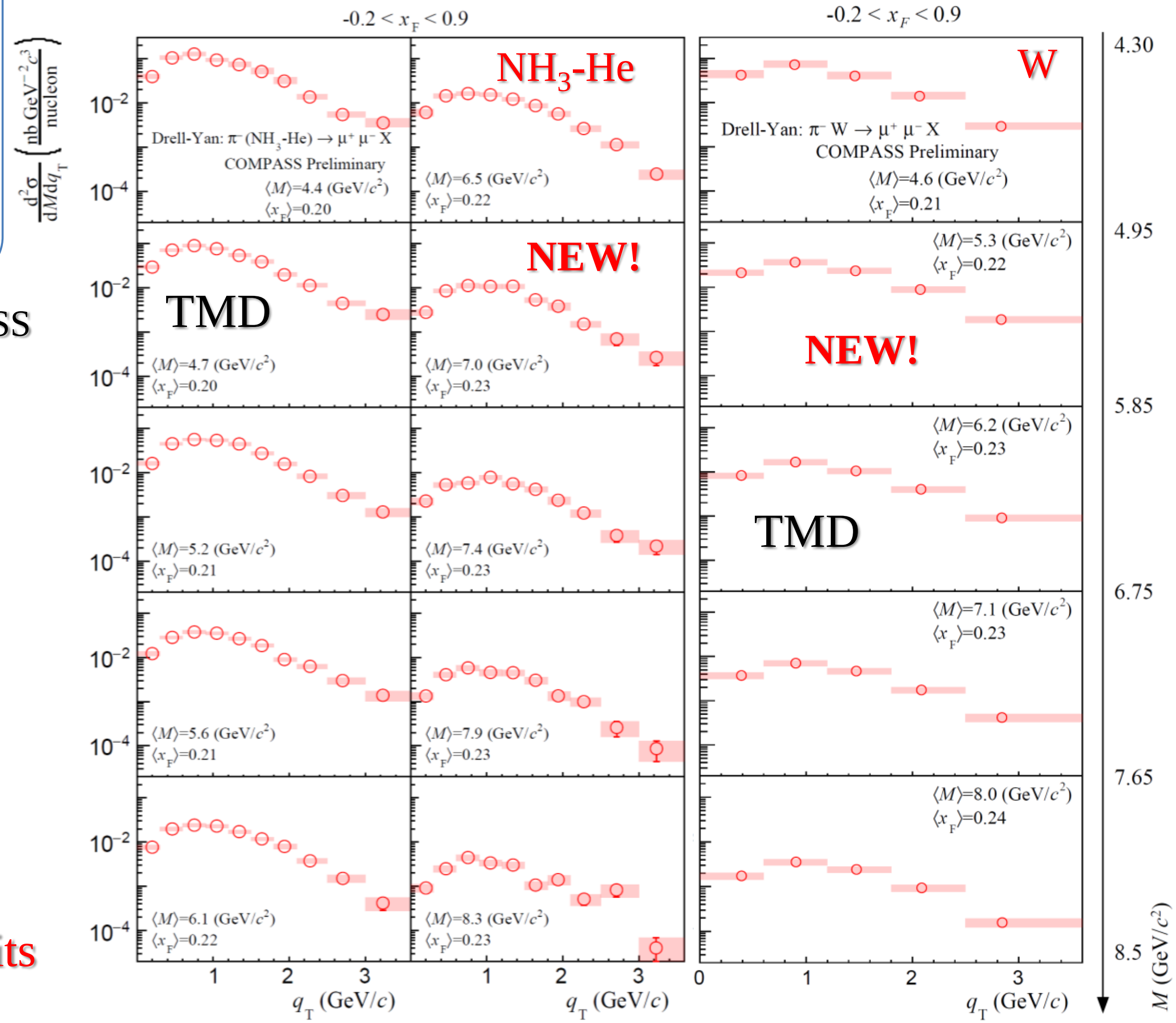
3D unpolarized Drell-Yan cross section on NH_3 and W



MAP collaboration
Phys. Rev. D. 107, 014014

recent global fit and projections for COMPASS





- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF
- To be included in future global fits (MAP, JAM, etc.)

SIDIS x-section and TMDs at twist-2

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

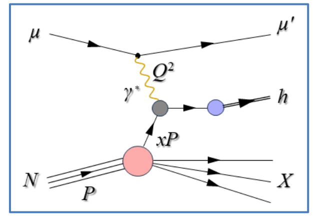
$$\times\Big\{1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos2\phi_h}\cos2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin2\phi_h}\sin2\phi_h\right]$$

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

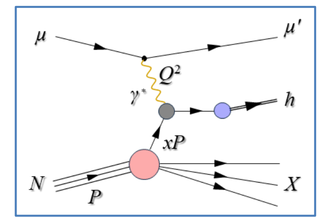
$$+S_T\left[\begin{array}{l}A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)\\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S\\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\end{ar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

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



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
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



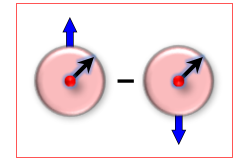
$$\frac{d\sigma^{LO}}{dq^4d\Omega}\propto F_U^1\left(1+\cos^2\theta_{CS}\right)$$

$$\times\Big\{1+D_{[\sin^2\theta_{CS}]}A_U^{\cos2\varphi_{CS}}\cos2\varphi_{CS} + S_L\sin^2\theta_{CS}A_L^{\sin2\varphi_{CS}}\sin2\varphi_{CS}$$

$$+S_T\left[A_T^{\sin\varphi_S}\sin\varphi_S + D_{[\sin^2\theta_{CS}]}\left(A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S)+A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S)\right)\right]\Big\}$$

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

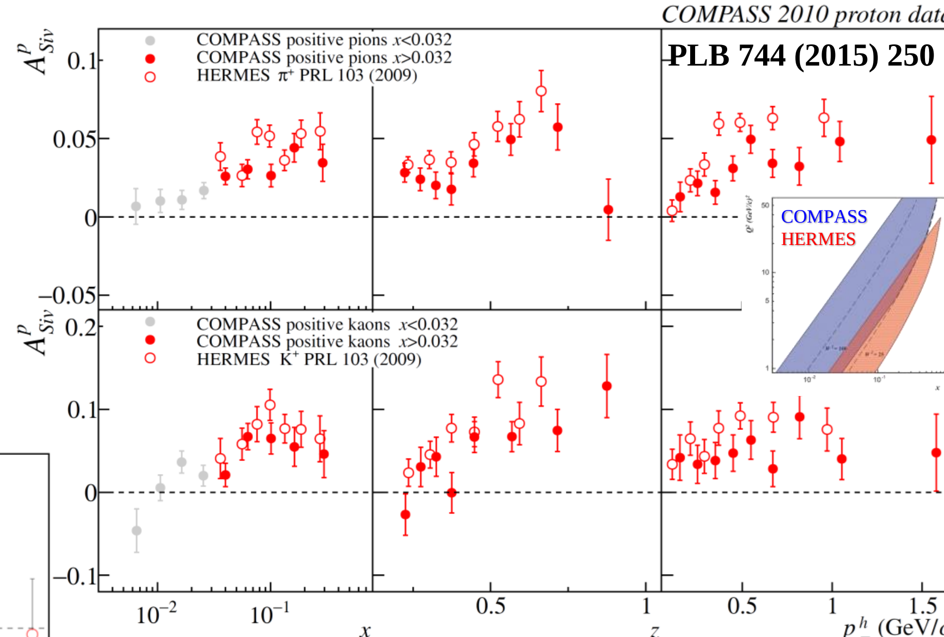
SIDIS TSAs: Sivers effect

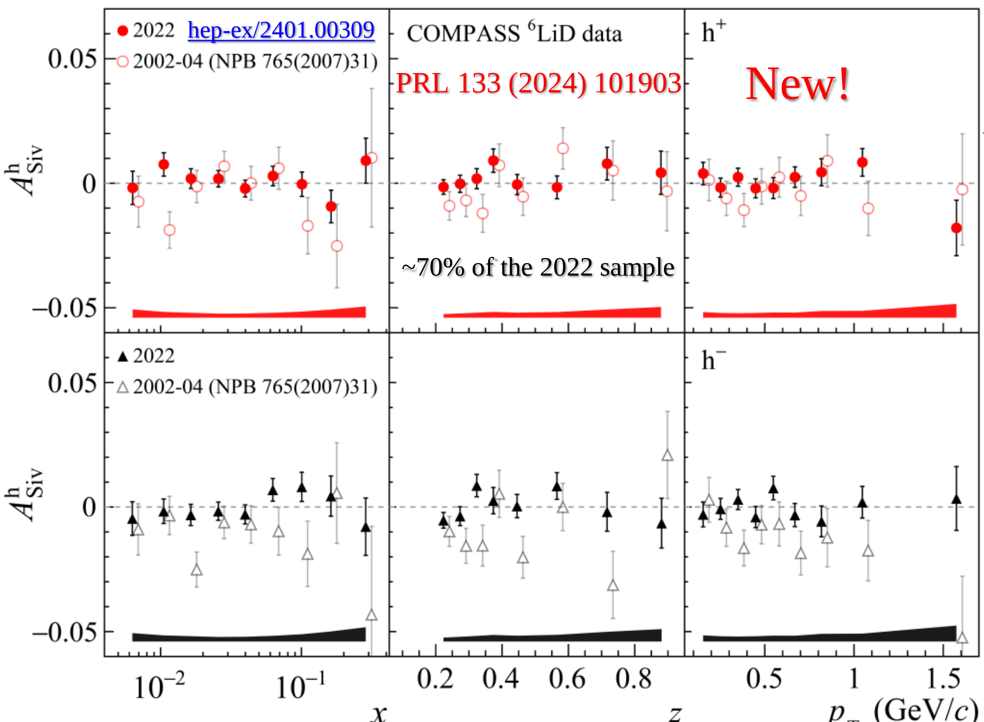


$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\;S_T\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+\ldots\right\}$$

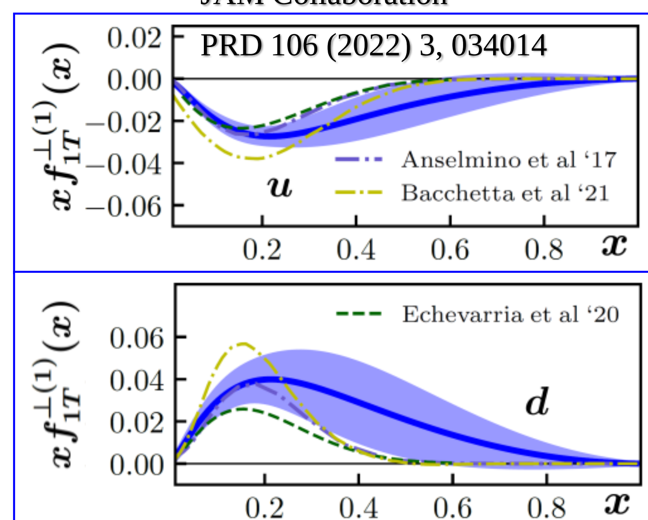
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\,f_{1T}^{\perp q}D_{1q}^{h}\right],\; F_{UT,L}^{\sin(\phi_h-\phi_S)}=0$$

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





JAM Collaboration



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

$Q^2 \geq 1.4$ GeV² $\quad 0.2 \leq z \leq 0.7$

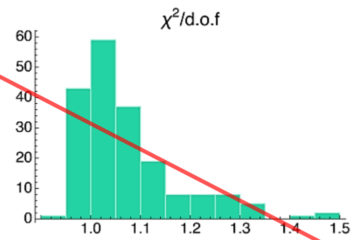
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

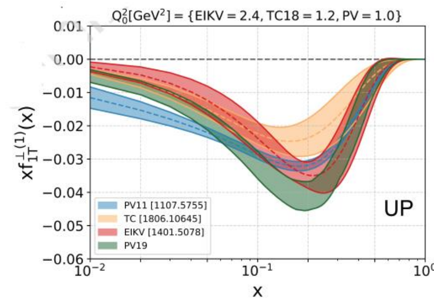
x, z, P_{hT} data projections

300 data points → **118** data fitted

14 free parameters

χ^2/d.o.f. = 1.06 ± 0.10

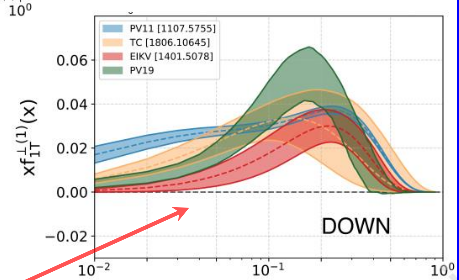




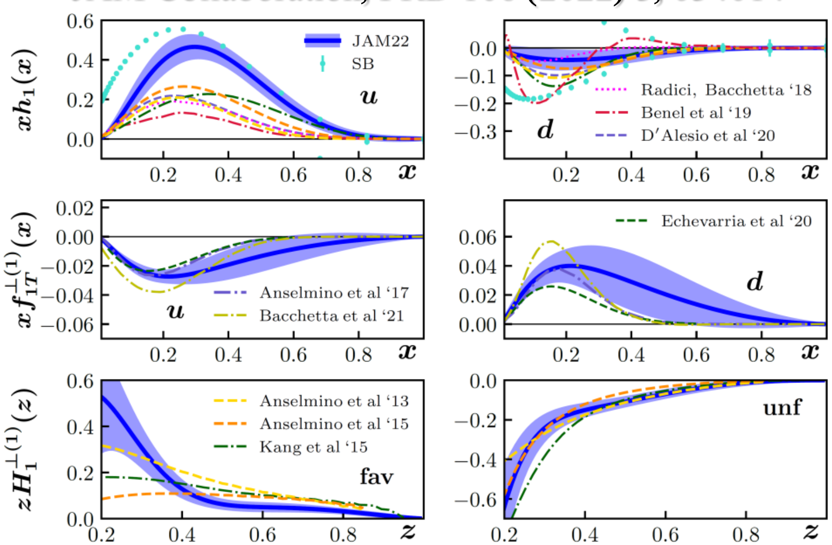
PV11	*Bacchetta & Radici, P.R.L.* ***107*** *(11)*
EIKV	*Echevarria et al., P.R. D**89** (14)*
TC	*Boglione et al., JHEP* ***1807*** *(18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

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

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

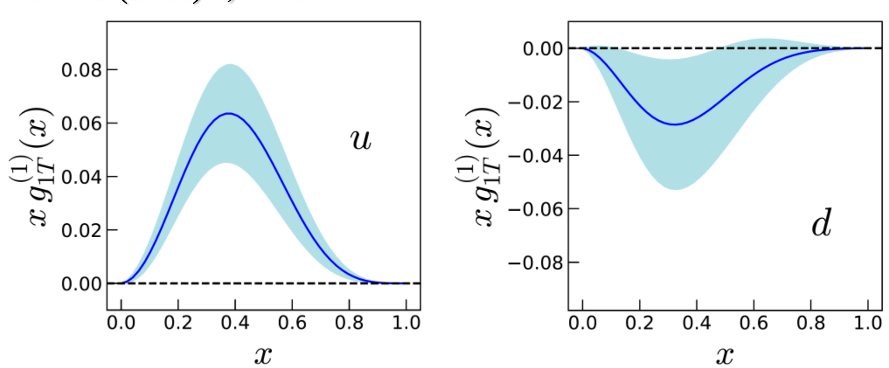


JAM Collaboration, PRD 106 (2022) 3, 034014



COMPASS 2022 deuteron run

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



More news soon…

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

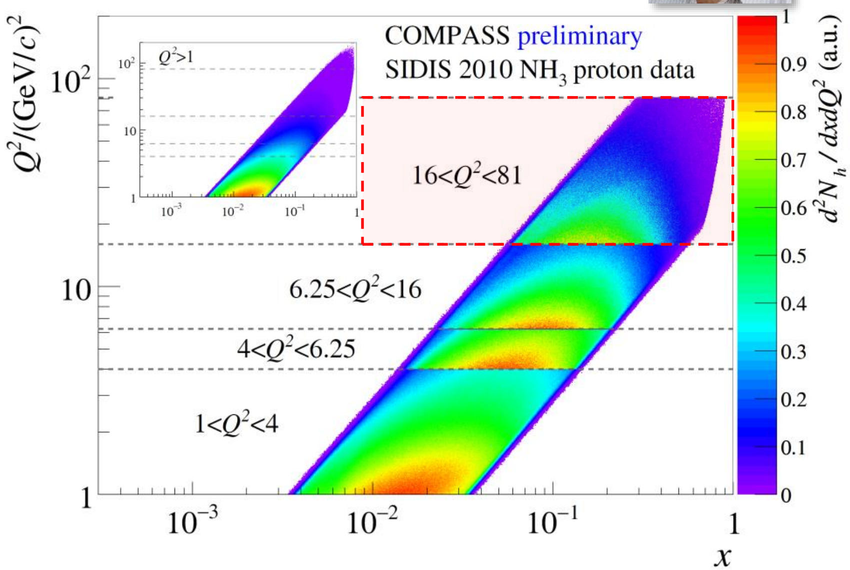
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin\left(\phi_h - \phi_S\right) + \ldots\right\}$$

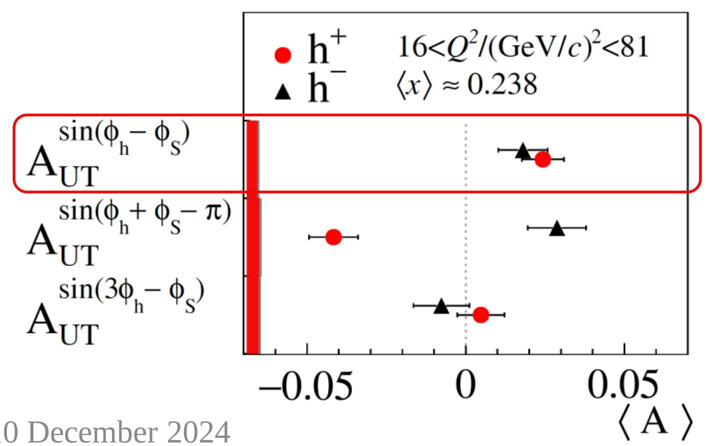
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{k_T}}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

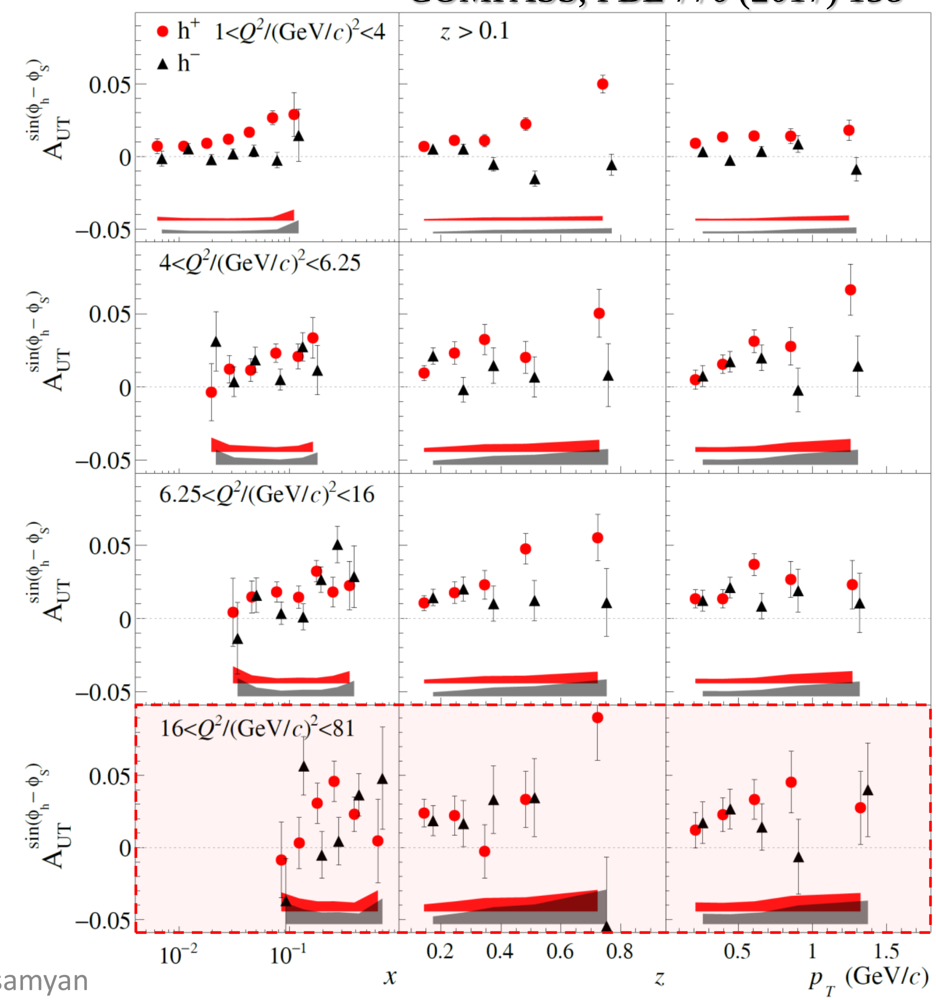
- COMPASS-HERMES discrepancy
- Q^2-evolution effect?

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

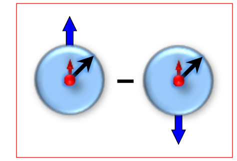
COMPASS, PBL 770 (2017) 138







SIDIS TSAs: Collins effect and Transversity



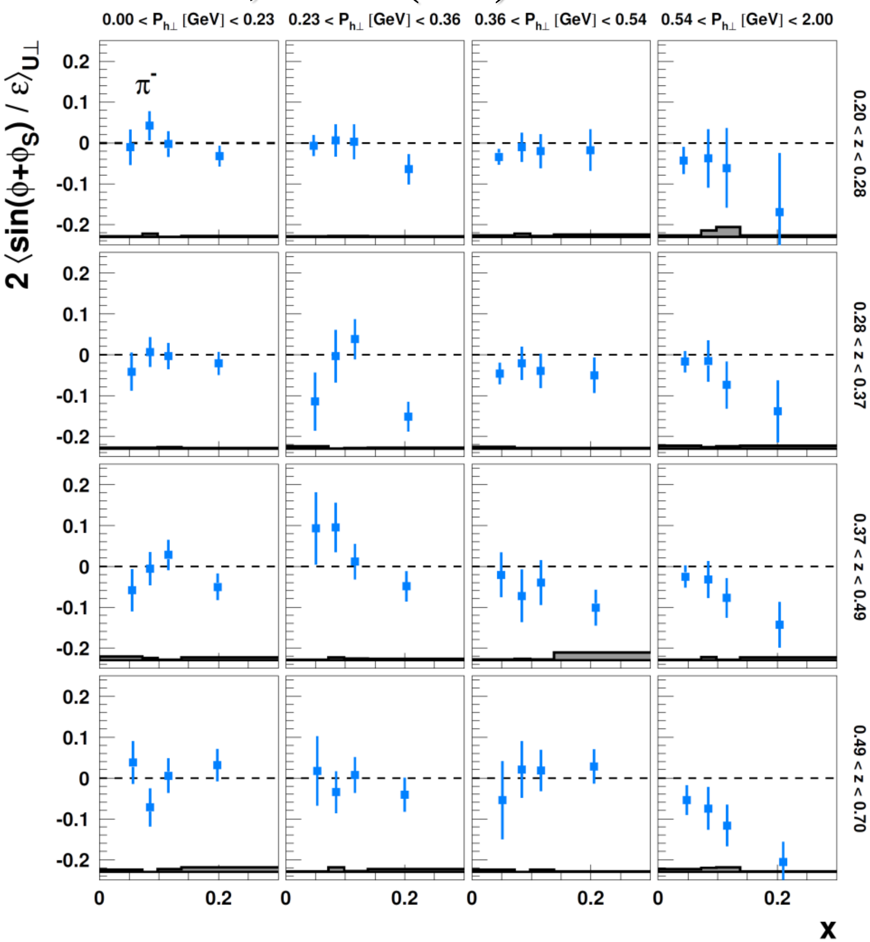
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

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

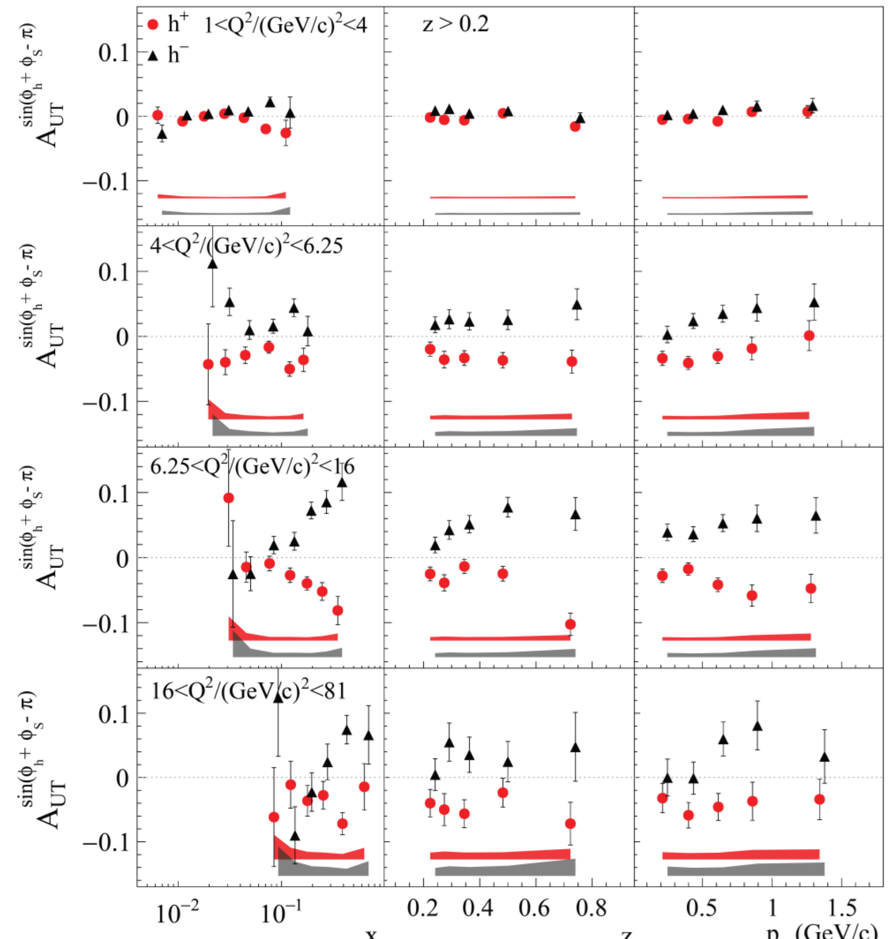
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

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

HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138

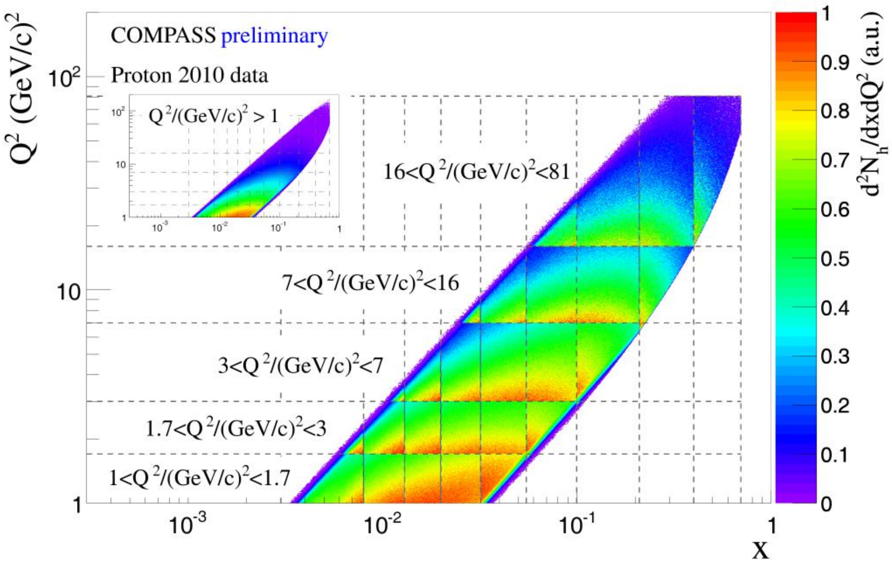


COMPASS Multi-D TSA analyses

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

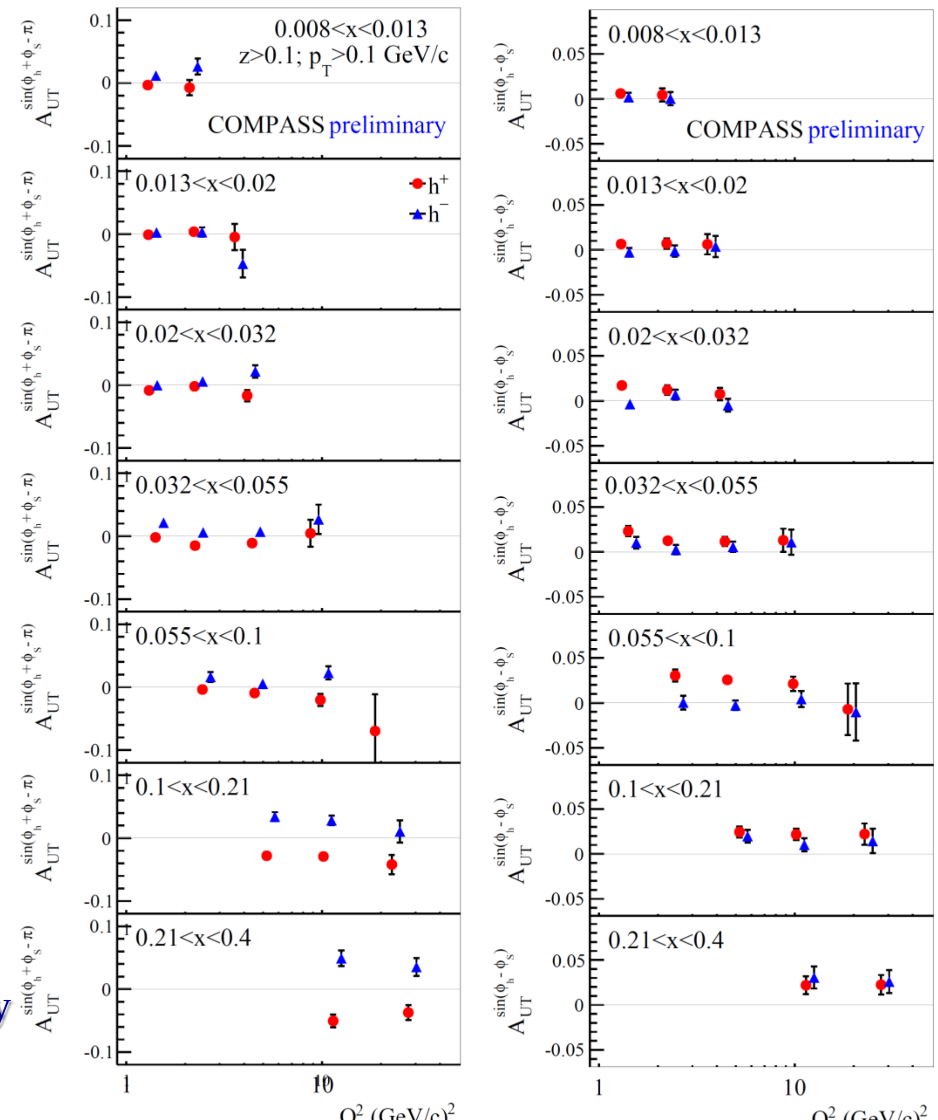
$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{h}\cdot \boldsymbol{k_T}}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

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



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

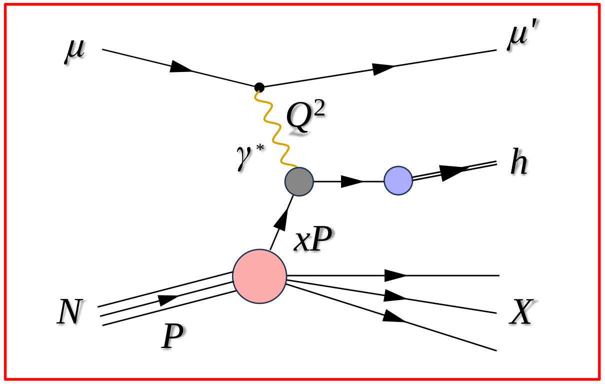
B.Parsamyan (for COMPASS) arXiv:1504.01599 [hep-ex] (SPIN-2014)



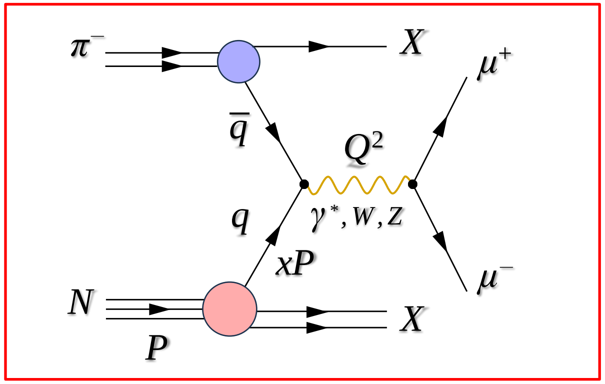
- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

Polarized SIDIS and DY – factorization and kinematic regions

Semi-inclusive DIS



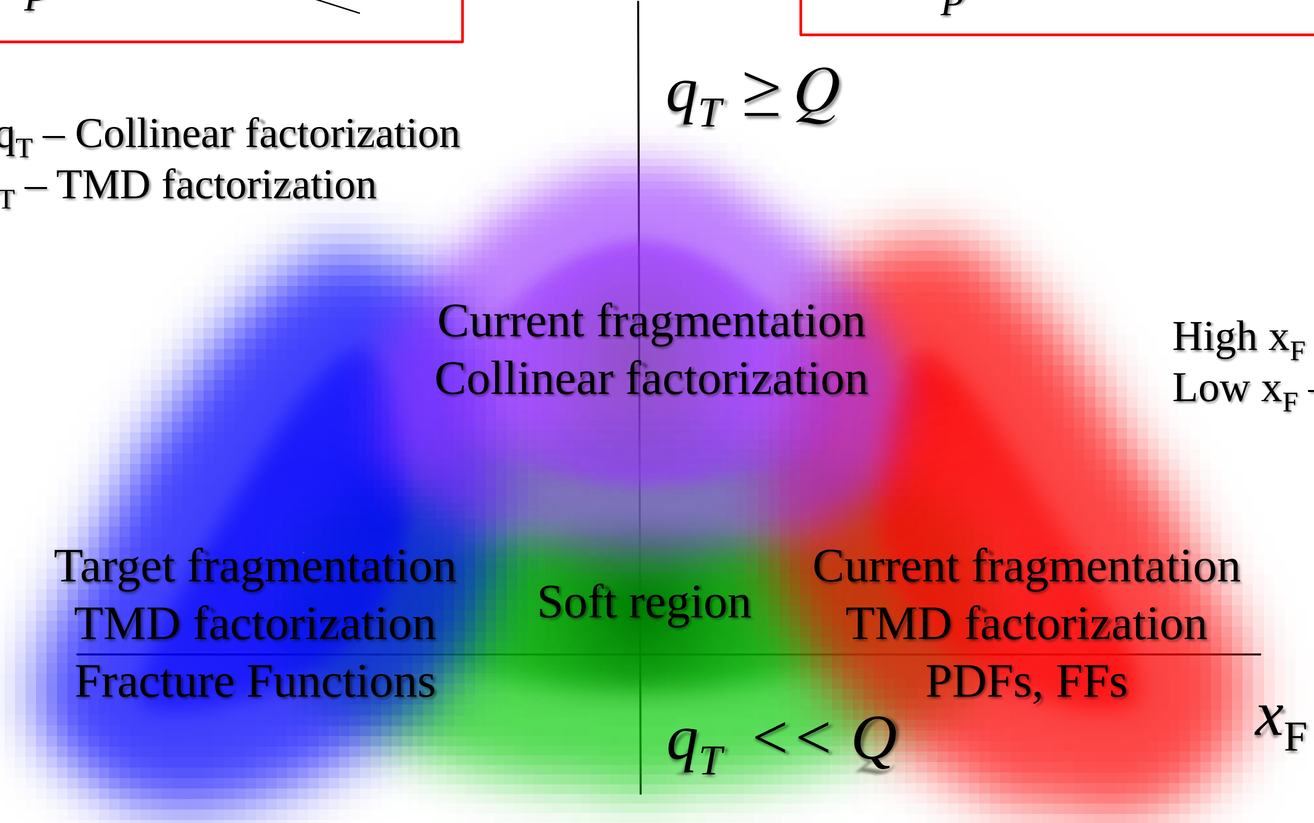
Drell-Yan process



T-odd TMD PDFs

sign change

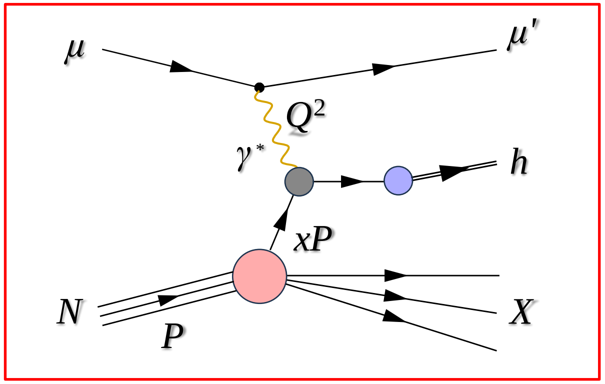
High q_T – Collinear factorization
Low q_T – TMD factorization

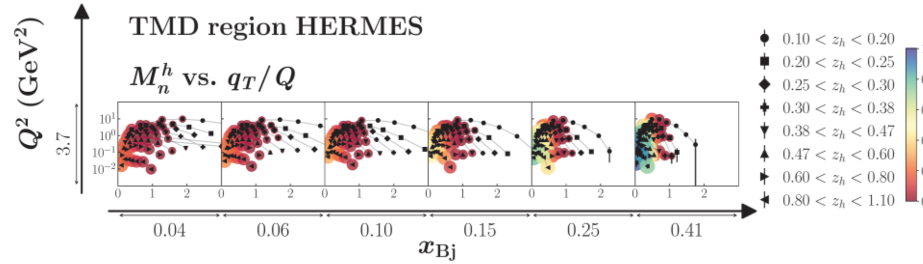


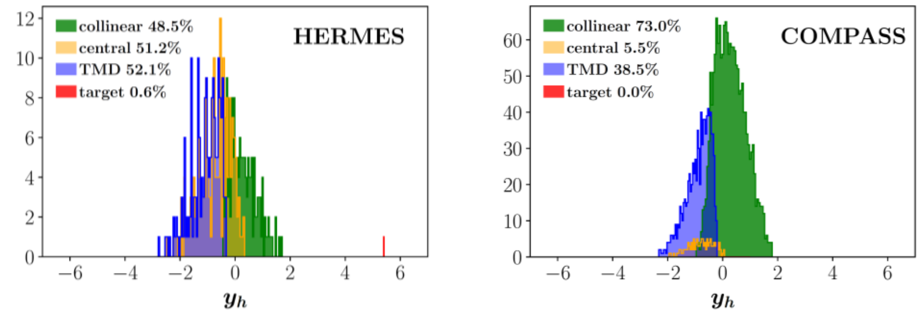
High x_F – Current fragmentation
Low x_F – Target fragmentation

Polarized SIDIS and DY – factorization and kinematic regions

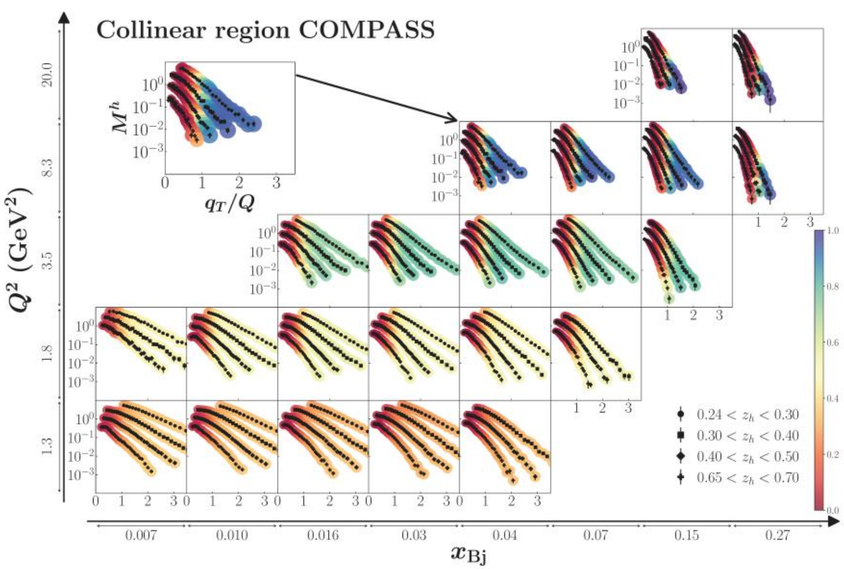
Semi-inclusive DIS

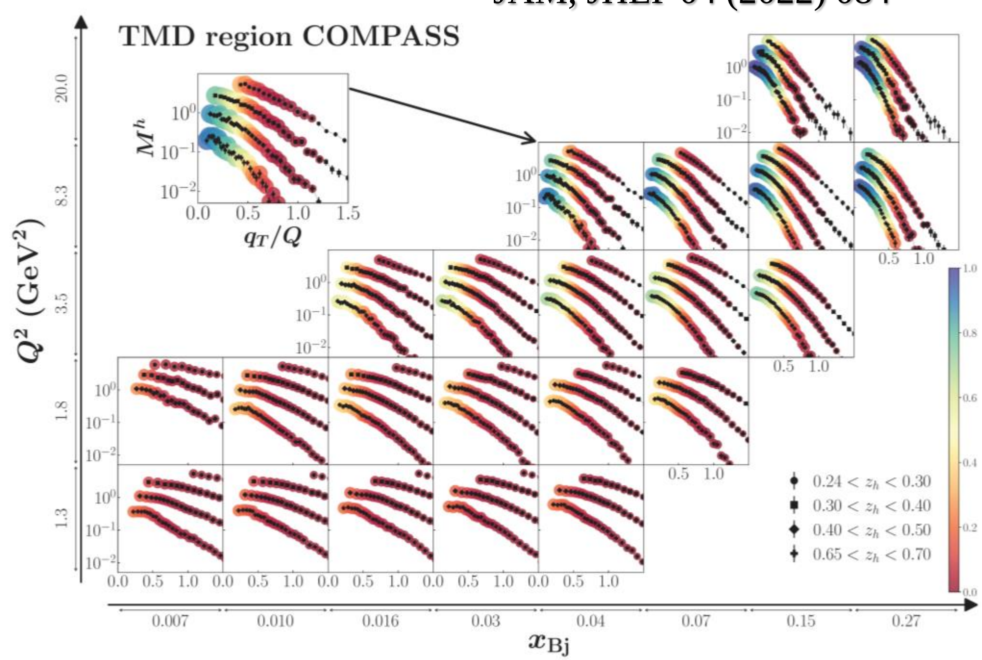






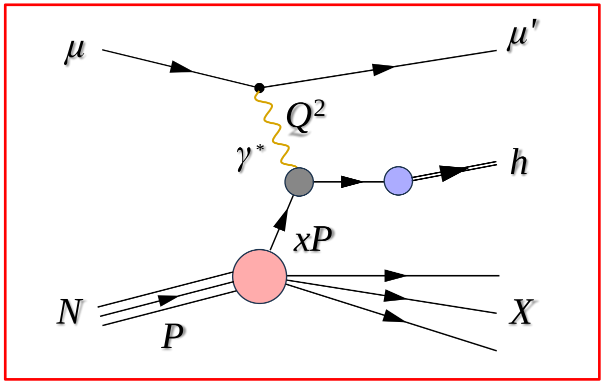
JAM, JHEP 04 (2022) 084

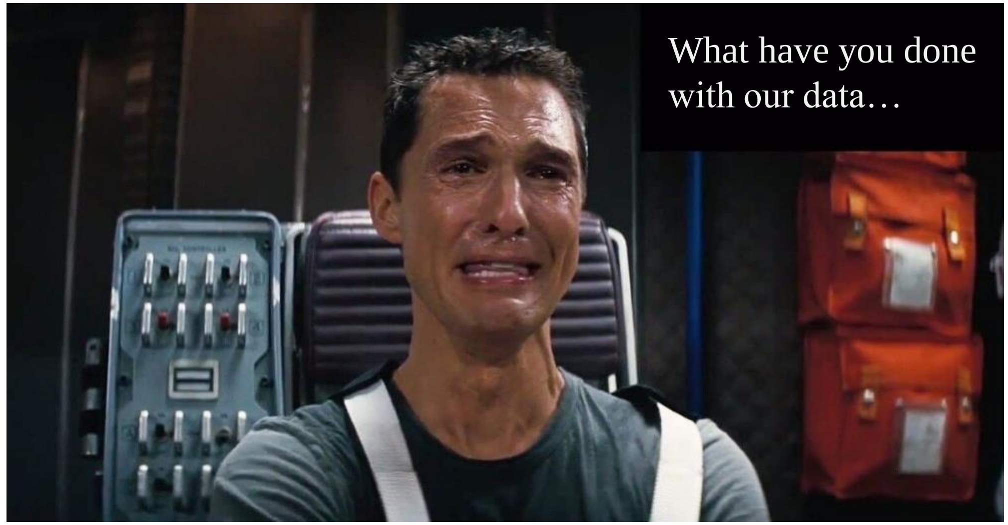




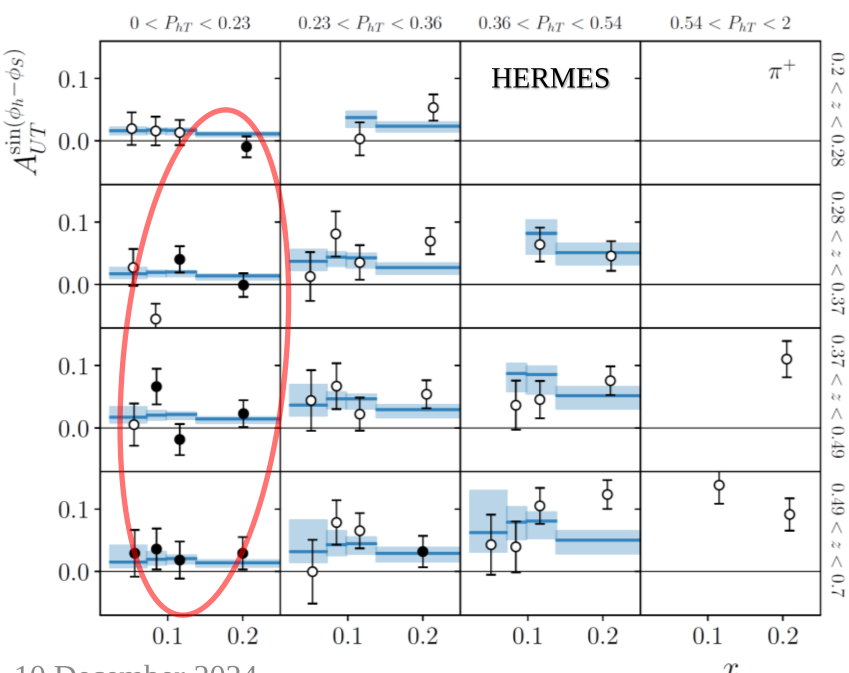
Polarized SIDIS and DY – factorization and kinematic regions

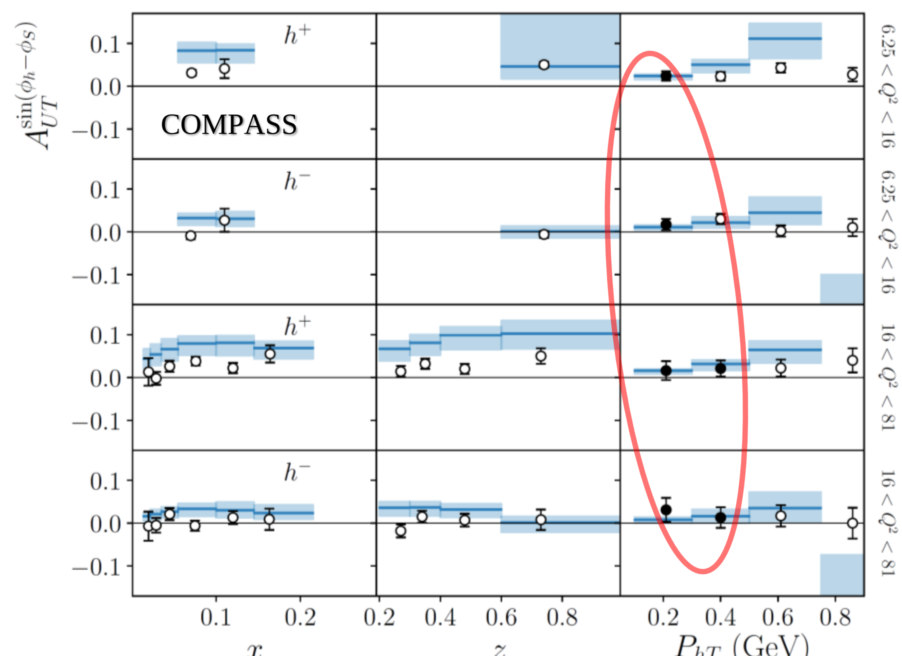
Semi-inclusive DIS





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





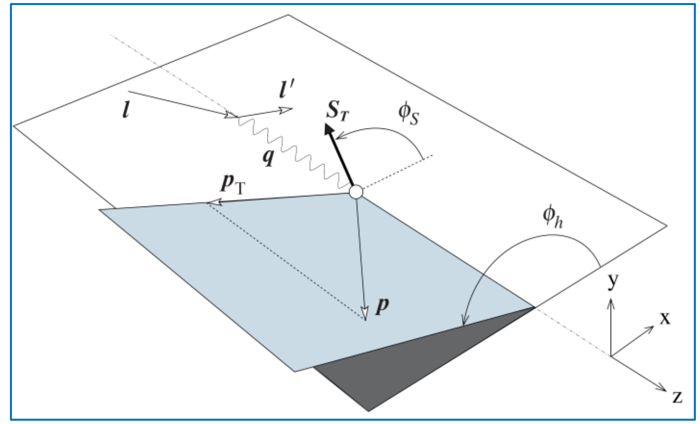
Cahn effect in SIDIS

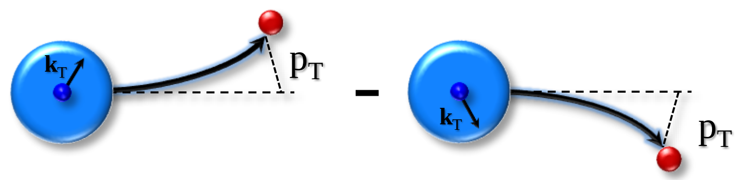
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\varepsilon F_{UU,L})$$

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

Cahn effect

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



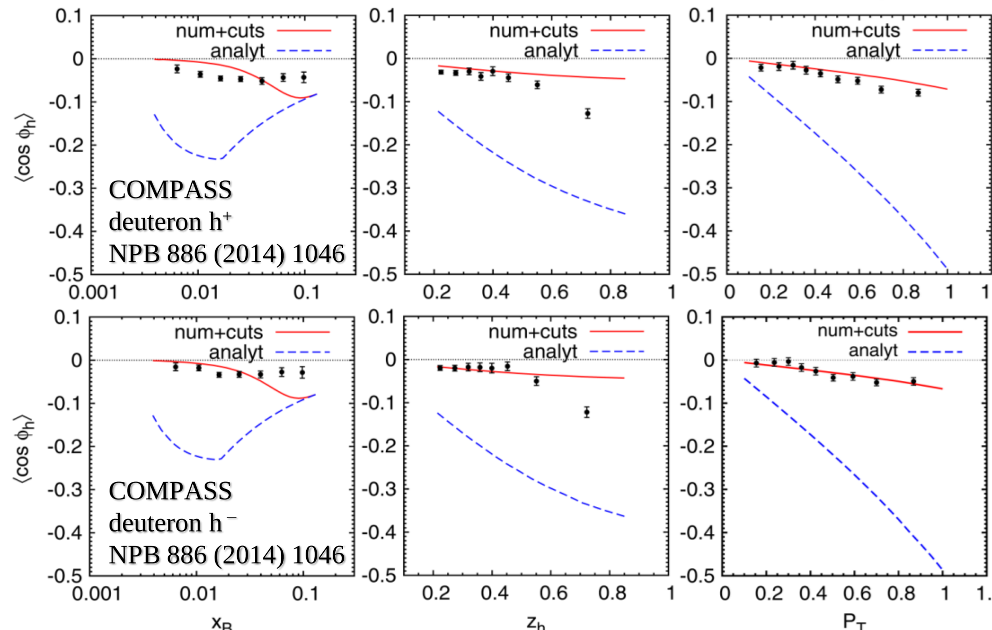


As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

- Measurements by different experiments

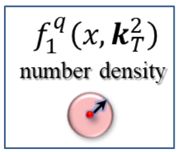


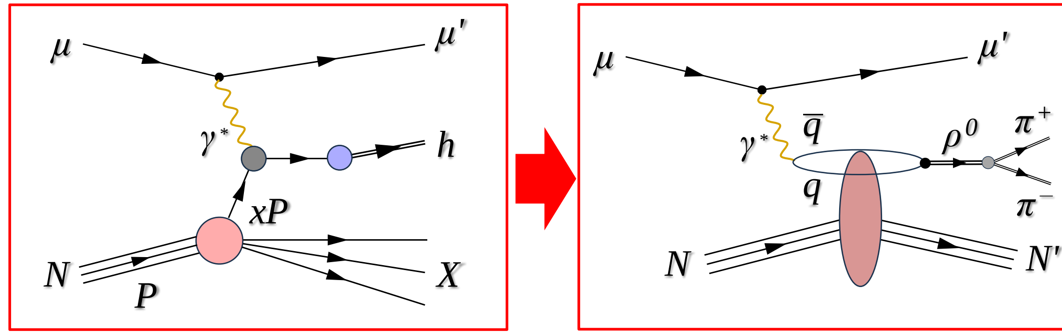
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

Cahn effect in SIDIS: DVMs

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

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





?

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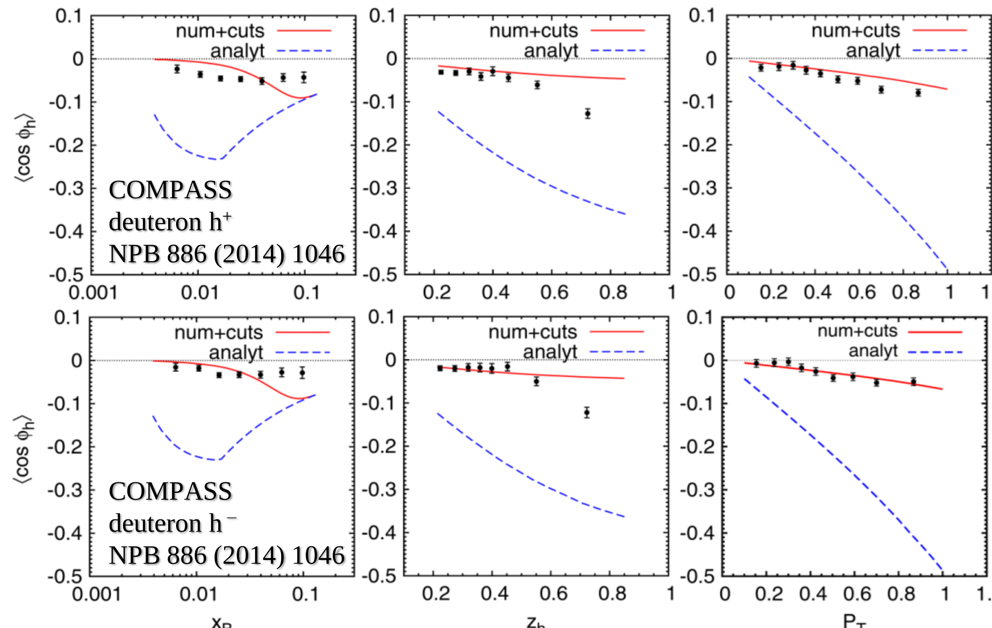

$$F_{UU}^{\cos\phi_h}=\frac{2M}{Q}C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

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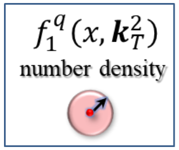
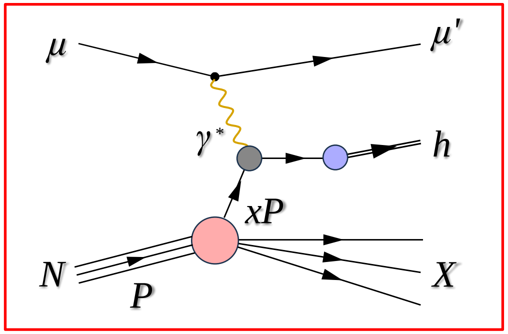
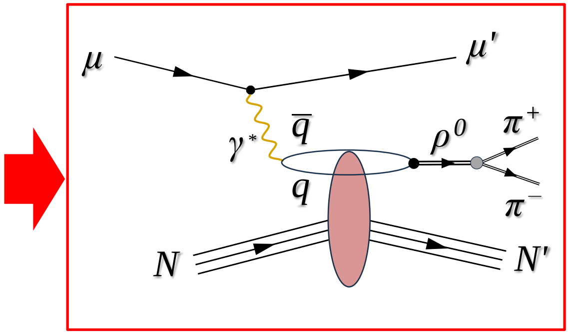
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

Cahn effect

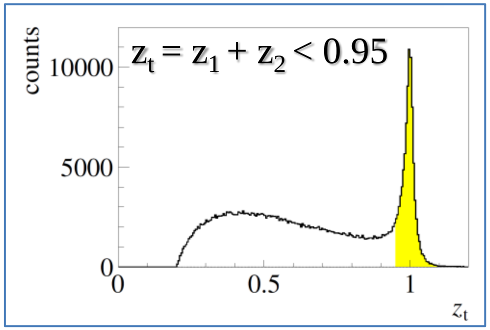


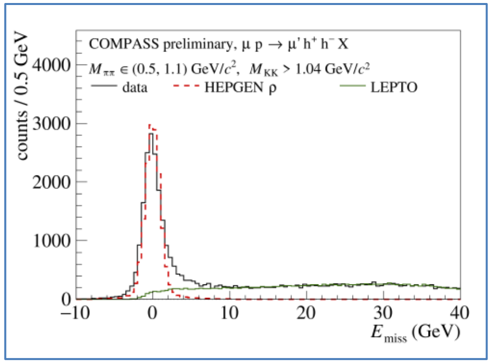




As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

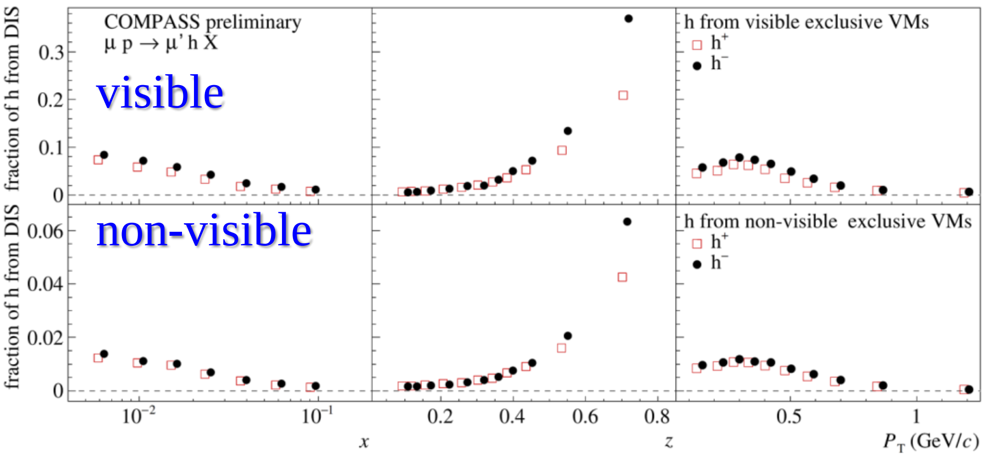




As of 2023 – complex SF (twist-2/3 functions)

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

VM fractions



Cahn effect in SIDIS: DVMs

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

Cahn effect

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

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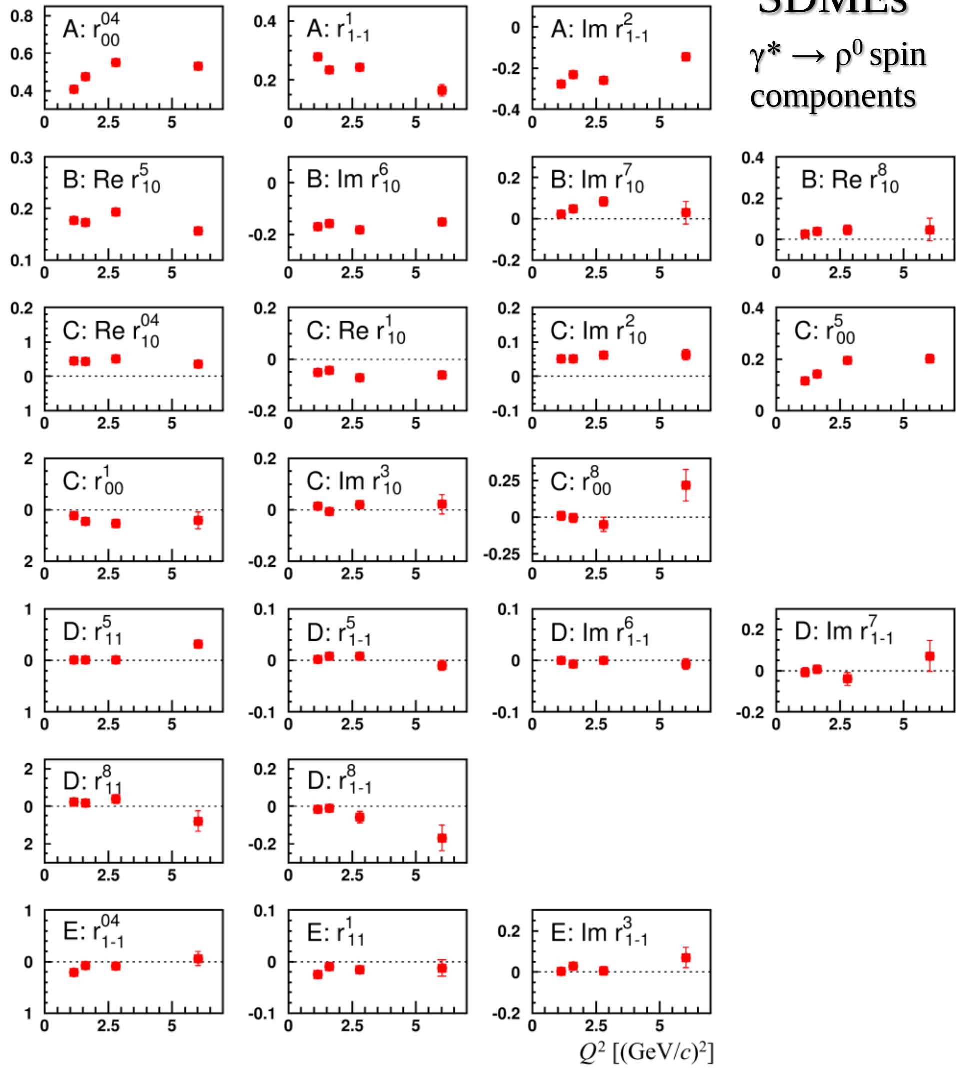
COMPASS, EPJC (2023) 83 924

SDMEs

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



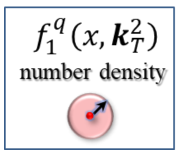
Kinematic dependences of SDMEs
Measured (1D), not yet implemented in HEPgen

Cahn effect in SIDIS: DVMs

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

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

Cahn effect



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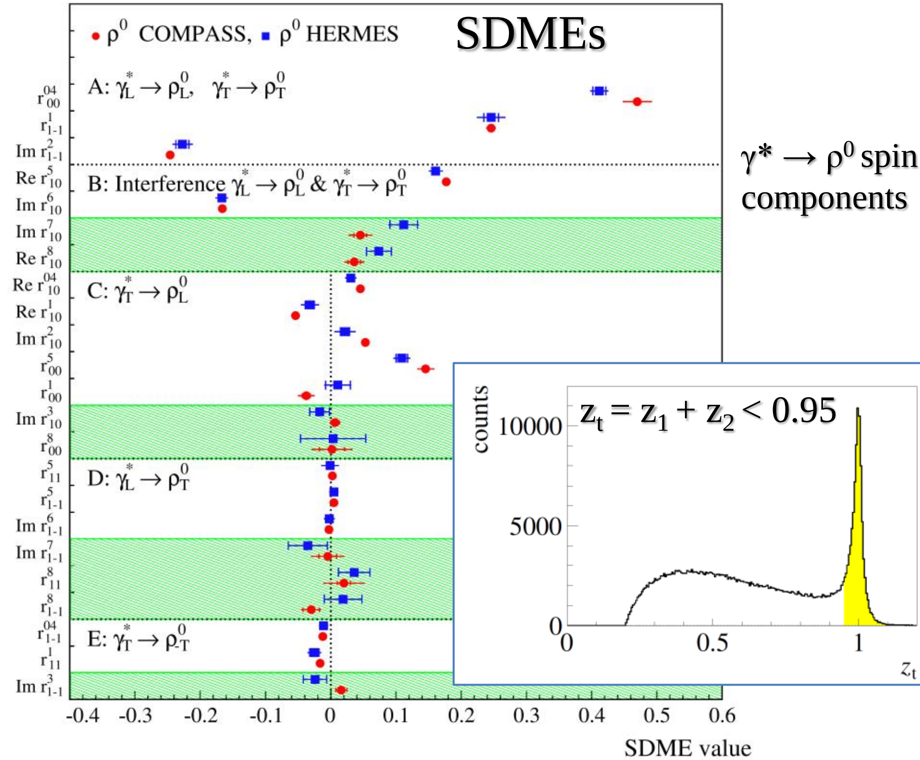
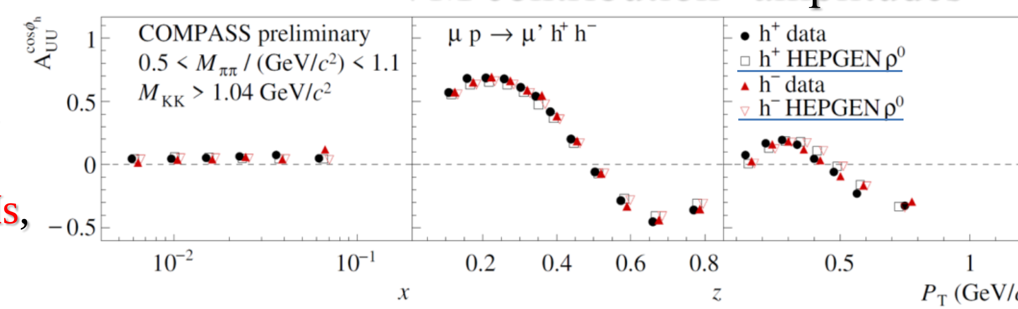
COMPASS, EPJC (2023) 83 924



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

VM contribution "amplitudes"



Only "average" SDMEs are implemented in HEPgen
They seem to describe the data well

Cahn effect in SIDIS: DVMs

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

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

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

Cahn effect

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

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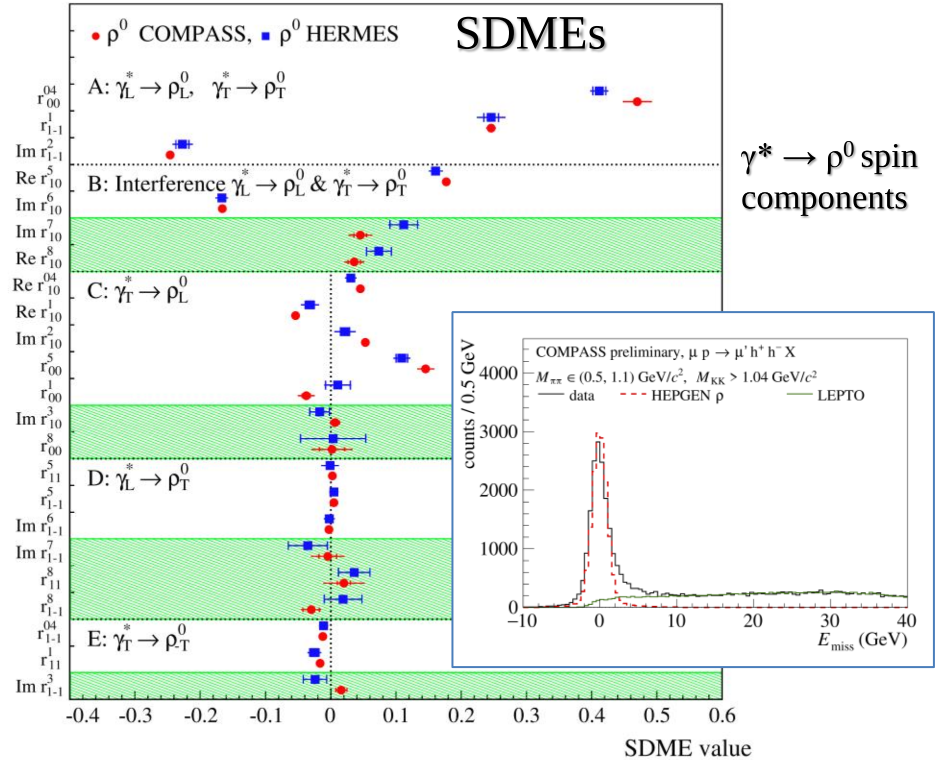
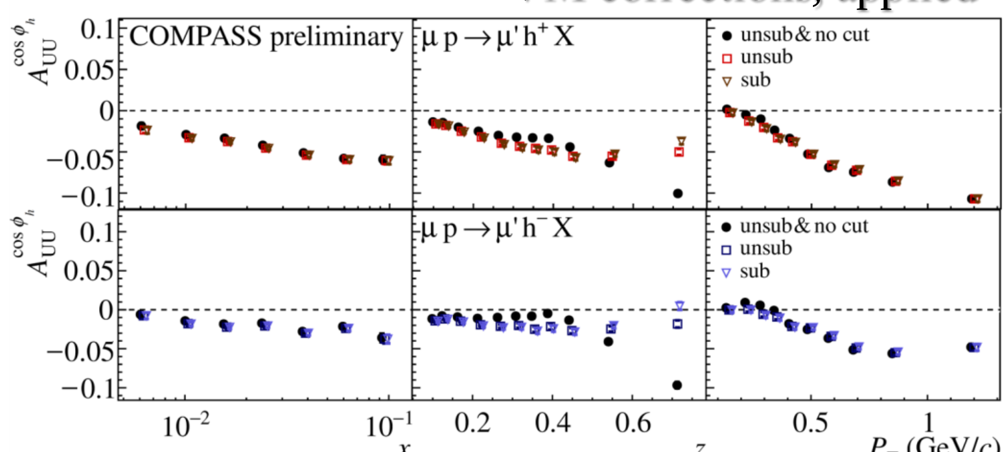
COMPASS, EPJC (2023) 83 924



γ* → ρ⁰ spin components

VM corrections, applied



Cahn effect in SIDIS: DVMs

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

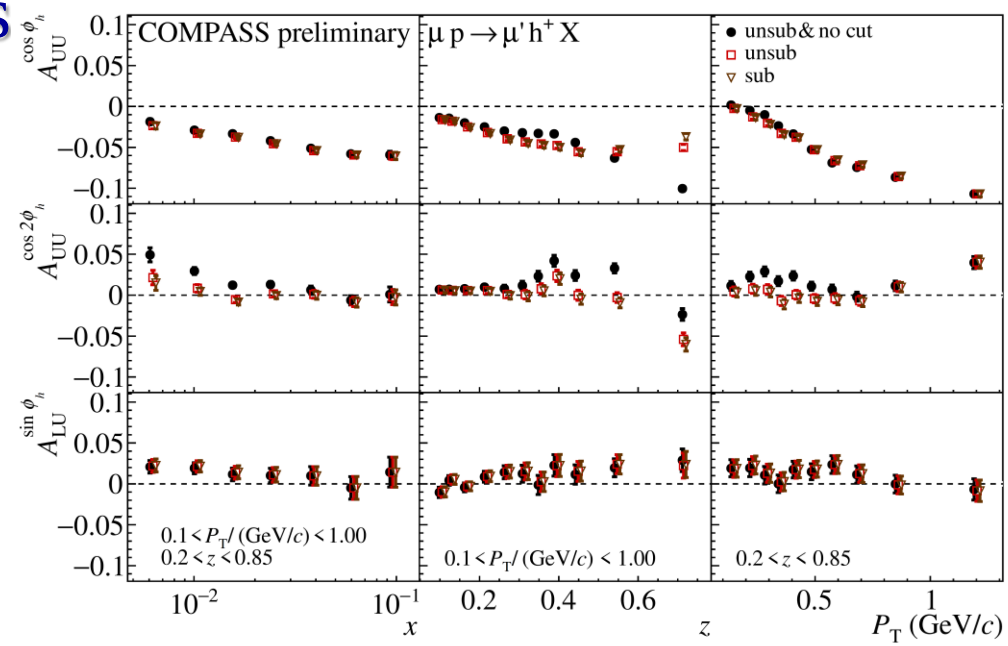
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

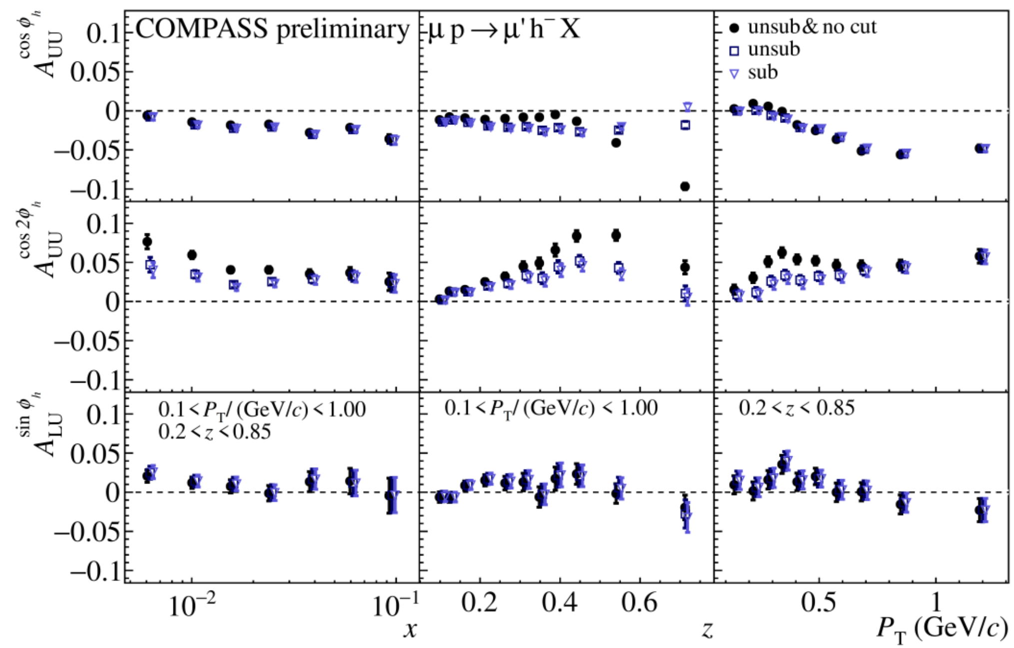
$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right.$$

$$\left.+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h+\ldots\right)$$

Cahn, Boer-Mulders and beam-spin UAs

- 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.
- Sizable effect of corrections for the Boer-Mulders asymmetry (low x)
- Corrections for the beam-spin asymmetry appear to be small

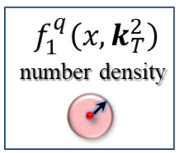




Cahn effect in SIDIS: DVMs and RCs

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

Cahn effect



As of 1978 – simplistic kinematic effect:

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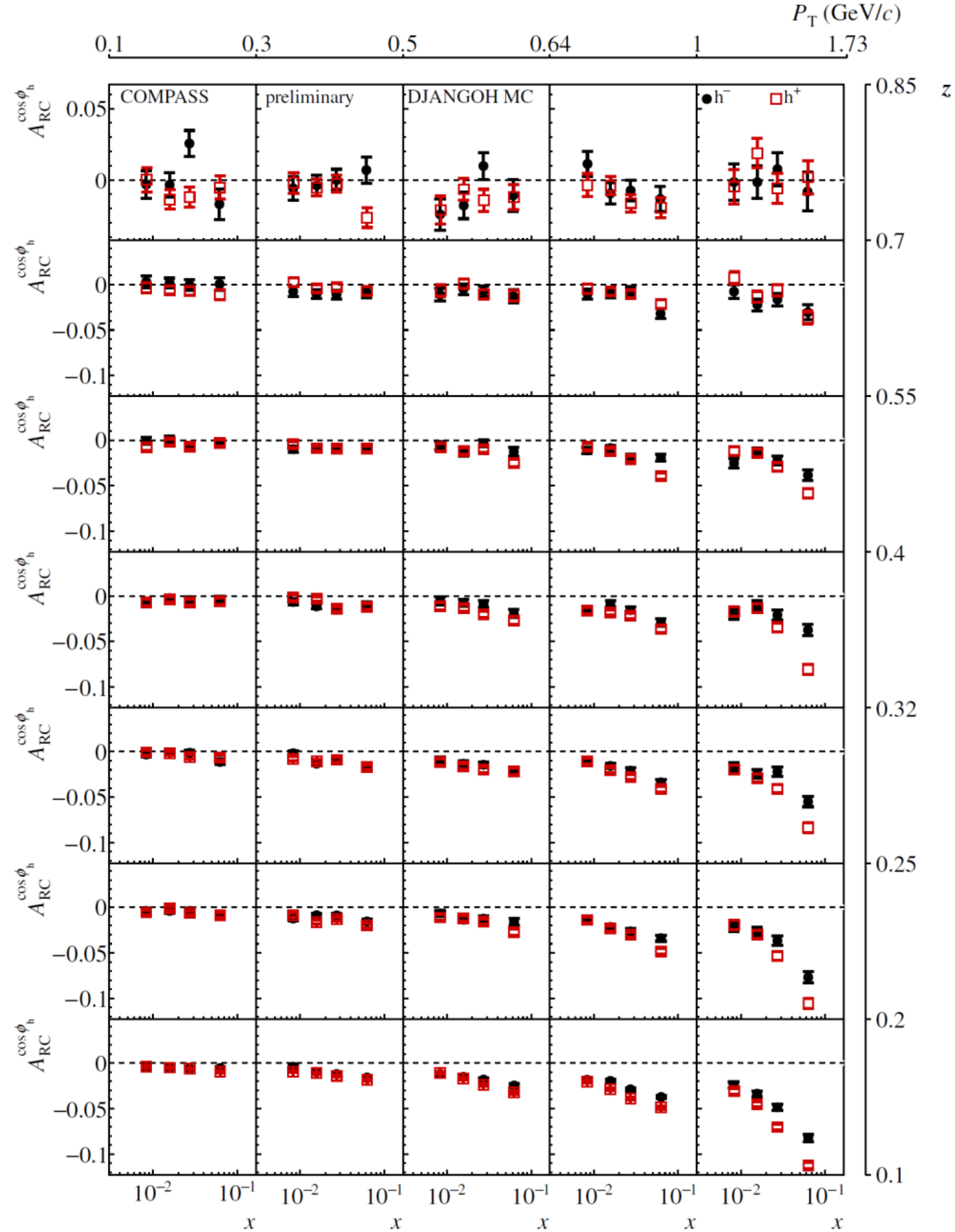
As of 2023 – complex SF (twist-2/3 functions)

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

RC corrections

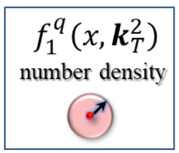


Cahn effect in SIDIS: DVMs and RCs

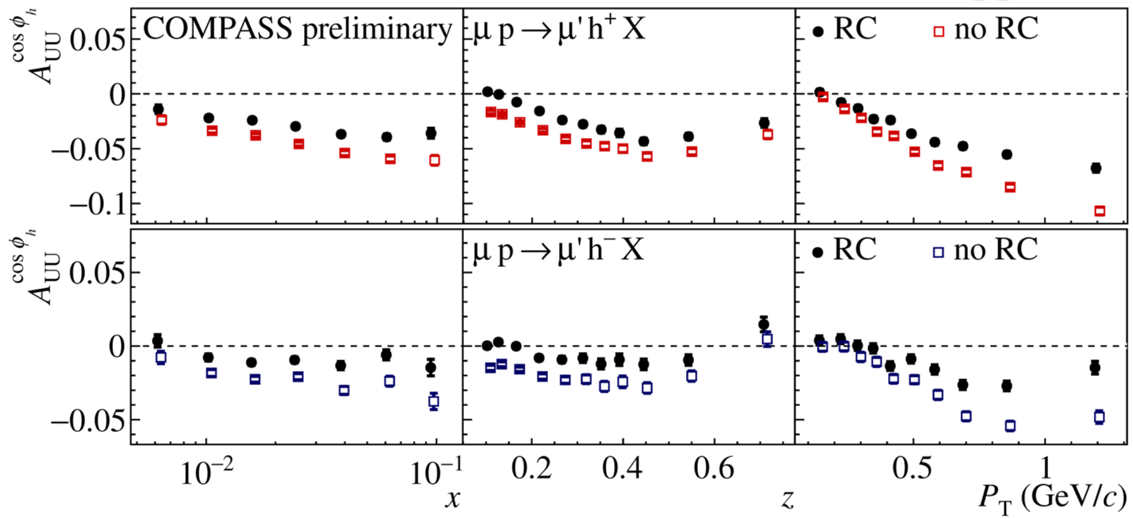
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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

Cahn effect



RC corrections, applied



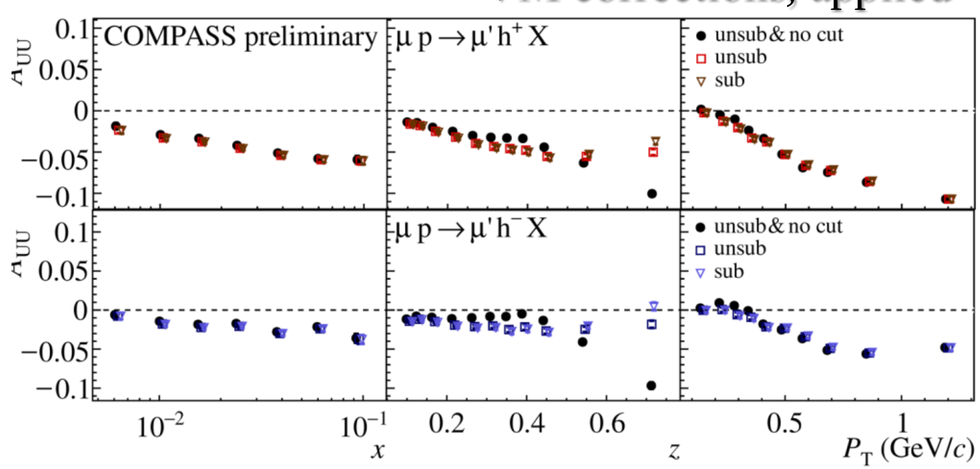
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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

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

VM corrections, applied



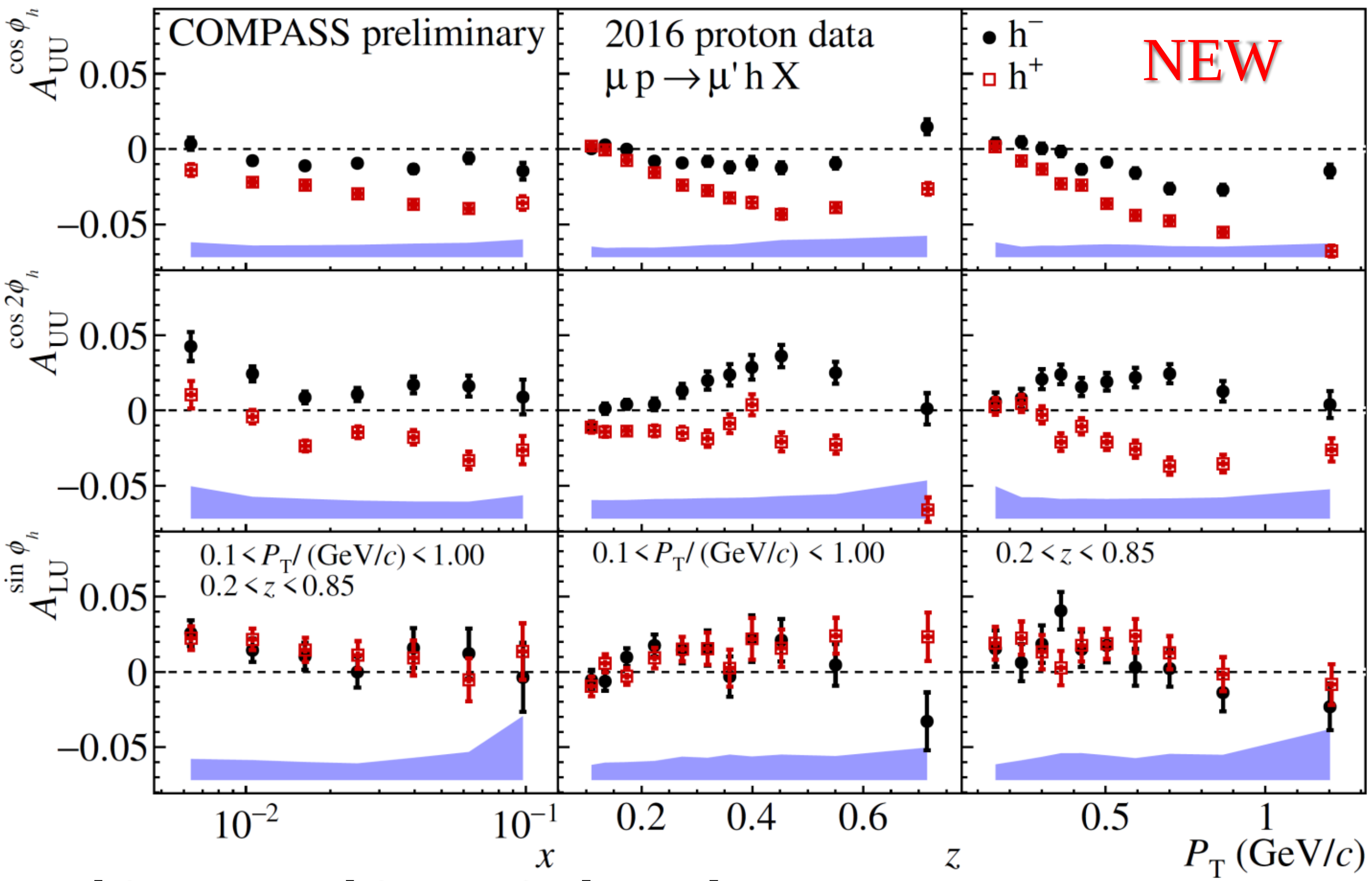
Azimuthal effects in unpolarized SIDIS

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

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

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

Target spin independent part of the cross-section: three asymmetries



Cahn effect
Different for h+, h−
Non-trivial Q^2 dependence

Boer-Mulders effect
Collins-like behavior
(h^+h^- - mirror symmetry)

Beam-spin asymmetry
higher-twist effect
non-zero, positive trend

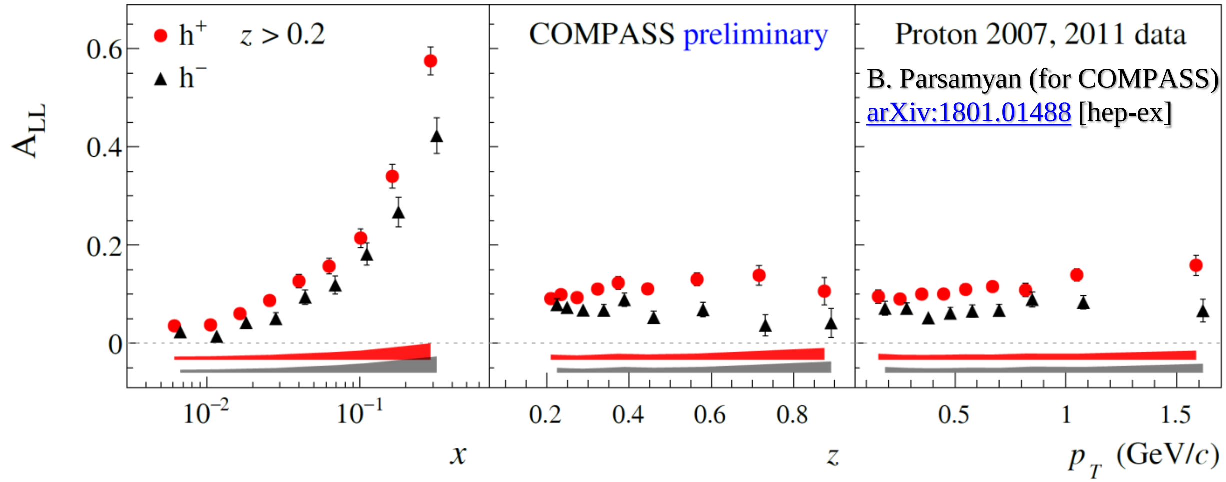
Working on 3D kinematic dependences

SIDIS: target longitudinal spin dependent asymmetries

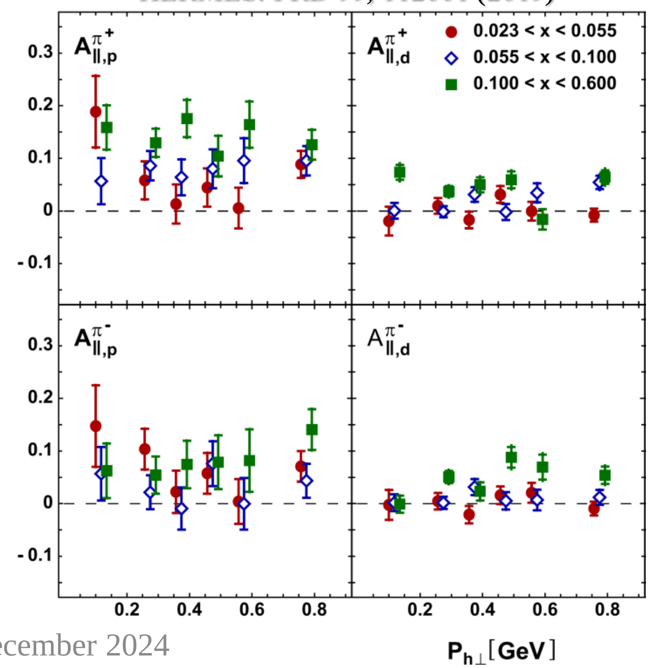
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} + \ldots\right\}$$

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

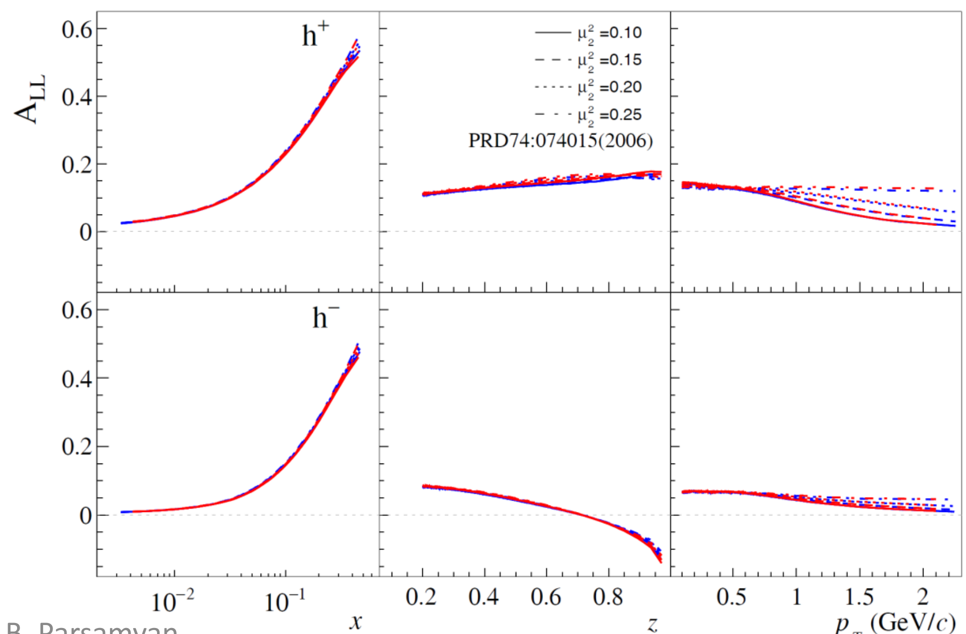
- Measurement of (semi-)inclusive A_1(A_{LL}) is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed



HERMES: PRD 99, 112001 (2019)



COMPASS Proton-2007, -2011 kinematics



SIDIS: target longitudinal spin dependent asymmetries

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

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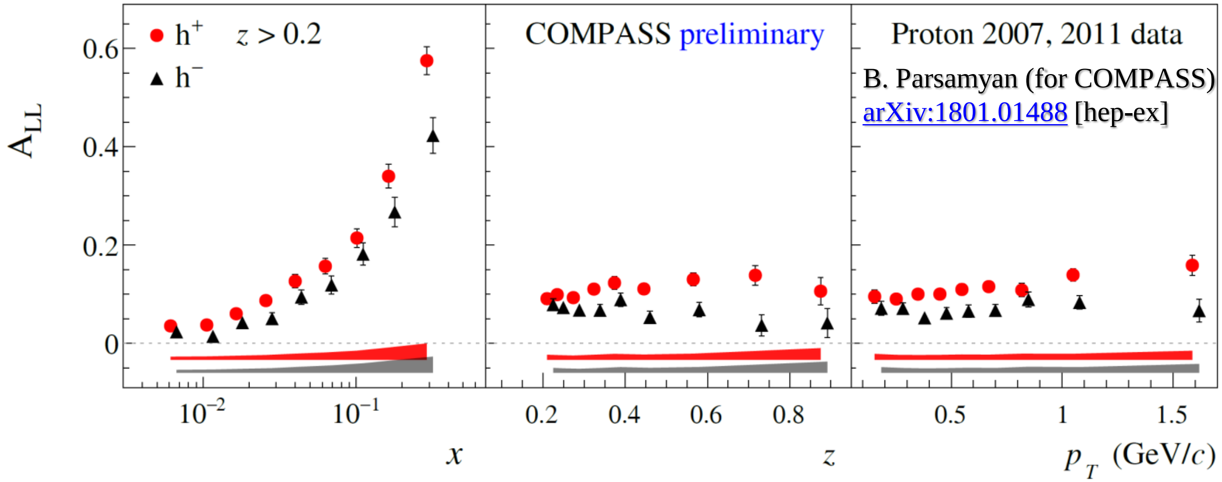
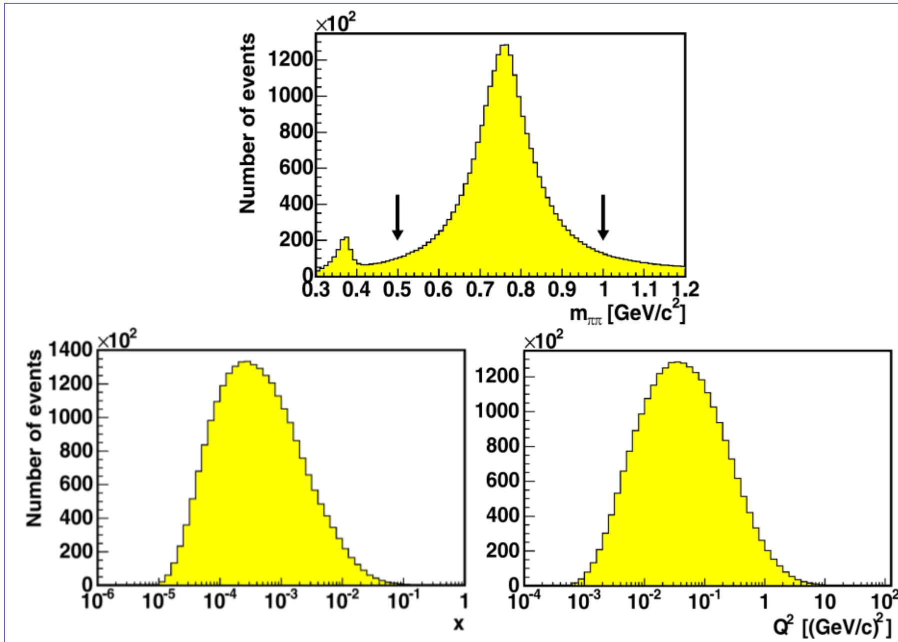
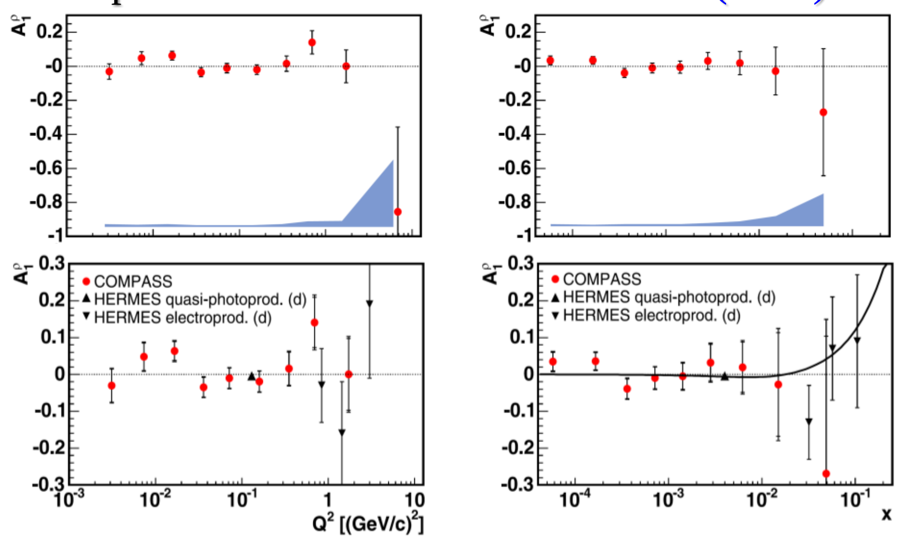
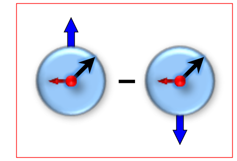




Double spin asymmetry in exclusive ρ^0 muoproduction at COMPASS EPJ C52 (2007) 255



SIDIS TSAs: Kotzinian-Mulders asymmetry



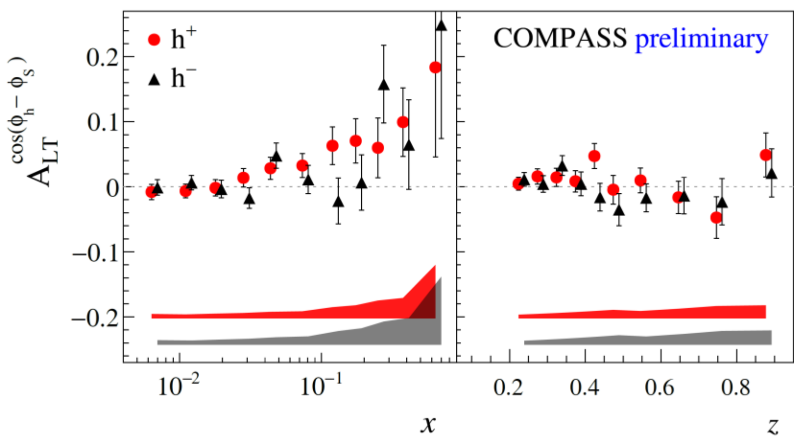
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + \lambda S_T \sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h - \phi_S) + \ldots\right\}$$

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

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

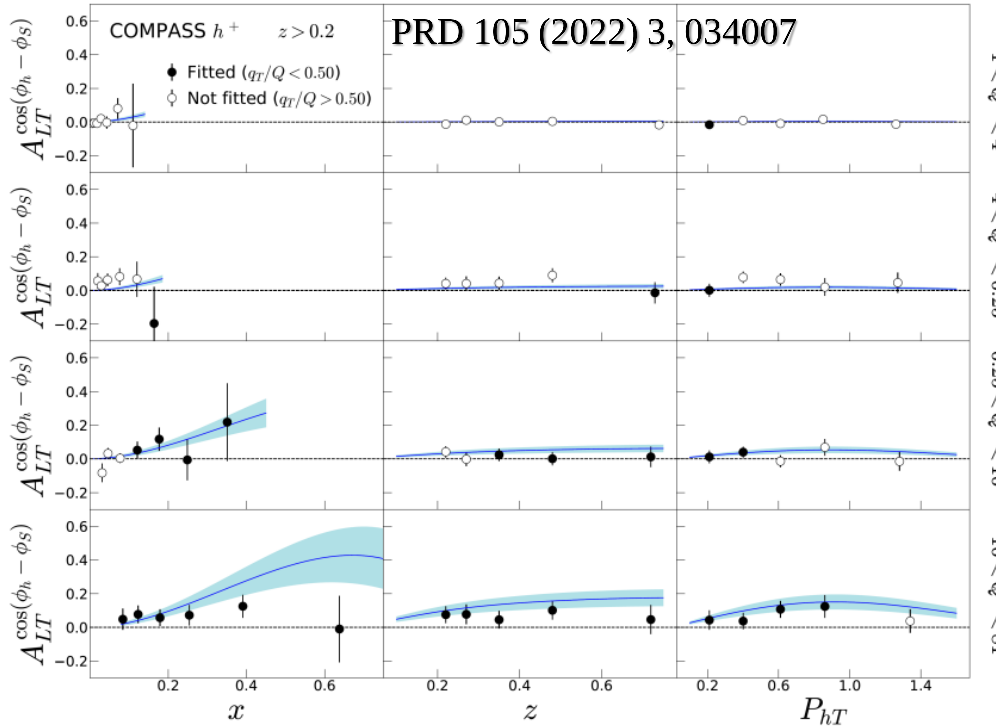
- Only "twist-2" ingredients
- Sizable non-zero effect for h^+ !
- Similar effect at HERMES

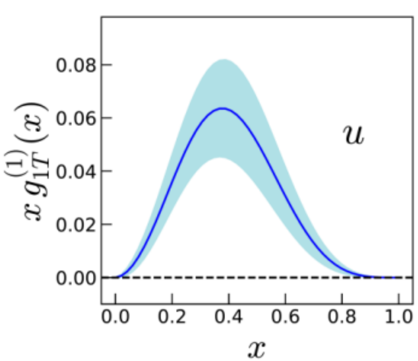
COMPASS, PBL 770 (2017) 138;
PoS QCDEV2017 (2018) 042

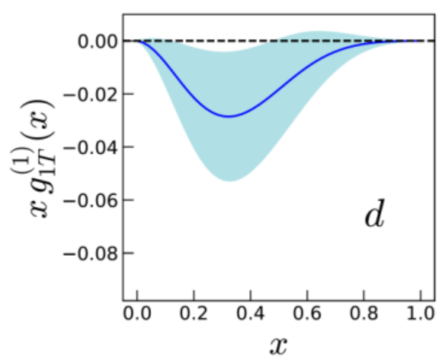


See also, PRD 107, (2023) 034016 – global fit by: M. Horstmann, A. Schafer and A. Vladimirov

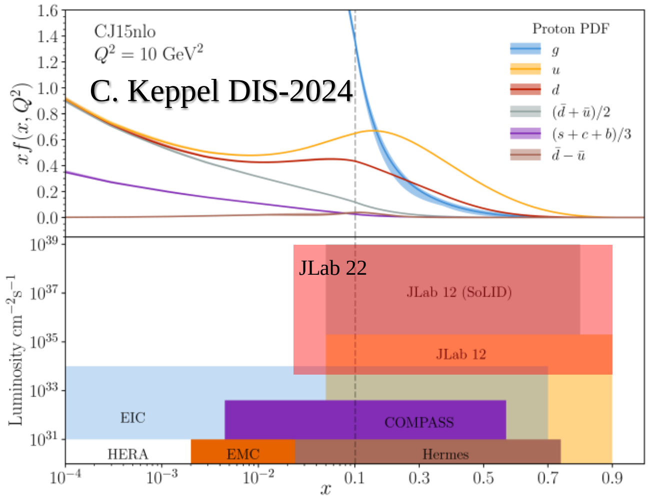
First global QCD analysis of the g_{1T} TMD PDF using SIDIS data



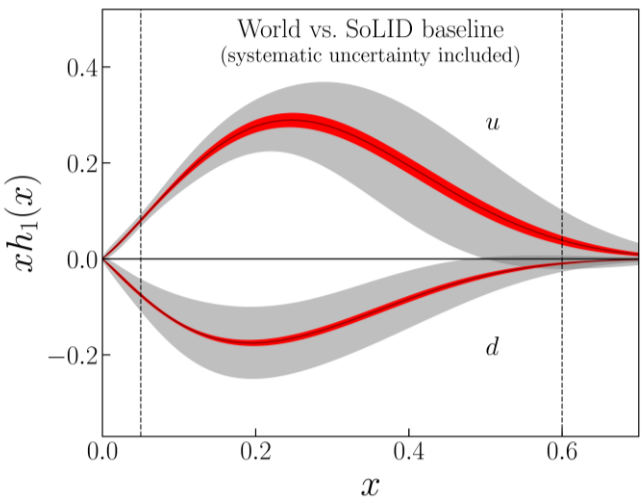


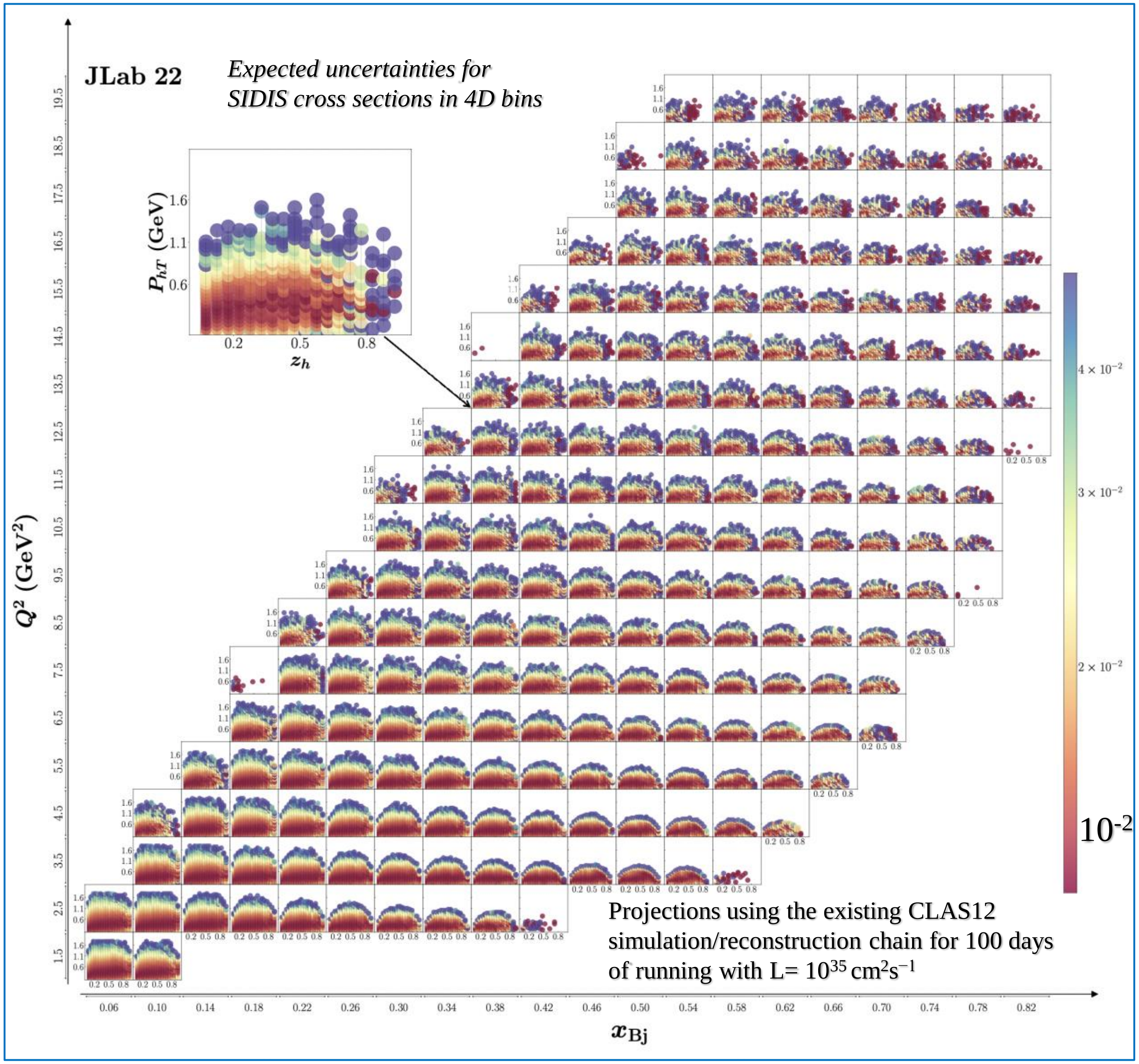


JLab from 12 GeV, SoLID to 22 GeV



CEBAF at 12 GeV and Future opportunities
arXiv:[2112.00060](https://arxiv.org/abs/2112.00060) [nucl-ex]





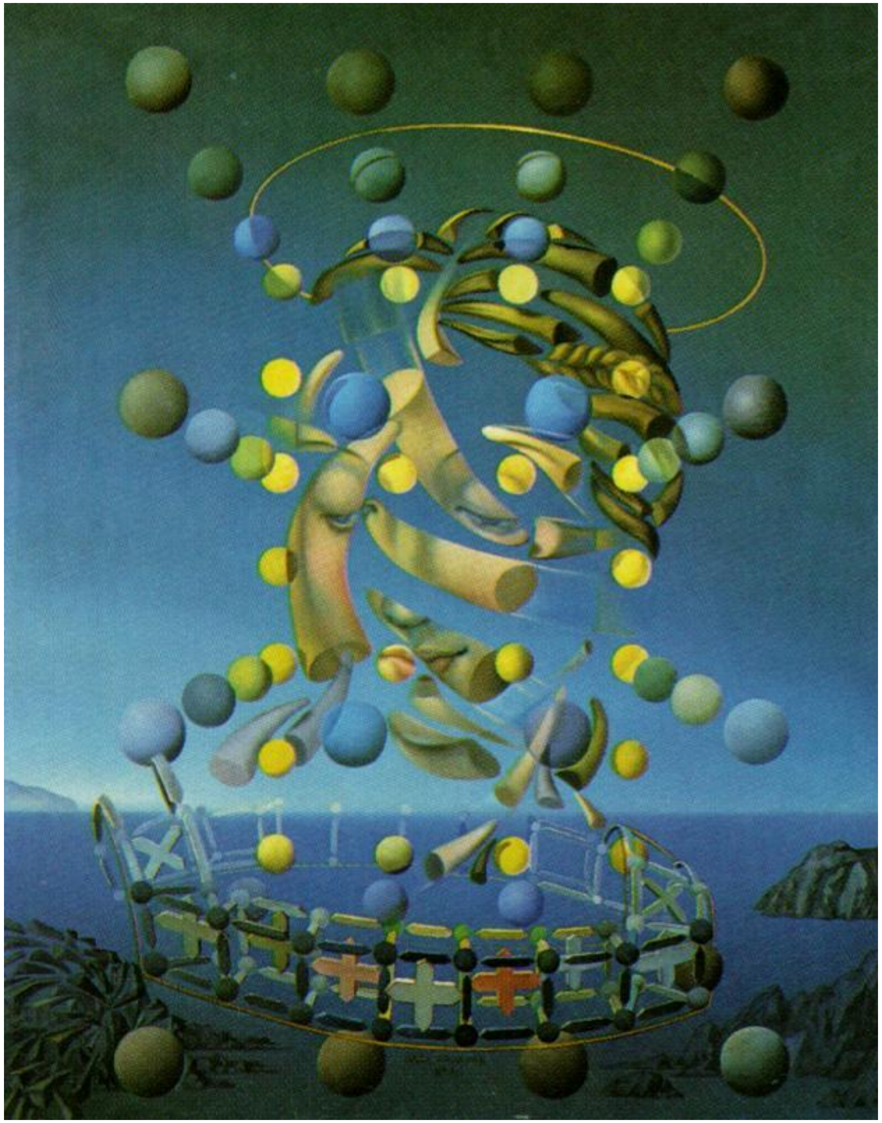
- High luminosity, complementary kinematic coverages, evolution studies, all TMDs, etc.
- Together with EIC/EICc - complete picture!

Conclusions

"Nature"

Raphael "Madonna del Prato"

"1D"



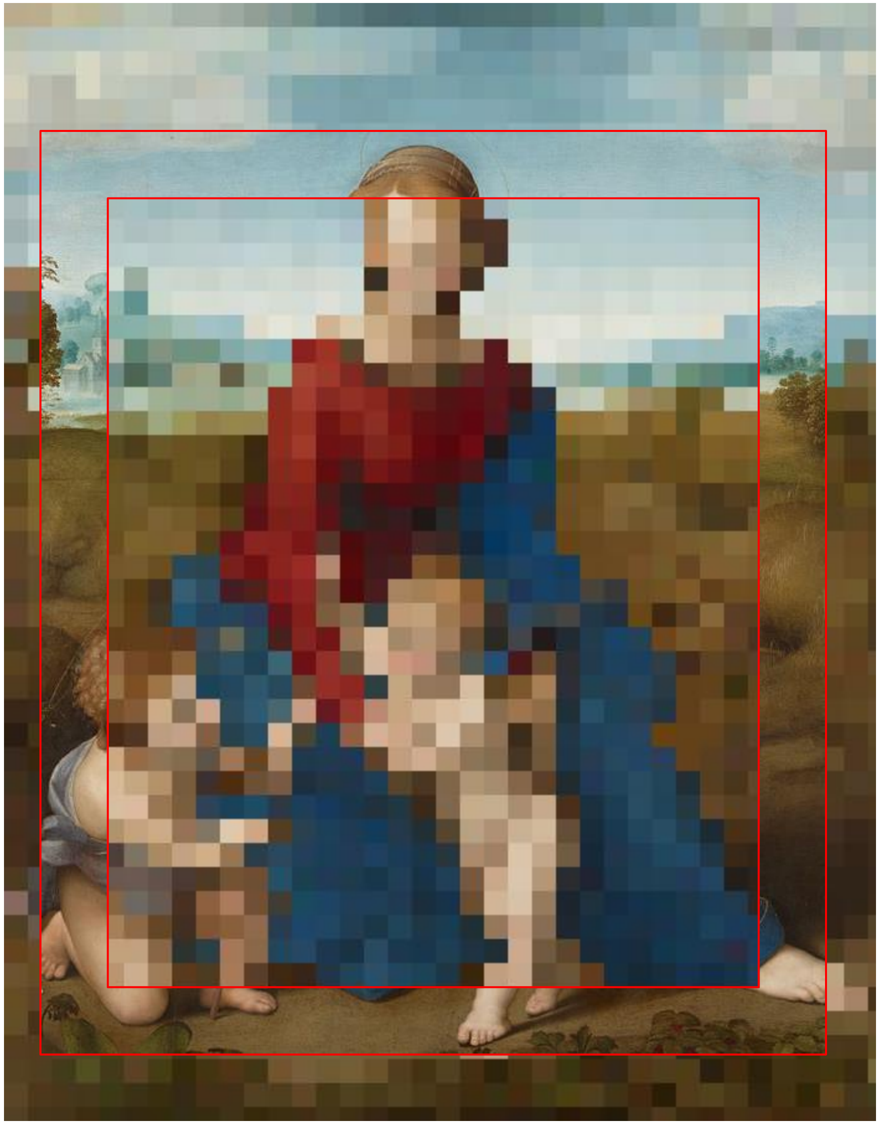
Salvador Dali "Maximum Speed of Raphael's Madonna"

Thank you!

"Nature"

Raphael "Madonna del Prato"

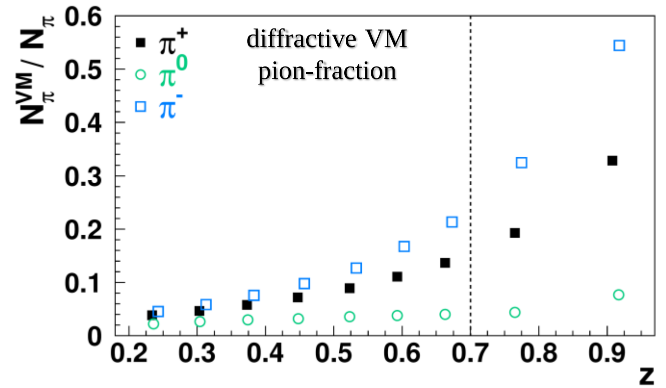
"multi-D" with available statistics



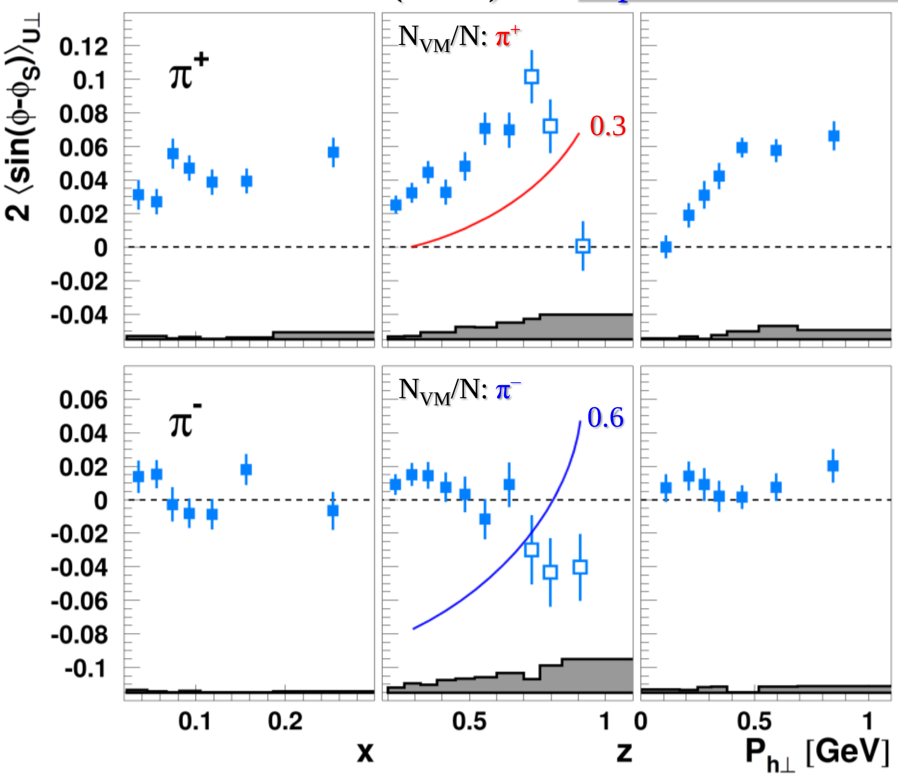
Raphael "Madonna del Prato" (poor resolution)

HERMES: Sivers effect and diffractive VMs

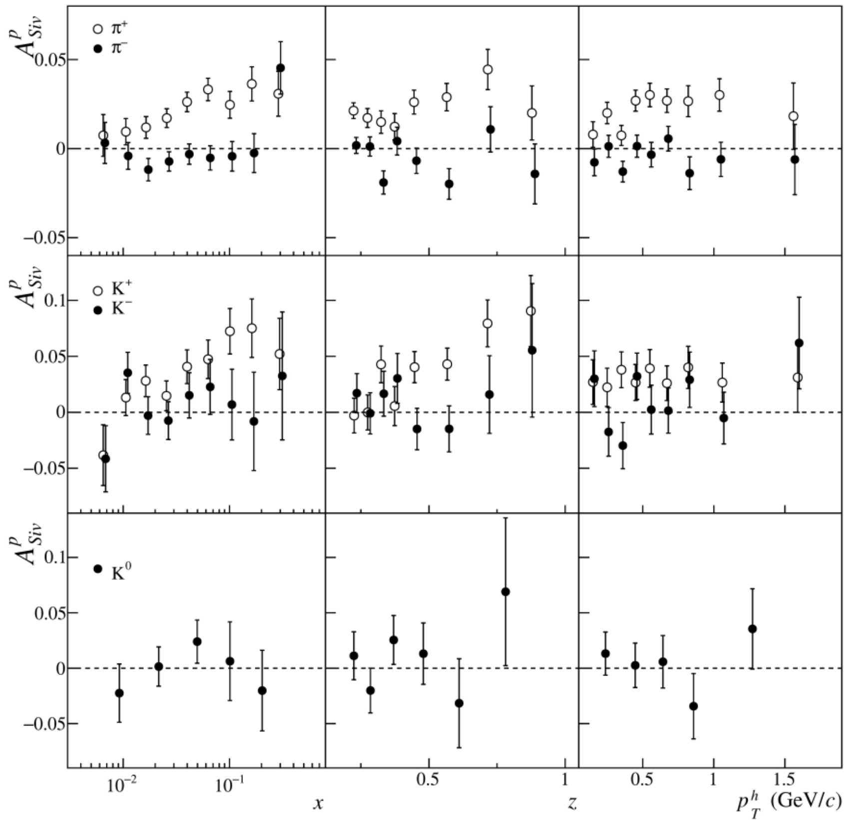
- The asymmetry drops at large z for pion
  - Not the case for kaons
- Can it be caused by exclusive diffractive VMs?
- The contamination indeed grows with *z* for pions
  - At the level of 10% for kaons



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

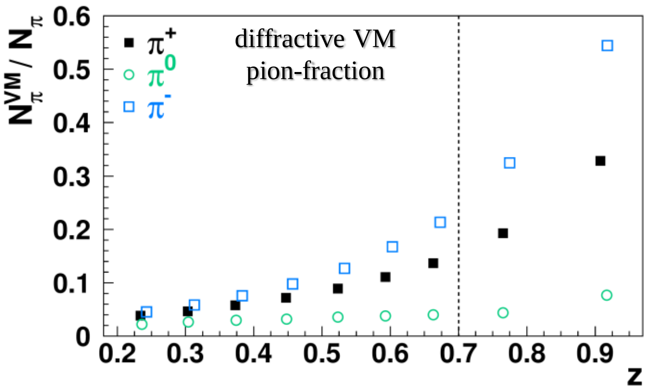


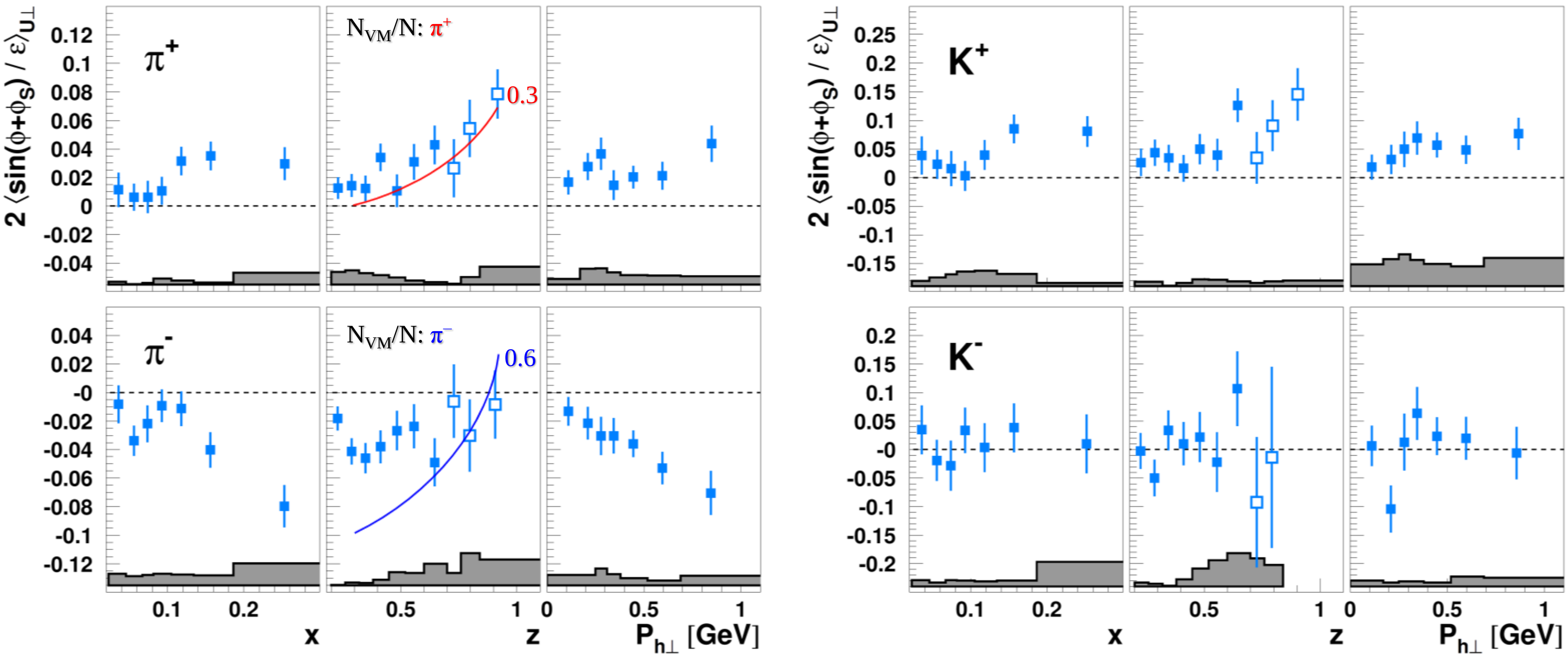
COMPASS: PLB 744 (2015) 250



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
- Similar effect in COMPASS?
- Not clear with Collins



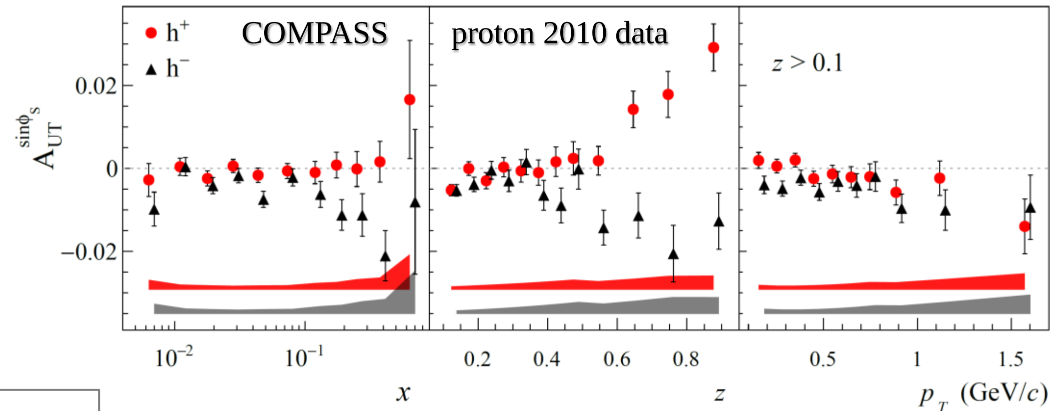


SIDIS TSAs: subleading twist effects

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

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

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



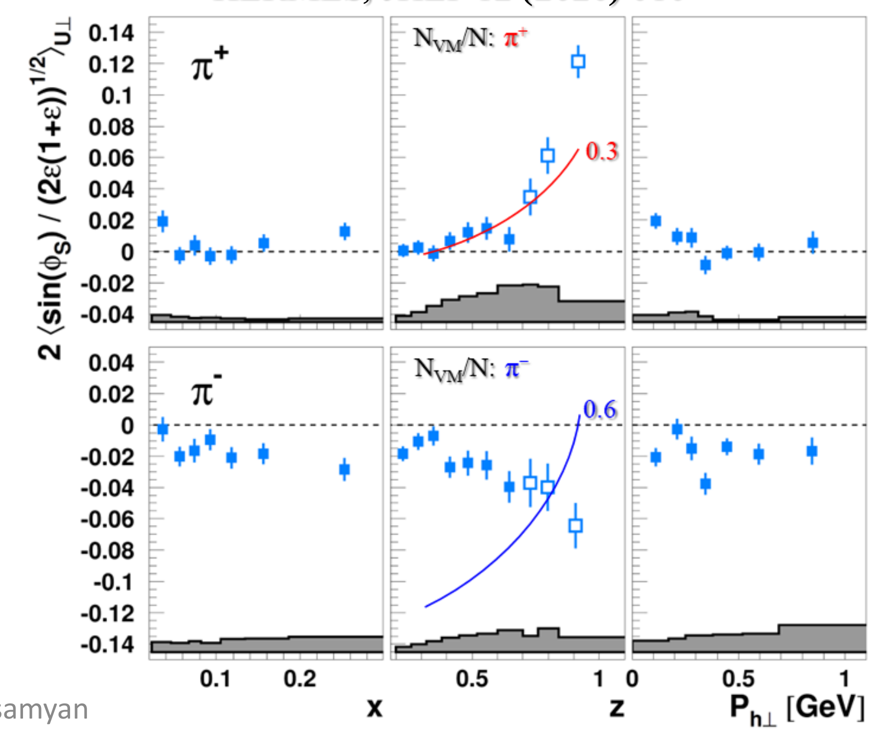
COMPASS/HERMES results

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

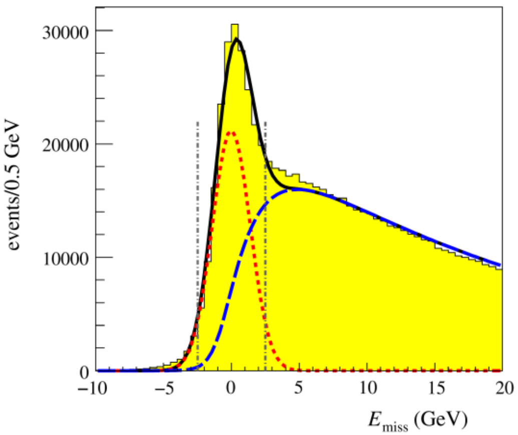
- Q-suppression
- various "twist-2/3" ingredients
- non-zero signal for $h^{\pm}$ at large z?
- Survives integration of hadron p_T
    - gives access to transversity PDF (without involving convolution over k_T)

See Daniel Pitonyak's talk

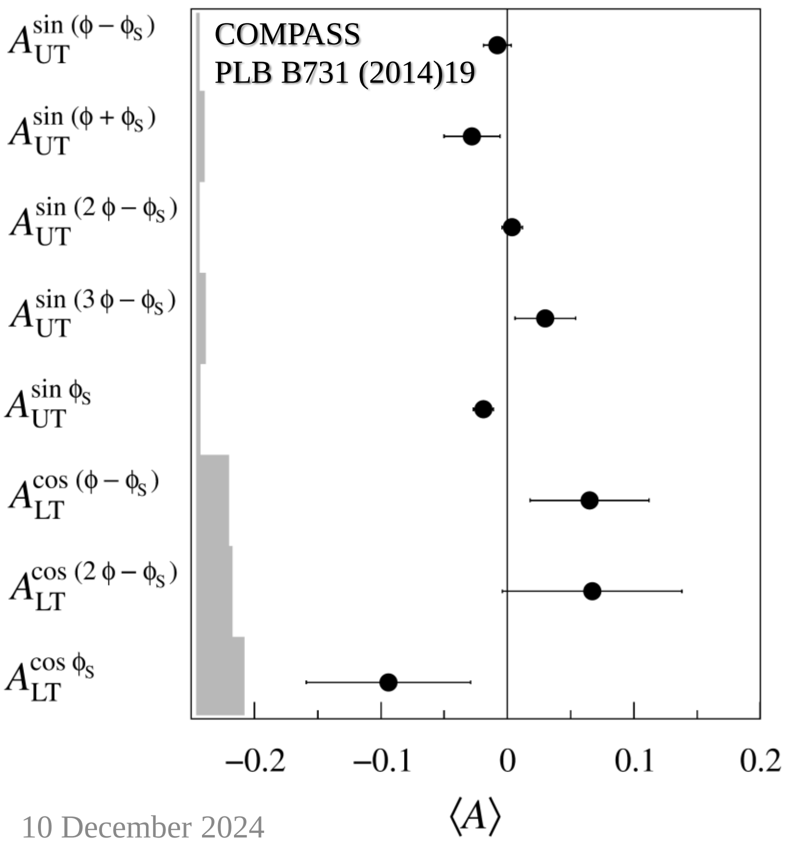
HERMES, JHEP 12 (2020) 010



COMPASS: Exclusive and Inclusive ρ^0 TSAs



exclusive



inclusive