The role of diffractively produced VMs: COMPASS experience

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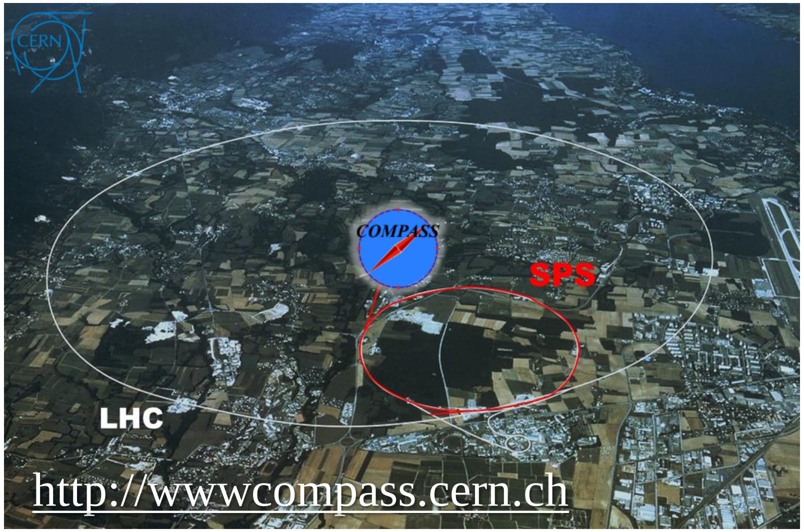
AANL, CERN and Yamagata University

XI^th COMPASS Analysis Phase international mini-workshop
(COMAP-11)
February 3, CERN, Geneva, Switzerland

COMPASS timeline

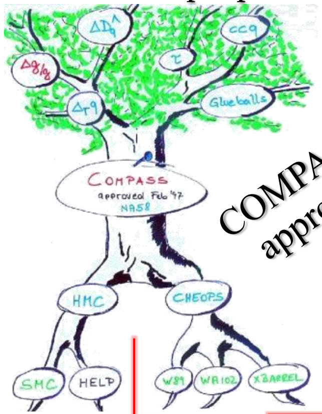
- CERN SPS north area – M2 beamline
- Fixed target experiment
- Approved in 1997
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

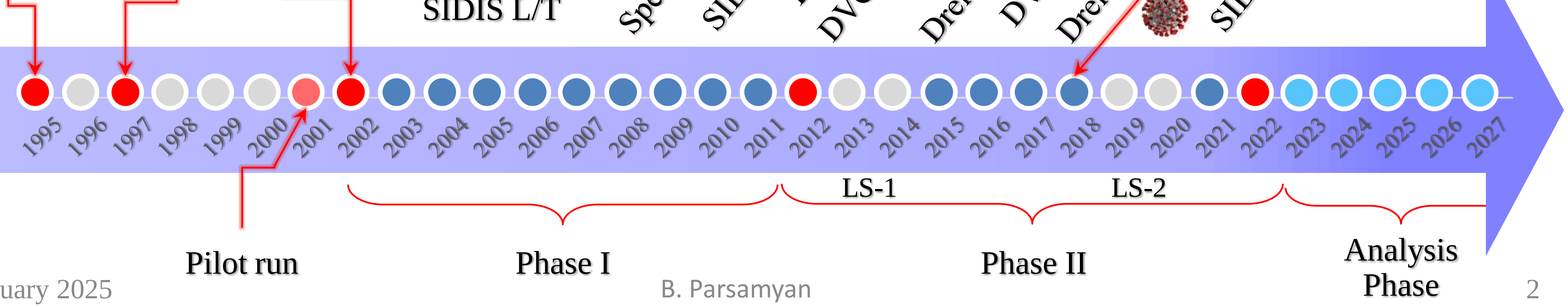
33 institutions from 15 countries: ~ 200 members



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

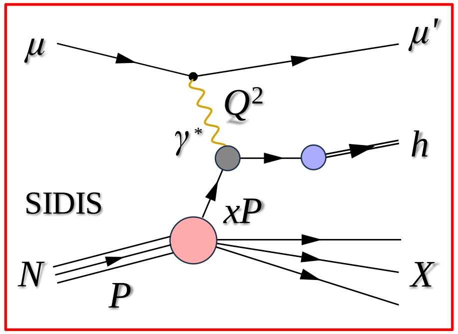


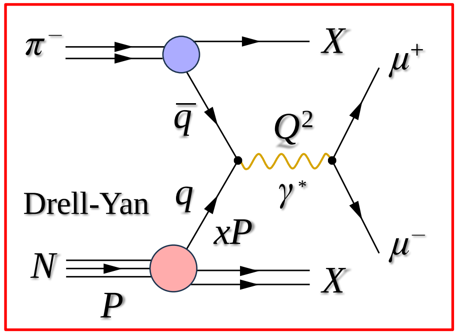


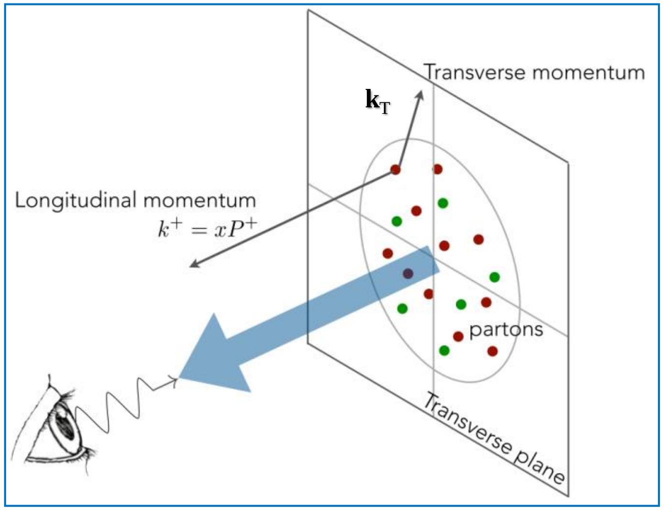
COMPASS Physics Program

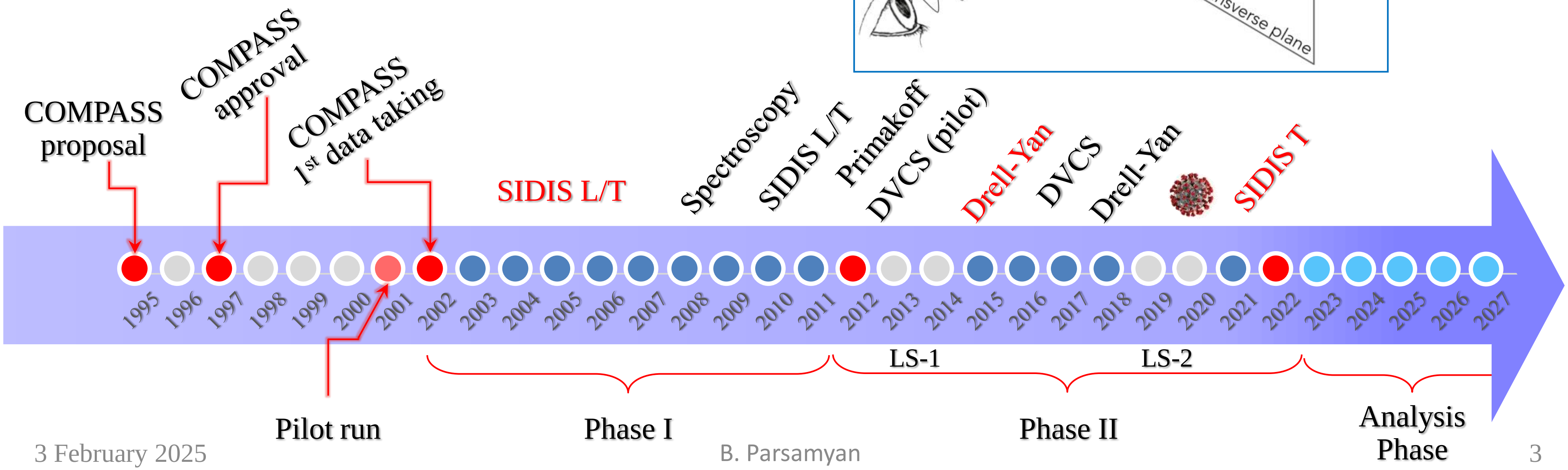
Nucleon structure

- 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









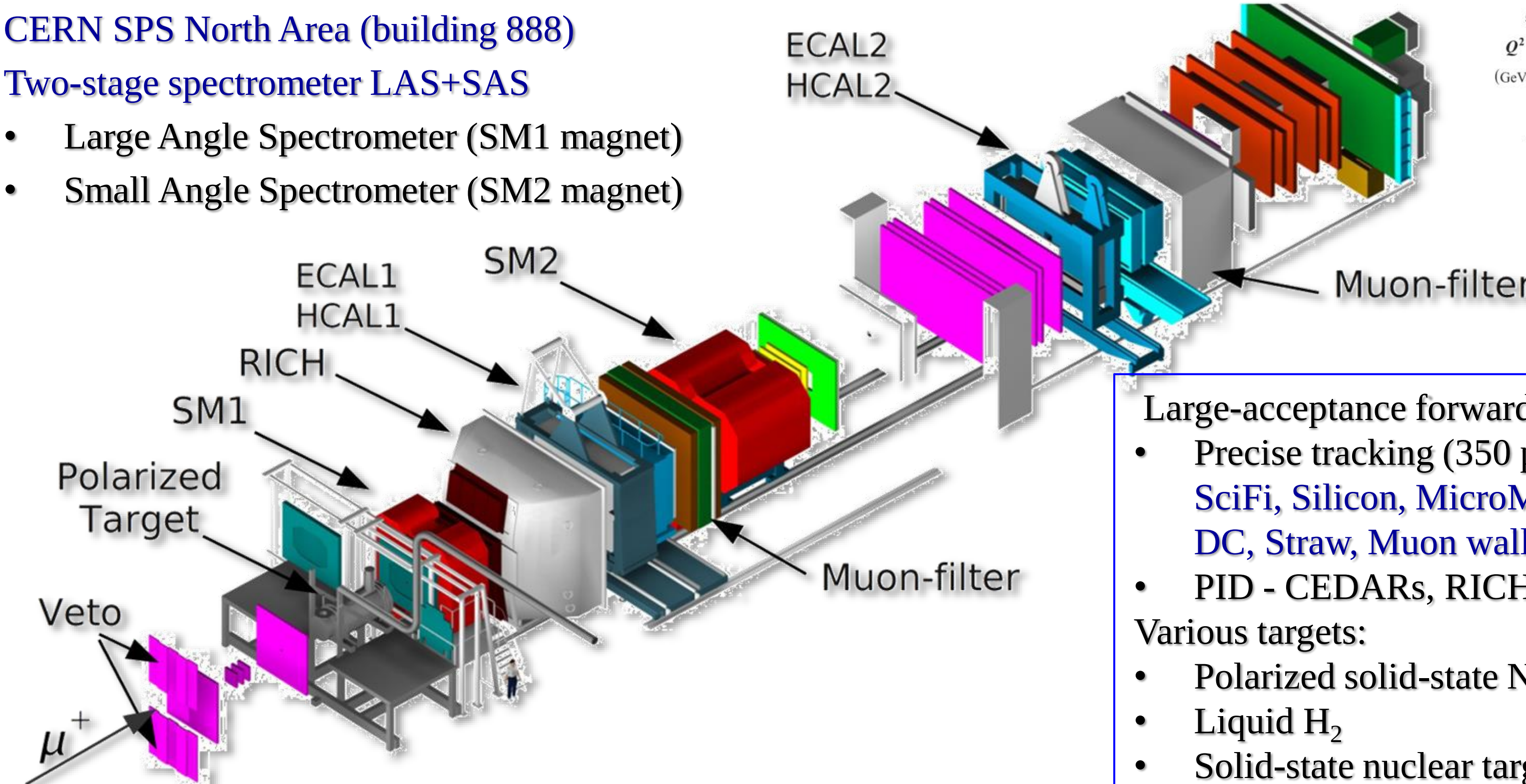
COMPASS experimental setup

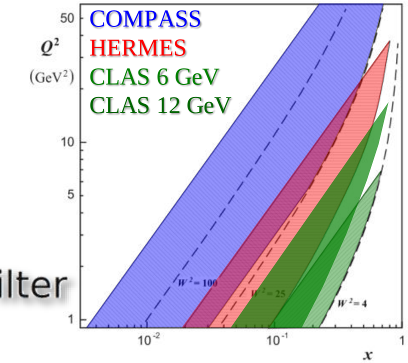
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





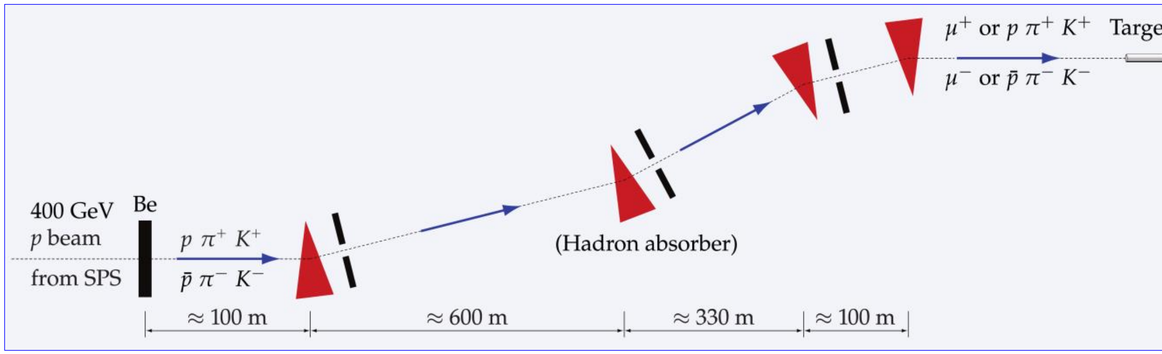
Large-acceptance forward spectrometer

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

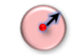
Various targets:

- 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

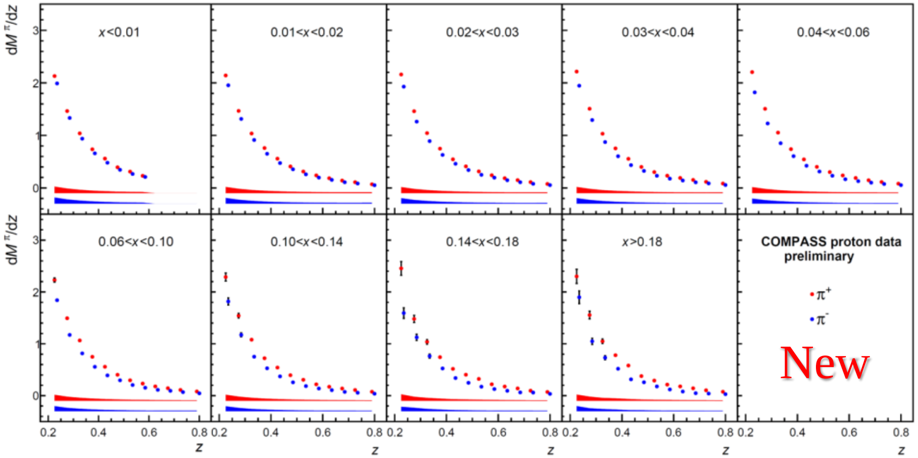


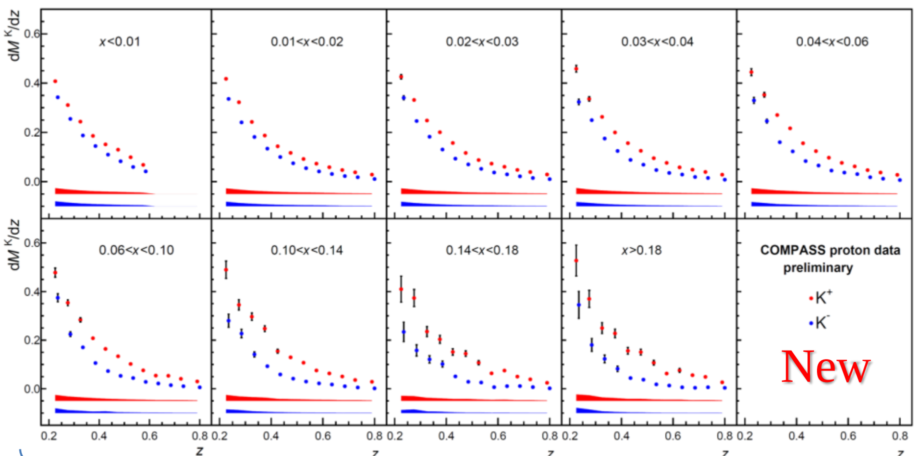
Hadron multiplicities; h±, π± and K± (2016 data)

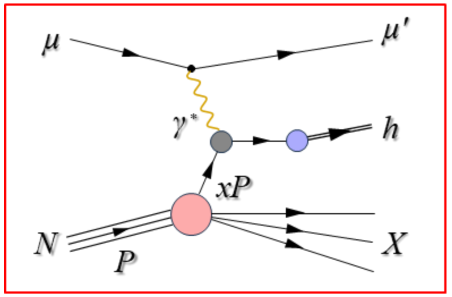
$f_1^q(x, \boldsymbol{k}_T^2)$
number density


collinear

A set of complex corrections:
- Acceptance, rad. corrections, PID, diffractive VMs, etc.







New radiative corrections (DJANGOH)
hep-ex/2410.12005 submitted to PRD

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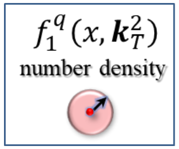

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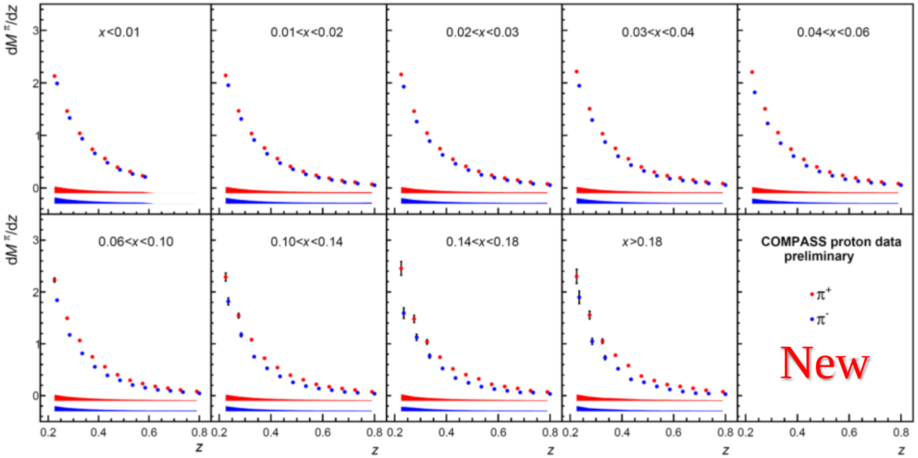

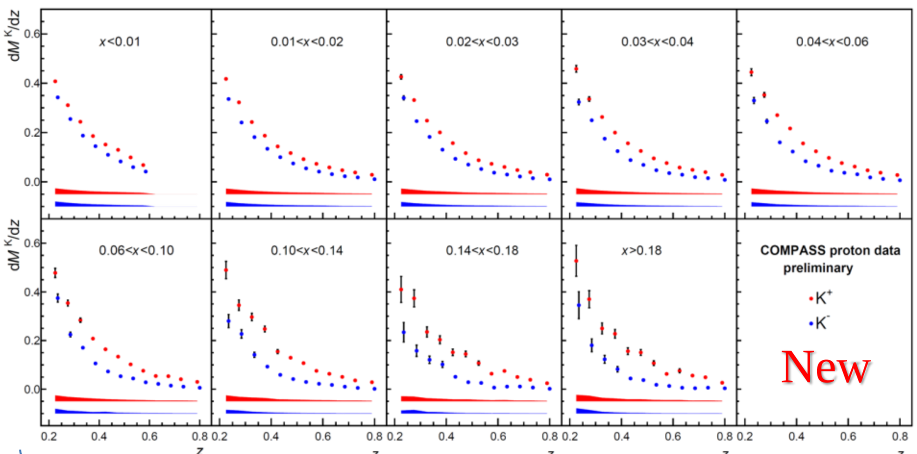

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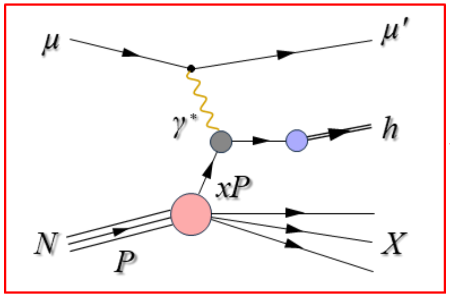
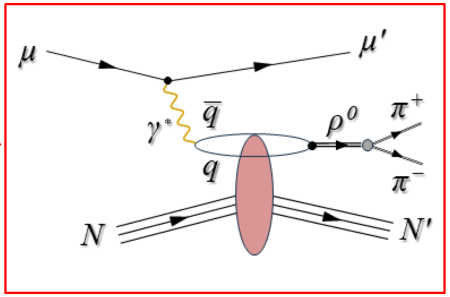




Diffractive VM production

- In DIS γ^* interacts with a single quark
- DVMP - γ^* fluctuates into a VM
  - VM then interacts diffractively with the nucleon through multiple gluon exchange
- DVMP correction: two MC samples are used

SIDIS

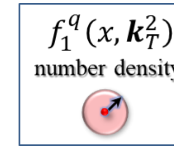
- LEPTO 6.5 MC (diffractive contributions off)

Diffractive ρ^0 and ϕ mesons

- HEPGEN generator

Obtained HEPGEN and LEPTO E_{miss} spectra are normalized to the data (better MC/RD description)

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



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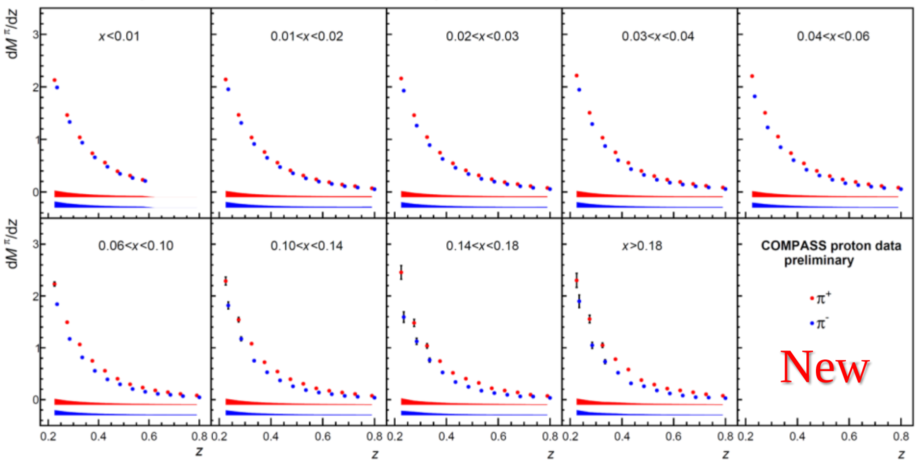

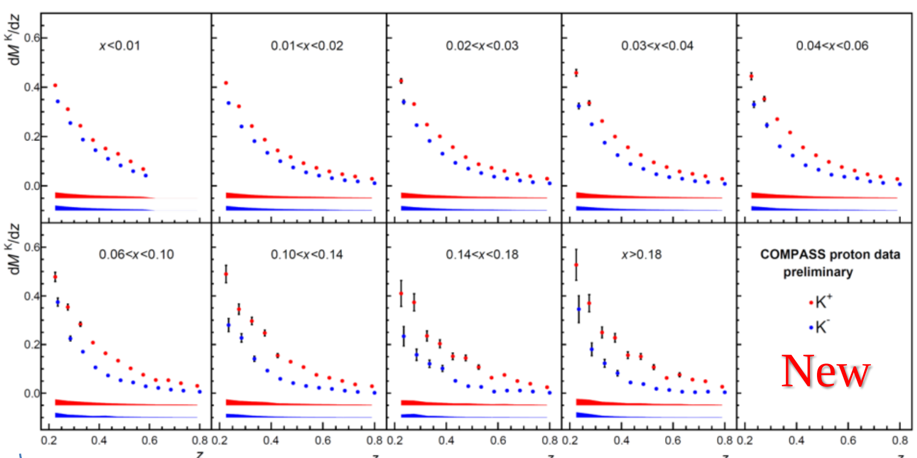

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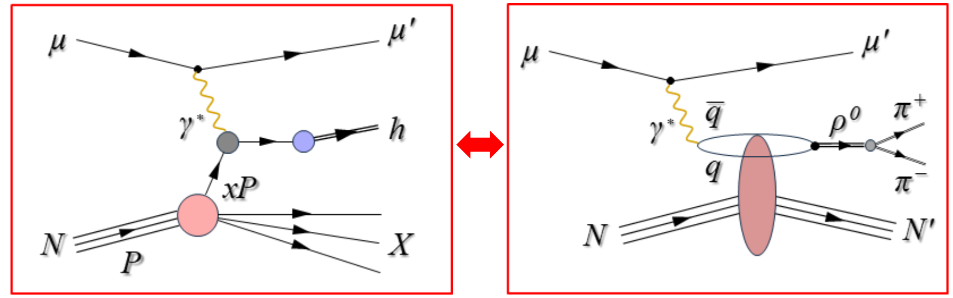

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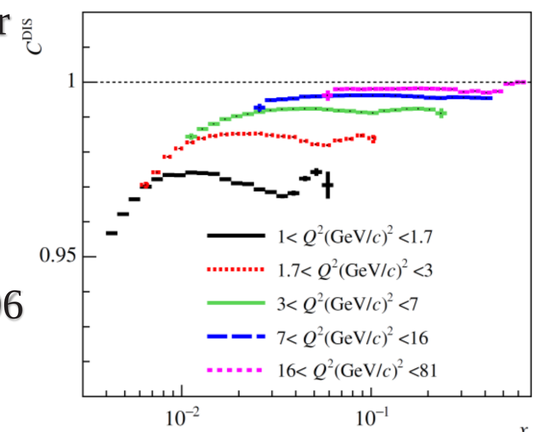
DIS correction
COMPASS
PRD97(2018),032006



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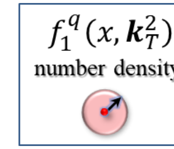

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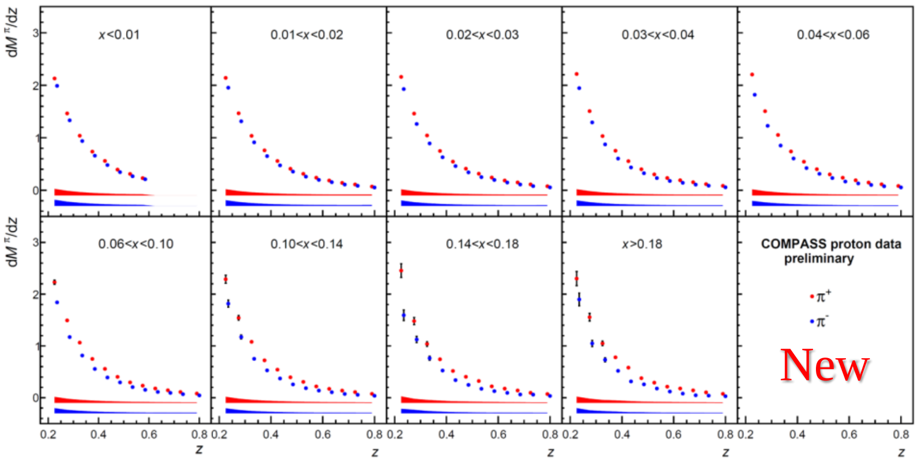

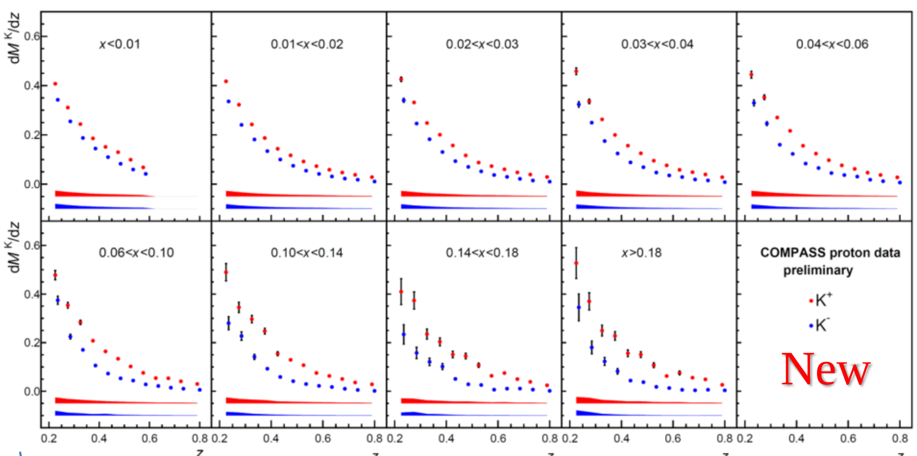

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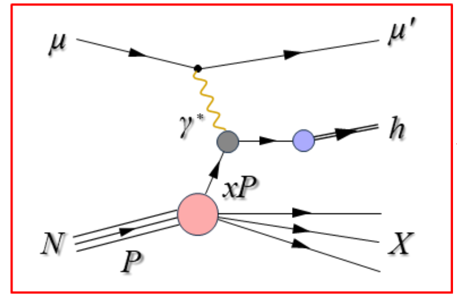

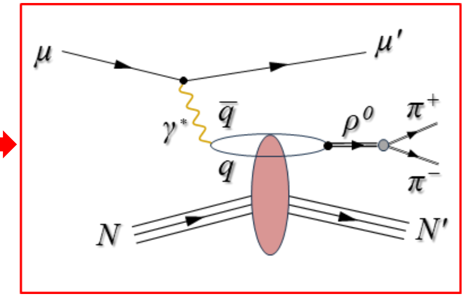

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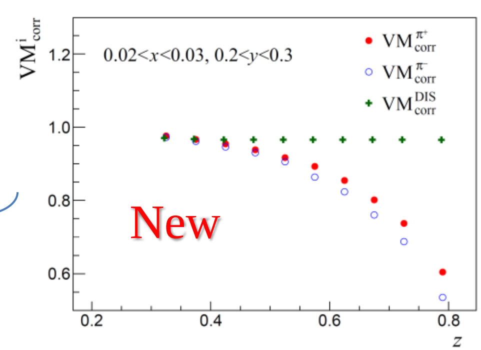

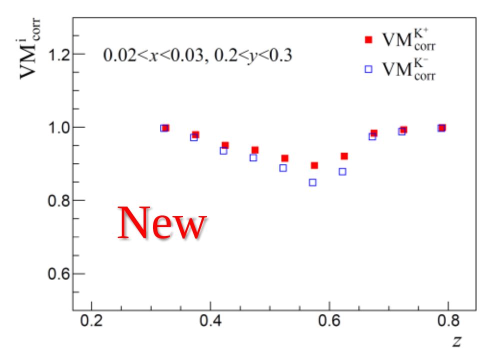

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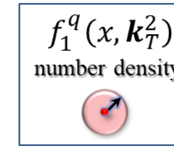

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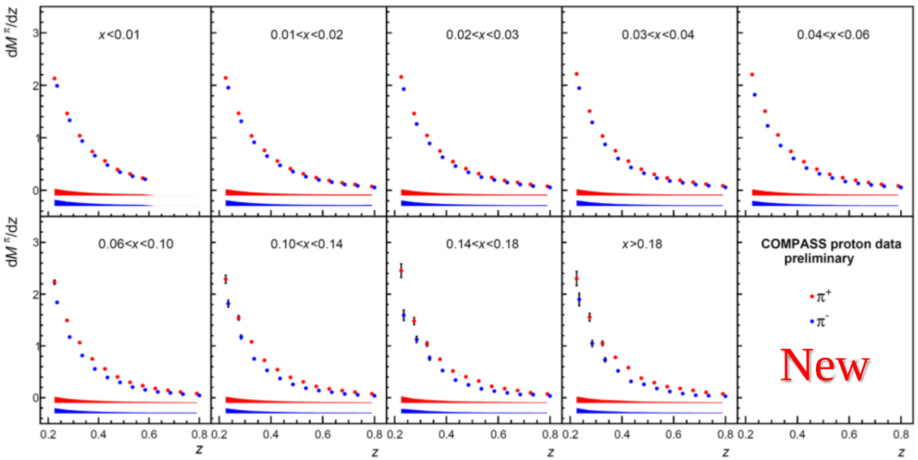

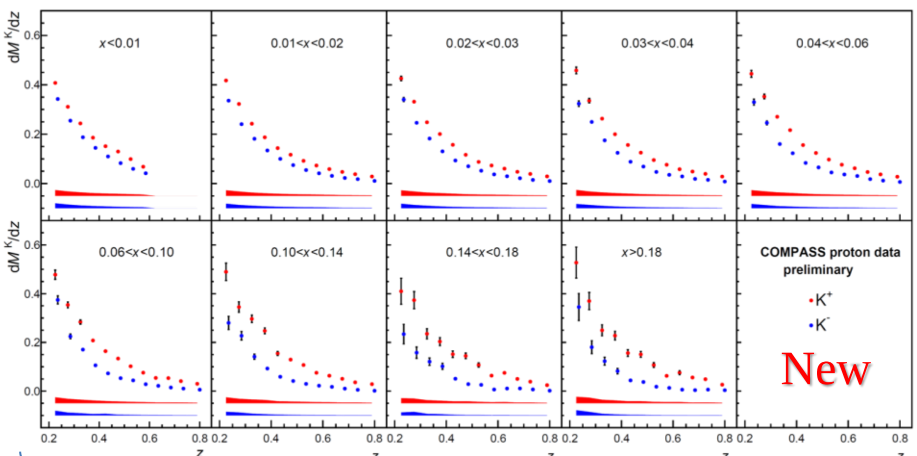

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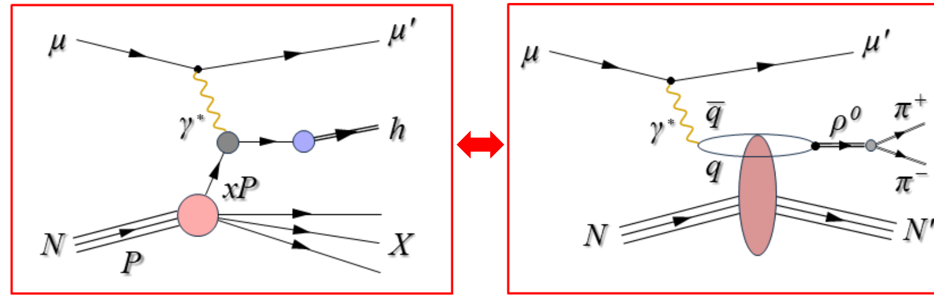

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Diffractive ρ^0 and ϕ mesons

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Diffractive events enhance at low x and Q^2

- Pions from ρ^0 decay (at high z)

For pions maximum correction can reach even 50%

- Kaons from ϕ decay ($0.4 < z < 0.6$)

For kaons maximum correction ~24% for ($z \approx 0.6$ and $Q^2 \approx 1$ (GeV/c)^2.

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

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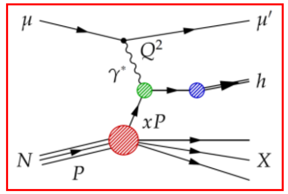

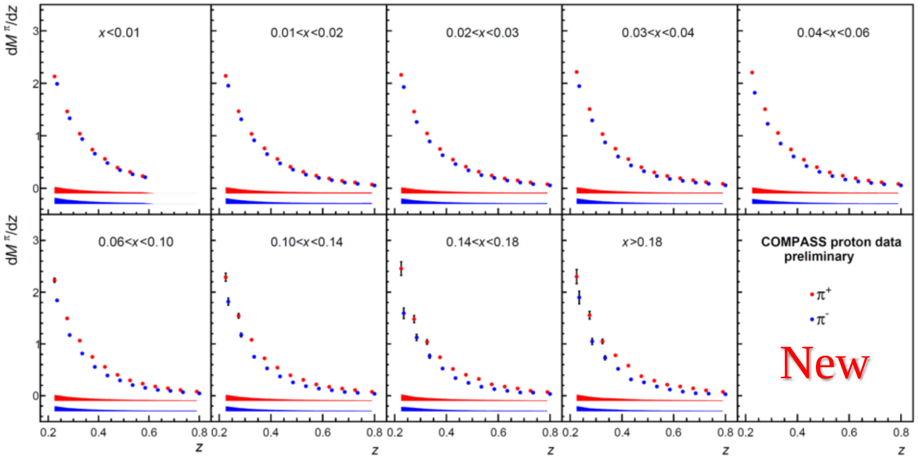

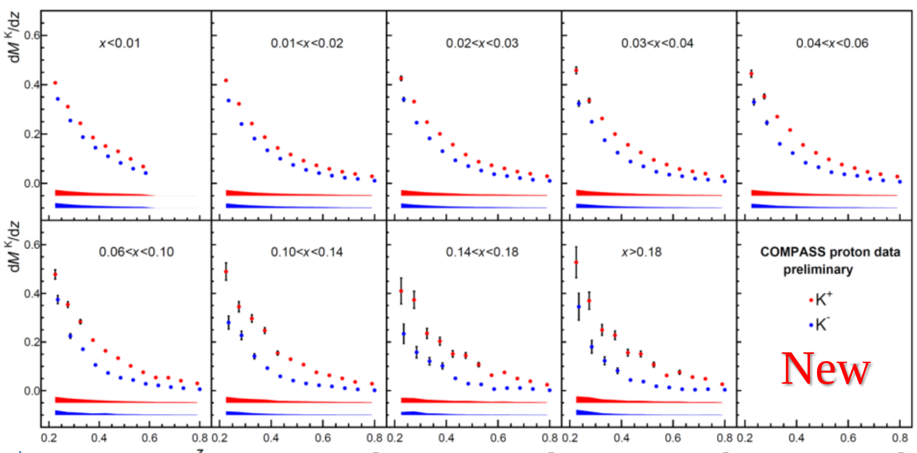

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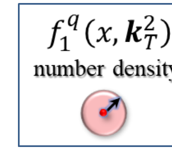

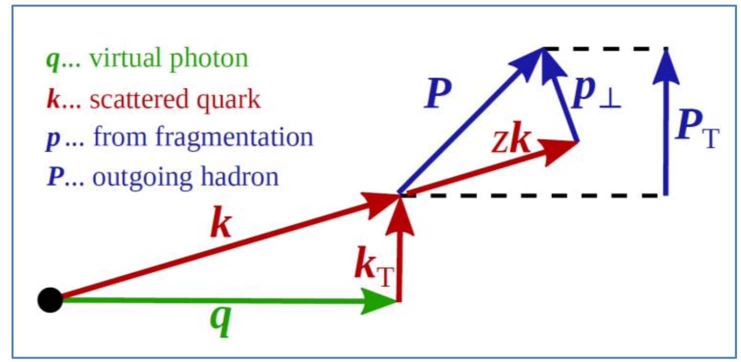

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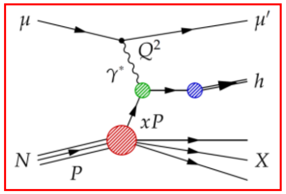
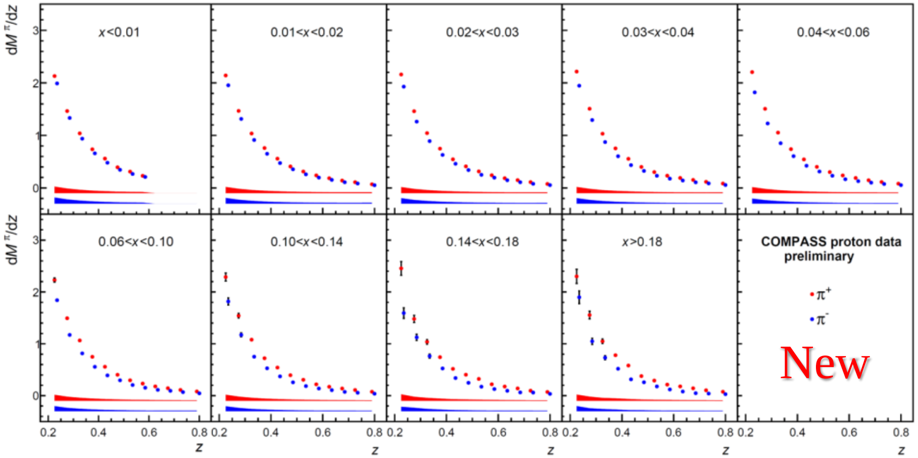
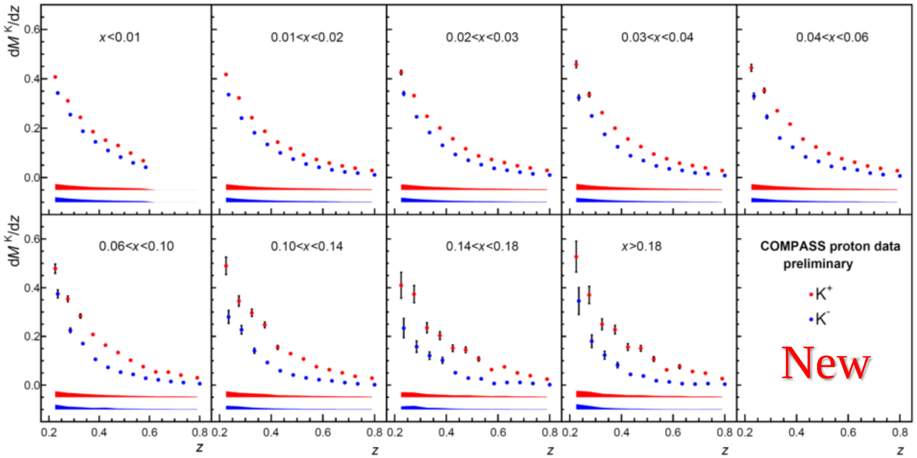
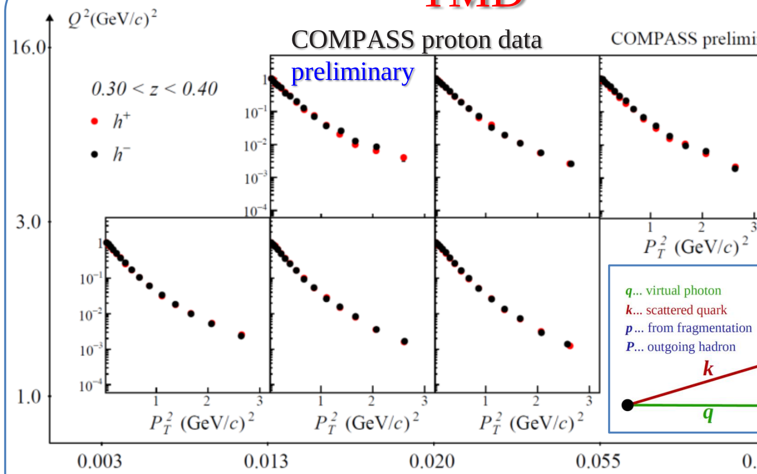


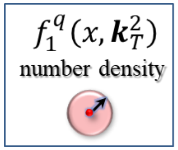


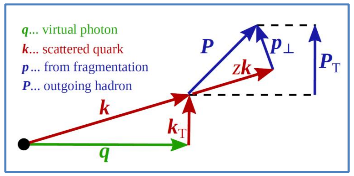


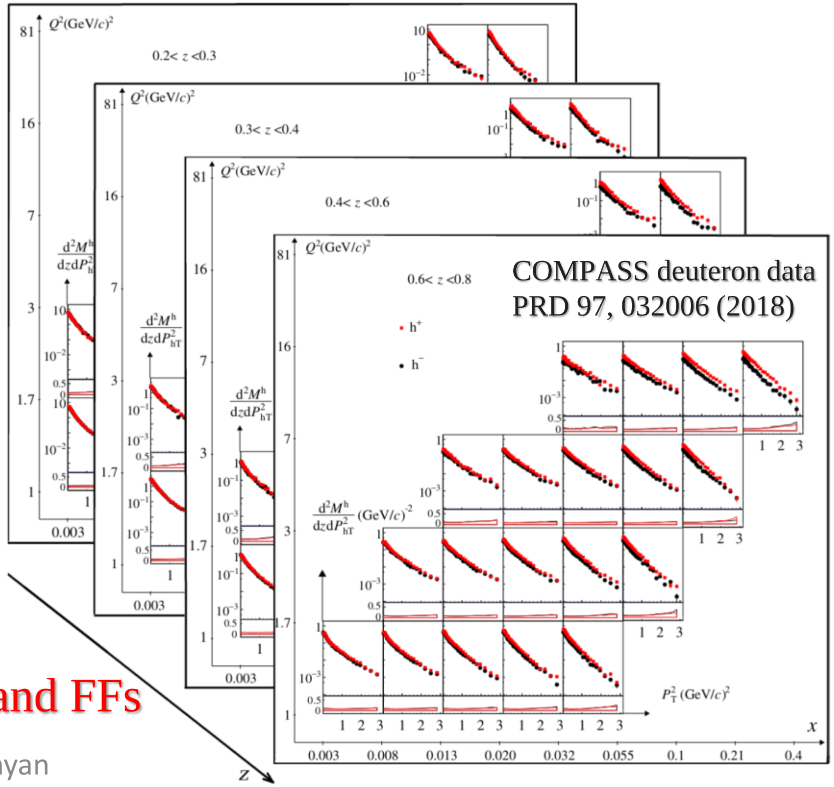
New radiative corrections being applied

TMD









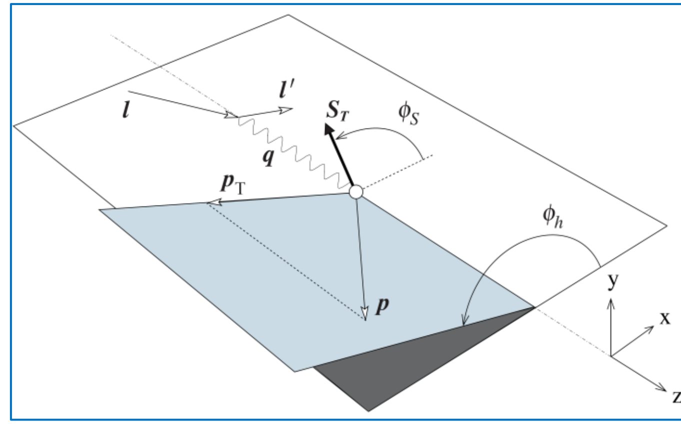
Multi-D is crucial to explore all features of PDFs and FFs

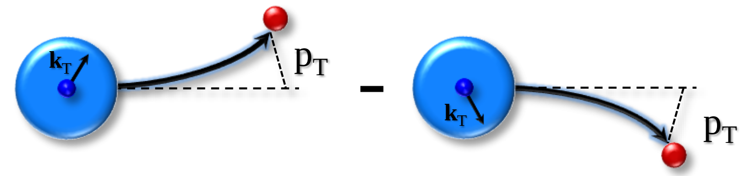
Cahn effect in SIDIS

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

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

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





Cahn effect

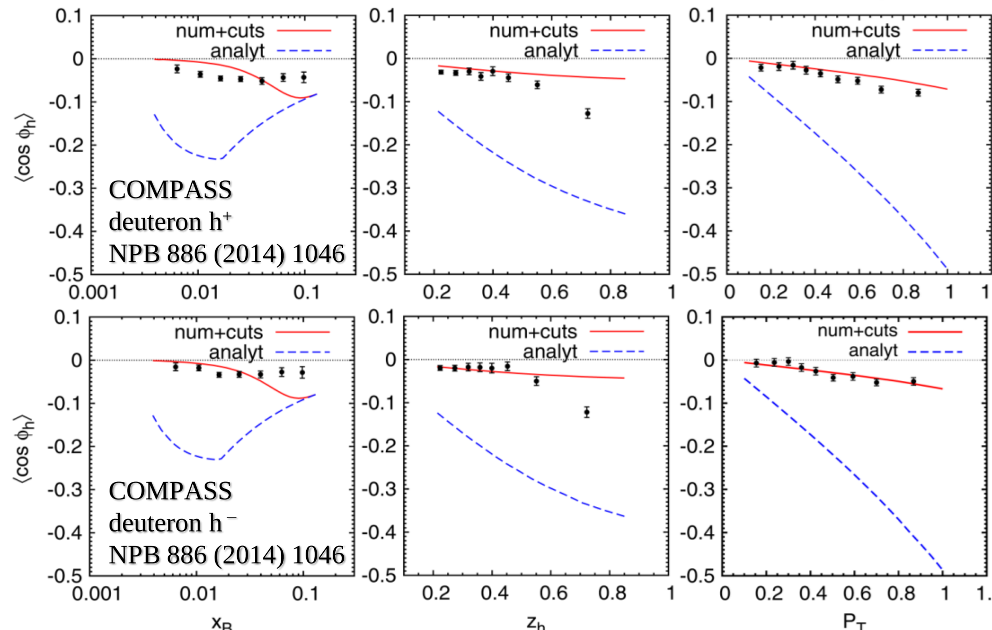
$f_1^q(x,\boldsymbol{k}_T^2)$
number density

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

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

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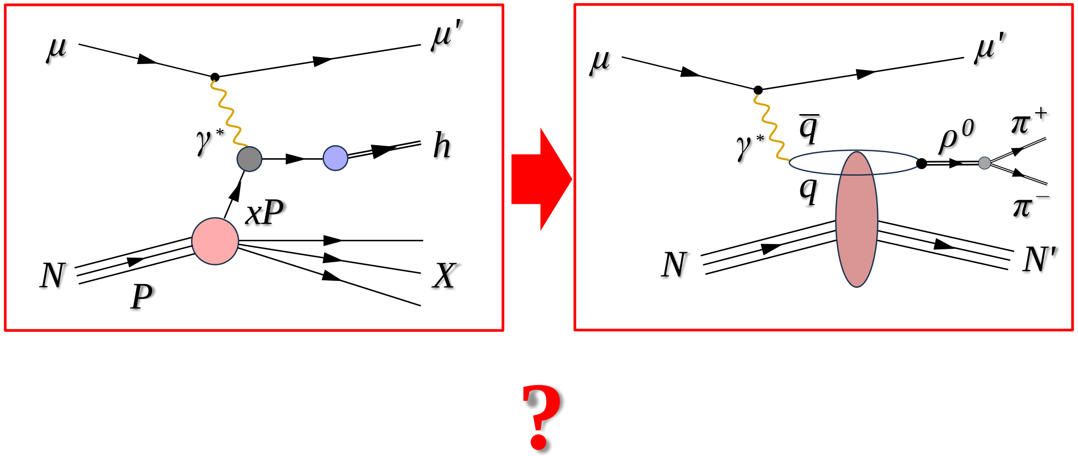

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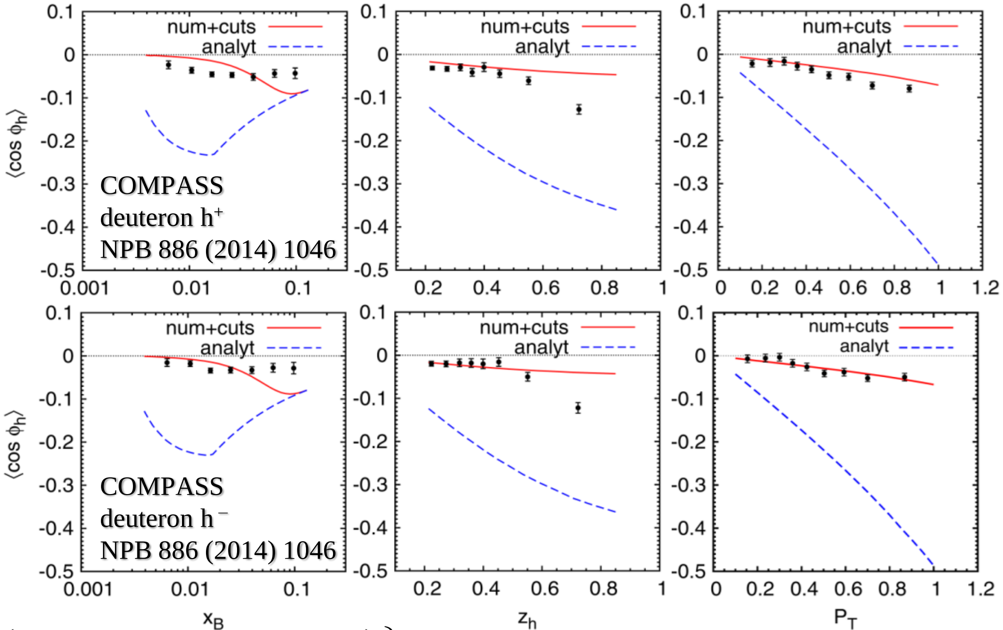

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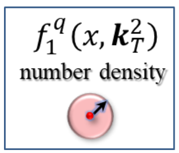
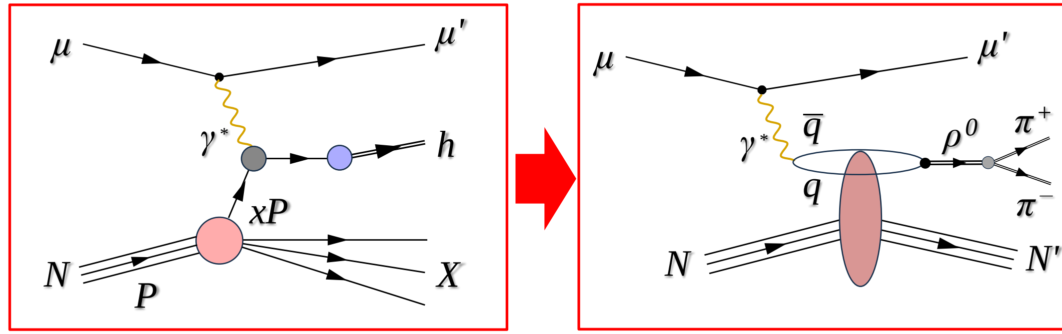
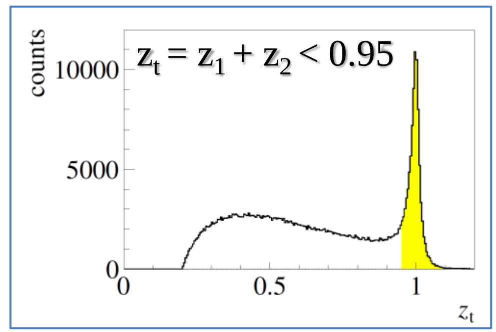
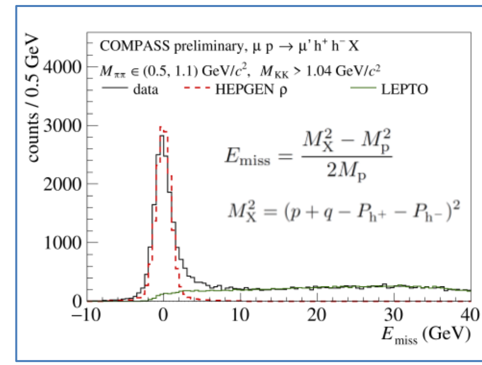
Cahn effect

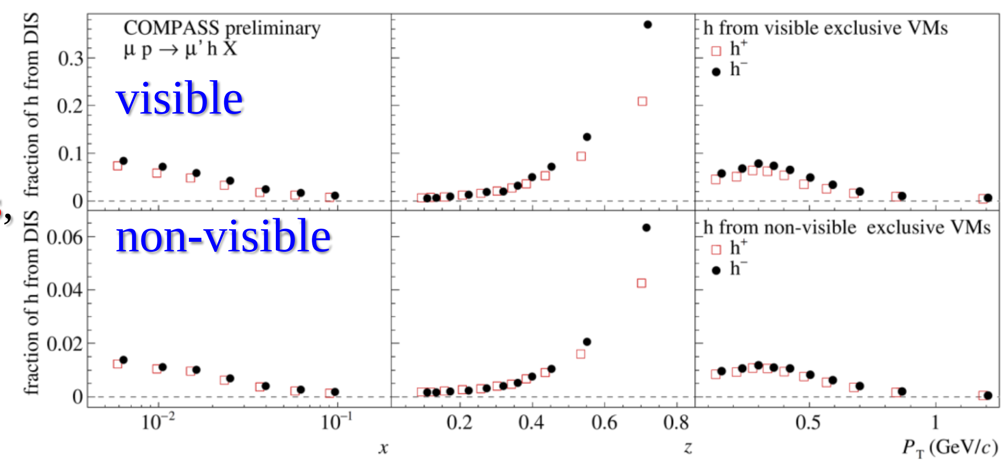








VM fractions



As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

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- Measurements by different experiments
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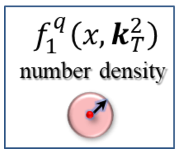
Cahn effect in SIDIS: DVMs

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

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

Cahn effect



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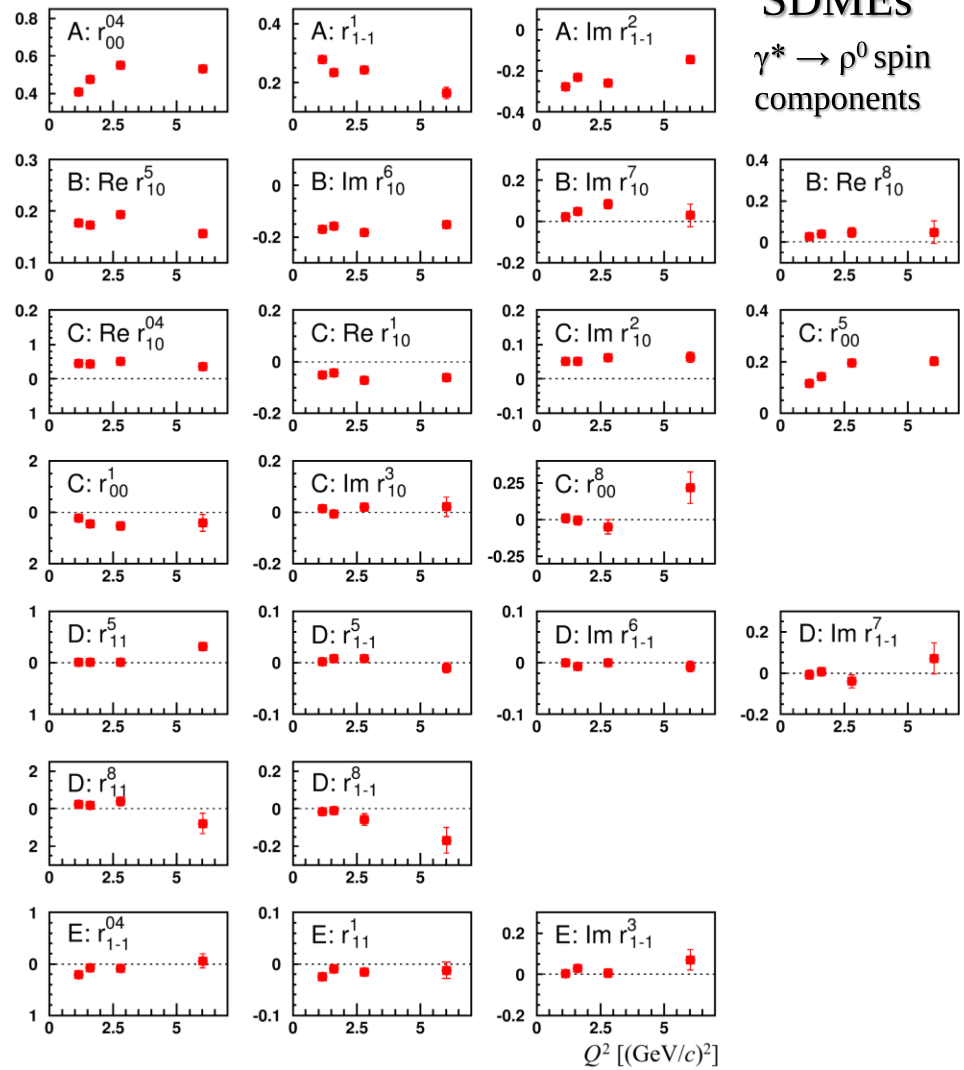
COMPASS, EPJC (2023) 83 924

SDMEs

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



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

Cahn effect in SIDIS: DVMs

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

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

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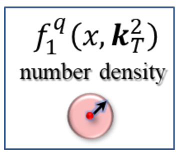
Cahn effect



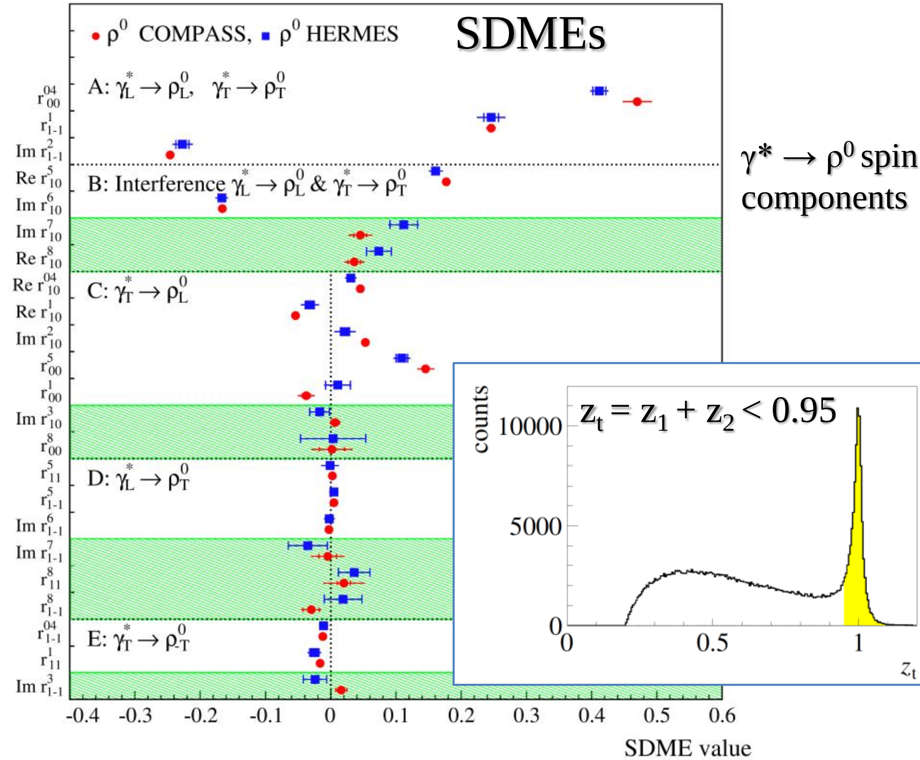
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

"Visible" hadron pairs

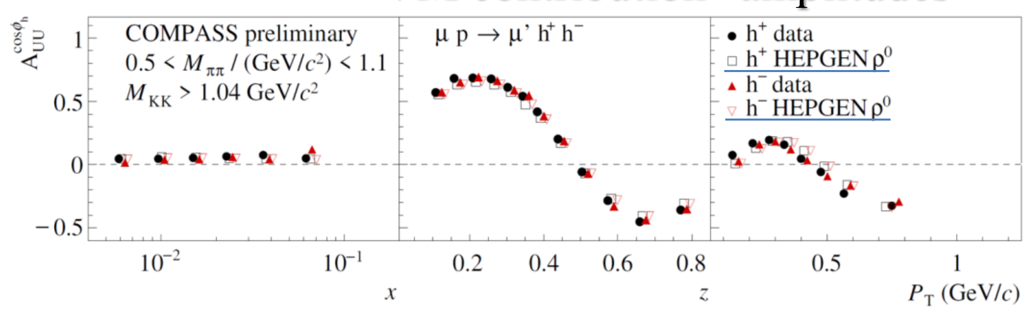
- Both hadrons reconstructed
- Removed by selecting: $z_t = z_{h+} + z_{h-} < 0.95$

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

As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

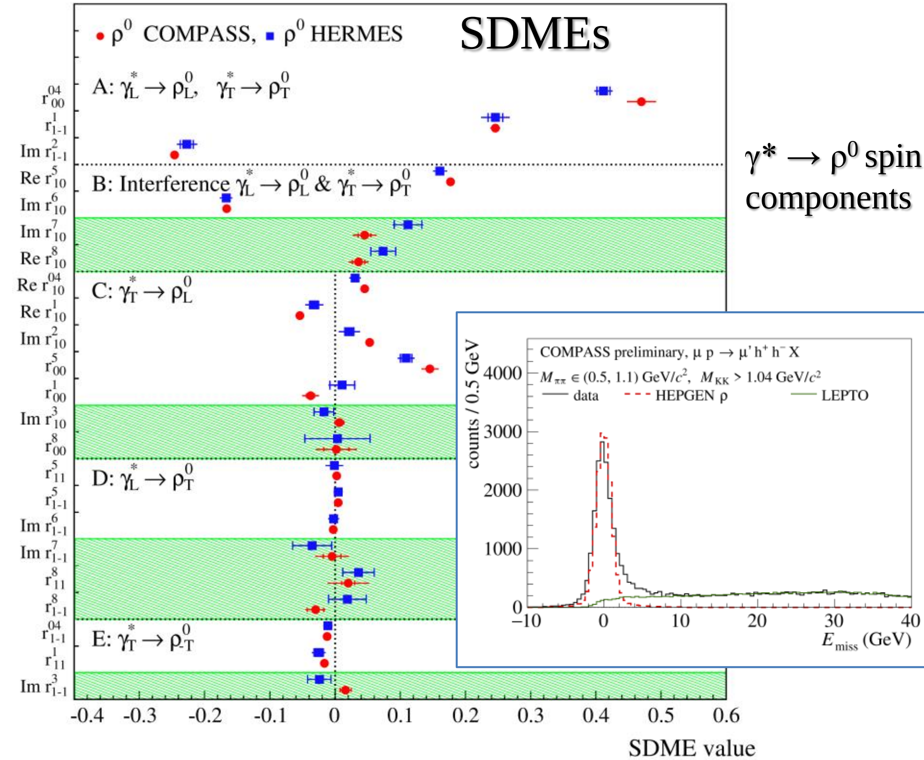
"Visible" hadron pairs

- Both hadrons reconstructed
- Removed by selecting: $z_t = z_{h+} + z_{h-} < 0.95$

"Invisible" hadron pairs

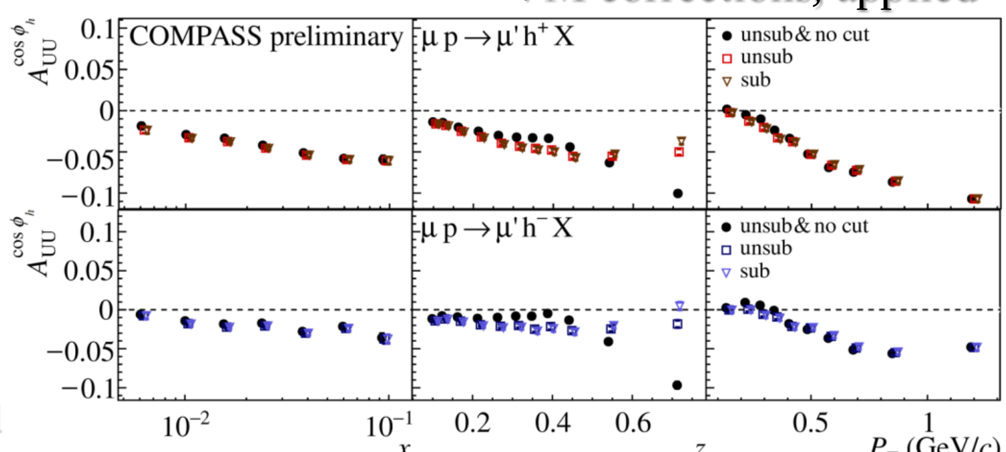
- Only one hadron out of two is reconstructed
- Subtraction done at the level of ϕ_h using simulated HEPGEN distribution for VMs
- HEPGEN and Lepto are normalized to the data using E_{miss} distribution, SIDIS tail is subtracted

COMPASS, EPJC (2023) 83 924



γ* → ρ^0 spin components

VM corrections, applied



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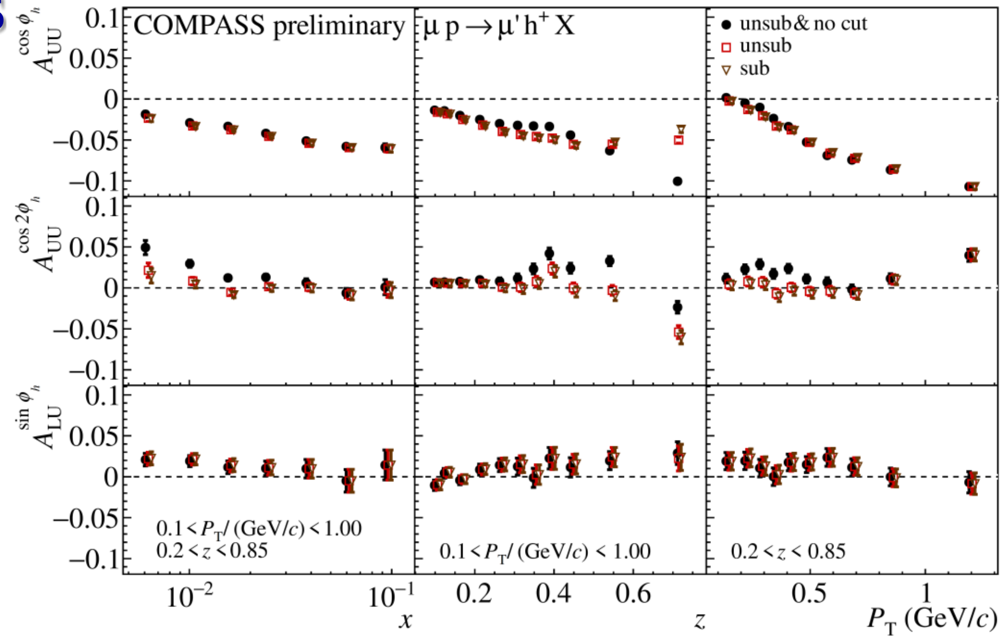
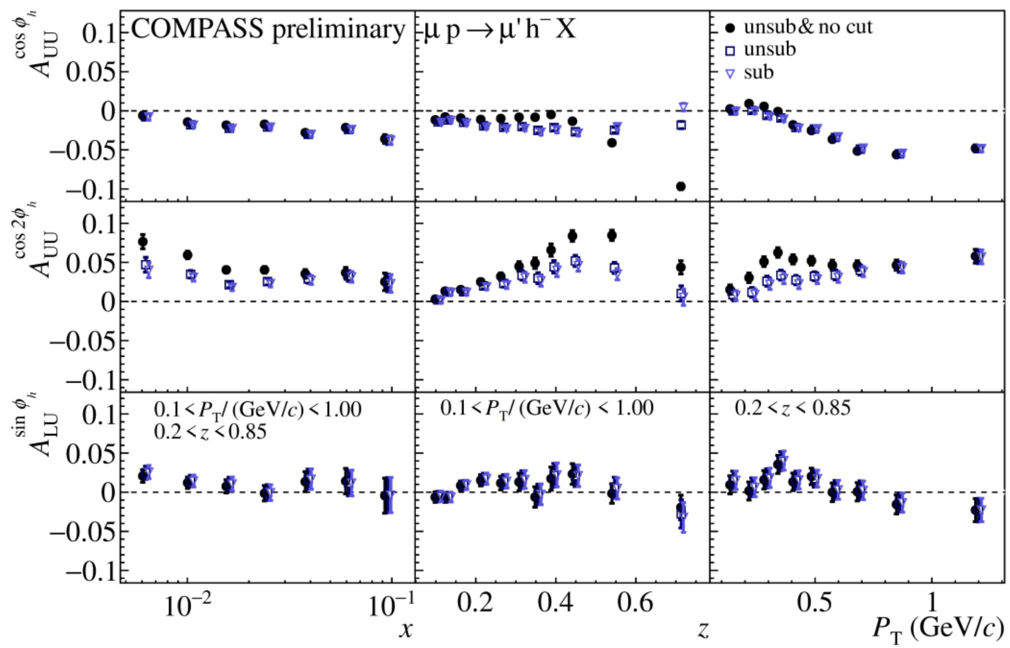
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} =$$

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

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

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





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

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

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

Cahn effect

$f_1^q(x,\boldsymbol{k}_T^2)$
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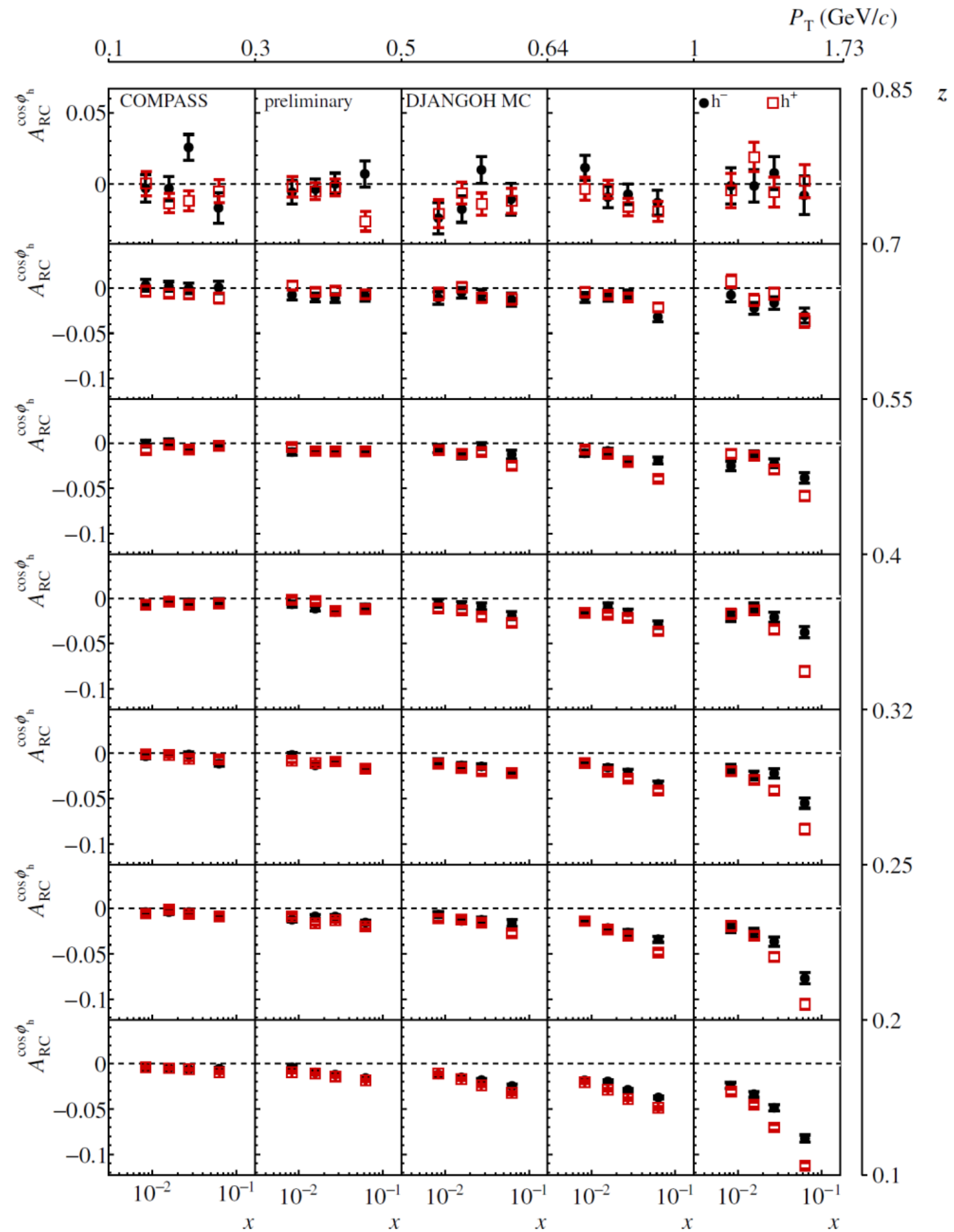
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
- Strong Q^2 dependence – unexplained
  - Do not seem to come from RCs
  - Transition TMD ↔ collinear regions?

RC corrections



Cahn effect in SIDIS: DVMs and RCs

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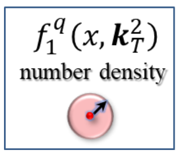
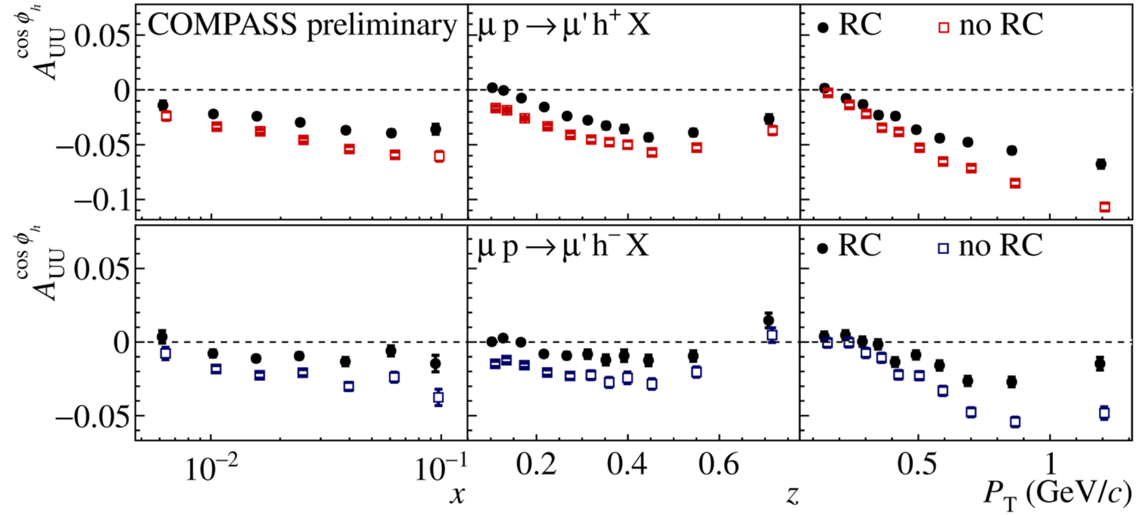
Cahn effect



RC corrections, applied



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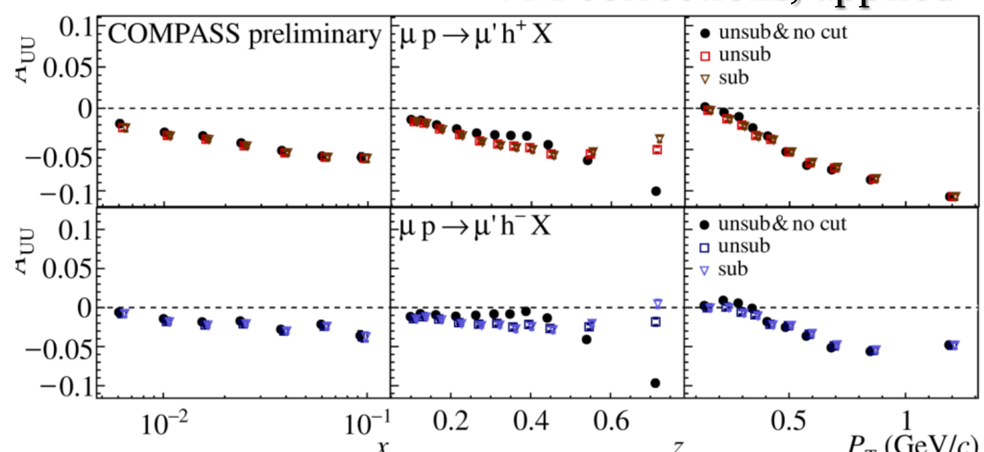
VM corrections, applied

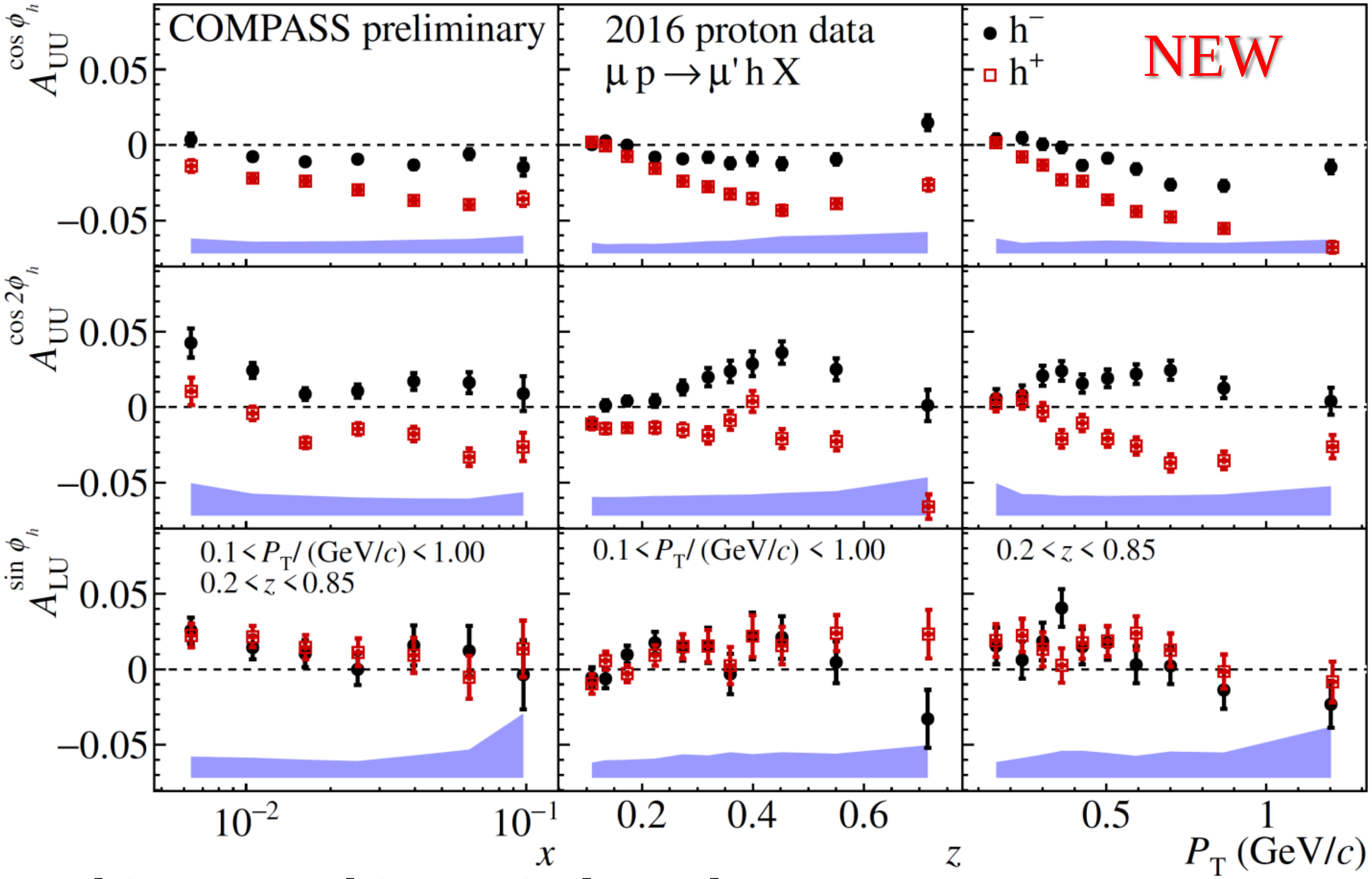


Azimuthal effects in unpolarized SIDIS

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

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

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

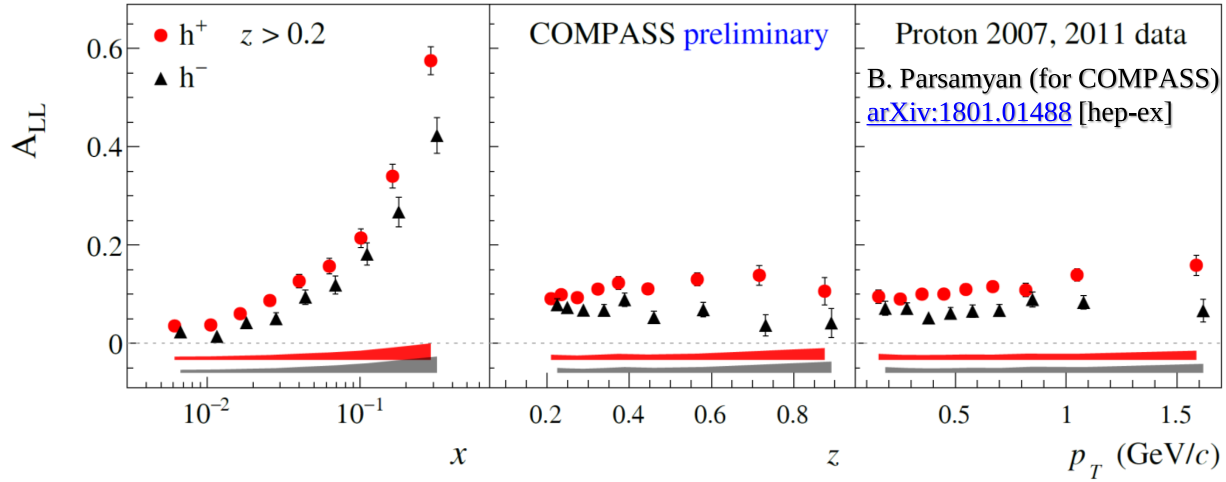
Working on 3D kinematic dependences

SIDIS: target longitudinal spin dependent asymmetries

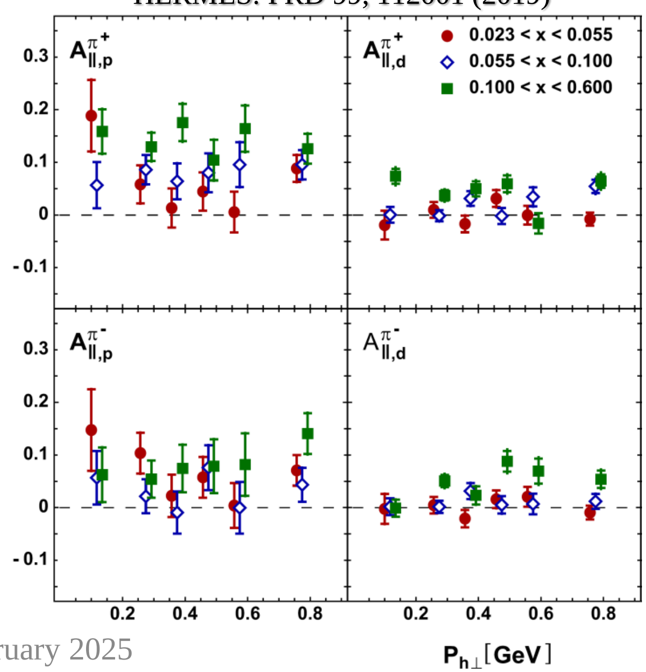
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} + \ldots\right\}$$

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

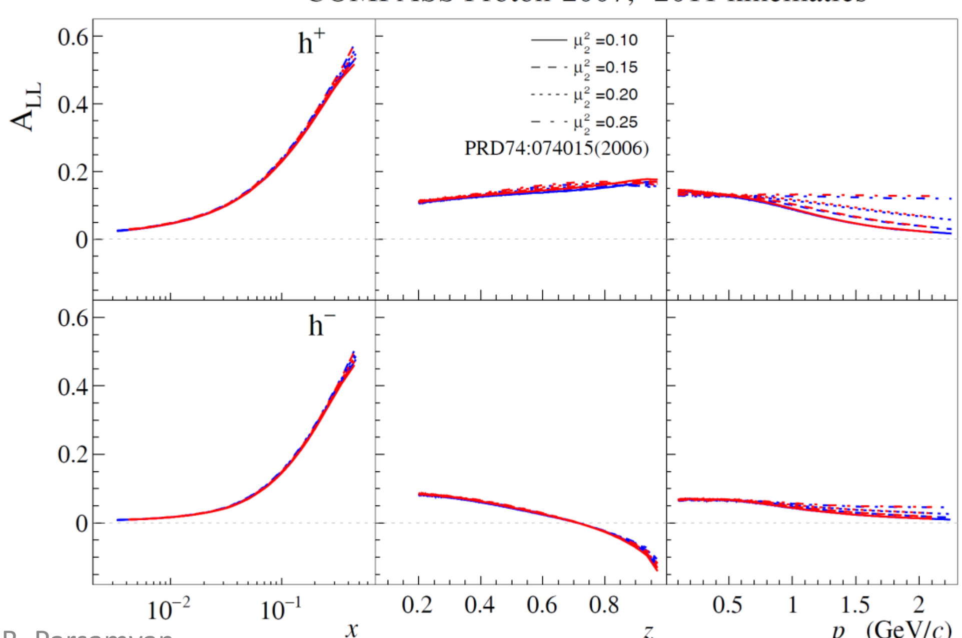
- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed



HERMES: PRD 99, 112001 (2019)



COMPASS Proton-2007, -2011 kinematics



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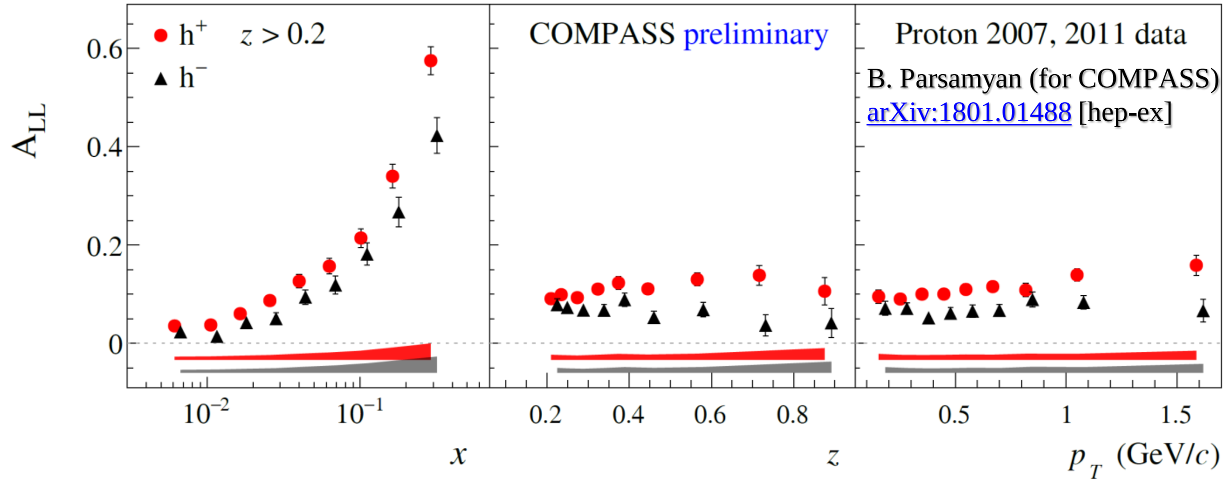
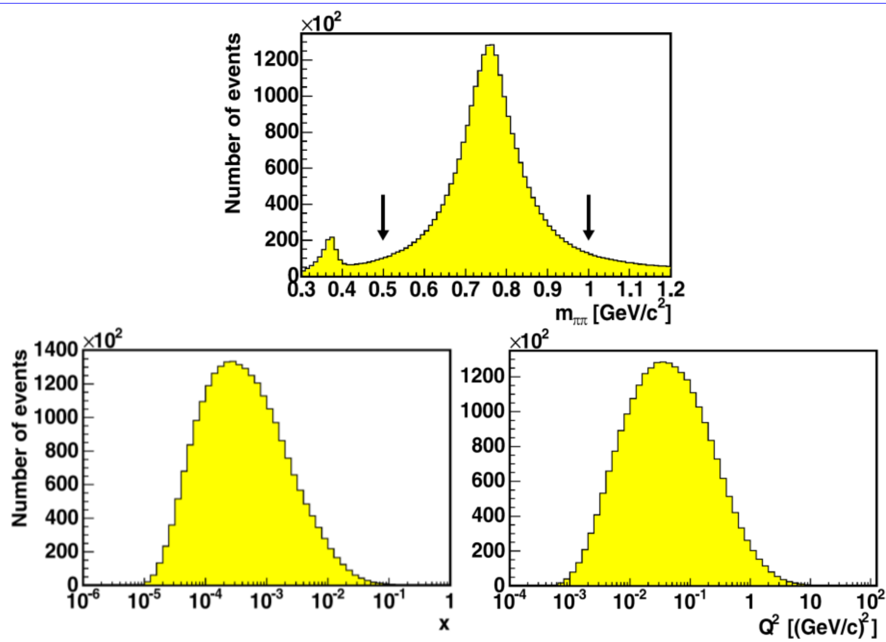
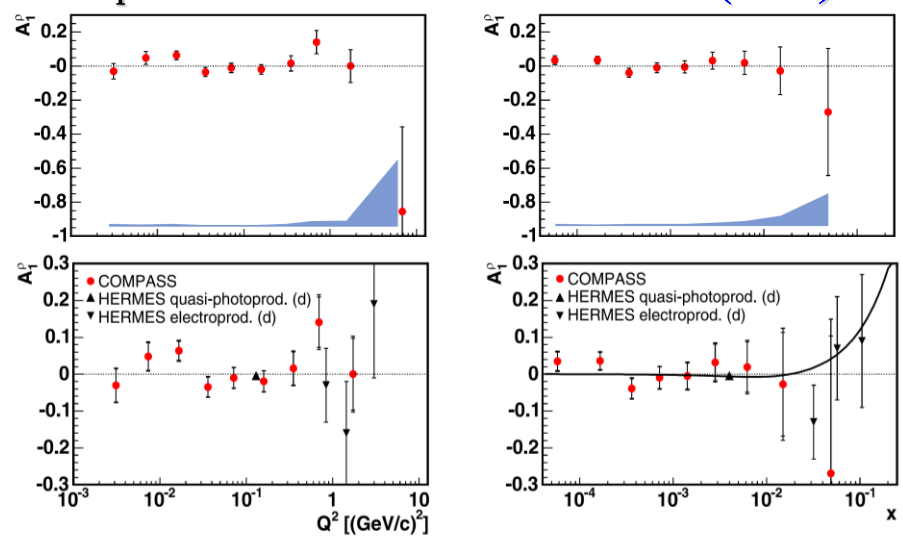




Double spin asymmetry in exclusive ρ^0 muoproduction at COMPASS EPJ C52 (2007) 255



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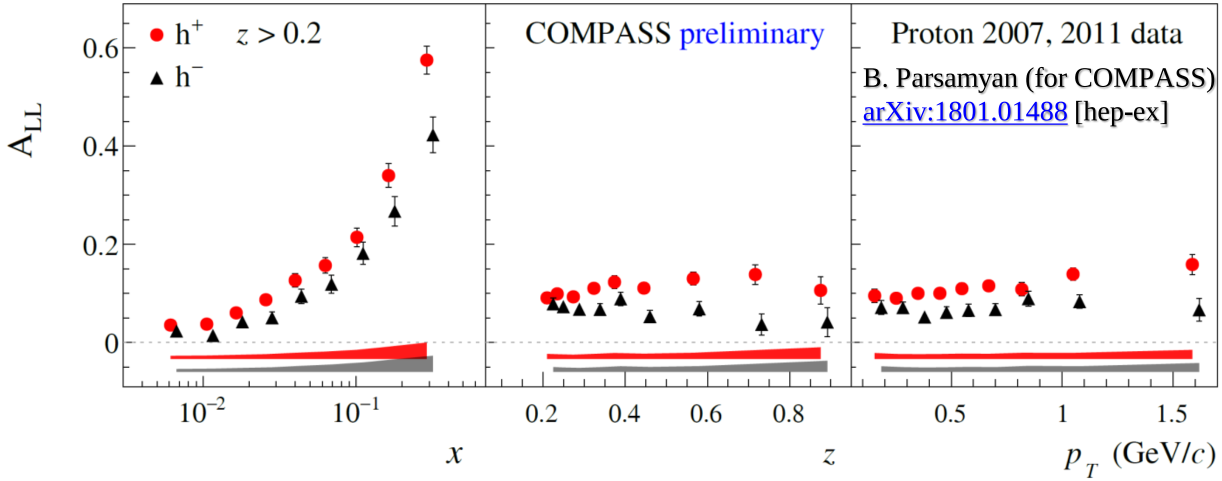
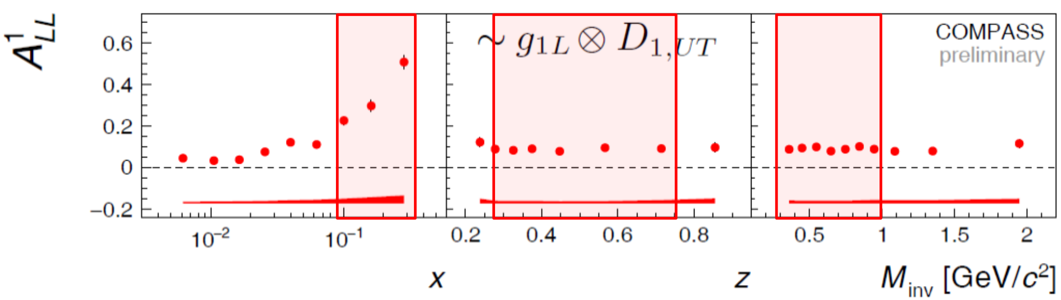
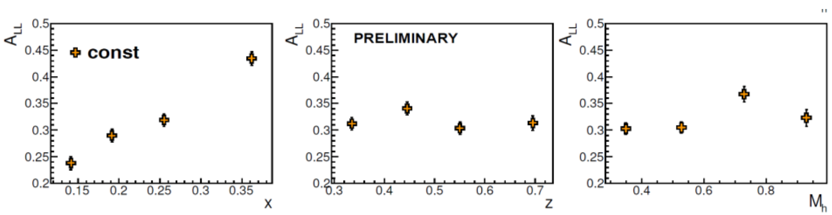


Double spin asymmetry in dihadron production at COMPASS and JLab 6

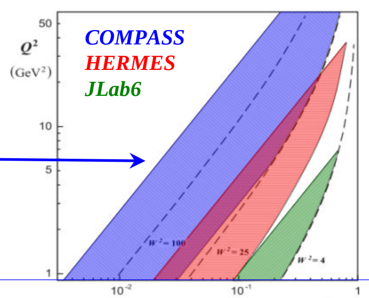


CLAS 6 GeV (NH_3)

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



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

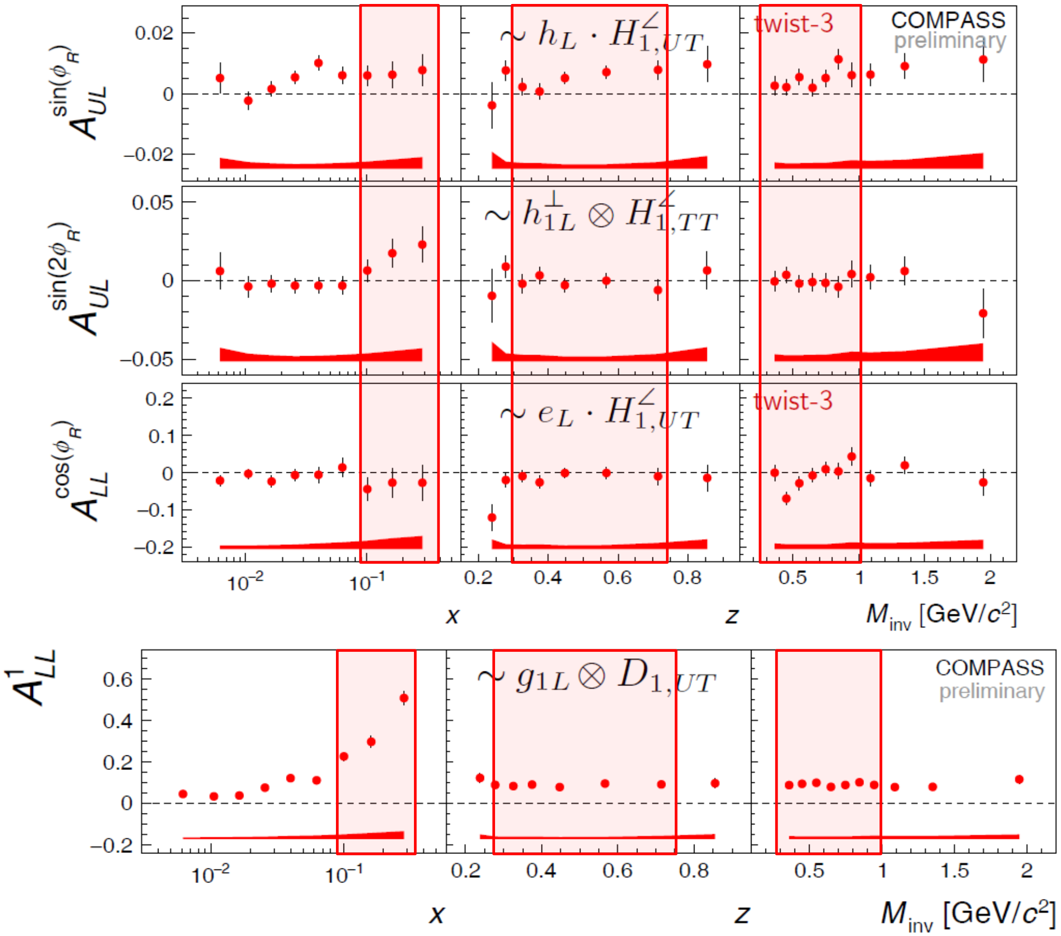


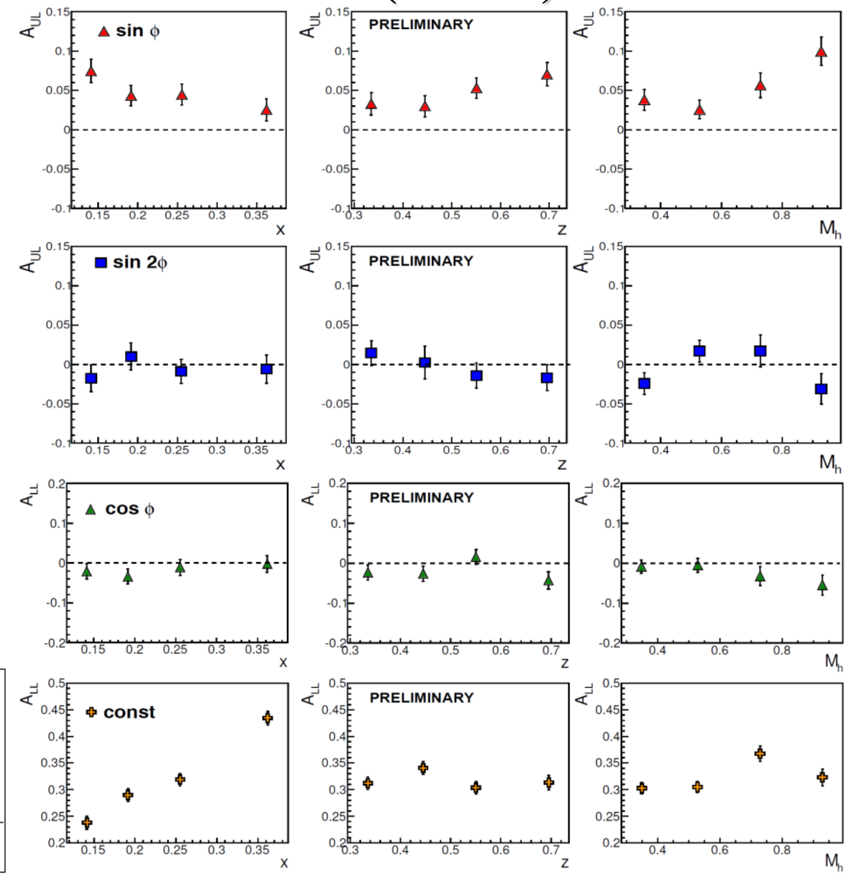
- Alternative way to access various twist-2/-3 distributions
- Non zero signal for A_{LL}^1

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





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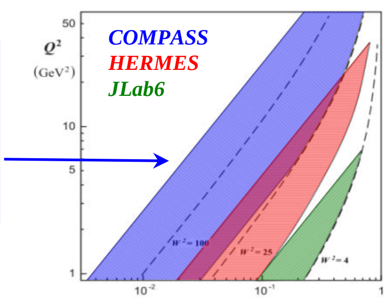


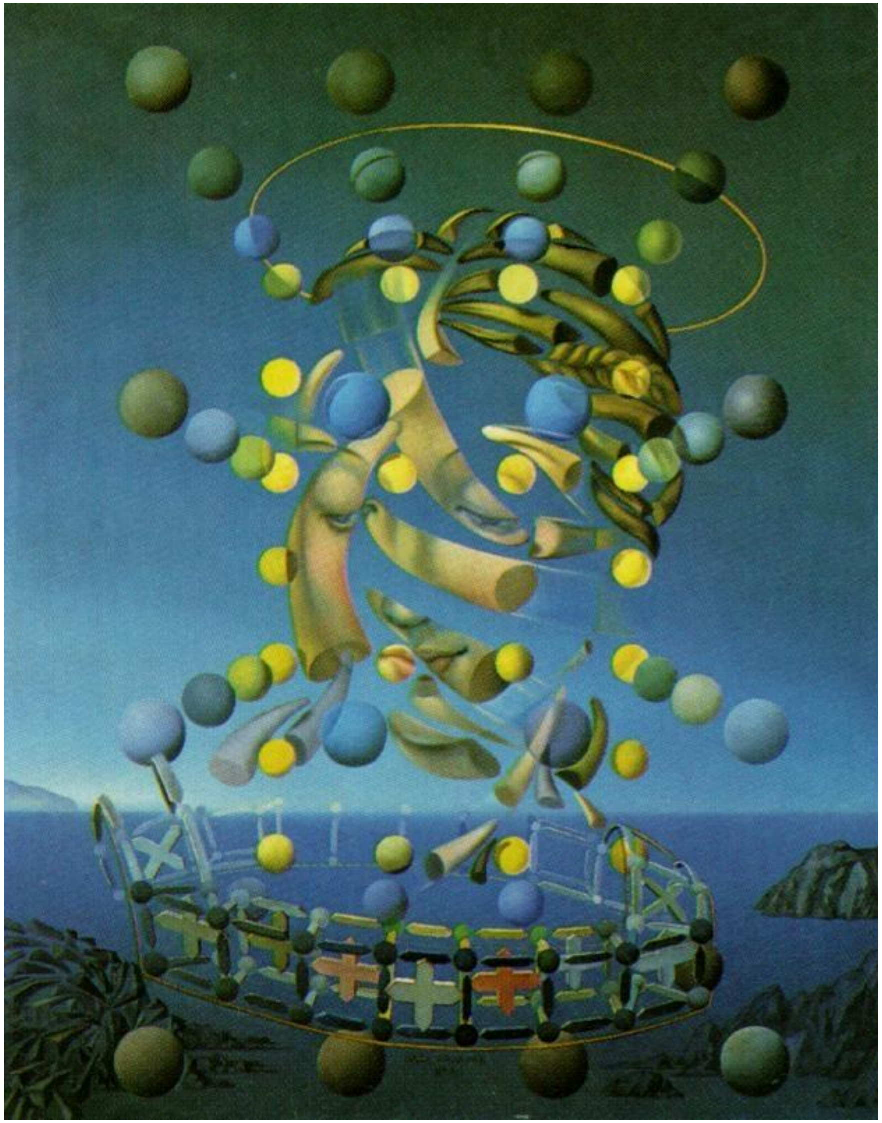
- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A_{LL}^{1}
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?

Conclusions

"Nature"

Raphael "Madonna del Prato"

"1D"



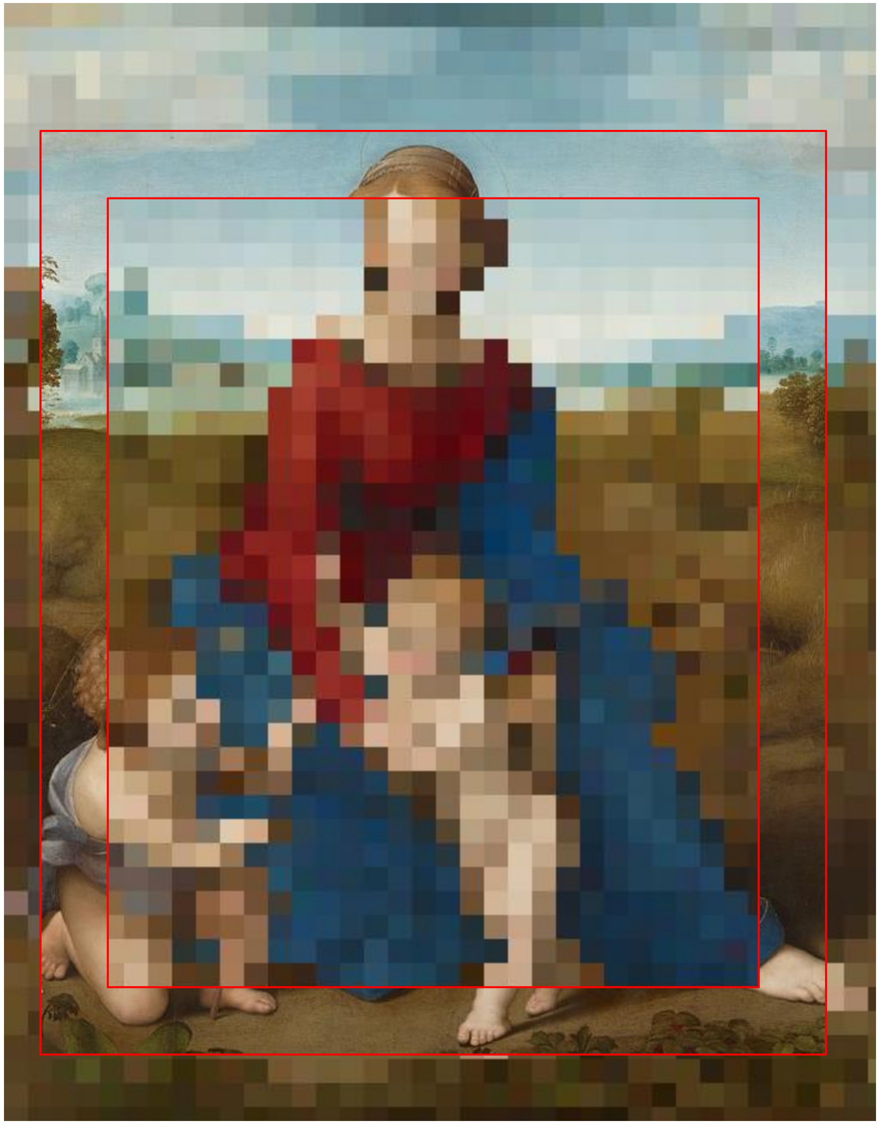
Salvador Dali "Maximum Speed of Raphael's Madonna"

Thank you!

"Nature"

Raphael "Madonna del Prato"

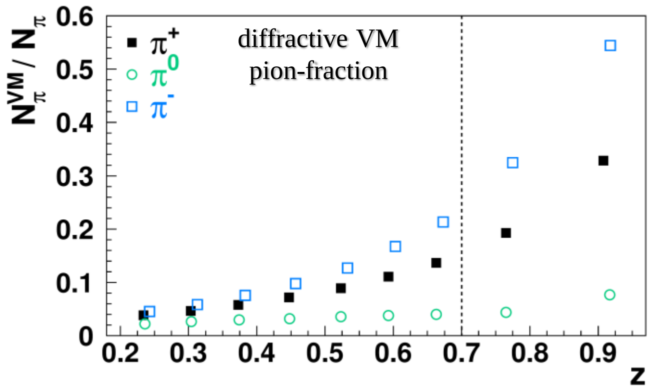
"multi-D" with available statistics



Raphael "Madonna del Prato" (poor resolution)

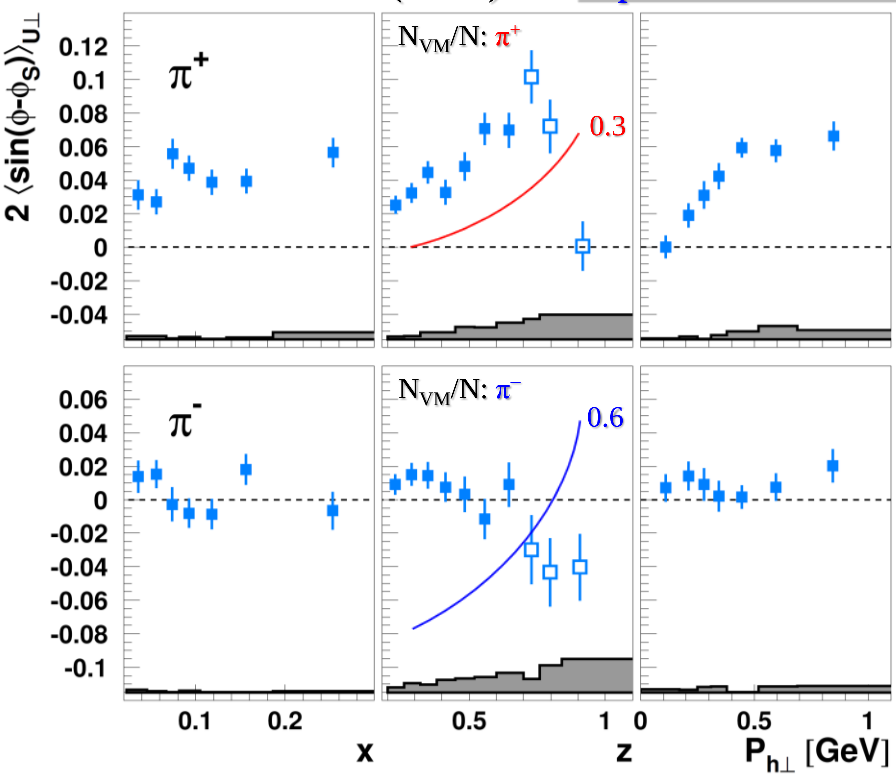
HERMES: Sivers effect and diffractive VMs

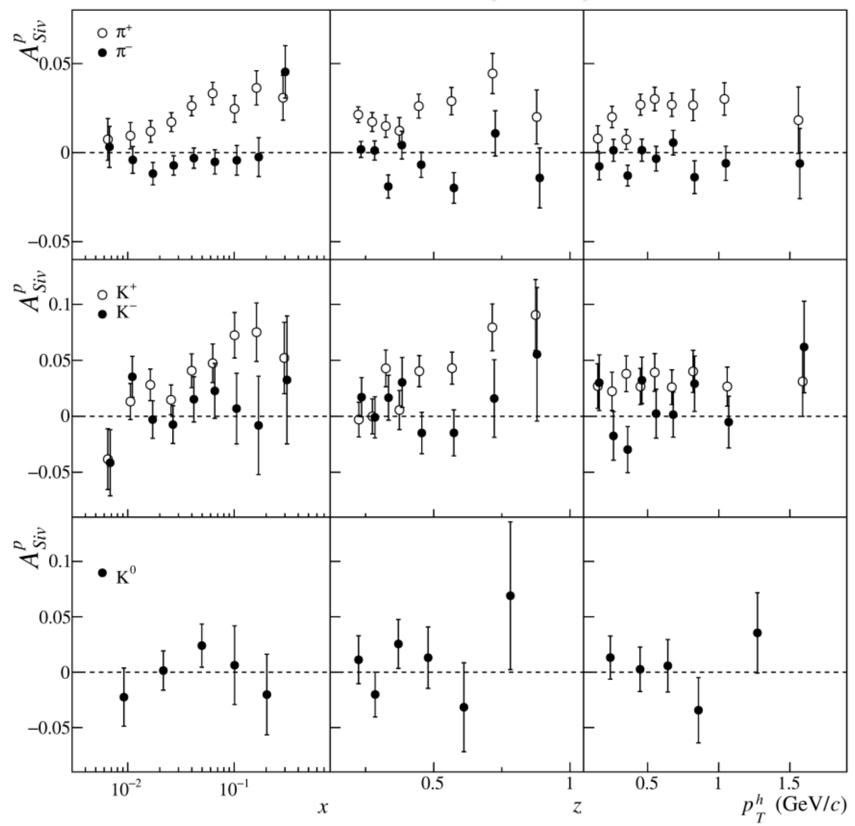
- The asymmetry drops at large z for pion
  - Not the case for kaons
- Can it be caused by exclusive diffractive VMs?
- The contamination indeed grows with *z* for pions
  - At the level of 10% for kaons



COMPASS: PLB 744 (2015) 250

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





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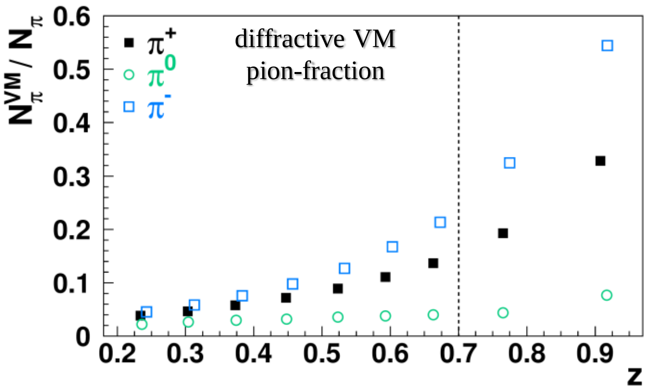
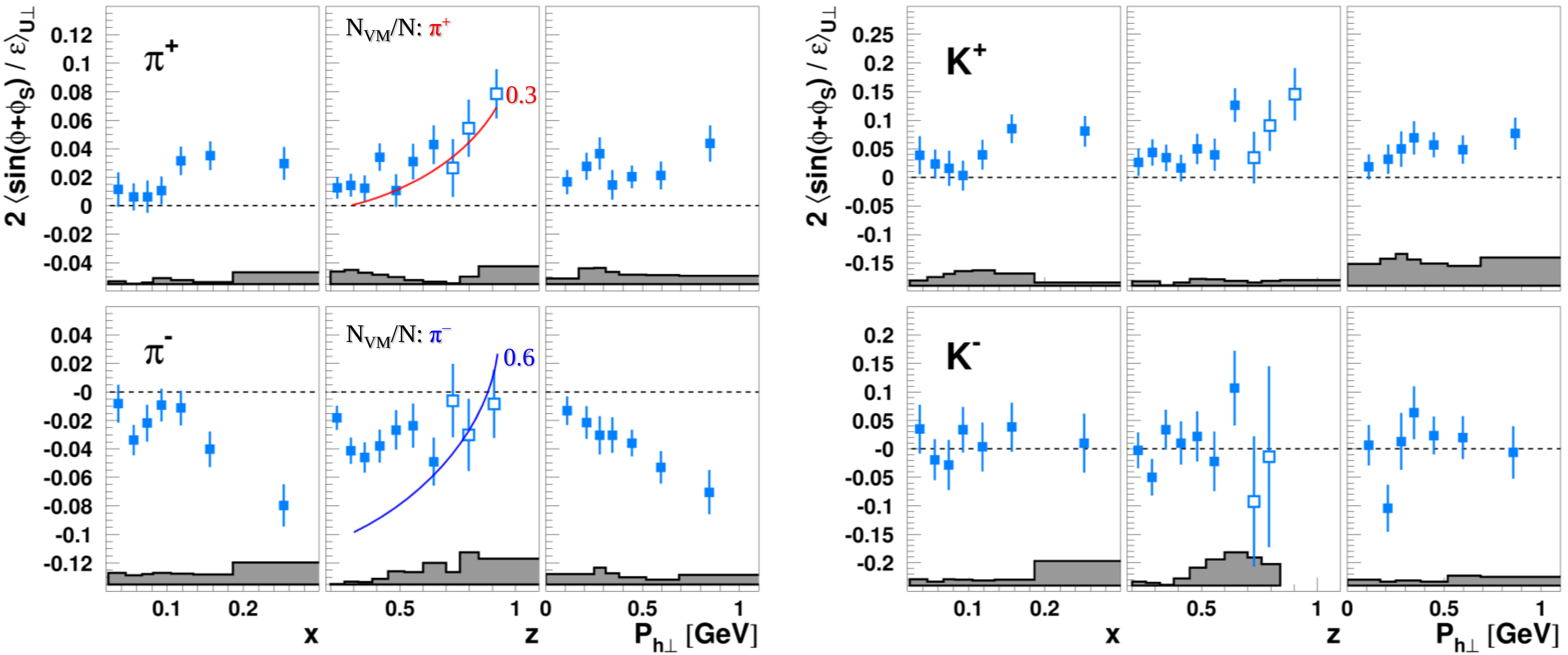
- The asymmetry drops at large z for pion
  - Not the case for kaons
- Can it be caused by exclusive diffractive VMs?
- The contamination indeed grows with *z* for pions
  - At the level of 10% for kaons
- Similar effect in COMPASS?
- Not clear with Collins



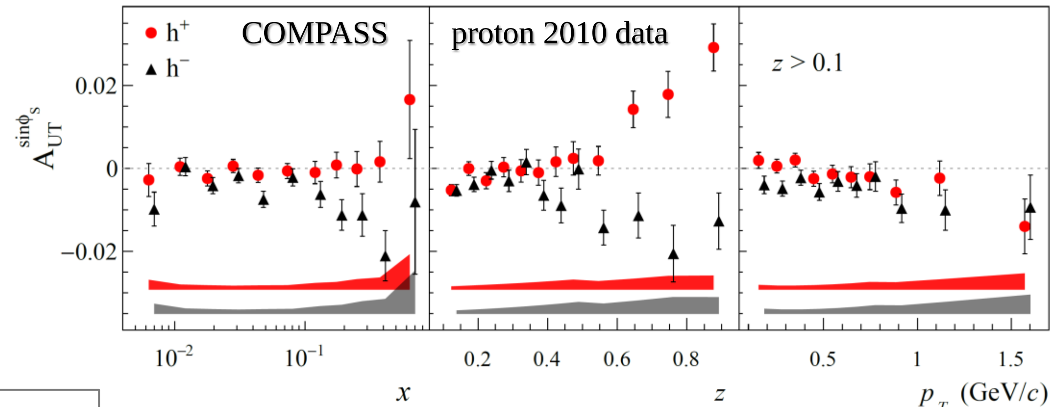


SIDIS TSAs: subleading twist effects

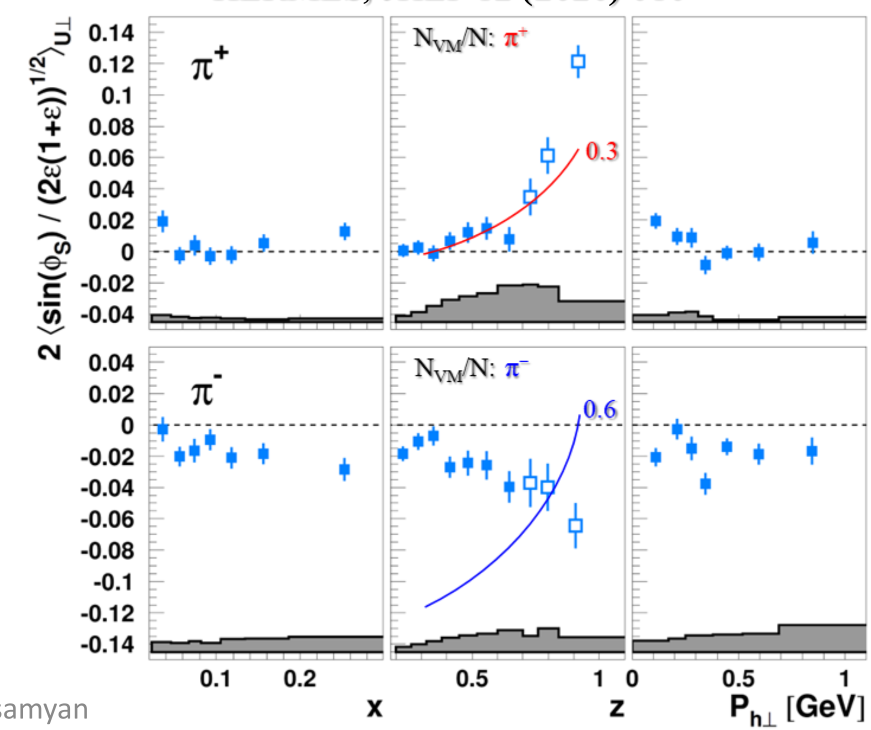
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T \sqrt{2\varepsilon(1+\varepsilon)} A_{UT}^{\sin\phi_S} \sin\phi_S + \ldots\right\}$$

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

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



HERMES, JHEP 12 (2020) 010

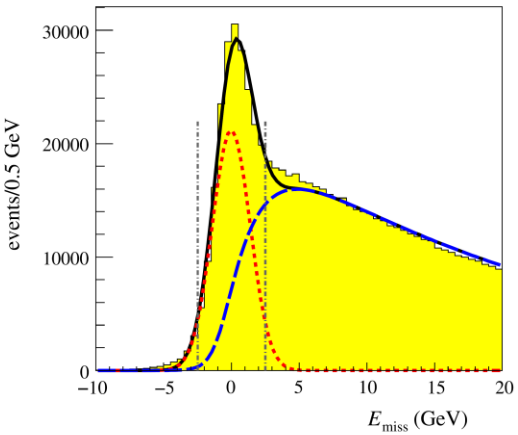


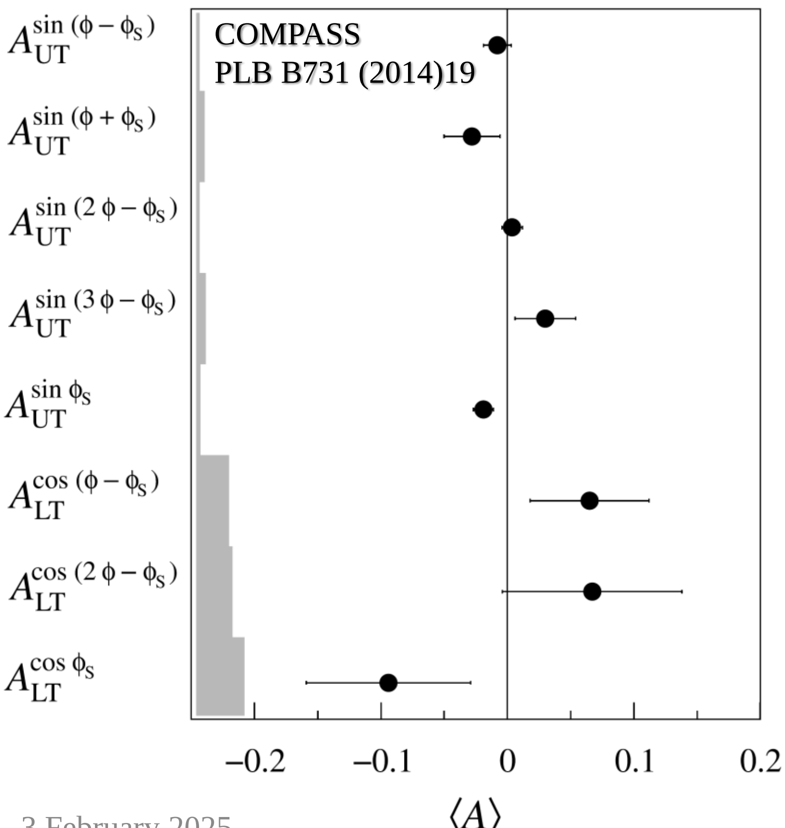
COMPASS/HERMES results

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

- 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)

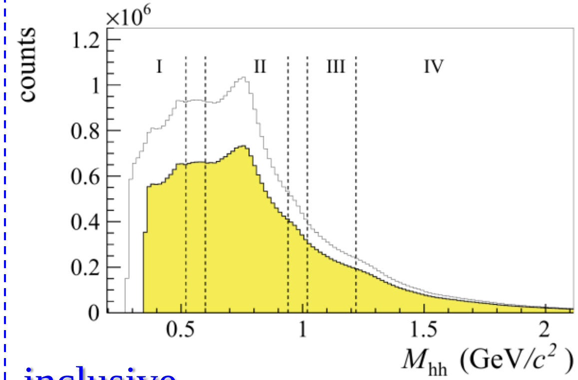
COMPASS: Exclusive and Inclusive ρ^0 TSAs

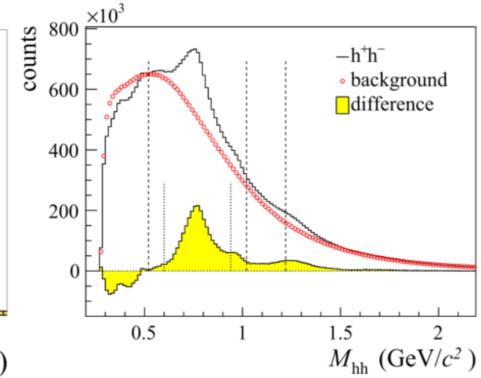


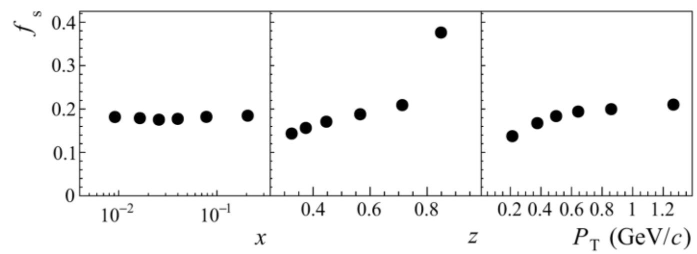


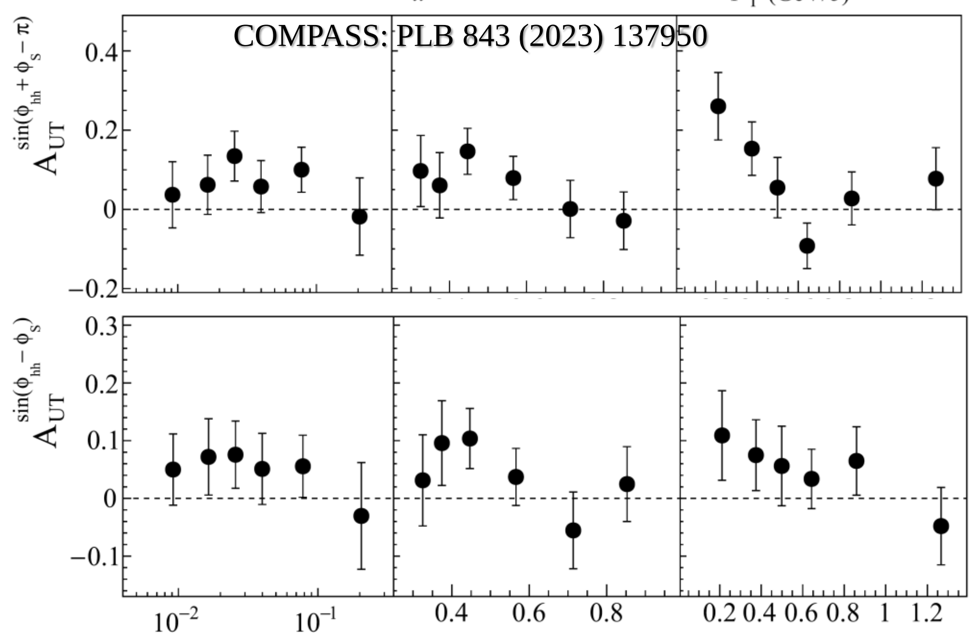
exclusive

inclusive

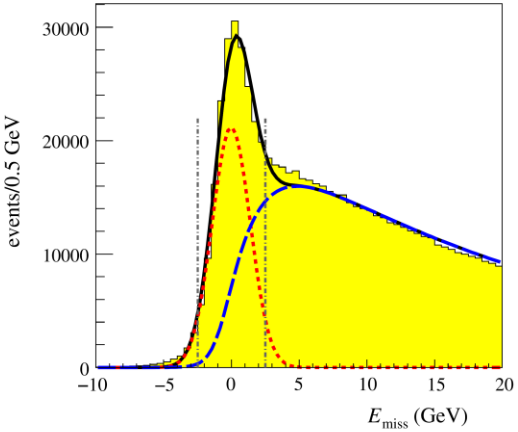




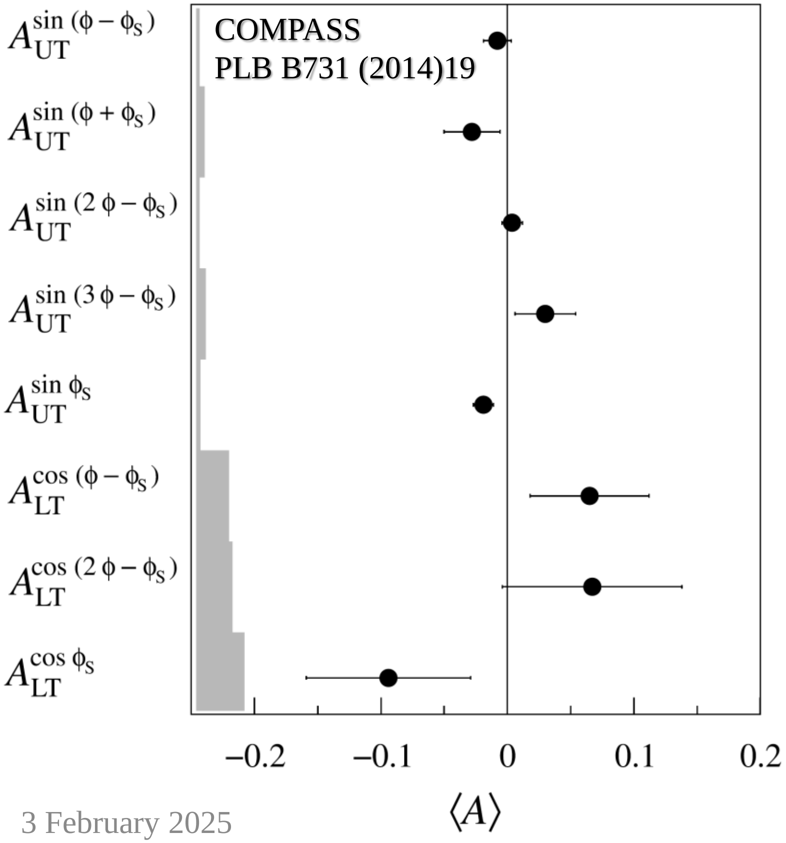




COMPASS: Exclusive ρ^0 TSAs

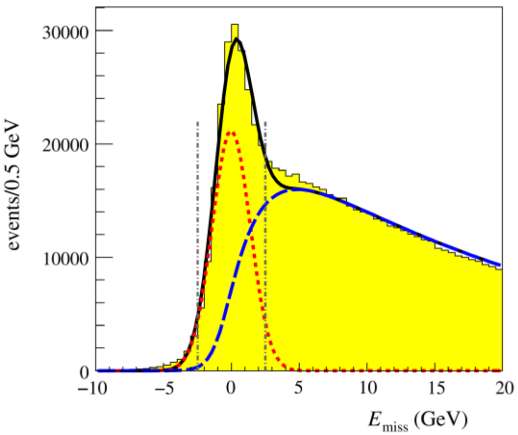


exclusive

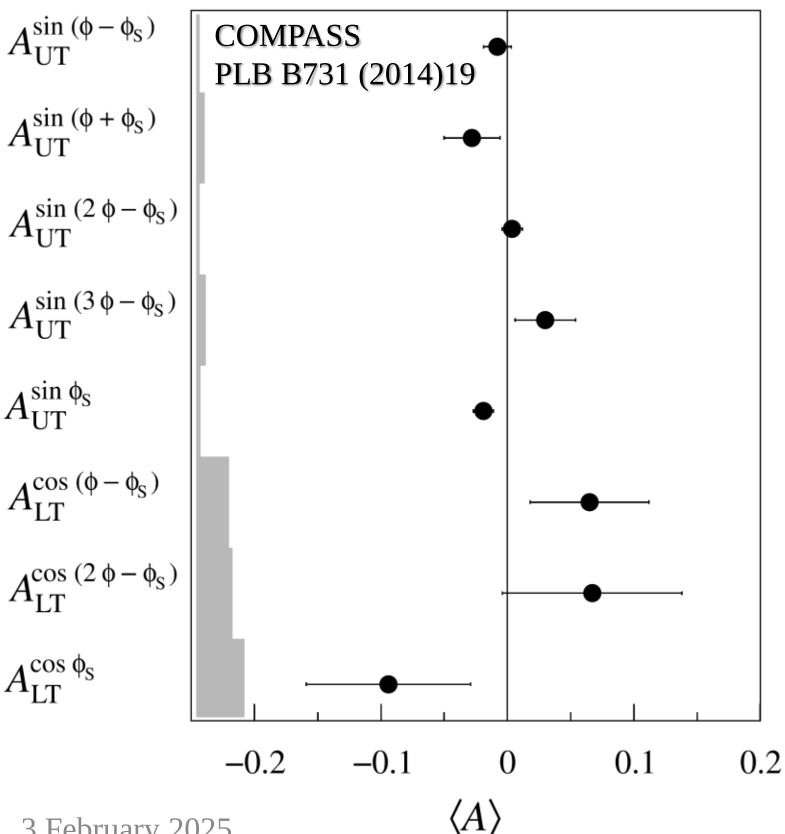


- Both Collins and Sivers TSAs are small an compatible with zero
  - $\sin(\varphi_S)$ is small, but possibly non zero
  - Can VM pion asymmetries still be large?

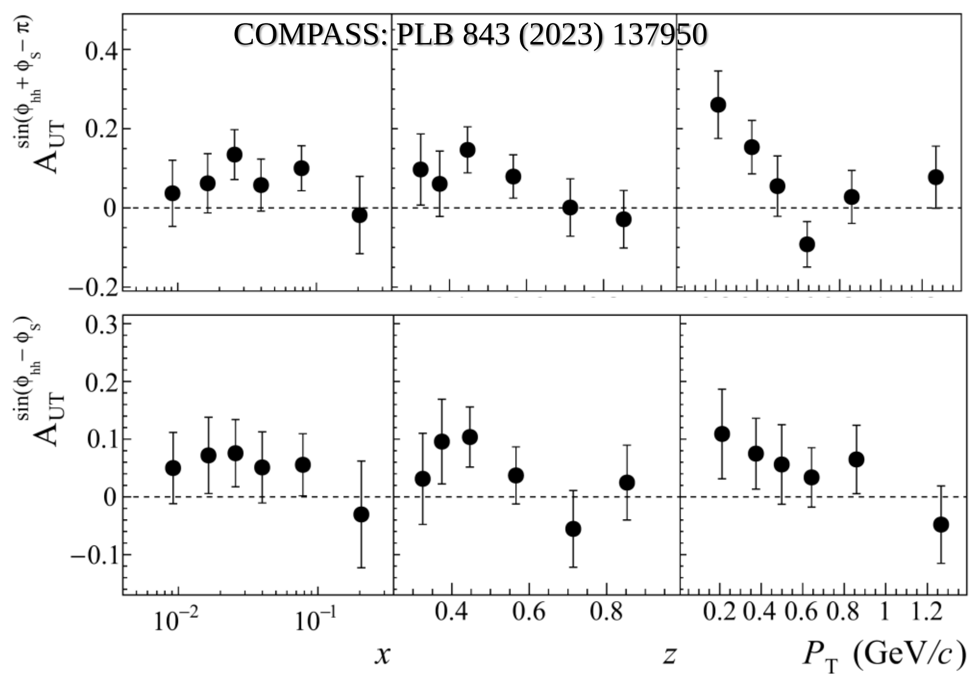
COMPASS: Exclusive ρ^0 TSAs



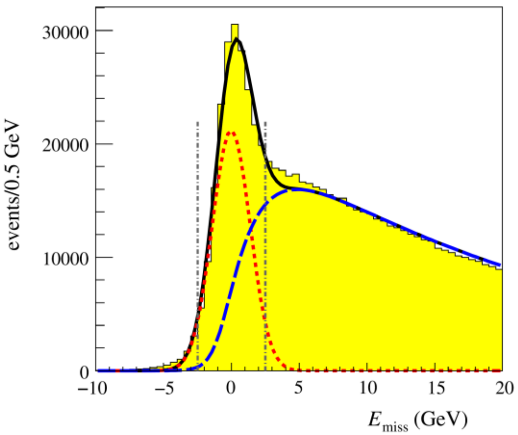
exclusive

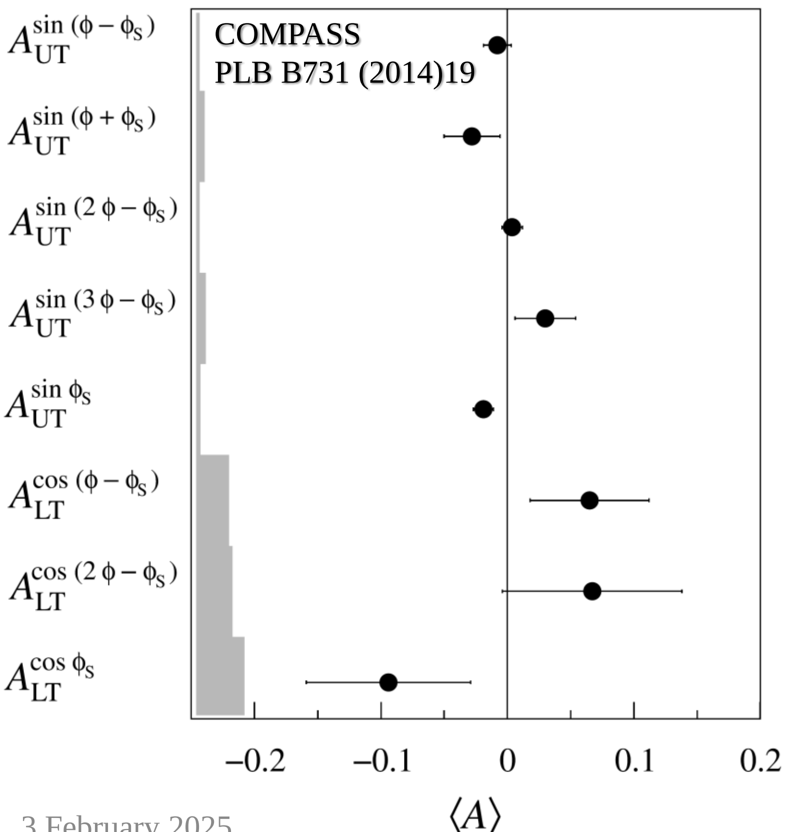


- Both Collins and Sivers TSAs are small an compatible with zero
  - $\sin(\varphi_S)$ is small, but possibly non zero
  - Can VM pion asymmetries still be large?
- COMPASS has checked also the inclusive ρ^0 Collins and Sivers asymmetries
  - Both tend to be positive
  - The fraction of inclusive ρ^0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



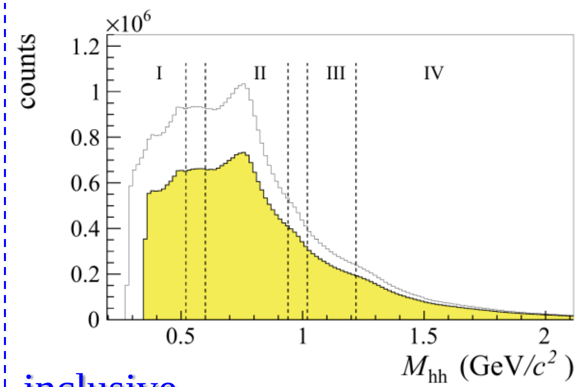
COMPASS: Exclusive and Inclusive ρ^0 TSAs

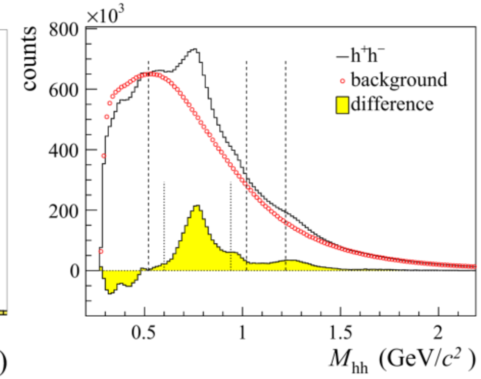


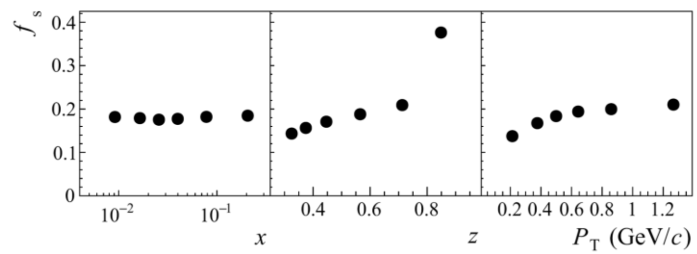


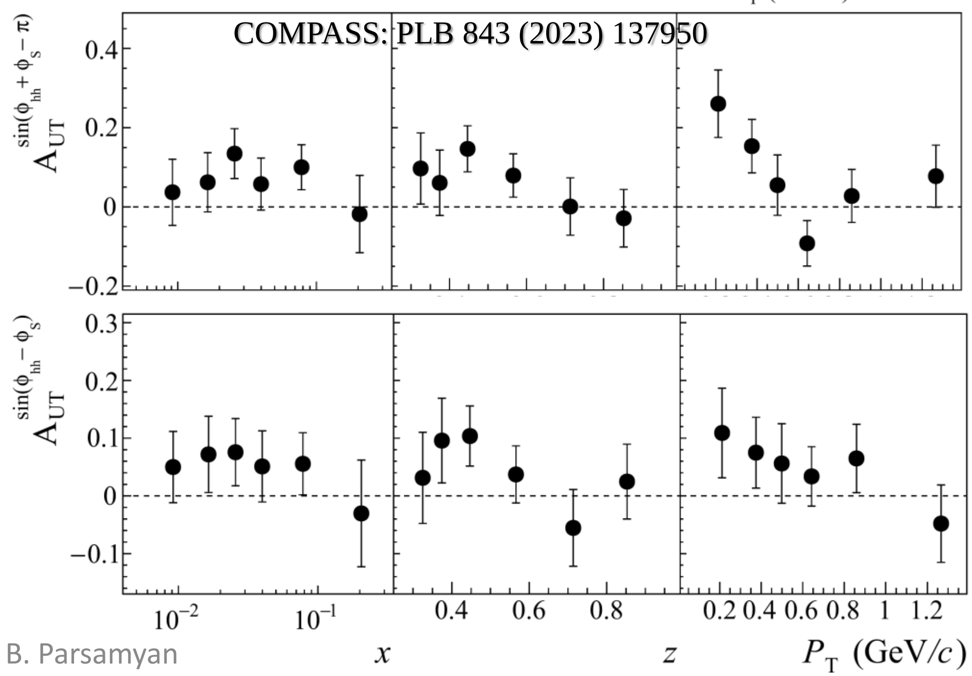
exclusive

inclusive







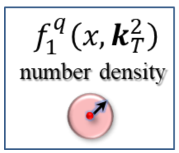


Cahn effect in SIDIS

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

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

Cahn effect



As of 1978 – simplistic kinematic effect:

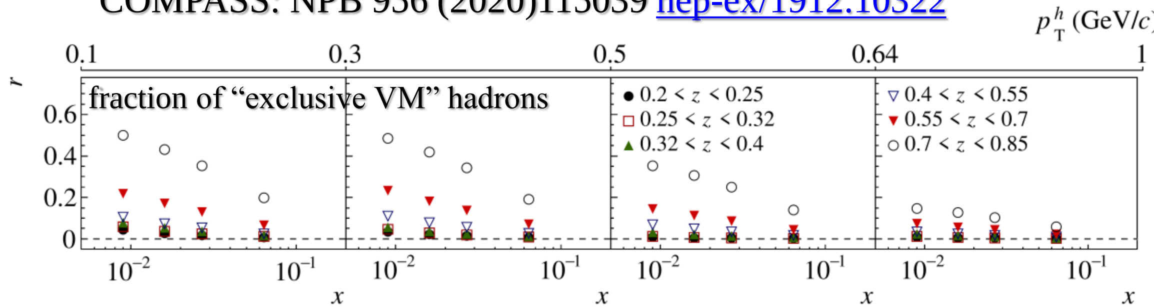
- non-zero k_T induces an azimuthal modulation

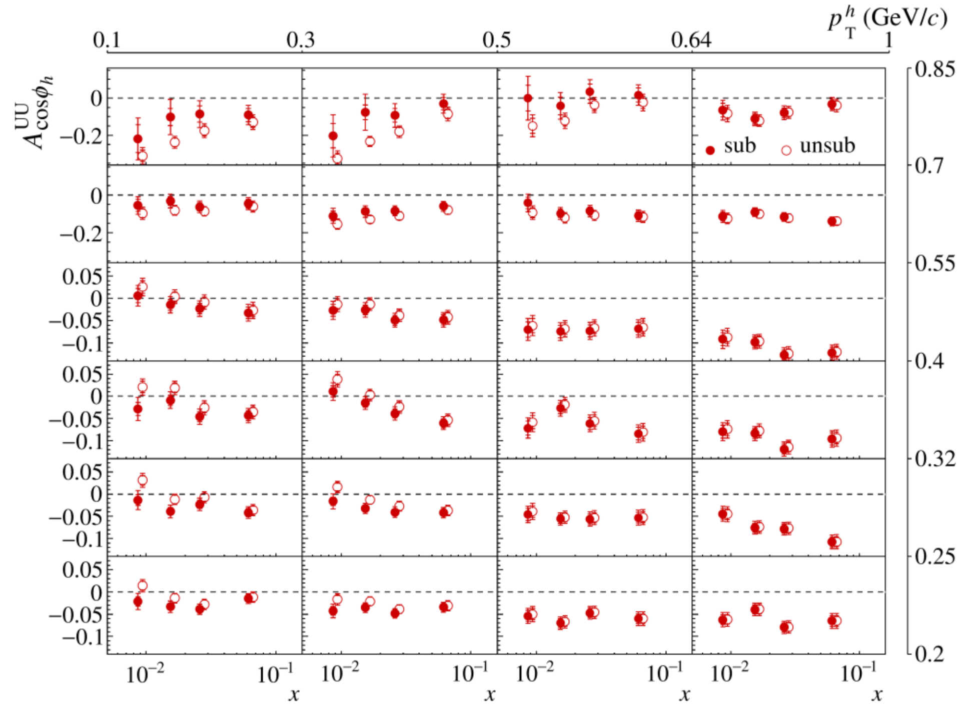
As of 2023 – complex SF (twist-2/3 functions)

- 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.

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

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





HEPGEN generator to simulate diffractively produced ρ^0 and ϕ events. Further channels, which are characterized by smaller cross sections, are not taken into account. Events with diffractive dissociation of the target nucleon represent about 25% of those with the nucleon staying intact and are also simulated. The simulation of these events includes nuclear effects, i.e. coherent production and nuclear absorption (see HEPGEN paper).