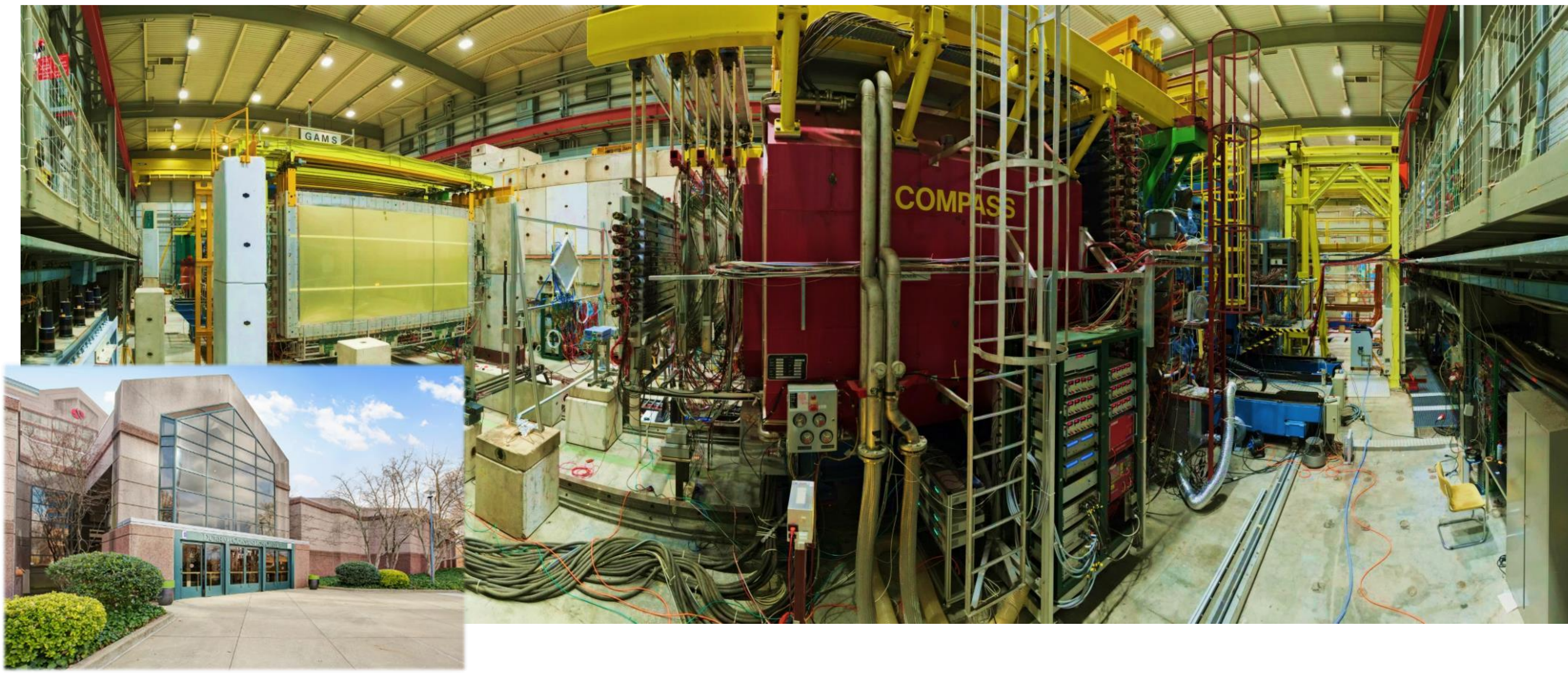
COMPASS Spin Physics Program

BAKUR PARSAMYAN

AANL, INFN section of Turin and CERN

on behalf of the COMPASS Collaboration

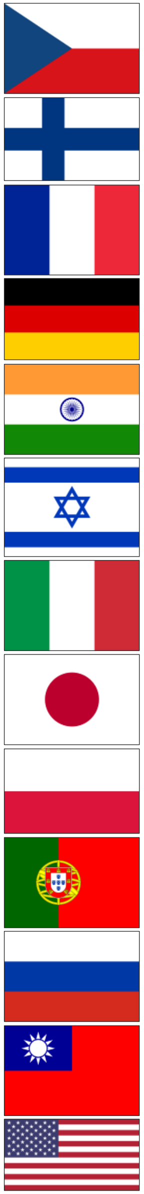


The 25th International Spin Symposium (SPIN 2023)

September 24-30, Duke University, Durham Convention Center, US

COMPASS collaboration

Co**m**mon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



25 institutions from 13 countries
– nearly 200 physicists (in 2022)

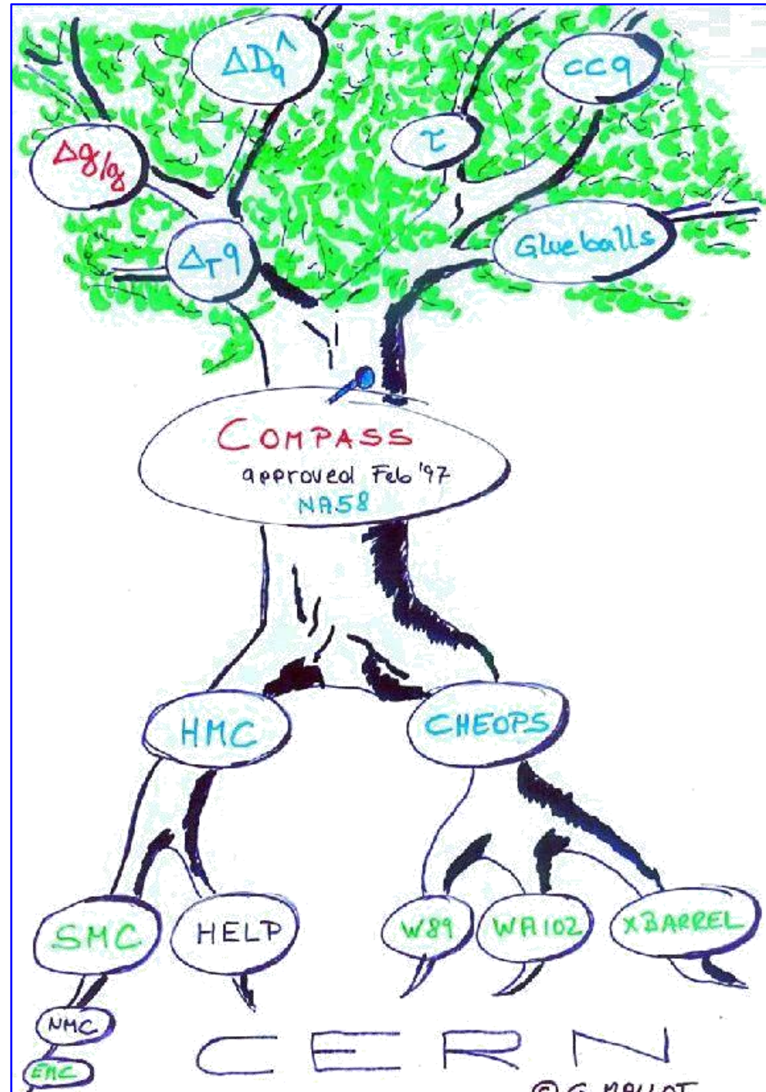
- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

International Workshop on Hadron Structure and Spectroscopy

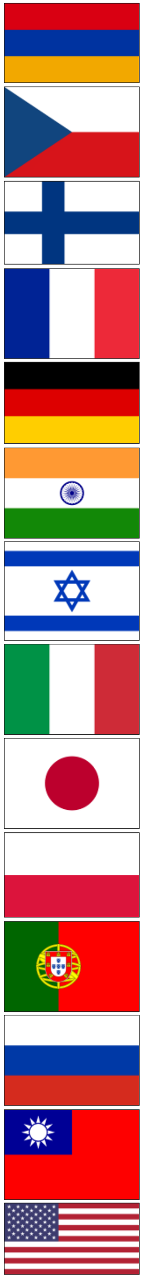
IWHSS-2022 workshop (anniversary edition)

CERN Globe, August 29-31, 2022

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



COMPASS collaboration



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

28 institutions from 14 countries
– nearly 210 physicists (in 2023: start of the Analysis Phase)

3 new groups joined the COMPASS collaboration in 2023
UCon (US), AANL (Armenia), NCU (Taiwan)

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

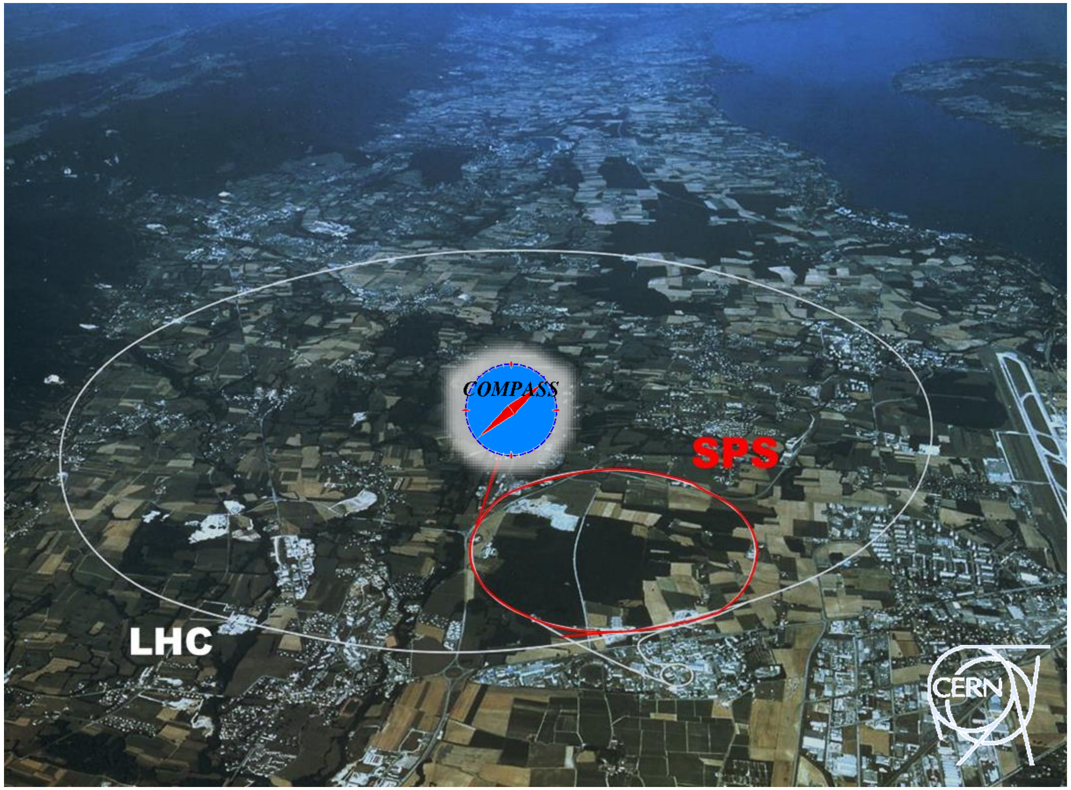
Wide physics program

COMPASS-I

- **Data taking 2002-2011**
- **Muon and hadron beams**
- **Nucleon spin structure**
- **Spectroscopy**

COMPASS-II

- **Data taking 2012-2022**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
- **Polarized Drell-Yan**
- **Transverse deuteron SIDIS 2022**



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

See talks by: V. Andrieux, A. Kerbizi, A. Martin, J. Matousek, G. Reicherz, A. Vijayakumar

The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

Nucleon structure

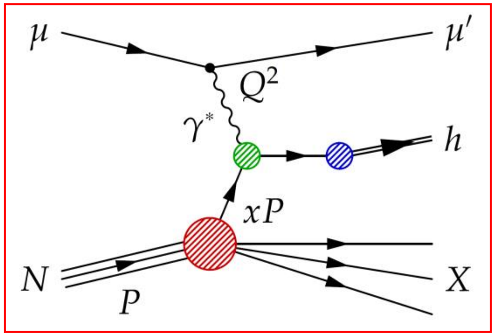
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

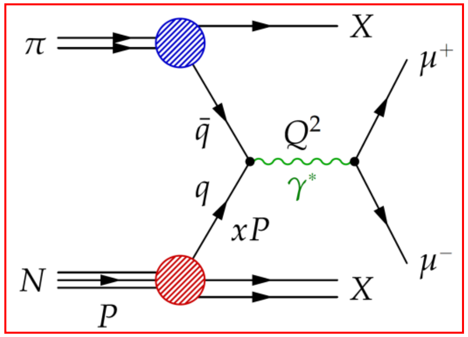
Hadron spectroscopy

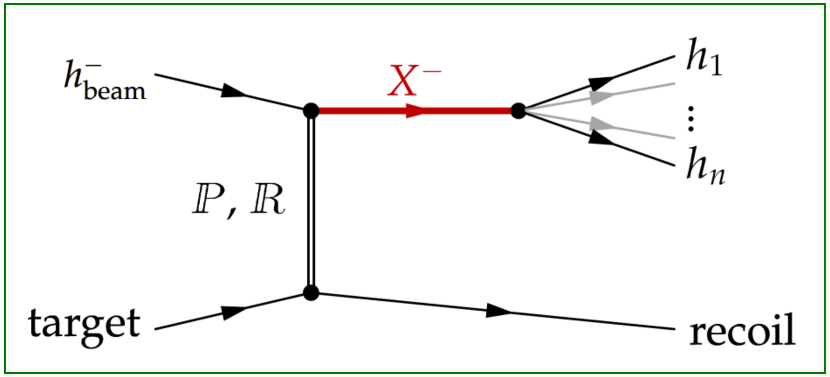
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

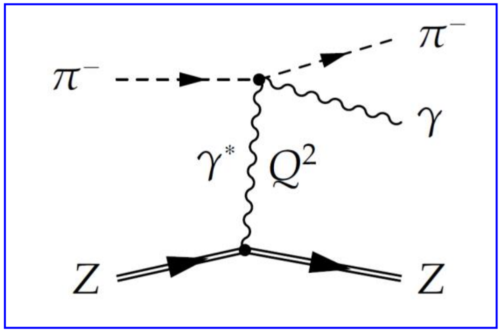
Chiral dynamics

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









The COMPASS Experiment at the CERN SPS

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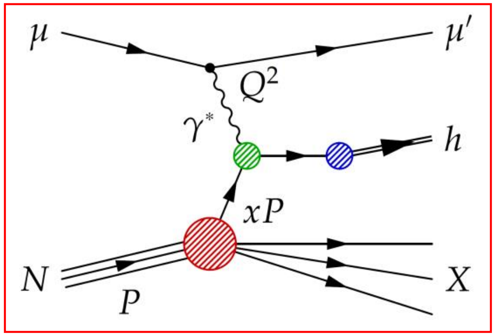
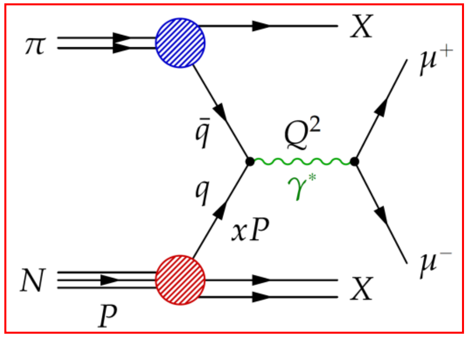
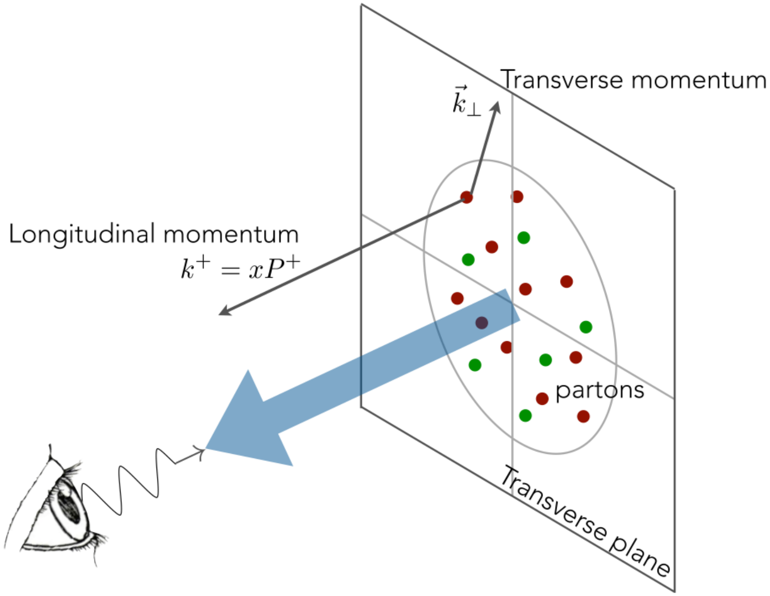


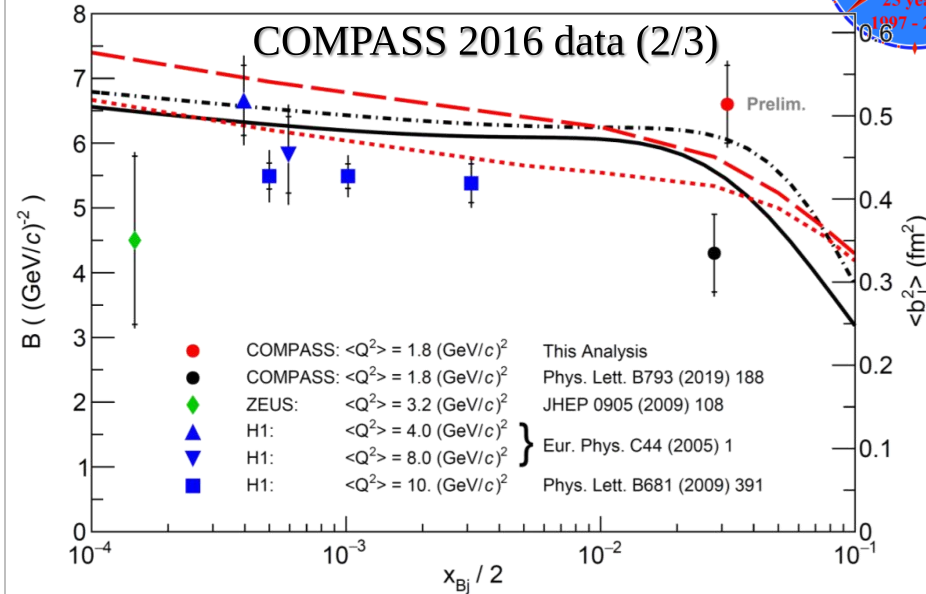


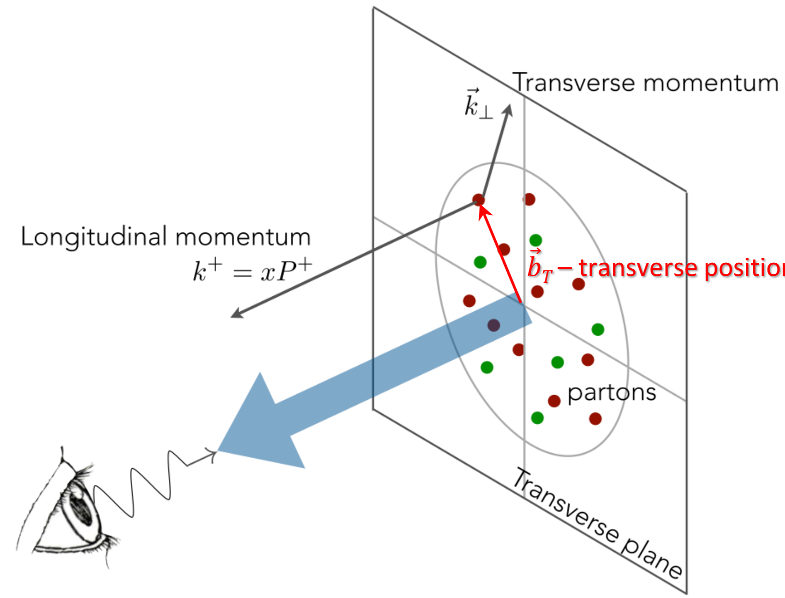


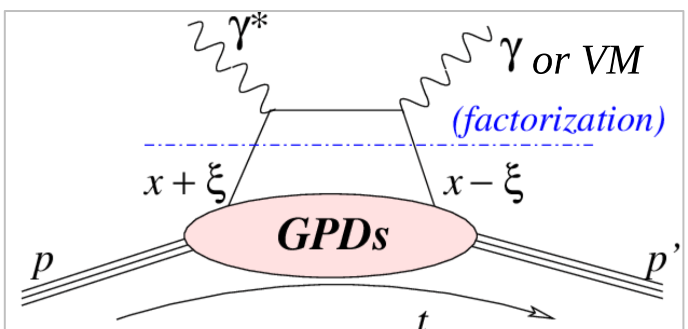
Nucleon 3D structure

See the COMPASS GPD program overview talk by J. Matousek

- Transverse position $\vec{b}_T$ of partons
  - Correlation between $\vec{b}_T$ and x
  - Complementary to TMD PDFs
- 8 generalized parton distribution functions (GPDs)
  - Contain information about parton orbital angular momentum
  - Mostly unknown
- Measured in exclusive processes:
  - Deeply virtual Compton scattering (DVCS): $\mu + \mathrm{N} \rightarrow \mu + \gamma + \mathrm{N}$
  - Hard exclusive meson production (HEMP): $\mu + \mathrm{N} \rightarrow \mu + \mathrm{VM} + \mathrm{N}$ with VM = π^0, $\rho(770)$, $\omega(782)$,..







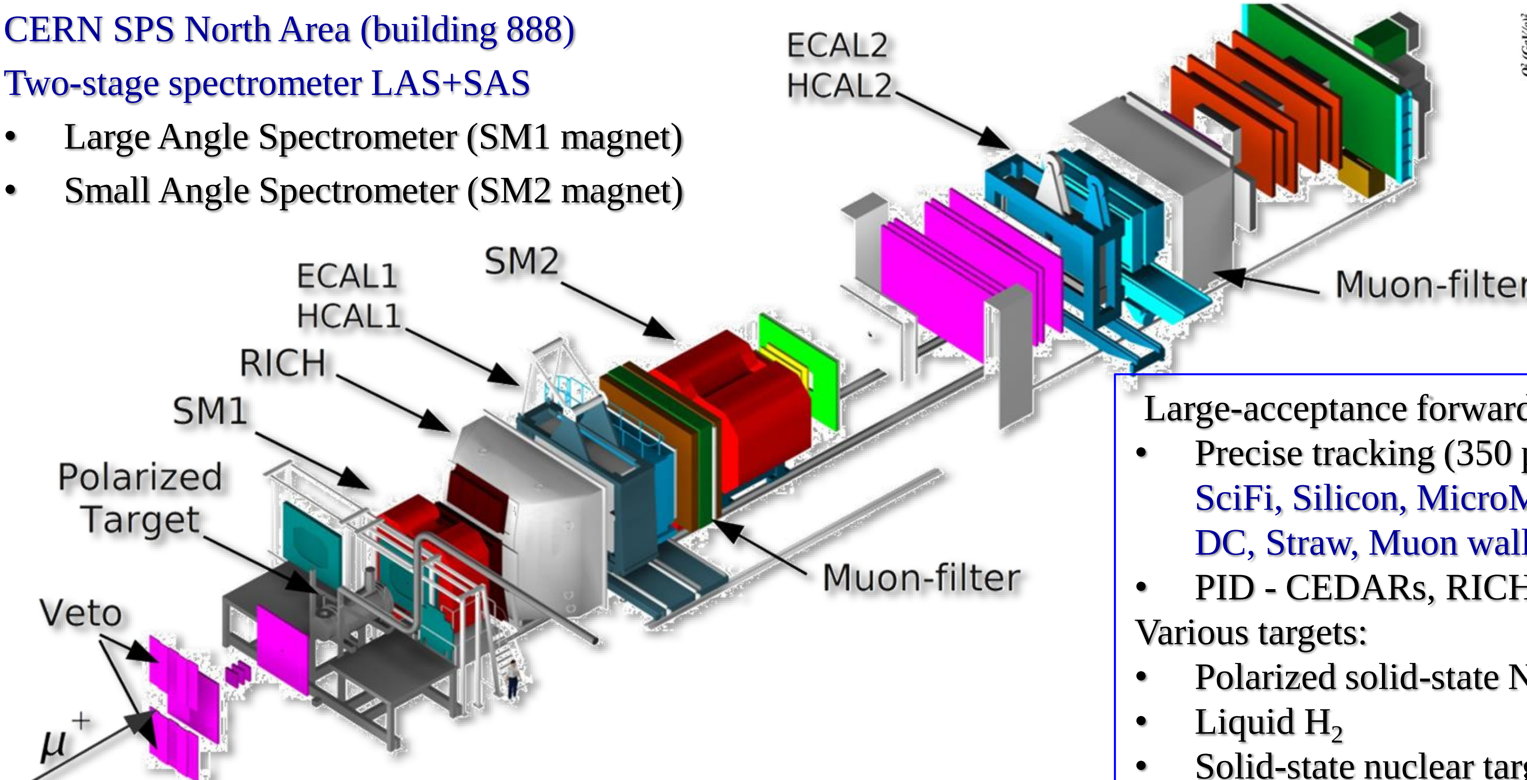
COMPASS experimental setup

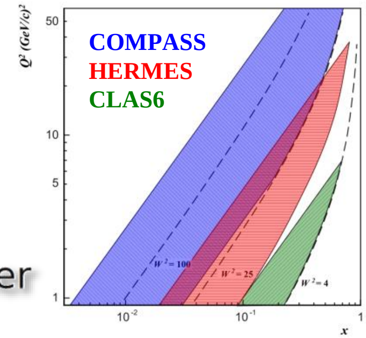
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





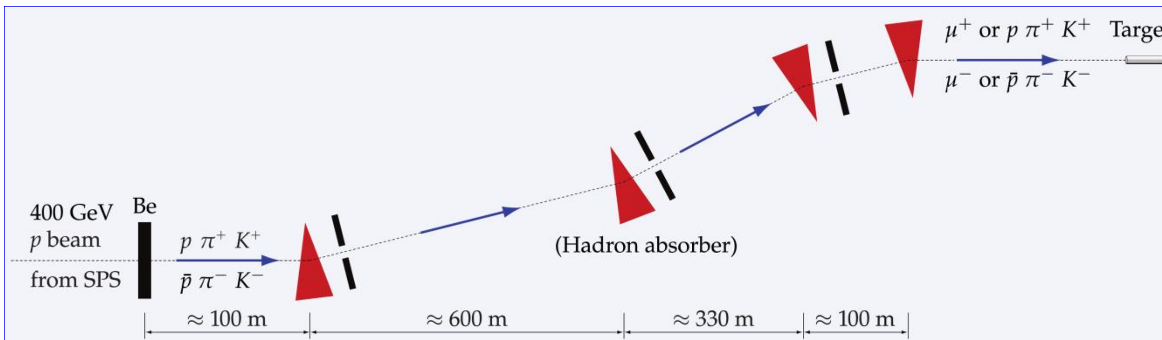
Large-acceptance forward spectrometer

- 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



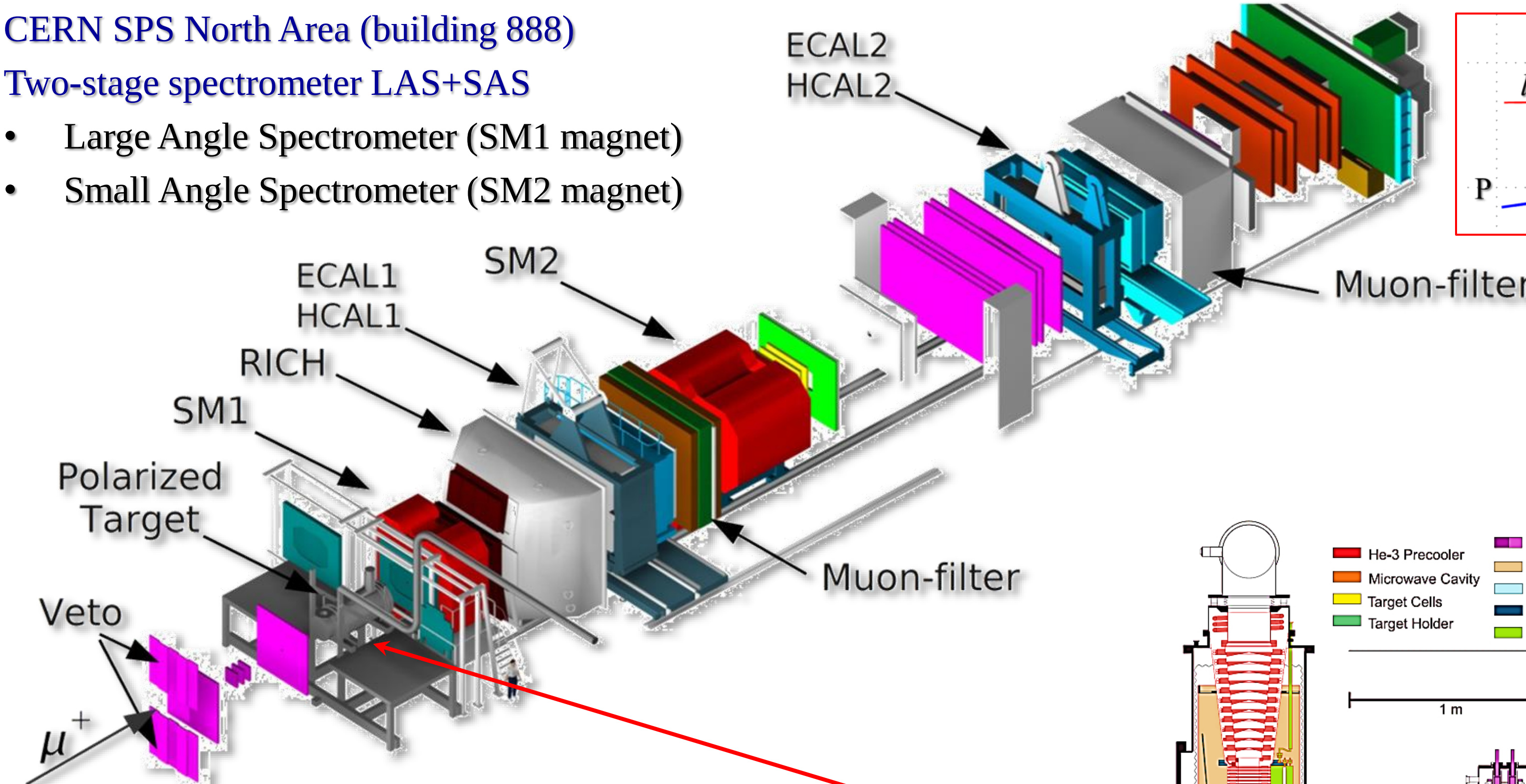
COMPASS experimental setup: Phase II (SIDIS programme)

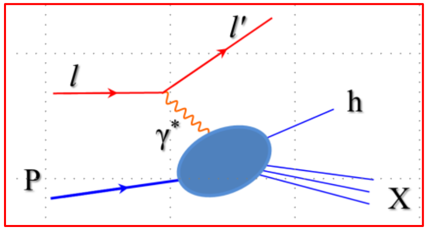
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





- Primary beam - 400 GeV p from SPS
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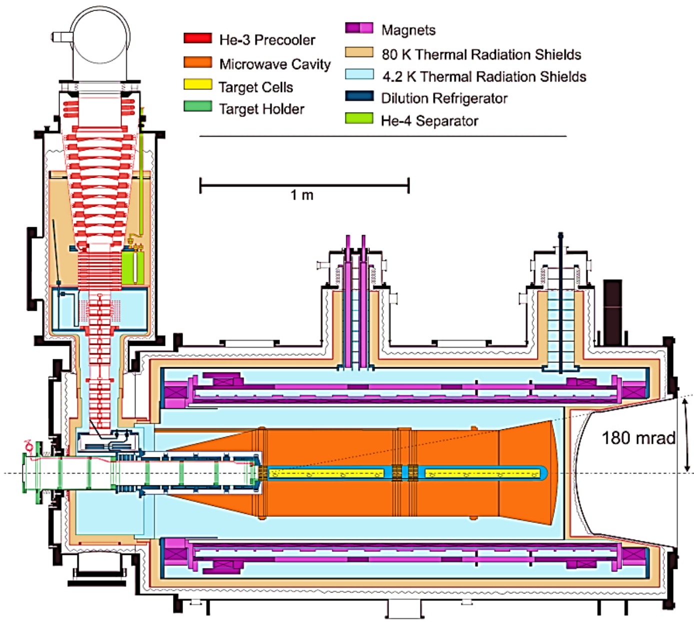
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - μ^+ longitudinally polarized



see Gerhard Reicherz' talk

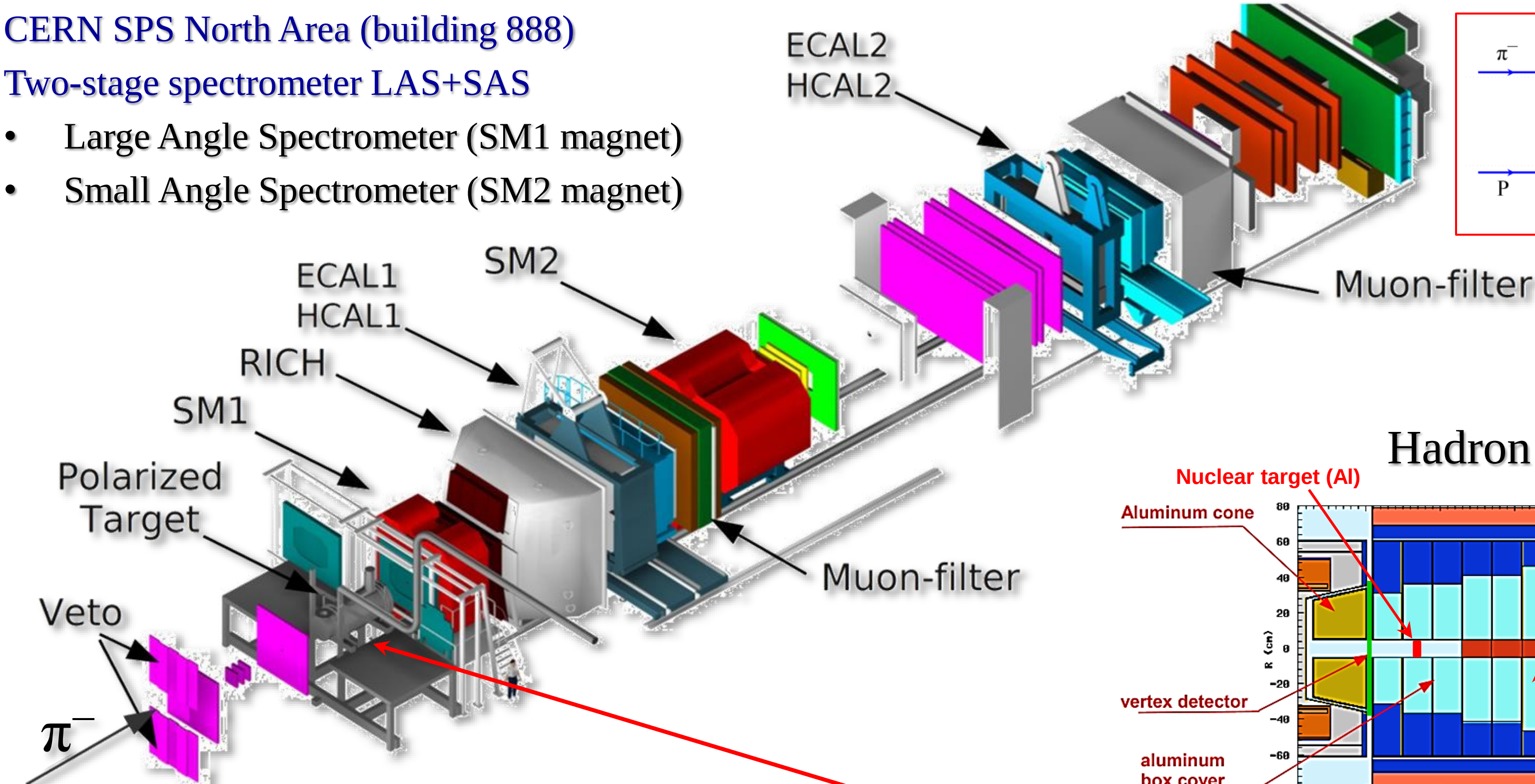
COMPASS experimental setup: Phase II (DY programme)

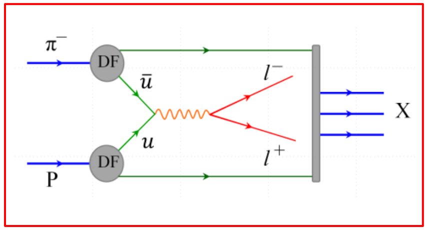
COmmon Muon Proton Apparatus for Structure and Spectroscopy

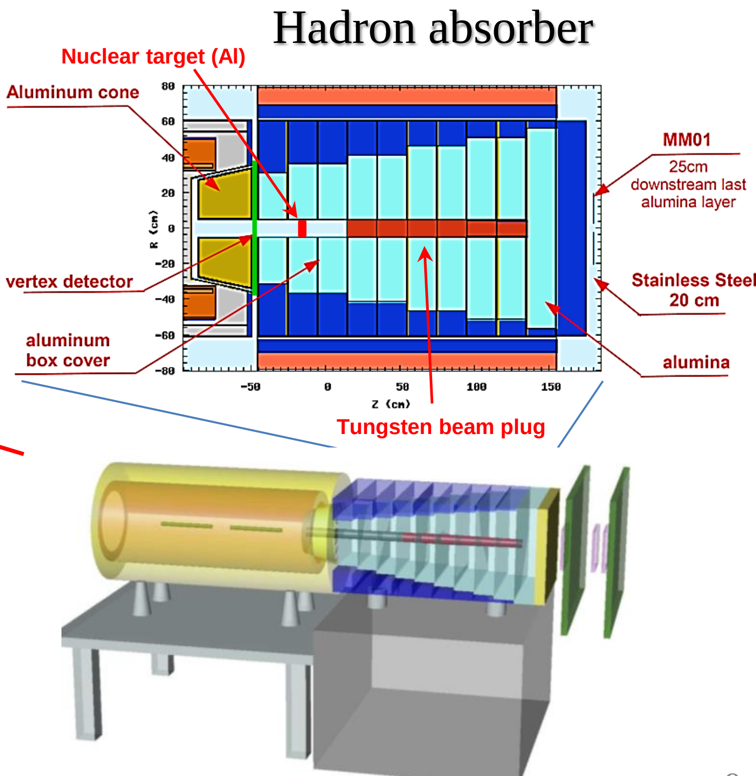
CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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







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

COMPASS data taking campaigns

Beam	Target	year	Physics programme
μ^+	Polarized deuteron (^{6}LiD)	2002 2003 2004	80% Longitudinal $\mid$ 20% Transverse SIDIS
		2006	Longitudinal SIDIS
	Polarized proton (NH_3)	2007	50% Longitudinal $\mid$ 50% Transverse SIDIS
$\pi \mid K \mid p$	LH_2, Ni, Pb, W	2008 2009	Spectroscopy
μ^+	Polarized proton (NH_3)	2010	Transverse SIDIS
		2011	Longitudinal SIDIS
$\pi \mid K \mid p$	Ni	2012	Primakoff
$\mu^\pm$	LH_2	2012	Pilot DVCS & HEMP & unpolarized SIDIS
π^-	Polarized proton (NH_3)	2014	Pilot Drell-Yan
		2015 2018	Transverse Drell-Yan
$\mu^\pm$	LH_2	2016 2017	DVCS & HEMP & unpolarized SIDIS
μ^+	Polarized deuteron (^{6}LiD)	2021 2022	Transverse SIDIS

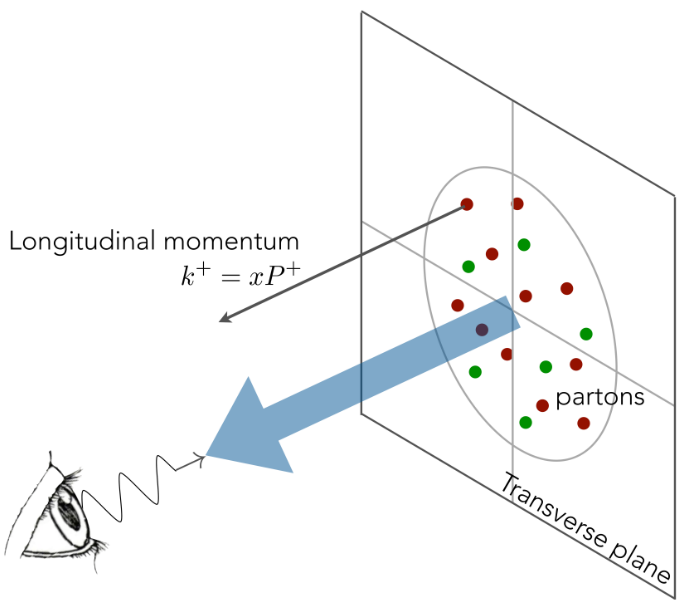
Nucleon spin structure: collinear approach ↔TMDs

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		$h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ Boer-Mulders
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	$g_{1T}^q(x, \boldsymbol{k}_T^2)$ worm-gear T	$h_1^q(x, \boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ pretzelosity

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



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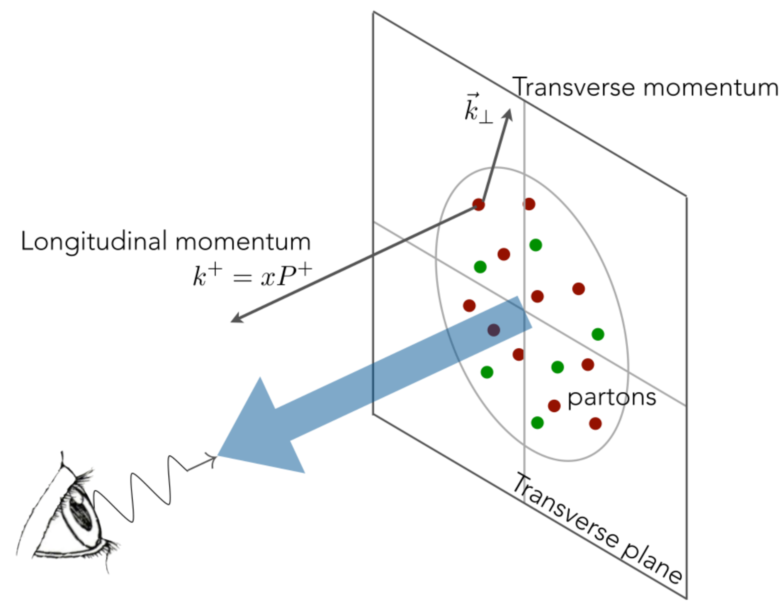
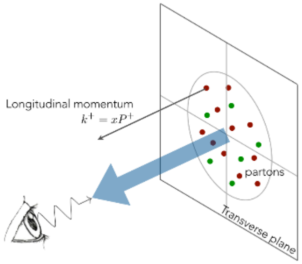
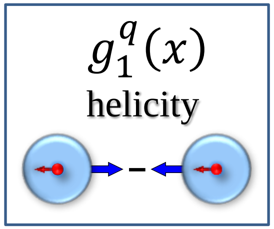
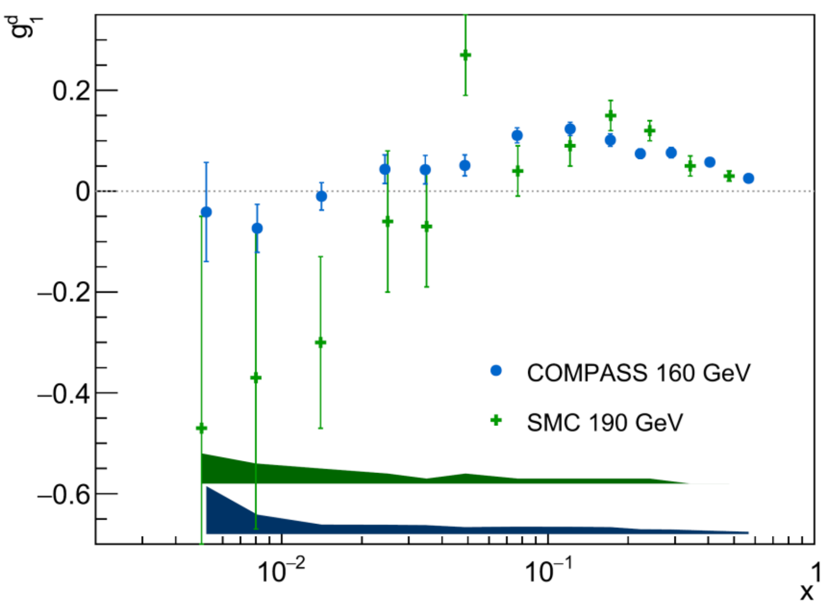


Nucleon spin structure: helicity $g_{1,d}^{q}(x)$





- COMPASS contribution:
  lowest x and highest Q^2 regions



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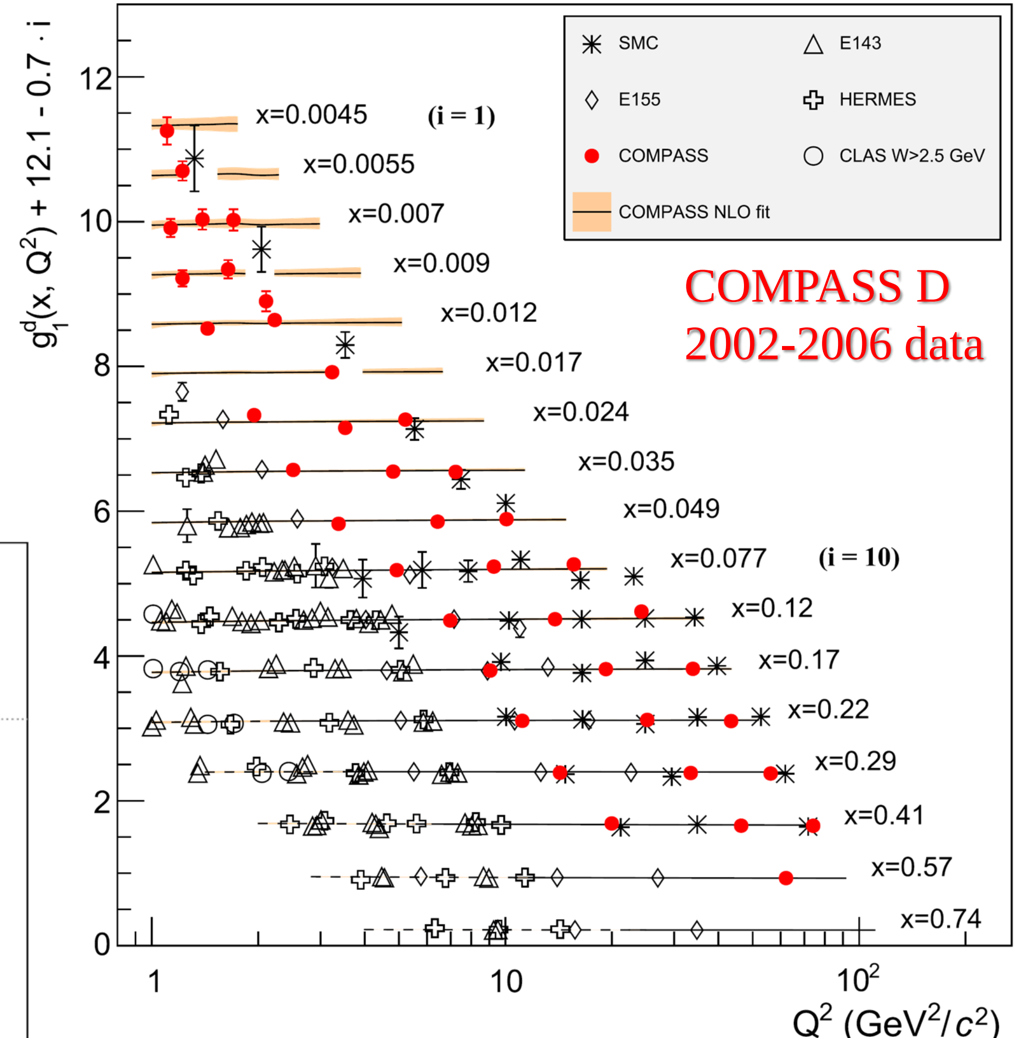
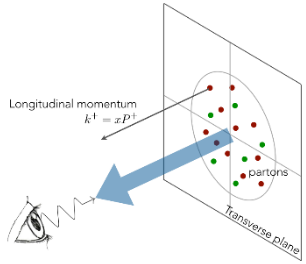
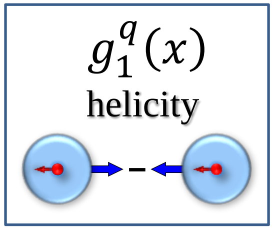
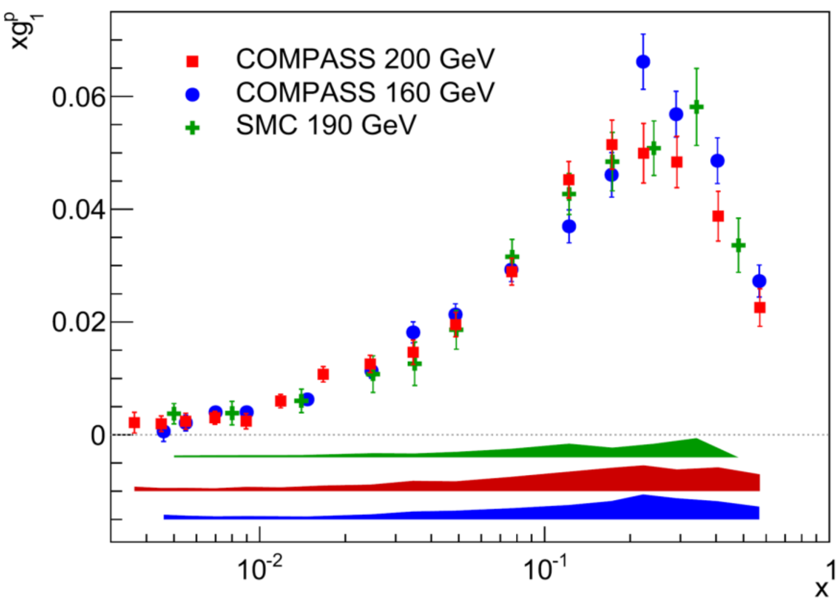


Nucleon spin structure: helicity $g_{1,p}^{q}(x)$





- COMPASS contribution:
  lowest x and highest Q^2 regions
- Both deuteron and proton target data



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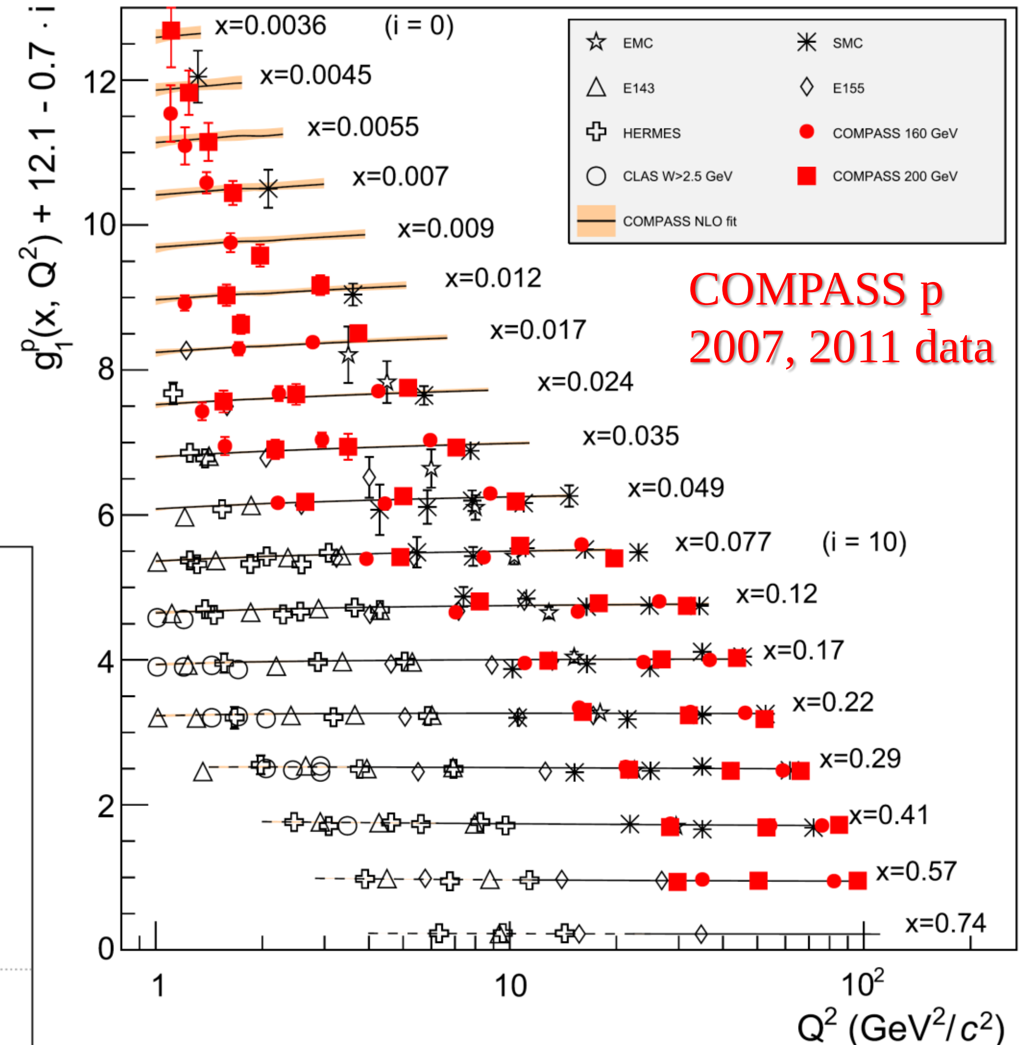
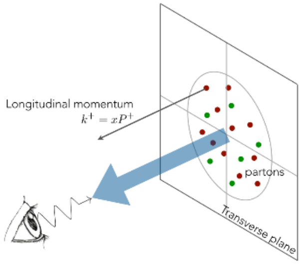
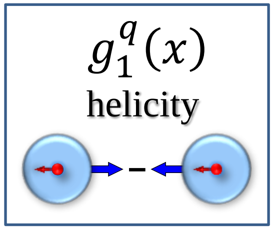
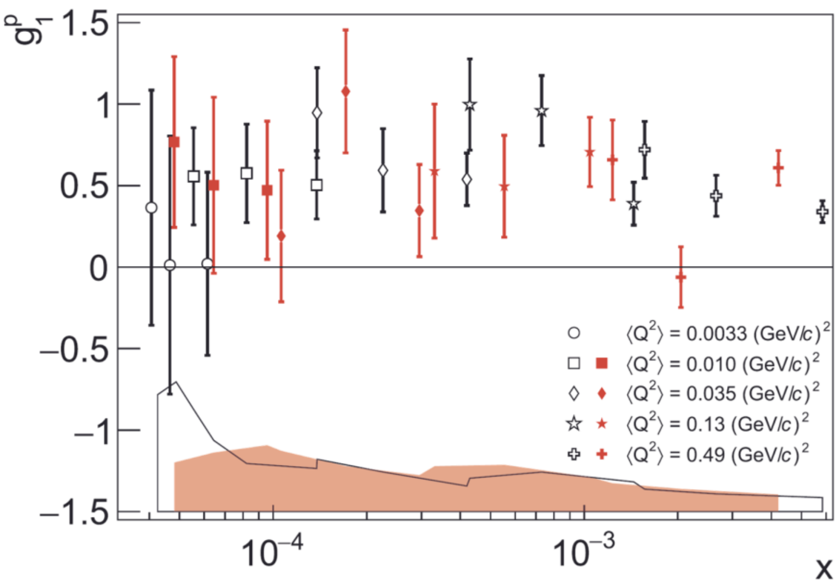


Nucleon spin structure: helicity $g_{1,p}^{q}(x)$

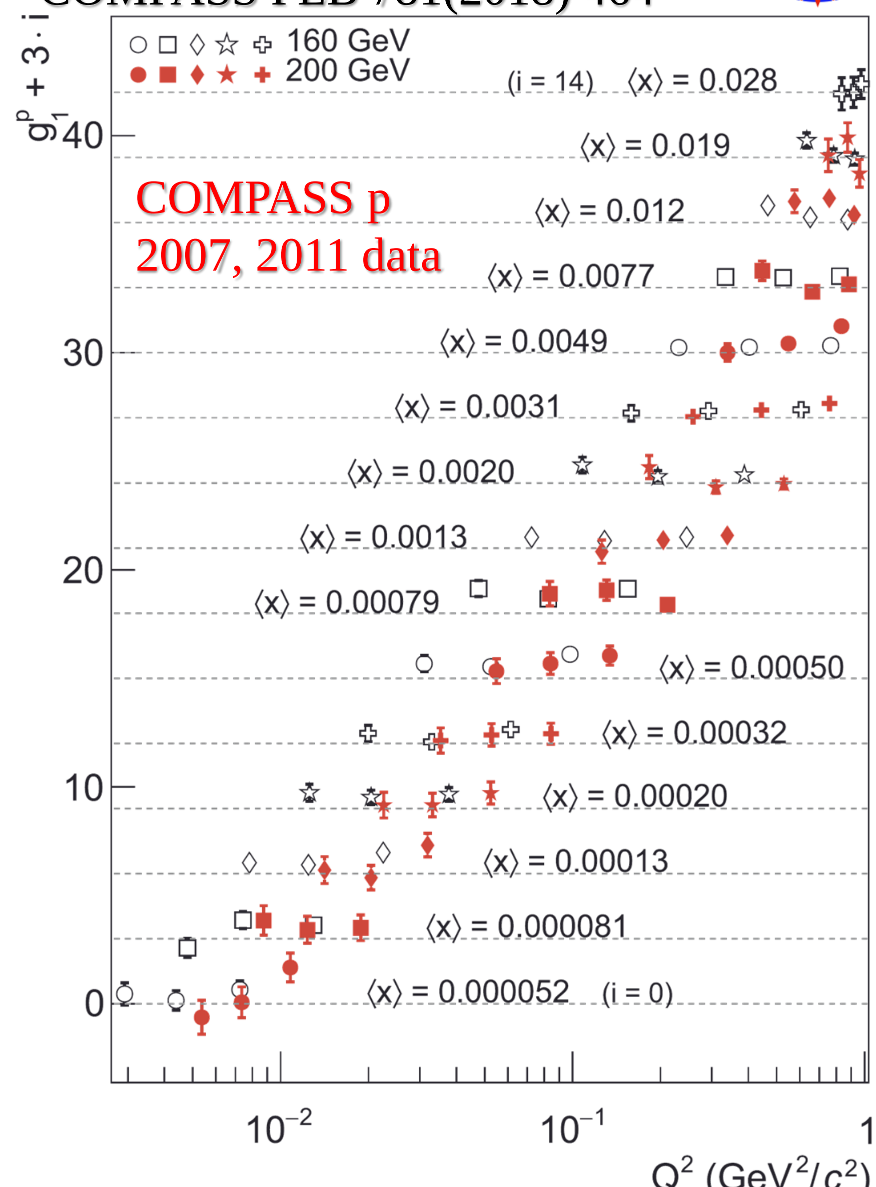




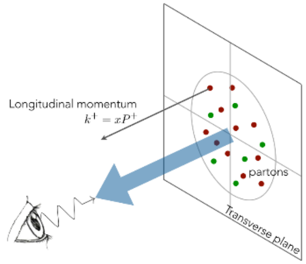
- COMPASS contribution:
  lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$

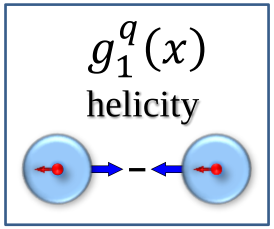


COMPASS PLB 781(2018) 464



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 $g_1^p(x)$
- Gluon polarization measurements
  via open charm and SIDIS
- COMPASS - first to rule out a large gluon polarization in the nucleon!
  Precise test of Bjorken sum rule (9% level)

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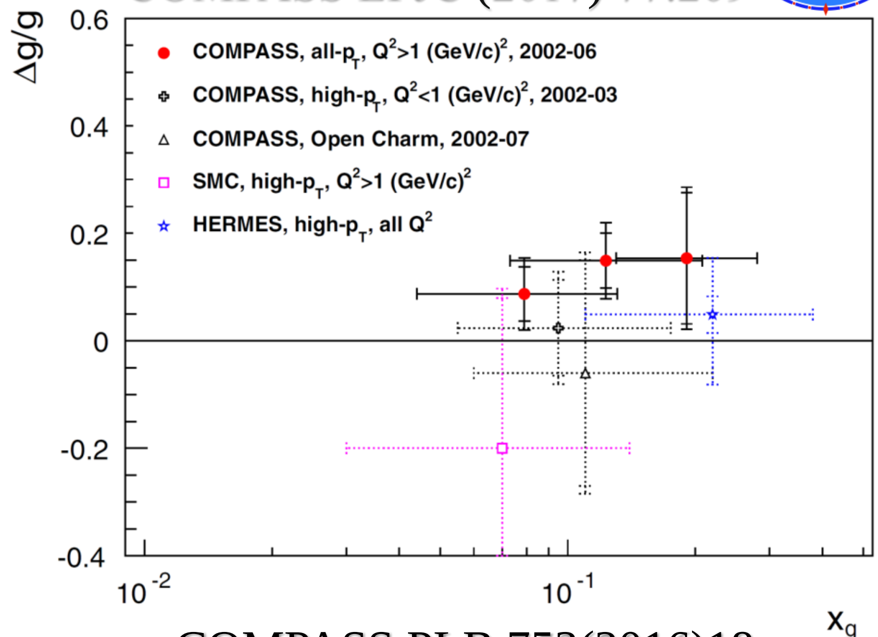

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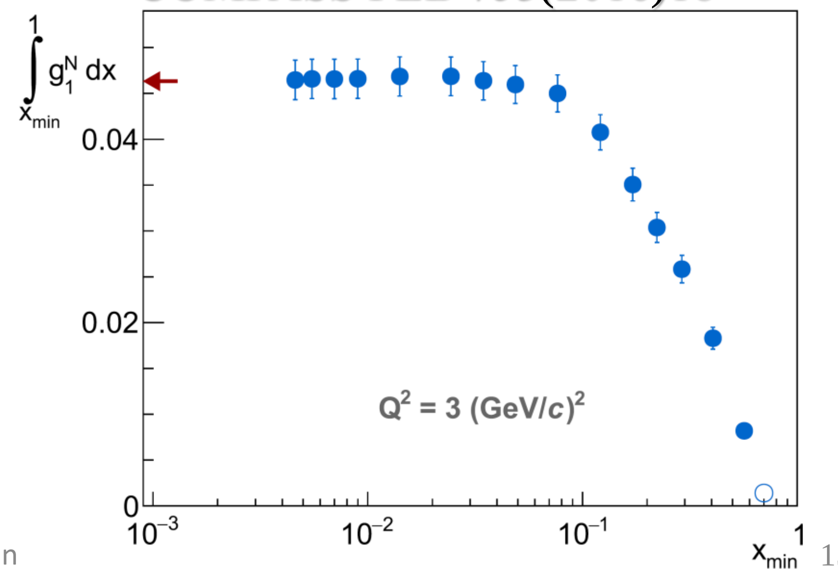
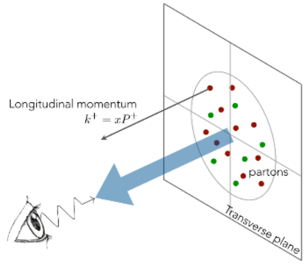
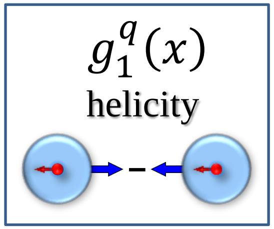


Nucleon spin structure: helicity $g_{1,d(p)}^{q}(x)$





- 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

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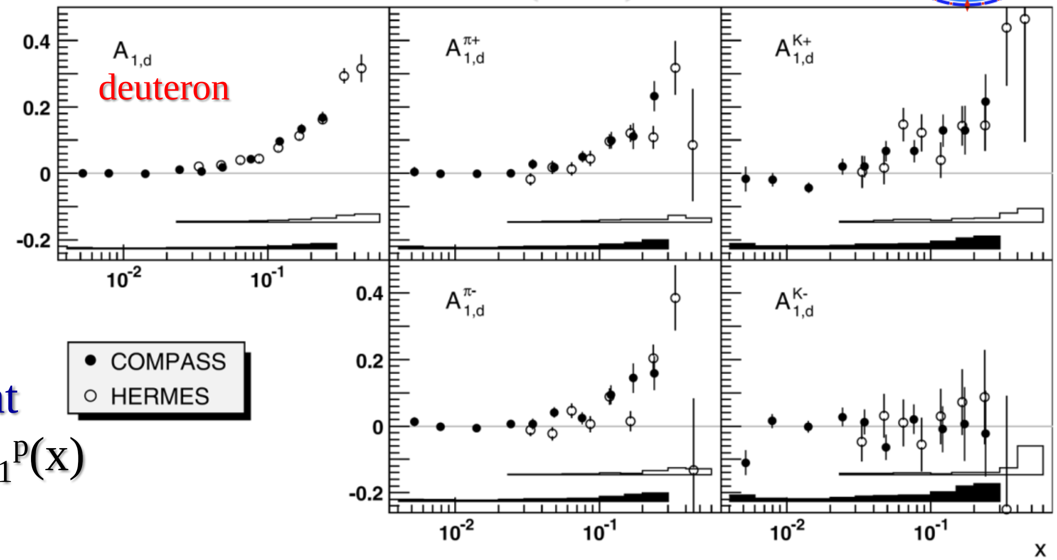

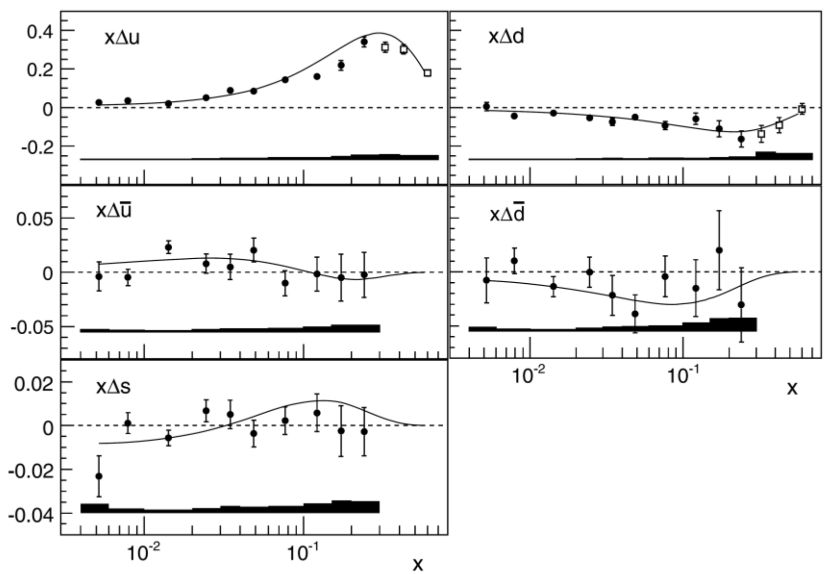

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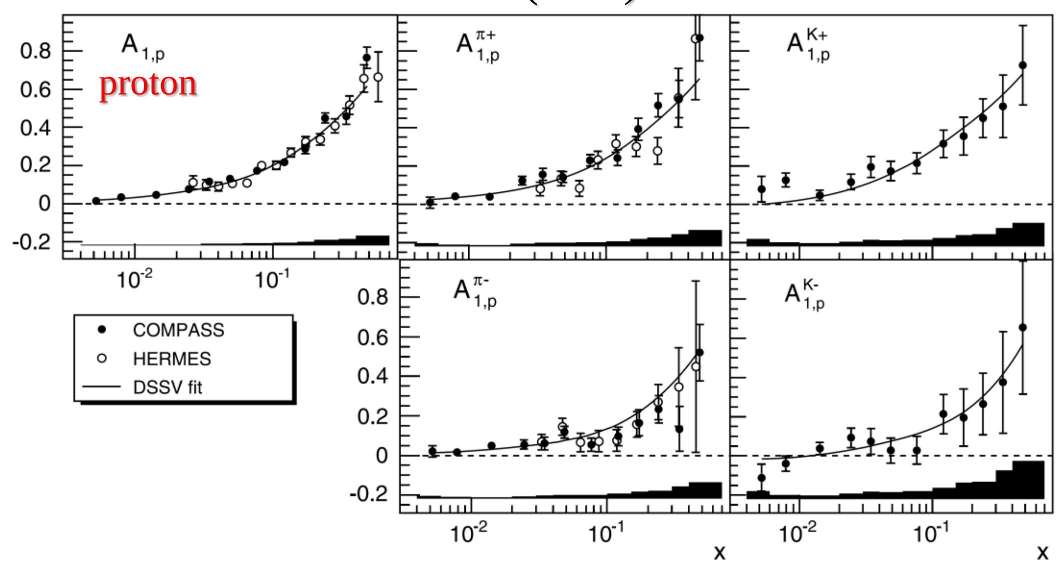
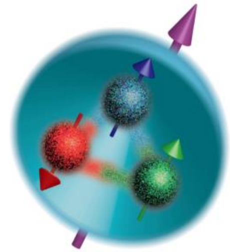
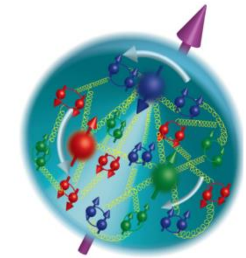


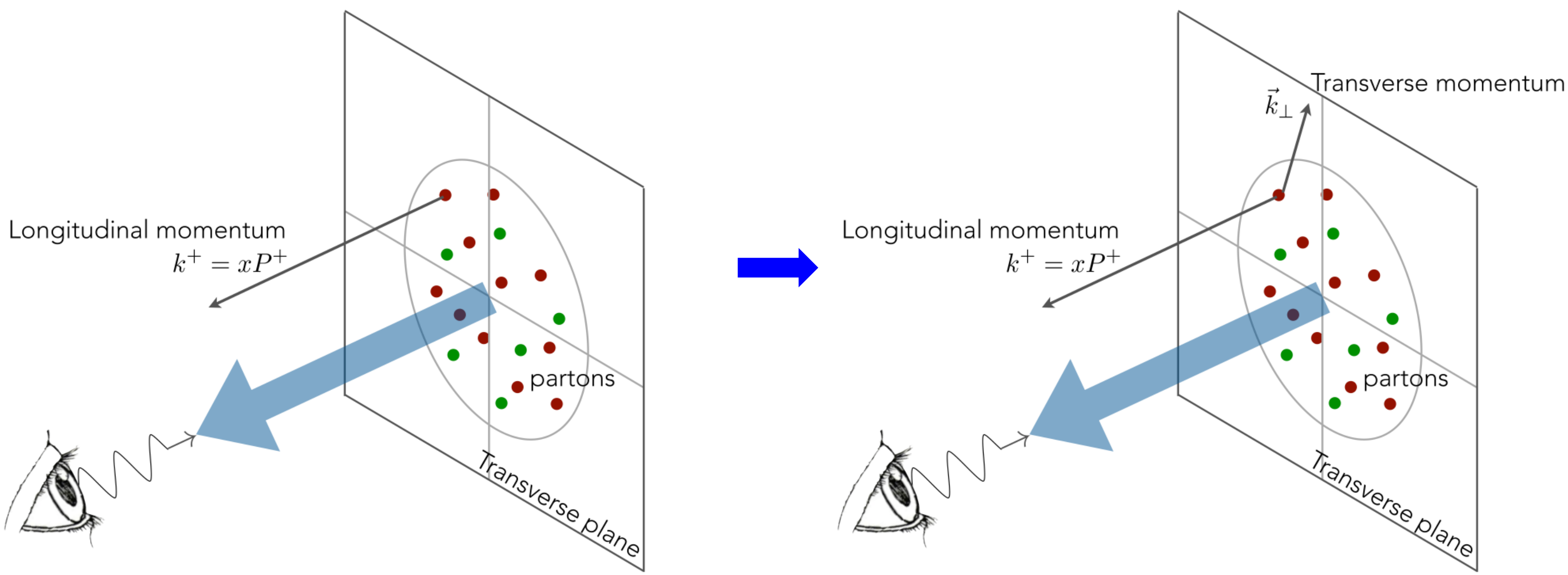
Nucleon spin structure



- 1964 Quark model 
- 1969 Parton model 
- 1973 asymptotic freedom and QCD 



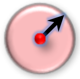
- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries 

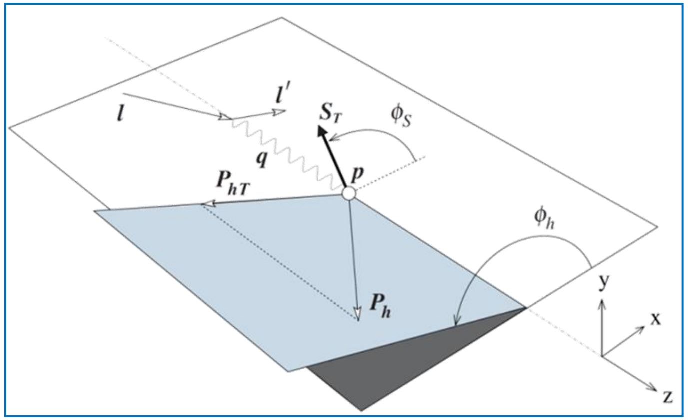


Cahn effect in SIDIS

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

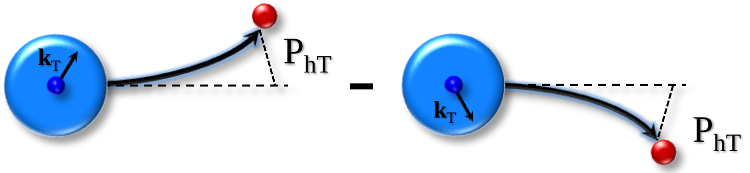
$f_1^q(x,\boldsymbol{k}_T^2)$
number density





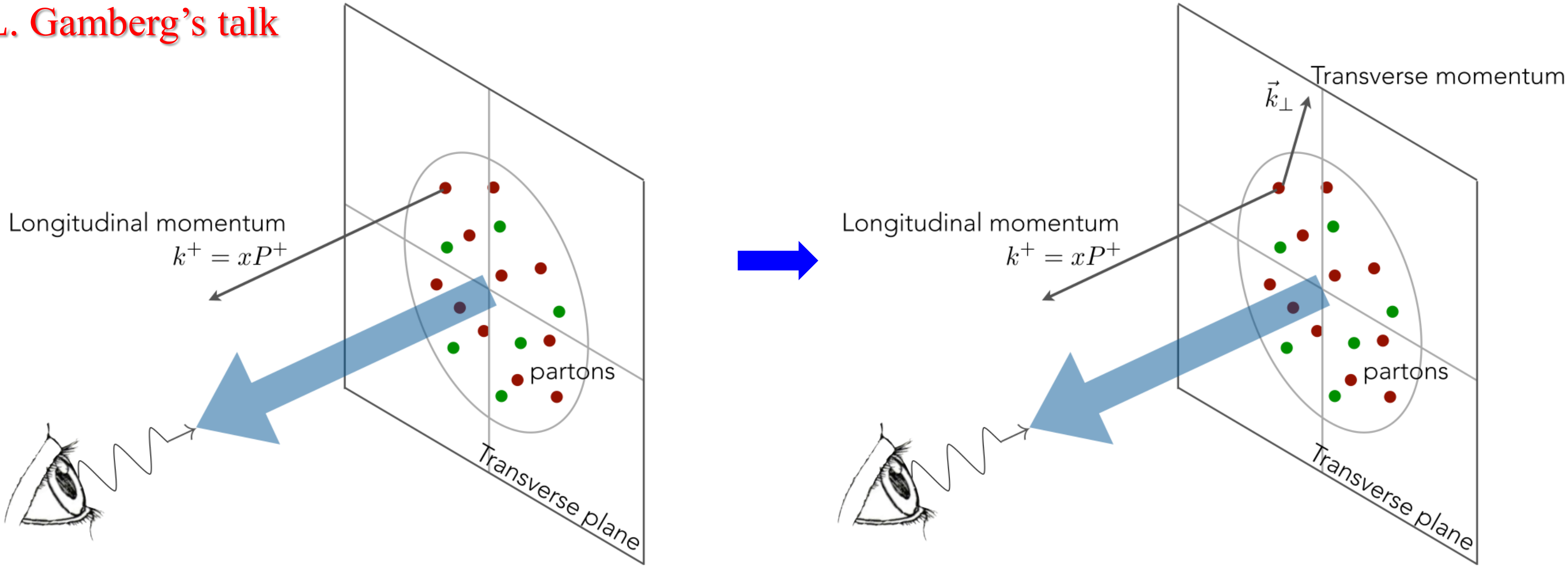
Cahn effect - R. N. Cahn, PLB 78 (1978)

The point that there are azimuthal dependences, which arise from the transverse momenta of the partons was clearly stated in this papers: T.P. Cheng and A. Zee, **Phys. Rev. D6** (1972) 885; F. Ravndal, **Phys. Lett. 43B** (1973) 301.R.L. Kingsley, **Phys. Rev. D10** (1974) 1580; A.M. Kotsinyan, **Teor. Mat. Fiz. 24** (1975) 206;



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

See L. Gamberg's talk

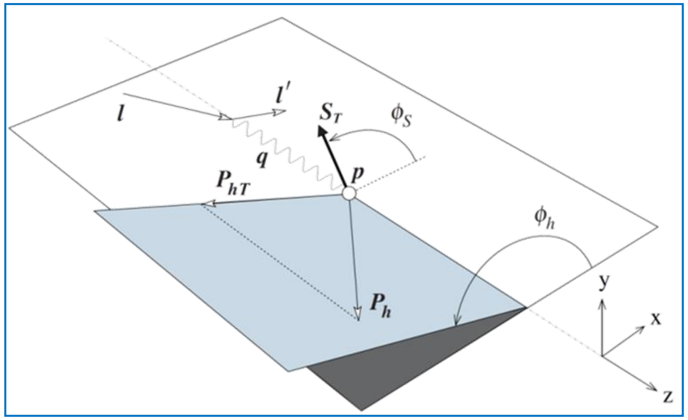


Cahn effect in SIDIS

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

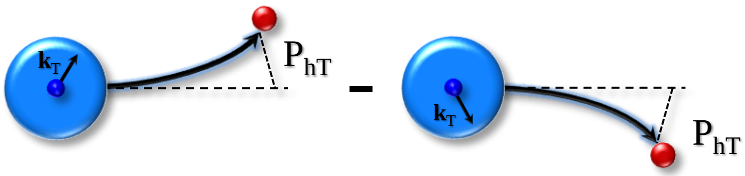
$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

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



Cahn effect

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

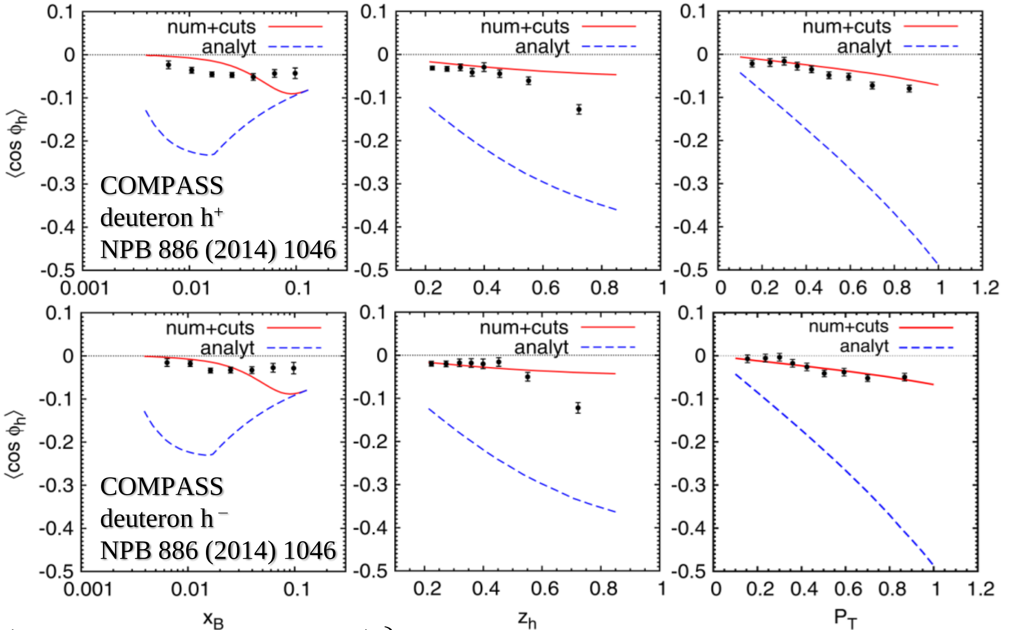


As of 1978 – simplistic kinematic effect:

- 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

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

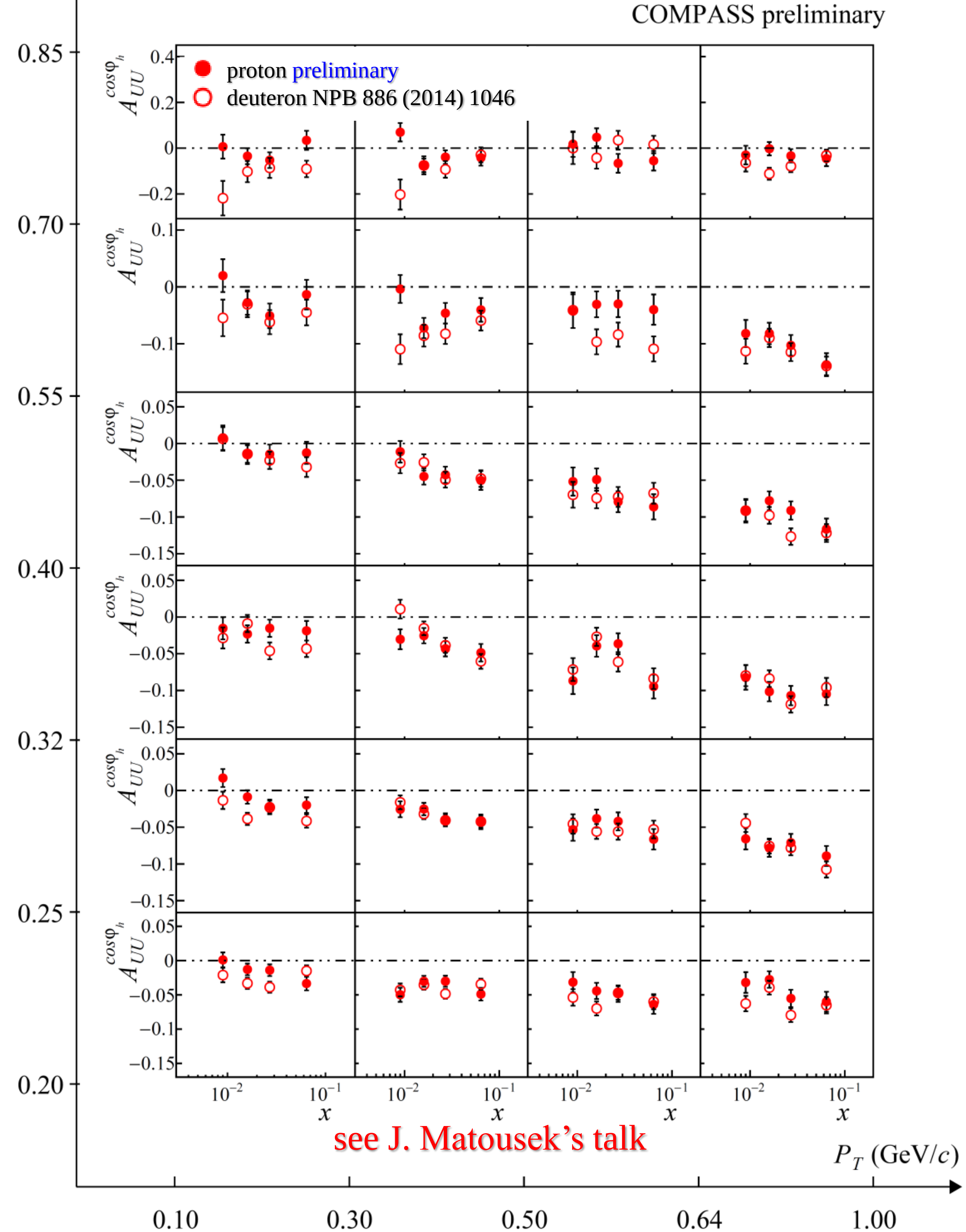
$$\times\Big(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\ldots\Big)$$

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

Recent COMPASS results



see J. Matousek's talk

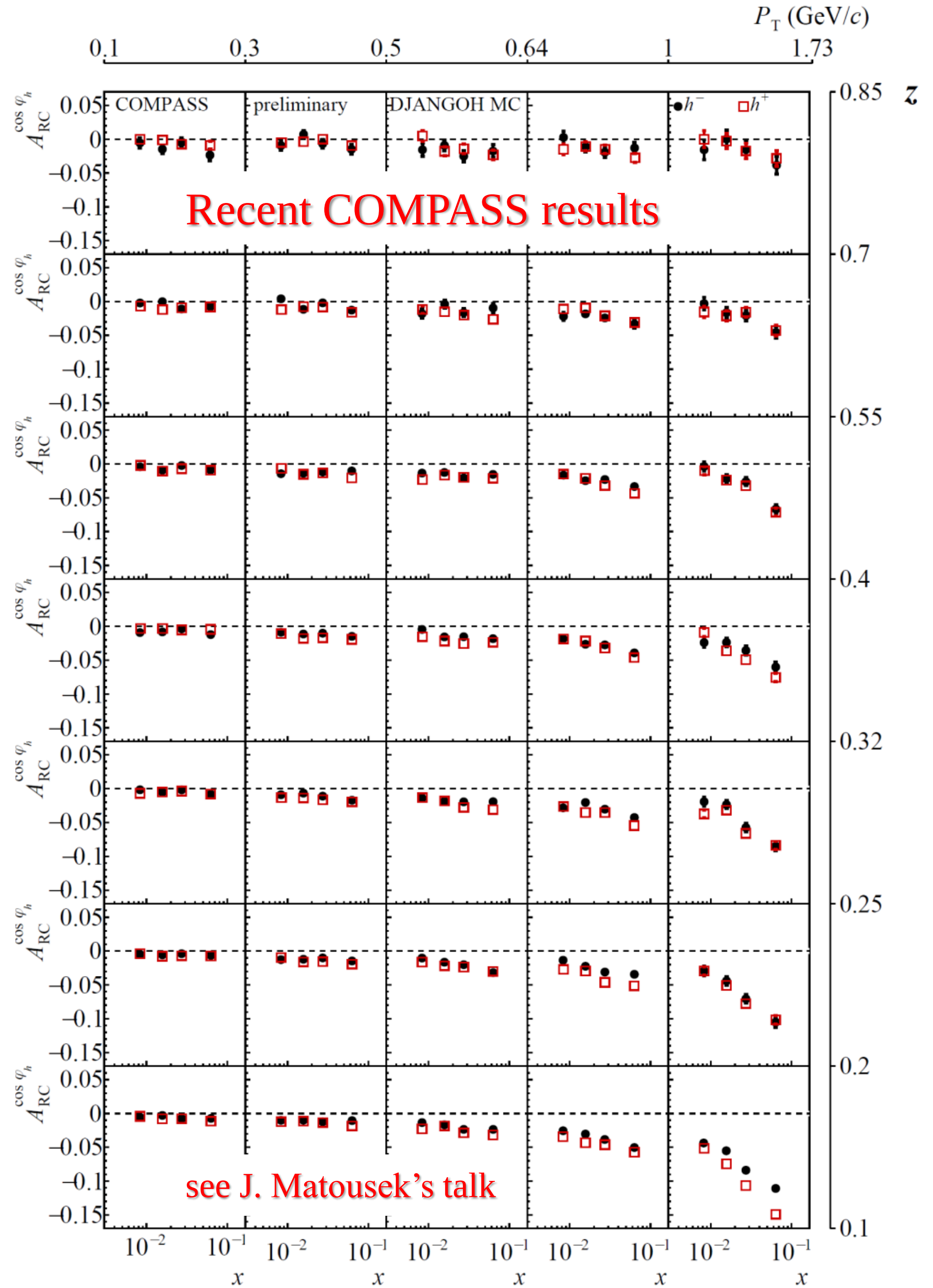
Cahn effect in SIDIS

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

$f_1^q(x,\boldsymbol{k}_T^2)$
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 clear interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections, etc.



$\cos\phi_h$ amplitude of the radiative corrections

Cahn effect in SIDIS

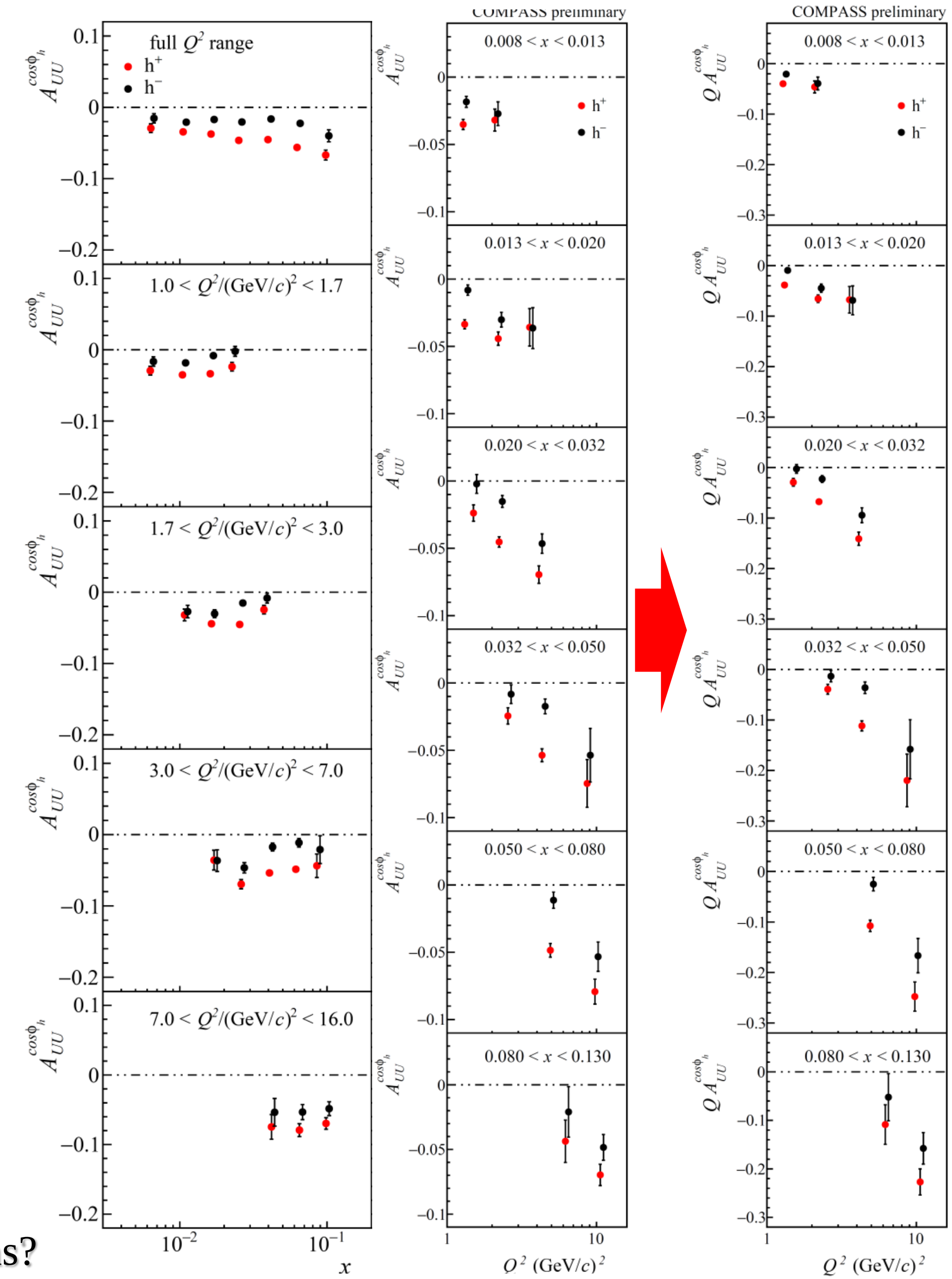
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times \Big(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\ldots\Big)$$

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

Recent COMPASS results

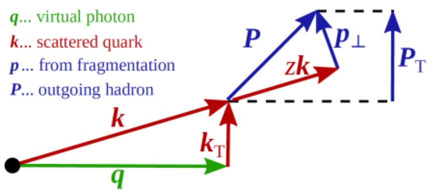


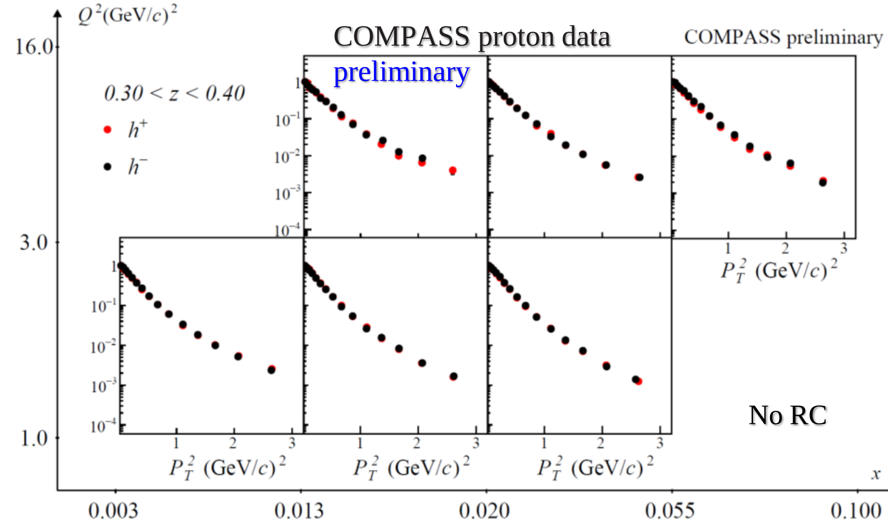
see J. Matousek's talk

Cahn effect in SIDIS

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

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

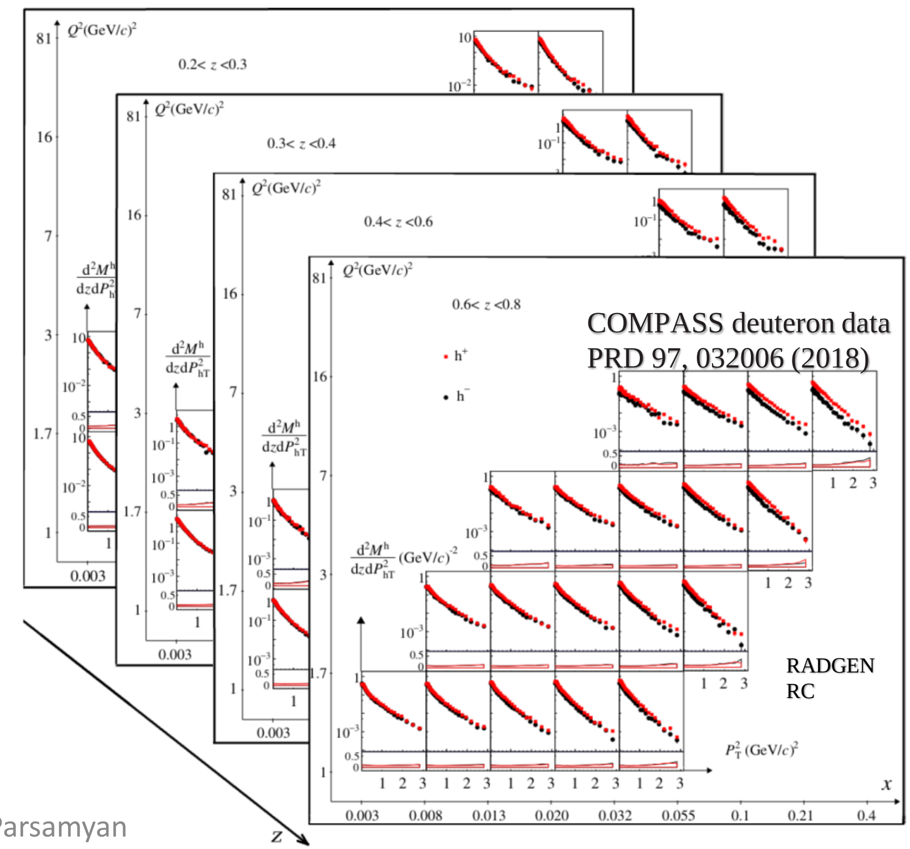




see J. Matousek's talk

P$_T$-dependent distributions

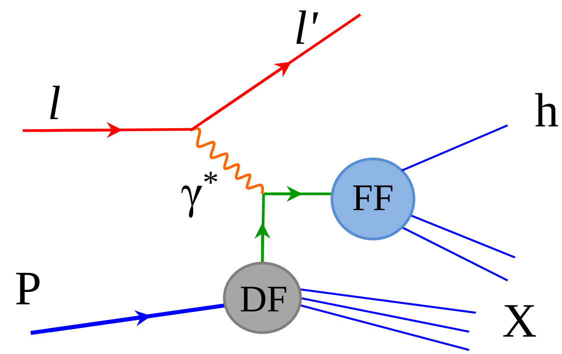
- Extracted in multi-D kinematic bins
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections, etc.
- Global fits by different groups (SIDIS-DY)
  - Normalization issues
    (See A. Baccehtta's talk)
- COMPASS measurements
  - isoscalar target data - published
  - proton data – ongoing analysis
- COMPASS-2022 data
  - More deuteron data points to be expected



SIDIS x-section and TMDs at twist-2

All measured by COMPASS

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = {} & \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right) \\
\times \Bigg\{ & 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\
& +\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\
& +S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] \\
& +S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
& +S_T\left[\begin{aligned} & A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ & +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ & +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ & +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ & +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\end{aligned}\right] \\
& +S_T\lambda\left[\begin{aligned} & \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ & +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ & +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\end{aligned}\right]\Bigg\}
\end{aligned}
$$



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

spin of the nucleon · spin of the quark · k_T

SIDIS: target longitudinal spin dependent asymmetries

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

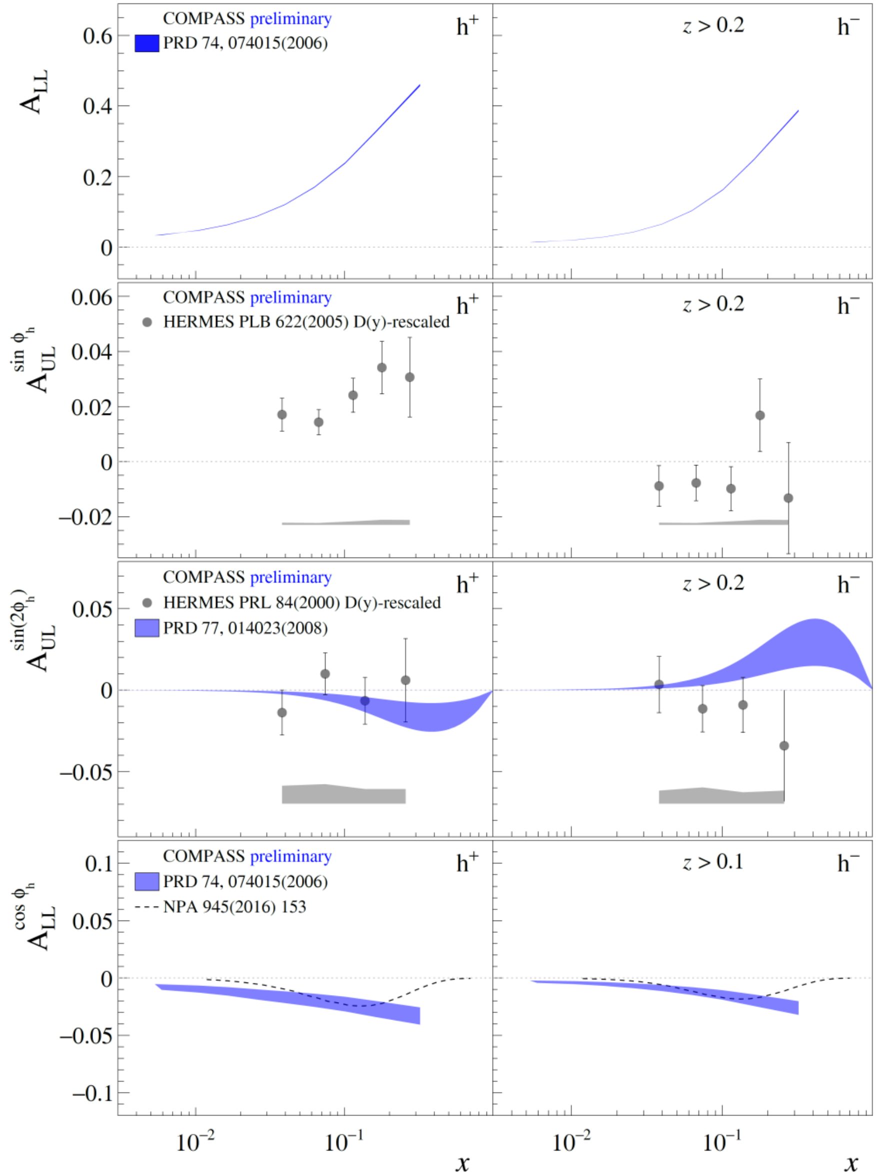
$$+ S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h\right]$$
$$\left. + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h\right]\right\}$$

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

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

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

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

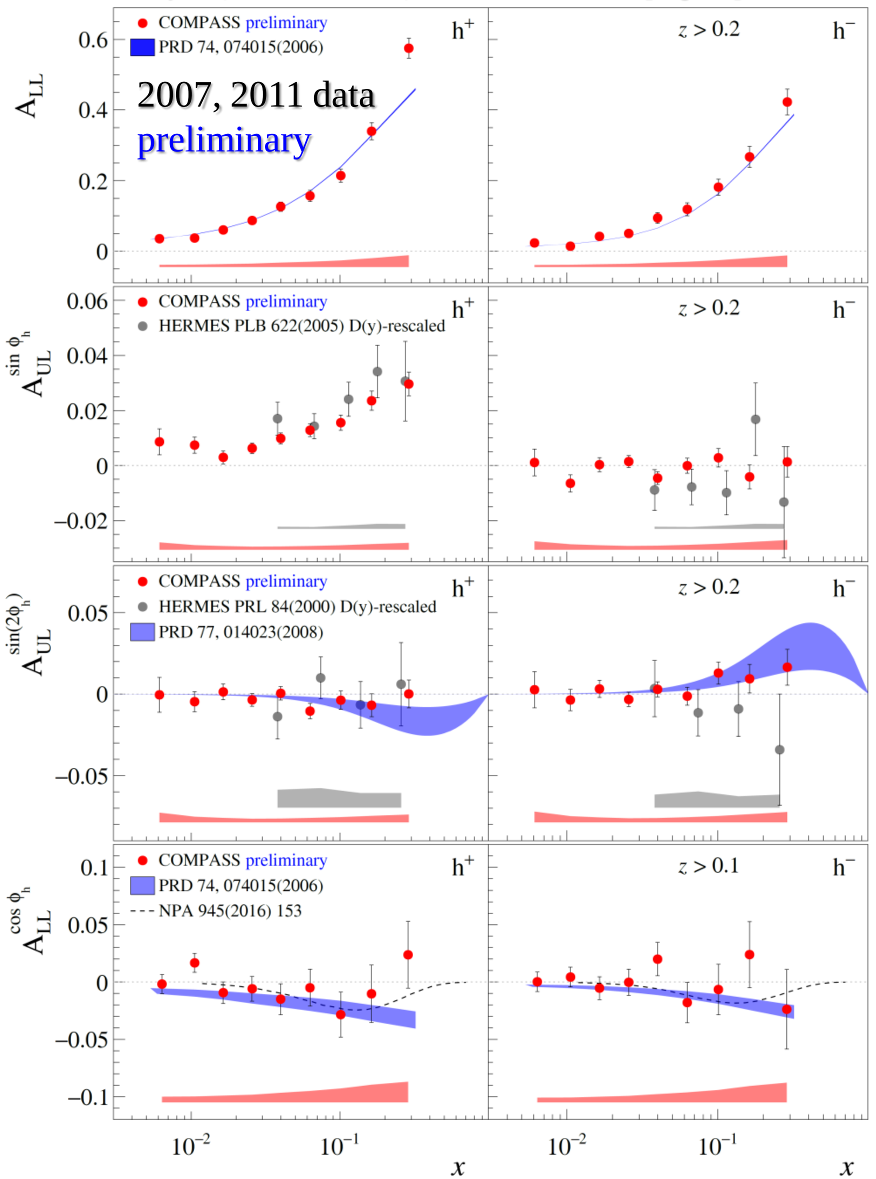


SIDIS: target longitudinal spin dependent asymmetries

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

$$\boxed{\begin{aligned} &+ S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \\ &+ S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h \right] \end{aligned}}\left.\vphantom{\boxed{\begin{aligned}a\\b\end{aligned}}}\right\}$$

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



COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

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

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

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

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

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

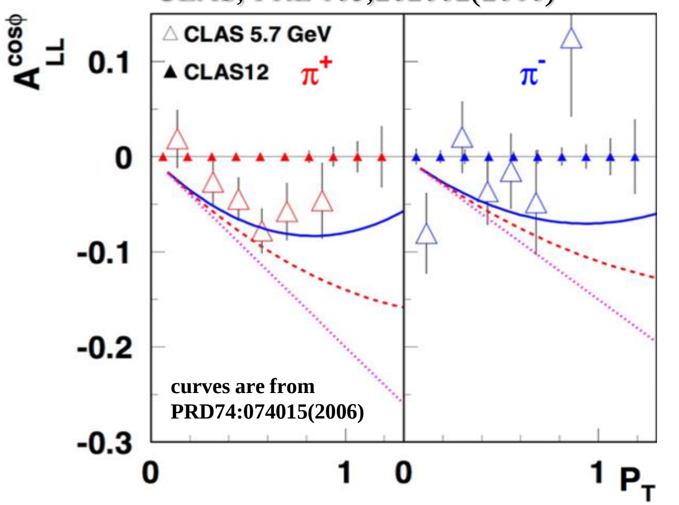
- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models

SIDIS: target longitudinal spin dependent asymmetries

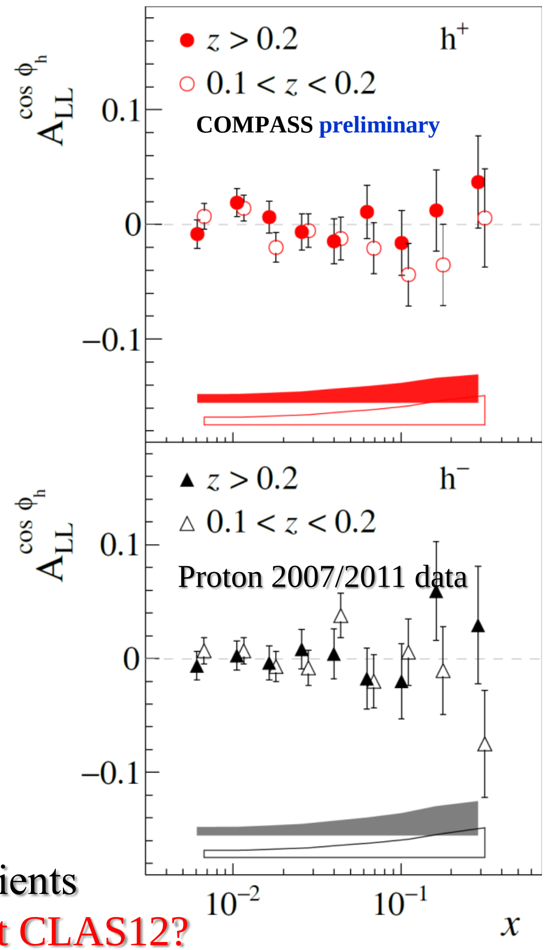
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_L \lambda \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos\phi_h} \cos\phi_h + \ldots\right\}$$

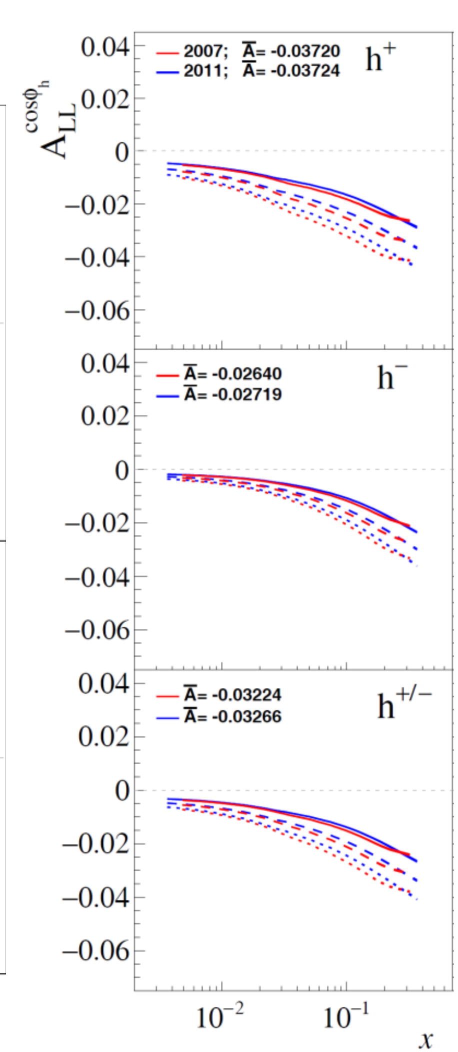
$$\boxed{F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xe_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xg_L^{\perp q} D_{1q}^h - \frac{M_h}{M}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

CLAS, PRL 105,262002(2010)



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

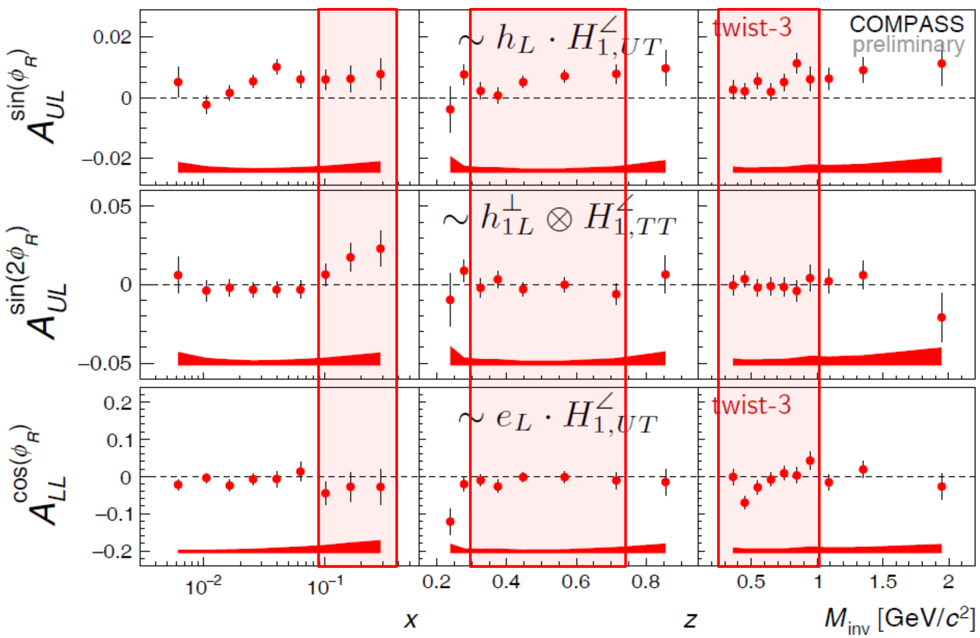


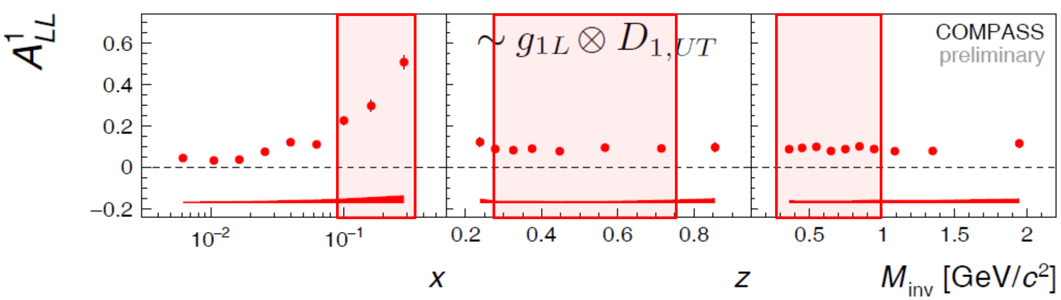


- Q-suppression, various different “twist” ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

Selected results for di-hadron LSAs

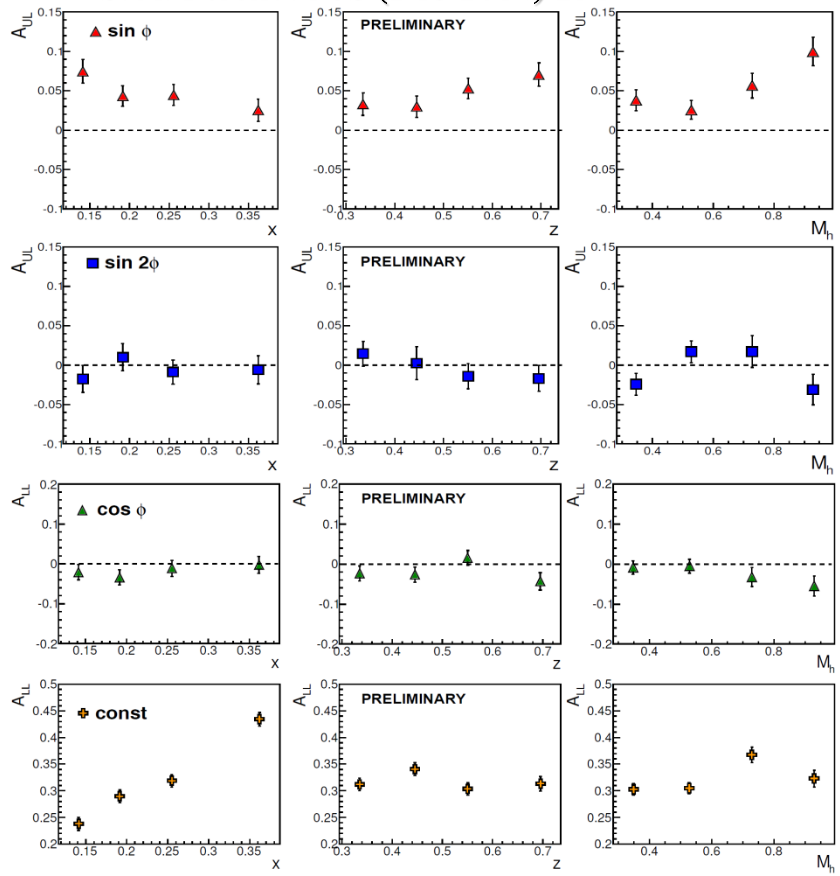
COMPASS (NH_3) 2007+2011 data: preliminary



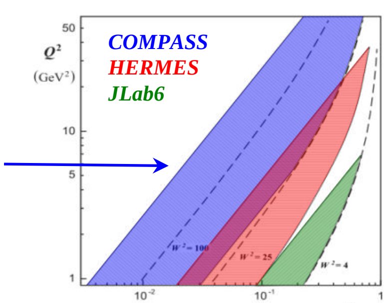


CLAS 6 GeV (NH_3)

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



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



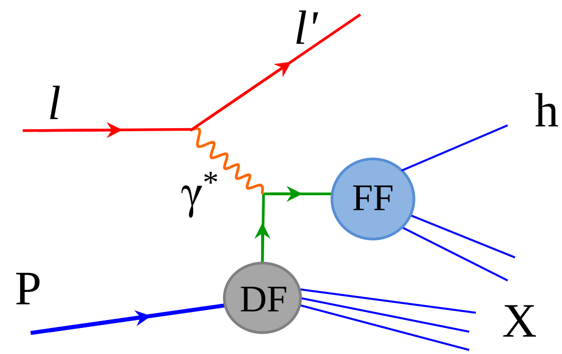
- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A_{LL}^{1}
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?

SIDIS x-section and TMDs at twist-2: TSAs

All measured by COMPASS

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

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



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

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

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

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

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

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

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

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

Twist-2

Twist-3

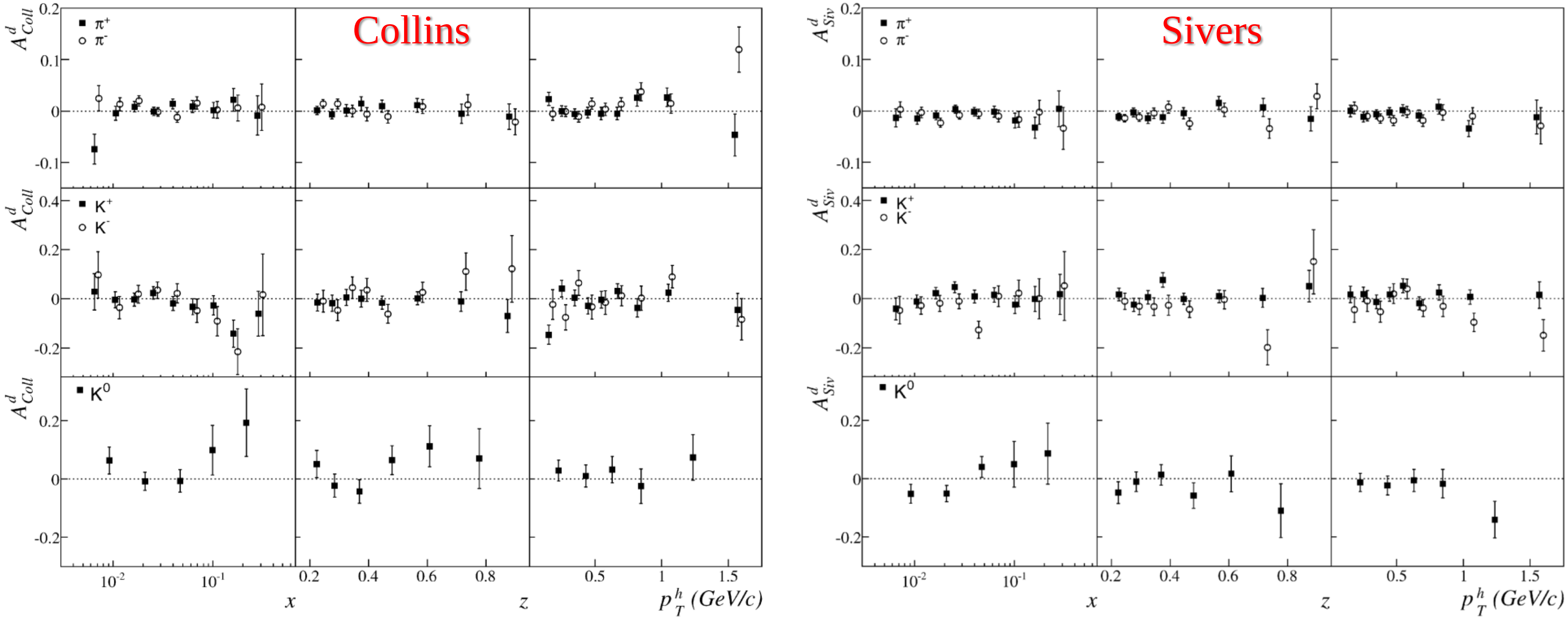
SIDIS TSAs: Collins and Sivers effects (deuteron)

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

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

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

COMPASS PLB 673 (2009) 127



- 1st COMPASS deuteron measurements
- Collins and Sivers asymmetries compatible with zero within uncertainties.

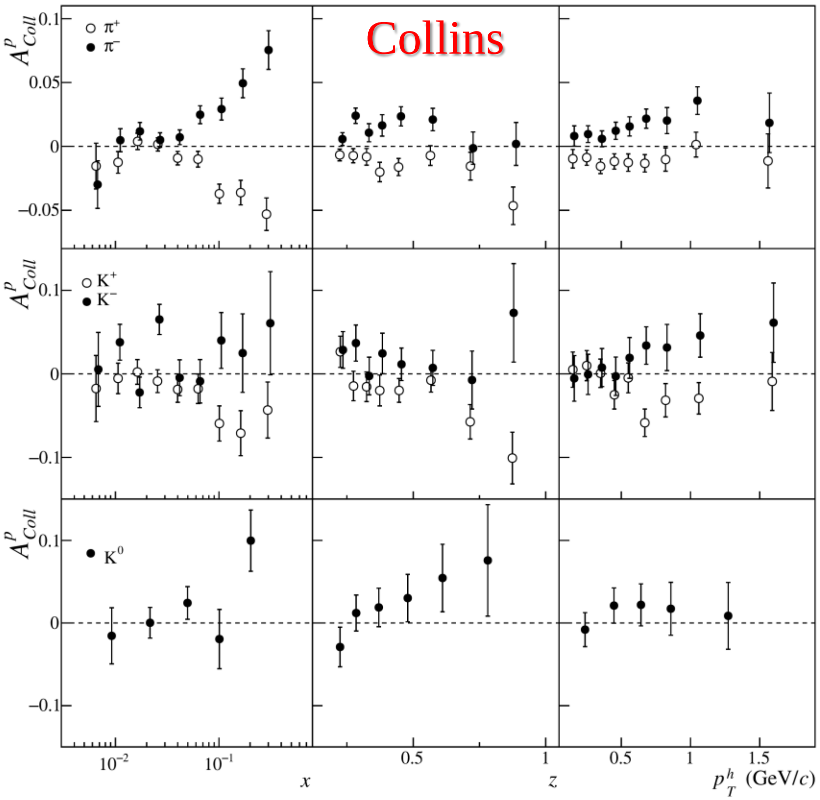
SIDIS TSAs: Collins and Sivers effects (proton)

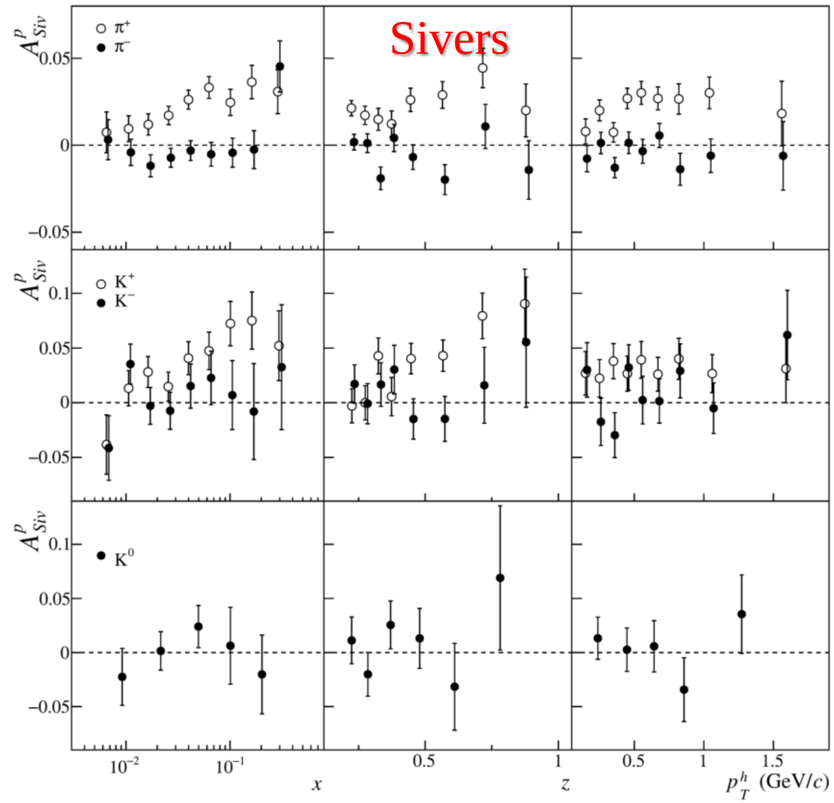
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) + S_T \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \ldots \right\}$$

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

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

COMPASS PLB 744(2015)250





- 1st COMPASS deuteron measurements – Collins and Sivers asymmetries compatible with zero
- COMPASS proton measurements – clear non-zero signal for both asymmetries

SIDIS TSAs: Collins effect and Transversity

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

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

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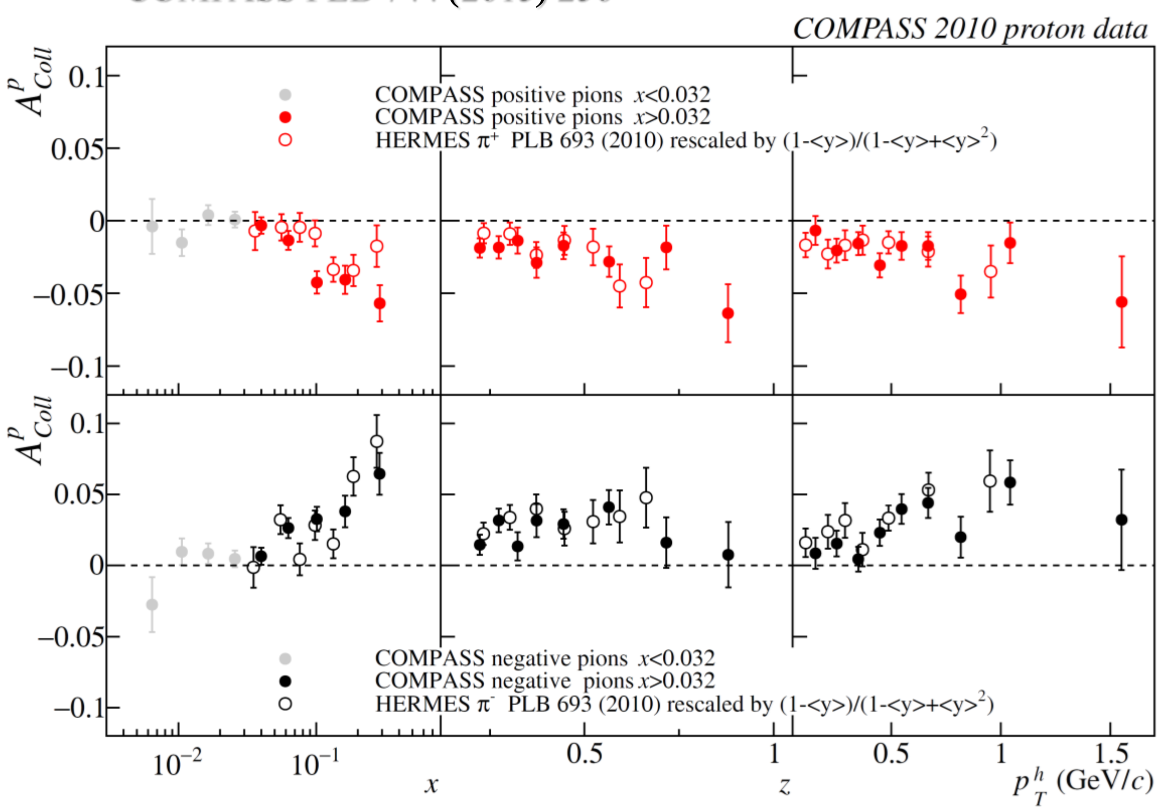
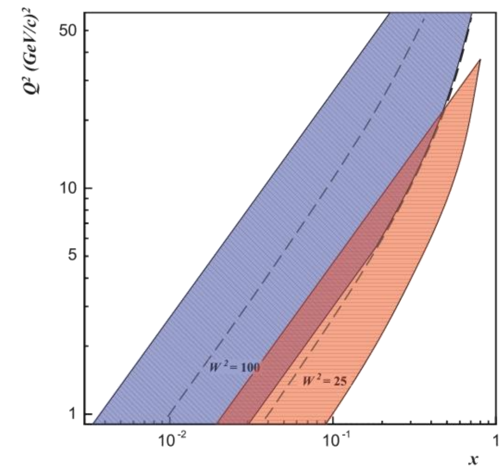
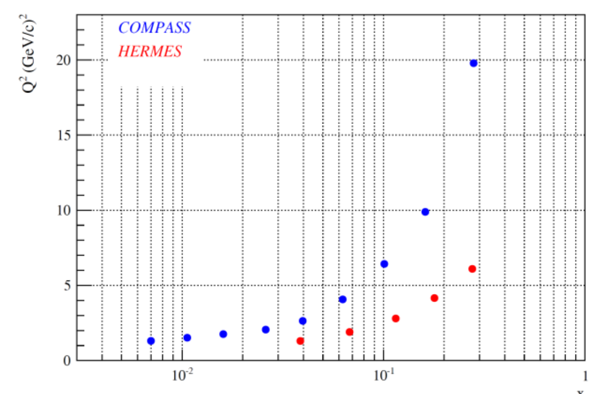
- No impact from Q^2-evolution?

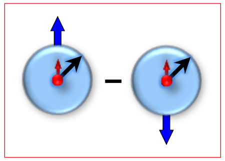
COMPASS PLB 744 (2015) 250







SIDIS TSAs: Collins effect and Transversity



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

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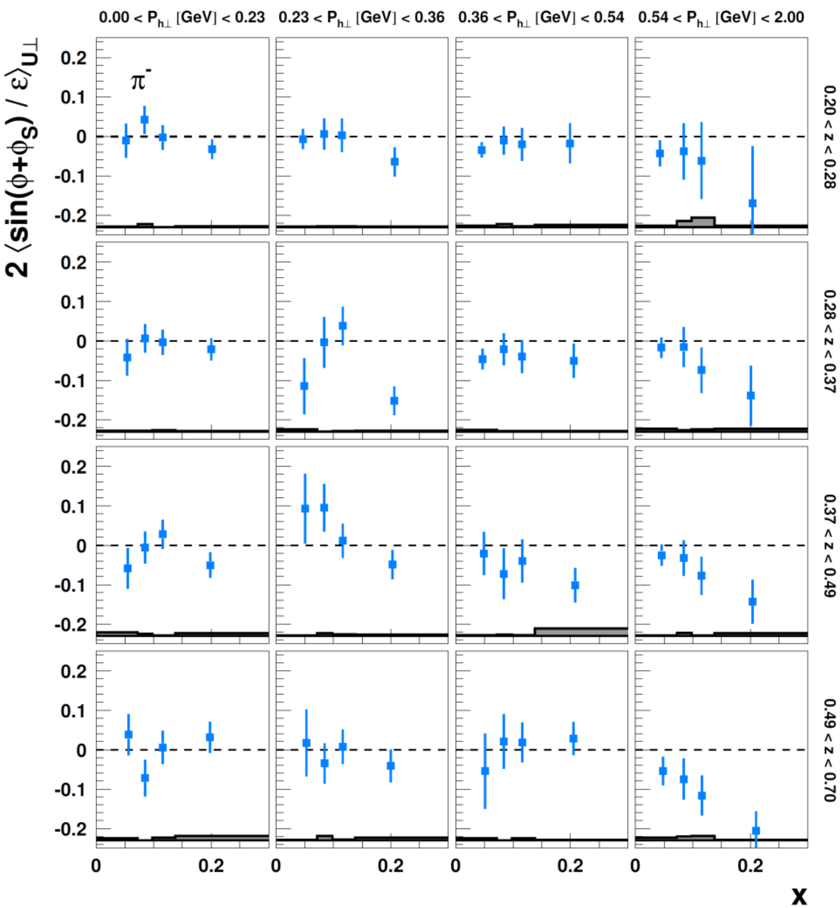
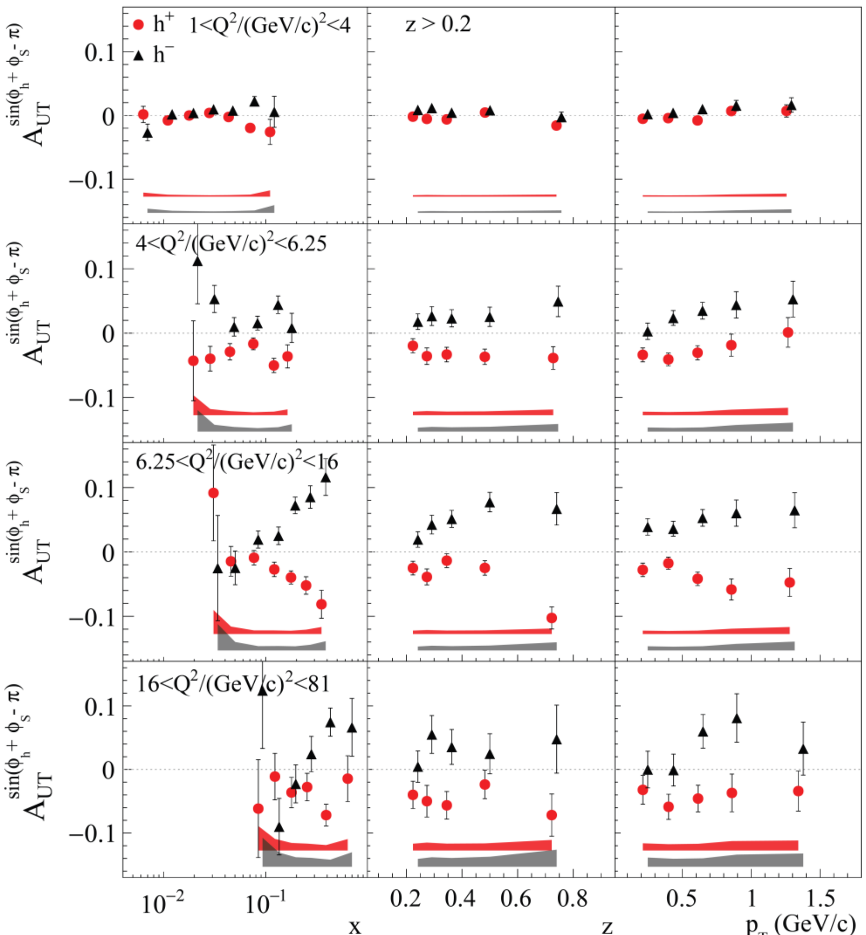
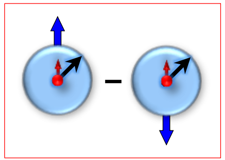
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



SIDIS TSAs: Collins effect and Transversity



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

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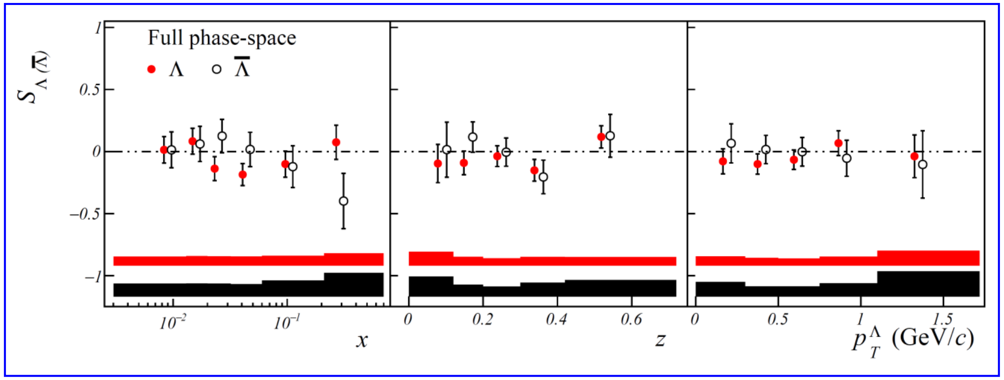
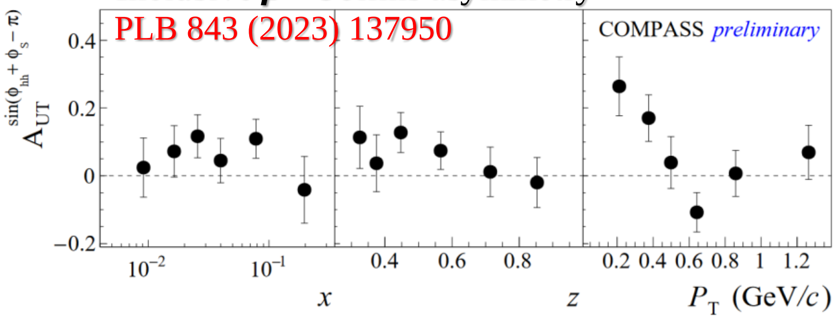
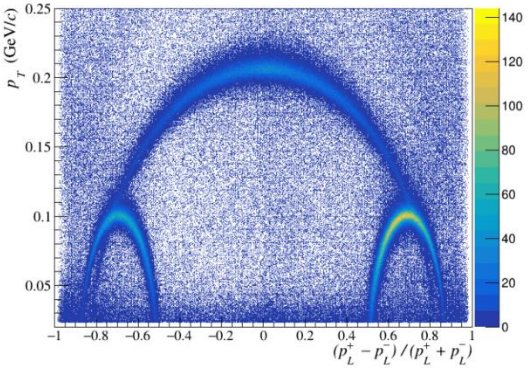
PLB 824 (2022) 136834

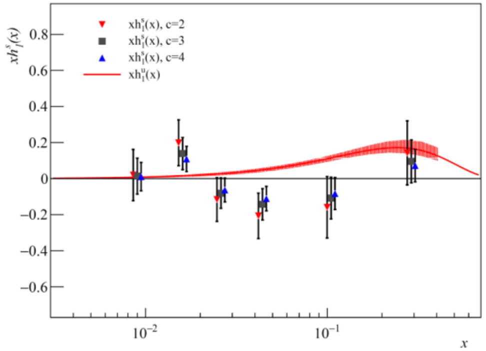


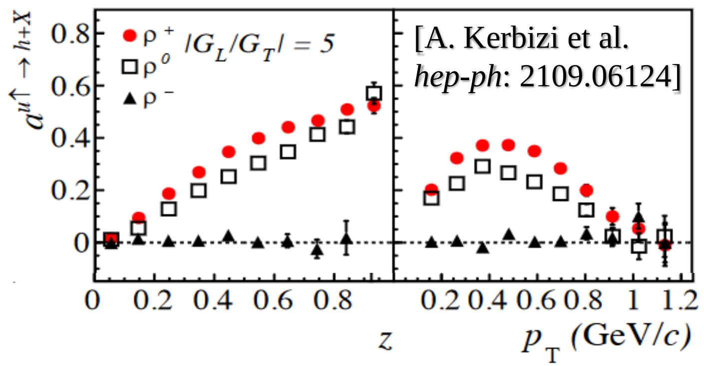
Inclusive ρ^0 Collins asymmetry



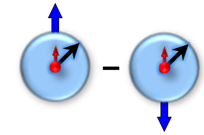
- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T







SIDIS TSAs: Collins effect and Transversity



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

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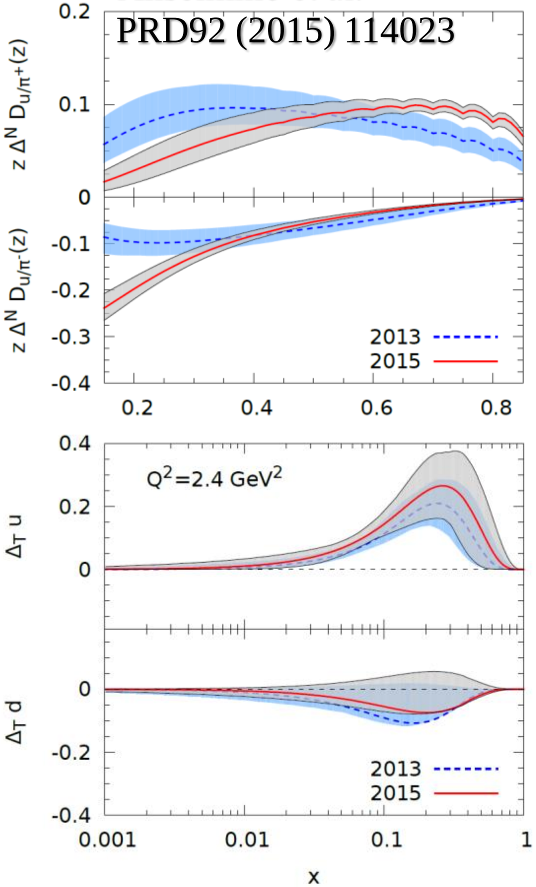
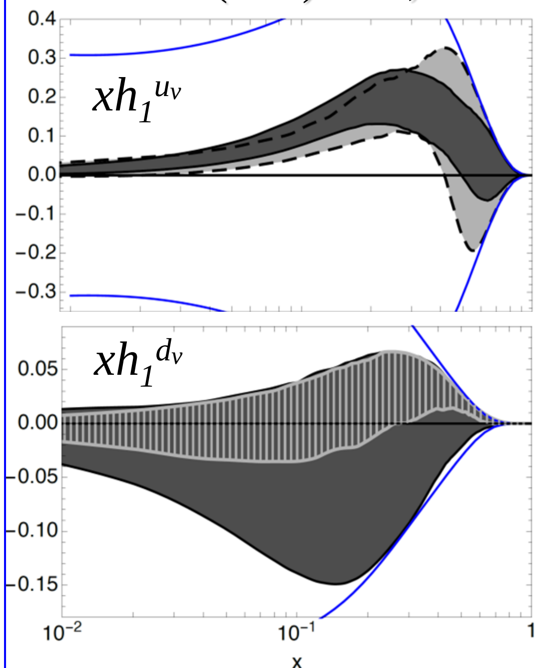
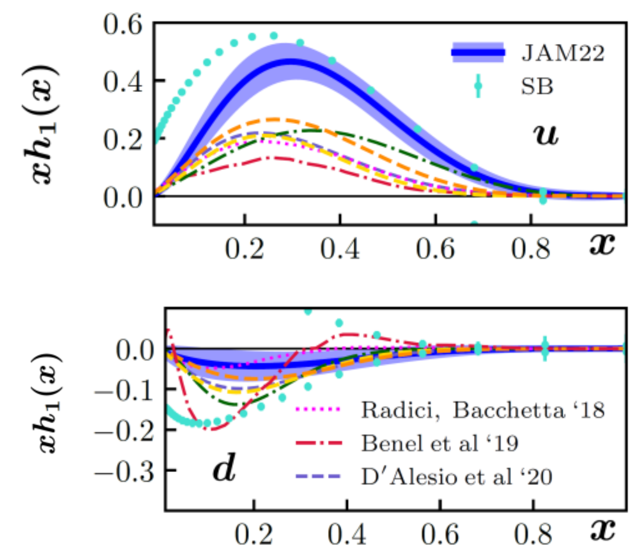
Anselmino et al.
PRD92 (2015) 114023



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



JAM Collaboration,
PRD 106 (2022) 3, 034014



SIDIS TSAs: Collins effect and Transversity

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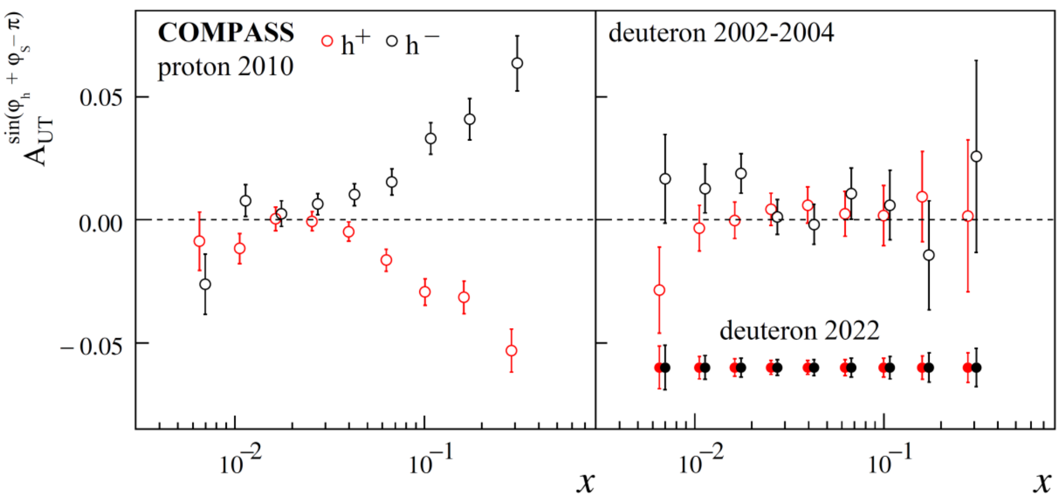
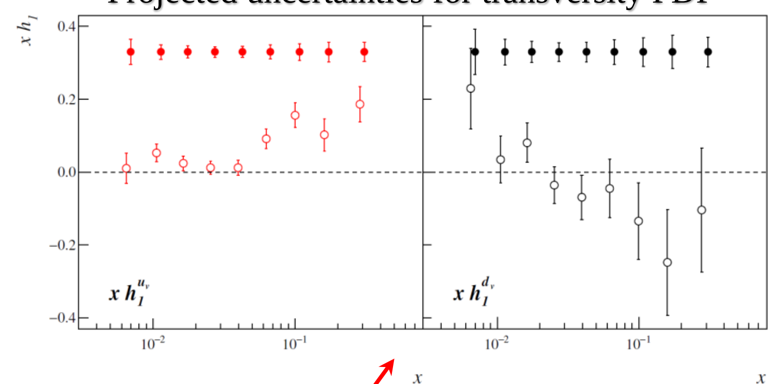
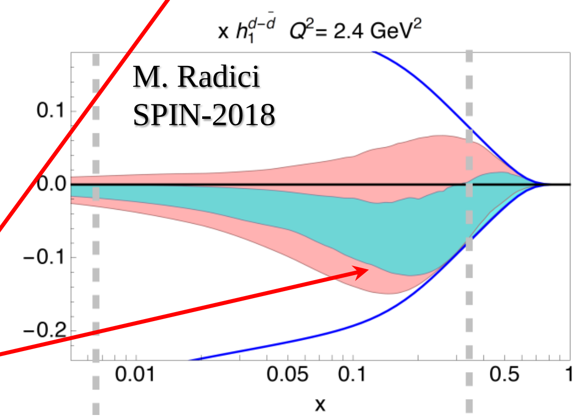
[Addendum to the COMPASS-II Proposal]

Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF

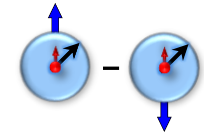




COMPASS-II (2022)

- 2nd COMPASS deuteron measurements performed
- Crucial to constrain the transversity TMD PDF for the d-quark

SIDIS TSAs: Collins effect and Transversity



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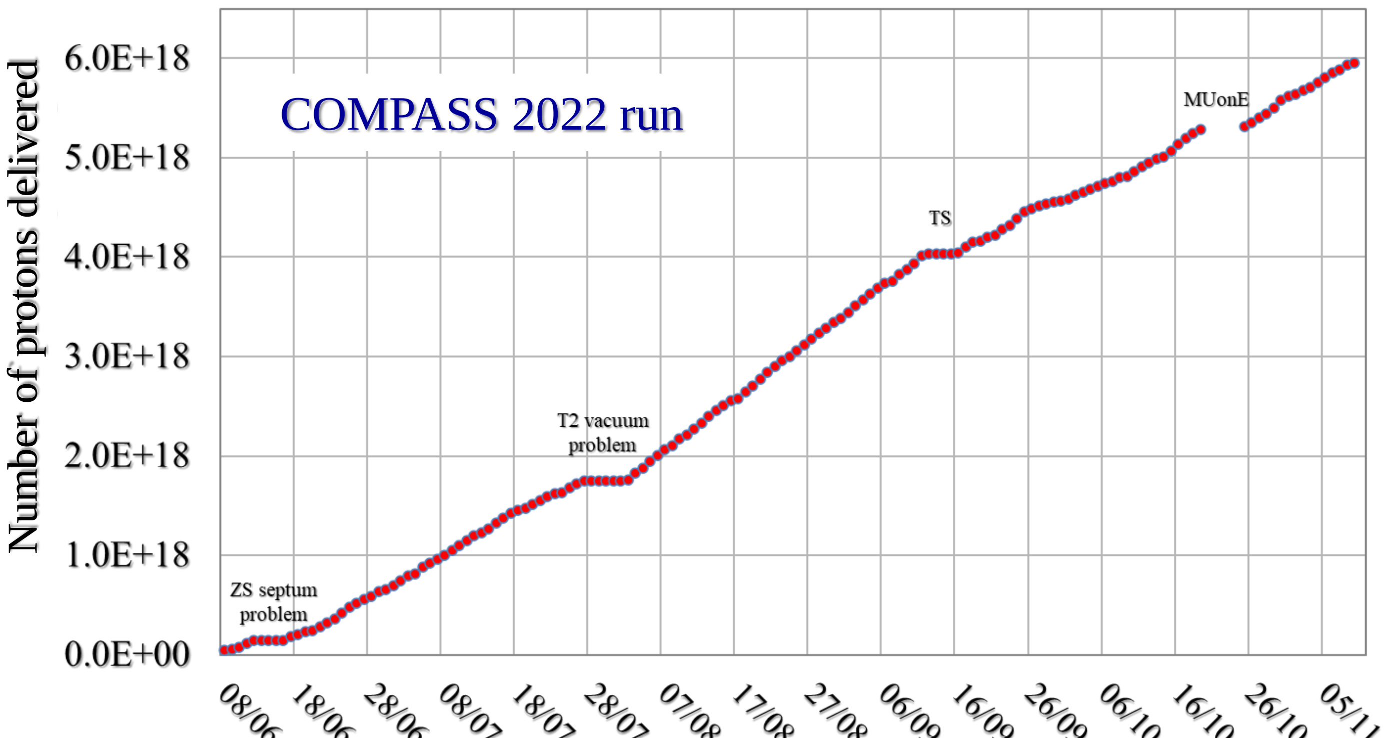
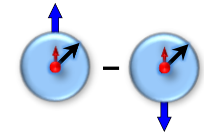
Total protons delivered on the production target: ~5.95×10^{18} (98% of the request) in ~150 days



SPS efficiency: ~ 73%
Spectrometer efficiency: ~ 90%
Physics data collection efficiency: ~ 75%

Highly successful Run in 2022!

SIDIS TSAs: Collins effect and Transversity



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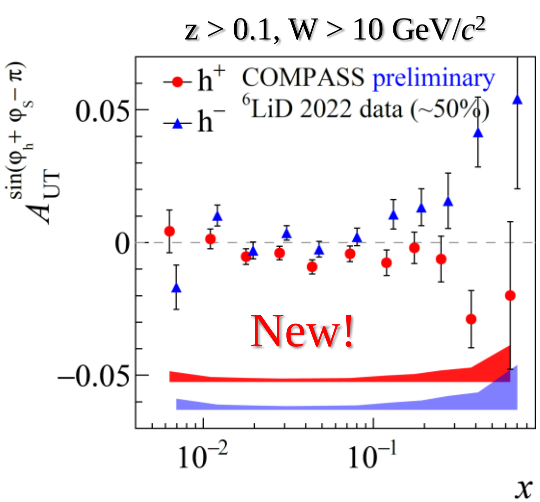
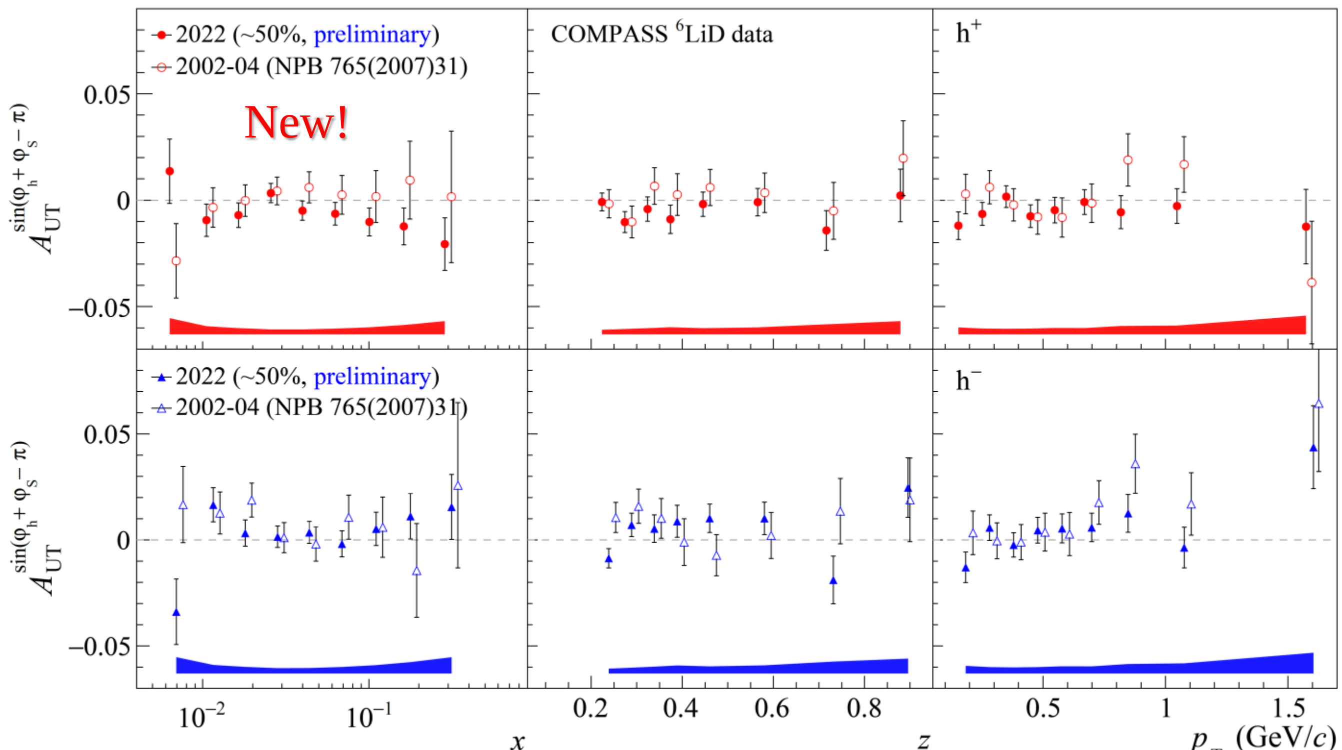


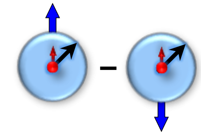


COMPASS-II (2022)

- 2^{nd} COMPASS deuteron measurements performed
- Crucial to constrain the transversity TMD PDF for the d-quark

See A. Martin's slides

SIDIS TSAs: Collins effect and Transversity



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

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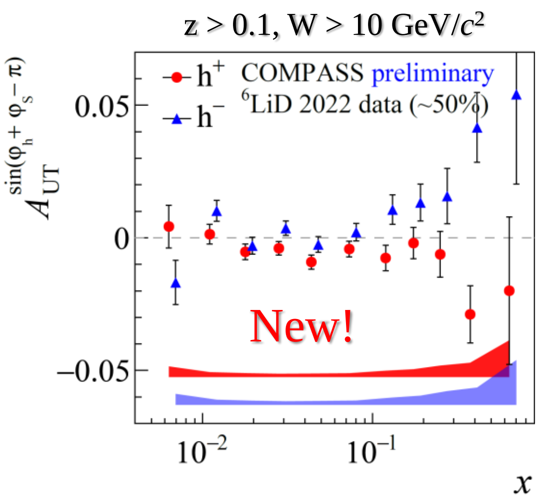

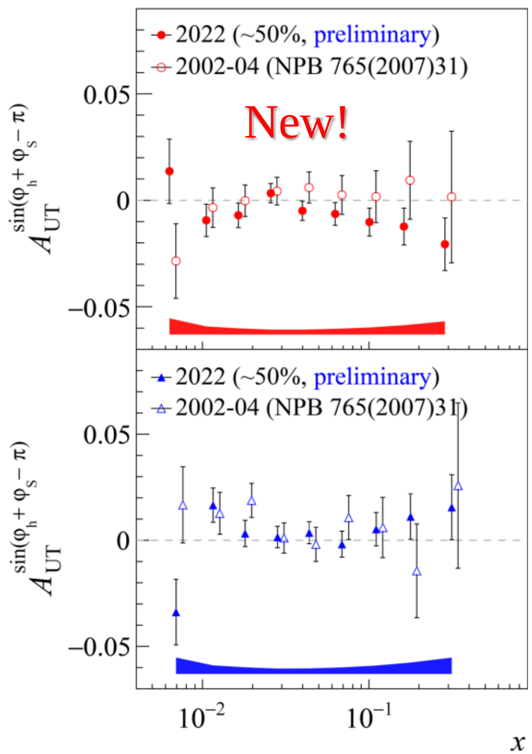

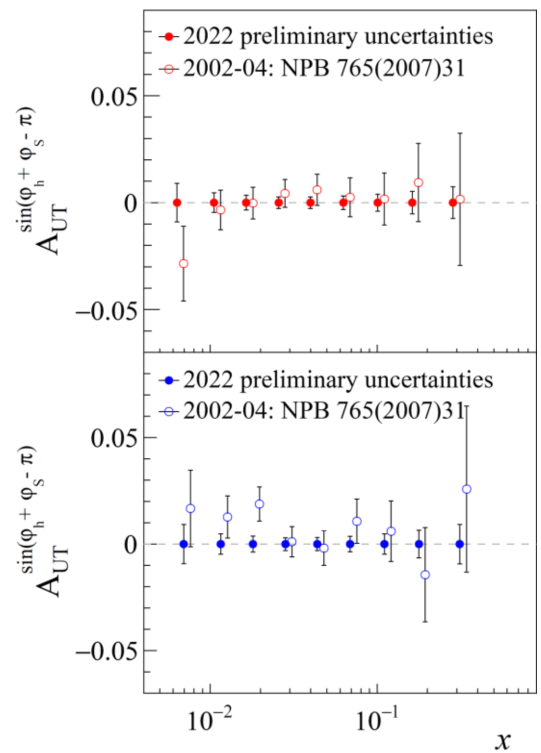

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COMPASS 2022 run: new unique deuteron data

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 $\quad 0.2 \leq z \leq 0.7$

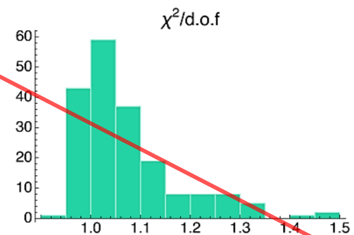
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

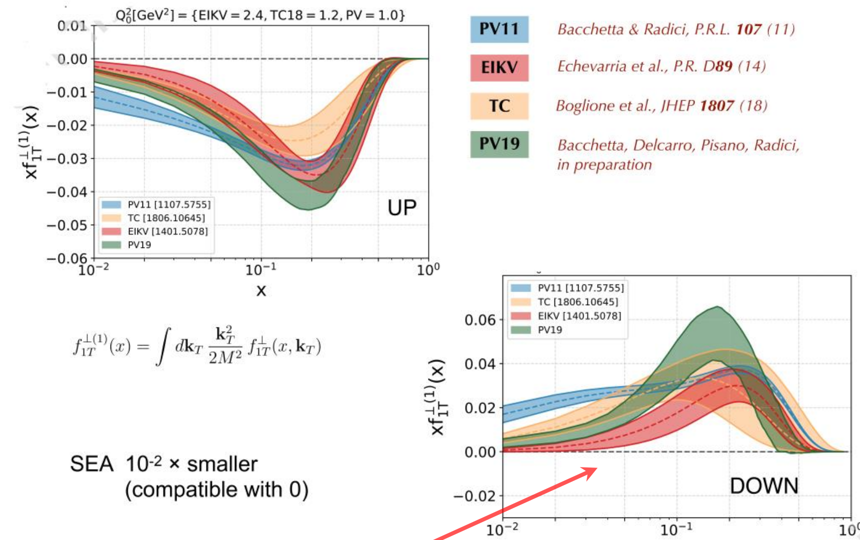
x, z, P_{hT} data projections

300 data points → **118** data fitted

14 free parameters

χ²/d.o.f. = 1.06 ± 0.10





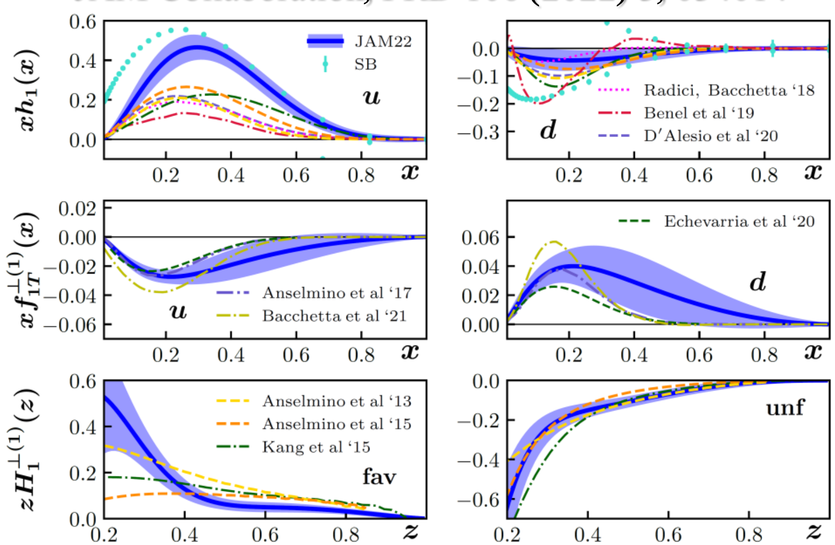
PV11	*Bacchetta & Radici, P.R.L. **107** (11)*
EIKV	*Echevarria et al., P.R. **D89** (14)*
TC	*Boglione et al., JHEP **1807** (18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

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

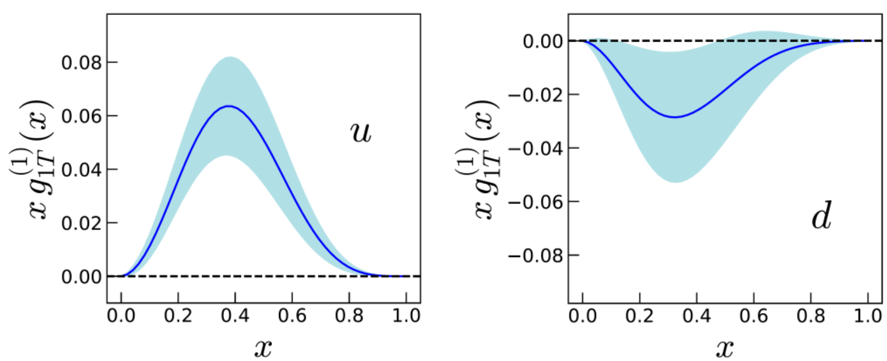
SEA 10^{-2} × smaller (compatible with 0)

COMPASS 2022 deuteron run

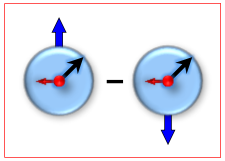
JAM Collaboration, PRD 106 (2022) 3, 034014



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



SIDIS TSAs: Kotzinian-Mulders asymmetry



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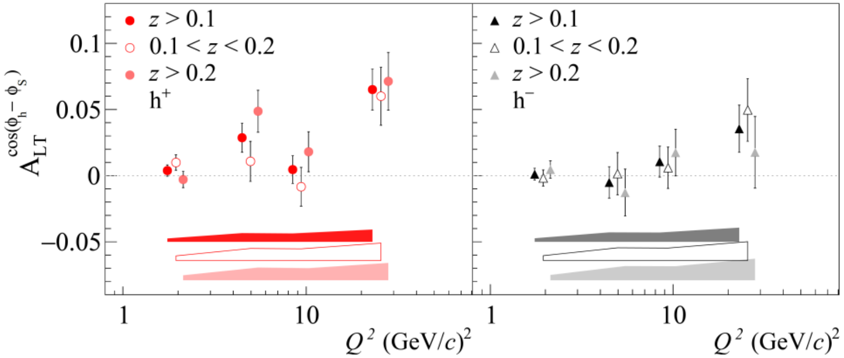
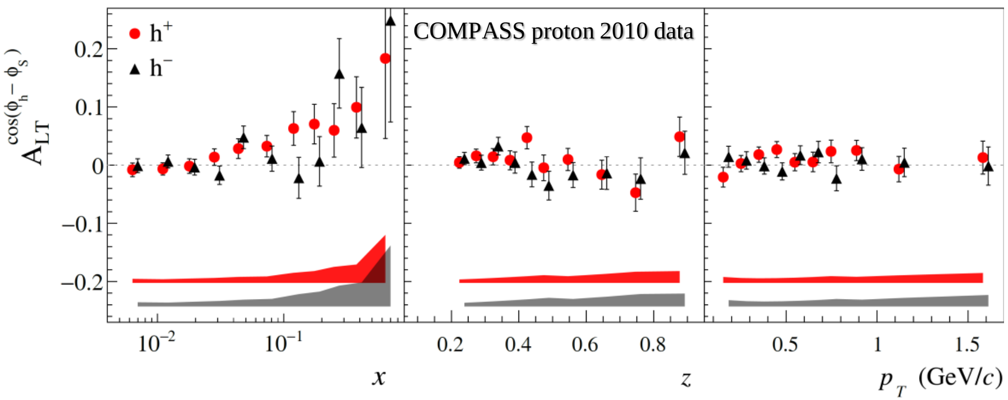
$$\boxed{F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} g_{1T}^{q} D_{1q}^{h}\right]}$$

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

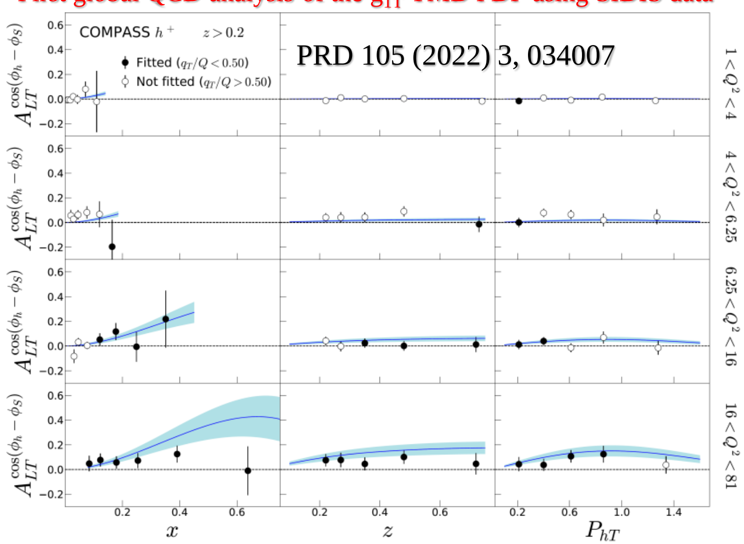
- Only "twist-2" ingredients
- Sizable non-zero effect for h^+ !
- Similar effect at HERMES

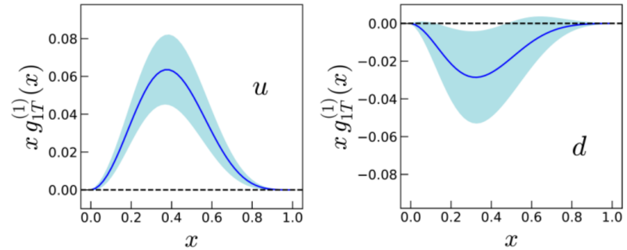


COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



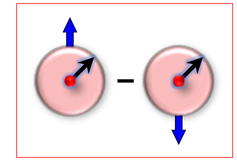
First global QCD analysis of the g_{1T} TMD PDF using SIDIS data





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

SIDIS TSAs: Sivers effect



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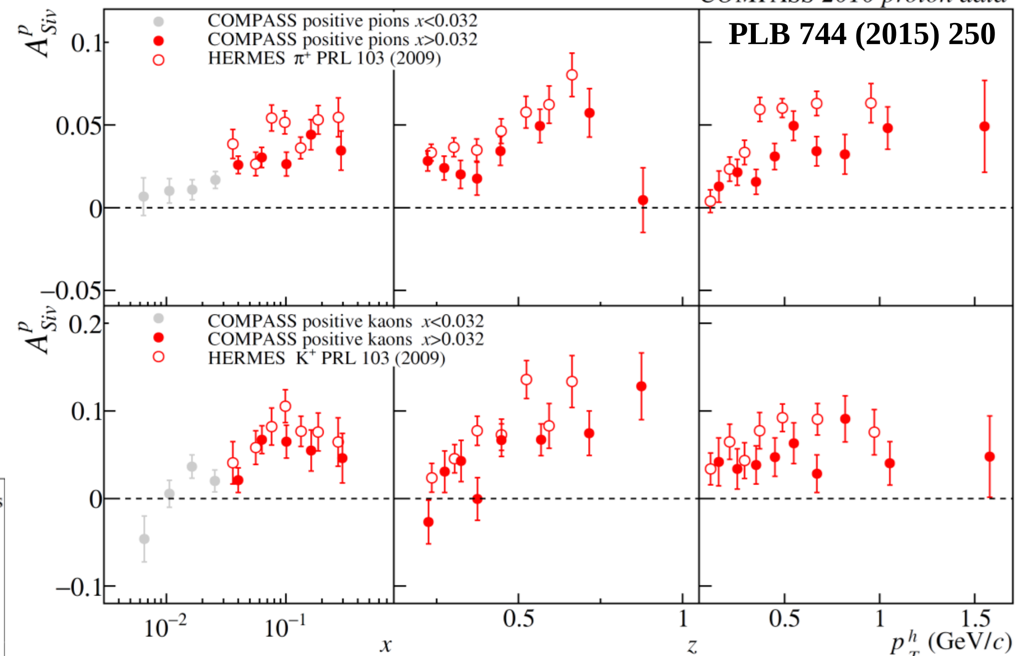
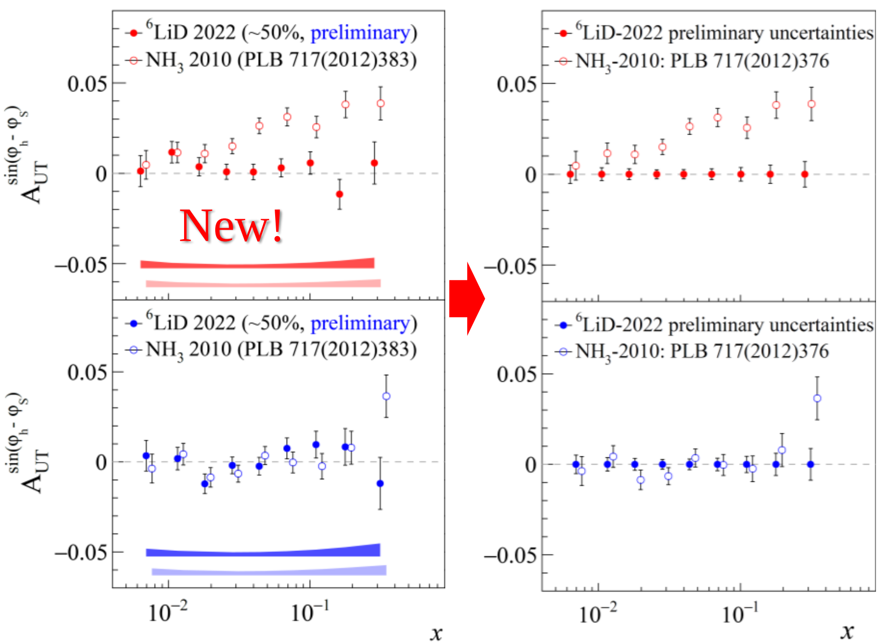
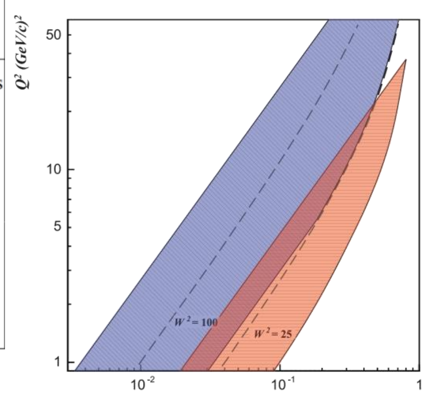
$$\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^{h}\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0}$$

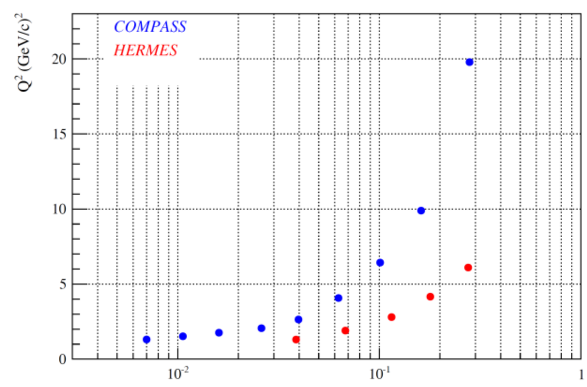
COMPASS 2010 proton data



- COMPASS-HERMES discrepancy
  - Q^2-evolution?
- T-odd TMD PDF: Expected to change sign between SIDIS and Drell-Yan
- New precise deuteron data



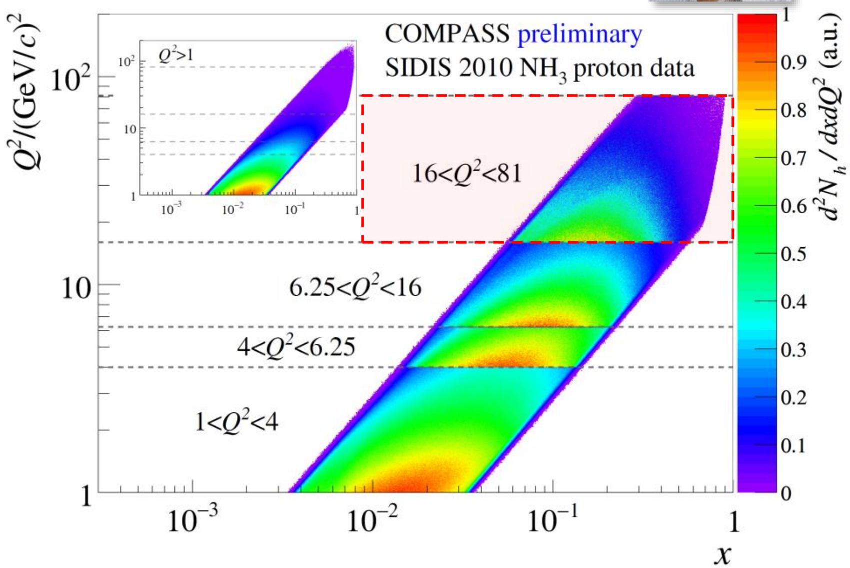


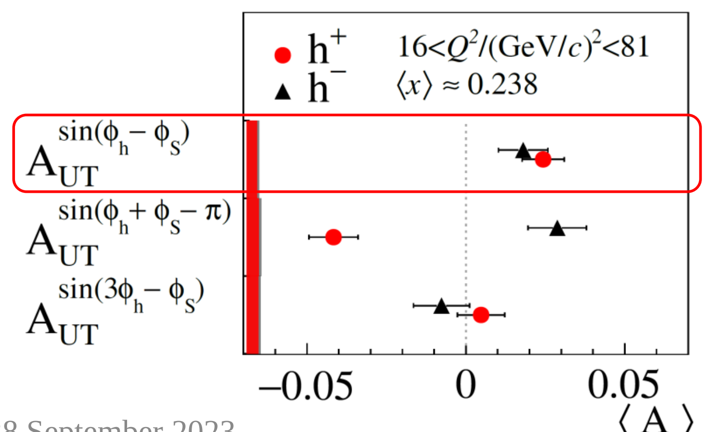


SIDIS Sivers TSA in COMPASS Drell-Yan Q^2-ranges

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

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





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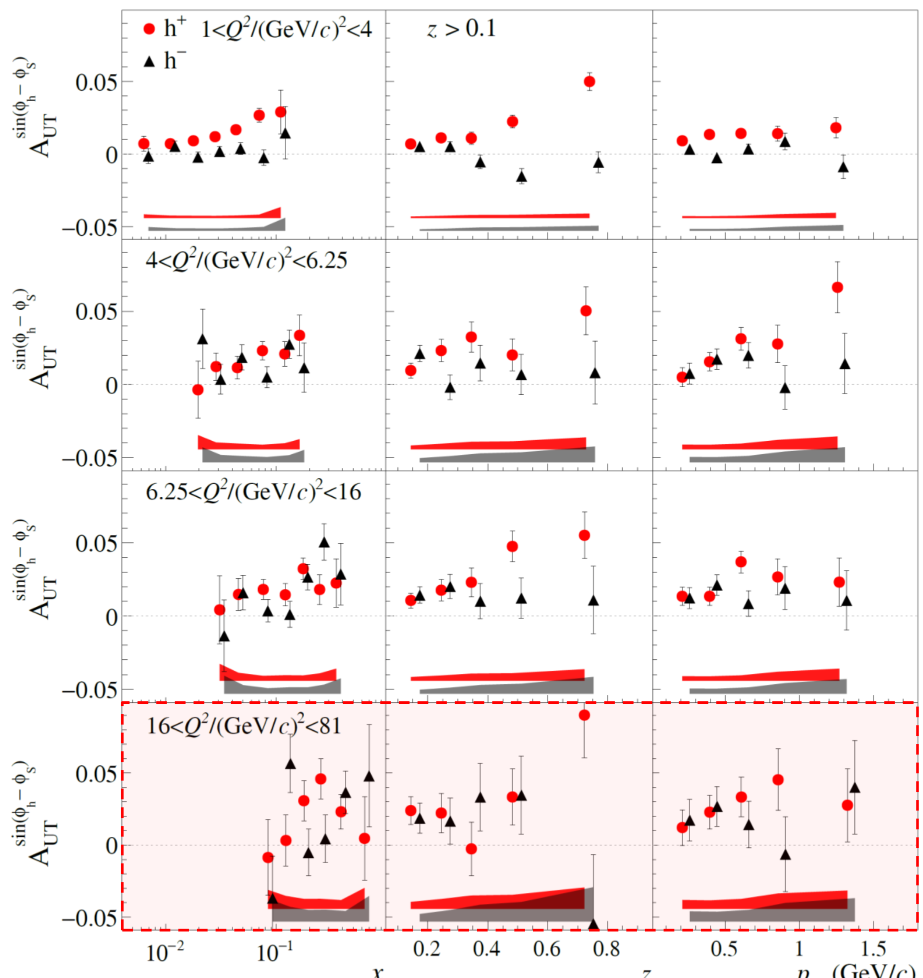


1st COMPASS multi-D fit done for all eight TSAs

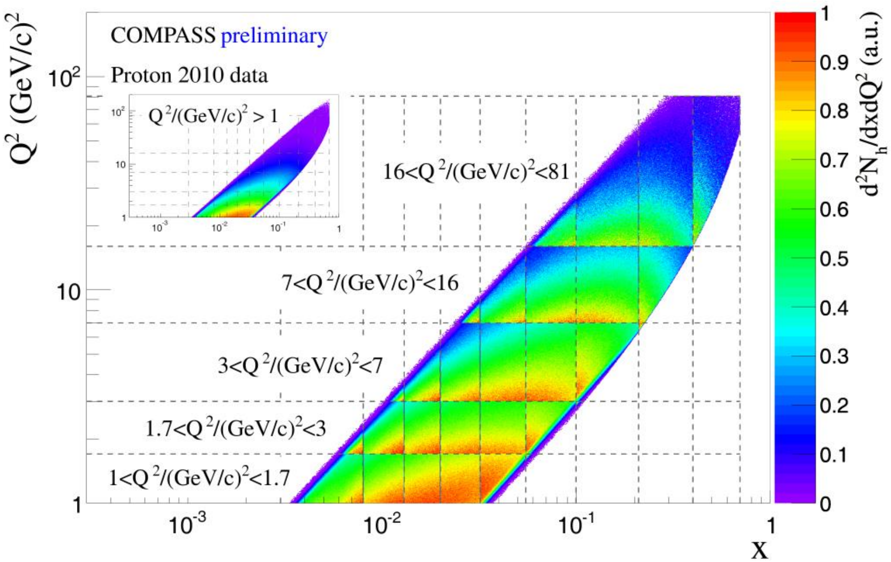
COMPASS Multi-D TSA analyses

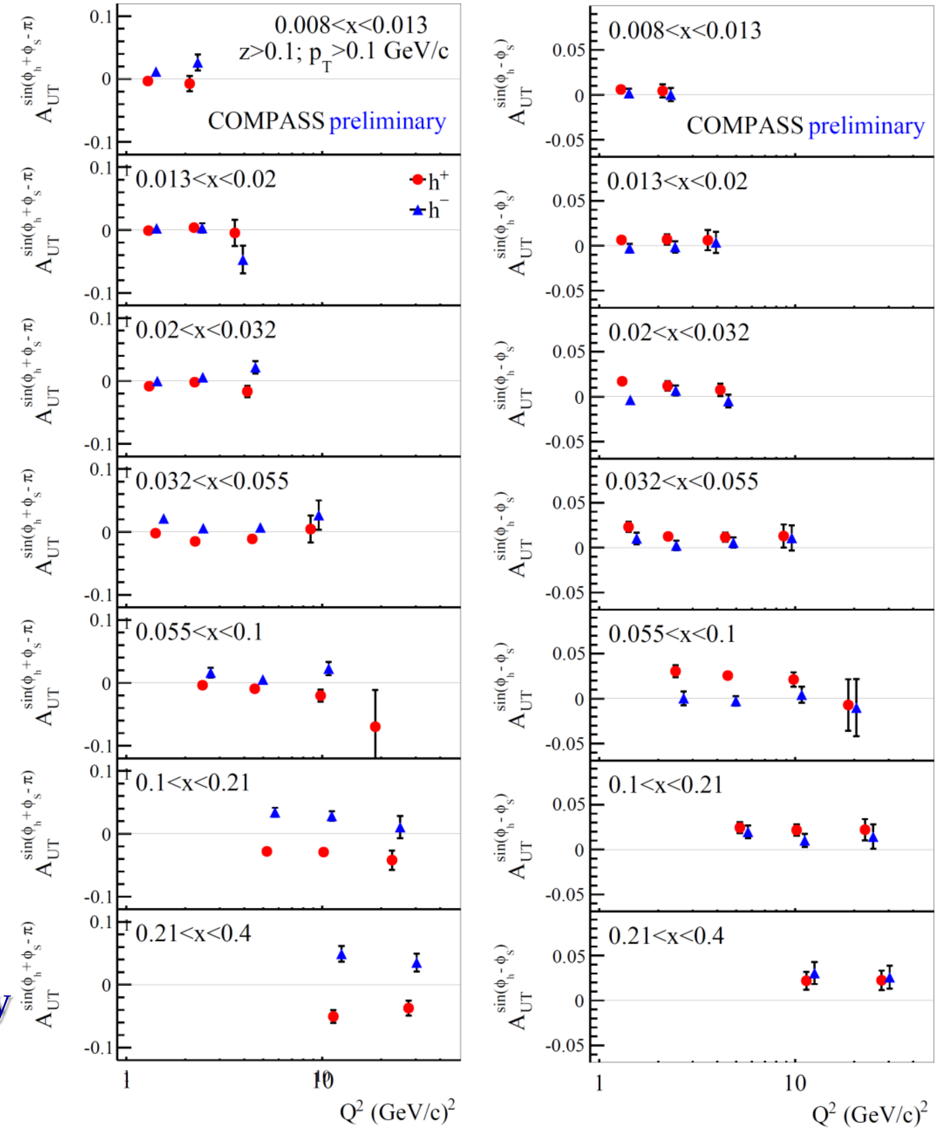
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) \ldots\right\}$$

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

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

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

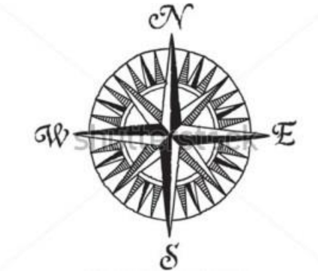


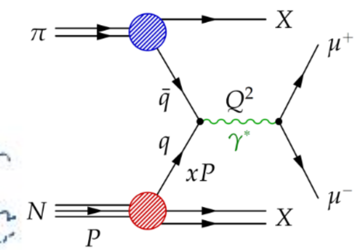


3D $x{:}Q^2{:}z$ or $x{:}Q^2{:}p_T$ $x{:}z{:}p_T$

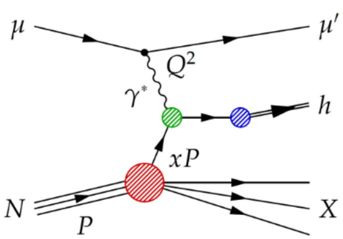
- No clear Q^2-dependence within statistical accuracy
- Possible decreasing trend for Sivers TSA?

COMPASS bridge





Drell-Yan



SIDIS

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

SIDIS

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

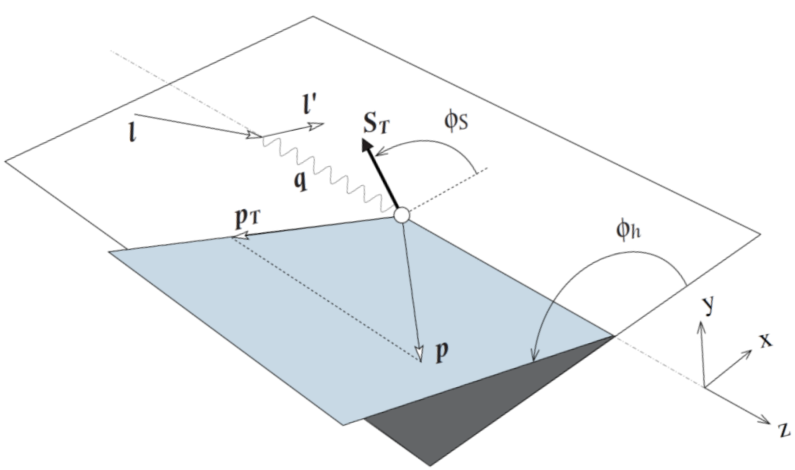
$$\times \left\{ \begin{aligned} &1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ &+ S_L\, \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L \lambda\sqrt{1-\varepsilon^2}\, A_{LL} \\ &+ S_T \left[\begin{aligned} &A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ &+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)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

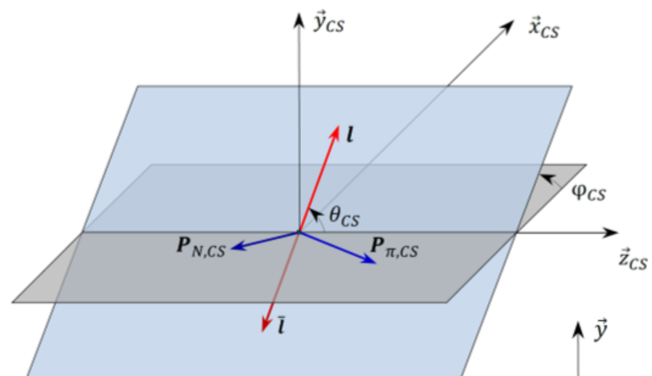
DY

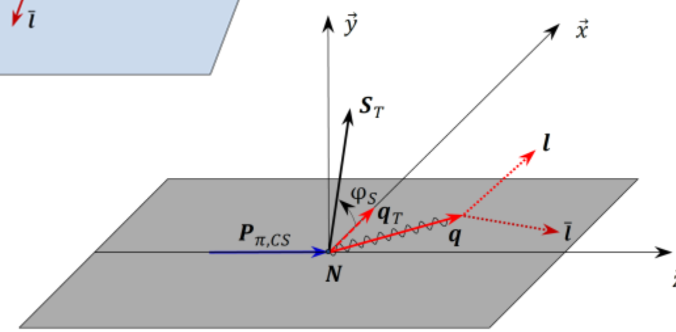
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right)$$

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

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



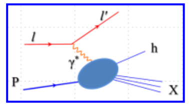




See A. Vijayakumar's poster

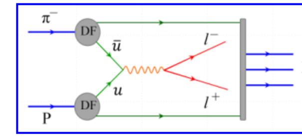
SIDIS and single-polarized DY x-sections at twist-2 (LO)

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



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

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



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

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

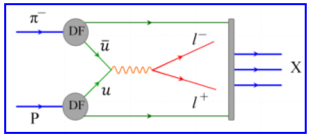
SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \ldots$	Boer-Mulders	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$	Sivers	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$	Transversity	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretzelosity	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$

- Sign-change of T-odd Sivers and Boer-Mulders TMD PDFs;
- Multiple access to Collins FF $H_{1q}^{\perp h}$ and pion Boer-Mulders PDF $h_{1,\pi}^{\perp q}$

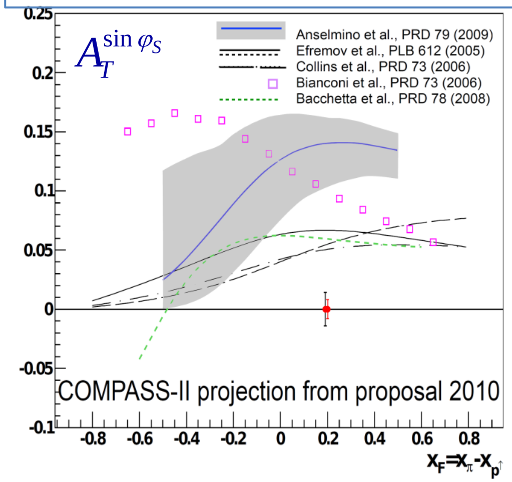
SIDIS and single-polarized DY x-sections at twist-2 (LO)

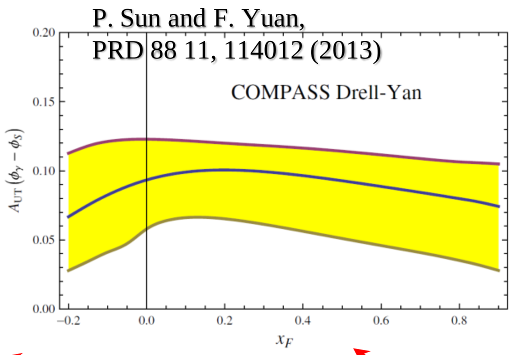
- $2.5 < M/(\mathrm{GeV}/c^2) < 4.3$ “Charmonia mass”
  - Strong J/ψ-signal → study of J/ψ physics
  - Good signal/background
- $4.3 < M/(\mathrm{GeV}/c^2) < 8.5$ “High mass”
  - Low DY cross-section
  - Beyond charmonium region, background < 3%
  - Valence region → largest asymmetries

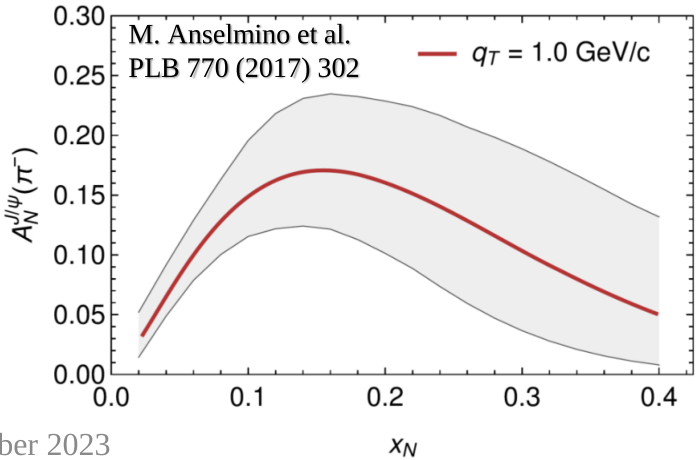
$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1\left(1+\cos^2\theta_{CS}\right) \times \left\{ 1 + \boxed{D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}} + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} + \boxed{S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta_{CS}]}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

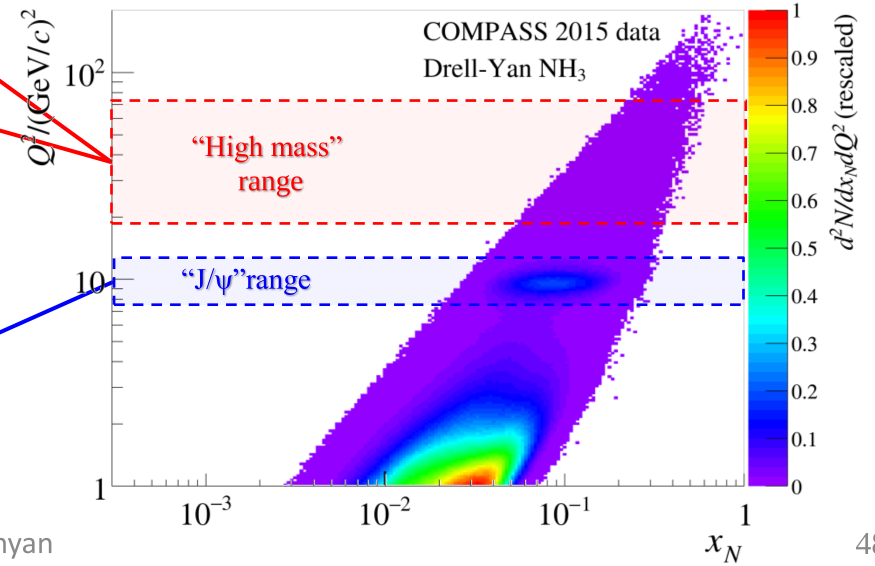


$$D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$$

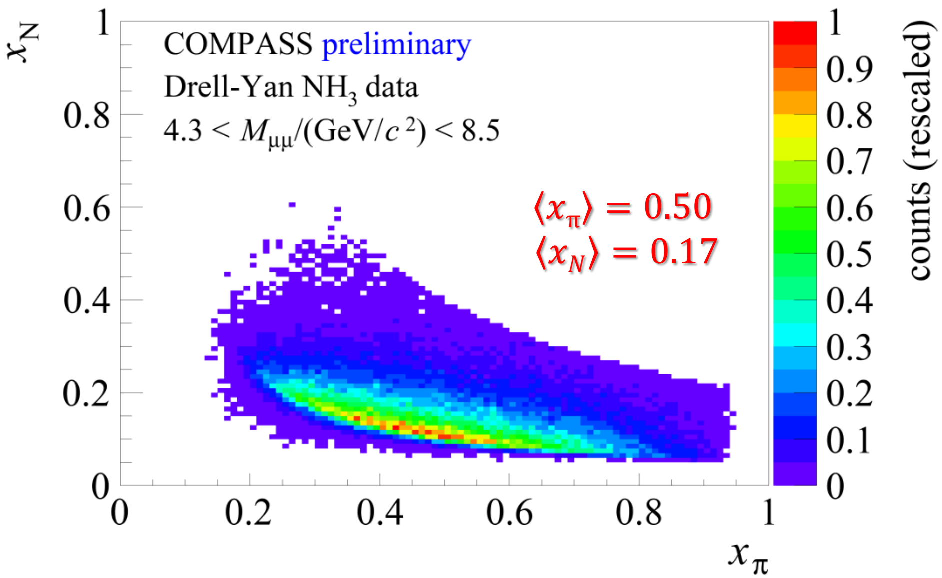




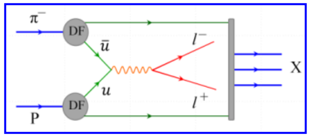




Single-polarized DY measurements at COMPASS

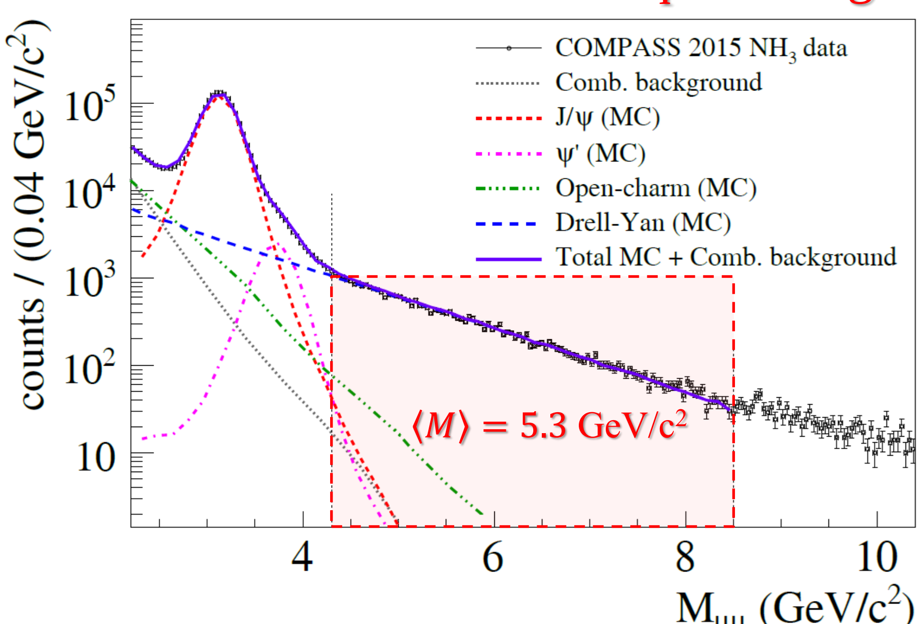


$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + \boxed{D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ \boxed{+ S_T \left[\begin{array}{l}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



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

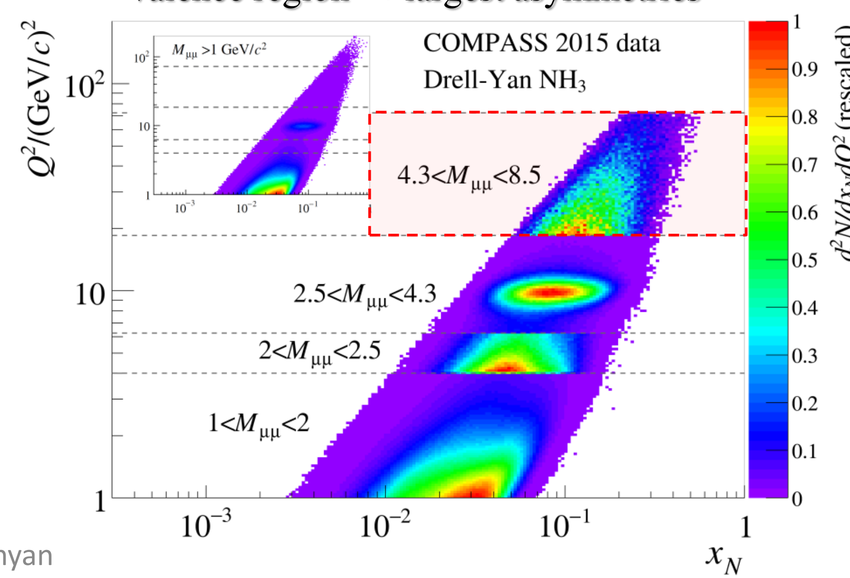
HM events are in the valence quark range



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

Beyond charmonium region, background < 3%

Valence region → largest asymmetries

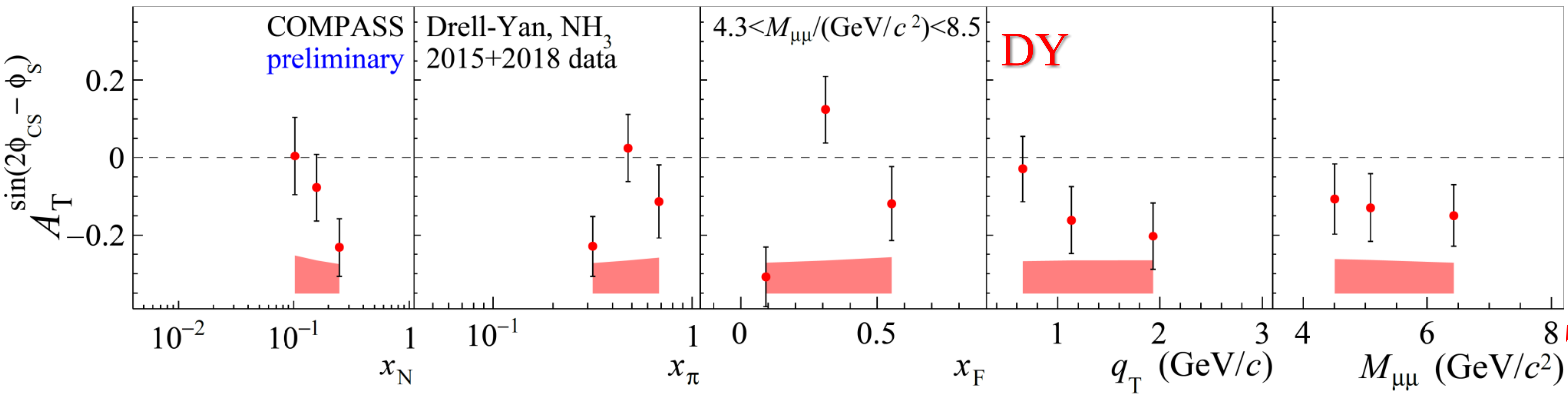


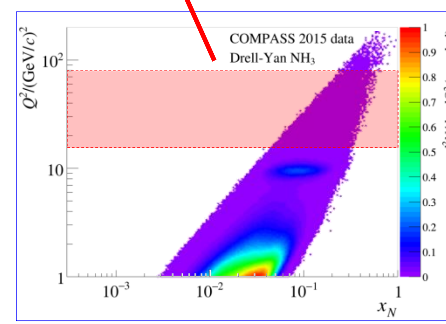
Drell-Yan TSAs – Transversity

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

Transversity DY TSA

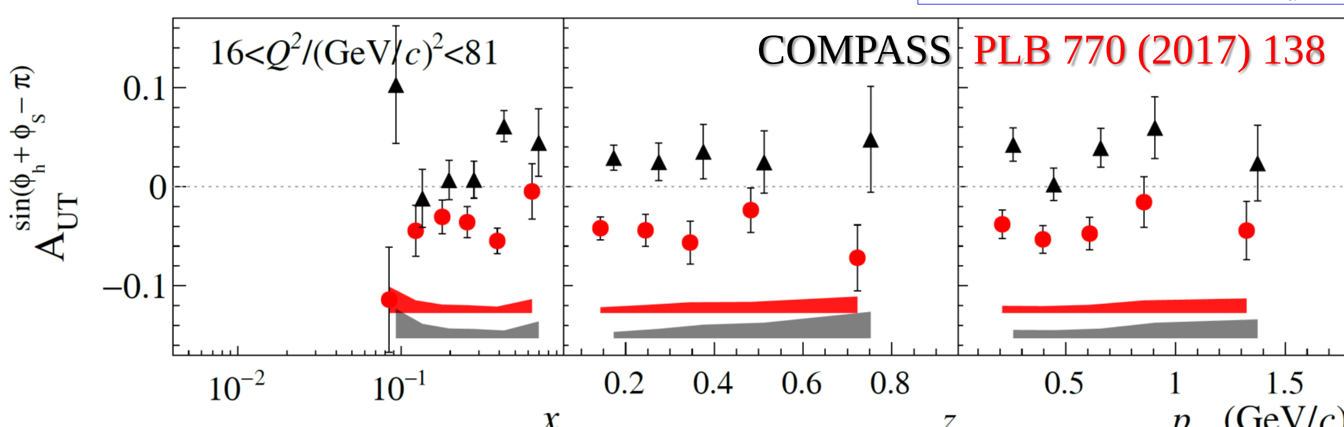
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$





Collins SIDIS TSA

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

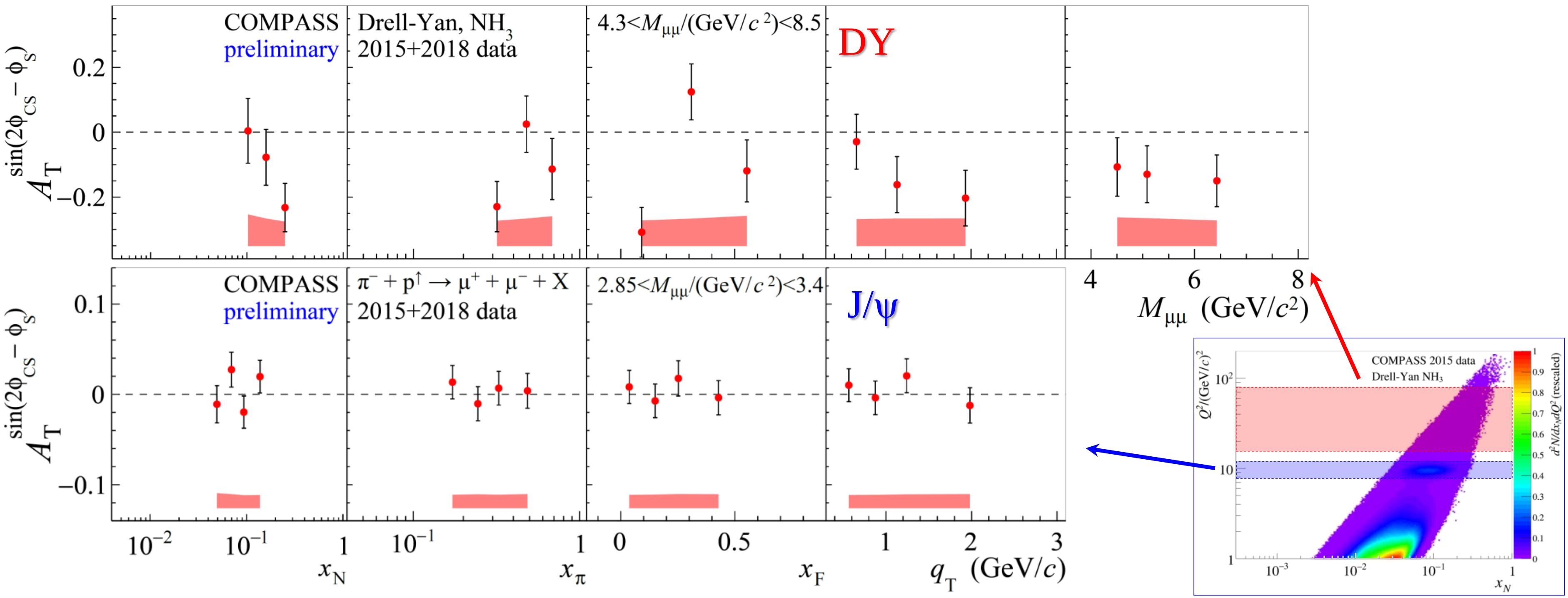


Drell-Yan TSAs – Transversity

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

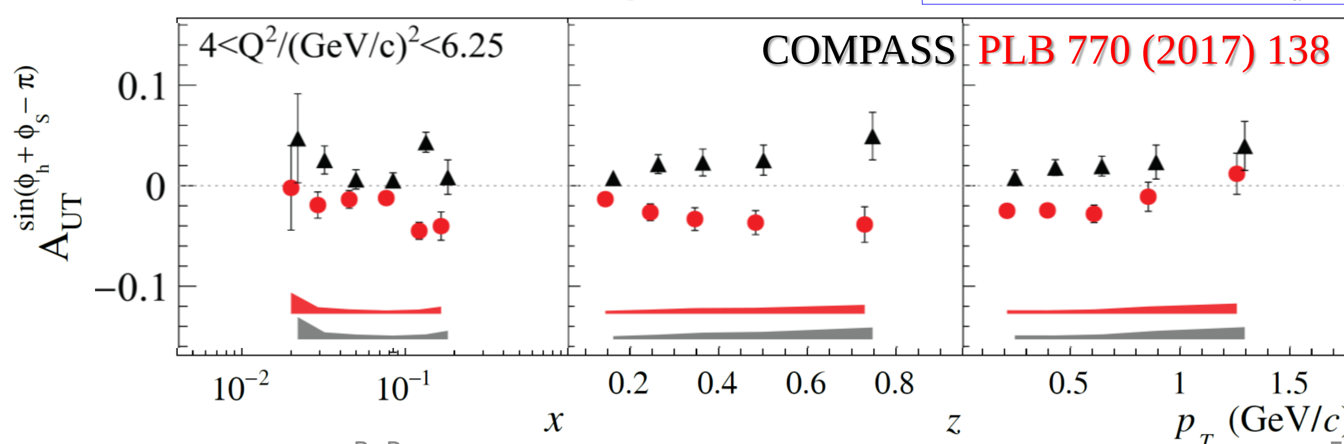
Transversity DY TSA

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



Collins SIDIS TSA

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

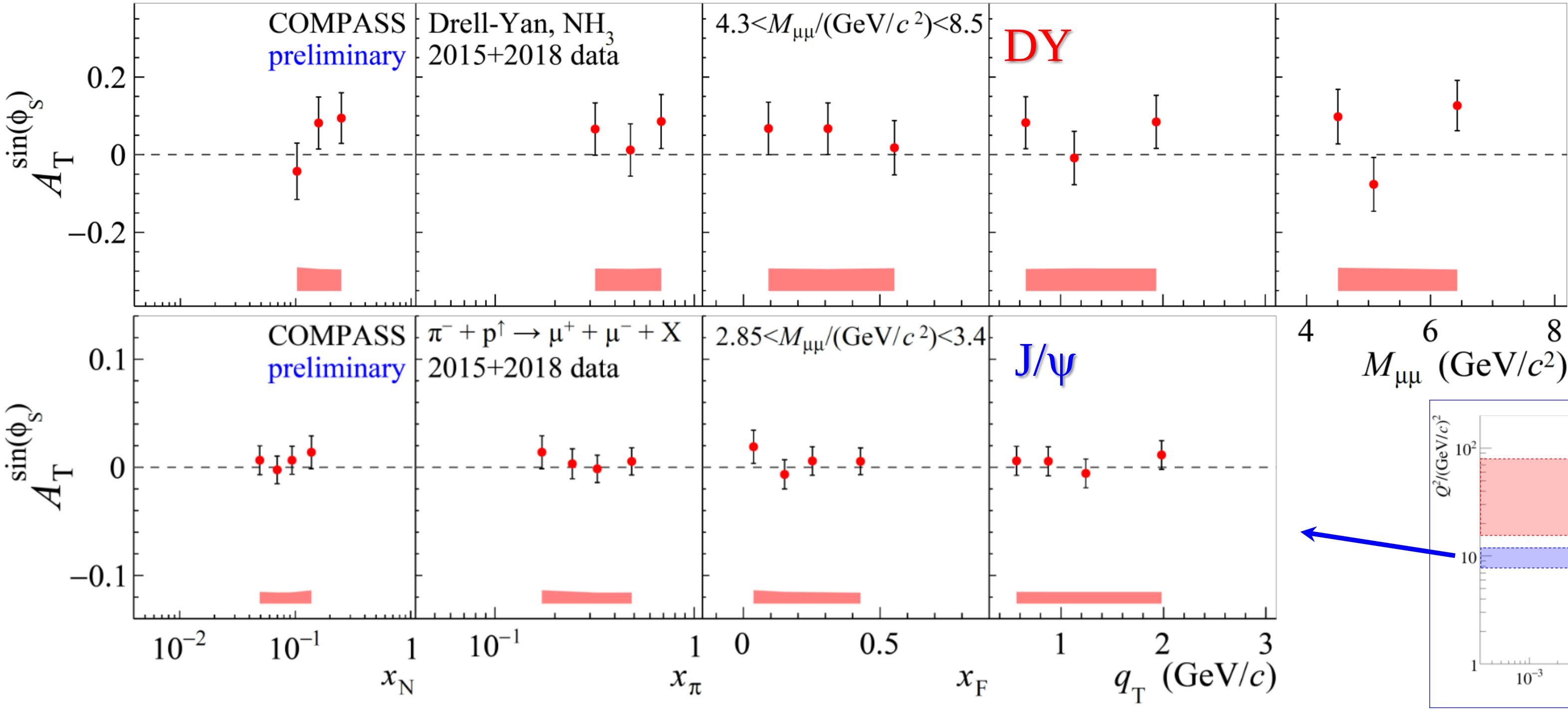


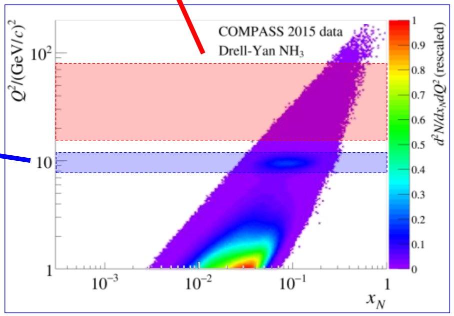
Drell-Yan TSAs – Sivers

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

Sivers DY TSA

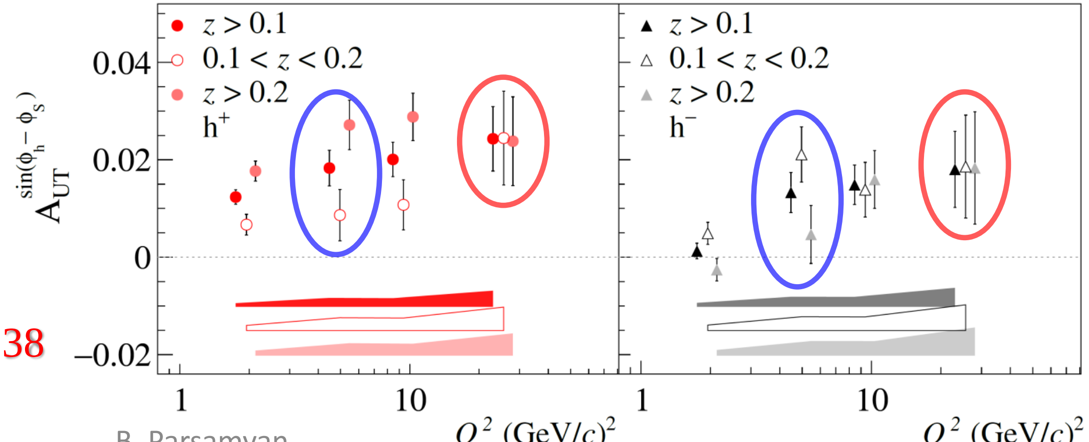
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$





Sivers SIDIS TSA

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



COMPASS
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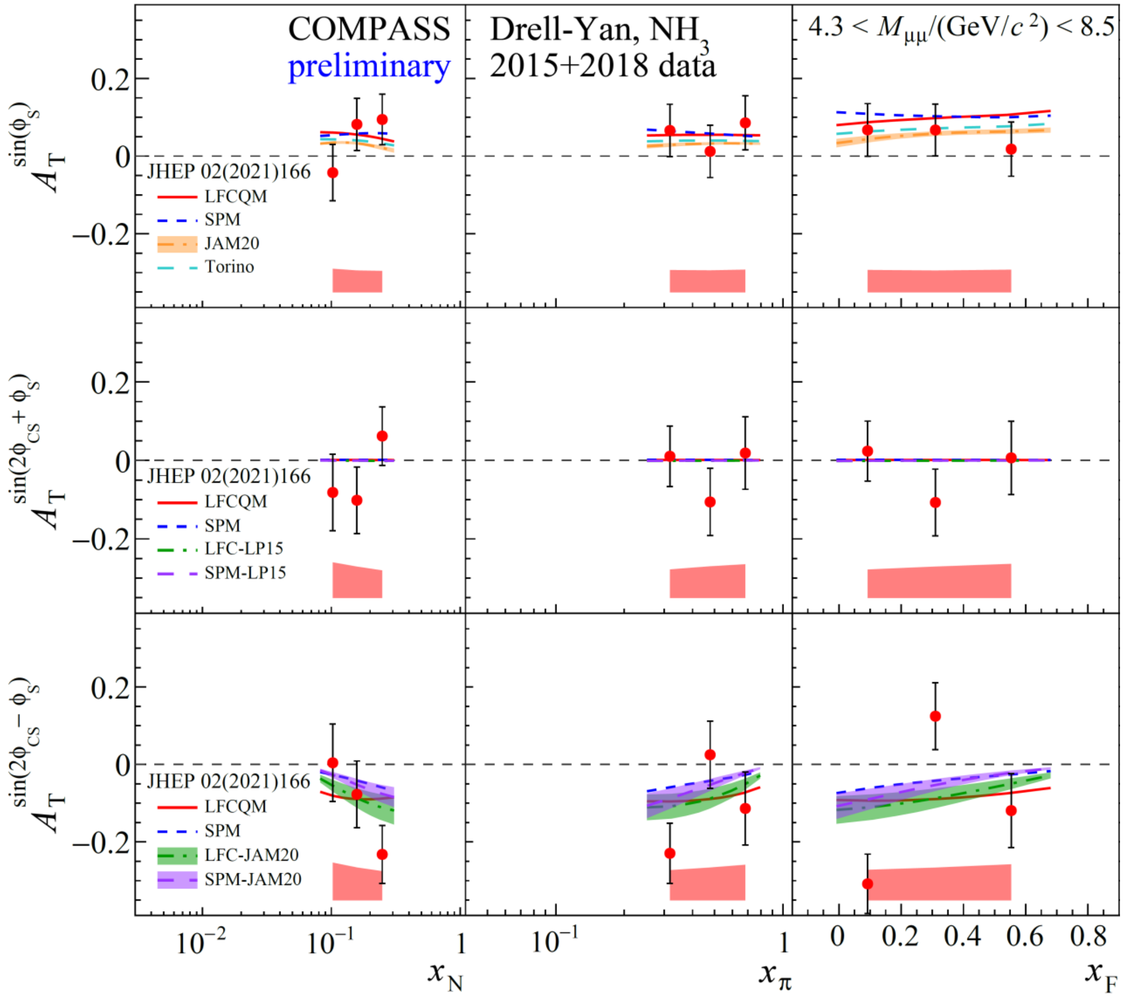
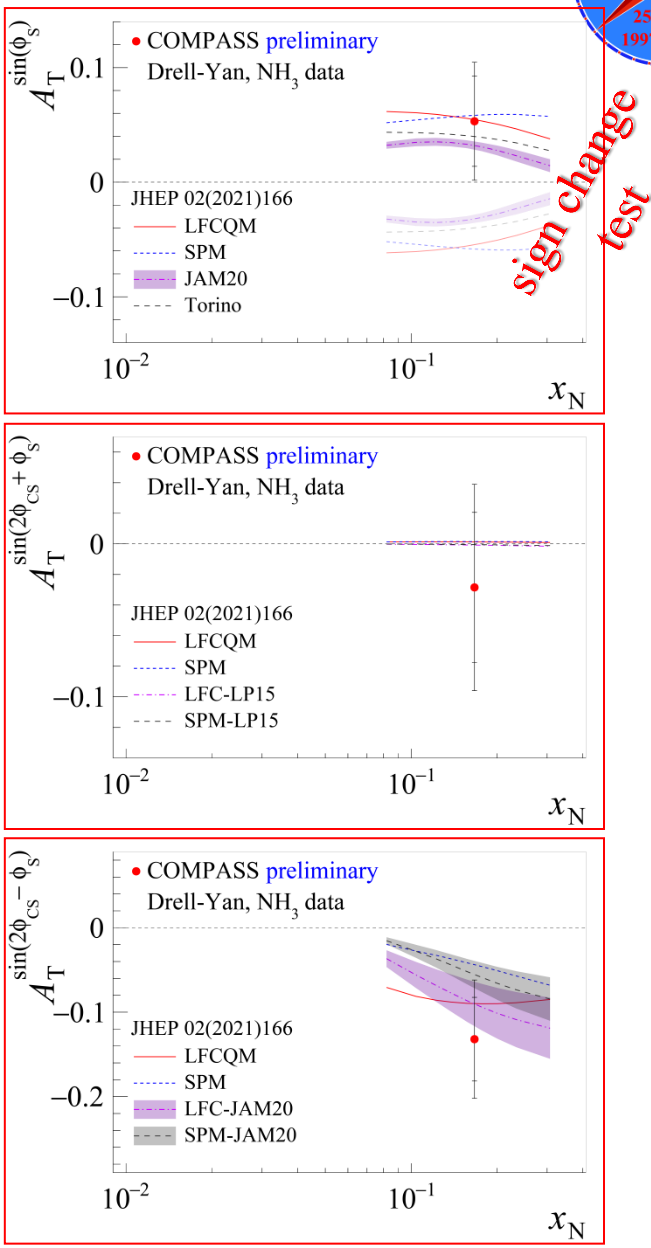
DY TSAs at COMPASS (high-mass range)

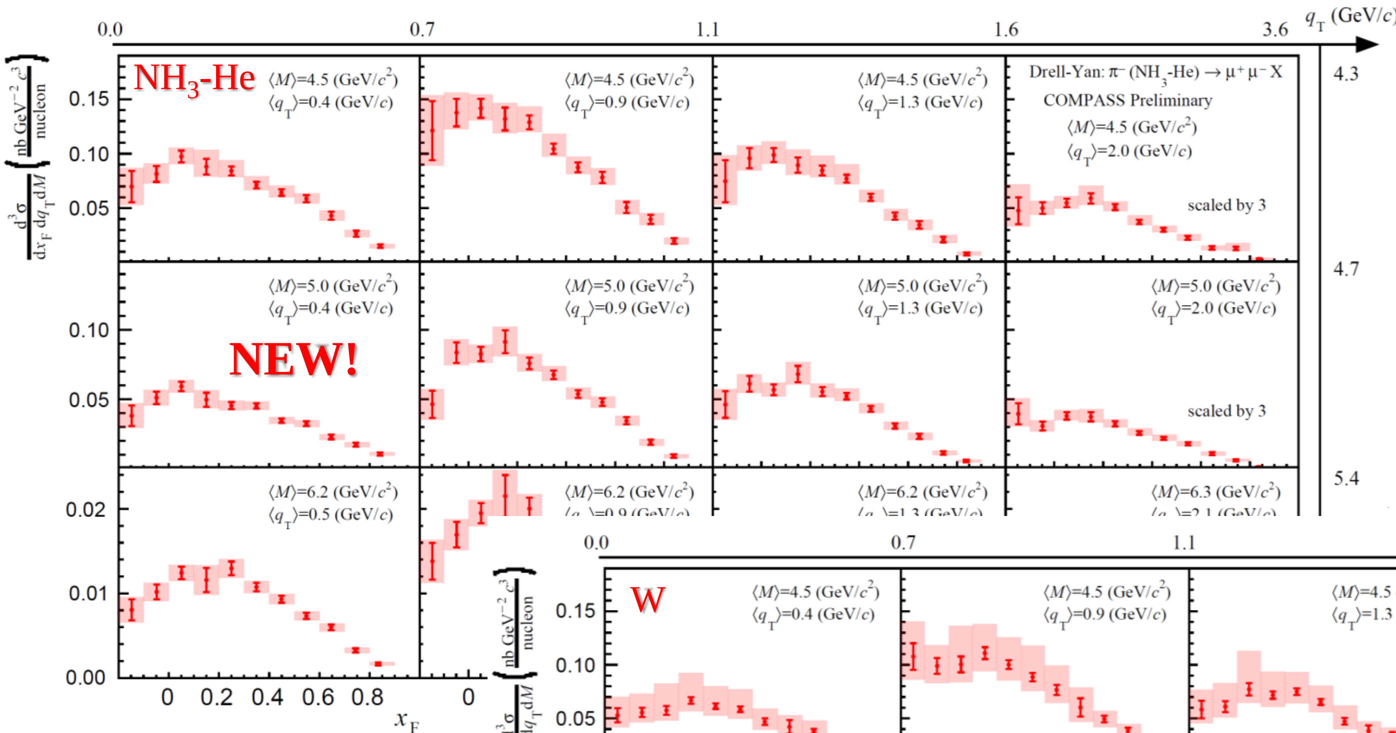
Theory curves based on S. Bastami et al. JHEP 02, (2021),166

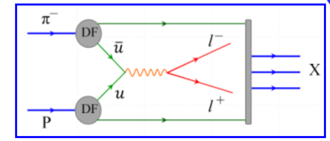


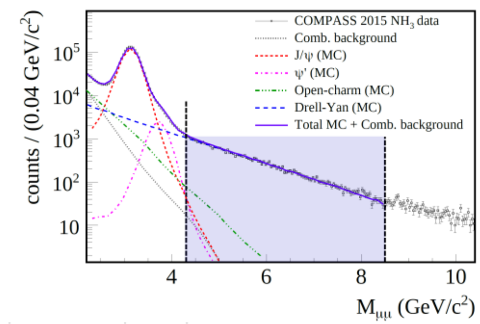


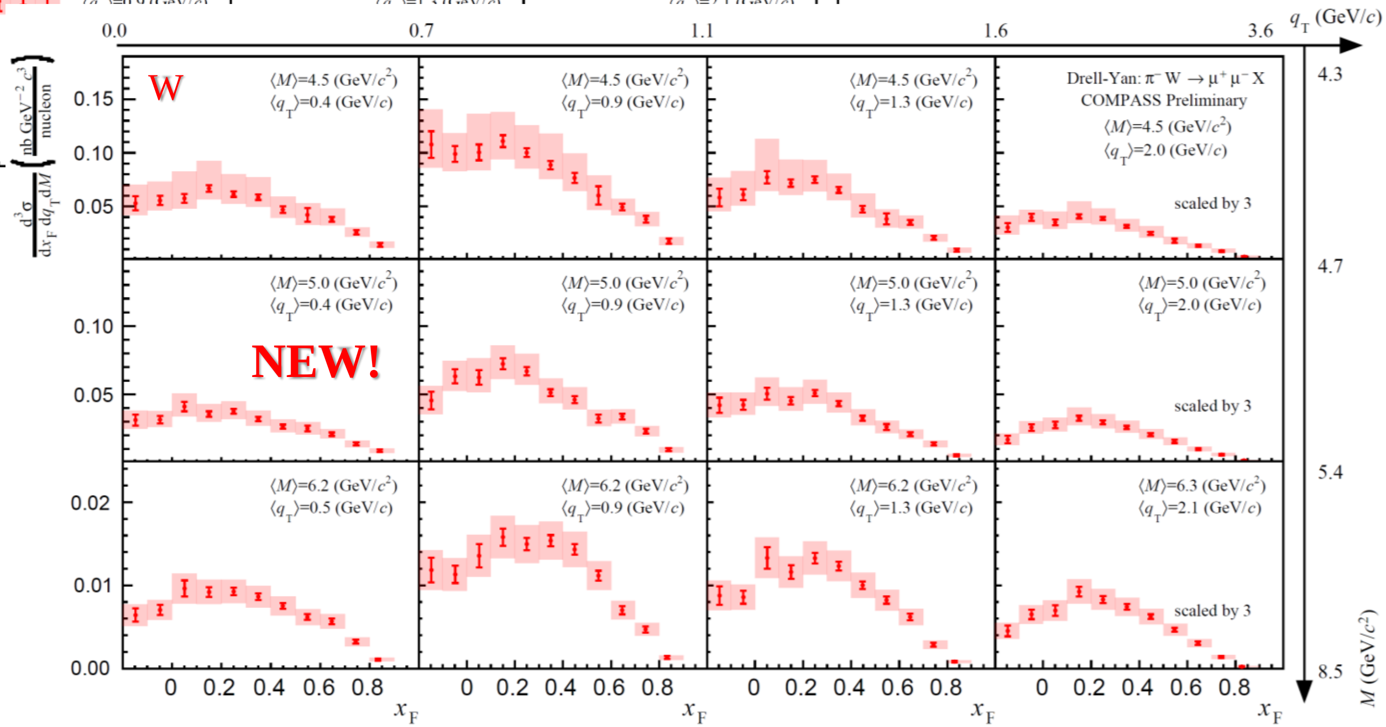
- General agreement with available theory predictions

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









- Data from light and heavy targets
- 3D representation
- Larger systematics for tungsten

See V. Andrieux's slides

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

Conclusions

- COMPASS holds the record for the longest-running CERN experiment (20 years of data-taking)
- Series of successful and important measurements addressing nucleon spin-structure
  - Inclusive measurements, unpolarized and polarized SIDIS (longitudinal/transverse)
  - First-ever polarized Drell-Yan measurements
- A wealth of (SI)DIS, Drell-Yan, DVCS, HEMP data collected across the years
  - Petabytes of data available for analysis
- Wide and unique kinematic domain accessing low x and large Q^2
  - Will remain unique for at least another decade
- World-unique SIDIS deuteron data collected in 2022
  - Highly successful run, promising preliminary results
- Since 2023 the experiment entered the Analysis Phase
  - The spectrometer has been transferred to the COMPASS successor in the M2 beamline – the AMBER collaboration
  - 3 new groups joined COMPASS in the course of 2023 for the Analysis Phase
  - If you are interested – don't hesitate to get in touch!

Thank You!

CPHI

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