What has COMPASS taught us on spin of hadrons?

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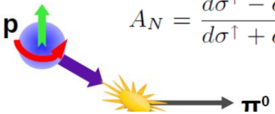
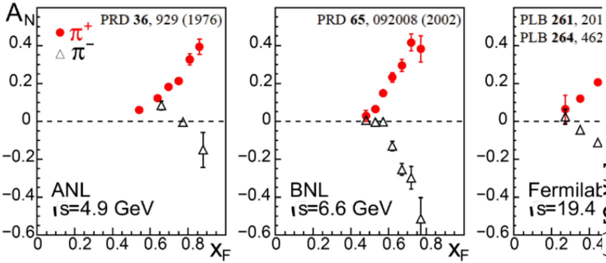
22 - 24 September, 2025

Why?

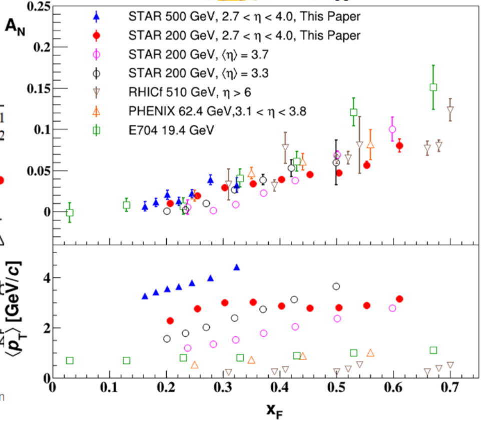
- Single spin asymmetries...
  puzzling in collinear pQCD
  at leading twist



$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



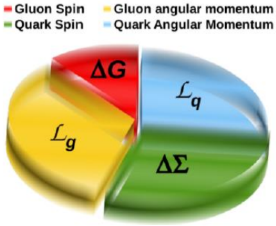
U. D'Alesio & B. Badelek Diffraction

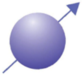


Why?

- Origin of the proton spin

How the constituents of the proton contribute to the proton spin?





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

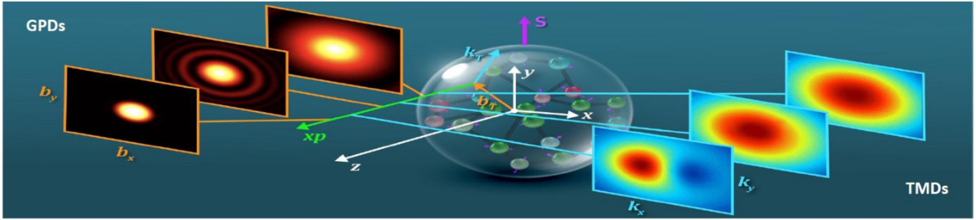
$\frac{1}{2}\Delta\Sigma$	ΔG	$L^q + L^g$
Best known	**How well do we know?**	**???????**
Quark helicity $\sim 30\%$	Gluon helicity $\sim 40\%$	OAM of quarks & gluons

U. D'Alesio & B. Badelek Diffraction and low x 2024

What: TMDs and GPDs

❑ **3D hadron structure:**

NO quarks and gluons can be seen in isolation!



U. D'Alesio & B. Badelek Diffraction and low x 2024

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

A fixed-target facility at the SPS at CERN ($\sim$ 200 physicists, 33 institutes from 15 countries)

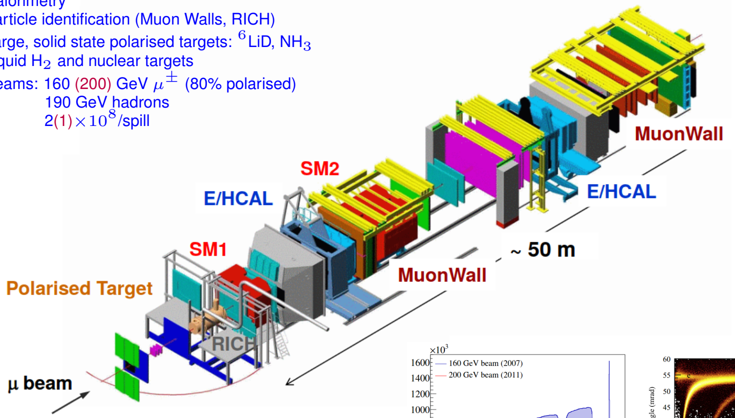
Nucleon structure via muon programme
Spin dependent structure function g_1 Gluon polarisation in the nucleon Quark helicity distributions 1-D and 3-D (TMD) nucleon structure Vector meson production Λ polarisation DVCS/GPD
Hadron spectroscopy via hadron programme
Primakoff effect, π and K polarisabilities Exotic (multiquark) states, glueballs (Double) charmed barions Precision studies of light meson spectrum Drell–Yan process and J/Ψ prduction on a $\perp$ polarised target

- Longest running experiment at CERN, since 2002
- Since 2023 in the analysis stage
- Variety of beams, targets (polarised/unpolarised), inc. energies

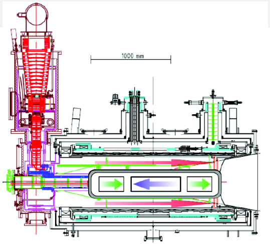
PHASE I (2002 - 2011)	2002 – 2004	nucleon structure μ–d, 160 GeV, L and T polarised target
	2005	CERN accelerator shutdown, increase of acceptance
	2006	nucleon structure μ–d, 160 GeV, L polarised target
	2007	nucleon structure μ–p, 160 GeV, L and T polarised target
	2008 – 2009	hadron spectroscopy; Primakoff reaction
	2010	nucleon structure μ–p, 160 GeV, T polarised target
	2011	nucleon structure μ–p, 200 GeV, L polarised target
PHASE II (2012 - 2023)	2012	Primakoff reaction; DVCS/SIDIS test
	2013	CERN accelerator shutdown, LS1
	2014	Drell-Yan π–p reaction with T polarised target (test)
	2015	Drell-Yan π–p reaction with T polarised target
	2016 – 2017	DVCS/SIDIS μ–p, 160 GeV, unpolarised target
	2018	Drell-Yan π–p reaction with T polarised target
	2019 – 2020	CERN accelerator shutdown, LS2
	2021 – 2023	nucleon structure μ–d, 160 GeV, T polarised target

Versatile COMPASS facility

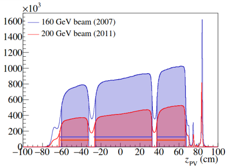
Two stages
Calorimetry
Particle identification (Muon Walls, RICH)
Large, solid state polarised targets: ^{6}LiD, NH_3
Liquid H_2 and nuclear targets
Beams: 160 (200) GeV $\mu^{\pm}$ (80% polarised)
190 GeV hadrons
$2(1) \times 10^8$/spill

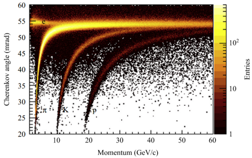


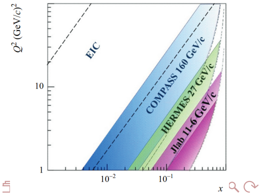
COMPASS NIM A 779 (2015) 69



* Material: solid ^{6}LiD (NH_3)
* Polarisation: ~ 50% (~90%), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15)
* Polar acceptance: ~70 mrad (~180 mrad after 2005)





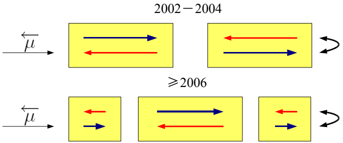


Observables in a $\vec{\mu}\vec{\mathrm{N}}$ (h$\vec{\mathrm{N}}$) fixed-target experiment

- Inclusive asymmetry, $A_{meas}(x, Q^2)$; γ^*-N asymmetry, $A_1(x, Q^2)$:

$$A_{meas} = \frac{1}{f P_T P_B}\left(\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}}\right) \approx D A_1 = D\,\frac{g_1(x, Q^2)}{F_1(x, Q^2)} \overset{\mathrm{LO}}{=} D\,\frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)}$$

f, D: dilution and depolarisation factors; P_T, P_B: target and beam polarisations;
$N^{\leftrightarrows, \leftleftarrows}$: number of $\vec{\mu}$ interactions in each target cell:
(upstream, downstream) or (outer, central)

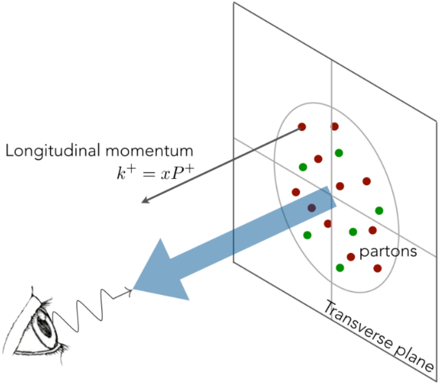


- At LO, semi–inclusive asymmetry, A_1^h:

$$A_1^h(x, z, Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)} \qquad z = \frac{E_h}{\nu} \qquad D_q^h \neq D_{\bar{q}}^h$$

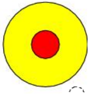
Nucleon in 1-D

$\Longrightarrow$ Longitudinal spin structure

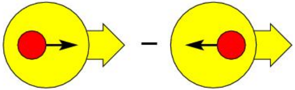


Partonic structure of the nucleon; distribution functions

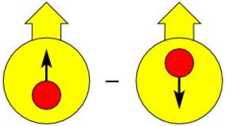
Three twist-two quark distributions in QCD (momentum, helicity & transversity) after integrating over the quark intrinsic k_t

$q(x) =$ 

Quark momentum DF;
well known (unpolarised DIS $\rightarrow \mathbf{F_{1,2}(x, Q^2)}$).

$\Delta q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a longitudinaly polarised nucleon;
less well known (polarised DIS $\rightarrow \mathbf{g_1(x, Q^2)}$).

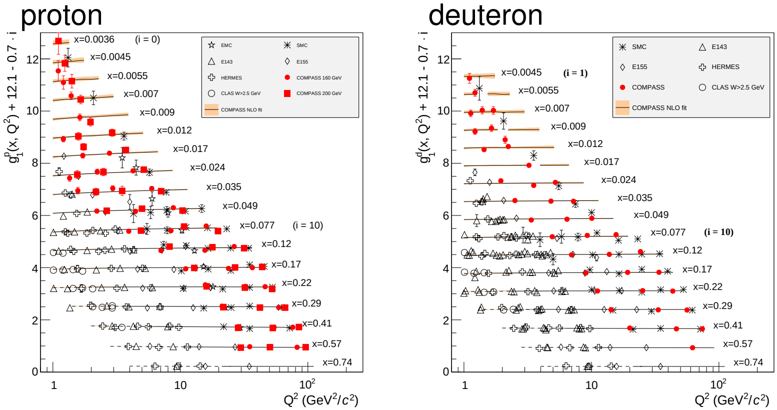
$\Delta_T q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow \mathbf{h_1(x, Q^2)}$).

Nonrelativistically: $\Delta_T q(x, Q^2) \equiv \Delta q(x, Q^2)$. OBS.! $\Delta_T q(x, Q^2)$ are C-odd and chiral-odd ;
may only be measured with another chiral-odd partner, e.g. fragmentation function $\Longrightarrow$ SIDIS.

COMPASS and world data: $g_1^{\rm p}$ and $g_1^{\rm d}$, $Q^2 > 1$ (GeV/c)^2

COMPASS NLO QCD fit to the world data at $W^2 > 10$ (GeV/c^2)^2; dashed line: extrapolation to $W^2 < 10$ (GeV/c^2)^2

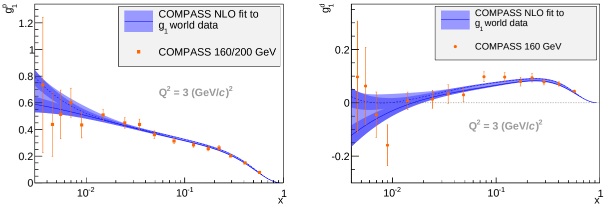


Phys.Lett.B753(2016)18

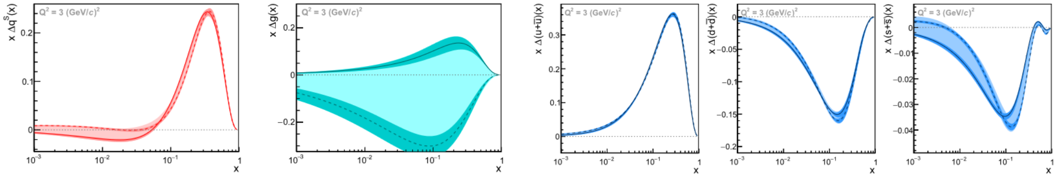
COMPASS PL B769 (2017) 034

COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

COMPASS NLO QCD fit to p, d, ^{3}He world data



- g_1^{p} clearly positive at low x and raising with decreasing x
- g_1^{d} consistent with zero at low x ?

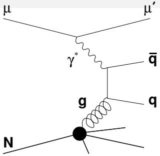


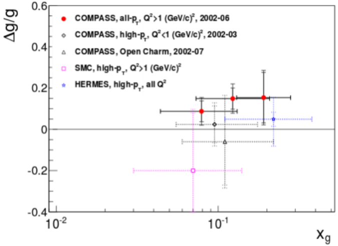
COMPASS PL B **753** (2016) 18

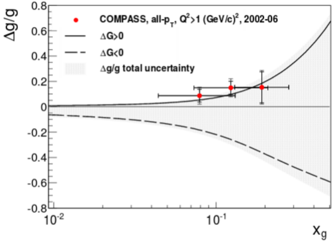
- $-1.5 < \Delta G < 0.5$, poorly constraint $\Longrightarrow$ “direct methods”
- $\sigma_{stat.}$ (dark bands) $\ll$ $\sigma_{syst.}$ (light bands)

Direct measurements of $\Delta g(x)$

Direct measurements – *via* the cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ (LO, NLO) or $q\bar{q}$ (high p_{T} hadron pair (LO)): $A_{\gamma\mathrm{N}}^{\mathrm{PGF}} \approx \langle a_{\mathrm{LL}}^{\mathrm{PGF}} \rangle \dfrac{\Delta g}{g}$







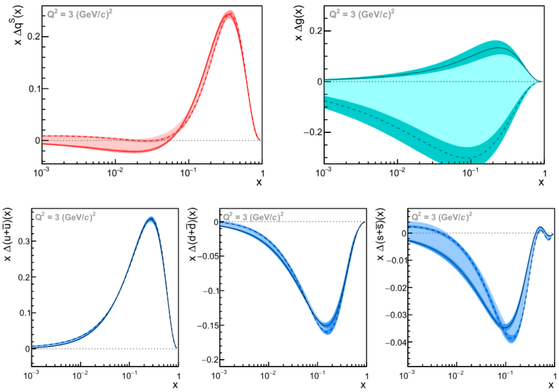
COMPASS from SIDIS on d for any $(p_{\mathrm{T}})_{\mathrm{h}}$ and at LO:

$$\Delta g/g = 0.113 \pm 0.038(\mathrm{stat.}) \pm 0.036(\mathrm{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ (\mathrm{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

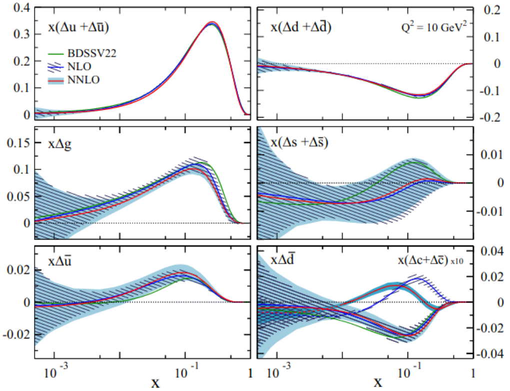
Clearly positive gluon polarisation but not large!

COMPASS, EPJC 77(2017) 209

Global NNLO QCD fit to DIS, SIDIS and pp polarised RHIC data



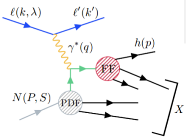
COMPASS PL B **753** (2016) 18



NNLO, Borsa *et al.*, Phys.Rev.Lett. **133** (2024) 151901

Important impovement of Δg!

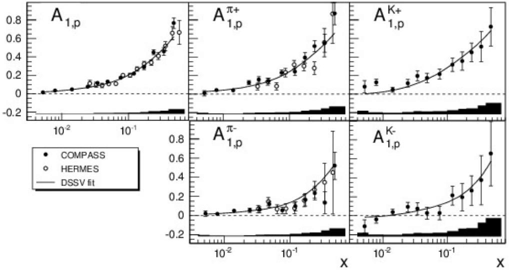
Semi-inclusive asymmetries and parton distributions

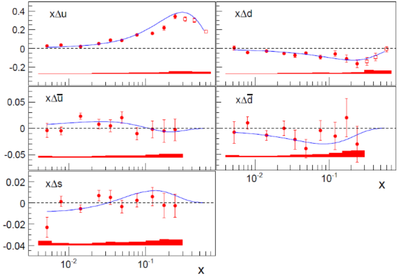


- COMPASS: measured on both proton and deuteron targets for identified π^+, π^- and (for the first time) K^+, K^-

  COMPASS, Phys. Lett. B **693** (2010) 227

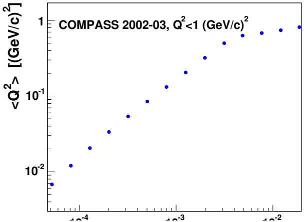
  DSSV, Phys. Rev. D **80** (2009) 034030

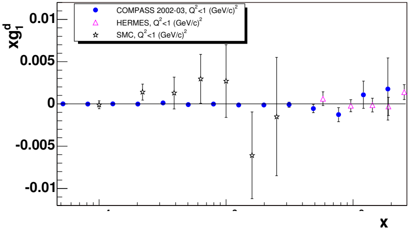




- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV (without these results) describes the data well.

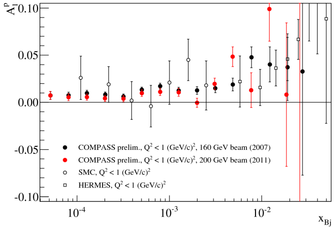
g_1^{N} in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)

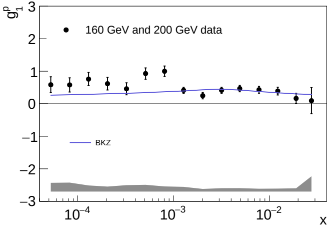




Spin effects in g_1^{d} at low x and Q^2 absent ?

COMPASS PL B **647** (2007) 330





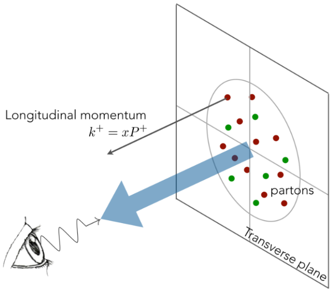
Very clear spin effects in g_1^{p} at low x and Q^2

COMPASS PL B 781 (2018) 464

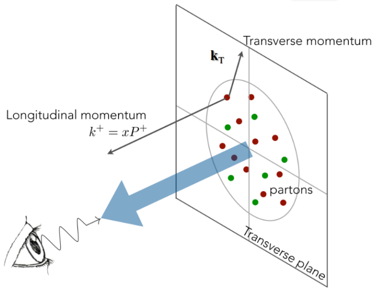
At low x and Q^2: nonperturbative effects and suitable extension of parton mechanisms must be considered

Nucleon in 3-D

$\Longrightarrow$ Transverse Momentum Distributions (TMD)

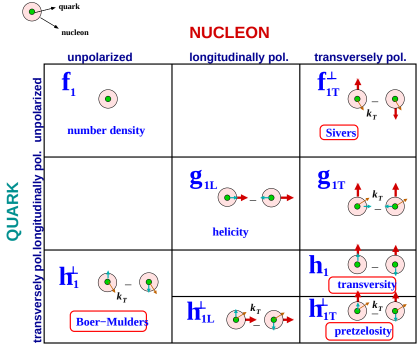


$\Longrightarrow$



Partonic structure of the nucleon; distribution functions

- In LT and considering $k_{\rm T}$, 8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- QCD-TMD approach valid $k_{\rm T} \ll \sqrt{Q^2}$
- After integrating over $k_{\rm T}$ only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY by measuring azimuthal asymmetries with different angular modulations
- SIDIS: e.g. $A_{\rm Sivers} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\rm Sivers} \propto$ PDF$^{\rm beam} \otimes$ PDF$^{\rm target}$
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent



$$h_1^\perp({\rm SIDIS}) = -h_1^\perp({\rm DY}) \qquad f_{1\rm T}^\perp({\rm SIDIS}) = -f_{1\rm T}^\perp({\rm DY})$$

(follows from QCD gauge invariance)

- OBS! transversity PDF is chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation funct.
- TMD parton distributions need TMD Fragmentation Functions!

THE 18 SIDIS STRUCTURE FUNCTIONS in SIDIS

Unpolarized structure function

$f_1 \otimes D_1$

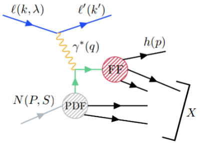
$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&+ S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\quad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Bigg\}
\end{aligned}
$$

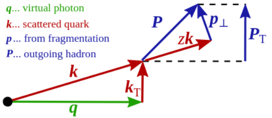
Sivers structure function

$f_{1T}^{\perp} \otimes D_1$

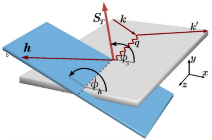
Collins structure function

$h_1 \otimes H_1^{\perp}$





$P_{\rm T}$, $\phi_{\rm h}$ defined in γ^*N system



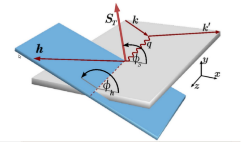
All Fs measured by COMPASS!

Slide courtesy A. Bacchetta, IWHSS2022 (with changes)

Transversity (h_1^q) measurements in SIDIS

Properties of h_1^q:

- is chiral-odd
- simple QCD evolution (no gluons involved)
- sum rule for transverse spin
- first moment gives a tensor charge (important!)



Measured *e.g. via* Collins asymmetry
(spin asymmetry in the azimuthal distribution
of hadrons):

$$N_h^{\pm}(\phi_c) = N_h^0\,[1 \pm f P_T D_{NN} A_{Coll} \sin\phi_c]$$
$$\phi_C = \phi_h + \phi_S - \pi$$

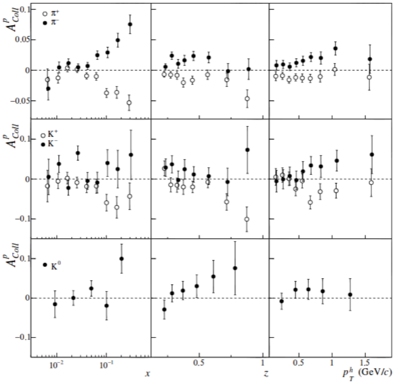
($f, P_T; D_{NN}$: target dilution, polarisation; $\perp$ spin transfer coeff)

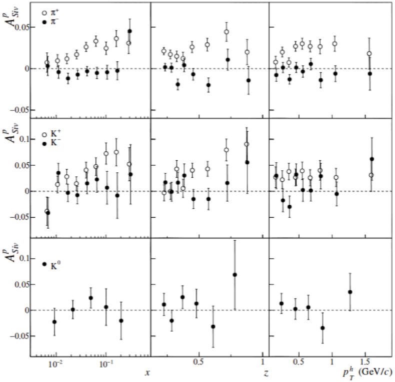
At LO:

$$A_{Coll} = \frac{F_{UT}^{\sin(\phi_C)}}{F_{UU}} = \frac{\sum_q e_q^2 \cdot h_1^q(x) \otimes H_1^{\perp q}(z)}{\sum_q e_q^2 \cdot f_1^q(x) \otimes D_1^q(z)}$$

Transverse fragmentation functions $H_1^{\perp q}$ needed to extract h_1^q; recently measured by BELLE, BaBar, BESIII.

COMPASS results for Collins and Sivers asymmetries for protons





- Collins asymmetries for proton measured for +/– unidentified and identified hadrons...
- ...are large at $x \gtrsim$ 0.03 and consistent with HERMES (in spite of different Q^2!)
- Transversity also obtained from 2-hadron asymmetries (and “Interference Fragmentation Function”)

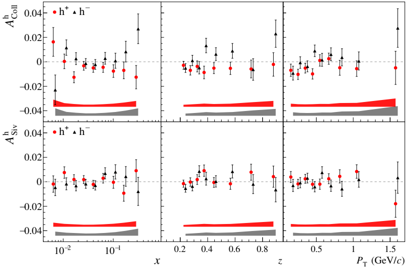
- Sivers asymmetries for proton measured for +/– identified hadrons are large for π^+, K$^+$...
- ...and even larger at smaller Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry

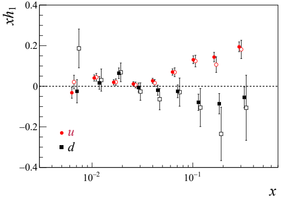
COMPASS, Phys.Lett. B744 (2015) 250

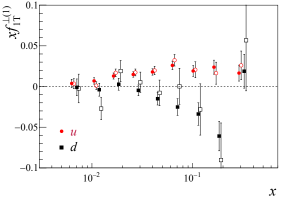
NEW A_{Coll}, A_{Siv} measurements for deuteron $\Longrightarrow xh_1^q,\ xf_{1T}^{\perp(1)}$

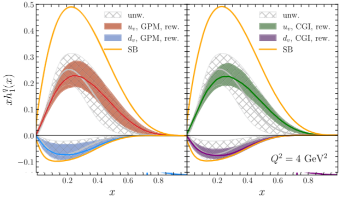
New point-by-point determination of $xh_1^{u_v}, xh_1^{d_v}$ and of the first k_T^2 moments of the Sivers functions, $xf_{1T}^{\perp(1)}$
(NEW COMPASS p,d SIDIS data, Belle e$^+$e$^-$ $\rightarrow$ hadrons data)

Martin et al., Phys.Rev. D91 (2015) 014034
COMPASS, PRL 133 (2024) 101903









Several global fits
e.g. xh_1^q, Boglione et al., PL B 854 (2024) 138712

- A_{Coll} at high x similar to that on the proton
- A_{Siv} compatible with zero

Fundamental nucleon charges: $g_{\mathrm{A}}/g_{\mathrm{V}}$ and improved g_T measurement

- The nonsinglet structure function: $g_1^{\mathrm{NS}} = g_1^{\mathrm{p}}(x,Q^2) - g_1^{\mathrm{n}}(x,Q^2)$ and its moment connected to the Bjorken sum rule: $\int_0^1 g_1^{\mathrm{NS}}(x,Q^2)\mathrm{d}x = \frac{1}{6}\left|\frac{g_{\mathrm{A}}}{g_{\mathrm{V}}}\right| C_1^{\mathrm{NS}}(Q^2)$, NLO QCD fitted and fit-extrapolated $x \to 0, 1$ gave
  $\left|\frac{g_{\mathrm{A}}}{g_{\mathrm{V}}}\right| = 1.29 \pm 0.05_{\mathrm{stat.}} \pm 0.10_{\mathrm{syst.}} \Longrightarrow$ validation of Bjorken sum rule to 9%
  (neutron β decay: $|g_{\mathrm{A}}/g_{\mathrm{V}}| = 1.2701 \pm 0.002$) COMPASS PLB 753 (2016) 18

- New 2022 deuteron data: equalised statistics collected on d (^{6}LiD) and p (NH_3) targets $\Longrightarrow$ optimal separation of d and u quark TMDs $\Longrightarrow$ better determination of the (truncated) nucleon tensor charge, $g_T = \delta u - \delta d$ where
  $\delta q(Q^2) = \int_{x_{min}}^{x_{max}} \mathrm{d}x \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$,

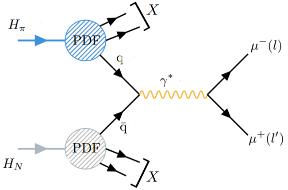
data	$\delta u = \int_{0.008}^{0.210} \mathrm{d}x\, h_1^{u_v}(x)$	$\delta d = \int_{0.008}^{0.210} \mathrm{d}x\, h_1^{d_v}(x)$	$g_{\mathrm{T}} = \delta u - \delta d$
previous [25, 28, 29]	0.187 ± 0.030	-0.178 ± 0.097	0.365 ± 0.078
previous [25, 28, 29] and present	0.214 ± 0.020	-0.070 ± 0.043	0.284 ± 0.045

This is a very important measurement as g_T is least known and fundamental for nucleon 3D $\otimes$ BSM $\otimes$ LQCD!

COMPASS, PRL 133 (2024) 101903

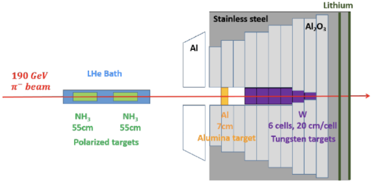
First ever

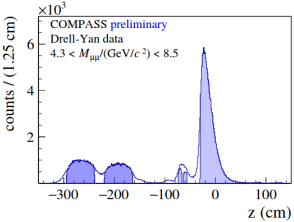
polarised Drell-Yan reaction measurements



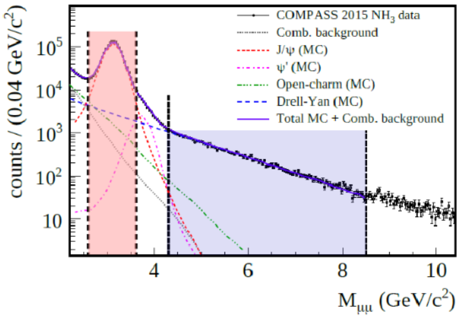
- $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$
  π^- beam of 190 GeV/c, CERN SPS $\langle I \rangle \approx 7 \times 10^7 s^{-1}$, ~97% π^-

- Transversely polarized NH_3 target (2×55 cm)
  + Al target (7 cm) + W beam plug (120 cm)





COMPASS DY programme: goals



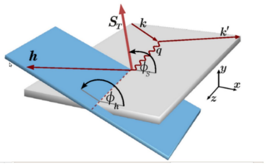
- study of TMD PDFs of transversely polarised nucleon (complementary to SIDIS)
- Drell-Yan process cross section for different targets
- unique access to TMD PDFs of pion
- study of (inclusive) charmonium production mechanisms (transverse spin asymmetries, cross sections, J/Ψ pair production)

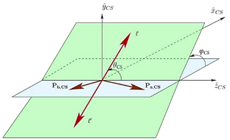
SIDIS and Drell-Yan compatibility; unique access to TMD PDFs of π

$$A_{SIDIS} \propto PDF_p \otimes FF \qquad A_{DY} \propto PDF_\pi \otimes PDF_p$$

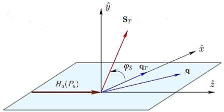
SIDIS		Drell-Yan
$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$	Boer-Mulders	$A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp,q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$	Sivers	$A_T^{\sin\varphi_S} \propto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

(courtesy of R. Longo, COMPASS)



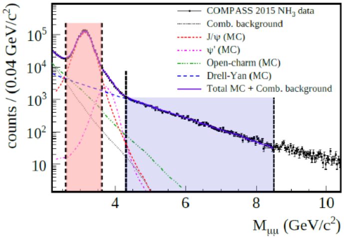


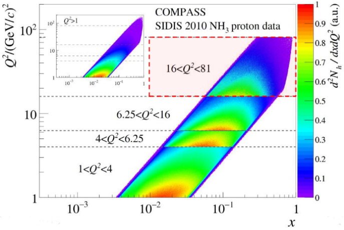
Collins-Soper ref. frame (CS)

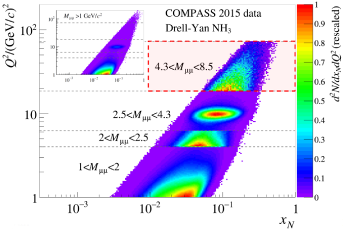


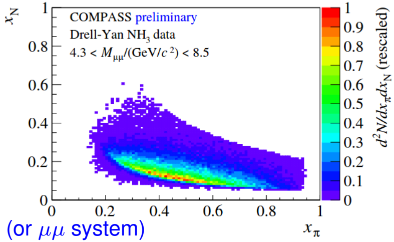
Target rest frame (S)

COMPASS Drell-Yan results







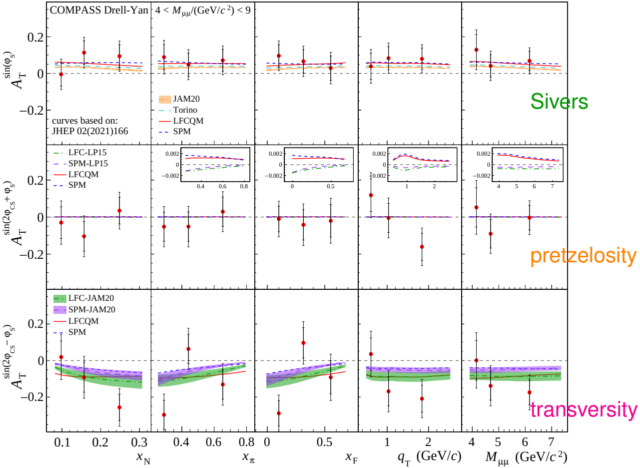


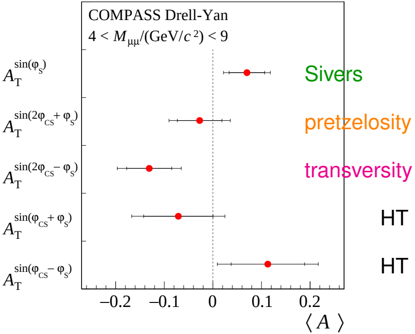
- Events of $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$ are DY events with background: ∼4%
- DY events in the valence regions of π, $\langle x_\pi \rangle$ =0.50, and N $\langle x_N \rangle$ =0.17
- Here Q is the $\mu\mu$ invariant mass, $M_{\mu\mu}$ and q_T is the transverse momentum of γ^* (or $\mu\mu$ system)

TMD factorisation holds:
$q_T \ll M_{\mu\mu}, \quad k_\perp \approx q_T$

Final COMPASS results on TSAs extended mass range: $4 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 9$

Full 2015+2018 data set ($\sim$100k $\mu^+\mu^-$ events)

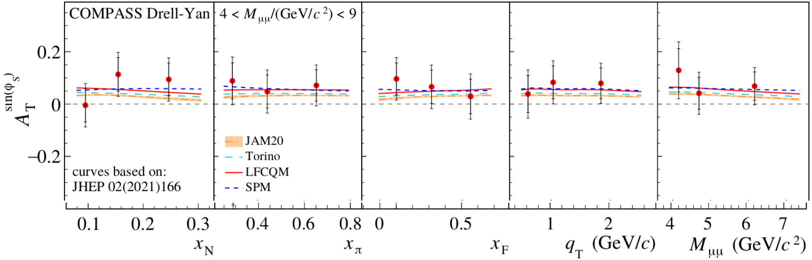




Theory: S. Bastami et al., JHEP 02 (2021) 166.

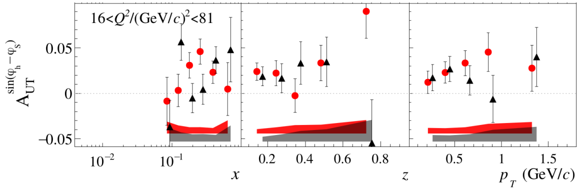
COMPASS, PRL 133 (2024) 071902

Sivers TSA in DY and SIDIS



DY

COMPASS, PRL 133 (2024) 071902



SIDIS

COMPASS, PL B770 (2017) 138

q_T-weighted TSAs in DY

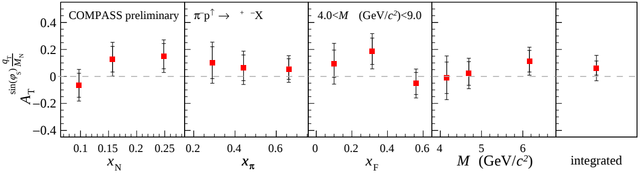
Resolving convolutions in asymmetries requires assumptions about k_T distributions in PDFs;
avoiding these assumptions and accessing n-th moments of the TMD PDFs

$f^{(n)}(x) = \int d^2\mathbf{k_T} \left(\frac{k_T^2}{2M^2}\right)^n f(x, k_T^2)$ possible if asymmetries weighed with powers of q_T

TSA		WTSA
$\mathbf{A_T^{\sin(\varphi_S)}} \propto \mathbf{f^q_{1,\pi}} \otimes \mathbf{f^{q\perp}_{1T,N}}$	Sivers	$\mathbf{A_T^{\sin(\varphi_S)\frac{q_T}{M_N}}} \propto \mathbf{f^q_{1,\pi}} \times \mathbf{f^{q\perp(1)}_{1T,N}}$
$\mathbf{A_T^{\sin(2\varphi_{CS}+\varphi_S)}} \propto \mathbf{h^{q\perp}_{1,\pi}} \otimes \mathbf{h^{q\perp}_{1T,N}}$	pretzelosity	$\mathbf{A_T^{\sin(2\varphi_{CS}+\varphi_S)\frac{q_T^3}{2M_N^2 M_\pi}}} \propto \mathbf{h^{q\perp(1)}_{1,\pi}} \times \mathbf{h^{q\perp(2)}_{1T,N}}$
$\mathbf{A_T^{\sin(2\varphi_{CS}-\varphi_S)}} \propto \mathbf{h^{q\perp}_{1,\pi}} \otimes \mathbf{h^q_{1,N}}$	transversity	$\mathbf{A_T^{\sin(2\varphi_{CS}-\varphi_S)\frac{q_T}{M_\pi}}} \propto \mathbf{h^{q\perp(1)}_{1,\pi}} \times \mathbf{h^q_{1,N}}$

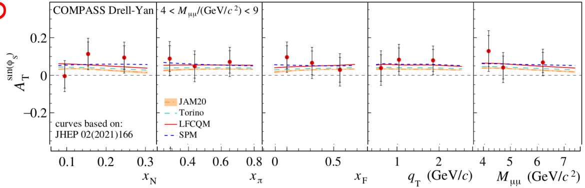
q_T-weighted TSAs in DY,... cont'd

Weighted DY TSA for Sivers: $A_T^{\sin(\phi_s)\frac{q_T}{M_N}} \propto f_{1,\pi}^q \times f_{1T,N}^{q\perp(1)} \ldots$



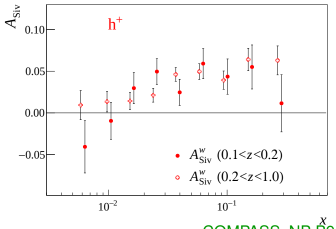
COMPATIBLE!

...compared to standard DY TSA: $A_T^{\sin(\phi_s)} \propto f_{1,\pi}^q \otimes f_{1T,N}^{q\perp}$



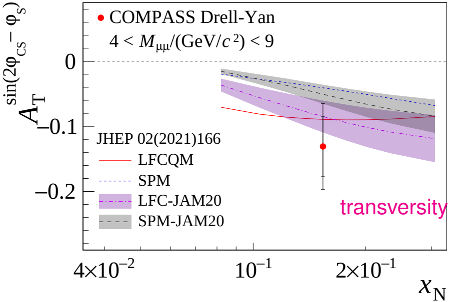
COMPASS, PRL 133 (2024) 071902

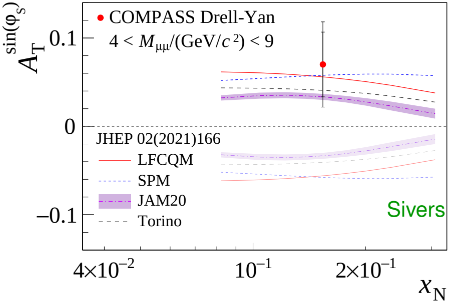
and SIDIS wTSA: $A_{UT}^{\sin(\phi_h-\phi_S)\frac{P_T}{zM_N}} \propto f_{1T,N}^{q\perp(1)} \times D_{1q}^h$



COMPASS, NP B940 (2019) 34

COMPASS DY results: universality of TMDs





sign change

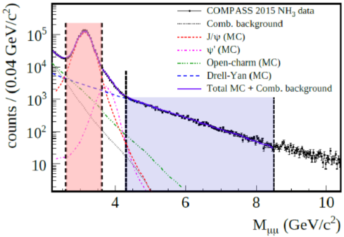
no sign change

COMPASS DY result for **Sivers** asymmetry, $A_T^{\sin(\phi_S)}$
consistent with (predicted) **sign change** of the Sivers TMD, $f_{1T}^{\perp}$

Boer-Mulders TMD PDF ?

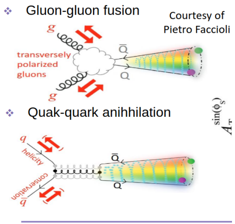
COMPASS, PRL 133 (2024) 071902

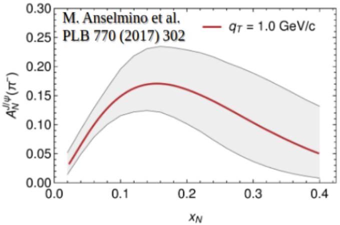
Charmonium in COMPASS: $\pi^- A \to J/\Psi\ X \to \mu^+\mu^- X$



- production mechanism not fully understood
- only inclusive production studied (due to hadron absorber)
- limited mass resolution:
  $\to J/\Psi$(1S) visible, Ψ(2S) not

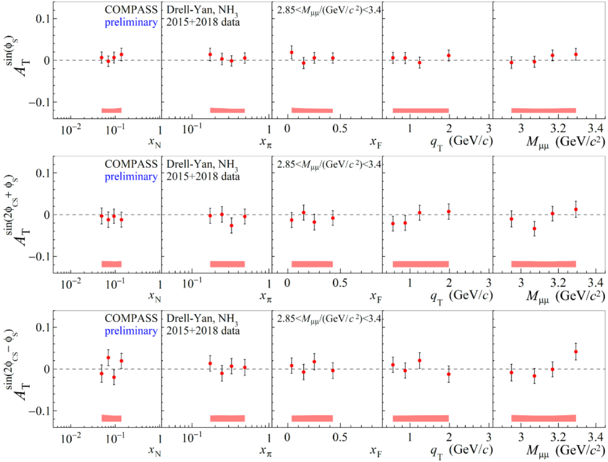
Possible charmonium production mechanisms





- in COMPASS $\bar{q}q$ more probable
- very large predicted TSA
- sensitive to Sivers TMD PDF of u in the proton

COMPASS TSAs in the J/Ψ mass range, 2.85 $< M_{\mu\mu}/(\text{GeV}/c^2) <$ 3.4



Sivers

pretzelosity

transversity

All asymmetries are compatible with zero

Unpolarised DY cross-section and the Lam-Tung relation

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \left[1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}\right]$$

$$\Longrightarrow \frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1 + \lambda\cos^2\theta_{CS} + \mu \sin 2\theta_{CS}\cos\varphi_{CS} + \frac{\nu}{2}\sin^2\theta_{CS}\cos 2\varphi_{CS}\right]$$

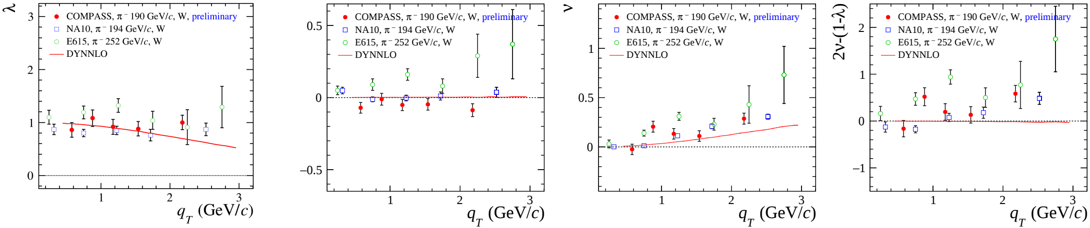
where: $\lambda = A_U^1$, $\mu = A_U^{\cos\varphi_{CS}}$, $\nu = 2A_U^{\cos 2\varphi_{CS}}$ and $A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$

$A_U^{\cos 2\varphi_{CS}}$ gives a convolution of Boer-Mulders TMD functions of π and p.

Observe that:

- In DY QPM we expect: λ = 1, $\nu = \mu = 0$
- ν may be non-zero at NLO
- In collinear QCD, the Lam-Tung relation: $1 - \lambda = 2\nu$ expected to hold (its breaking might suggest a necessity of going beyond a collinear approximation)

Unpolarised DY cross-section and the Lam-Tung relation..., cont'd



- A hint for violation of Lam-Tung relation
- A possible Boer-Mulders effect?
- A corresponding coefficient (ν) larger than predicted by QCD?

What has COMPASS taught us on spin of hadrons?

- COMPASS is the longest running CERN experiment – 20 years of data taking!
- Since 2023 in an analysing phase; lots of data awaiting analysis (3 new groups joined recently)
- Many important measurements concerning the nucleon structure in wide and unique (x, Q^2) ranges:
  - inclusive and semi-inclusive (polarised and unpolarised) reactions
  - polarised Drell-Yan process (first ever)
  - DVCS (not covered here)
- Will remain unique at least in a decade
- A successor of CERN family of nucleon structure experiments with M2 beam in the EHN2:
  EMC $\Longrightarrow$ NMC $\Longrightarrow$ SMC $\Longrightarrow$ COMPASS... $\Longrightarrow$ AMBER!