Overview of the spin programme of COMPASS

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8-14 September, 2024

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

A fixed-target experiment at the SPS at CERN (∼ 210 physicists, 28 institutes from 14 countries)

Muon programme

- Spin dependent structure functions g_1
- Gluon polarisation in the nucleon
- Quark polarisation distributions
- Transversity
- Vector meson production
- Λ polarisation
- DVCS/GPD

Hadron programme

- Primakoff effect, π and K polarisabilities
- Exotic (multiquark) states, glueballs
- (Double) charmed barions
- Precision studies of light meson spectrum
- Drell–Yan process on a polarised target

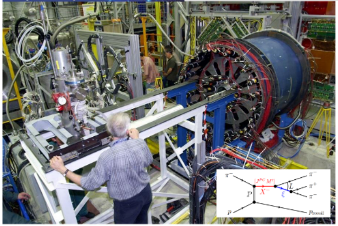
PHASE I (2002 - 2011)

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
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

PHASE II (2012 - 2023)

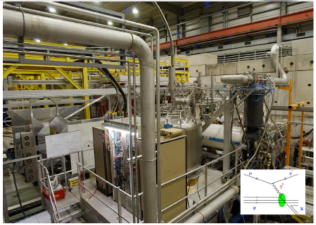
Versatile COMPASS in EHN2

Slide courtesy G. Mallot, PBC 2017



Hadron Spectroscopy & Polarisability

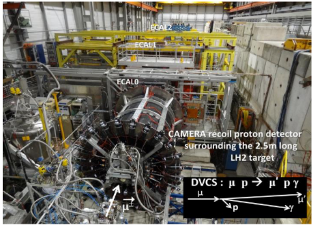
COMPASS-I
1997-2011



Polarised SIDIS

Polarised Drell-Yan

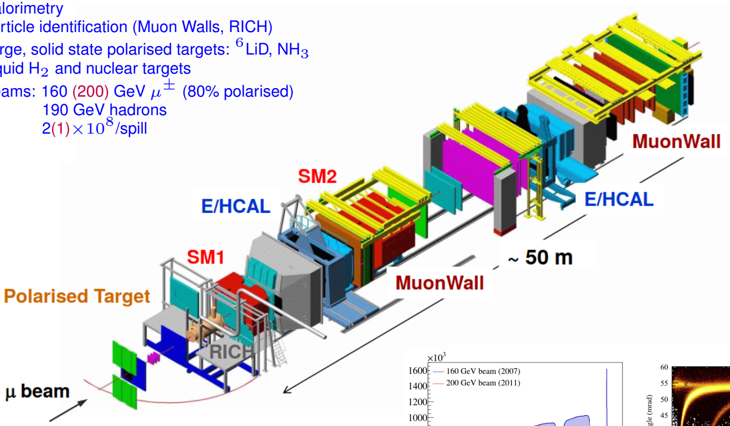
COMPASS-II
2012-2018

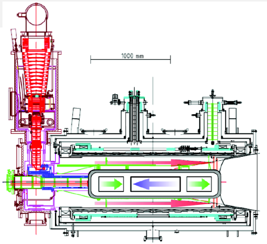


DVCS (GPDs) + unp. SIDIS

Versatile COMPASS facility

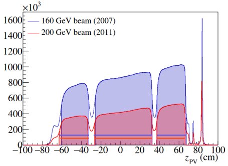
Two stages
Calorimetry
Particle identification (Muon Walls, RICH)
Large, solid state polarised targets: ^{6}LiD, NH_3
Liquid H_2 and nuclear targets
Beams: 160 (200) GeV $\mu^{\pm}$ (80% polarised)
190 GeV hadrons
$2(1)\times 10^8$/spill

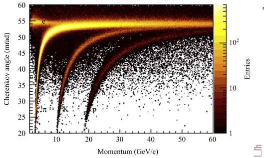


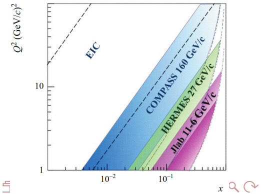


* Material: solid ^{6}LiD (NH_3)
* Polarisation: ~ 50% (~90%), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15)
* Polar acceptance: ~70 mrad (~180 mrad after 2005)

COMPASS NIM A 779 (2015) 69





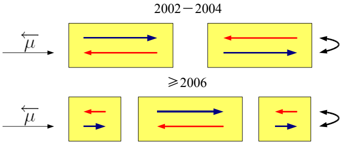


Observables in a $\vec{\mu}\vec{\rm N}$ (h$\vec{\rm N}$) fixed-target experiment

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

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

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)

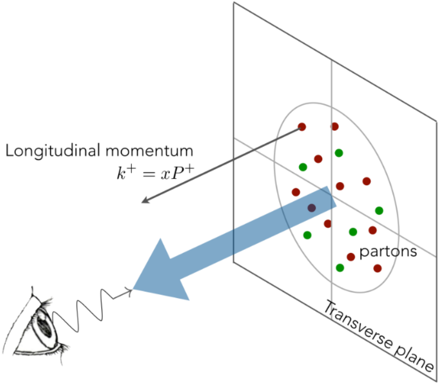


- At LO, semi–inclusive asymmetry, A_1^h:

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

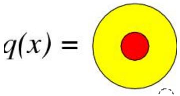
Nucleon in 1-D

$\Longrightarrow$ Longitudinal spin structure

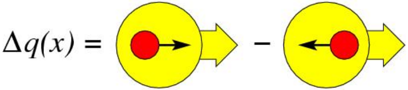


Partonic structure of the nucleon; distribution functions

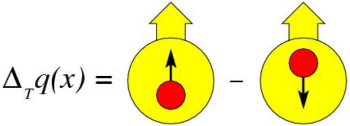
Three twist-two quark distributions in QCD (momentum, helicity & transversity) after integrating over the quark intrinsic k_t



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



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 $\rightarrow \mathbf{g_1(x, Q^2)}$).

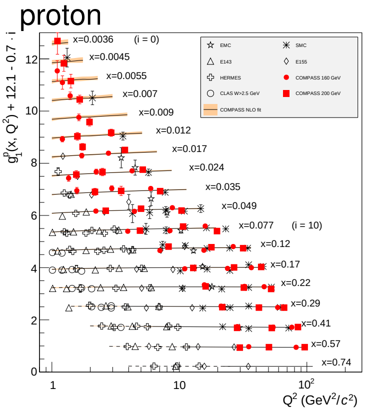


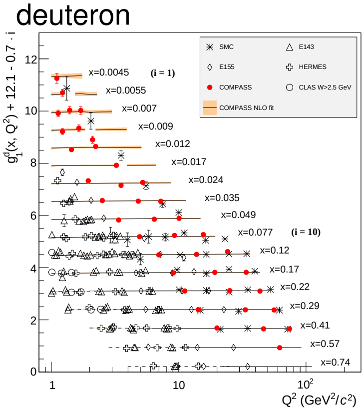
Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow \mathbf{h_1(x, Q^2)}$).

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^{p} and g_1^{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



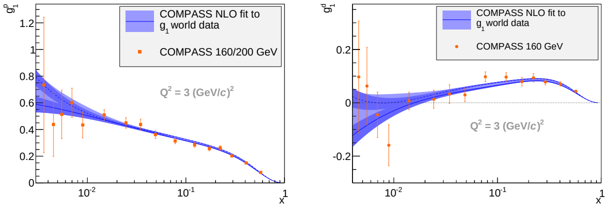


Phys.Lett.B753(2016)18

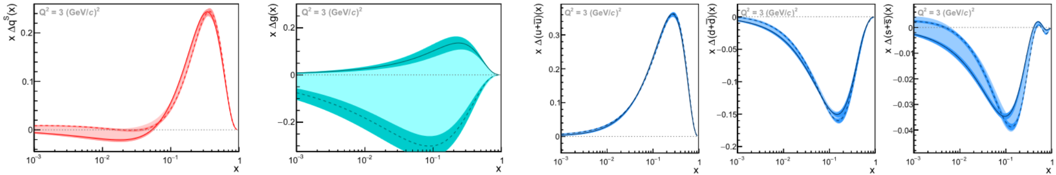
COMPASS PL B769 (2017) 034

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



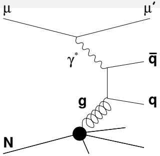
- $g_1^{\rm p}$ clearly positive at low x and raising with decreasing x
- $g_1^{\rm d}$ consistent with zero at low x ?



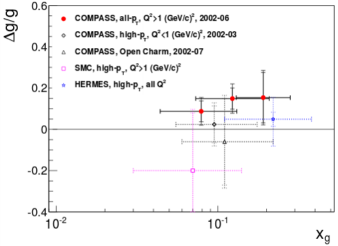
COMPASS PL B **753** (2016) 18

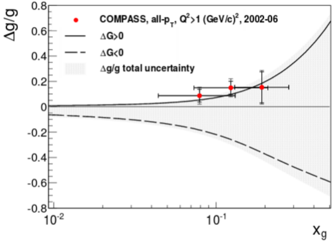
- $-1.5 < \Delta G < 0.5$, poorly constraint $\Longrightarrow$ “direct methods”
- $\sigma_{stat.}$ (dark bands) $\ll$ $\sigma_{syst.}$ (light bands)

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 $p_{\rm T}$ hadron pair (LO)): $A_{\gamma \rm N}^{\rm PGF} \approx \langle a_{\rm LL}^{\rm PGF} \rangle \frac{\Delta g}{g}$





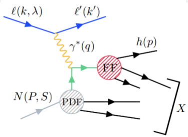
COMPASS from SIDIS on d for any $(p_{\rm T})_{\rm h}$ and at LO:

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

Clearly positive gluon polarisation but not large!

COMPASS, EPJC 77(2017) 209

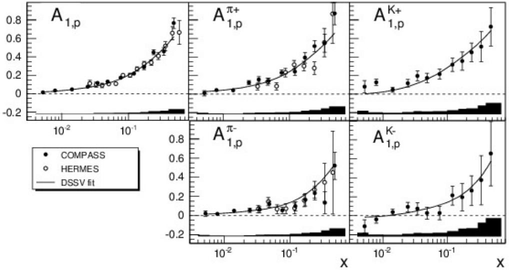
Semi-inclusive asymmetries and parton distributions

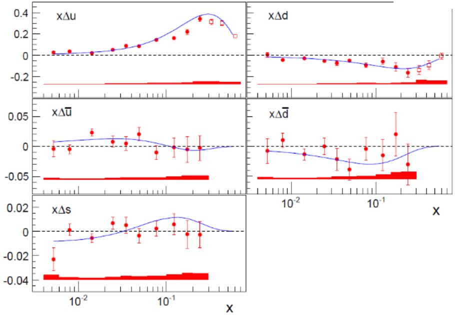


- COMPASS: measured on both proton and deuteron targets for identified π^+, π^- and (for the first time) K^+, K^-

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

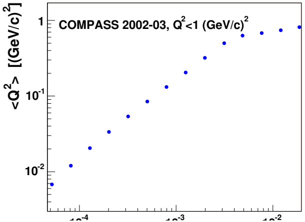
DSSV, Phys. Rev. D **80** (2009) 034030

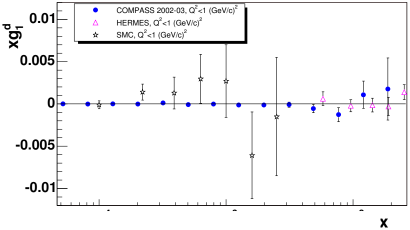




- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV (without these results) describes the data well.

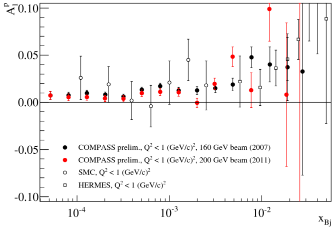
g_1^N in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)

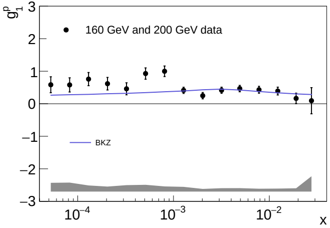




Spin effects in g_1^d at low x and Q^2 absent ?

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





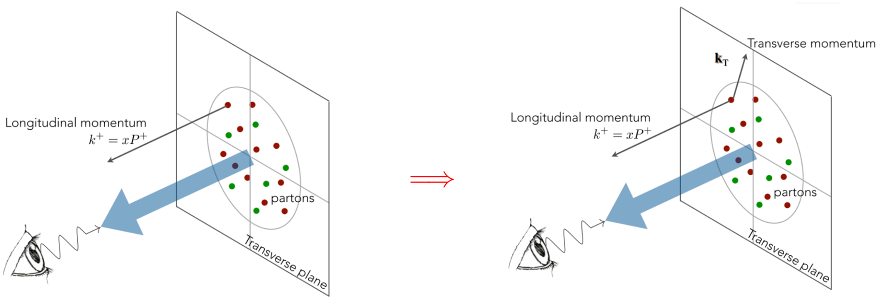
Very clear spin effects in g_1^p at low x and Q^2

COMPASS PL B 781 (2018) 464

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

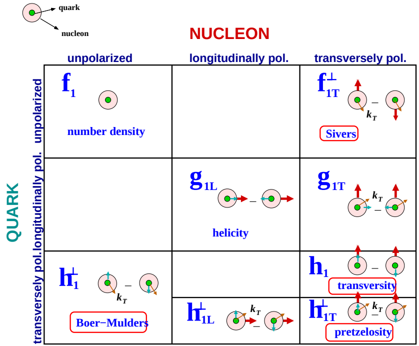
Nucleon in 3-D

$\Longrightarrow$ Transverse Momentum Distributions (TMD)



Partonic structure of the nucleon; distribution functions

- In LT and considering k_{T}, 8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{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. $A_{\mathrm{Sivers}} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\mathrm{Sivers}} \propto$ PDF$^{\mathrm{beam}} \otimes$ PDF$^{\mathrm{target}}$
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent



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

(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

$f_1 \otimes D_1$

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{ F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h}$$

$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\Big]$$

$$+ S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\, F_{LL}^{\cos\phi_h}\Big]$$

$$+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ \varepsilon\,\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S}$$

$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)}$$

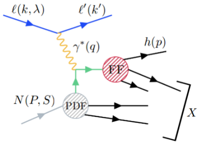
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]$$

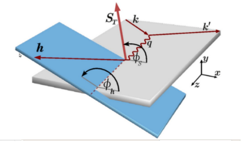
Sivers structure function

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

Collins structure function

$h_1 \otimes H_1^{\perp}$





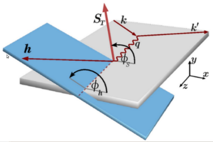
All Fs measured by COMPASS!

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):

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

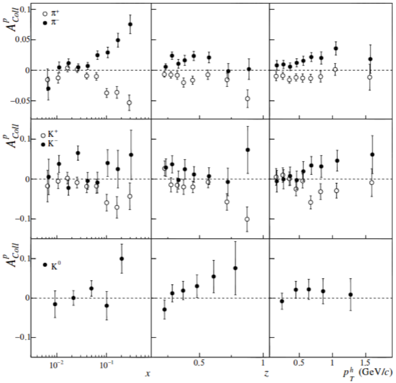
($f, P_T; D_{NN}$: target dilution, polarisation; $\perp$ spin transfer coeff)

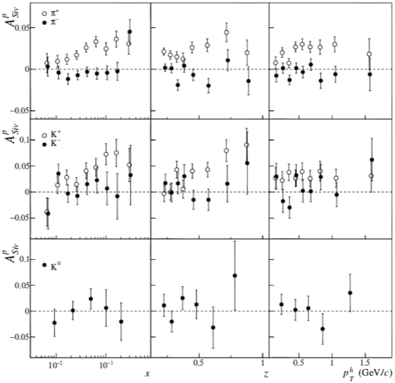
At LO:

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

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")

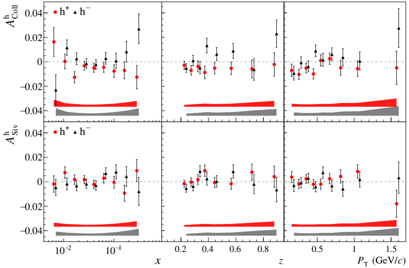
- Sivers asymmetries for proton measured for +/– identified hadrons are large for π^+, K$^+$...
- ...and even larger at smaller Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry

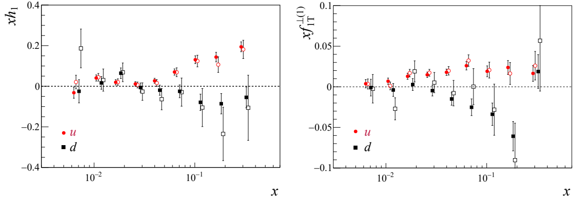
COMPASS, Phys.Lett. B744 (2015) 250

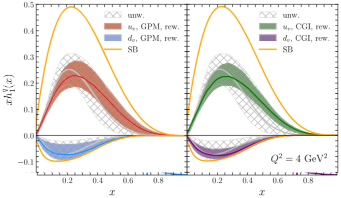
NEW A_{Coll}, A_{Siv} measurements for deuteron $\Longrightarrow xh_1^q,\ xf_{1T}^{\perp(1)}$

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_A/g_V and improved g_T measurement

- The nonsinglet structure function: $g_1^{NS} = g_1^p(x,Q^2) - g_1^n(x,Q^2)$ and its moment connected to the Bjorken sum rule:
$\int_0^1 g_1^{NS}(x,Q^2)\mathrm{d}x = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$, NLO QCD fitted and fit-extrapolated $x \to 0,1$ gave
$\left|\frac{g_A}{g_V}\right| = 1.29 \pm 0.05_{\mathrm{stat.}} \pm 0.10_{\mathrm{syst.}} \Longrightarrow$ validation of Bjorken sum rule to 9%
(neutron β decay: $|g_A/g_V| = 1.2701 \pm 0.002$) 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	$\delta u = \int_{0.008}^{0.210} \mathrm{d}x\, h_1^{u_v}(x)$	$\delta d = \int_{0.008}^{0.210} \mathrm{d}x\, h_1^{d_v}(x)$	$g_T = \delta u - \delta d$
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!

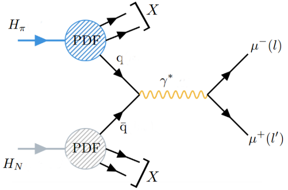
COMPASS, PRL 133 (2024) 101903

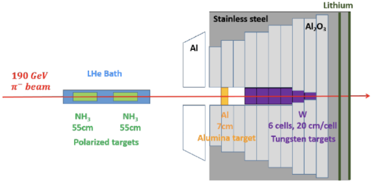
First ever

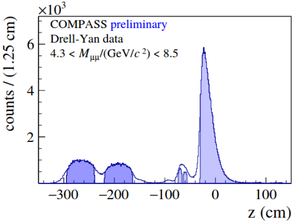
polarised Drell-Yan reaction measurements

- $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$
  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)







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

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

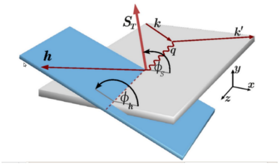
$$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h} \quad \xleftrightarrow{\text{Boer-Mulders}} \quad A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp,q} \otimes h_{1,p}^{\perp q}$$

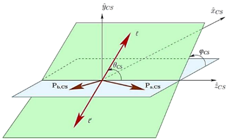
$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h} \quad \xleftrightarrow{\text{Sivers}} \quad A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

$$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h} \quad \xleftrightarrow{\text{Pretzelosity}} \quad A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

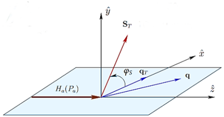
$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h} \quad \xleftrightarrow{\text{Transversity}} \quad A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$$

(courtesy of R. Longo, COMPASS)



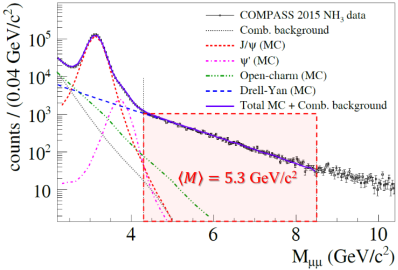


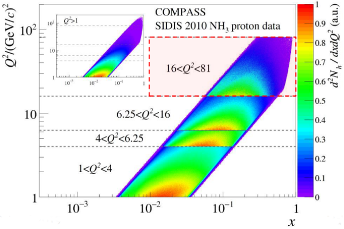
Collins-Soper ref. frame (CS)

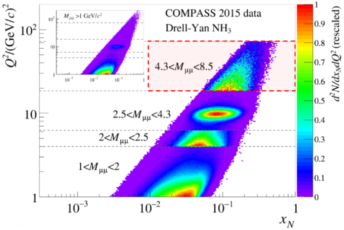


Target rest frame (S)

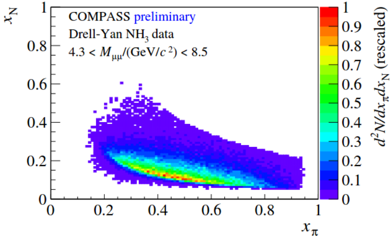
COMPASS Drell-Yan results



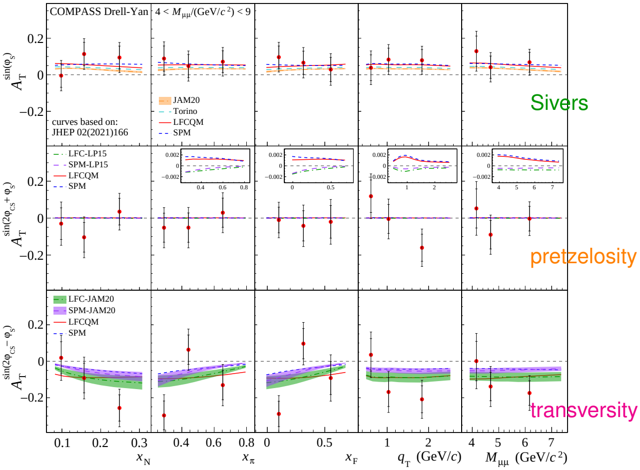


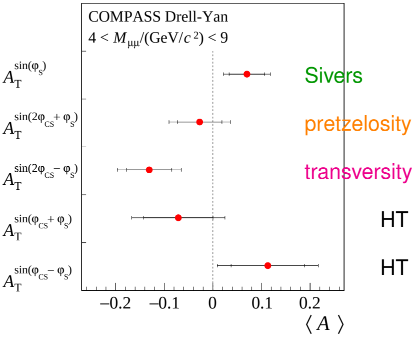


- Events of $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$ are DY events with background: ∼4%
- DY events in the valence regions of π and N $\langle x_\pi \rangle$ =0.50, $\langle x_N \rangle$ =0.17
- Here Q is the $\mu\mu$ invariant mass, $M_{\mu\mu}$



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

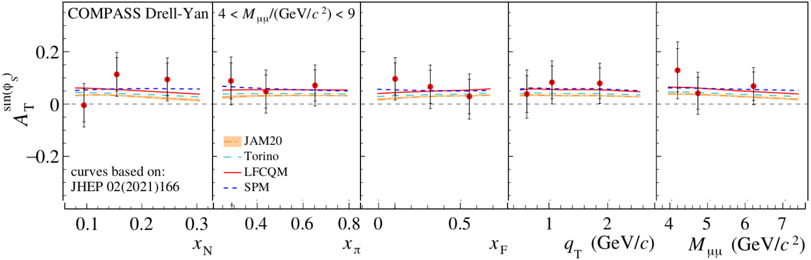




Theory: S. Bastami et al., JHEP 02 (2021) 166.

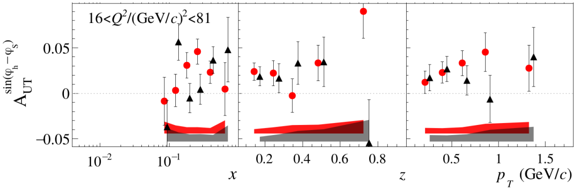
COMPASS, PRL 133 (2024) 071902

Sivers TSA in DY and SIDIS



DY

COMPASS, PRL 133 (2024) 071902



SIDIS

COMPASS, PL B770 (2017) 138

q_T-weighted TSAs in DY

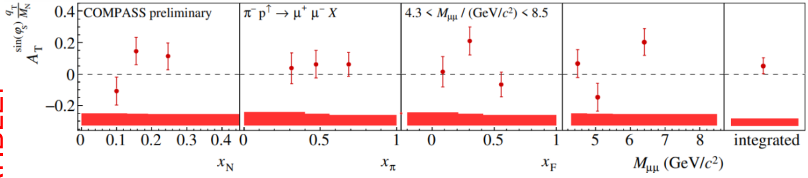
Resolving convolutions in asymmetries requires assumptions about k_T distributions in PDFs;
avoiding these assumptions and accessing n-th moments of the TMD PDFs

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

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

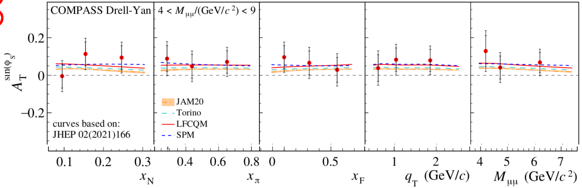
q_T-weighted TSAs in DY,... cont'd

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



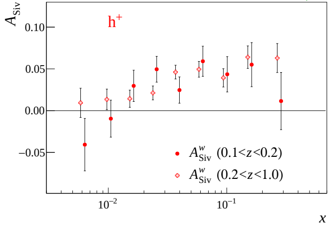
COMPATIBLE!

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



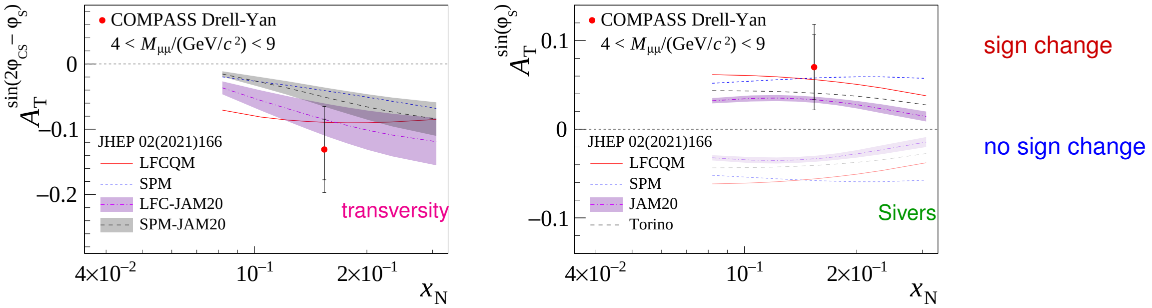
COMPASS, PRL 133 (2024) 071902

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



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

Summary of COMPASS spin programme

- 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
- 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!