Overview of the spin programme of COMPASS

Barbara Badełek
University of Warsaw

Seminar at Section of Particles and Fundamental Interactions, University of Warsaw, 18 X 2024

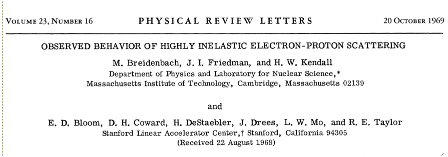
Diffraction and Low-x

Trabia, Italy
8-14 September, 2024

Yerevan, Armenia
30 September-4 October, 2024

Two anniversaries

55th anniversary of ‘pointlike partons’ idea



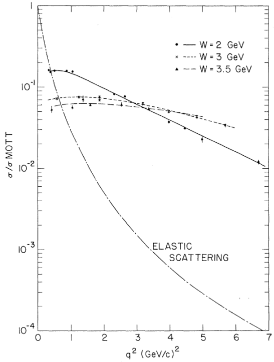
Volume 23, Number 16 PHYSICAL REVIEW LETTERS 20 October 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

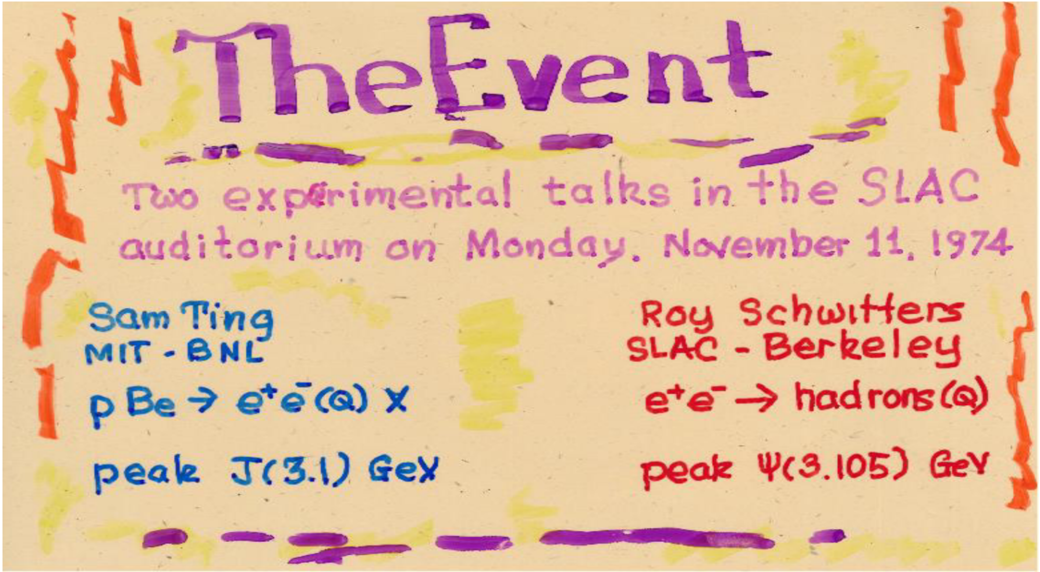
and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)



- Nucleon is composite (1933; O. Stern)
- SLAC-MIT e-p INelastic scattering @ 7-17 GeV
  (J.I. Friedman, H.W. Kendall, R.E. Taylor,... PRL 23 (1969) 935)
- Cross-section independence of q^2
  $\Longrightarrow$ Experimental proof of pointlike partons in the nucleon
  $\Longrightarrow$ QCD formulation on the way

D. Sivers, 5-th Workshop on Correlations in Partonic and Hadronic Interactions, Yerevan 2024



D. Sivers, 5-th Workshop on Correlations in Partonic and Hadronic Interactions, Yerevan 2024

The Nobel winning data

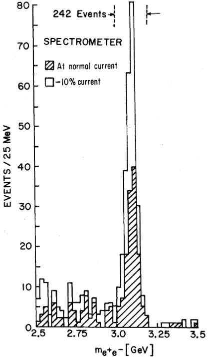
Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.



Discovery of a Narrow Resonance in e^+e^- Annihilation*

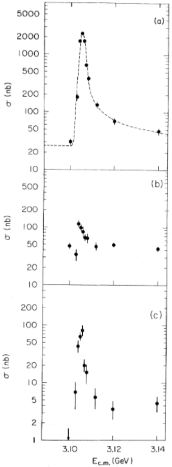
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

- BNL – SLAC/SPEAR S. Ting – B. Richter
- Both papers submitted to Phys.Rev.Lett. on Nov. 12
- and published December 2 (PRL 33 (1974) 1404)
- Now cited ∼3 000 times each
- The only explanation: J/Ψ is a $c\bar{c}$ state $\Longrightarrow$ new, 4th quark!



{Bj's pre-revolution Clutter List}

nuclear democracy	current algebra
Regge poles	bootstrap
dispersion theory	field algebra
field-current identities	vector dominance
chiral dynamics	Melosh transformation
$SU(6)_W$ / $U(12)$	light-cone current algebra
Mandelstam representation	Kallen-Lehman representation
strings	flavor groups
LSZ	Wightman axioms

D. Sivers, 5-th Workshop on Correlations in Partonic and Hadronic Interactions, Yerevan 2024

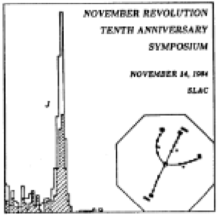
SLAC BEAM LINE

Bj, I think you had better go to the lab now.

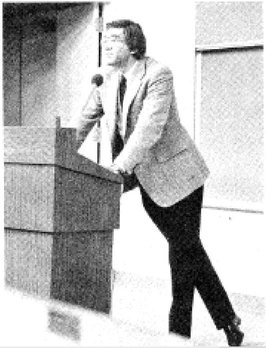
Special Issue Number 8 — *July 1985*

— THE NOVEMBER REVOLUTION —
A THEORIST REMINISCES

James D. Bjorken



The discovery of the J/ψ, announced in the fall of 1974, resulted in such a rich flow of new physics and new experimental technique that physicists call the era the 'November Revolution.'



Half a century later...

$\Longrightarrow$ View of the nucleon seen with the eyes of COMPASS

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

A fixed-target experiment at the SPS at CERN ($\sim$ 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

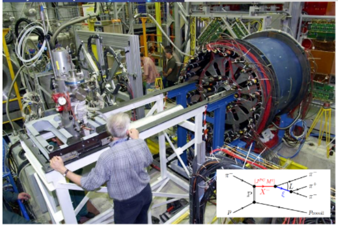
Hadron programme

- 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
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

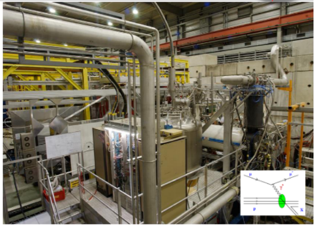
Versatile COMPASS in EHN2

Slide courtesy G. Mallot, PBC 2017



Hadron Spectroscopy & Polarisability

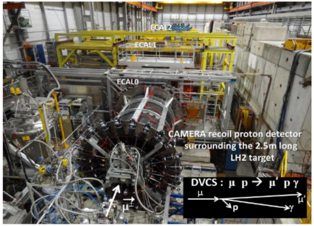
COMPASS-I
1997-2011



Polarised SIDIS

Polarised Drell-Yan

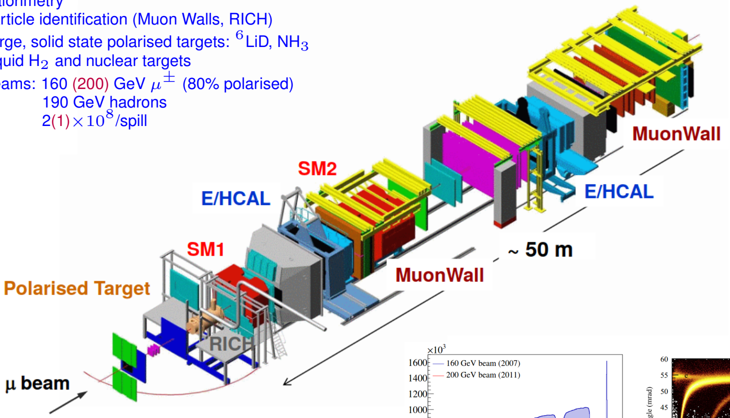
COMPASS-II
2012-2018

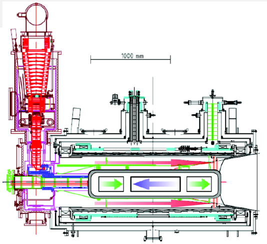


DVCS (GPDs) + unp. SIDIS

Versatile COMPASS facility

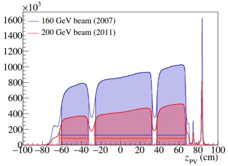
Two stages
Calorimetry
Particle identification (Muon Walls, RICH)
Large, solid state polarised targets: ^{6}LiD, NH_3
Liquid H_2 and nuclear targets
Beams: 160 (200) GeV $\mu^{\pm}$ (80% polarised)
190 GeV hadrons
$2(1) \times 10^8$/spill

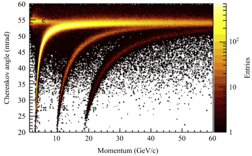


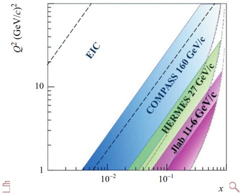


* Material: solid ^{6}LiD (NH_3)
* Polarisation: ~ 50% (~90%), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15)
* Polar acceptance: ~70 mrad (~180 mrad after 2005)

COMPASS NIM A 779 (2015) 69

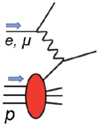






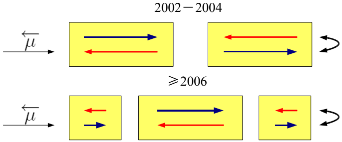
Observables in a $\vec{\mu}\vec{\mathrm{N}}$ ($\mathrm{h}\vec{\mathrm{N}}$) fixed-target experiment

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

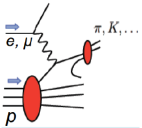


$$A_{meas} = \frac{1}{f P_T P_B}\left(\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}}\right) \approx D A_1 = D\,\frac{g_1(x,Q^2)}{F_1(x,Q^2)} \overset{\mathrm{LO}}{=} D\,\frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

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)



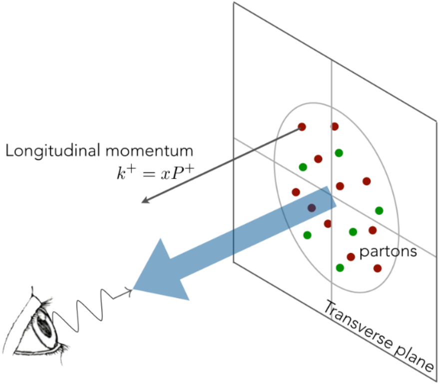
- At LO, semi–inclusive (SIDIS) asymmetry, A_1^h:



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

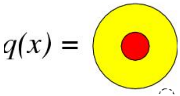
Nucleon in 1-D

$\Longrightarrow$ Longitudinal spin structure

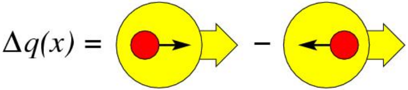


Partonic structure of the nucleon; distribution functions

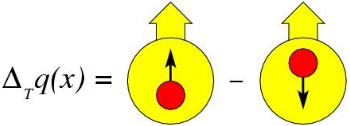
Three twist-two quark distributions in QCD (momentum, helicity & transversity) after integrating over the quark intrinsic k_t



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



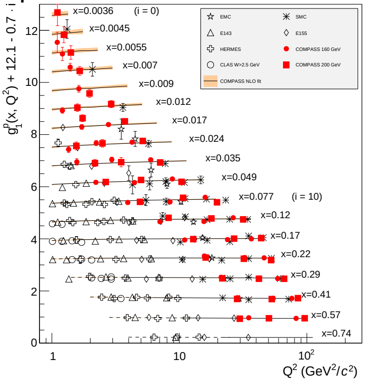
Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow \mathbf{h_1(x, Q^2)}$).

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.

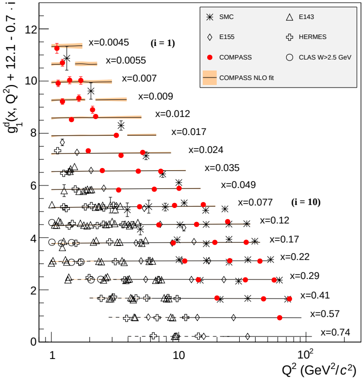
COMPASS and world data: $g_1^{\rm p}$ and $g_1^{\rm d}$, $Q^2 > 1\ ({\rm GeV}/c)^2$

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

proton



deuteron

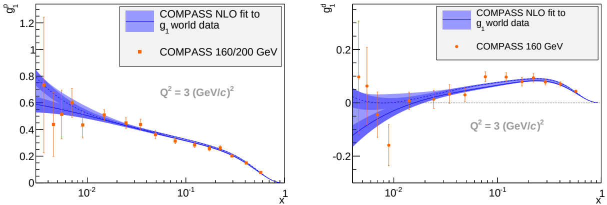


Phys.Lett.B753(2016)18

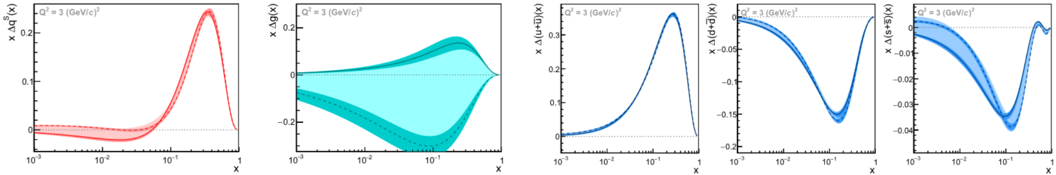
COMPASS PL B769 (2017) 034

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 ?

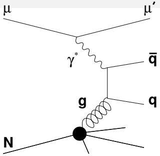


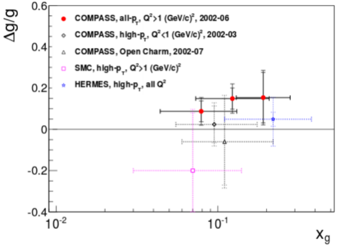
COMPASS PL B **753** (2016) 18

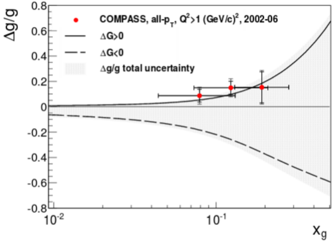
- $-1.5 < \Delta G < 0.5$, poorly constraint $\Longrightarrow$ "direct methods"
- $\sigma_{stat.}$ (dark bands) $\ll$ $\sigma_{syst.}$ (light bands)

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_{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:

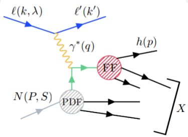
$$\Delta g/g = 0.113 \pm 0.038(\mathrm{stat.}) \pm 0.036(\mathrm{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ (\mathrm{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

Clearly positive gluon polarisation but not large!

COMPASS, EPJC 77(2017) 209

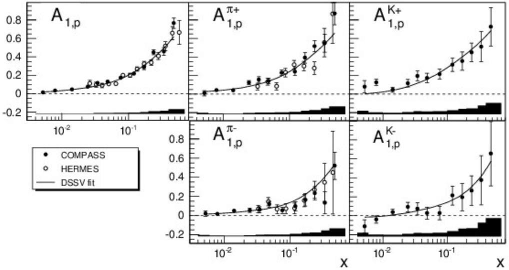
Semi-inclusive asymmetries and parton distributions

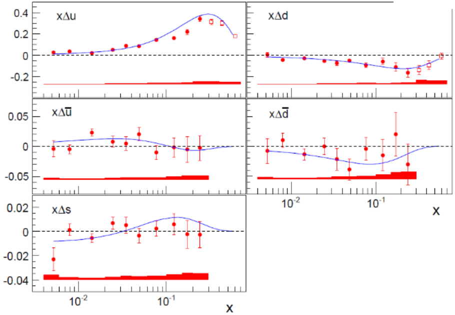
- COMPASS: measured on both proton and deuteron targets for identified π^+, π^- and (for the first time) K^+, K^-



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

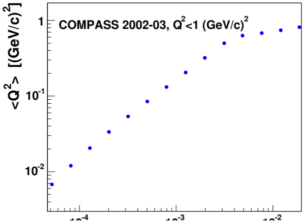
DSSV, Phys. Rev. D **80** (2009) 034030

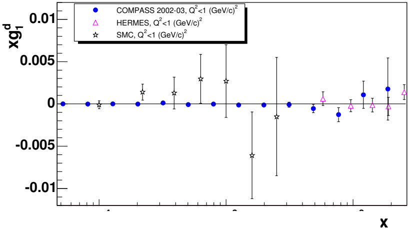




- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV (without these results) describes the data well.

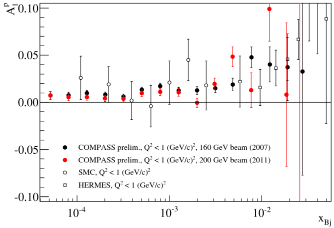
g_1^{N} in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)

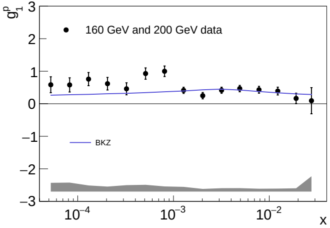




Spin effects in g_1^{d} at low x and Q^2 absent ?

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





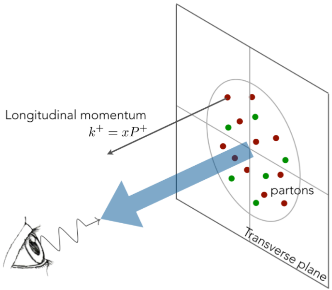
Very clear spin effects in g_1^{p} at low x and Q^2

COMPASS PL B 781 (2018) 464

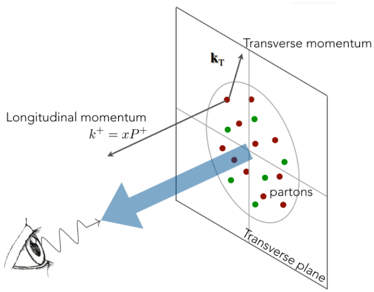
At low x and Q^2: nonperturbative effects and suitable extension of parton mechanisms must be considered

Nucleon in 3-D

$\Longrightarrow$ Transverse Momentum Distributions (TMD)

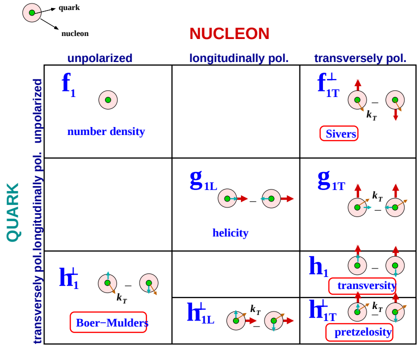


$\Longrightarrow$



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



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

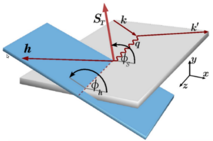
(follows from QCD gauge invariance)

- 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!

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):

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

($f, P_T; D_{NN}$: 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.

THE 18 SIDIS STRUCTURE FUNCTIONS

Unpolarized structure function

$f_1 \otimes D_1$

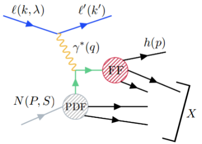
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\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

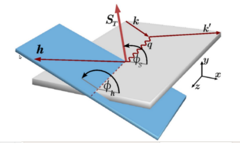
Sivers structure function

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

Collins structure function

$h_1 \otimes H_1^{\perp}$

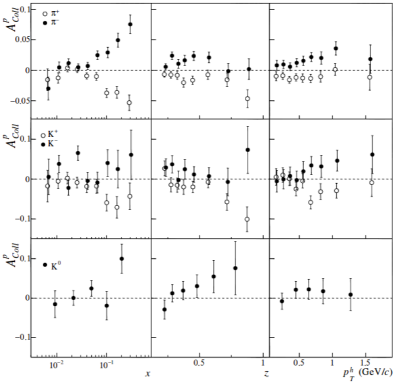


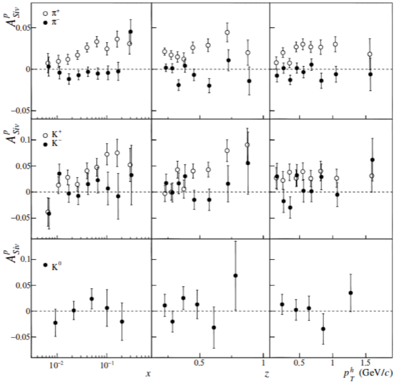


All Fs measured by COMPASS!

Slide courtesy A. Bacchetta, IWHSS2022 (with changes)

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")

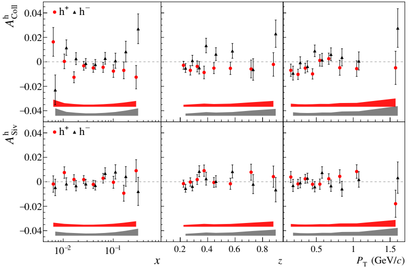
- Sivers asymmetries for proton measured for +/– identified hadrons are large for π^+, K$^+$...
- ...and even larger at smaller Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry

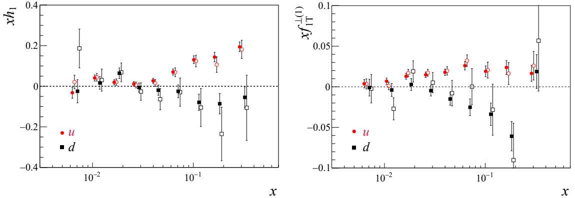
COMPASS, Phys.Lett. B744 (2015) 250

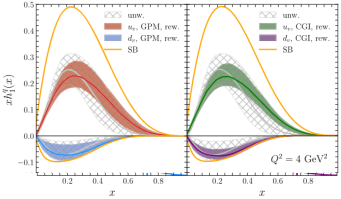
NEW A_{Coll}, A_{Siv} measurements for deuteron $\Longrightarrow xh_1^q,\ xf_{1T}^{\perp(1)}$

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: $\int_0^1 g_1^{NS}(x,Q^2)dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$, NLO QCD fitted and fit-extrapolated $x \to 0, 1$ gave $\left|\frac{g_A}{g_V}\right| = 1.29 \pm 0.05_{stat.} \pm 0.10_{syst.} \Longrightarrow$ validation of Bjorken sum rule to 9%
(neutron β decay (PDG): $|g_A/g_V| = 1.2701 \pm 0.002$) COMPASS PL B753 (2016) 18

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

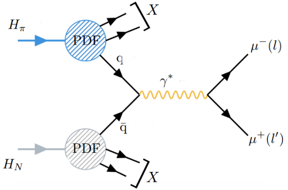
data	$\delta u = \int_{0.008}^{0.210} dx\, h_1^{u_v}(x)$	$\delta d = \int_{0.008}^{0.210} dx\, h_1^{d_v}(x)$	$g_T = \delta u - \delta d$
previous [25, 28, 29]	0.187 ± 0.030	-0.178 ± 0.097	0.365 ± 0.078
previous [25, 28, 29] and present	0.214 ± 0.020	-0.070 ± 0.043	0.284 ± 0.045

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

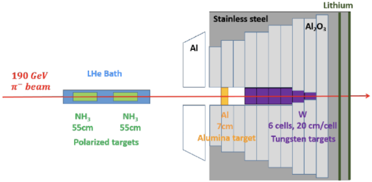
COMPASS, PRL 133 (2024) 101903

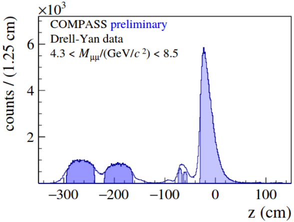
First ever

polarised Drell-Yan reaction measurements



- $\pi^- + p^\uparrow \to \mu^+\mu^- + X$
  π^- beam of 190 GeV/c, CERN SPS $\langle I\rangle \approx 7\times10^7 s^{-1}$, ~97% π^-
- Transversely polarized NH_3 target (2×55 cm)
  + Al target (7 cm) + W beam plug (120 cm)



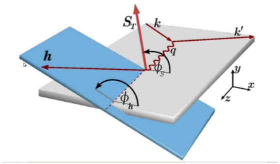


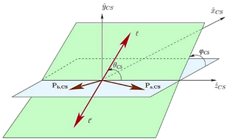
SIDIS and Drell-Yan compatibility; unique access to TMD PDFs of π

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

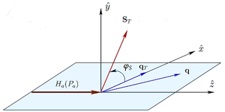
SIDIS		Drell-Yan
$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$	Boer-Mulders	$A_{U}^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp,q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$	Sivers	$A_{T}^{\sin\varphi_S} \propto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



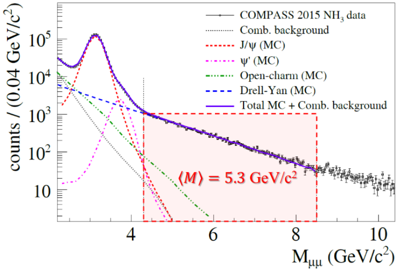


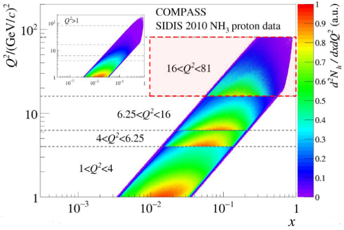
Collins-Soper ref. frame (CS)

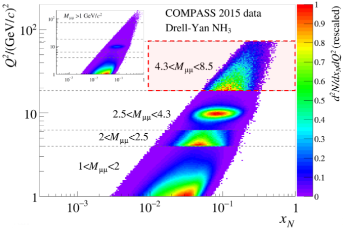


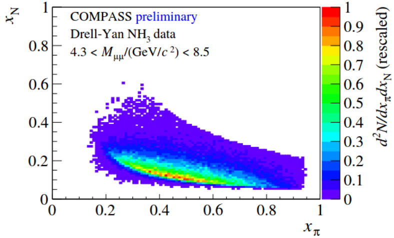
Target rest frame (S)

COMPASS Drell-Yan results



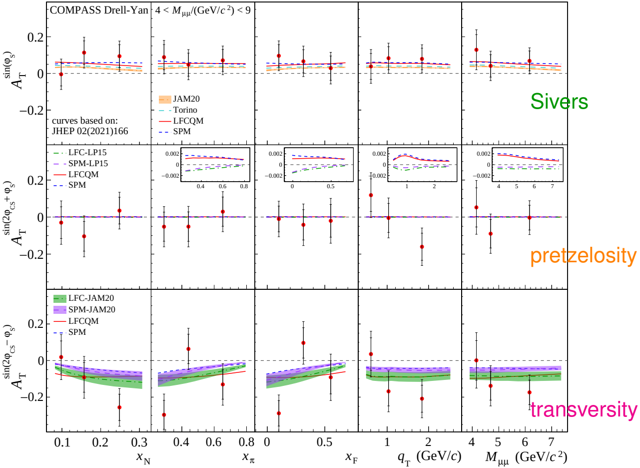


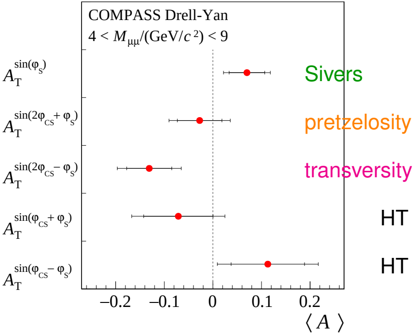




- Events of $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$ are DY events with background: ∼4%
- DY events in the valence regions of π and N $\langle x_\pi \rangle$ =0.50, $\langle x_N \rangle$ =0.17
- Here Q is the $\mu\mu$ invariant mass, $M_{\mu\mu}$

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

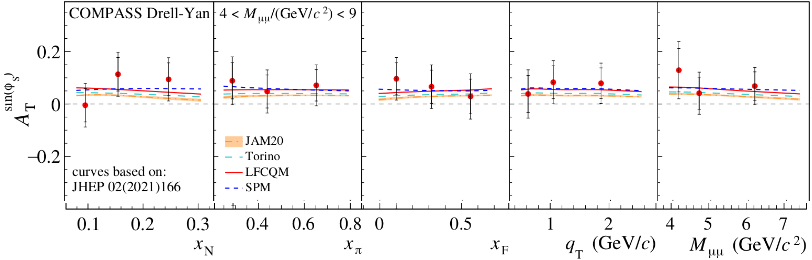




Theory: S. Bastami et al., JHEP 02 (2021) 166.

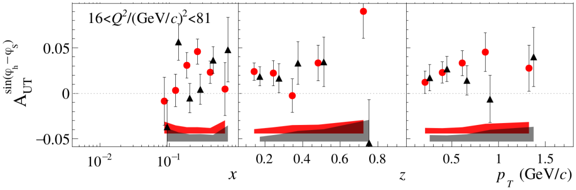
COMPASS, PRL 133 (2024) 071902

Sivers TSA in DY and SIDIS



DY

COMPASS, PRL 133 (2024) 071902



SIDIS

COMPASS, PL B770 (2017) 138

q_T-weighted TSAs in DY

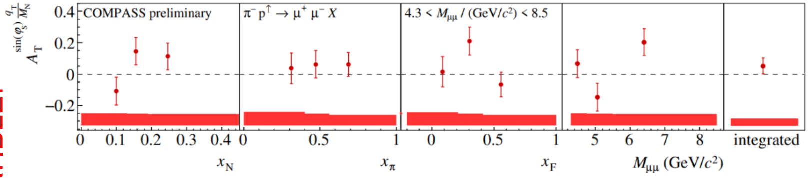
Resolving convolutions in asymmetries requires assumptions about k_T distributions in PDFs;
avoiding these assumptions and accessing n-th moments of the TMD PDFs

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

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

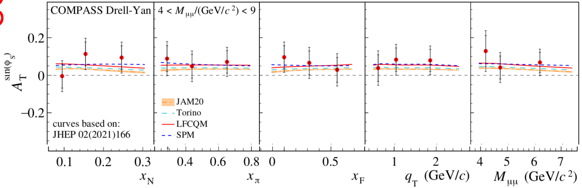
q_T-weighted TSAs in DY,... cont'd

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



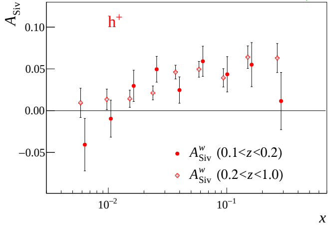
COMPATIBLE!

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



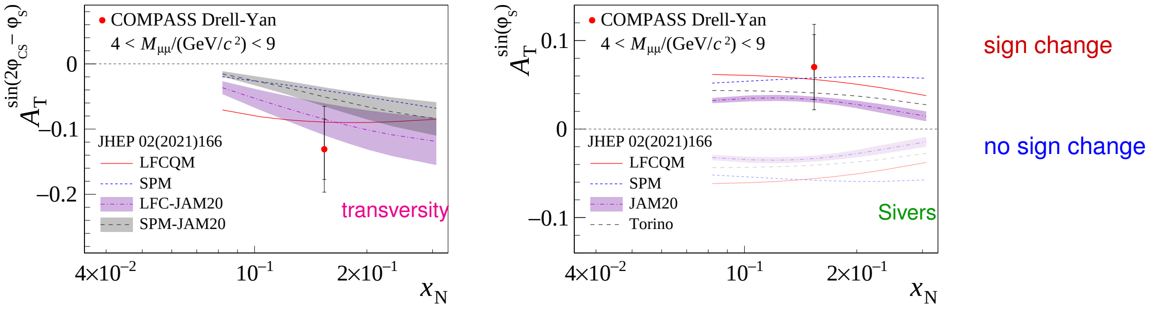
COMPASS, PRL 133 (2024) 071902

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



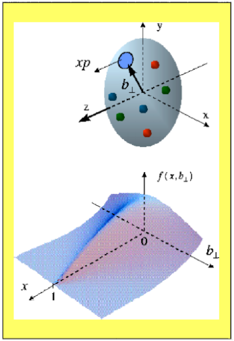
COMPASS DY result for **Sivers** asymmetry, $A_T^{\sin(\phi_S)}$

consistent with (predicted) **sign change** of the Sivers TMD, $f_{1T}^{\perp}$

Boer-Mulders TMD PDF ?

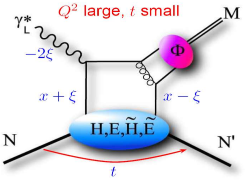
COMPASS, PRL 133 (2024) 071902

3-D (1D + 2D) proton
(in a different way $\Longrightarrow$ GPD)



After V.D. Volker, LANL 2007

Generalised Parton Distributions (GPD)

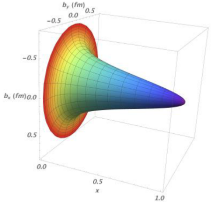


		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\tilde{H}_T + E_T$
	L		$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

Table and figure from: S. Niccolai, 5-th Workshop on Correlations in Partonic and Hadronic Interactions, Yerevan 2024

- Accessible via Deeply Virtual Compton Scattering (Deeply Virtual Meson Production): $\mu p \to \mu p \gamma(M)$
- 4 GDPs $(H, E, \tilde{H}, \tilde{E})$ for each flavour and for gluons plus 4 chiral odd ones $(H_T, E_T, \tilde{H}_T, \tilde{E}_T)$
- All depend on 4 variables: x, ξ, t, Q^2; $x \neq x_B$! DIS @ $\xi = t = 0$;
- $H, \tilde{H}$ conserve nucleon helicity $E, \tilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions $\tilde{H}, \tilde{E}$ refer to polarised distributions
- $H^q(x,0,0) = q(x), \quad \tilde{H}^q(x,0,0) = \Delta q(x)$

Proton tomography from *local fits* to HERMES, CLAS, and Hall-A data (**Im$\mathcal{H}$** + **model dependent** assumptions for x dependence)



High-momentum quarks (valence) are at the core of the nucleon, low-momentum quarks (sea) spread to its periphery

R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95 (2017)

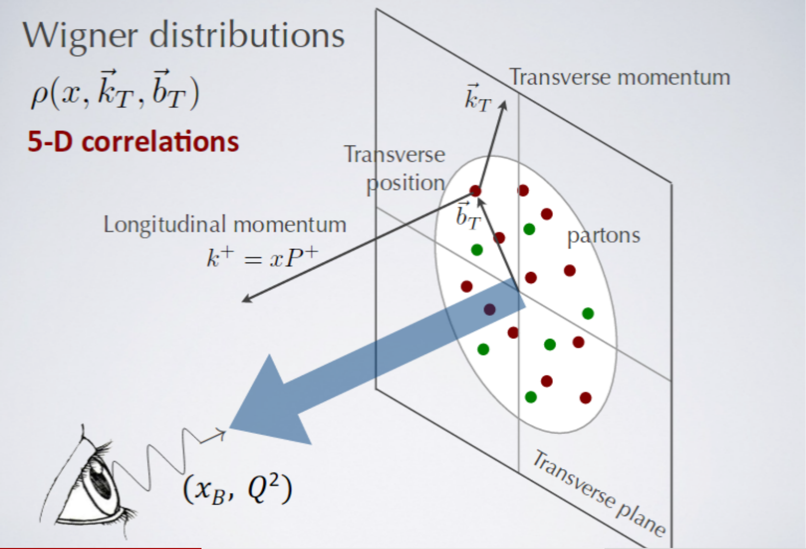
Important:

$$J_z^q = \frac{1}{2}\int dx\, x\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = \frac{1}{2}\Delta\Sigma + L_z^q \quad \text{(X. Ji)}$$

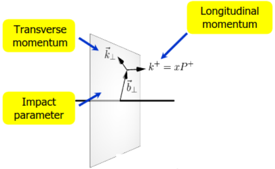
...Proton even 5-D!

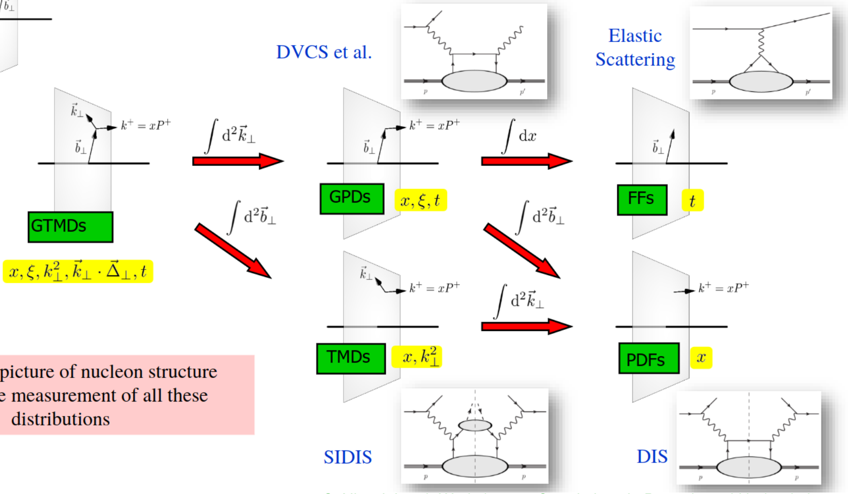
(ultimate goal)

Nucleon in 5-D



Multi-dimensional mapping of the nucleon





A complete picture of nucleon structure requires the measurement of all these distributions

S. Niccolai, 5-th Workshop on Correlations in Partonic and Hadronic Interactions, Yerevan 2024

Summary of COMPASS spin programme

- COMPASS is the longest running CERN experiment – 22 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!