COMPASS – a versatile facility at CERN

25 years since approval and **20** years since first data-taking
100 years after the Stern-Gerlach exp. and **35** years after EMC ‘spin crisis’

Barbara Badelek
University of Warsaw

QNP2022, Florida State University, 5-9 September, 2022

International Workshop on Hadron Structure and Spectroscopy - 2022

CERN, 29–31 August, 2022

Happy 25th Birthday COMPASS

Congratulations; what a great ride you've had!

Arguably the most comprehensive experimental detector system & collaboration to study hadron structure using complementary tools:
Muon (L,T) DIS, Hadron Scattering, DVCS and Drell-Yan

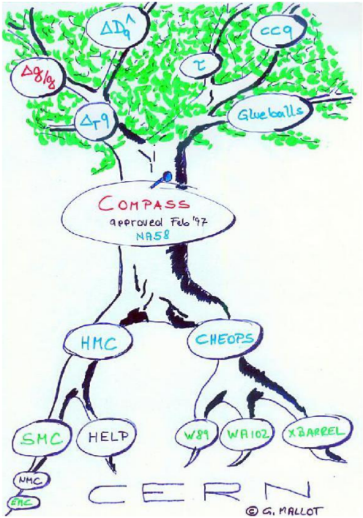
From 1995 (letter of intent) until to today:
~130 Diploma/Masters/Bachelor's Theses
~130 Ph.D. Theses
~10 Habilitation Theses
~75 Peer Reviewed Publications

A high bar for future experimental ventures

Slide courtesy A. Deshpande, IWHSS2022

COMPASS Proposal

Slide courtesy G. Mallot, IWHSS2022



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSLC 96-14
SPSC/P 297
March 1, 1996

PROPOSAL

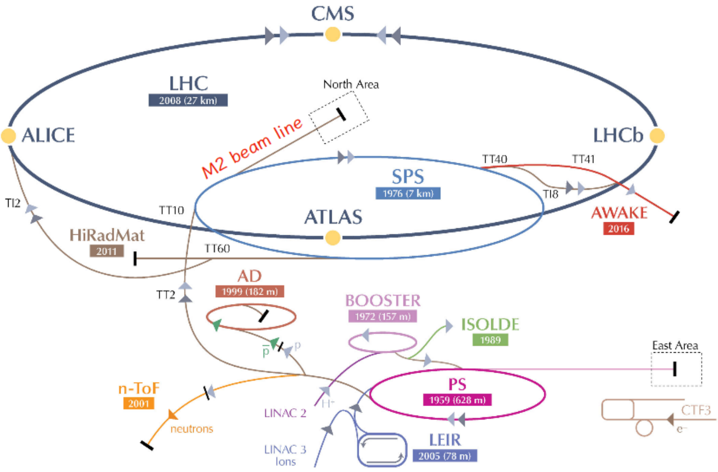
Common Muon and Proton Apparatus for Structure and Spectroscopy

The COMPASS Collaboration

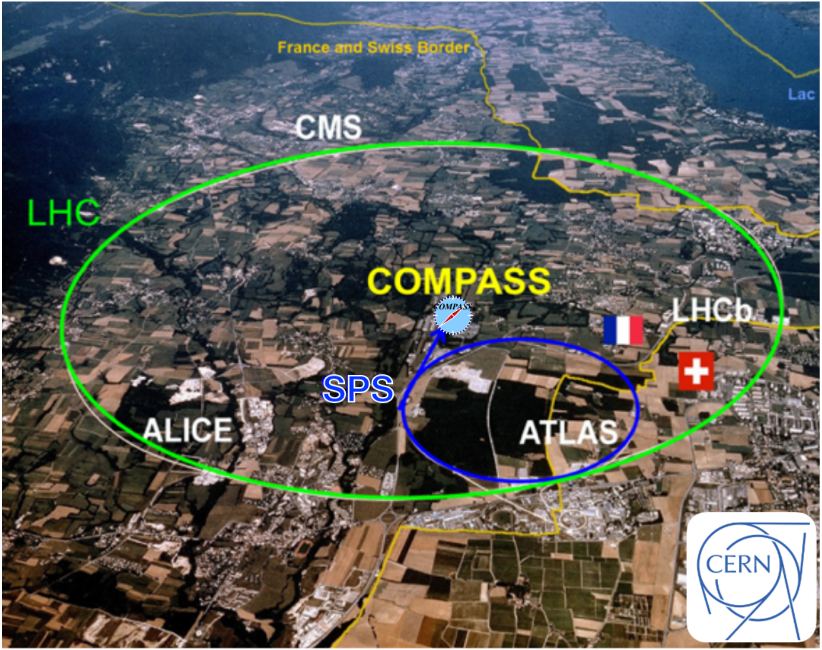
Abstract

We propose to study hadron structure and hadron spectroscopy with high-rate hadron and muon beams and a new spectrometer to be built at the CERN SPS. The experiment can start up in 1999 and a program of physics measurements for an initial period of 5 more years is planned.

CERN acelerators and beam lines



The M2 beam line supplies muons ($\mu^{\pm}$) and hadrons ($\pi^{\pm}$, K$^{\pm}$, p, $\bar{\mathrm{p}}$) to the North Area.


France and Swiss Border
Lac
CMS
LHC
COMPASS
LHCb
SPS
ALICE
ATLAS
CERN

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

∼ 200 physicists, ∼ 25 institutes from 13 countries

A fixed-target experiment at the SPS at CERN

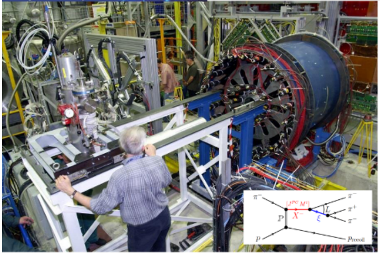
Muon programme	Hadron programme
Spin dependent structure functions g_1	Primakoff effect, π and K polarisabilities
Gluon polarisation in the nucleon	Exotic (multiquark) states, glueballs
Quark polarisation distributions	(Double) charmed barions
Transversity	Precision studies of light meson spectrum
Vector meson production	
Λ polarisation	
DVCS/GPD	Drell–Yan process on a polarised target

Panorama of COMPASS data taking

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 - 2022)	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 – 2022	nucleon structure μ–d, 160 GeV, T polarised target

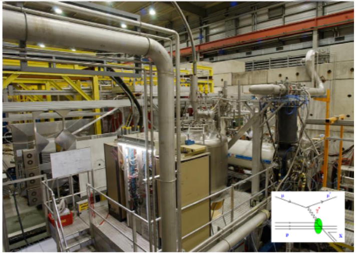
Versatile COMPASS in EHN2

Slide courtesy G. Mallot, PBC 2017



Hadron Spectroscopy & Polarisability

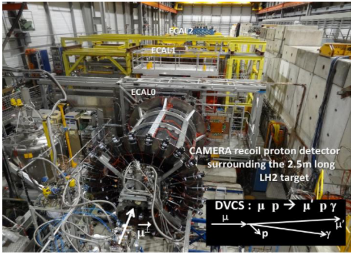
COMPASS-I
1997-2011



Polarised SIDIS

Polarised Drell-Yan

COMPASS-II
2012-2018



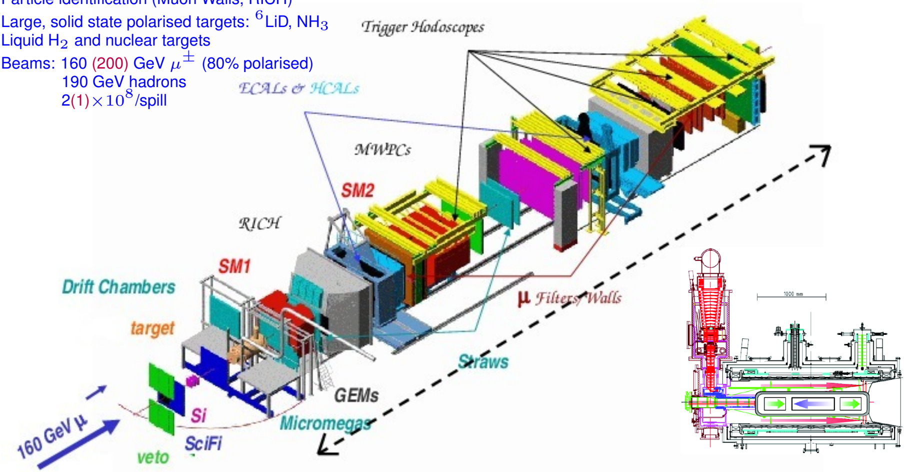
DVCS (GPDs) + unp. SIDIS

Versatile COMPASS facility at the M2 beam line at CERN

COMPASS Spectrometer (muon run)

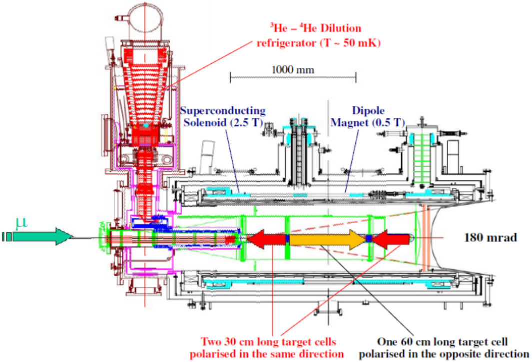
Nucl. Instr. Meth. A577 (2007) 455

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
$2(1)\times10^{8}$/spill

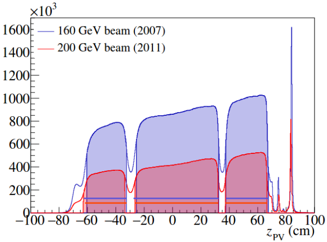


Examples of COMPASS facility performance:

target in the muon setup



Interaction point position in the NH_3 target, Q^2 <1 (GeV/c)^2



* 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)
* Polarisation reversal by $\vec{B}$ rotation

Courtesy A.S. Nunes, PhD, University of Lisbon, 2017

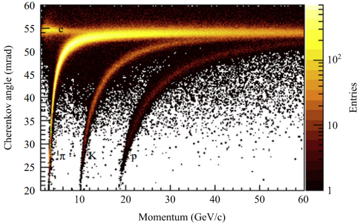
Examples of COMPASS facility performance:

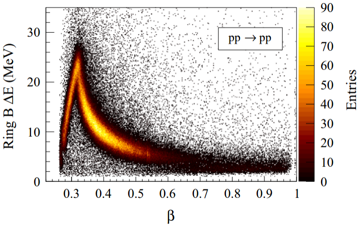
RICH and RPD in the hadron beam setup; kinem.acceptance

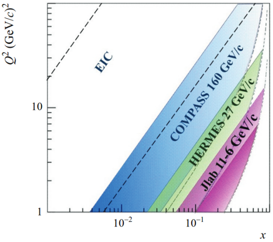
RICH particle identification, C_4F_{10} radiator

Proton Recoil Detector (outer ring)

COMPASS, NIM A **779** (2015) 69



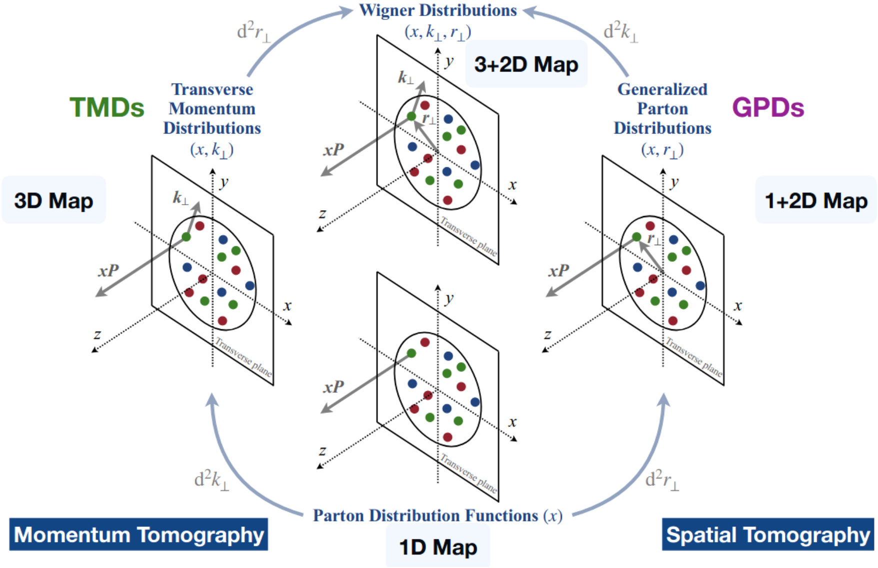




Lowest x in COMPASS (and SMC)

Nucleon in 1-D, 3-D and 5-D

Nucleon partonic structure (courtesy of Yu-Hsiang Lien, COMPASS)

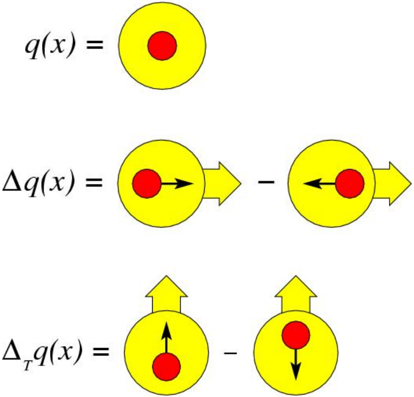


Nucleon in 1-D

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

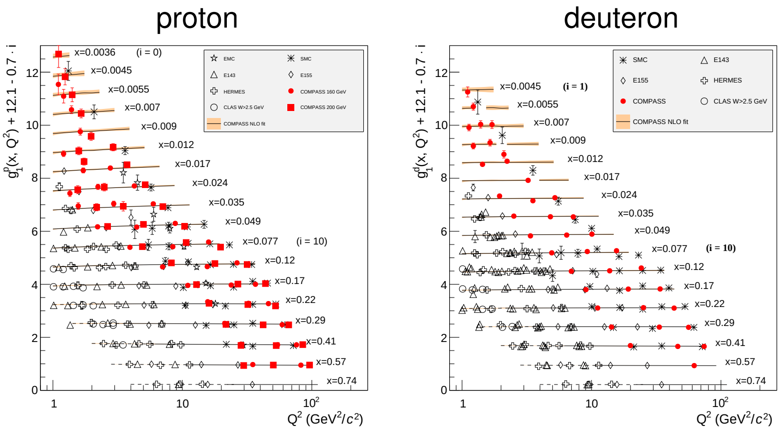
Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow$ $\mathbf{h_1(x, Q^2)}$).

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.

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

COMPASS NLO QCD fit to the world data at $W^2 > 10$ (GeV/c^2)^2

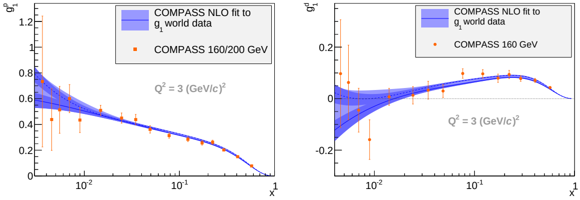
dashed line: extrapolation to $W^2 < 10$ (GeV/c^2)^2



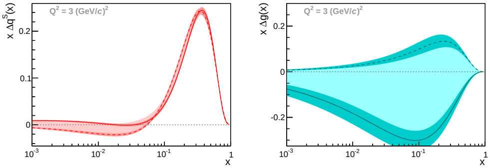
Phys.Lett.B753(2016)18 COMPASS PL B769 (2017) 034

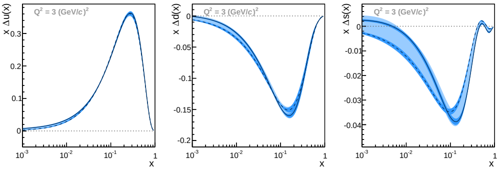
COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

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 ?



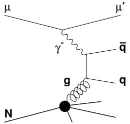


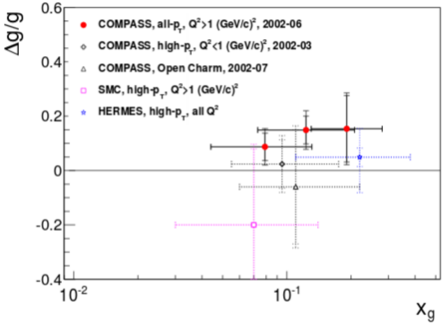
- $-1.5 < \Delta G < 0.5$, poorly constraint $\Longrightarrow$ "direct methods"
- $\sigma_{stat.}$ (dark bands) $\ll \sigma_{syst.}$ (light b.)

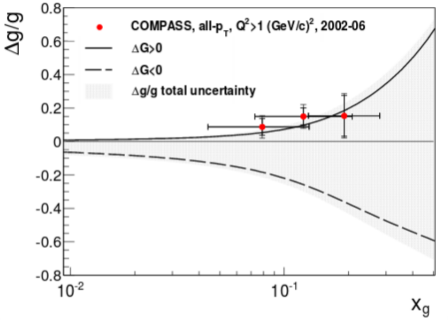
COMPASS PL B **753** (2016) 18

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)): $A_{\gamma N}^{PGF} \approx \langle a_{LL}^{PGF} \rangle \frac{\Delta g}{g}$







COMPASS from SIDIS on d for any $(p_T)_h$ and at LO:

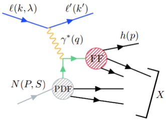
$$\Delta g/g = 0.113 \pm 0.038(\text{stat.}) \pm 0.036(\text{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ (\text{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

Clearly positive gluon polarisation but not large!

COMPASS, EPJC 77(2017) 209

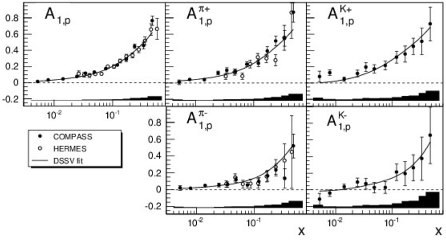
Semi-inclusive asymmetries and parton distributions

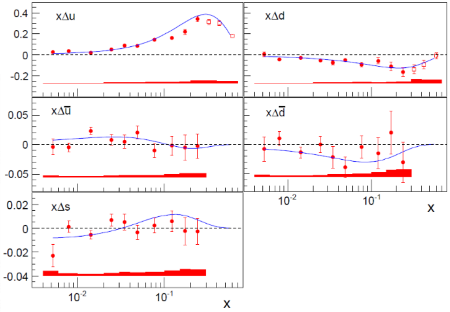
- COMPASS: measured on both proton and deuteron targets for identified π^+, π^- and (for the first time) K^+, K^-



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

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

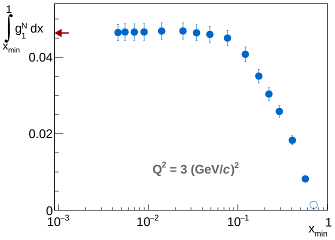




- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV (without these results) describes the data well.

First moments of g_1 and singlet axial charge a_0

COMPASS PL B769 (2017) 034



- First moments $\Gamma_1^p, \Gamma_1^d, \Gamma_1^N$
  where $\Gamma_1^i = \int_0^1 g_1^i(x, Q^2)\mathrm{d}x$
- In particular:
  $$\Gamma_1^N(Q^2) = \frac{1}{36}\left[4a_0 C_S(Q^2) + a_8 C_{NS}(Q^2)\right]$$
  $$= \int_0^1 \frac{g_1^d(x, Q^2)}{1 - 1.5\omega_D}\mathrm{d}x$$
- In the $\overline{\mathrm{MS}}$: $a_0 = \Delta\Sigma = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})$
- Γ_1^N approaches asymptotic value already at Q^2 = 3 (GeV/c)^2
- From COMPASS data alone:
  $\Gamma_1^N(Q^2$ = 3 (GeV/c)^2) = 0.046 $\pm 0.002_{\mathrm{stat.}} \pm 0.004_{\mathrm{syst.}} \pm 0.005_{\mathrm{evol.}}$
- From COMPASS data alone (and a_8 from PRD 82 (2010) 114018):
  $a_0(Q^2$ = 3 (GeV/c)^2)= 0.32 $\pm 0.02_{\mathrm{stat.}} \pm 0.04_{\mathrm{syst.}} \pm 0.05_{\mathrm{evol.}}$
  (consistent with value from the COMPASS NLO QCD fit of world data).

Non-singlet structure function, $g_1^{\mathrm{NS}}(x, Q^2)$

- Non-singlet structure function:

$$g_1^{\mathrm{NS}} = g_1^{\mathrm{p}}(x, Q^2) - g_1^{\mathrm{n}}(x, Q^2)$$
$$= 2\left[g_1^{\mathrm{p}}(x, Q^2) - g_1^{\mathrm{N}}(x, Q^2)\right]$$

- Its moment connected to the Bjorken sum rule:

$$\Gamma_1^{\mathrm{NS}}(Q^2) = \int_0^1 g_1^{\mathrm{NS}}(x, Q^2)\mathrm{d}x = \frac{1}{6}\left|\frac{g_{\mathrm{A}}}{g_{\mathrm{V}}}\right| C_1^{\mathrm{NS}}(Q^2)$$

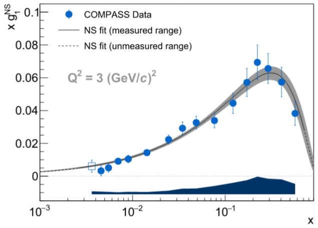
- g_1^{NS} calculated, NLO QCD fitted (only Δq_3), evolved to Q^2= 3 (GeV/c)^2 and fit-extrapolated $x \to 0, 1$:

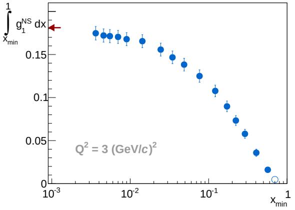
$$\Gamma_1^{\mathrm{NS}} = 0.192 \pm 0.007_{\mathrm{stat.}} \pm 0.015_{\mathrm{syst.}}$$
$$\left|\frac{g_{\mathrm{A}}}{g_{\mathrm{V}}}\right| = 1.29 \pm 0.05_{\mathrm{stat.}} \pm 0.10_{\mathrm{syst.}}$$

- Neutron β decay gives: $|g_{\mathrm{A}}/g_{\mathrm{V}}| = 1.2701 \pm 0.002$

PDG, PRD86 (2012) 010001

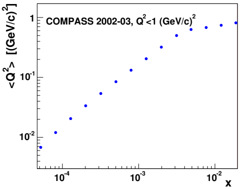
COMPASS PL B753 (2016) 18

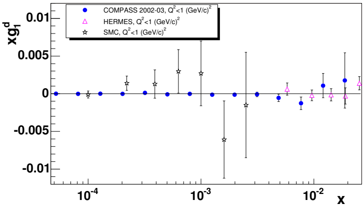




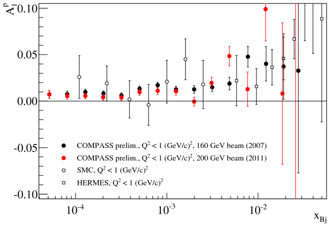
- This validates the Bjorken sum rule with an accuracy of 9%

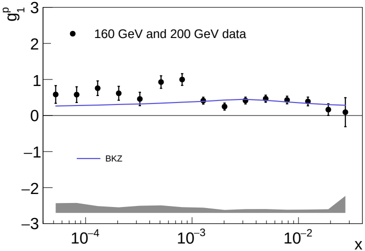
g_1^{N} in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)





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





COMPASS PL B 781 (2018) 464

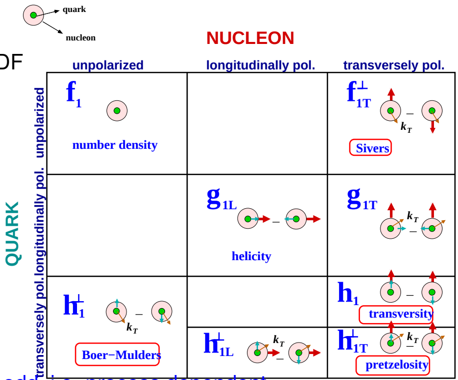
Spin effects in g_1^{d} at low x and Q^2 absent ? Very clear spin effects in g_1^{p} at low x and Q^2

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$^{\mathrm{target}}$



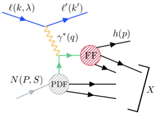
- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

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

(follows from QCD gauge invariance)

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

THE 18 SIDIS STRUCTURE FUNCTIONS



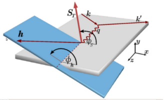
Unpolarized structure function

$f_1 \otimes D_1$

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

Sivers structure function

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

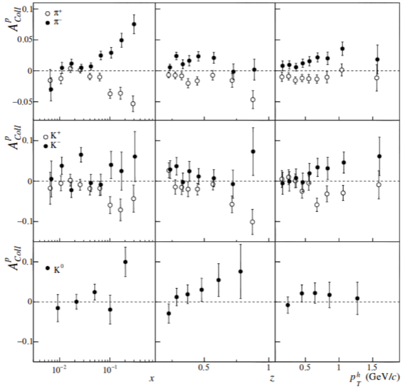


Collins structure function

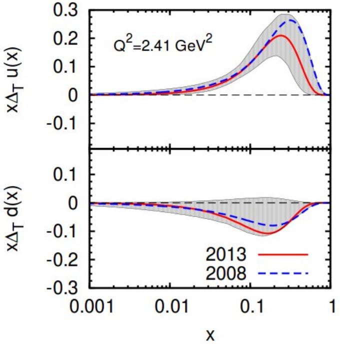
$h_1 \otimes H_1^{\perp}$

Slide courtesy A. Bacchetta, IWHSS2022 (with changes)

Results for Collins asymmetry for protons $\Longrightarrow \Delta_T q$



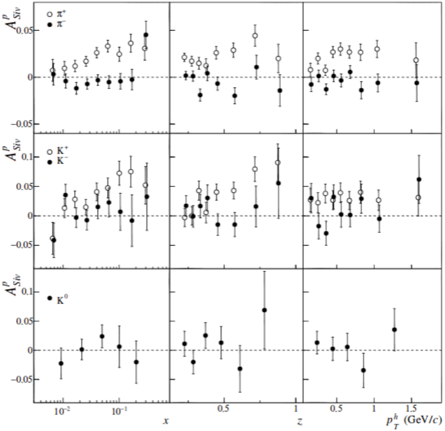
COMPASS, Phys.Lett. B744 (2015) 250



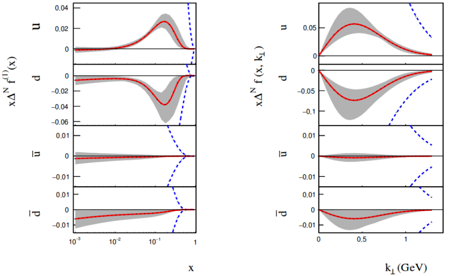
M. Anselmino et al., Phys.Rev. D87 (2013) 094019

- 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!)
- but negligible for the deuteron
- COMPASS data on p,d + HERMES data on p + BELLE on e$^+$e$^-$: $\Longrightarrow \Delta_T u,\ \Delta_T d$

Results for the Sivers asymmetry for protons



First moment of Sivers function vs x at $Q^2 = 2.4$ GeV^2
and Sivers function vs k_T at $x = 0.1$ and $Q^2 = 2.4$ GeV^2



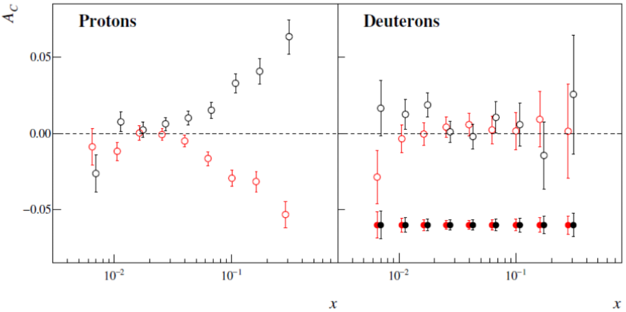
COMPASS, Phys.Lett. B744 (2015) 250

M.Anselmino et al.,JHEP 1704(2017)046

- 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 2022 run with transverse deuteron target

- Goal: measurement of h_1^d, h_1^p and TMD PDFs for separate flavours
- Optimal separation $\Longrightarrow$ comparable statistics on d (^{6}LiD) and p (NH_3) targets
- COMPASS d data sets have 4 times less statistics than p
- Expected: deuteron statistics $\approx$ proton statistics on d$^{\uparrow}$.



Collins asym. presently

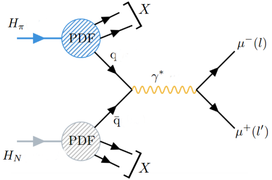
Collins asym. accuracy expected

CERN-SPSC-2017-034

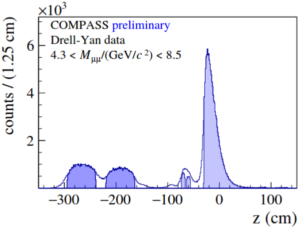
(red - positive hadrons, black - negative hadrons)

First ever

polarised Drell-Yan reaction measurements



- $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$
  π^- beam of 190 GeV/c, $\langle I \rangle \approx 7 \times 10^7 s^{-1}$, from CERN SPS
- Transversely polarized NH_3 target (2×55 cm)
  + Al target (7 cm) + W beam plug (120 cm)

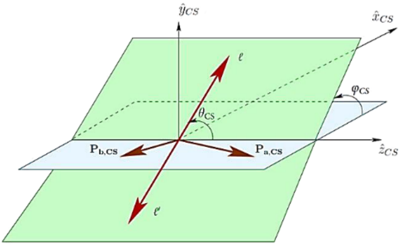


SIDIS and Drell-Yan compatibility

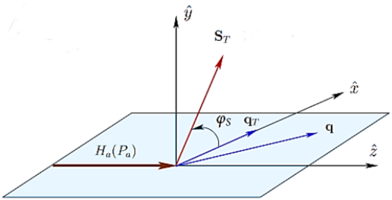
$$A_{SIDIS} \propto PDF_p \otimes FF \qquad A_{DY} \propto PDF_\pi \otimes PDF_p$$

SIDIS		DY
$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$	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)

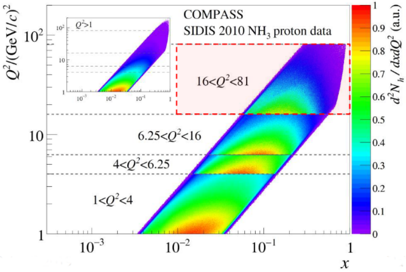


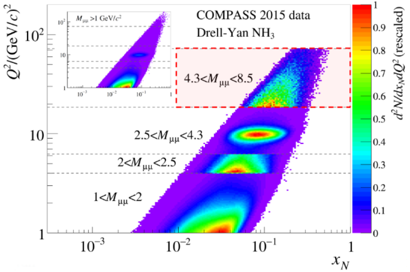
Collins-Soper ref. frame (CS)



Target rest frame (S)

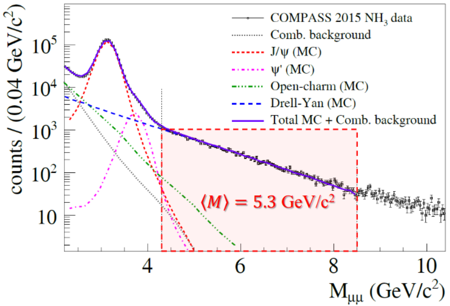
SIDIS and Drell-Yan acceptances in COMPASS

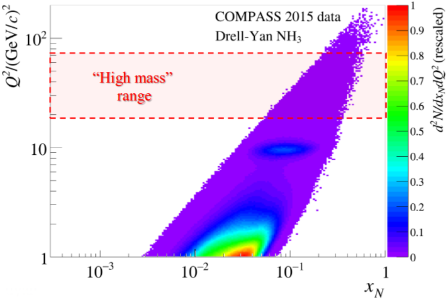


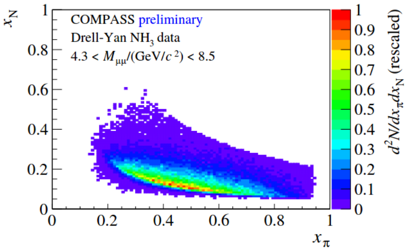


- COMPASS goals: test of the TMD PDFs universality; test of the Lam-Tung relation.
- In COMPASS, comparable (x, Q^2) acceptance in SIDIS and DY. Unique!
- In both cases, cross-sections depend on (polar and azimuthal) asymmetries described by contributions of twist-2 (or higher) TMD PDFs.
- SIDIS and DY reactions for transversaly polarised proton analysed and the asymmetries measured in bins of x_N, x_π, x_F, q_t
- Measured asymmetries agree with models

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

COMPASS TSA results

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

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

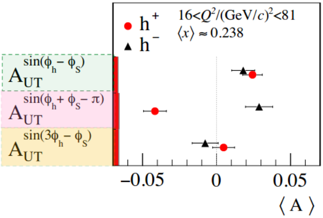
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^h$ ← **Sivers** → $A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$

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

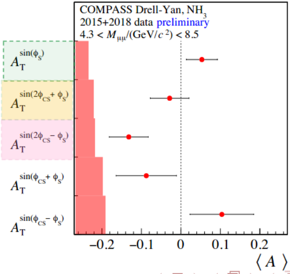
$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^q \otimes H_{1q}^{\perp h}$ ← **Transversity** → $A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$

(courtesy of R. Longo, COMPASS)

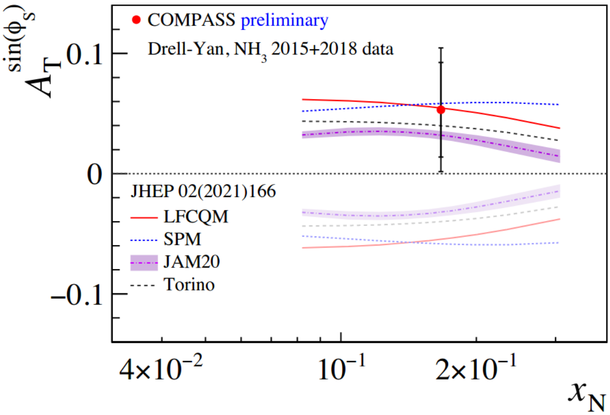
COMPASS SIDIS Data,
PLB 770 (2017) 138



NEW RESULTS!



COMPASS DY results: universality of the Sivers TMD



sign change

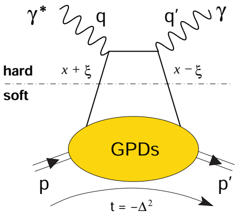
no sign change

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

Nucleon in 1+2D

$\Longrightarrow$ Generalised Parton Distributions (GPD)

Access GPD through the DVCS/DVMP mechanism

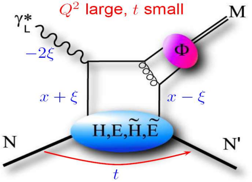


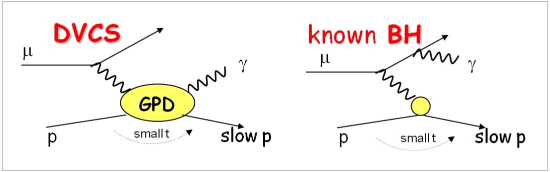
Bjorken limit:
$Q^2 \to \infty$,
fixed $x_{\mathrm{B}}, t \implies |t|/Q^2$ small

- 4 GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons plus 4 chiral odd ones $(H_T, E_T, \widetilde{H}_T, \widetilde{E}_T)$
- DVMP: factorisation proven for σ_L only
- All depend on 4 variables: x, ξ, t, Q^2; DIS @ $\xi = t = 0$; Later Q^2 dependence omitted. Careful ! Here $x \neq x_{\mathrm{B}}$!
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions
- $H^q(x, 0, 0) = q(x), \quad \widetilde{H}^q(x, 0, 0) = \Delta q(x)$

- H, E accessed in vector meson production *via* A_{UT} asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* A_{UT} asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over x give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors respectively.
- Important: $J_z^q = \frac{1}{2} \int dx\, x\, [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)] = \frac{1}{2}\Delta\Sigma + L_z^q$ (X. Ji)

DVCS/DVMP: $\mu p \to \mu p \gamma(M)$; observables

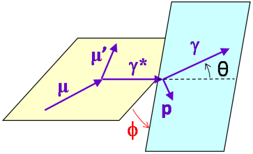




$$\mathrm{d}\sigma^{\mu p \to \mu p \gamma} = \mathrm{d}\sigma^{\mathrm{BH}} + (\mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}}) + e_\mu(\mathrm{Re}I + P_\mu \mathrm{Im}I)$$

Observables for unpolarised target (Phase 1):

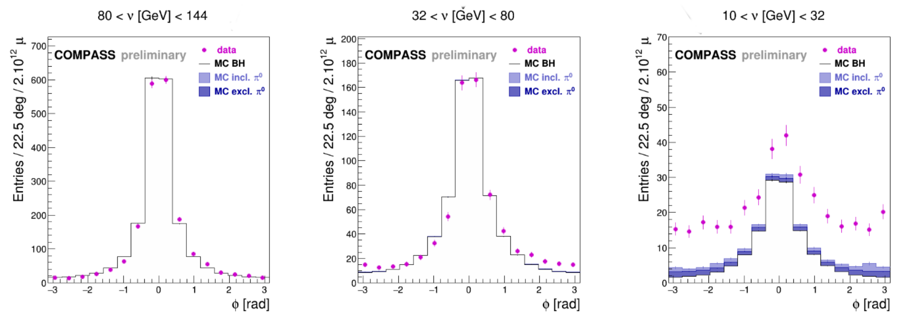
- $\mathcal{S}_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(\mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + e_\mu P_\mu \mathrm{Im}I\right)$
- $\mathcal{D}_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2\left(P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}} + e_\mu \mathrm{Re}I\right)$
- $\mathcal{A}_{\mathrm{CS,U}} \equiv \frac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \frac{\mathcal{D}_{\mathrm{CS,U}}}{\mathcal{S}_{\mathrm{CS,U}}}$
- Each term ϕ-modulated
  If ϕ-dependence integrated over $\Longrightarrow$ twist-2 DVCS contribution;
  if ϕ-dependence analysed: $\Longrightarrow$ Im $(F_1 H)$ and Re $(F_1 H)$; H dominance @ COMPASS kin.



Analogously for transversely polarised target (Phase 2): $\mathcal{S}_{\mathrm{CS,T}}, \mathcal{D}_{\mathrm{CS,T}}, \mathcal{A}_{\mathrm{CS,T}} \Longrightarrow E$

COMPASS DVCS signal at E_μ = 160 GeV; $S_{CS,U}$

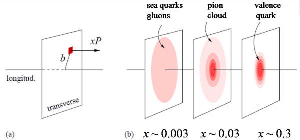
Pure BH	Interference BH/DVCS	DVCS (above the BH)
$\langle x \rangle \approx 0.0085$	$\langle x \rangle \approx 0.020$	$\langle x \rangle \approx 0.063$
$Q^2 \approx 1.8$ GeV^2	$Q^2 \approx 2.0$ GeV^2	$Q^2 \approx 2.1$ GeV^2



2012+2016 (part of) data

Approximately 5× higher statistics from 2016 still being analysed
2012 data published in Phys.Lett.B **793** (2019) 188

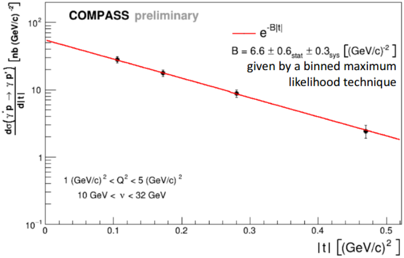
COMPASS DVCS signal,...cont'd

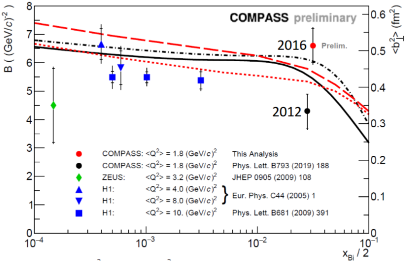


- Nucleon transverse imaging ("tomography"):

From

$$S_{CS,U} \Longrightarrow \frac{d\sigma^{DVCS}}{dt} \propto e^{-B(x_B)|t|} \quad \text{where at low } x_B : B(x_B) \approx \frac{1}{2}\langle r_\perp^2(x_B)\rangle$$





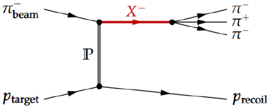
Analysis of the 2016 data (ongoing!) is more refined; binning is in 3 or 4 variables (Q^2, t, ν, ϕ)

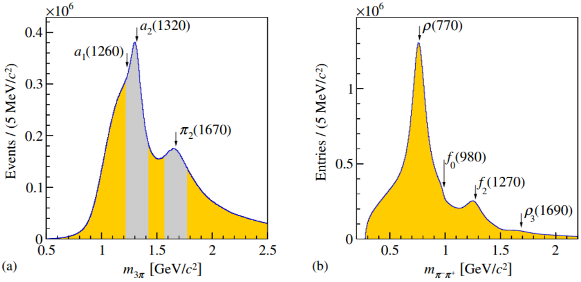
To determine the full x_{Bj} dependence of the transverse extension of partons, a global analysis of DVCS data of HERA, JLab, CERN needed.

QCD at low energies

$\Longrightarrow$ hadron spectroscopy at COMPASS

Example: production of light mesons at COMPASS by 190 GeV π^-p(A)

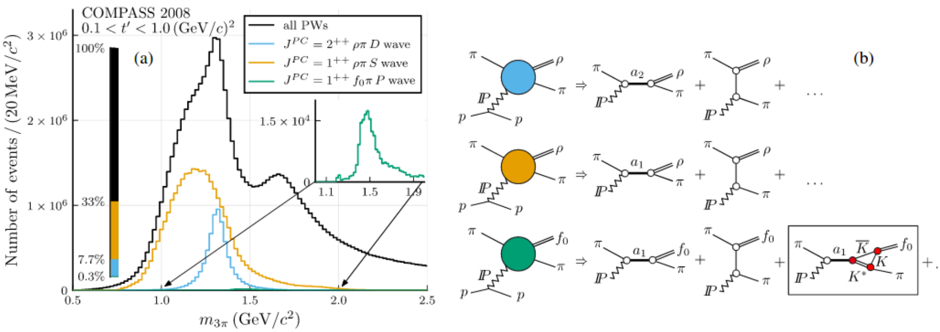




COMPASS, PR D**95** (2017) 032004

- Diffraction golden channel (“workhorse” reaction)
- About 150×10^6 events collected (more then $10\times$ the statistics of other experiments)
- Most detailed and comprehensible analysis of $\pi^-\pi^-\pi^+$ final state so far;
  $\Longrightarrow$ several mesons appearing in 2π and 3π spectra measured
- AMBER (and RF separated beam): high precision spectroscopy of strange mesons
  $\Longrightarrow$ rewrite the PDG tables for strange mesons, in a single and self-consistent meas.

Example: resonance-like $a_1(1420)$ in π^-+p→ $\pi^-\pi^-\pi^+$+p

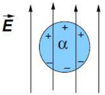


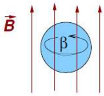
COMPASS PRL**127** (2021) 082501

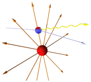
- An incredibly tiny signal extracted
- The signal consistent with prediction of $a_1(1260)$ decay via triangle singularity (Landau & Cutkosky, 1959) (other ways of distinguishing between a triangle singularity and resonance are under study)

COMPASS pion polarisability via Primakoff process

- Electric (α) and magnetic (β) polarisabilities (measured in fm^3):

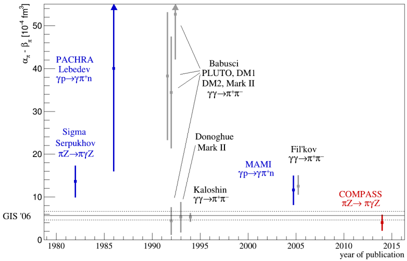






COMPASS: $\pi^- \mathrm{Ni} \to \pi^- \gamma\, \mathrm{Ni}$
(nucleus is a source of quasi-real γ)

- For an extended object they are related to inner forces determinig the substructure $\longrightarrow$ QCD at low energy (e.g. chiral perturbation theory, χPT)
- Polarisabilities measured through modifications of *bremsstrahlung* (or Primakoff) reaction.



assuming $\alpha_\pi + \beta_\pi = 0$:
$\alpha_\pi = (2.0 \pm 0.6 \pm 0.7) \times 10^{-4}\ \mathrm{fm}^3$
χPT prediction:
$\alpha_\pi = (2.9 \pm 0.5) \times 10^{-4}\ \mathrm{fm}^3$

COMPASS, PRL **114** (2015) 062002
Cartoons courtesy J. Friedrich;
plot: T. Nagel, PhD TUM, 2012 (COMPASS)

Another definite test of χPT, $F_{3\pi}$, accessible in a Primakoff $\pi^-\gamma \to \pi^-\pi^0$, measured recently by COMPASS together with $\Gamma_{\rho\to\pi\gamma}$: (10.3±0.1±0.6) GeV $^{-3}$, in agreement with χPT (9.78±0.05) GeV^{-3} MORE DATA TO COME!

COMPASS time axis (A. Bacchetta, IWHSS2022)

Old Chinese compass

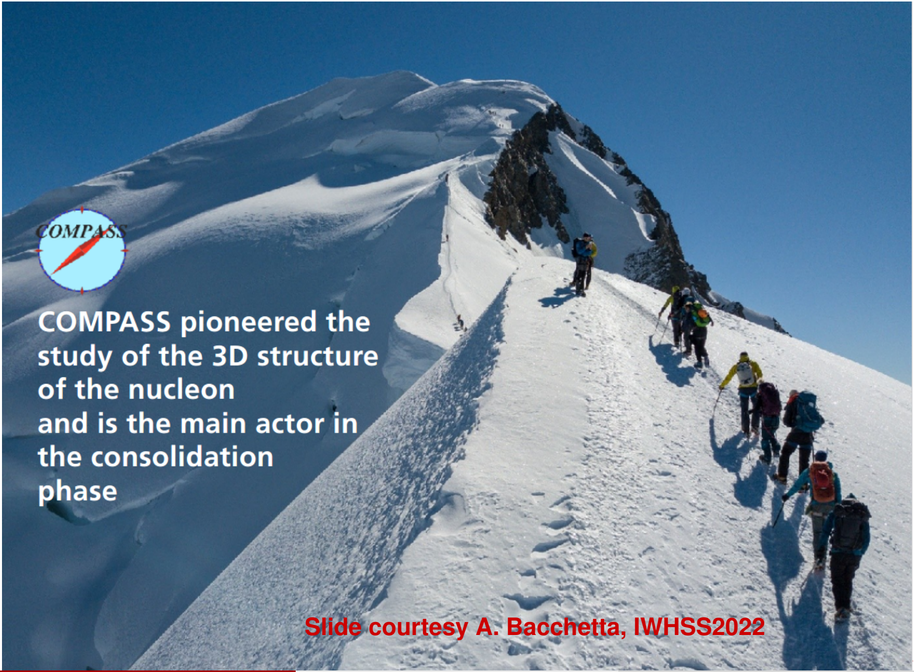
Exploration

Hand-held compass

Consolidation

GPS compass

Precision


COMPASS
COMPASS pioneered the study of the 3D structure of the nucleon
and is the main actor in the consolidation phase
Slide courtesy A. Bacchetta, IWHSS2022