COMPASS physics programme: highligts and recent results

Fulvio Tessarotto (INFN. – Trieste)
on behalf of the COMPASS Collaboration

The COMPASS Experiment at SPS

Spectroscopy

Longitudinal polarisation measurements

Trnsversity and TMD-dependent effects

Drell-Yan measurements

DVCS and DVMP

SLIDE MATERIAL FROM COMPASS COLLEAGUES

COMPASS at CERN

COMPASS at CERN

The COMPASS Collaboration

~ 200 physicists, ~ 25 institutes from 13 countries

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

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

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

International Workshop on Hadron Structure and Spectroscopy

IWHSS-2022 workshop (anniversary edition)

https://indico.cern.ch/event/1121975/

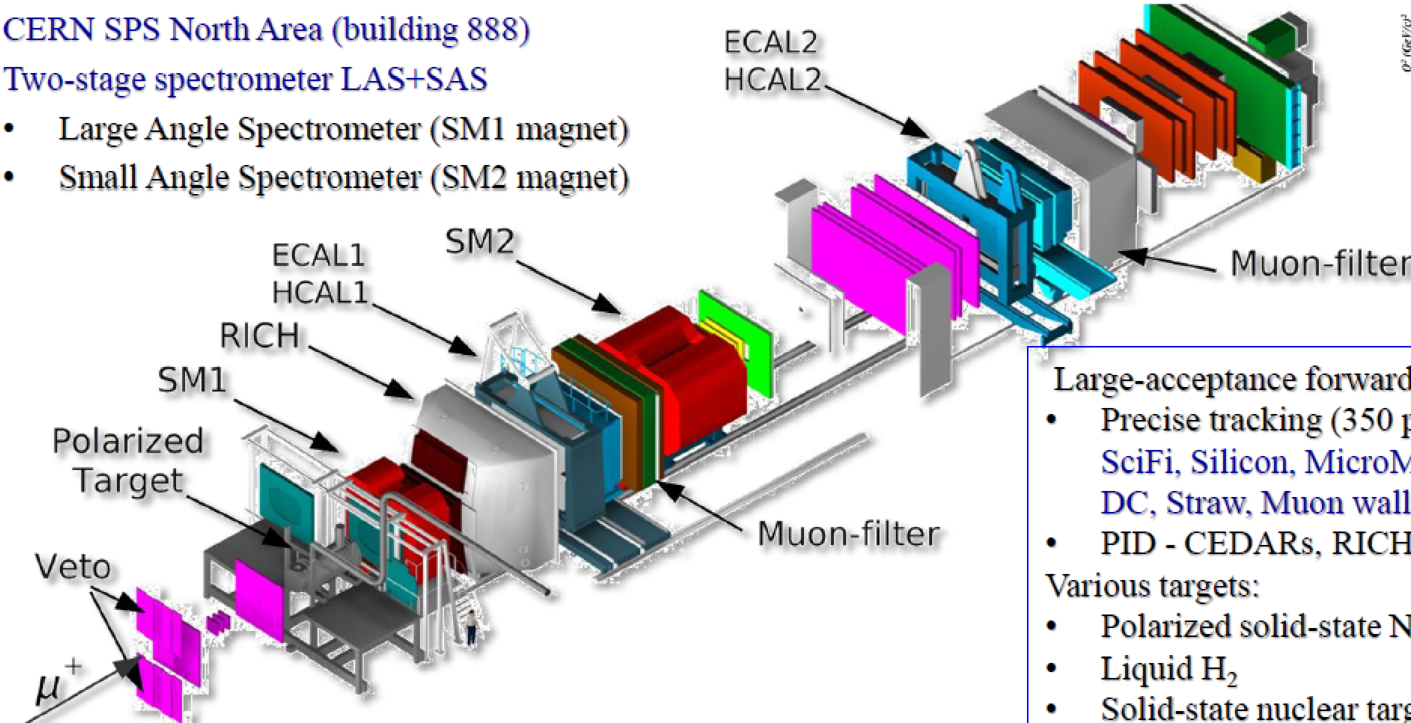
COMPASS experiemental setup

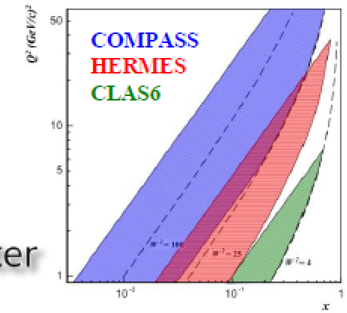
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

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





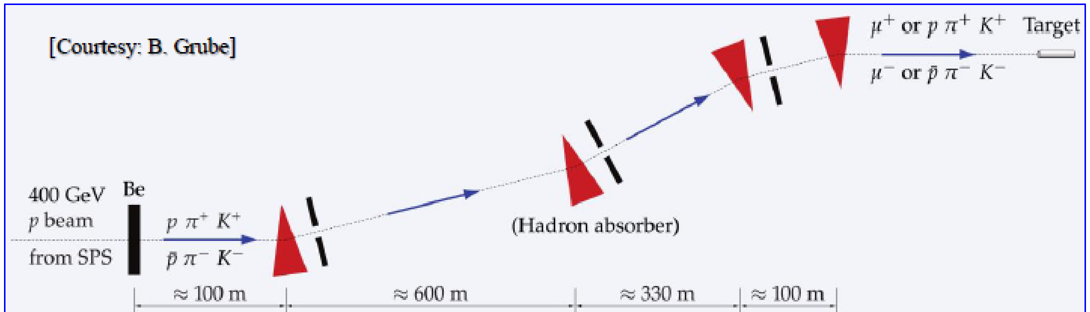
Large-acceptance forward spectrometer

- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon walls
- PID - CEDARs, RICH, calorimeters, MWs

Various targets:

- Polarized solid-state NH_3 or ^6LiD
- Liquid H_2
- Solid-state nuclear targets (e.g. Ni, W, Pb)

- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h⁻ beam: 97% π^-, 2% K^-, 1% $\bar{p}$
  - h⁺ beam: 75% p, 24% π^+, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized



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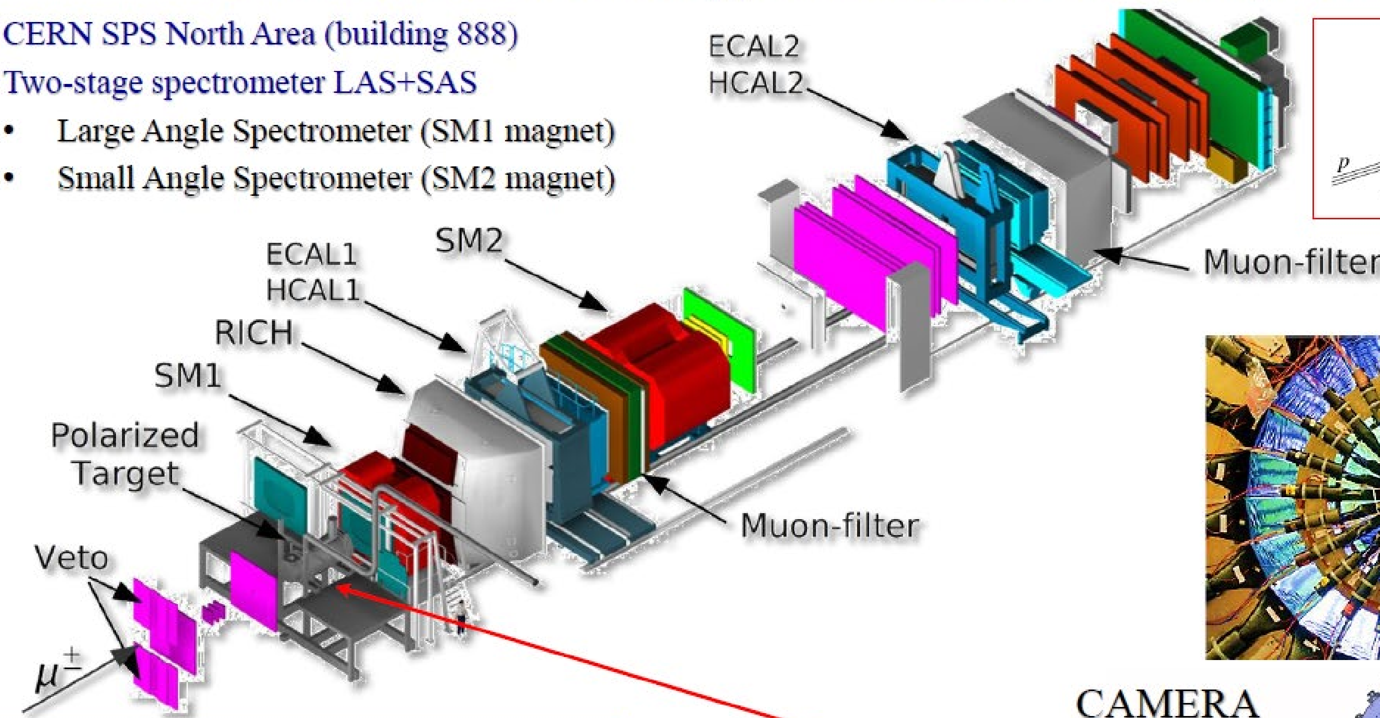
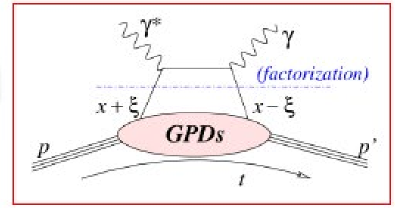
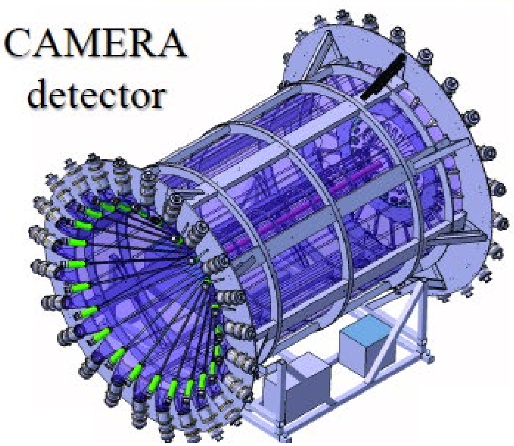




CAMERA detector



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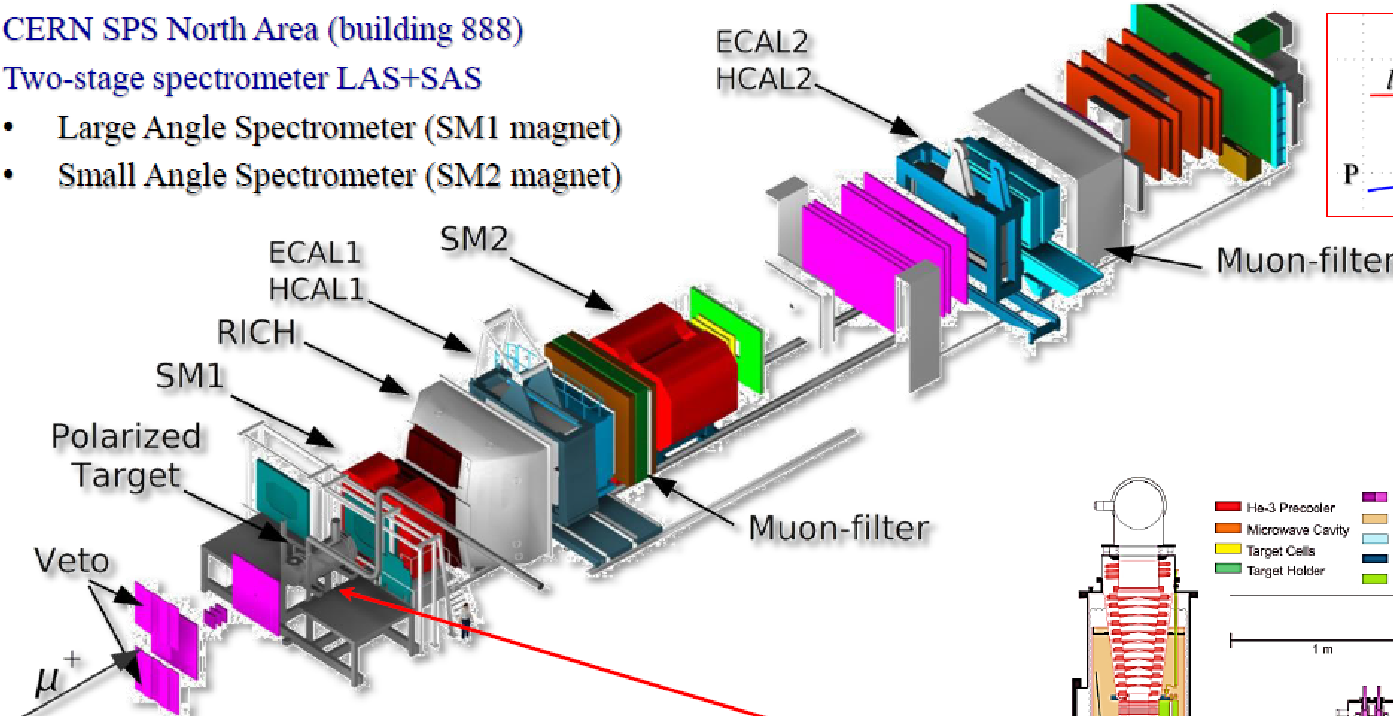

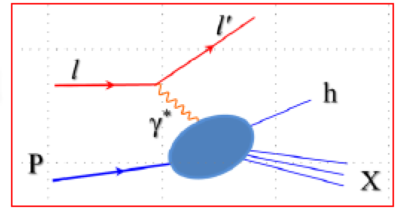

- Primary beam - 400 GeV p from SPS
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- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
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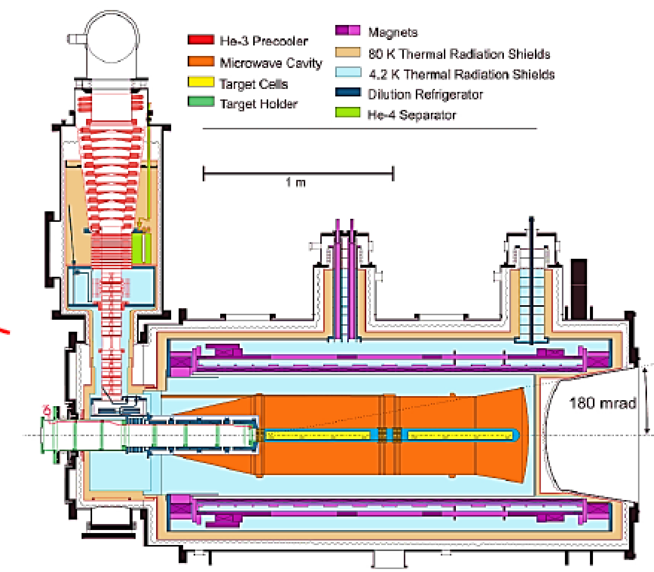
- 160 GeV tertiary muon beams
  - μ^+ longitudinally polarized



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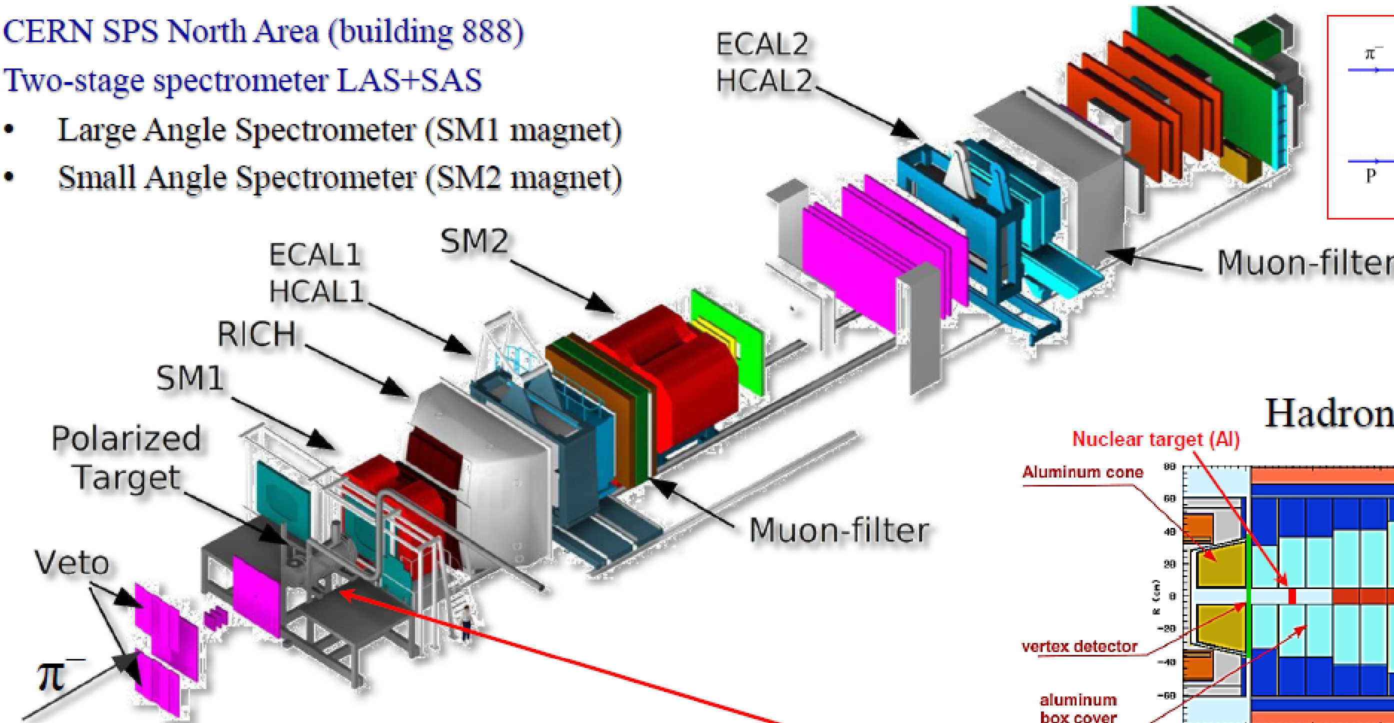
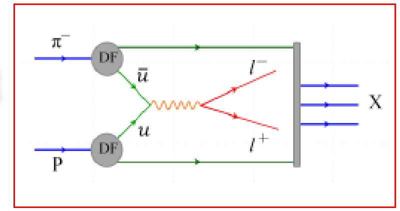
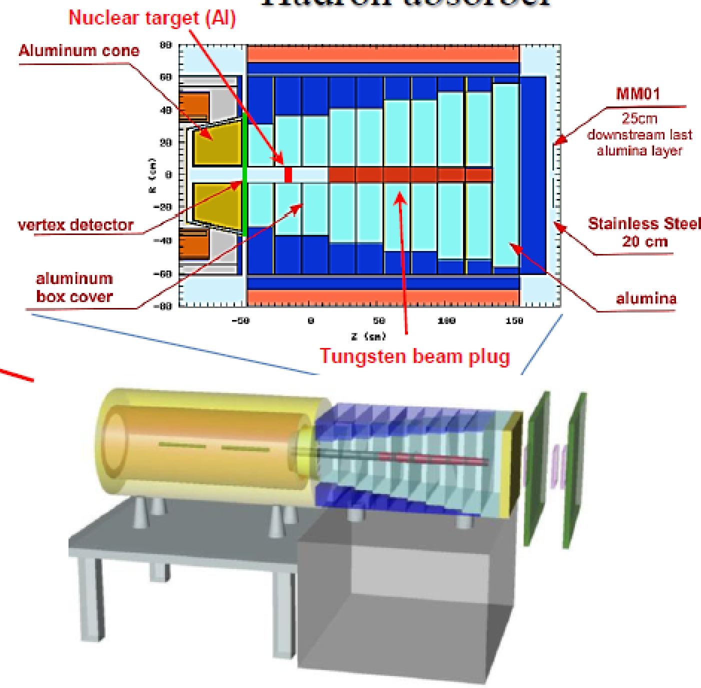




Hadron absorber



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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

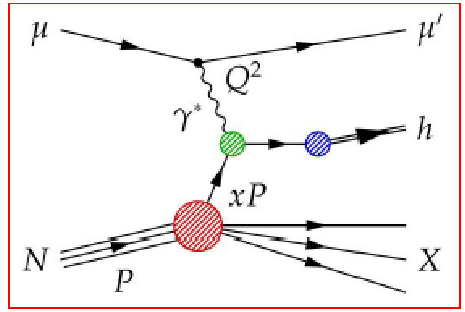
COMPASS physics program

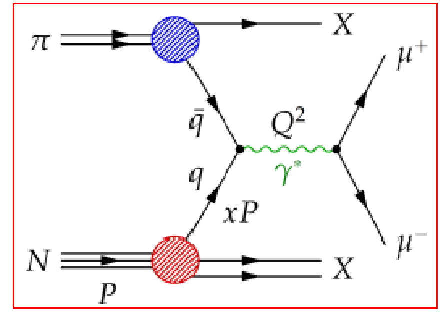
Increasing resolution scale (momentum transfer)

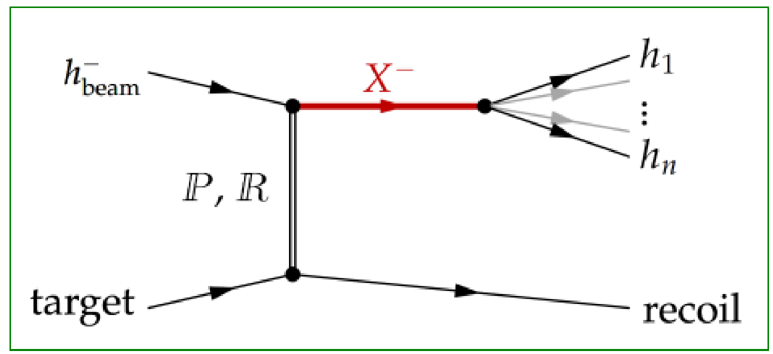
Nucleon structure
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

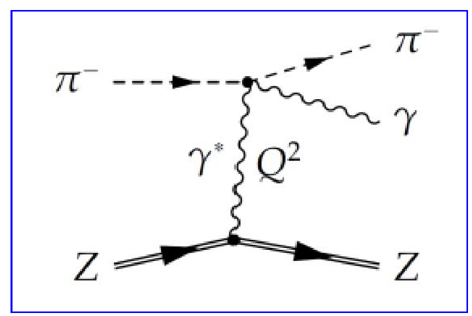
Hadron spectroscopy
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

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



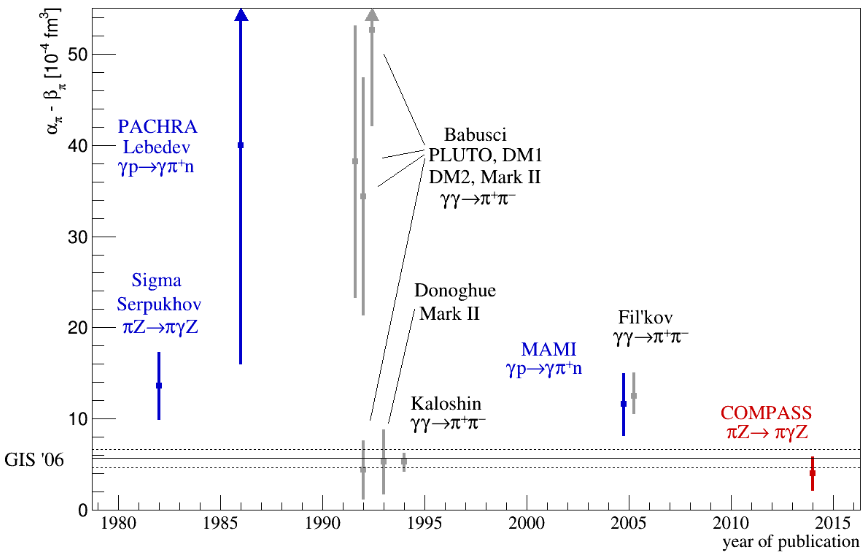






Chiral dynamics studies

PRL **114** (2015) 062002



T. Nagel, PhD TUM, 2012 (COMPASS)

Measurement of the Charged-Pion Polarizability

(COMPASS Collaboration)

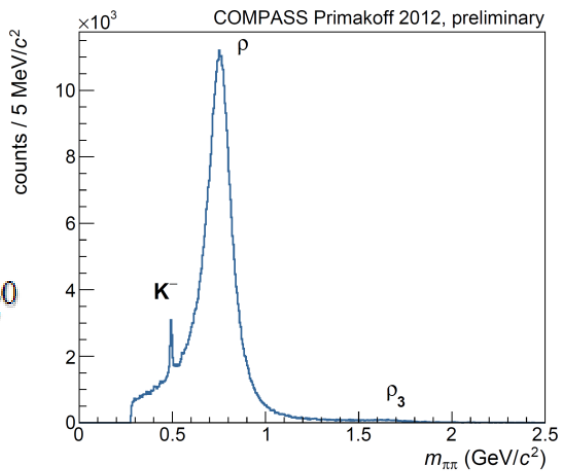
(Received 2 June 2014; revised manuscript received 24 December 2014; published 10 February 2015)

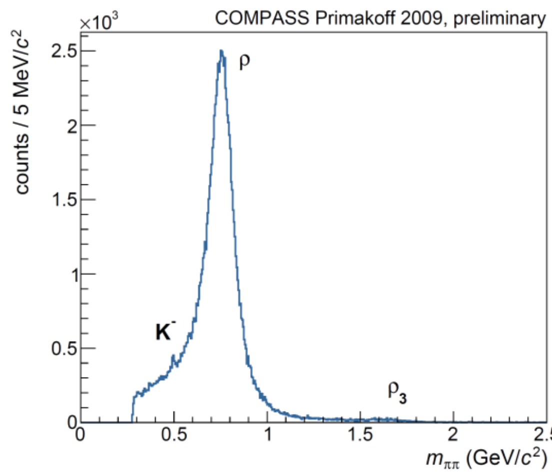
The COMPASS collaboration at CERN has investigated pion Compton scattering, $\pi^-\gamma \to \pi^-\gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^-\mathrm{Ni} \to \pi^-\gamma\mathrm{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasireal photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, $Q^2 < 0.0015\ (\mathrm{GeV}/c)^2$. From a sample of 63 000 events, the pion electric polarizability is determined to be $\alpha_\pi = (2.0 \pm 0.6_{\rm stat} \pm 0.7_{\rm syst}) \times 10^{-4}\ \mathrm{fm}^3$ under the assumption $\alpha_\pi = -\beta_\pi$, which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong interaction that has been addressed since long by various methods with conflicting outcomes. While this result is in tension with previous dedicated measurements, it is found in agreement with the expectation from chiral perturbation theory. An additional measurement replacing pions by muons, for which the cross-section behavior is unambiguously known, was performed for an independent estimate of the systematic uncertainty.

$$\alpha_\pi = (2.0 \pm 0.6_{\rm stat} \pm 0.7_{\rm syst}) \times 10^{-4}\ \mathrm{fm}^3$$

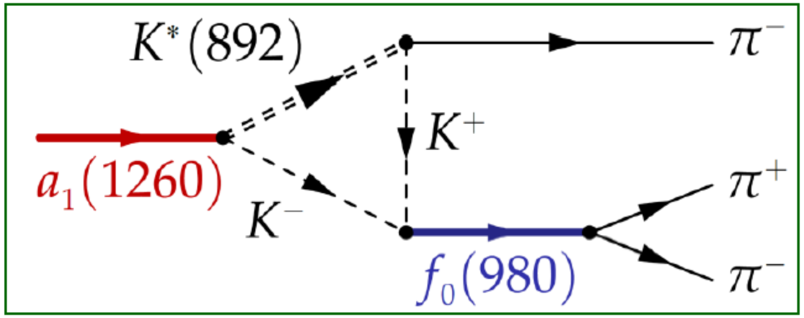
ongoing analysis:

study of chiral anomaly in $\pi^-\gamma \to \pi^-\pi^0$





Hadron spectroscopy



PHYSICAL REVIEW LETTERS **127,** 082501 (2021)

Triangle Singularity as the Origin of the $a_1(1420)$

(Received 3 July 2020; revised 4 May 2021; accepted 26 May 2021; published 18 August 2021)

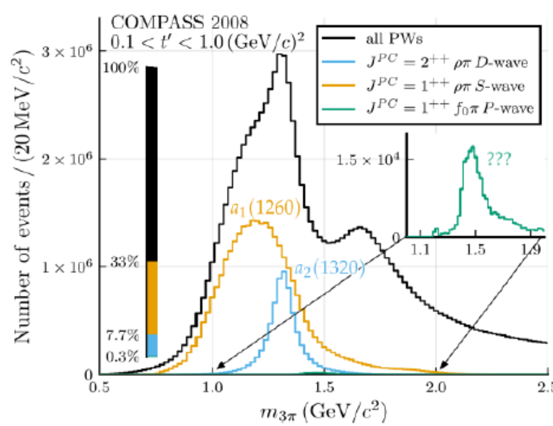
The COMPASS Collaboration experiment recently discovered a new isovector resonancelike signal with axial-vector quantum numbers, the $a_1(1420)$, decaying to $f_0(980)\pi$. With a mass too close to and a width smaller than the axial-vector ground state $a_1(1260)$, it was immediately interpreted as a new light exotic meson, similar to the X, Y, Z states in the hidden-charm sector. We show that a resonancelike signal fully matching the experimental data is produced by the decay of the $a_1(1260)$ resonance into $K^*(\to K\pi)\bar{K}$ and subsequent rescattering through a triangle singularity into the coupled $f_0(980)\pi$ channel. The amplitude for this process is calculated using a new approach based on dispersion relations. The triangle-singularity model is fitted to the partial-wave data of the COMPASS experiment. Despite having fewer parameters, this fit shows a slightly better quality than the one using a resonance hypothesis and thus eliminates the need for an additional resonance in order to describe the data. We thereby demonstrate for the first time in the light-meson sector that a resonancelike structure in the experimental data can be described by rescattering through a triangle singularity, providing evidence for a genuine three-body effect.

Hadron spectroscopy

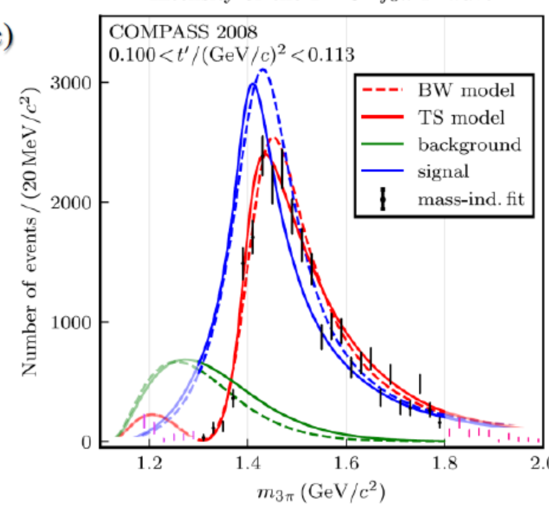
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

COMPASS, PRD 95 (2017) 032004

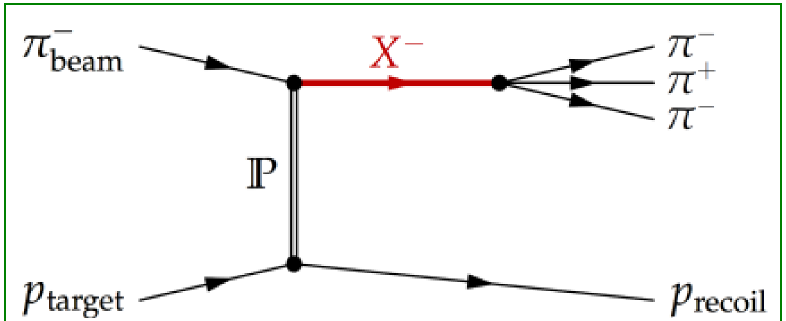
Surprising Signal with $J^{PC} = 1^{++}$ (1.4 GeV/c)



Intensity of the $1^{++}0^+$ $f_0\pi$ P-wave



Hadron spectroscopy



Hadron spectroscopy

- Diffractive $\pi(K)$ dissociation reaction with proton target
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- Search for exotic states

PHYSICAL REVIEW D **105,** 012005 (2022)

Exotic meson $\pi_1(1600)$ with $J^{PC} = 1^{-+}$ and its decay into $\rho(770)\pi$

(Received 6 August 2021; accepted 8 September 2021; published 12 January 2022)

We study the spin-exotic $J^{PC} = 1^{-+}$ amplitude in single-diffractive dissociation of 190 GeV/c pions into $\pi^-\pi^-\pi^+$ using a hydrogen target and confirm the $\pi_1(1600) \to \rho(770)\pi$ amplitude, which interferes with a nonresonant 1^{-+} amplitude. We demonstrate that conflicting conclusions from previous studies on these amplitudes can be attributed to different analysis models and different treatment of the dependence of the amplitudes on the squared four-momentum transfer and we thus reconcile these experimental findings. We study the nonresonant contributions to the $\pi^-\pi^-\pi^+$ final state using pseudodata generated on the basis of a Deck model. Subjecting pseudodata and real data to the same partial-wave analysis, we find good agreement concerning the spectral shape and its dependence on the squared four-momentum transfer for the $J^{PC} = 1^{-+}$ amplitude and also for amplitudes with other J^{PC} quantum numbers. We investigate for the first time the amplitude of the $\pi^-\pi^+$ subsystem with $J^{PC} = 1^{--}$ in the 3π amplitude with $J^{PC} = 1^{-+}$ employing the novel freed-isobar analysis scheme. We reveal this $\pi^-\pi^+$ amplitude to be dominated by the $\rho(770)$ for both the $\pi_1(1600)$ and the nonresonant contribution. These findings largely confirm the underlying assumptions for the isobar model used in all previous partial-wave analyses addressing the $J^{PC} = 1^{-+}$ amplitude.

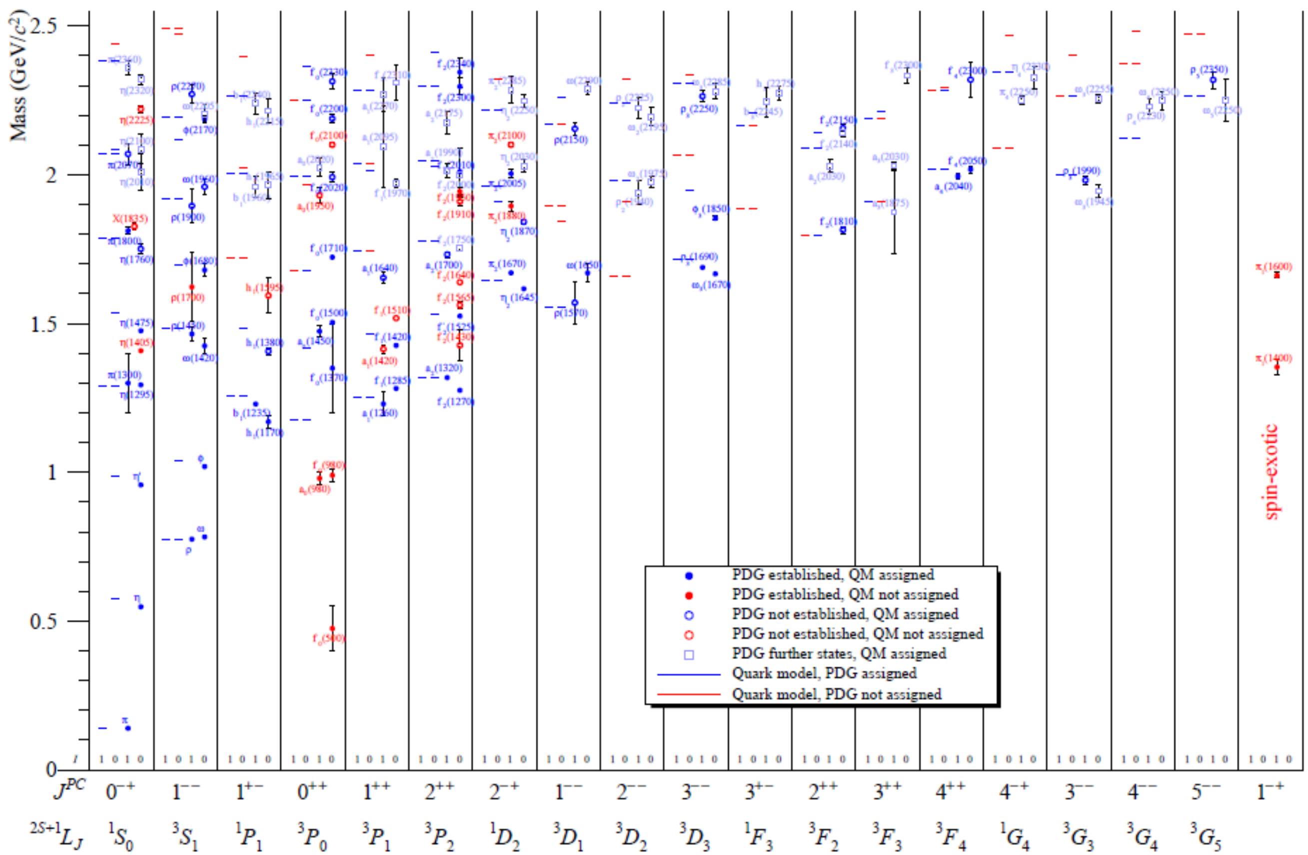
For an overview see the CERN-EP seminar by Mikhail Mikhasenko:
https://cds.cern.ch/record/2776989

A review on COMPASS light meson spectroscopy

Light-Meson Spectroscopy with COMPASS

https://arxiv.org/abs/1909.06366

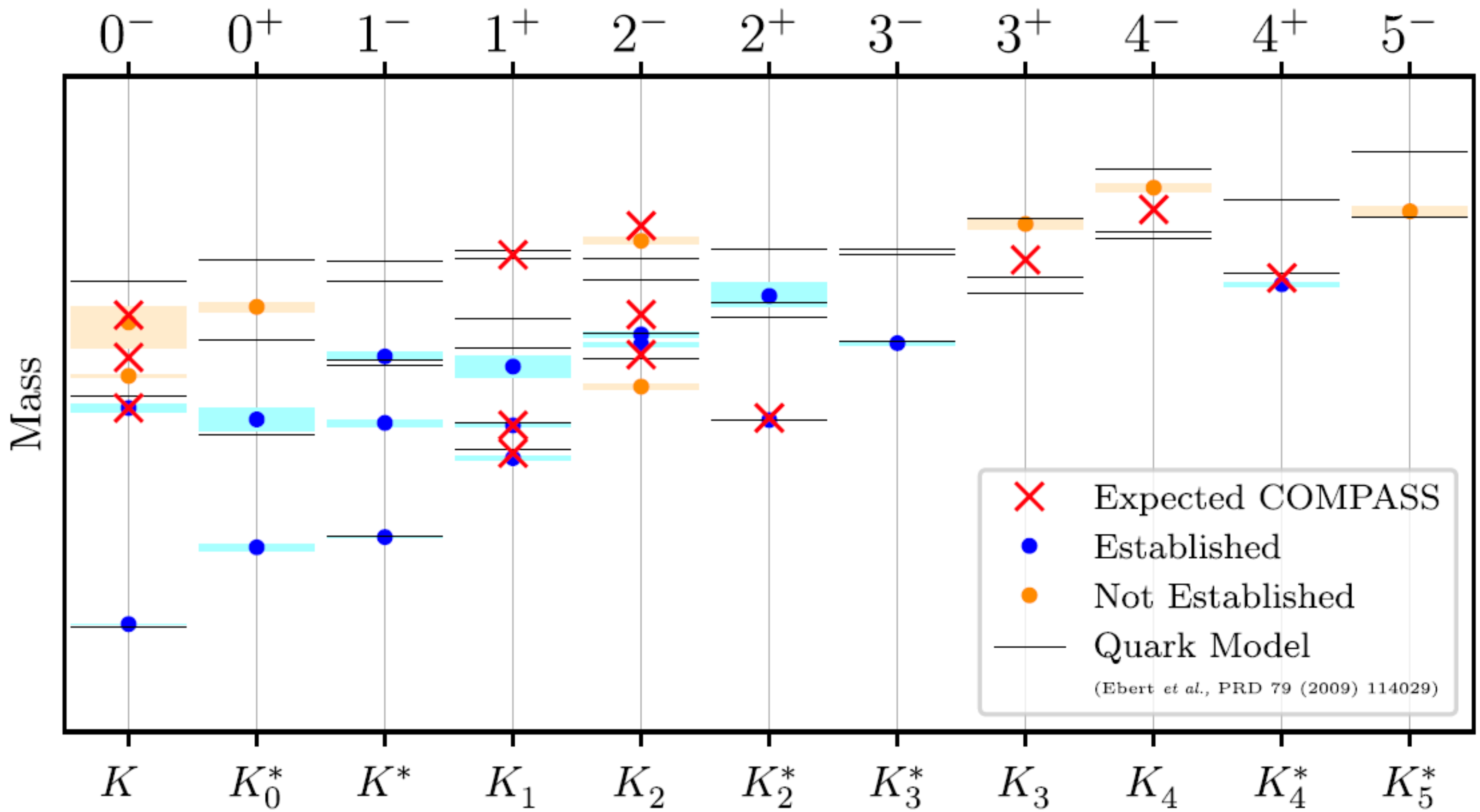
B. Ketzer[a], B. Grube[b], D. Ryabchikov[c,b]



Strange mesons spectroscopy

COMPASS will release m_0/Γ of 13 strange mesons using $K^-\pi^-\pi^+$

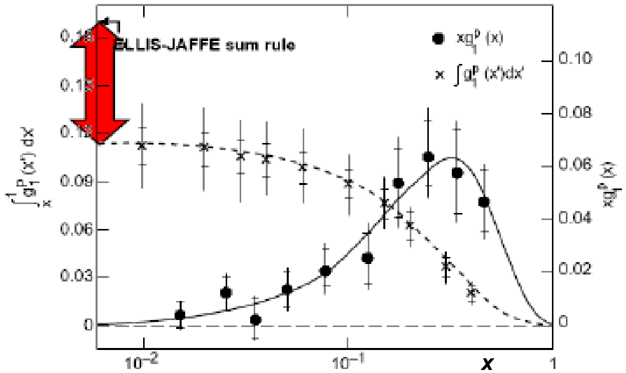
- K, K_1, K_2^*, K_2, K_3^*, K_3, K_4^*, K_4



Spin puzzle reminder

1987: EMC nucleon spin puzzle

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.12 \pm 0.17$$
$$\Delta s = -0.19 \pm 0.06$$



$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x$$

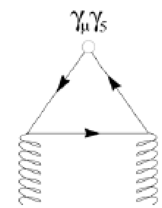
1989 G.G. Ross:

to recover the parton model: ΔG ~ 6

1988/9: axial anomaly may mask quark polarisation

– Altarelli,Ross; Efremov, Teryaev

$$a_0 = \Delta\Sigma - n_f \frac{\alpha_s}{2\pi}\Delta G$$



1993: SMC measures deuteron g_1

in agreement with Bjorken sum rule

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_a$$

1995 new SMC and SLC data:

to recover the parton model

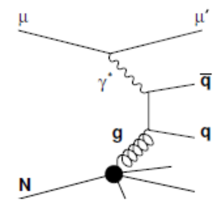
$\Delta G \sim 2.5$ at $Q^2 \sim 10\,\mathrm{GeV}^2$

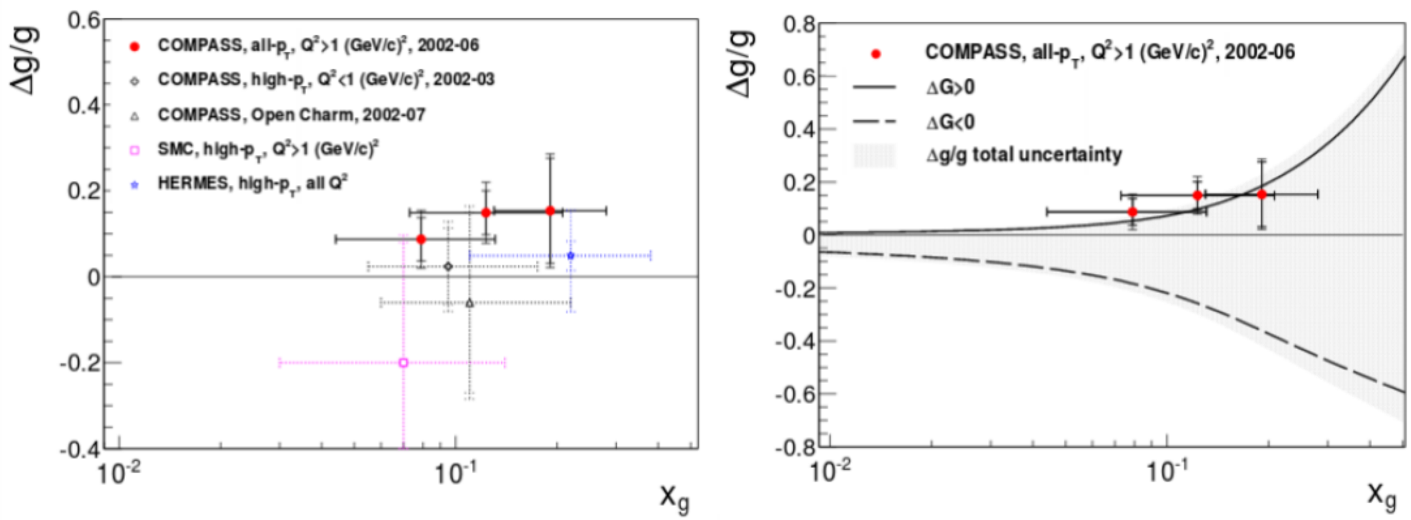
Gluon polarisation

Direct measurements of $\Delta g(x)$

EPJC 77 (2017) 209

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:

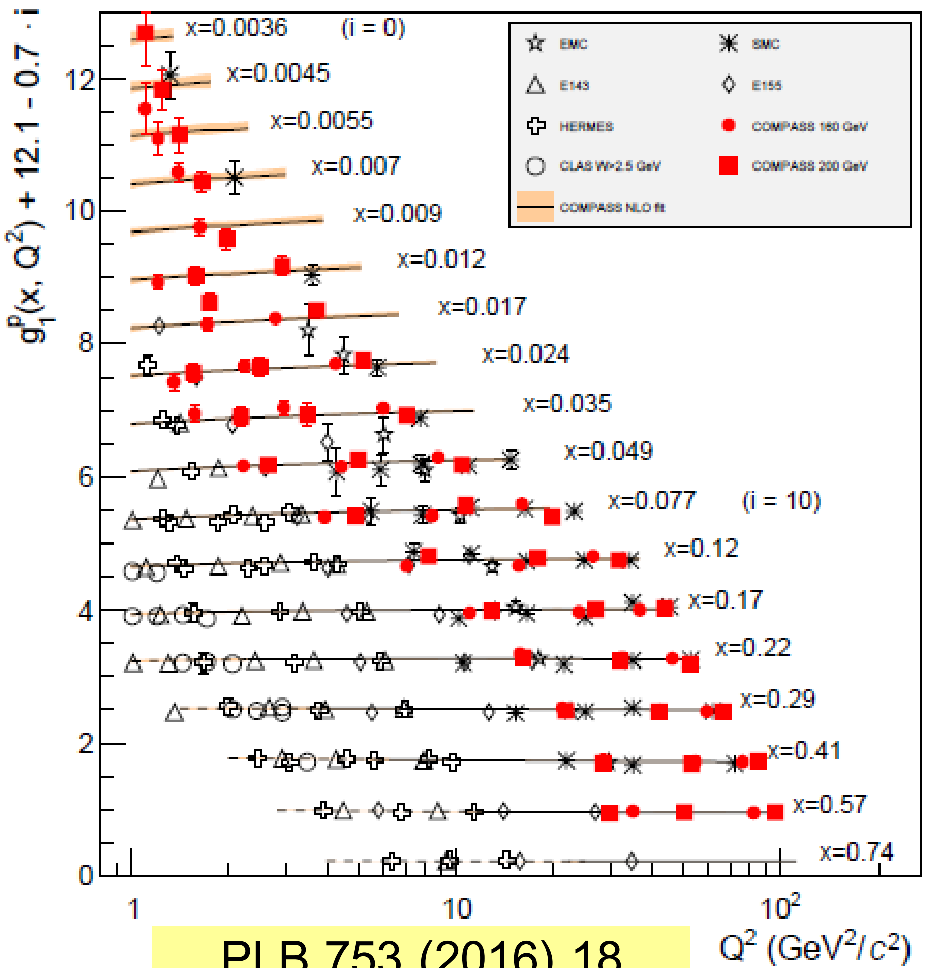
$$\Delta g/g = 0.113 \pm 0.038(\text{stat.}) \pm 0.036(\text{syst.})$$

$$\text{at} \quad \langle Q^2 \rangle \approx 3\ (\text{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

Inclusive DIS: g_1

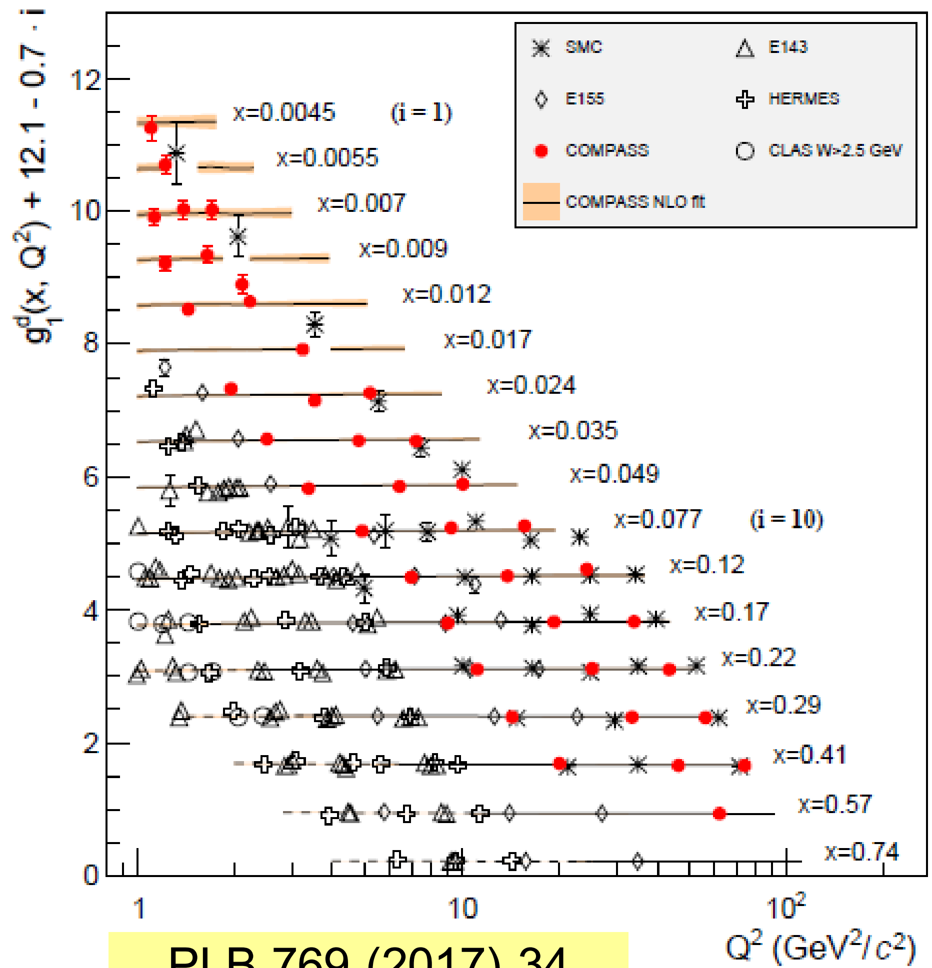
g_1^p and g_1^d, $Q^2 > 1\ (\mathrm{GeV}/c)^2$

proton



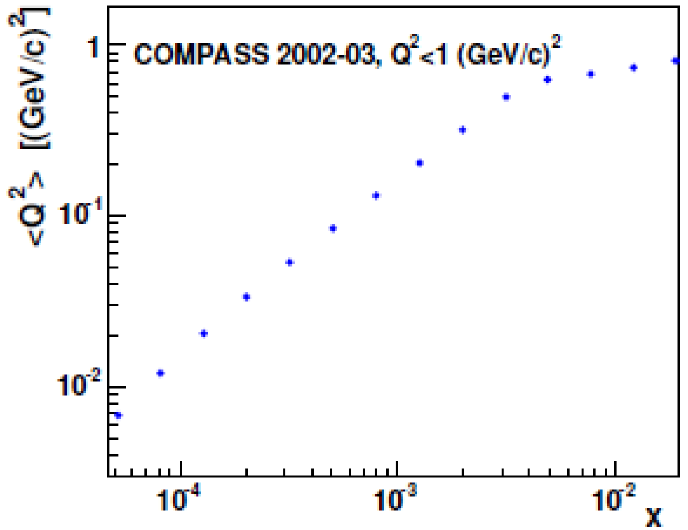
PLB 753 (2016) 18

deuteron

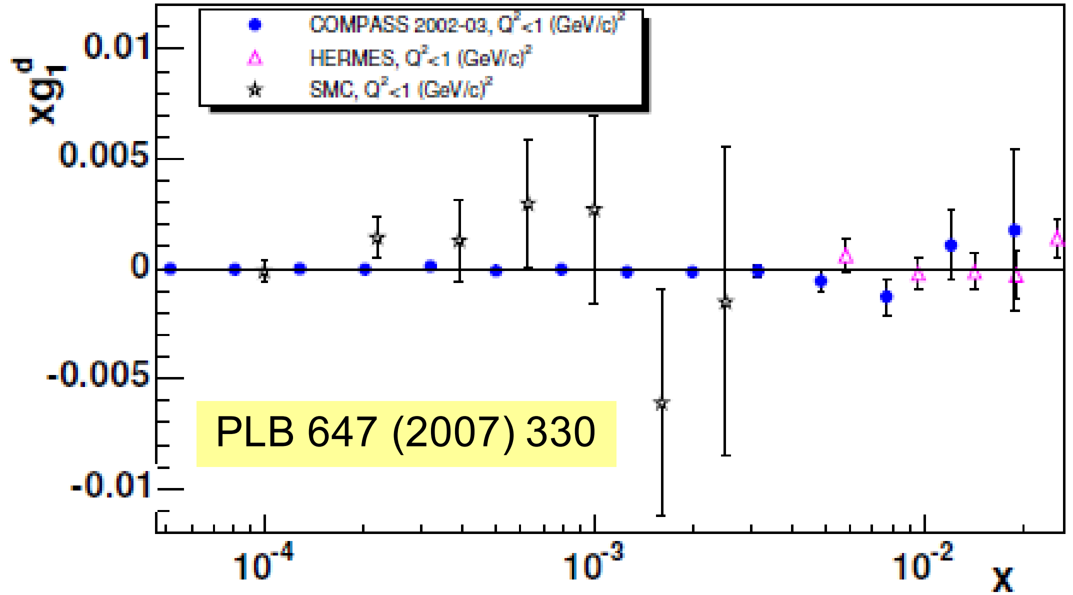


PLB 769 (2017) 34

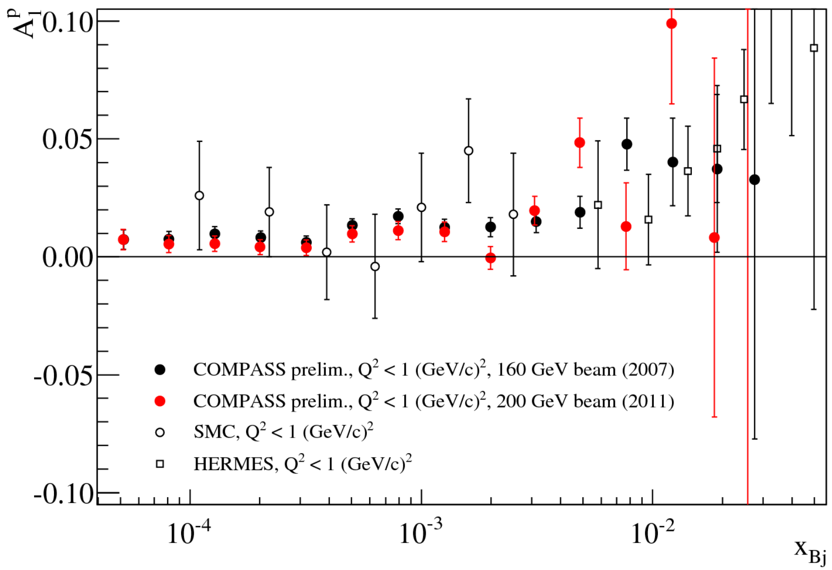
g_1 for $Q^2 < 1$



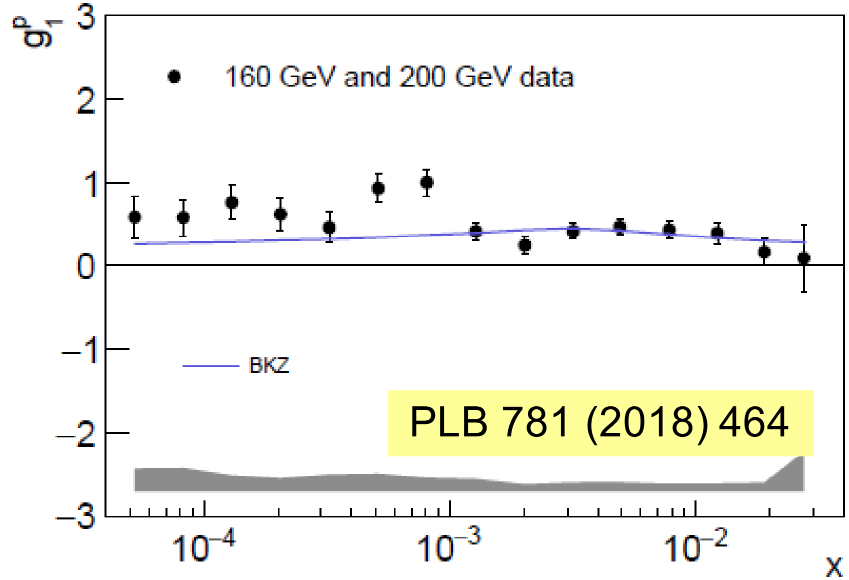
COMPASS 2002-03, Q²<1 (GeV/c)²
<Q²> [(GeV/c)²]
x



COMPASS 2002-03, Q²<1 (GeV/c)²
HERMES, Q²<1 (GeV/c)²
SMC, Q²<1 (GeV/c)²
xg₁ᵈ
x
PLB 647 (2007) 330



A₁ᵖ
COMPASS prelim., Q² < 1 (GeV/c)², 160 GeV beam (2007)
COMPASS prelim., Q² < 1 (GeV/c)², 200 GeV beam (2011)
SMC, Q² < 1 (GeV/c)²
HERMES, Q² < 1 (GeV/c)²
x_Bj



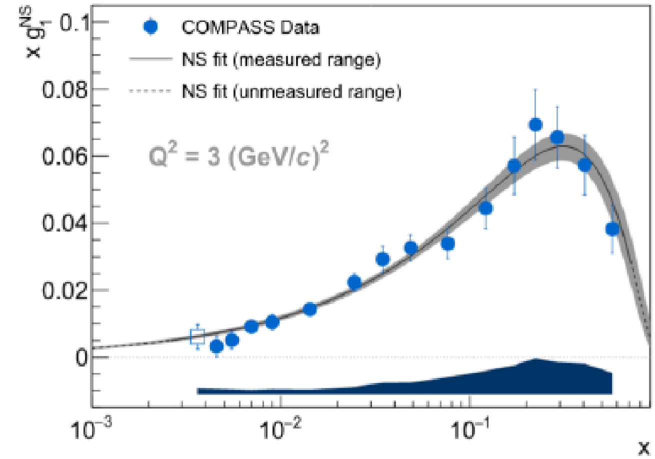
g₁ᵖ
160 GeV and 200 GeV data
BKZ
PLB 781 (2018) 464
x

Bjorken sum rule

COMPASS PL B753 (2016) 18

Non-singlet structure function:

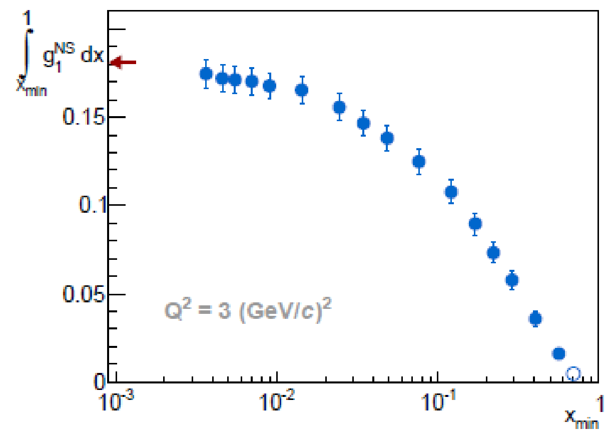
$$g_1^{\rm NS} = g_1^{\rm p}(x,Q^2) - g_1^{\rm n}(x,Q^2)$$
$$= 2\left[g_1^{\rm p}(x,Q^2) - g_1^{\rm N}(x,Q^2)\right]$$



Its moment connected to the Bjorken sum rule:

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

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



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

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

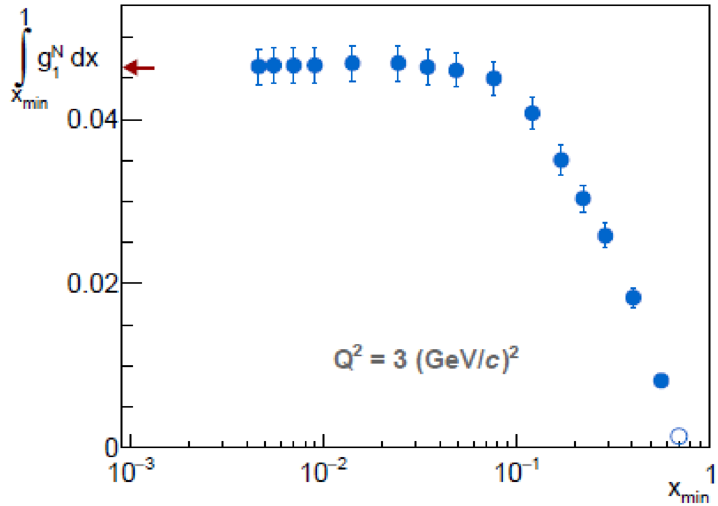
PDG, PRD86 (2012) 010001

COMPASS data provided validation of the Bjorken sum rule at 9%

Singlet axial charge a_0

First moments $\Gamma_1^{\mathrm{p}}, \Gamma_1^{\mathrm{d}}, \Gamma_1^{\mathrm{N}}$

where $\Gamma_1^{\mathrm{i}} = \int_0^1 g_1^{\mathrm{i}}(x, Q^2)\mathrm{d}x$



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In particular:

$$\Gamma_1^{\mathrm{N}}(Q^2) = \frac{1}{36}\left[4a_0 C_{\mathrm{S}}(Q^2) + a_8 C_{\mathrm{NS}}(Q^2)\right]$$

$$= \int_0^1 \frac{g_1^{\mathrm{d}}(x, Q^2)}{1 - 1.5\omega_{\mathrm{D}}}\mathrm{d}x$$

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:

$\Gamma_1^{\mathrm{N}}(Q^2$ = 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 $\pm 0.02_{\mathrm{stat.}} \pm 0.04_{\mathrm{syst.}} \pm 0.05_{\mathrm{evol.}}$

transversity

collinear description at leading twist

nucleon polarisation (columns) / **quark polarisation** (rows)

	U	L	T
U	f_1		
L		g_1	
T			h_1

number density $f_1\ (q)$

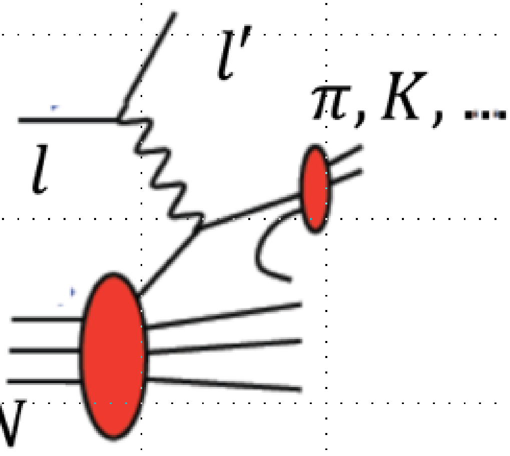
very well known

helicity distribution $g_1\ (\Delta q)$

well known

transversity distribution $h_1\ (\Delta_T q)$

- correlation between the transverse polarisation of the nucleon and the transverse polarisation of the quark
- related to **tensor charge**
- a chirally-odd distribution, not observable in DIS, accessible in SIDIS



$$x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot \ell} =_{LAB} \frac{E-E'}{E}$$

$$Q^2 = -q^2 \qquad W^2 = (P+q)^2$$

$$z = \frac{P\cdot P_h}{P\cdot q} =_{LAB} \frac{E_h}{E-E'}$$

Collins asymmetry

Collins effect

→ **azimuthal distribution of the hadrons produced in** $lN^{\uparrow} \rightarrow l' h X$

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C\right]$$

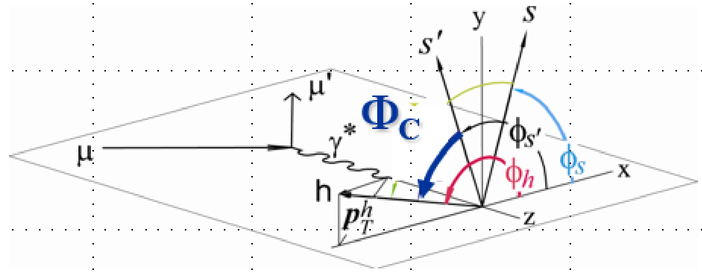
± refer to the opposite orientation of the transverse spin of the nucleon

P_T is the target polarisation; D_{NN} is the transverse spin transfer coefficient initial → struck quark

"Collins angle"

$$\Phi_C = \phi_h - \phi_{s'} = \phi_h + \phi_S - \pi$$

$\phi_{h,s',S}$ azimuthal angles of hadron momentum, of the spin of the fragmenting quark and of the nucleon in the GNS



from the azimuthal distribution of the hadrons one measures the "Collins Asymmetry"

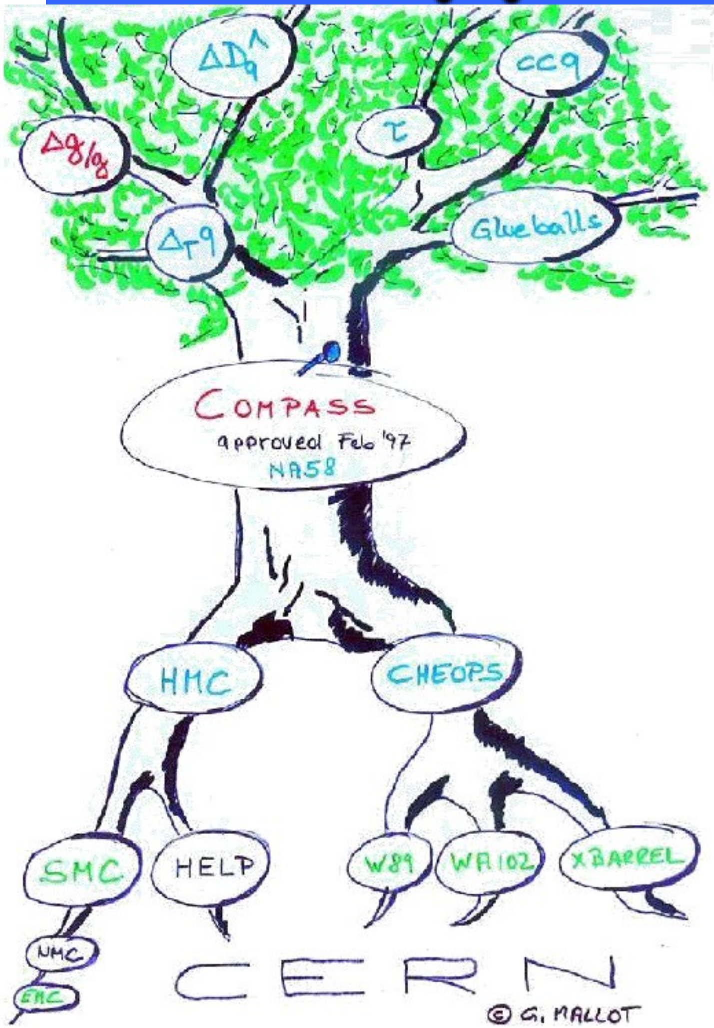
$$A_{Coll} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

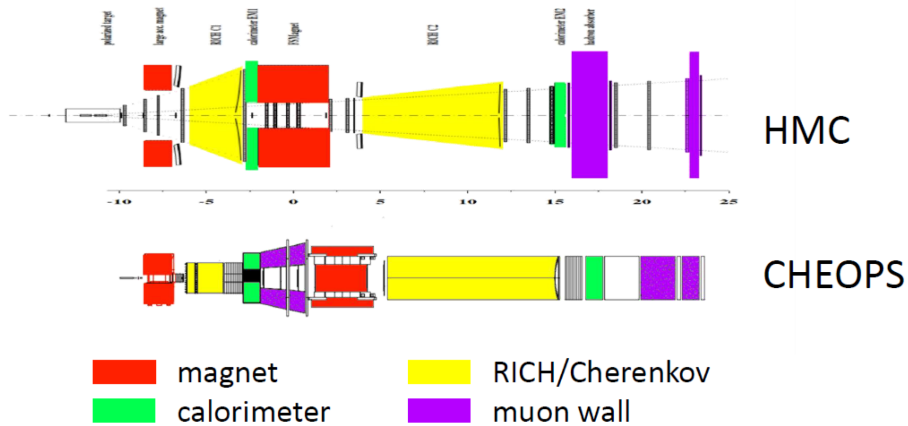
$\Delta_T q \leftrightarrow h_1^q$

$\Delta_T^0 D_q^h \leftrightarrow H_{1\,q}^{\perp h}$ Collins function

HELP proposal (L. Dick, B. Vuaridel, R. Hess, 1993) rejected by CERN

COMPASS Proposal approved in 1997





EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

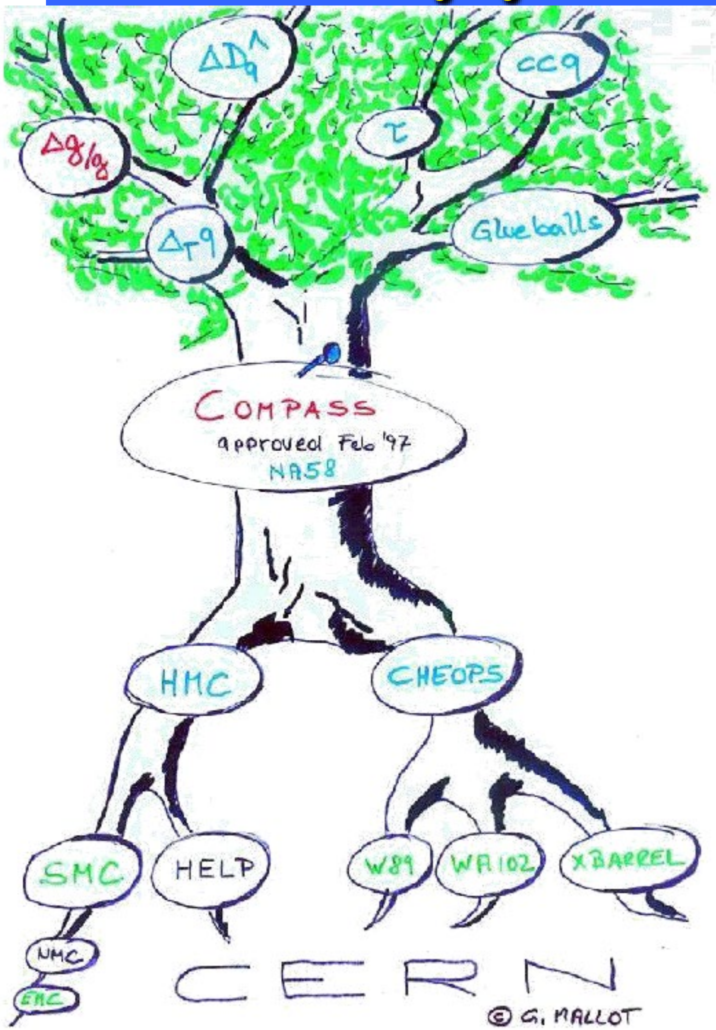
CERN/SPSLC 96-14
SPSC/P 297
March 1, 1996

PROPOSAL

Common Muon and Proton Apparatus for Structure and Spectroscopy

The COMPASS Collaboration

COMPASS Proposal approved in 1997



The Sivers function:

a long debate

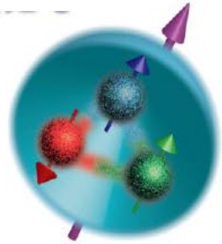
- 1992 introduced by D. Sivers
- 1993 J. Collins demonstrate that it must vanish
- 2002 S. Brodsky et al.: it can be ≠ 0 because of FSI
- 2002 J. Collins: process dependent, change of sign SIDIS ↔ DY

….

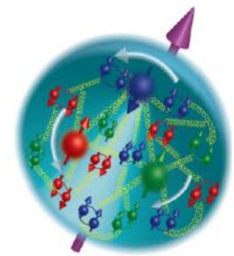
1996: not in our Proposal

Intrinsic transverse momentum

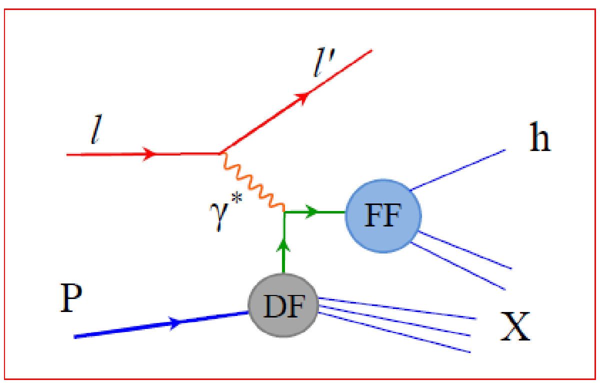
- 1964 Quark model 

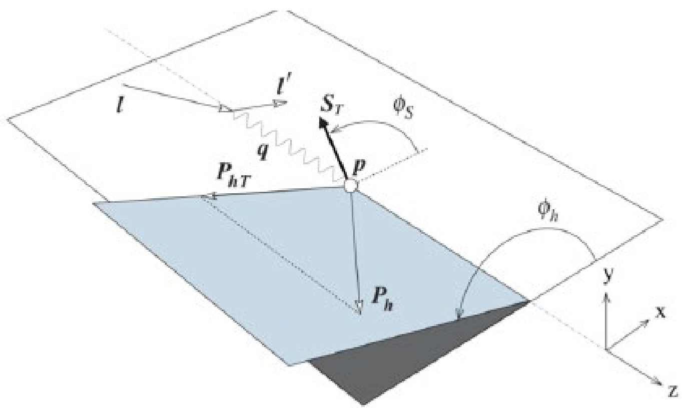


- 1969 Parton model 
- 1973 asymptotic freedom and QCD 



- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries 





$$\hat{s} \simeq xs\left[1 - 2\sqrt{1-y}\,\frac{k_T}{Q}\cdot\cos\varphi_q\right]$$

$$\hat{u} \simeq -xs\left(1-y\right)\left[1 - \frac{2k_T}{Q\sqrt{1-y}}\cdot\cos\varphi_q\right]$$

$$\hat{t} = -Q^2 = -xys, \quad where \quad s = \left(l + P\right)^2$$

$$d\sigma^{lp\to l'hX} \propto d\sigma^{lq\to lq} \propto \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$$

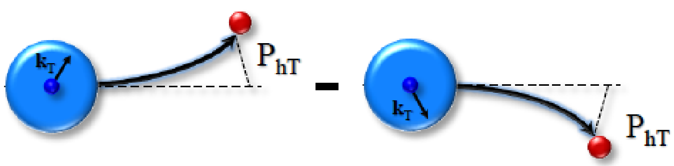
Intrinsic transverse momentum

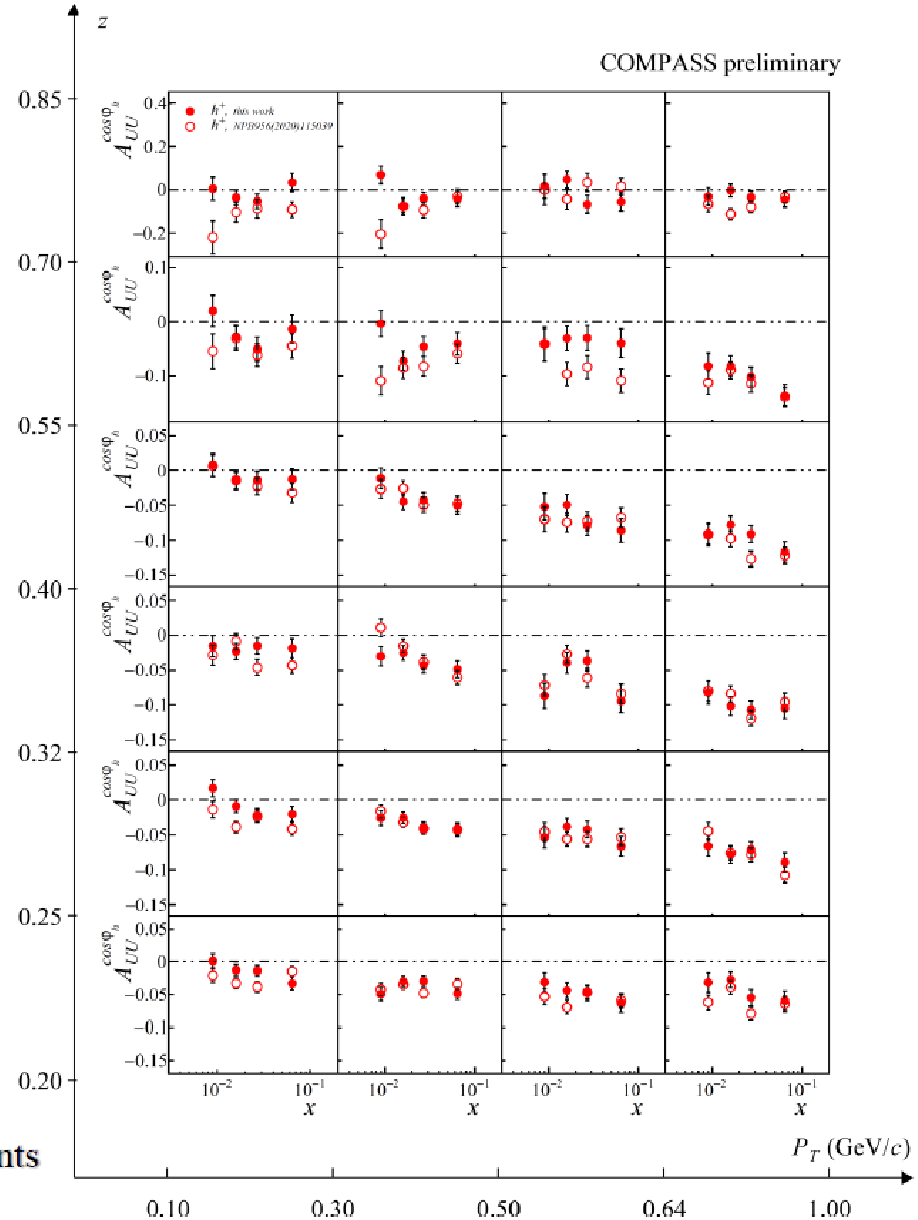
Cahn effect in SIDIS

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

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\right)$$

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





As of 1978 – simplistic kinematic effect:
non-zero k_T induces an azimuthal modulation
As of 2022 – complex SF (twist-2/3 functions)
A number of measurements by different experiments

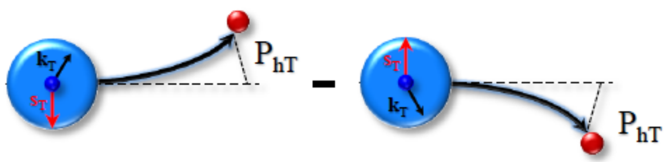
Intrinsic transverse momentum

Boer-Mulders effect in SIDIS

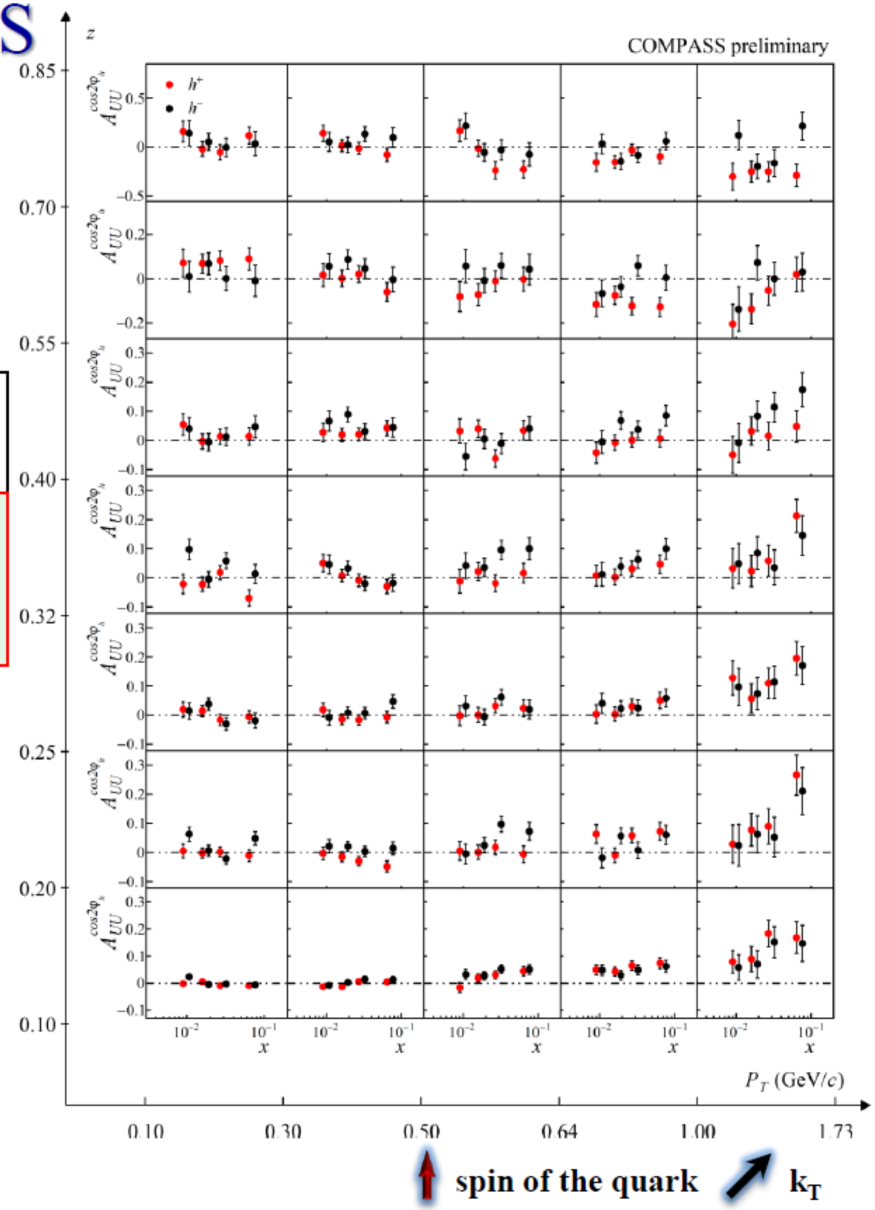
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\ldots\right)$$

Quark / Nucleon	U		T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ Boer-Mulders



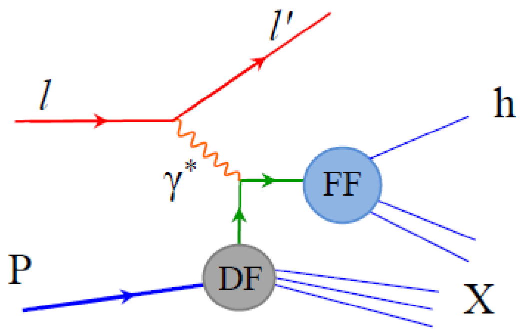
Arises due to the correlation between quark transverse spin and intrinsic transverse momentum



SIDIS x-section and TMD at twist 2

All measured by COMPASS

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



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

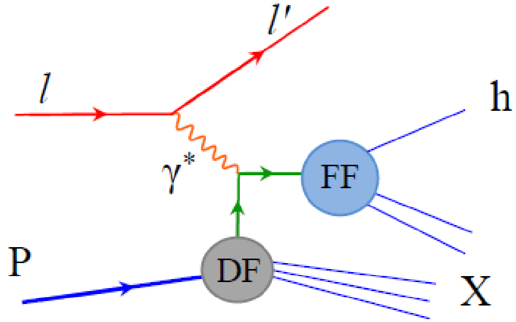
↑ spin of the nucleon ↑ spin of the quark ↗ k_T

SIDIS x-section and TMD at twist 2

All measured by COMPASS

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

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



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

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

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

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

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

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

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

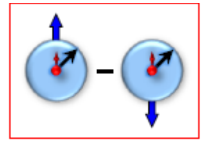
$$A_{LT}^{\cos(2\phi_h-\phi_S)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^h+\ldots\right)$$

Twist-2

Twist-3

Intrinsic transverse momentum

SIDIS TSAs: Collins effect and Transversity

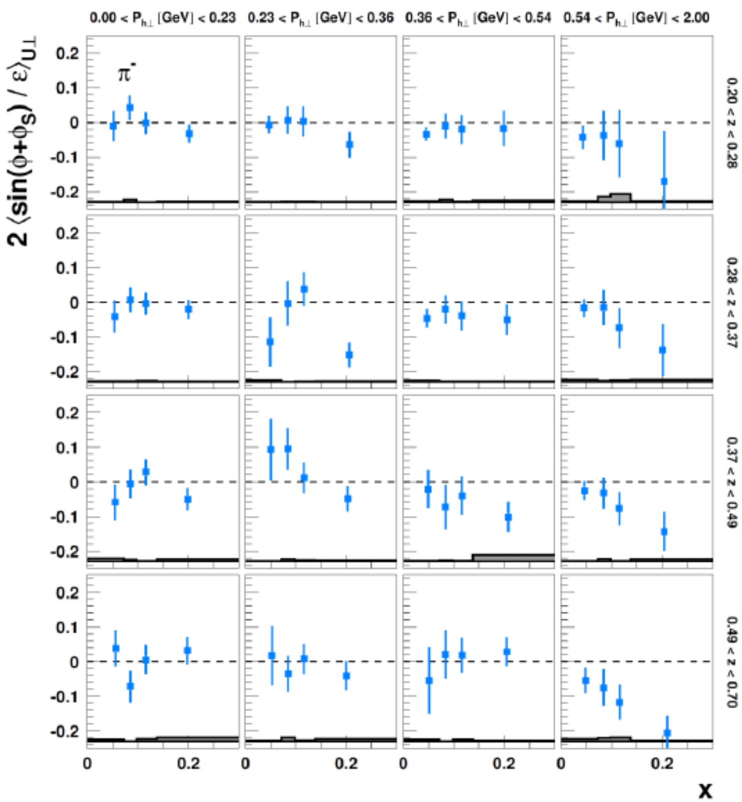


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\right\}$$

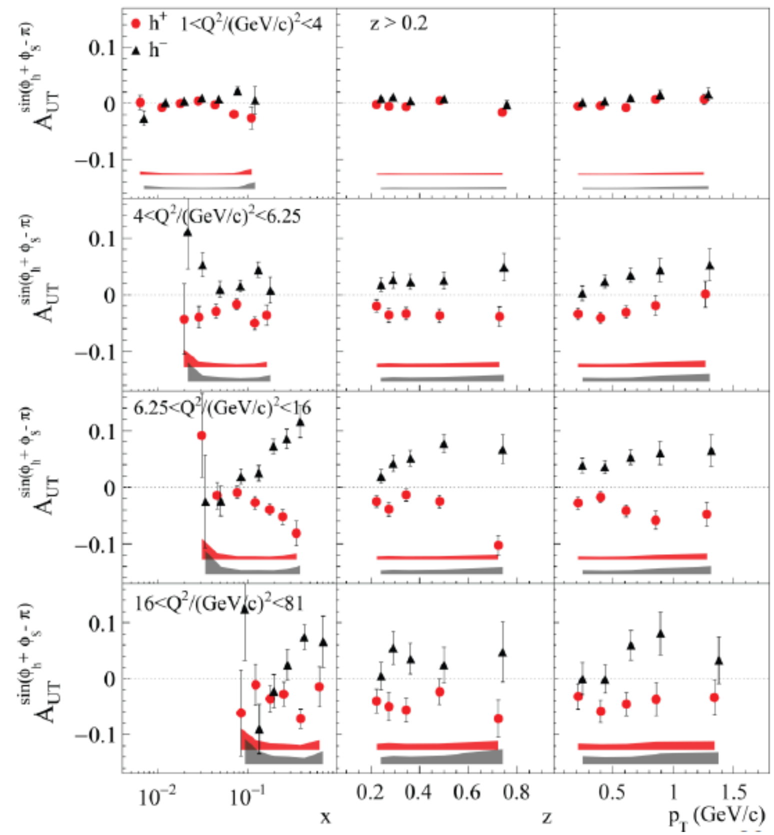
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{h}\cdot p_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

HERMES, JHEP 12 (2020) 010

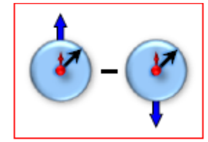


COMPASS, PBL 770 (2017) 138



Intrinsic transverse momentum

SIDIS TSAs: Collins effect and Transversity



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

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

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
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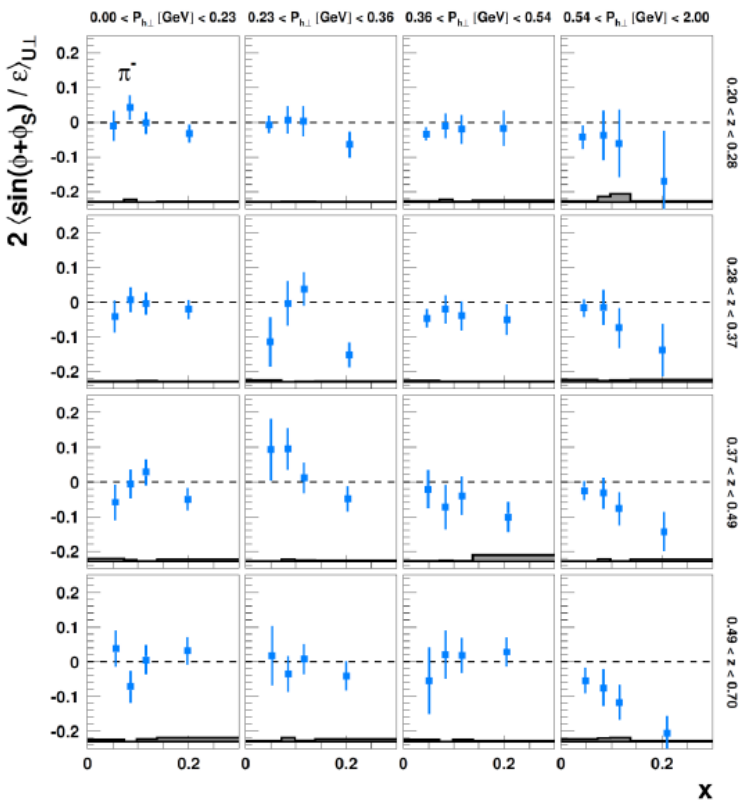
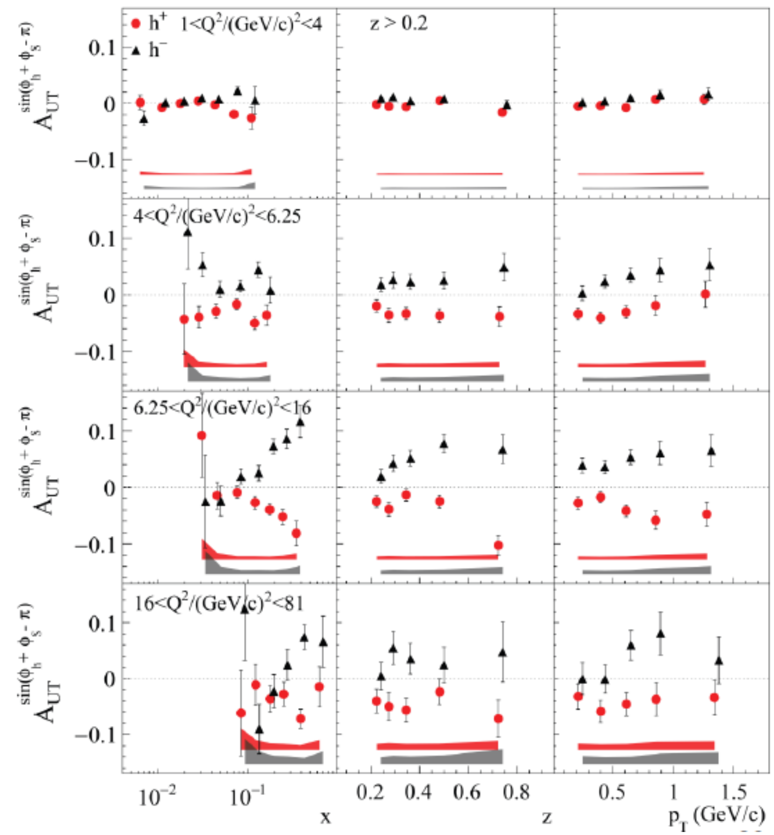
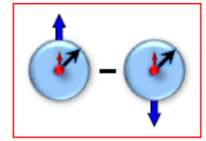


COMPASS, PBL 770 (2017) 138



Intrinsic transverse momentum

SIDIS TSAs: Collins effect and Transversity

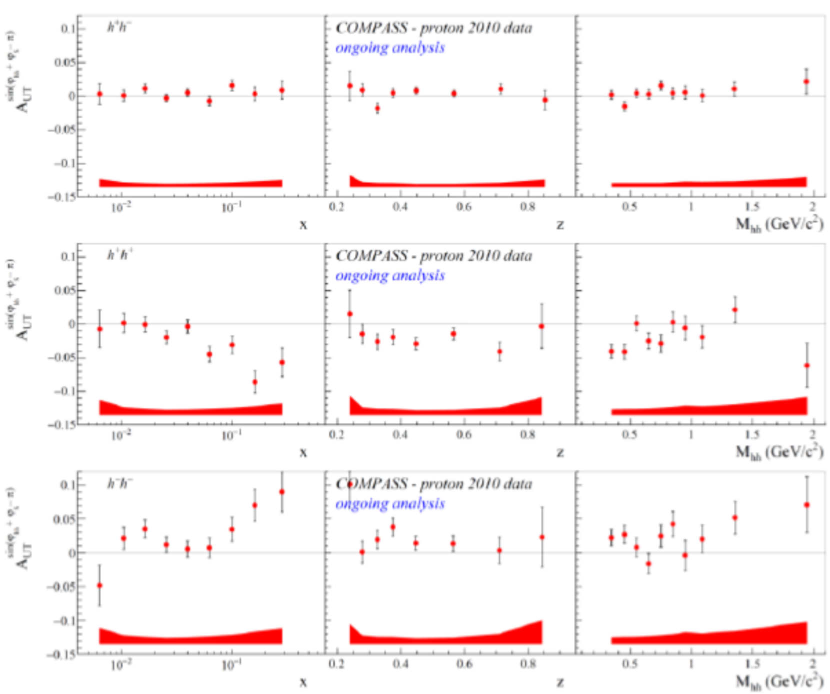


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\right\}$$

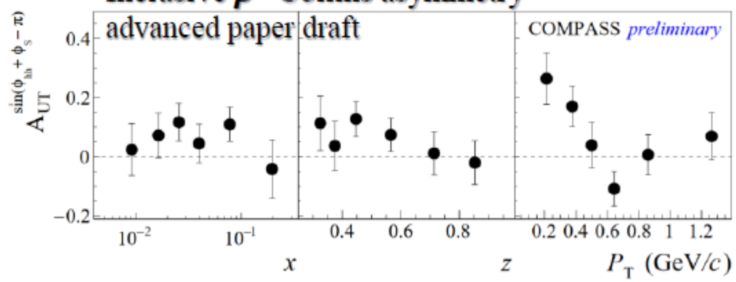
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{h}\cdot p_T}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

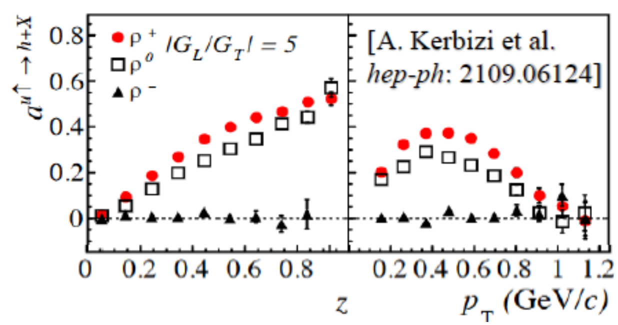
Ongoing analysis: Collins-like dihadron TSAs



Inclusive ρ^0 Collins asymmetry

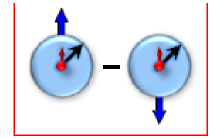


- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T



Intrinsic transverse momentum

SIDIS TSAs: Collins effect and Transversity

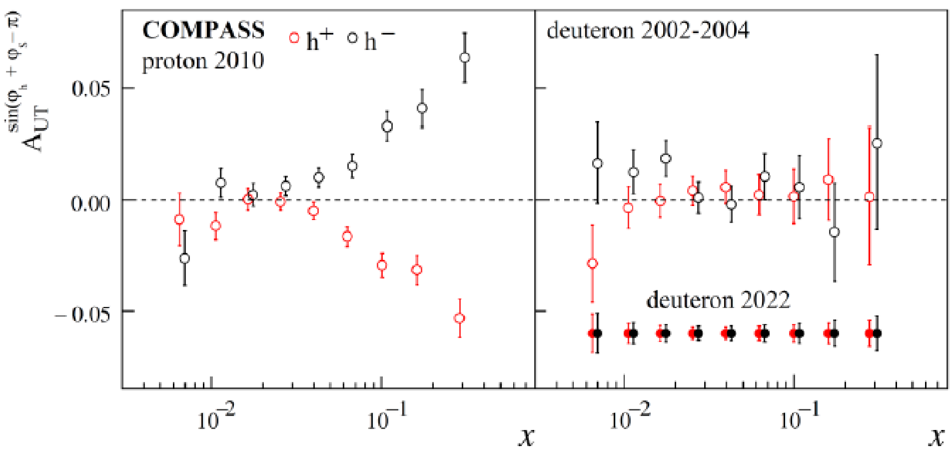


$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

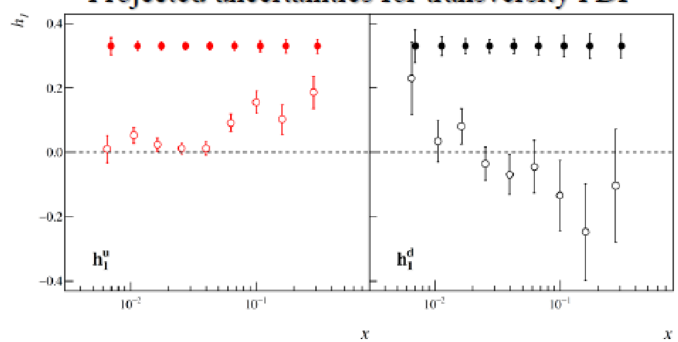
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{h}\cdot p_T}{M_h}\,h_1^q H_{1q}^{\perp h}\right]$$

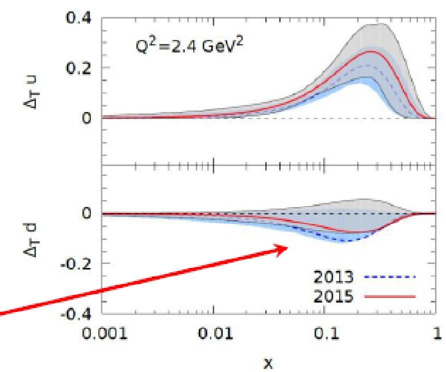
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

[Addendum to the COMPASS-II Proposal]
Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF





COMPASS-II (2022)

- Deuteron measurement to be repeated
- Will be crucial to constrain the transversity TMD PDF for the d-quark

COMPASS 2022 data

Pavia group fits

proton [H] — hermes — 95 data points — *Airapetian et al., P.R.L. **103** (09) 152002*

neutron [³He] — Jefferson Lab — 6 data points — *Qian et al., P.R.L. **107** (11) 072003*

deuteron [⁶LiD] — COMPASS 2009 — 88 data points — *Alekseev et al., P.L. **B673** (09) 127*

Proton [NH₃] — COMPASS 2017 — 111 data points — *Adolph et al., P.L. **B770** (17) 138*

Bacchetta, Delcarro, Pisano, Radici, in preparation

Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

$Q^2 \geq 1.4$ GeV² $0.2 \leq z \leq 0.7$

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

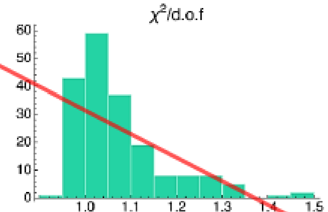
300 data points → **118** data fitted

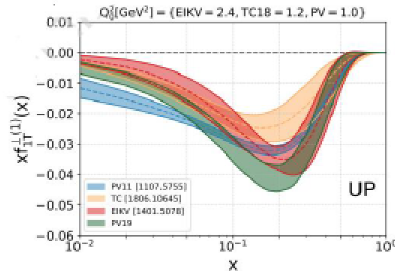
14 free parameters

χ^2/d.o.f. = 1.06 ± 0.10

analysis of statistical error with replica method (200)

68% confidence level

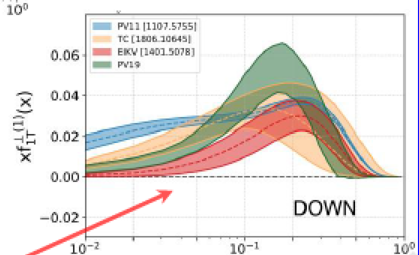




PV11	*Bacchetta & Radici, P.R.L. **107** (11)*
EIKV	*Echevarria et al., P.R. D**89** (14)*
TC	*Boglione et al., JHEP **1807** (18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

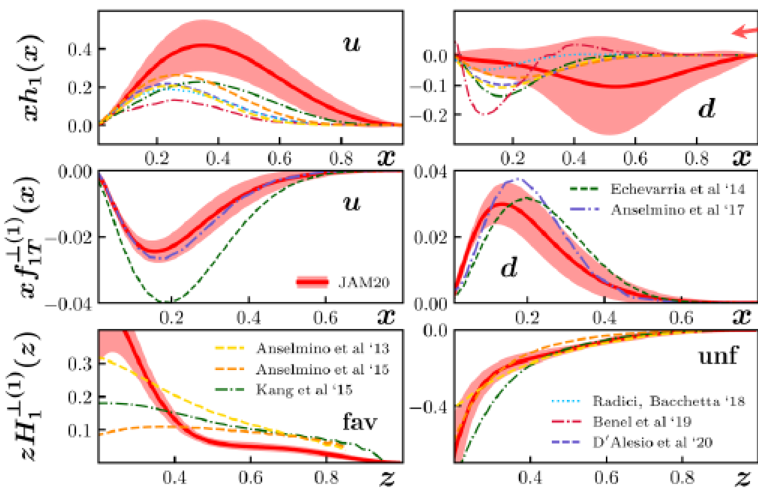
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \frac{\mathbf{k}_T^2}{2M^2} f_{1T}^{\perp}(x, \mathbf{k}_T)$$

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

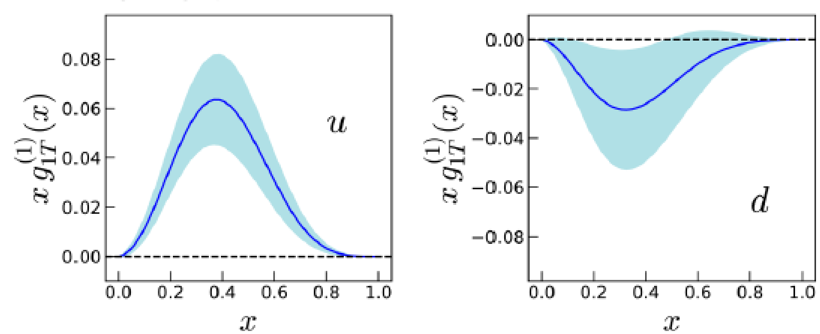


COMPASS 2022 deuteron run

JAM Collaboration, PRD 102, 054002 (2020)

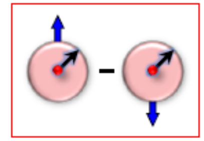


S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D.Pitonyak
PRD 105 (2022) 3, 034007



Intrinsic transverse momentum

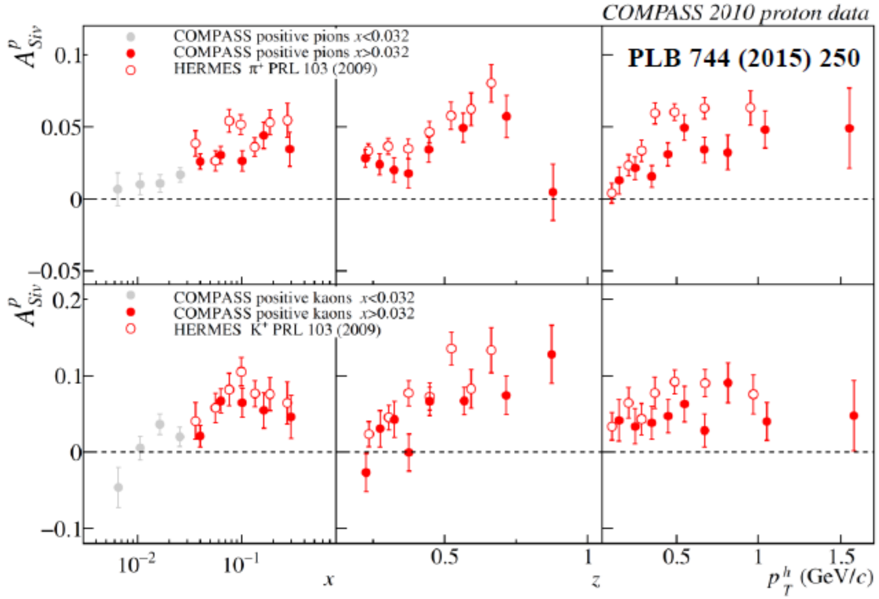
SIDIS TSAs: Sivers effect



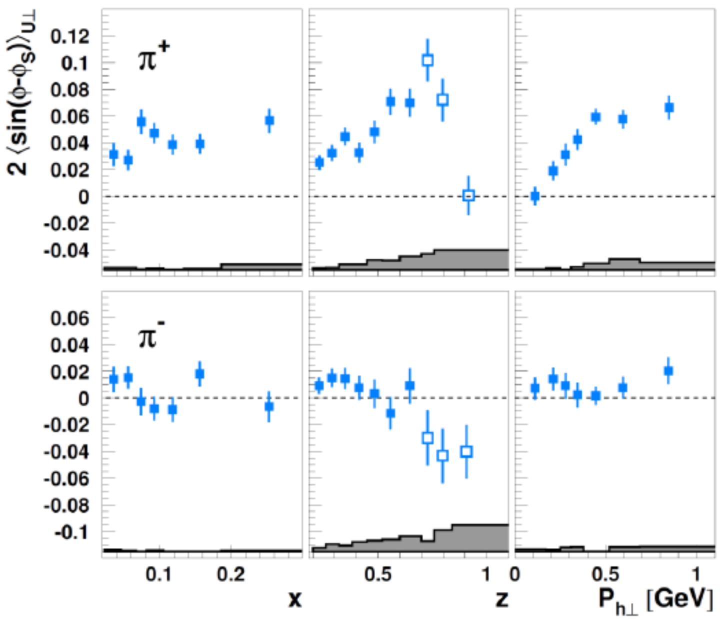
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h - \phi_S) + \ldots\right\}$$

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

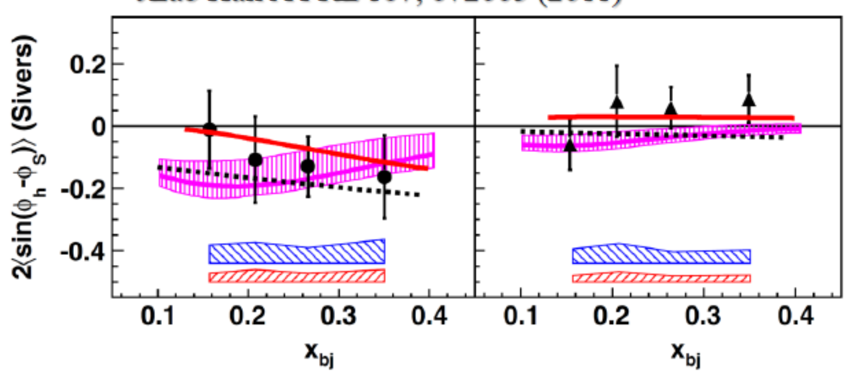
- Measured on proton and deuteron
- Expected to change sign between SIDIS and Drell-Yan



HERMES, JHEP 12 (2020) 010



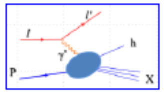
JLab Hall A PRL 107, 072003 (2011)



Polarised Drell-Yan

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

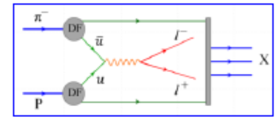
$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$



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

SIDIS-DY bridge

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



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

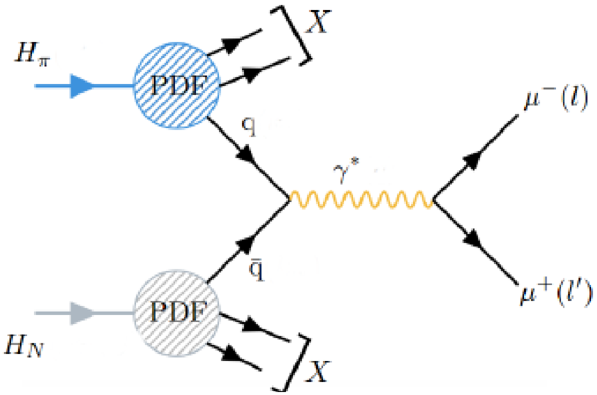
where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

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

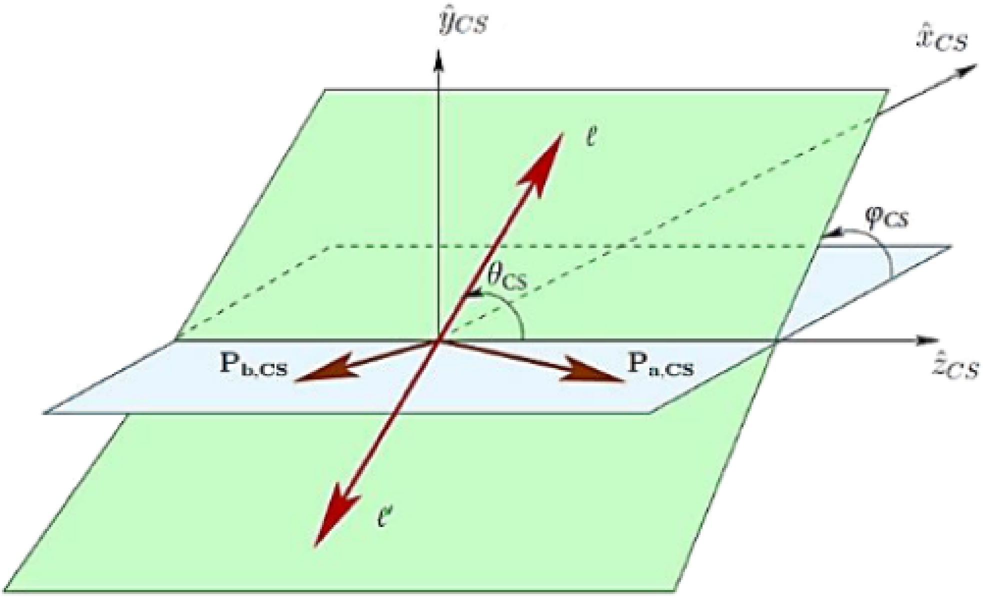
Complementary information from two different channels :

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

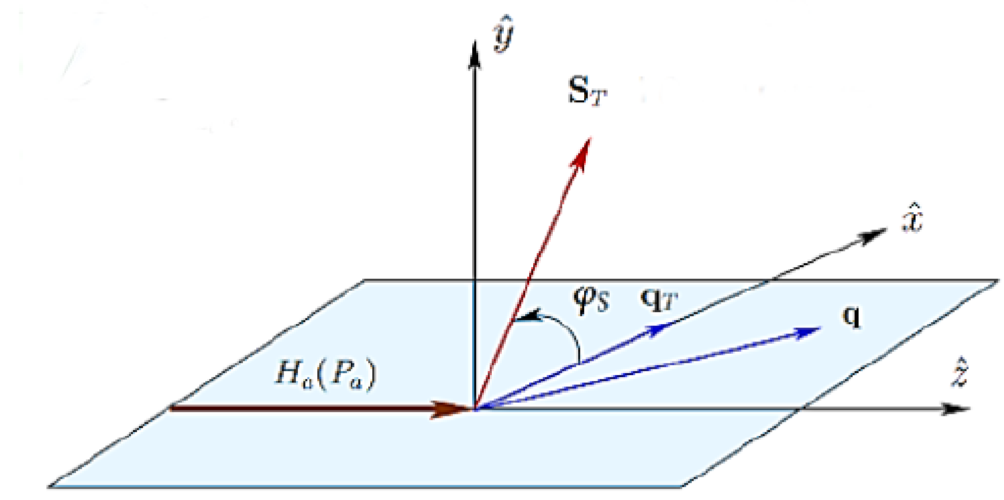
Polarised Drell-Yan



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

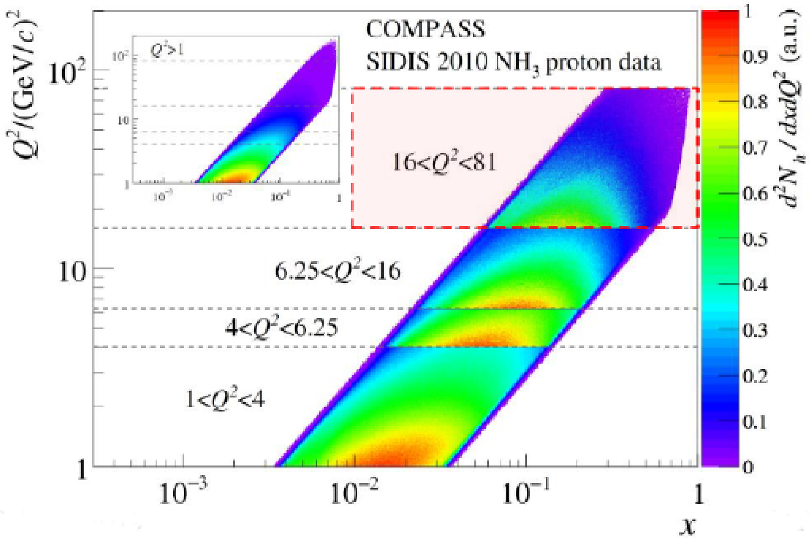


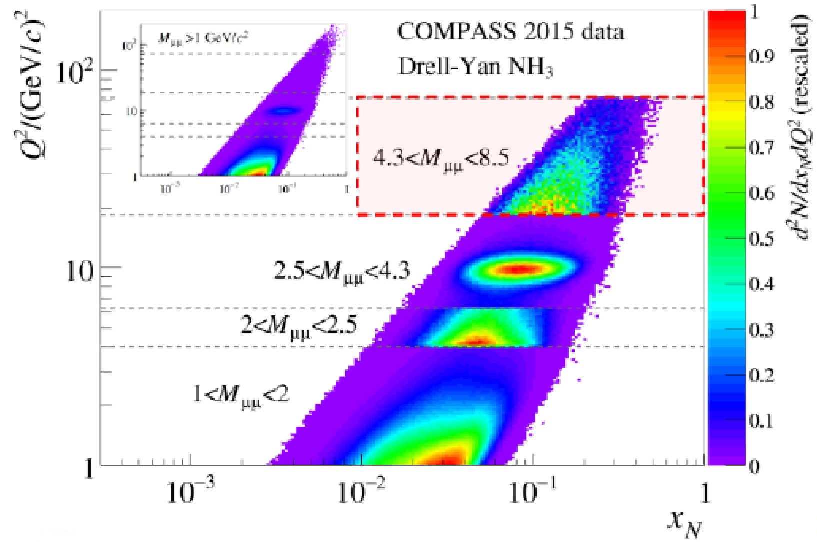
Collins-Soper ref. frame (CS)



Target rest frame (S)

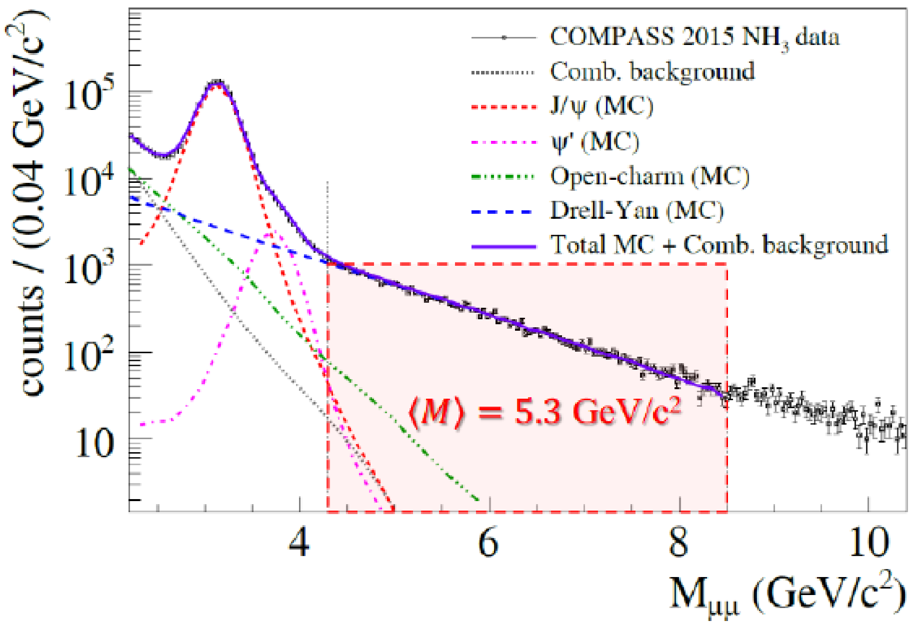
Aceptances

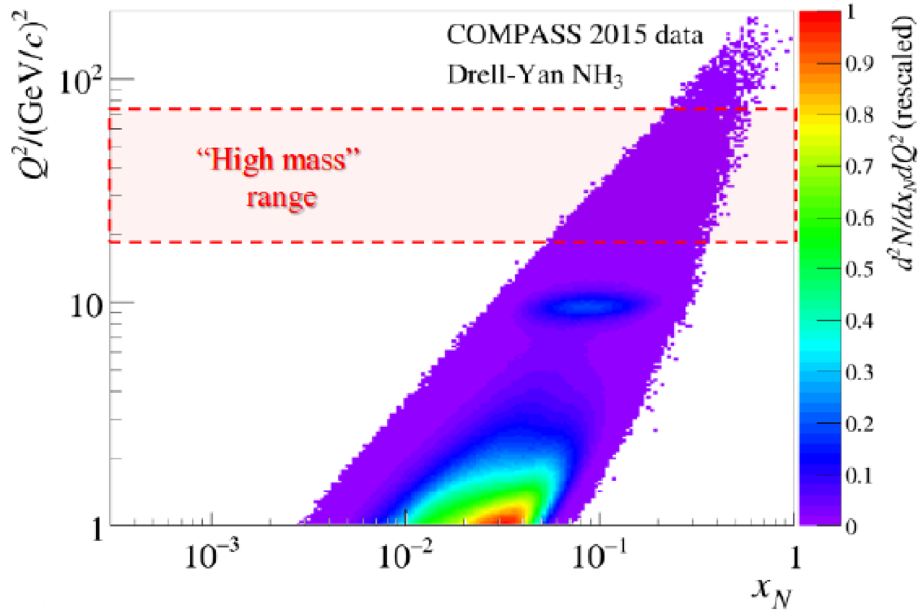


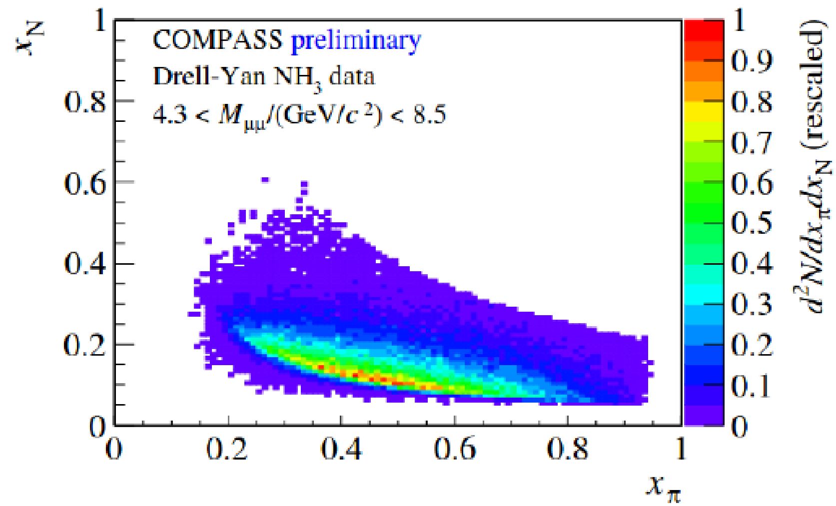


- COMPASS goals: test of the TMD PDFs universality; test of the Lam-Tung relation.
- In COMPASS, comparable (x, Q^2) acceptance in SIDIS and DY. Unique!
- In both cases, cross-sections depend on (polar and azimuthal) asymmetries described by contributions of twist-2 (or higher) TMD PDFs.
- SIDIS and 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 DY 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

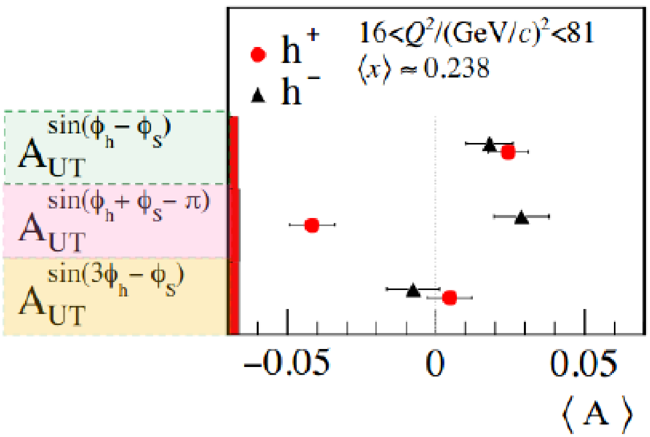
  $\langle x_\pi \rangle$ =0.50, $\langle x_N \rangle$ =0.17

COMPASS DY results

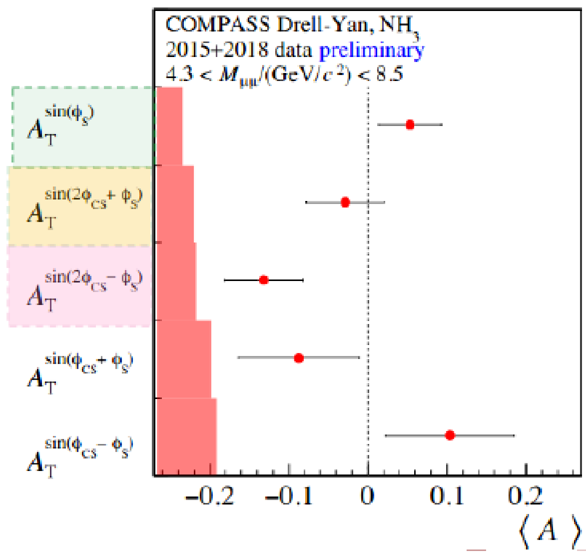
$$A_{SIDIS} \propto PDF_p \otimes FF \qquad\qquad A_{DY} \propto PDF_\pi \otimes PDF_p$$

$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$	**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** ⟷	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$

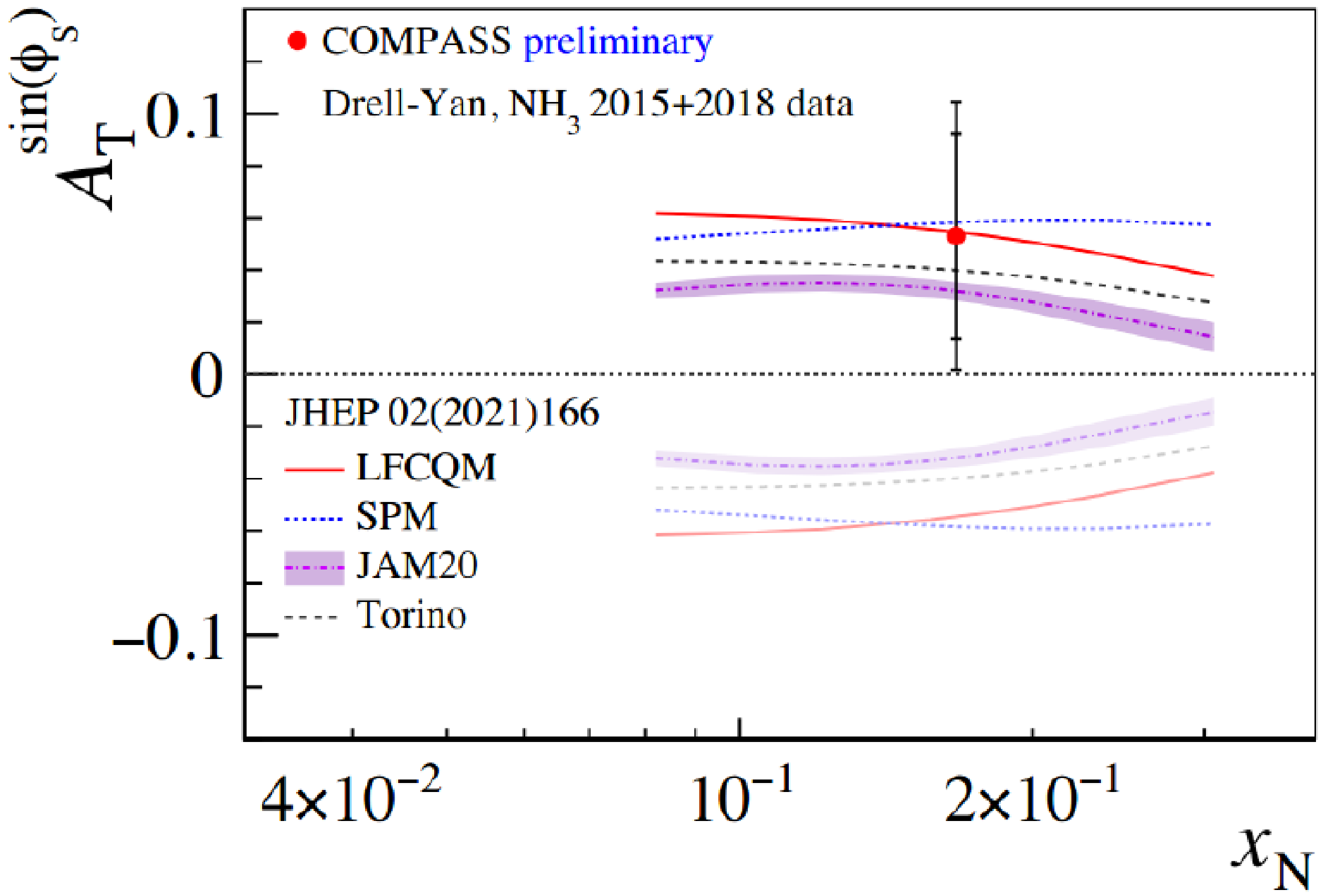
COMPASS SIDIS Data,
PLB 770 (2017) 138



NEW RESULTS!



Sivers sign change



sign change

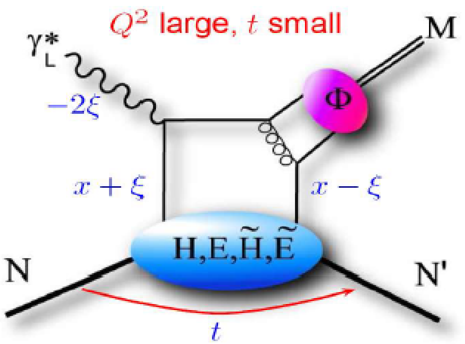
no sign change

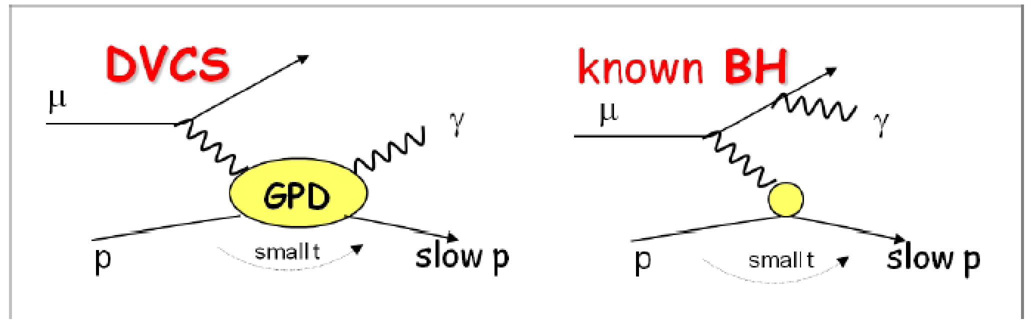
COMPASS DY result for Sivers asymmetry, $A_T^{\sin(\phi_S)}$

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

DVCS and DVMP

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

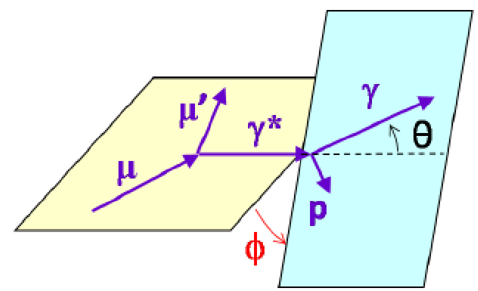




$$\mathrm{d}\sigma^{\mu p\to\mu p\gamma} = \mathrm{d}\sigma^{\mathrm{BH}} + (\mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}}) + e_\mu(\mathrm{Re}I + P_\mu \mathrm{Im}I)$$

Observables for unpolarised target (Phase 1):

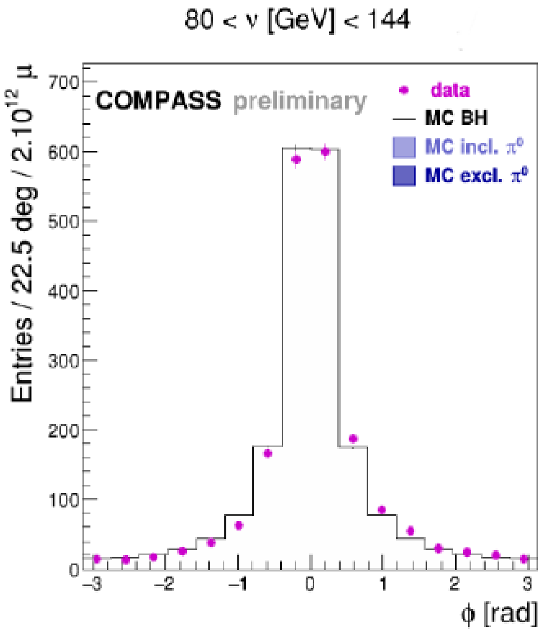
- $S_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(\mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + e_\mu P_\mu \mathrm{Im}I\right)$
- $D_{\mathrm{CS,U}} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2\left(P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}} + e_\mu \mathrm{Re}I\right)$
- $A_{\mathrm{CS,U}} \equiv \dfrac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \dfrac{D_{\mathrm{CS,U}}}{S_{\mathrm{CS,U}}}$
- 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.

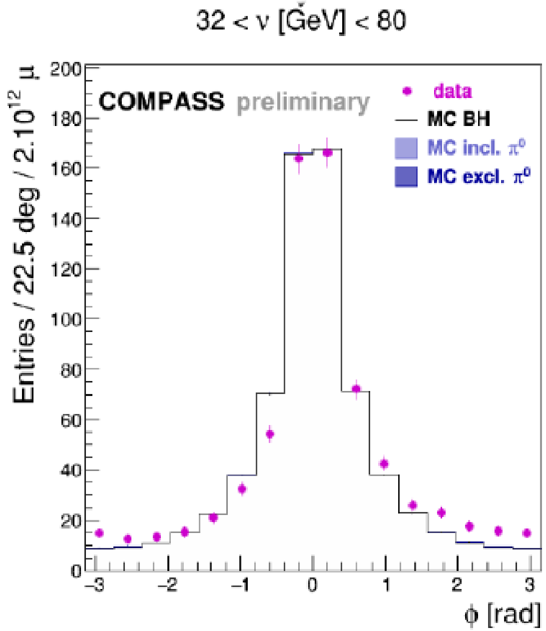


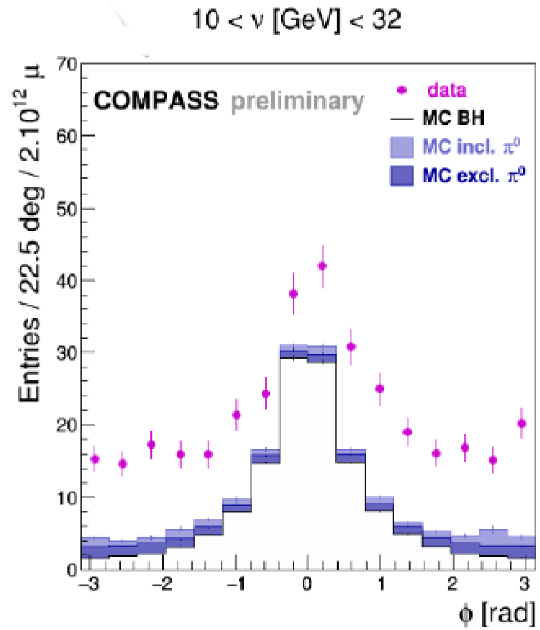
Analogously for transversely polarised target (Phase 2): $S_{\mathrm{CS,T}}, D_{\mathrm{CS,T}}, A_{\mathrm{CS,T}} \Longrightarrow E$

DVCS and BH

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





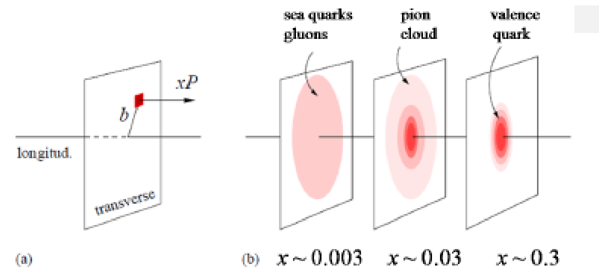


2012+2016 (part of) data

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

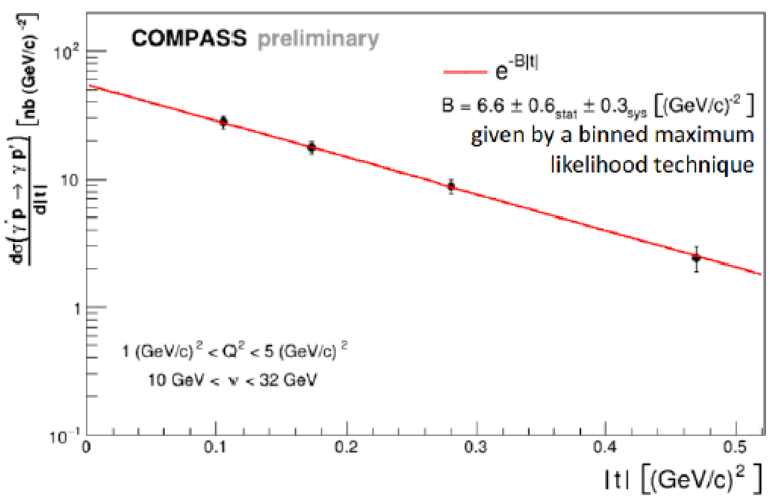
DVCS results

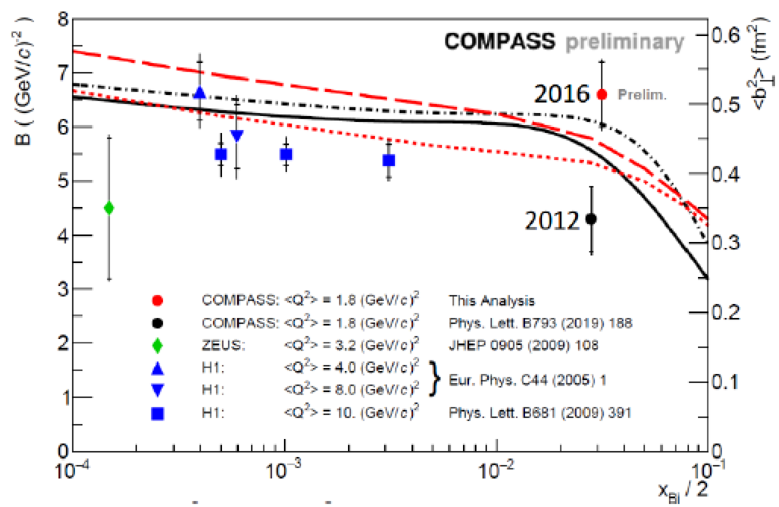
- Nucleon transverse imaging ("tomography"):



From

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





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.

COMPASS anniversaries and last run

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 <u>1995</u> (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

Old Chinese compass

Exploration

Hand-held compass

Consolidation

GPS compass

Precision

Courtesy

A. Bacchetta