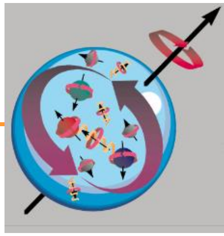


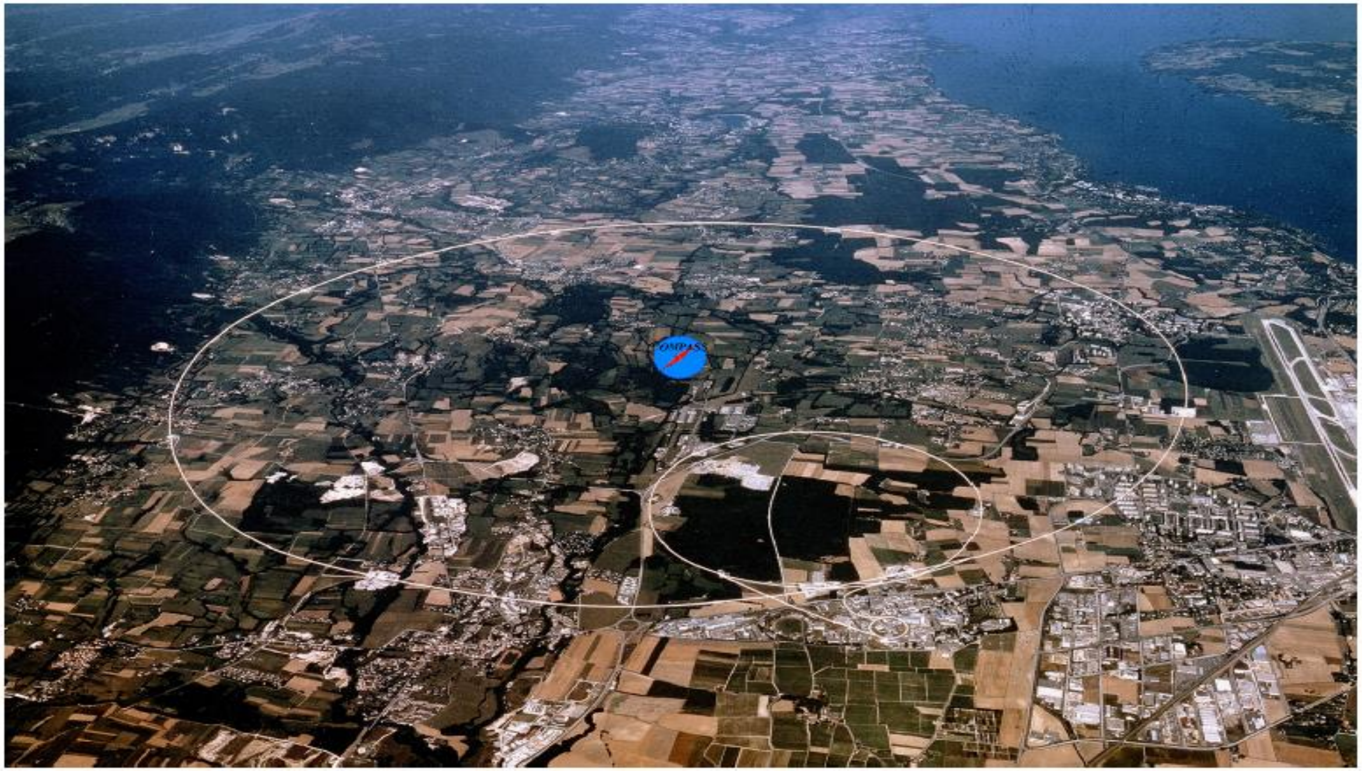
Nucleon spin and structure studies at COMPASS

Fabienne KUNNE
CEA /IRFU Saclay, France

- **Nucleon spin:** **Quark and gluon helicities**
- **Quark Fragmentation Functions**
- **Transversity**
- **Future**

ICNFP16, Kolymbari, Crete, Greece, July 7-14 2016

COmmon Muon Proton Apparatus for Structure and Spectroscopy



~240 physicists, 12 countries, 24 institutions

Fixed target experment, multi-purpose set-up.
Secondary ~200 GeV muon and hadron beams from CERN SPS
Various targets

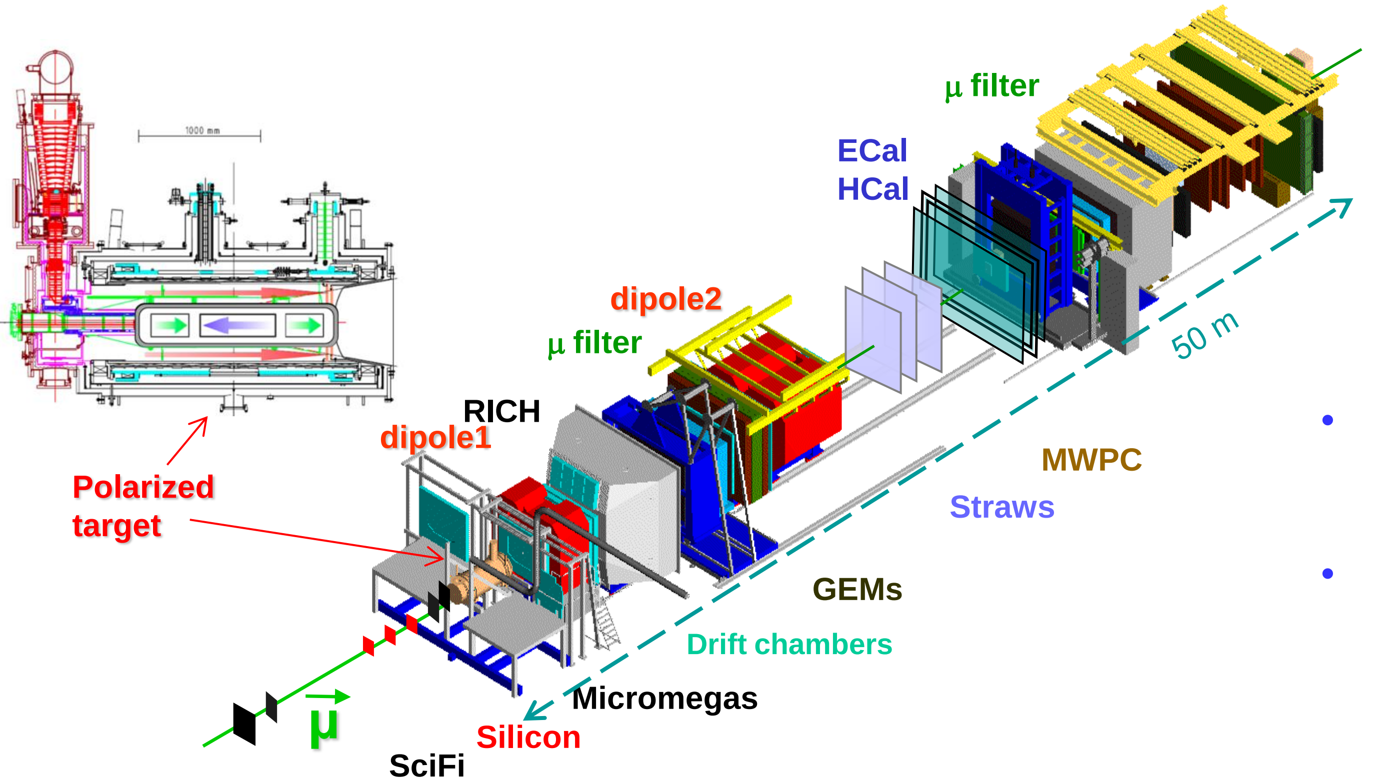
COMPASS at CERN

Results from:

Polarized muon beam & polarized target: d, p: Nucleon spin structure

Hadron beam π / K / p & LH_2 or nuclei targets: Meson spectroscopy → *Talk of S.Uhl*

π, K polarisabilities



NIMA 577 (2007) 455

Ongoing program:

- Generalized Parton Distributions from DVCS
- Transverse Momentum Dependent distributions from Polarized Drell-Yan

Nucleon spin

How is the nucleon spin distributed among its constituents?

Nucleon Spin $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$

quark gluon orbital momentum

$\Delta\Sigma$: sum over u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$
can take non half-integer value:
superposition of several spin states

$\Delta q = \overrightarrow{q} - \overleftarrow{q}$

Parton spin parallel or anti parallel to nucleon spin

Past:

Theory: QPM estimations, with relativistic effects $\Delta\Sigma \sim 0.6$

Experiment: "Spin crisis" in 1988, when EMC measured $a_0 = \Delta\Sigma = 0.12 \pm 0.17$

$\overline{\text{MS}}$ scheme

Quark spin contribution ~ 0 ?

Today:

Precise world data on polarized DIS $g_1 + SU_f(3)$ $a_0 = \Delta\Sigma \sim 0.3$

Quark spin contribution ~ 30%

Confirmed by first results from Lattice QCD on $\Delta\Sigma_{u,d}$. (Results exist also on $L_{u,d}$)

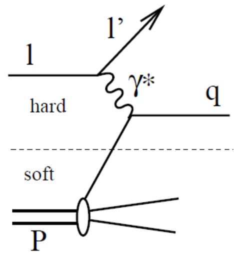
Large experimental effort on ΔG measurement

also because $a_0 = \Delta\Sigma - n_f(\alpha_s/2\pi)\,\Delta G$ (AB scheme)

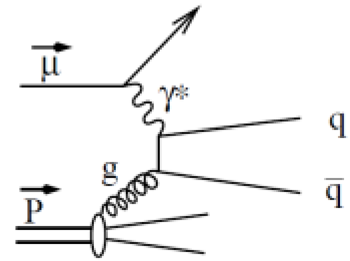
Quark and gluon helicity

Quarks and gluons from nucleon, probed with lepton beams

quarks
Deep inelastic scattering
QCD Leading order



gluons
Photon-gluon fusion: γg→qq



Helicities of partons measured via spin asymmetries using polarized beams and targets

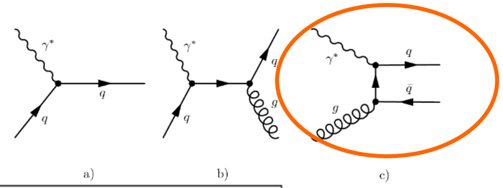
- **Acces $\Delta\Sigma$ et ΔG : contributions of quark and gluon spin to nuceon spin** $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$
- **Comparison to lattice QCD calculations**

Gluon helicity ΔG/G from hadron production

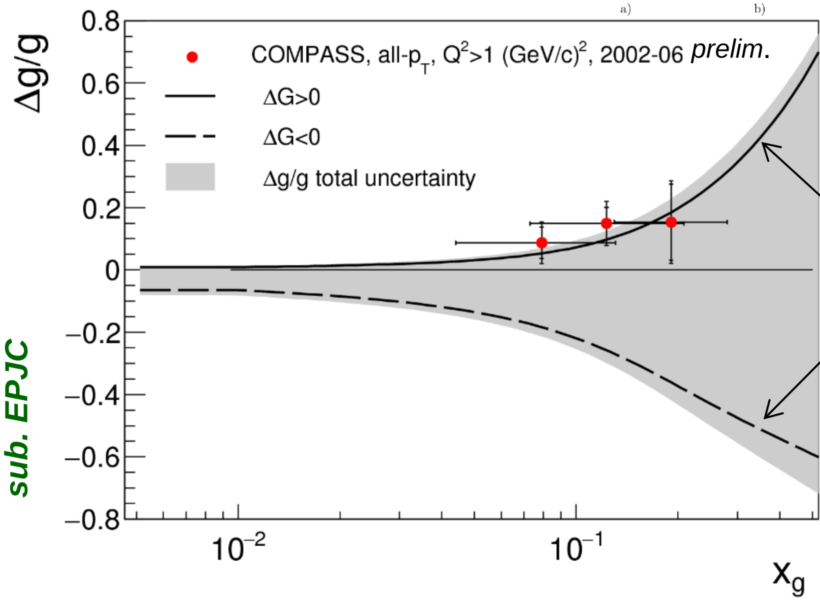
Photon Gluon Fusion

($Q^2>1 (GeV/c)^2$)

$\vec{\mu}\ \overleftarrow{\vec{p}} \rightarrow \mu'\ h + h\ + X$



ArXiv hep-ex1512.05053
sub. EPJC



$\Delta g/g$ $(x=0.1)$ = 0.11 ± 0.04 ± 0.04

Solutions from COMPASS NLO QCD fit of g_1 world data (see later)

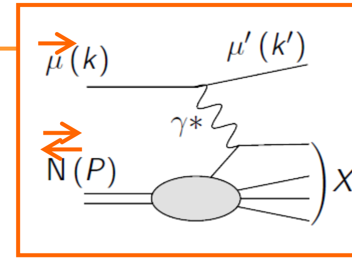
COMPASS data indicate ΔG >0 at x ~0.1

Results are in agreement with latest fits from NNPDF and DSSV++ using RHIC $\vec{p}\vec{p}$ data, which give

$$\int_{0.05}^{0.2} \Delta g(x)\,dx \simeq 0.20$$

QCD fits- World data on $g_1^{\,p}$ and $g_1^{\,d}$

DIS

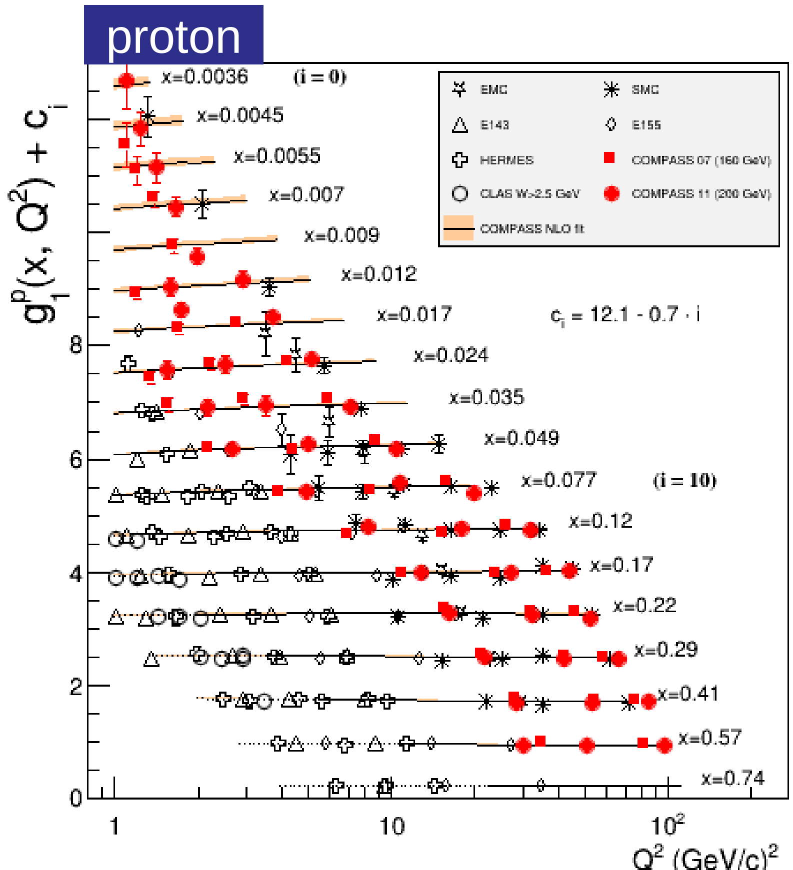


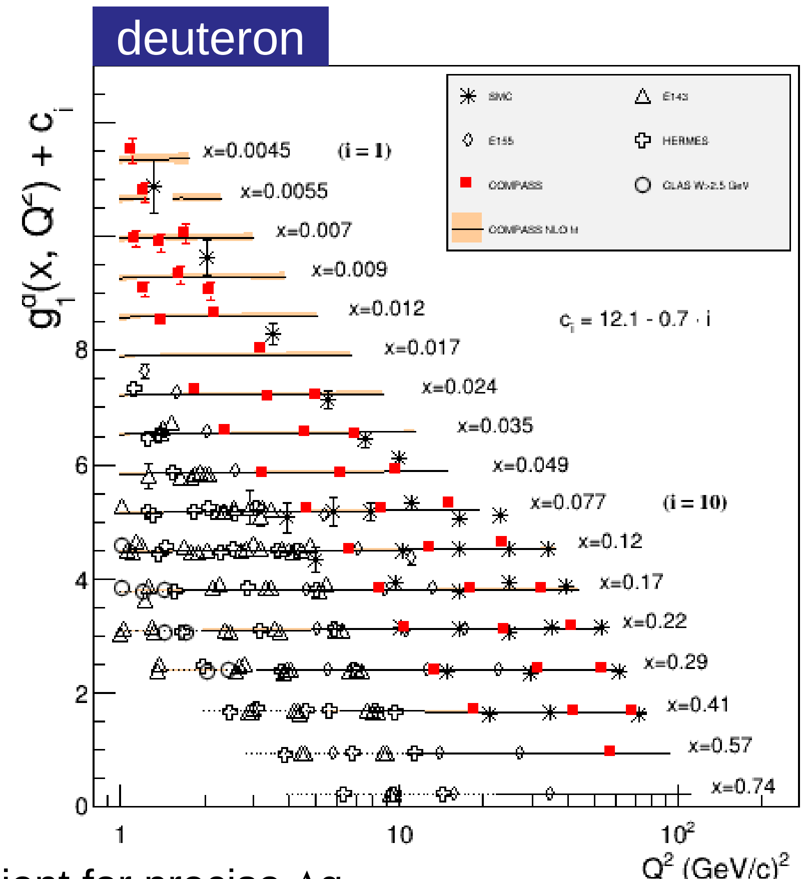
Polarized Deep Inelastic Scattering

➔ Nucleon spin structure functions g_1

➔ g1 (x,Q2) as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

$$\frac{d\, g_1}{d\, Log(Q^2)} \propto -\Delta g(x,Q^2)$$





However x and Q^2 coverage not yet sufficient for precise Δg

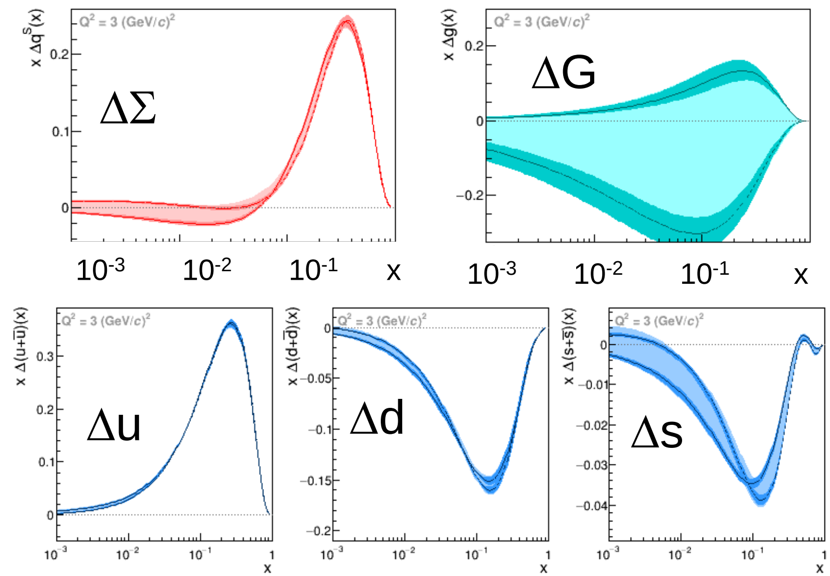
Would need to use constraint from pp data (as DSSV, NNPDF)

PLB753 (2016) 18

COMPASS NLO pQCD fit to g_1 DIS world data

- Assume functional forms for ΔΣ, ΔG and Δq^{NS} , and assume SU3 symmetry
- Use DGLAP equations, relating ΔΣ, ΔG evolutions .
- Fit g_1^p, g_1^d, g_1^n DIS world data
- Extract ΔΣ Quarks ΔG Gluons

→ Solutions ΔG>0 and ΔG<0



$0.82 \leq \Delta U \leq 0.85$ $-0.45 \leq \Delta D \leq -0.42$ $-0.11 \leq \Delta S \leq -0.08$

PLB 753 (2016) 18

→ Quark spin contribution :

ΔΣ= 0.31 (5) at Q^2=3 $(GeV/c)^2$

Largest uncertainty comes from the bad knowledge of functional forms.

Results in fair agreement with other global fits

→ Gluon spin contribution: ΔG not well constrained, even the sign, using DIS only

Solution with ΔG>0 agrees with result from DSSV++ using RHIC pp data

Summary on nucleon spin from COMPASS

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Quarks $\tfrac{1}{2}\Delta\Sigma \sim 0.15\ (3)$
largest uncertainty due to uncertainty on ΔG

Gluons $\Delta G/G$ positive at $x \sim 0.1$ (PGF)
agrees with precise RHIC result ($\Delta G \sim 0.2$ for integral $0.05<x<0.2$))
Low x contribution to integral still unknown.

Orbital momenta Lq, Lg
Ongoing measurements of GPDs

There exist promising results from lattice QCD calculations:
Confirm already $\Delta\Sigma$, and predictions for L_u et L_d.

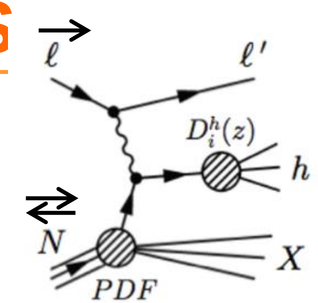
→ The main question raised in 'Nucleon spin crisis' resolved:

- Quark spin represents a non zero fraction (0.3) of nucleon spin **(from measurements and from lattice QCD calculations**)
- The hypothesis of very large ΔG (2 to 3, associated to L~ -2 ou -3) rejected (COMPASS 2005)
- Puzzle still pending: share between ΔG and L not known

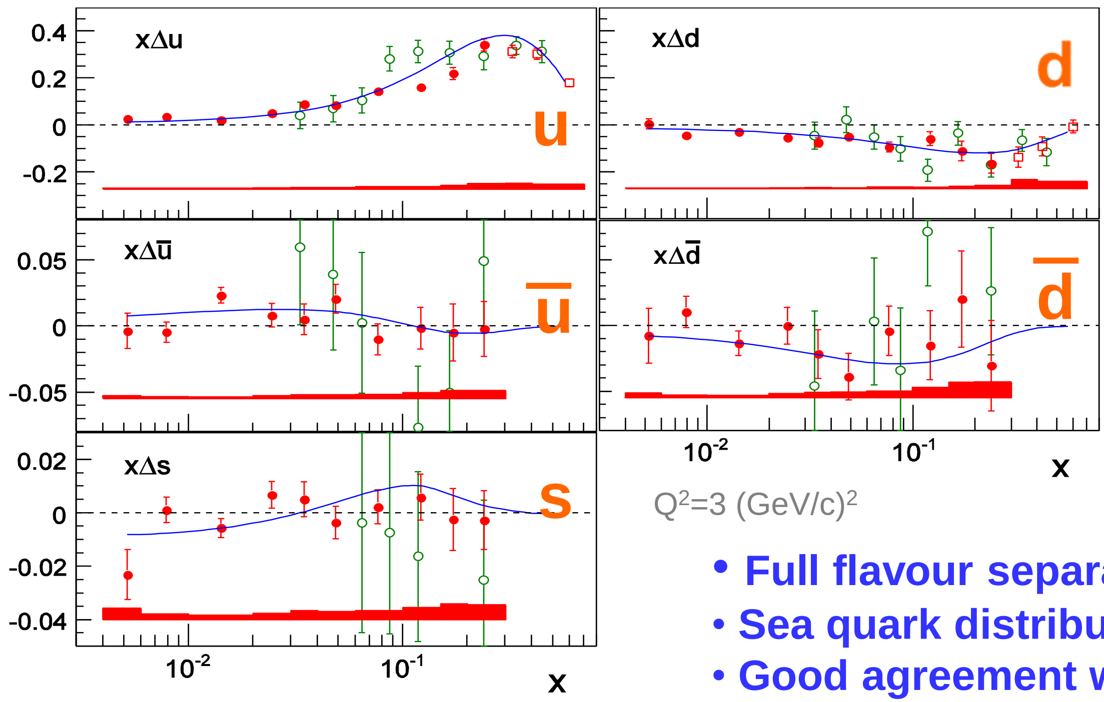
Quark helicities from semi-inclusive DIS

$l^{\rightarrow} p^{\rightarrow} \rightarrow l\, h^{+/-}\, x$

Outgoing hadron tags quark flavor
(quark fragmentation functions)



Leading order extraction of quark helicities from spin asymmetries:



- **COMPASS**
  PLB693(2010)227, using DSS quark FFs

o **HERMES**
  PRD71(2005)012003

__ DSSV at NLO

Q^2=3 (GeV/c)^2

- **Full flavour separation → x~0.004**
- **Sea quark distributions ~ zero**
- **Good agreement with global fits**

What about Δs? Integral is found negative from ***inclusive*** data (with SU3) while here from ***semi-inclusive*** data, x> ~0.005, Δs is compatible with zero.

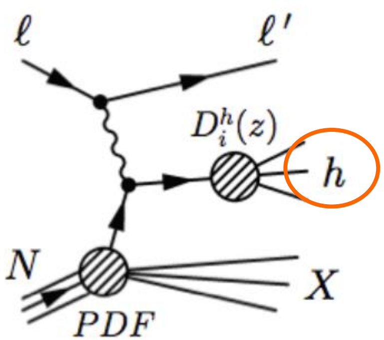
NB: - The extraction assumes quark Fragmentation Functions known (DSS here)
- No measurement at lower x

Quark Fragmentation Functions (FF)

FFs : - Non perturbative object; needed to describe various reactions
- Strange quark FF= **largest uncertainty in Δs extraction** from polarized SIDIS.

Data exist from e^+e^- and pp reactions, but unsufficient and at too high Q^2

→ Measure π, K, p multiplicities in **SIDIS** $\mu^+ d \rightarrow \mu^+ h^\pm X$



$z = E_h/(E_\mu - E_\mu')$

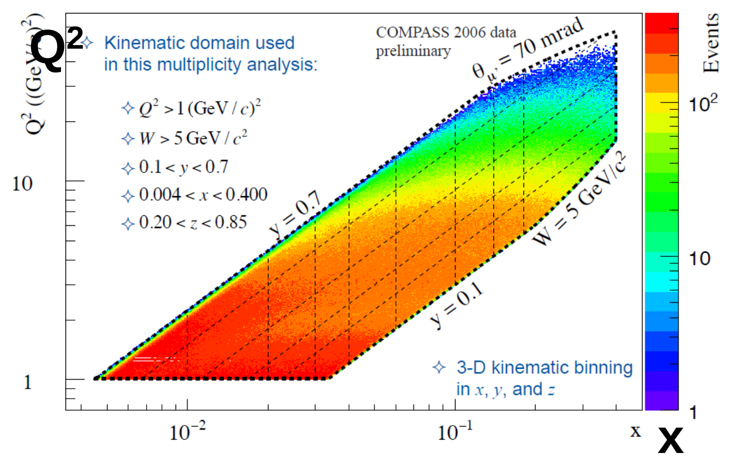
PDFs FFs

$$\frac{dM^h(x,Q^2,z)}{dz} \underset{\text{at LO}}{=} \frac{\sum_q e_q^2 f_q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 f_q(x,Q^2)}$$

PDFs depend on *x*, while FFs depend on *z*

Data obtained in a fine binning in x, z, Q^2

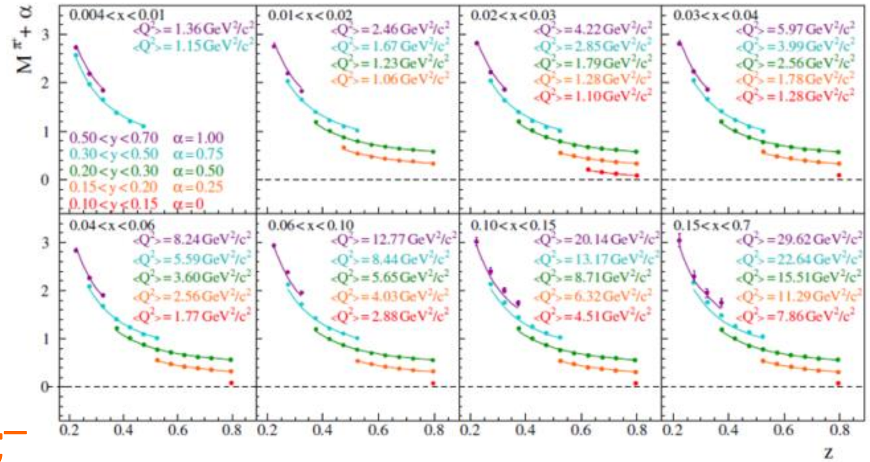
→ **Constitute an input to global NLO QCD analyses to extract quark FFs**



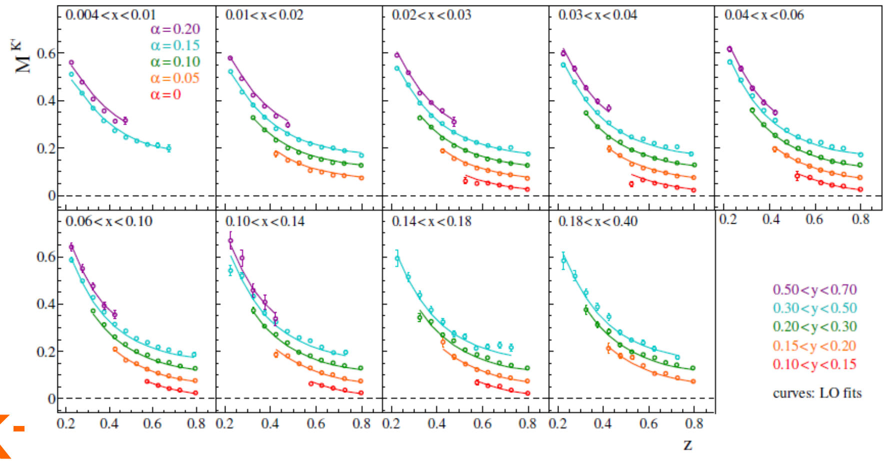
COMPASS π and K multiplicities vs z in (x,y) bins

preliminary

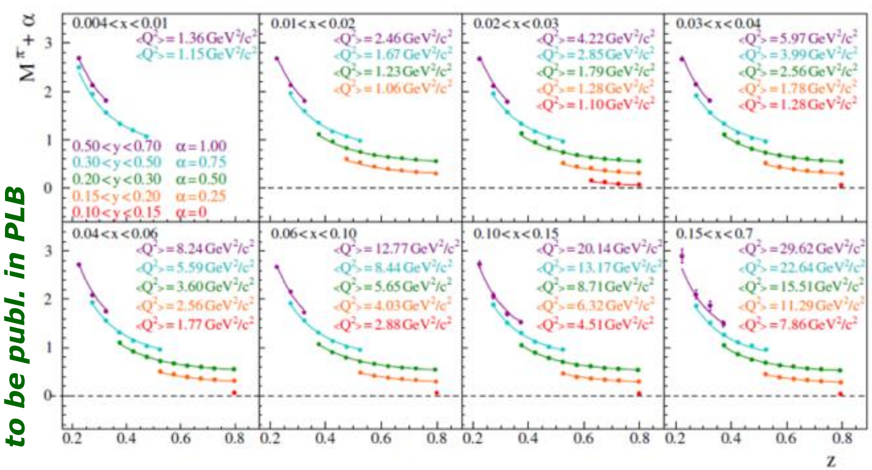
π^+



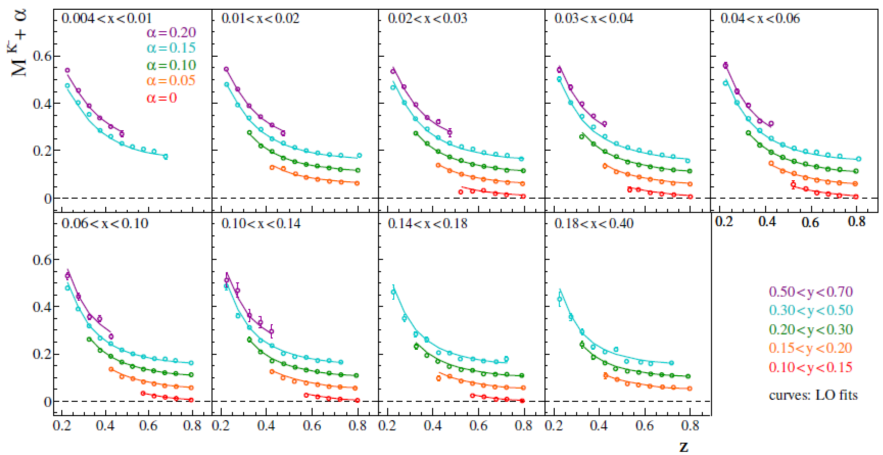
K+



π^-



K-



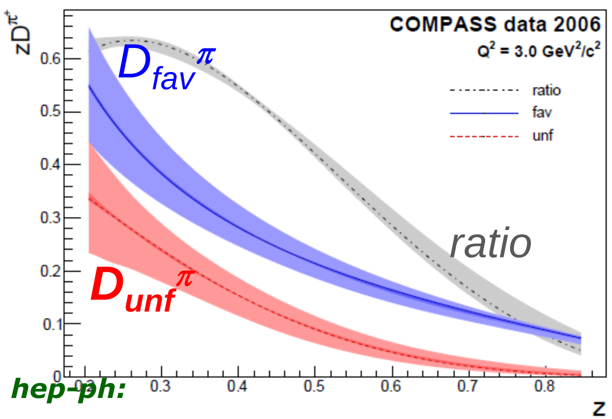
hep-ex:1604.02695
to be publ. in PLB

- ~360 data points for π and 360 for K
- Strong z dependance
- $M\pi^+ \sim M\pi^-$ and $MK^+ > MK^-$

Quark FFs from COMPASS LO fits

Pions

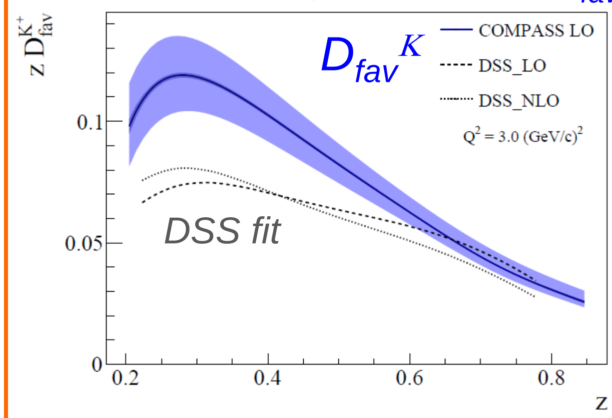
Assuming 2 independent FFs: D_{fav}^{π} D_{unf}^{π}

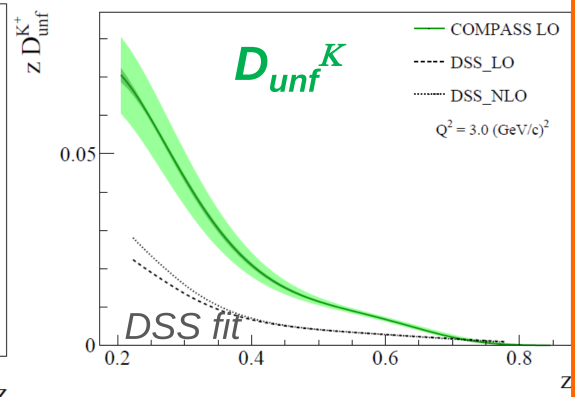


- As expected, $D_{fav}^{\pi} > D_{unf}^{\pi}$.
- COMPASS results ~agree with DSS and LSS NLO fits (not shown here)

Kaons

Assuming 3 independent FFs: D_{fav}^{K} D_{unf}^{K} D_{str}^{K}





- $D_{fav}^{K} > D_{unf}^{K}$.
- D_{fav}^{K} and D_{unf}^{K} **larger than DSS and LSS NLO fits (which do not include these kaon data)**
- D_{str}^{K} (not shown, not constrained enough by the fit)

Sum of *z* integrated multiplicities $\pi^+ + \pi^-$ & $K^+ + K^-$

For isoscalar target, simple dependence on FFs:

$M^{\pi^+ + \pi^-}$ = (1-~~2S/(5Q+2S)~~) $D_{fav} + D_{unf}$

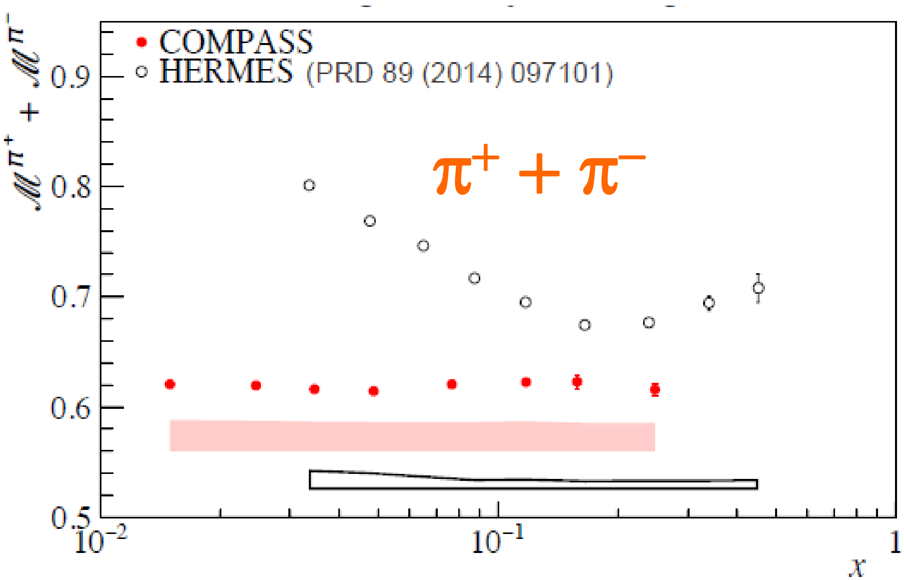
$5M^{K^+ + K^-} = D_Q^K$ + S/Q D_S^K

where:

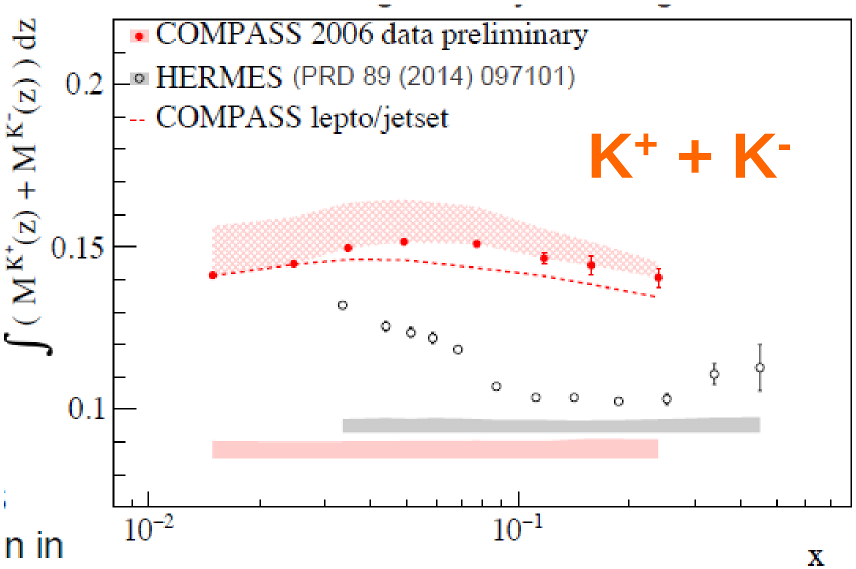
high x data ***low x data***

At high x, ~no *x* dependence expected

$$\begin{cases} Q = u + \bar{u} + d + \bar{d}, \\ S = s + \bar{s}, \\ D_Q^K = 4D_{fav}^K + 6D_{unf}^K \end{cases}$$



n in



COMPASS pion data:

- **significantly below HERMES ones**
- **no x dependence**

(as in EMC h, but not shown here)

COMPASS kaon data:

- **significantly above HERMES ones**
- **agree with MC simulation (LUND)**
- **Indicate smaller D_S^K, and larger D_Q^K**

Transversity- Collins and Sivers asymmetries

- Access via **SIDIS**, transversely polarized target $\mu\, p^{\uparrow} \rightarrow \mu\, h^{+/-}\, X$

- Measure simultaneously several azimuthal asymmetries, out of which :

  Collins: Outgoing hadron direction & quark transverse spin

  Sivers: Nucleon spin & quark transverse momentum k_T

  Sivers function = one of the TMDs = Transverse Momentum Dependent PDFs

at LO: **Collins** **Sivers**

q transverse spin distr.

$$A_{Coll} = \frac{\sum_q e_q^2\, \Delta_T q \otimes \Delta_T^{\circ} D_q^h}{\sum_q e_q^2 \cdot q \otimes D_q^h}$$

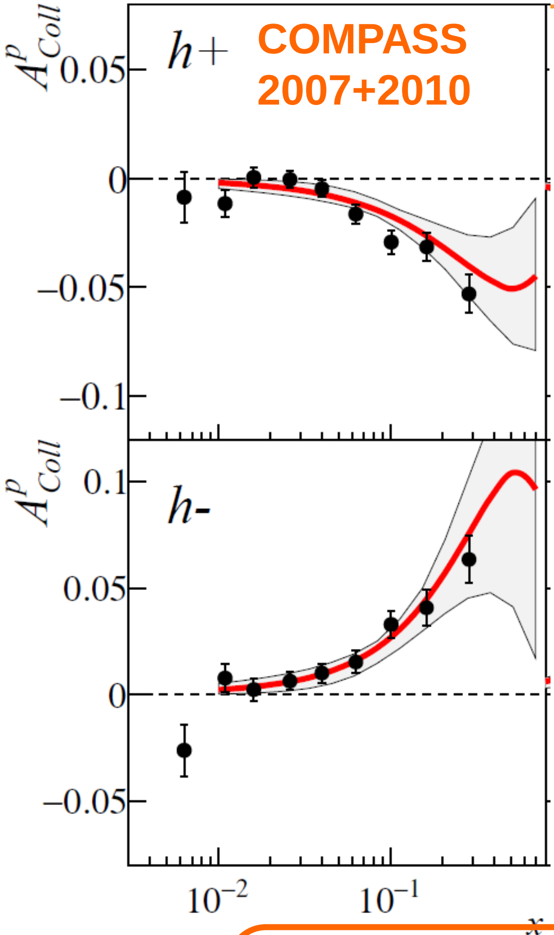
Collins TMD fragmentation function, depends on spin, and hadron p_T

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 \cdot q \otimes D_q^h}$$

Unpolarized quark TMD fragmentation function

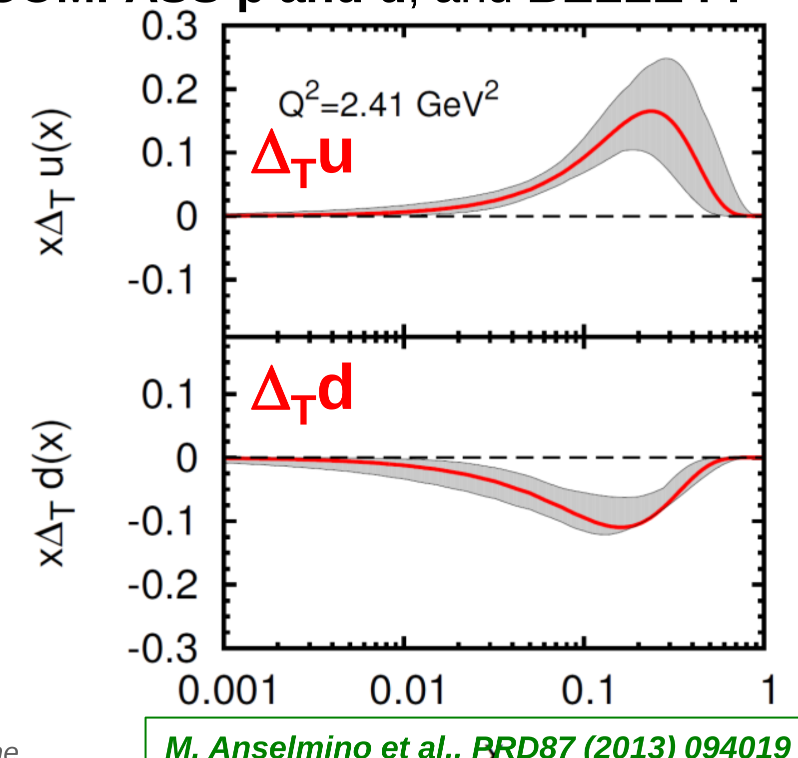
note: $\Delta_T q$ also measured in SIDIS using "Two hadron" fragmentation function

Collins asymmetry → Transversity $\Delta_T u$ $\Delta_T d$



- **Large signal for proton target.**
  (compatible with zero for deuteron target)
- **Same signal strength seen by HERMES and COMPASS, although different Q^2 (times 4)**

Several combined analyses of polarized SIDIS data
HERMES p, COMPASS p and d, and **BELLE FF**



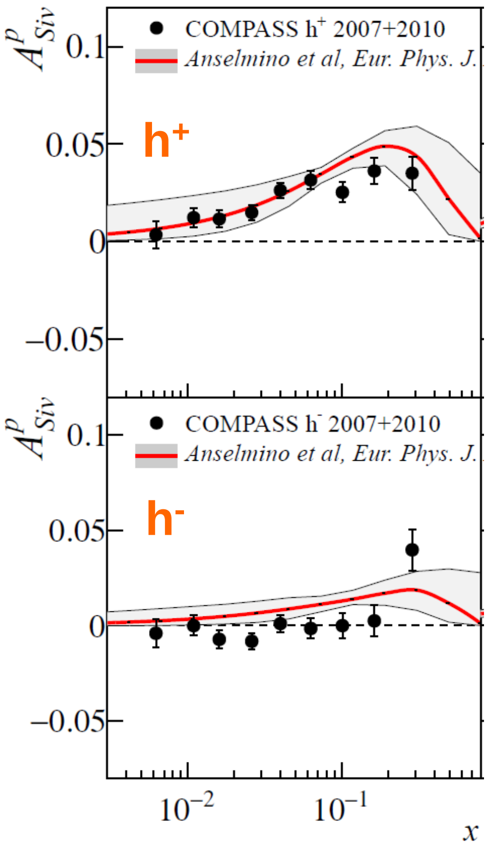
- **$\Delta_T u > 0$ and $\Delta_T d < 0$**
- Smaller than helicity
- Derived also from di-hadron

Nb: Asymmetry also measured for π and K
PLB 744 (2015) 250

M. Anselmino et al., PRD87 (2013) 094019

Sivers asymmetry → Sivers function

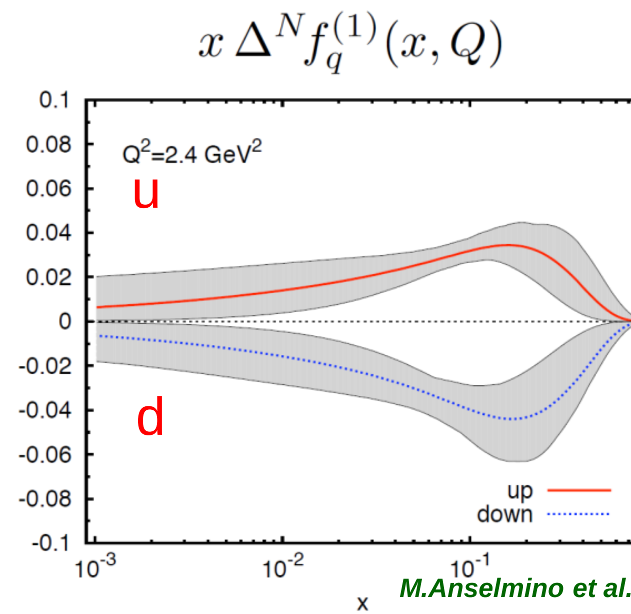
Correlation between Nucleon spin & quark transverse momentum k_T



Large signal with proton target and h+

Was measured compatible with zero on deuteron

When compared to HERMES, smaller strength at larger Q^2



M.Anselmino et al.,QNP2012

→ Opposite sign for u and d quark Sivers function

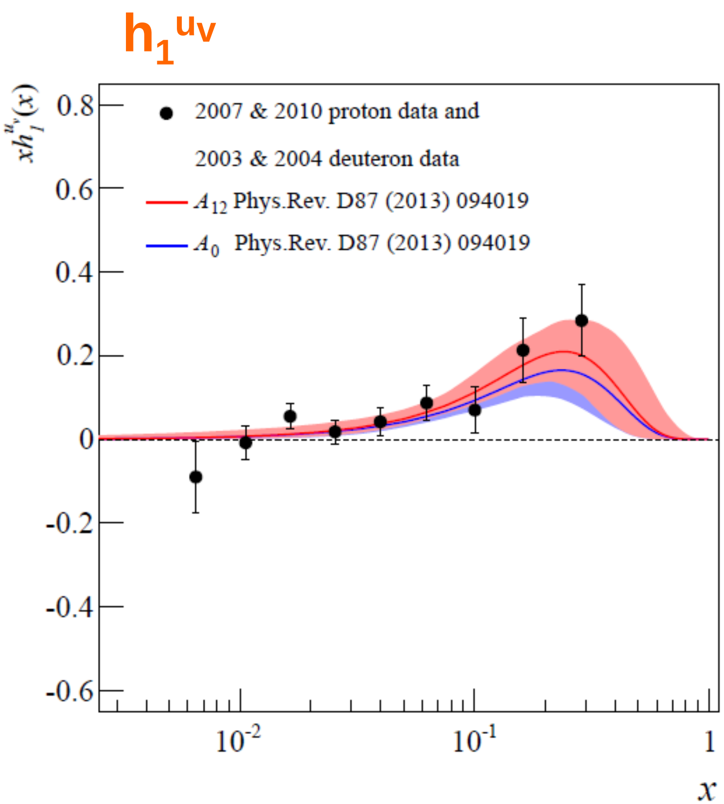
Nb: Asymmetry also measured for π and K

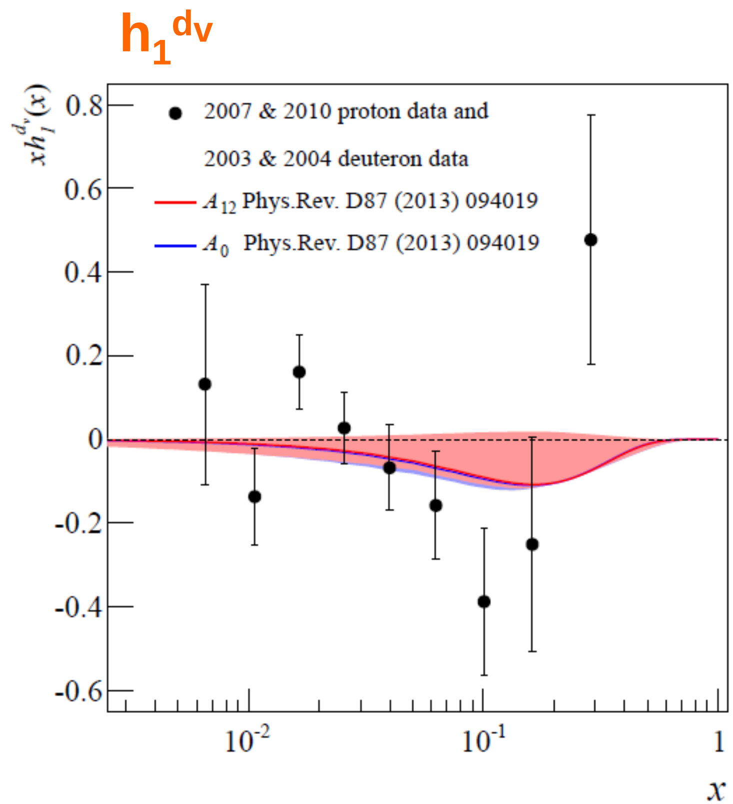
PLB 744 (2015) 250

Transversity from dihadrons – Extraction of h1

using :

- COMPASS proton and deuteron data on dihadron azimuthal asymmetries (different analysis from Collins)
- dihadron FF + Q^2 evolution from Bacchetta et al. ***JHEP03 (2013) 119***

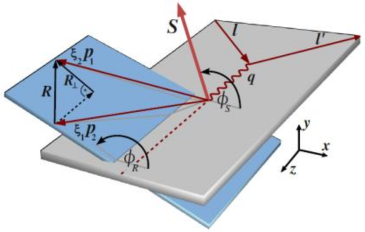




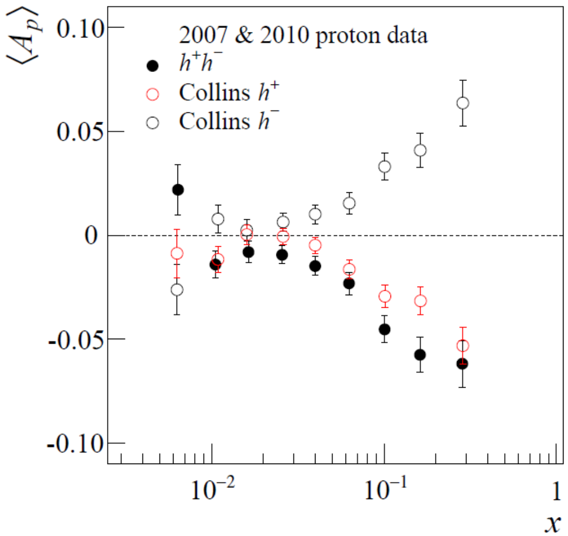
Comparison with Anselmino et al. (global fits of single hadron Collins asymmetries+FFs): Very good agreement for u quark, and fair agreement for d quark transversity.

Transversity from di-hadrons. Interplay with Collins

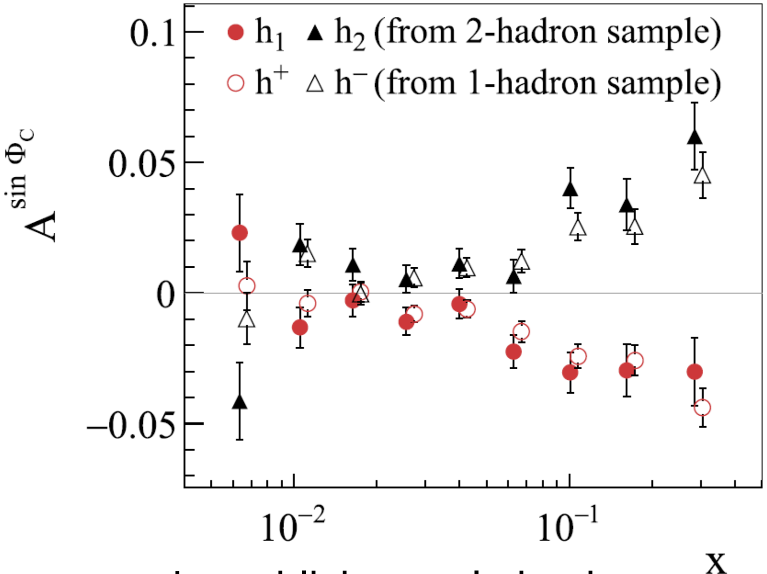
Fragmentation of a transversely polarized quark



Azimuthal asymmetries from production of :
- di-hadron (oppositely charged pair)
- single hadron (+ and -, mirror symmetric Collins asymmetries)



PLB 736 (2014) 124



PLB 753 (2016) 406

→ Observe similar behaviour … and establish correlation between the three

- **First experimental indication for a common physical origin to the two processes, di-hadron and Collins, as originally suggested by different models.**
- **Results for 'transversity' from the two measurements are NOT independent**

Six Transverse Target spin asymmetries

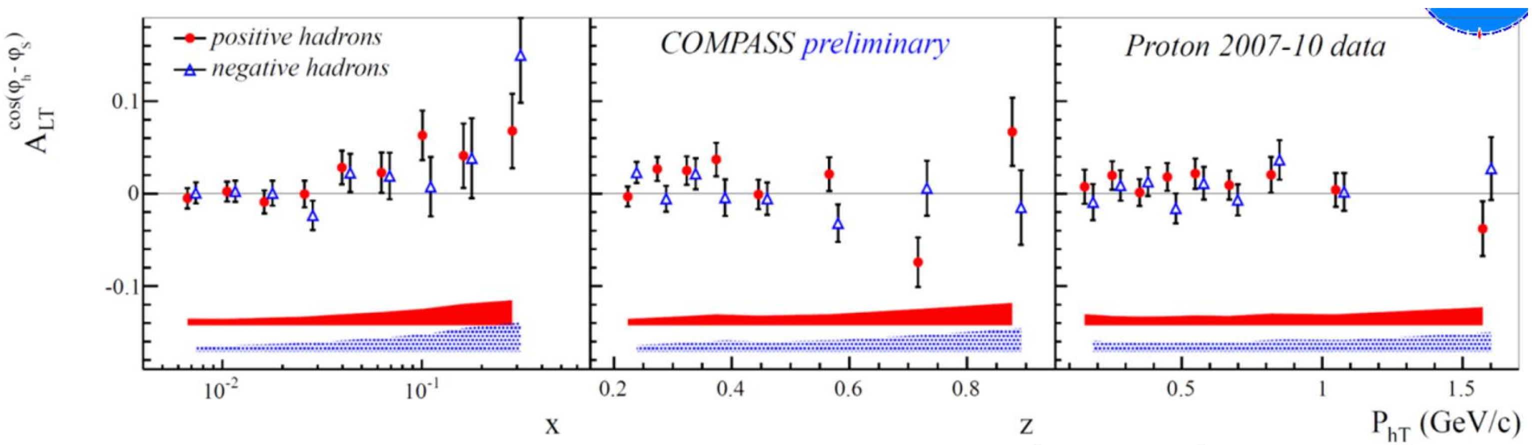
beyond Collins & Sivers, access TMDs

$\mu\, p^{\uparrow} \rightarrow \mu\, p\, h^{+/-}$

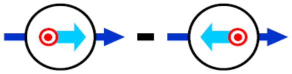
k_T effects → modulations in SIDIS cross-section

- **Major progress in TMD measurement**
- **Powerful tool to understand correlations**

$A_{LT}^{\cos(\varphi_h - \varphi_s)}$ shown as example



$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q :



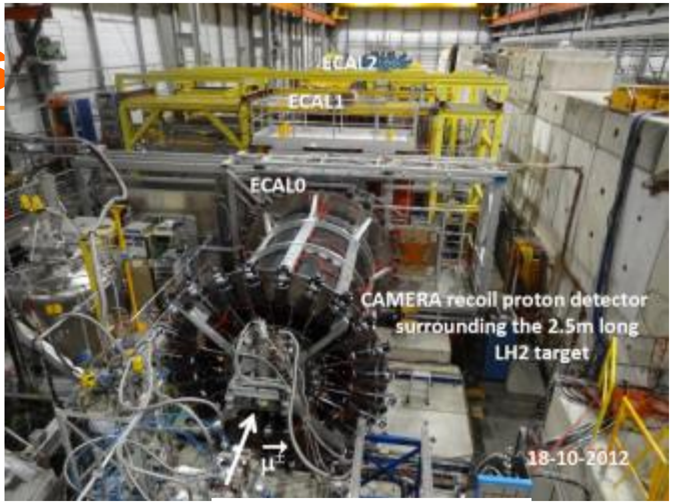
In agreement with HERMES prelim., and with theoretical predictions

COMPASS ongoing program 2015 - 2018:

- **GPDs** **(Generalized Parton Distributions)**
  via **Deep Virtual Compton Scattering** $\mu\, p \rightarrow \mu\, p'\, \gamma$

- **TMDs** **(Transverse Momentum Dependent distributions)**
  via spin dependent Drell-Yan $\pi\, p\uparrow \rightarrow \mu^{+}\, \mu^{-}$

Generalized parton distributions

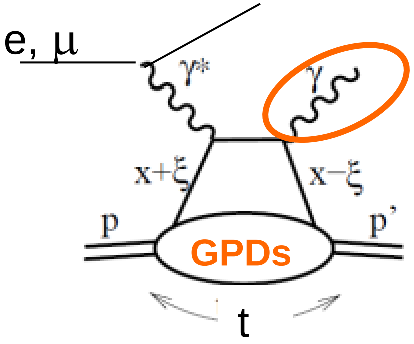


$\mu\ p \rightarrow\ \mu'\ p\ \gamma$

Study **correlation** between
parton longitudinal momentum
& parton transverse position in the nucleon '3D'

- **Nucleon '3D' structure**
- **Link to orbital momentum L_z**

Process:
Deep virtual Compton scattering (DVCS):
'exclusive' γ production $\mu\ p \rightarrow\ \mu\ p'\ \gamma$
or Meson Production ρ^0, ω, ϕ…



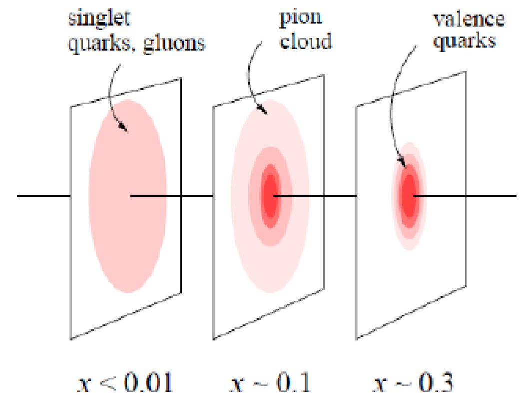
→ **Proton transverse size**

→ **Compton Form Factors in yet unexplored regions (160 GeV μ beam)**

DVCS- t-slope of Cross-section

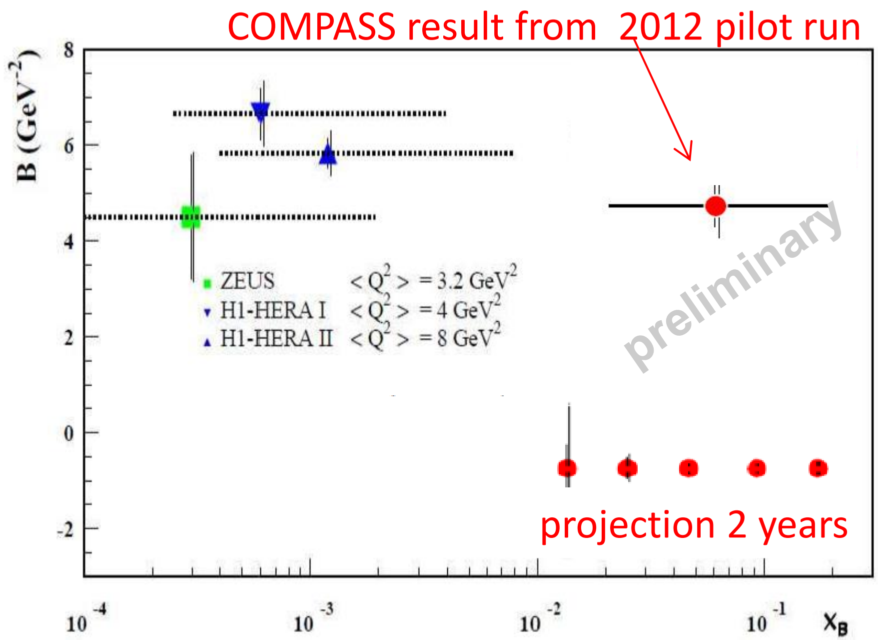
$\mu \; p \rightarrow \mu \; p \; \gamma$ x dependence of transverse size of the nucleon

$\sigma^{DVCS}/dt \sim \exp^{-B|t|}$ $B(x_B) = ½ < r_\perp^2 (x_B) >$

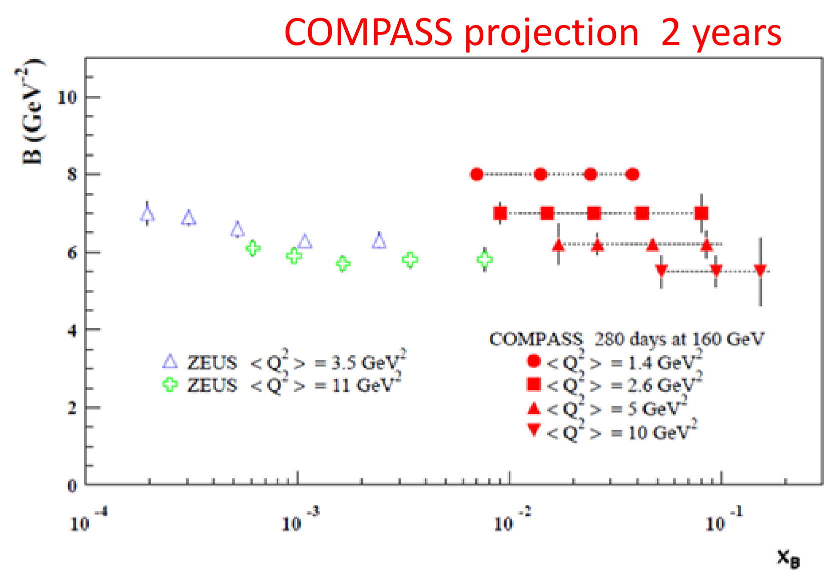


Also accessed via meson production ρ, ω, ϕ

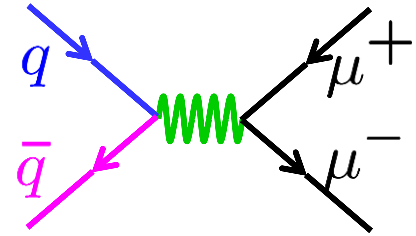
Deep Virtual Compton Scattering (γ)



Deep Virtual Meson Prod. (ρ)



COMPASS- Spin dependent Drell-Yan (2015 and 2018)



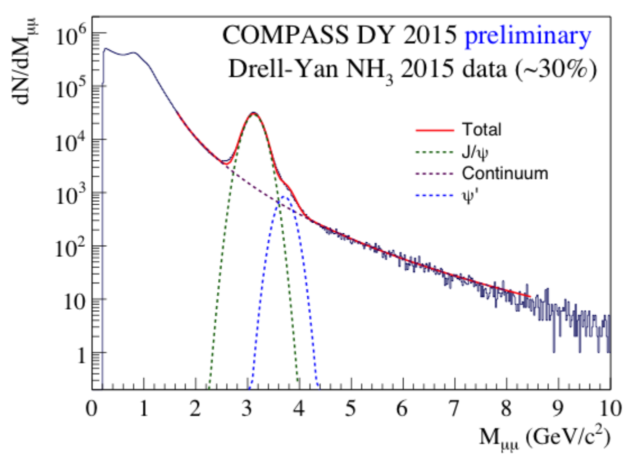
Pion beam on transversely polarized nucleon

Objectives for Drell-Yan measurements:

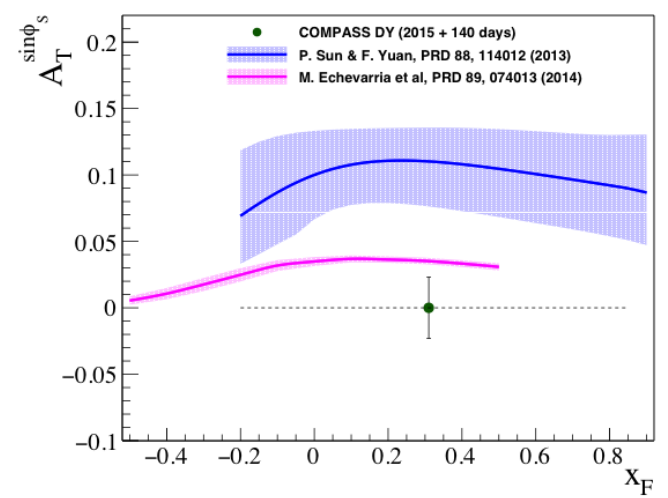
- **Polarised:** Sivers TMD PDF (correlation k_T vs nucleon transverse spin) sign change DY vs SIDIS → test of factorization in QCD
- **Unpolarized:** Other TMD PDFs (Boer-Muldres…) (k_T vs s_q)

COMPASS assets

- SIDIS and DY experiments: large acceptance, same spectrometer
- Unique hadron beam (π, K, p) with valence antiquarks
- Polarized target



Projection 2 years (2015+2018 data)



Summary

Gluon and quark contribution to nucleon spin

Gluon $\Delta G/G = 0.1$ at $x=0.1$ from measurement in PGF 2 hadrons

Quarks : Sum $0.26 < \Delta\Sigma < 0.34$ from global QCD fit of g_1 world data
Largest uncertainty comes from functional shape (of ΔG also)
Extraction for all flavours from SIDIS measurements, down to x ~0.004.
Towards agreement with Lattice QCD calculation

Pion and kaon multiplicities in semi-inclusive DIS:

Large discrepancies between COMPASS and HERMES data

Transversity and Transverse Momentum Dependent parton distributions

Precise results on Collins and Sivers asymmetries
Interplay Collins effect / di-hadron
Much progress on all azimuthal asymmetries for TMDs

Future

TMDs via polarized Drell-Yan $\pi\ p\uparrow \rightarrow \gamma\ \gamma$
GPDs via Deep Virtual Compton Scattering $\mu\ p \rightarrow \mu\ p\ \gamma$
First result on proton transverse size

COMPASS Plans

2015	**Polarized Drell-Yan $\pi\ p\uparrow$**
2016 **2017**	**DVCS μ p**
2018	**Polarized Drell-Yan $\pi\ p\uparrow$**
2019 2020	CERN Long Shutdown-2
2021 2022 2023	Ideas for future: - **Kaon & p-bar beams** (for **Drell-Yan** and **Meson Spectroscopy**) - **DVCS** on Polarized Target $\mu\ p\uparrow$ (sensitive to nucleon orbital angular momentum)