Overview of Spin Studies at COMPASS

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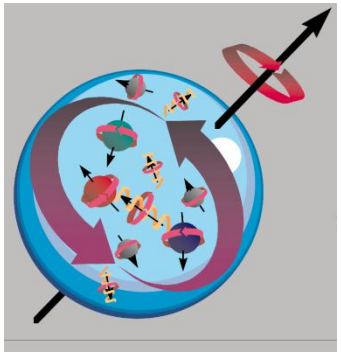
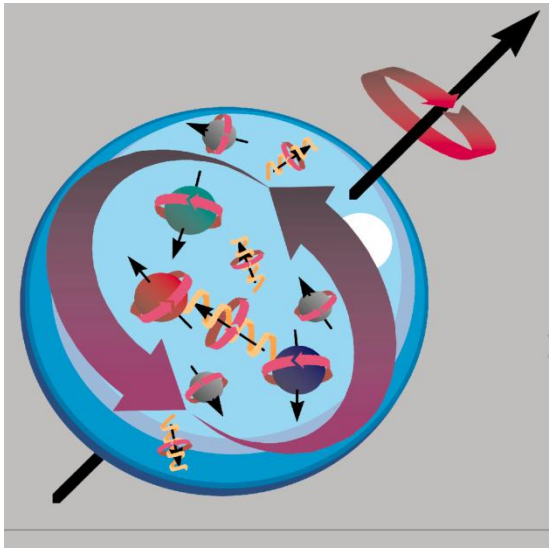
- **Gluon and Quark helicities**
- **Transversity**
- **Future: Polarized Drell-Yan & DVCS**



Nucleon spin structure

- Nucleon Almost all visible matter
- Spin Fundamental quantum number
  Pauli principle
  Important for symmetry tests: parity /time reversal



Nucleon contains
quarks, anti quarks, gluons

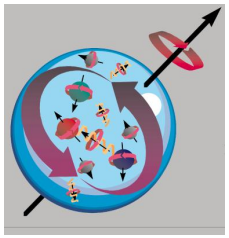
How is spin distributed in the nucleon?

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 any value: superposition of several 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)

Today:

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

First results from Lattice QCD on $\Delta\Sigma_{u,d}$ and $L_{u,d}$

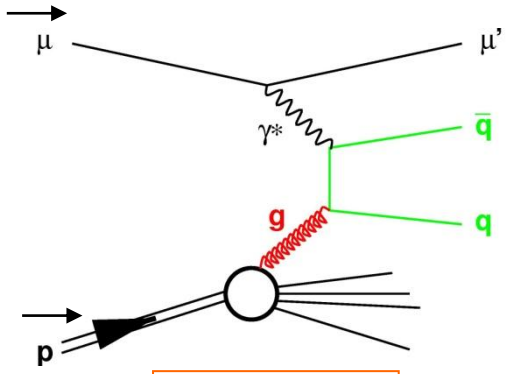
Large experimental effort on ΔG measurement

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

Three ways to study gluon contribution ΔG

1. Lepton Nucleon

Photon Gluon Fusion

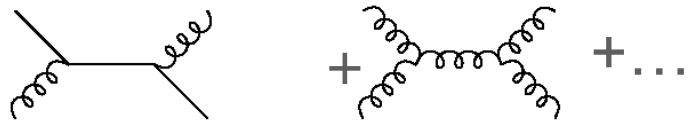


ΔG/G(x)

SMC, HERMES, COMPASS

2. Proton Proton collisions

Gluon-Quark + Gluon-Gluon +…



$$\frac{\Delta G}{G}\times\frac{\Delta q}{q} \qquad + \frac{\Delta G}{G}\times\frac{\Delta G}{G} + \ldots$$

A_{LL} (p_T)

RHIC : PHENIX & STAR

3. QCD Q^2 evolution of spin structure function $g_1(x,Q^2)$: Indirect determination assuming a functional form ΔG(x). Global fits include polarized DIS, SIDIS and pp data

COMPASS at CERN

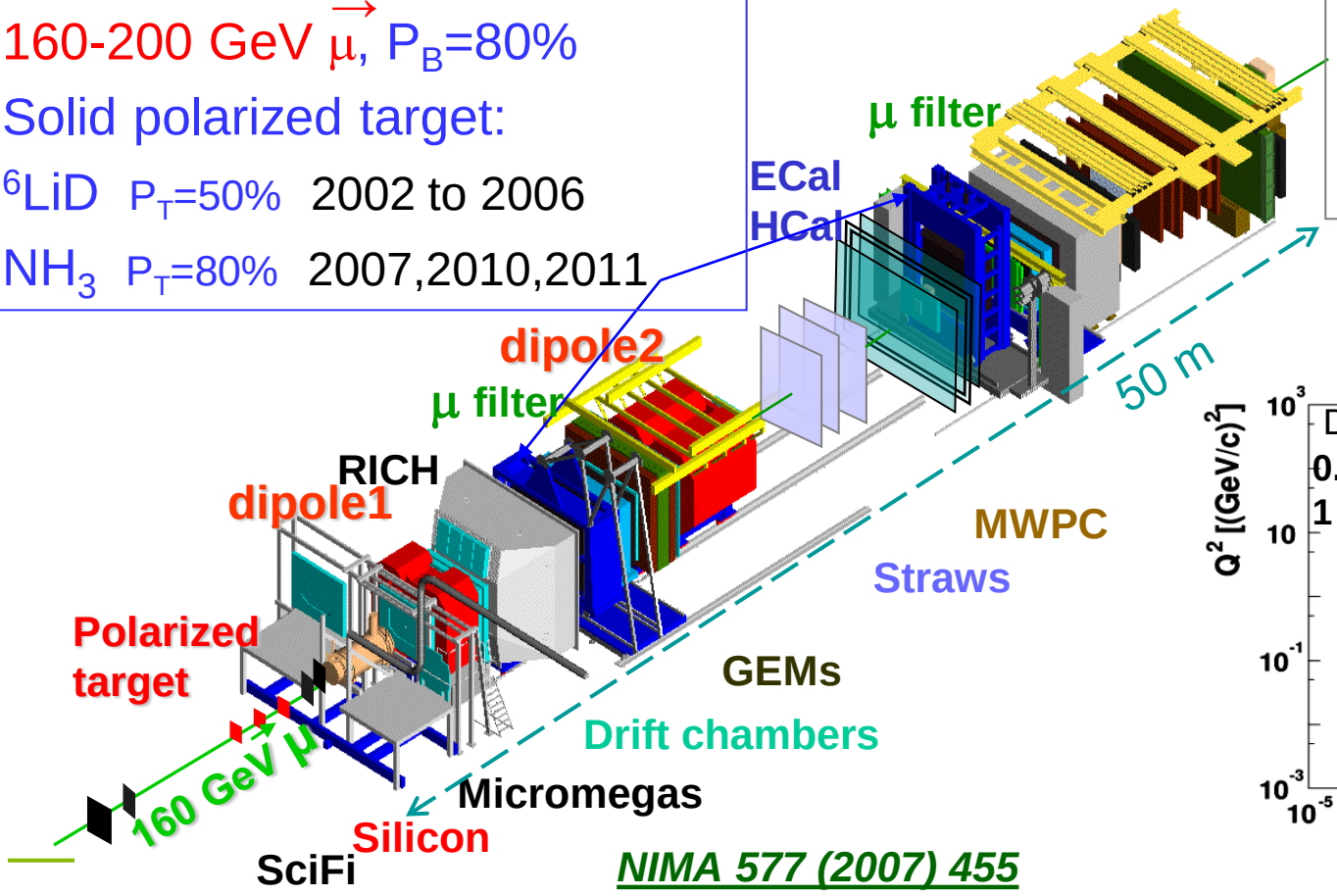
Fixed target
Secondary beams from SPS

Nucleon spin structure

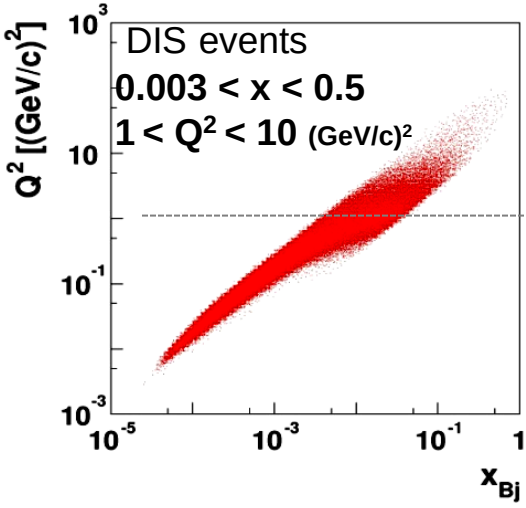
Polarized muon beam:
160-200 GeV $\vec{\mu}$, P_B=80%
Solid polarized target:
^{6}LiD P_T=50% 2002 to 2006
NH_3 P_T=80% 2007,2010,2011

Meson spectroscopy

Hadron beam :
190 GeV π / p
LH_2 2008, 2009, 2012



See talk of S.-U. Chung, Saturday



NIMA 577 (2007) 455

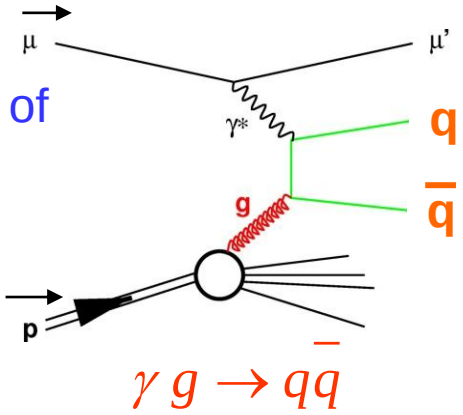
1. ΔG/G from *lepton* $\vec{N}$ scattering

Photon Gluon Fusion (PGF) process

Asymmetry of cross sections for longitudinal polarizations of beam and target, parallel and antiparallel

$$A_{LL} = R_{PGF} \langle a_{LL} \rangle \langle \Delta G/G \rangle + A_{background}$$

Fraction of process — Analyzing power



$\gamma g \rightarrow q\bar{q}$

Two signatures for PGF:

1/ q=c open charm c→ D^0 → K π

Clean signature of PGF
pQCD scale $\mu^2 = 4 (m_c^2 + p_T^2)$
Combinatorial background & limited statistics
→ Difficult experiment; 5 decay channels added

COMPASS :1 point

2/ q= u,d,s high p_T hadron pair q $\bar{q}$ → h h

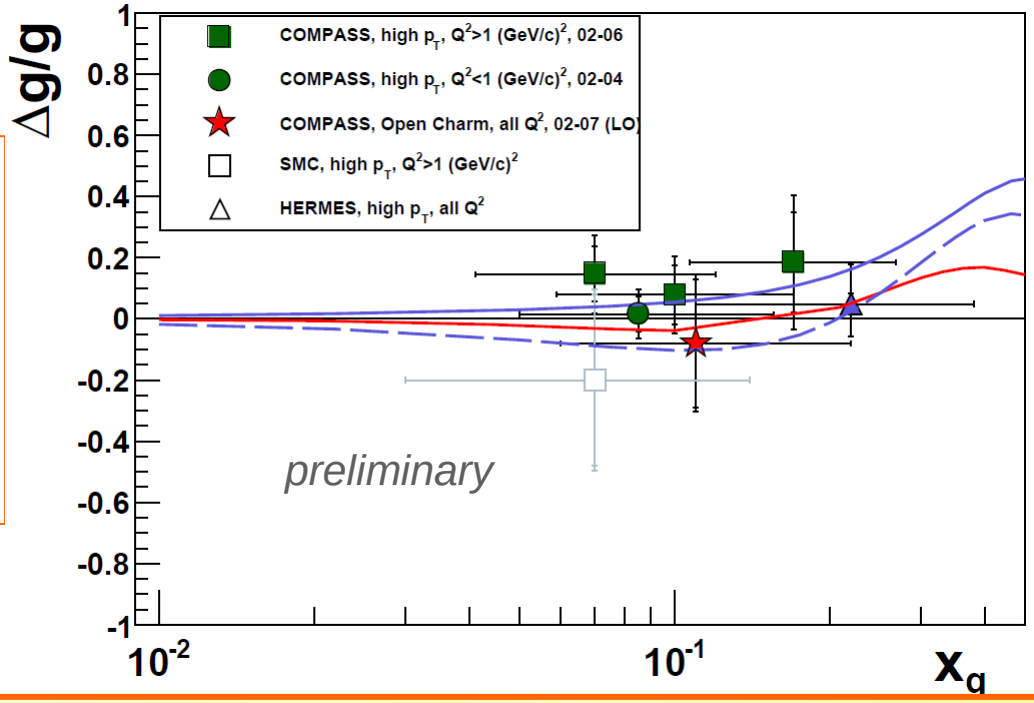
High statistics
pQCD scale Q^2 or Σp_T^2
Physical background
Differential Cross section now also extracted (New)

COMPASS : 4 points + HERMES &SMC

Δ G/G at LO : SMC, HERMES and COMPASS

High p_T hadrons:
Q^2~ 3
with model for physical background

Open charm:
Q^2= 13



LSS10, ΔG~ + 0.32

LSS10, ΔG~ - 0.33
at Q^2= 4

DSSV, ΔG= 0.02
at Q^2=3

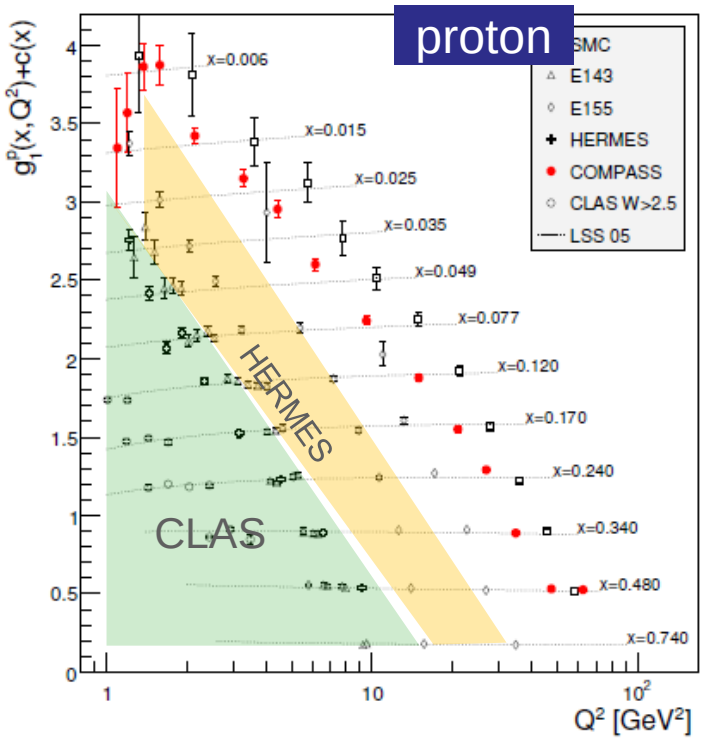
- **All measurements compatible with 0**
- **Constraint on <ΔG> for 0.05 < x < 0.3**
- **Results disfavour value of the integral > ~ ± 0.3**
  i.e. ± 60% of the ½ nucleon spin
- **Contribution to <ΔG> outside measured x range not excluded**

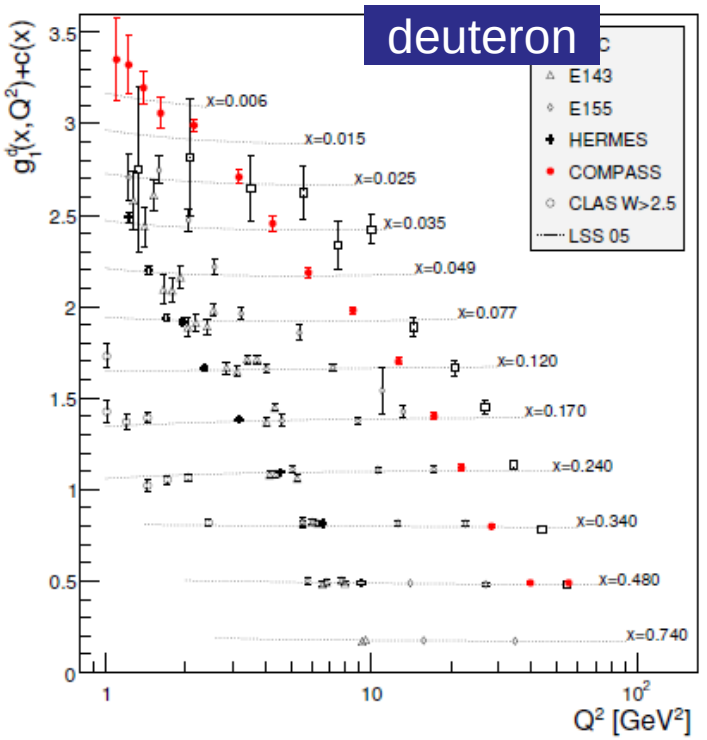
Note that these data are NOT included in global fits

3. ΔG from global fits

Spin structure functions g_1

$$A_1^{DIS} \propto g_1(x) \propto \frac{1}{2}\Sigma e_q^2\left(\Delta q(x) + \Delta\bar{q}(x)\right)$$





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

→ g_1 as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta G(x)$

However x and Q^2 coverage not yet sufficient for ΔG
Use also constraint from pp data (DSSV)

Note: new 200 GeV proton data to come from COMPASS 2011 run

3. ΔG(x) from global QCD fits of polarized data

LSS '10

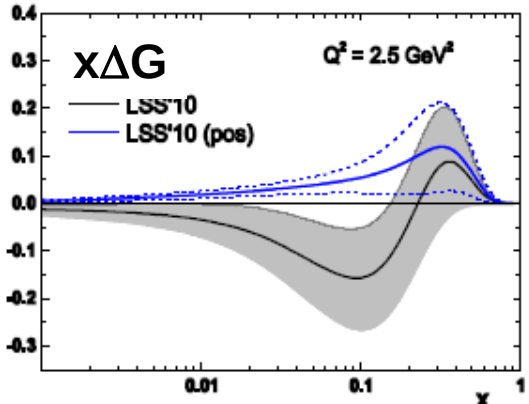
Only DIS & SIDIS data

Leader, Sidorov, Stamenov,

ΔG= 0.25± 0.19

ΔG= -0.40± 0.43

at Q^2=2.5GeV/c^2



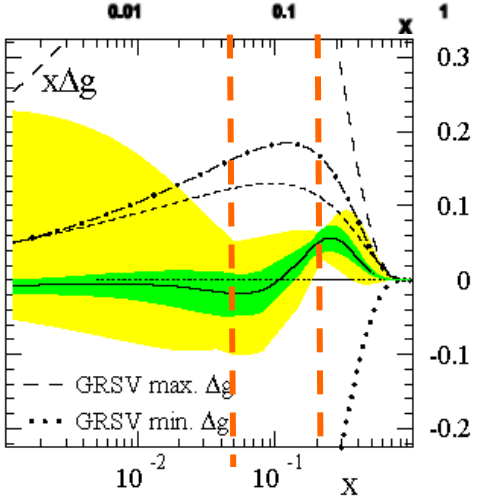
DSSV-2009 (old)

DIS, SIDIS & pp

De Florian, Sassot, Stratmann, Vogelsang PRL101 (2008)072001

ΔG= -0.08 ± ?

at Q^2= 10 GeV/c^2



~0 in measured range (node)

- **Data favored fits with ΔG close to 0, excluding ΔG std (DSSV-2009, LSS10)**
- **Strong constraint on <ΔG> , now > 0 (DSSV+) in x range probed**
- **No constraint outside 0.05 < x < 0.2**

Quark spin contribution $\Delta\Sigma$ from QCD fits

COMPASS $\Delta\Sigma = 0.30 \pm 0.01\,(\text{stat}) \pm 0.02\,(\text{evol})$

fit to $g_1^{p,n,d}$ world data, $\overline{\text{MS}}$ scheme, $Q^2=3\ (\text{GeV/c})^2$ *PLB 647 (2007) 8*

$\Delta s + \Delta\bar{s} = -0.08 \pm 0.01\,(\text{stat}) \pm 0.02\,(\text{evol})$ COMPASS data only

HERMES $\Delta\Sigma = 0.33 \pm 0.011\,(\text{stat}) \pm 0.025\,(\text{theo}) \pm 0.028\,(\text{evol})$

HERMES g_1^d data, $\overline{\text{MS}}$ scheme, $Q^2=5\ (\text{GeV/c})^2$, neglecting $x < 0.02$ contrib., *PRD75 (2007)012007*

$\Delta s + \Delta\bar{s} = -0.085 \pm 0.013\,(\text{th}) \pm 0.008\,(\text{exp}) \pm 0.009\,(\text{evol})$

DSSV $\Delta\Sigma = 0.24$ $Q^2=10\ (\text{GeV/c})^2$ *arXiv:0804.0422*

LSS '10

$\Delta\Sigma = 0.25 \pm 0.04$ ΔG with node $Q^2=10\ (\text{GeV/c})^2$,

$\Delta\Sigma = 0.21 \pm 0.03$ $\Delta G > 0$

Bjorken sum rule

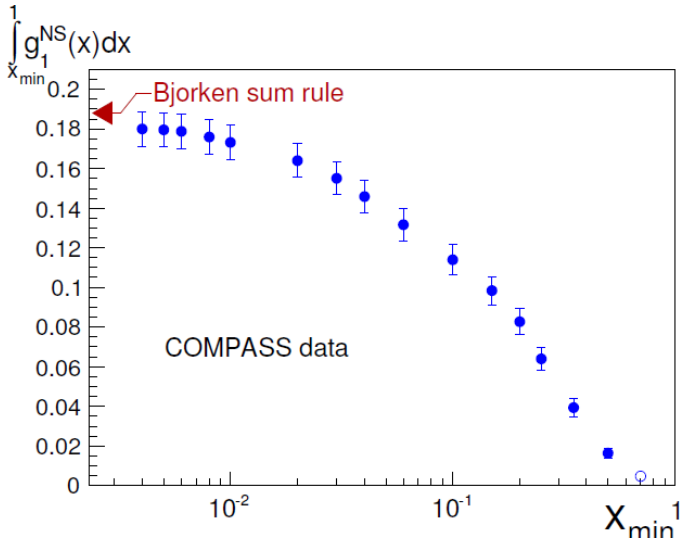
A fundamental result of QCD
on the non-singlet combination $g_1^{NS}(x) = g_1^p(x) - g_1^n(x)$
derived from current algebra:

$$\int_0^1 g_1^{NS}(x)dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C^{NS}$$

Measuring the first moments provides a test of the Bjorken sum rule,

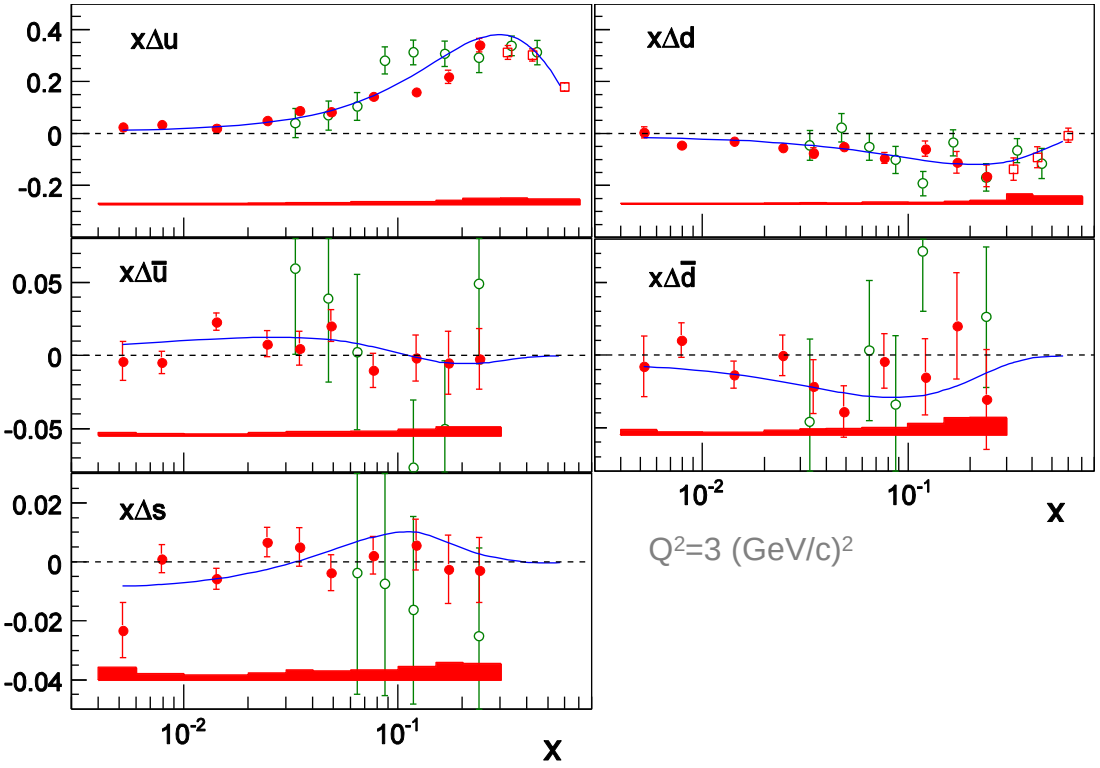
Fit to COMPASS data: g_A/g_V=
1.28 ±0.07(stat) ± 0.10(syst)

PDG value:
1.268 ±0.003



Quark helicities from Semi-incl. DIS

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



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

Extraction at LO

$$A_1^{h(p/d)}(x) = \frac{\sum_q e_q^2 D_q^h \Delta q(x)}{\sum_q e_q^2 D_q^h q(x)}$$

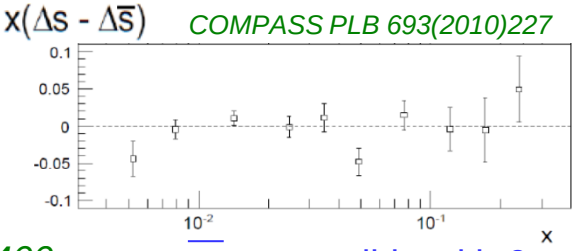
- **COMPASS**

PLB693(2010)227, using DSS FF

- **HERMES**

PRD71(2005)012003

— DSSV



HERMES $\Delta s+\overline{\Delta s}=0.037 \pm 0.019$ (stat) ± 0.027 (syst), *PLB666(2008)466*

COMPASS $\Delta s = -0.01 \pm 0.01$ (stat) ± 0.01 (syst), $0.003<x<0.3$

$\Delta s - \overline{\Delta s}$ compatible with 0

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

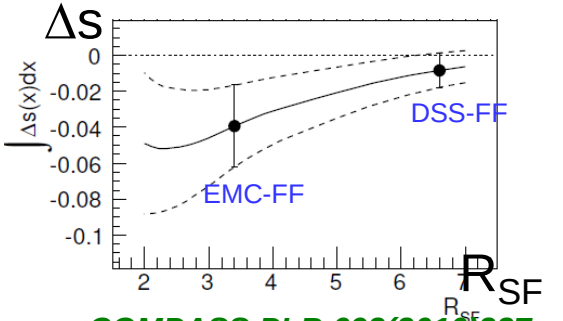
Δs puzzle

• **DIS data**: **Integral of Δs** can be extracted from the integral of g_1 using two other inputs (n and hyperon decay) & SU(3)

→ $\int \Delta s + \Delta\bar{s} = -0.08 \pm 0.01 \pm 0.02$

• **SIDIS data**: **Δs(x)** measured from SIDIS (**kaon)** spin asymmetries, using quark Fragmentation Functions

→ **Δs(x)≈ 0**

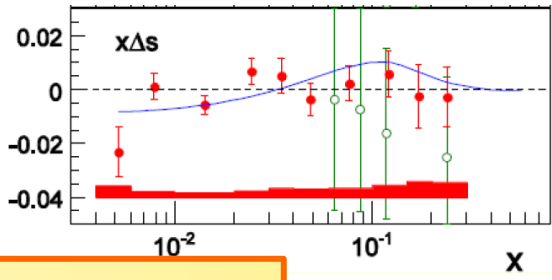


COMPASS PLB 693(2010)227

Several possible explanations to the discrepancy :

- Uncertainty on quark fragmentation function s→ K
- Global fits (DSSV, LSS) suggest negative Δs at low - reconciles the two approaches
- Assume SU(3) violation a_8 from 0.58 to 0.42

→ Δs=-0.02 *Bass &Thomas, PLB 684(2010)216*



Need more data on quark fragmentation functions

Need more data on Δs at low x

COMPASS run 2011 at 200 GeV

Certainly a physics case for EIC

Transversity- Collins and Sivers asymmetries

- Transversely polarized target, SIDIS: $l\,p^{\uparrow} \rightarrow l\,p\,h^{+/-}$
- Measure simultaneously several azimuthal asymmetries, out of which :

Collins: Outgoing hadron direction & quark transverse spin

Sivers: Nucleon spin & quark transverse momentum k_T

at LO:

Collins

q transverse spin distr.

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

Collins fragmentation function, depends on spin

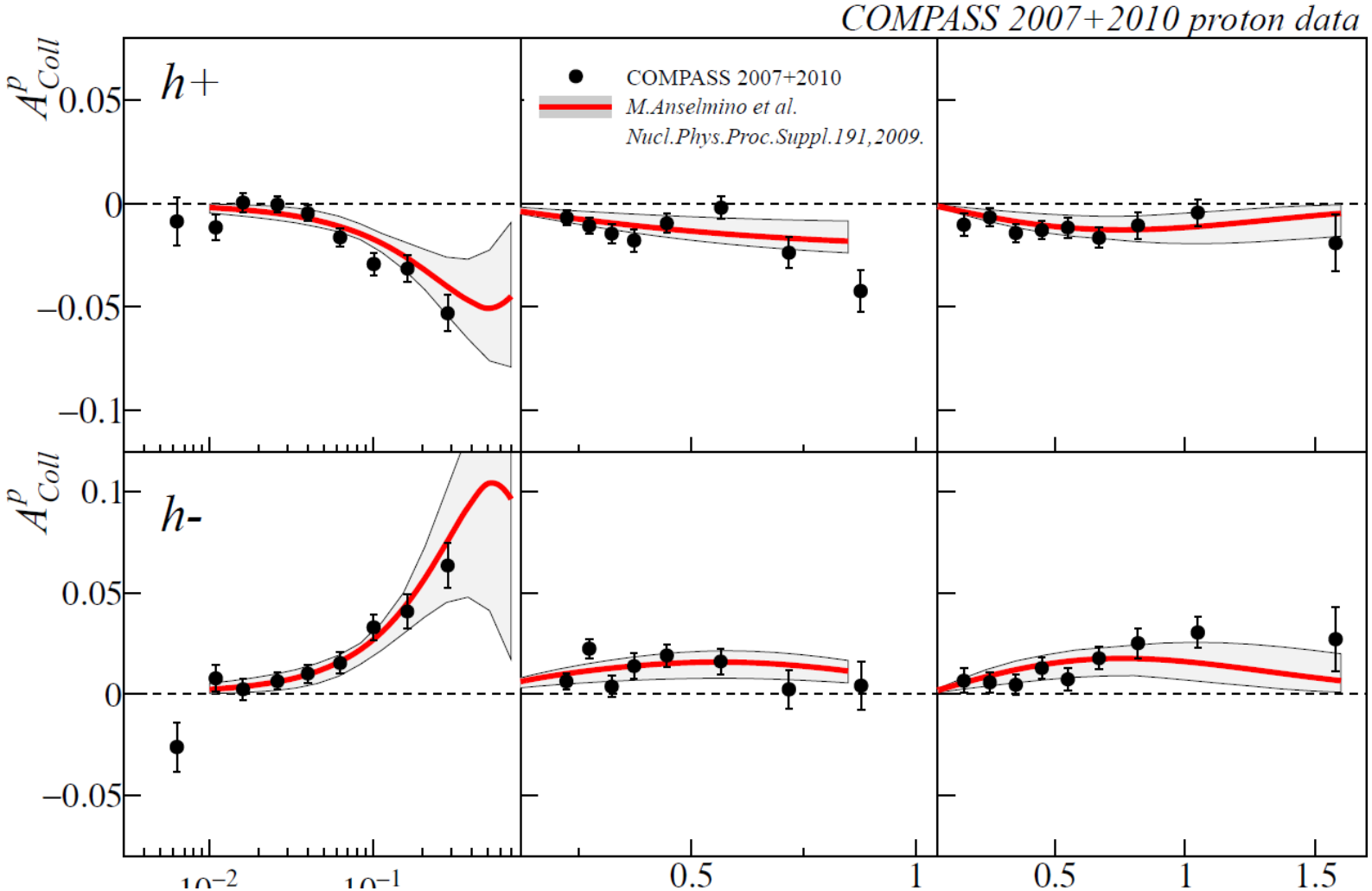
Sivers

Usual quark fragmentation function

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

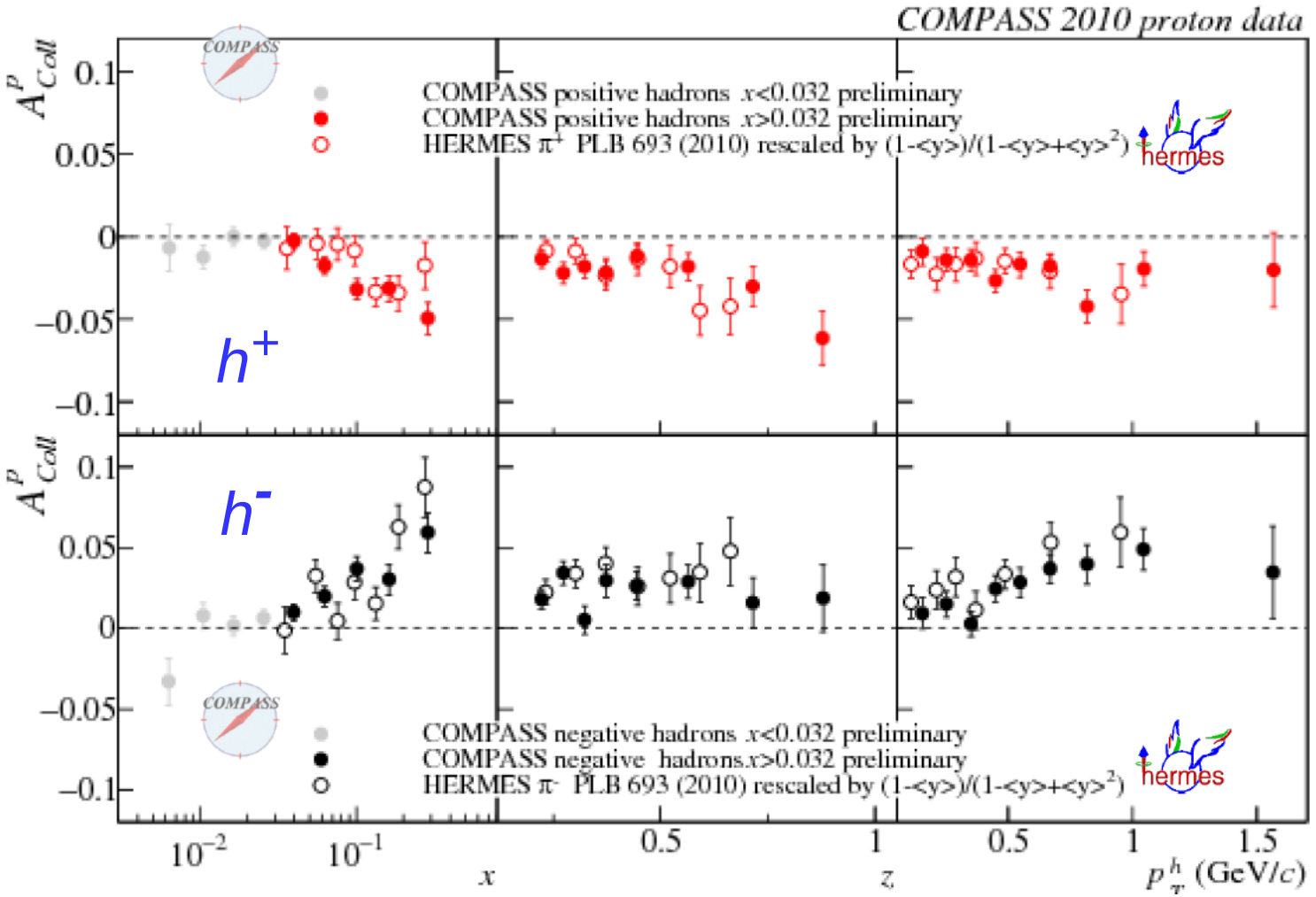
note: $\Delta_T q$ also measured using
- ''Two hadron'' fragmentation function
- lambda Transverse Polarization

Collins latest results on proton



Large signal with proton target, as seen by HERMES
(Is zero with deuteron target)

Collins. Comparison COMPASS vs HERMES



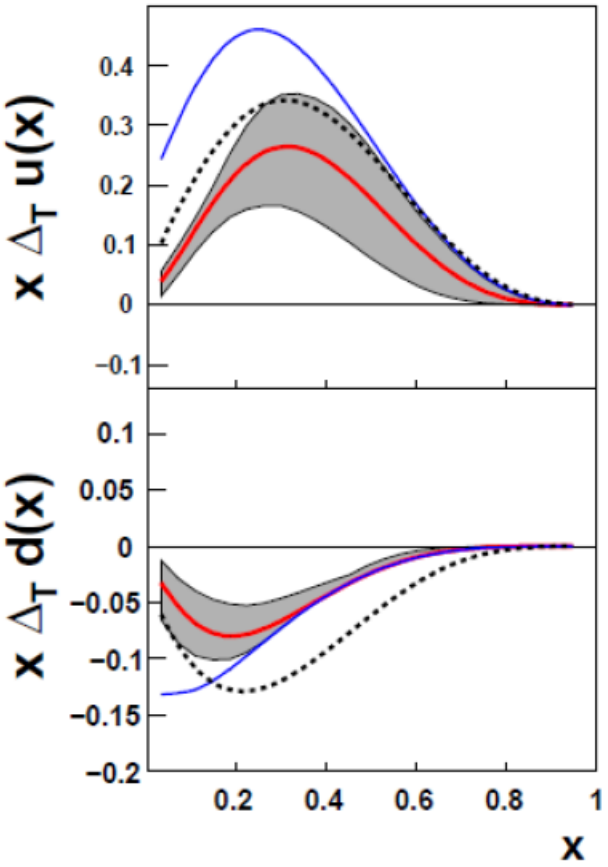
Same signal strength, although different Q^2 , by factor of ~4. (New)

Transversity – from Collins Asymmetry

Several combined analyses of

HERMES-proton, COMPASS–deuteron, and **BELLE fragm.fct.** data

Cloet, Bentz and Thomas PLB659 (08)
Bacchetta, Conti, Radici, PRD(09)
Anselmino et al 2009.



Ex: M. Anselmino et al. arXiv:0812.4366

- **$\Delta_T u > 0$ and $\Delta_T d < 0$**

u quark transversity along nucleon spin

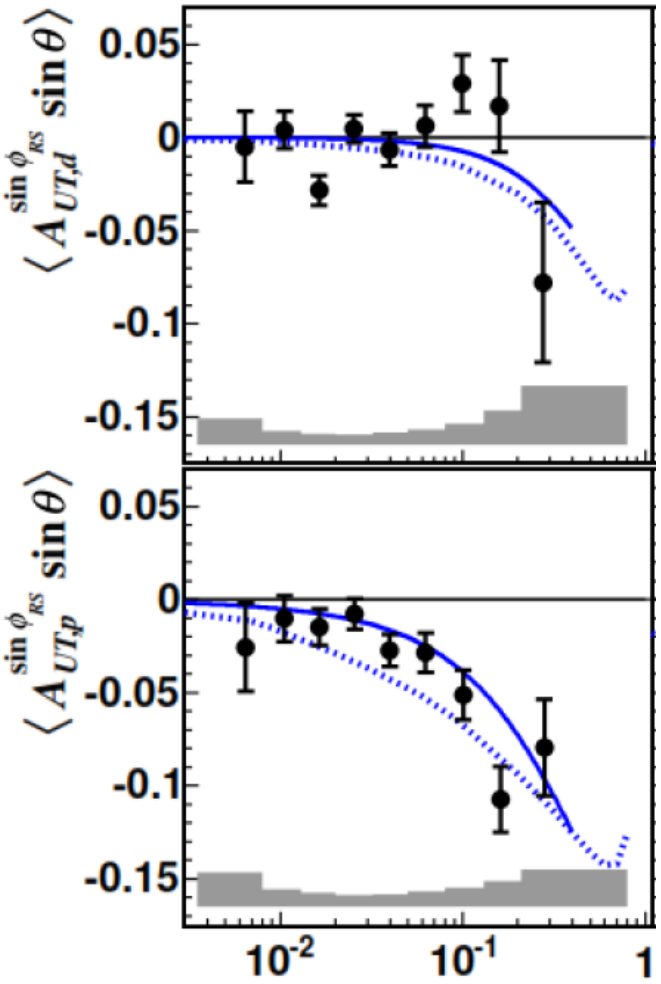
- Do not saturate Soffer bound
- Smaller than helicity

Also predictions for sea quarks

Transversity via ‘’two hadrons’’

deuteron target

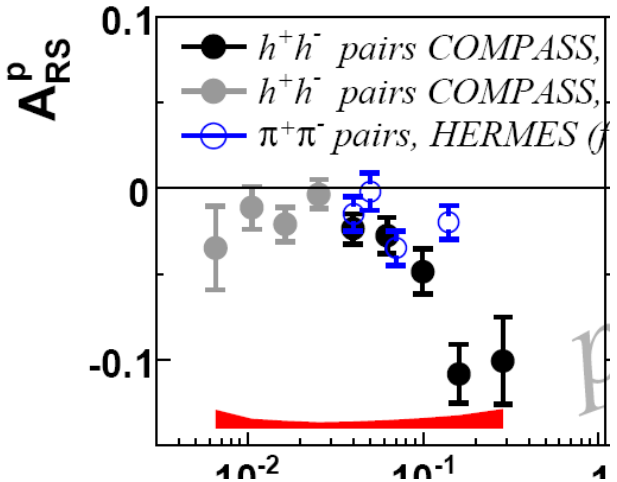
proton target 2007



as an alternative for $\Delta_T u$ and $\Delta_T d$.

COMPASS, PLB 713 (2012)10

Comparison COMPASS/HERMES:

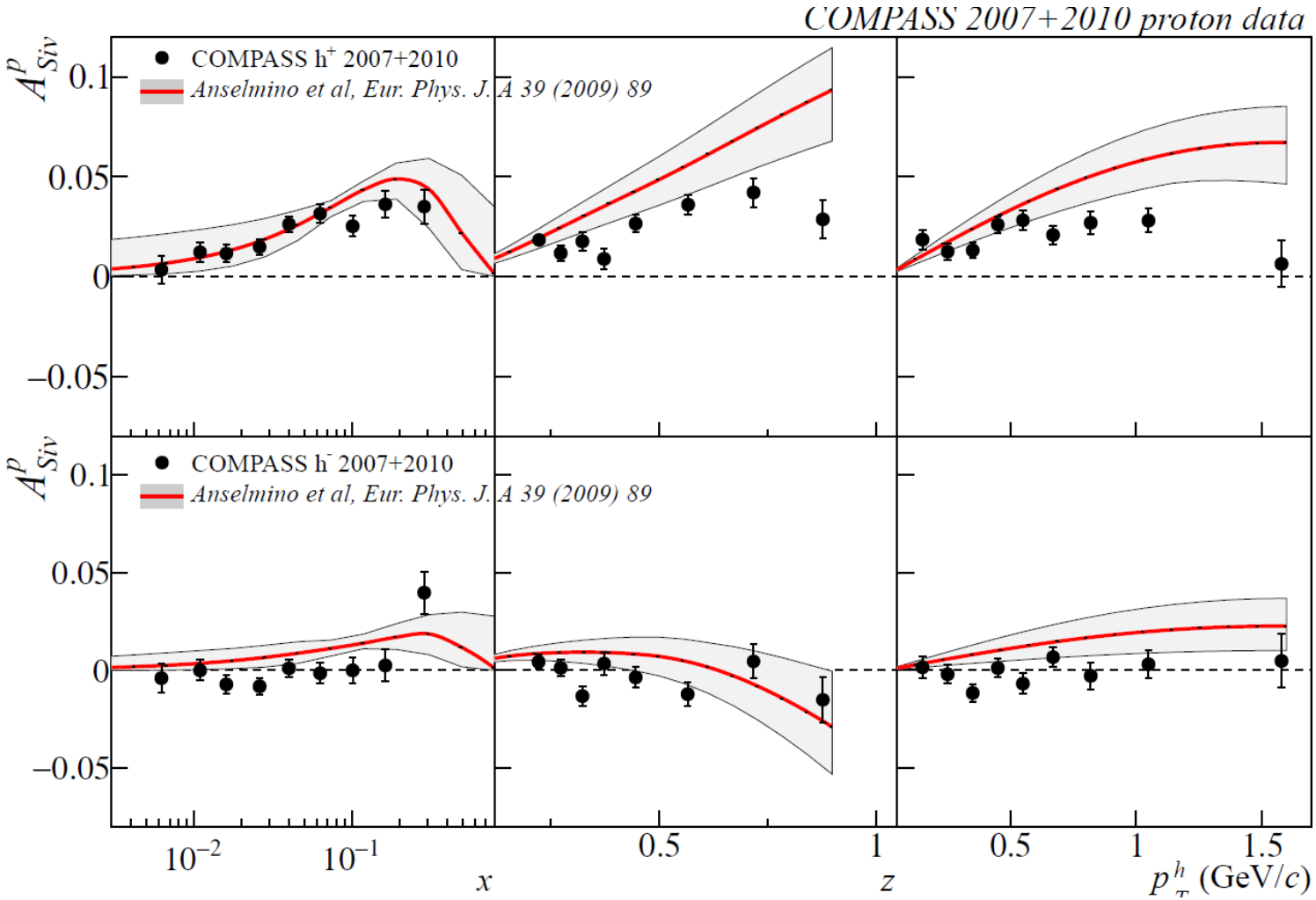


- **Confirms signal at large x.** larger than Collins asymmetry
  larger than HERMES signal, different phase space, but difficult to describe both simultaneously
  A.Bacchetta et al., Mah et al.
- **h_1^u & h_1^d extraction** ***(C.Elia Ph.D. Thesis 2012) following Bachetta, Courtoy, Radici***

irfu
cea
saclay

Sivers latest result on proton

Correlation between Nucleon spin & quark transverse momentum k_T

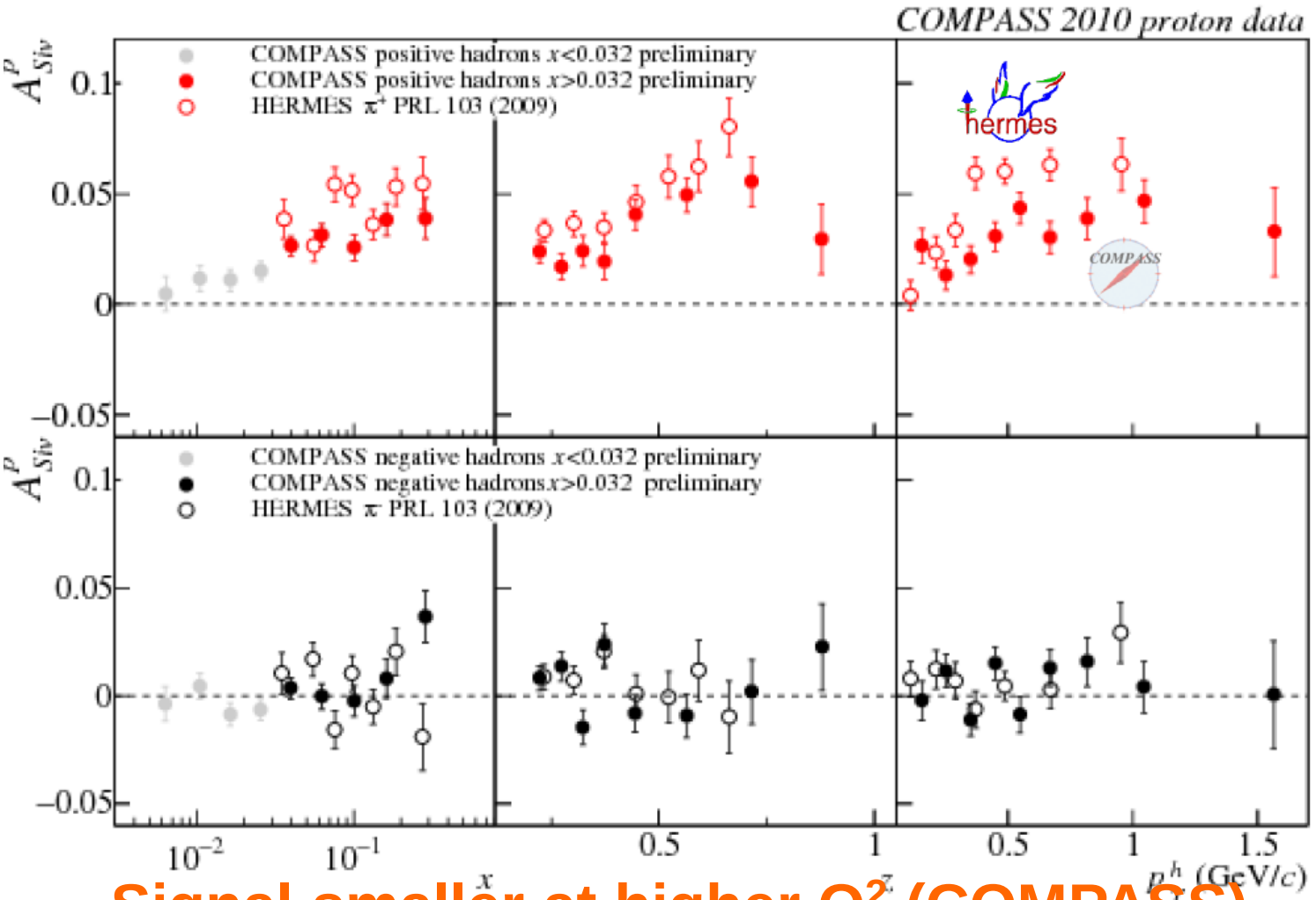


Large signal with proton target and h+

Was measured to be zero on deuteron.

Sivers. Comparison COMPASS vs HERMES

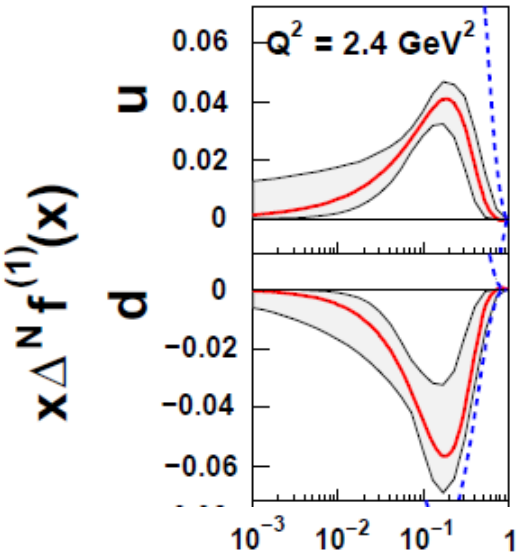
COMPASS 2010 data restricted to HERMES range x>0.32



Signal smaller at higher Q^2 (COMPASS)

Sivers function

Extraction of Sivers function
(from HERMES **p** and COMPASS **d)**



M.Anselmino et al., arXiv:0812.4366

- **Much progress in data on Sivers from polarized SIDIS**
  u and d quark Sivers function opposite
- **Still more statistics needed to separate all variables: x, z, p_T**

Other process:
- Future polarized Drell-Yan, where Sivers effect is expected, but with opposite sign.

COMPASS Future

Short term (accepted by CERN Research Board):

2012 : 1 month GPDs + SIDIS in parallel

2013 -2014 : CERN Long Shut Down

2014 -2017 :

- **TMDs** via Polarized Drell-Yan (1 year)
- **GPDs** via DVCS and DVMP reactions (2 years)

For GPD program, see A. Ferrero's talk,
for exclusive mesons,P. Sznajder

Future ideas, beyond 2018:

Drell-Yan Polarized and Unpolarized

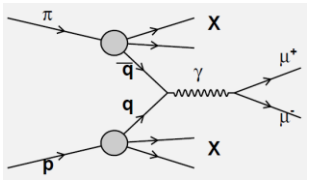
GPDs with Polarized target

Hadron spectroscopy

COMPASS Future : Polarized Drell-Yan

- **Polarized Drell-Yan** $\pi p^{\uparrow} \rightarrow \mu^+\mu^- X$

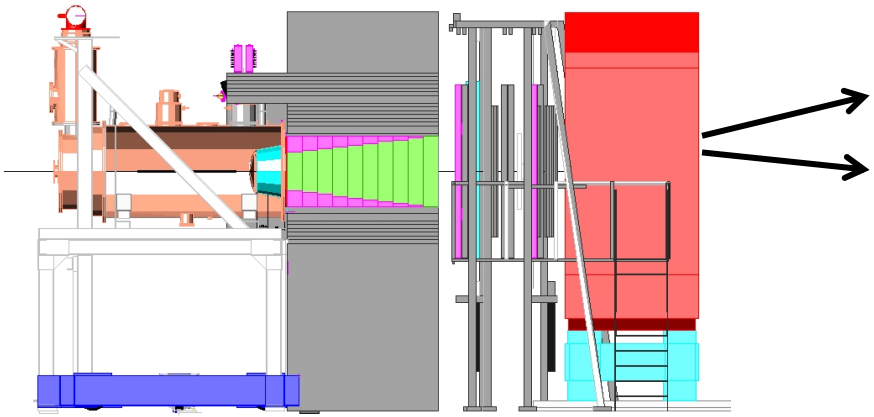
190 GeV pi beam on
transversely polarised proton target:
π^- valence u-antiquark picks nucleon's u quark
in valence region (u-quark dominance)



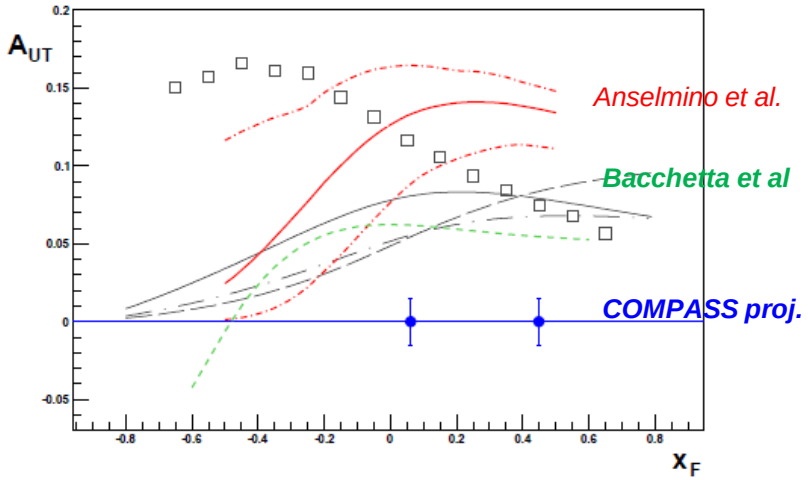
→ TMDs, Sivers & Boer-Mulders

Test of factorization approach:
comparison SIDIS/ Drell-Yan

Polarized target Absorber **Dipole magnet** muon pairs



Ex: A_{UT} asymmetry in Drell-Yan process



Conclusions

Gluon contribution to nucleon spin

All measurements point to zero or small contribution.

Quark contribution to nucleon spin

Extraction for all flavours from SIDIS

Towards agreement with Lattice QCD calculation for $\Delta\Sigma$

$\Delta s(x) \sim 0$ from SIDIS in measured region, and $\int \Delta s < 0$ from DIS:

need more precision and Fragmentation Function knowledge

Transversity and TMDs

Precise results on Collins and Sivers

Much progress on all Azimuthal asymmetries for TMDs (not shown)

Exciting future program in preparation:

- TMDs from Polarized Drell-Yan (2014)

- GPDs (end 2012 ; 2015)