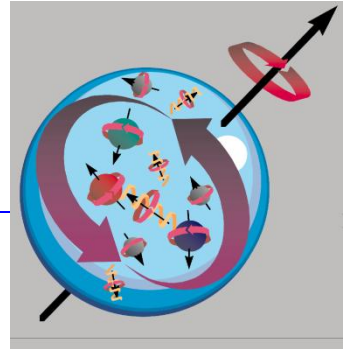


Recent results on the spin structure of the Nucleon from COMPASS

F.Kunne - CEA Saclay, France
on behalf of the COMPASS collaboration

- Longitudinal spin
Gluon and quark helicity distributions
- Transverse spin &
Transverse Momentum Dependent quark distributions
- Future measurements at COMPASS-II



COMPASS Collaboration at CERN

Fixed target experiment at the CERN-SPS
using secondary hadron beam & tertiary muon beam

Common Muon and Proton Apparatus
for Structure and Spectroscopy

220 physicists, 28 institutes , 11 countries

Czech Rep., France, Germany, India, Israel,
Italy, Japan, Poland, Portugal, Russia and CERN

Bielefeld, Bochum, Bonn, Burdwan and Calcutta, CERN, Dubna, Erlangen,
Freiburg, Lisbon, Mainz, Moscow, Munich, Prague, Protvino, Saclay, Tel Aviv,
Torino, Trieste, Warsaw, Yamagata

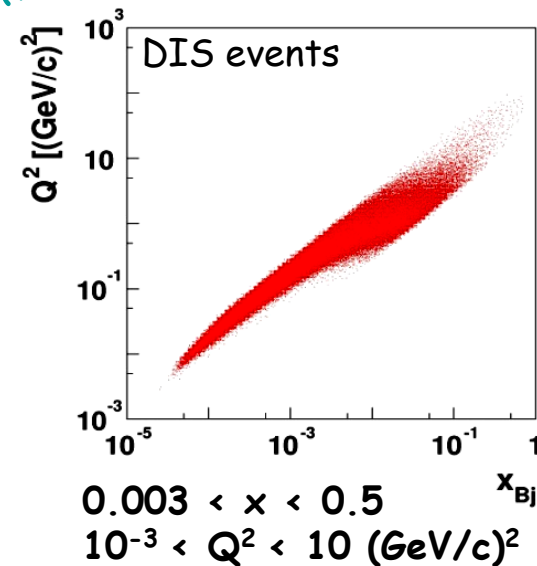
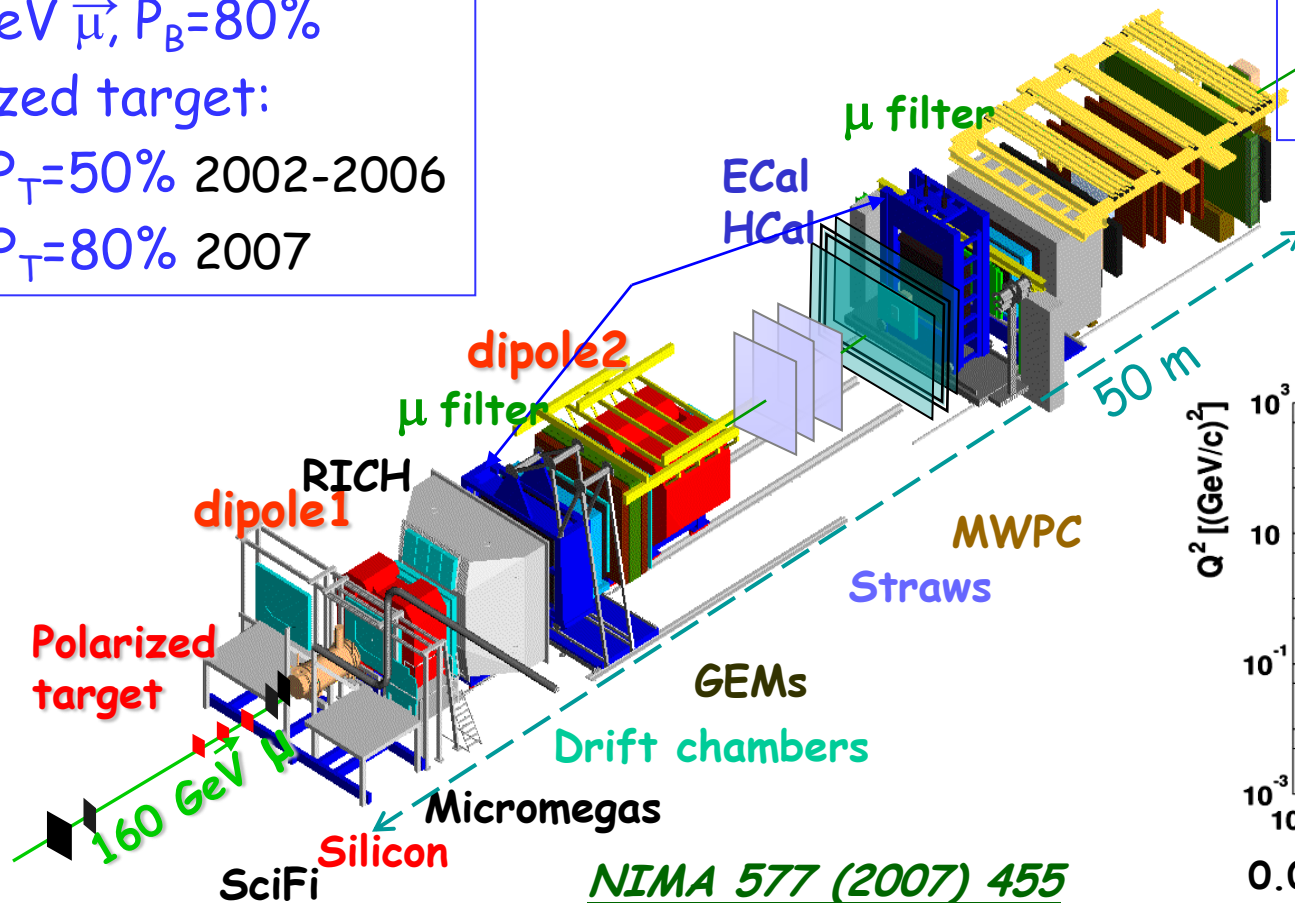
COMPASS

Nucleon spin structure

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

Meson spectroscopy

Hadron beam :
 190 GeV π / p
 LH_2 2008-2009



NIMA 577 (2007) 455

How is the nucleon spin distributed among its constituents?

$$\text{Nucleon Spin } \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_{q,g}$$

quark
gluon
orbital momentum

$$\Delta q = \overrightarrow{q} - \overleftarrow{q} \quad \text{Parton spin parallel or anti parallel to nucleon spin}$$

Theory : QCD, Ellis- Jaffe sum rule assuming $\Delta s = 0$, $\Delta\Sigma \sim 0.6$

Experiment: World data on polarized DIS $g_1 + SU_f(3) \rightarrow a_0 \sim 0.3$

QCD (\overline{MS} scheme) $a_0 = \Delta\Sigma$

\rightarrow "Spin crisis" 1988, EMC measured $a_0 = 0.12 \pm 0.17$

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

• For $a_0 \sim 0.3$, need $\Delta G \sim 2.5$ to restore $\Delta\Sigma \sim 0.6$. (Then $L_z \sim -2.3$)

• ΔG enters in the spin $\frac{1}{2}$ sum rule

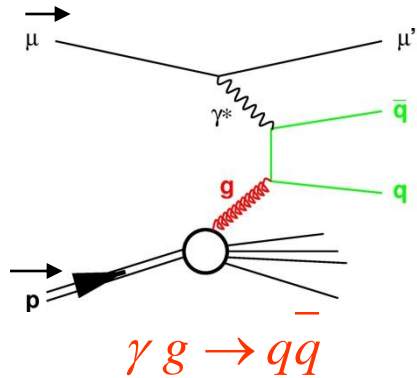
\rightarrow motivated direct measurements of gluon polarization ΔG

$\Delta G/G$ Measurement- Photon Gluon fusion PGF

Need:

- a process sensitive to gluon distribution \rightarrow Photon Gluon Fusion
- measure longitudinal spin asymmetry of cross sections \rightarrow incident **polarized lepton beam** and **polarized nucleon target**.

At leading order $A_{||} = R_{PGF} \langle a_{LL} \rangle \langle \Delta G/G \rangle$



Two signatures for PGF:

- $q=c$ open charm $c \rightarrow D^0 \rightarrow K \pi$

Clean signature of PGF

pQCD scale $\mu^2 = 4(m_c^2 + p_T^2)$

Combinatorial background & limited statistics

\rightarrow Difficult experiment

- $q=u,d,s$ high p_T hadron pair $q q \rightarrow h \bar{h}$

High statistics

pQCD scale Q^2 or Σp_T^2

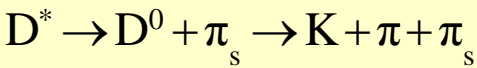
Physical background, better described for high Q^2

Open charm - D^0 and D^* events

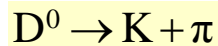
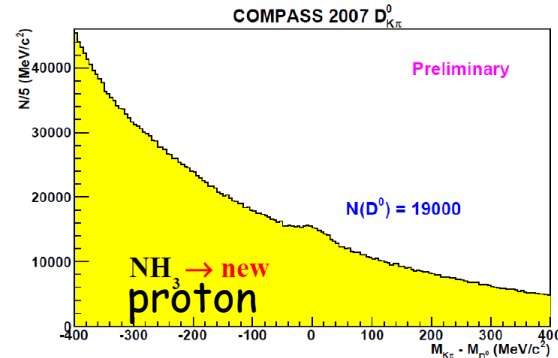
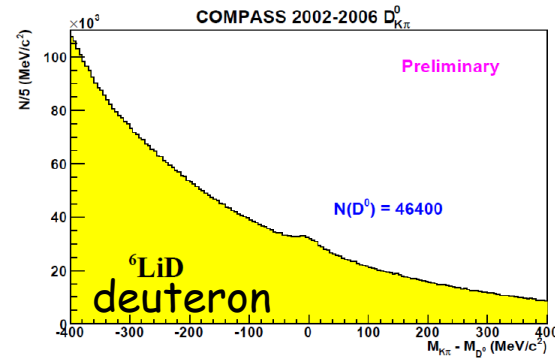
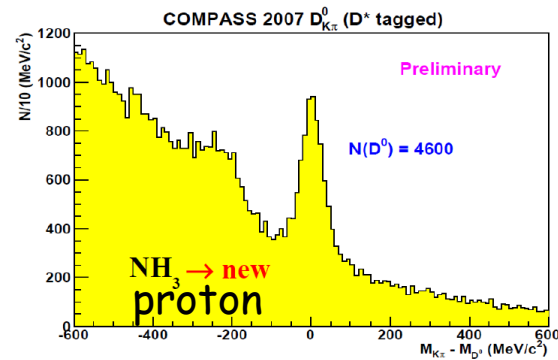
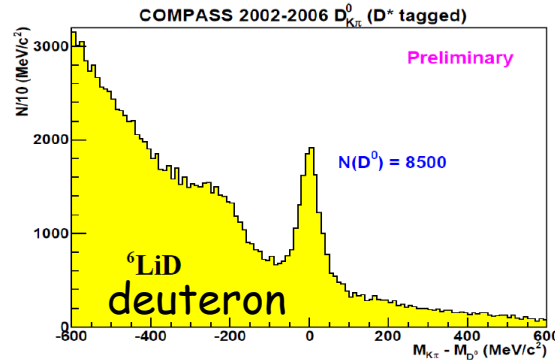
D^0 selection. Thick target, no D^0 vertex reconstruction: $K\pi$ invariant mass

D^* tagging :

cut on $MD^* - MD^0$



| | |
|--------------|-------|
| D^0 decay | BR |
| $K\pi$ | 4 % |
| $K\pi\pi^0$ | 13 % |
| $K\pi\pi\pi$ | 7.5 % |
| $(K)\pi$ | |



$\Delta G/G = -0.08 \pm 0.21$ (stat) ± 0.11 (syst)

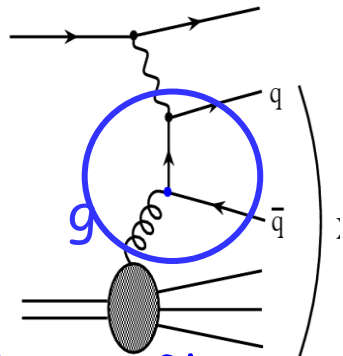
at $\langle x_g \rangle = 0.11$ and $\langle \mu^2 \rangle = 13$ (GeV/c)²

$\Delta G/G$ extracted at LO : compatible with 0.

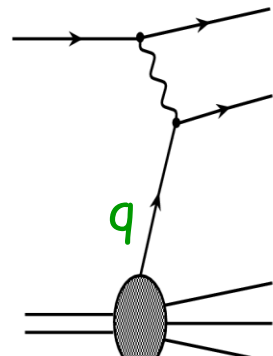
NLO extraction ongoing.

$\Delta G/G$ from high p_T hadron pairs

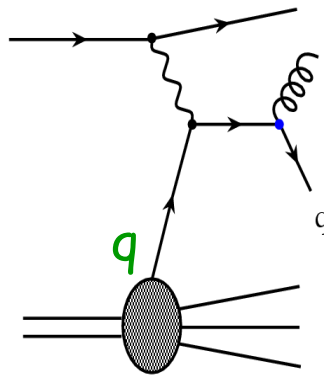
$Q^2 > 1 \text{ (GeV/c)}^2$



Photon Gluon Fusion $\sim 30\%$



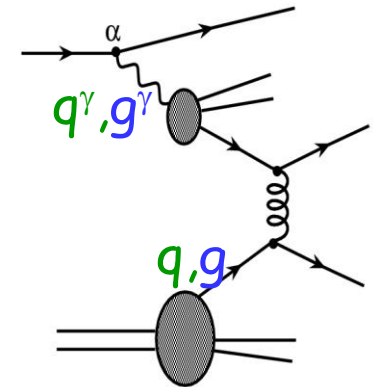
Leading Order



QCD Compton

+

$Q^2 < 1 \text{ (GeV/c)}^2$



Resolved $\gamma \sim 50\%$

- R (fraction of process) and a_{LL} (analysing power) calculated from effective model in Monte-Carlo for all processes
- Parameterized on event basis by Neural Network trained on MC

$\langle x_g \rangle = 0.08 \quad \mu^2 \sim 3 \text{ (GeV/c)}^2$

$Q^2 > 1 \text{ GeV/c}^2$

$\Delta G/G = 0.08 \pm 0.10 \text{ (stat)} \pm 0.05 \text{ (syst)}$

$Q^2 < 1 \text{ GeV/c}^2$

$\Delta G/G = 0.016 \pm 0.058 \text{ (stat)} \pm 0.055 \text{ (syst)}$

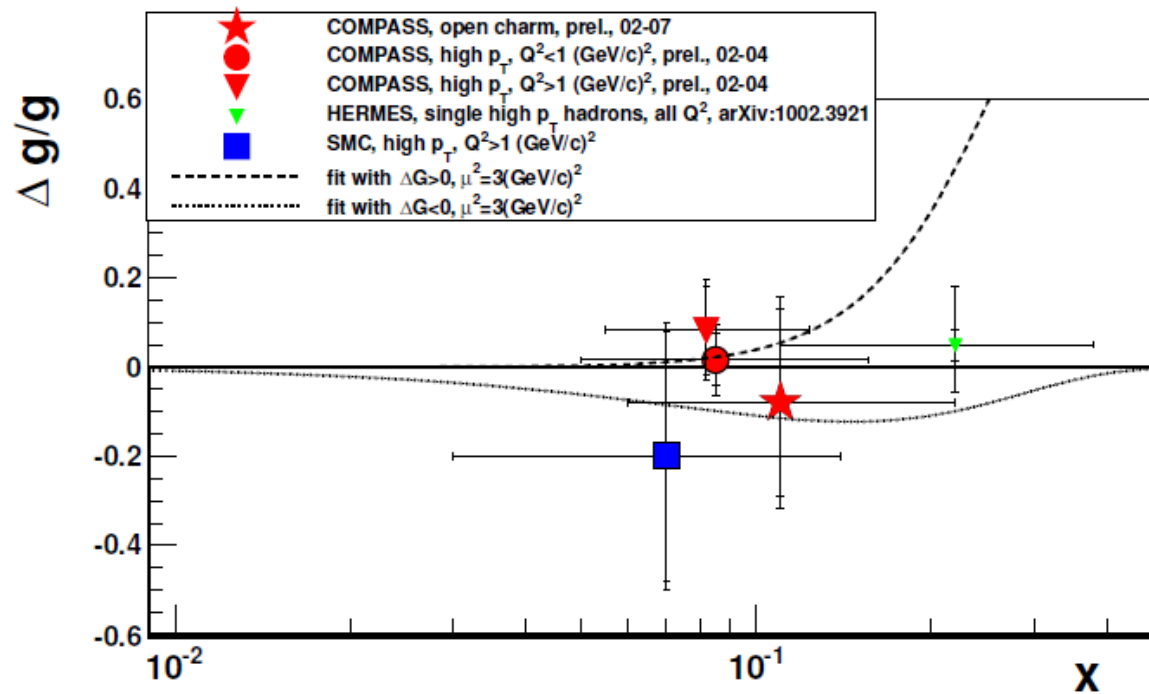
2002-2004 data preliminary

PLB 633(2006)25
2002-2003 data

Two independent results with $\Delta G/G$ compatible with 0

- Future:
- 2006 & 2007 data, still to come
 - Splitting in 2- 3 x bins

Results for $\Delta G/G$ direct measurements

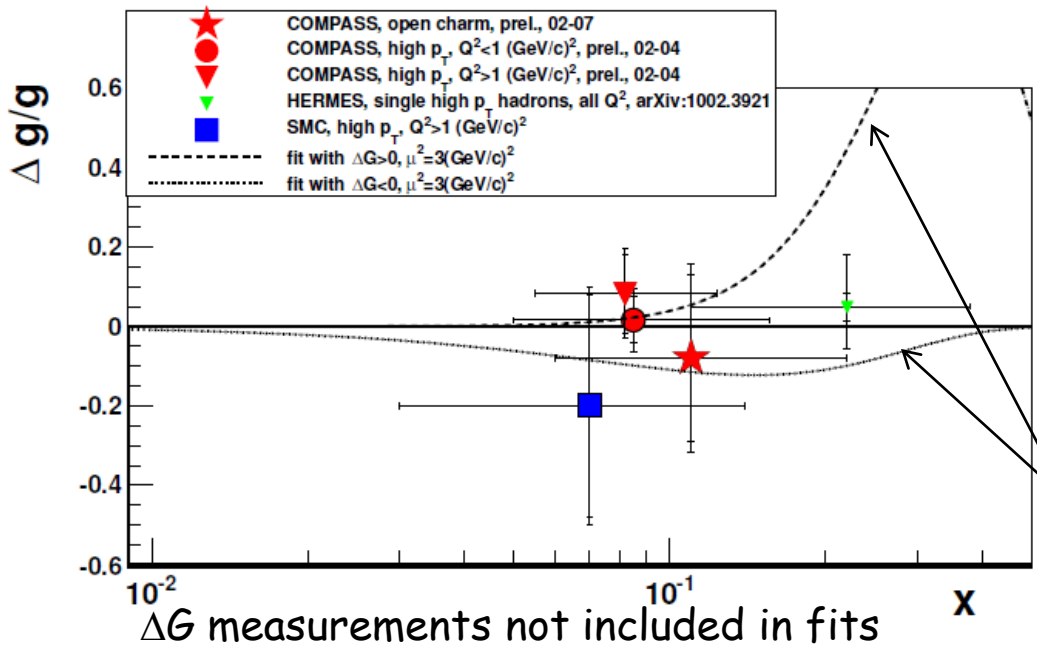


All measurements compatible with 0 for $0.04 < x < 0.2$

Also in agreement with RHIC results on double spin asymmetry in polarized pp reactions, which probe same kinematical range

Direct measurements exclude values for the integral of ΔG as large as 1 or 2

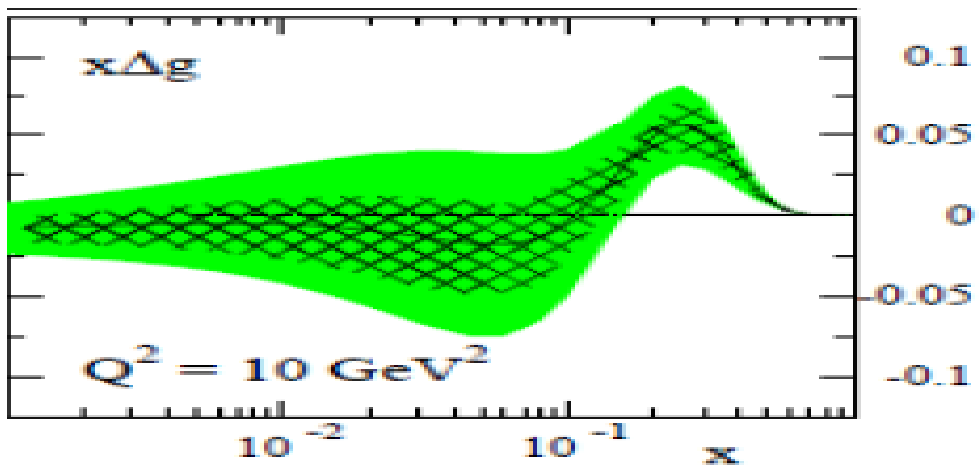
$\Delta G(x)$ from global QCD analysis of polarized DIS data $g_1(x, Q^2)$



Use Q^2 evolution of spin dependent gluon and singlet quark distribution.

Lack of polarized data
Fits not so well constrained, however some results

COMPASS NLO fit of g_1 data:
2 solutions with $|\Delta G| = 0.2 - 0.3$



DSSV NLO fit of g_1 and $\vec{p} \vec{p}$ data
De Florian, Sassot, Stratmann, Vogelsang

Consequence for nucleon spin

• $\Delta G = \int \Delta g(x) dx$ not large, both from direct measurements (essentially PGF + RHIC) and g_1 QCD fit: $|\Delta G| < 0.35$

$$\Delta\Sigma = a_0 + \underbrace{(3\alpha_s/2\pi) \Delta G}_{\text{within } 0.06 \text{ for } \Delta G \text{ within } \pm 0.35 \text{ at } Q^2=3}$$

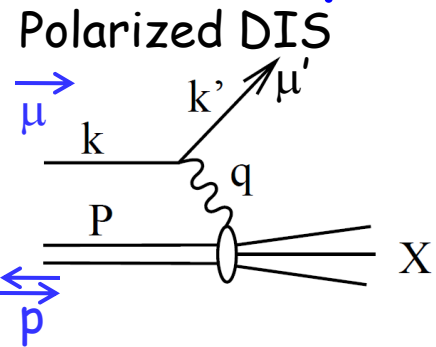
→ $\Delta\Sigma \sim 0.30$ **small** (\neq predictions)

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

possible scenarios:

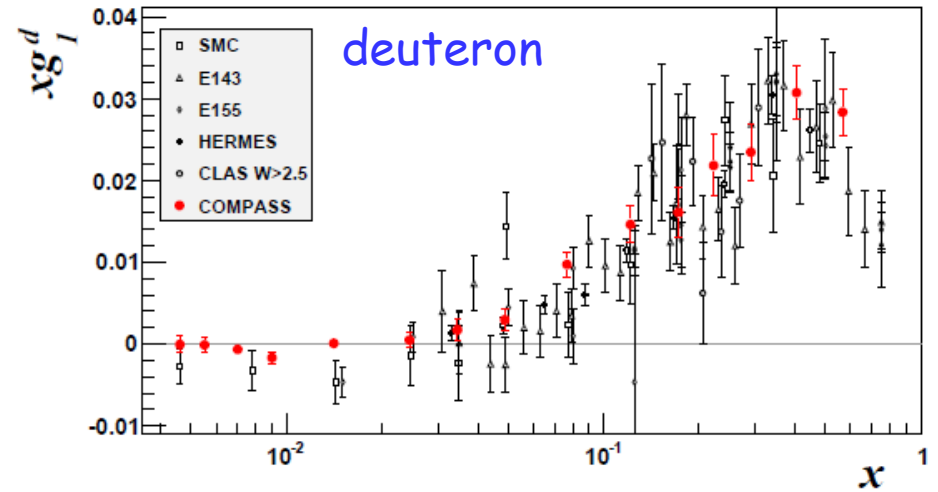
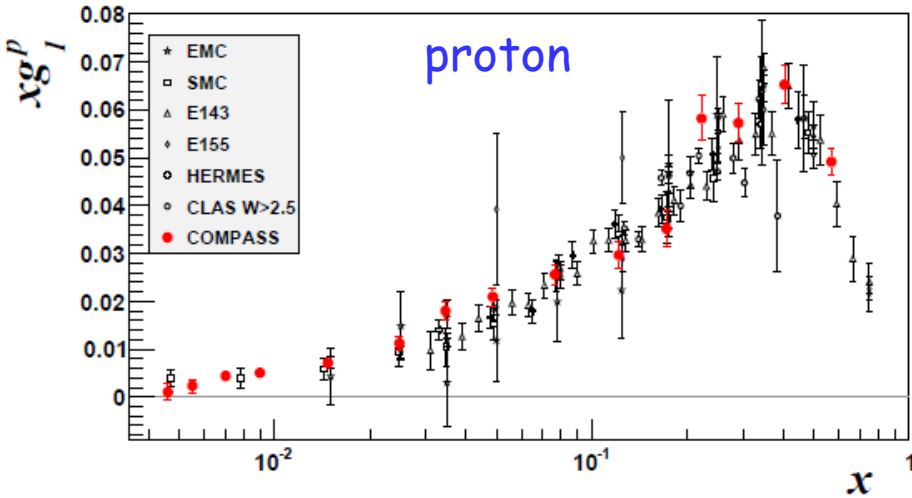
$$\left\{ \begin{array}{l} \frac{1}{2} 0.3 + 0.35 + 0.0 \\ \frac{1}{2} 0.3 + 0.0 + 0.35 \\ \frac{1}{2} 0.3 - 0.35 + 0.7 \end{array} \right.$$

Spin structure functions g_1^p and g_1^d



$$\sigma_{DIS}^{inclusive} \propto g_1(x) \propto \frac{1}{2} \sum e_q^2 (\Delta q(x) + \Delta \bar{q}(x))$$

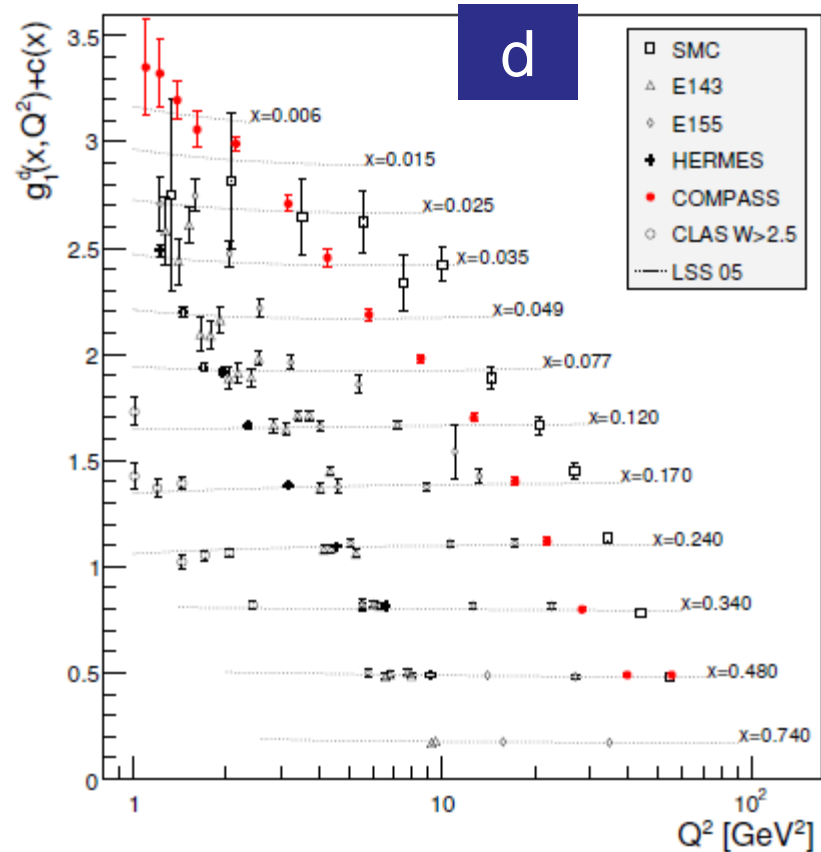
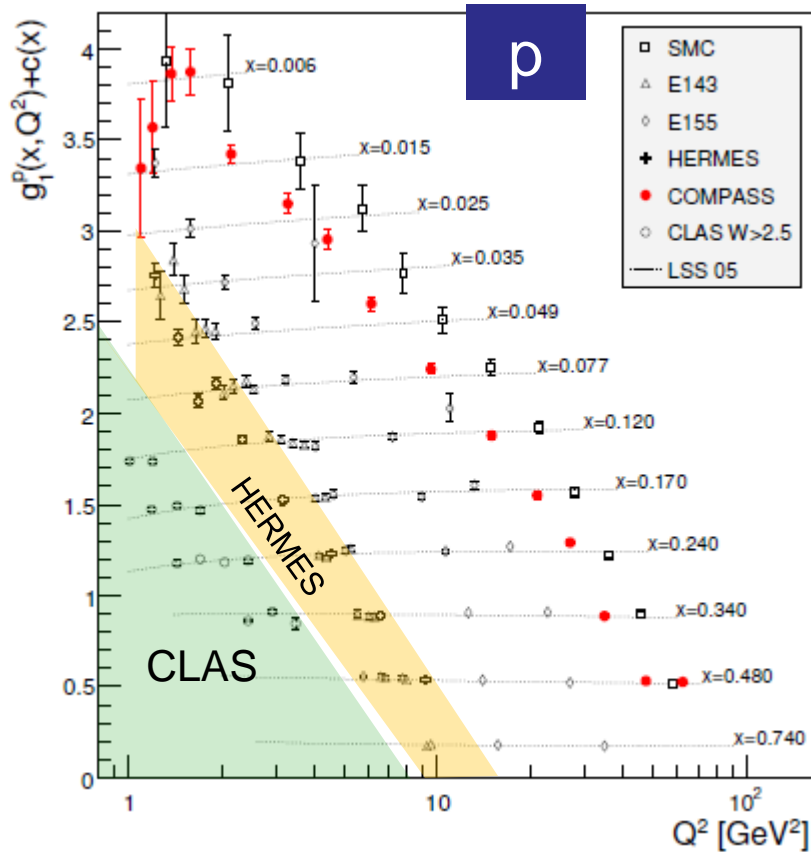
Polarized PDFs



From first moment of g_1 , at $Q^2 \rightarrow \infty$:

- $\Delta \Sigma = 0.30 \pm 0.01$ (stat.) ± 0.02 (evol.) All data
- $\Delta s + \Delta \bar{s} = -0.08 \pm 0.01 \pm 0.02$ Compass data alone

World data for proton & deuteron $g_1(x, Q^2)$



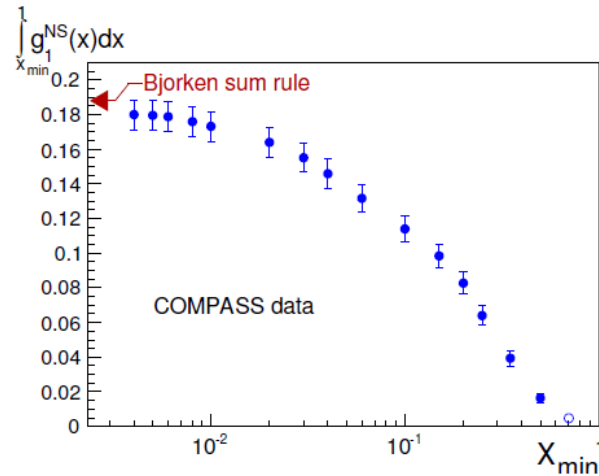
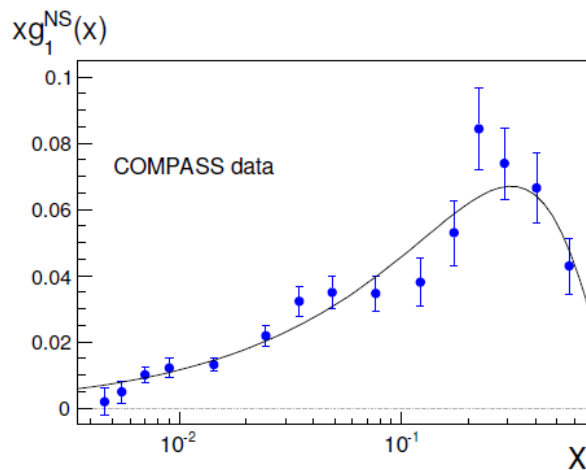
Input to global QCD fits
 → Extract polarized parton distribution functions including $\Delta G(x)$ through Q^2 evolution of spin dependent gluon and singlet quark distribution.

Non Singlet structure function and Bjorken sum rule

Non-singlet combination : $g_1^p(x) - g_1^n(x)$

The first moment provides a test of the Bjorken sum rule, a fundamental result of QCD derived from current algebra

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

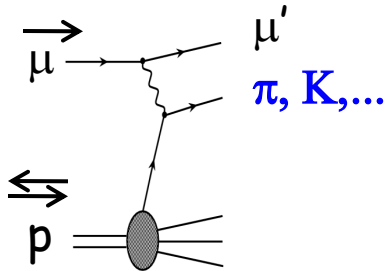


Fit to COMPASS data: $g_A/g_V = 1.28 \pm 0.07(\text{stat}) \pm 0.10(\text{syst})$

PDG value:
 1.268 ± 0.003

Helicity quark distributions

Polarized Semi inclusive DIS



- Outgoing hadron tags quark flavour
- Need to know fragmentation functions of quark q into hadron h : D_q^h

Spin asymmetry

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

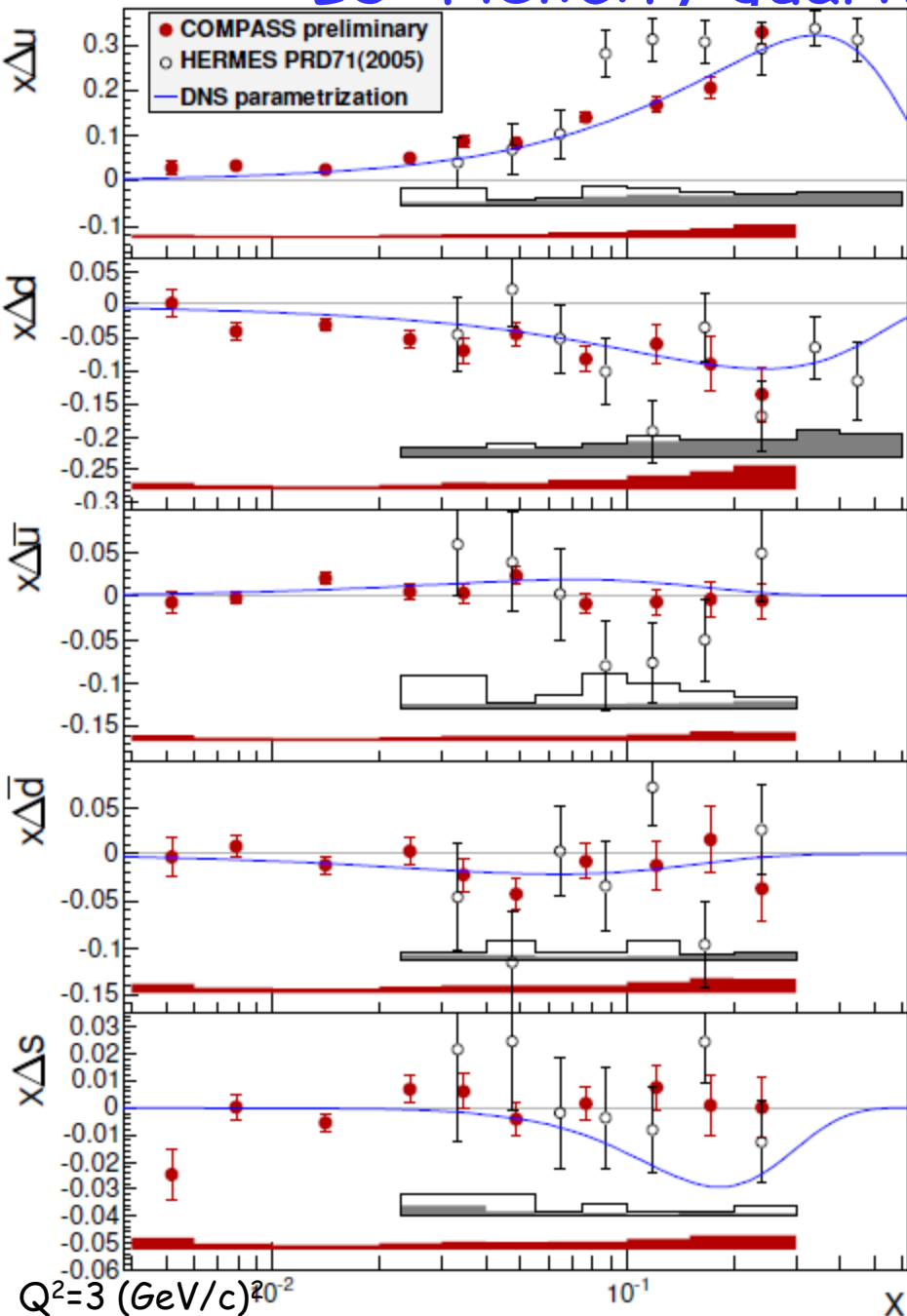
With deuterium + proton data, can separate all flavours at LO

Input: unpolarized PDFs (MRST04)

& parameterization of FFs (e^+e^- , DIS and hadron-hadron) (DSS)

De Florian, Sassot, Stratmann

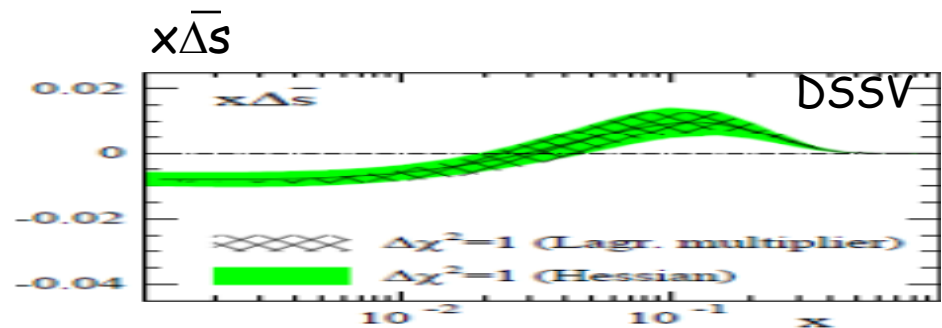
LO Helicity quark distributions



- Full flavour decomposition down to $x \sim 0.004$
- Sea quark distributions \sim zero
- Good agreement with previous global fits to g_1 inclusive data, except for Δs .

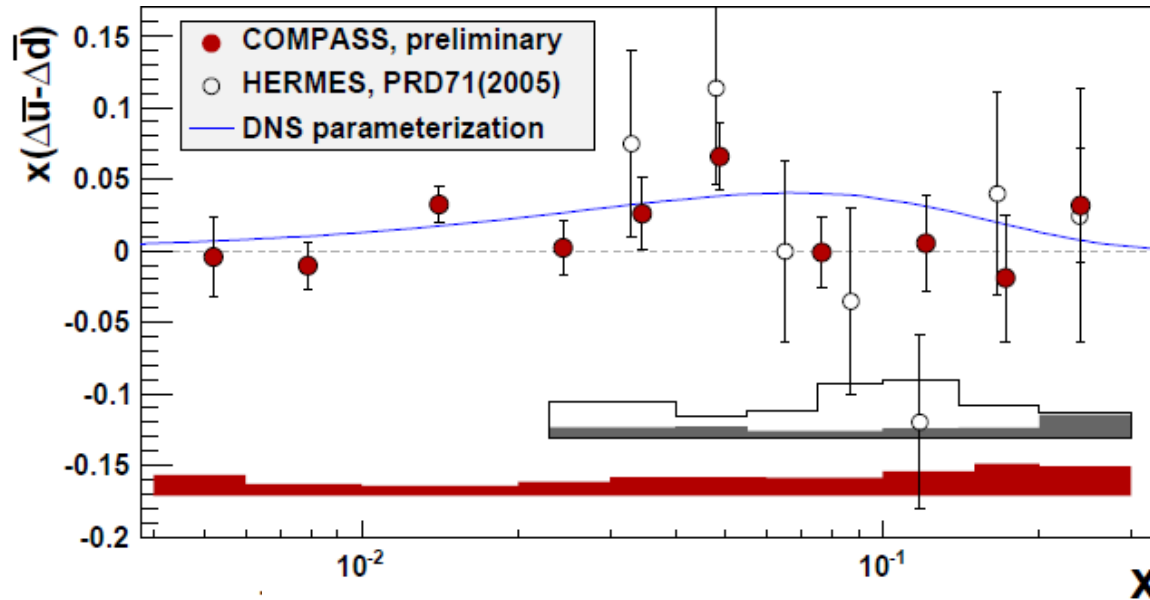
However, for Δs :

- Large uncertainty on strange quark fragmentation functions.
- New global fits (DSSV) suggest negative contribution at lower x ($x < 0.01$), in agreement with both inclusive result and semi inclusive data.



Light sea quark polarized distributions, flavour asymmetry

$x(\Delta\bar{u}-\Delta\bar{d})$ measured via polarized SIDIS

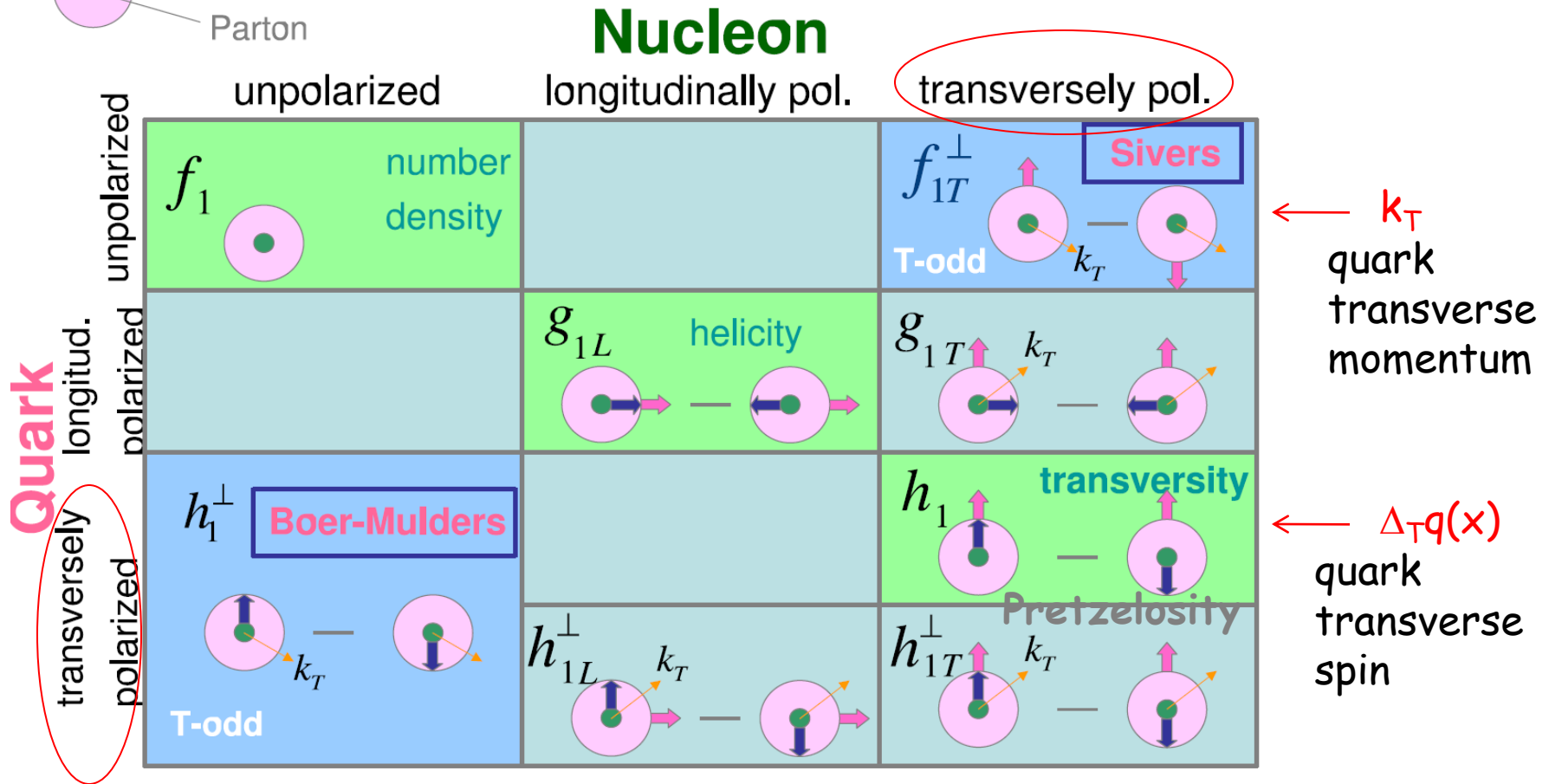


$$\int_{0.004}^{0.3} (\Delta\bar{u} - \Delta\bar{d}) dx = 0.052 \pm 0.035(\text{stat.}) \pm 0.013(\text{syst.})$$

Flavour asymmetry not as large as in unpolarized case:

$$\int_0^1 (\bar{u} - \bar{d}) dx = 0.118 \pm 0.012$$

Nucleon Structure Functions



Collins and Sivers asymmetries

- Transversely polarized target
- Measure simultaneously several azimuthal asymmetries of outgoing hadron in SIDIS $\mu p \rightarrow \mu p h$

Collins: Outgoing hadron direction & quark transverse spin
Sivers: nucleon spin & **quark transverse momentum**

Collins

q transverse spin distr.

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

Collins fragmentation function

Sivers

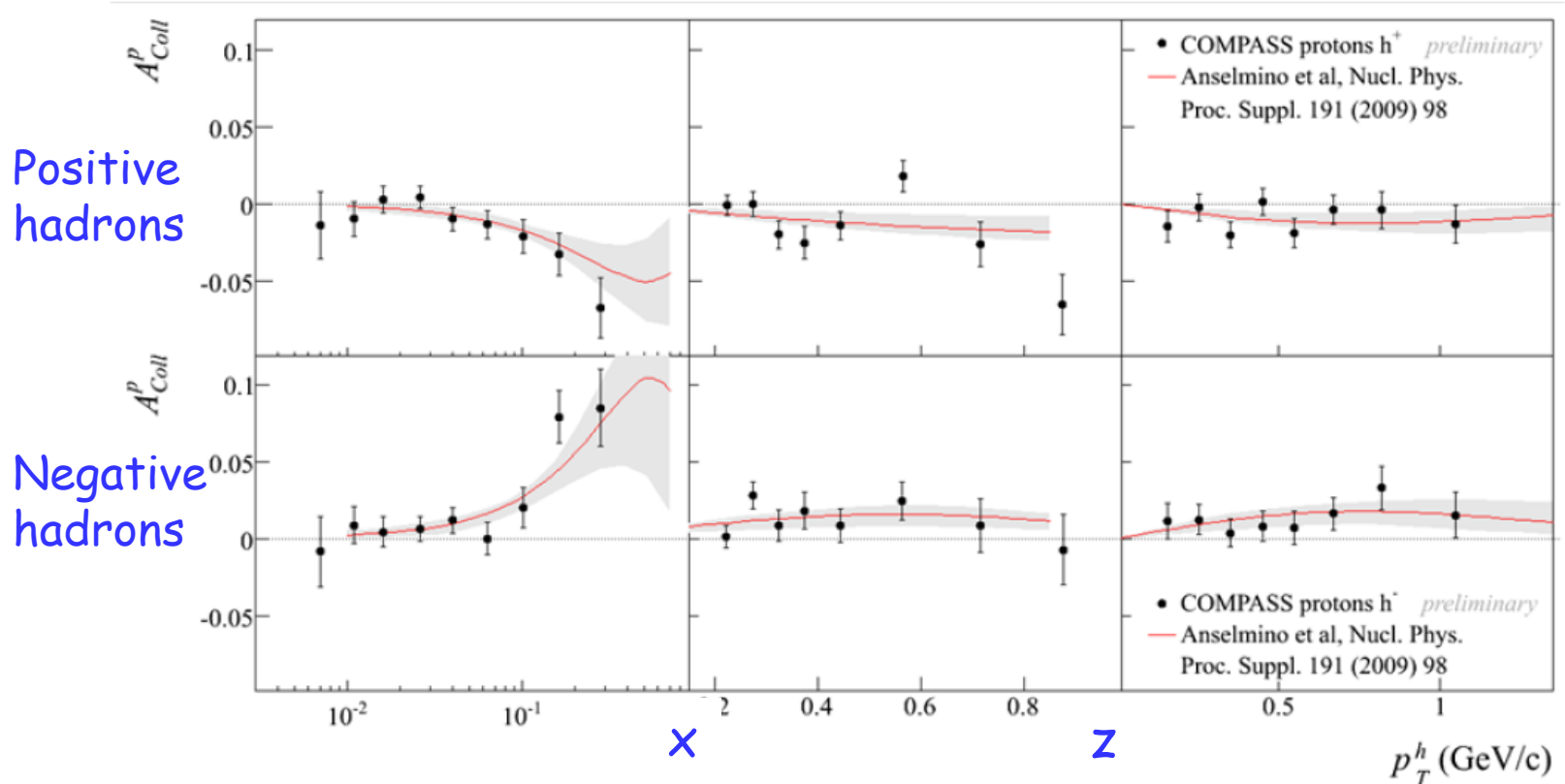
$$A_{\text{Siv}} = \frac{\sum_q e_q^2 \cdot f_{1Tq}^\perp \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

note: $\Delta_T q$ also measured using

- "Two hadron" fragm. fct.
- lambda Transverse Polarization

Transversity : Collins Asymmetry on proton

COMPASS data compared to predictions from Anselmino *et al.*,
based on fit of Hermes-p and Compass-d data

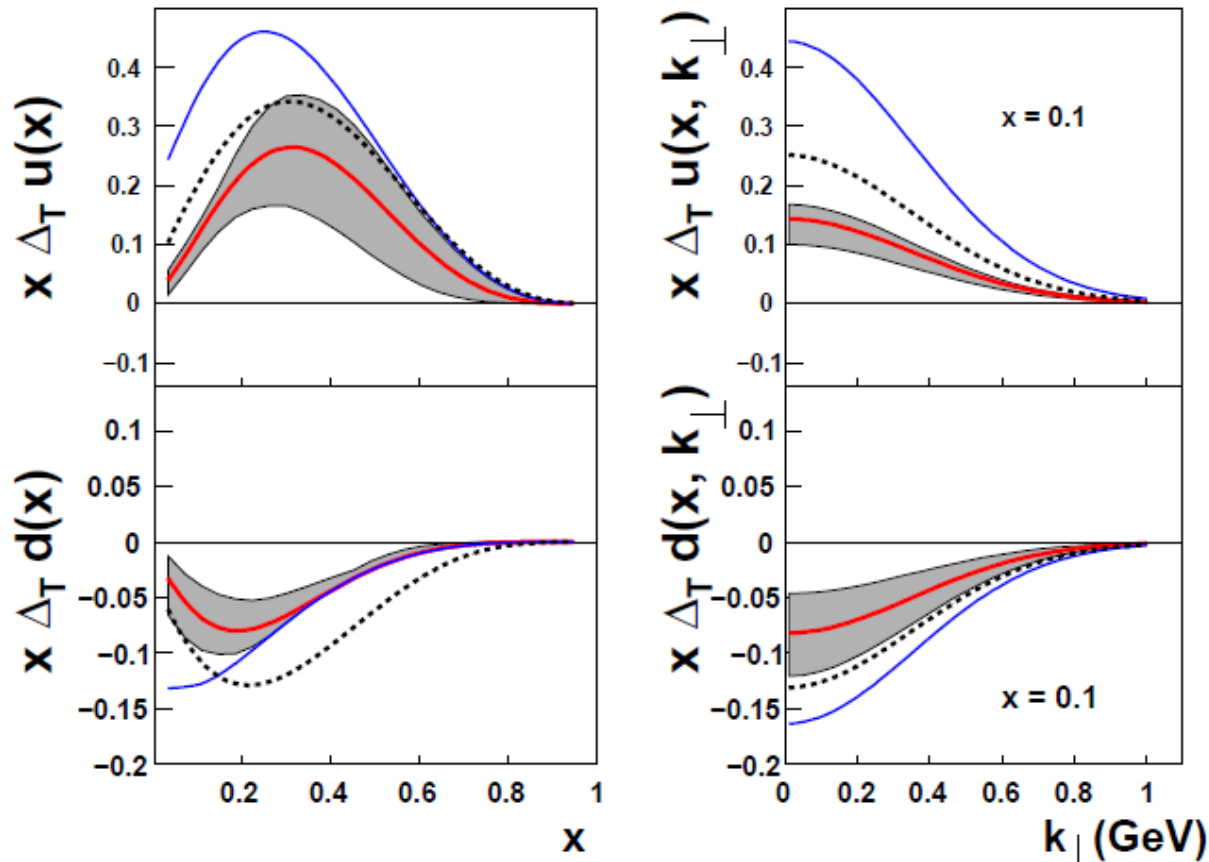


- Large signal in valence region as seen by HERMES, of opposite sign for + and - hadrons
- Data support the assumption of a weak Q^2 dependence in this energy range

Extraction of Δu_T and Δd_T

Several combined analyses of COMPASS deuteron, HERMES proton and BELLE fragmentation fct. data, by Anselmino et al., Efremov et al., Vogelsang et al. ... lead to extraction of $\Delta_T u$ and $\Delta_T d$

Ex: M. Anselmino et al. arXiv:0812.4366



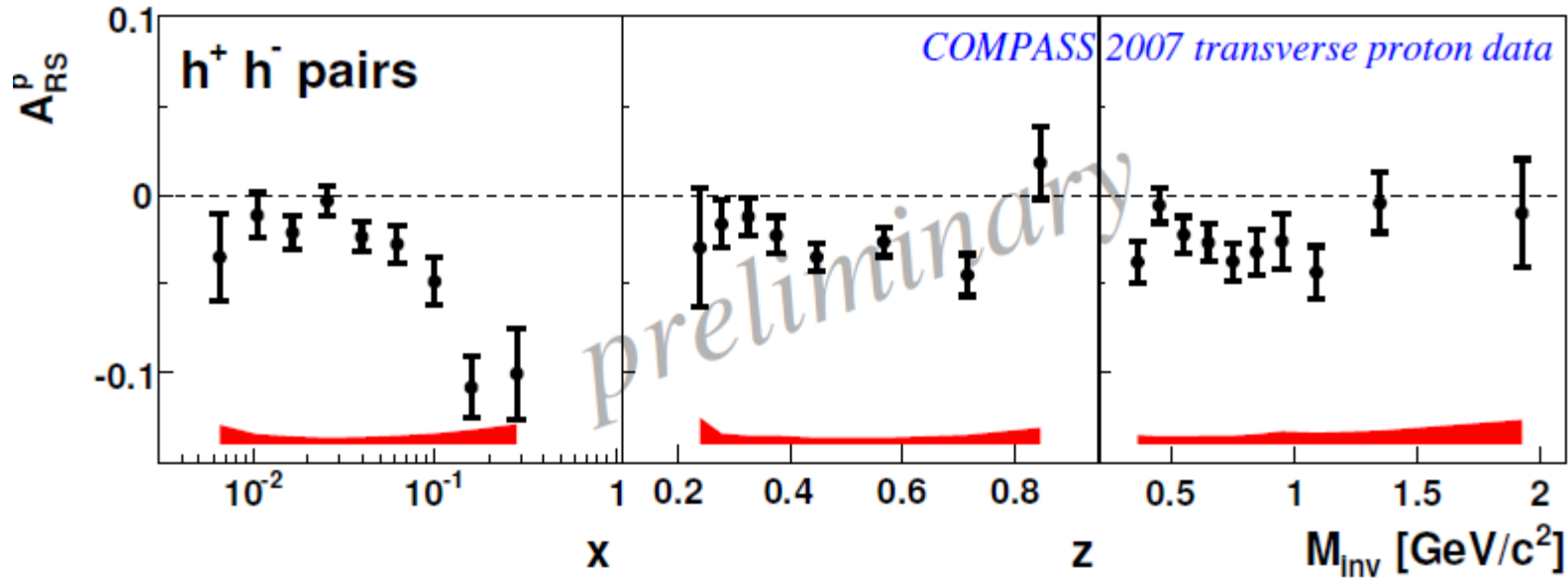
• $\Delta_T u > 0$ and $\Delta_T d < 0$

• Do not saturate Soffer bound

• Smaller than helicity

Transversity via "two hadron"

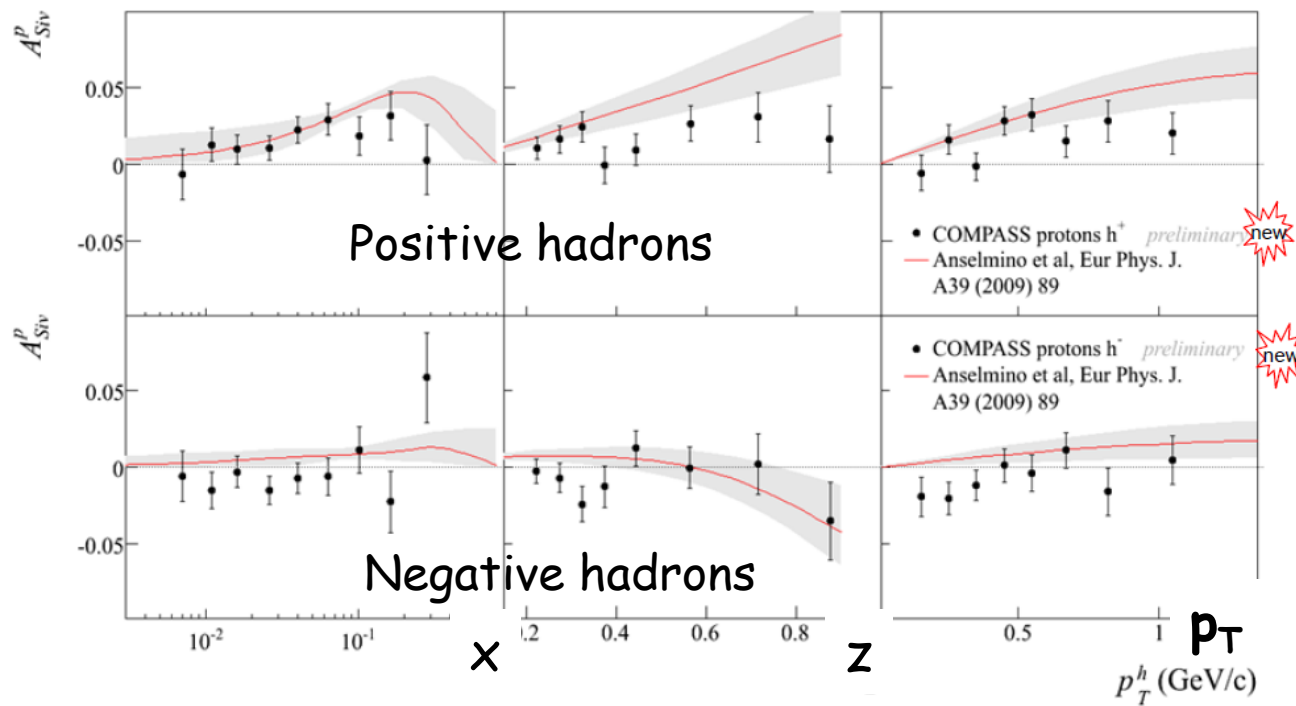
as an alternative for $\Delta_T u$ and $\Delta_T d$



- Confirms non zero effect at large x ; larger than Collins asymmetry
- (Smaller) signal was also seen in HERMES in different phase space; difficult to describe both simultaneously *A. Bacchetta et al., Mah et al.*

Sivers Asymmetry- proton

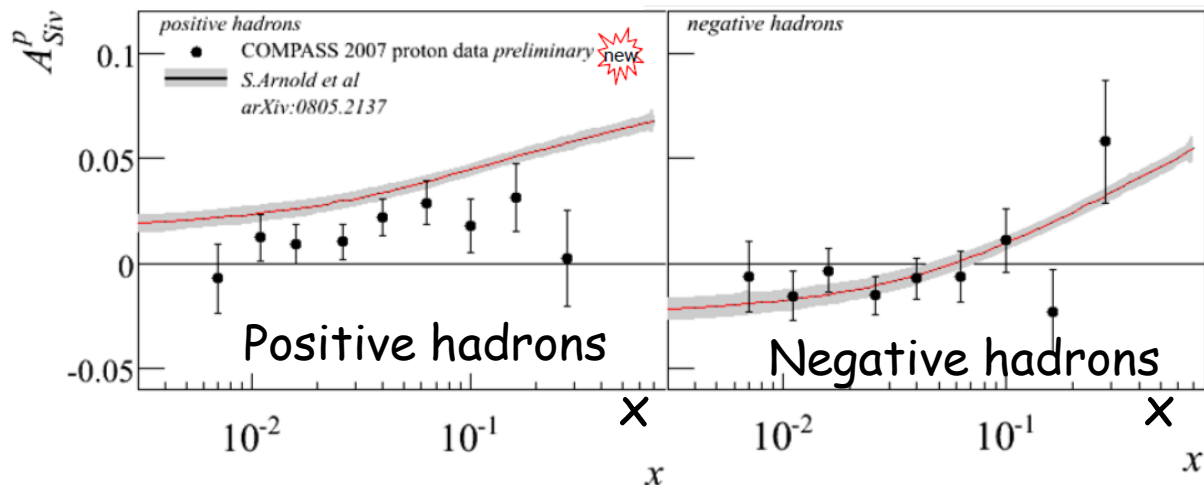
Comparison with predictions from Anselmino *et al.*, based on fit of Hermes-p and Compass-d data



Present data not in fit

-COMPASS signal at high x smaller than HERMES
-Possible W dependence

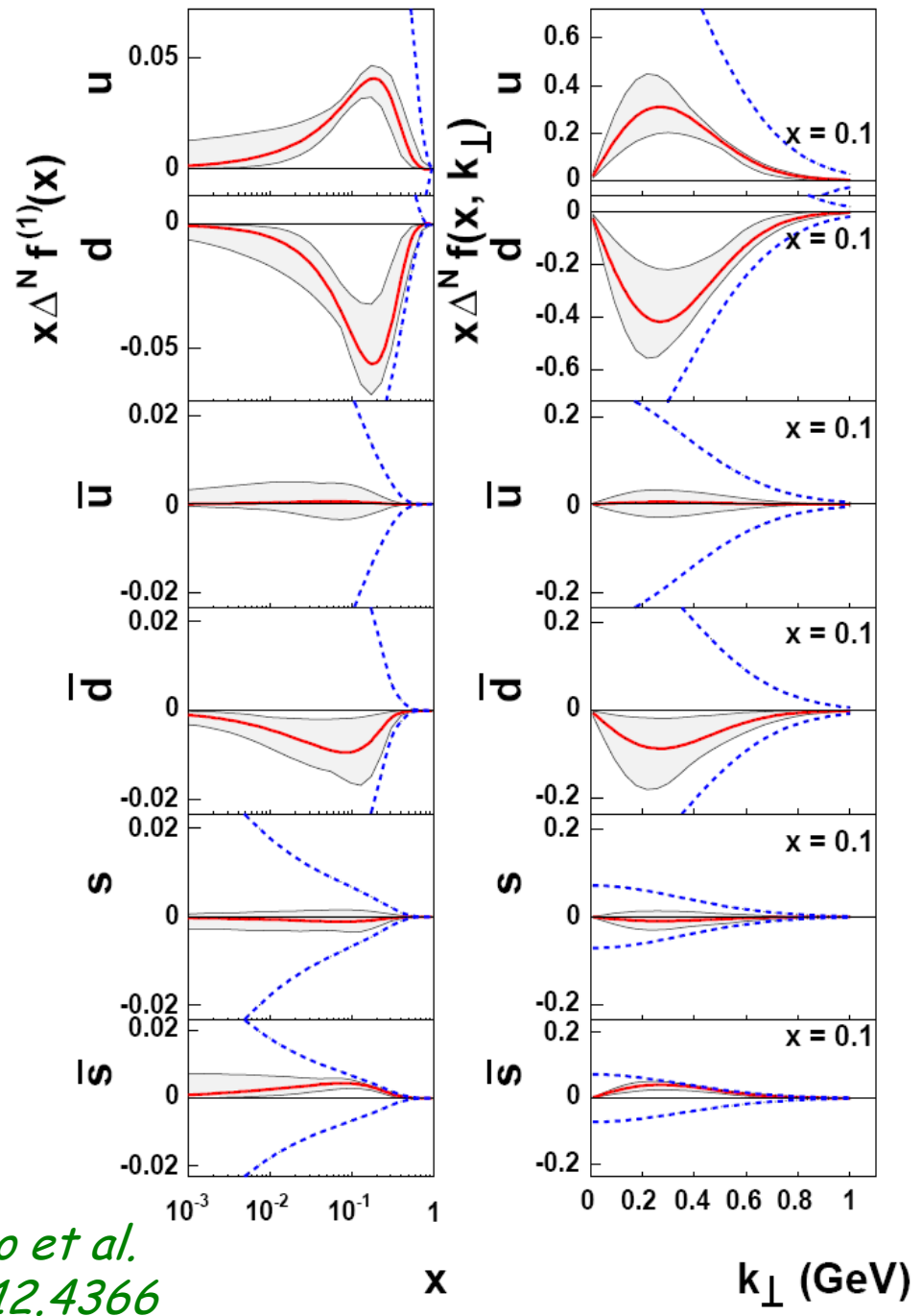
Comparison with calculations of Arnold *et al.*, which are in agreement with Hermes-p data.



Sivers functions from global analyses

There exist several combined analyses of
COMPASS deuteron Sivers asym.
HERMES proton Sivers asym.

(Anselmino et al.,
 Efremov et al.,
 Vogelsang et al. ...)



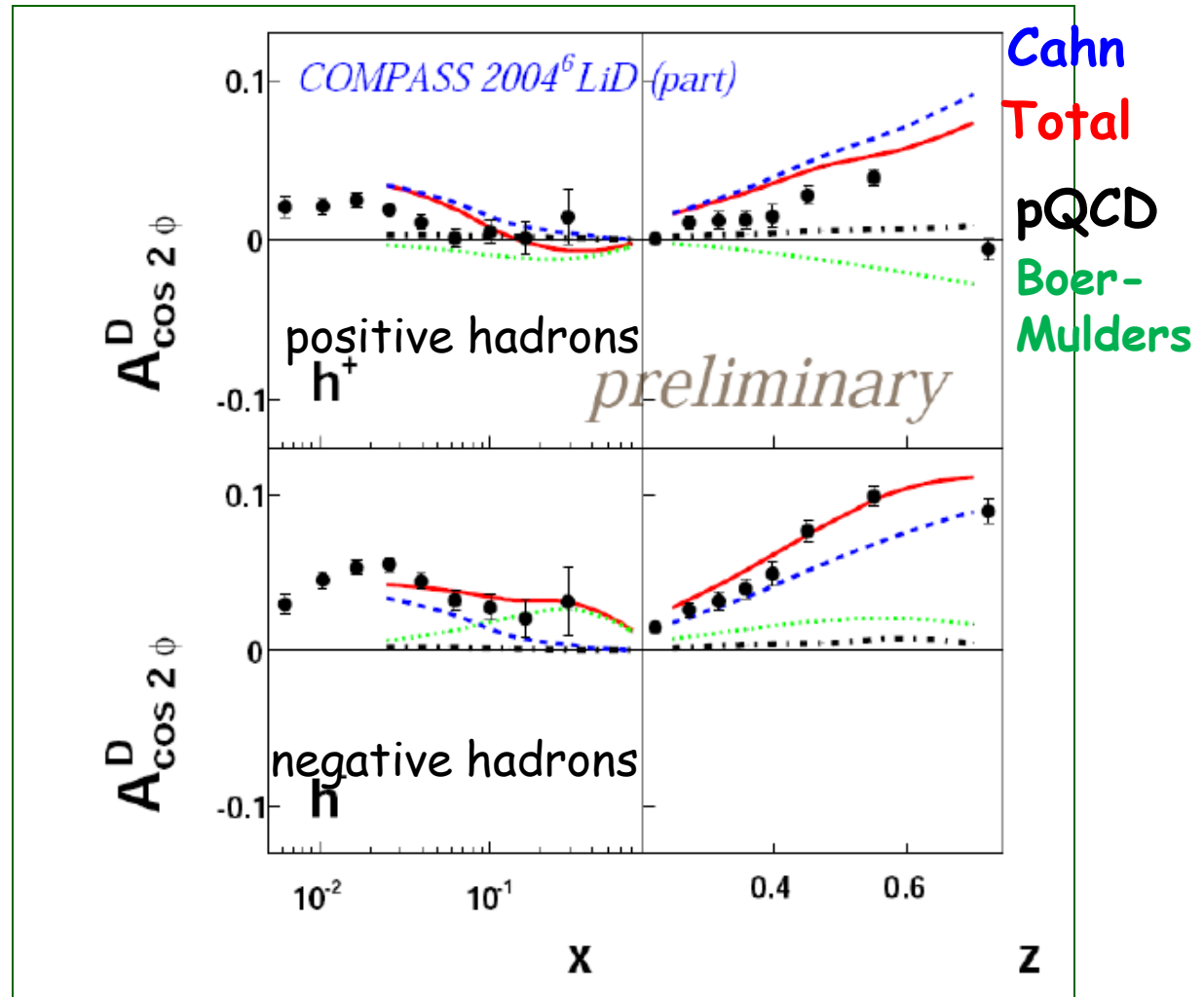
Anselmino et al.
 arXiv:0812.4366

Example of one azimuthal asymmetry

$\cos(2\phi)$ modulation
comparison with theory

— total ⋯ Boer Mulders
- - - Cahn ⋯ pQCD

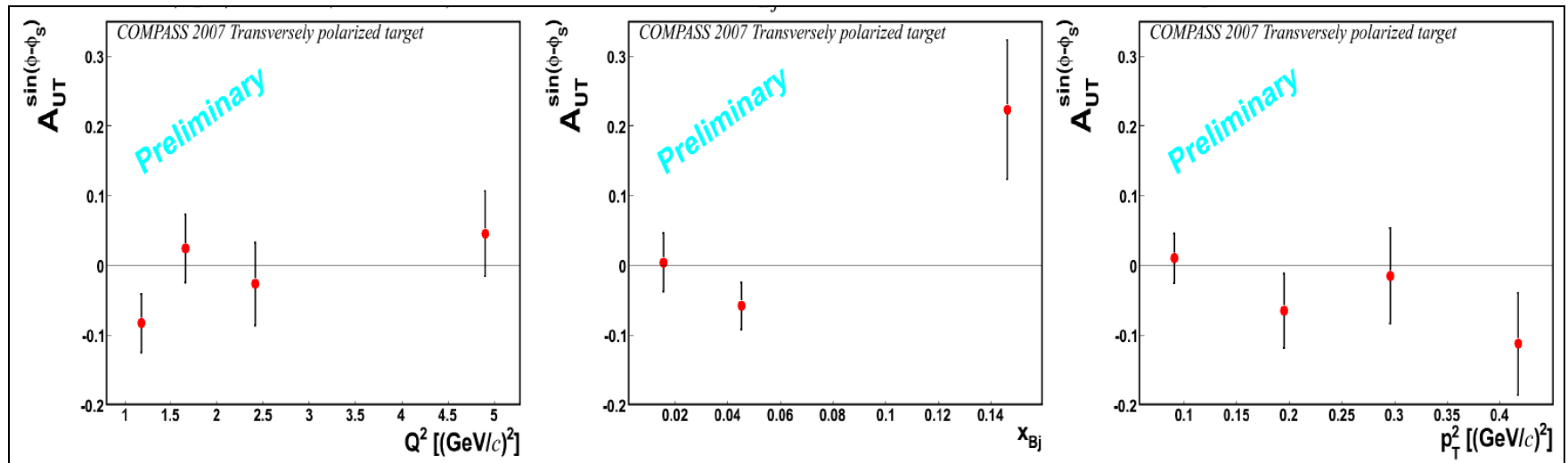
V.Barone, A.Prokudin, B.Q.Ma
arXiv:0804.3024 [hep-ph]



Sensitivity to Transverse Momentum Distributions

Exclusive ρ^0 - Transverse Target SSA

- Asymmetry on **proton** sensitive to **GPD E**, part of Ji sum rule on L_q -flip of nucleon helicity (and not of quark). Overall helicity not conserved
- angular momentum conservation \rightarrow transfer of orbital ang. momentum



Asymmetry compatible with 0

In agreement with Goloskokov & Kroll prediction

- For ρ^0 , value of 0.02 in *EPJC 59 (2009); hep-ph/0809.4126*
- For ω , larger value expected : 0.10
- ρ^0 : Asymmetry on deuteron measured to be 0 by COMPASS

Future QCD studies at COMPASS II

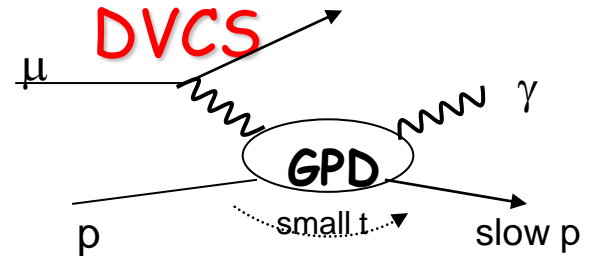
COMPASS-II proposal submitted to CERN SPSC, June 2010

- **GPD (Generalized Parton Distributions)** $\mu p \rightarrow \mu p \gamma$

by exclusive reactions **DVCS** (Deep Virtual Compton Scattering)

and **DVMP** (Meson production),

2 year 'beam charge and spin asymmetry' measurement

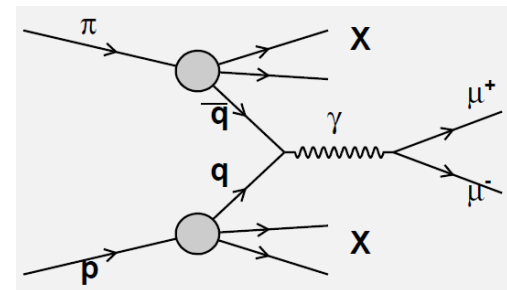


- **Polarized Drell-Yan** $\pi p^\uparrow \rightarrow \mu^+ \mu^- X$

Sivers & Boer-Mulders TMDs

2 years transversely polarised proton target

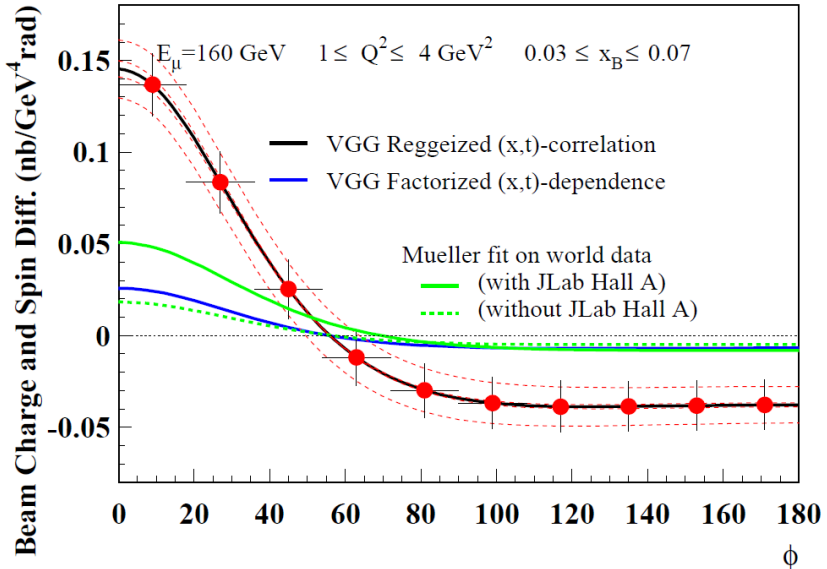
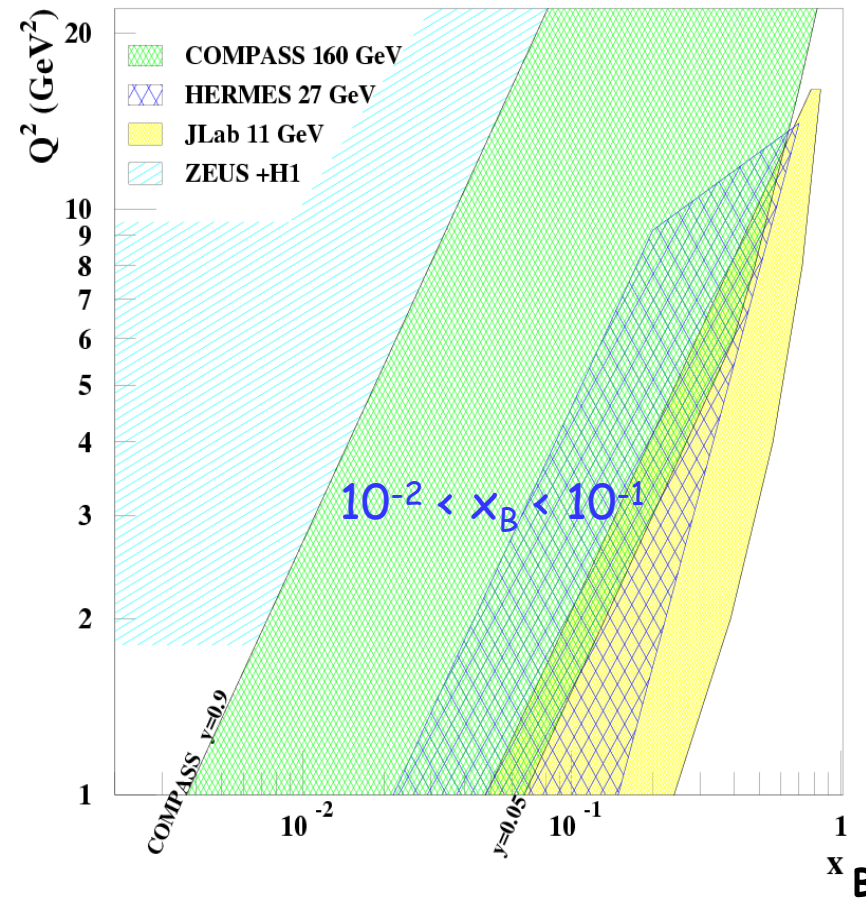
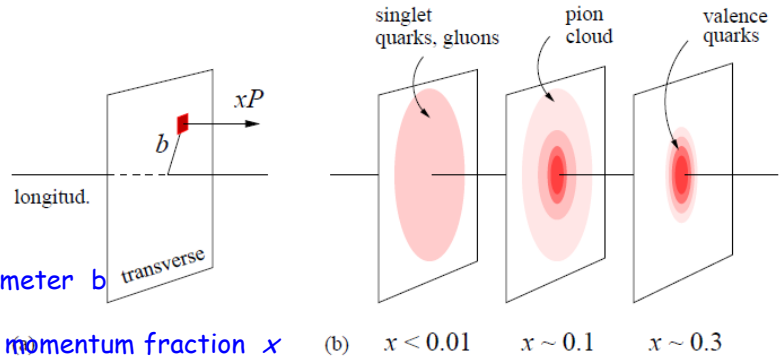
Test of factorization approach



Generalized Parton Distributions

- Unified description of form factors and parton distribution functions
- **Transverse imaging** = nucleon tomography and (in far future) sensitivity to the **quark angular momentum**

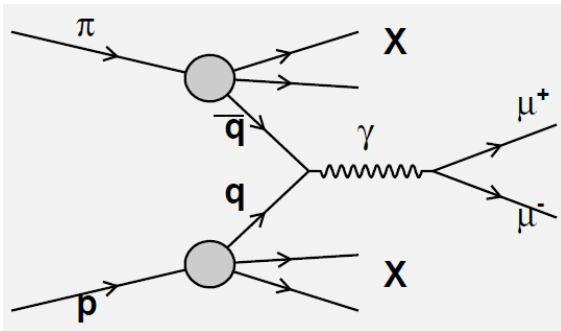
Accessible through **DVCS** process (which interferes with known Bethe-Heitler process)



Polarized Drell-Yan

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

transversely polarised NH_3 target



$$\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}$$

→ Transverse Momentum Dependent (TMD) parton distribution functions

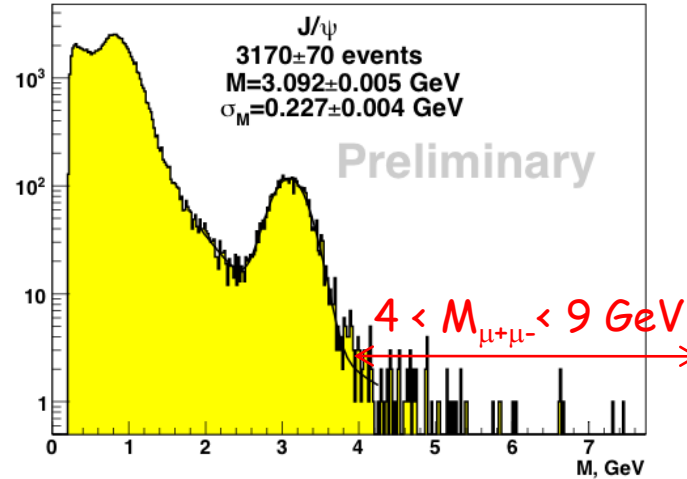
Sivers and Boer Mulders fct will be measured :

- in Drell-Yan process
- in μp SIDIS process

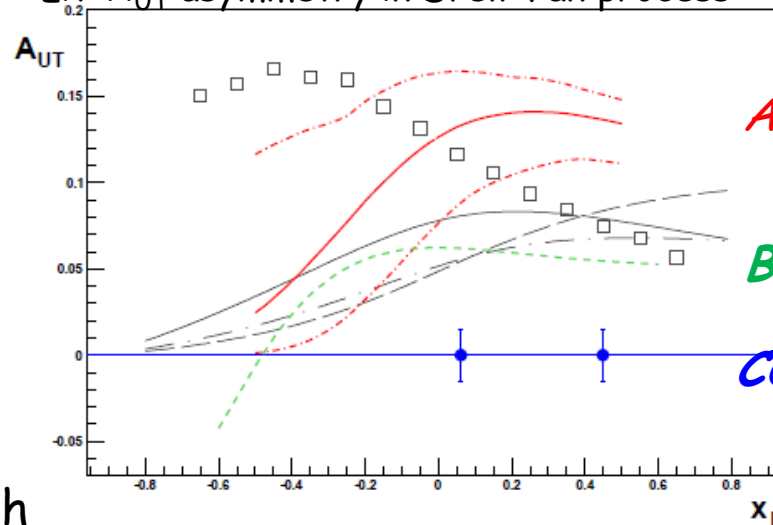
Expect opposite sign

→ Test of factorization approach

COMPASS DY beam test 2009



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



Anselmino et al.

Bacchetta et al

COMPASS proj.

COMPASS (Spin) Summary

- **Gluon polarization**
 - High p_T : at LO, $\Delta G/G \sim 0$ at $x \sim 0.1$ two independent & precise results
 - Charm: at LO, $\Delta G/G = -0.08 \pm 0.21 \pm 0.11$
- **Quark helicity**: extraction at LO for all flavours
 $\Delta s \sim 0$ from SIDIS in measured region
- **Transversity**:
Collins and Sivers deuteron, compatible ~ 0
 - $\Delta_T q$ and **Sivers DF** from BELLE (FF) + HERMES (p) + COMPASS (d)
 $\Delta_T u > 0$ and $\Delta_T d < 0$
 - Collins proton**: Signal in valence region, for pos. and neg. hadrons
 - Sivers proton**: Signal for positive hadrons; possible W dependence

And exciting future program in preparation