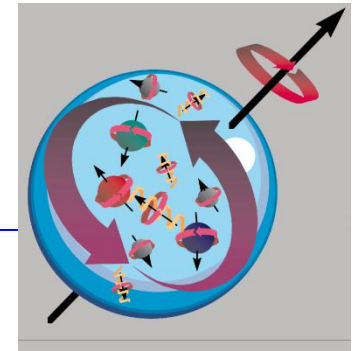


Spin, TMDs and DVCS at COMPASS

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

*ICHEP, International Conference High Energy Physics,
Paris, France, 2010, July 22-28*

COMPASS

Fixed target experiment at the CERN SPS:

Use secondary muon or hadron beams. 220 physicists from 26 institutes

Nucleon spin structure

Polarized muon beam:

$160 \text{ GeV } \vec{\mu}, P_B=80\%$

Polarized target:

${}^6\text{LiD } P_T=50\% \text{ 2002-2006}$

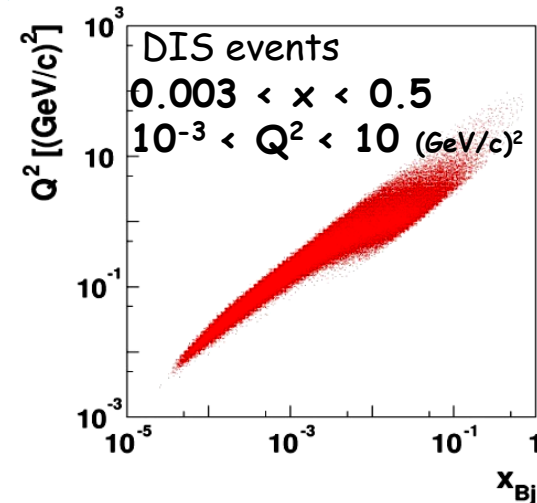
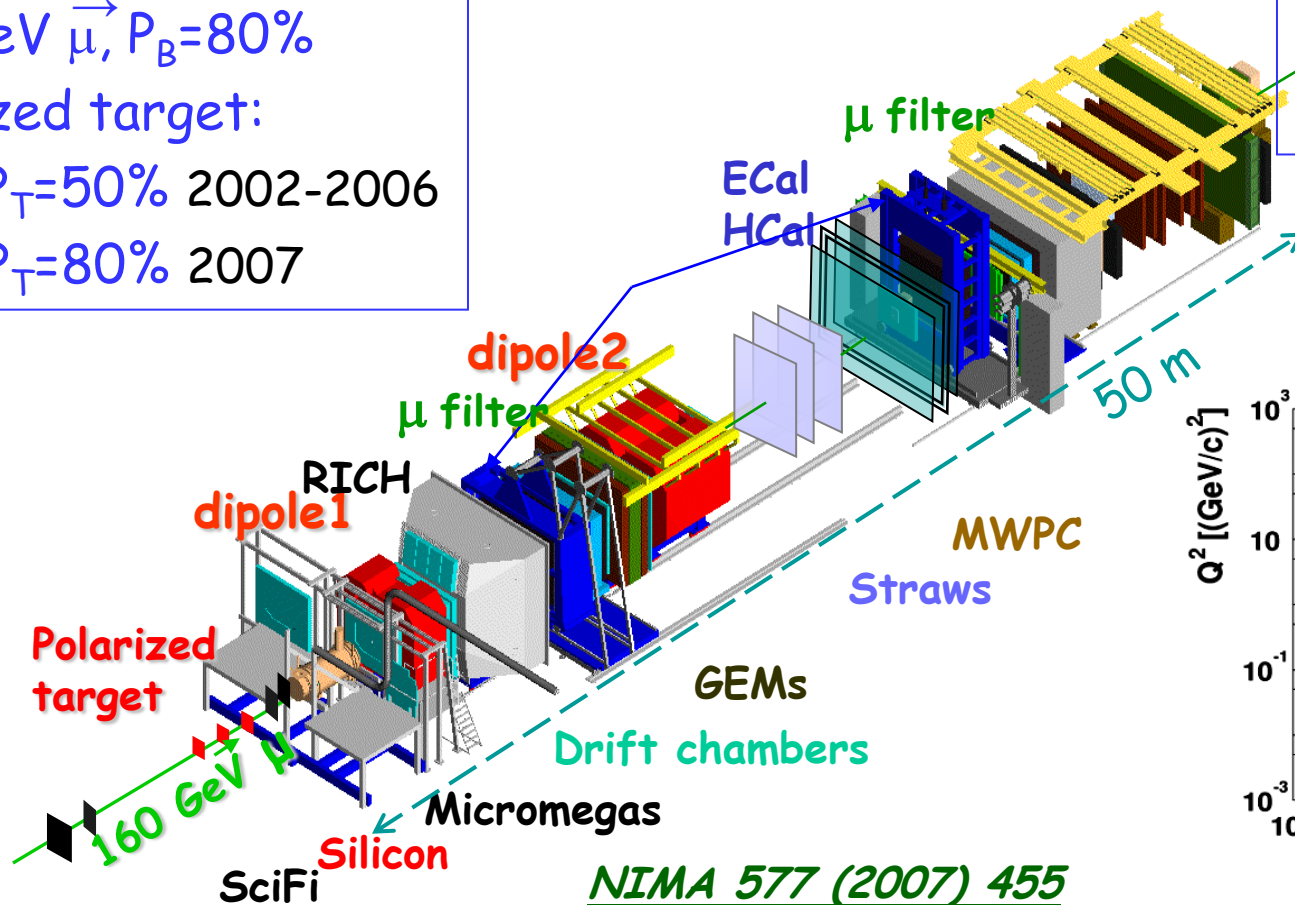
$\text{NH}_3 P_T=80\% \text{ 2007}$

Meson spectroscopy

Hadron beam:

$190 \text{ GeV } \pi / p$

$\text{LH}_2 \text{ 2008-2009}$



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

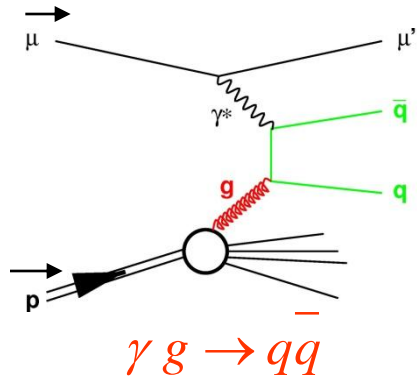
\rightarrow motivated direct measurements of gluon polarization ΔG

$\Delta G/G$ 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

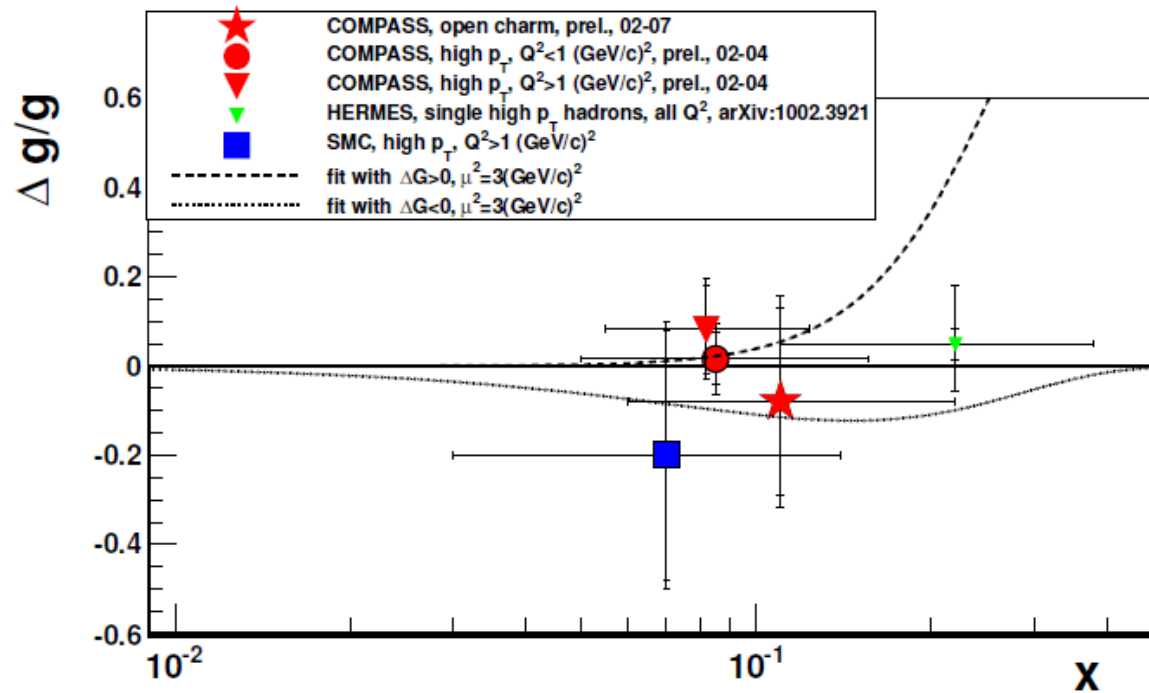
- $q=u,d,s$ high p_T hadron pair $q q \rightarrow h \bar{h}$

High statistics

pQCD scale Q^2 or Σp_T^2

Physical background, better described for high Q^2

Results for $\Delta G/G$ direct measurements

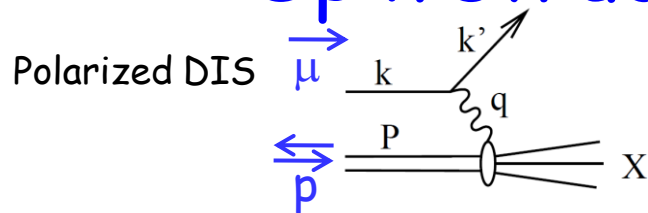


All measurements compatible with 0 for $0.04 < x < 0.2$

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

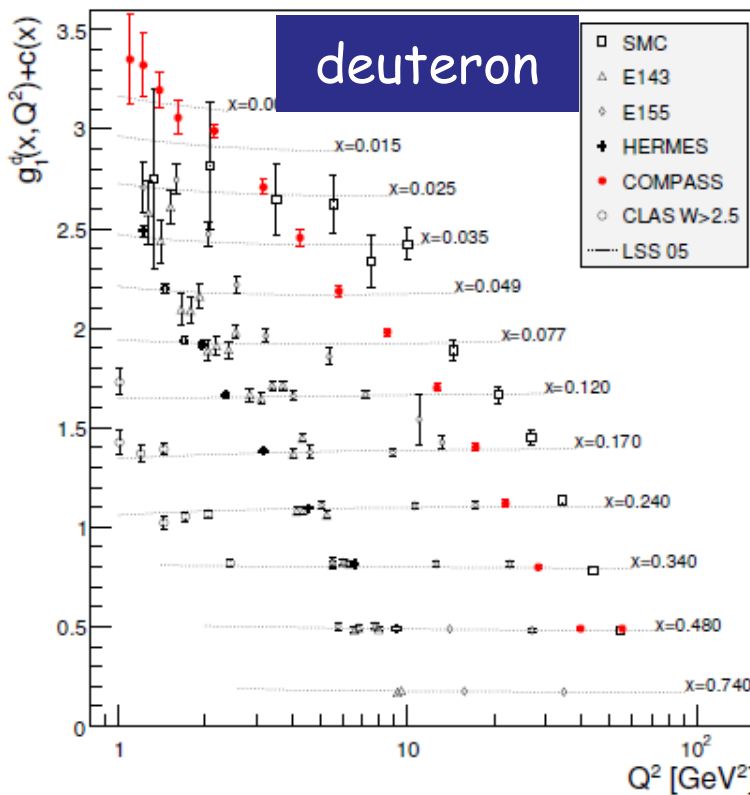
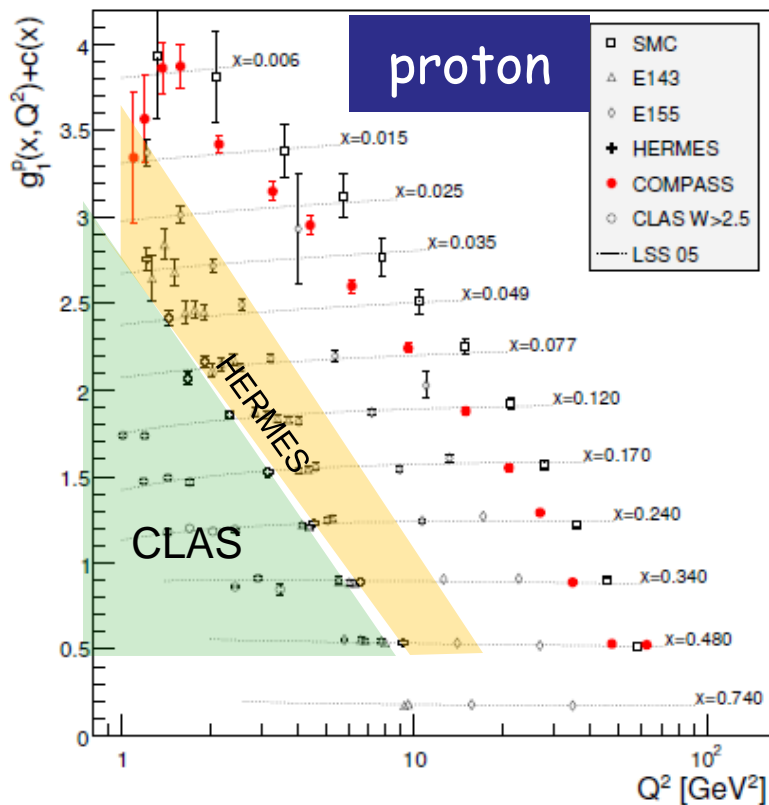
Direct measurements exclude values for the integral of ΔG as large as 1 or 2

Spin structure functions - world data



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

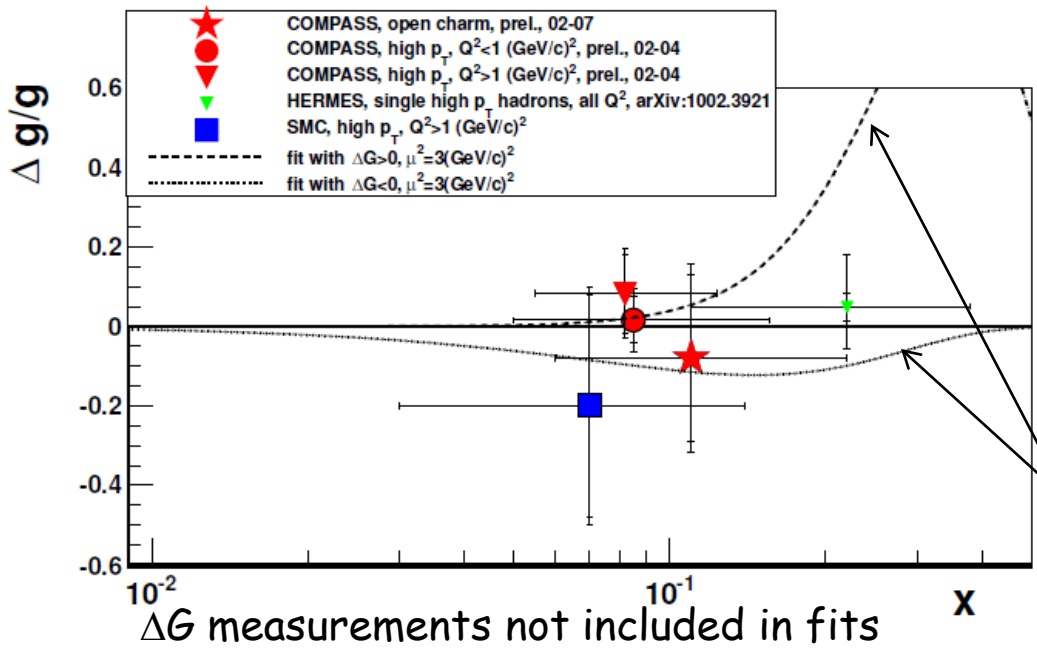
Polarized PDFs



- 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

Input to global QCD fits \rightarrow Extract $\Delta q_f(x)$ and $\Delta G(x)$ through Q^2 evolution

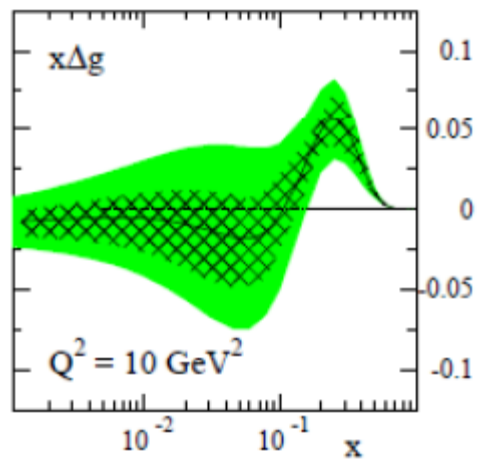
$\Delta G(x)$ from global QCD analysis of polarized DIS data $g_1(x, Q^2)$



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
 (different scale)

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:

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

Non Singlet structure function and Bjorken sum rule

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

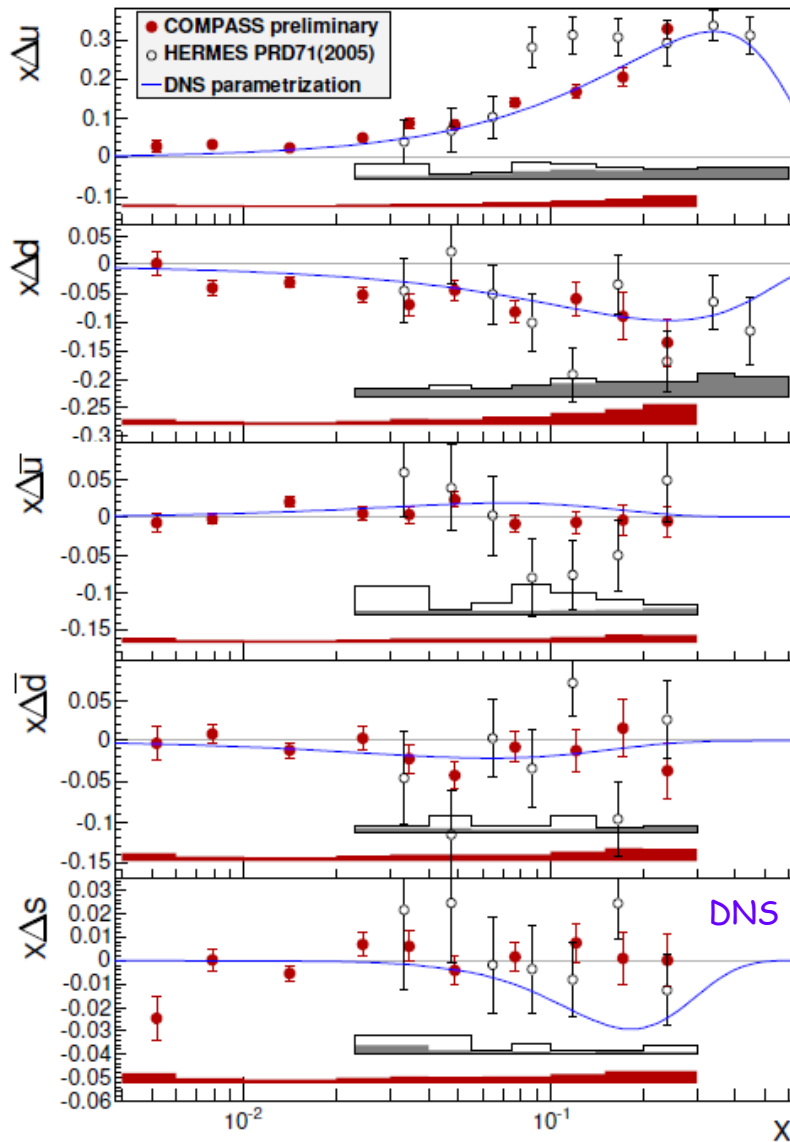
The first moment provides a test of the Bjorken sum rule, a fundamental result of QCD derived from current algebra

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

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

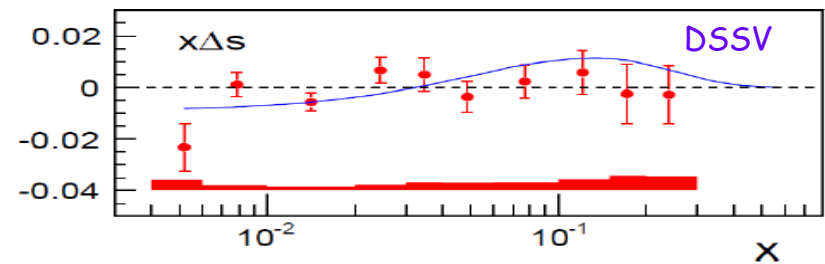
LO Helicity quark distributions



- 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 , in agreement with both inclusive result and semi inclusive data.



Transversity - 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

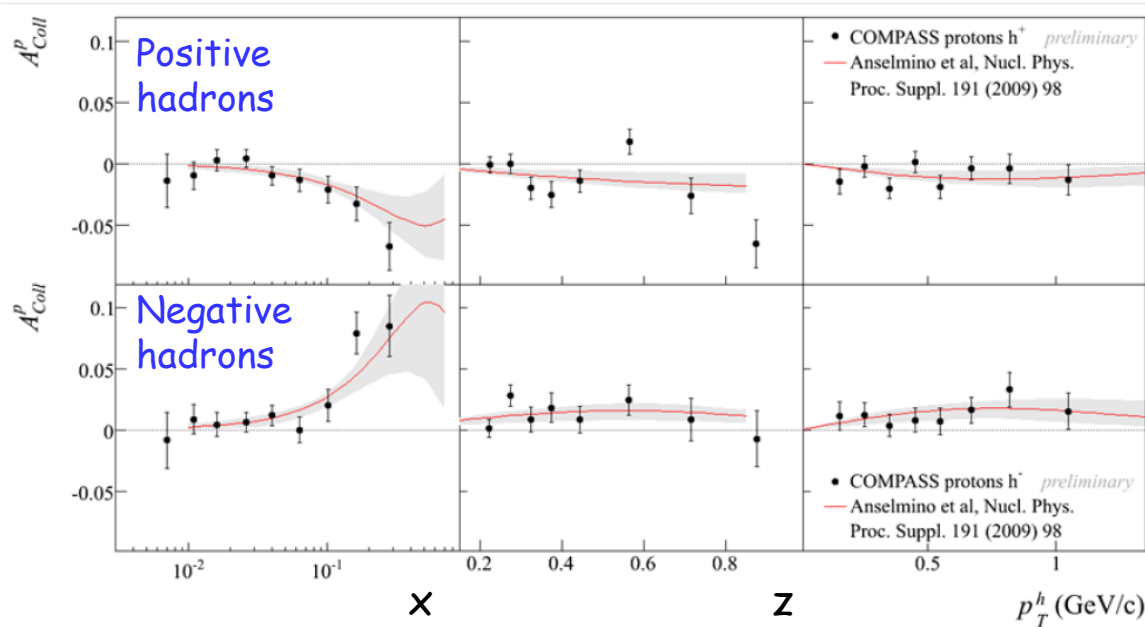
$$A_{\text{Siv}} = \frac{\sum_q e_q^2 \cdot f_{1Tq}^\perp \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

note: $\Delta_T q$ also measured using

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

Transversity : Collins Asymmetry on proton

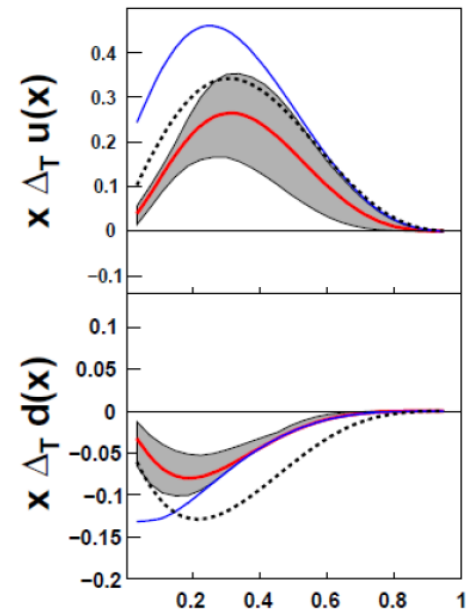
COMPASS data compared to predictions from Anselmino *et al.*, based on fit of HERMES-p and COMPASS-d data, and BELLE FF.



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

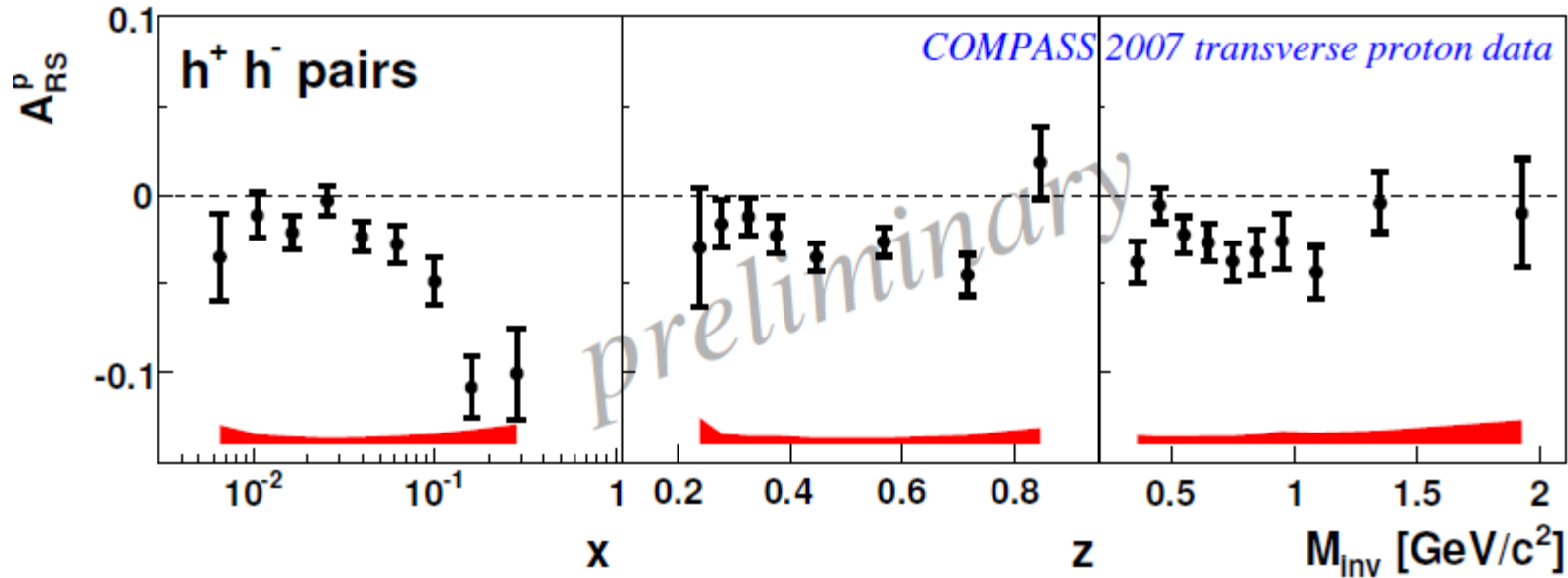
Several combined analyses of HERMES p and COMPASS d data :

- $\Delta_T u > 0$ 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 $\Delta_T d$



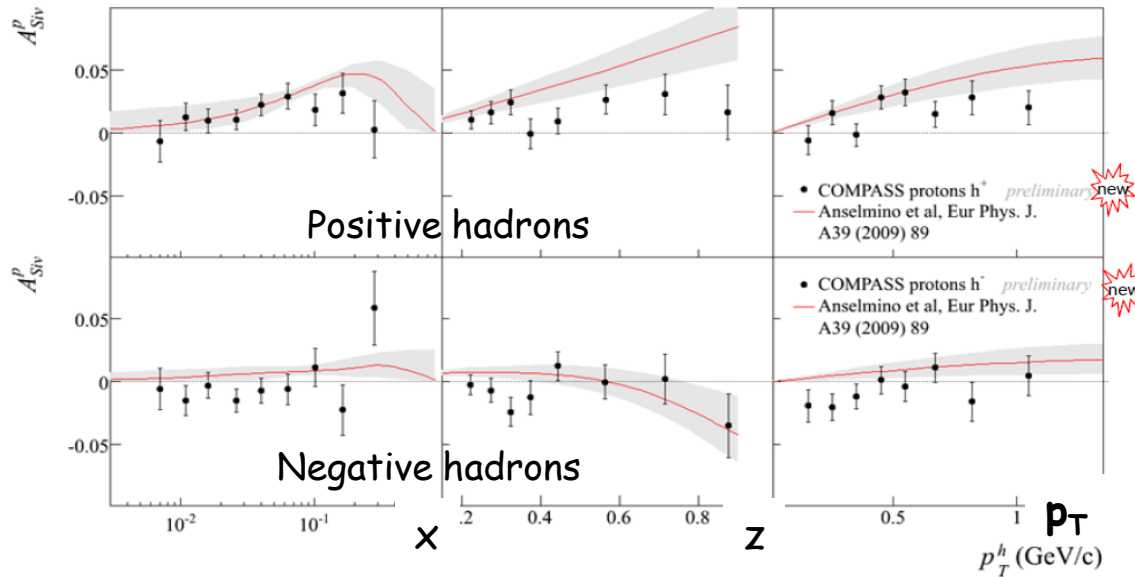
- Confirms non zero effect at large x ; larger than Collins asymmetry
- (Smaller) signal was also seen in HERMES in different phase space; difficult to describe both simultaneously *A. Bacchetta et al., Mah et al.*

Sivers Asymmetry- proton

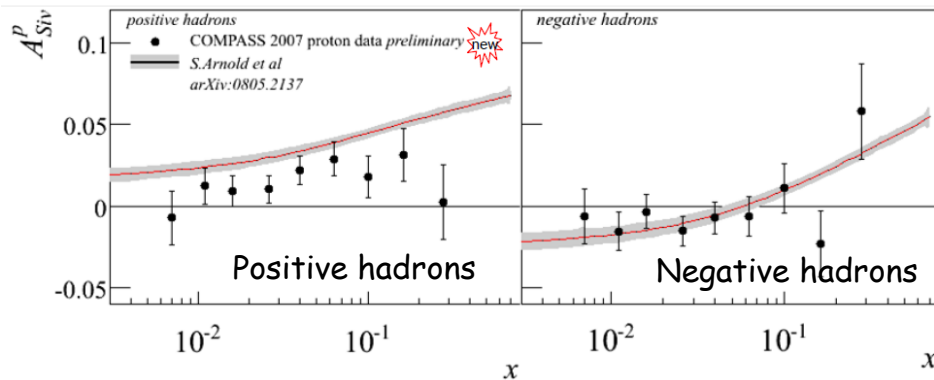
Comparison with predictions from Anselmino *et al.*, based on fit of Hermes-p and Compass-d data

Present data not in fit

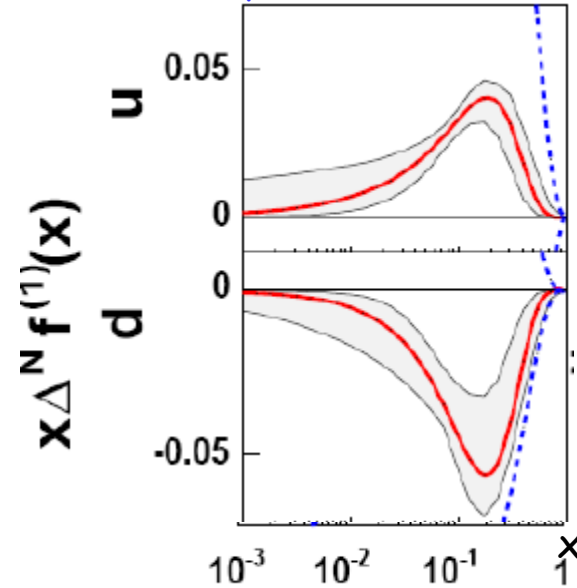
-COMPASS signal < HERMES signal
-Possible W dependence



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



Extraction of Sivers fct (HERMES p and COMPASS d)



Ex: M. Anselmino et al. arXiv:0812.4366

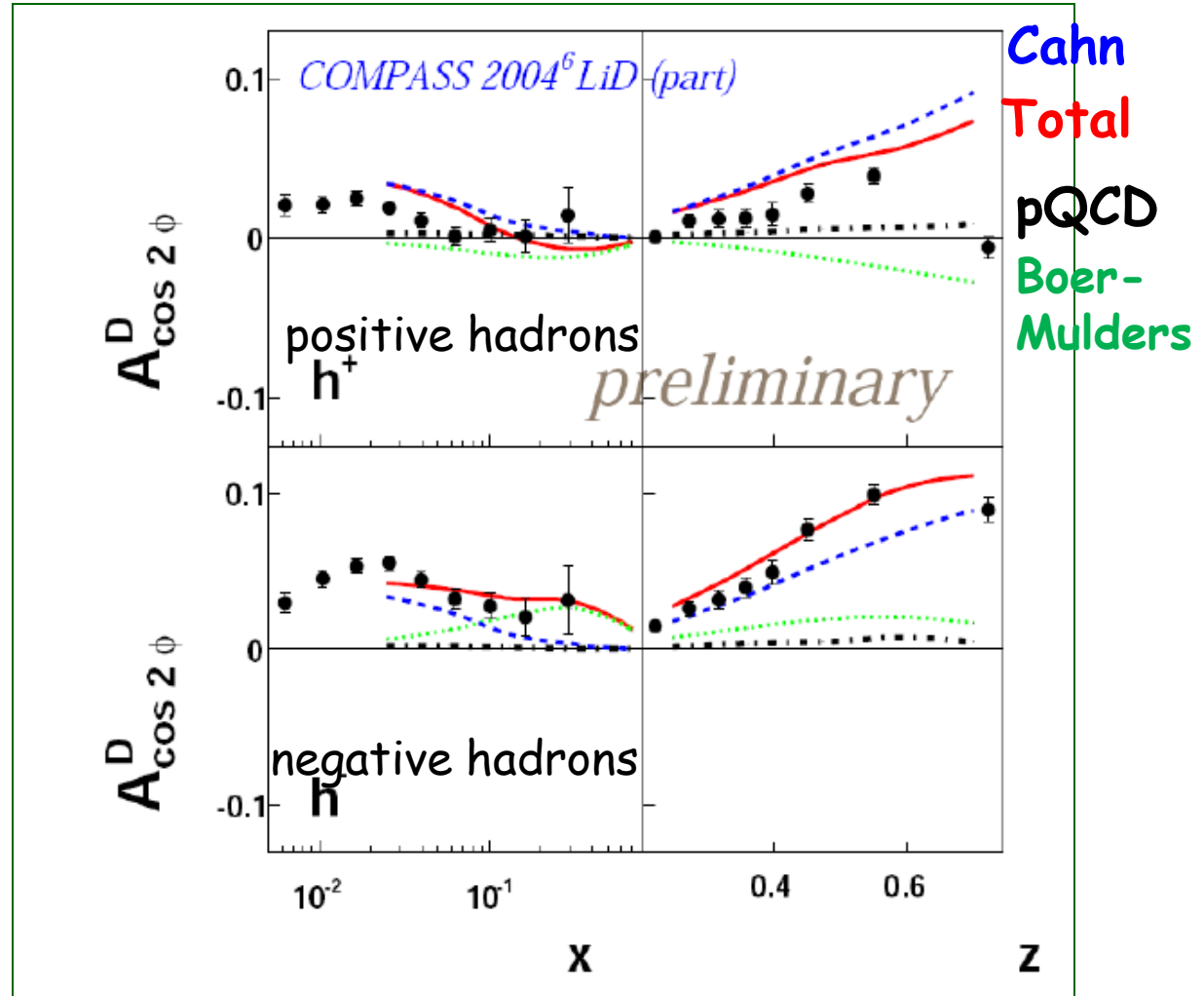
Example of one azimuthal asymmetry

Unpolarized target.

$\cos(2\phi)$ 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

Future QCD studies at COMPASS II

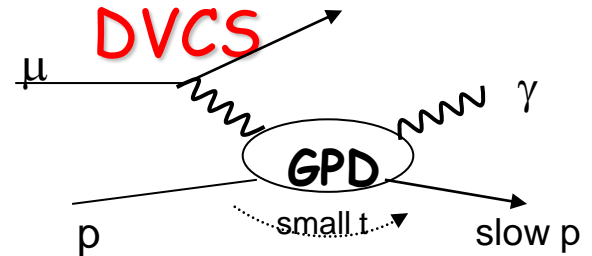
COMPASS-II proposal submitted to CERN SPSC, June 2010

- **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



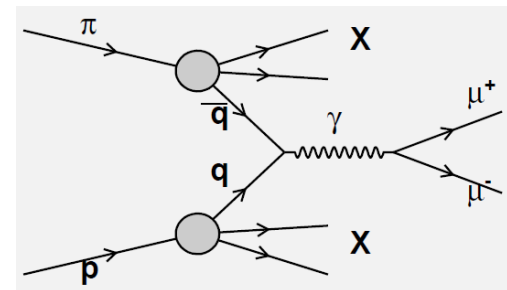
- **Polarized Drell-Yan** $\pi p^\uparrow \rightarrow \mu^+ \mu^- X$

Sivers & Boer-Mulders

Transverse Momentum Dependent distributions

2 years transversely polarised proton target

Test of factorization approach

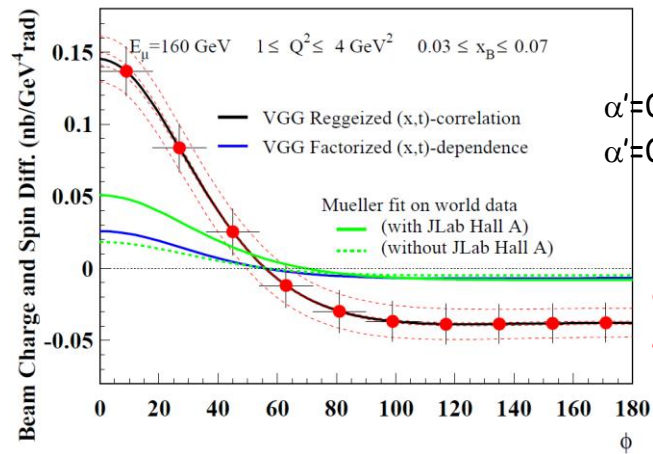


Generalized Parton Distributions

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

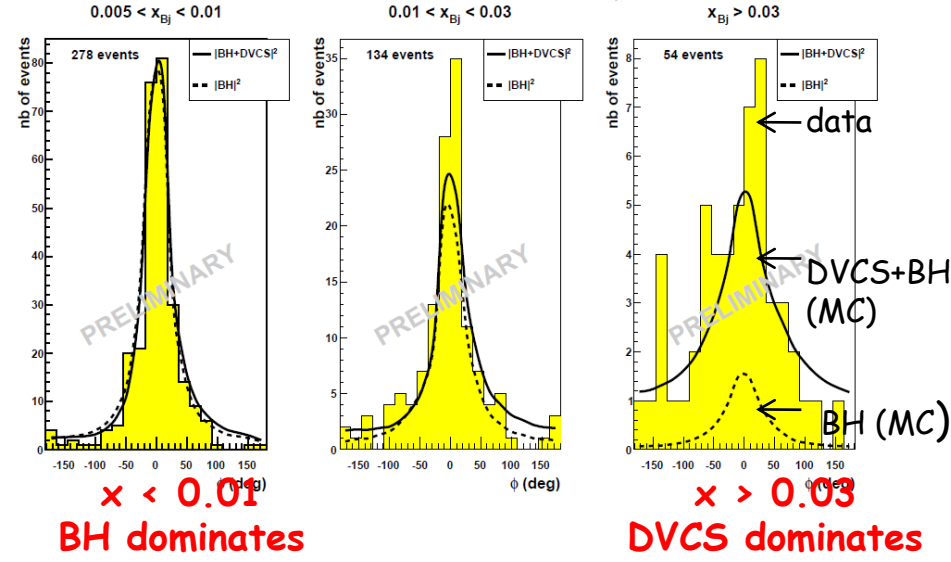
Kinematic domain : intermediate between HERA and JLab $10^{-2} < x_B < 10^{-1}$

Ex: Beam charge & spin asymmetry in DVCS process (interfering with BH):



COMPASS proj. 2years

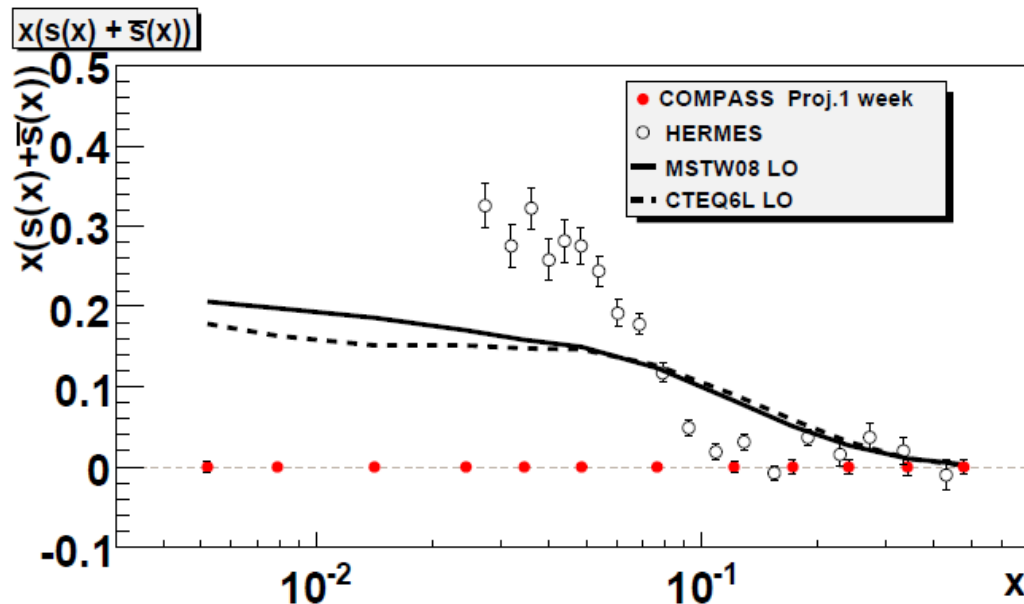
First signal of DVCS&BH from 2009 short test run, compared to simulations



Measurement of unpolarized PDFs

- In parallel to the DVCS/DVMP program, get (for free) SIDIS data on LH_2 target
- Extract strange quark PDF $s(x)$ as well as quark fragmentation functions from kaon multiplicities

Short term goal: LO analysis from COMPASS data alone integrated over z

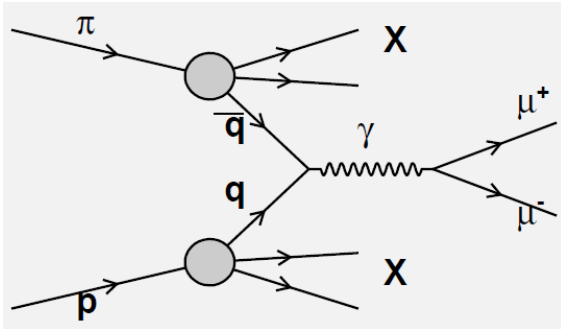


Longer term goal : provide p and K multiplicities as fct of x, z for global QCD analyses

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

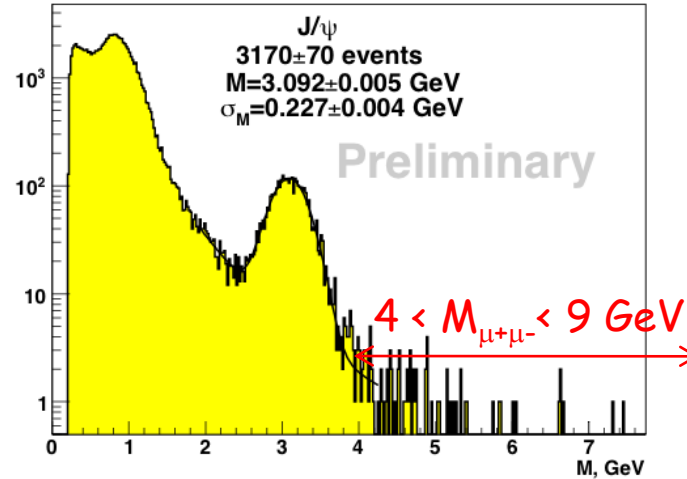
Sivers and Boer Mulders fct will be measured :

- in Drell-Yan process
- in μp SIDIS process

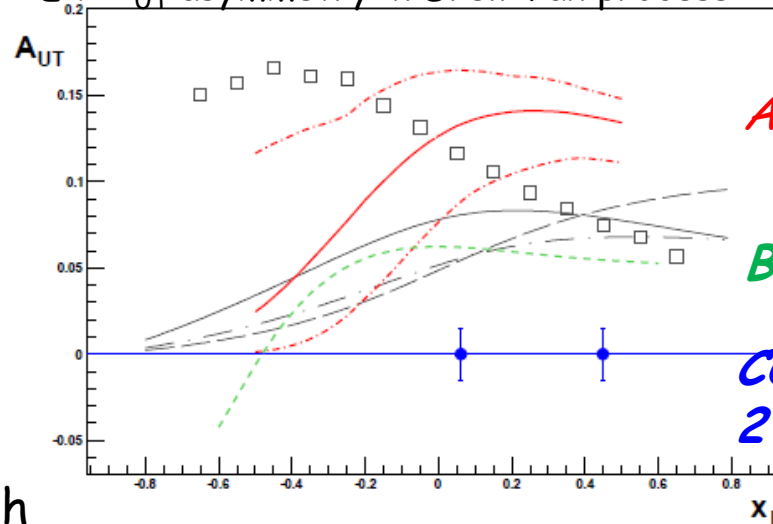
Expect opposite sign

→ Test of factorization approach

COMPASS DY beam test 2009



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



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
 - Collins proton**: Signal in valence region, for pos. and neg. Hadrons
Extract $\Delta_{T u} > 0$ and $\Delta_{T d} < 0$
 - Sivers proton**: Signal for positive hadrons; possible W dependence

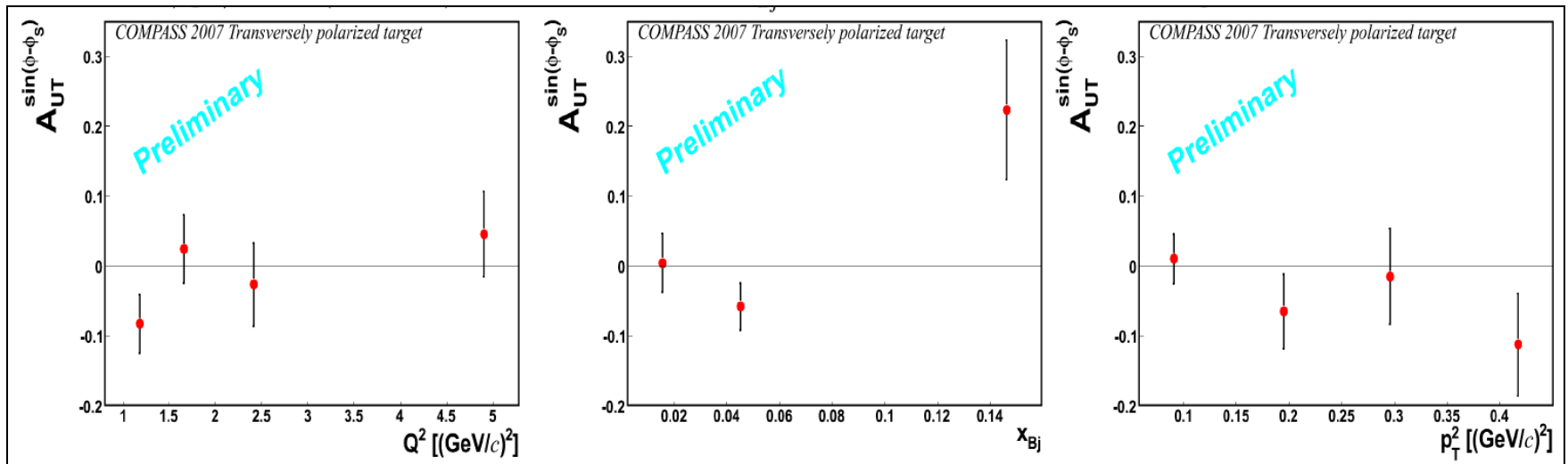
And exciting future program in preparation

2010	Precision measurement on Transverse Spin (Sivers)
2011	Longitudinal Spin
2012 & beyond:	New proposal COMPASS II

Spares

Exclusive ρ^0 - Transverse Target SSA

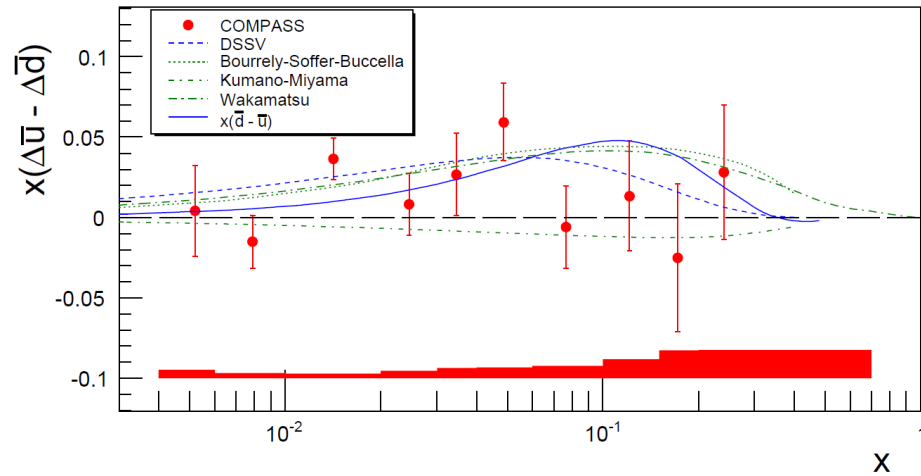
- Asymmetry on **proton** sensitive to **GPD E**, part of Ji sum rule on L_q -flip of nucleon helicity (and not of quark). Overall helicity not conserved
- angular momentum conservation \rightarrow transfer of orbital ang. momentum



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



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

Flavour asymmetry not as large as in unpolarized case:

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