Spin physics with COMPASS

Stephane Platchkov
Institut de Recherche sur les lois Fondamentales de l'Univers
Saclay, France

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20 years ago : the spin “crisis”...

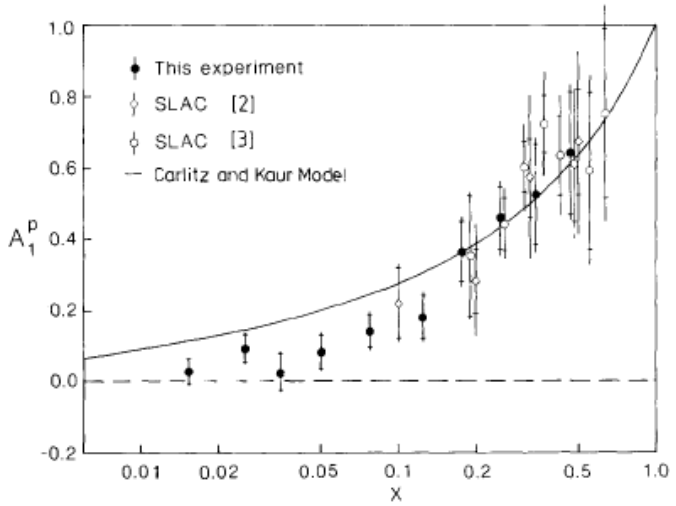
- EMC paper on the spin structure of the nucleon

Nuclear Physics B328 (1989) 1–35
North-Holland, Amsterdam

AN INVESTIGATION OF THE SPIN STRUCTURE OF THE PROTON IN DEEP INELASTIC SCATTERING OF POLARISED MUONS ON POLARISED PROTONS

The European Muon Collaboration

$\Delta\Sigma = 2 \langle S_z \rangle$ is small:



$$\langle S_z \rangle_{\text{quarks}} = \tfrac{1}{2}(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$$

$$= \tfrac{1}{2}\sqrt{\tfrac{3}{2}}\, a_0 = +0.060 \pm 0.047 \pm 0.069 .$$

→ = ~12% of 1/2

... instead of (the expected) ~60% of 1/2!

Since then: tremendous effort of both ....

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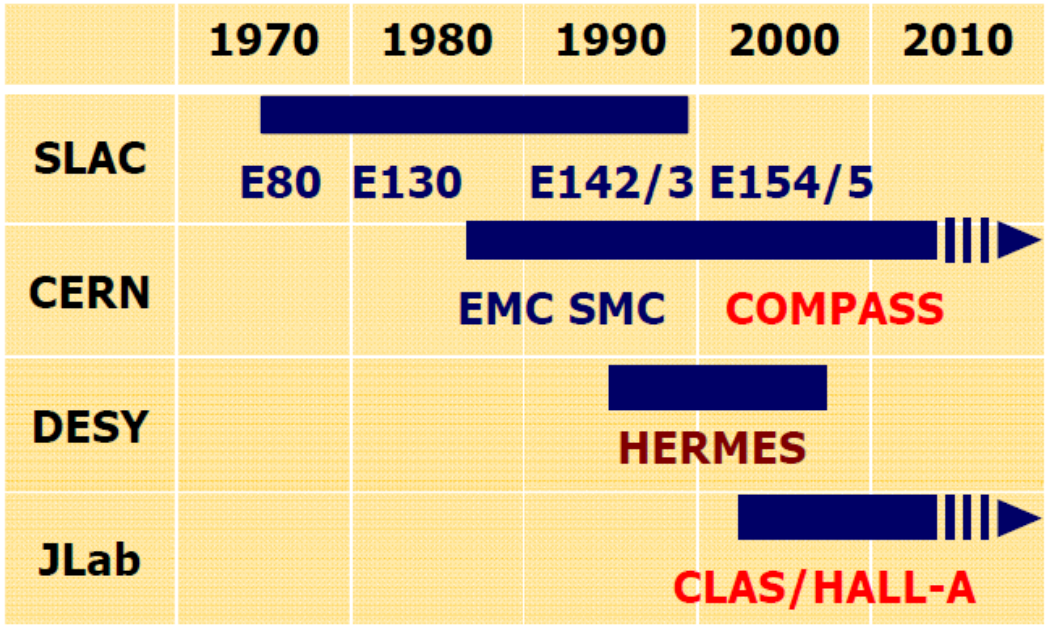
- Experiments (with lepton beams):

E80, E130	$\vec{e}\,\vec{p}$	≤ 20 GeV
EMC	$\vec{\mu}\,\vec{p}$	100–200 GeV
E142, 143	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 28 GeV
SMC	$\vec{\mu}\,\vec{p},\vec{d}$	100, 190 GeV
E154, 155	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 50 GeV
HERMES	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	27.5 GeV
COMPASS	$\vec{\mu}\,\vec{p},\vec{d}$	160 GeV
HALL A	$\vec{e}\,\vec{n}$	6 GeV
CLAS	$\vec{e}\,\vec{p},\vec{d}$	6 GeV



+ STAR, PHENIX, BRAHMS **@RHIC**

- and theory:
  - (from arXiv), “nucleon spin”: “Your query resulted in too many hits, only 1000 hits are being displayed.”

The COMPASS experiment at CERN

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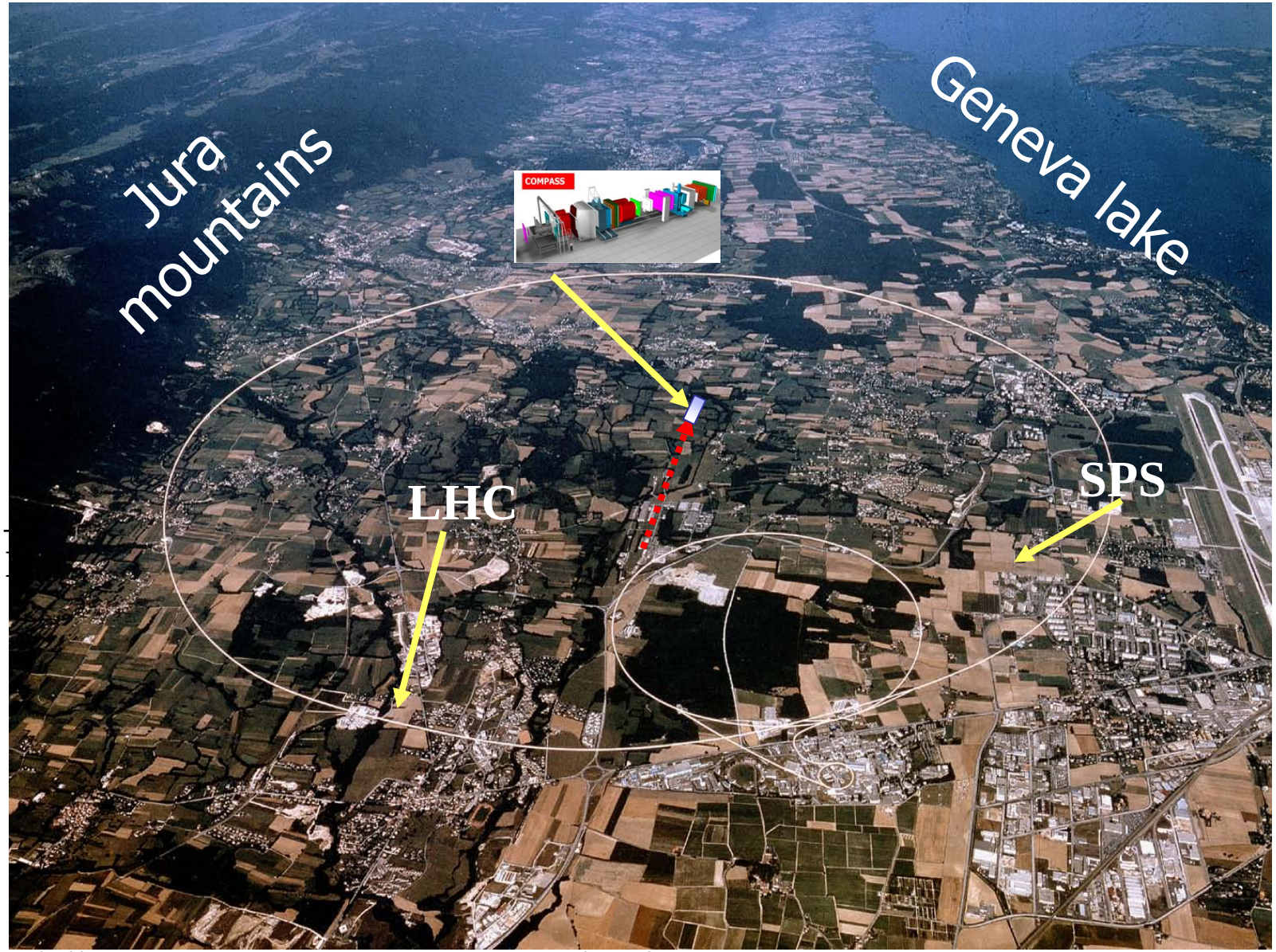

COMPASS experimental set-up

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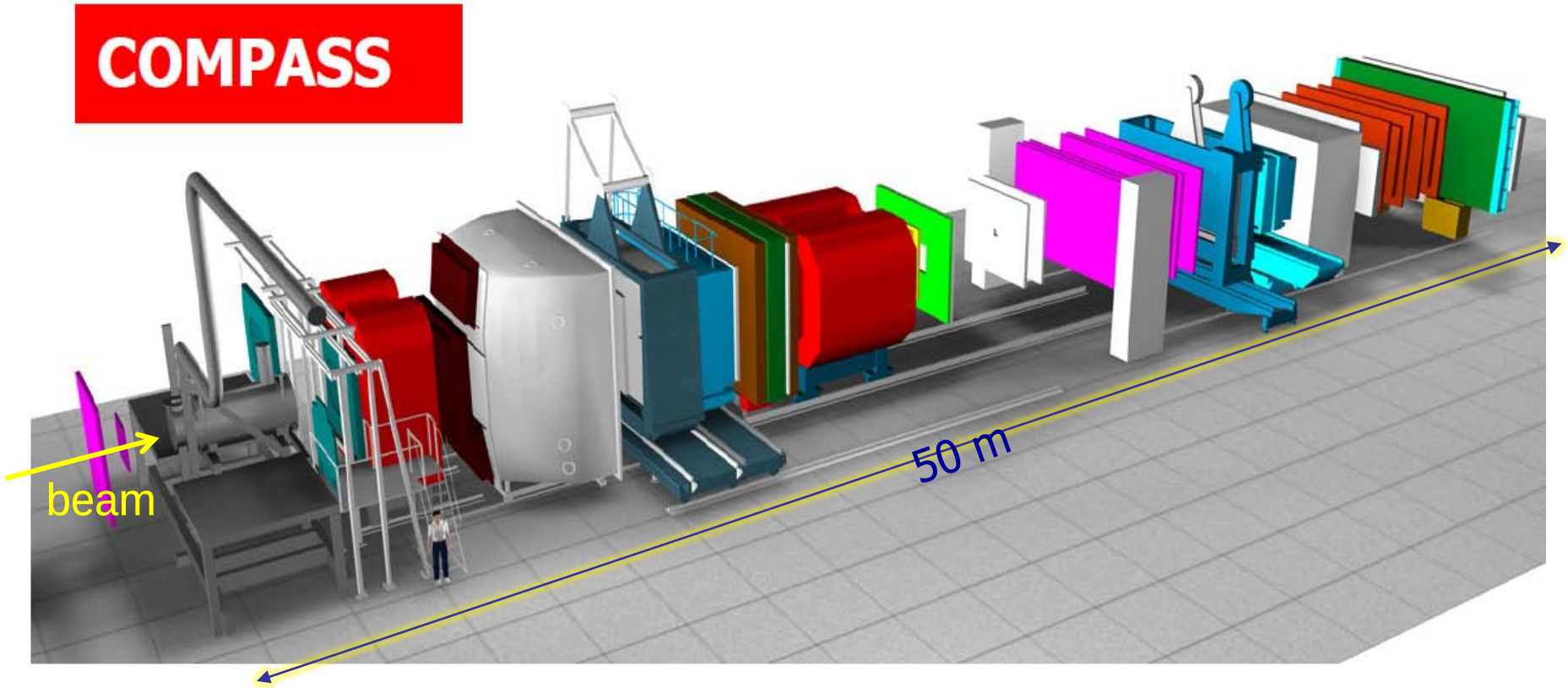

- High beam energy: 160 GeV, polarized μ+/μ- beam (Pμ=80%)
- Large acceptance, Particle identification detectors
- Low intensity beam – good luminosity thanks to a large polarized target

COMPASS nucleon spin structure studies

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- DIS :
  - Update on the Bjorken Sum Rule
- SIDIS with a longitudinally polarized target :
  - Polarized Distribution Functions
  - Polarization of the strange quark sea
  - Asymmetry of the polarized sea
- Gluon contribution to the nucleon spin
- SIDIS with a transversely polarized target :
  - Transversity measurements
  - Transverse momentum dependent asymmetries

COMPASS

DIS deuteron and proton $g_1(x)$: world data

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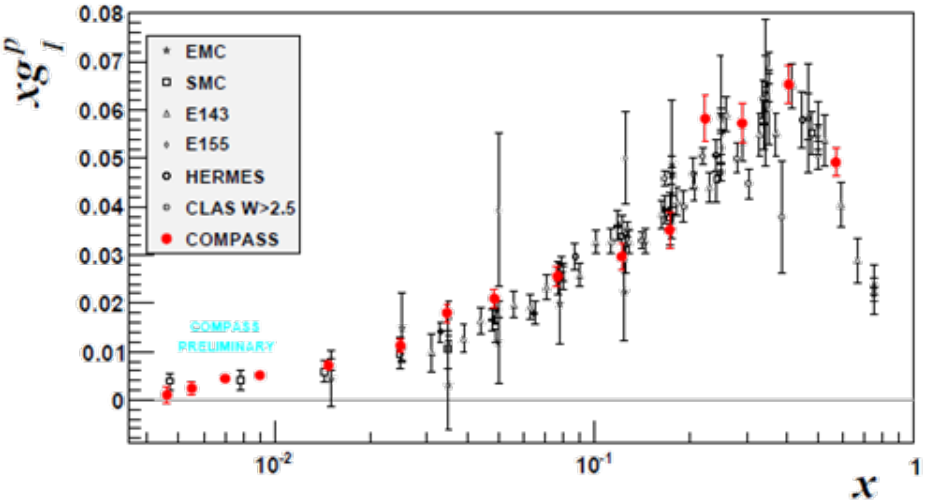
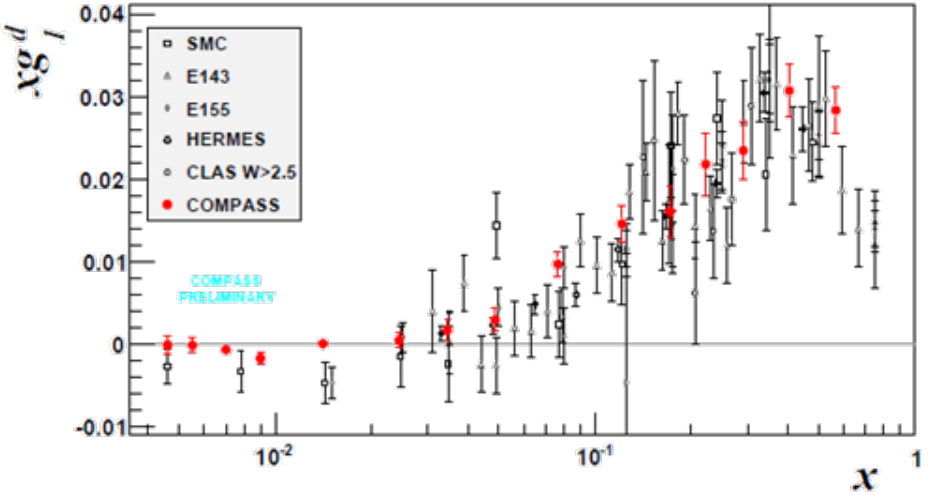
Proton data - world



COMPASS data: 2007

Deuteron data - world



COMPASS data: 2002 – 2006

From measurements of the polarized structure functions $g_1(x,Q^2)$ alone we can :

1. Learn about the quark contribution to the nucleon spin

   $\Delta\Sigma = 0.30 \quad 0.01(\text{stat.}) \quad 0.02(\text{syst.})$

   Fit to COMPASS deuteron data Phys. Lett. B647 (2007) 8.

2. Test the Bjorken sum rule

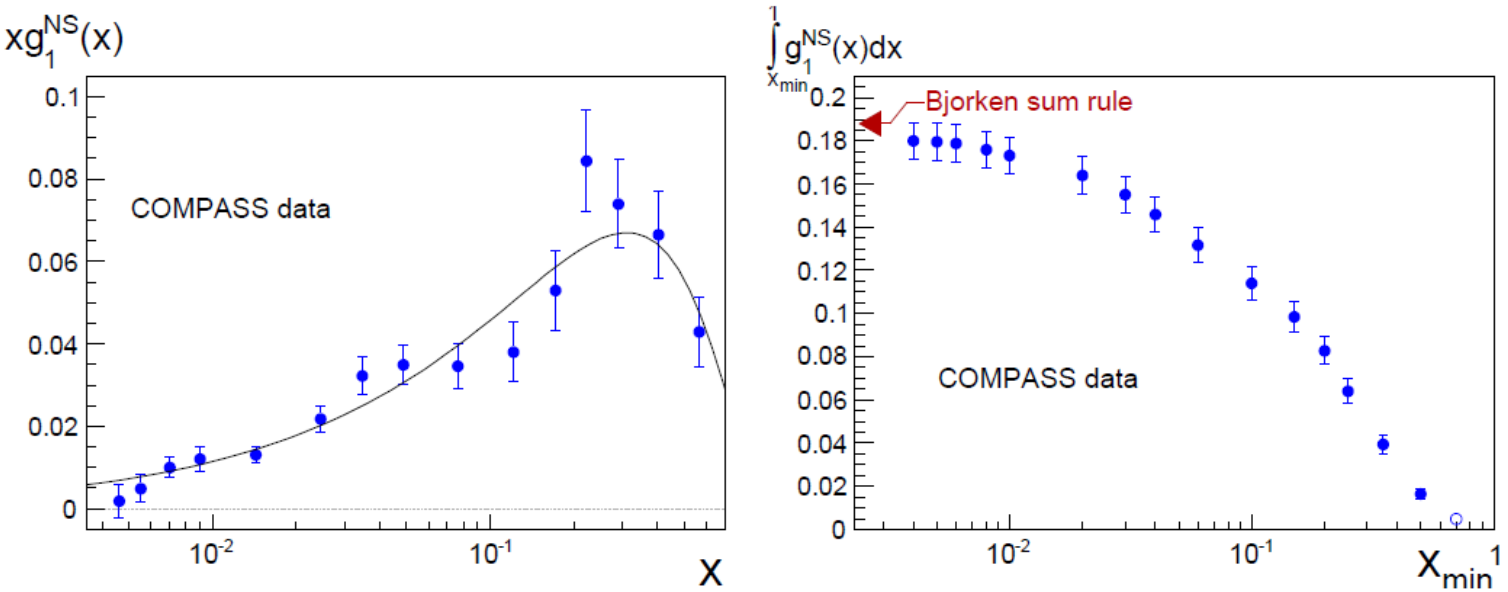
3. Infer the polarized gluon distribution

g_1 structure functions and the Bjorken sum rule

- BjSR:: $\Gamma_1^{NS} = \int_0^1 \left[g_1^p(x) - g_1^n(x) \right] dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_1^{NS}(Q^2);$

electromagnetic — weak

Only assumption: isospin invariance: fundamental test of QCD



g_A/g_V from n weak decay (PDG) : 1.269 0.003

g_A/g_V from $g_1(x)$ first moments : 1.280 0.070(stat.)

Proton and deuteron $g_1(x)$ world data

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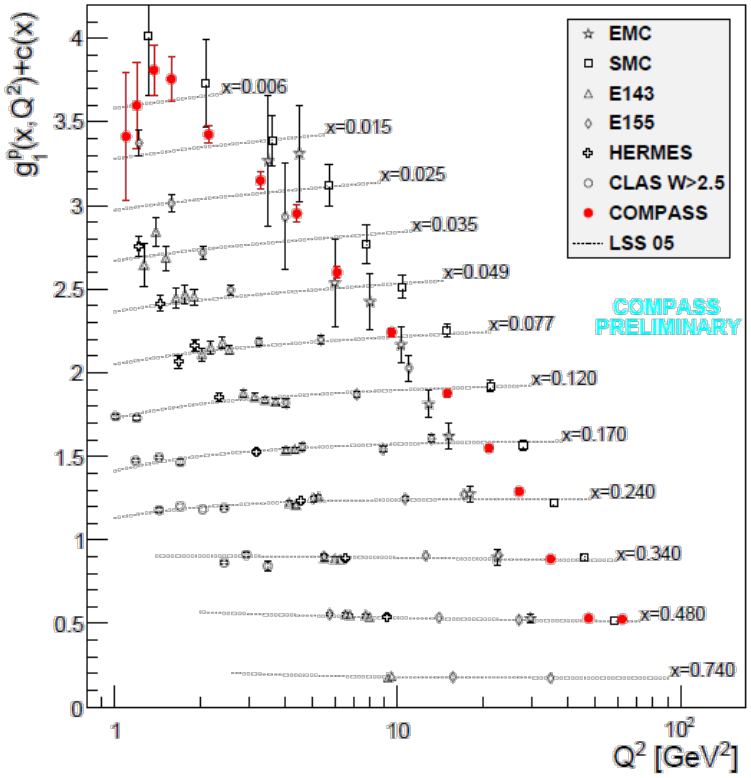
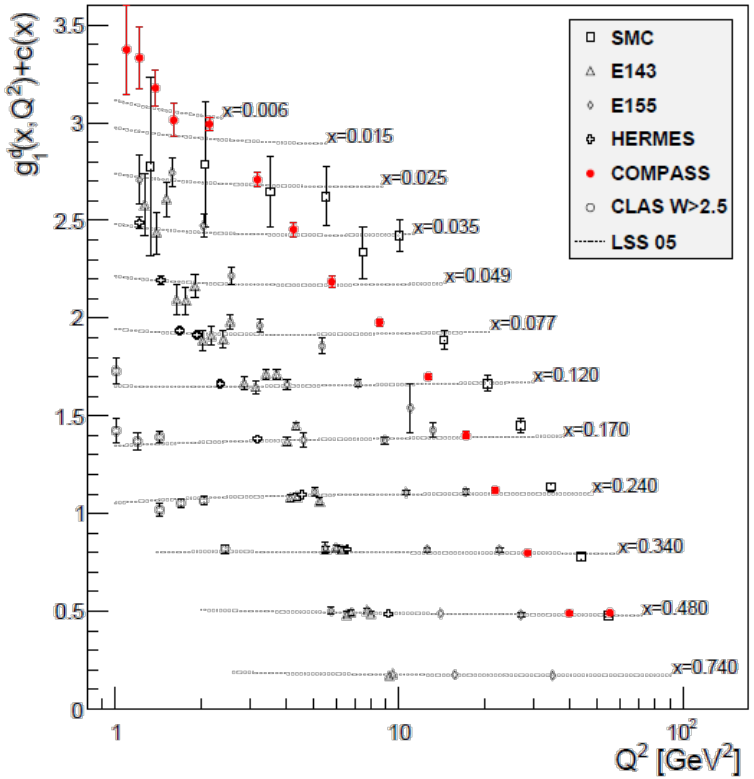
proton



deuteron



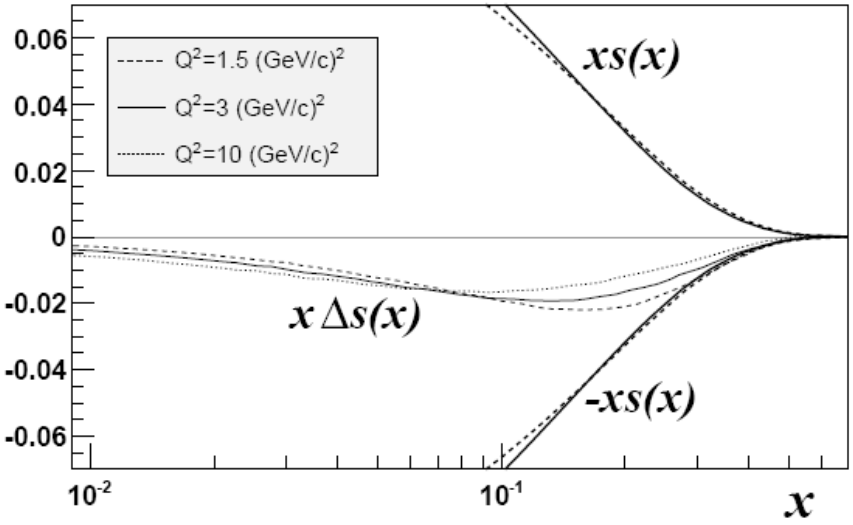
► data used to perform a NLO QCD fit -> PDFs

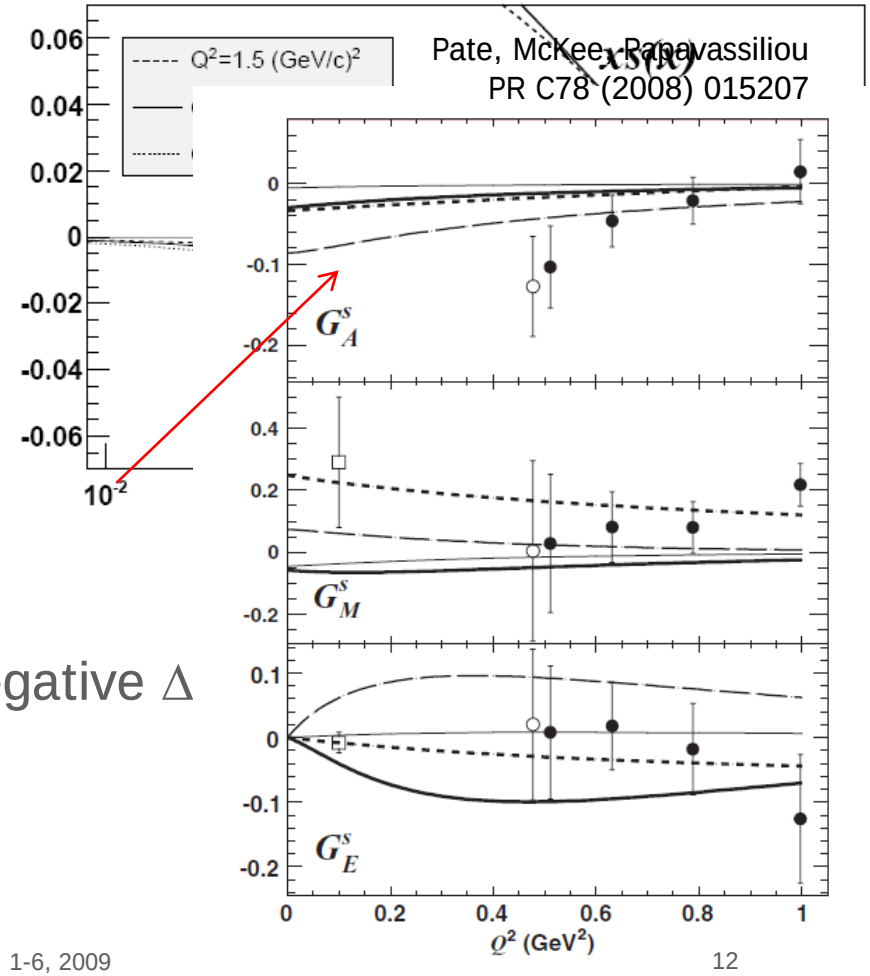
What do we know about the strange quark distribution $\Delta s(x)$?

Δs is negative ...

- QCD fit to world DIS data (COMPASS, and many other groups...)

Phys.Lett. B660(2008)458. $\int(\Delta s(x)+\Delta\bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.01$



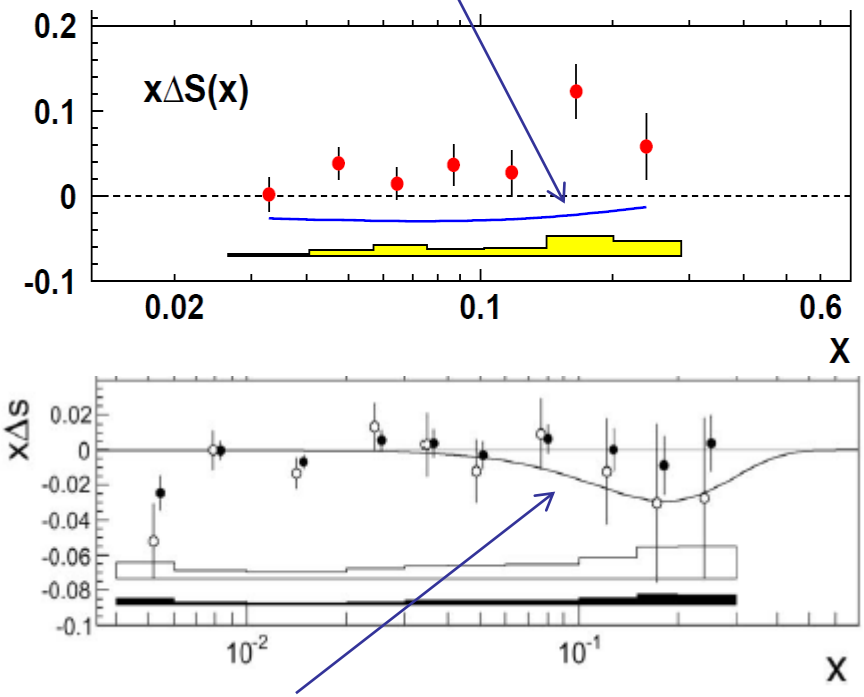


► PV + ν data also favor a negative Δ

Δs(x) is close to zero, or positive!

- DIS and SIDIS data from the deuteron (HERMES, COMPASS)

Leader, Sidorov, Stamenov, Phys. Rev. D73, 2006.



De Florian, Navarro, Sassot, Phys. Rev. D71, 2005.

Hermes Coll., Phys. Lett. B666 (2008) 446

$$(\Delta s + \Delta\bar{s})_t = +0.037 \pm 0.019 \pm 0.027$$

Also in Phys. Rev. D71, 2005

Compass Coll., Phys. Lett. B680 (2009) 617

$$(\Delta s + \Delta\bar{s})_t = -0.001 \pm 0.001 \pm 0.002$$

-> SIDIS data and QCD results (DIS) do not agree!

COMPASS: SIDIS asymmetries - deuteron

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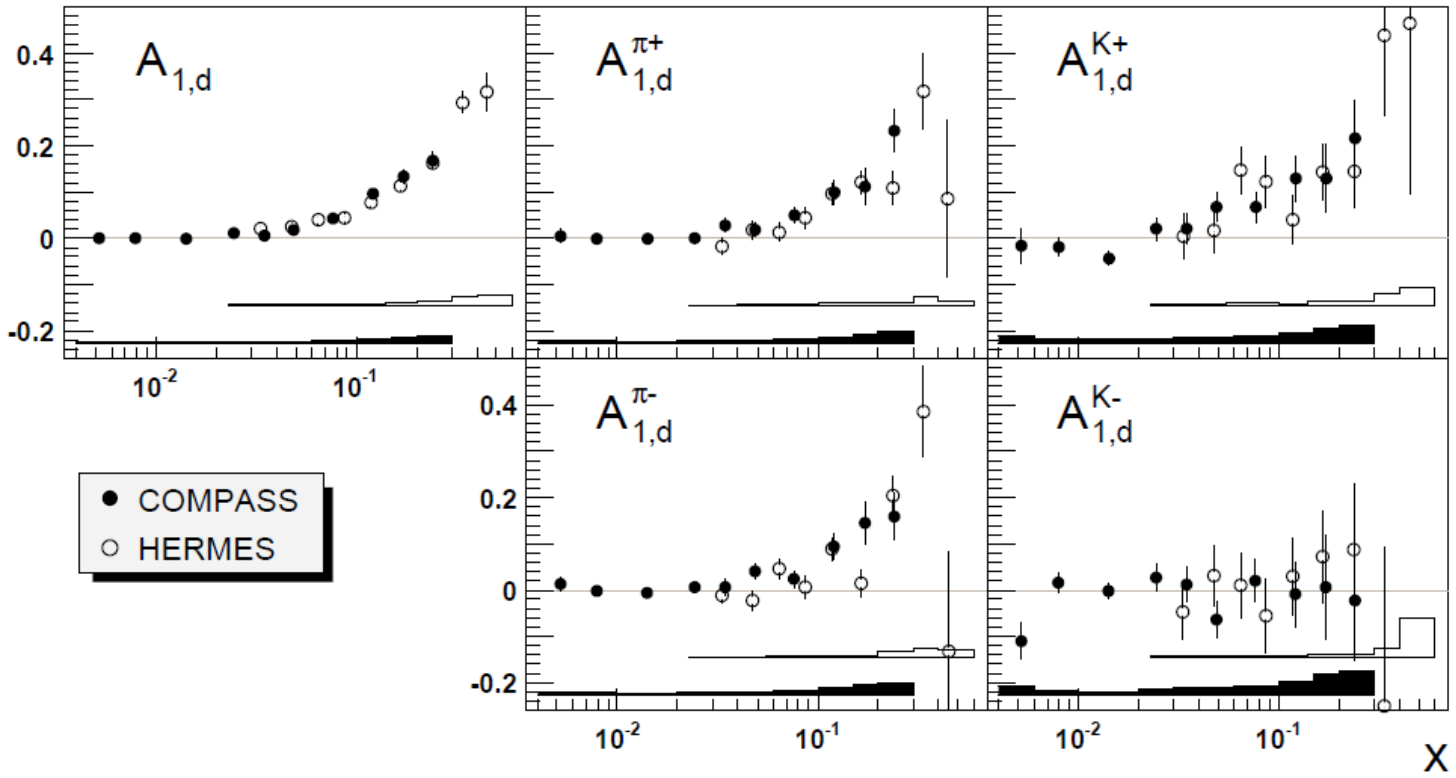
Deuteron data: 2002 – 2004, 2006



- Pions and kaons are identified
- Good agreement with HERMES

COMPASS: SIDIS asymmetries - proton

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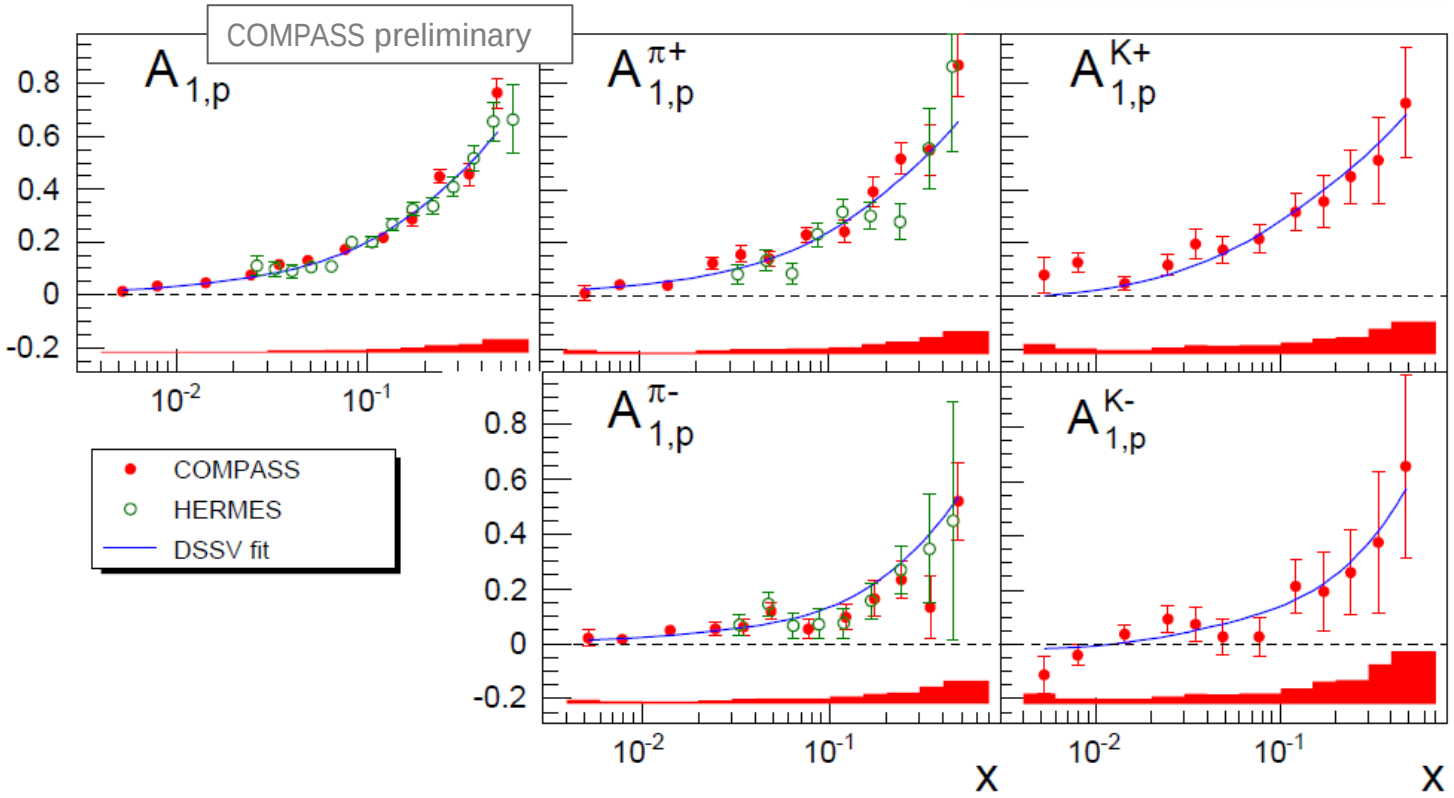
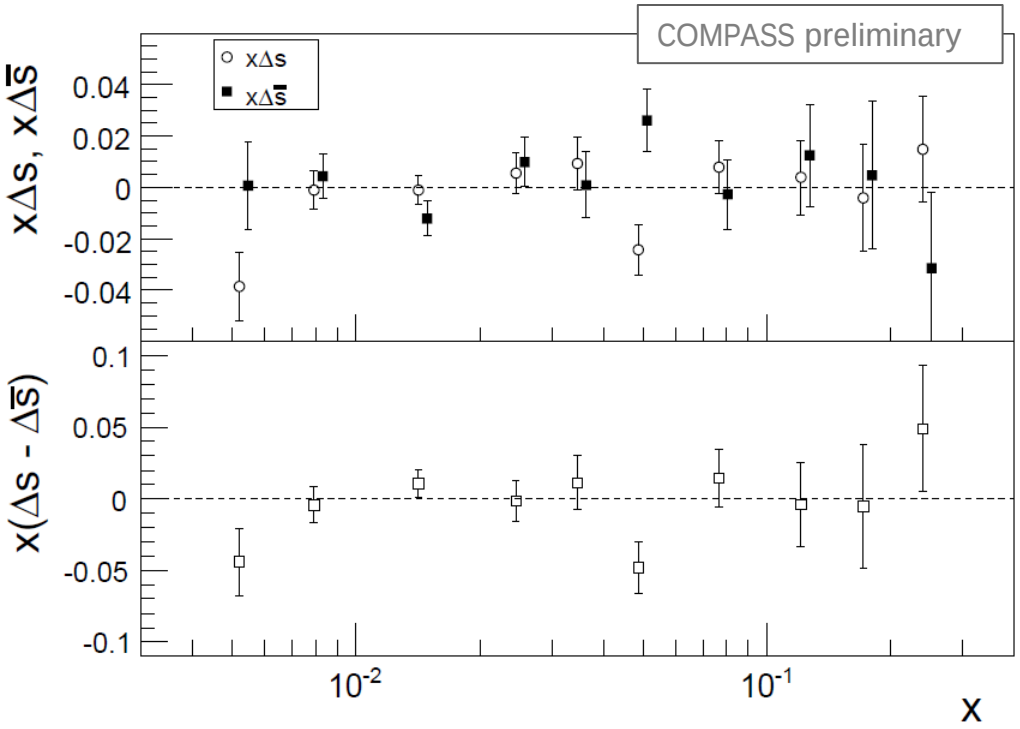
Proton data: 2007 (hep-ex/1007.4061)



Next step:

- Leading Order (LO) fit of the 10 asymmetries (2x5)
- Determine 6 flavor separated PDFs : $\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}, \Delta s, \Delta \bar{s}$

Check the assumption $\Delta s = \Delta\bar{s}$ (a 6 flavors fit)

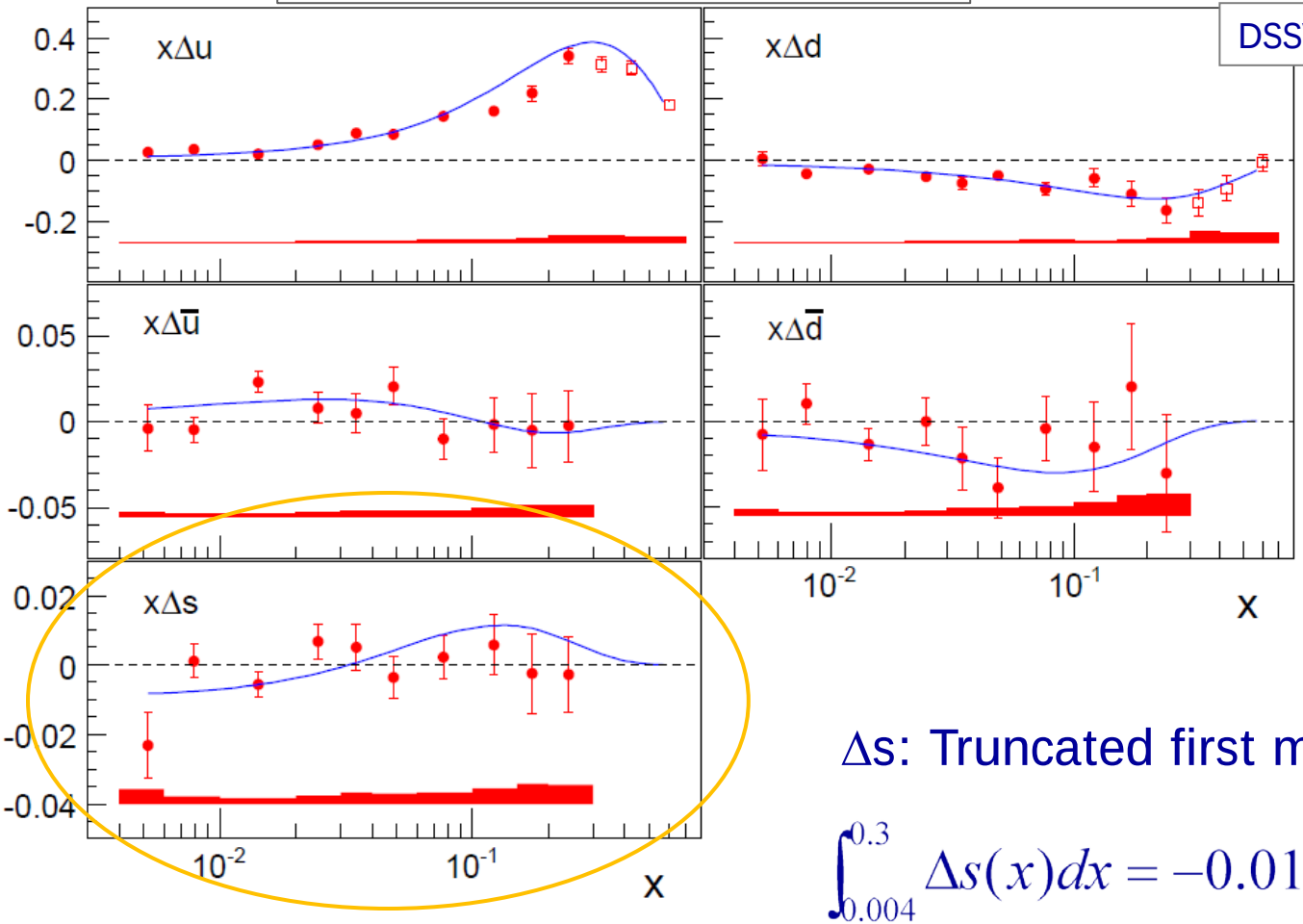


Both strange and anti-strange distributions are compatible with 0

Compass results for Δu(x), Δd(x), Δs(x)

COMPASS preliminary, hep-ex/1007.4061

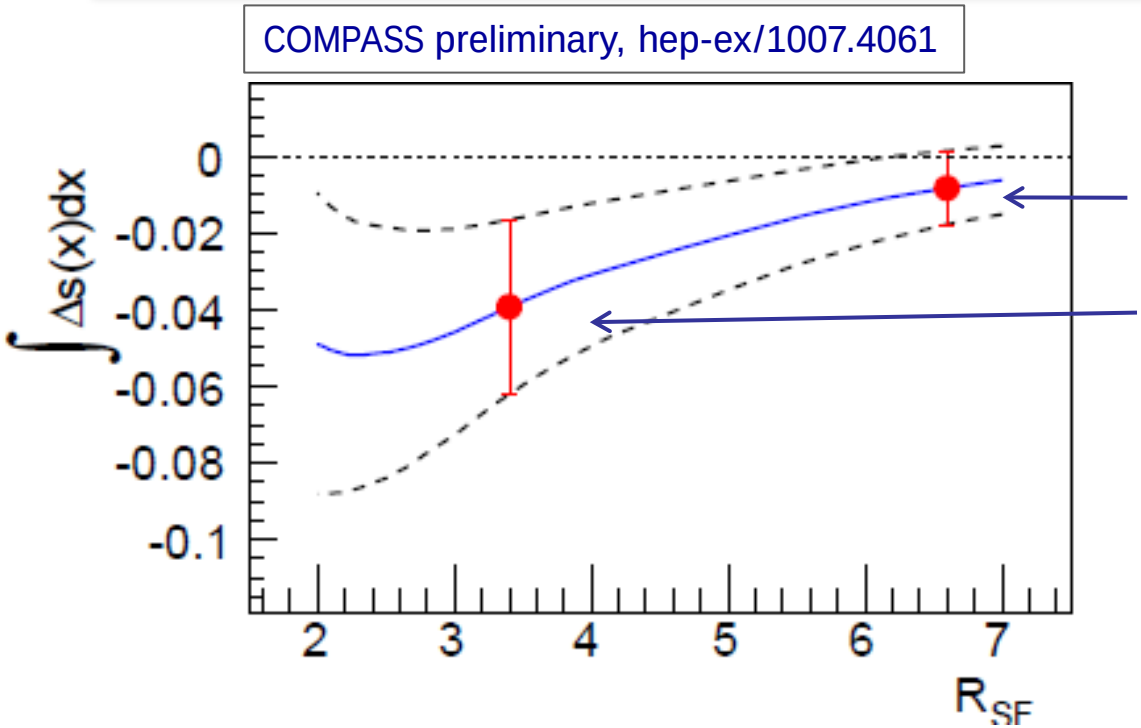
DSSV, Phys. Rev. D80, 2009



Δs: Truncated first moment:

$$\int_{0.004}^{0.3} \Delta s(x)dx = -0.01 \pm 0.01 \pm 0.01$$

Δs: dependence on the Fragmentation Functions



DSS: De Florian, Sassot, Stratman, Phys. Rev. D75, 2007

EMC: EMC collaboration, Arneodo et al, Nucl. Phys. B321, 1989

$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$$

First moments: FF from DSS = -0.01 0.01 0.01

FF from EMC = -0.04 0.03 0.01

→ The value of the Δs first moment depends on the FF used

ΔS and Global analysis of DIS, SIDIS, pp data

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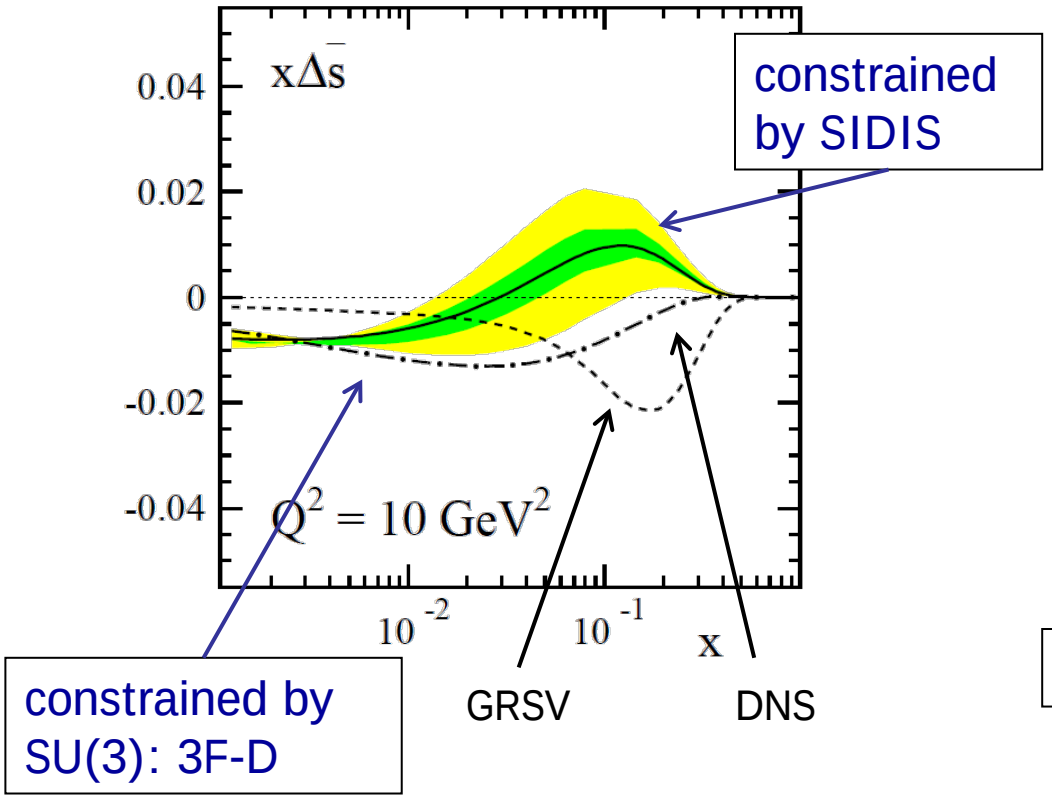
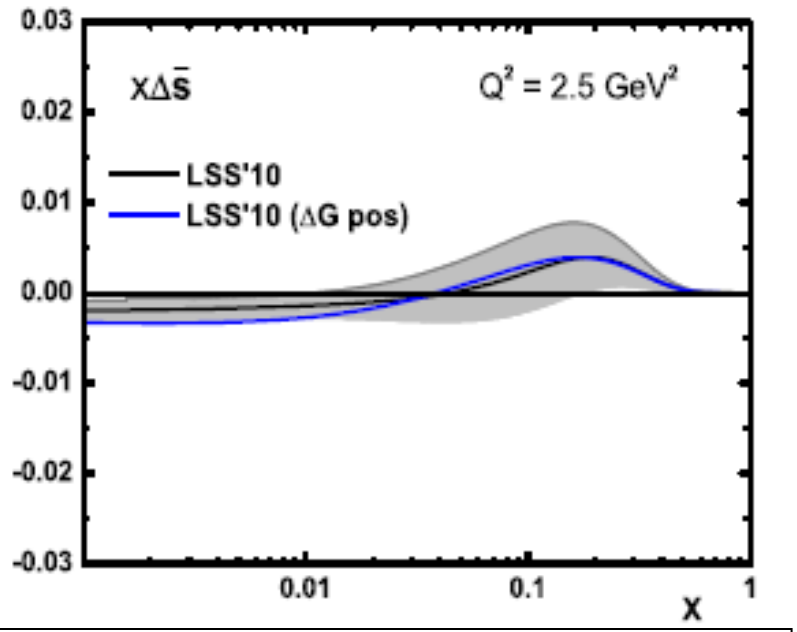
From De Florian, Sassot, Stratman, Vogelsang, PRL 101, 2008





DIS+SIDIS combined fit, 2010

Sidorov, Spin-Praha 2010 and Stamenov, priv. comm.

- The shape of Δs(x) at low x remains unknown

COMPASS

Is the polarized sea flavor symmetric?

Flavor asymmetry of the light quark sea

- Gottfried sum rule is violated

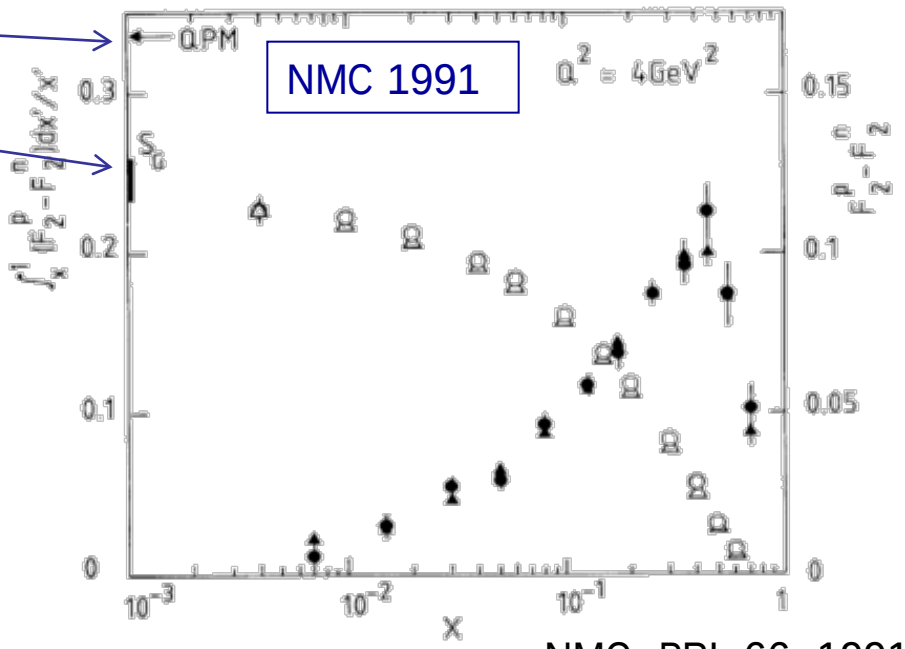
$$I_G = \int \frac{dx}{x} F_2^p(x,Q^2) - F_2^n(x,Q^2)$$

  - Quark Model prediction = 1/3
  - Data = 0.22 0.01 0.02 !

Table 1. Values of the integral $\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ determined from the DIS, semi-inclusive DIS, and Drell-Yan experiments.

Experiment	$\langle Q^2 \rangle$ (GeV$^2/c^2$)	$\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$
NMC/DIS	4.0	0.147 ± 0.039
HERMES/SIDIS	2.3	0.16 ± 0.03
FNAL E866/DY	54.0	0.118 ± 0.012

From J.C.Peng, Eur. Phys. J. A18, 2003

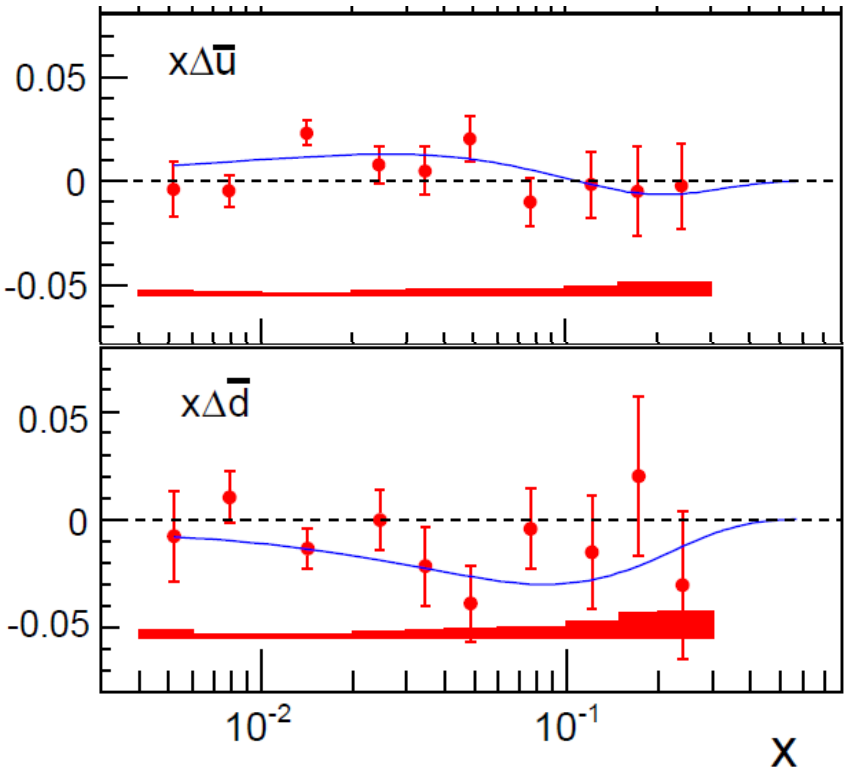


NMC: PRL 66, 1991

- The unpolarized sea is asymmetric ($\bar{d} > \bar{u}$)
- What about the polarized one?

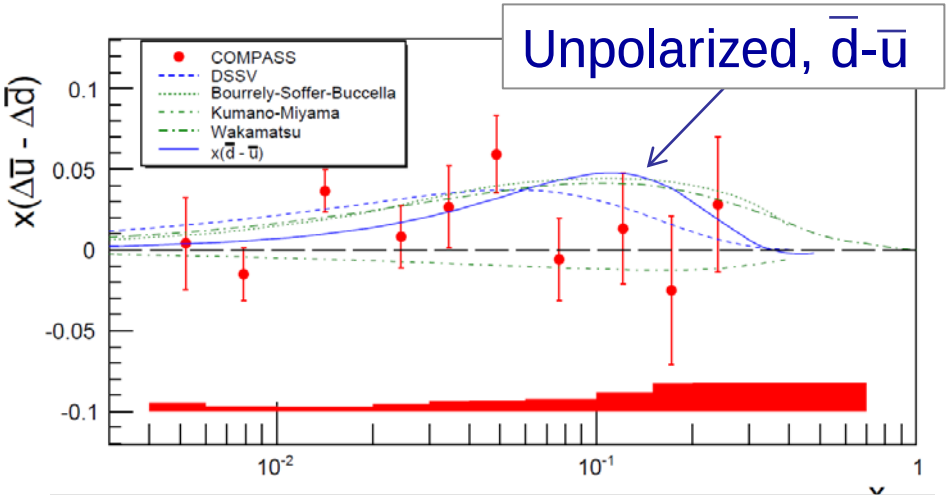
Flavor asymmetry of the polarized sea

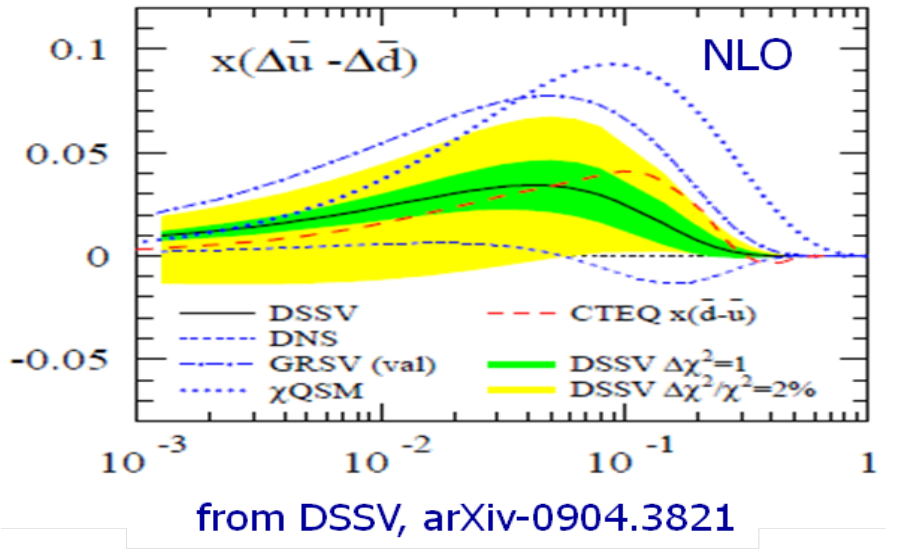
COMPASS preliminary, hep-ex/1007.4061



$$\Delta\bar{u} - \Delta\bar{d} = 0.06 \pm 0.04 \pm 0.02$$

Unpolarized, $\bar{d}$-$\bar{u}$



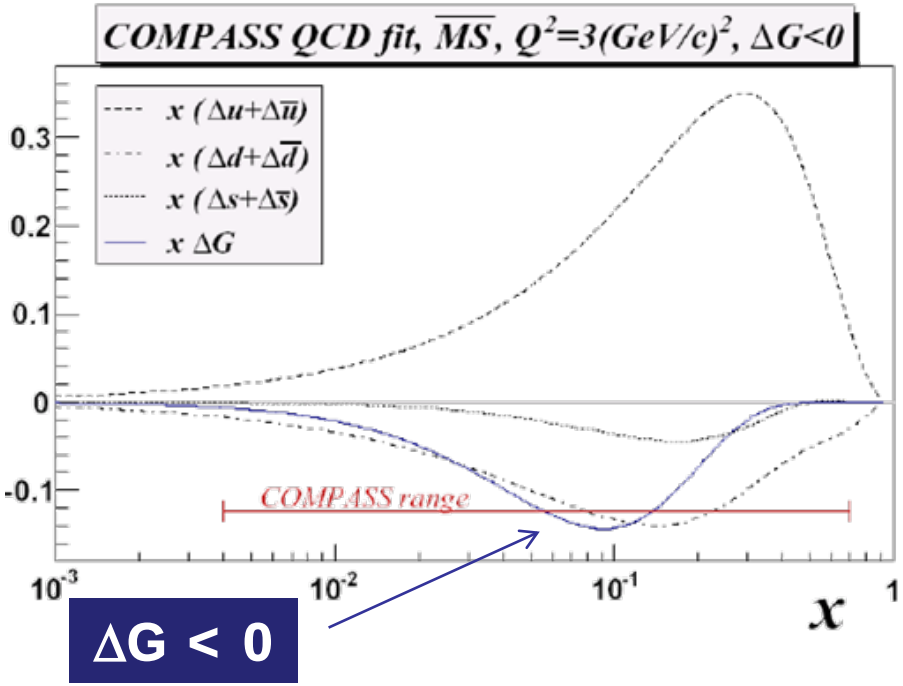


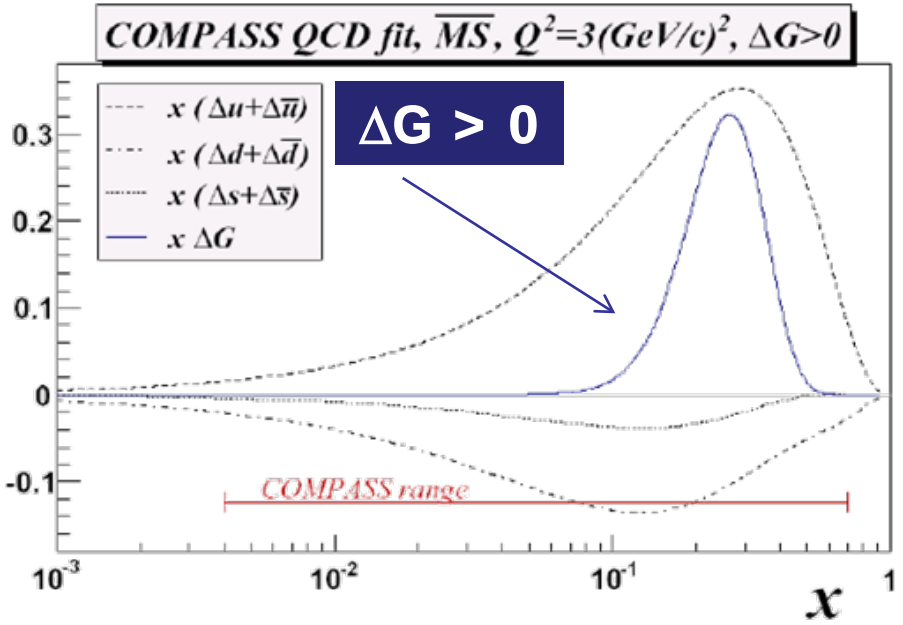
from DSSV, arXiv-0904.3821

Gluon contribution to the nucleon spin

QCD fit results – Polarized parton distributions

Compass deuteron + world data (Compass proton data not included)



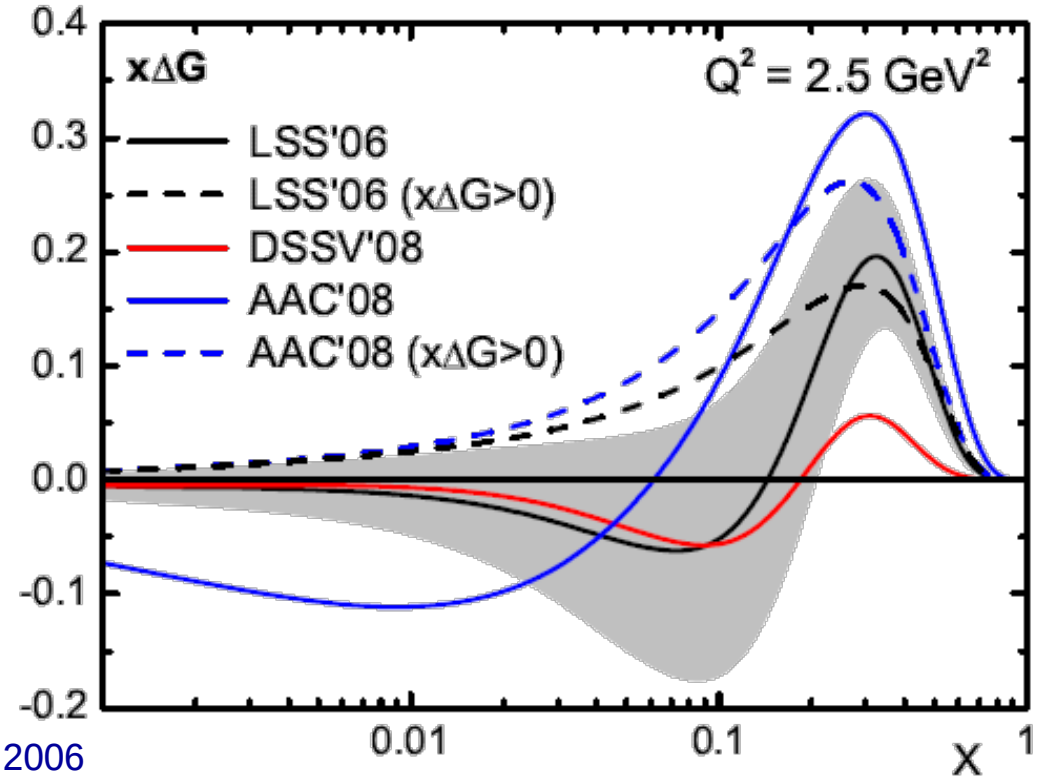


Compass, PL B647 (2007) 8.

- Both negative and positive solutions for ΔG(x)
- Range of (x,Q2) is DIS data is limited – fit results are imprecise

ΔG is calculated by many other groups...

From Leader, Spin-2008



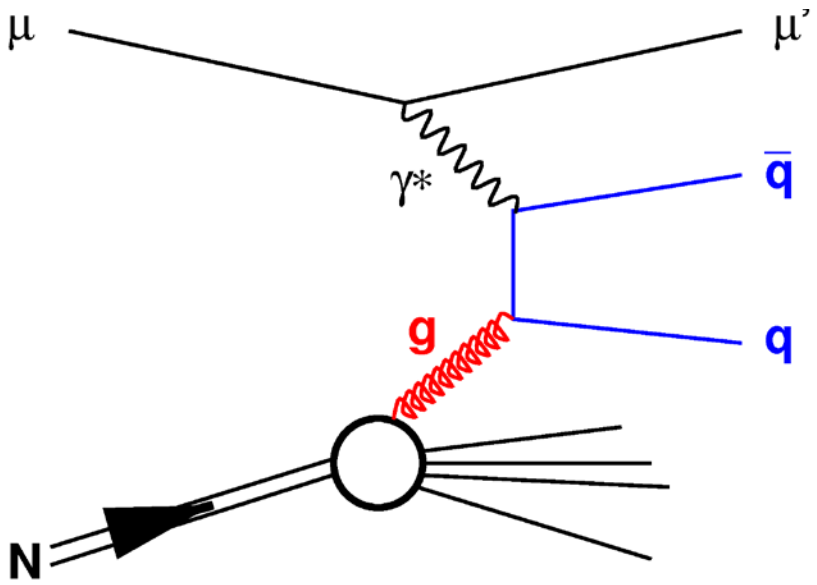
LSS-06 : Phys. Rev. D73, 2006
AAC'06 : Phys. Rev. D74, 2006
DSSV-08: Phys. Rev. Lett. 101, 2008

ΔG(x) is positive, negative, or sign-changing!

- Shape of ΔG(x)?
- Needed are dedicated measurements of ΔG(x)

Determination of ΔG/G – two methods

- Via High-pt hadron pairs (q=u, d, s)
  - Good S/B ratio
  - Physics background
    - Rely on MC estimates
  - 2 cases: $Q^2>1$ (GeV/c)^2 -LEPTO MC
    $Q^2<1$ (GeV/c)^2 -PYTHIA MC



Photon-Gluon Fusion

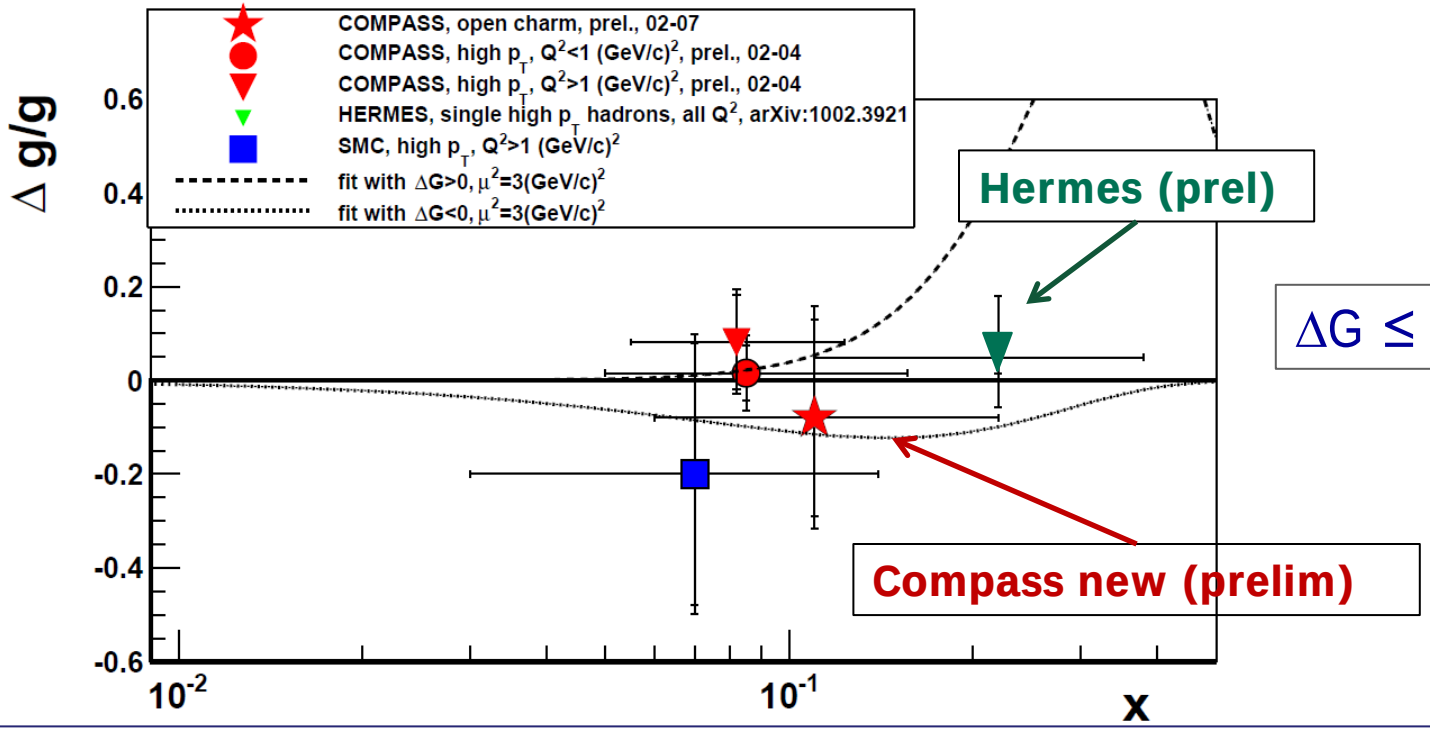
- Via Open Charm production (q=c)
  - Detect D → K^-p^+ and D^*→D π^+
  - Clean channels (no u, d, s quarks)
  - High combinatorial background
  - Limited S/B ratio

NEW: + 3 channels:

D^0-> Kppp, Kpp^0, [subK]p

Deuteron and Proton data

Gluon polarization measurements - summary



$\Delta G \leq |0.3|$

Open charm: $\Delta G/G(x) = -0.08 \quad 0.21 \ (\quad 0.11)$ $\quad x=0.11, \mu^2=13\ GeV^2$

Measurements are compatible with 0 – large values of ΔG are excluded

Similar conclusions from RHIC results (e.g. Adare et al, hep-ex/0810.0694)

But: Sign is yet ambiguous, the shape is still unknown

Not yet possible to quantify the ΔG contribution to $\Delta\Sigma$

Transverse spin (and momentum)

The eight leading-twist PDFs (TMDs)

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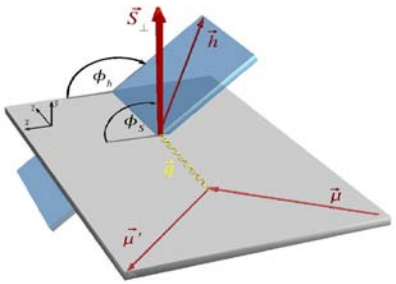
Symbol	$k_\perp$-dep	Azimuth	Beam	Tgt	X-odd	T-odd	PDF name
f_1		—	U	U			Mom. density
$h_1^\perp$	yes	cos(2ϕ)	U	U	X-odd	T-odd	Boer-Mulders
$h_{1L}^\perp$	yes	sin(2ϕ)	U	L	X-odd		Worm-gear 1
g_1		—	L	L			Helicity
h_1		$\sin(\phi+\phi_s)$	U	T	X-odd		Transversity
$f_{1T}^\perp$	yes	$\sin(\phi-\phi_s)$	U	T		T-odd	Sivers
$h_{1T}^\perp$	yes	$\sin(3\phi-\phi_s)$	U	T	X-odd		Pretzelosity
$g_{1T}^\perp$	yes	$\cos(\phi-\phi_s)$	L	T			Worm-gear 2

NB: Amsterdam notation

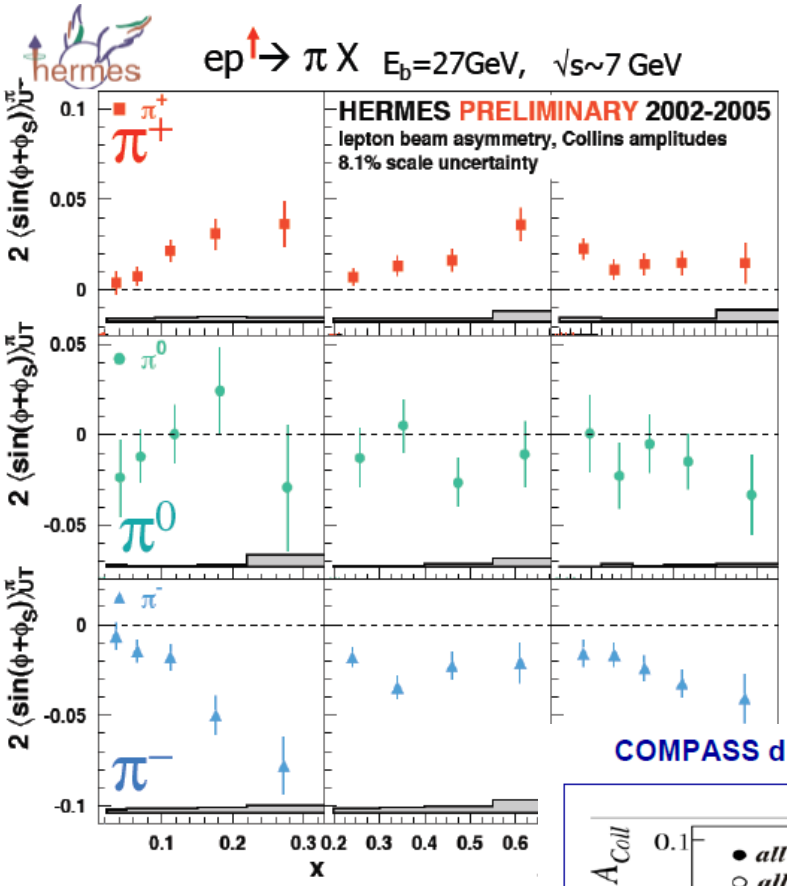
$f_1(x)$, $g_1(x)$ and $h_1(x)$ are integrated over $k_\perp$

There are also Twist-3, Twist-4 contributions....



COMPASS

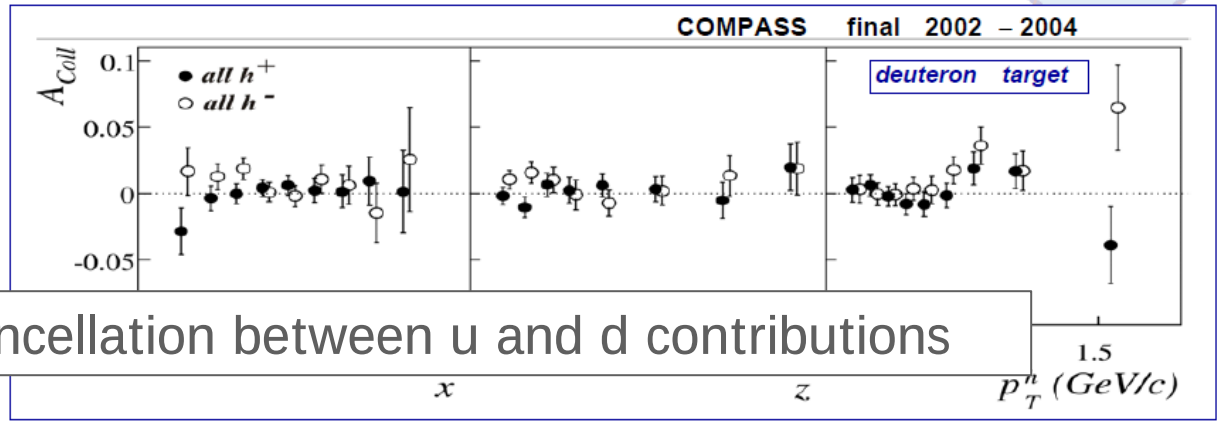
Transversity: COMPASS (d) vs HERMES (p)



Clear signal from HERMES

Not confirmed by COMPASS

COMPASS d results: *PRL 94 (2005) 202002, NPB 765 (2007) 31, PLB 673 (2009) 127*

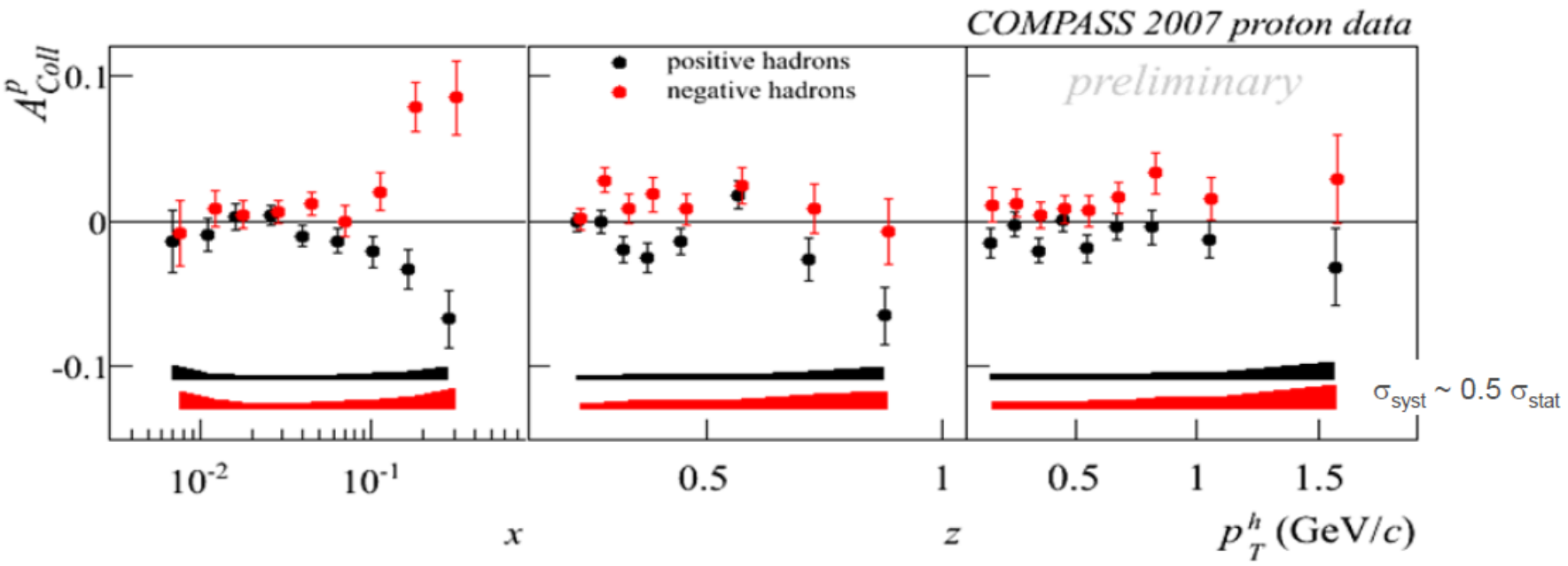


Interpreted as a cancellation between u and d contributions

Transverse asymmetries: Compass proton data

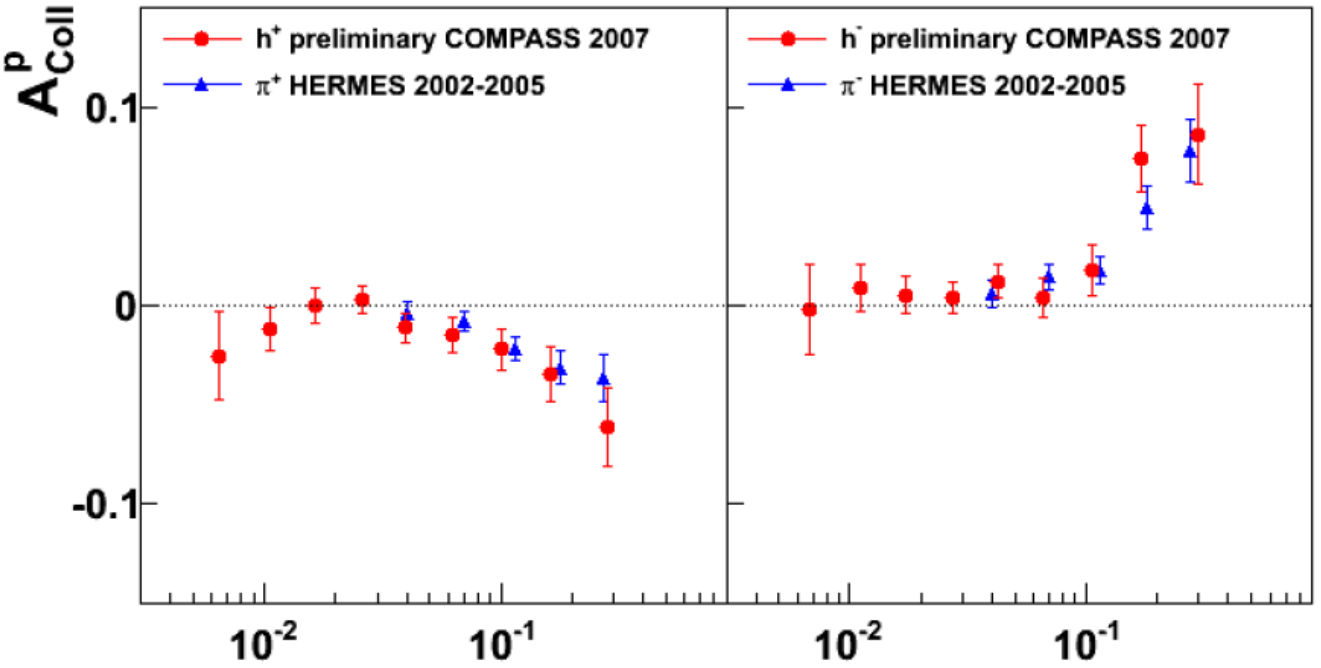
$$A_{Coll} \propto \frac{\sum_q e_q^2 h_1^q(x) H_1^{\perp q}(z, p_T^h)}{\sum_q e_q^2 q(x) D_q^h(z, p_T^h)}$$

Collins FF -> measured at BELLE



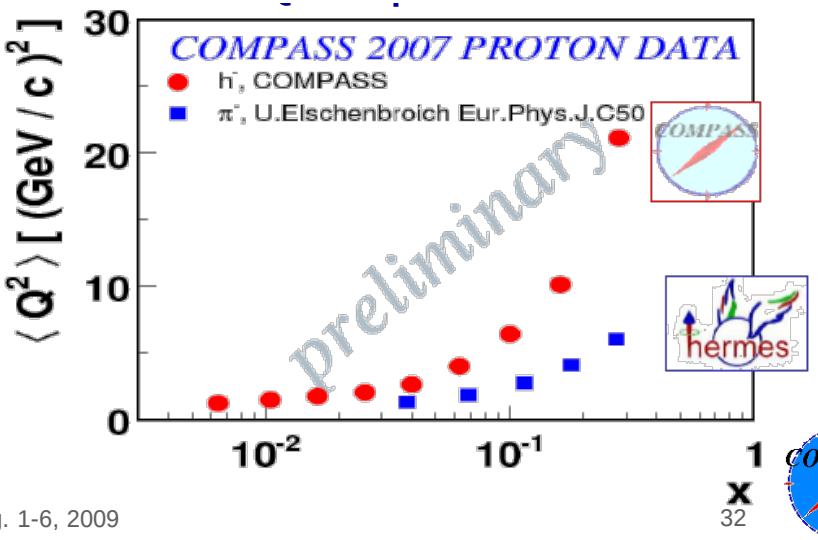
Strong dependence on x for both positive and negative hadrons

Transversity $h_1(x)$: Compass vs Hermes

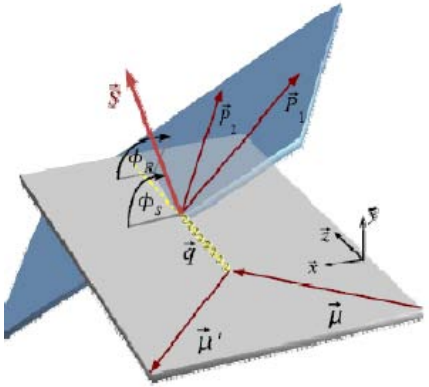


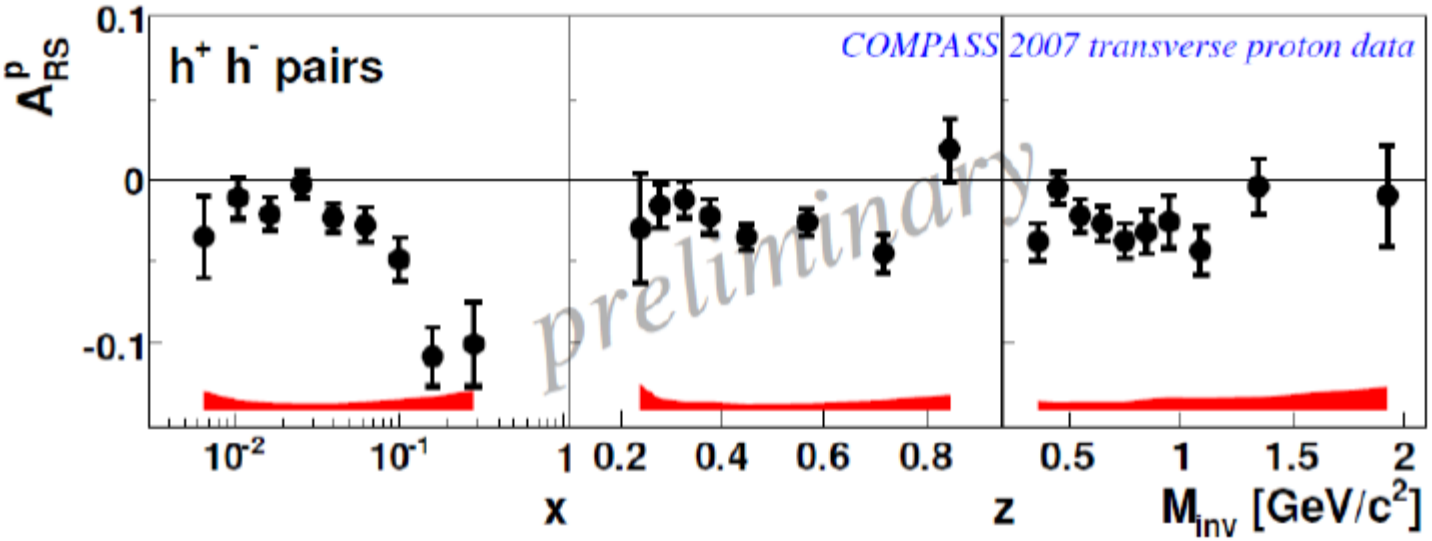
Compass and Hermes: nice agreement

Indicates no/weak Q^2-dependence



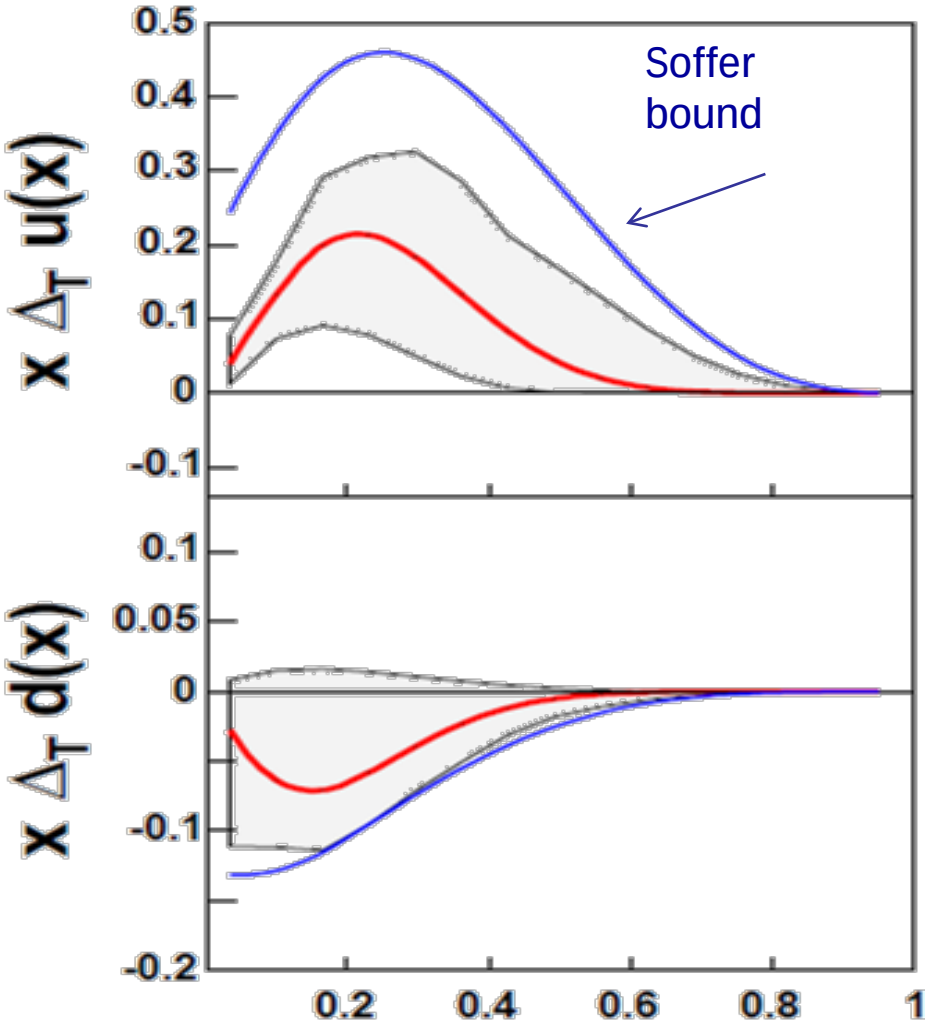
Transverse asymmetries: two hadron interference





Transversity: global fit (without COMPASS proton)

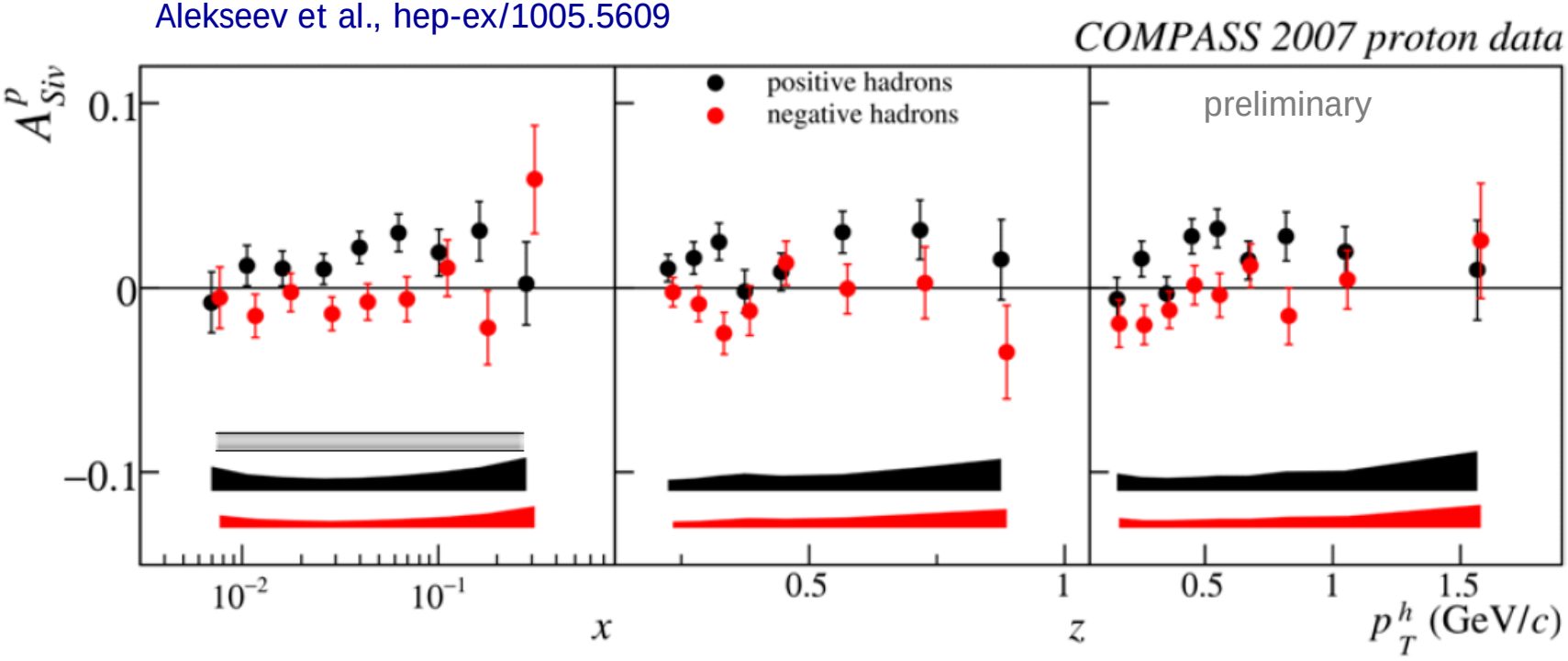
- Fit includes:
  - COMPASS (deuteron)
  - HERMES (proton)
  - BELLE (Collins FF)
    ($e^+e^- \rightarrow \pi^+\pi^- X$)



Anselmino et al., Phys. Rev. D75, 2007

Sivers asymmetry

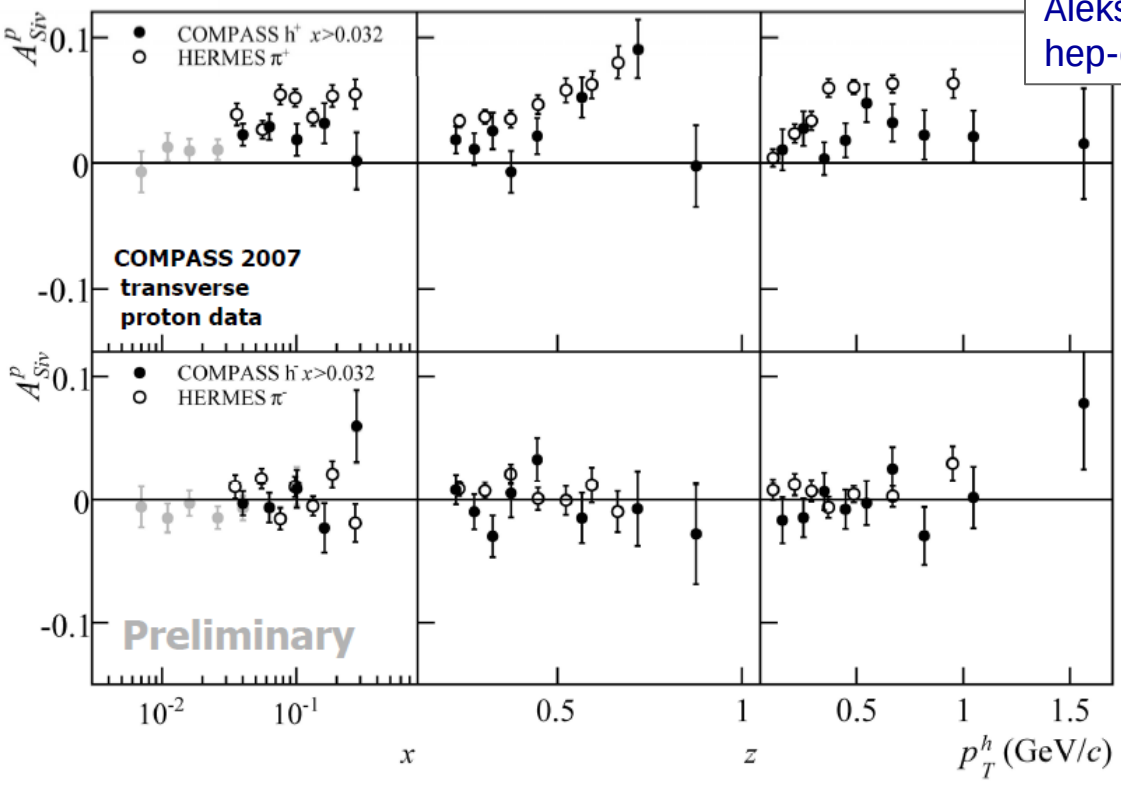
Alekseev et al., hep-ex/1005.5609



Positive hadrons: small positive signal

Negative hadrons: the asymmetry is compatible with zero

Sivers: COMPASS vs HERMES



Alekseev et al., hep-ex/1005.5609

Overall agreement for h^-, small differences for h^+

Asymmetries seem to be small below x = 0.03

Non-zero asymmetries: indicate a non-zero orbital momentum!

Sivers: COMPASS data vs fit (Anselmino et al.)

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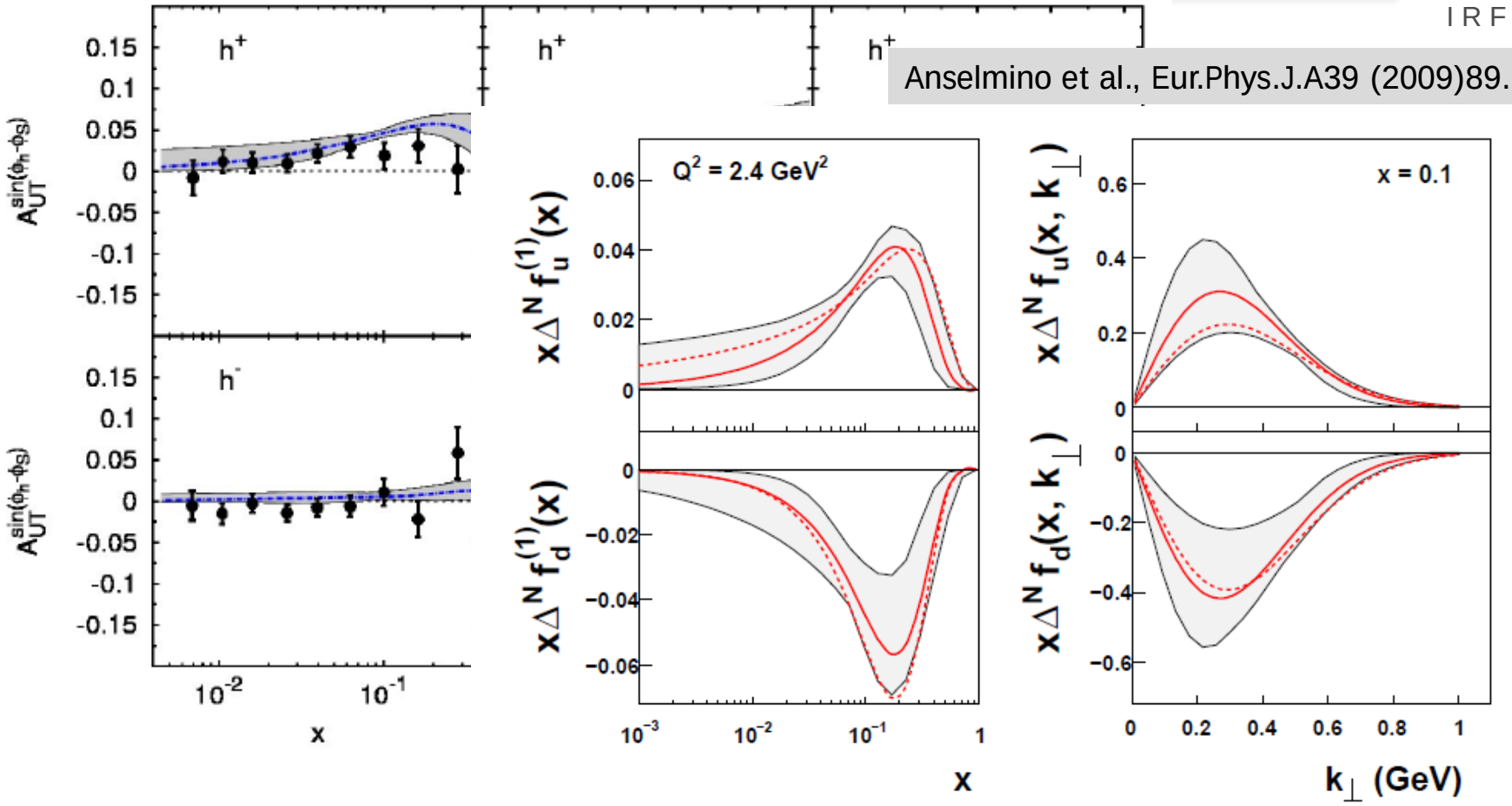
Anselmino et al., Eur.Phys.J.A39 (2009)89.



The fit is made without COMPASS proton data

Result is: opposite transverse momentum for u and d quarks

Additional results in Arnold et al., arXiv: 0805.2137 (2008).

Summary

IRFU

- Recent achievements by COMPASS
  - New proton data with both L and T polarized target
  - New results on $\Delta G/G$, $g_1(x)$, flavor-sep. PDFs, Collins, Sivers, TMDs

- The COMPASS near future
  - Data taking underway with a NH_3 target : 2010 (T); 2011(L)
  - COMPASS II proposal (GPDs, DY, ...): 2012 and beyond

- Open questions (a few, among many)
  - Understand the Δs problem. Shape of $\Delta s(x)$, FF, etc...?
  - ΔG looks small. But what about the sign + the shape of ΔG (x)?
  - Can we quantify the relation between the TMDs and L?