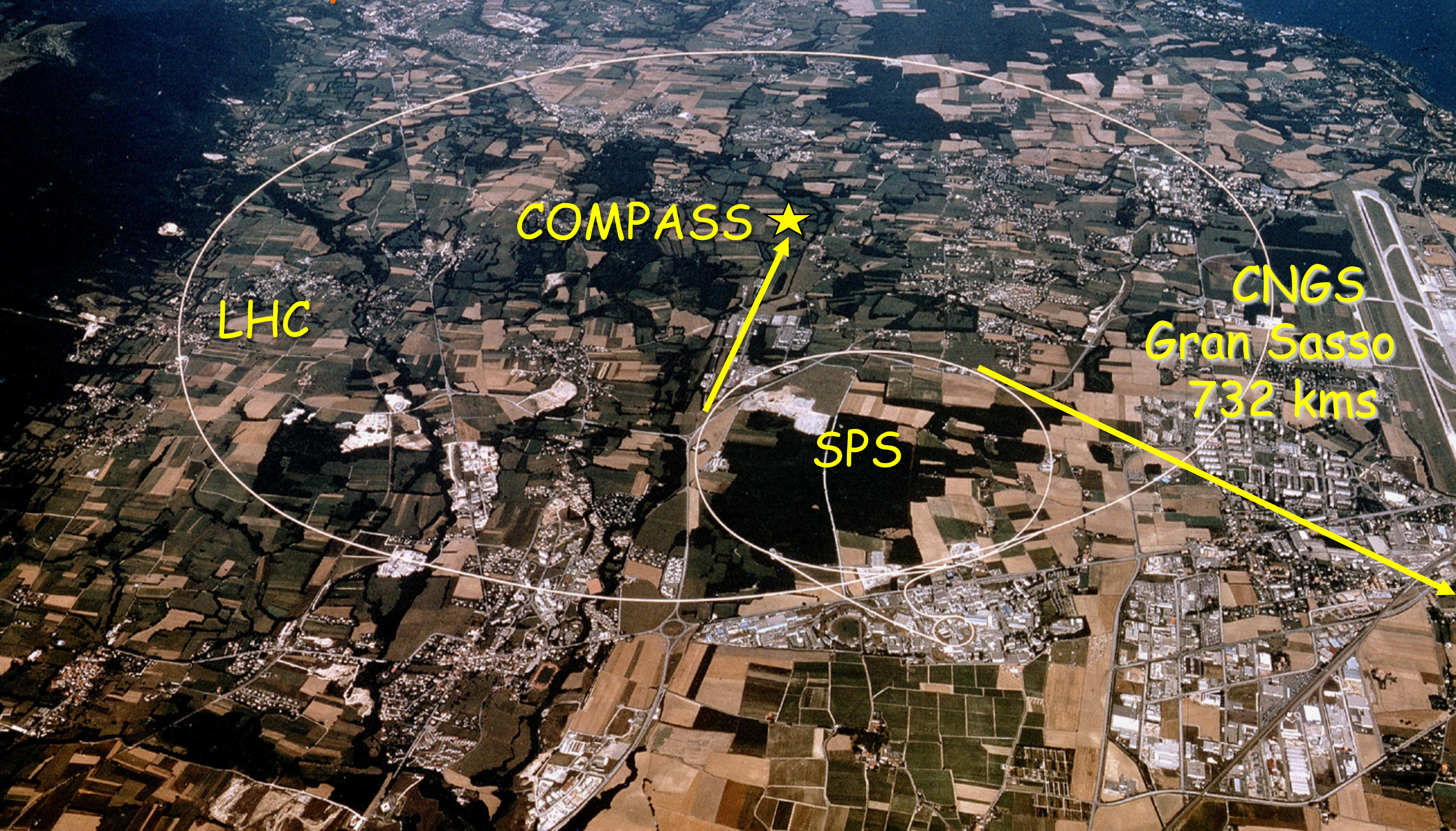
The nucleon Spin Structure from COMPASS @ CERN

Alain Magnon
CEA-IRFU/SPhN & COMPASS

SPS beam: protons up to 400 GeV/c, 4.8s/16.2s spills

- Secondary hadron beams ($p, \pi, K, \ldots$): 2.10^8 /spill, 150-270 GeV
- Tertiary muons: 2.10^8 /spill, 100-200 GeV, 80% polarisation

  -> Luminosity $\sim 5 \times 10^{32}\ cm^{-2}\ s^{-1}$

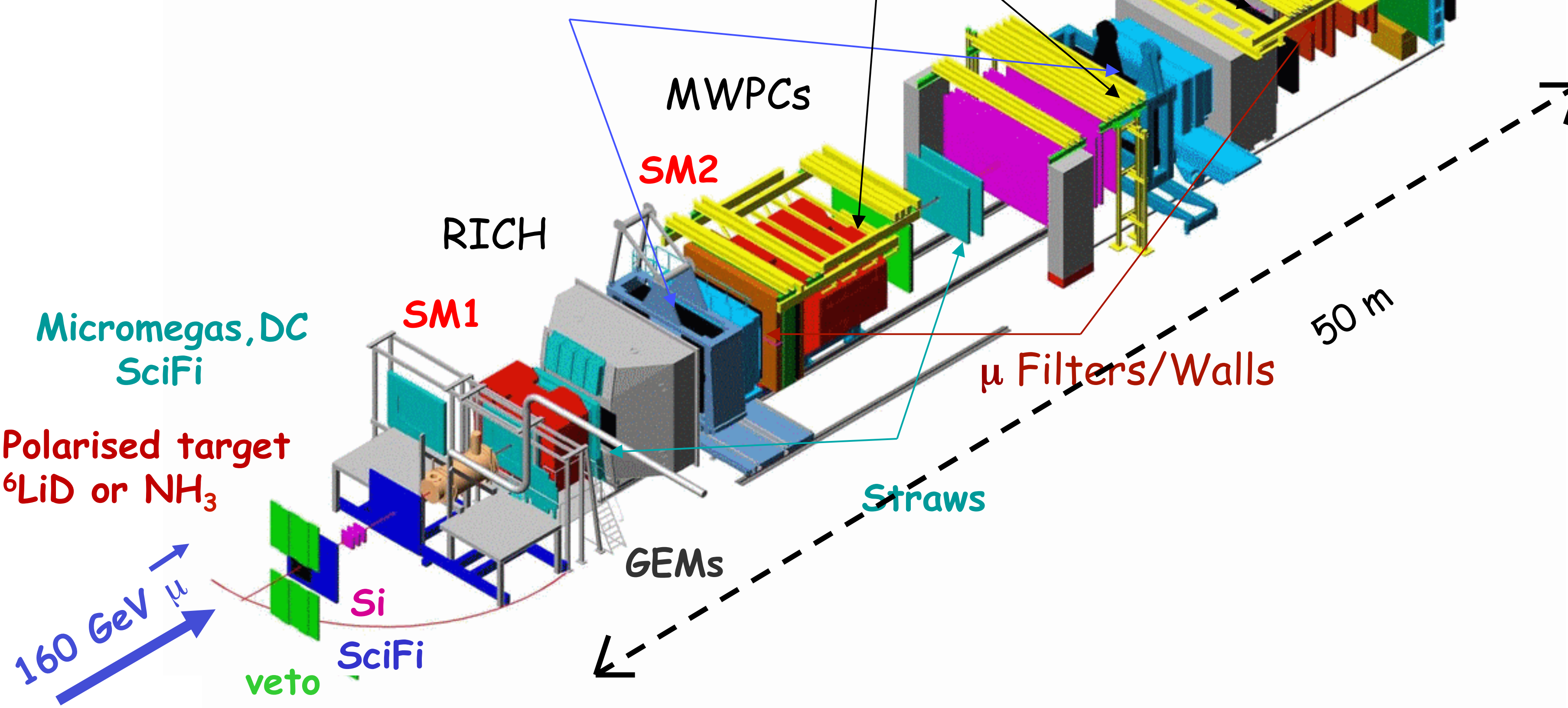


COMPASS at CERN

Highly polarized beam, 160 GeV muons

Large acceptance high flux spectrometer

Solid polarized target Longitudinal/Transverse Polarisations



high energy beam(s), large angular acceptance, broad kinematical range

Nucleon partonic structure

Nucleon polarisation (columns) / Quark polarisation (rows)

	U	L	T
U	f_1 number density q		$f_{1T}^{\perp}$ Sivers – T-odd
L		g_1 helicity Δq	g_{1T}
T	T-odd – $h_1^{\perp}$ Boer Mulders	$h_{1L}^{\perp}$	h_1 transversity; $h_{1T}^{\perp}$

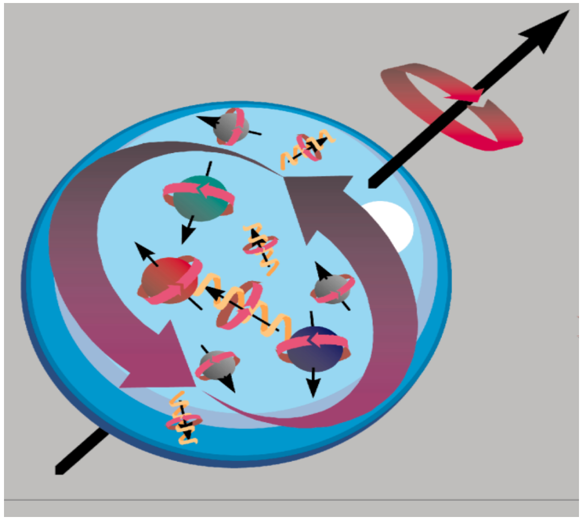
$\Delta_0^T q$ Sivers

$\Delta^T q$ Collins

Nucleon spin structure: Longitudinal

- Longitudinally polarised DIS
  - $A_1^{d/p}$, $g_1^{d/p}$, $\Delta\Sigma$ and the Bjorken Sum Rule
- Semi-Inclusive DIS asymmetries and flavour separation
  Δu, Δd, … etc
- Gluon polarisation in LO
  - Open Charm
  - High p_T hadron pairs
- Gluon polarisation in NLO (new)
  - Open Charm

Where does the spin come from ?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q+g}$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

The European Muon Collaboration, EMC @ CERN
J. Ashman *et al.*, Phys Lett B 206 (1988) 364

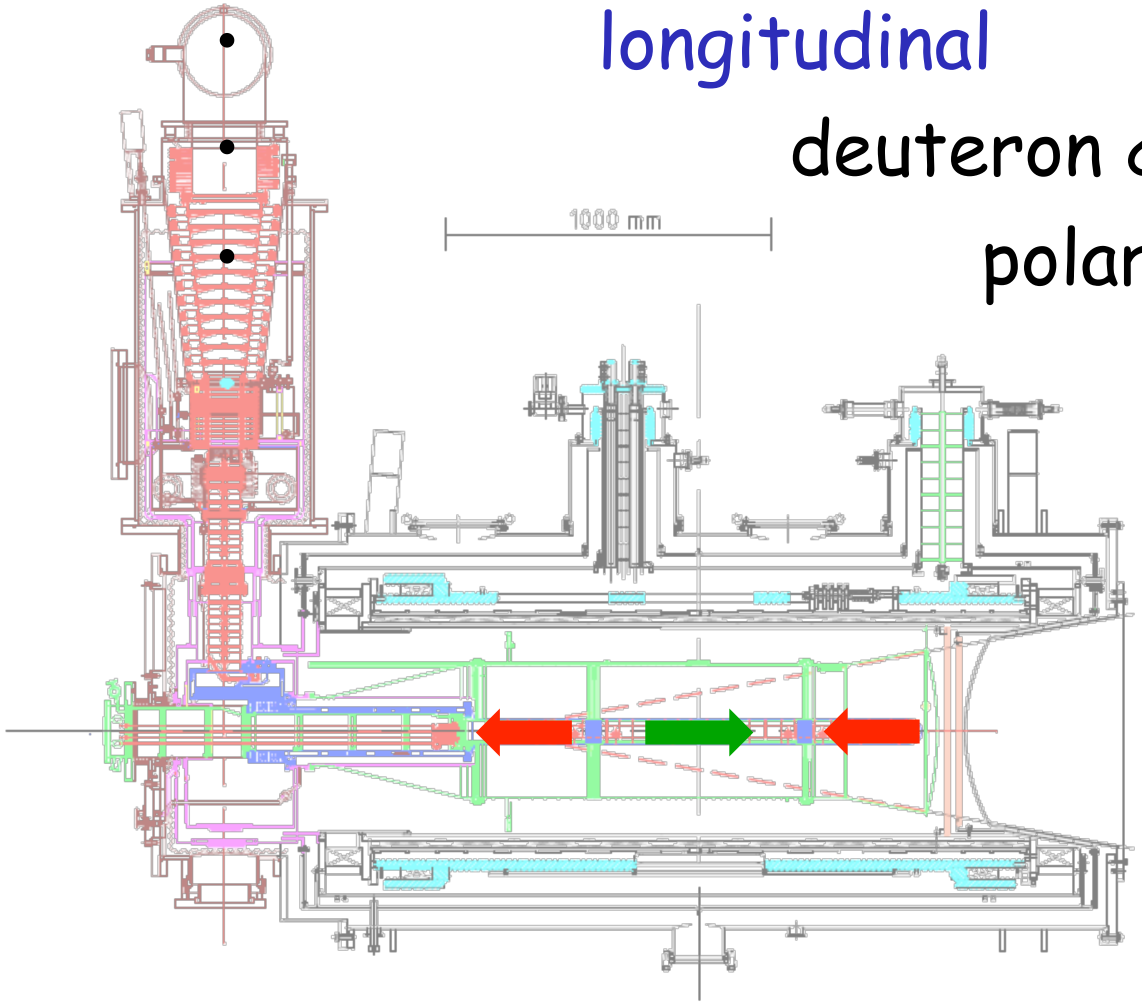
$$a_0 = \Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$$

"Spin Crisis"

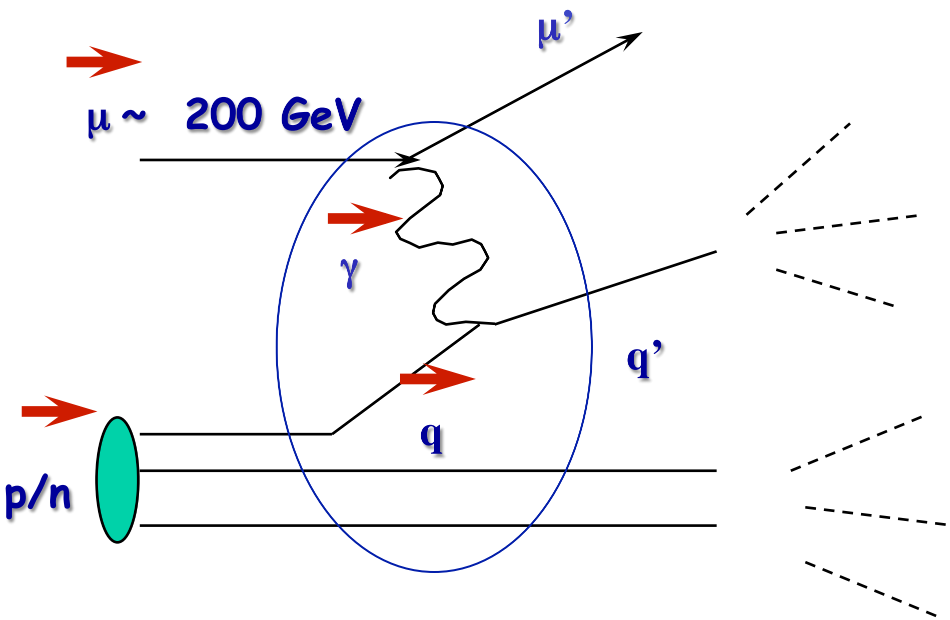
Expected, $\Delta\Sigma \sim 0.6$ if $\Delta s = 0$

COMPASS polarised target

- Results from
- longitudinal
- deuteron & proton
- polarisation



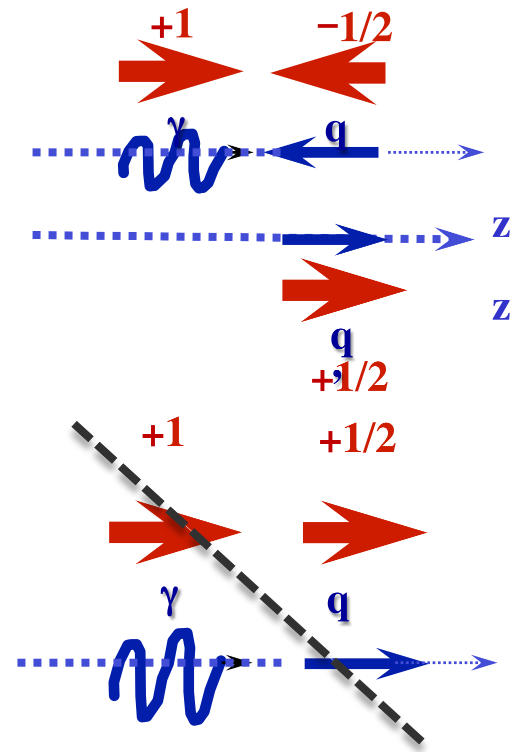
Polarized Deep Inelastic Scattering



$Q^2=(\mu-\mu')^2$

$x_{Bj}=Q^2/(2Pq)$

- Quadri-momentum transfer
- fraction of momentum carried by quark



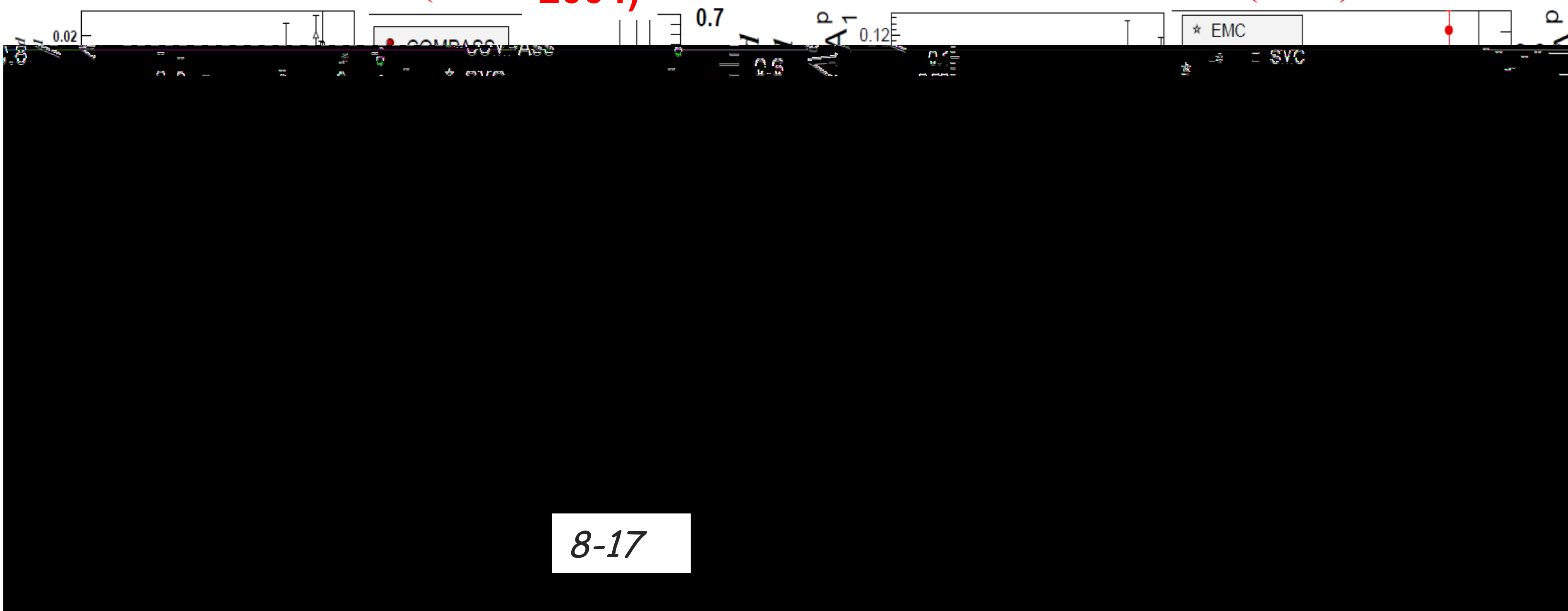
Forbidden

- Measurement of cross section spin asymmetry A_1 gives g_1
- g_1 allows one to calculate $\Delta\Sigma$, fraction of nucleon spin due to the spin of quarks

Inclusive asymmetries $A_1^{d/p}$ $Q^2 > 1\ (\mathrm{Gev}/c)^2$

A_1^d A_1^p

Deuteron data (2002-2004) **Proton data (2007)**

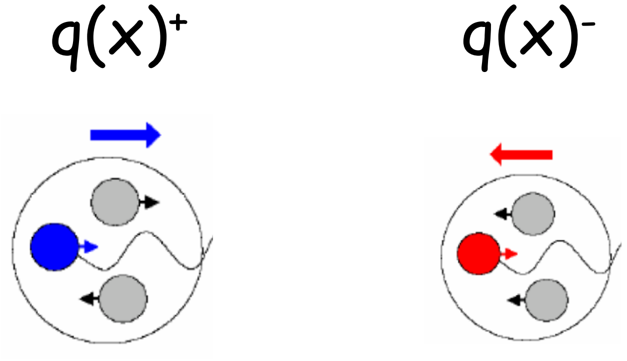


- Good agreement between all experimental points
- Significant improvement in precision at low x
- No negative trend for A_1^d

From $A_1^{d/p}$ to $g_1^{d/p}$

$\Delta q = q(x)^+ - q(x)^-$

$q(x) = q(x)^+ + q(x)^+$

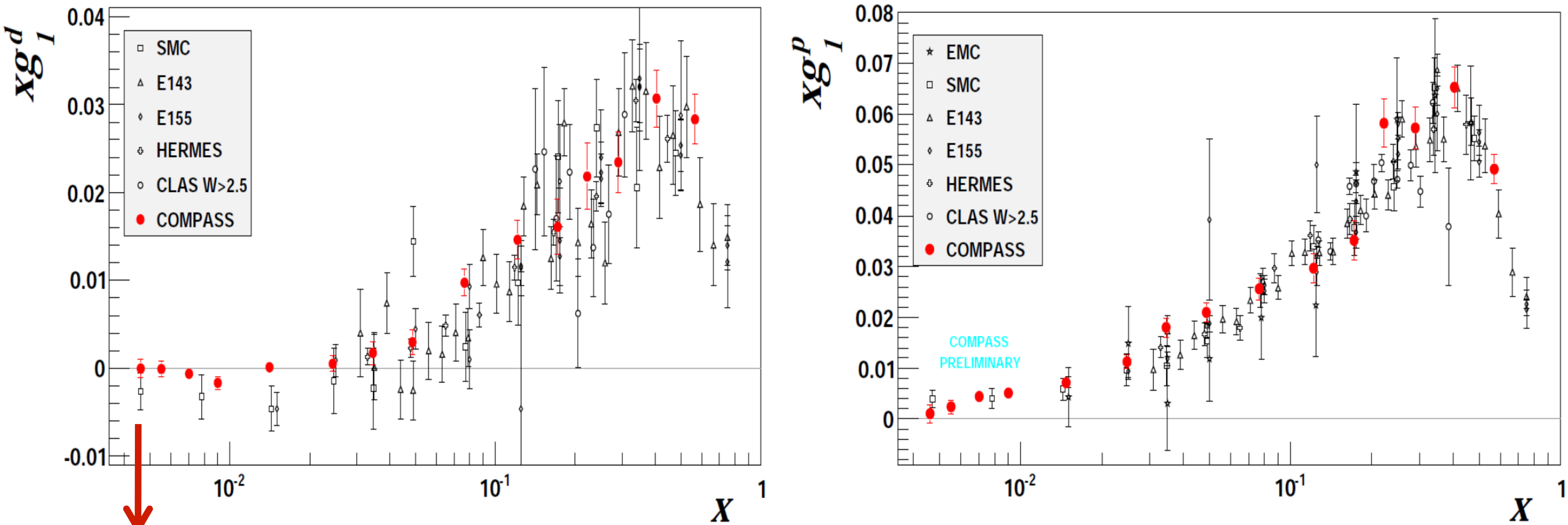


$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)} = \frac{g_1(x,Q^2) 2x(1+R)}{F_2(x,Q^2)}$$

g_1, polarised structure function is derived from A_1 using:

F_2 (SMC parameterisation) and $R = \sigma_L/\sigma_T$ (SLAC param.)

COMPASS results for $g_1^{d/p}$ and first moment of g_1^N



$$\Gamma_1^N(Q_0^2=3(\mathbf{GeV/c})^2) = \int_0^1 \mathbf{g}_1(\mathbf{x})\,\mathbf{dx} = 0.0502 \pm 0.0028(\mathbf{stat}) \pm 0.0020(\mathbf{evol}) \pm 0.0051(\mathbf{syst})$$

$$= \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2)\right)\left(\mathbf{a}_0(Q^2) + \frac{1}{4}\mathbf{a}_8\right) \Rightarrow \mathbf{a}_0 = 0.35 \pm 0.03(\mathbf{stat}) \pm 0.05(\mathbf{syst})$$

$$N = \frac{n+p}{2}$$

$$\Delta\Sigma^{\overline{MS}} = 0.33 \pm 0.03(\mathbf{stat}) \pm 0.05(\mathbf{syst}) \quad (\Delta\Sigma^{\overline{MS}} = \mathbf{a}_0 \ @ Q^2 \to \infty)$$

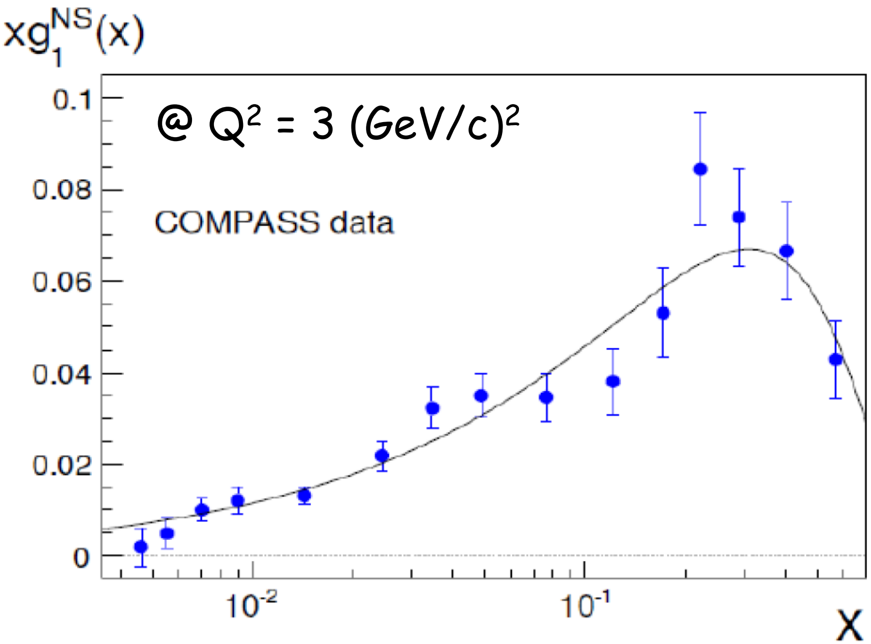
$$(\Delta s + \Delta\bar{s}) = \frac{1}{3}(\Delta\Sigma^{\overline{MS}} - \mathbf{a}_8) = -0.08 \pm 0.01(\mathbf{stat}) \pm 0.02(\mathbf{syst})$$

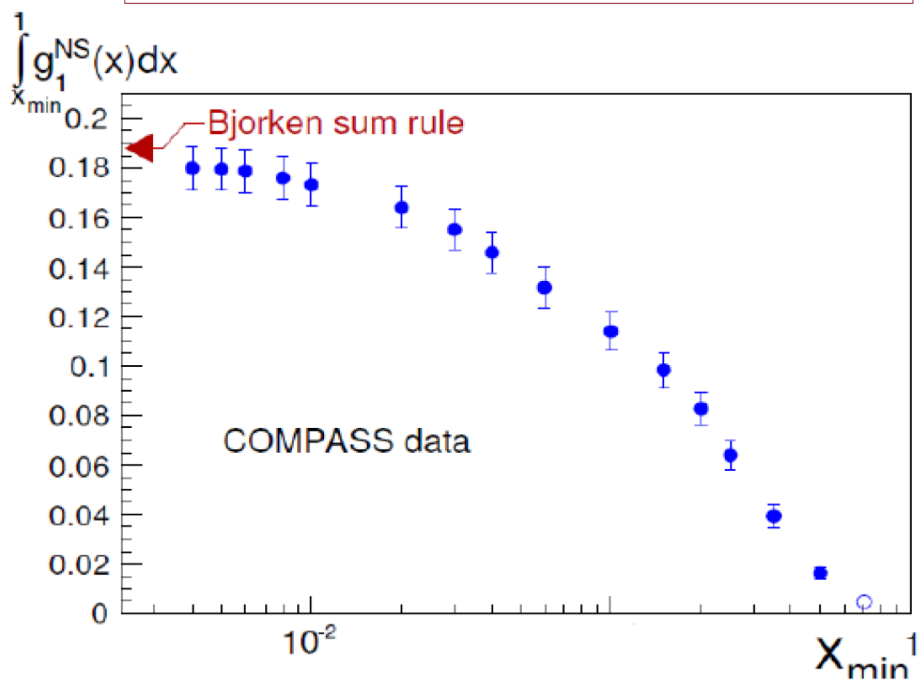
Bjorken sum rule from COMPASS g_1^p and g_1^d

$$\int_0^1 g_1^{NS}(x,Q^2)\,dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

using $\longrightarrow$

$$g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2)$$
$$= 2g_1^p - 2g_1^d/(1-1.5\,\omega_D)$$





- QCD fit of COMPASS data using $\Delta q^{NS} = |g_A / g_V|\, x^{\alpha}(1 - x)^{\beta}$:

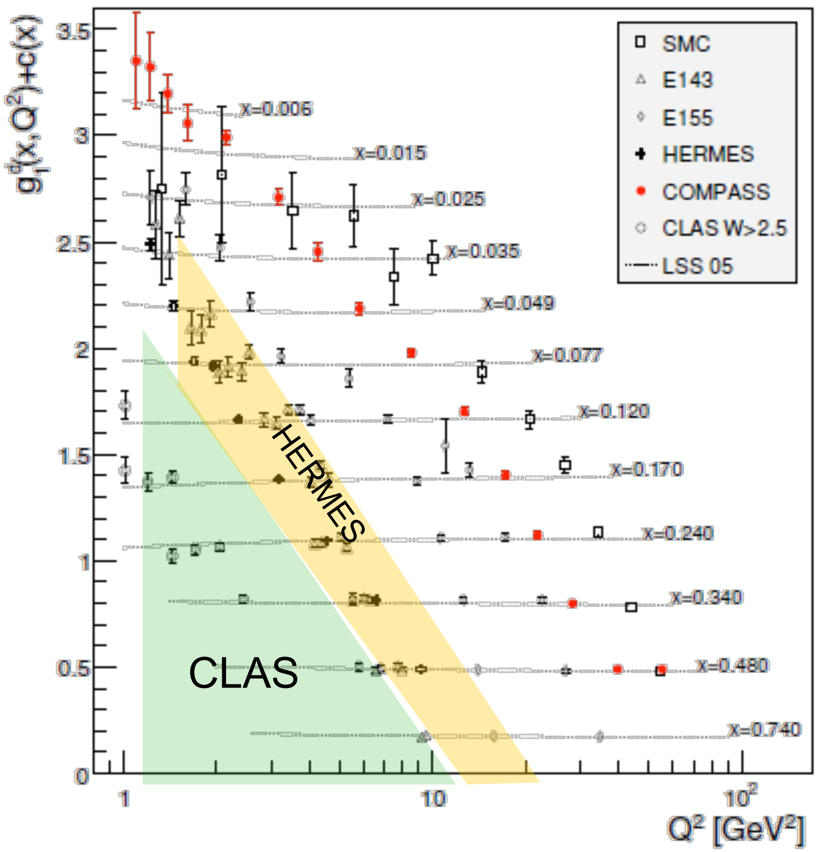
$$\left|\frac{g_A}{g_V}\right| = 1.28 \pm 0.07(\mathbf{stat}) \pm 0.10(\mathbf{sys})$$

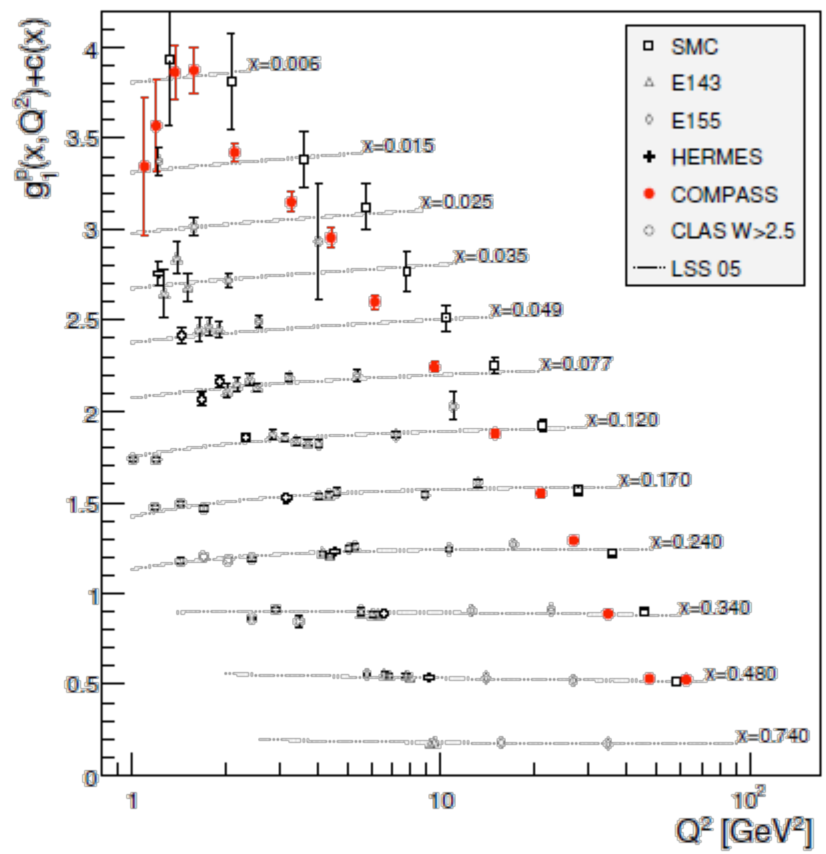
(PDG value : $|g_A/g_V| = 1.269 \pm 0.003$)

The Q^2 dependence of $g_1(x,Q^2)$

The DGLAP evolution equations which rule the $\partial/\partial \ln Q^2$ dependence of parton distribution functions allow to perform a Global NLO g_1 analysis and to extract gluon polarisation ΔG **(result provided later)**

The kinematical range is still limited (compared to F_2).
Data at colliders are required !





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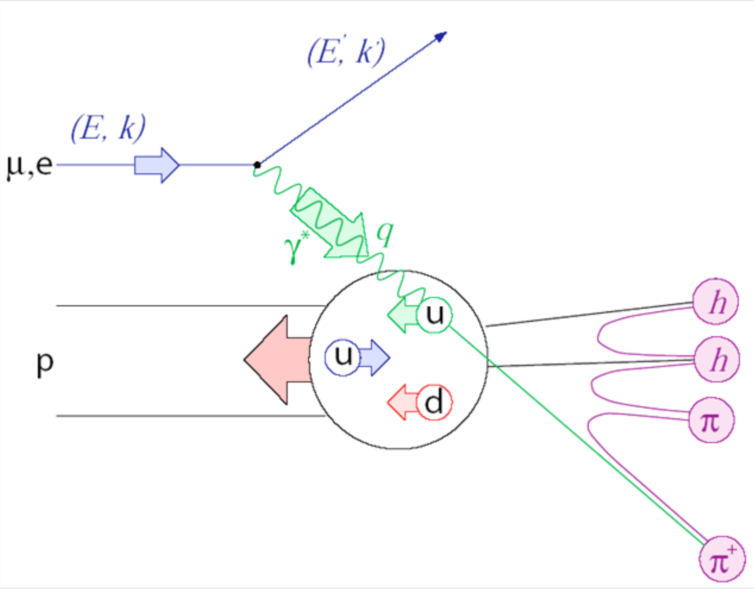
Flavor separation Δu, Δd, $\Delta\bar{q}$, Δs



- The outgoing hadron tags the quark flavor
- Required are the fragmentation function of a quark q to a hadron h:

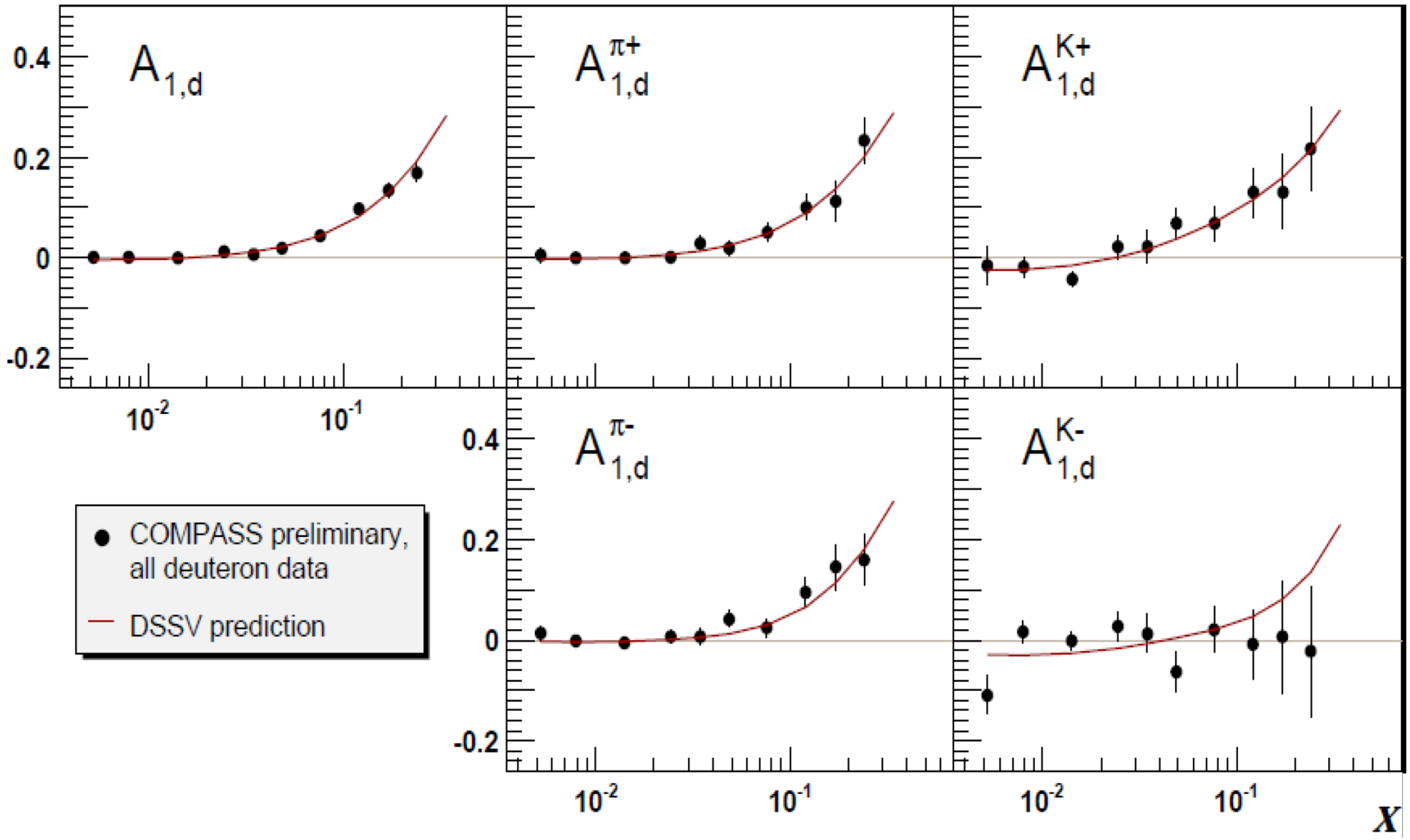
$$D_q^h(z,Q^2),\ z = E_h/(E_\mu - E'_\mu)$$

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

Need to combine proton (uud) & neutron (udd) results

Inclusive and Semi-Inclusive asymmetries

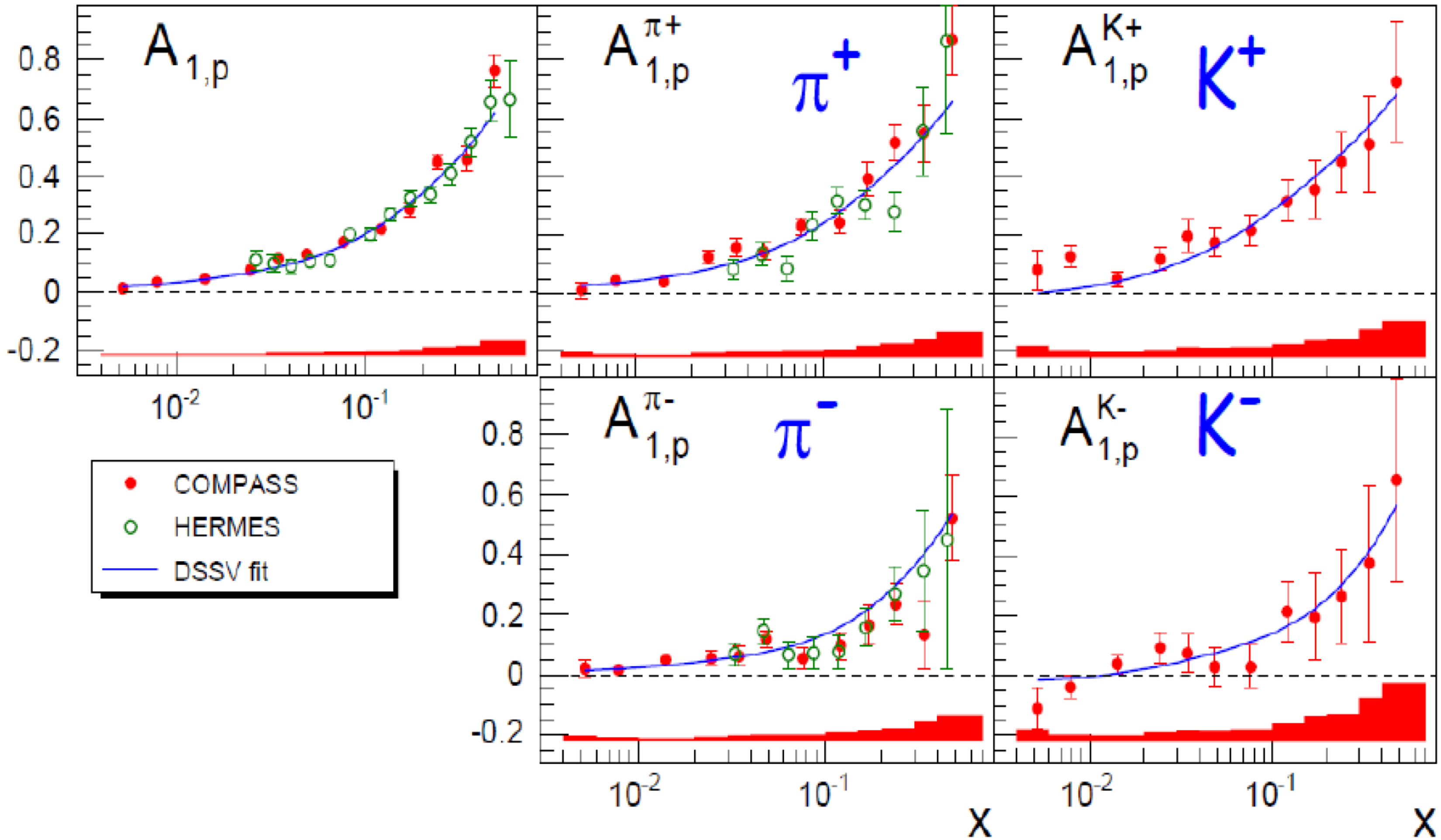
Deuteron data 2002-2006



Inclusive and Semi-Inclusive asymmetries

Proton data 2007

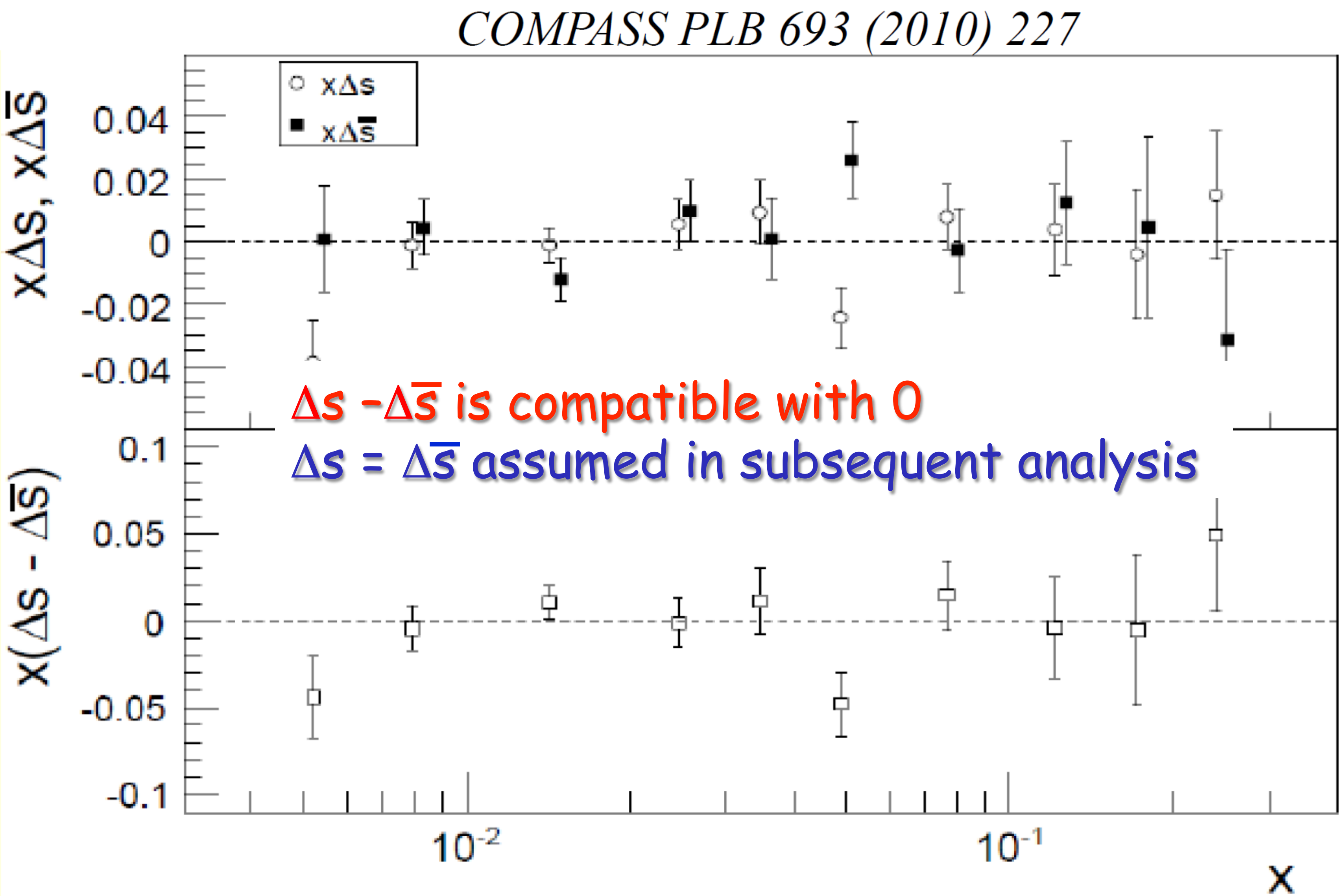
First measurement ever of $A^{K}_{1,p}$



Using $A^{h}_{1,p}$ and $A^{h}_{1,d}$ we can extract separately

Δu, Δd, $\Delta\bar{u}$, $\Delta\bar{d}$, Δs and $\Delta\bar{s}$

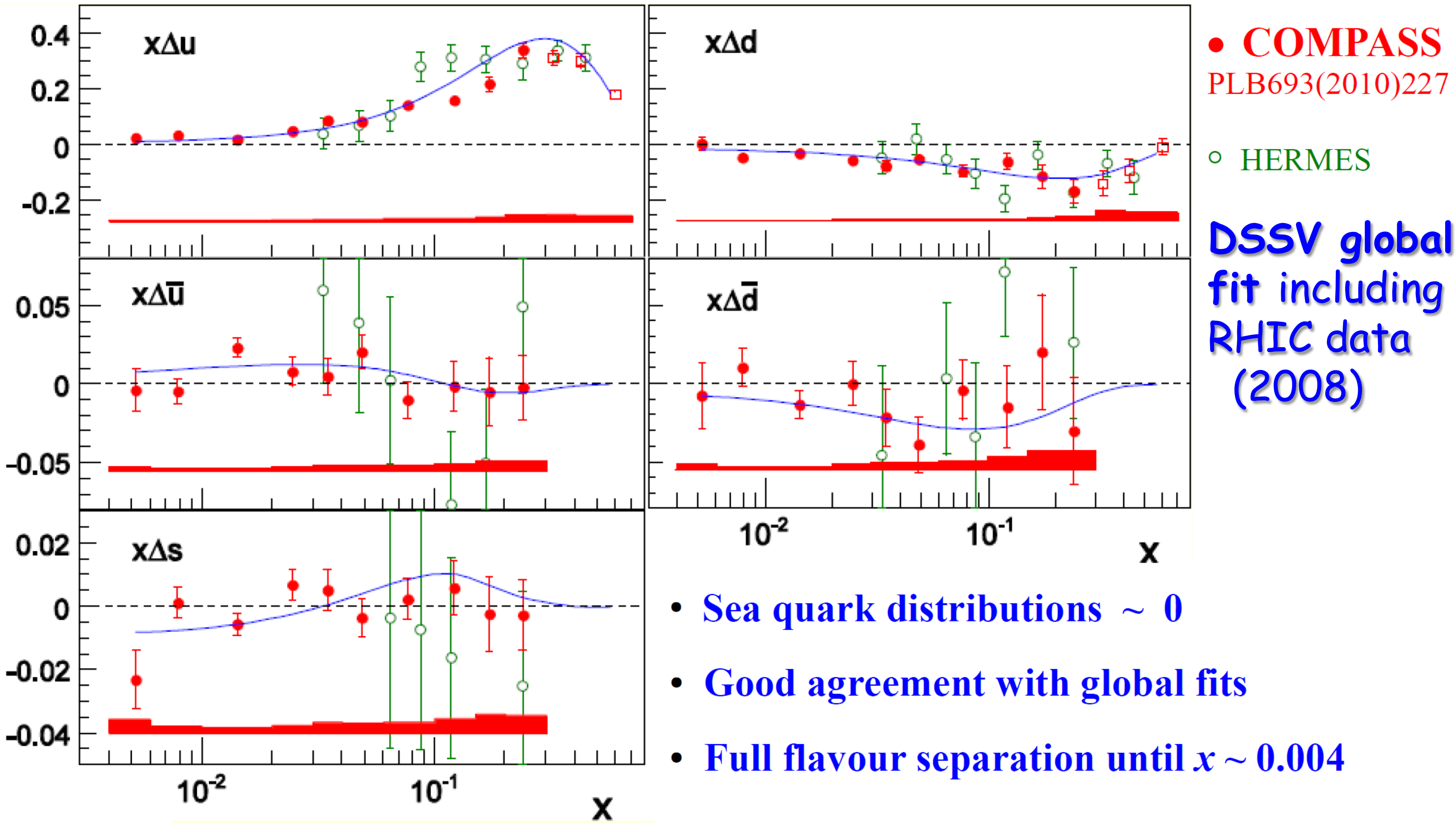
Comparison of Δs with $\Delta\bar{s}$



$\Delta s - \Delta\bar{s}$ is compatible with 0

$\Delta s = \Delta\bar{s}$ assumed in subsequent analysis

Quark helicities from SIDIS ($Q^2 = 3(\mathrm{GeV}/c)^2$)



- Sea quark distributions ~ 0
- Good agreement with global fits
- Full flavour separation until $x \sim 0.004$

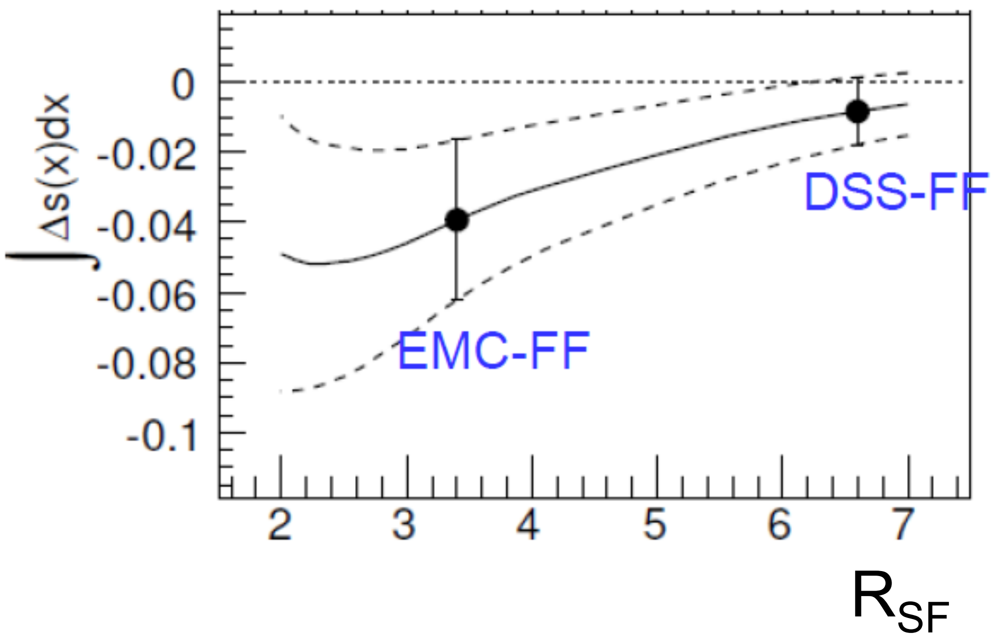
$$\Delta s(\mathbf{SIDIS}) = -0.01 \pm 0.01(\mathbf{stat}) \pm 0.01(\mathbf{syst}) \quad @\ 0.003 < \mathbf{x} < 0.3$$

Δs puzzle ?

From the g_1 1st moment (+ neutron and hyperon decay + SU3)
we get $\Delta s + \Delta\bar{s} = -0.08 \pm 0.01\ (stat) \pm 0.02\ (syst)$

From SIDIS
we get $\Delta s = -0.01 \pm 0.01\ (stat) \pm 0.01\ (syst)$
$(0.003 < x)$

Δs vs R_{SF}



Uncertainty on R_{SF}, the ratio of strange to favoured Fragmentation Functions (FFs) could explain discrepancy.

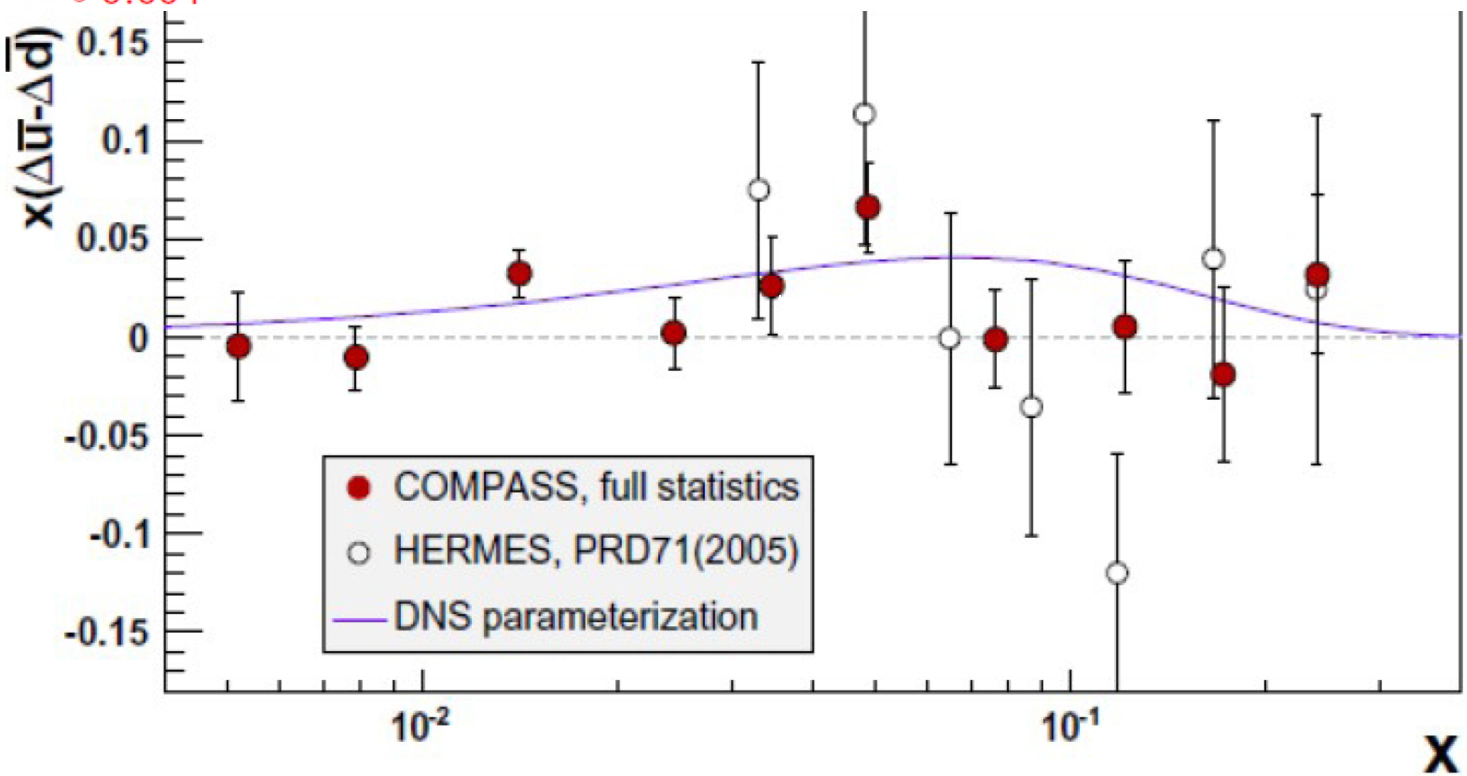
Need more data on FFs

Need more Δs data at low x

$\Delta\bar{u} - \Delta\bar{d}$: Flavour asymmetry ?

$\Delta\bar{u} - \Delta\bar{d}$ is compatible with zero (slightly > 0)

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



Asymmetry for $\bar{u} - \bar{d}$ not verified in polarised case

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

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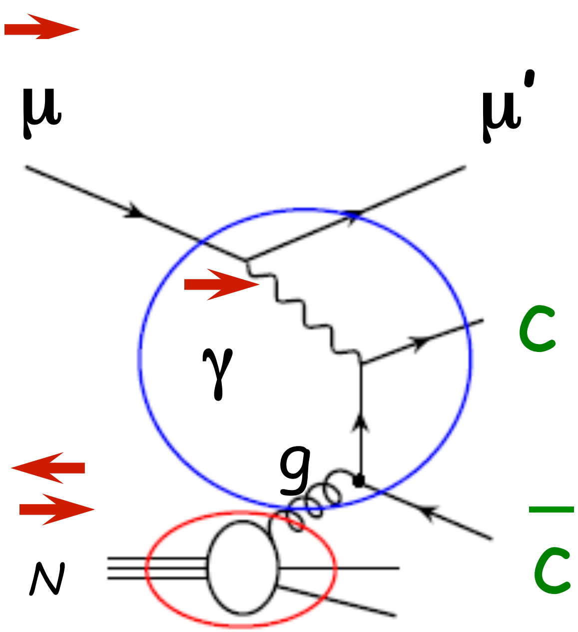
ΔG/G from Open Charm

- Photon Gluon Fusion (PGF) probes polarised gluons



- Open charm, single D meson
  c -> (D*) -> (π_s) D^0 -> $K\pi(\pi_s)$

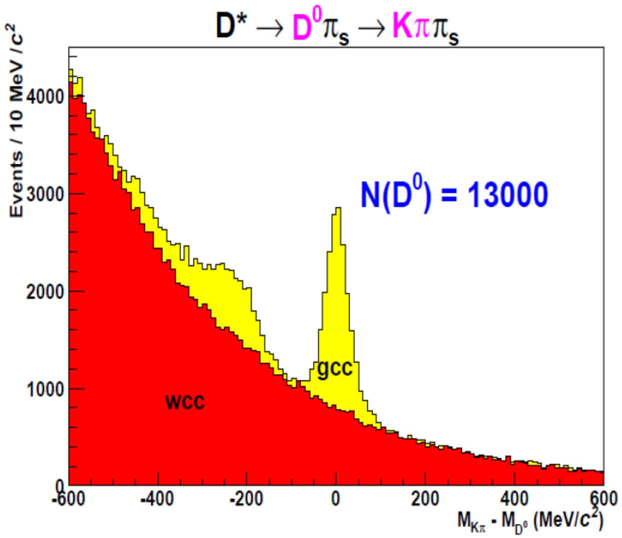
- no physical background
- … but limited statistics

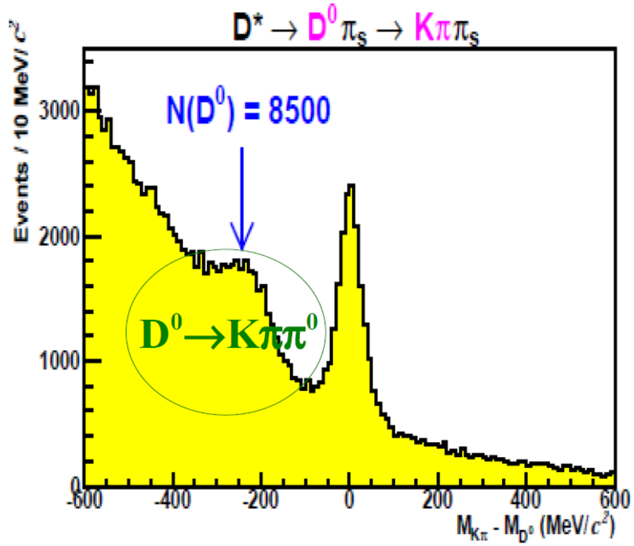
$$A_{LL} = R_{PGF} \times a_{LL}^{PGF} \times \frac{\Delta G}{G} + \cancel{A_{BKGR}}$$

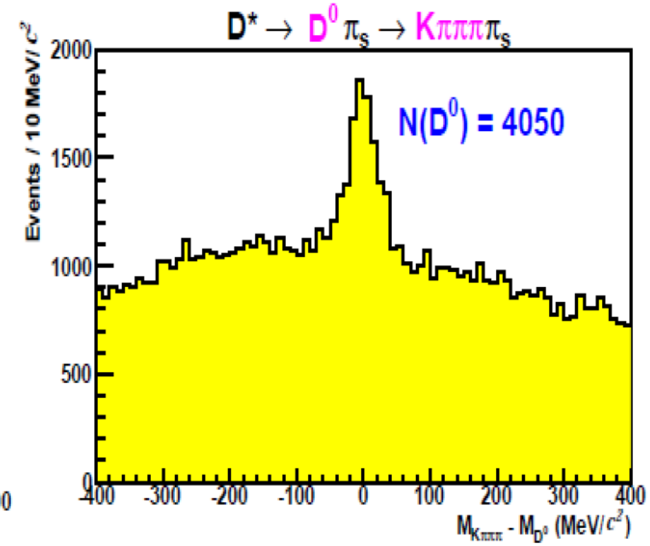
R_{PGF} ~ 1.0

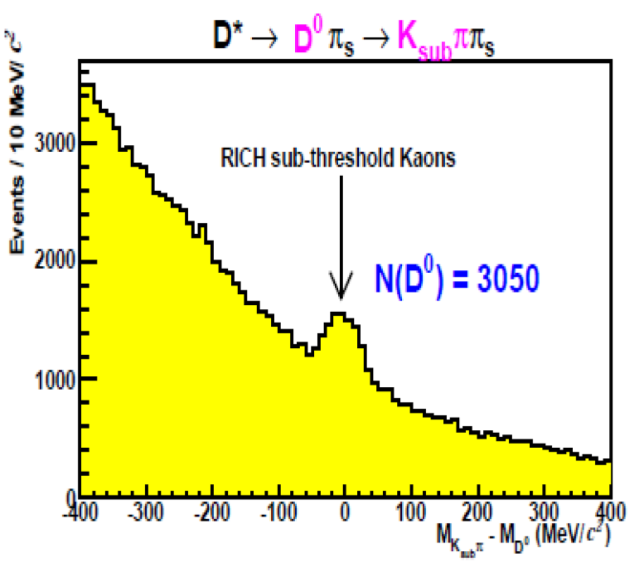
D^0 invariant mass spectra

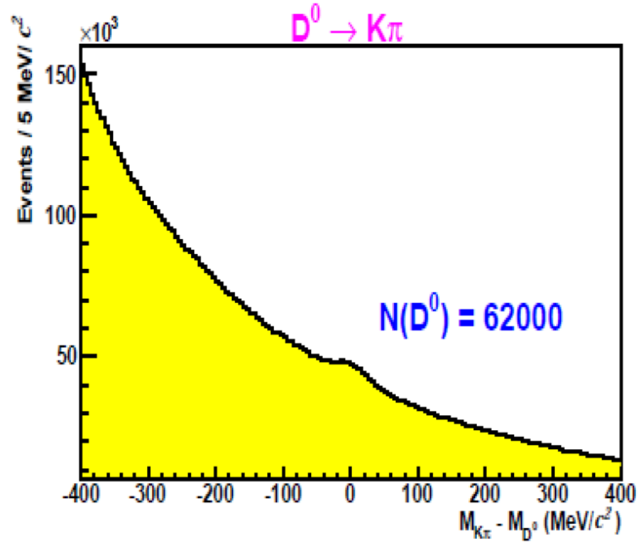
All samples (2002 – 2007 deuteron + proton data)











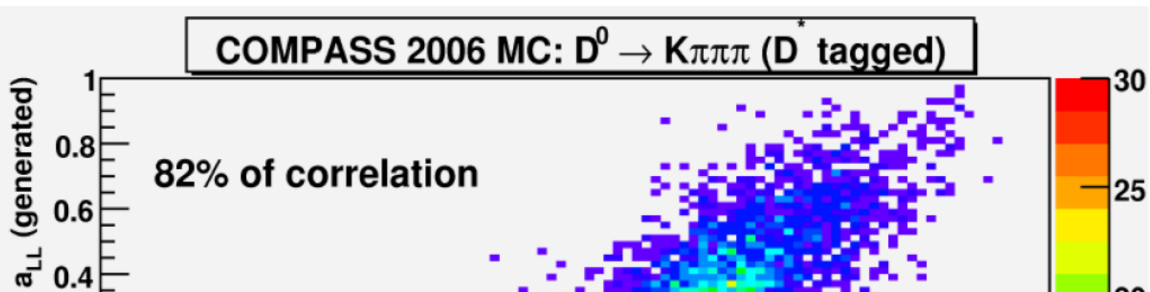
Number of D^0:

- Total → 90600
- ^{6}LiD → 65600
- NH_3 → 25000

Analysing power (μ-gluon asymmtery a_{LL})

a_{LL} dependent on the full knowledge of parton kinematics (can't be experimentally obtained)

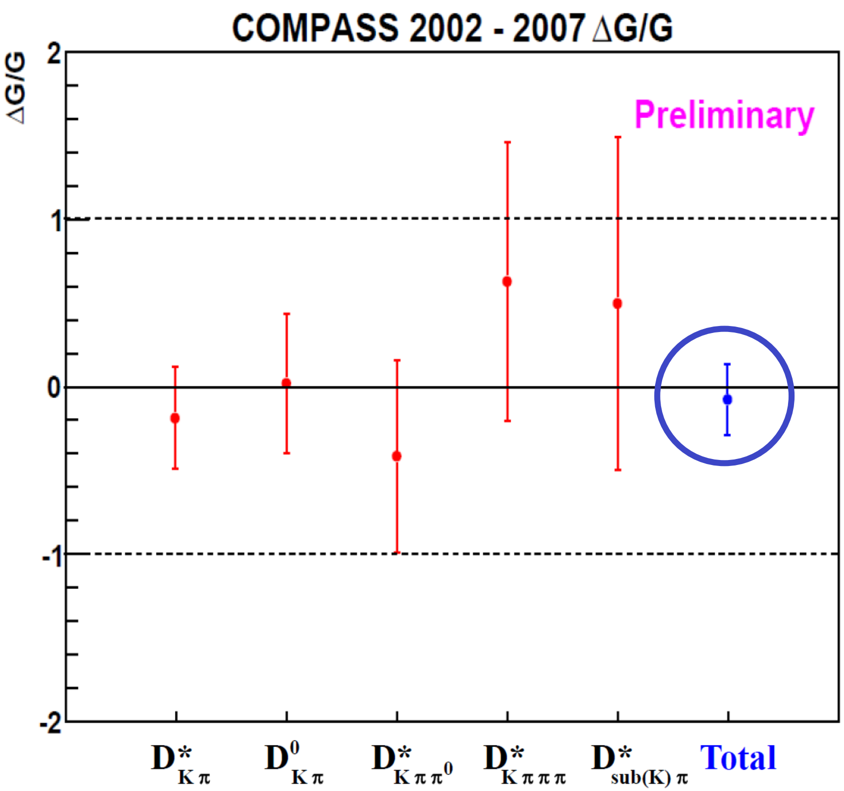
a_{LL}, obtained from Monte Carlo (in LO), serves as input for Neural Network parameterisation vs y, x_{Bj}, Q^2, z and p_T

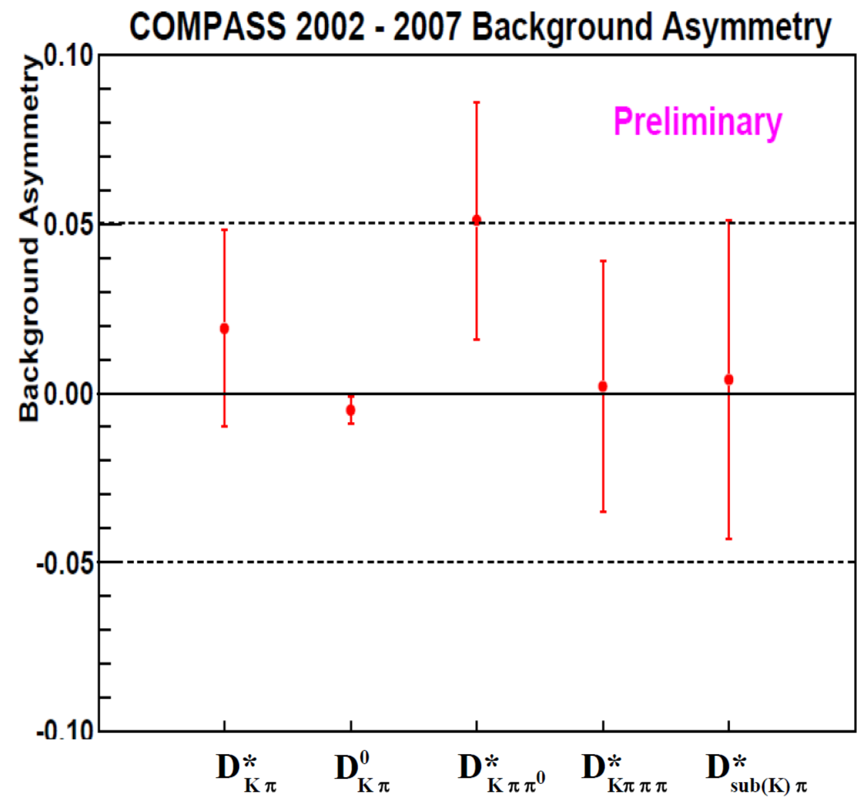


[redacted]

Parameterised-a_{LL} shows strong correlation with generated-a_{LL}

ΔG/G from Open Charm (LO)

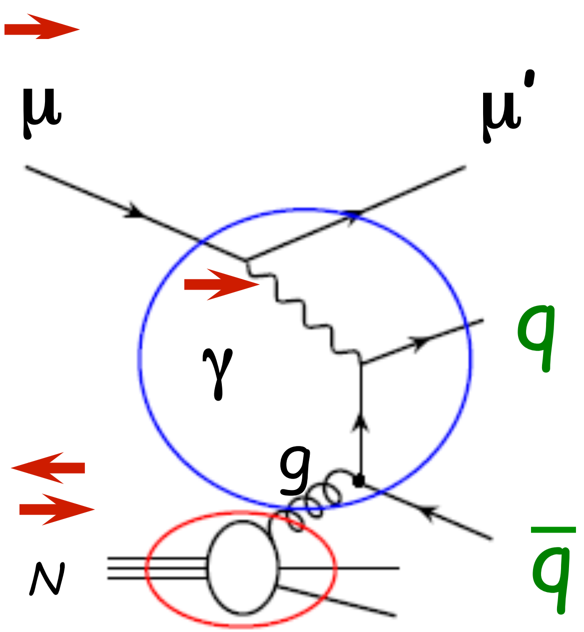




$$\frac{\Delta \mathbf{G}}{\mathbf{G}} = -0.08 \pm 0.21(\mathbf{stat}) \pm 0.08(\mathbf{syst}) \qquad @ < \mathbf{x_g} > = 0.11^{+0.11}_{-0.05}, \ < \mu^2 > = 13 \ (\mathbf{GeV/c})^2$$

$\Delta G/G$ from High-p_T hadron pairs

- Photon Gluon Fusion (PGF) probes polarised gluons



- High p_T hadron pair

  $q\bar{q}$ -> hh'

- High statistics
- Monte Carlo needed to estimate physical background

$$A_{LL} = R_{PGF} \times a_{LL}^{PGF} \times \frac{\Delta G}{G} + A_{BKGR}$$

~ 0.3

High-p_T asymmetries (2002-2006)
$Q^2 > 1\ (\mathrm{GeV}/c)^2$

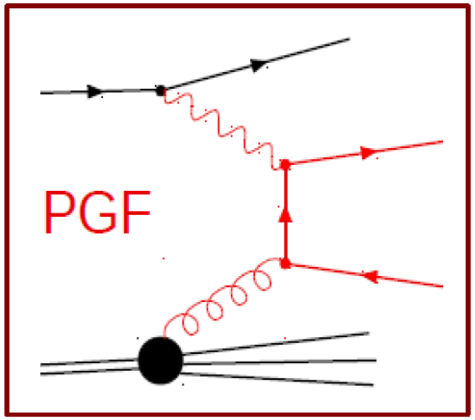
- **Two samples are considered:**

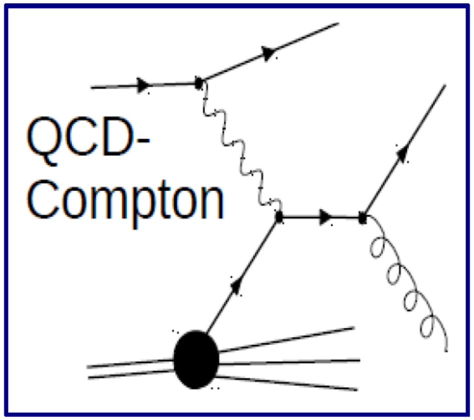
Inclusive asymmetry

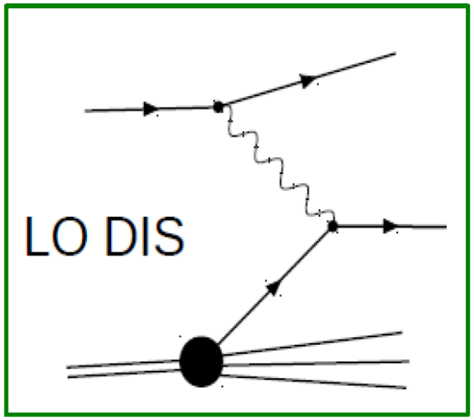
$$A_1^d(x) = \frac{\Delta G}{G}(x_g)\left(a_{LL}^{PGF,inc}\frac{\sigma^{PGF,inc}}{\sigma^{Tot,inc}}\right) + A_1^{LO}(x_C)\left(a_{LL}^{C,inc}\frac{\sigma^{C,inc}}{\sigma^{Tot,inc}}\right) + A_1^{LO}(x_{Bj})\left(D\frac{\sigma^{LO,inc}}{\sigma^{Tot,inc}}\right)$$

$$A_{LL}^{2h}(x) = \left(\frac{A^{exp}}{f P_\mu P_T}\right) = \frac{\Delta G}{G}(x_g)\left(a_{LL}^{PGF}\frac{\sigma^{PGF}}{\sigma^{Tot}}\right) + A_1^{LO}(x_C)\left(a_{LL}^{C}\frac{\sigma^{C}}{\sigma^{Tot}}\right) + A_1^{LO}(x_{Bj})\left(D\frac{\sigma^{LO}}{\sigma^{Tot}}\right)$$

high-p_T hadron pairs $(p_{T1} / p_{T2} > 0.7 / 0.4\ \mathrm{GeV}/c) \Rightarrow$ enhancement of the PGF contribution

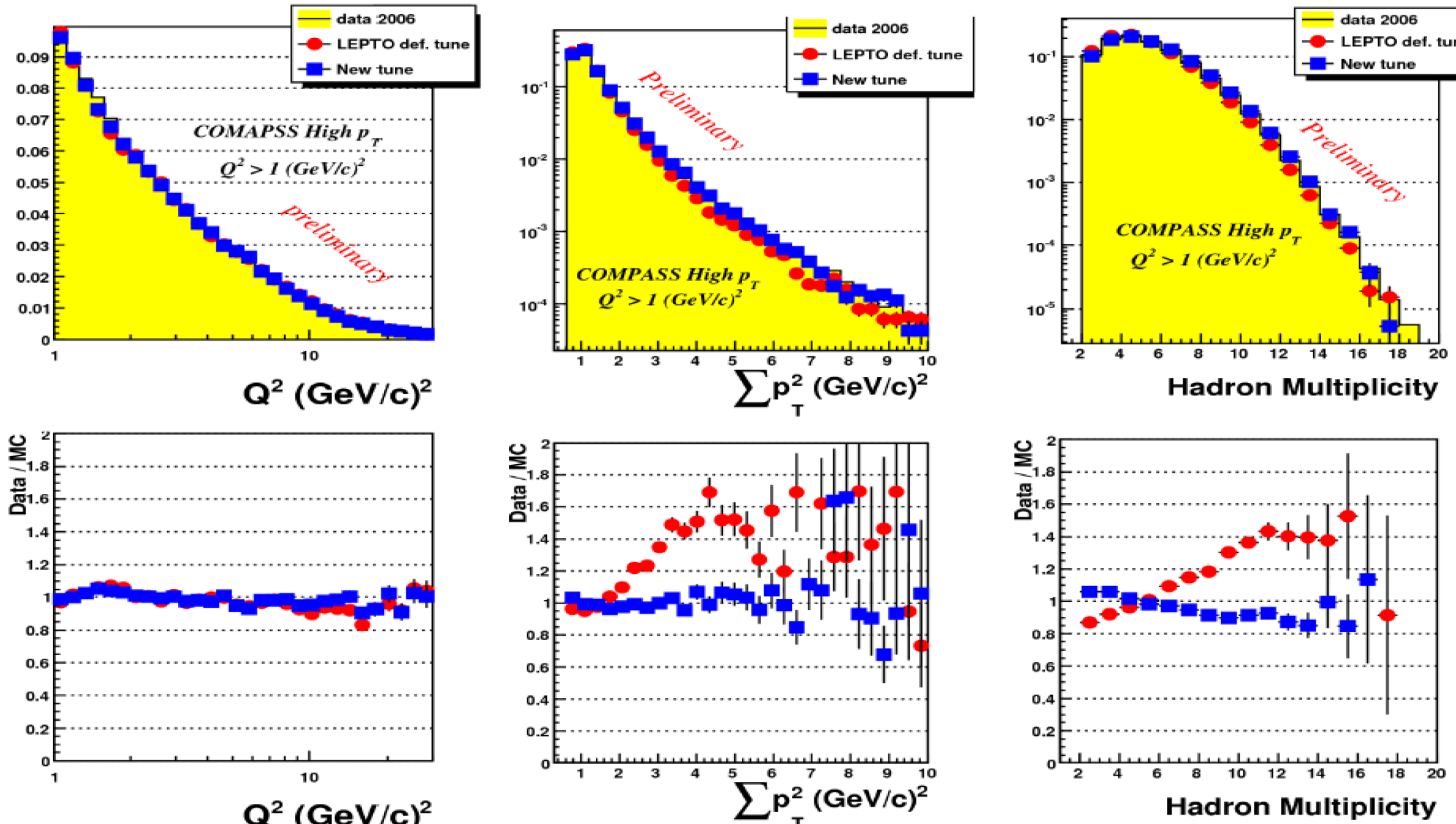






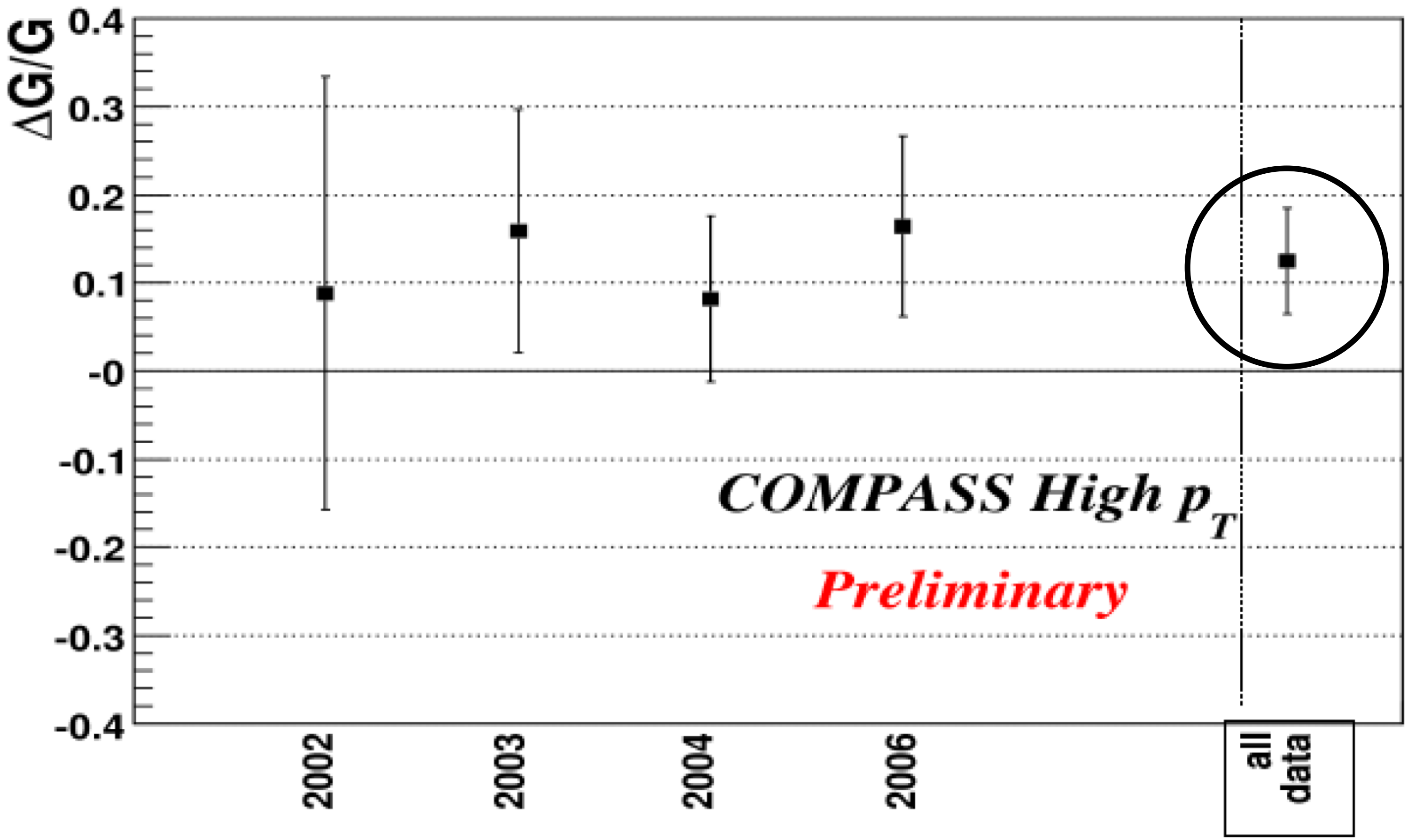
Data vs Monte Carlo: comparison of Q^2 and hadron variables

Monte Carlo (PS on): LEPTO generator with PDFs from MSTW2008LO

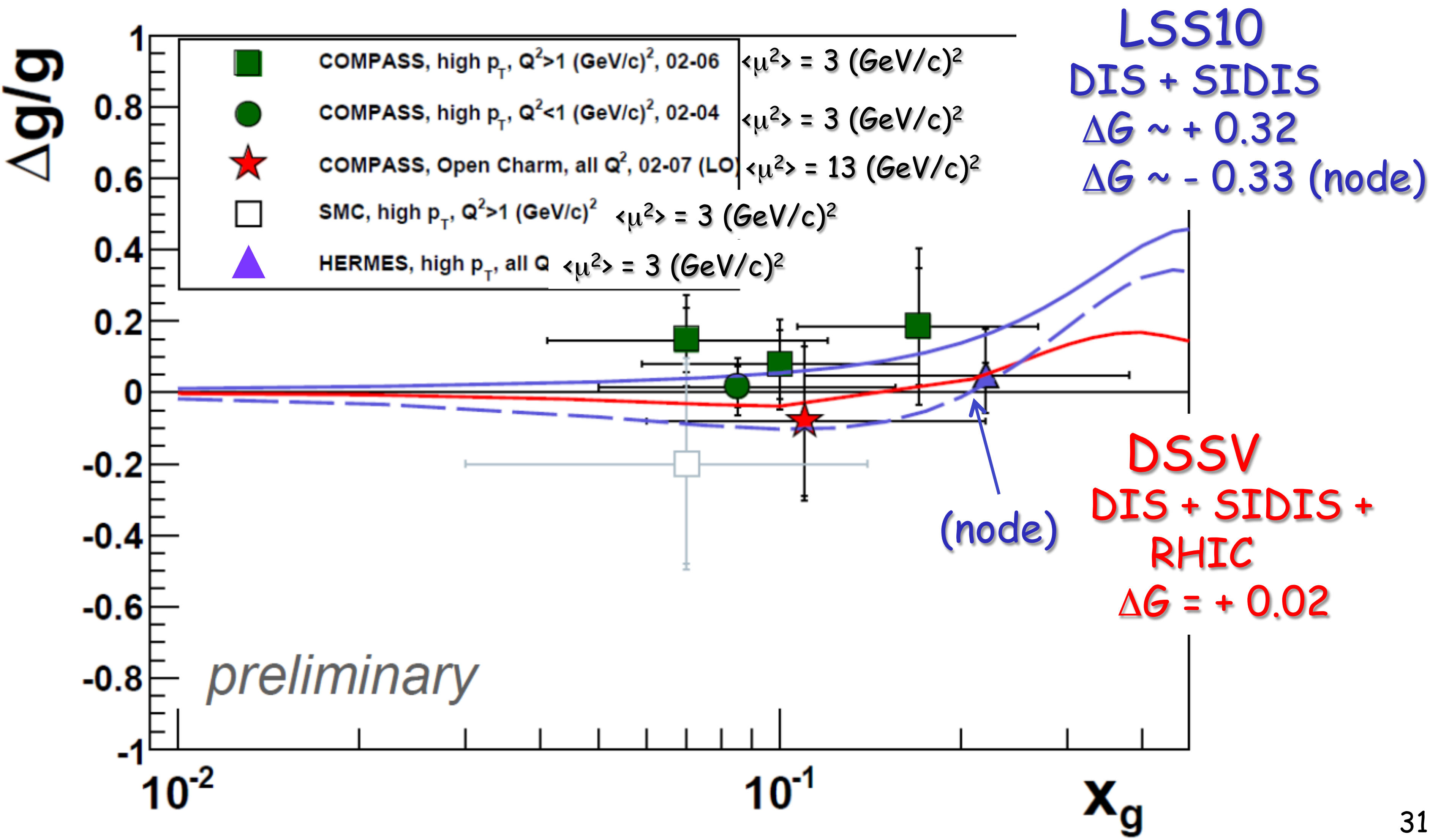


$\Delta G/G$ High-p_T, $Q^2 > 1\ (GeV/c)^2$ (LO)

$$\frac{\Delta G}{G} = 0.125 \pm 0.060(\mathbf{stat}) \pm 0.063(\mathbf{syst}) \quad @ < x_g > = 0.09^{+0.08}_{-0.04}\ ,\ <\mu^2> = 3.4\ (\mathbf{GeV/c})^2$$



World measurements of $\Delta G/G$ (LO)



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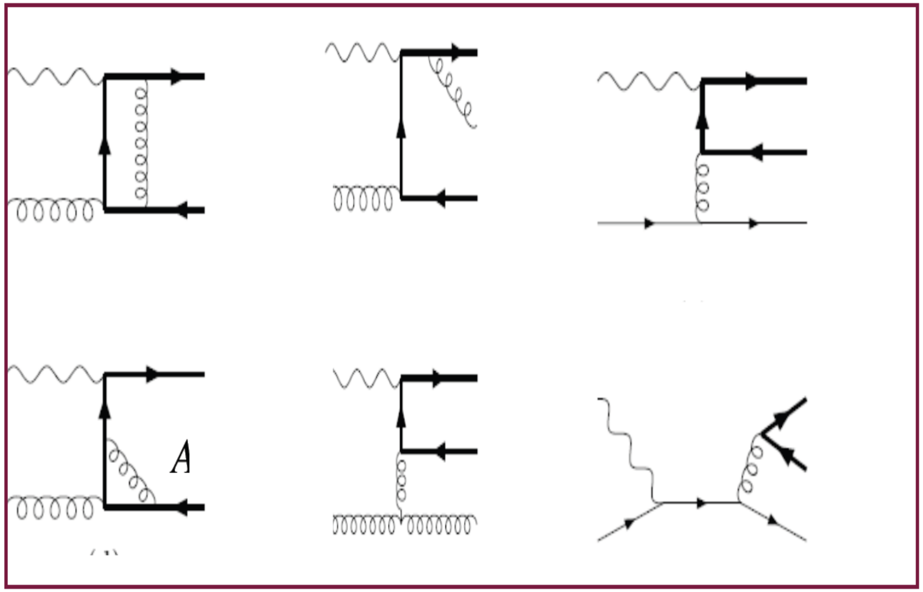
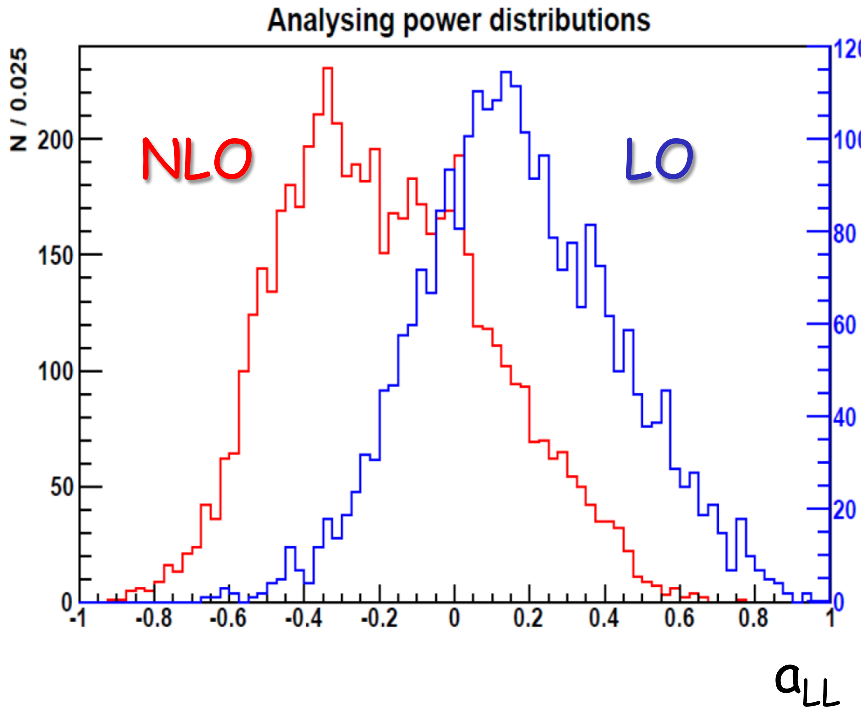
ΔG/G from Open Charm from LO to NLO

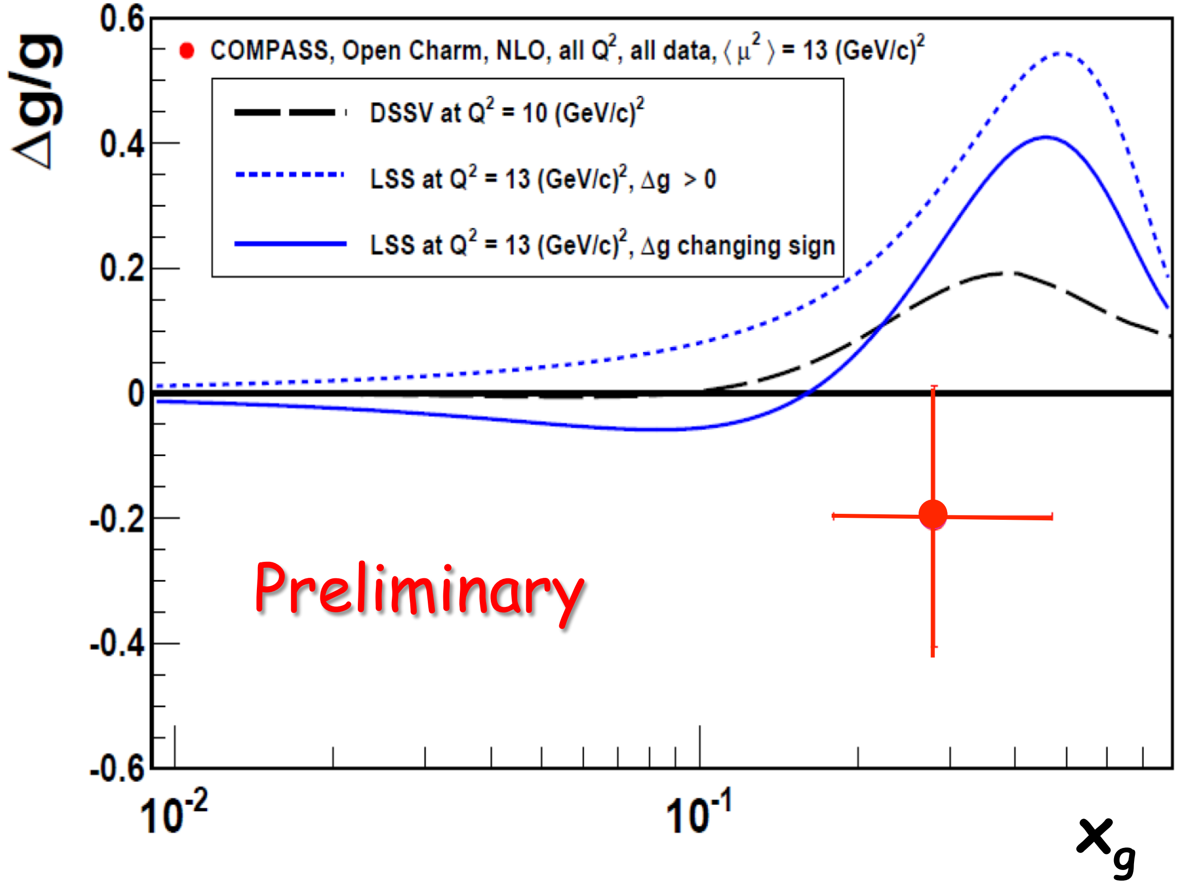
- Aroma MC generator with Parton Shower (PS) which describes COMPASS data very well is used to calculate a_{LL} at NLO (PS on)

- a_{LL} is calculated on event-by-event basis





ΔG/G from Open Charm in NLO



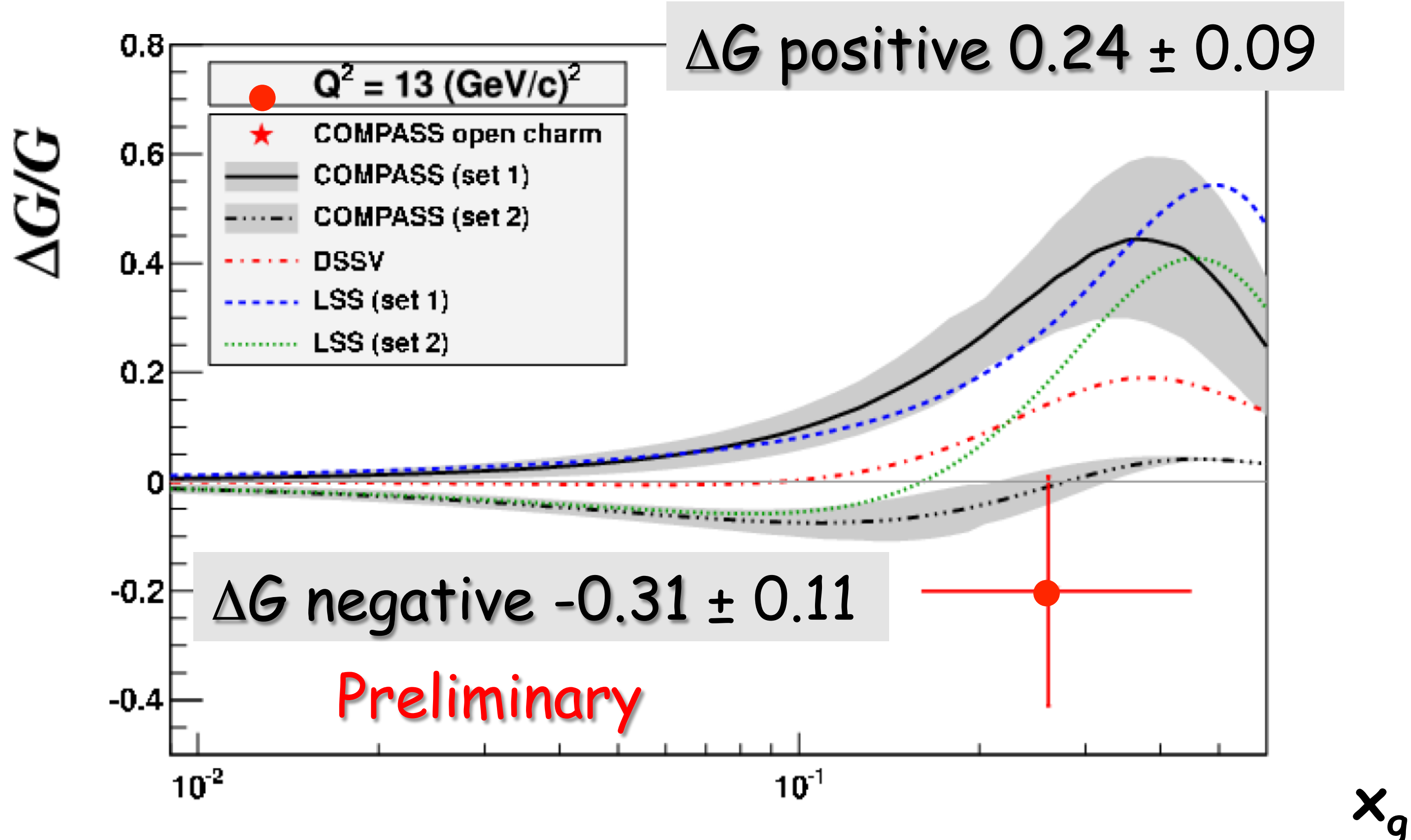
$$\frac{\Delta G}{G} = -0.20 \pm 0.21 \pm 0.08\,(\mathbf{syst}) \qquad @ < x_g > = 0.28^{+0.19}_{-0.10}\ ,\ <\mu^2> = 13\ (\mathbf{GeV/c})^2$$

Preliminary, theoretical errors still under study (a_{LL})

QCD fits of COMPASS $g_1(x,Q^2)$ + OC/NLO

(before, PLB 647, 2007, 8-17) ΔG positive 0.34 ± 0.07 (stat)

R. Windmolders (private communication) + Open Charm/NLO result



Conclusions (Longitudinal)

- Quark spin contribution to Nucleon spin, $\Delta\Sigma \sim 0.33$
- Bjorken Sum Rule perfectly verified
- precise separation of polarised flavors Δq for $0.003 < x < 0.3$
- From Open Charm and High-pT (at LO), $\Delta G/G \sim 0$
- QCD fit + NLO Open Charm (from measured region) suggests $|\Delta G| \sim 0.3$
- More global & consistent NLO analysis are needed

Conclusions (Longitudinal)

- As a consequence of the "axial anomaly", the measured quantity is:

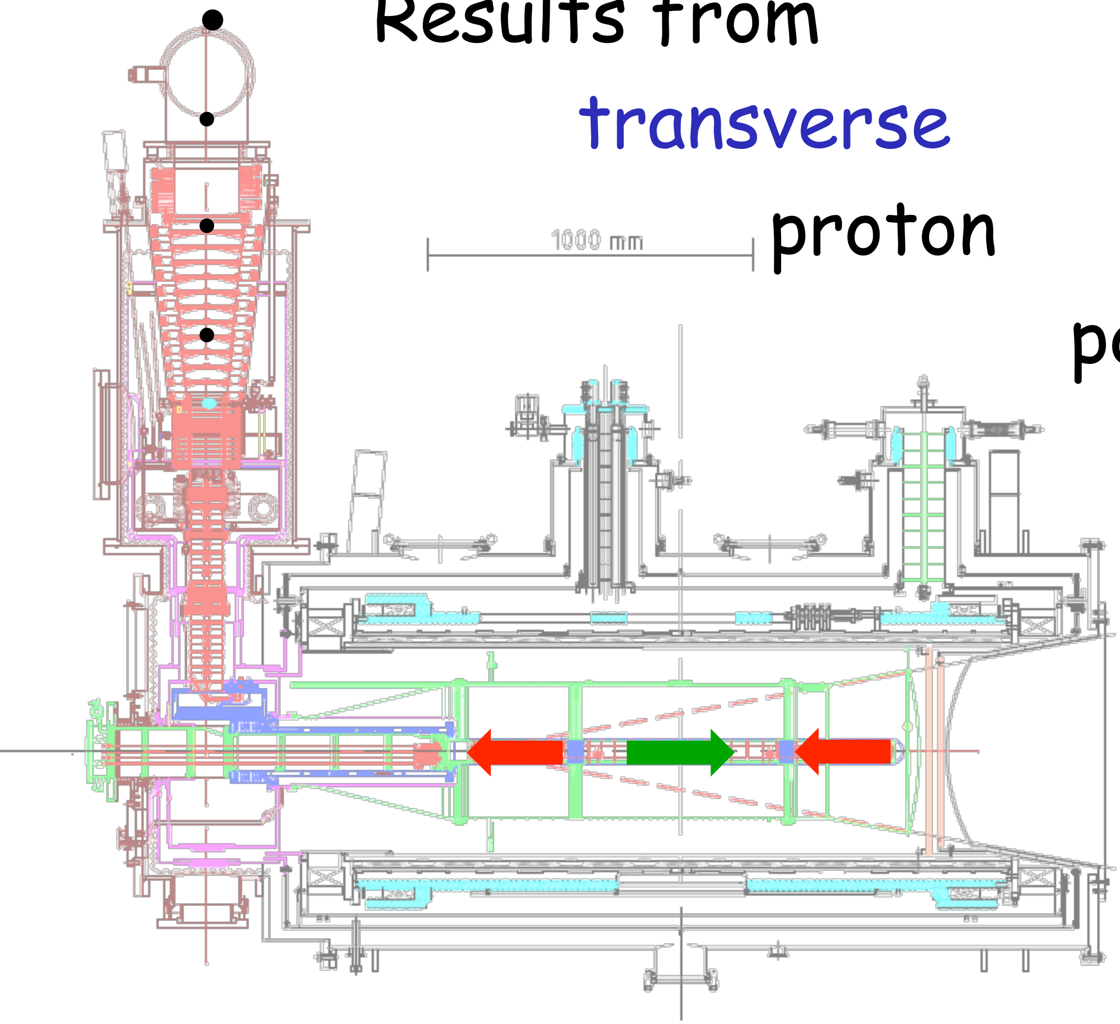
$$a_0 = \Delta\Sigma - (3\alpha_S/2\pi)\,\Delta G$$

$$\Downarrow$$

Within ± 0.06 for ΔG within ± 0.35

- Solution of spin crisis with ΔG ~ 2,3 and orbital angular momentum L_{q+g} ~ -2 <u>highly improbable</u>

Results from transverse proton polarisation



Nucleon partonic structure

Nucleon polarisation

Quark polarisation	U	L	T
U	f_1 number density q		$f_{1T}^{\perp}$ Sivers T-odd
L		g_1 helicity Δq	g_{1T}
T	T-odd $h_1^{\perp}$ Boer Mulders	$h_{1L}^{\perp}$	h_1 transversity; $h_{1T}^{\perp}$

$\Delta_0{}^T q$ Sivers

$\Delta^T q$ Collins

Nucleon spin structure: Transverse

- Transversity
  - Collins asymmetries
  - 2-hadron asymmetries

- k_T and Transverse spin
  - Sivers asymmetries

Transverse spin: Collins asymmetry

Transversity Collins FF

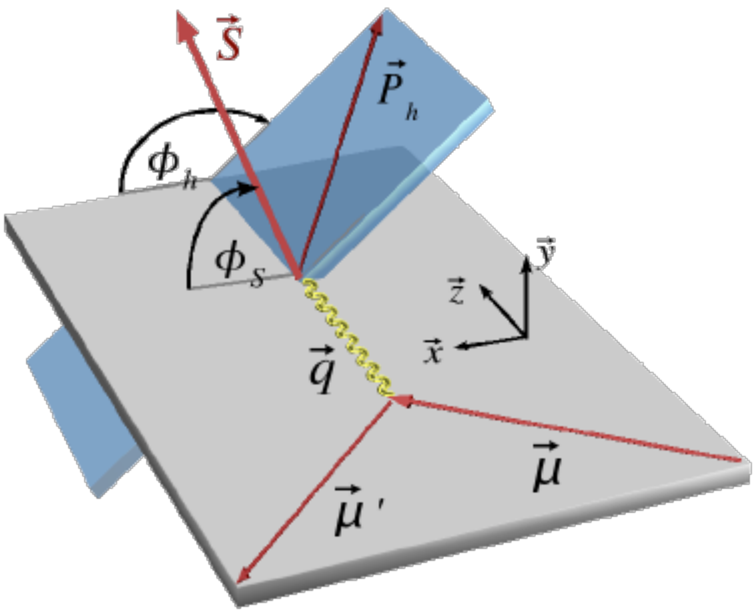
$$A_{Coll} = \frac{\sum_q e_q^2 \times \Delta_T q(x) \times \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 \times q(x) \times D_q^h(z, p_T^h)}$$

Couple $\Delta_T q$ to chiral odd Collins FF $\Delta_T^0 D_q^h$

cross-section asymmetry:

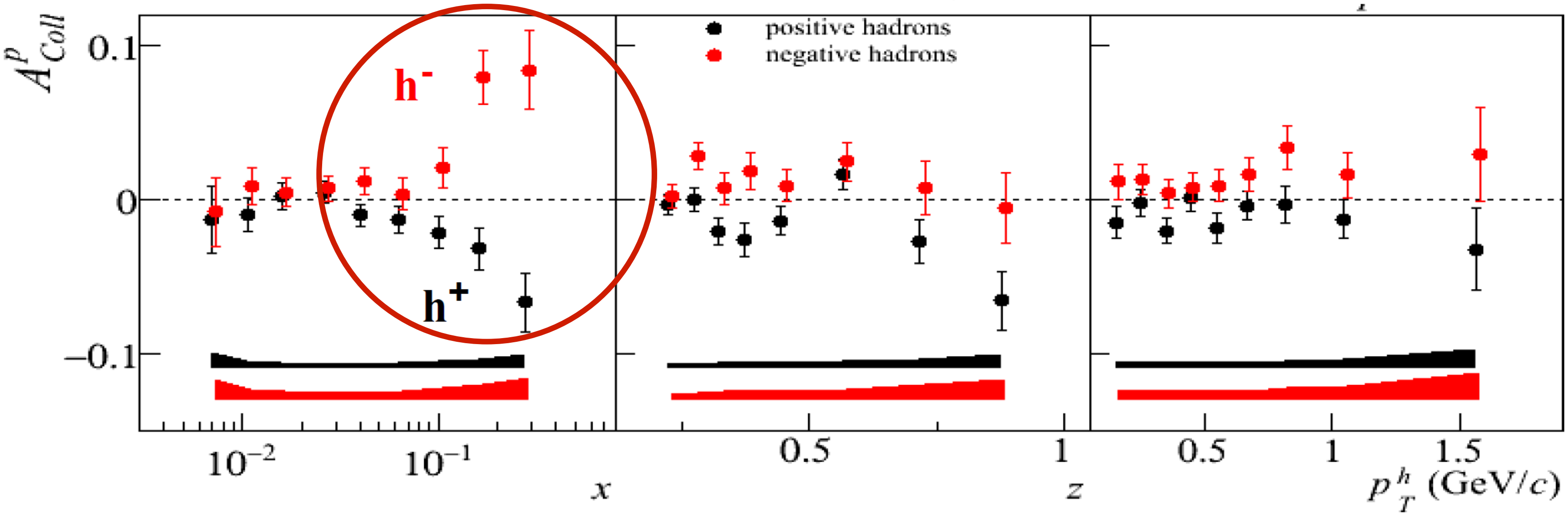
$$\frac{\Delta\sigma}{\sigma} \propto A_{Coll} \sin \Phi_C$$

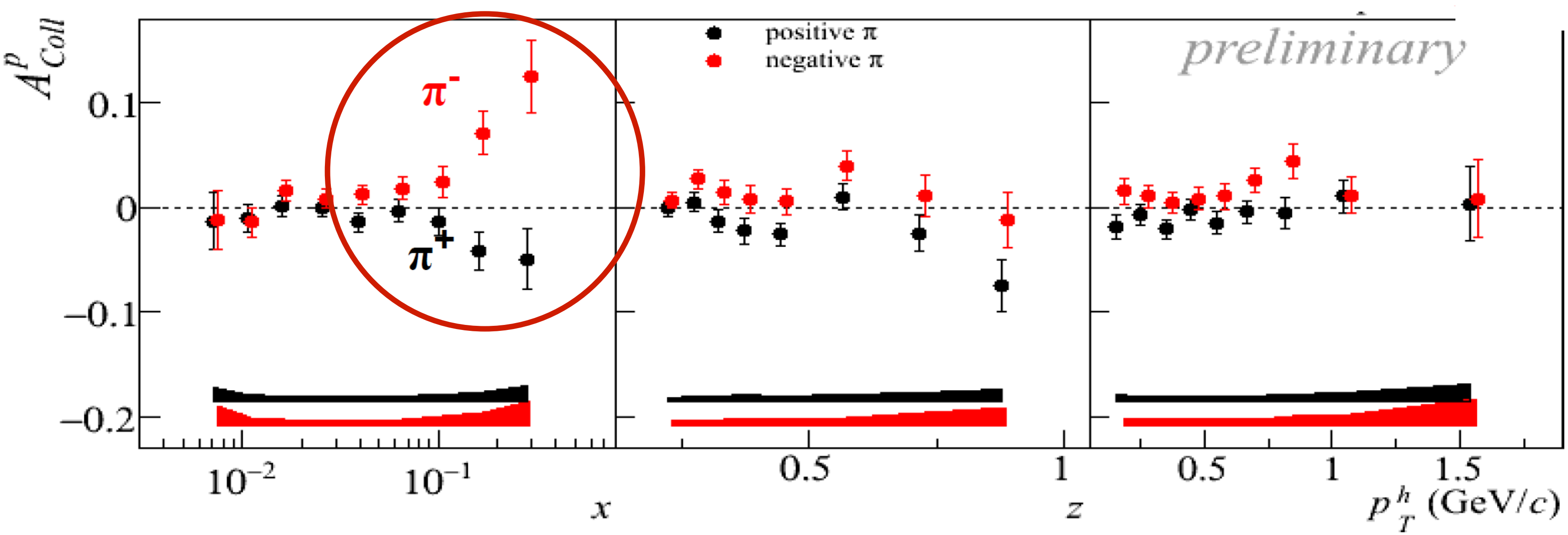
$$\Phi_C = \phi_h - \phi_s - \pi$$



COMPASS Collins asymmetry (proton)

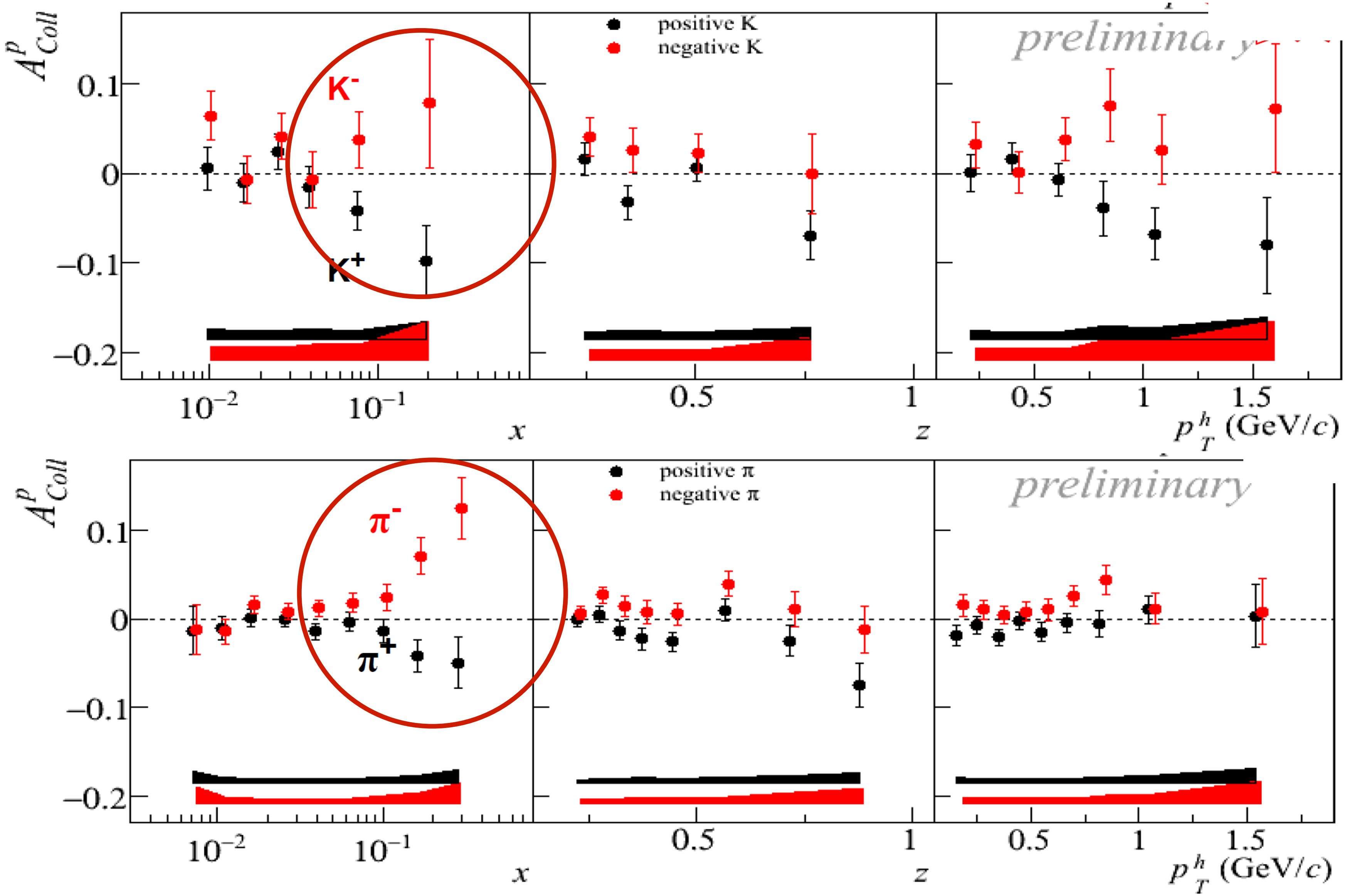
Final COMPASS results, 2007 data PLB 692 (2010) 240



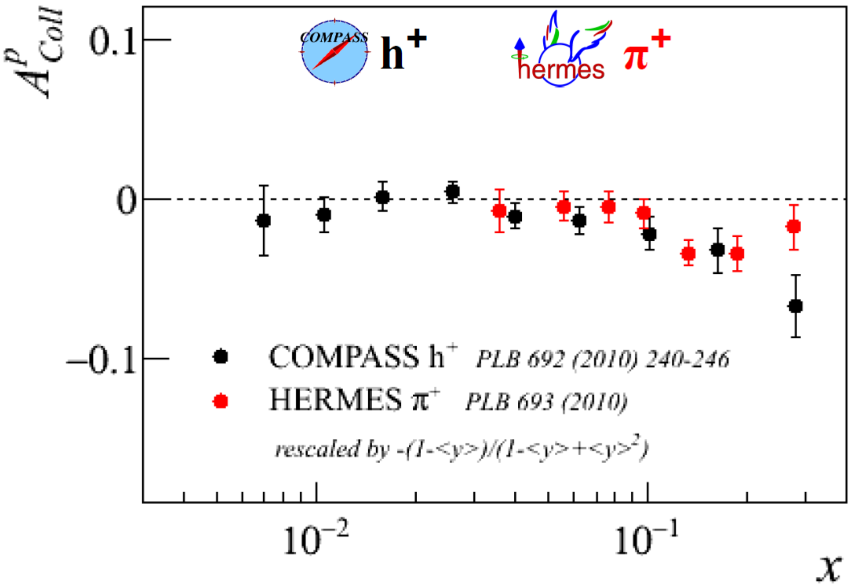


COMPASS Collins asymmetry (proton)

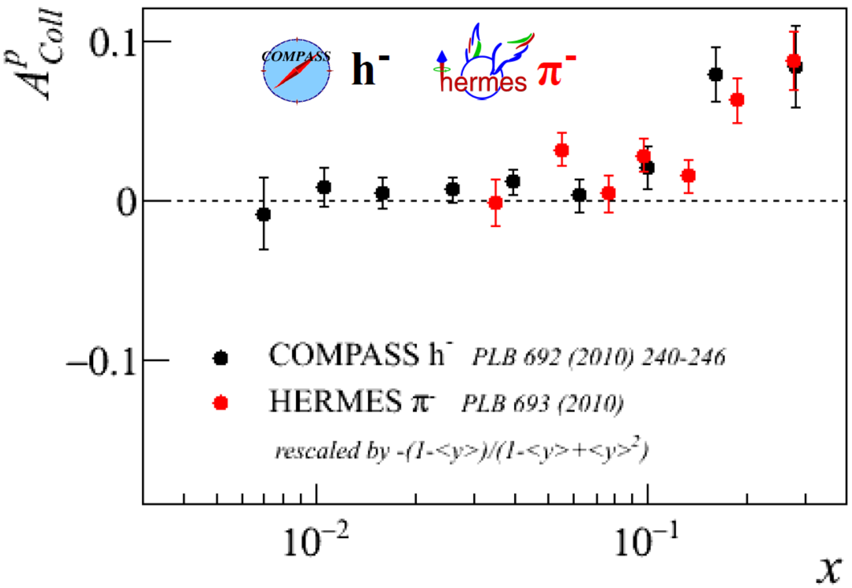
Final COMPASS results, 2007 data



Collins proton (COMPASS vs HERMES)



$A_{Collins}$ have at COMPASS and HERMES, the same sign/strength - a very important (not obvious) result.



Indication for: not a higher twist effect, weak Q2 dependence of the Collins FF

Transverse spin: 2-hadron asymmetry

Transversity 2-hadron interference FF

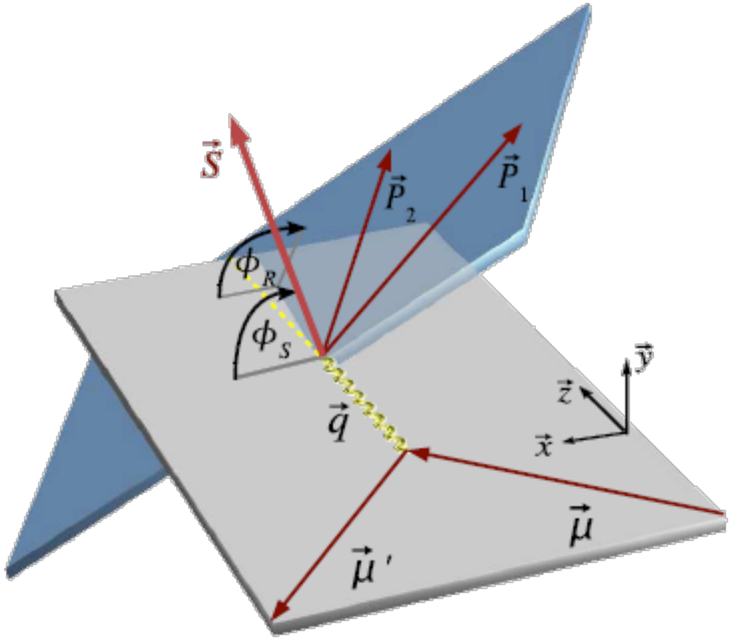
$$A_{RS} = \frac{\sum_q e_q^2 \times \Delta_T q \times H_1^{\triangleleft}(z, M_h^2)}{\sum_q e_q^2 \times q \times D_q^h(z, M_h^2)}$$

Couple $\Delta_T q$ to chiral odd 2-hadron interference FF $H_1^{\triangleleft}$

cross-section asymmetry:

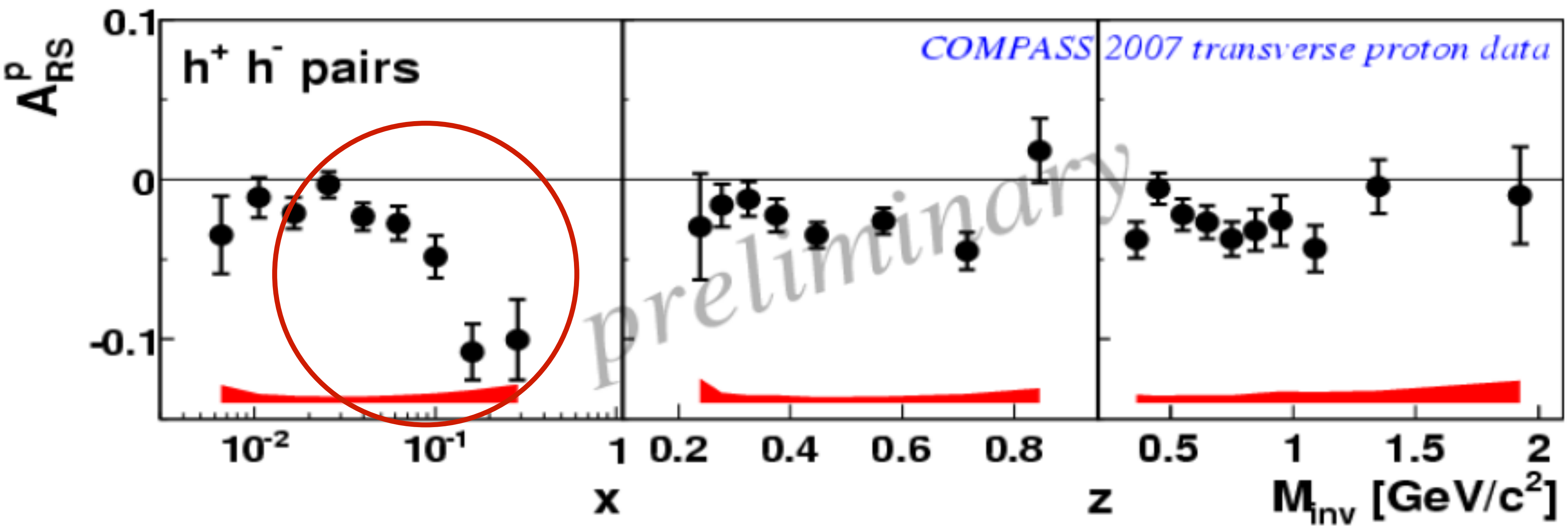
$$\frac{\Delta\sigma}{\sigma} \propto A_{RS} \sin\phi_{RS} \sin\theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi; \quad \sin\theta \simeq 1$$



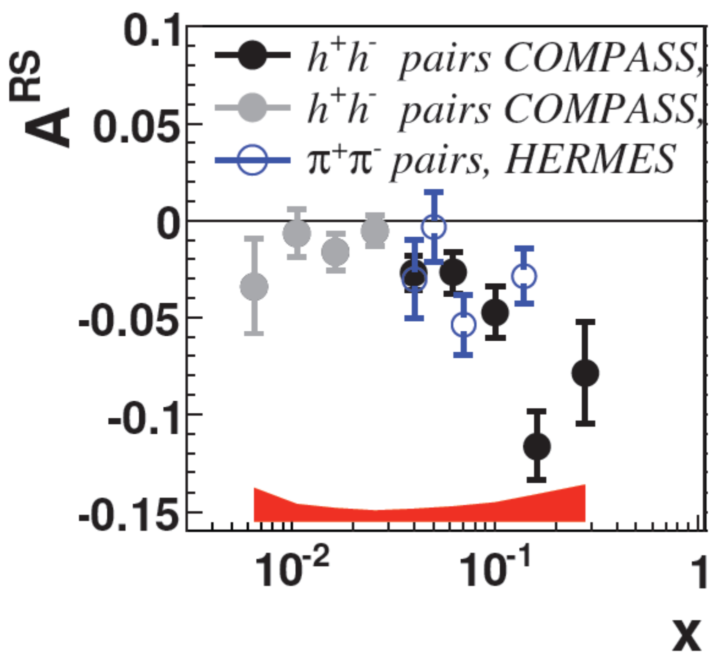
COMPASS 2-hadron asymmetry (proton)

- Sign in agreement with the Collins asymmetry
- Strength ~ larger than Collins asymmetry



2-hadron asymmetry proton (COMPASS vs HERMES)

- COMPASS signal larger than HERMES' one
- Different phase space but difficult to describe both together



Preliminary

Sivers asymmetry

$$A_{Siv} = \frac{\sum_q e_q^2 \times \Delta_0^T q(x, k_T) \otimes D_q^h(z)}{\sum_q e_q^2 \times q(x, k_T) \otimes D_q^h(z)}$$

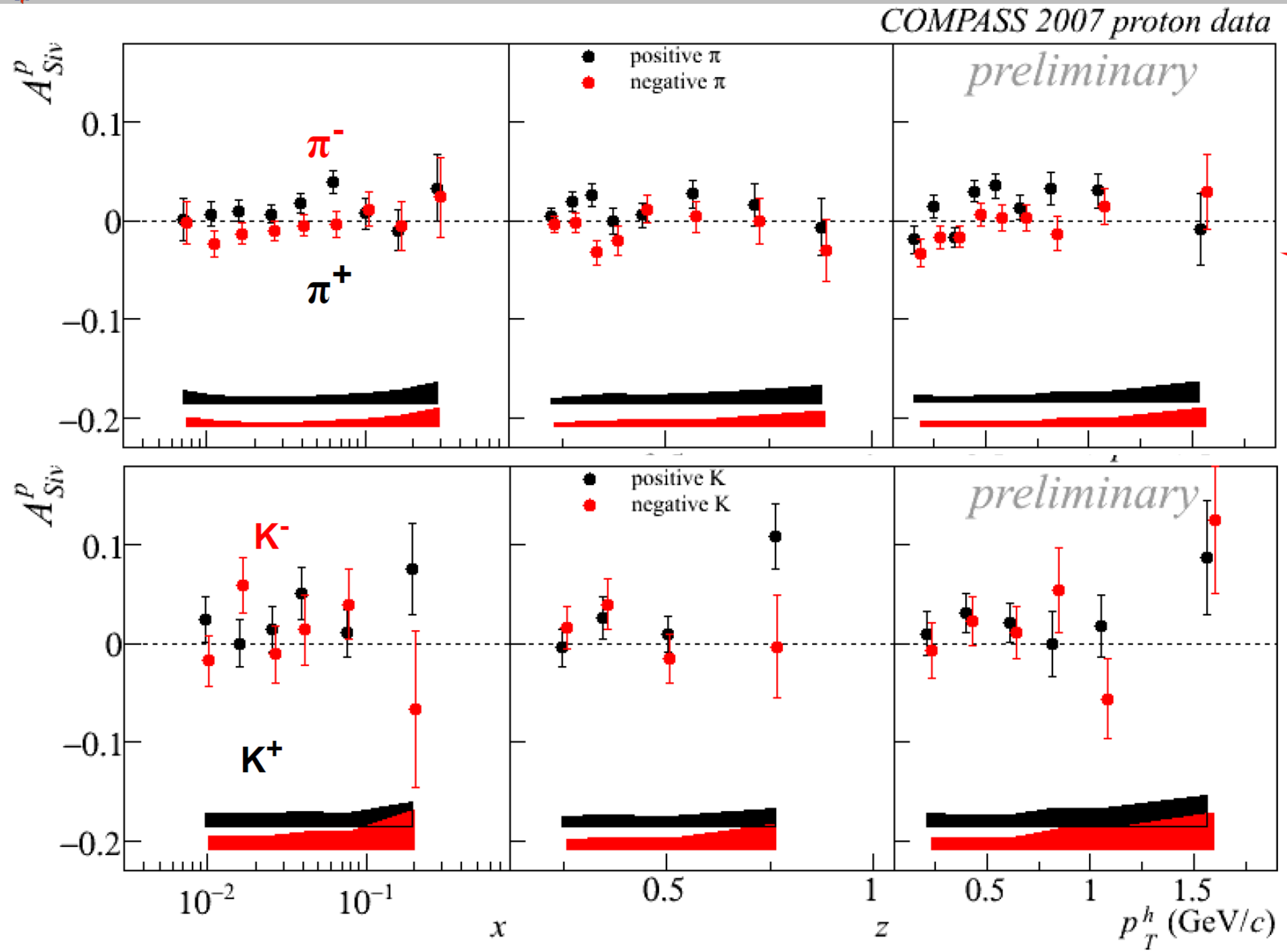
Correlation between k_T (transverse momentum) and transverse spin

cross-section asymmetry:

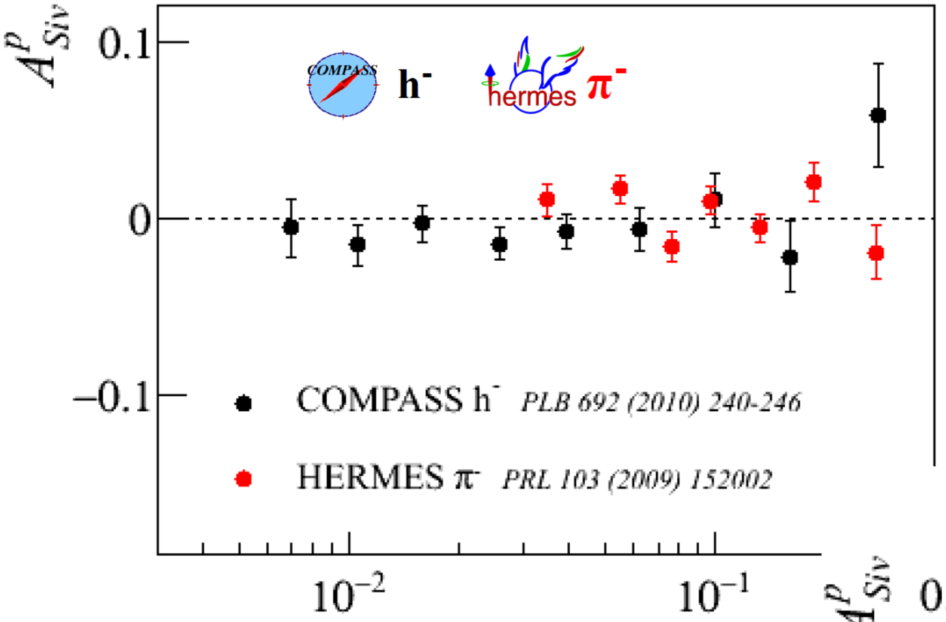
$$\frac{\Delta\sigma}{\sigma} = |\vec{S}_\perp| \times A_{Siv} \times \sin(\phi_S)$$

$$\phi_S = \phi_h - \phi_S$$

COMPASS Sivers asymmetry (proton)

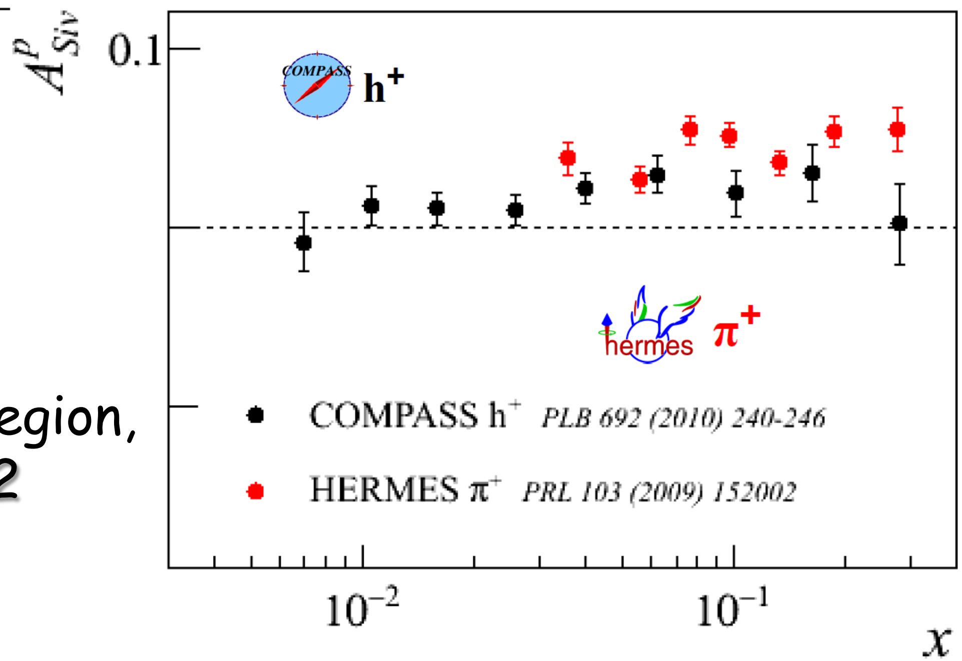


Sivers proton (COMPASS vs HERMES)



gc

- Good agreement



- Same sign
- Compass result in overlap region, smaller by a factor of ~2

Conclusions (Transverse)

- SIDIS is an excellent tool to study the transverse structure of the nucleon

- Solid evidence for:
  - Transversity PDF to be different from zero
  - Sivers function to be different from zero

- Still important points to be clarified
  - New results expected from 2010 COMPASS

to know more: http//ecsac.ictp.it/transversity2011

Possible scenarios

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q+g}$$

$$\frac{1}{2}0.3 + 0.35 + 0.0$$

$$\frac{1}{2}0.3 + 0.0 + 0.35$$

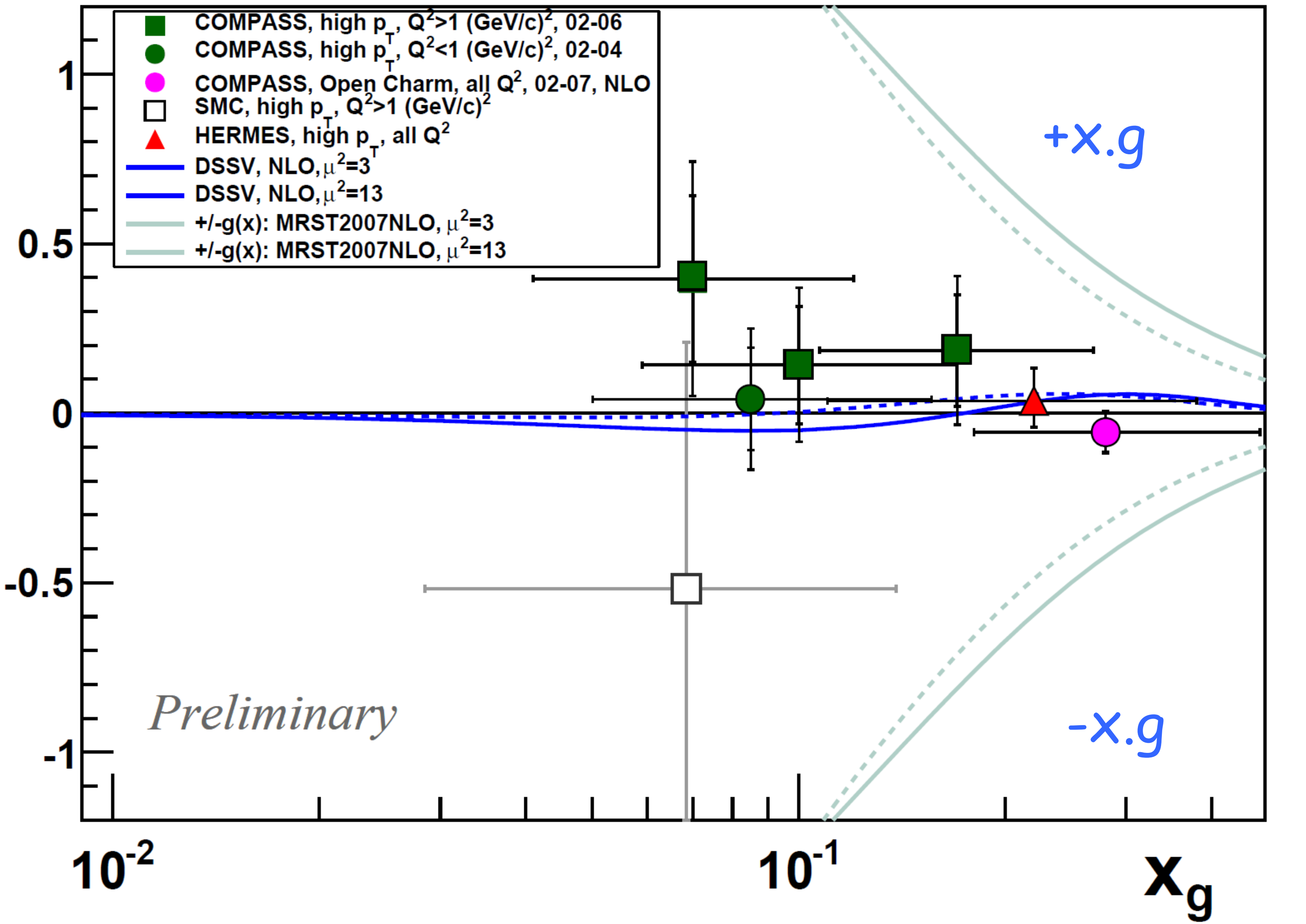
$$\frac{1}{2}0.3 - 0.35 + 0.70$$

- Orbital momentum ?
- Need to study GPDs, also TMDs

COMPASS-II programme

Spare slides

xΔG



COMPASS, high p_T, Q^2>1 (GeV/c)^2, 02-06
COMPASS, high p_T, Q^2<1 (GeV/c)^2, 02-04
COMPASS, Open Charm, all Q^2, 02-07, NLO
SMC, high p_T, Q^2>1 (GeV/c)^2
HERMES, high p_T, all Q^2
DSSV, NLO, μ^2=3
DSSV, NLO, μ^2=13
+/-g(x): MRST2007NLO, μ^2=3
+/-g(x): MRST2007NLO, μ^2=13
+x.g
-x.g
Preliminary
xΔg
1
0.5
0
-0.5
-1
10^{-2}
10^{-1}
x_g