Helicity distributions from DIS

Eva-Maria Kabuß

Institut für Kernphysik, Mainz

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bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

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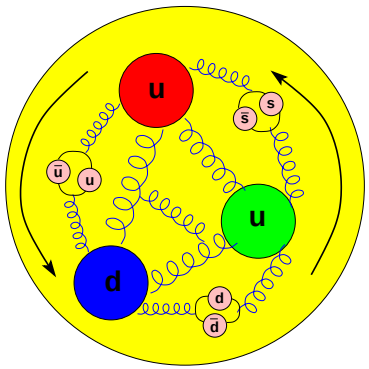
Motivation: Nucleon spin puzzle

$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



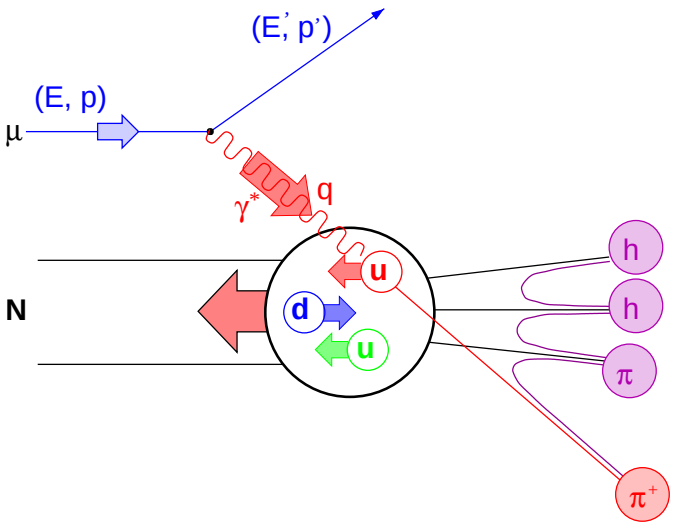
Accessible in

$\Delta\Sigma$, Δs	inclusive DIS
Δu,Δd,Δs	semi-inclusive DIS
ΔG	PGF in DIS
L_q	DVCS

Content

- Experiments
- Spin structure functions
- Sum rules
- Gluonpolarisation
- Quarkpolarisation

Deep inelastic scattering



$$Q^2 = -q^2$$
$$\nu = E - E'$$
$$x = Q^2/2M\nu$$

$$z = E_\mathrm{h}/\nu$$
p_T^h : transverse momentum

- **Inclusive cross section**

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}E'} \sim \underbrace{c_1 F_1(x, Q^2) + c_2 F_2(x, Q^2)}_{\text{spin independent}} + \underbrace{c_3 g_1(x, Q^2) + c_4 g_2(x, Q^2)}_{\text{spin dep. structure functions}}$$

- **measured**

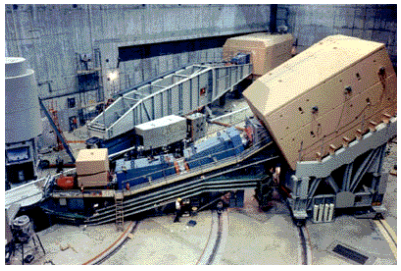
$$A_\parallel(x, Q^2) = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}} = D(A_1 + \eta A_2)$$

photon-nucleon asymmetry

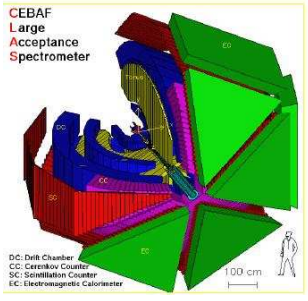
D depolarisation factor, $\uparrow$ photon, $\uparrow$ nucleon

Experiments

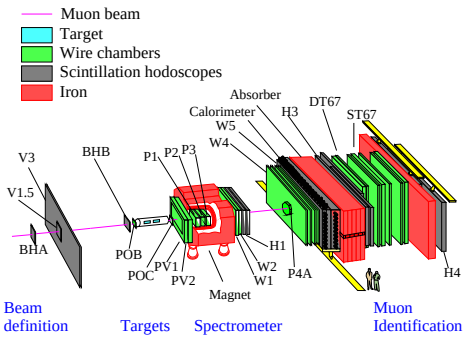
SLAC: Endstation A



JLAB: CLAS

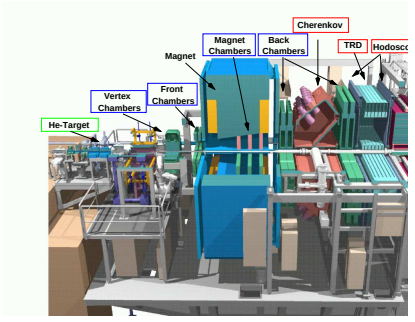


CERN: EMC,SMC

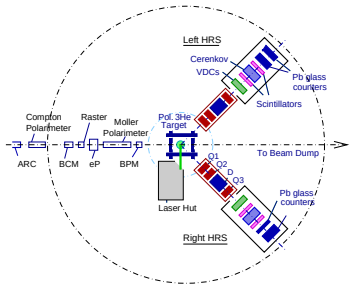


E80, E130	$\vec{e}\,\vec{p}$	$\leq$ 20 GeV
EMC	$\vec{\mu}\,\vec{p}$	100–200 GeV
E142, 143	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	$\leq$ 28 GeV
SMC	$\vec{\mu}\,\vec{p},\vec{d}$	100, 190 GeV
E154, 155	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	$\leq$ 50 GeV
HERMES	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	27.5 GeV
COMPASS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

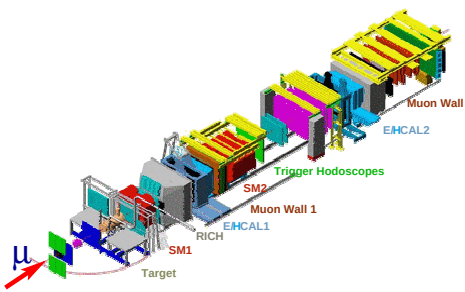
DESY: HERMES



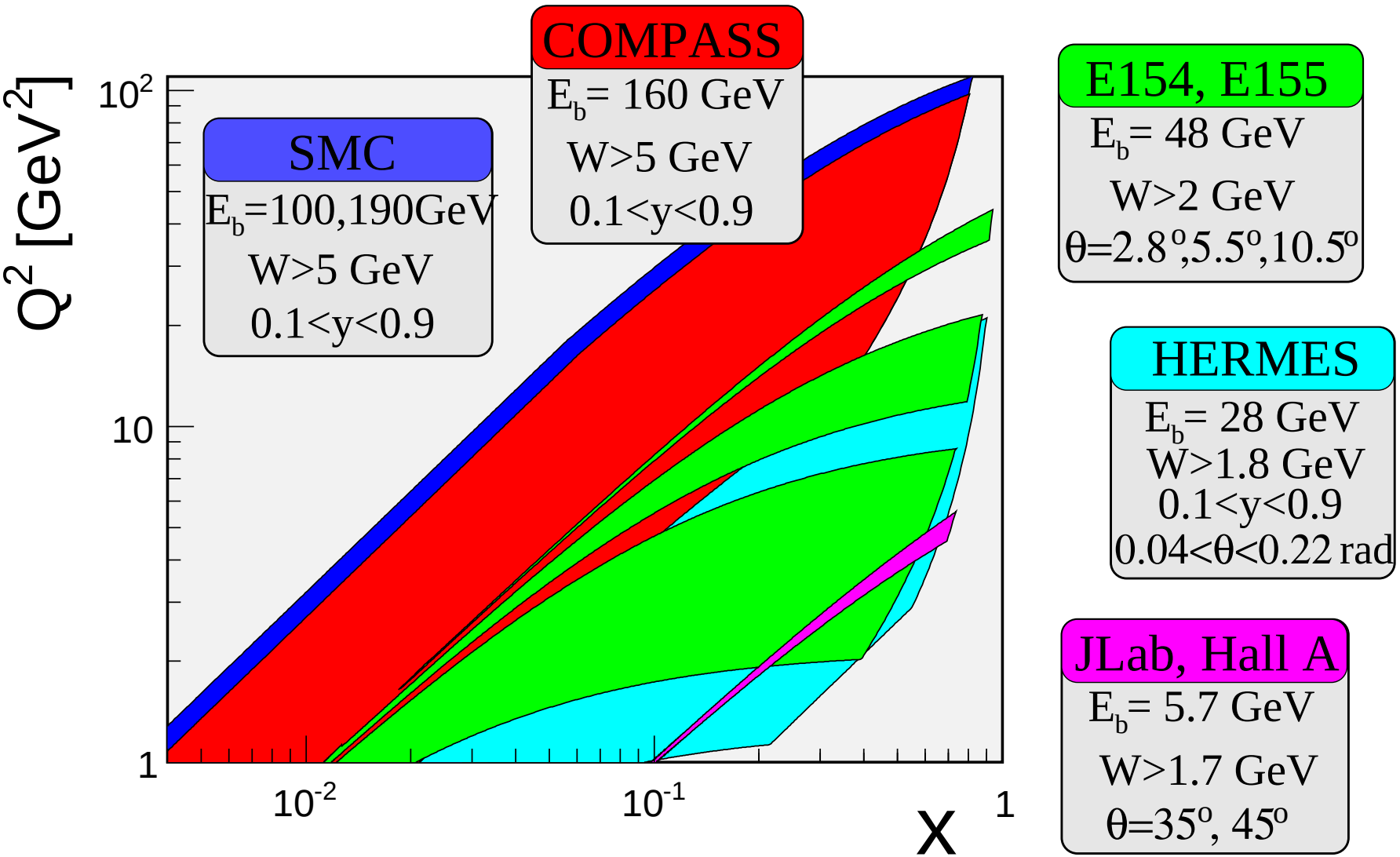
JLAB: E99-117



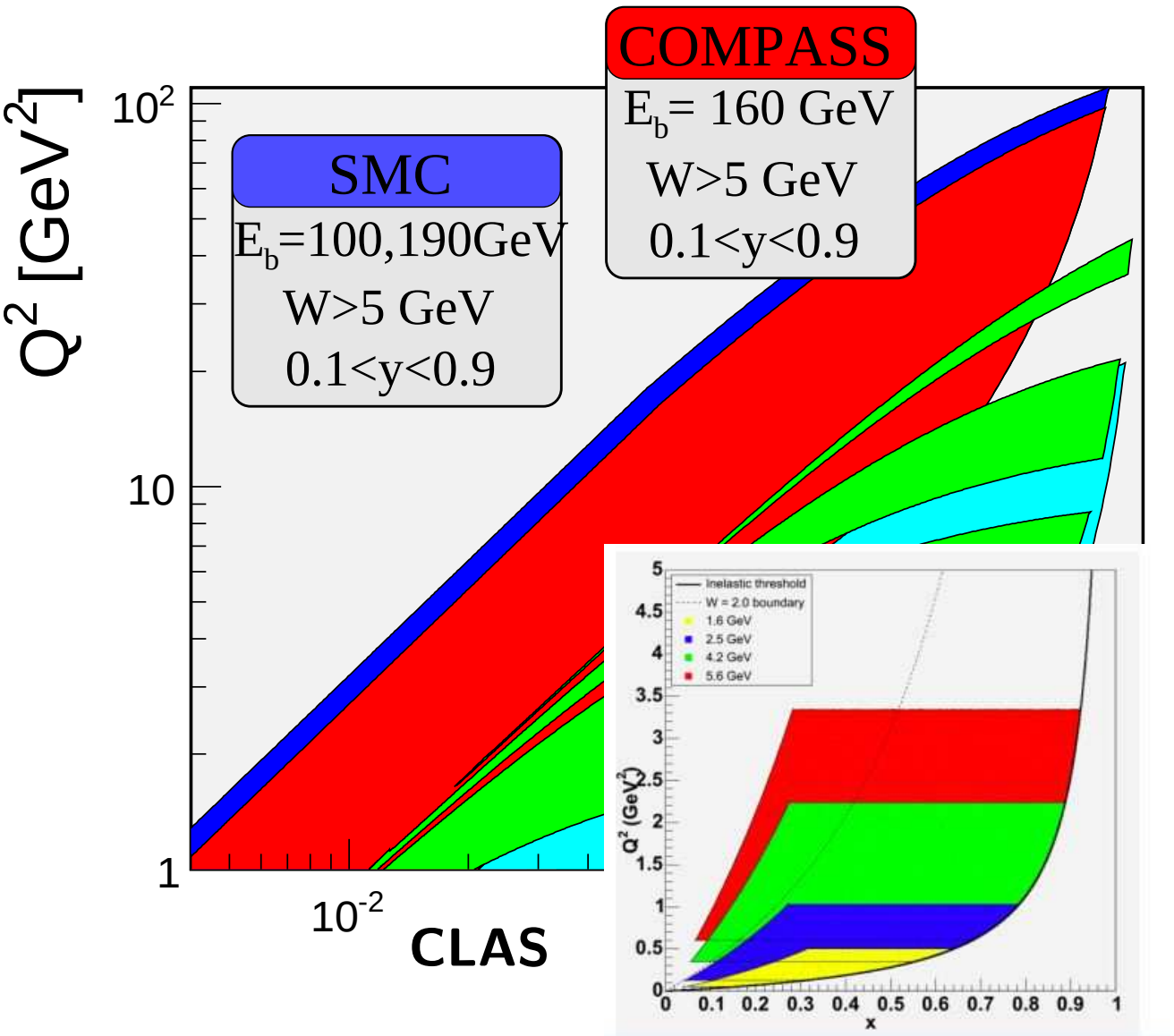
CERN: COMPASS



Kinematic domain of pDIS experiments



Kinematic domain of pDIS experiments



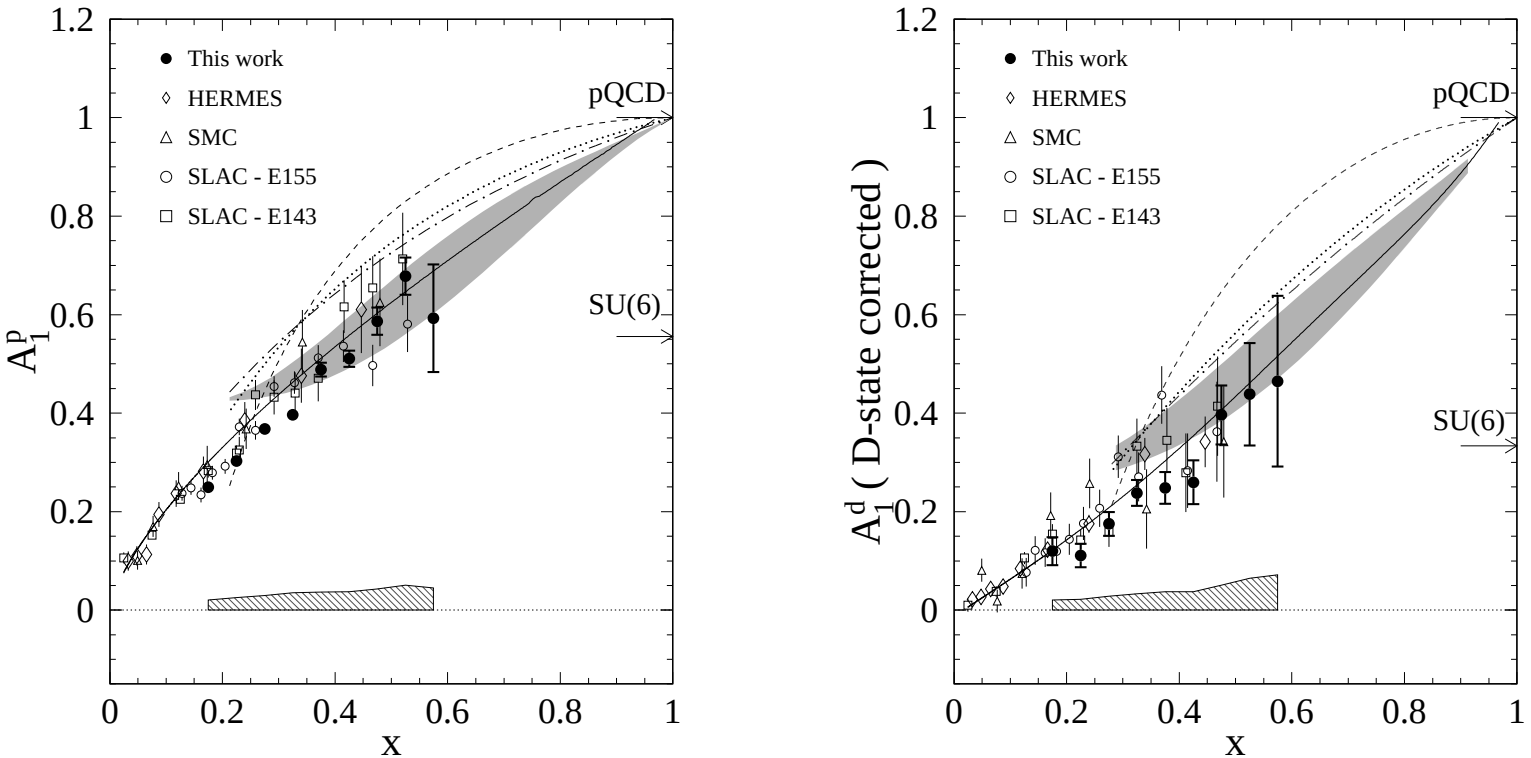
E154, E155
E_b= 48 GeV
W>2 GeV
θ=2.8°,5.5°,10.5°

HERMES
E_b= 28 GeV
W>1.8 GeV
0.1<y<0.9
0.04<θ<0.22 rad

JLab, Hall A
E_b= 5.7 GeV
W>1.7 GeV
θ=35°, 45°

Inclusive Asymmetries

$A_1^{p,d}$ at large x



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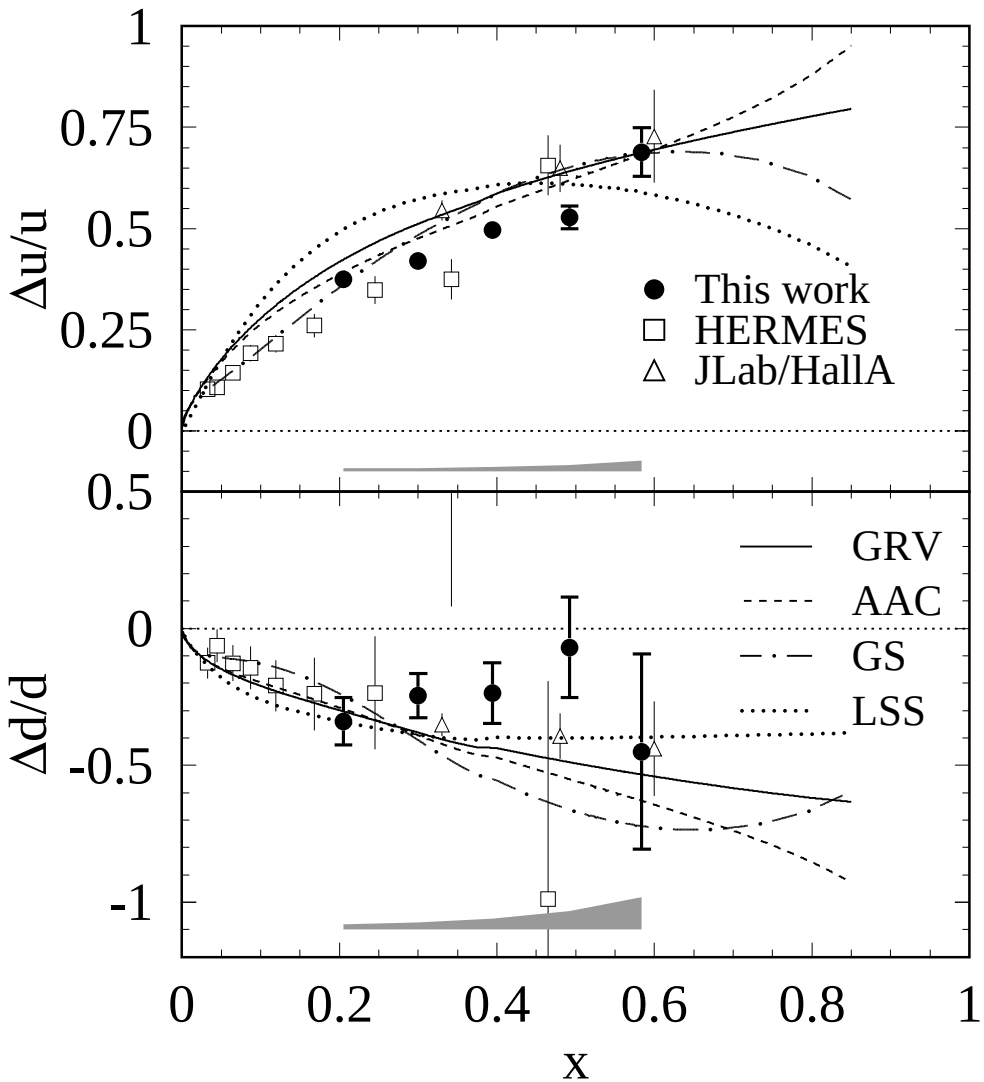
- CLAS data slightly below the other experiments at low x
- also slighlty below pQCD parametr. at 10 $(\mathrm{GeV}/c)^2$ (solid line)
- in reasonable agreement with model with SU(6) symmetry breaking (shaded area)

Quark polarisation in the valence region

$$A_1(x) \approx \frac{g_1(x)}{F_1(x)} \overset{LO}{=} \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)}$$

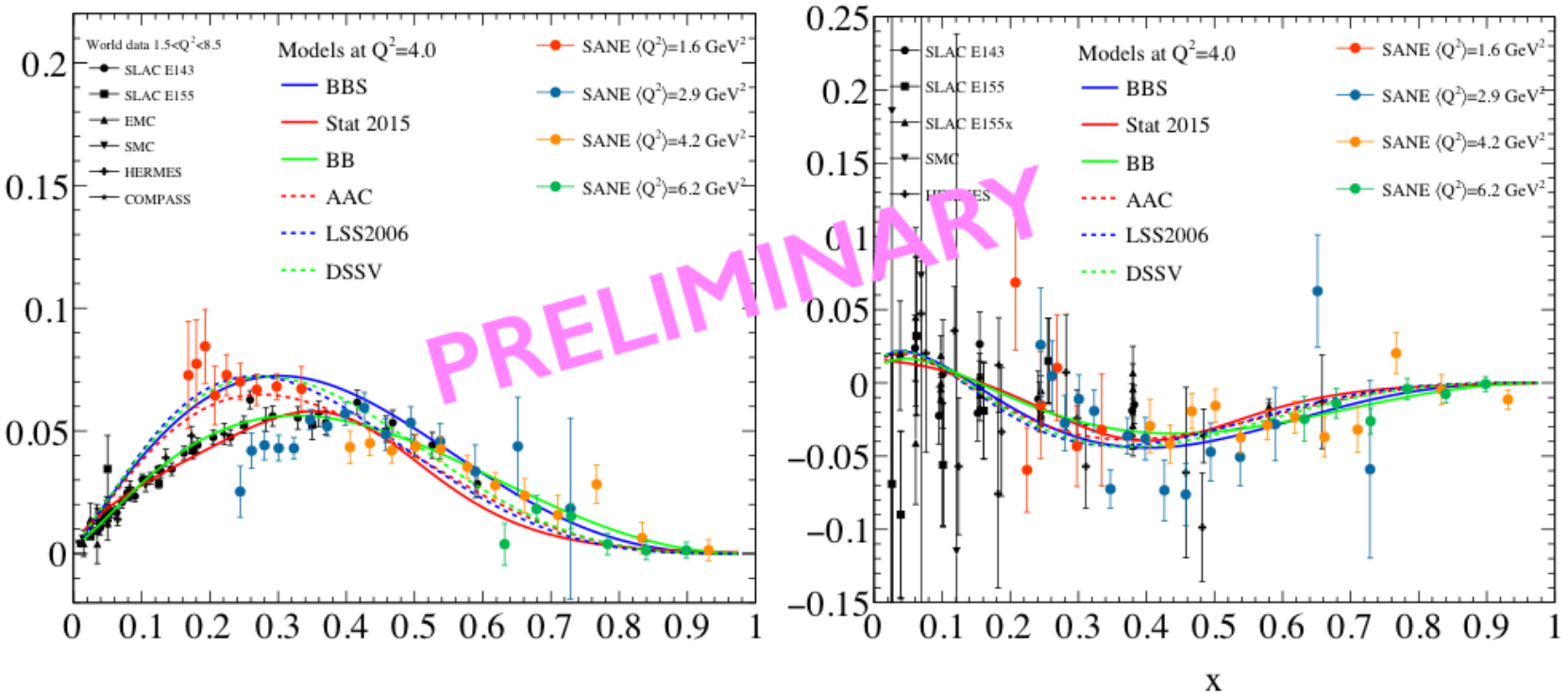
with $q(x)$ unpol., $\Delta q(x)$ pol. PDFs

- $A_1^{p,d}$ can be used to extract $\Delta u/u$ and $\Delta d/d$ in the valence region assuming negligible sea contribution
- $\Delta u/u > 0$
  $\Delta u/u \to 1$ for $x \to 1$
- $\Delta d/d < 0$
  up to highest $x \sim 0.6$
- consistent with recent pQCD parametrisation

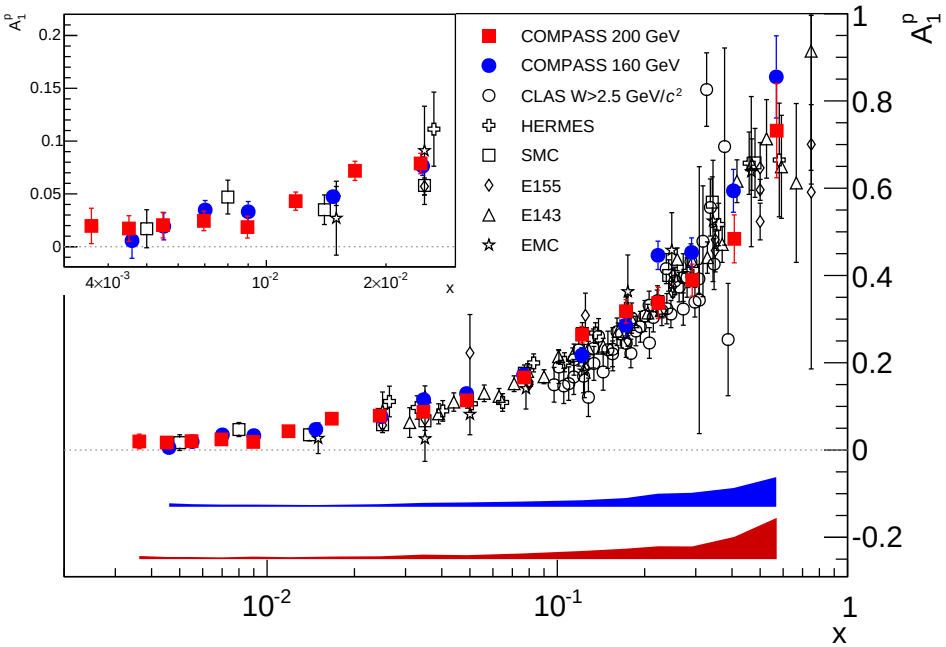


New data at large **x** from SANE

Proton g_1 and g_2



Proton Asymmetry for $Q^2 > 1\,\mathrm{GeV}^2/c^2$



- Measurement at 160 and 200 GeV
- Improvement at low x obvious
- Kinematic domain:

$$Q^2 > 1\ (\mathrm{GeV}/c)^2$$
$$0.1 < y < 0.9$$
$$0.0025 < x < 0.7$$

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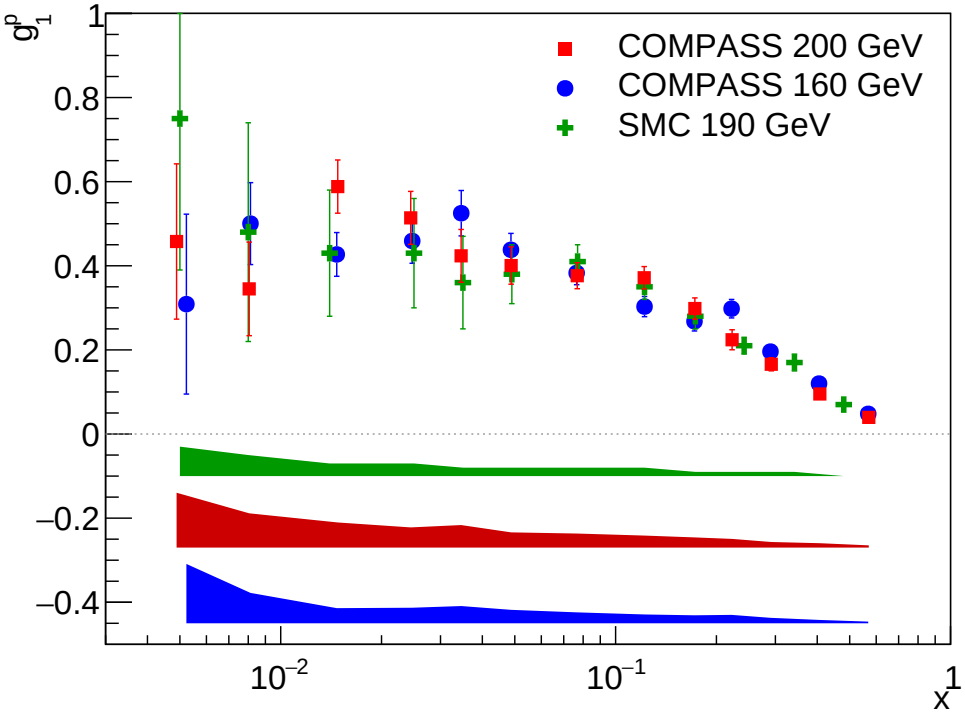
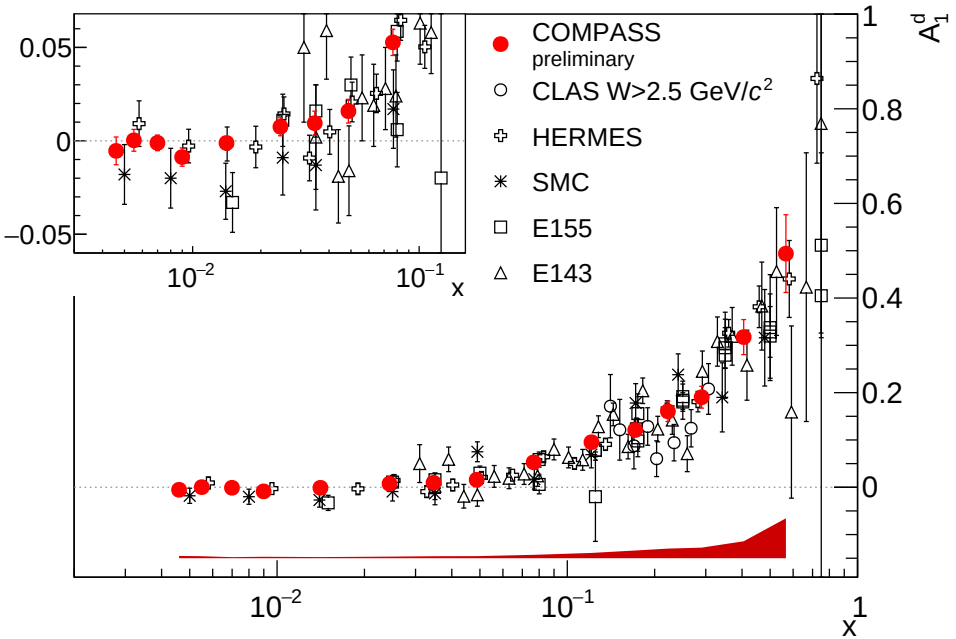
- Final proton results from COMPASS
- Good agreement of world data
- Extraction of g_1:

$$g_1 = A_1\, F_1 = A_1 \frac{F_2}{2x(1+R)}$$



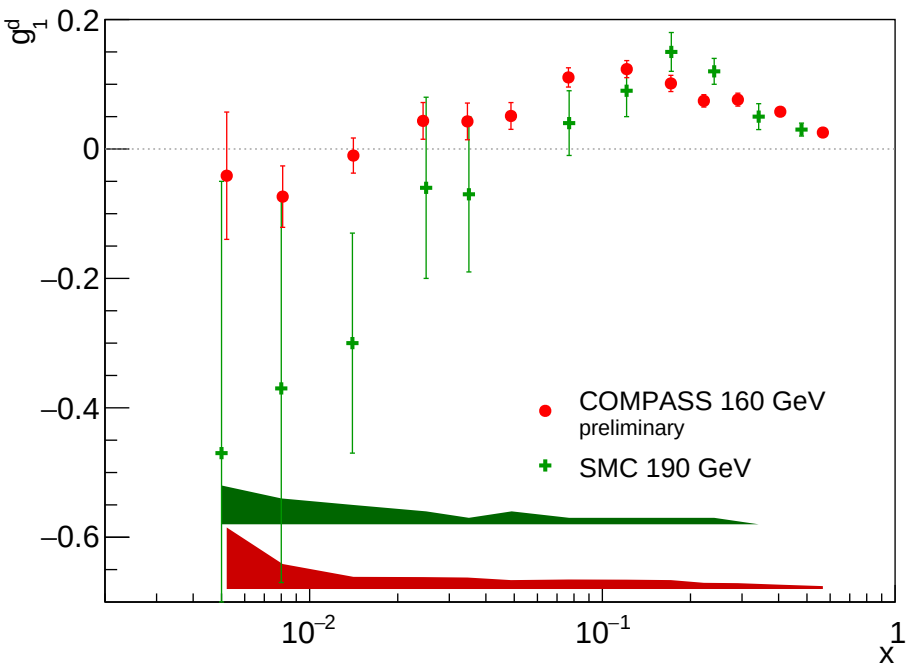
Deuteron asymmetry for $Q^2 > 1\,\mathrm{GeV}^2/c^2$



- Published results from 2002-2004
- 2006 data added (factor 2)
- Kinematic domain:

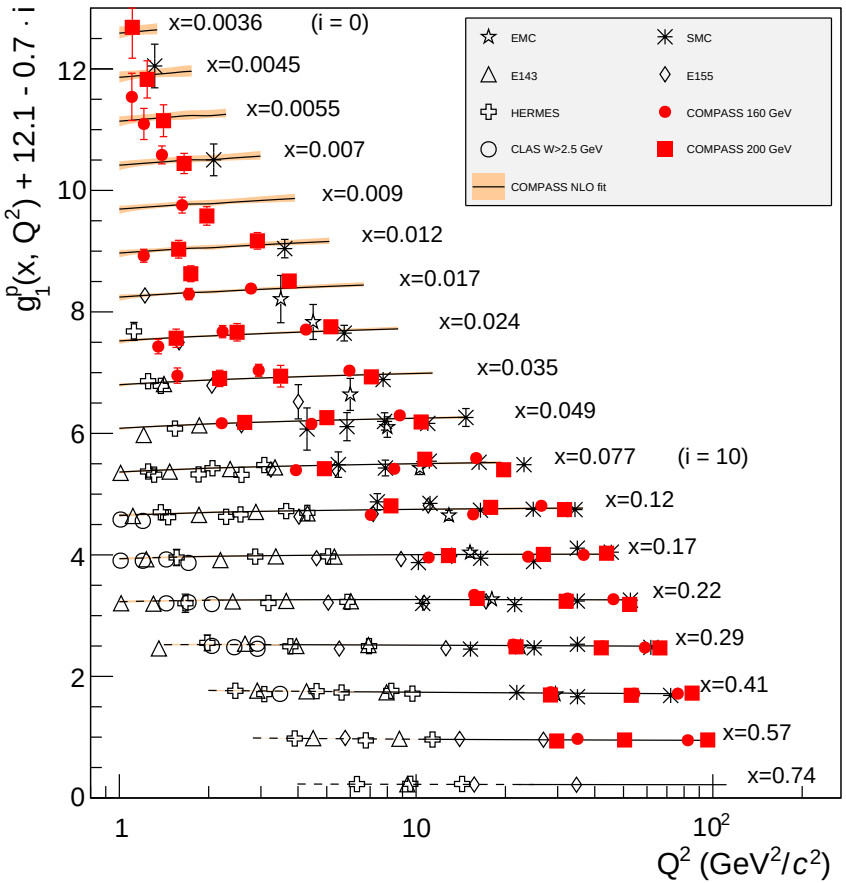
$$Q^2 > 1\ (\mathrm{GeV}/c)^2$$
$$0.1 < y < 0.9$$
$$0.004 < x < 0.7$$

- Final deuteron results from COMPASS
- Supercede PLB 647 (2007) 8
- g_1^{d} compatible with zero at low x

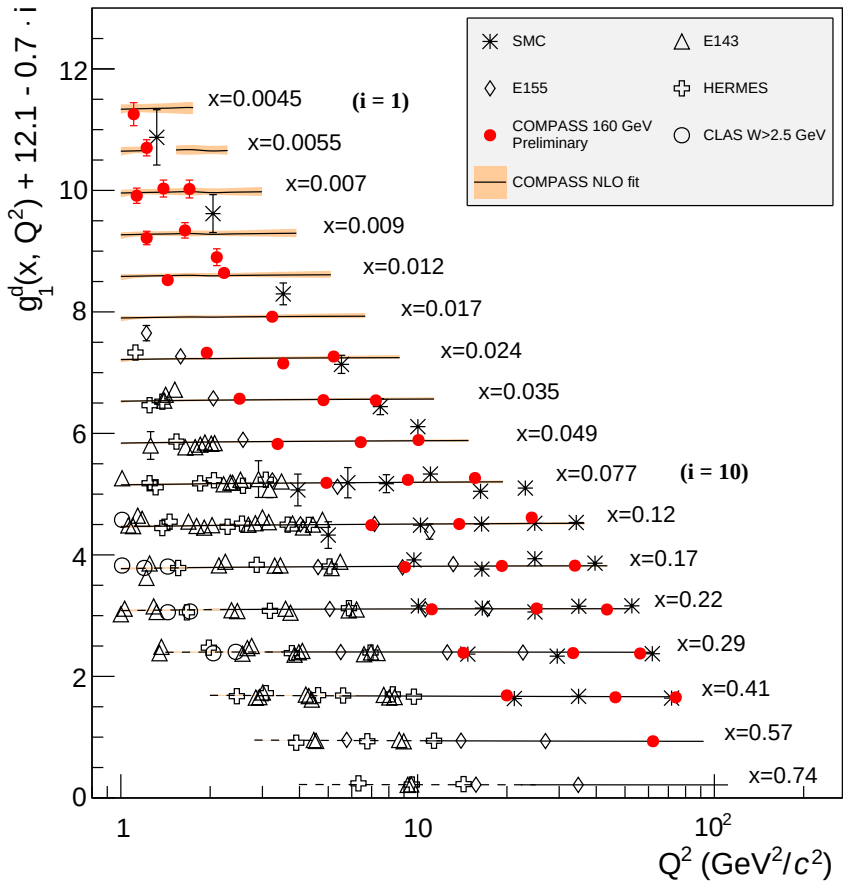


World data for spin structure functions

Proton



Deuteron



- good coverage in x and Q^2
- NLO pQCD analysis of proton, deuteron and neutron (^{3}He) data
- detailed study of systematics related to functional form

COMPASS QCD analysis

- **spin structure function g_1**

$$g_1(x,Q^2) = \frac{1}{2}\langle e^2\rangle \left[C_{NS} \otimes \Delta q_{NS} + C_S \otimes \Delta q_S + 2n_f C_g \otimes \Delta g\right]$$

- **DGLAP equations**

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\Delta q_{NS} = \frac{\alpha_s(Q^2)}{2\pi}\,\Delta P_{qq}^{NS} \otimes \Delta q_{NS}$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\begin{pmatrix}\Delta q_S\\ \Delta g\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}\Delta P_{qq}^S & 2n_f\Delta P_{qg}\\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q_S\\ \Delta g\end{pmatrix}$$

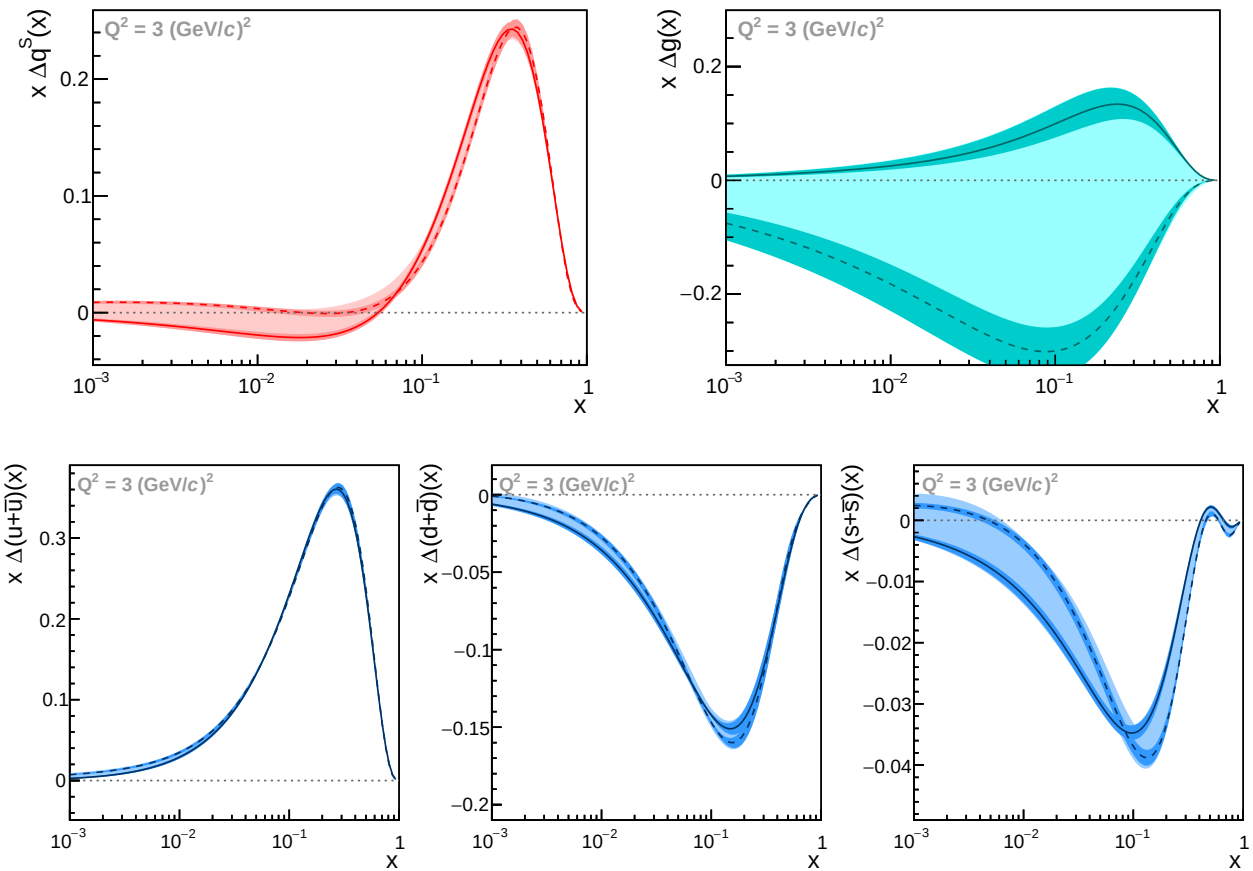
- **input parameterization at Q_0^2**

$$(\Delta q_S, \Delta q_3, \Delta q_8, \Delta g) = \eta\frac{x^\alpha(1-x)^\beta(1+\gamma x)}{\int_0^1 x^\alpha(1-x)^\beta(1+\gamma x)\mathrm{d}x}$$

with $\Delta q_s = \Delta u + \Delta d + \Delta s$, $\Delta q_3 = \Delta u - \Delta d$,
$\Delta q_8 = \Delta u + \Delta d - 2\Delta s$

- **constraints used for first moments of $\Delta q_{3,8}$**

Polarised PDFs at $Q^2 = 3\ (\mathrm{GeV}/c)^2$



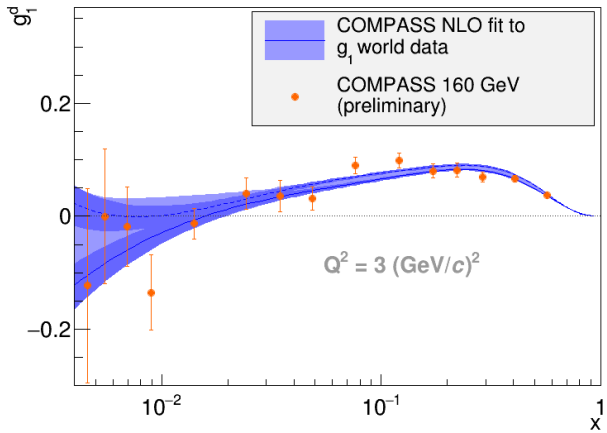
- quark contribution $0.26 < \Delta\Sigma < 0.36$,
  dominant uncertainty functional form of Δg
- strange quark contribution small and negative (constraint on Δq_8)
- gluon contribution $\Delta G = \int \Delta g(x)\mathrm{d}x$ not well constrained

$\Longrightarrow$ **direct measurement needed**

First moment of g_1^d $(Q^2 = 3\,(\mathrm{GeV}/c)^2)$

$$\Gamma_1^{\mathrm{N}}(Q^2) = \int_0^1 \frac{1}{1-1.5\omega_d} g_1^{\mathrm{d}}(x, Q^2)\mathrm{d}x = \frac{1}{36}[4a_0\Delta C^{\mathrm{S}} + a_8\Delta C^{\mathrm{NS}}]$$

- axial charges:
  a_8, a_3 first moments of Δq_8, Δq_3
  in $\overline{\mathrm{MS}}$: $a_0 = \Delta\Sigma$ (first moment of Δq_S)
- only COMPASS g_1^{d} used (prelim.)
- g_1^{d} evolved using QCD fit



- 97% of Γ_1^{N} in measured range, extrapolation using NLO QCD fit

$$\Gamma_1^{\mathrm{N}} = 0.047 \pm 0.002(\mathrm{stat}) \pm 0.004(\mathrm{syst}) \pm 0.004(\mathrm{evol})$$

- using a_8 from hyperon decays (SU(3) symmetry)

$$a_0 = 0.32 \pm 0.02(\mathrm{stat}) \pm 0.04(\mathrm{syst}) \pm 0.04(\mathrm{evol})$$

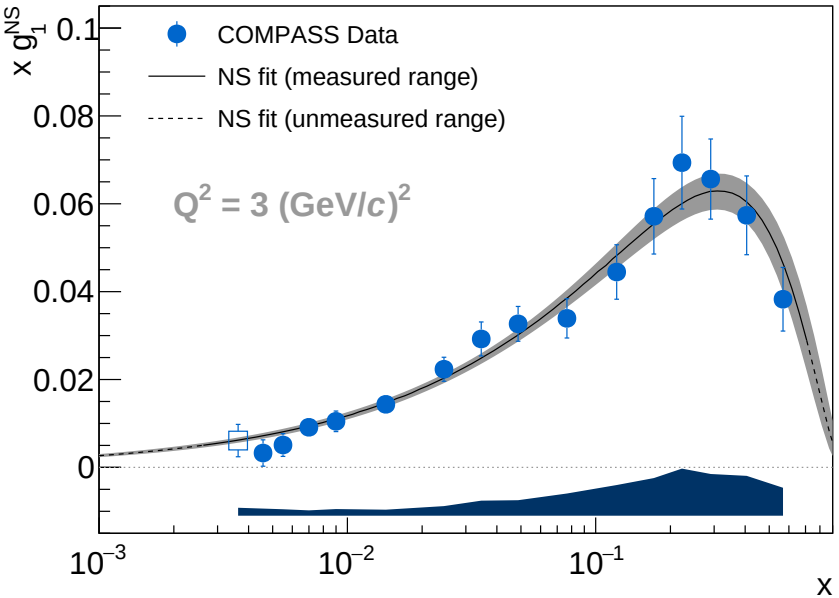
- with $\Delta S = \frac{1}{3}(a_0 + a_8)$: negative strange sea polarisation

$$\Delta S = -0.088 \pm 0.007(\mathrm{stat}) \pm 0.012(\mathrm{syst}) \pm 0.015(\mathrm{evol})$$

Non-singlet structure function

- **non-singlet structure function**

$$g_1^{\mathrm{NS}} = g_1^{\mathrm{p}} - g_1^{\mathrm{n}} = \frac{1}{6}(\Delta u - \Delta d)$$
$$= 2\left[g_1^{\mathrm{p}} - \frac{g_1^{\mathrm{d}}}{1 - 1.5\omega_{\mathrm{D}}}\right]$$



- **Bjorken sum rule**

$$\int_0^1 g_1^{\mathrm{NS}}\mathrm{d}x = \frac{1}{6}\underbrace{\left|\frac{g_A}{g_V}\right|}_{a_3}^{n\to p} C^{\mathrm{NS}}$$

  - QCD fit of COMPASS data alone: $\Delta q_{\mathrm{NS}} \sim x^{\alpha}(1-x)^{\beta}$

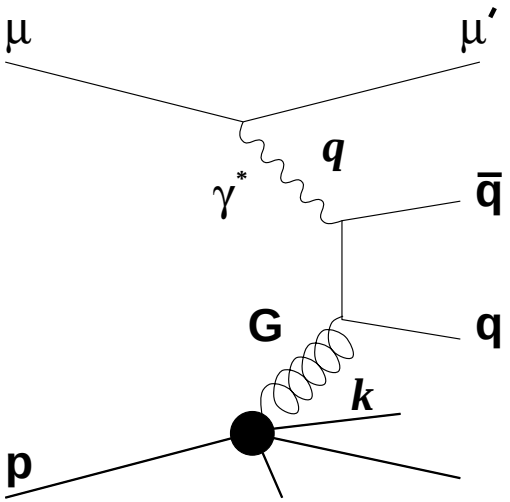
$$\mathbf{g_A/g_V = 1.22 \pm 0.05(stat) \pm 0.10(syst)}$$

  - dominant systematic errors: beam and target polarisation
  - PDG value: $g_A/g_V = 1.2701 \pm 0.0020$

Gluon polarisation

Direct measurements of gluon polarisation

Photon gluon fusion



$$A_{\gamma N}^{PGF} = \frac{\int d\hat{s}\, \Delta\sigma^{PGF} \Delta G(x_g, \hat{s})}{\int d\hat{s}\, \sigma^{PGF} G(x_g, \hat{s})}$$

$$\approx \langle a_{LL}^{PGF} \rangle \frac{\Delta G}{G}$$

$\langle a_{LL}^{PGF} \rangle$ analysing power

Direct methods

- **Open charm production**

  $\gamma g \to c\bar{c}$

  $\to D^0, D^*$

  hard scale: M_c^2
  theoretically clean channel,
  low staticstics

- **High p_T hadron pairs**

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

  $\to$ 2 jets or H^+H^-

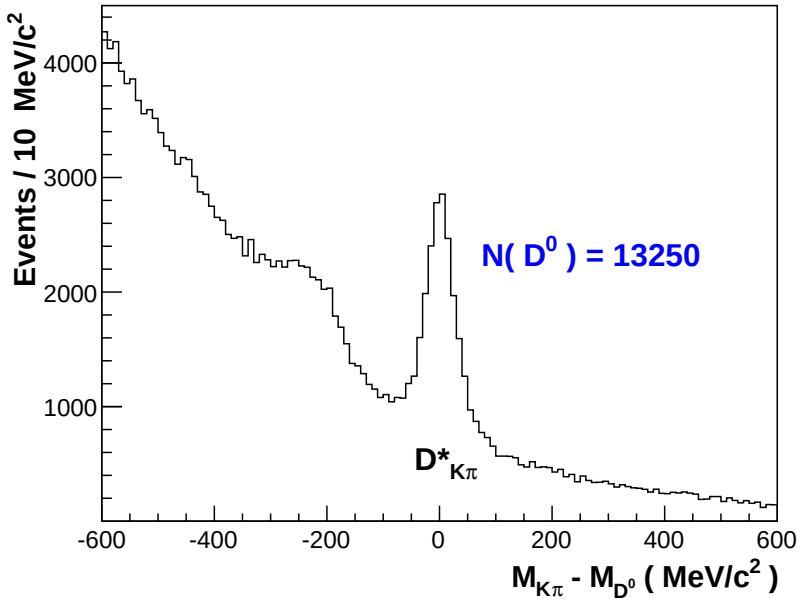
  hard scale: Q^2 or Σp_T^2
  high statistics
  contributions from background processes

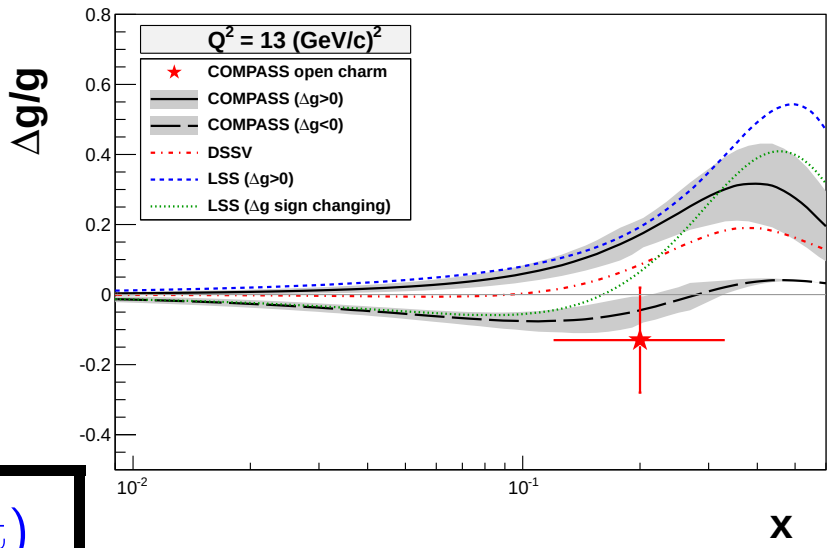
Open charm production

- **channels investigated**

$$
\begin{aligned}
D^* &\rightarrow D^0\pi_{\mathrm{slow}} \rightarrow K\pi\pi_{\mathrm{slow}} \\
D^* &\rightarrow D^0\pi_{\mathrm{slow}} \rightarrow K\pi\pi^0\pi_{\mathrm{slow}} \\
D^* &\rightarrow D^0\pi_{\mathrm{slow}} \rightarrow K\pi\pi\pi_{\mathrm{slow}} \\
D^0 &\rightarrow K\pi
\end{aligned}
$$

- all deuteron and 2007 proton data
  PRD 87 (2013) 052018
- all Q^2, a_{LL} in NLO
- scale $\mu^2 \approx 13\ (\mathrm{GeV}/c)^2$
- improved analysis method
- result at $x_{\mathrm{g}} = 0.11$



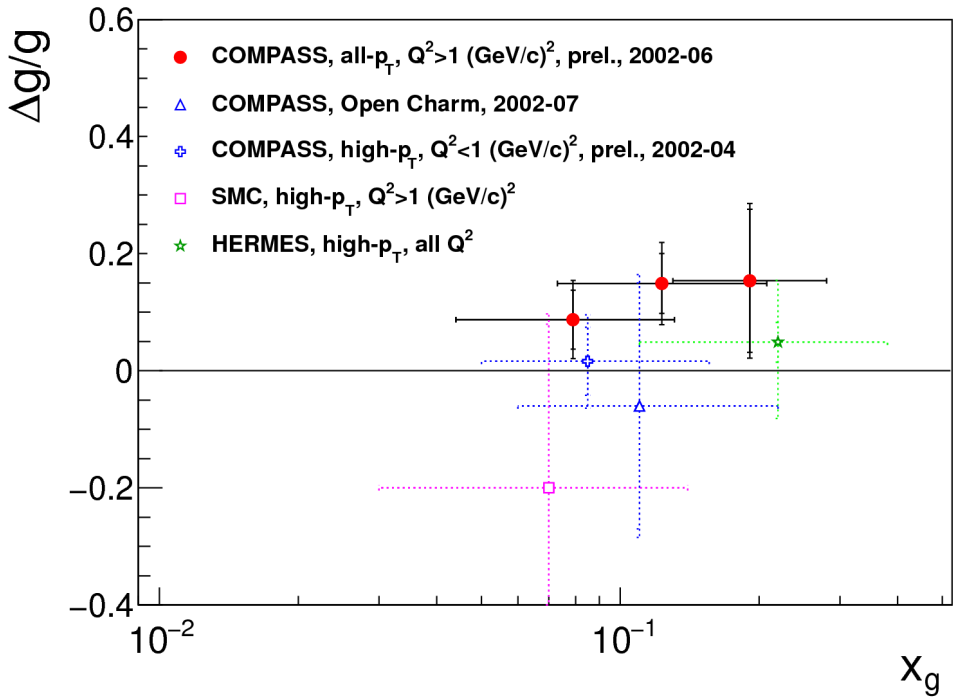


$$\Delta g/g^{\mathrm{NLO}} = -0.13 \pm 0.15(\mathrm{stat}) \pm 0.15(\mathrm{syst})$$

LO Results for gluon polarisation

High p_T hadrons (pairs): $\gamma g \to q\bar{q} \to H^+H^-$ or H

- high statistics
- but contributions from several background processes
- estimated from MC simulation
- neural network to disentangle processes



- new analysis: single hadron production asXiv:1512.05053
- simultaneous extraction of leading process and PGF asymmetry

$$\Delta g/g^{\mathrm{LO}} = 0.113 \pm 0.038_{\mathrm{stat}} \pm 0.035_{\mathrm{syst}}$$

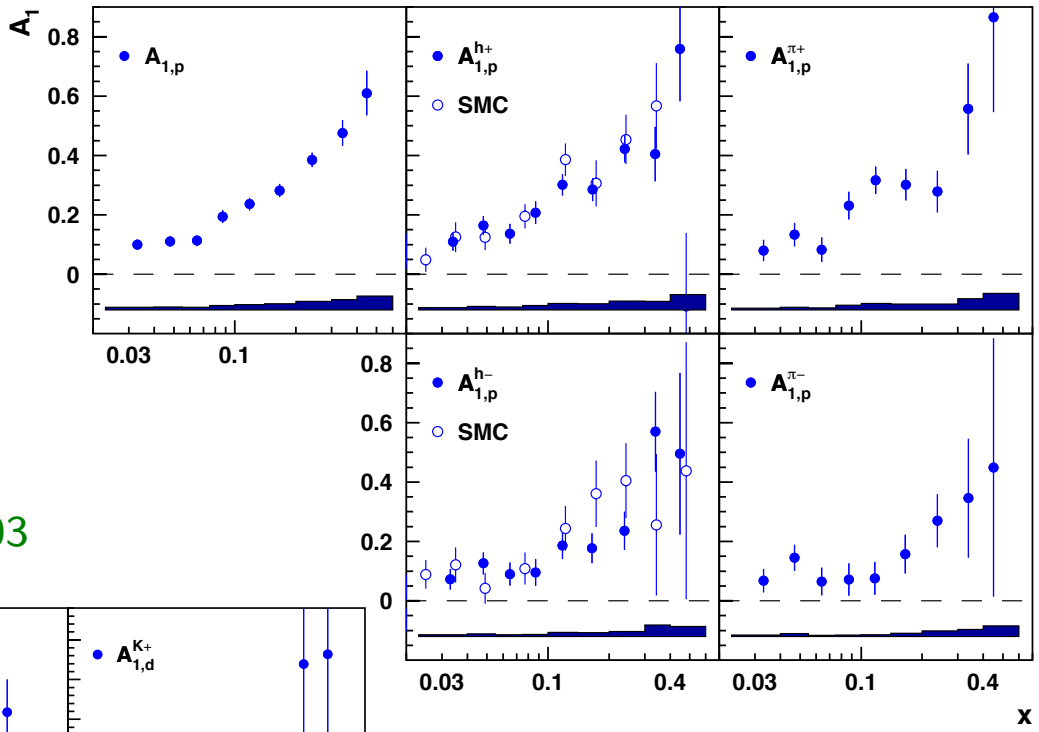
- first direct measurement of positive $\Delta g/g$, results also in 3 bins

Semi-Inclusive Asymmetries

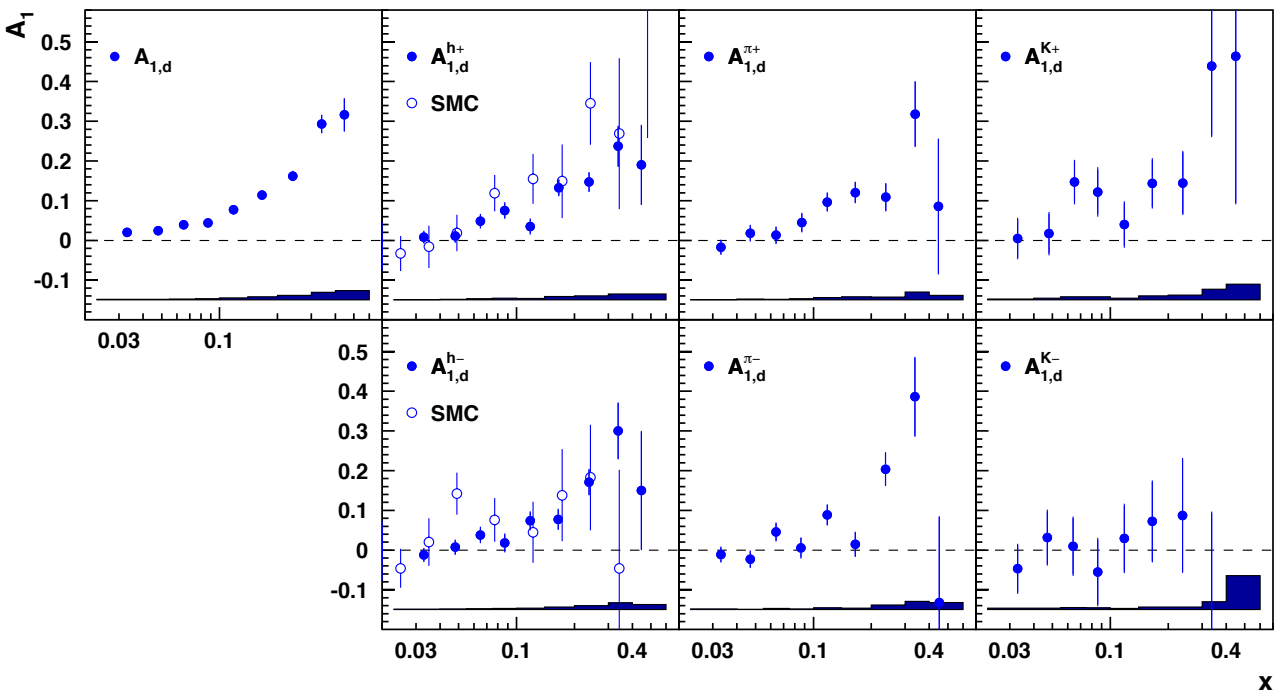
The data: HERMES

- **Kinematic domain:**

$Q^2 > 1\ (\mathrm{GeV}/c)^2$
$W^2 > 10\ \mathrm{GeV}/c^2$
$y < 0.85$
$0.2 < z < 0.8$
$0.023 < x < 0.6$



PRD 71 (2005) 012003

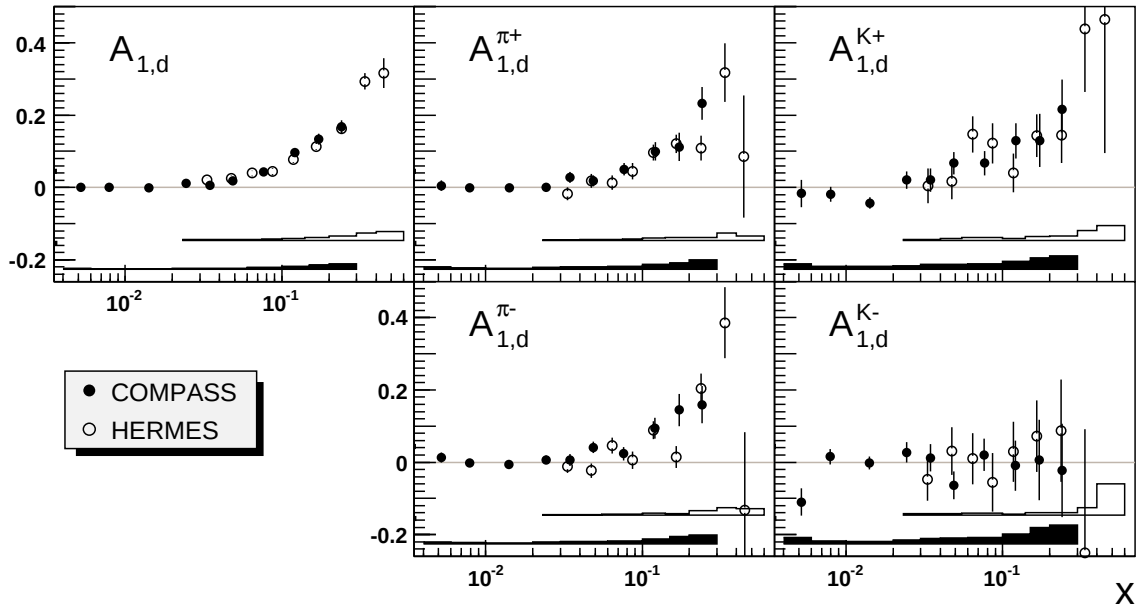


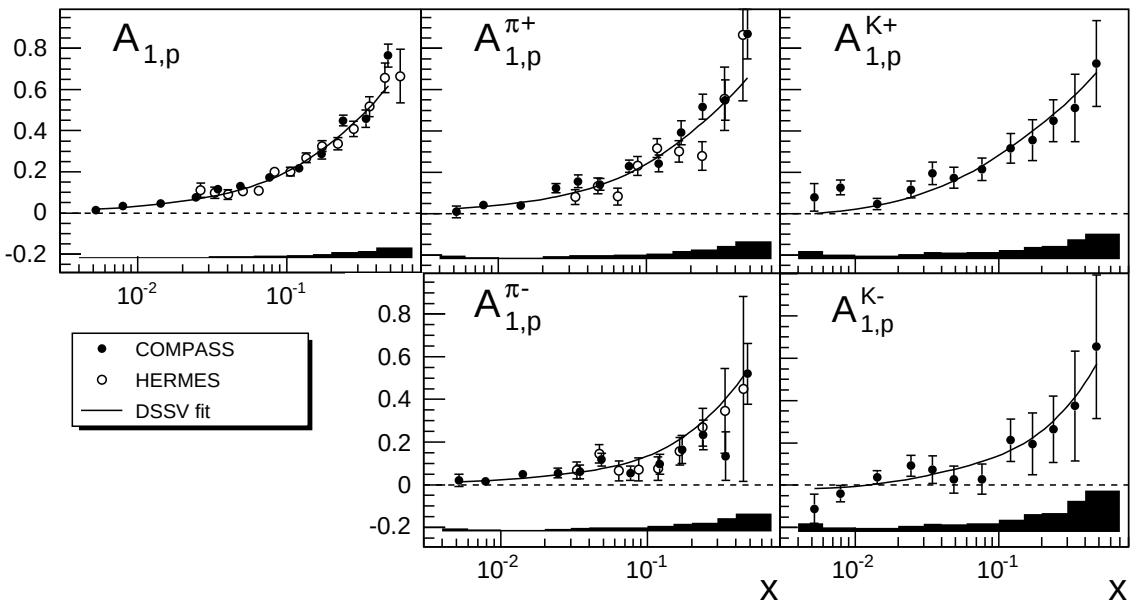
- deuteron, proton
- identified kaons and pions
- h^+ and h^- from SMC

The data: COMPASS

- **Kinematic domain:**

$Q^2 > 1\ (\mathrm{GeV}/c)^2$
$0.1 < y < 0.9$
$0.2 < z < 0.85$
$0.004 < x < 0.3$

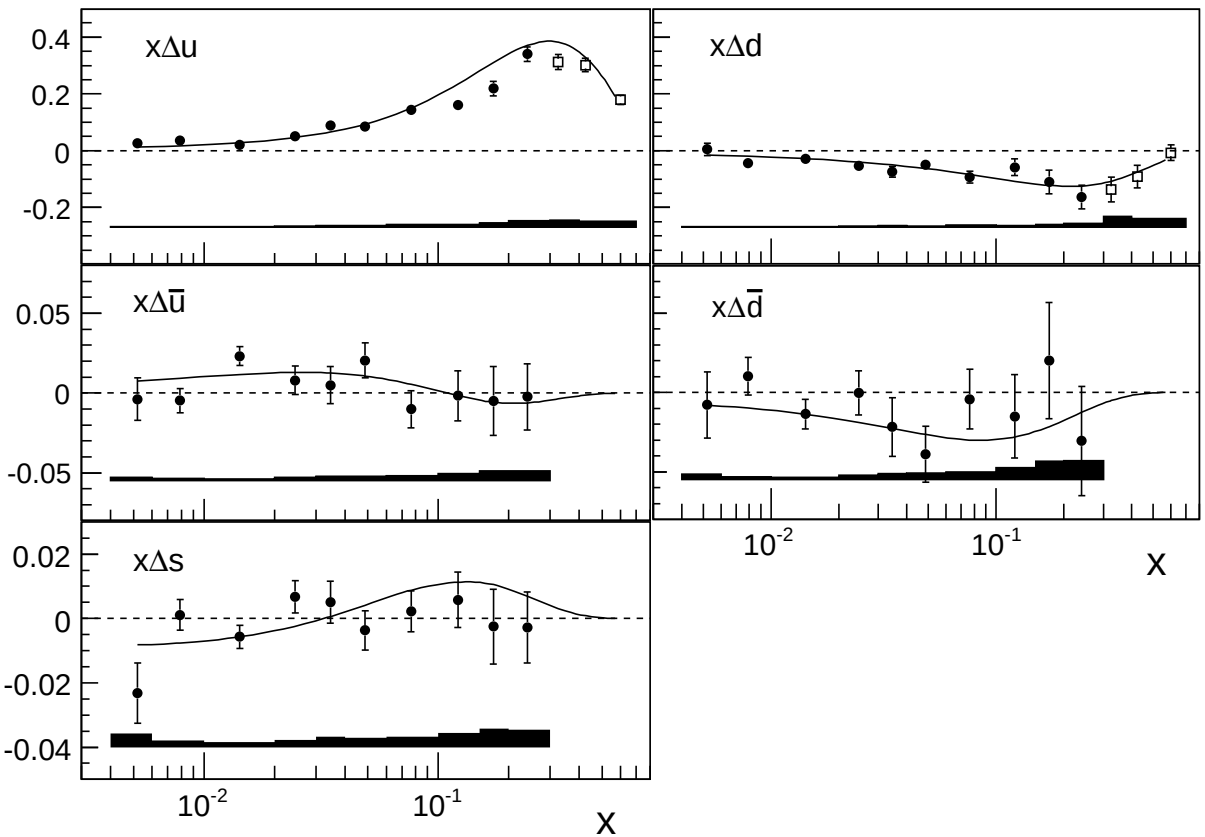




- Deuteron: 2002–2006
  PLB 680 (2009) 217
- Proton: 2007
  PLB 693 (2010) 227

Flavour separation

$$A_1^h = \frac{\sum_q e_q^2 \Delta q(x) \int D_q^h(z) \mathrm{d}z}{\sum_q e_q^2 q(x) \int D_q^h(z) \mathrm{d}z}$$



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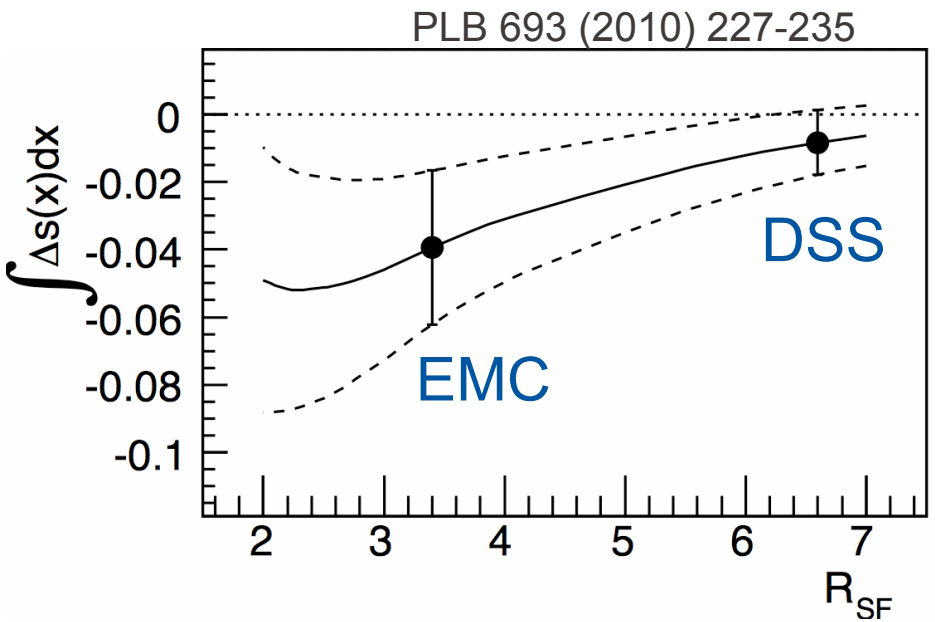
Basic concept

- **measured**:
  A_1^{d}, $A_{1\mathrm{d}}^{K^\pm}$, $A_{1\mathrm{d}}^{\pi^\pm}$,
  A_1^{p}, $A_{1\mathrm{p}}^{K^\pm}$, $A_{1\mathrm{p}}^{\pi^\pm}$
- **determined**:
  Δu, $\Delta \bar{u}$, Δd, $\Delta \bar{d}$,
  $\Delta s = \Delta \bar{s}$
- **inputs**:
  MRST04
  unpol. LO PDFs,
  DSS param.
  of FFs
- **curves:** DSSV param.

Observations

- all sea quark distributions compatible with zero
- good agreement with global fitfor Δu, $\Delta \bar{u}$, Δd, $\Delta \bar{d}$
- flavour symmetry breaking observed
  $\int(\Delta\bar{u} - \Delta\bar{d})\mathrm{d}x$ of similar size as $\int(\bar{u} - \bar{d})\mathrm{d}x$
- significant discrepancy of ΔS in SIDIS and in QCDfits to g_1
- result for ΔS depends on assumptions for FFs, especially strange-to-kaon FF



- large dependence on

$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{d}z}{\int D_{u}^{K^+}(z)\mathrm{d}z}$$

- better kaon FFs needed

Summary

from DIS measurements

- Inclusive measurement yield 30% contribution of quark helicity to nucleon helicity (NLO pQCD)
- Gluon polarisation small, but positive for $x \sim 0.1$ (LO pQCD)
- Non-strange quark polarisation well determined
- Discrepancy in strange quark polarisation from DIS and SIDIS measurements?
- Input from other processes like pp collisions (RHIC) needed

Future

- Data at large x from JLAB12
- Hopefully data at low x from EIC
- Investigation of orbital angular moments e.g. via deeply virtual Compton scattering