Experimental Overview on Polarised Quark Distributions

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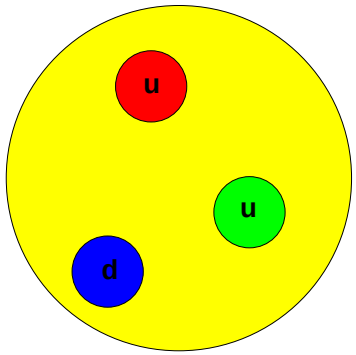
- **Introduction**
- **Longitudinal asymmetries**
- **Spin structure functions**
- **NLO QCD analysis**
- **Semi-inclusive asymmetries**
- **Flavourseparation**
- **Summary**

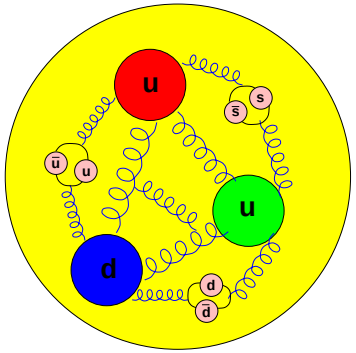
The spin of the nucleon



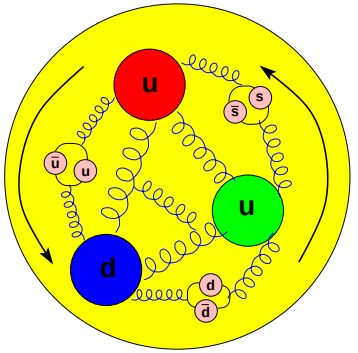
Naive parton model:
$\Rightarrow \Delta\Sigma = \Delta u_v + \Delta d_v = 1$

EMC (1987)
$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$

spin crisis (puzzle)



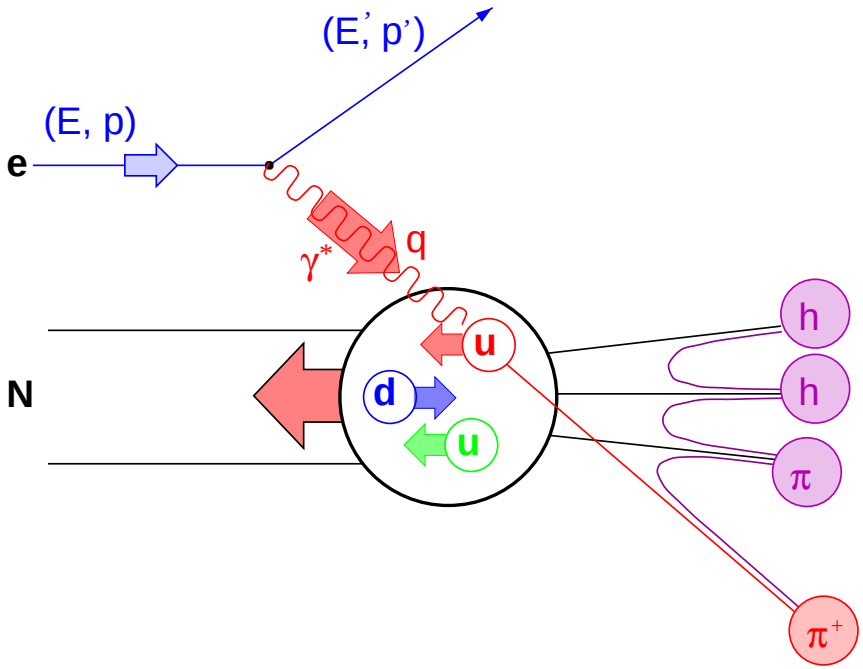
gluons important in
unpolarized case
ΔG



complete description:
orbital angular momenta

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

Deep inelastic scattering



$$Q^2 = -q^2$$
$$\nu = E - E'$$
$$x = Q^2/2M\nu$$
$$y = \nu/E$$
$$z = E_{\mathrm{h}}/\nu$$
p_{T} : hadron transverse momentum

- **Inclusive cross section**

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

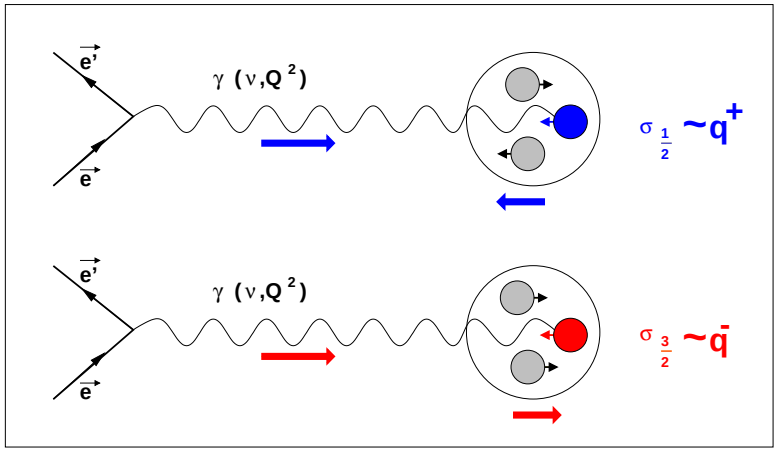
- **measured**

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

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

Polarised deep inelastic scattering

- **absorption of polarised photons (QPM)**



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

$+$ quark $\uparrow\uparrow$ nucleon
$-$ quark $\downarrow\uparrow$ nucleon

- **photon nucleon asymmetry**

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\Sigma_q\ e_q^2\ (q(x)^+ - q(x)^-)}{\Sigma_q\ e_q^2\ (q(x)^+ + q(x)^-)} = \frac{g_1(x)}{F_1(x)}$$

- **spin structure function**

$$g_1 = \frac{1}{2}\Sigma_q\ e_q^2\ \Delta q(x) \approx A_1 \cdot \frac{F_2}{2x(1+R)} \approx \frac{A_\parallel}{D} \cdot \frac{F_2}{2x(1+R)} = \frac{A_{\rm exp}}{D f P_{\rm B} P_{\rm T}} \cdot \frac{F_2}{2x(1+R)}$$

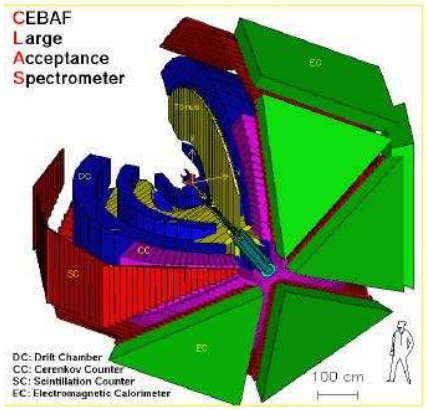
p_μ, $p_{\rm T}$ beam and target polarisation, f dilution factor

Experiments

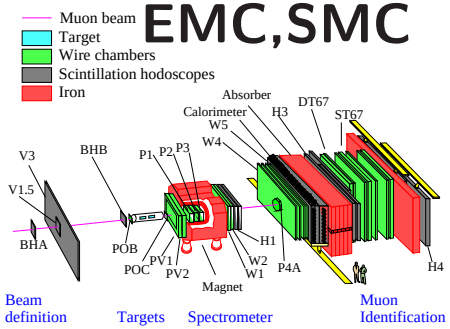
Experiments

SLAC: Endstation A

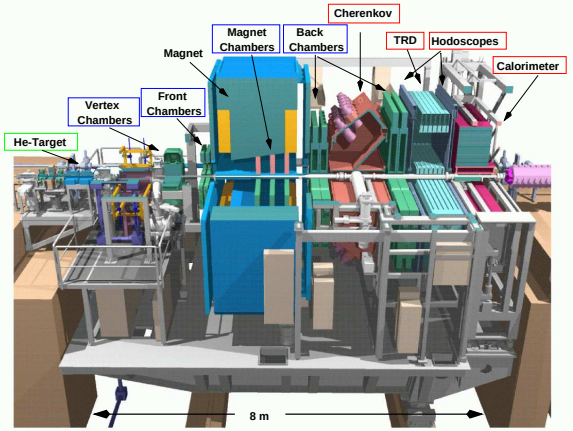
JLAB: CLAS



CERN: EMC,SMC

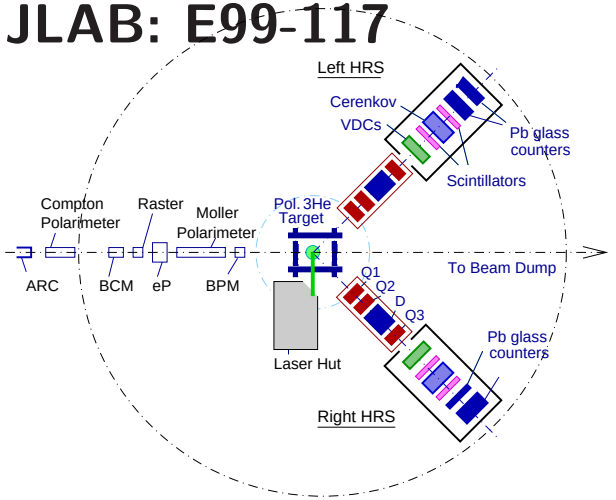


E80, E130	$\vec{e}\,\vec{p}$	≤ 20 GeV
EMC	$\vec{\mu}\,\vec{p}$	100–200 GeV
E142, 143	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 28 GeV
SMC	$\vec{\mu}\,\vec{p},\vec{d}$	100, 190 GeV
E154, 155	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	≤ 50 GeV
HERMES	$\vec{e}\,\vec{p},\vec{n},\vec{d}$	27.5 GeV
COMPASS	$\vec{\mu}\,\vec{p},\vec{d}$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

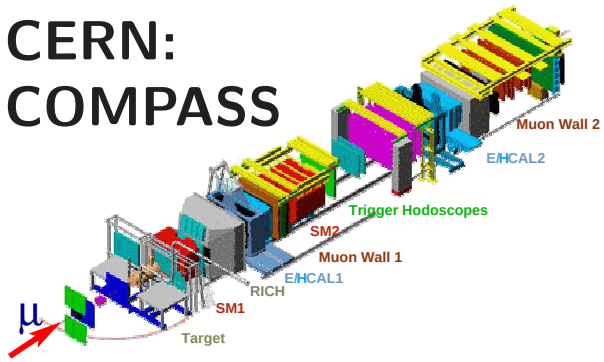


DESY: HERMES

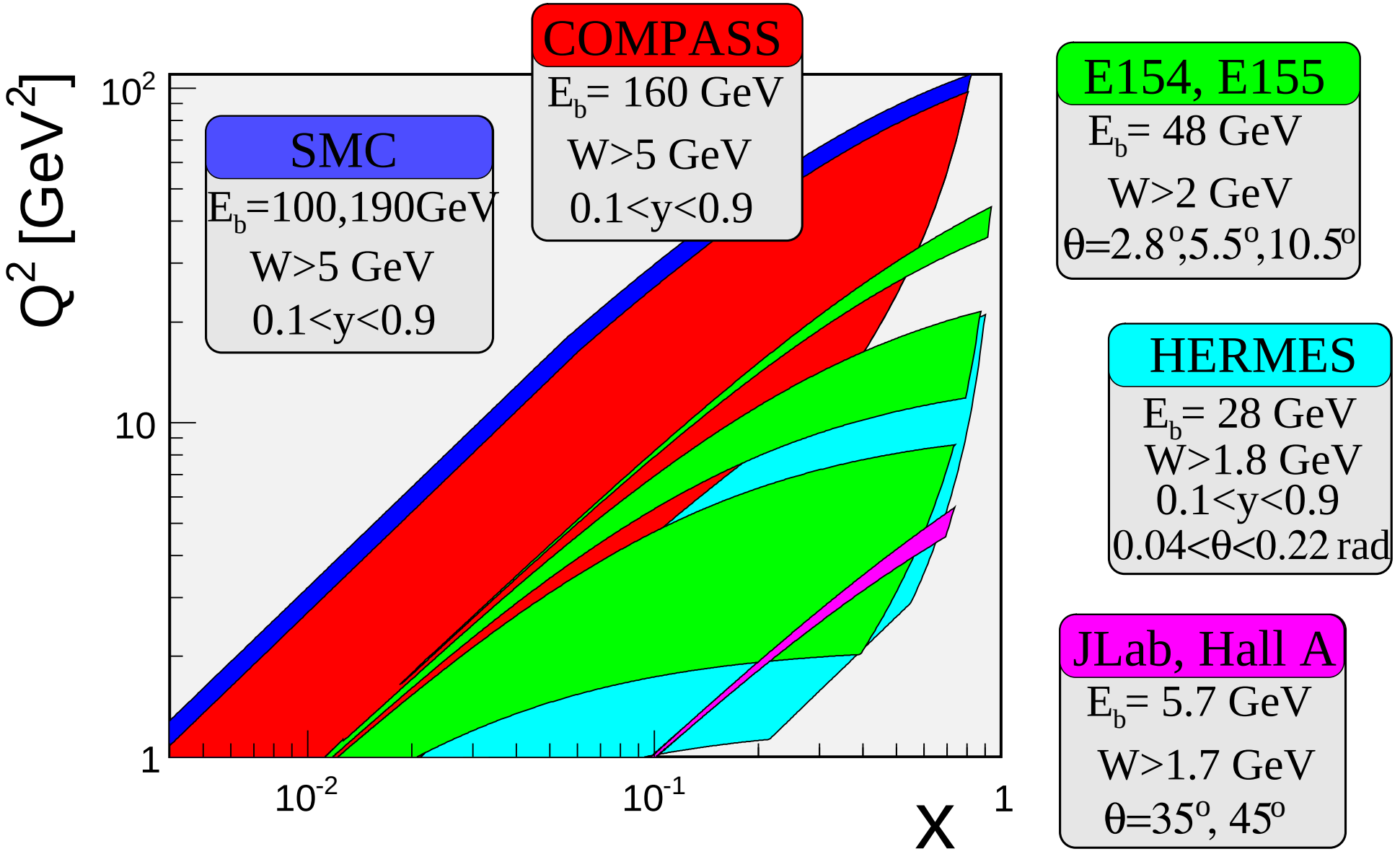
JLAB: E99-117



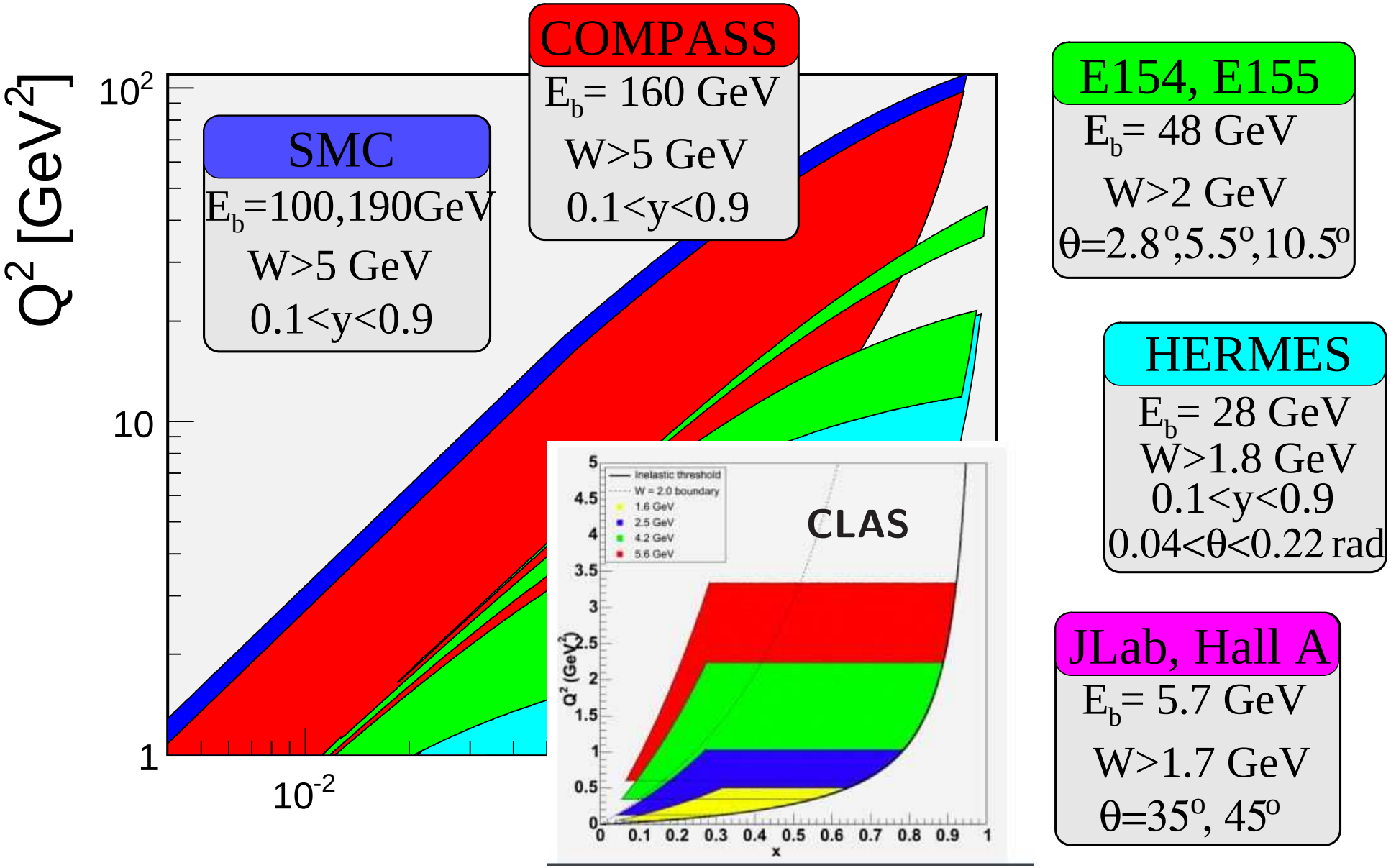
CERN: COMPASS



Kinematic domain of pDIS experiments

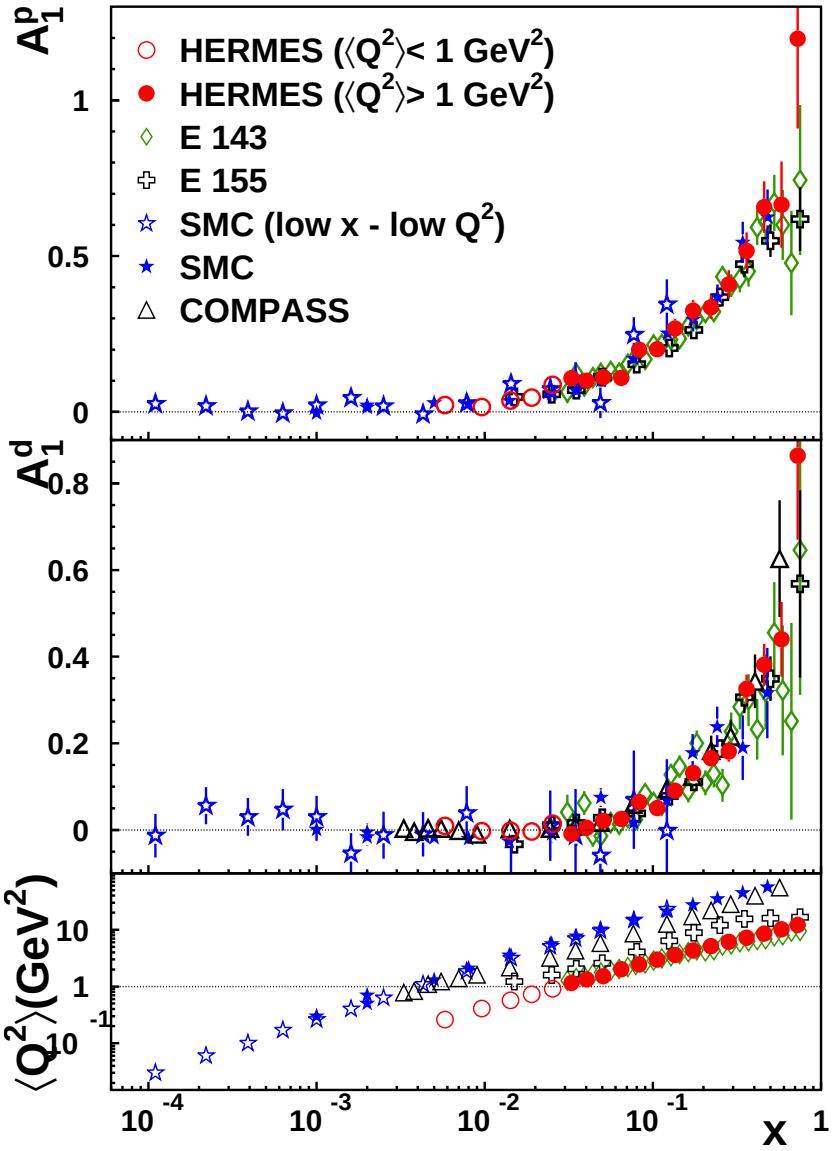


Kinematic domain of pDIS experiments



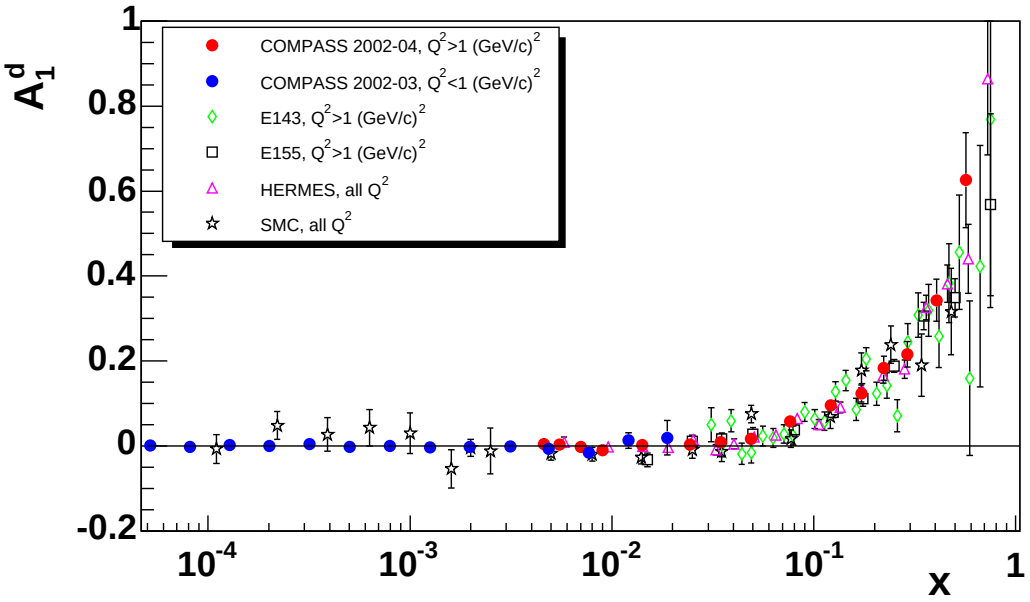
Inclusive asymmetries

World data for $A_1^{p,d}$ (all Q^2)



PRD 75 (2007) 012007

- A_1 compatible with 0 for $x < 0.01$
- good agreement between all experiments
  $\longrightarrow$ weak Q^2 dependence of A_1



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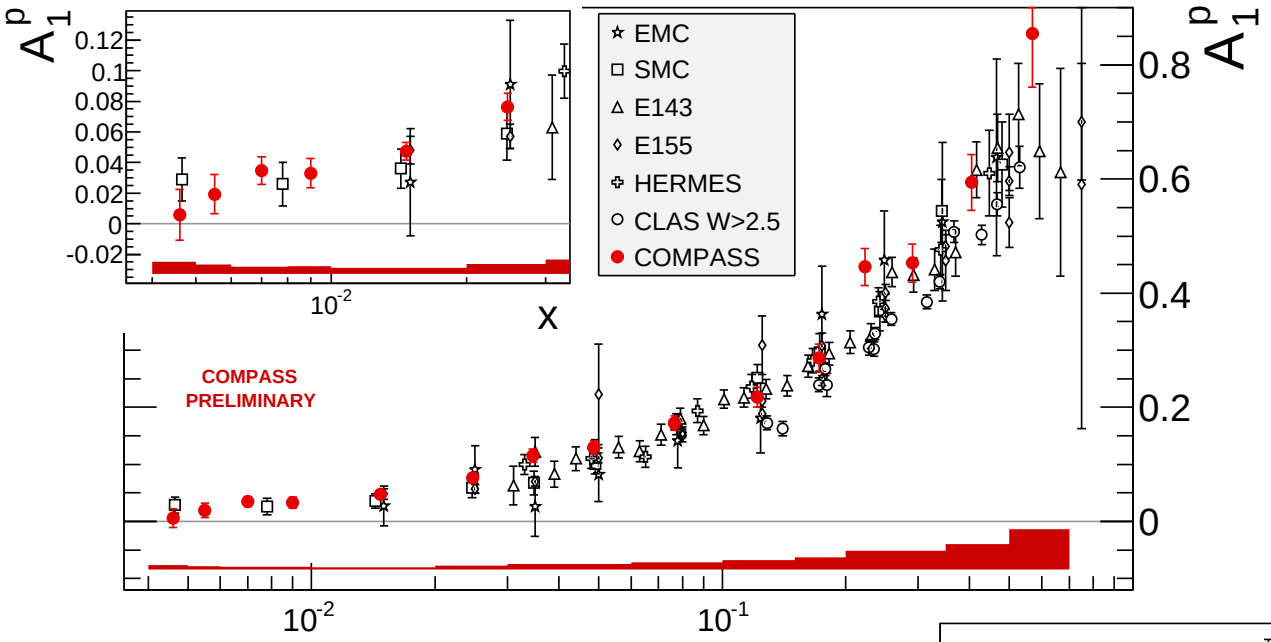
World data for $A_1^{p,d}$ $(Q^2 > 1\ (\mathrm{GeV}/c)^2)$



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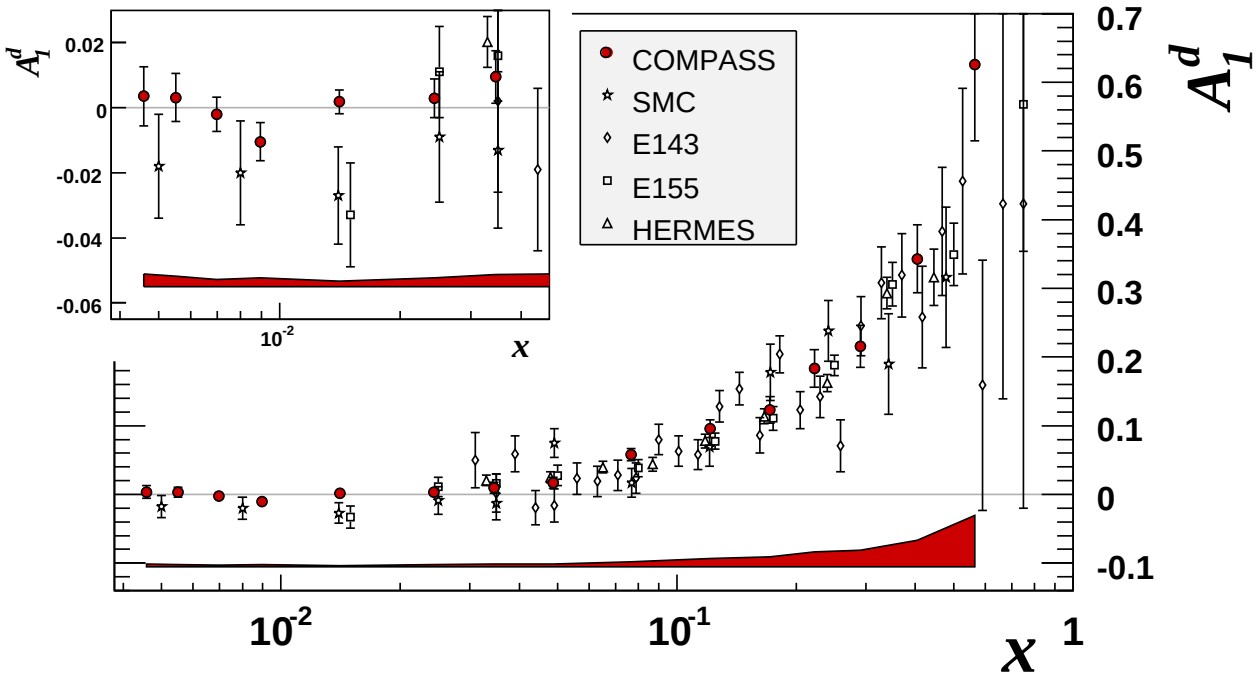
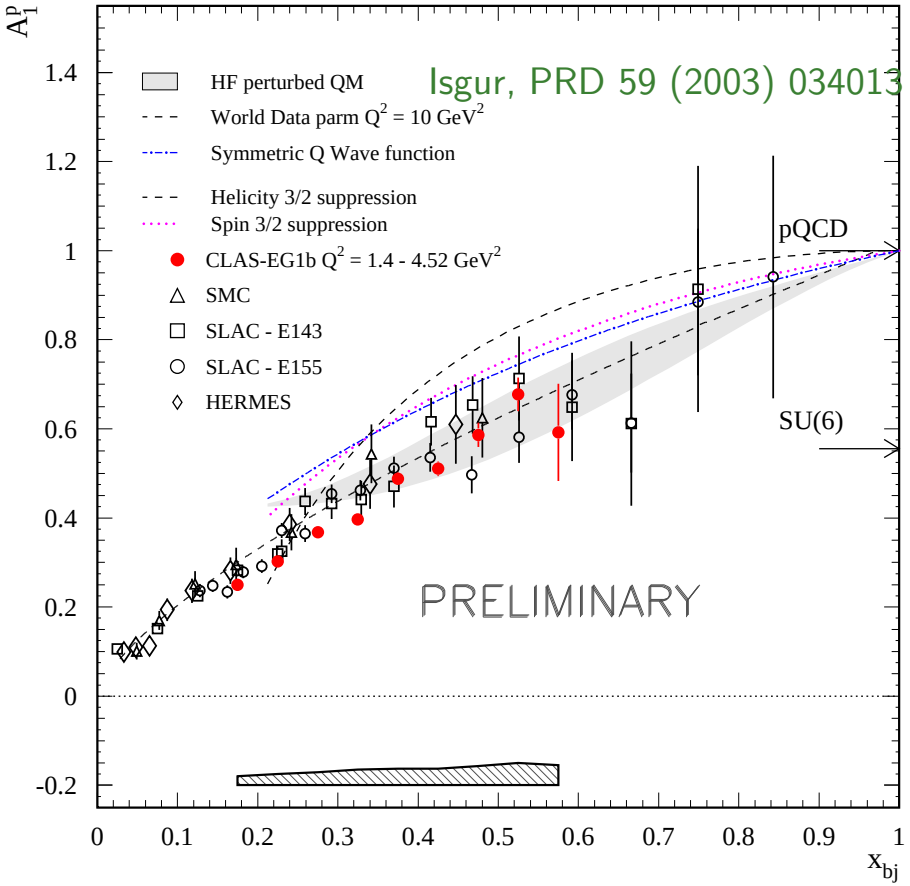
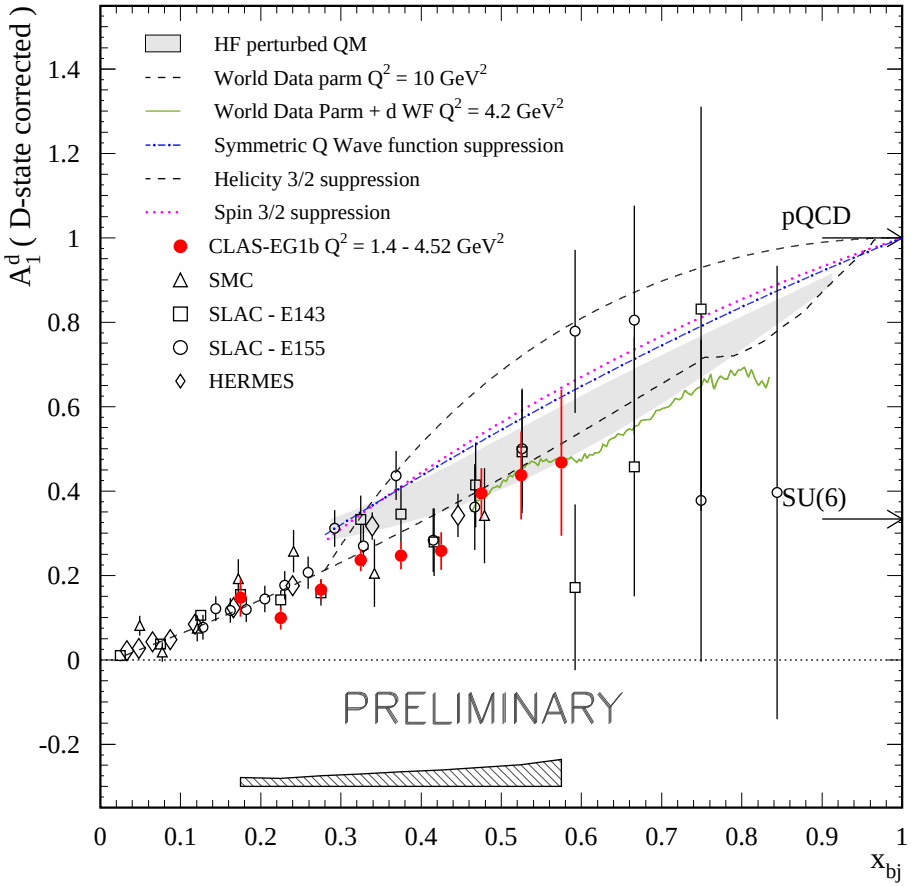
- COMPASS data for A_1^p added
- obvious improvement at low x
- good agreement with SMC
- no negative trend for d



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

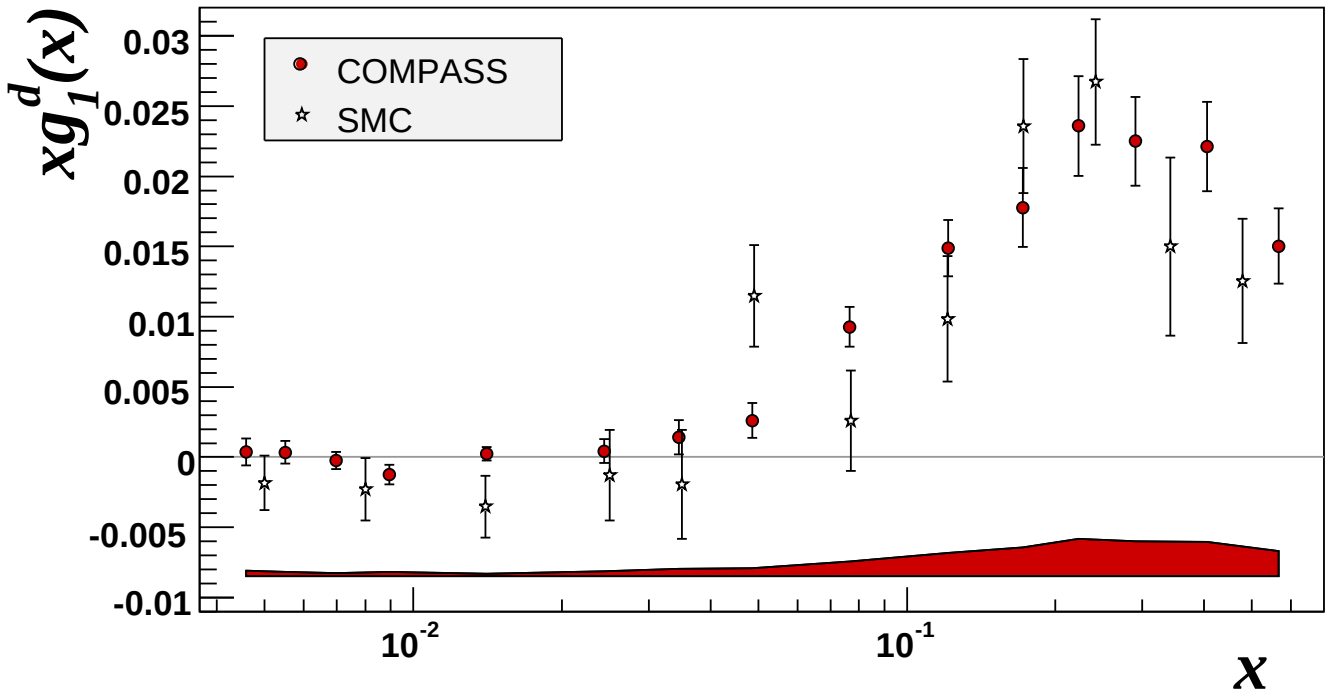




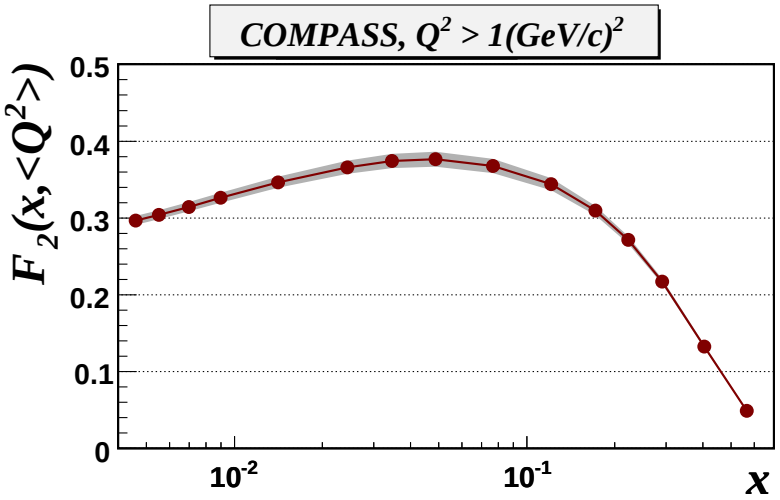
- CLAS data slightly below the other experiments
- in reasonable agreement with HFP(hyperfine perturbed) quark modell (shaded area)
- can be used directly to extract $\Delta u/u$ and $\Delta d/d$

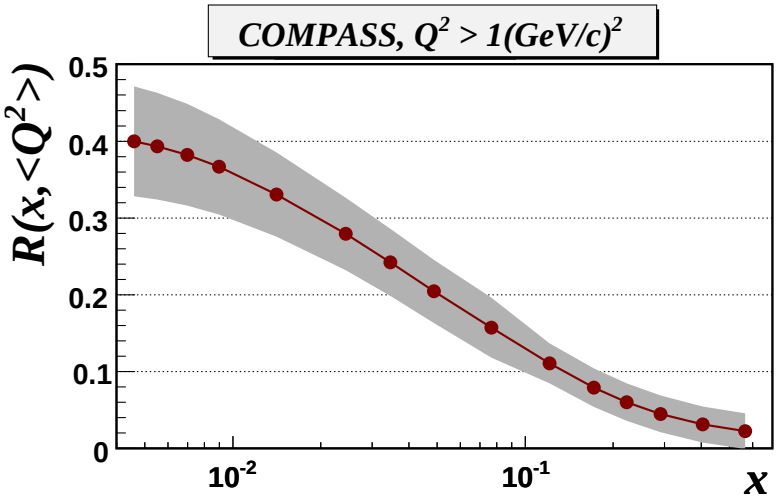
Spin structure functions

Next step: $g_1(x)$ at measured Q^2

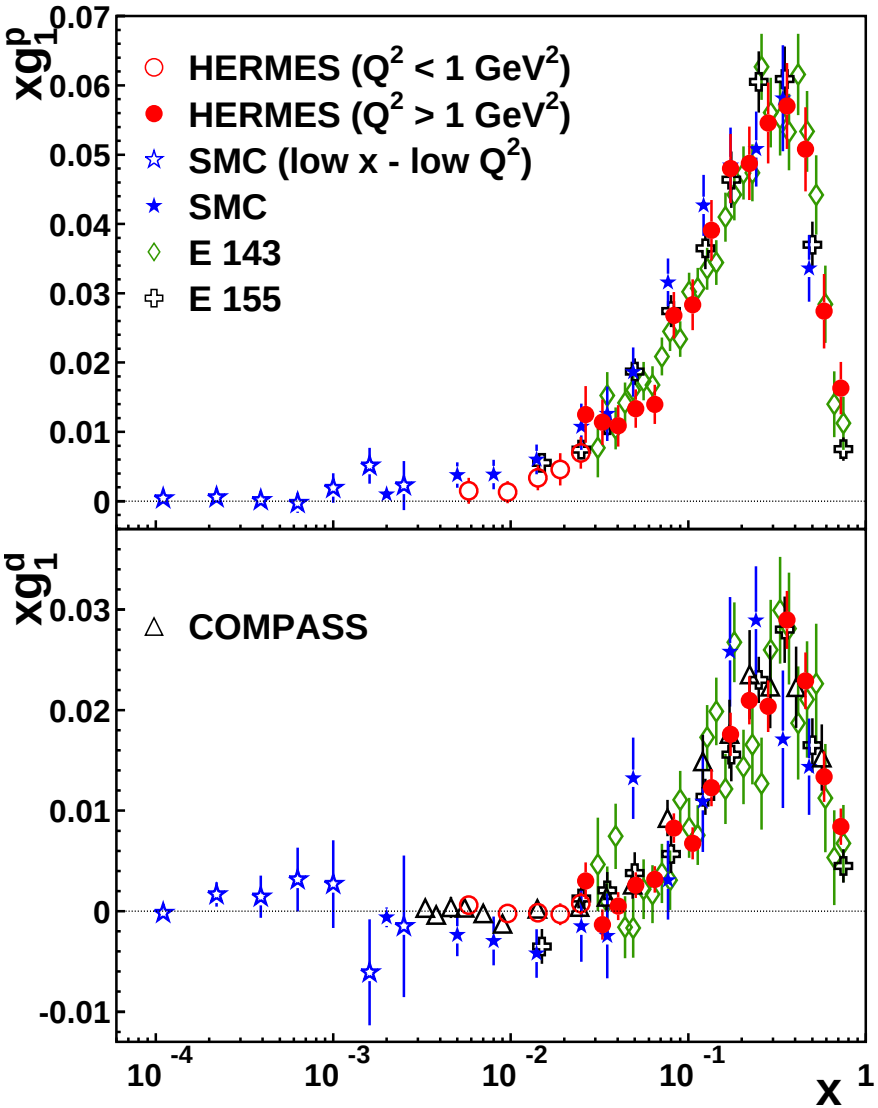


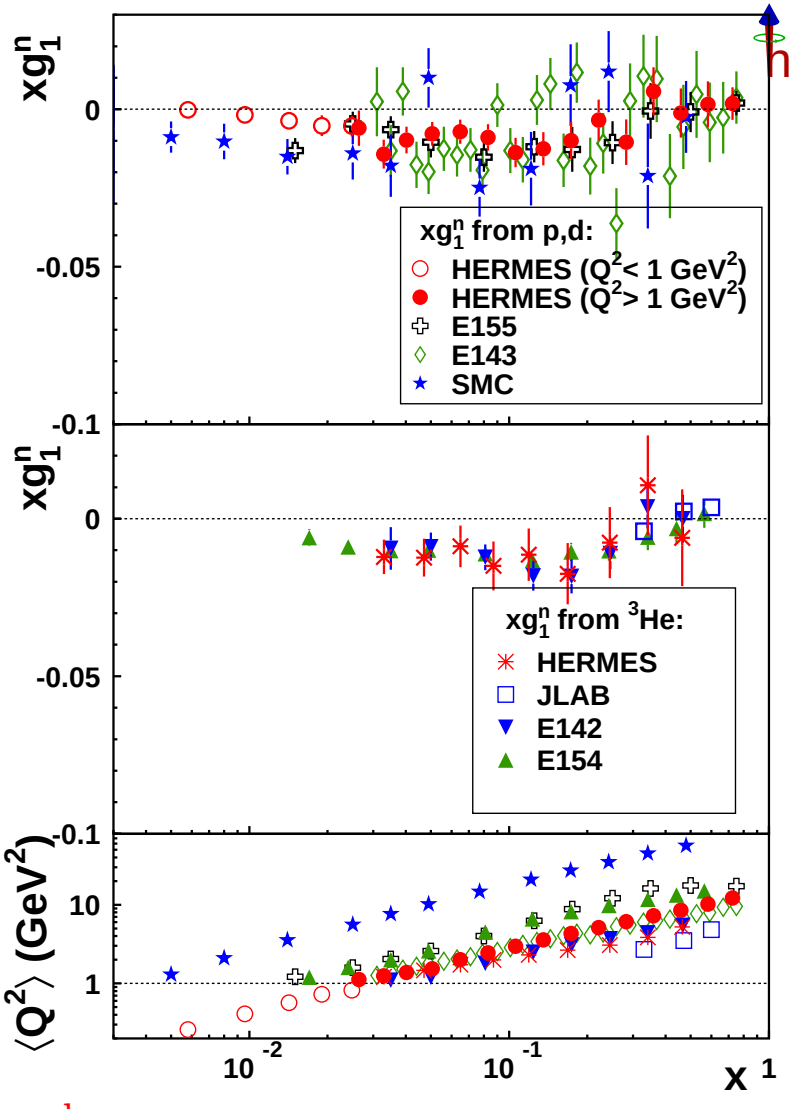
$$g_1 = A_1 \cdot \frac{F_2}{2x(1+R)}$$





Final g_1 data (HERMES)





- High statistics measurement of A_1^{p} and A_1^{d}
- New method for smearing corrections (rad. corr. and resolution)
- Statistical correlations between x bins

First moments of g_1^{d}

- **COMPASS and HERMES**: $\Gamma_1^{\mathrm{N}} = \int_0^1 g_1^{\mathrm{N}} \mathrm{d}x$ from deuteron data
  - data used in measured range QCD fit used for extrapolation
  - contribution of unmeasured region few %

- **using**: $a_0^{\overline{\mathrm{MS}}} = \Delta\Sigma$ and $\Gamma_1^{\mathrm{N}} = \frac{1}{9}(a_0 \Delta C_{\mathrm{S}}^{\overline{\mathrm{MS}}} + \frac{1}{4} a_8 \Delta C_{\mathrm{NS}}^{\overline{\mathrm{MS}}})$

$a_0(Q^2 = 3(\mathrm{GeV/c})^2) = 0.35 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ **COMPASS**

$a_0(Q^2 = 5(\mathrm{GeV/c})^2) = 0.33 \pm 0.025(\mathrm{exp}) \pm 0.028(\mathrm{evol}) \pm 0.011(\mathrm{theo})$ **HERMES**

- **assuming SU(3) symmetry**: $(\Delta s + \Delta \bar{s}) = \frac{1}{3}(\hat{a}_0 + a_8)$

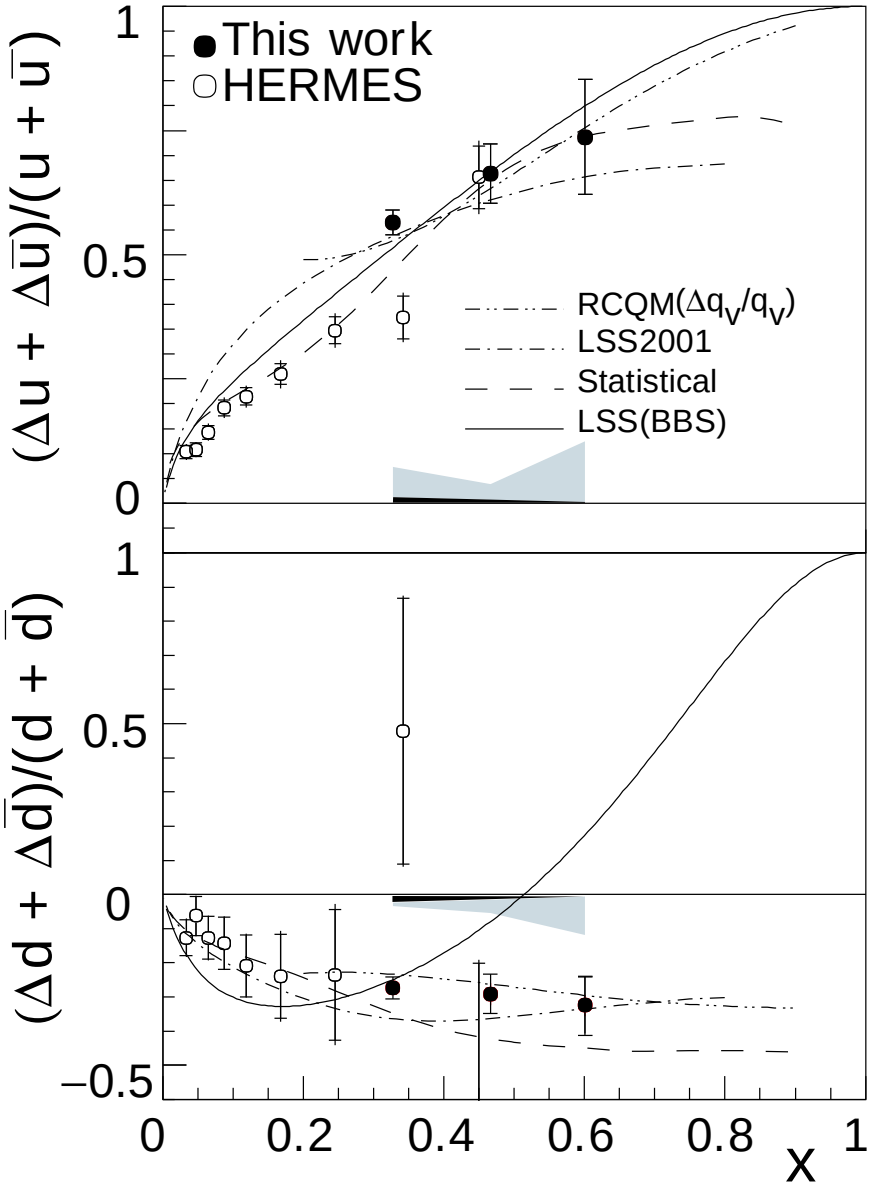
$(\Delta s + \Delta \bar{s}) = -0.08 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$ **COMPASS**

$(\Delta s + \Delta \bar{s}) = -0.085 \pm 0.008(\mathrm{exp}) \pm 0.009(\mathrm{evol}) \pm 0.013(\mathrm{theo})$ **HERMES**

- **negative strange sea polarisation**

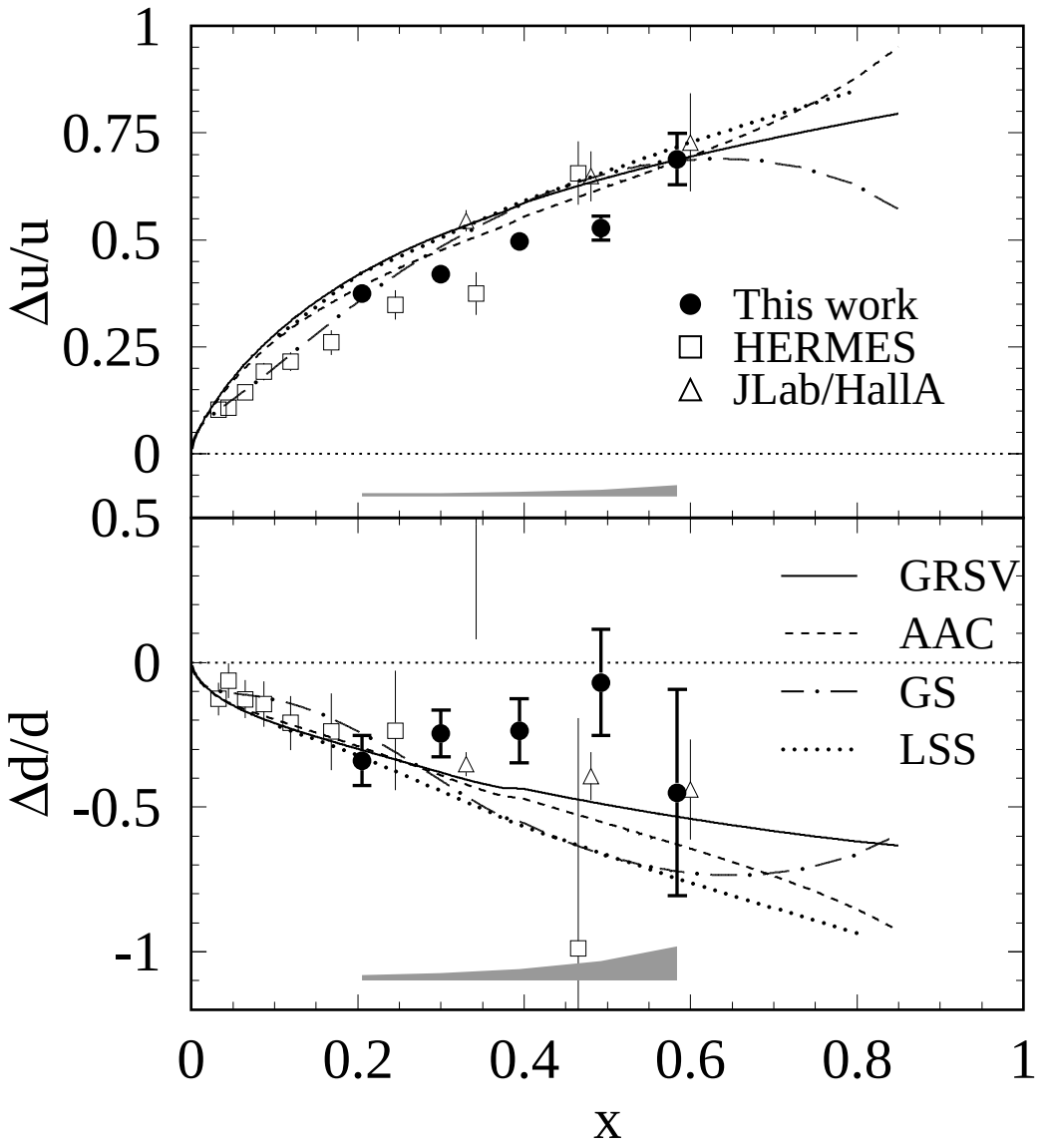
Quark polarisation in the valence region

- E99-117 result for A_1^n
- $A_1^n > 0$ at $x > 0.5$
- combining with A_1^p results:
  $\Delta u/u > 0$, but $\Delta d/d < 0$
- pQCD expectation:
  $\Delta u/u = \Delta d/d = 1$ at high x
- hint for quark orbital angular momentum

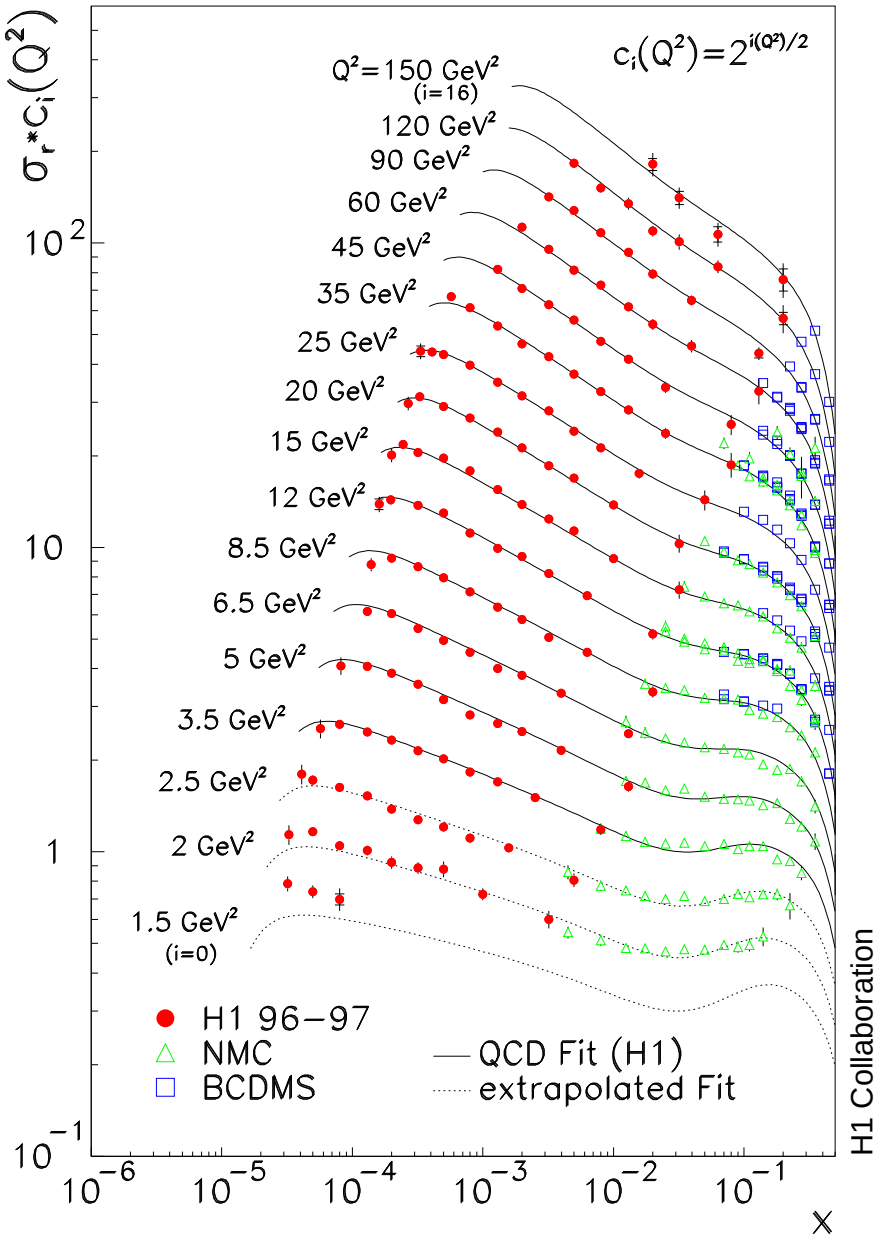


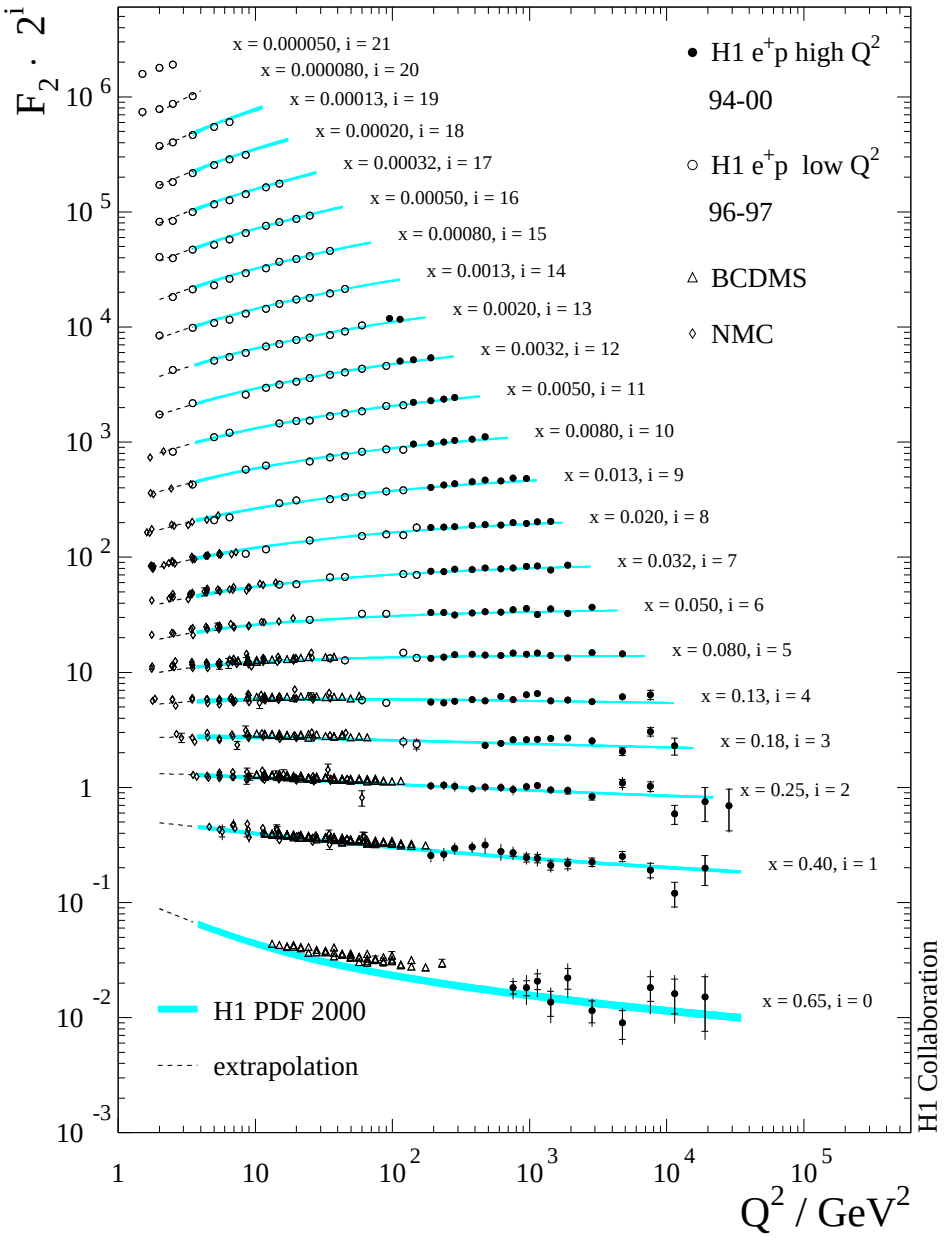
Update from CLAS

- CLAS EG1 result for $A_1^{\mathrm{p,d}}$
- assuming negligible sea contribution
- $\Delta u/u > 0$
- $\Delta u/u \to 1$ for $x \to 1$
  consistent with QM, pQCD, disagrees with SU(6)
- $\Delta d/d < 0$
  up to highest $x \sim 0.6$
- disagrees with pQCD without orbital angular momentum
  but agrees e.g. with HFP quark modell



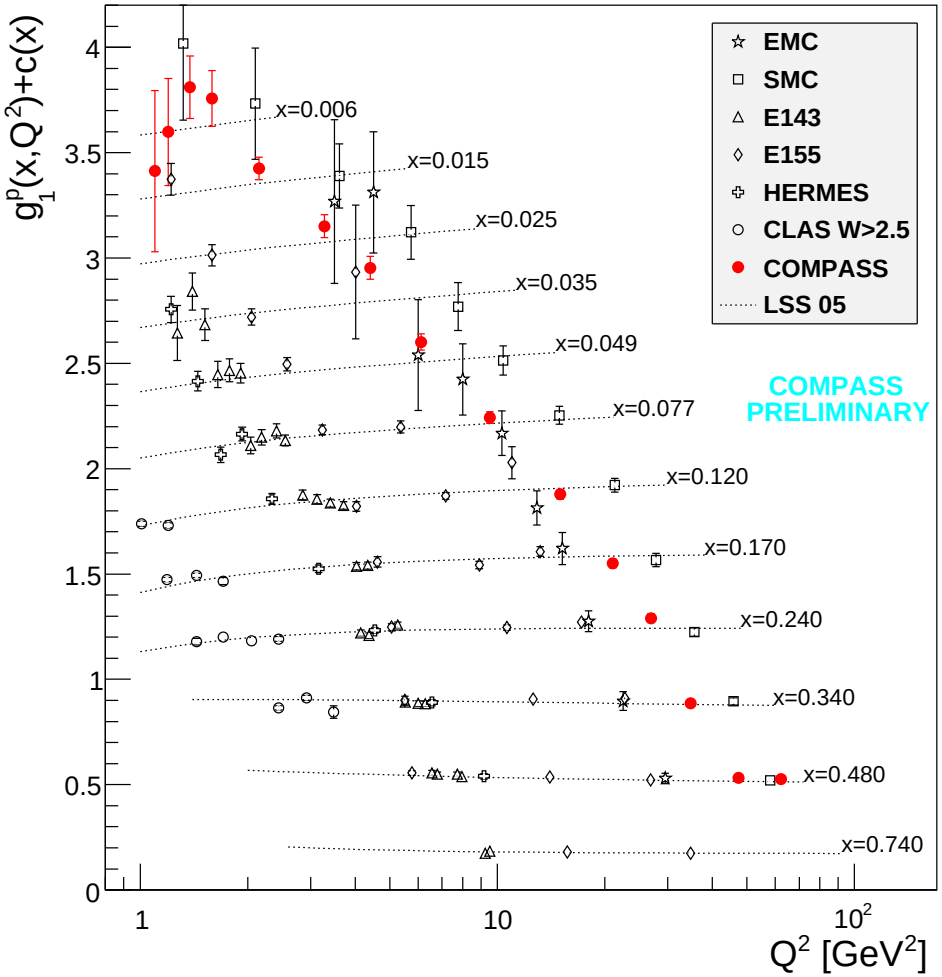
What you really would like to have:



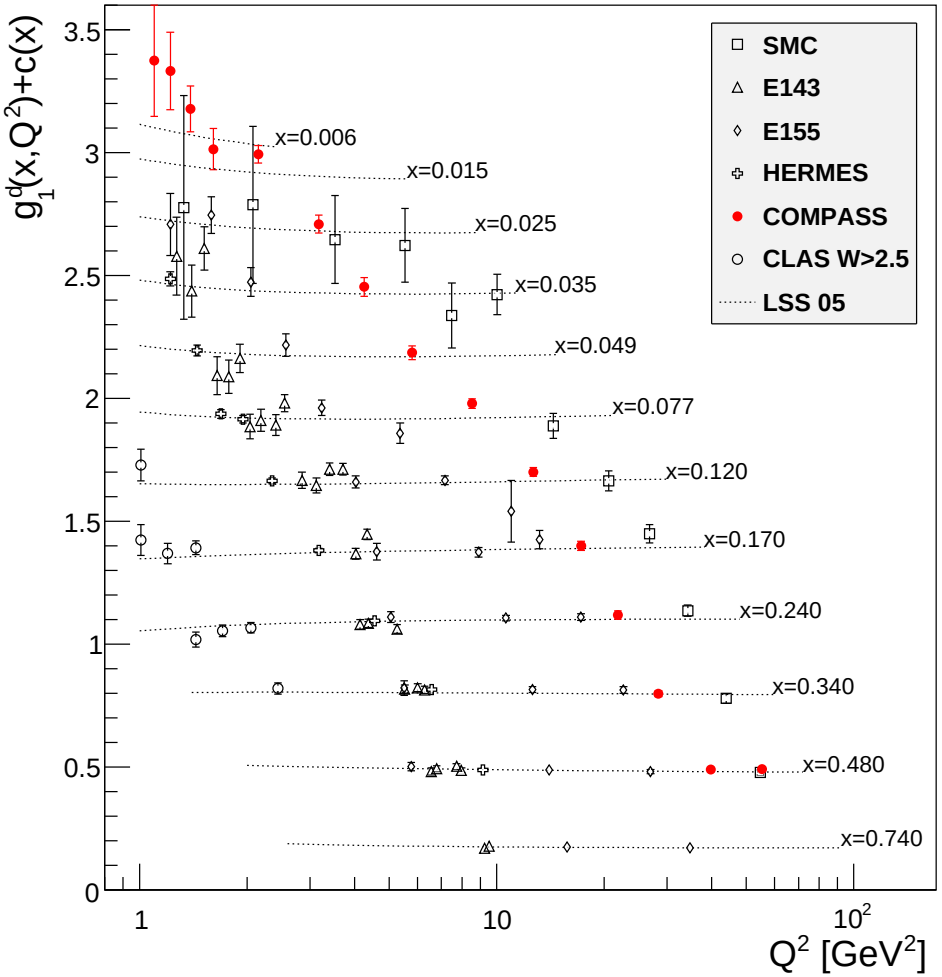


World data on $g_1(x, Q^2)$

Proton



Deuteron



It's getting better, but collider data clearly missing!

NLO pQCD analyses

- **DGLAP equations**

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

- input parameterization of parton distributions at $\boldsymbol{Q_0^2}$

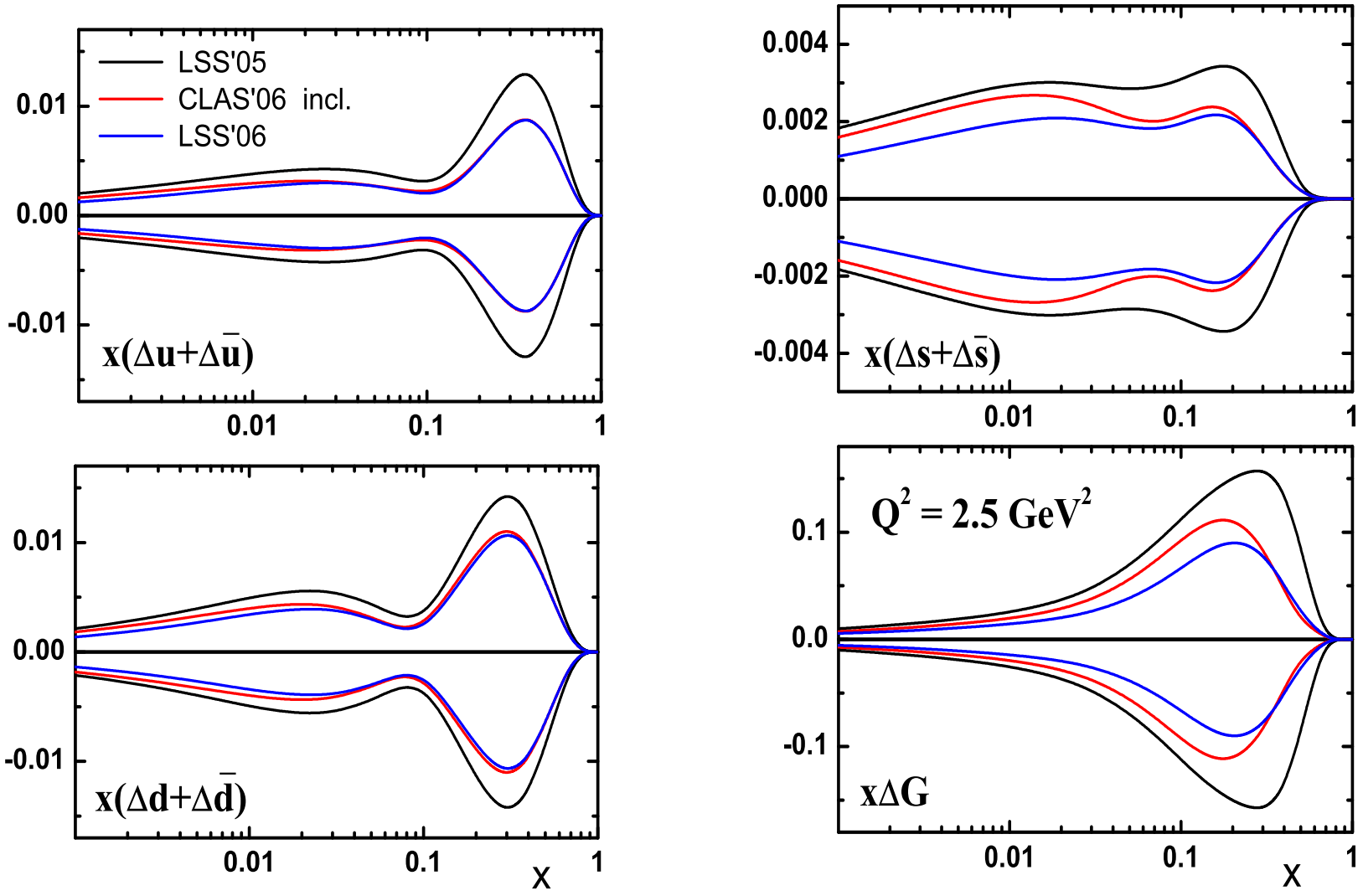
- using inclusive asymmetries only quarks and anitquarks cannot be disentangled **e.g.** determination of $\Delta u + \Delta\bar{u}$, $\Delta d + \Delta\bar{d}$, $\Delta s + \Delta\bar{s}$ and Δg

- many analyses from different groups (theor. and exp.)
  e.g. LSS, GRSV, BB, AAC, DNS.....

- limited kinematic range of data: some additional constraints are needed **e.g.** Bjorken sum rule

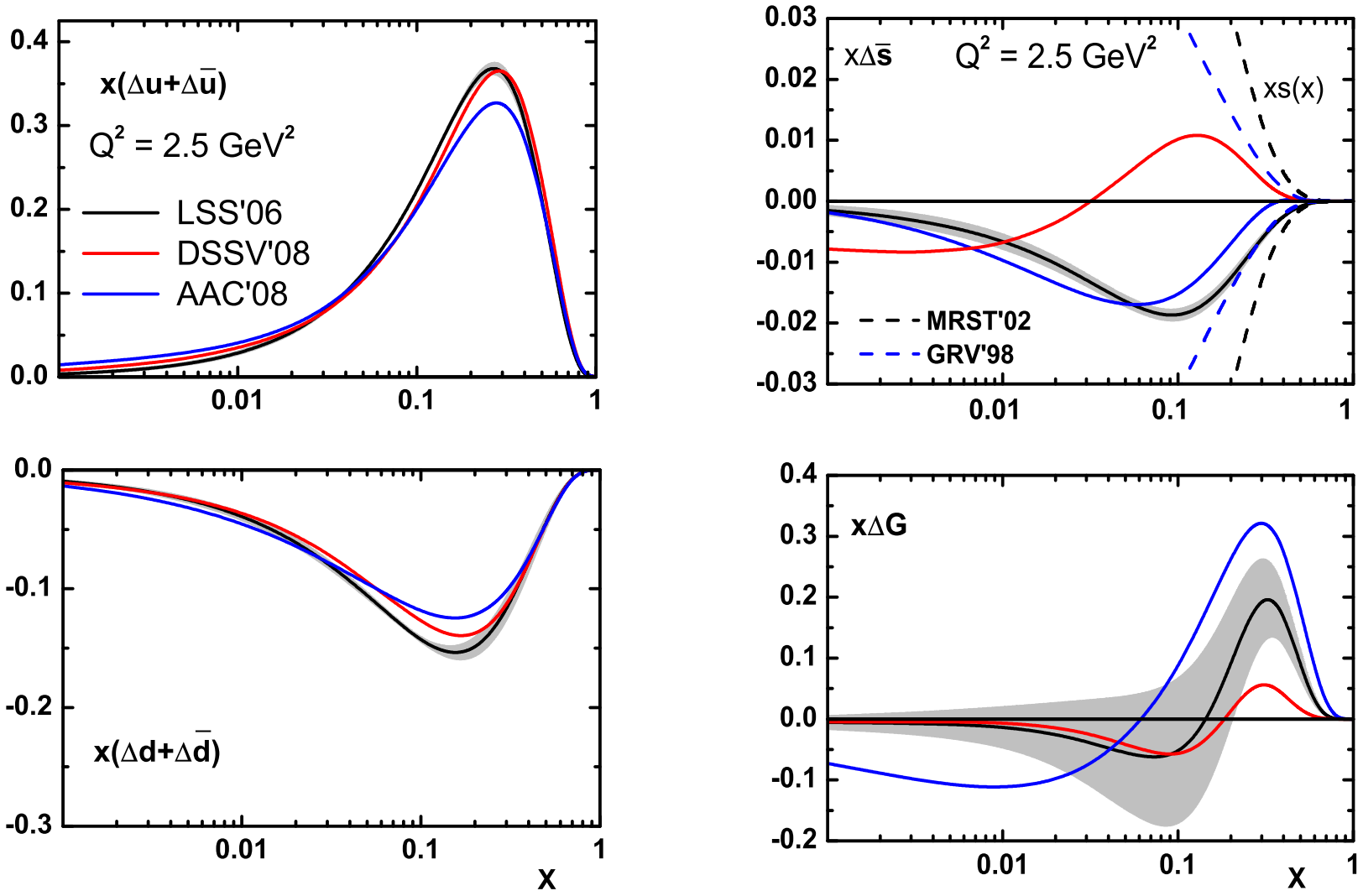
- data at relative small Q^2: TMC and higher twists are of concern **e.g.** taken into account by LSS

Impact of new data sets



central fits did not change much, but error bars of PDFs did shrink when adding CLAS data (red lines) and COMPASS deuteron data (blue lines) LSS arXiv:0901.2285

Polarised parton distributions



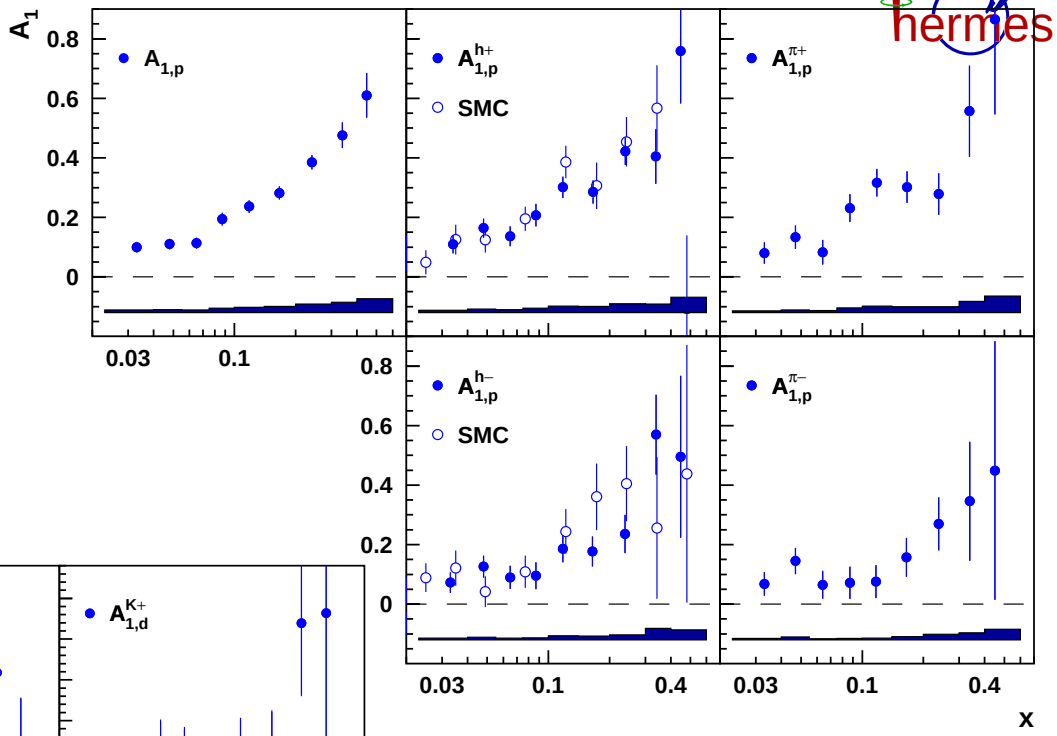
- $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$ well constrained by data LSS PRD 80 (2009) 054026
- Δs and Δg need other data in addition to inclusive data
- Δs comes out negative (except for DSSV) and ΔG small (< 0.5)

Semi-inclusive asymmetries

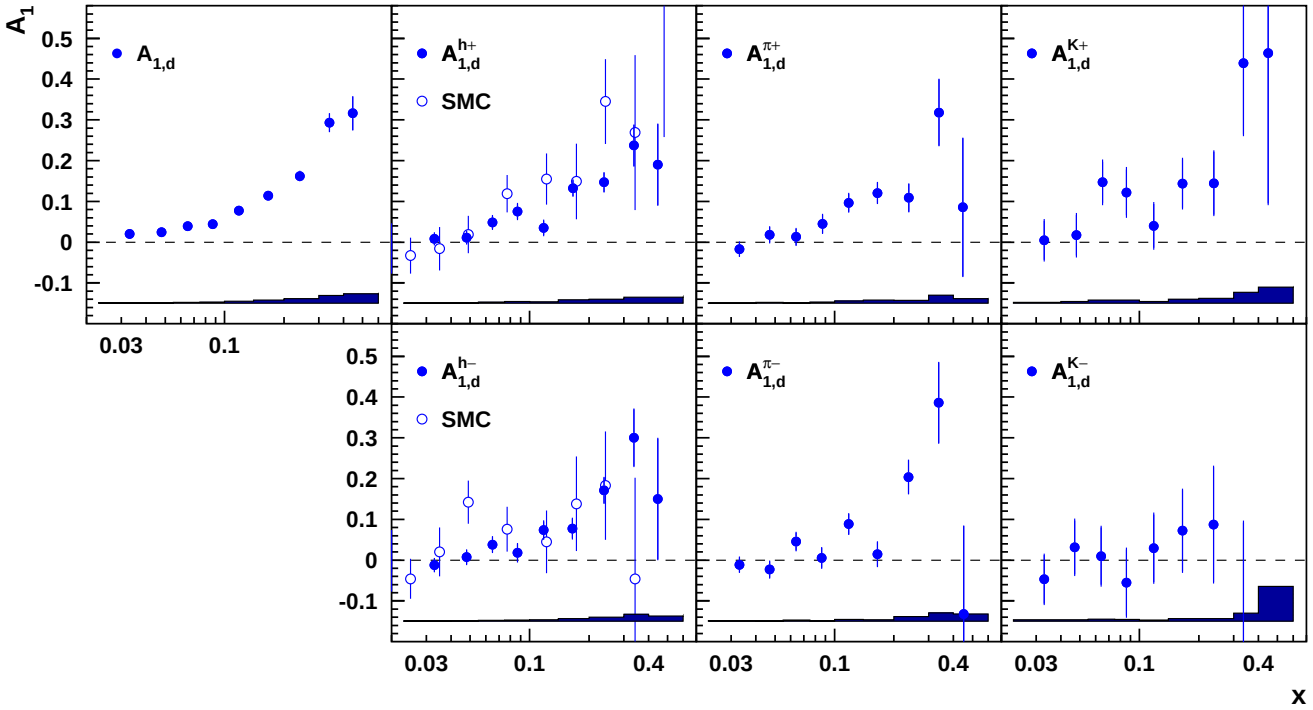
The data: HERMES

- **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

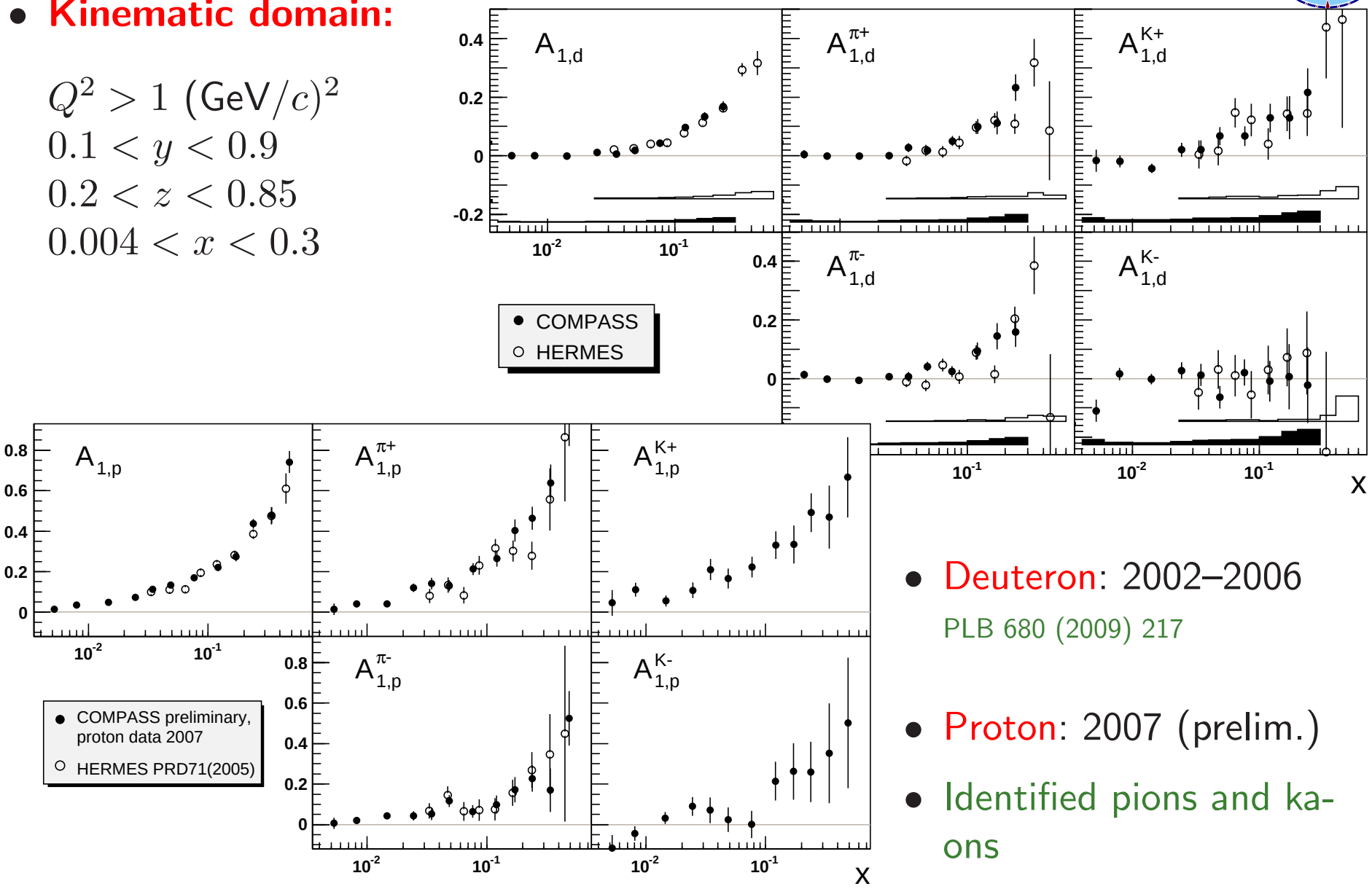


- deuteron, proton
- identified kaons and pions
- h^+ and h^- from SMC

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 (prelim.)
- Identified pions and kaons

Flavour separation

- **SIDIS** $A_1^h(x) = \Sigma_q P_q^h \frac{\Delta q(x)}{q(x)}$

  and

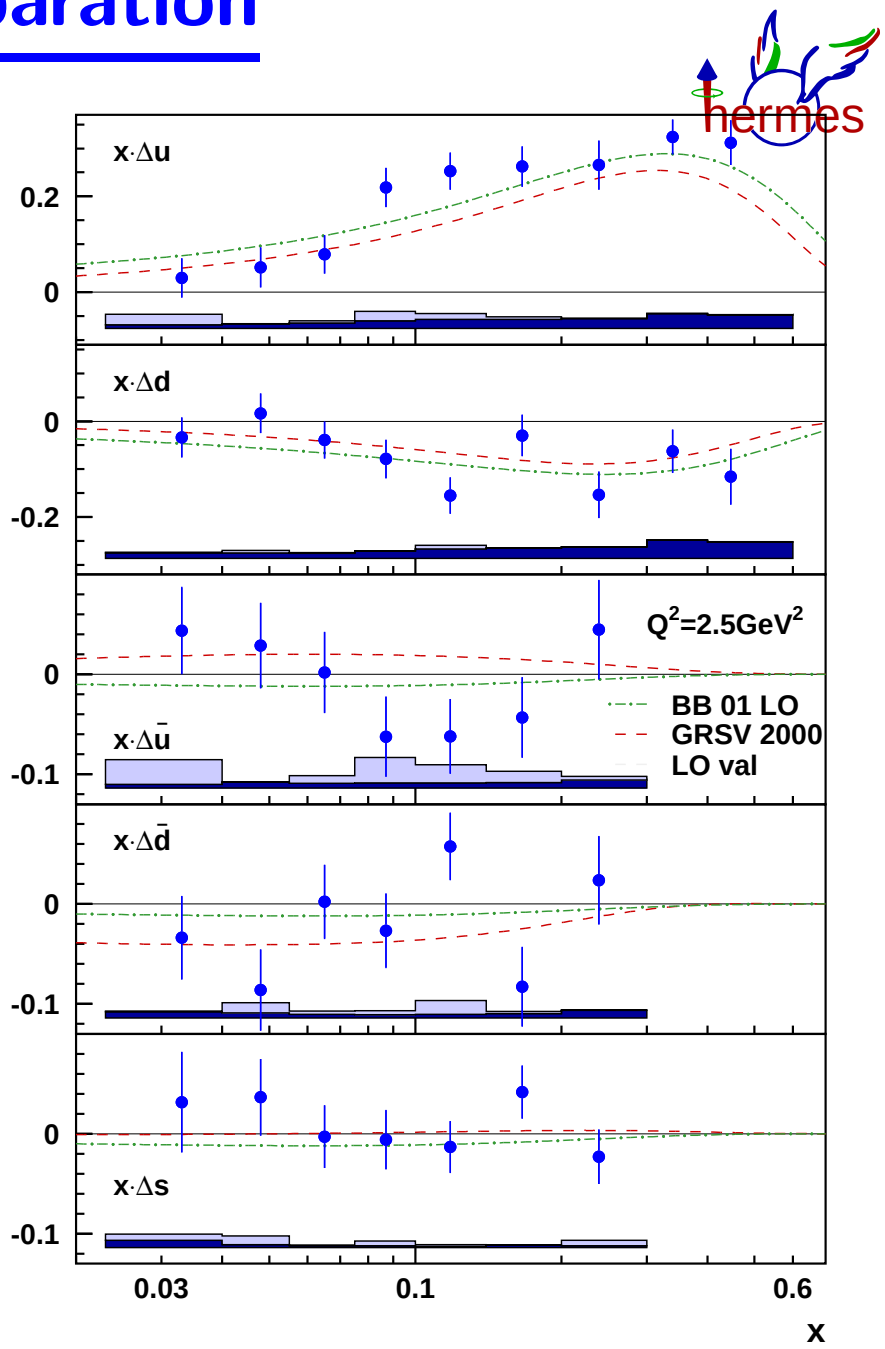
  $$P_q^h(x) = \frac{e_q^2 q(x) \int_{0.2}^{0.8} D_q^h(z)\mathrm{d}z}{\Sigma_{q'} e_{q'}^2 q'(x) \int_{0.2}^{0.8} D_{q'}^h(z)\mathrm{d}z}$$

- $D_q^h \neq D_{\bar{q}}^h$
  yields quark and antiquark separation

- **measured**:
  A_1^{d}, $A_{1\mathrm{d}}^{h\pm}$, $A_{1\mathrm{d}}^{K^\pm}$, $A_{1\mathrm{d}}^{\pi^\pm}$, A_1^{p}, $A_{1\mathrm{p}}^{h^\pm}$, $A_{1\mathrm{p}}^{\pi^\pm}$

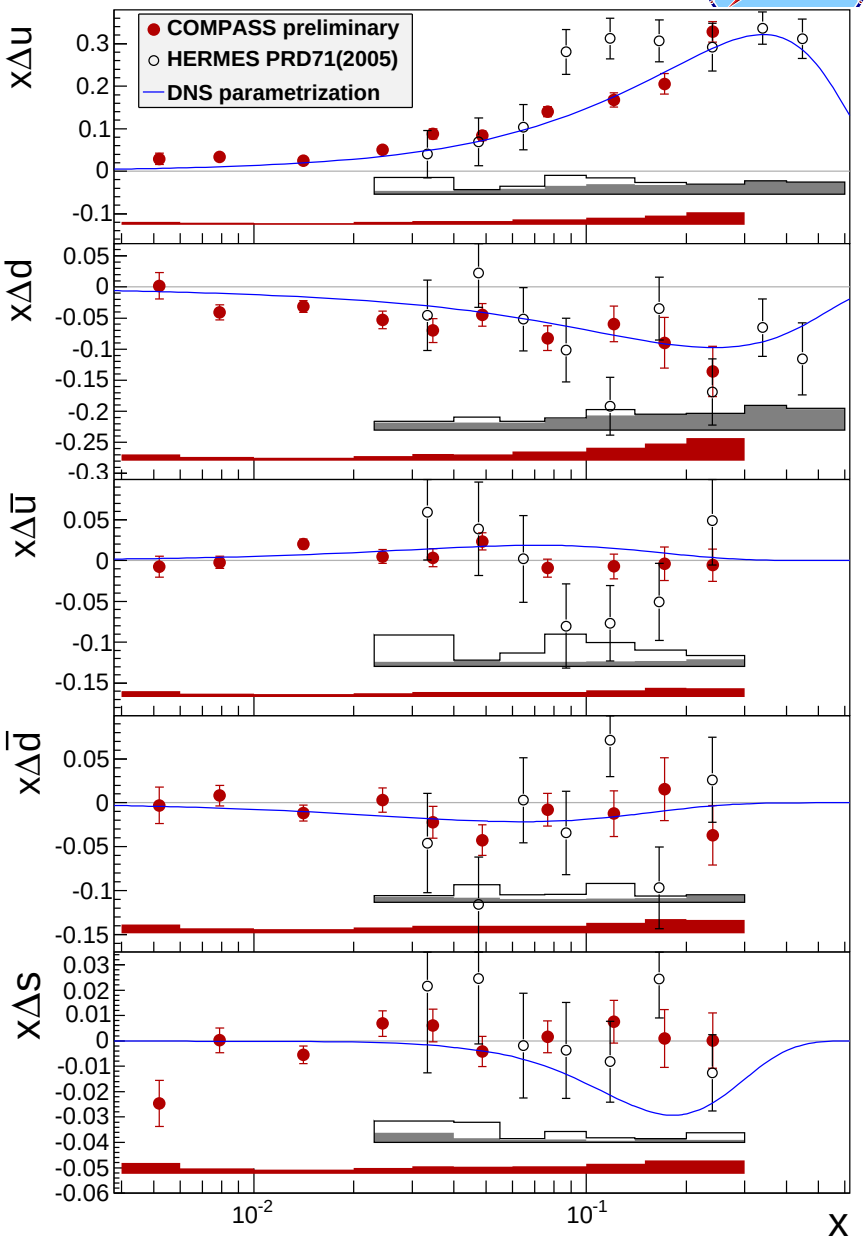
- **determined**: Δu, $\Delta \bar{u}$, Δd, $\Delta \bar{d}$, Δs
  assuming $\Delta \bar{s} = 0$
  all sea distrib. compatible with 0

- **inputs**:CTEQ5L unpolarised PDFs,
  FFs from LUND/JETSET tuned to HERMES multiplicities

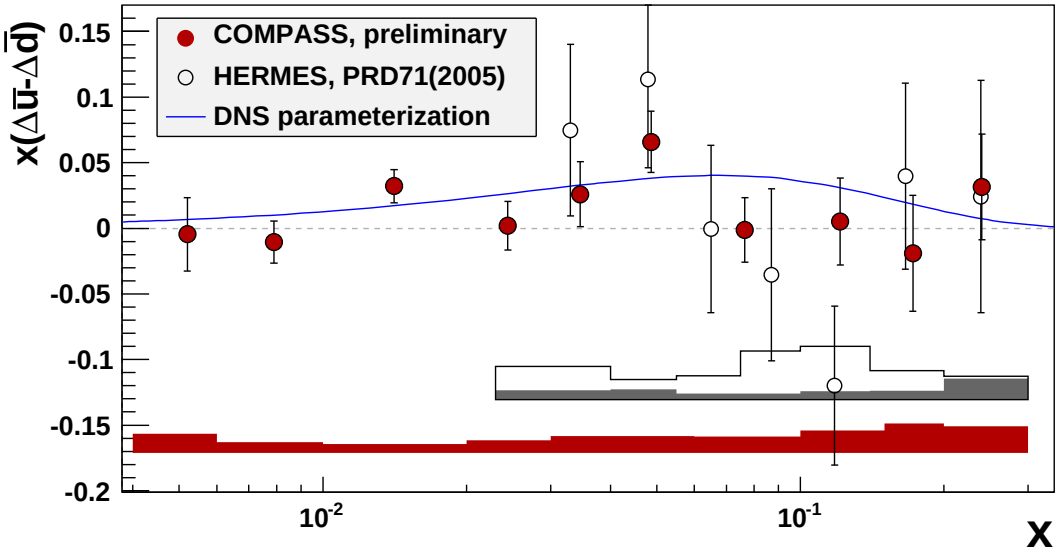


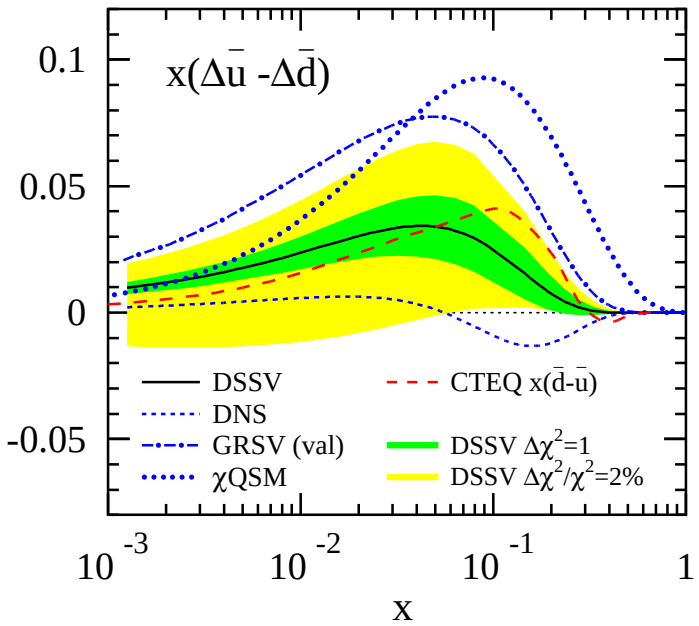
Flavour separation

- **SIDIS** $A_1^h = \dfrac{\Sigma_q e_q^2 (\Delta q(x) \int D_q^h(z) \mathrm{d}z}{\Sigma_q e_q^2 q(x) \int D_q^h(z) \mathrm{d}z}$
- **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 unpolarised LO PDFs, DSS parametr. of FFs
- **preliminary result** at $Q^2 = 3$ **(GeV/**c**)**^{2}
- all sea quark distributions compatible with zero
- good agreement with global fit for Δu, $\Delta \bar{u}$, Δd, $\Delta \bar{d}$
- significant discrepancy with Δs obtained from QCDfits to g_1



Flavour symmetry breaking





- presently only accessible via SIDIS
- uncertainty from FFs not yet estimated
- preliminary result at $Q^2 = 3\ (\mathrm{GeV}/c)^2$:

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

- compatible with HERMES result:

$$\int_{0.023}^{0.6}(\Delta\bar{u} - \Delta\bar{d})\mathrm{d}x = 0.048 \pm 0.057(\mathrm{stat}) \pm 0.028(\mathrm{syst})$$

- comparable with effect in unpolarised PDFs ($\int(\bar{u} - \bar{d})\mathrm{d}x = -0.118 \pm 0.012$)

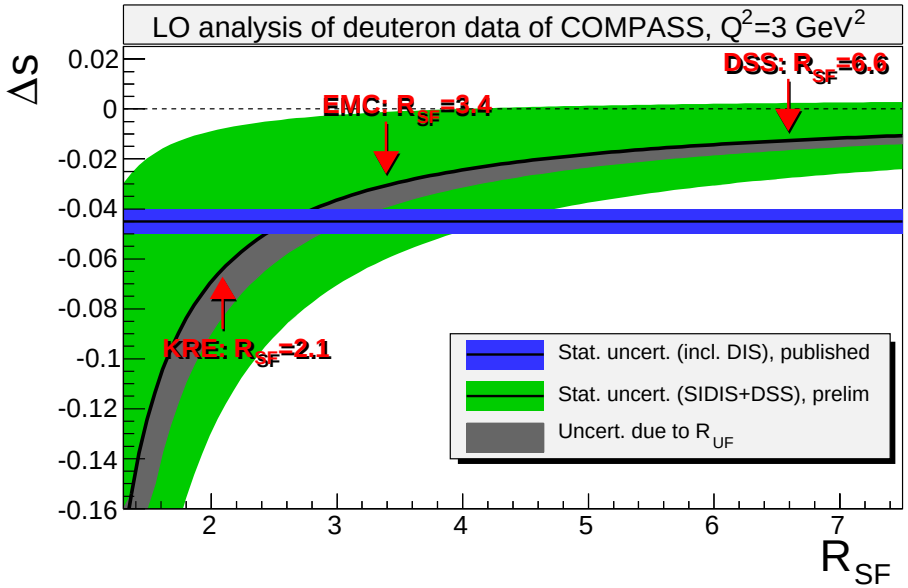
Dependence on FFs

- $K^{\pm}$ asymmetries from deuteron data

$$\frac{\Delta s}{s} = A_1^{\mathrm{d}} + \left(A_1^{K^+ + K^-} - A_1^{\mathrm{d}}\right) \frac{Q/s + \alpha}{\alpha - 0.8}$$

- $Q = u + \bar{u} + d + \bar{d},\ \alpha = \frac{2R_{UF} + 2R_{SF}}{3R_{UF} + 2}$

- $R_{UF} = \frac{\int D_d^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z},\ R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z}$



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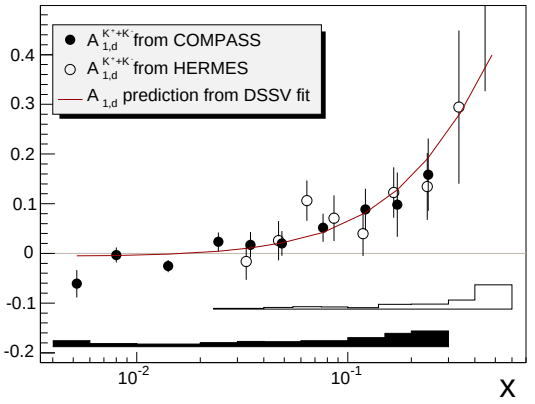
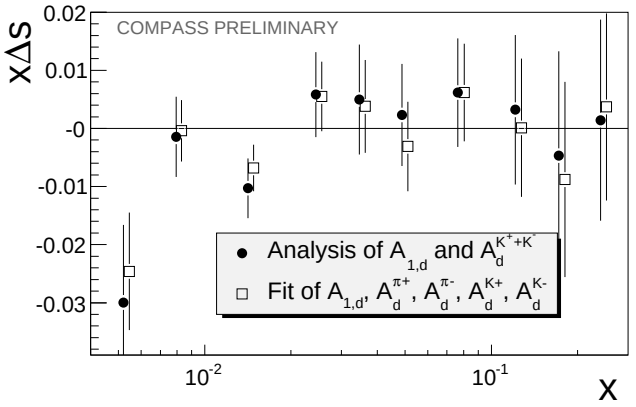




- large dependence on R_{SF}, slight dependence on R_{UF} for Δs

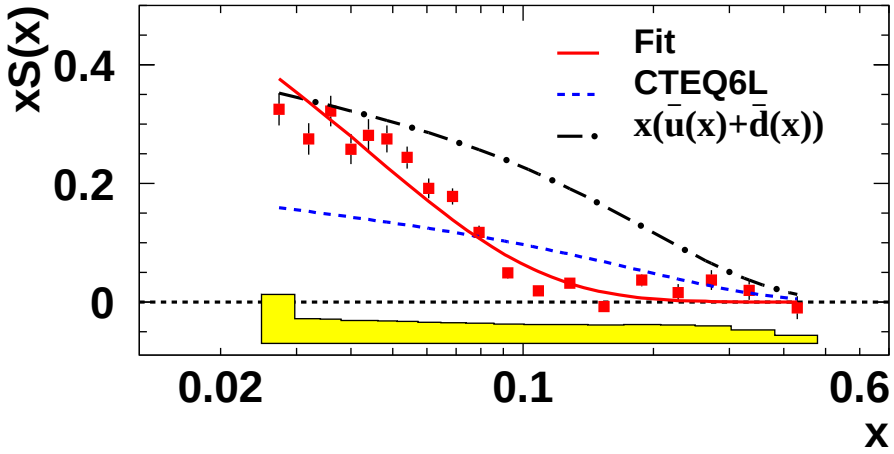
- determination of R_{SF} from data (hadron multiplicities) on the way

Strange quark distributions

for a deuteron target

$$s(x)\int D_s^K(z)\mathrm{d}z \approx Q(x)[5\frac{\mathrm{d}^2N^K(x)}{\mathrm{d}^2N^{\mathrm{DIS}}(x)} - \int D_Q^K(z)\mathrm{d}z]$$

- $\int D^k_{s,Q}(z)$ from DSS
- shape of $s(x)$ is incompatible with recent LO parametrisations



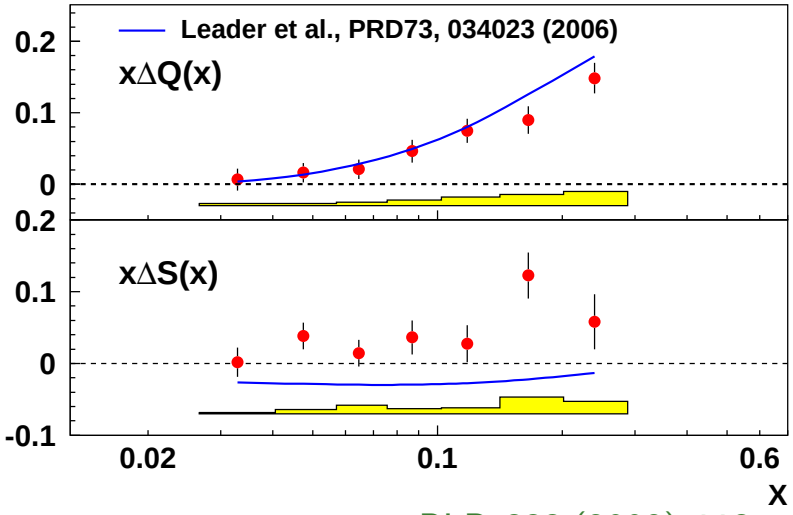
similar approach for

$$A_{\parallel,\mathrm{d}}(x)\frac{\mathrm{d}^2N^{\mathrm{DIS}}(x)}{\mathrm{d}x\mathrm{d}Q^2}$$

and

$$A_{\parallel,\mathrm{d}}(x)\frac{\mathrm{d}^2N^{K}(x)}{\mathrm{d}x\mathrm{d}Q^2}$$

- allow to determine $\Delta Q(x)$ and $\Delta s(x)$
- ΔQ is compatible with the g_1 data
- Δs is compatible with the result from the other measurements



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Analysis including SIDIS data

- **first global NLO $\overline{\rm MS}$ QCD analysis by DSSV**
  (PRL 101 (2008) 071001, PRD 80 (2009) 034030)

- **data sets:**
  - all inclusive asymmetries (except new COMPASS proton data)
  - SIDIS from SMC, HERMES, COMPASS ($h^{\pm}$)
  - PHENIX (π^0, STAR (jets)

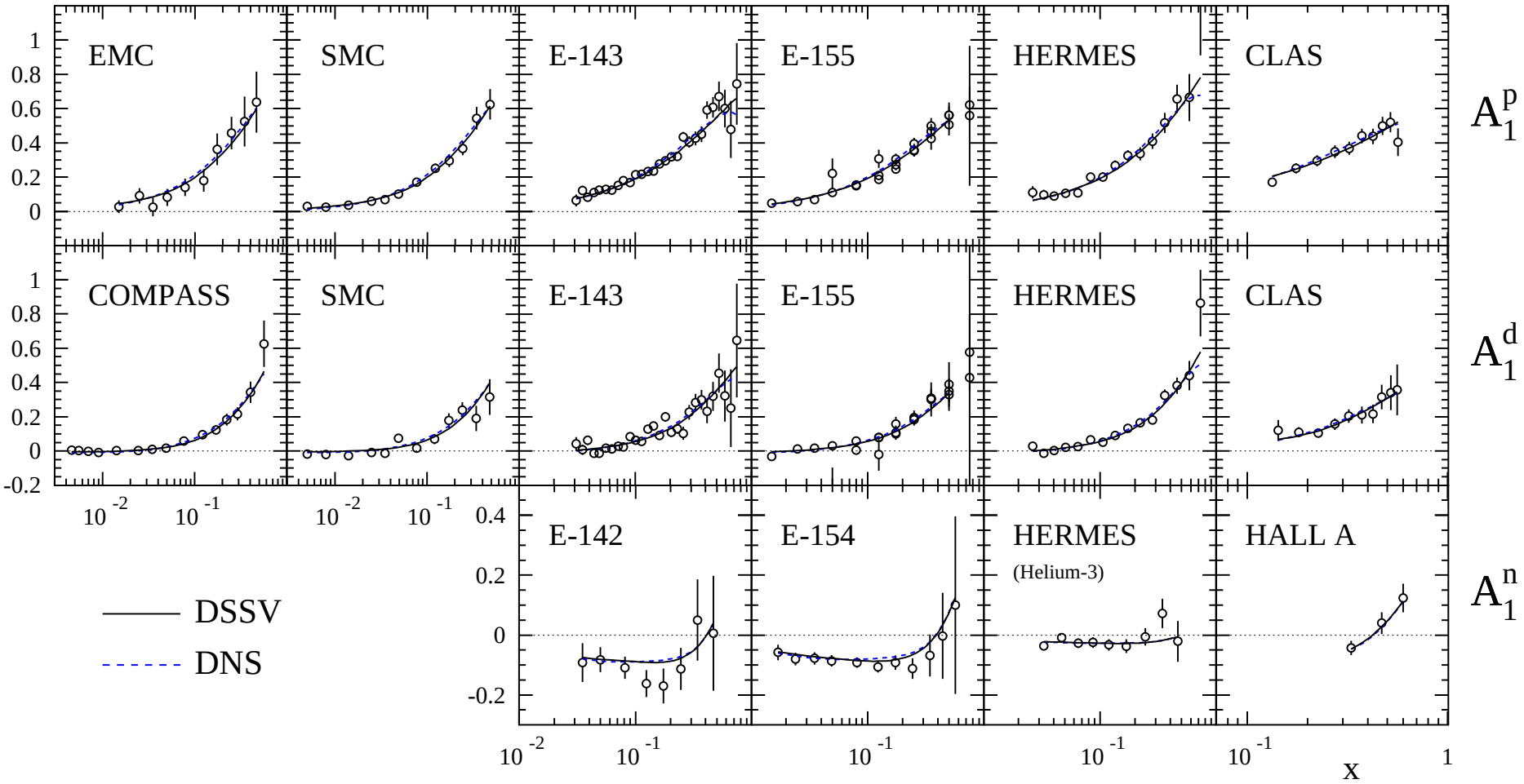
- **DSS fragmentation functions** from e^+e^-, ep and pp collisions

- few constraints added

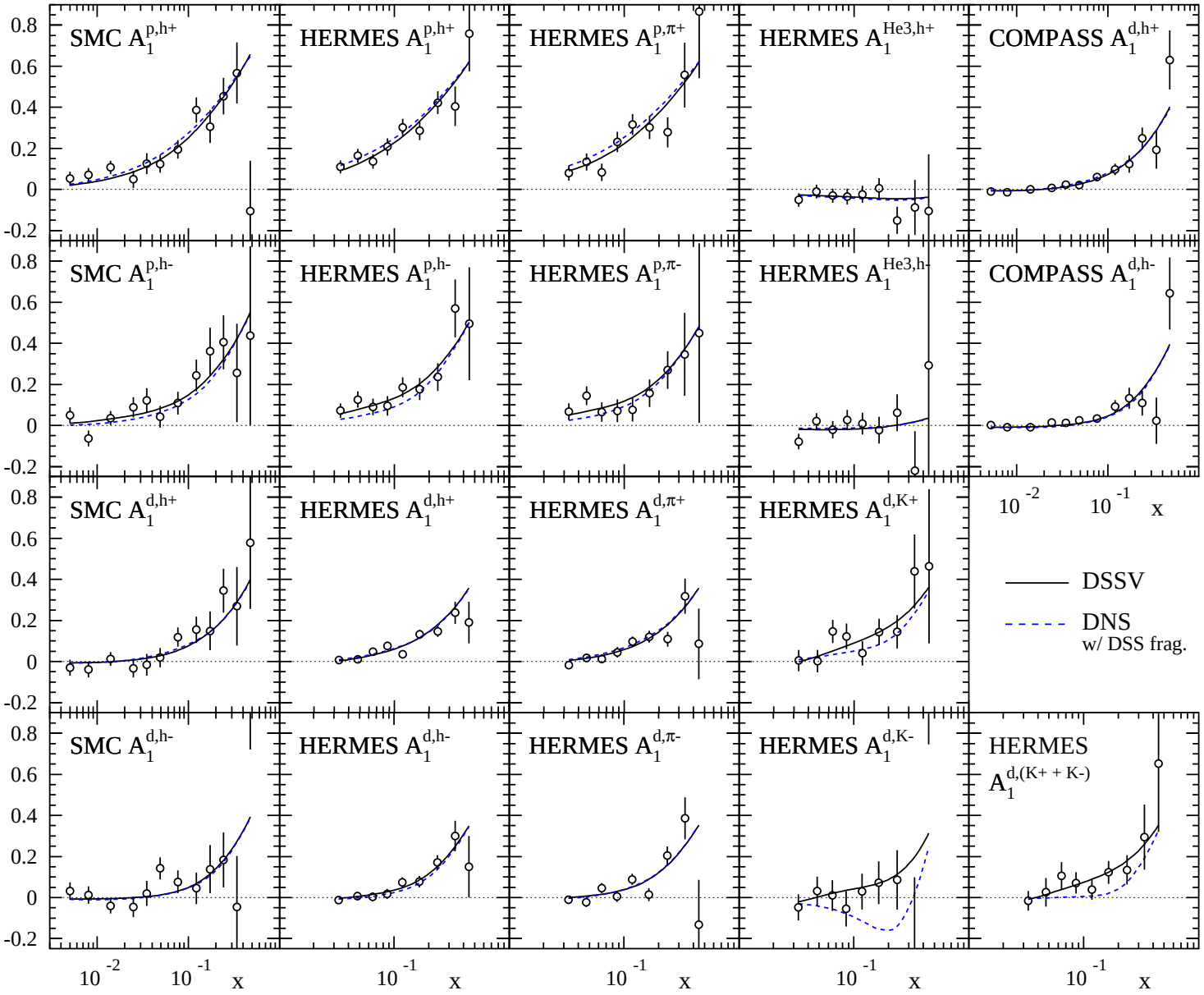
- no TMC or higher twists

- **results**
  - best determined $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$, consistent with previous determinations
  - flavour symmetry breaking in the light sea $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$
  - $\Delta\bar{u} - \Delta\bar{d}$ compatible with COMPASS and HERMES results

Fit results for inclusive asymmetries



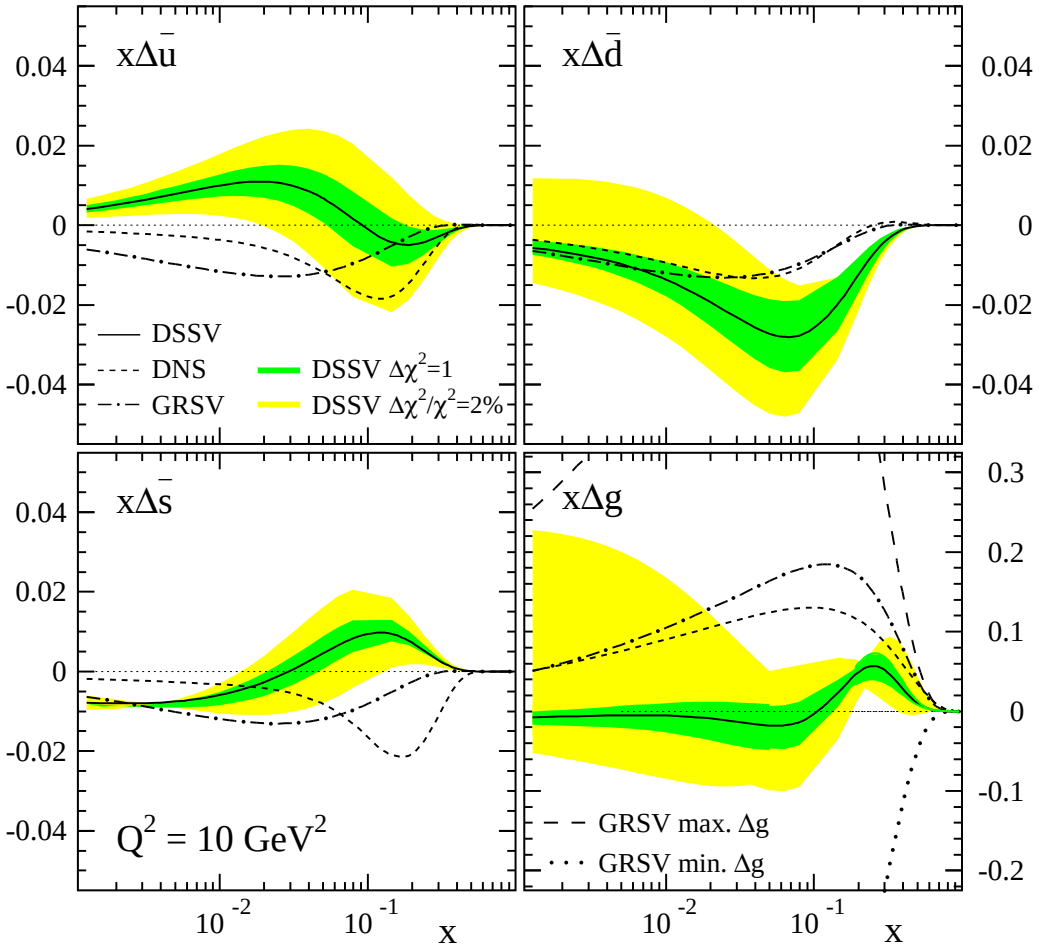
Fit results for semi-inclusive asymmetries



few clear differences to previous fits, especially in kaon asymmetries

Polarized sea quark distributions

- **light quark sea**
  flavour asymmetric
- **strange quarks**
  - $\Delta s(x) > 0$ for large x (SIDIS)
  - $\Delta s(x) < 0$ for small x (SU(3) $3F - D$)
  - Δs negative
- **gluon polarisation**
  ΔG small, but negative
- indication of $\frac{1}{2}\Delta\Sigma \approx -\Delta G$



Summary

Results

- in the last 20 years a lot of effort to measure polarised PDFs at SLAC, CERN, DESY and JLAB
- precise results for $A_1^{\mathrm{p,d,n}}$ available, although in a limited kinematic range
- NLO QCD analyses allow a precise determination of u and d quark polarisation
- more recent: semi-inclusive asymmetries from identified hadrons from COMPASS and HERMES
- full flavour separation of polarised quark distributions now possible
- first NLO analysis including all data (+ RHIC)
- still limited knowledge on strangeness and gluon polarisation

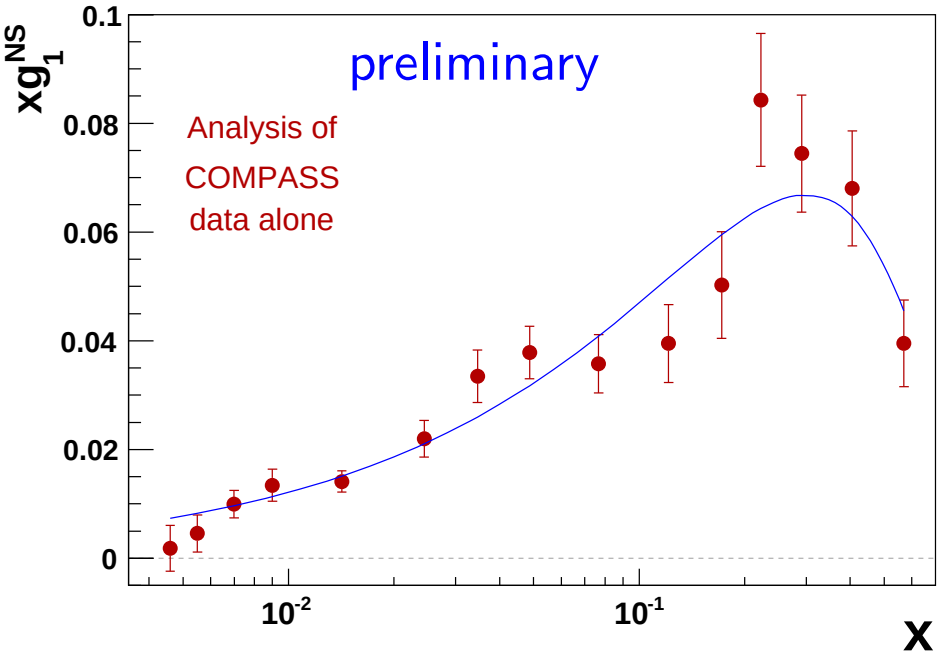
To be done

- hadron multiplicities from COMPASS will shed more light on strange quark fragmentation
- more high x data will come from JLAB
- $\Delta\bar{u}$, $\Delta\bar{u}$ will be measured in W production at RHIC
- more data taking planned at COMPASS (polarised and unpolarised)
- low x region needs collider data

Non-singlet structure function

- **non-singlet structure function**

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



- **Bjorken sum rule**

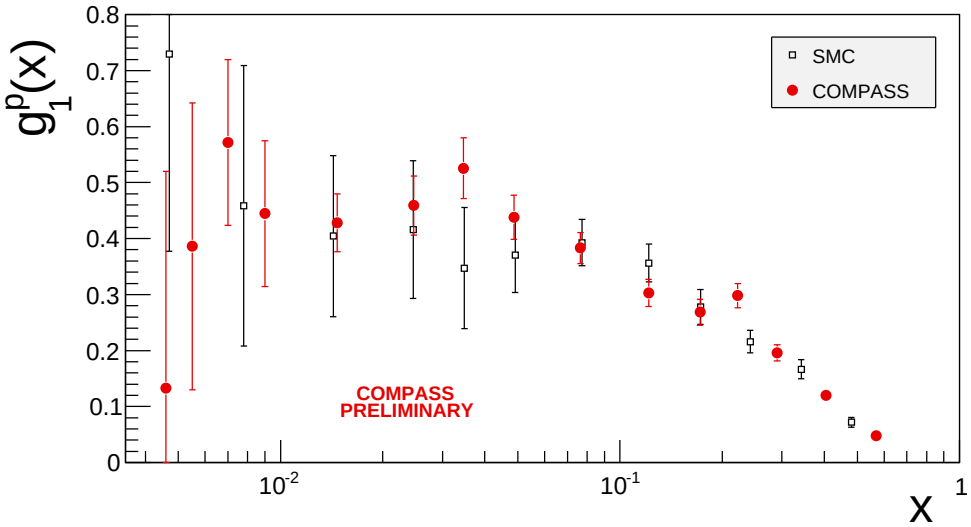
$$\int_0^1 g_1^{\mathrm{NS}} \mathrm{d}x = \left|\frac{g_A}{g_V}\right| C^{\mathrm{NS}}$$

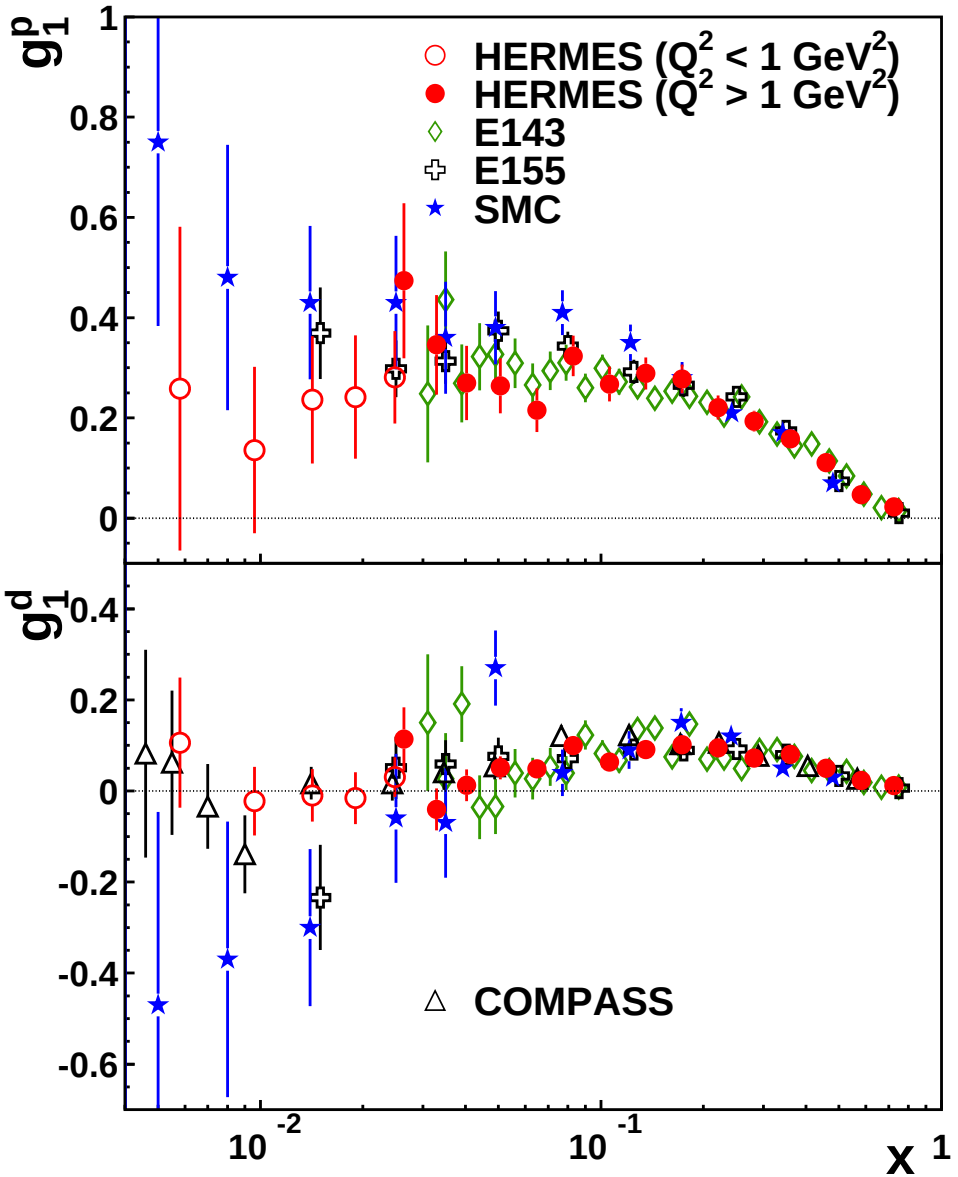
- QCD fit of COMPASS data alone: $\Delta q_{\mathrm{NS}} = \left|\frac{g_A}{g_V}\right| x^{\alpha}(1-x)^{\beta}$

$$\boldsymbol{g_A/g_V = 1.30 \pm 0.07(\mathrm{stat}) \pm 0.10(\mathrm{syst})}$$

- dominant systematic errors: beam and target polarisation
- PDG value: $g_A/g_V = 1.269 \pm 0.003$

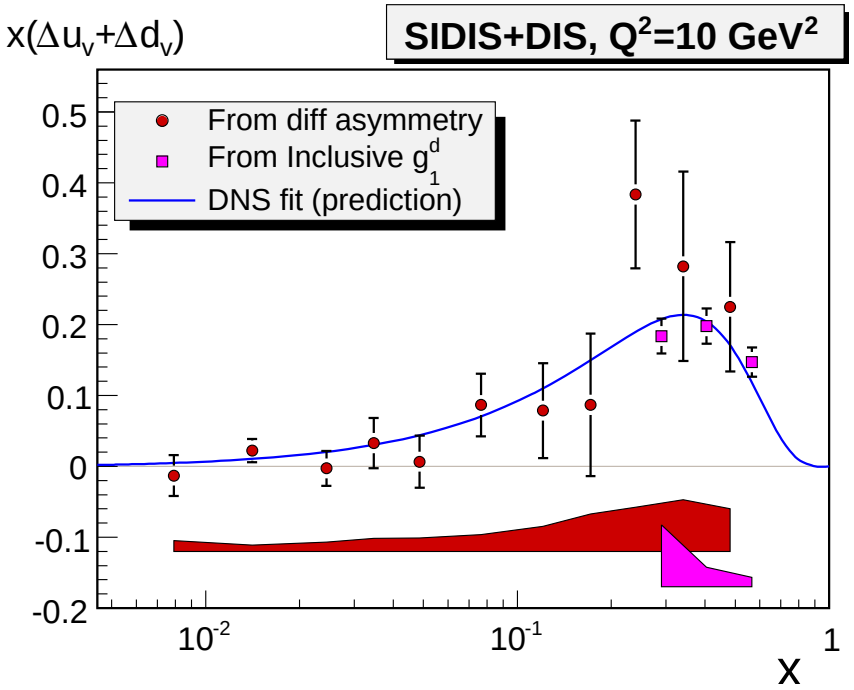
$g_1^{p,d}$ at small x

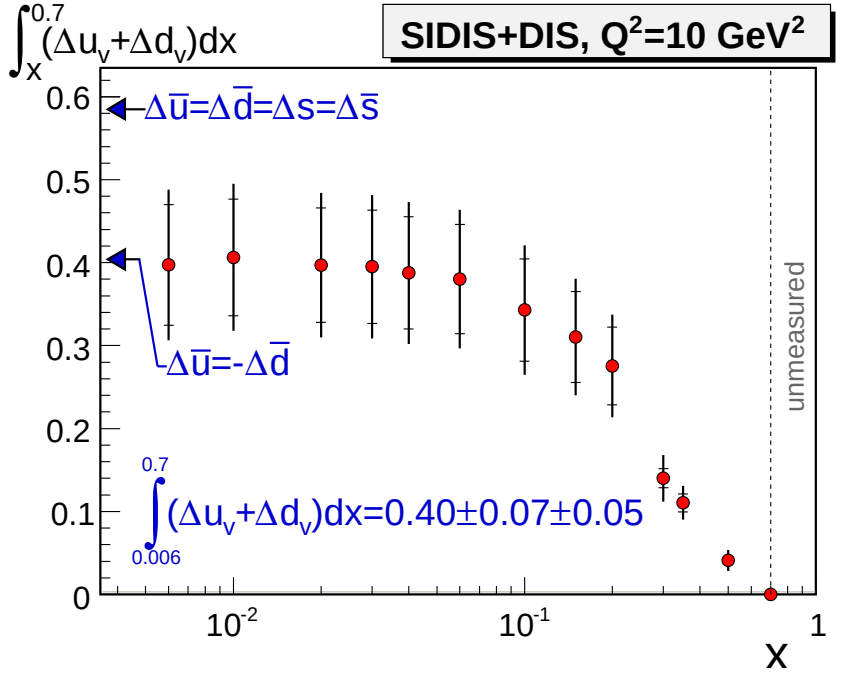




Towards polarised sea quarks

Difference asymmetry (LO): $A_d^{\pi^+-\pi^-}(x) = A_d^{K^+-K^-}(x) = \frac{\Delta u_v(x)+\Delta d_v(x)}{u_v(x)+d_v(x)}$





- first moment $\Gamma_v = \int_0^1 (\Delta u_v(x) + \Delta d_v(x))\mathrm{d}x$
- with Γ_1^{N} and a_8: $\Delta\bar{u} + \Delta\bar{d} = 3\,\Gamma_1^{\mathrm{N}} - \frac{1}{2}\Gamma_v + \frac{1}{12}a_8$ a_8 from hyperon decays
- disentangle between flavour **symmetric** ($\Delta\bar{u}{=}\Delta\bar{d}{=}\Delta s{=}\Delta\bar{s}$) and **asymmetric** ($\Delta\bar{u}{=}{-}\Delta\bar{d}$) sea: **asymmetric** sea favoured ($2.5\ \sigma_{\mathrm{stat}}$) (PLB 660 (2008) 458)
- next step: $\mathrm{K}^{\pm}$ asymmetries $\longrightarrow \Delta s$