The Status of the COMPASS Experiment

– Inclusive and Semi-inclusive Asymmetries –

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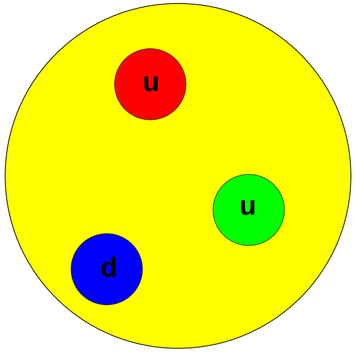
6th Circum-Pan-Pacific
Symposium on High Energy Spin Physics,
Vancouver, July 30 – August 2, 2007

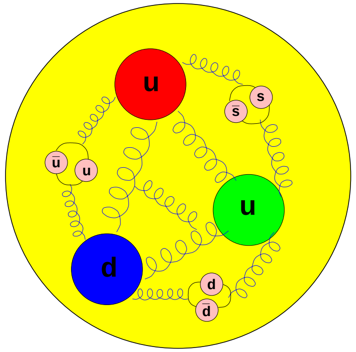
- COMPASS experiment
- Inclusive asymmetries
- Semi-inclusive asymmetries
- Upgrade 2006
- Status and outlook

The spin of the nucleon

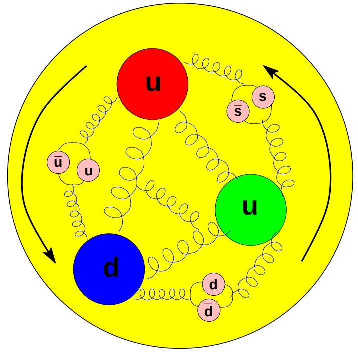


Naive parton model:
$\Rightarrow \Delta\Sigma = \Delta u_v + \Delta d_v = 1$

E155
$\Delta\Sigma = 0.23 \pm 0.07 \pm 0.19$



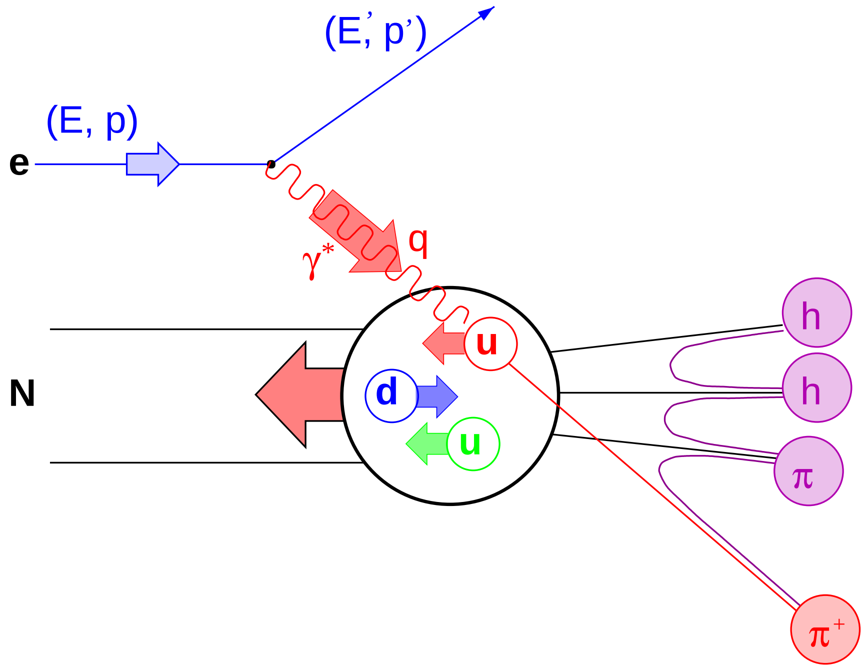
gluons important in
unpolarized case
ΔG?



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

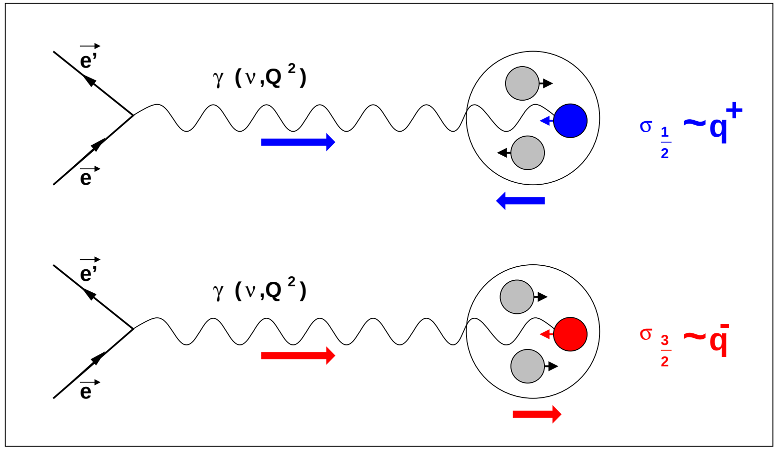
- **Inclusive cross section**

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

F_1, F_2, g_1, g_2 structure functions

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**

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

COMPASS at CERN

Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna, Erlangen, Freiburg, Lissabon, Mainz, Moscow, Munic, Prague, Protvino, Saclay, Tel Aviv, Turino, Trieste, Warsaw, Yamagata
(29 institutes, 240 physicists)

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

Muon beam

Gluon polarisation

Spin dependent structure functions

Polarised quark distributions

Transversity

Lambda polarisation

Vector meson production

DVCS

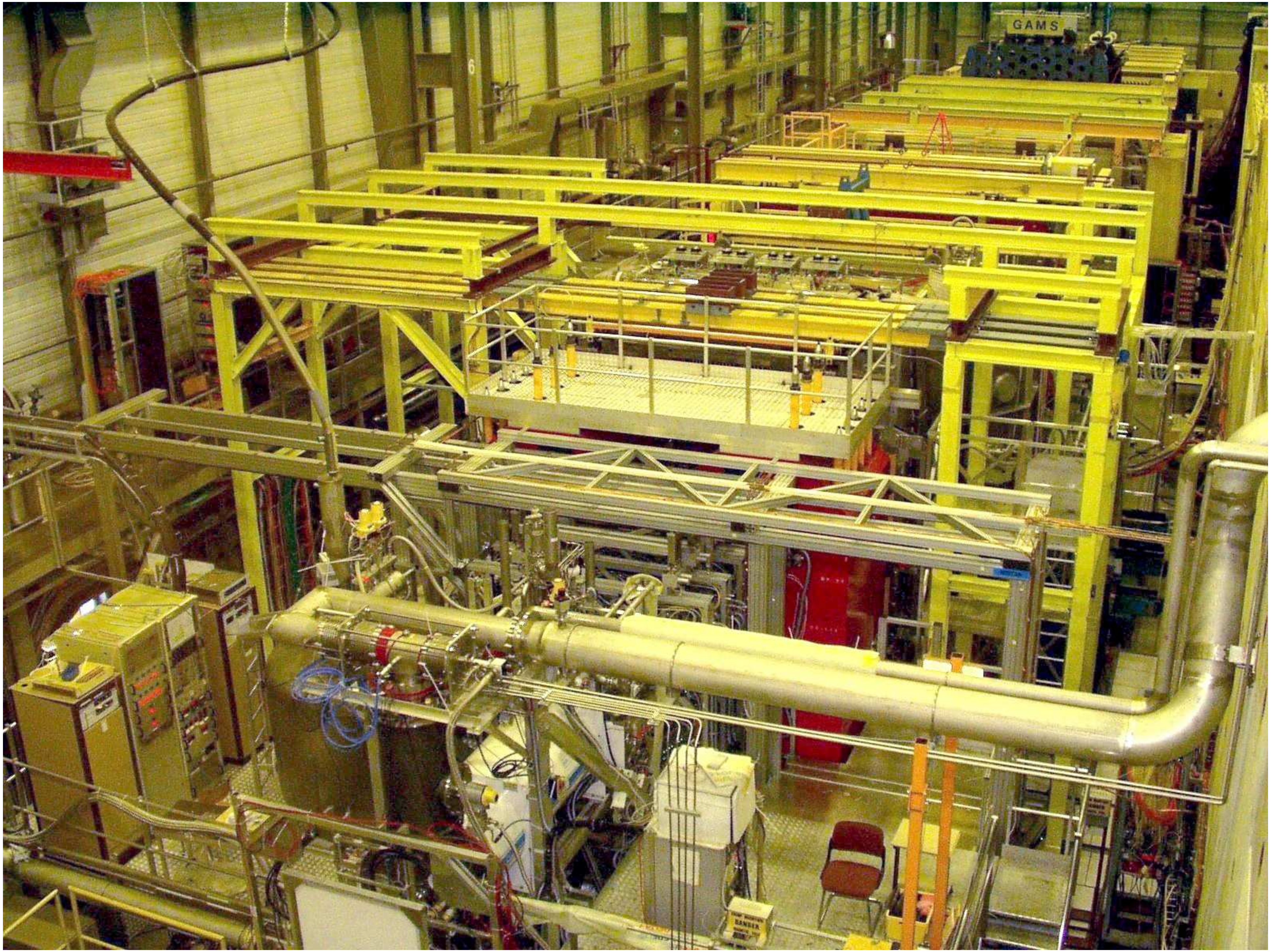
Hadron beam

Primakoff scattering

Exotic hadrons

- Glueballs
- Hybrids
- Multi-quark states

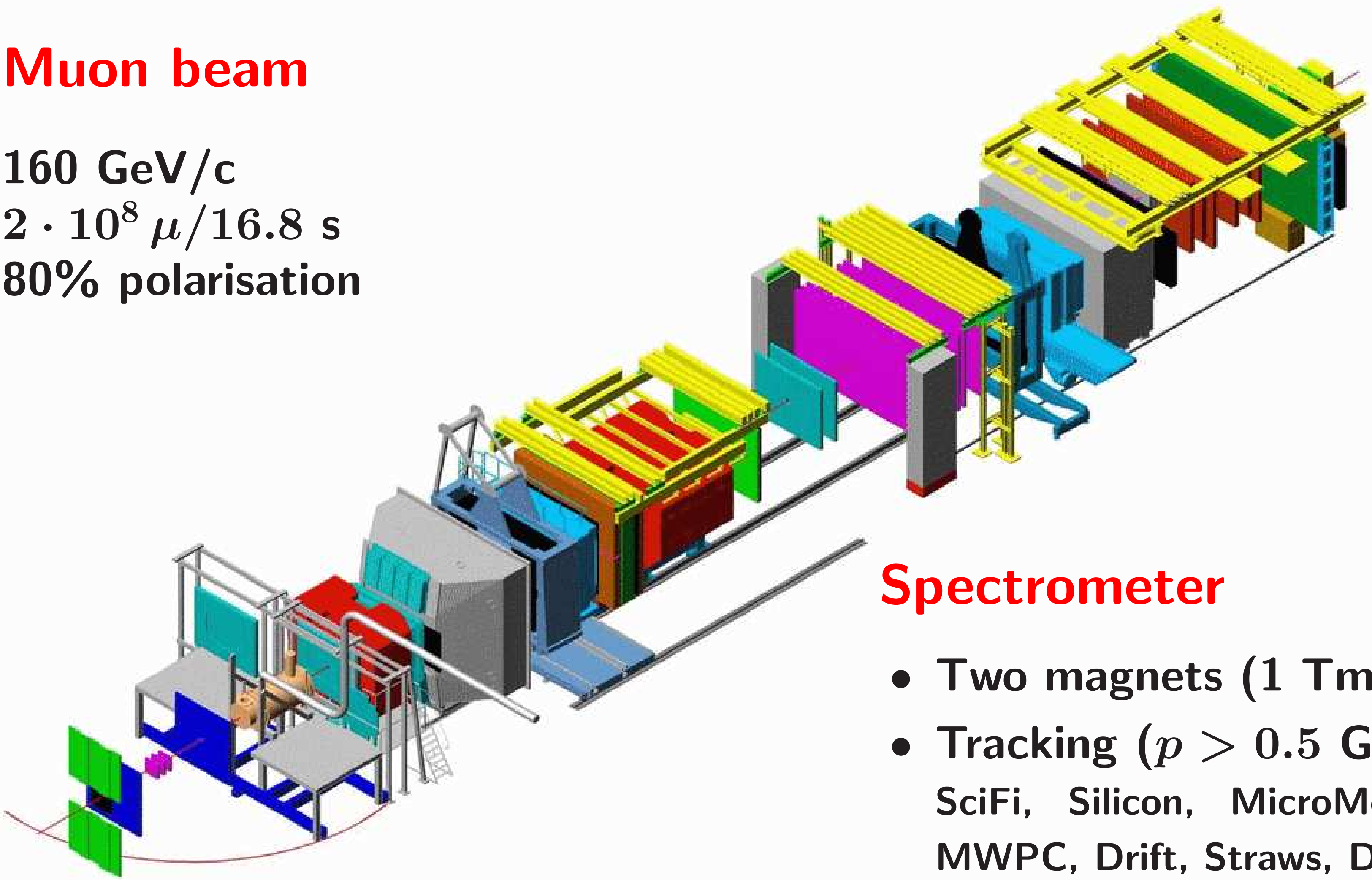
Charmed hadrons


GAMS

Spectrometer

Muon beam

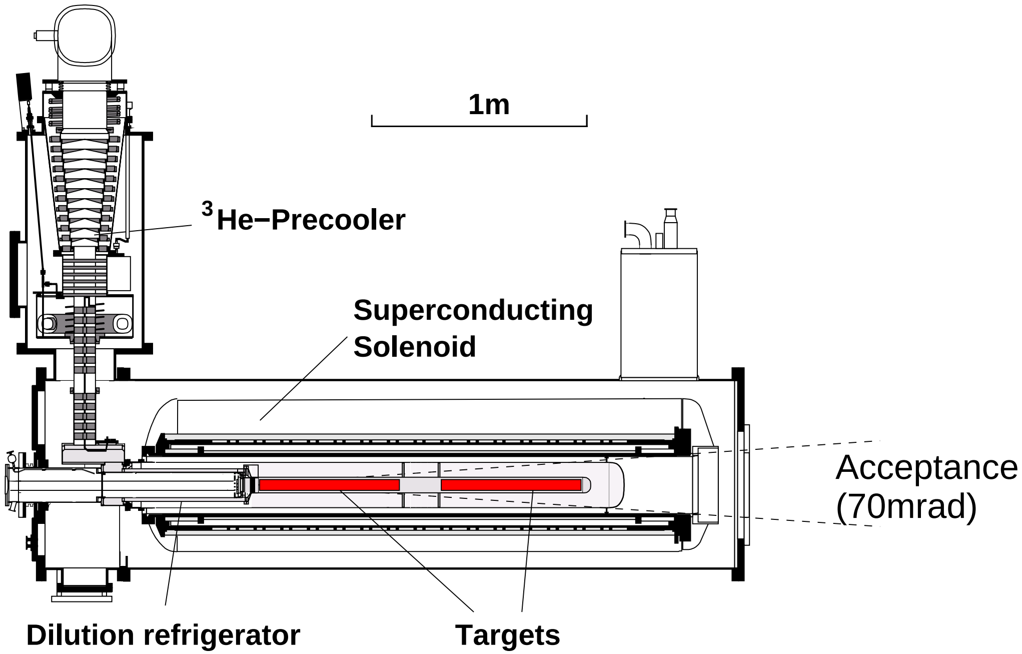
160 GeV/c
$2 \cdot 10^8 \mu/16.8$ s
80% polarisation

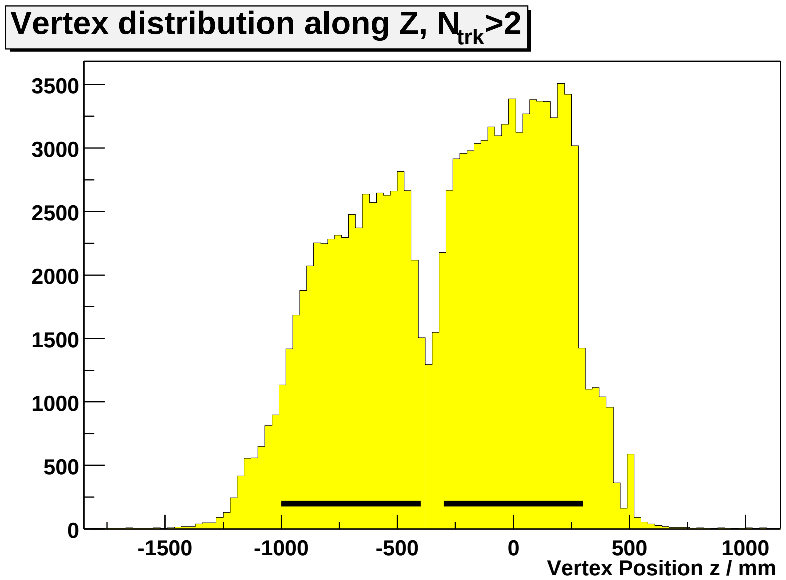


Spectrometer

- **Two magnets (1 Tm, 4.5 Tm)**
- **Tracking ($p > 0.5$ GeV/c):**
  SciFi, Silicon, MicroMega, GEM, MWPC, Drift, Straws, Driftubes
- **PID: π, k, p (RICH)**
  above 2, 9, 18 GeV/c
- **ECAL, HCAL, muon filter**

The polarised target



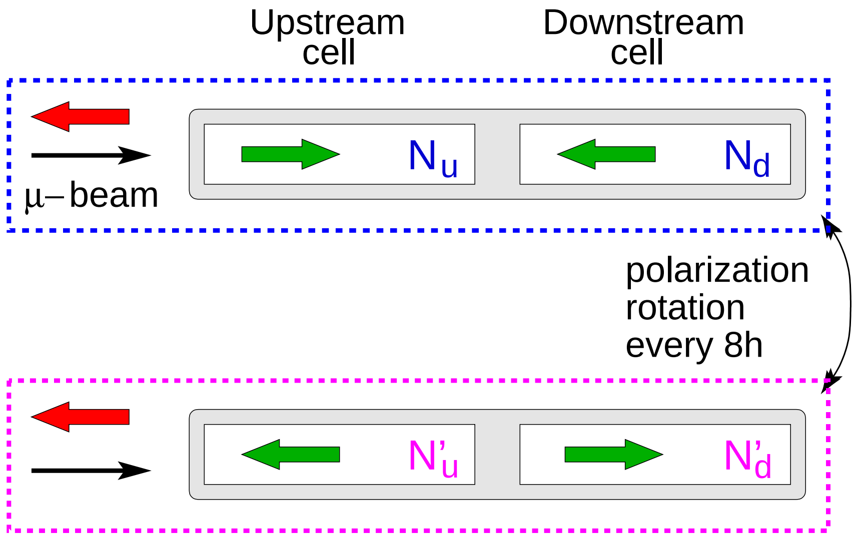


- target material: ^{6}**LiD**
- polarisation: $> \mathbf{50\%}$
- dilution factor: $\sim \mathbf{0.4}$
- Dynamic Nuclear Polarization
- solenoid field: 2.5 T
- ^{3}He/^{4}He: $T_{min} \approx 50\,\mathrm{mK}$
- two 60 cm long target cells with opposite polarisation
- 2006 new solenoid with 180 mrad acceptance
- regular polarisation reversal by field rotation

Method

- **to be measured:**

$$A_{\parallel} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$



- **flux normalization:**

$$A_{\text{exp}} = \frac{N_u - N_d}{N_u + N_d}$$

- **acceptance difference:**
  Polarisation rotation

- **take average asymmetry:**

$$\Rightarrow A_{\text{exp}} = \frac{A + A'}{2} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_u + N'_d}\right)$$

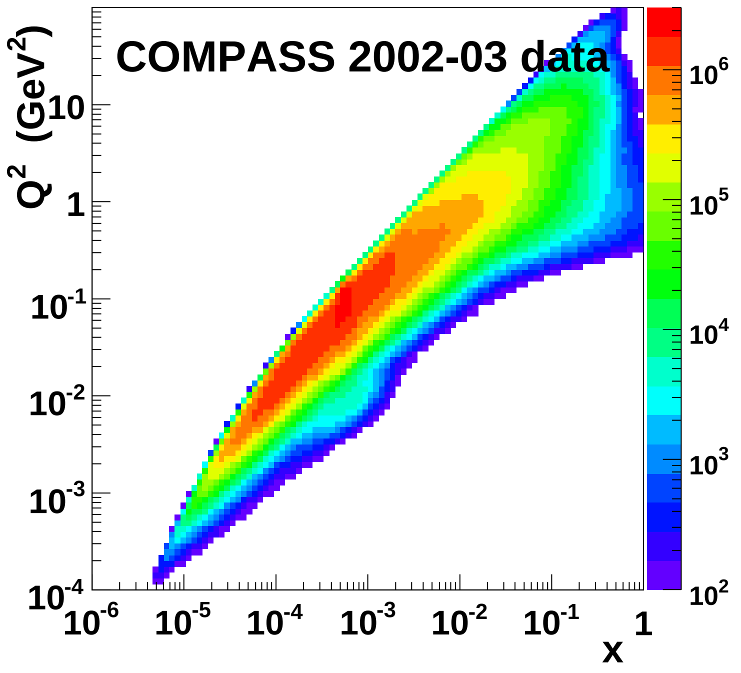
$\Rightarrow$ minimization of bias

- **experimental asymmetry**

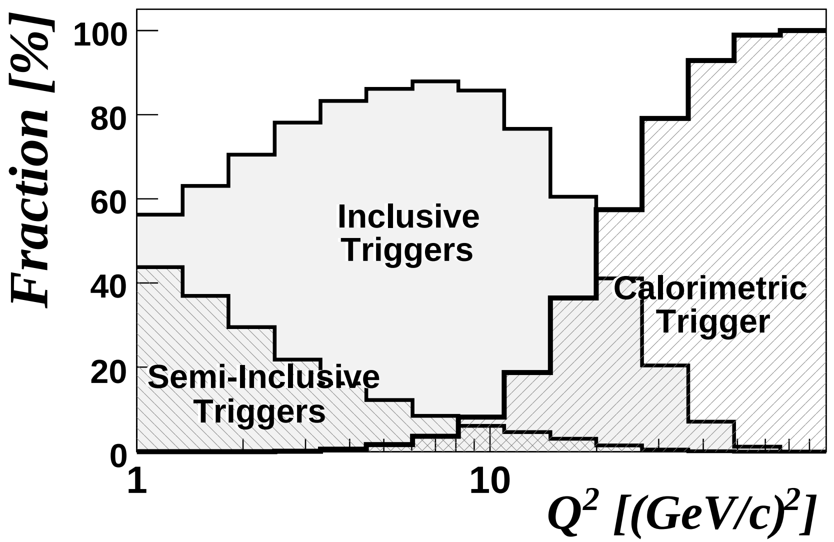
$$A_{\text{exp}} = p_\mu \; p_{\text{T}} \; f \; A_{\parallel}$$

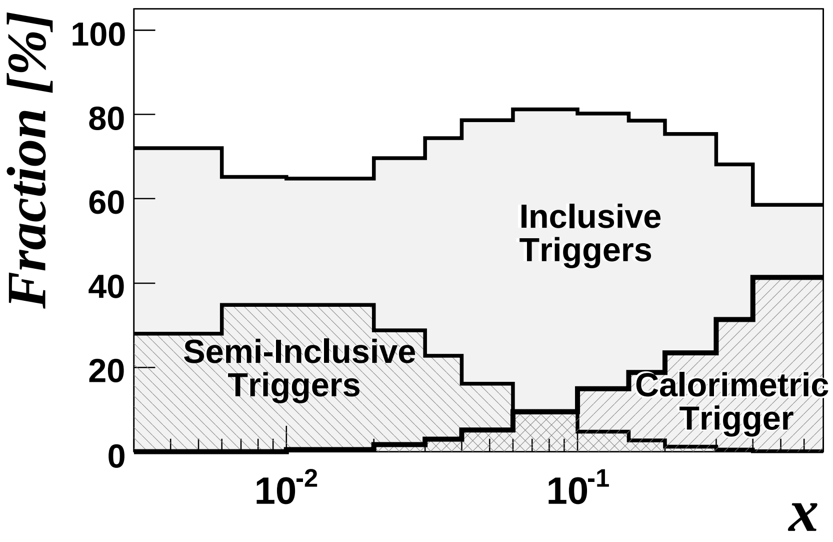
p_μ, p_{T} beam and target polarisation
f dilution factor

Kinematic range



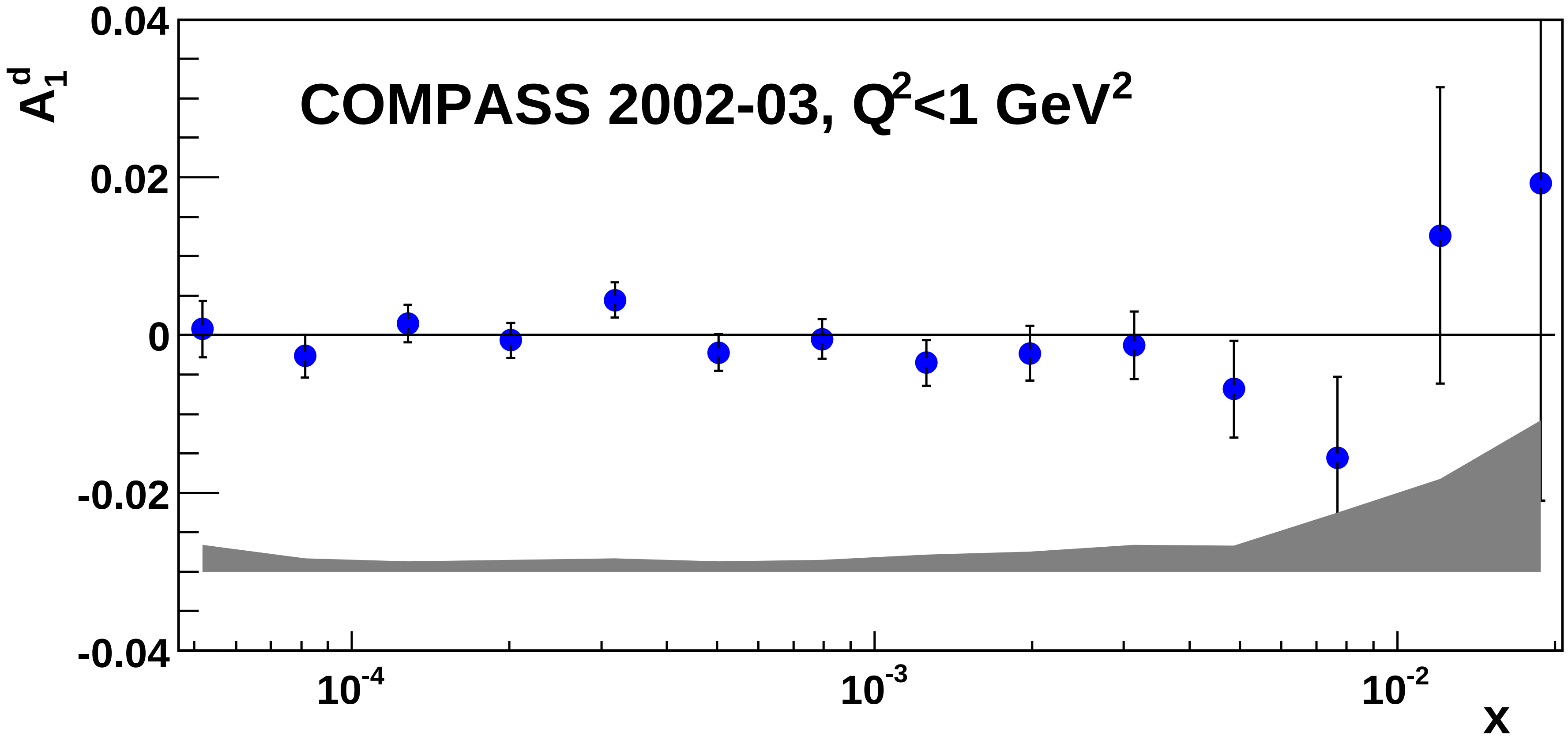
- strong corellation between x and Q^2
- inclusive triggers
- semi-inclusive triggers: dominant at low x and Q^2
- calorimetric trigger: dominant for $Q^2 > 30$ (GeV/c)^2





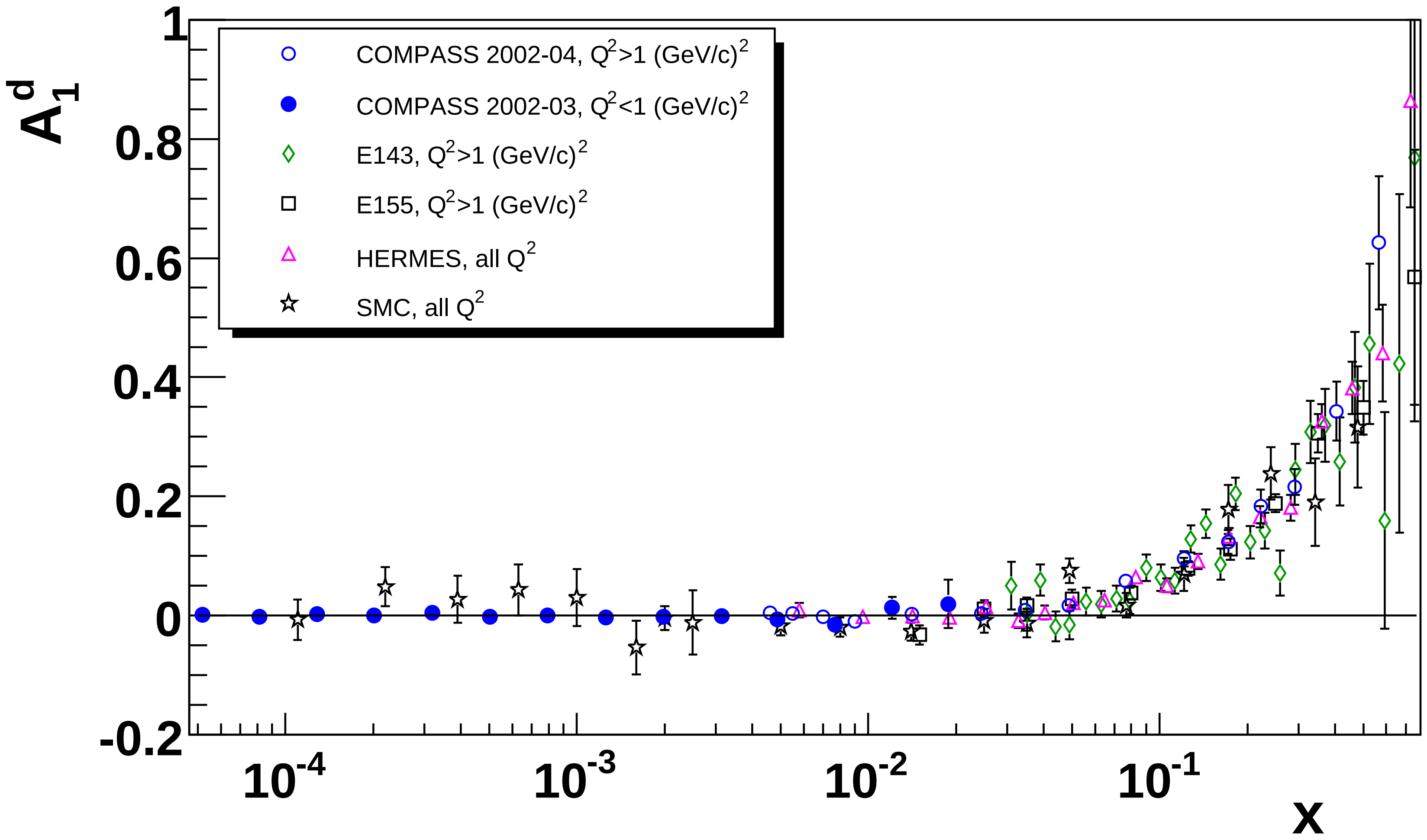
Inclusive asymmetries

Asymmetry for $Q^2 < 1$ (GeV/c)^2



- results from 2002/2003 published (PLB 647(2007)330): $300 \cdot 10^6$ events
- systematic error mainly due to false asymmetries
- A_1^{d} is compatible with 0 at small x

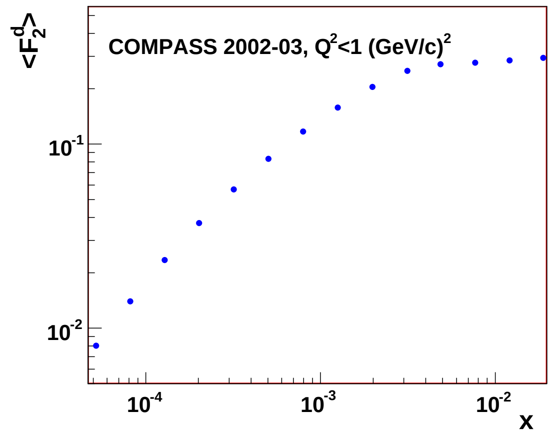
Comparison with other experiments



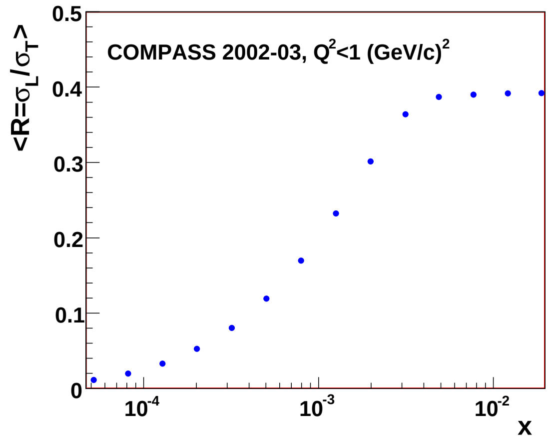
- very good agreement with SMC (the only other experiment at low x)
- factor 10–20 improvement of statistical errors compared to SMC

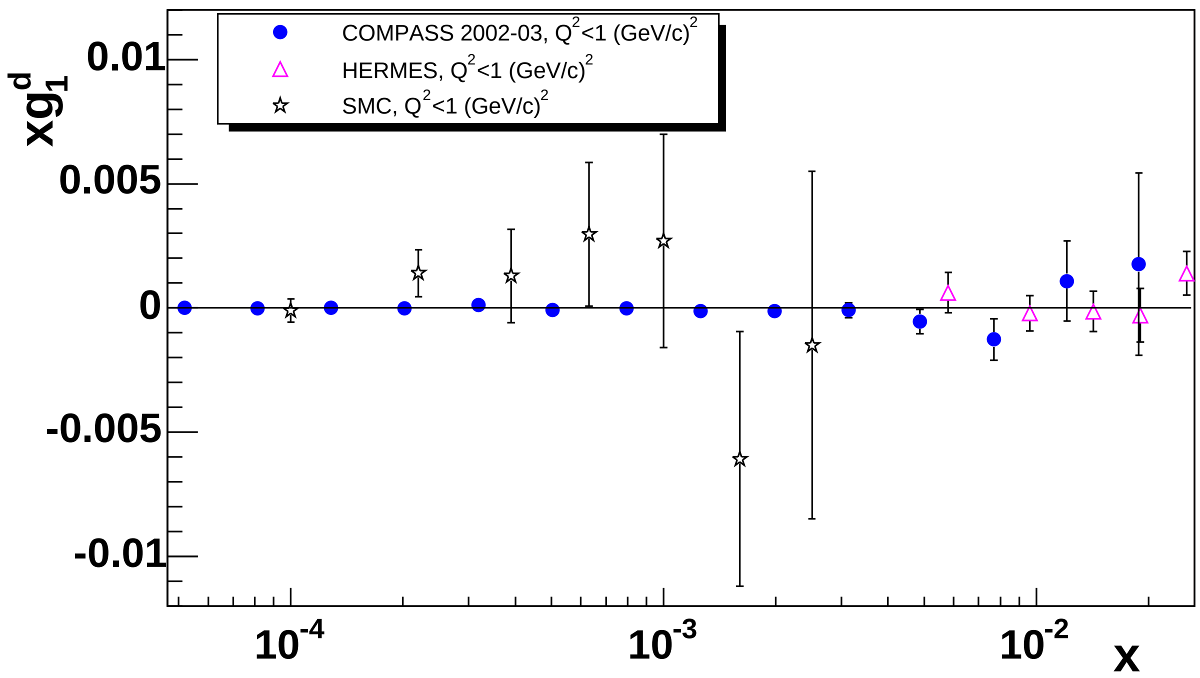
g_1 structure function ($Q^2 < 1$ (GeV/c)^2)

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



F2 from
SMC parametrisation
(extrapolation
with JKBB model)





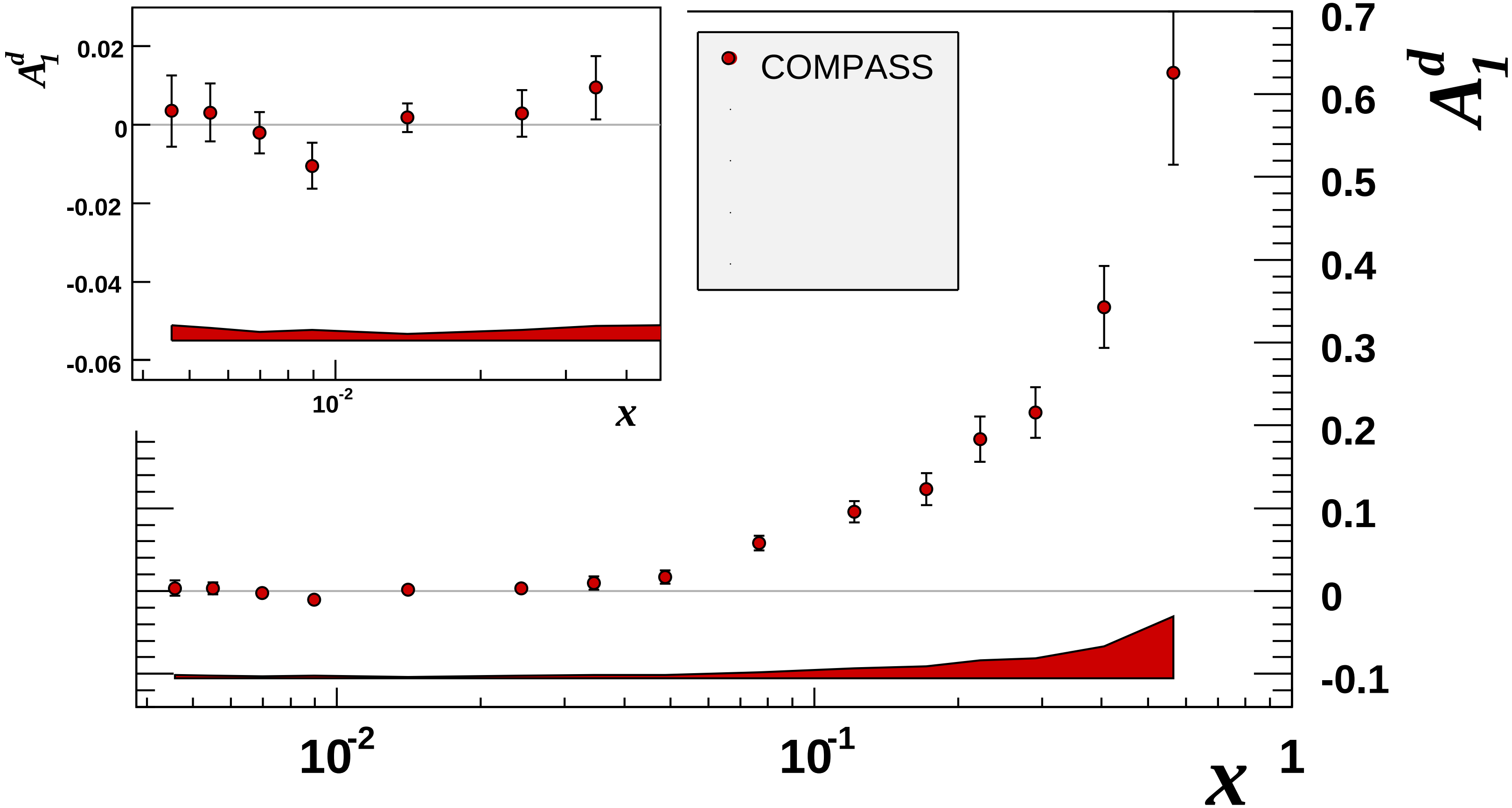
R parametr.:

$x > 0.12$ SLAC

$0.003 < x < 0.12$ NMC

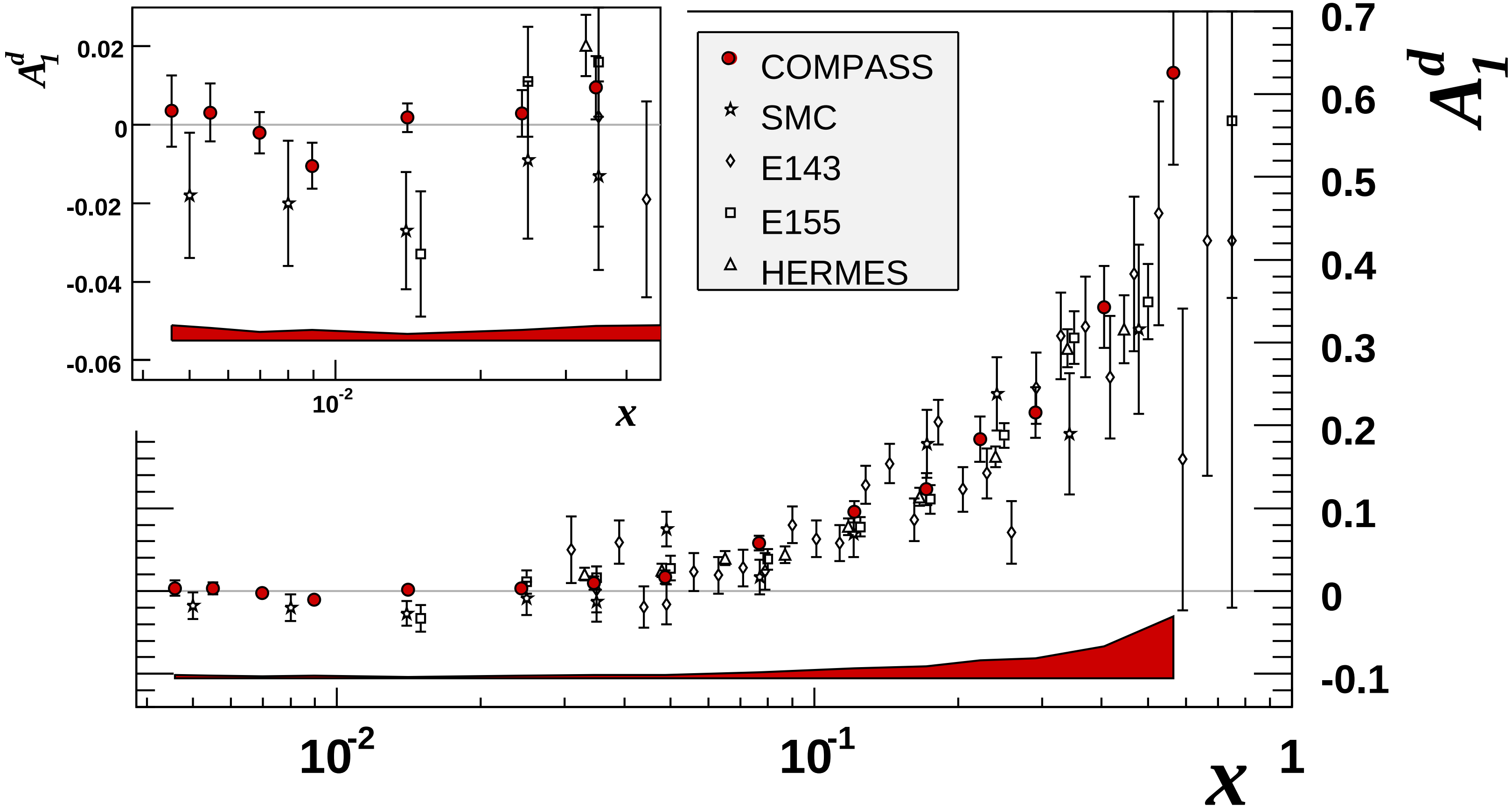
$x < 0.003$ ZEUS

Asymmetry for $Q^2 > 1\ (\mathrm{GeV/c})^2$



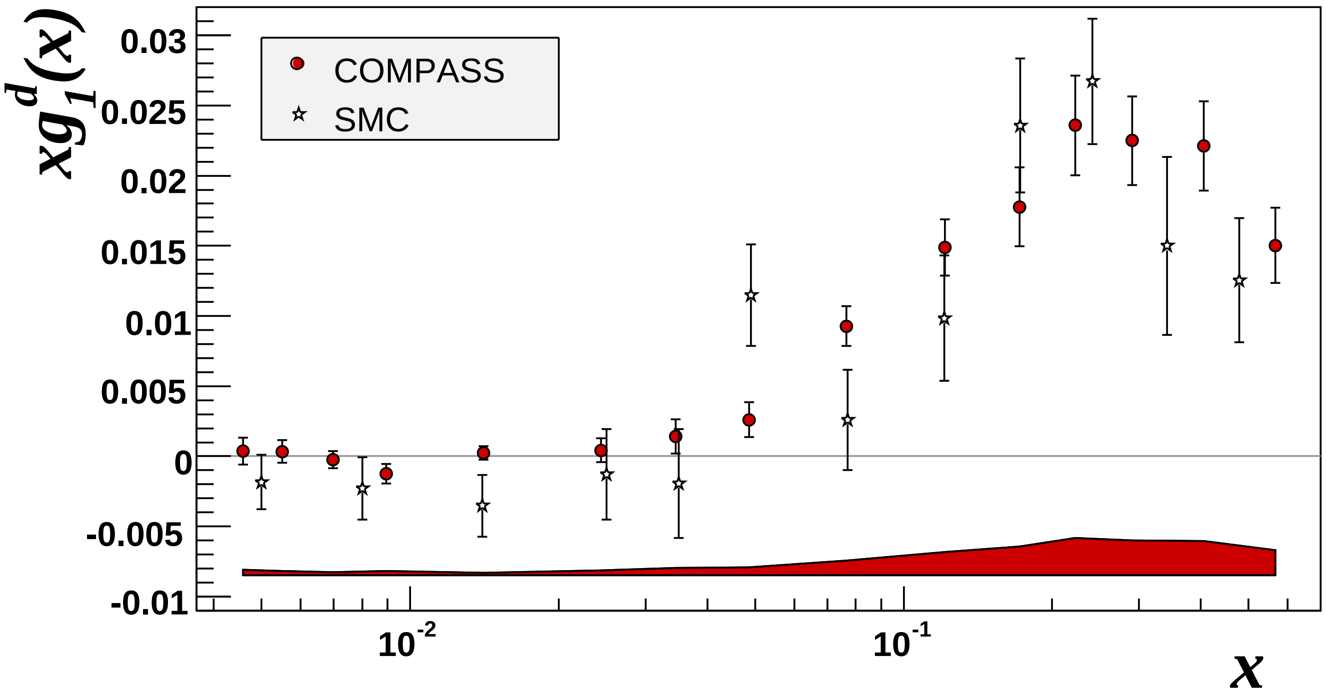
- results from 2002–2004 published in PLB 647 (2007) 8
- $88 \cdot 10^6$ events with $x > 0.004,\ 0.1 < y < 0.9$
- systematic errors: p_μ (5%), p_T (5%, f (2–3%), D (6%) $\Longrightarrow \delta A_1 \approx 0.1 A_1$
- additional contributions from false asymmetries, radiative corrections

Asymmetry for $Q^2 > 1$ (GeV/c)^2

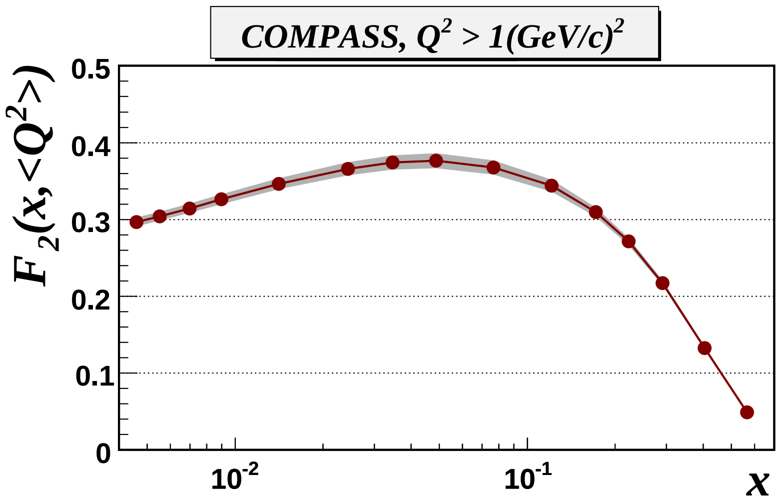


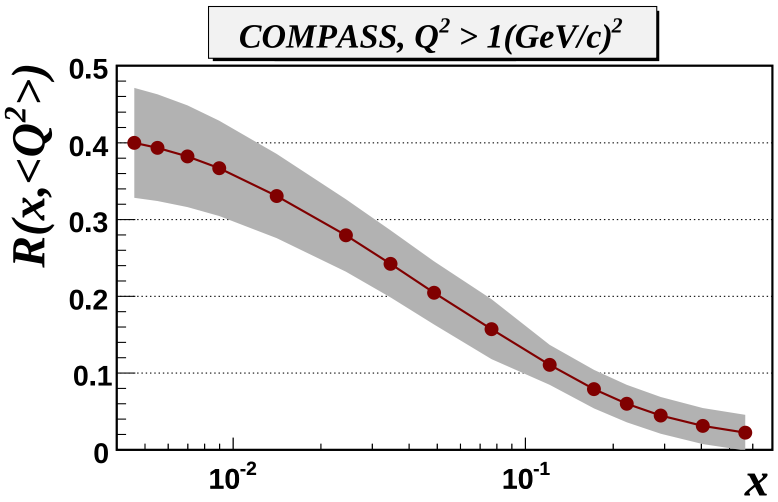
- results from 2002–2004 published in PLB 647 (2007) 8
- A_1^d compatible with 0 for $x < 0.05$
- good agreement with previous experiments
- significant improvement at low x, no tendency towards negative values

$g_1(x)$ at measured Q^2



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





First moment of g_1

$$\Gamma_1^{\mathrm{N}} \; (Q^2 = 3(\mathrm{GeV/c})^2) = \int_0^1 g_1^{\mathrm{N}} \mathrm{d}x$$

$$= 0.0502 \pm 0.0028(\mathrm{stat}) \pm 0.0020(\mathrm{evol.}) \pm 0.0051(\mathrm{syst.})$$

- data for $0.004 < x < 0.7$, QCD fit used for extrapolation
- contribution of unmeasured region about 3 %
- using: $\Gamma_1^{\mathrm{N}} = \frac{1}{9}(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha + s^2))(a_0(Q^2) + \frac{1}{4}a_8)$

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

- extrapolating towards $Q^2 \to \infty$: $\hat{a}_0 = 0.33 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst}) = \Delta\Sigma$

$$(\Delta s + \Delta \bar{s}) = \frac{1}{3}(\hat{a}_0 + a_8) = -0.08 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

- negative strange sea polarisation

QCD analysis

COMPASS

- **spin structure function g_1**

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

- **DGLAP equations**

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

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

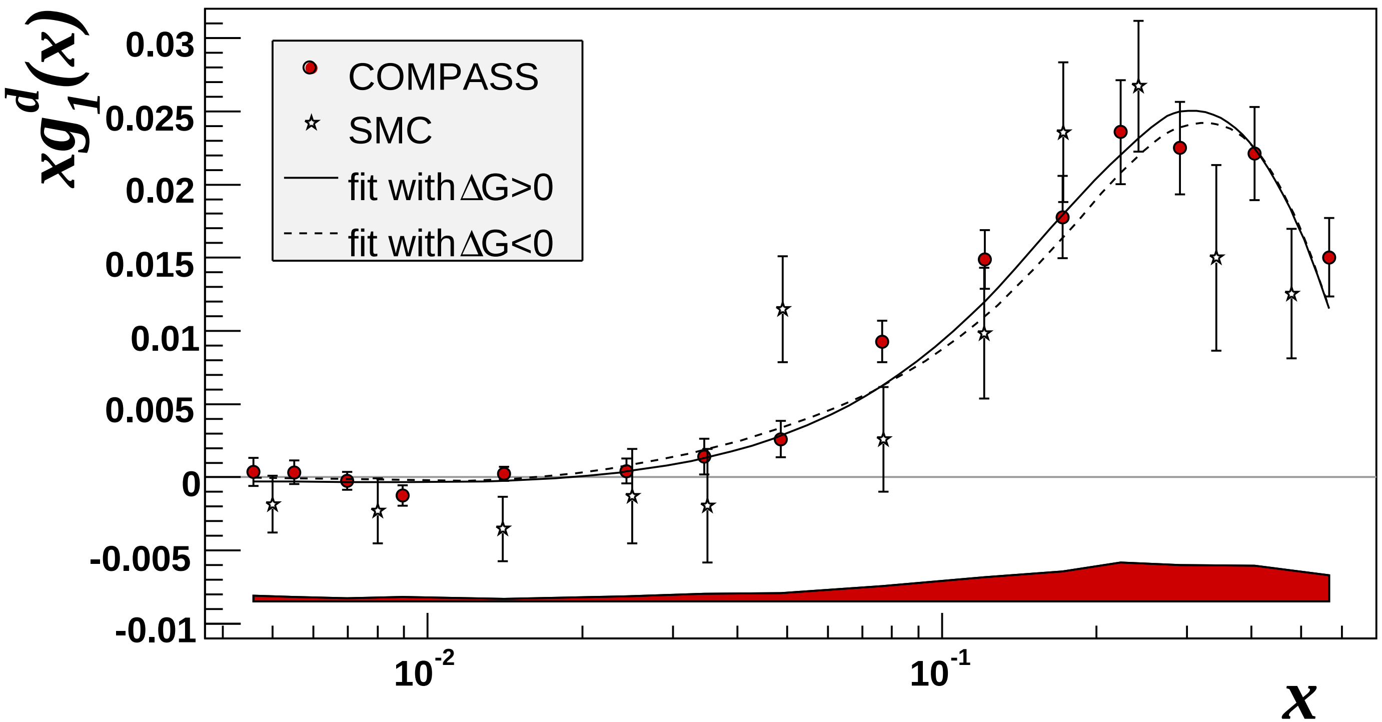
- **input parameterization at Q_0^2**

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

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

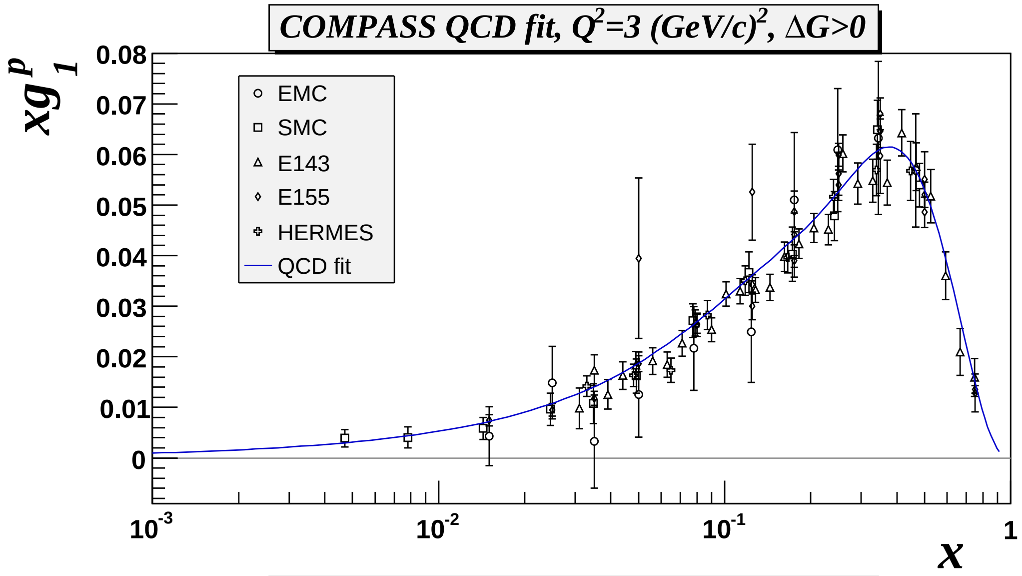
QCD fits

- **two different approaches**
  - numerical integration in (x, Q^2) space (PRD 58 (1998) 112002)
  - solution of DGLAP in space of moments (PRD 70 (2004) 074032)
- **fit to world data (except final g_1^d from HERMES)**
- **NLO analysis in $\overline{\text{MS}}$ scheme**



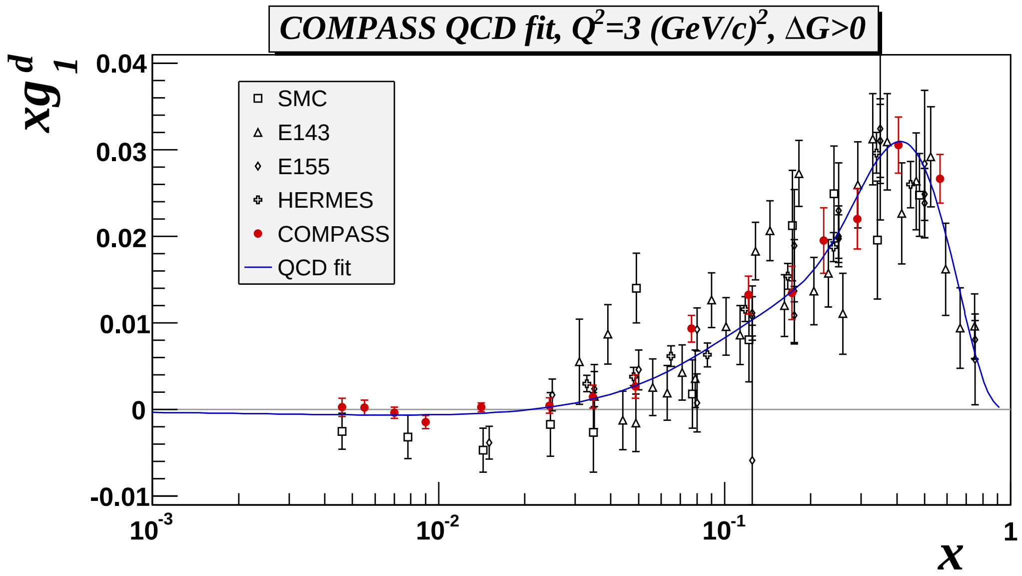
- **well described by two solutions with $\Delta G > 0$ and $\Delta G < 0$**

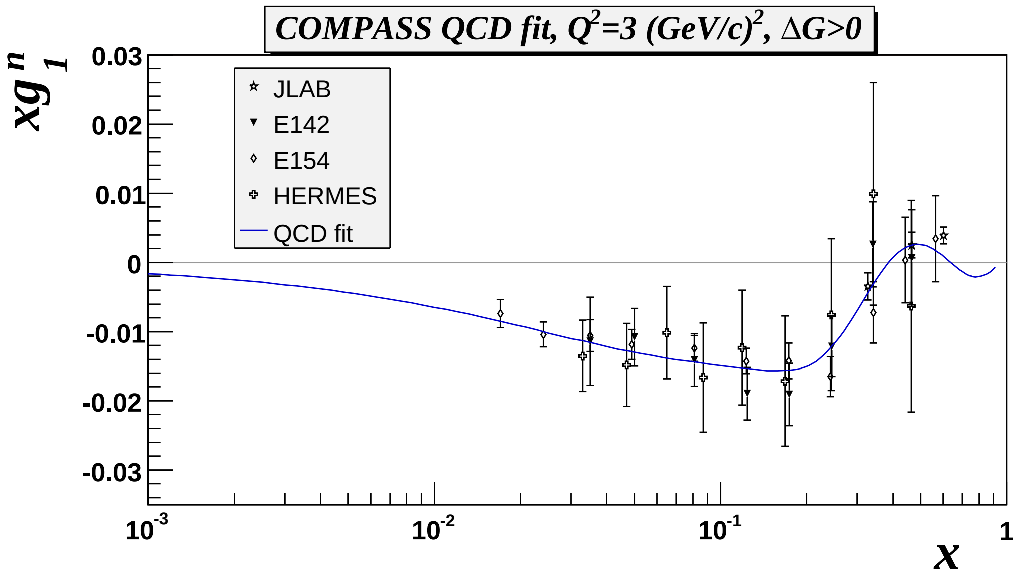
Results for p, d and n



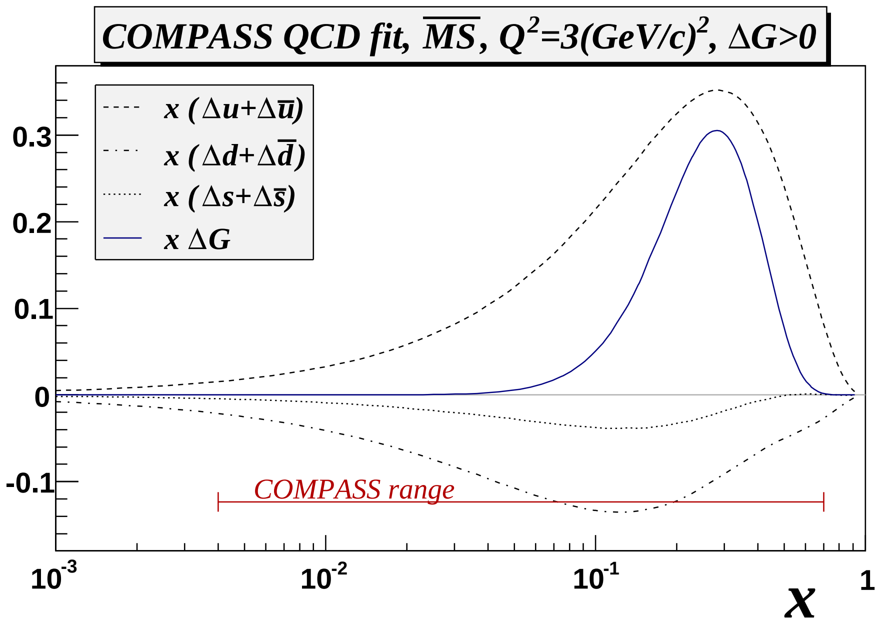
world data at $Q^2 = 3$ (GeV/c)^2

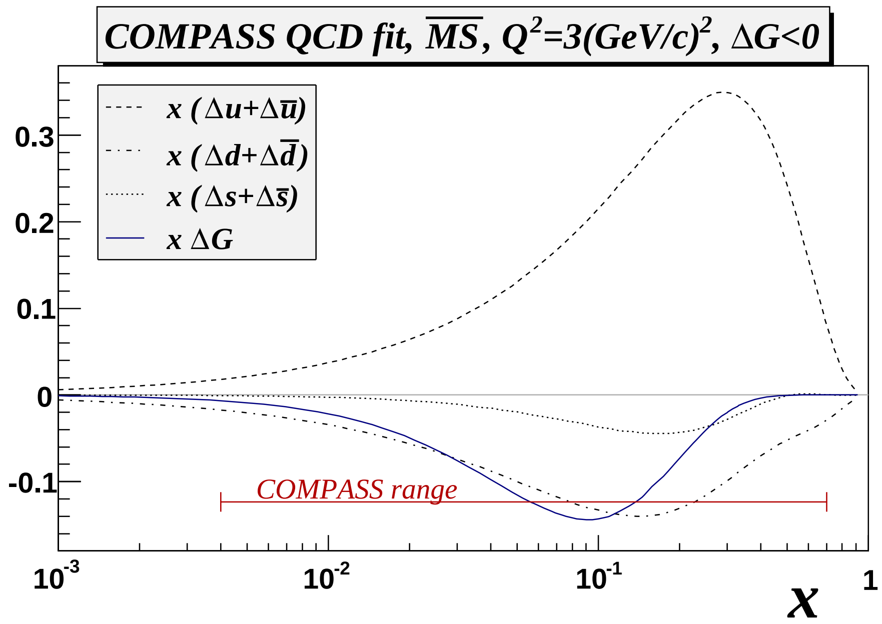
fit with $\Delta G > 0$





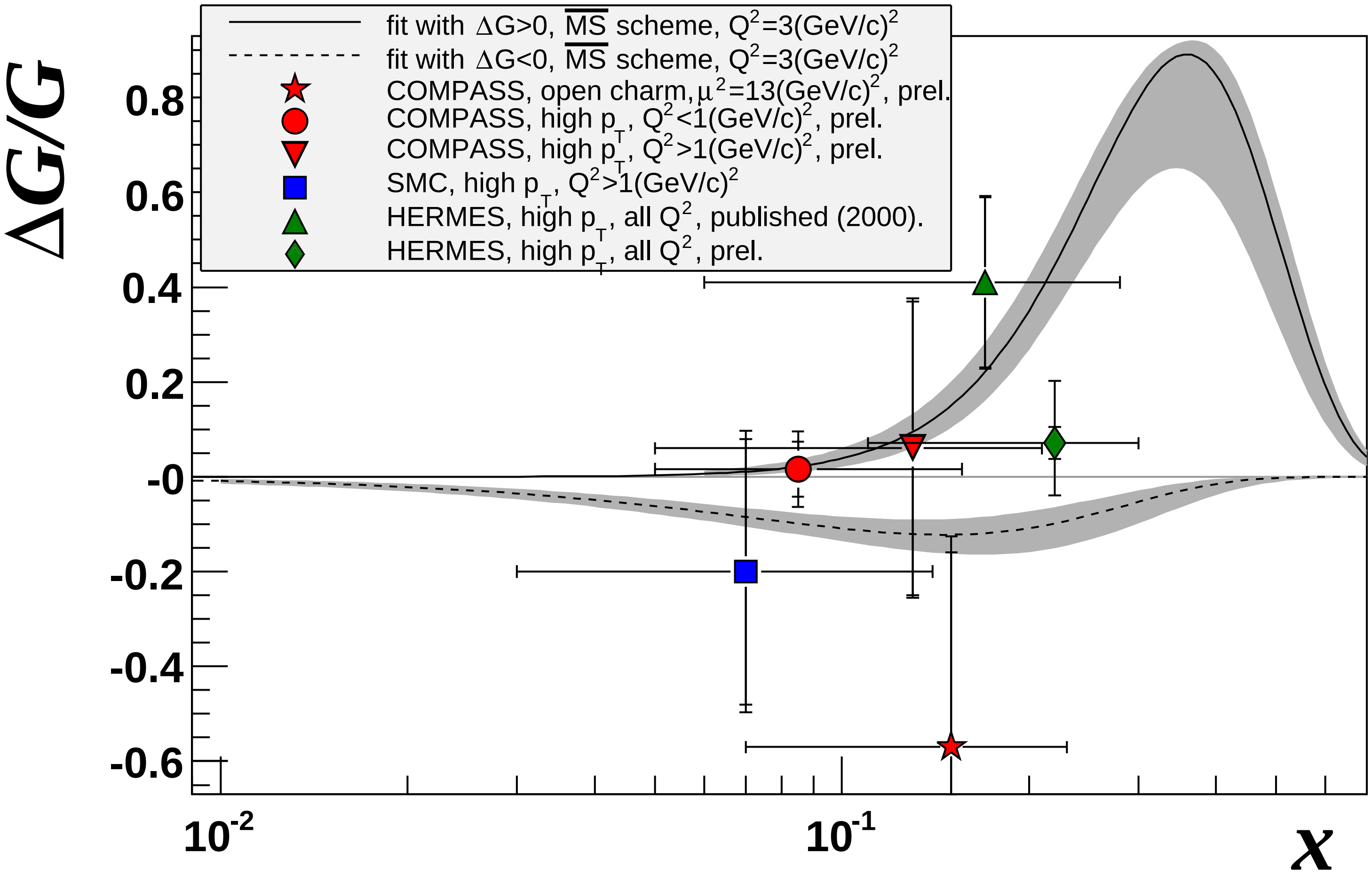
Polarised parton distributions





- **small sensitivity to light sea and gluon polarisation**
- **quark polarisation:** $\eta_\Sigma = 0.30 \pm 0.01(\text{stat}) \pm 0.02(\text{evol})$
  (error factor 2 larger without COMPASS)
- **gluon polarisation:** $|\eta_G| \approx 0.2 - 0.3$

Gluon polarisation



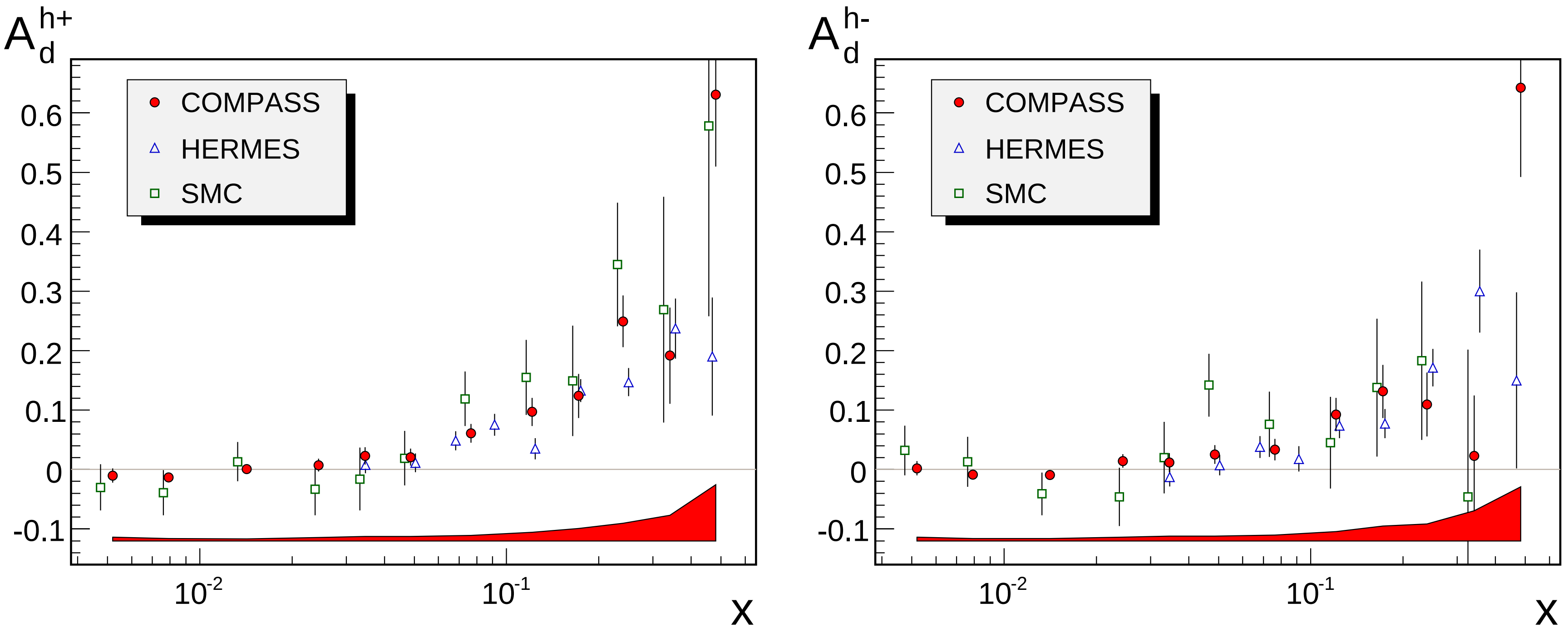
- bands correspond to statistical errors
- uncertainty due to parameterization not included
- unpolarised PDFs from MRST
- direct measurements of ΔG (see talk from N. Doshita)

Semi-inclusive asymmetries

Hadron asymmetries

$$A_1^h(x) = \frac{\sum_q e_q^2(\Delta q(x) D_q^h + \Delta\bar{q}(x) D_{\bar{q}}^h)}{\sum_q e_q^2(q(x) D_q^h + \bar{q}(x) D_{\bar{q}}^h)}$$

$$A^+ = \frac{\sigma_{\uparrow\downarrow}^{h+} - \sigma_{\uparrow\uparrow}^{h+}}{\sigma_{\uparrow\downarrow}^{h+} + \sigma_{\uparrow\uparrow}^{h+}} \qquad A^- = \frac{\sigma_{\uparrow\downarrow}^{h-} - \sigma_{\uparrow\uparrow}^{h-}}{\sigma_{\uparrow\downarrow}^{h-} + \sigma_{\uparrow\uparrow}^{h-}}$$



- **selection:** $Q^2 > 1$ (GeV/c)^2, $0.1 < y < 0.9$, $0.2 < z < 0.85$
- **events:** $N^+ = 30 \cdot 10^6$, $N^- = 25 \cdot 10^6$, $corr(N^+, N^-) \approx 20\%$

Difference asymmetry

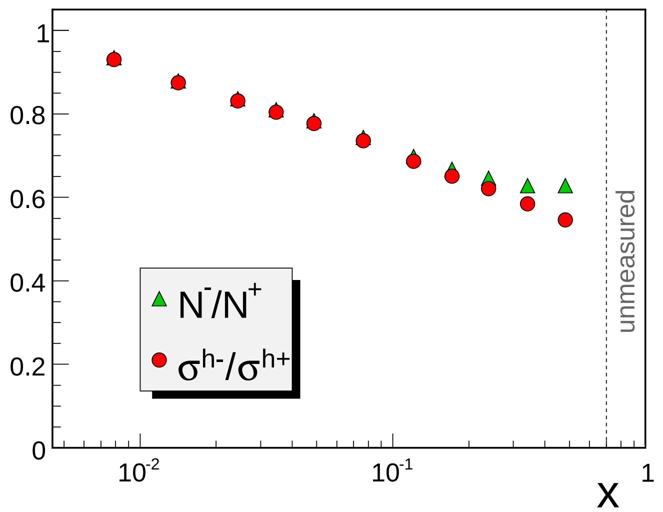
$$A^{+-} = \frac{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) - (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) + (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}$$

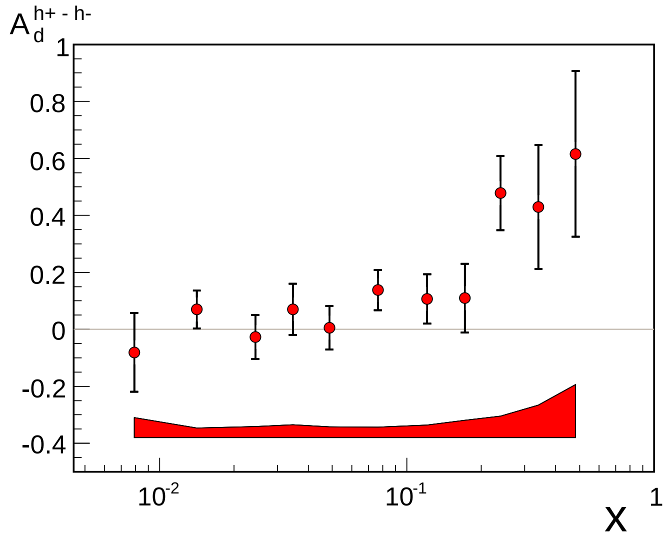
- LO analysis: fragmentation functions cancel, for deuteron PID not neccessary

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

- A^{+-} asymmetry obtained from A^+ and A^- asymmetries

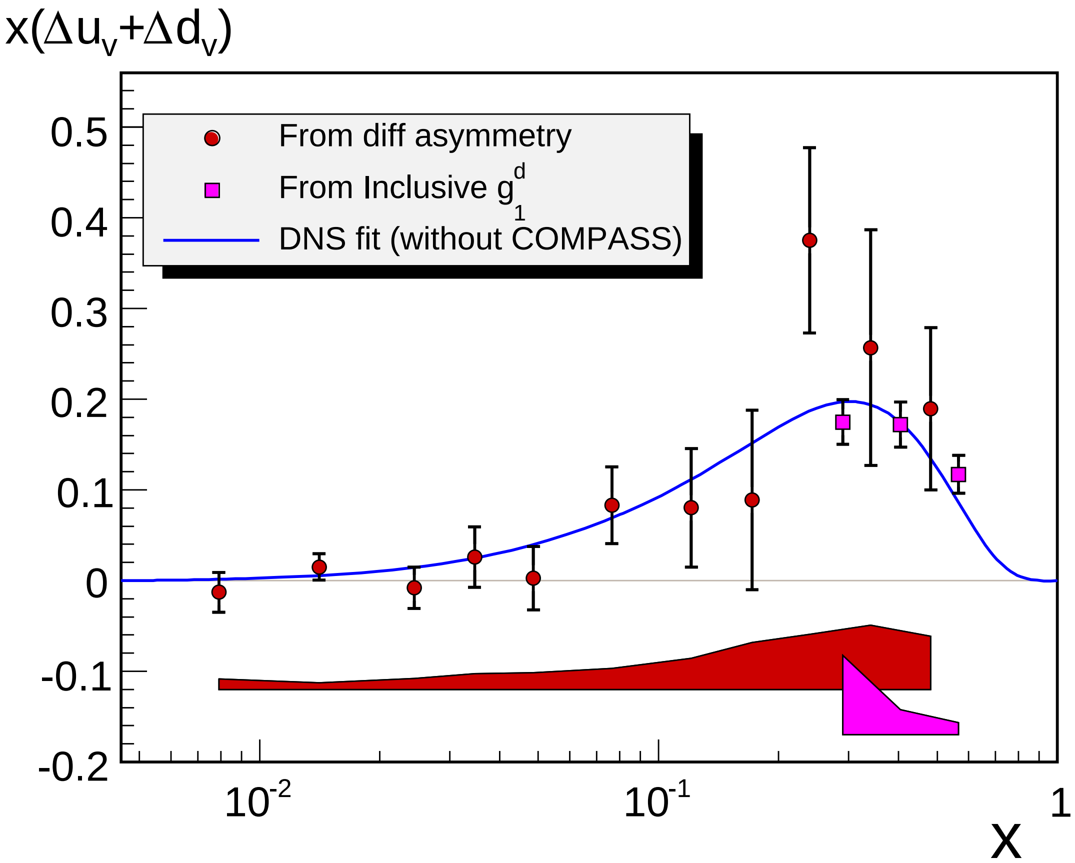
$$A^{+-} = \frac{1}{1-r}(A^+ - rA^-) \quad \text{with} \quad r = \frac{\sigma^{h-}_{\uparrow\downarrow} + \sigma^{h-}_{\uparrow\uparrow}}{\sigma^{h+}_{\uparrow\downarrow} + \sigma^{h+}_{\uparrow\uparrow}} = \frac{\sigma^{h-}}{\sigma^{h+}} = \frac{N^-/a^-}{N^+/a^+}$$





Polarised valence distribution

$$x(\Delta u_v(x) + \Delta d_v(x)) = \frac{x(u_v(x) + d_v(x))}{(1 + R(x))(1 - 1.5\omega_D)} A^{+-}(x)$$

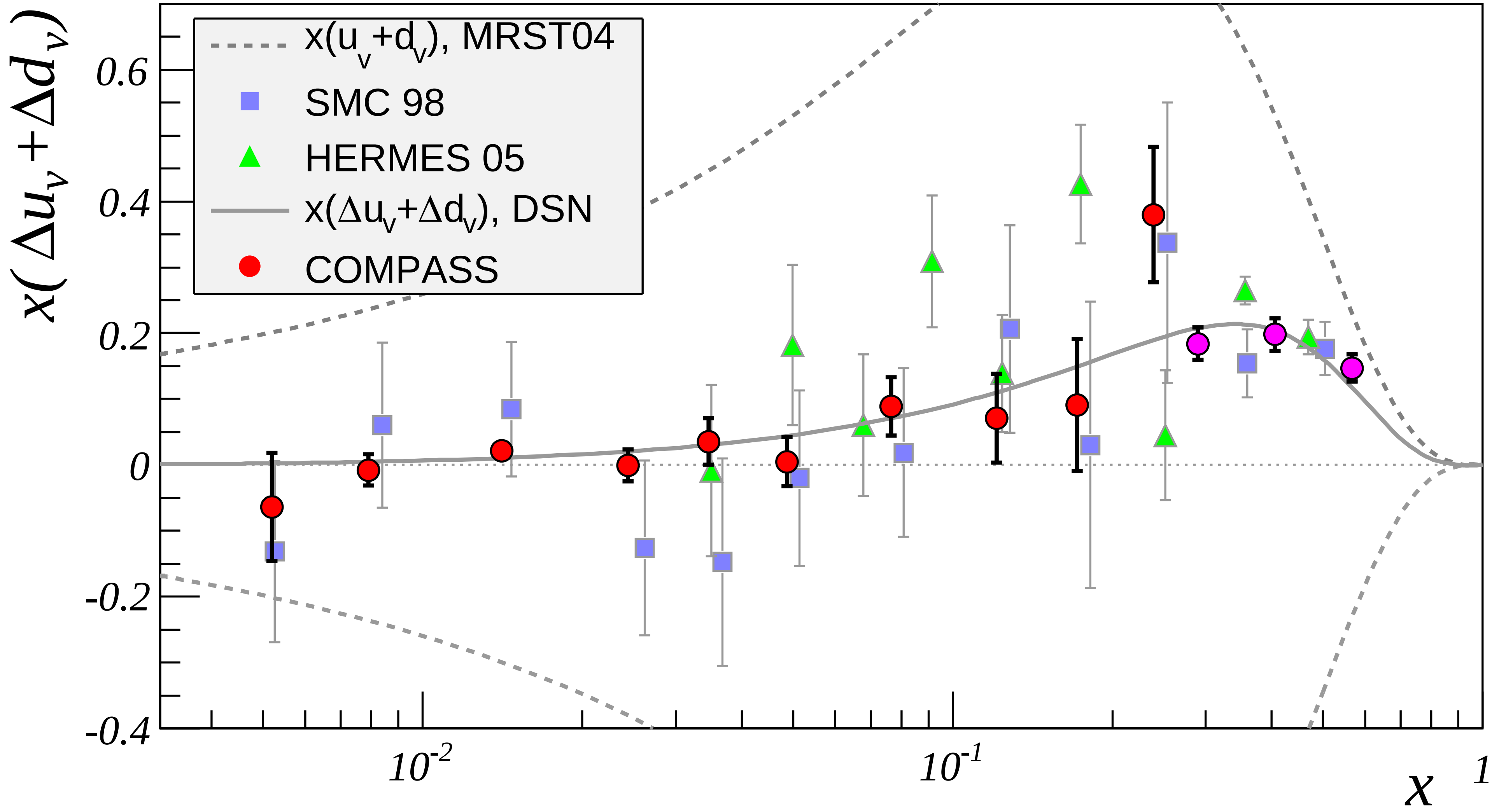


- evolved to $Q^2 = 10\ (\text{GeV/c})^2$
- using LO DNS parameterization (PRD 71(2005)094018)
- DNS predicts COMPASS data
- for $u_v + d_v$ MRST04(LO) used

- sea very small at large x, with inclusive asymmetry much better precision

$$\Delta u_v + \Delta d_v = \frac{36}{5} \frac{g_1^d(x, Q^2)}{(1 - 1.5\omega_D)} - \left[2(\Delta\bar{u} + \Delta\bar{d}) + \frac{2}{5}(\Delta\bar{s} + \Delta\bar{s})\right]$$

Comparison with other experiments



Towards polarised sea quarks

- using $\Gamma_1^{\rm N}$ at $Q^2 = 10\,{\rm GeV/c^2}$

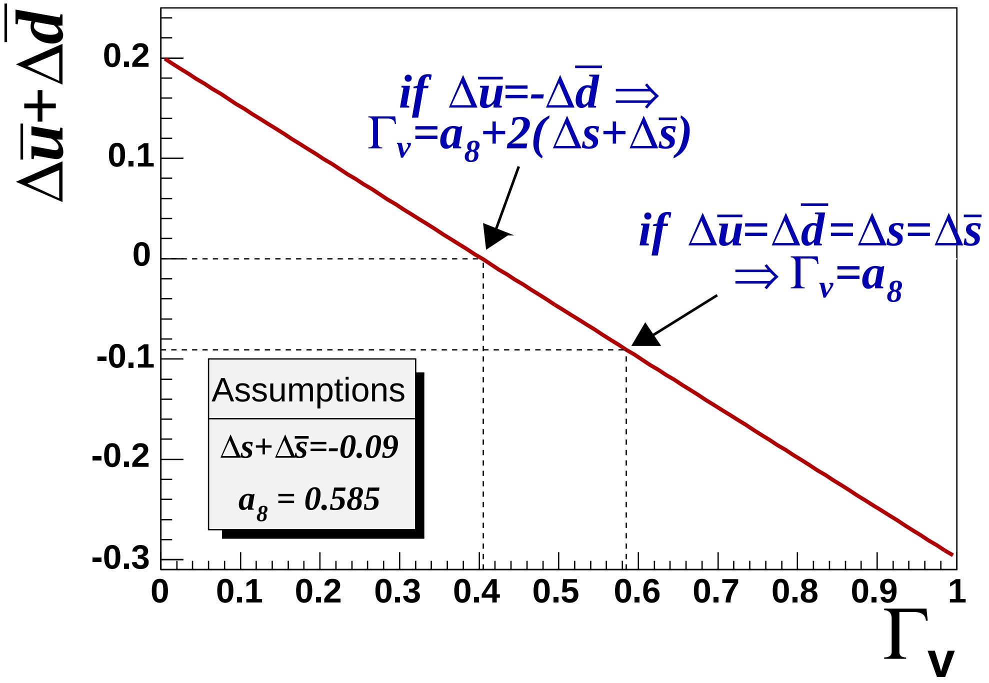
$$\Gamma_1^{\rm N}(Q^2 = 10\,{\rm GeV/c^2}) = \frac{1}{9}\Big(a_0 + \frac{1}{4}a_8\Big)$$
$$= 0.051 \pm 0.003({\rm stat}) \pm 0.003({\rm evol}) \pm 0.005({\rm syst})$$

- combining with $\Gamma_1^{\rm N}$ and a_8

$$\Gamma_v = \int_0^1 (\Delta u_v(x) + \Delta d_v(x)){\rm d}x$$

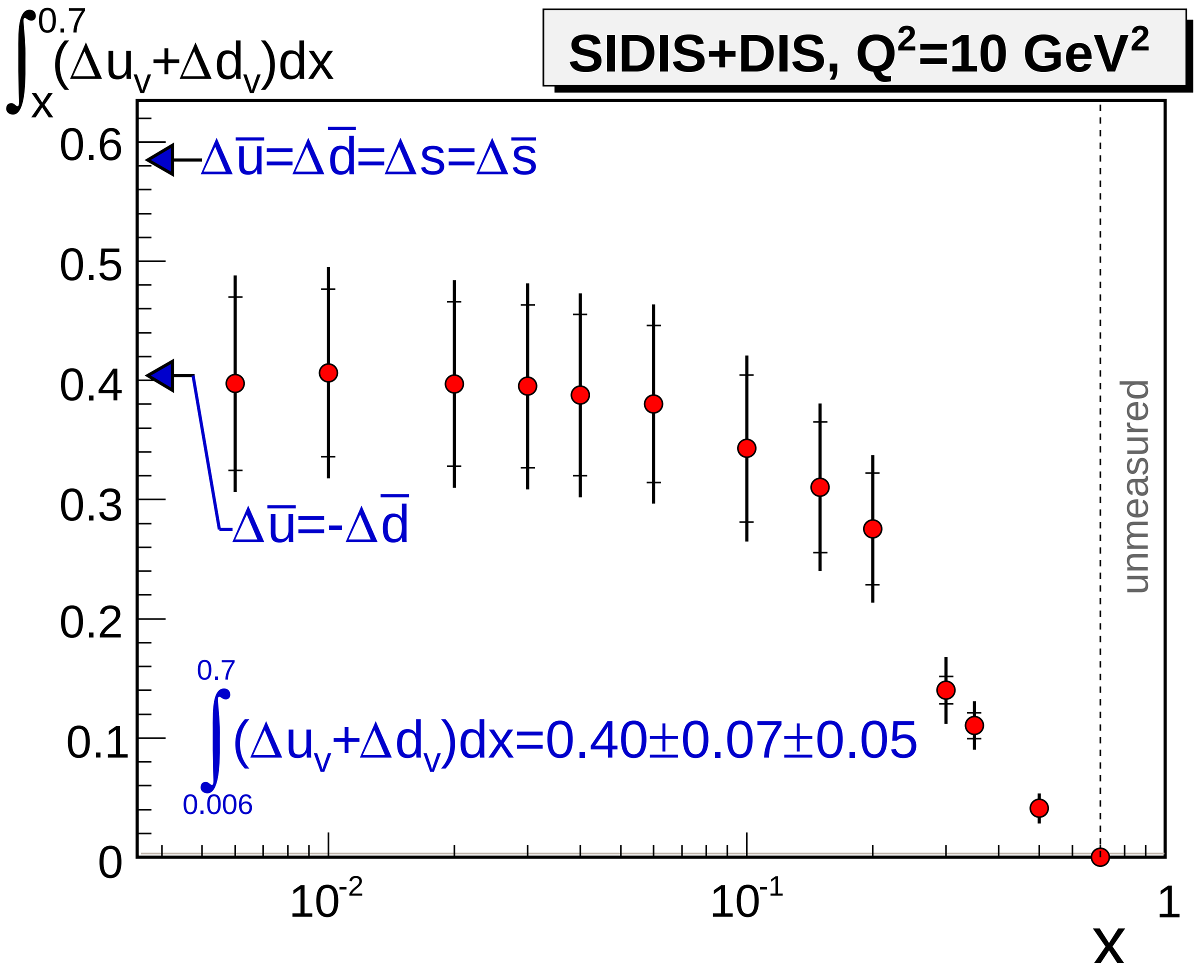
- contribution of sea quarks

$$\Delta\bar{u} + \Delta\bar{d} = 3\,\Gamma_1^{\rm N} - \frac{1}{2}\Gamma_v + \frac{1}{12}a_8$$
$$= (\Delta s + \Delta\bar{s}) + \frac{1}{2}(a_8 - \Gamma_v)$$



- disentangle between flavour **symmetric** ($\Delta\bar{u}=\Delta\bar{d}=\Delta s=\Delta\bar{s}$) and **asymmetric** ($\Delta\bar{u}=-\Delta\bar{d}$) sea, precision $\delta\Gamma_v < |\Delta s + \Delta\bar{s}|$ needed

Estimate of first moment (LO)



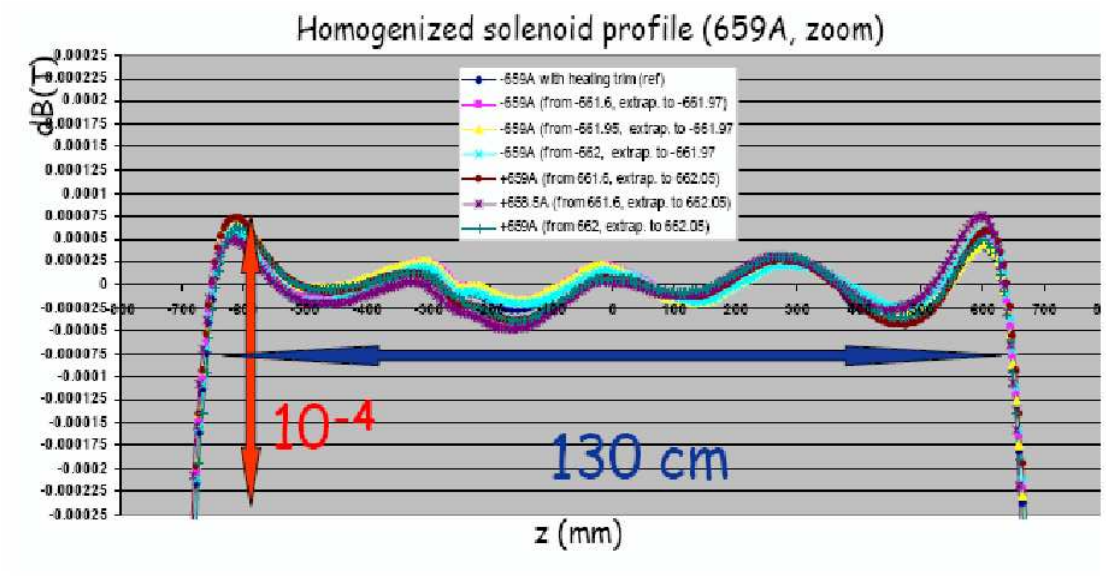
- contribution from $0.7 < x < 1$ about 0.004 (DNS fit)
- Γ_v is 2.5 σ_{stat} away from flavour **symmetric** sea scenario
- **asymmetric** sea favoured

2006 upgrade

2006 Upgrade

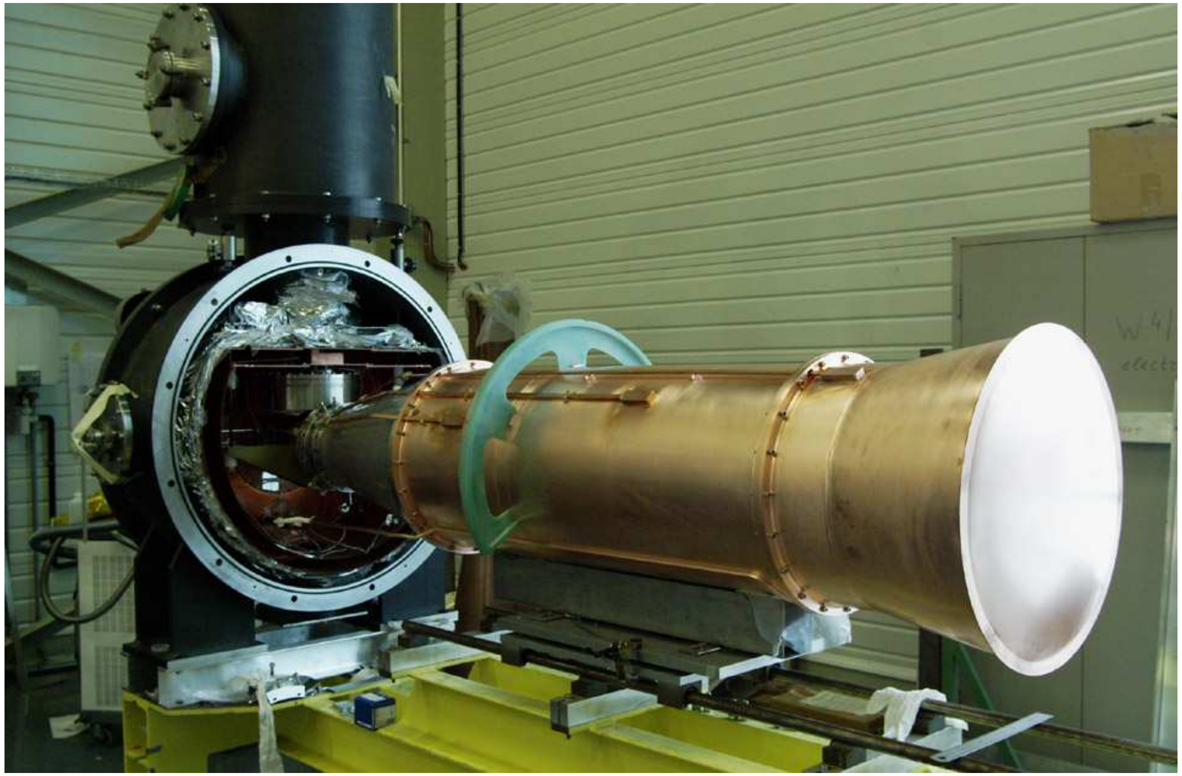
- **Polarised target**: large acceptance magnet system
- **RICH1**: central photon detectors replaced by MAPMTs
- new read out using APVs for outer photon detectors
- **RICH wall** (preshower for ECAL1)
- **ECAL1** Electromagnetic calorimeter in first stage
- More **large angle tracking** in first stage
- **DAQ** and **DCS** consolidation and upgrades
- Other small additions

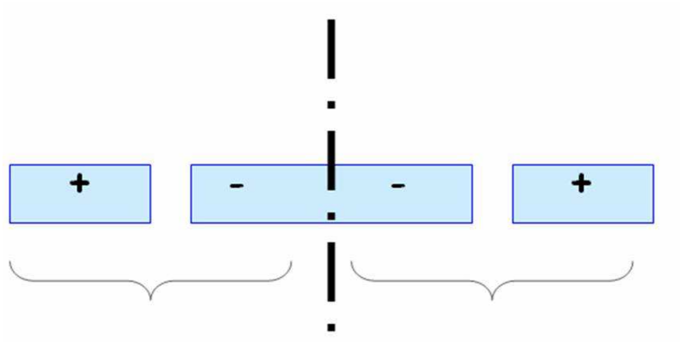
Polarised target magnet



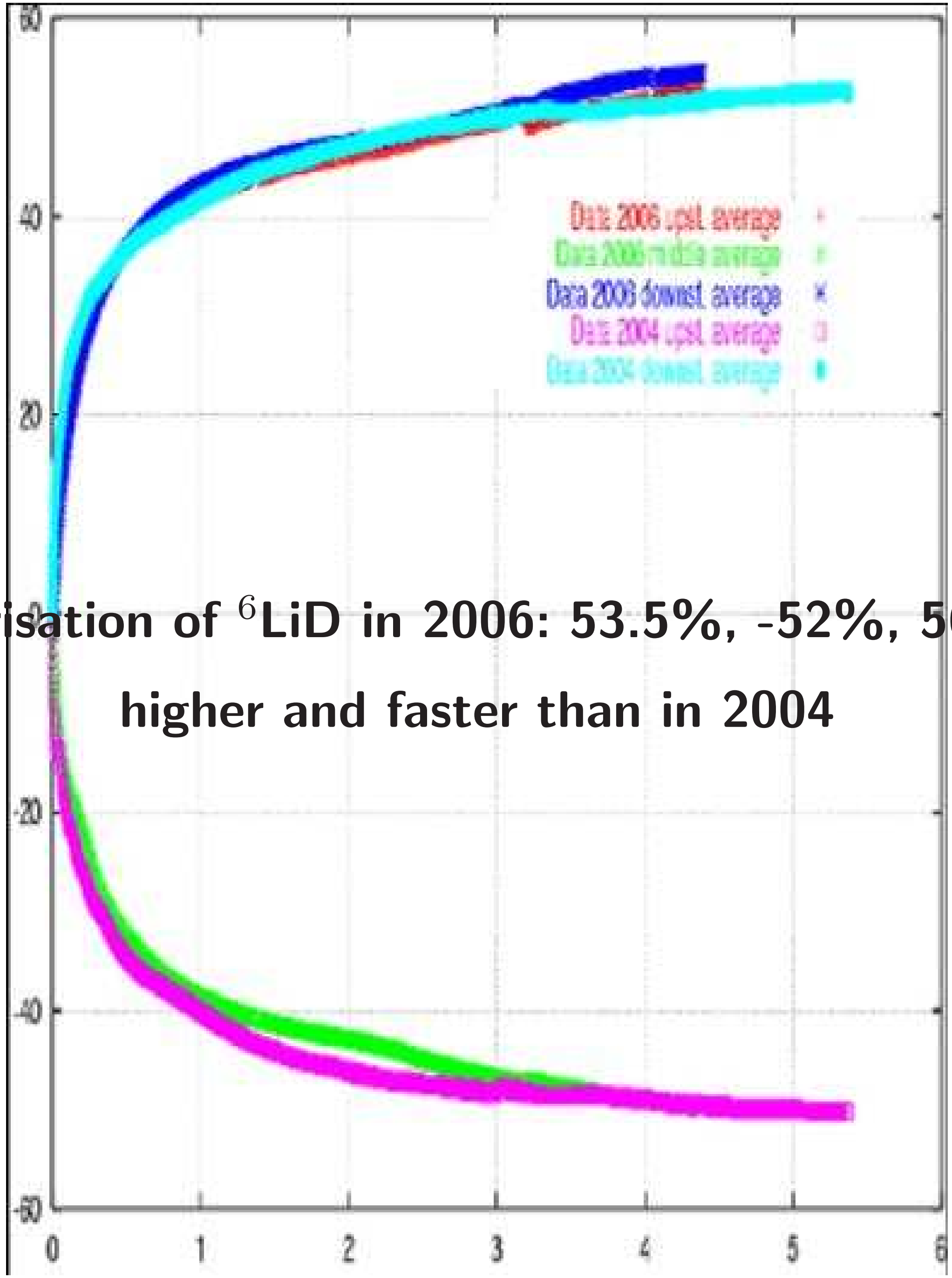
- new target magnet: SMC (70 mrad) $\Longrightarrow$ COMPASS (180 mrad)
- gain in statistics at least 30%
- field homogeneity of $3 \cdot 10^{-5}$ at Saclay
- $7 \cdot 10^{-5}$ reached in presence of SM1 dipole field
- delicate operation due to short in one correction coil, however reliable

Polarised target microwave cavity





to match larger acceptance: new 3 cell microwave cavity
reduction of false asymmetries



Polarisation of ^{6}LiD in 2006: 53.5%, -52%, 56.2%

higher and faster than in 2004

RICH upgrade

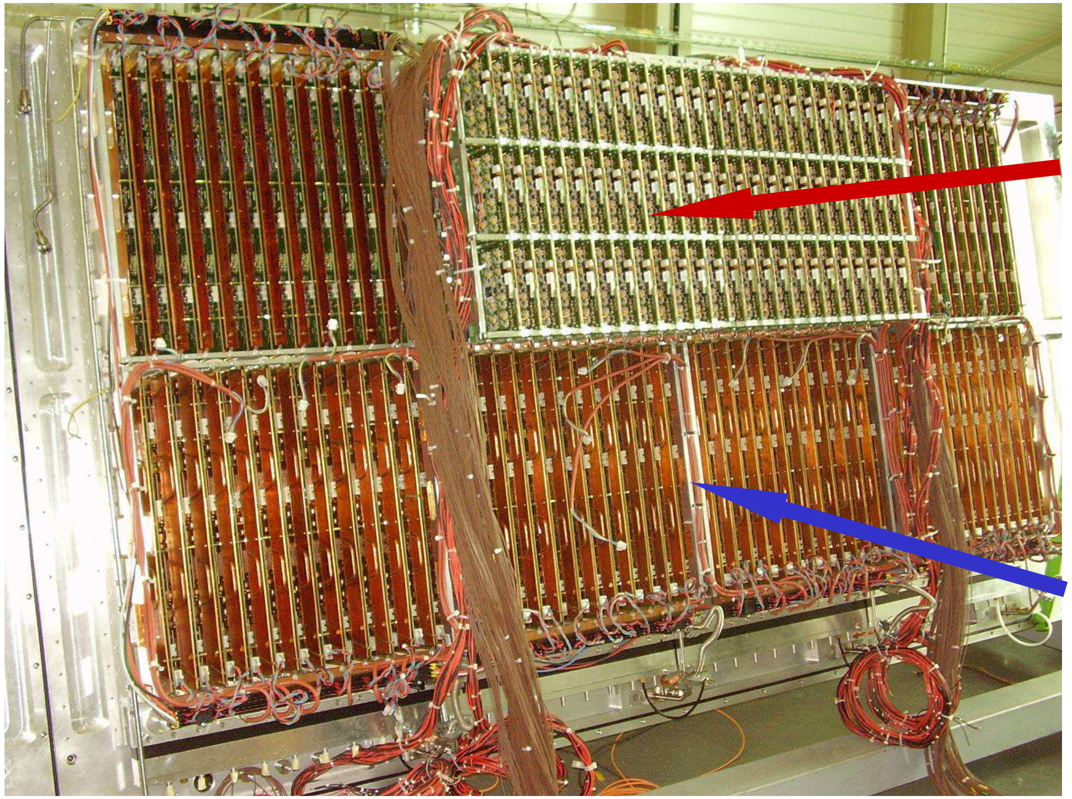
Inner photon detectors

- read out changed from MWPCs to MAPMTs for the inner quarter
- telescope in front of MAPMT for cost effectiveness and to avoid dead regions
- significant increase in number of photons
- space resolution a bit worse but in total increase in precision
- excellent timing, no dead time, improved efficiency

Outer photon detectors

- new APV readout for the outer 75% of the photon detectors
- reduction of uncorellated background by at least a factor 6
- much smaller dead time

RICH upgrade



Lens system
+ MAPMTs
+ MAD4
+ F1

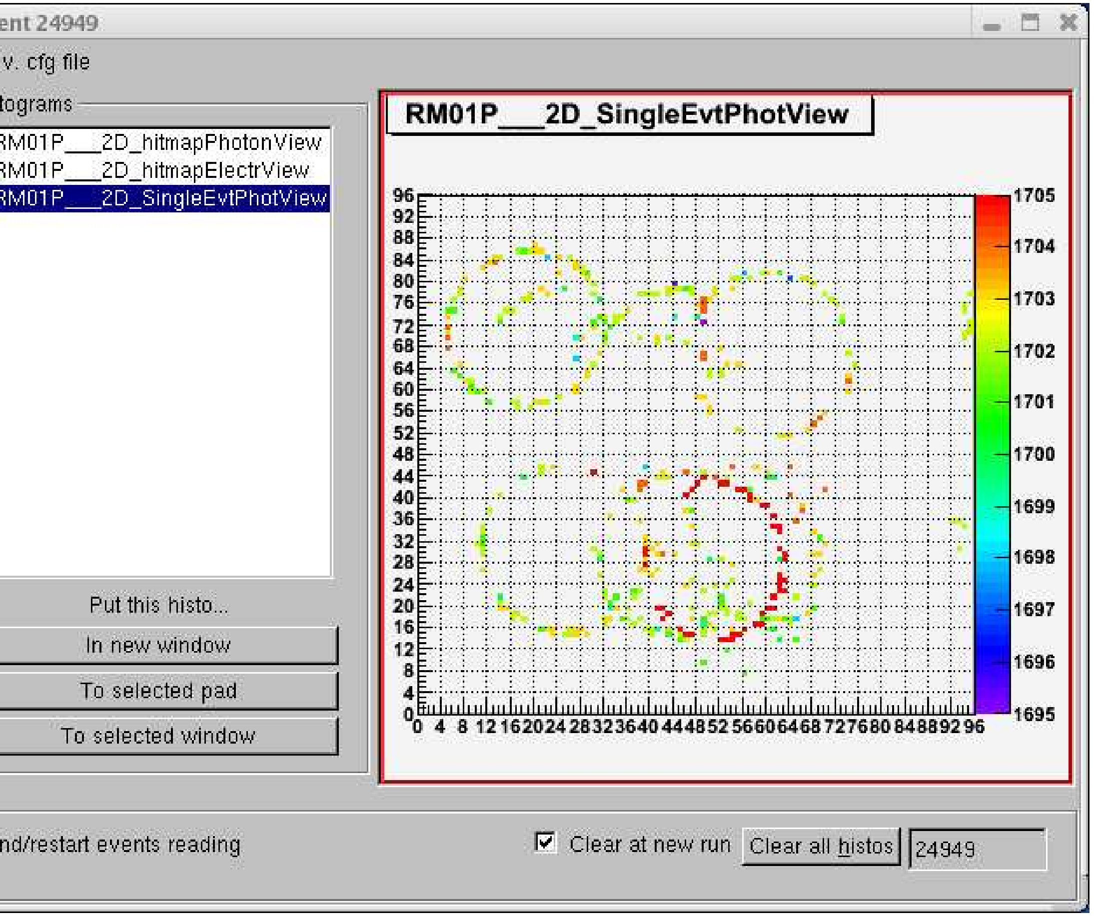
CsI MWPC
+ APV25S1
+ ADC

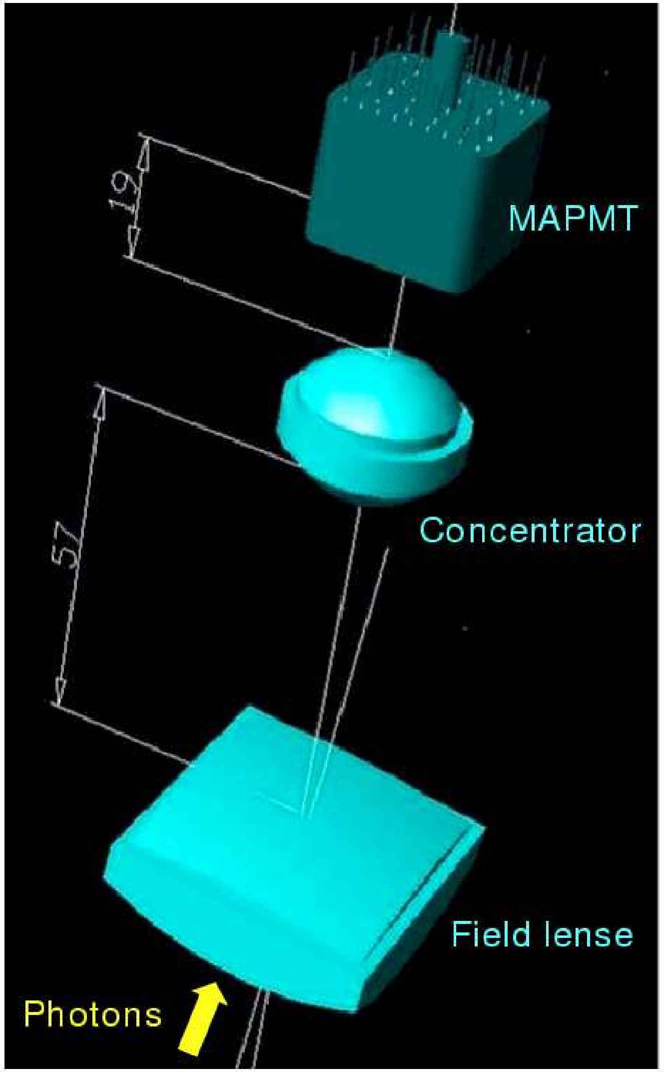
G. Mallot

SPSC 82, 26 June 2007

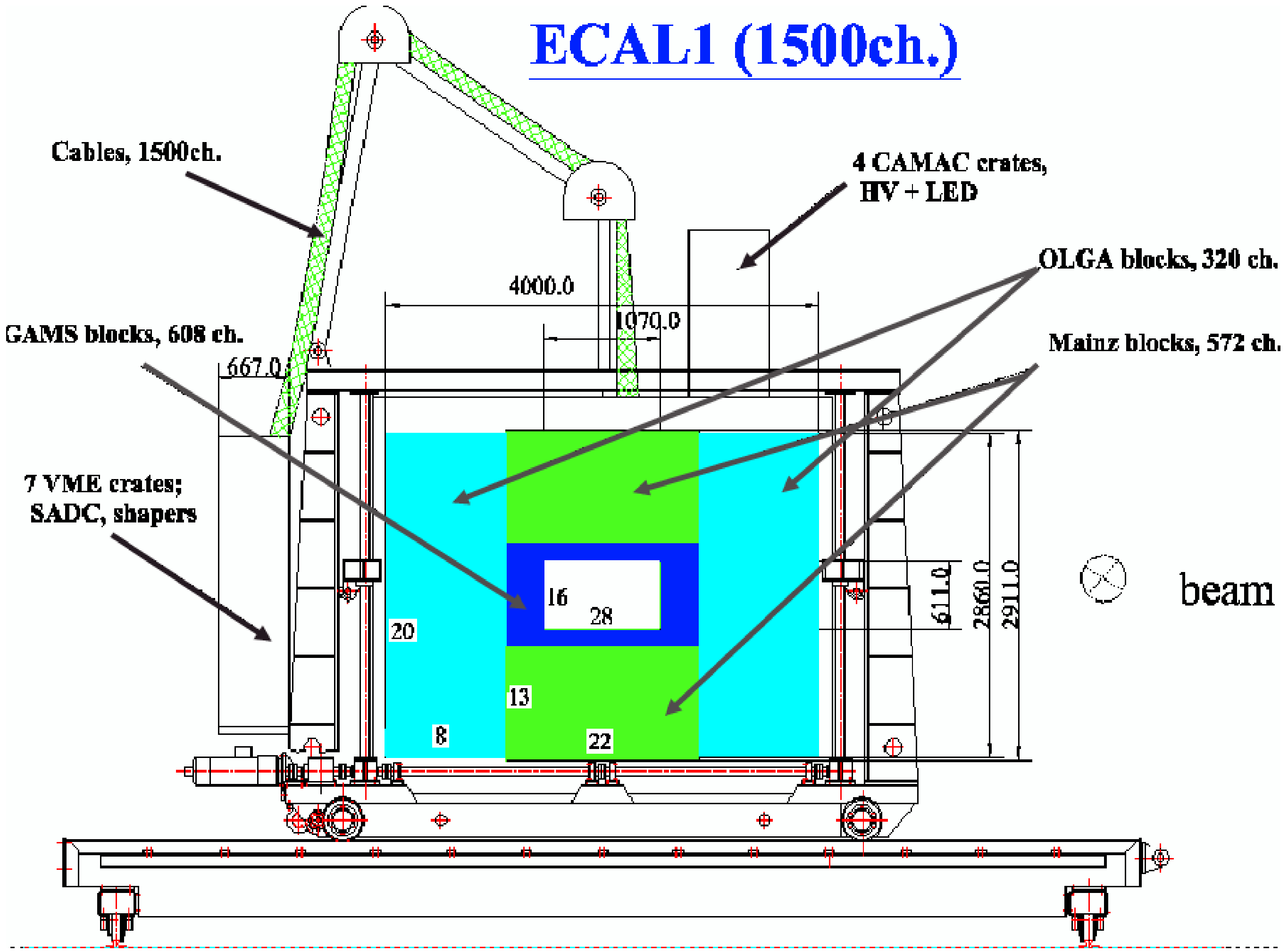
RICH1 central photon detectors

- sketch of telescope in front of MAPMT
- single event with 10 ns timing cut



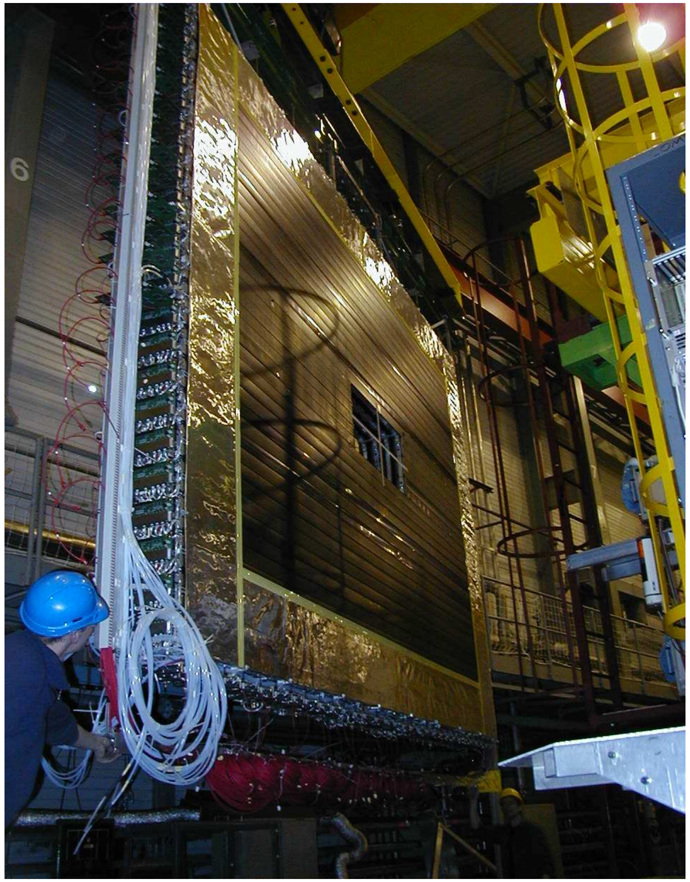


ECAL1

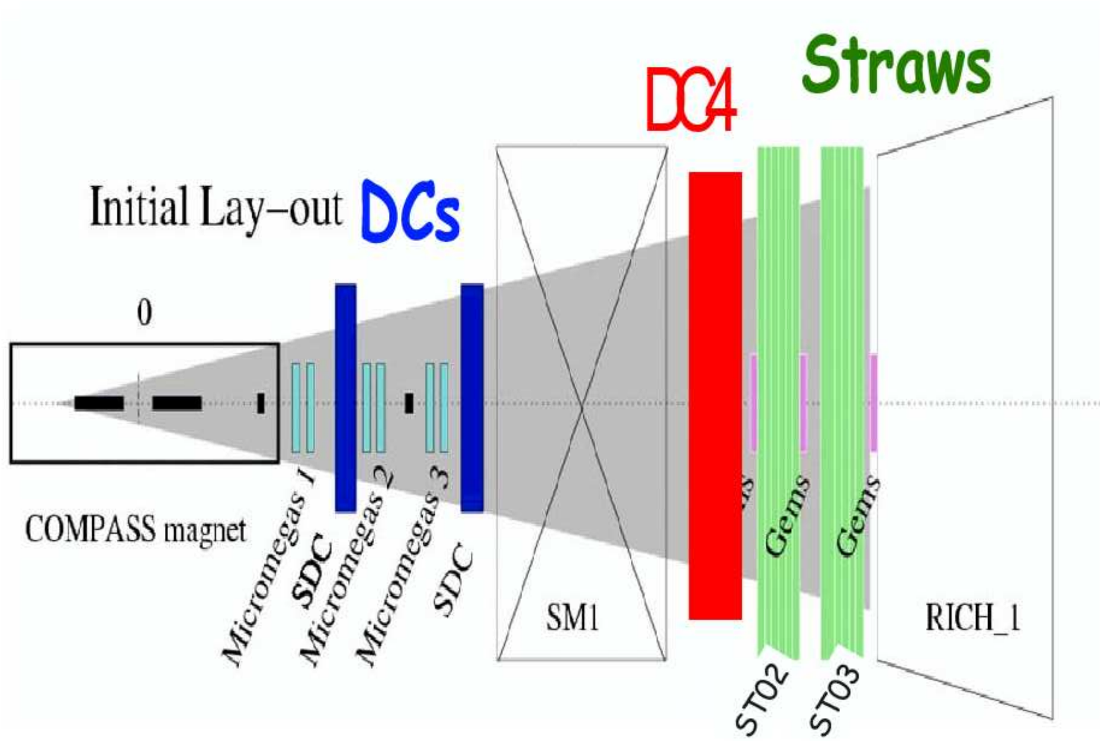


electromagnetic calorimeter (1500 lead glass blocks) in first stage in 2007 included into semi-inclusive and calorimetric triggers

Large angle tracking



large area tracker (drift tubes)
with lead converter
behind RICH
also used as preshower for
ECAL1



large area detectors in first stage:
straw modules
large drift chamber DC4

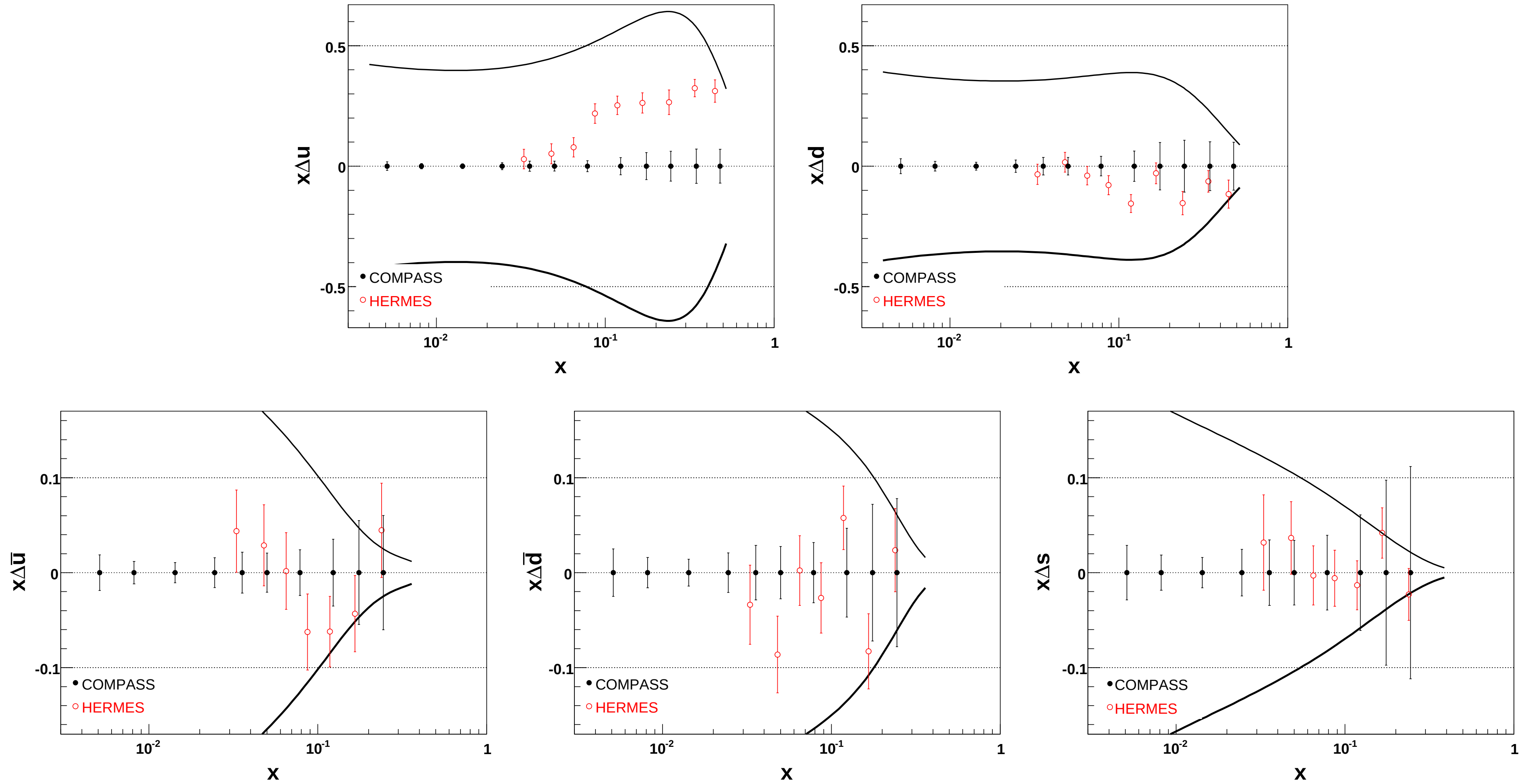
Data taking 2007

- **Different target material: NH_3**
  - fragile and difficult to handle
  - successfully polarised, very long relaxation time (~ 4000 h)
  - magnetic field rotation without polarisation loss
  - FOM factor 2 smaller for proton than for deuteron, partly compensated by 2006 upgrade

- **Main goals:**
  - **longitudinal target polarisation:**
    flavour separation of PDFs
    sign of strange sea polarisation at low x
    shape g_1^{p} at low x
  - **transverse target polarisation:**
    Collins and Sivers asymmetries
    flavour separation
  - **2007 proton data to complement 2002-2006 deuteron data:**
    needs stable beam conditions, high intensity,
    excellent spectrometer performance
  - **started with transversity measurement**

Flavour separated PDFs

with 2007 proton and 2002–2006 deuteron data



COMPASS unique at small x

Summary and outlook

- Results from 2002–2004 deuteron data
  - Inclusive and semi-inclusive data discussed
  - First moment of g_1^{d} and QCD-analysis
  - Valence quark polarisation from difference asymmetry
- 2006 data being analysed
- 2007 proton data taking
- 2008 masurements with hadron beam prepared
- future plans
  - measurement of DVCS
    (recoil detector and ECAL studies started)
  - polarised Drell-Yann measurement
    (beam and target test planned this year)