LONGITUDINAL SPIN STRUCTURE OF THE NUCLEON @ COMPASS (CERN)

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Outline

Deep Inelastic Scattering

The direct evidence for the existence of quarks inside the nucleon is provided by deep inelastic scattering. The idea is to accelerate leptons to very high energies, then allow them to interact with a stationary nucleon, and investigate what happens.

- Inclusive DIS

$$\mu^+ + d(p) \to \mu^{+\prime} + X$$

- Semi-Inclusive DIS

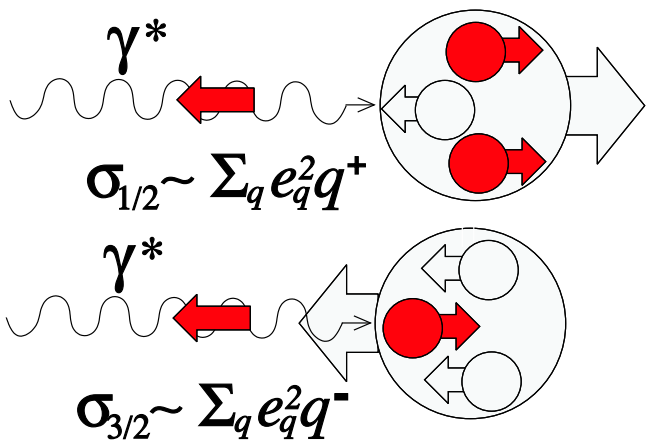
$$\mu^+ + d(p) \to \mu^{+\prime} + h + X \ ,$$

where h is hadron π^+, π^-, K^+ or K^-

Deep Inelastic Scattering

Beam and Target	
E (E')	Energy of a beam (scattered) lepton in lab.
$k = (E, \vec{k})$	4-momentum of the beam lepton
$k' = (E', \vec{k'})$	4-momentum of the scattered lepton
θ	Polar angle
$p \overset{lab}{=} (M, \vec{0})$	4-momentum of the target nucleon
Inclusive DIS	
$\nu = \frac{Pq}{M} \overset{lab}{=} E - E'$	Energy of a virtual photon γ^*
$q = k - k' = (\nu, \vec{q})$	4-momentum of γ^*
$Q^2 = -q^2 \overset{lab}{\simeq} 4EE' \sin^2 \frac{\theta}{2}$	Square of the invariant mass of γ^*
$x \overset{lab}{=} \frac{Q^2}{2M\nu}$	Bjorken scaling variable
$y \overset{lab}{=} \frac{\nu}{E}$	Fraction of the energy carried by γ^*
Semi-Inclusive DIS	
$z \overset{lab}{=} \frac{E_h}{\nu}$	Fraction of the energy of γ^*, carried by hadron h

Polarised DIS and quark-parton model



Absorption of polarised photons (QPM):

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

$q^+(x)$ ($q^-(x)$): spins of quark and nucleon follow in the same (opposite) direction.

- Inclusive Asymmetry:

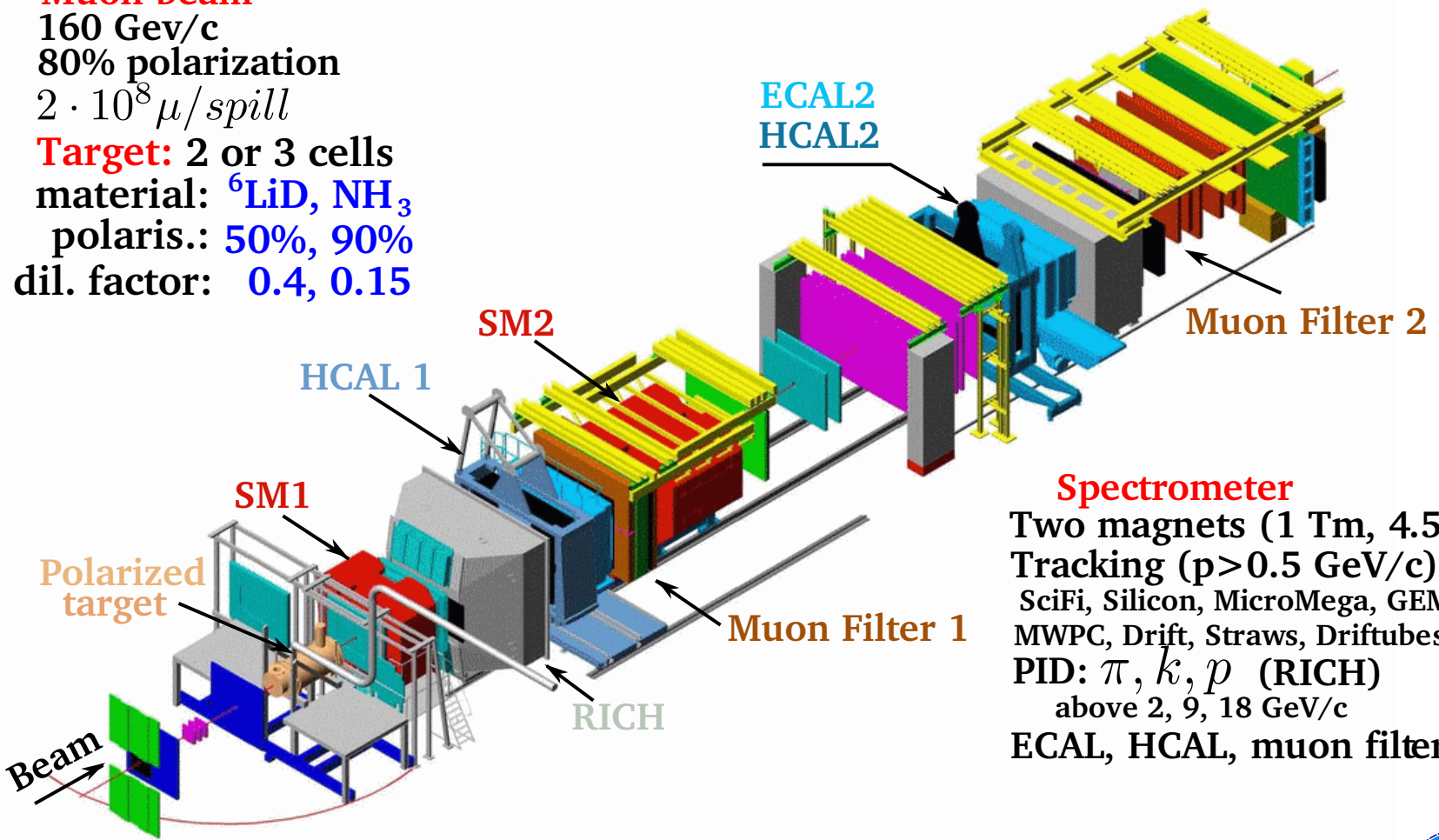
$$A_1 \equiv A^{\gamma N} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1}{F_1} = \frac{2x}{F_2} g_1 = \frac{\Sigma_q e_q^2 \Delta q}{\Sigma_q e_q^2 q}$$

- Semi-Inclusive Asymmetry:

$$A_1^h = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} = \frac{\Sigma_q e_q^2 \Delta q D_q^h}{\Sigma_q e_q^2 q D_q^h}, \qquad A_{||} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \approx D A_1$$

COMPASS Spectrometer

Muon beam
160 Gev/c
80% polarization
$2 \cdot 10^8 \mu/spill$
Target: 2 or 3 cells
material: ^{6}LiD, NH_3
polaris.: 50%, 90%
dil. factor: 0.4, 0.15



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 filters

(NIMA 577 (2007) 455)

A short review of COMPASS DIS and SIDIS results

2007	$g_1^d(x)$, $\int g_1^d(x)dx$	$\Delta\Sigma = \sum_{q=u,d,s}(\Delta q + \Delta\bar{q})$
2008	$A_{1,d}^{h^+-h^-}$	$\Delta u_v + \Delta d_v$
2009	$A_{1,d}$, $A_{1,d}^{\pi^{+,-}}$, $A_{1,d}^{K^{+,-}}$	$\Delta u_v + \Delta d_v$, $\Delta\bar{u} + \Delta\bar{d}$, Δs $(\equiv \Delta\bar{s})$
2010	$g_1^p(x)$, $\int g_1^{NS}(x)dx$	$\lvert g_A/g_V \rvert$
2010	$A_{1,d}$, $A_{1,d}^{\pi^{+,-}}$, $A_{1,d}^{K^{+,-}}$ $A_{1,p}$, $A_{1,p}^{\pi^{+,-}}$, $A_{1,p}^{K^{+,-}}$	Δu, Δd, $\Delta\bar{u}$, $\Delta\bar{d}$, Δs, $\Delta\bar{s}$
2012	$g_1^p(x)$ @ 200 GeV	$x > 0.0025$

Spin asymmetries (method)

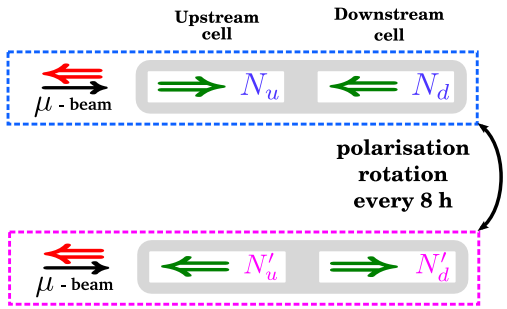
Number of interactions:

$$N = a\Phi n\bar{\sigma}(1 \pm fP_B P_T A_{||})$$

a is acceptance of the spectrometer;

Φ is beam flux;

$n = n_d + \sum_A n_A$ is full density of target nuclears;



$\overline{\sigma} = \frac{\overline{\sigma}_d n_d + \sum_A \overline{\sigma}_A n_A}{n}$ – full cross-section;

$f = \frac{n_d \overline{\sigma}_d}{n\overline{\sigma}}$ – dilution factor

$$\delta \equiv \frac{N_{up}}{N_{dn}} \frac{N'_{dn}}{N'_{up}} \Rightarrow \alpha A^2 + bA + c = 0$$

Necessary conditions:

- ✓ Beam tracks cross all target cells $\Rightarrow$ Flux cancelation
- ✓ $\frac{\langle a_{up} \rangle}{\langle a_{dn} \rangle} = \frac{\langle a'_{dn} \rangle}{\langle a'_{up} \rangle}$, $\langle a \rangle = \frac{\int a\Phi n\sigma d\vec{x}}{\int \Phi n\sigma d\vec{x}}$

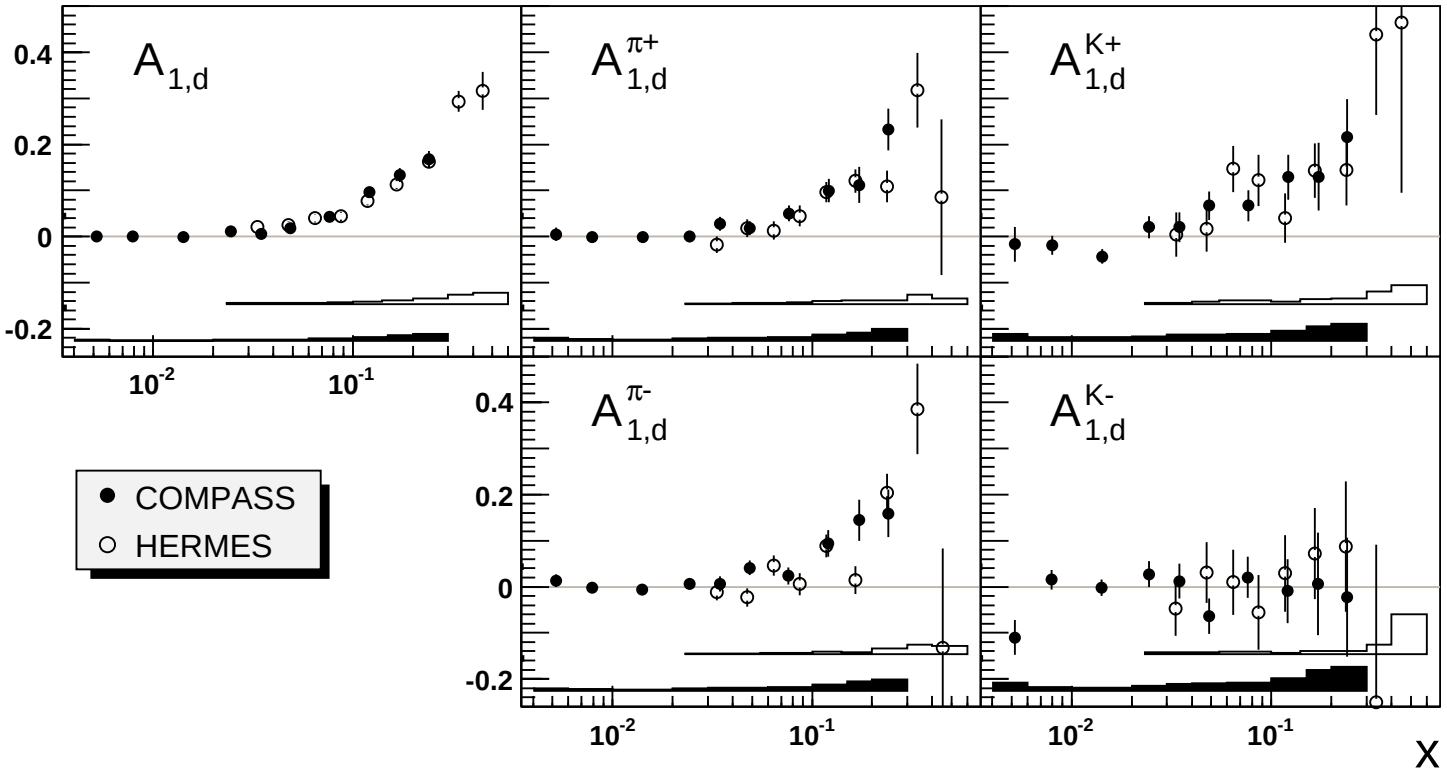
Event selection

- 2002-04, 2006 data taking (@160 GeV, target – ^{6}LiD)
- 2007 (@160 GeV) and 2011 (@200 GeV) (target – NH_3)
- Kinematical cuts:
  - ✓ $Q^2 > 1$ (GeV/c)^2
  - ✓ $0.1 < y < 0.9$ – fraction of energy, carried by virtual photon
  - ✓ $0.004 < x < 0.7$ ($0.0025 < x < 0.7$ @200 GeV)
  - ✓ $0.2 < z < 0.85$ – beam fragmentation region, false identification
- Hadron ID by RICH:
  - ✓ $10 < P_h < 50$ (GeV/c) – RICH acceptance
  - ✓ Purity:
    - NH_3 target: $\pi^{\pm}$ – 0.98; K^+ (K^-) – up 0.73 to 0.93 (0.91)
    - ^{6}LiD target: $\pi^{\pm}$ – 0.98; K^+ (K^-) – up 0.8 to 0.93

Total, [$\times 10^6$ events]

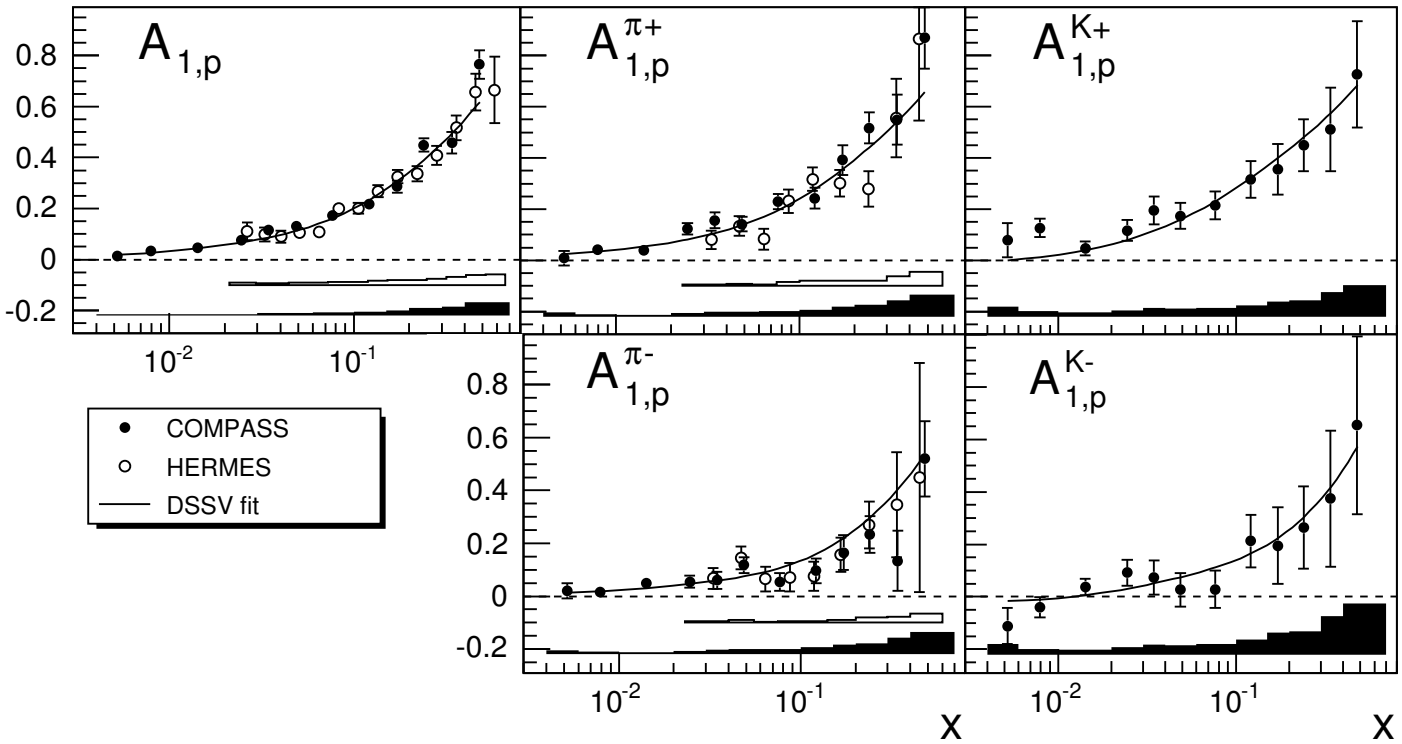
	target		
	^{6}LiD	$NH_3'07$	$NH_3'11$
incl.	135.1	85.3	78
π^+	22.8	12.3	
π^-	20.5	10.9	
K^+	4.8	3.6	
K^-	3.3	2.3	

COMPASS asymmetries on deuteron (2009) comparison with HERMES



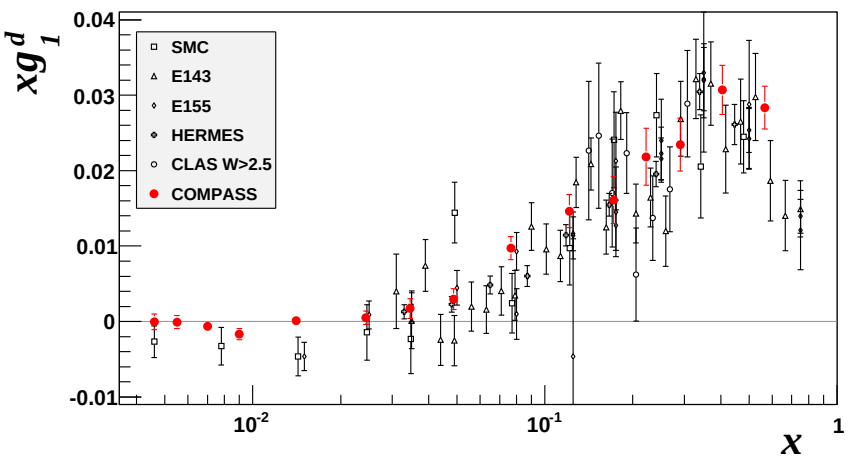
- Good agreement in the common x-region
- Stat. and syst. uncertainties are comparable in the common x-region
- The lowest x of measurement $x = 0.004$ (vs. 0.023 in HERMES)

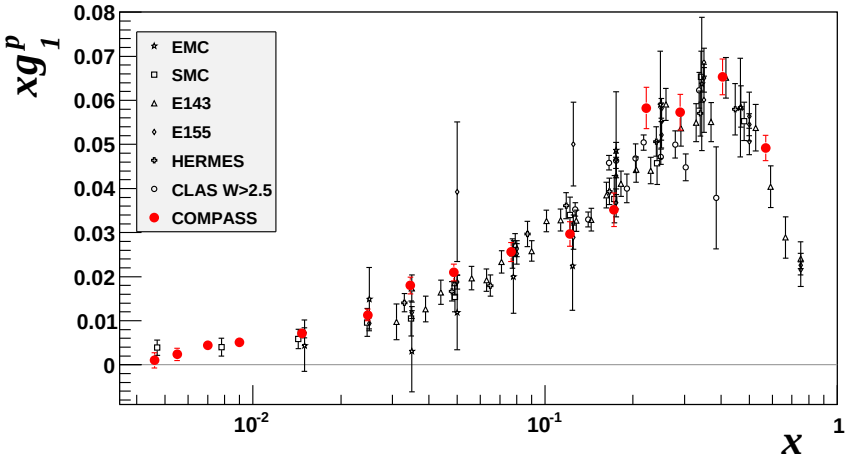
COMPASS asymmetries on proton (2010) comparison with HERMES



- Good agreement in the common x-region
- $A_{1,p}^{K^+}$ and $A_{1,p}^{K^-}$ have been measured for the first time
- The lowest x of measurement $x = 0.004$ (vs. 0.023 in HERMES)

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





$$\Gamma_1^N(Q_0^2 = 3(\mathrm{GeV}/c)^2) = \int_0^1 g_1(x)dx$$

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

$$= \frac{1}{9}(1 - \frac{\alpha_s(Q^2)}{\pi} - O(\alpha_s^2))(a_0(Q^2) + \frac{1}{4}a_8),$$ hyperon β-decay: $a_8 = 0.585 \pm 0.025$

$$\Rightarrow a_0 = 0.35 \pm 0.03(stat.) \pm 0.05(syst.)$$

$$\Delta\Sigma^{\overline{MS}} = 0.33 \pm 0.03(stat.) \pm 0.05(syst.)(\Delta\Sigma^{\overline{MS}} = a_0 @ Q^2 \to \infty)$$

$$(\Delta s + \Delta\bar{s}) = \frac{1}{3}(\Delta\Sigma^{\overline{MS}} - a_8) = -0.08 \pm 0.01(stat.) \pm 0.02(syst.)$$

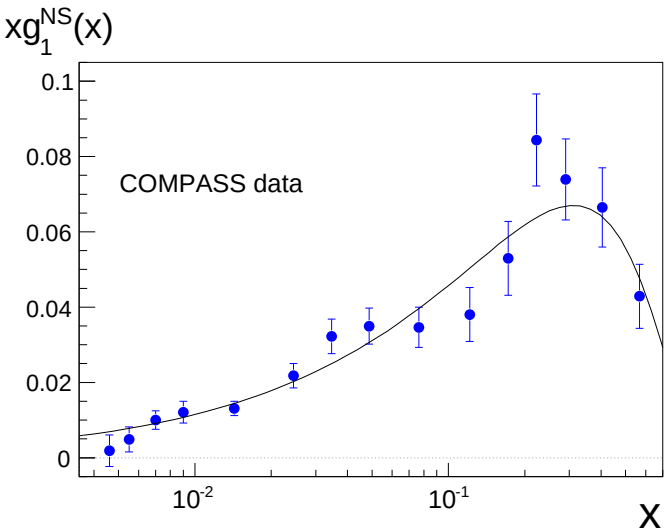
Test of the Bjorken Sum Rule

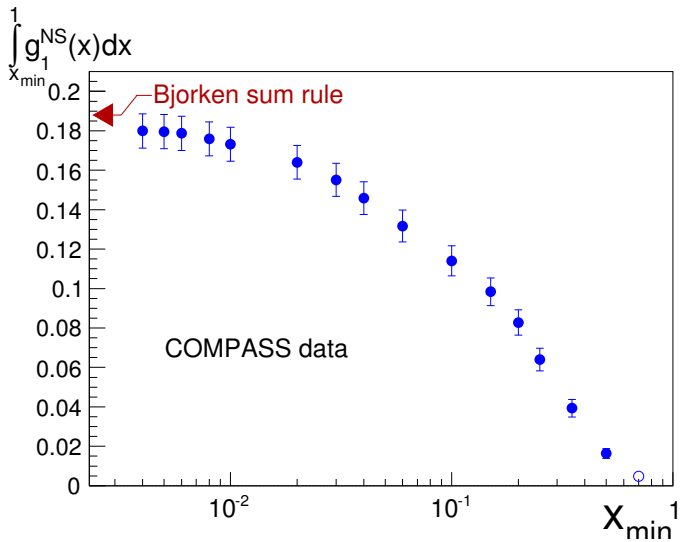
- $g_1^{NS}(x, Q2)$ is interesting because its Q^2 dependence decouples from the singlet and gluon densities
- Non-singlet spin structure function g_1^{NS}

  $g_1^{NS}(x) = g_1^p(x) - g_1^n(x) = 2\left[g_1^p(x) - \frac{g_1^d(x)}{(1-3/2\omega_D)}\right], \omega_D = 0.05$

  $\int_0^1 g_1^{NS}(x, Q^2)dx = \Gamma_1^{NS} = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C^{NS}(Q^2)$ or $\Delta u - \Delta d = \left|\frac{g_A}{g_V}\right|$

  where $C_1^{NS}(Q^2)$ has been calculated in pQCD up to $\alpha_s^3(Q^2)$
- a ratio of the axial and vector coupling constants g_A/g_V can be obtained from neutron beta decay: $g_A/g_V = 1.2694 \pm 0.0028$





COMPASS result at $Q^2 = 3$ (GeV/c)^2: $g_A/g_V = 1.28 \pm 0.07 \pm 0.10$

LO extraction of polarised PDFs

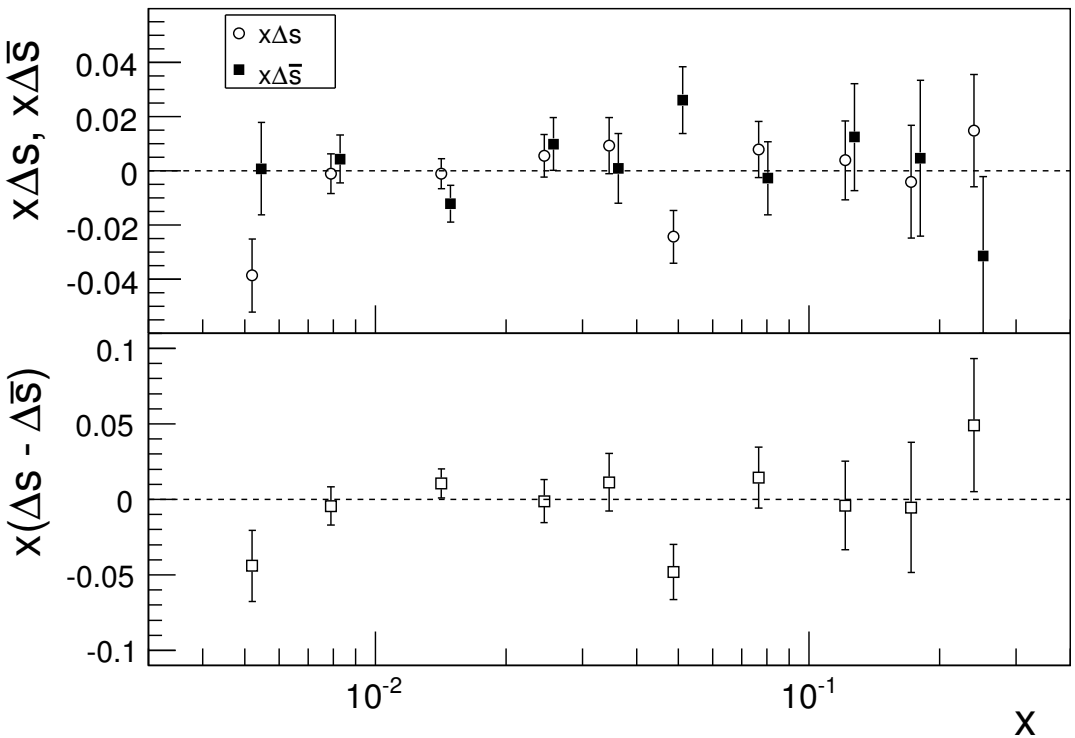
$$A^h(x,z) = \frac{\Sigma_q e_q^2 \left[\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z)\right]}{\Sigma_q e_q^2 \left[q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right]}$$

- Inputs: 10 asymmetries for each interval of x

$$A_{1,d}, A_{1,d}^{\pi+}, A_{1,d}^{\pi-}, A_{1,d}^{K+}, A_{1,d}^{K-}$$
$$A_{1,p}, A_{1,p}^{\pi+}, A_{1,p}^{\pi-}, A_{1,p}^{K+}, A_{1,p}^{K-}$$

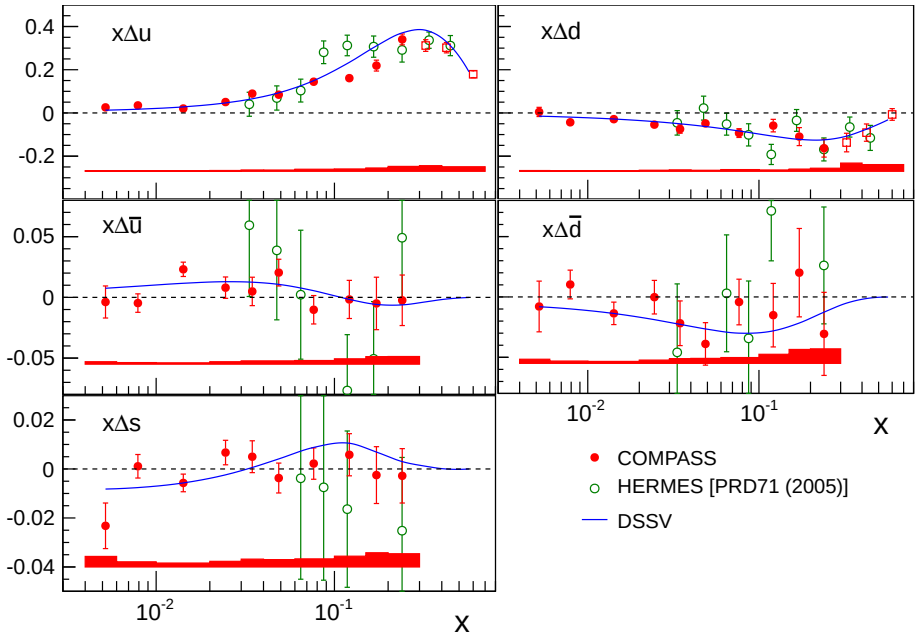
- Unknowns: 6 polarised PDFs $\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s, \Delta\bar{s}$ $\Longrightarrow$ (reduced to 5 if $\Delta s = \Delta\bar{s}$ is assumed)
- Q^2 dependence of asymmetries neglected $\Longrightarrow$ $Q^2 = 3(GeV/c)^2$
- $q(x)$; $\bar{q}(x)$ from MRST2004LO, corrected by $(1 + R(x;Q^2))$
- D_q^h; $D_{\bar{q}}^h$ fragmentation functions (FF) from DSS fit at LO

Δs and $\Delta\bar{s}$ from COMPASS asymmetries and the Difference $\Delta s - \Delta\bar{s}$



- Fixed $Q^2 = 3(GeV/c)^2$
- FF from DSS
- No signiffcant difference: one point at 2.7σ
- Stable for changes in $s(x)$, $\bar{s}(x)$ or FFs
- $\Delta s = \Delta\bar{s}$ assumed for subsequent analysis

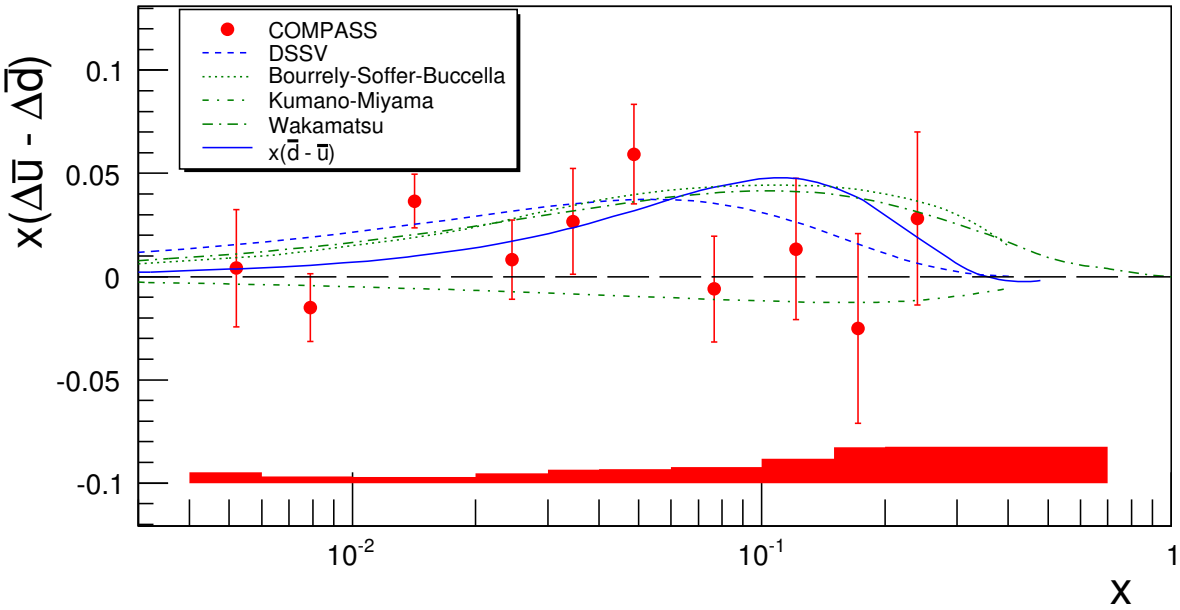
Extraction of PDFs assuming $\Delta s \equiv \Delta \bar{s}$



- Least square fit in each interval of x ($0.004 < x < 0.3$):
  10 asymmetries, 5 unknowns
- Data compatible with LO formula:
  $1.8/5 < (\chi^2/NDF) < 8.5/5$
- Errors reduced at least by factor 1.5

- Valence quarks
  - $\Delta u > 0$, $\Delta d < 0 \Rightarrow$ dominant
  - 3 points at $x > 0.3$ derived assuming $\Delta \bar{q} = 0$
  - shapes $\approx$ DSSV curves
  - Syst.error mainly from P_μ (5%)
- Sea quarks
  - All compatible with zero
  - Slight indication for $\Delta \bar{d} < 0$
  - No indication for $\Delta s < 0$ or changing sign
  - Syst.error mainly from “false asymmetries”

The flavour asymmetry of the sea $\Delta\bar{u} - \Delta\bar{d}$



- $\Delta\bar{u} - \Delta\bar{d} \geq 0$ and $\Delta\bar{u} - \Delta\bar{d} \leq \bar{d} - \bar{u}$
- First moment: $\Gamma^{0.7}_{0.004} = 0.06 \pm 0.04 \pm 0.02$
- Consistent with *statistical model* (BSB) and CQSM (*Wakamatsu*) (≥ 0)
- Within errors also consistent with *meson cloud model* (KM) (< 0)
- Need reduction of error by factor ≥ 2 to discriminate between models

Dependence of moments of PDFs on fragmentation functions

- $D^{\pi}_{q,\bar{q}}$ better constrained by data than $D^{K}_{q,\bar{q}}$
- Relation asymmetries $\Leftrightarrow$ PDFs depends on two ratios of FFs into kaons:

  "unfavoured to favoured" $R_{UF} = \frac{\int D_d^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$

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

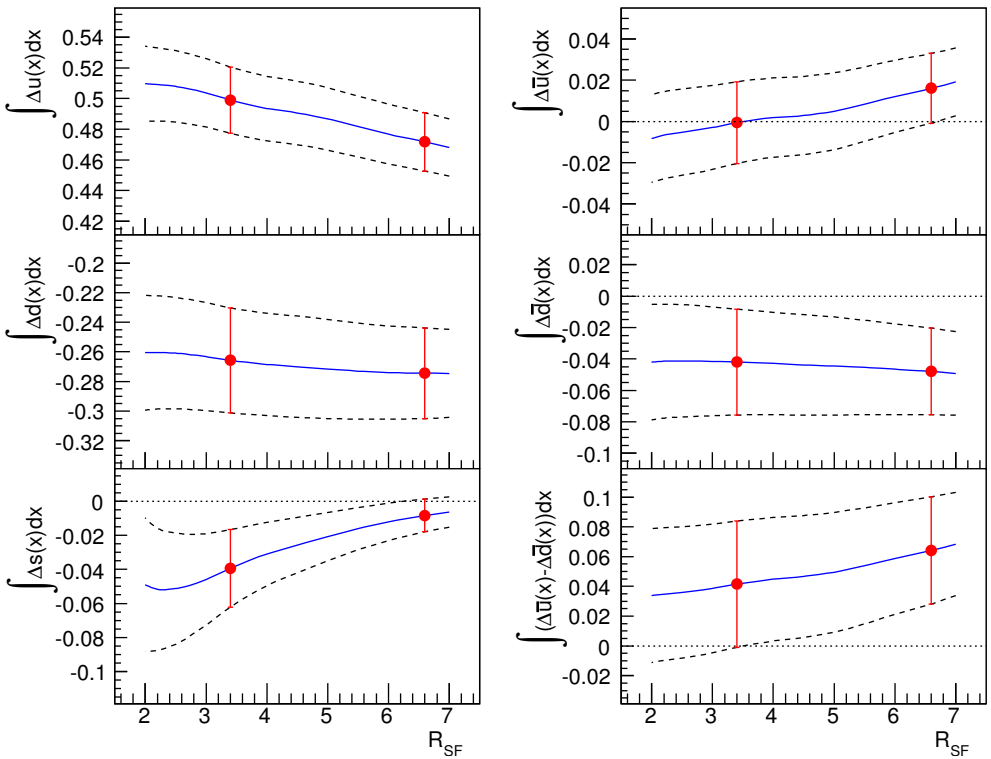
- At $Q^2 = 3(GeV/c)^2$:

	DSS	EMC
R_{UF}	0.14	0.35
R_{SF}	6.6	3.4

- Move simultaneously R_{SF} and R_{UF} from DSS to EMC values and check variation of moments Δq, $\Delta \bar{q}$

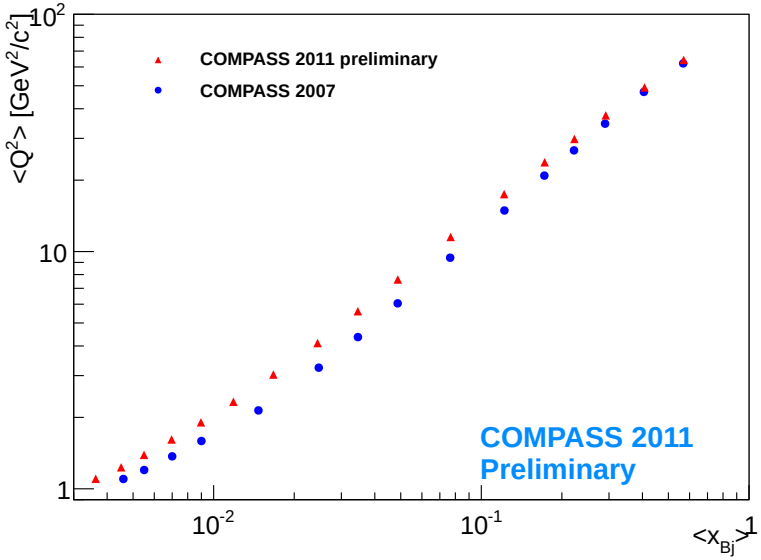
Moments of PDFs vs. fragmentation functions

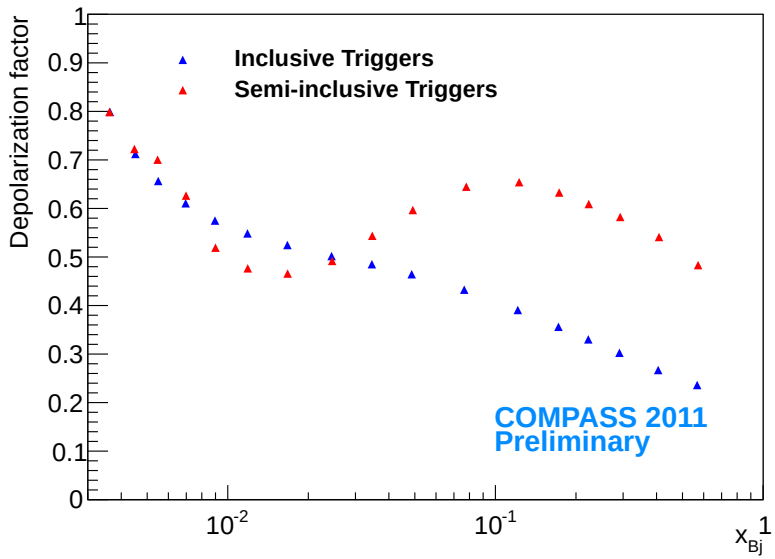
(decrease of R_{SF} and increase of R_{UF} from DSS to EMC values)



- Increase of Δu by $\approx 1.0\sigma_{stat}$.
- Decrease of $\Delta\bar{u}$ by $\approx 1.0\sigma_{stat}$.
- Negligible effect on Δd and $\Delta\bar{d}$
- Decrease of $\Delta\bar{u} - \Delta\bar{d}$ by $0.5\sigma_{stat}$.
- Decrease of Δs to -0.04 with two times larger statistical error
- Limited effect on K^+ and K^- rates

New measurement @ 200 GeV (2012)





2011 data taking:

$78 \cdot 10^6$ events

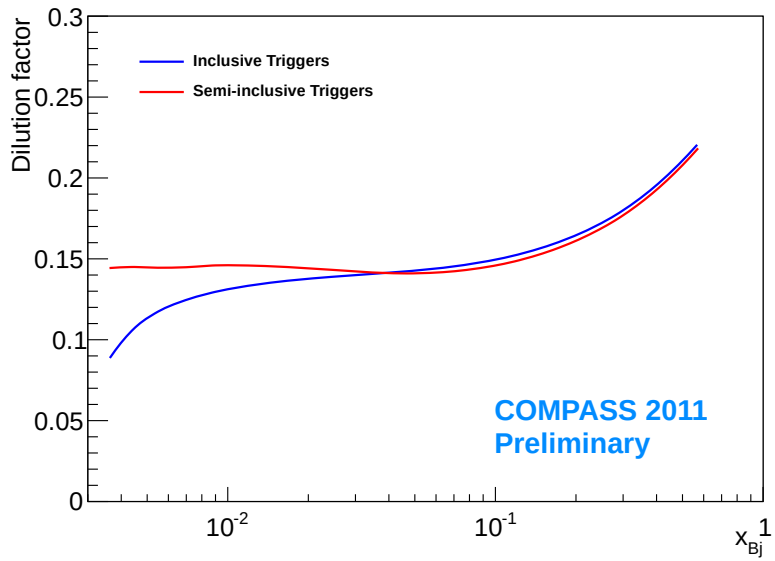
$E_{beam} = 200 GeV$

$Q^2 > 1 (GeV/c)^2$ and $0.1 < y < 0.9$

$0.0025 < x < 0.7$

NH_3: $P_T \approx 85\%$

2007 and 2011 at slightly different Q^2



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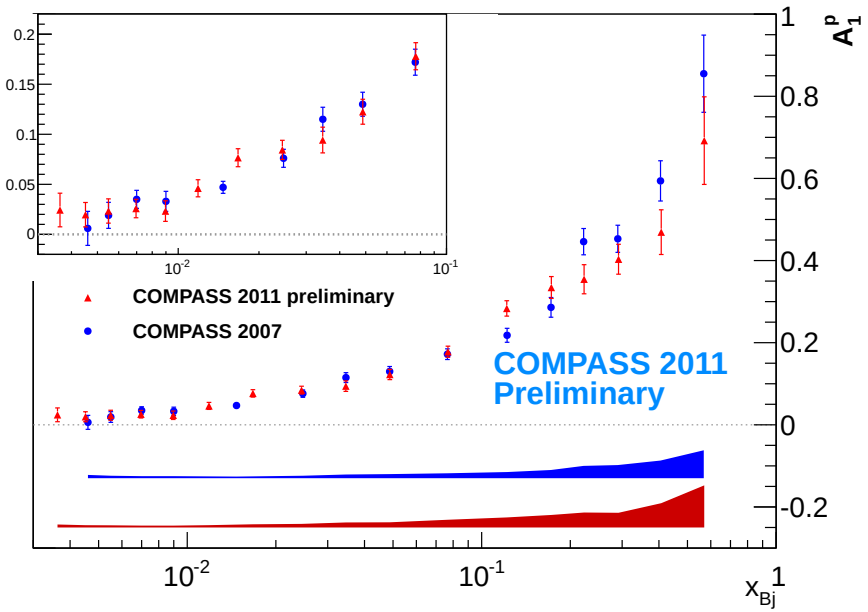
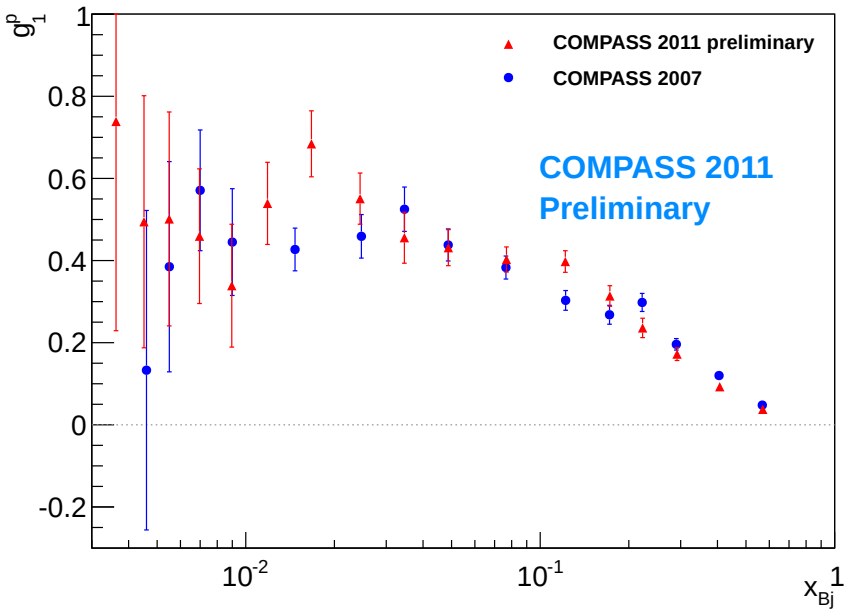
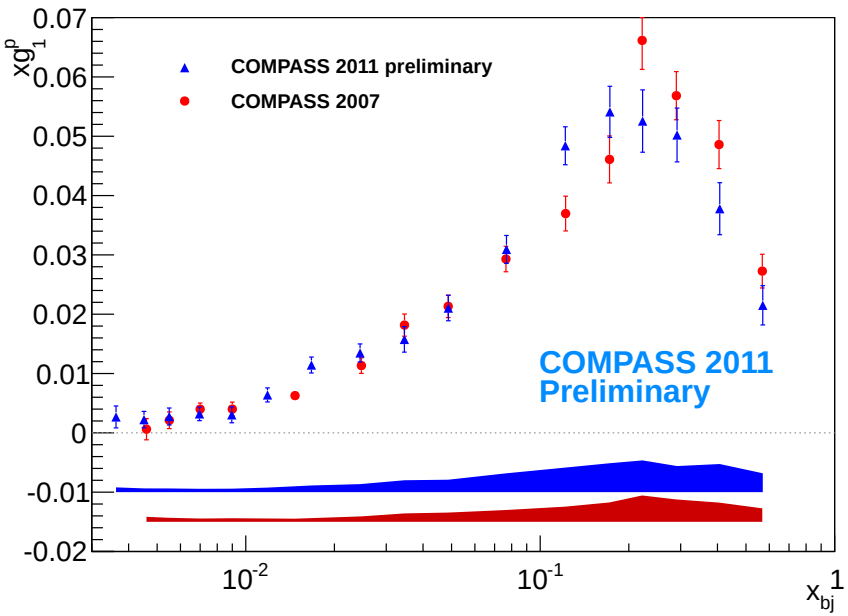




$$g_1^p = \frac{F_2^p}{2x(1+R)} A_1^p$$

F_2^p from SMC parametrisation; for R the same parametrisation as in the evaluation of the depolarisation factor D



Conclusions and prospects

- Evaluation of polarised PDFs at LO
  - Δq, $\Delta \bar{q}$ from COMPASS DIS and SIDIS $K^{+,-}$ and $\pi^{+,-}$ asymmetries on ^{6}LiD and NH_3 targets
  - $\Delta \bar{q}$ distributions are small over measured range of x ($0.004 < x < 0.3$)
  - No significant difference between $\Delta s(x)$ and $\Delta \bar{s}(x)$
  - $(\Delta u - \Delta d) > 0$ (at $1.5\sigma_{stat}$ but not larger than $\bar{d} - \bar{u}$)
  - Moments of Δu, $\Delta \bar{u}$ and Δs found to vary with choice of kaon FFs. Variation is critical for Δs (becomes negative with large error for $R_{SF} \leq 4$)
- New measurement of g_1^p @ 200 GeV (2011 data)
  - Measurement of an additional point for smaller x ($0.0025 < x < 0.004$)
- Future
  - 2011 COMPASS data on NH_3 target will improve precision on $(\Delta \bar{u} - \Delta \bar{d})$ and help discriminate between models
  - Ongoing investigations on FFs from COMPASS K^+ and K^- rates will at least clarify (if not solve) the Δs puzzle