Spin structure functions of deuteron from COMPASS

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On behalf of the COMPASS collaboration

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

The Workshop "Hadron Structure and Hadron Spectroscopy", Prague

August 1-3, 2005

[a] on leave from JINR, Dubna

Overview

- Inclusive asymmetry A_1^d and structure function g_1^d
- COMPASS experiment
- Asymmetry extraction procedure & results
- QCD analysis to world data
- Semi-inclusive asymmetries
- Summary and outlook

Virtual photon-deuteron asymmetry

$$A^{\gamma d} \equiv A_1 = \frac{\frac{1}{2}(\sigma_0 - \sigma_2)}{\frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_0)} \approx \frac{\sum_q e_q^2 (q^+ - q^-)}{\sum_q e_q^2 (q^+ + q^- + q^0)}$$

- Structure functions in QPM

$$F_1(x) = \frac{1}{3} \sum_q e_q^2 (q^+ + q^- + q^0)$$

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 (q^+ - q^-)$$

- Measurement of A_1 gives access to structure functions

$$A_1 \simeq \frac{g_1}{F_1}$$

- μ-deuteron asymmetry is measured in experiment

$$A^{\mu d} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$$

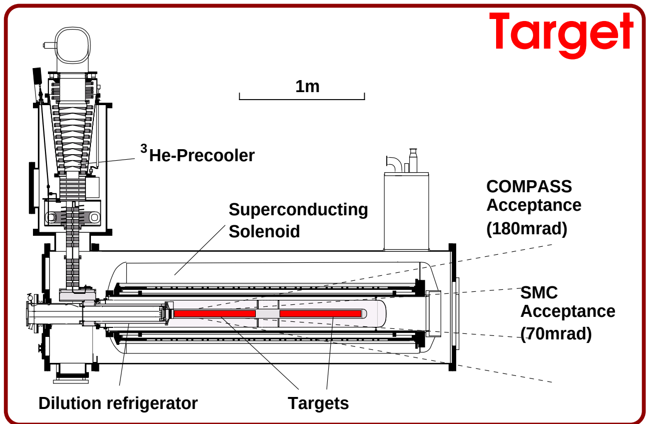
- Relation to A_1

$$A^{\mu d} = D\,(A_1 + \eta A_2)$$

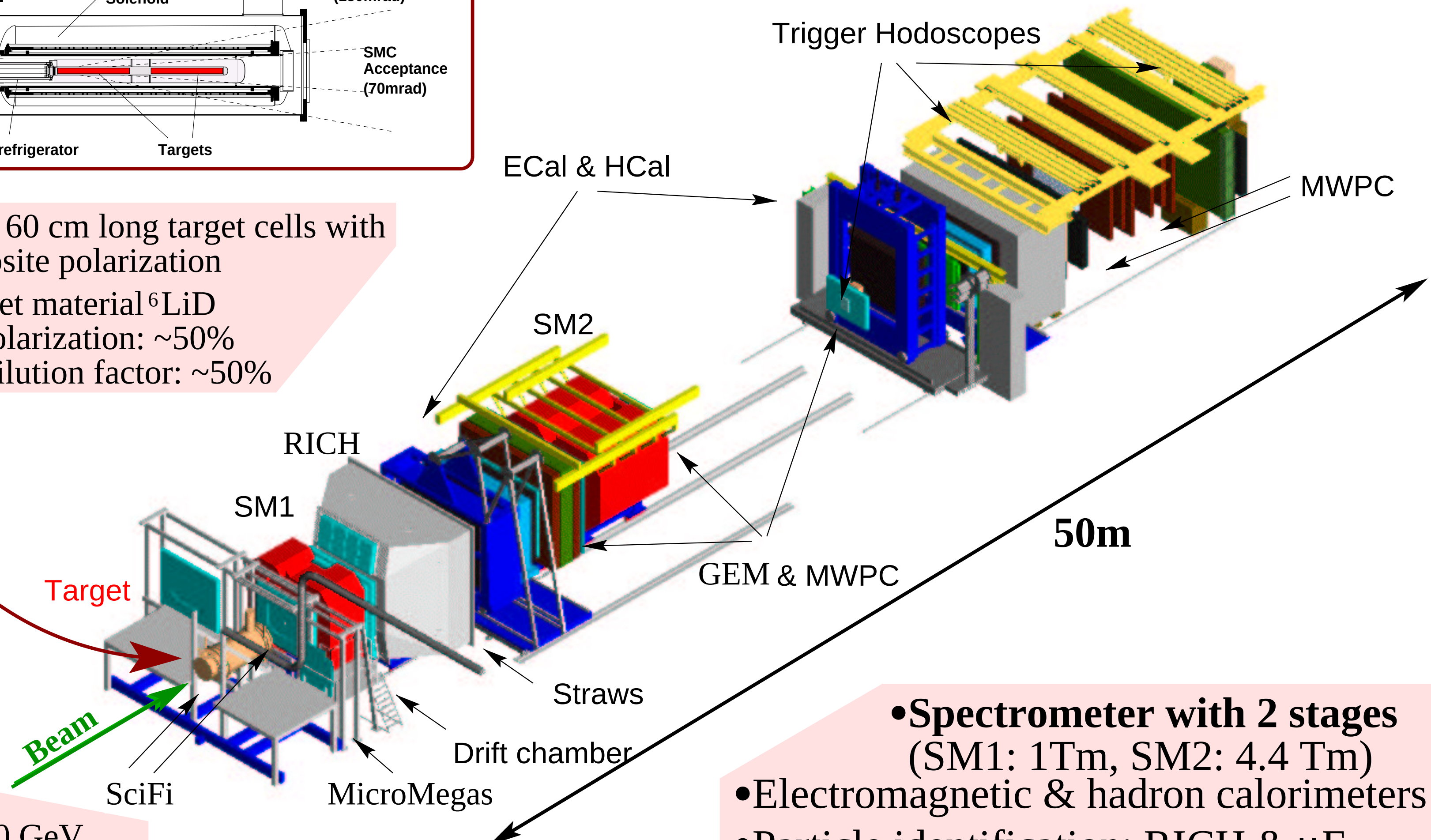
- $|\eta A_2| \ll |A_1|$

$$A_1 \simeq \frac{A^{\mu d}}{D}$$

Spectrometer



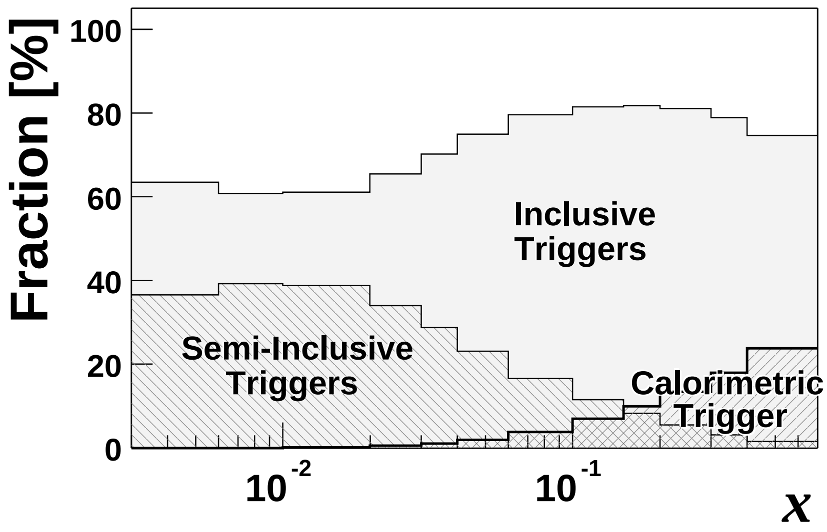
- Two 60 cm long target cells with opposite polarization
- Target material ^{6}LiD
  - Polarization: ~50%
  - Dilution factor: ~50%

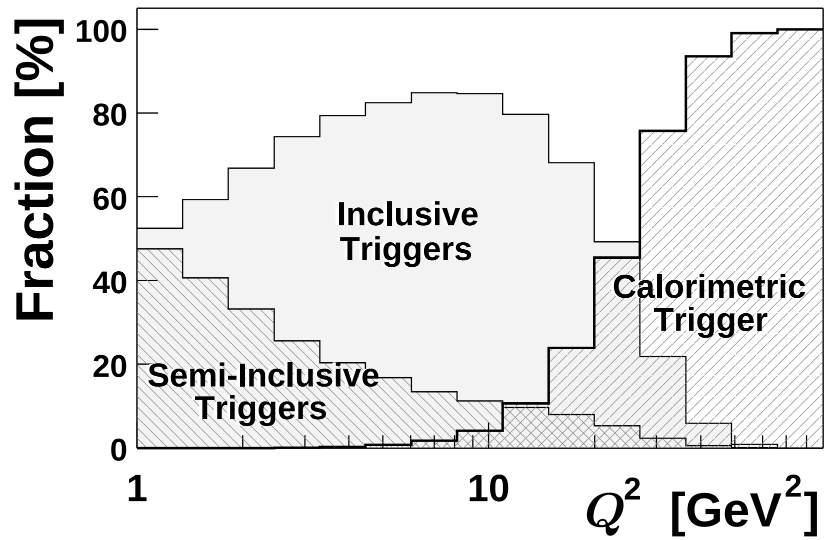


- μ−beam
  - Energy: 160 GeV
  - Intensity: $2 \cdot 10^8 \mu$/spill
  - Polarization: −76%

- **Spectrometer with 2 stages**
  (SM1: 1Tm, SM2: 4.4 Tm)
- Electromagnetic & hadron calorimeters
- Particle identification: RICH & μF

Triggers

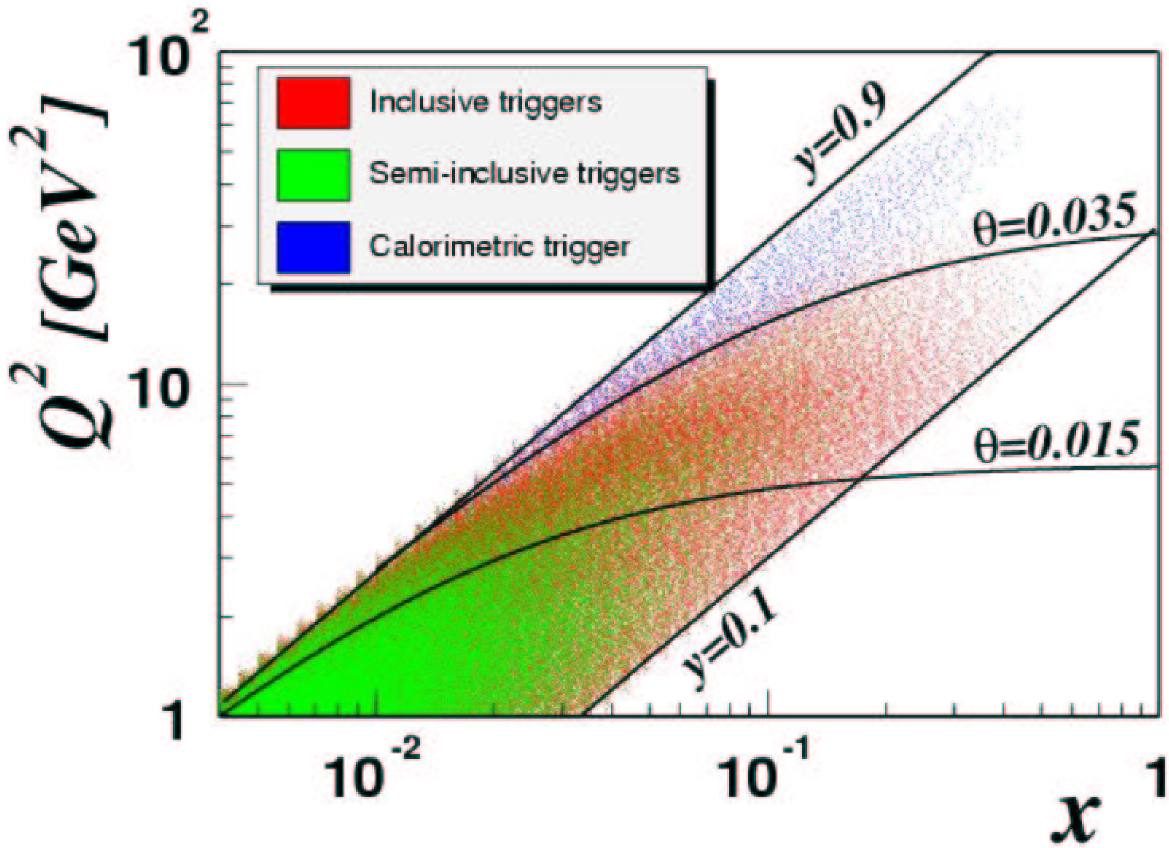




- Inclusive triggers (μ')
- Hadronic triggers
  - Semi-Inclusive triggers (μ'+2MIP)
  - Calorimetric trigger (9MIP)

- Parallel analysis for inclusive and hadronic events
- Hadronic triggers are check with MC study for possible bias

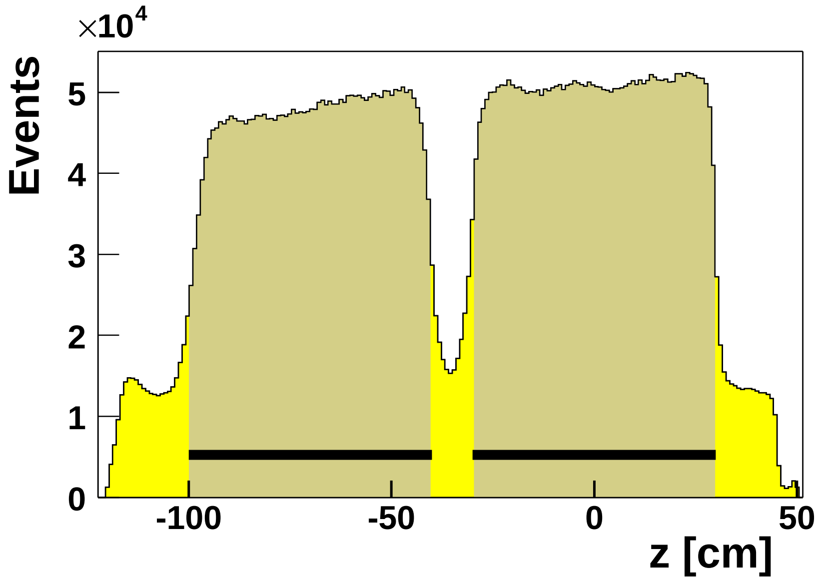
Kinematic region



$$Q^2 > 1\,\mathrm{GeV}^2$$
$$0.004 < x < 0.03$$
$$0.1 < y < 0.9$$

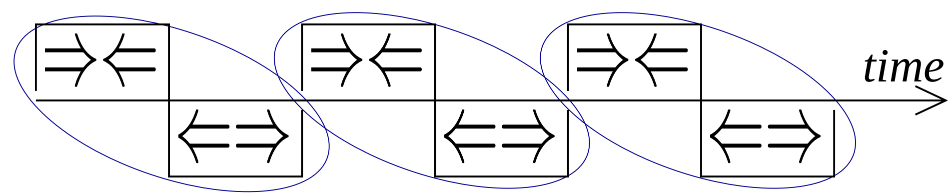
- Data of 2002 + 2003
- $34 \cdot 10^6$ events
- 71% – data collected in 2003

Combining of data



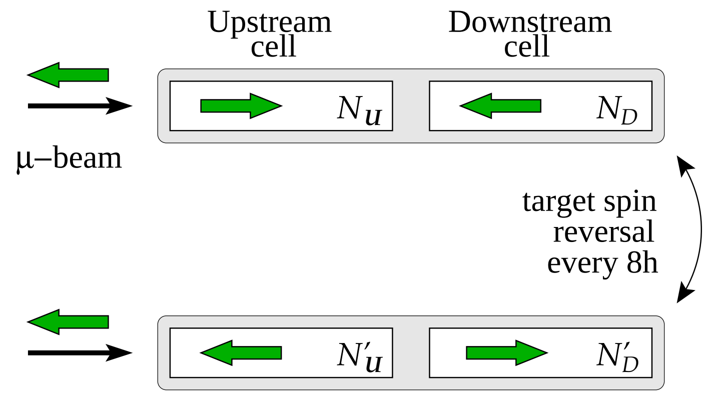
- To cancel acceptance effects two sets of data with opposite target spin orientations are combined together
  - spin reversal every 8 h
  - polarization reversal few times per year

- To minimize influence of spectrometer instability data sets are split into pairs consecutively



2-nd order method for asymmetry extraction

$$N_u = a_u \Phi n_u \bar{\sigma}(1 + f P_b P_u D A_1)$$
$$N_d = a_d \Phi n_d \bar{\sigma}(1 - f P_b P_d D A_1)$$
$$N'_u = a'_u \Phi' n_u \bar{\sigma}(1 - f P_b P'_u D A_1)$$
$$N'_d = a'_d \Phi' n_d \bar{\sigma}(1 + f P_b P'_d D A_1)$$



$$\frac{N_u N'_d}{N_d N'_u} = \frac{a_u a'_d}{a_d a'_u} \frac{(1 + \langle\beta_u\rangle A_1)(1 + \langle\beta'_d\rangle A_1)}{(1 - \langle\beta_d\rangle A_1)(1 - \langle\beta'_u\rangle A_1)}, \quad \text{where } \langle\beta_u\rangle = \frac{\sum_u f P_b P_u D}{N_u}$$

$$\delta = \frac{N_u N'_d}{N_d N'_u}$$
$$a = \frac{\delta}{\kappa}\langle\beta'_u\rangle\langle\beta_d\rangle - \langle\beta_u\rangle\langle\beta'_d\rangle$$
$$b = -\frac{\delta}{\kappa}(\langle\beta'_u\rangle + \langle\beta_d\rangle) - (\langle\beta_u\rangle + \langle\beta'_d\rangle)$$
$$c = \frac{\delta}{\kappa} - 1$$

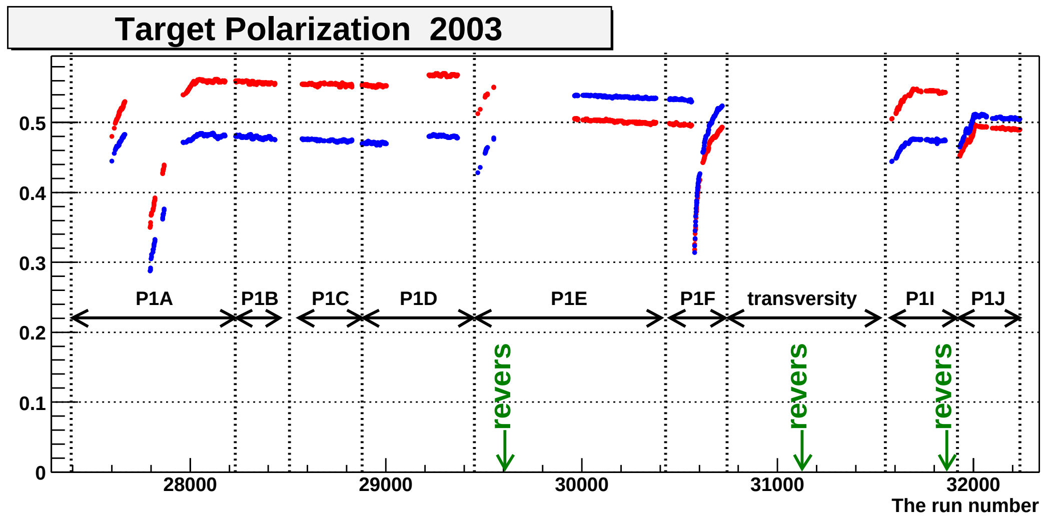
- 2-nd order equation:

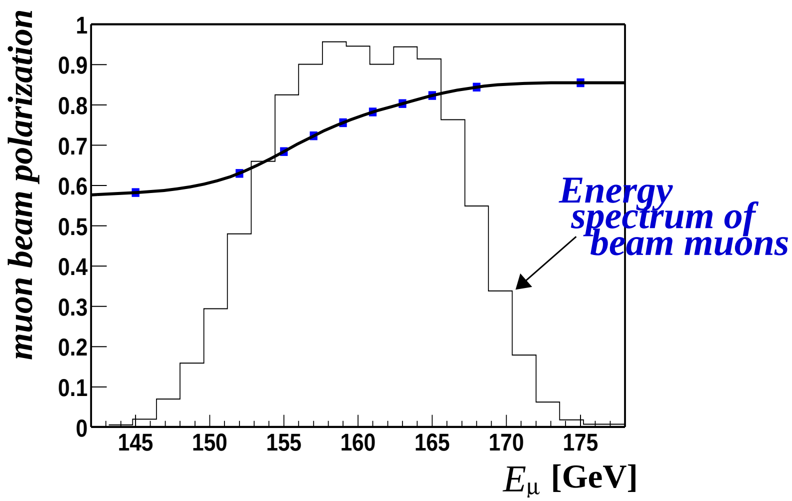
$$a {A_1}^2 + b A_1 + c = 0$$
$$A_1 = \frac{\pm\sqrt{b^2 - 4ac} - b}{2a}$$

- Stability in time: $\kappa = \frac{a_u}{a_d}\frac{a'_d}{a'_u} \approx 1$

Target polarization

- After 5 days of build-up time: +0.53 and −0.50
- Average polarization over 2 years is 0.5
- Measurement by NMR coils with relative precision of 5%



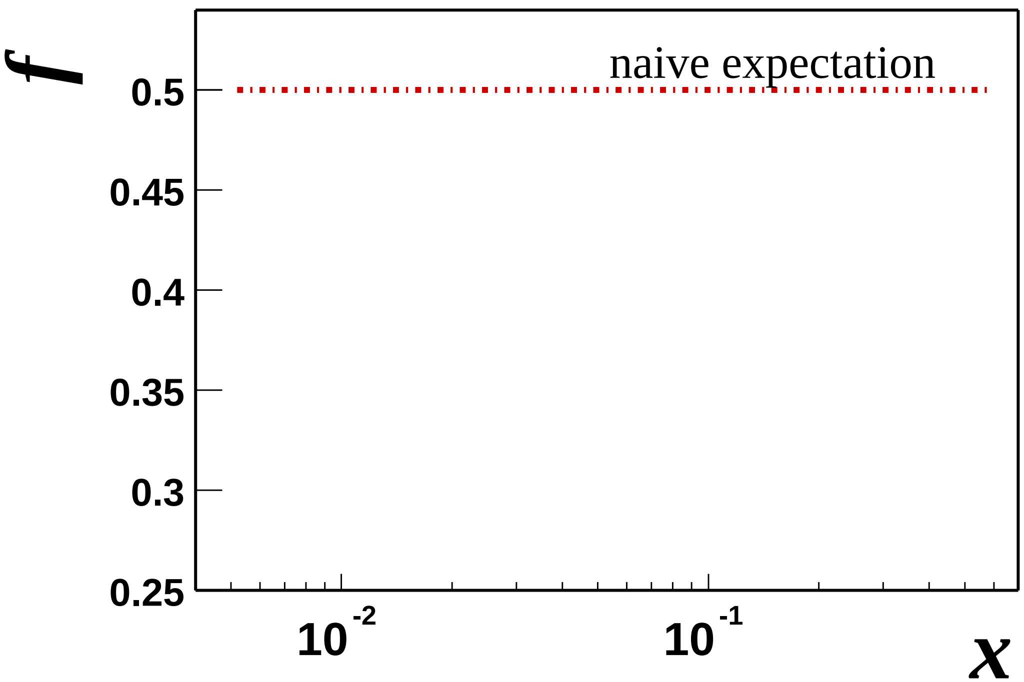


Beam polarization

- MC simulation of the beam line
- Energy range: $[140, 180]$ GeV
- Systematic uncertainty is 0.04
- Average polarization is 0.76

Dilution Factor:

$$f = \frac{\bar{\sigma}^{1\gamma}}{\bar{\sigma}} \frac{n_D \bar{\sigma}_D}{n_D \bar{\sigma}_D + \sum_A (n_A \bar{\sigma}_A)}$$



- Naive expectation ($f = 0.5$)
  ^{6}LiD = (^{4}He + D) + D
- Packing factor = 0.55 ⇒
  Fraction of polarized material.
  Nuclear effects. ($f \approx 0.42$)
- Radiative corrections ($f \approx 0.36$)
  - small x: elastic scattering
  - high x: different kinematic region

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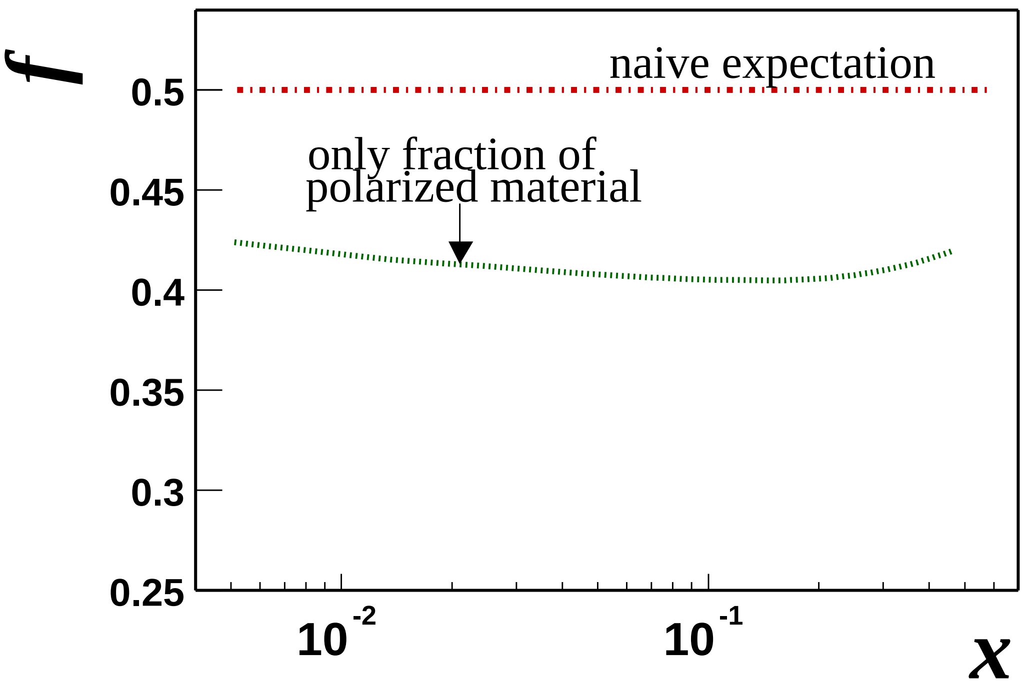

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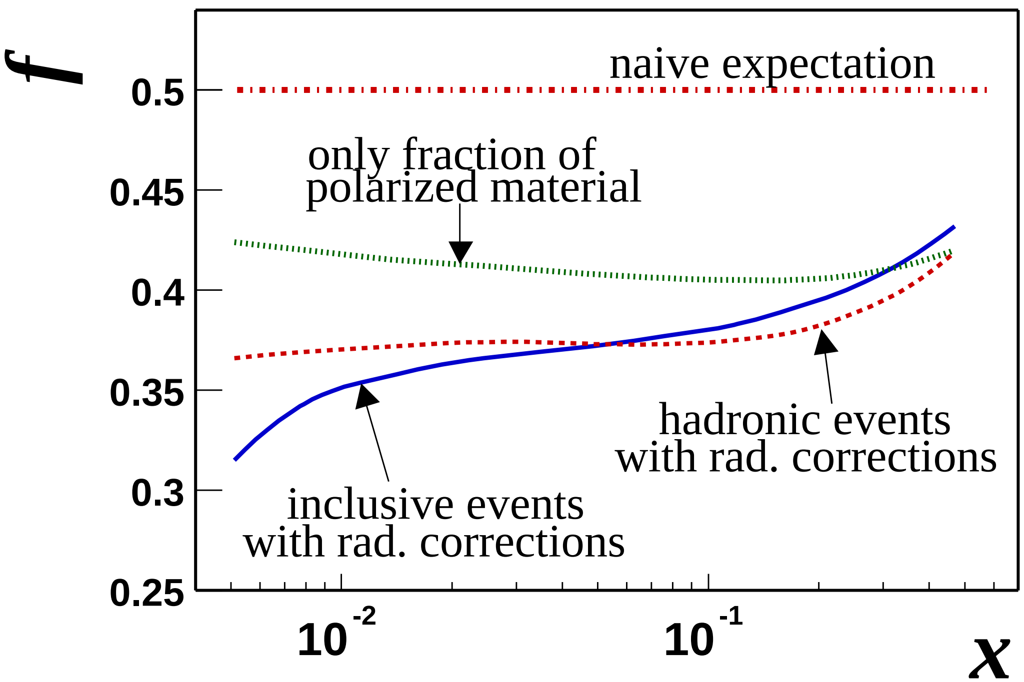

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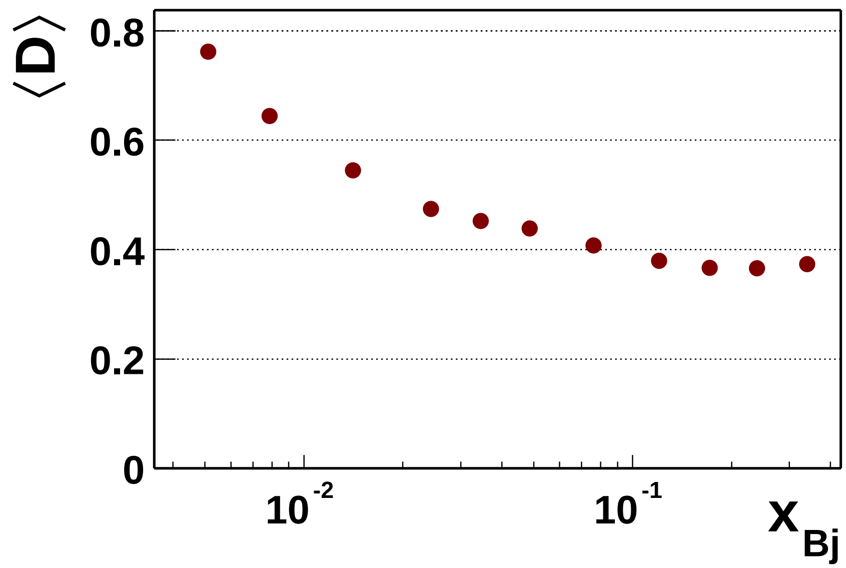
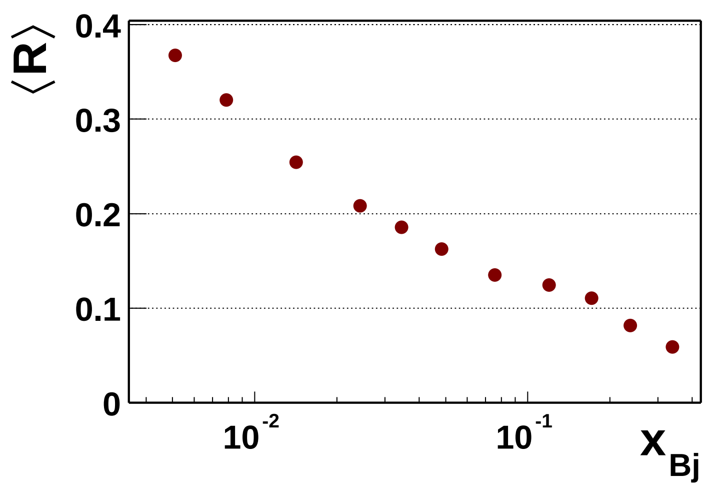
Depolarization Factor

- it accounts for polarization transfer from μ to virtual photon

$$D \simeq \frac{y(2-y)}{y^2 + 2(1+R)(1-y)}$$





$R = \sigma_L / \sigma_T$

- $x < 0.12$ – NMC parametrization
- $x > 0.12$ – SLAC parametrization

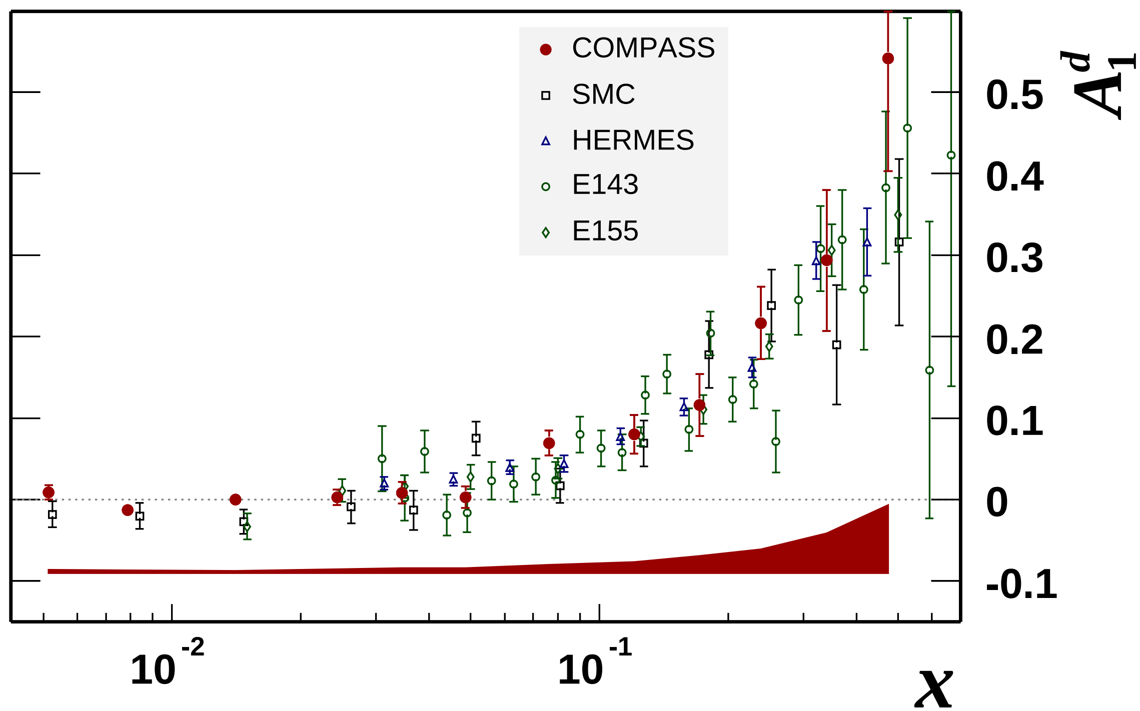
Main sources of systematic error

Multiplicative error for A_1	Beam polariz.	$4-5$ %
	Target polariz.	5%
	Depolariz. fact.	$4-5$ %
	Dilution. fact.	6%
	Sum	$\delta A_1 \simeq 0.1 A_1$

Additive error for A_1	$A_2 \cdot \eta$	$< 0.005 \cdot \eta$
	Rad. correct.	$0.1 \cdot A^{RC}, \quad (A^{RC} < 0.01)$
	A_{false}	$< 0.5 \cdot \sigma_{stat}$

Results on Inclusive Asymmetry A_1^d

- Good agreement over the full range of x
- For $x < 0.03$ statistical error is reduced by factor of 2.5
- Results show no tendency toward negative values



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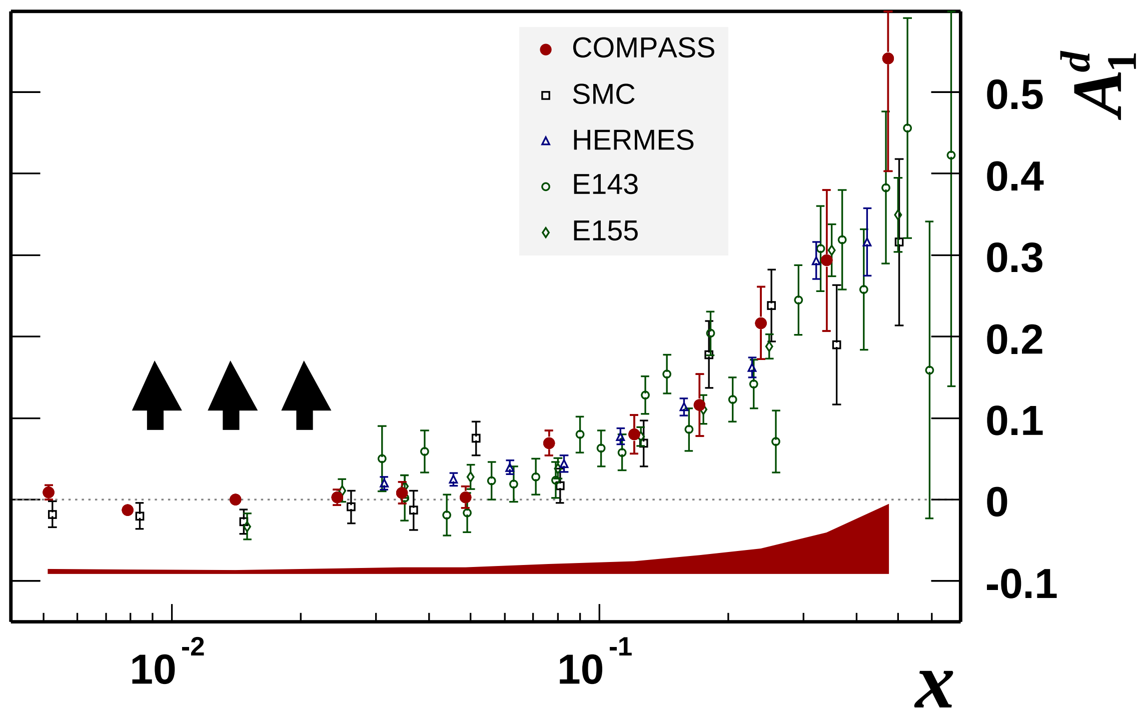

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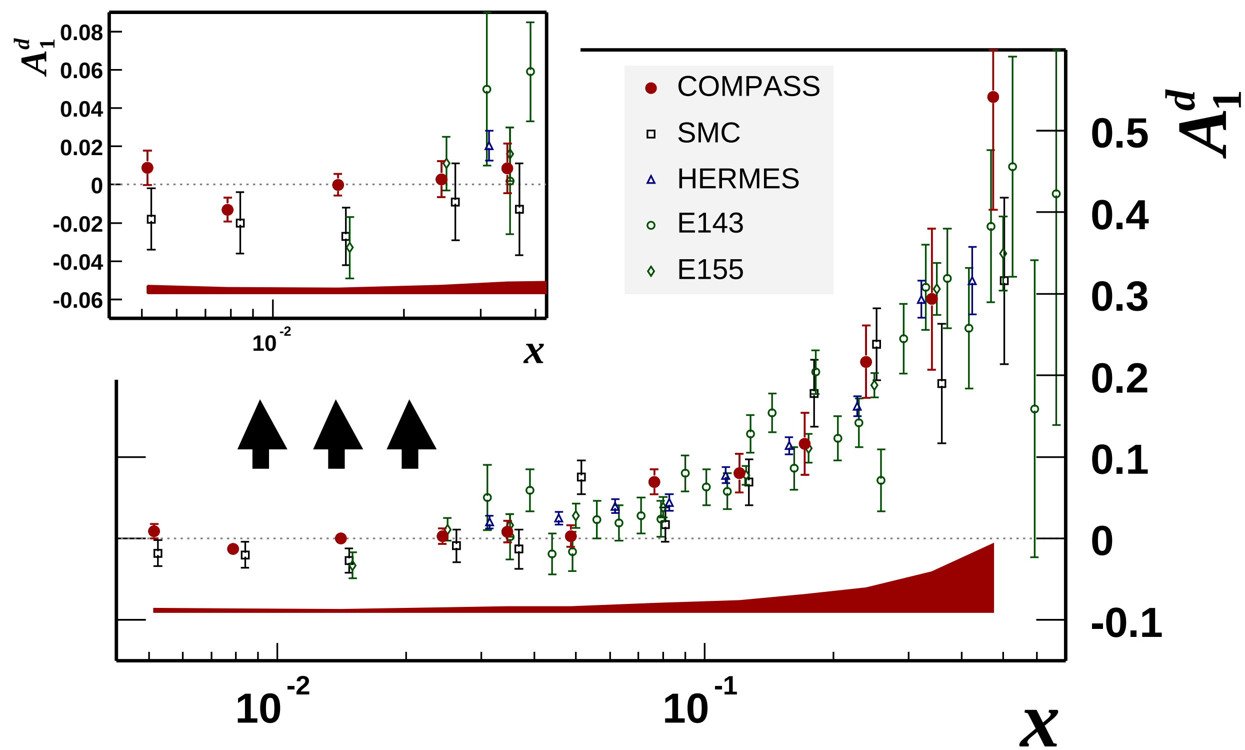

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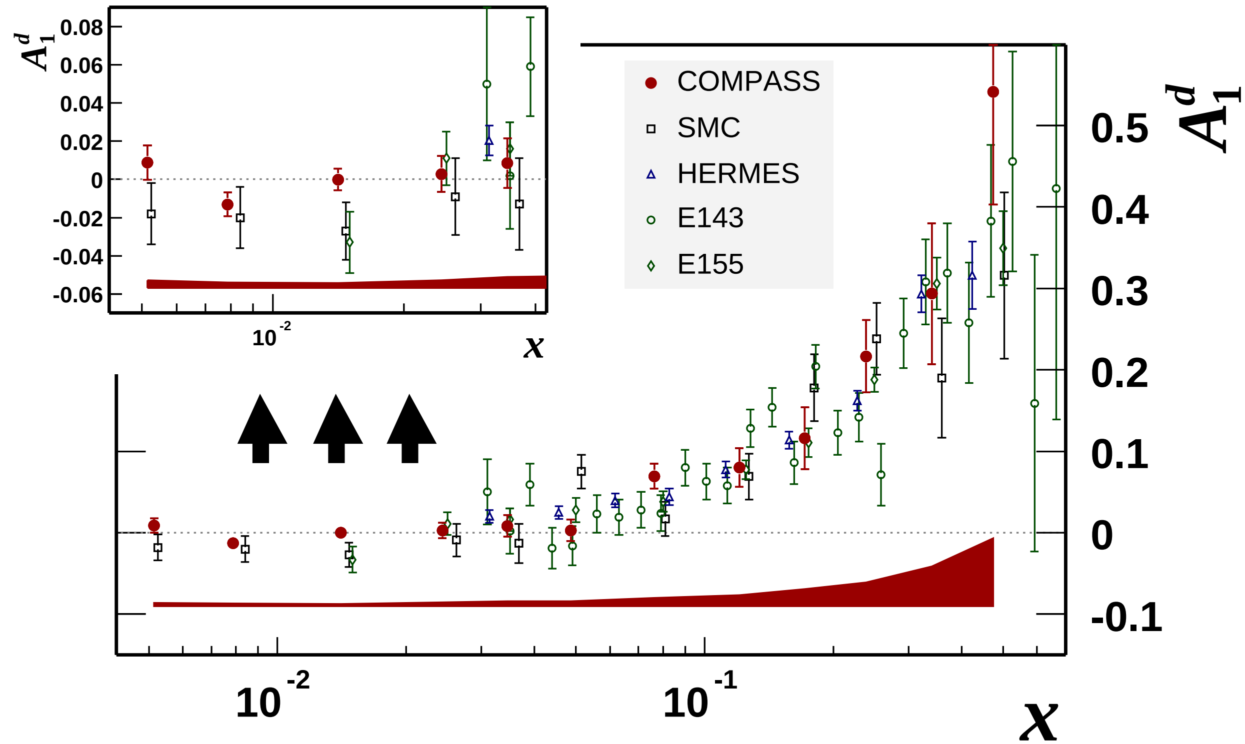

Results on Structure Function g_1^d

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

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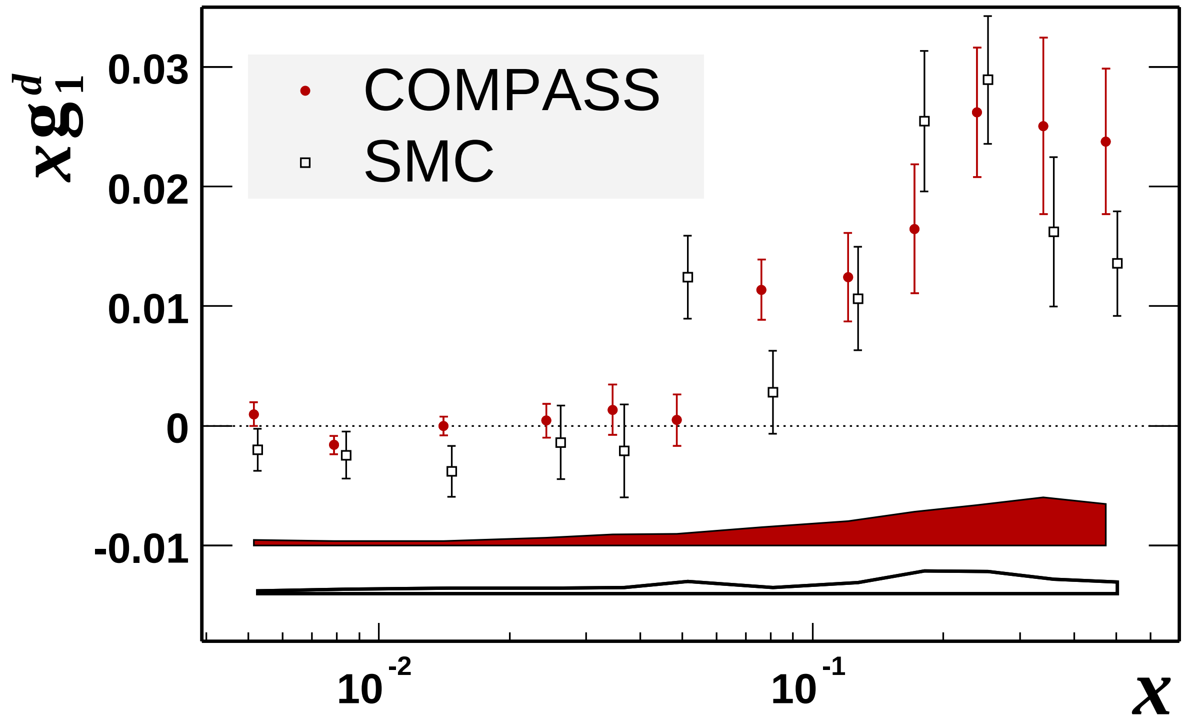

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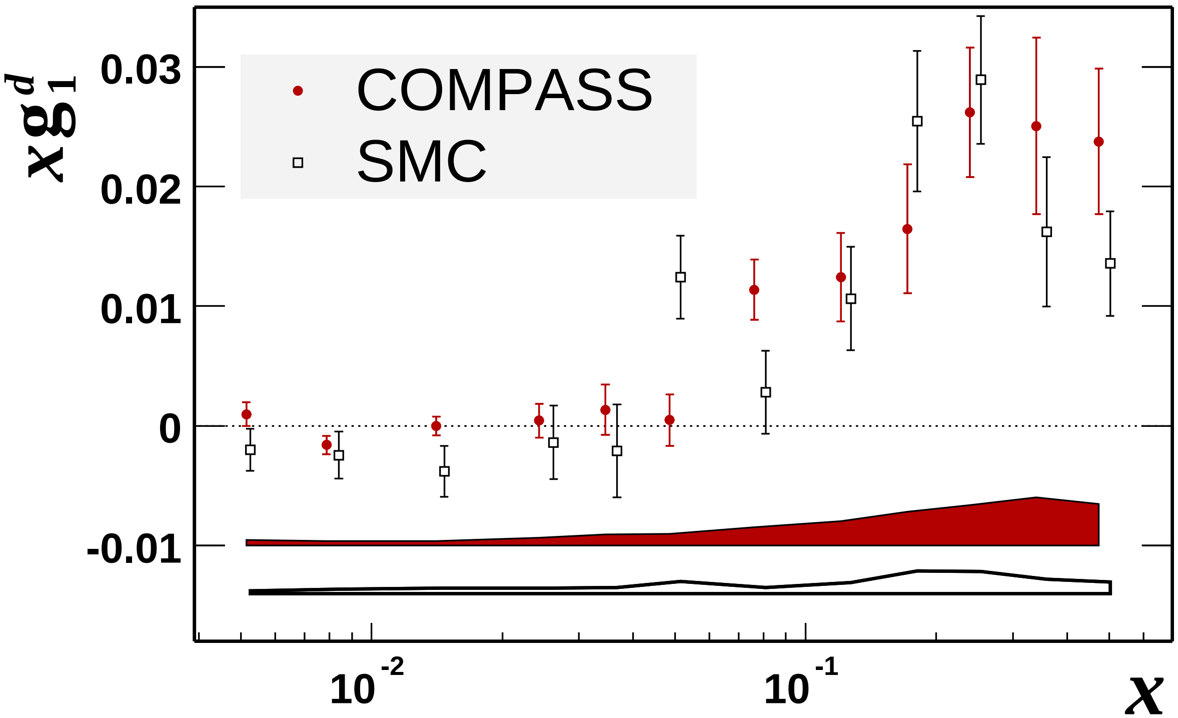


- Integral over the range $0.004 < x < 0.03$
  - ◇ SMC: $(-5.3 \pm 2.3) \cdot 10^{-3}$
  - ◇ COMPASS: $(-0.3 \pm 1.0) \cdot 10^{-3}$
- Improved extrapolation of g_1^d toward $x = 0$
- If compared to SMC no improvement in Γ_1^d

QCD analysis

- Measured structure functions $g_1^{p,d,n}$ (different x, Q^2)

$$g_1(x,Q^2) = \frac{1}{2}\langle e^2\rangle \left[C_q^S \otimes \Delta\Sigma + C_q^{NS} \otimes \Delta q^{NS} + 2n_f\, C_G \otimes \Delta G\right]$$

- DGLAP equations (Q^2-dependence)

$$\begin{aligned} \frac{d}{dt}\Delta q^{NS} &= \frac{\alpha_s(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q^{NS} \\ \frac{d}{dt}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} &= \frac{\alpha_s(t)}{2\pi}\begin{pmatrix} P_{qq}^S & 2n_f P_{qG}^S \\ P_{Gq}^S & P_{GG}^S\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} \end{aligned}, \qquad t = \log\left(\frac{Q^2}{\Lambda^2}\right)$$

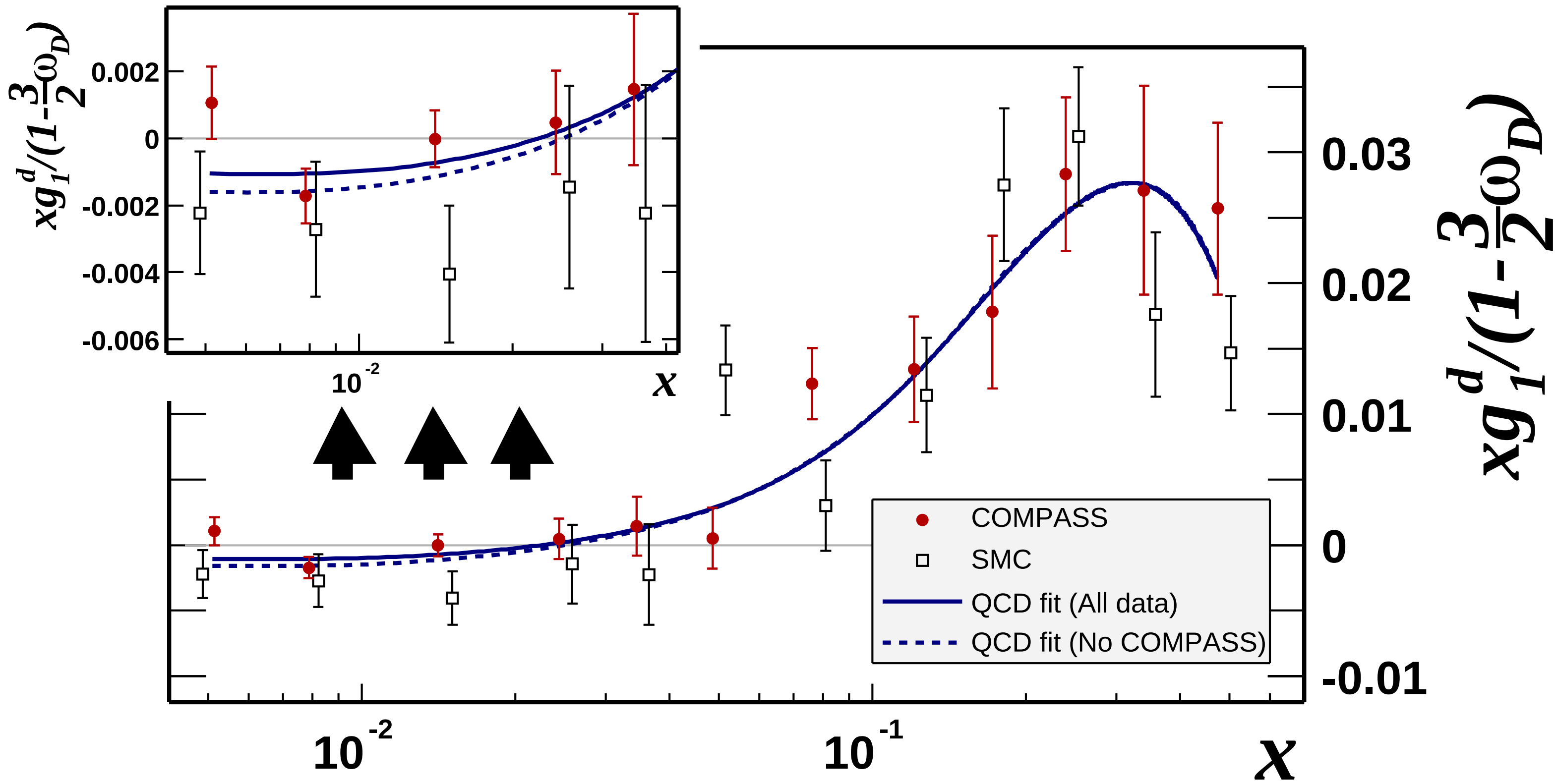
- Initial parametrization (x-dependence at fixed Q^2)

$$(\Delta\Sigma, \Delta q^{NS}, \Delta G) = \eta\, \frac{x^\alpha(1-x)^\beta(1+\gamma x)}{\int_0^1 x^\alpha(1-x)^\beta(1+\gamma x)dx}$$

- Minimization routine

$$\chi^2 = \sum_{i=1}^{N} \frac{\left[g_1^{\rm calc}(x,Q^2) - g_1^{\rm exp}(x,Q^2)\right]^2}{\left[\sigma_{\rm stat}^{\rm exp}(x,Q^2)\right]^2}$$

Results QCD fit



- Program "2" in SMC notation (D.Fasching, hep-ph/9610261)
- Numerical calculation in NLO ($\overline{MS}$ scheme)
- World data fit

Quark spin content ($\Delta\Sigma$ in $\overline{MS}$)

with
COMPASS
data

without
COMPASS
data

Quark spin content ($\Delta\Sigma$ in $\overline{MS}$)

with COMPASS data	without COMPASS data
SMC"2"	$Q^2=4$ GeV^2
$0.237^{+0.024}_{-0.029}$	$0.202^{+0.042}_{-0.077}$

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LSS05 Q^2=1 GeV^2

0.189 ± 0.054

AAC03 Q^2=1 GeV^2

0.213 ± 0.039

LLS05: E.Leader,A.V.Sidorov,D.B.Stamenov hep−ph/0503140
AAC03: M.Hirai,S.Kumano,N.Saito,Phys.Rev.D69(2004)054021

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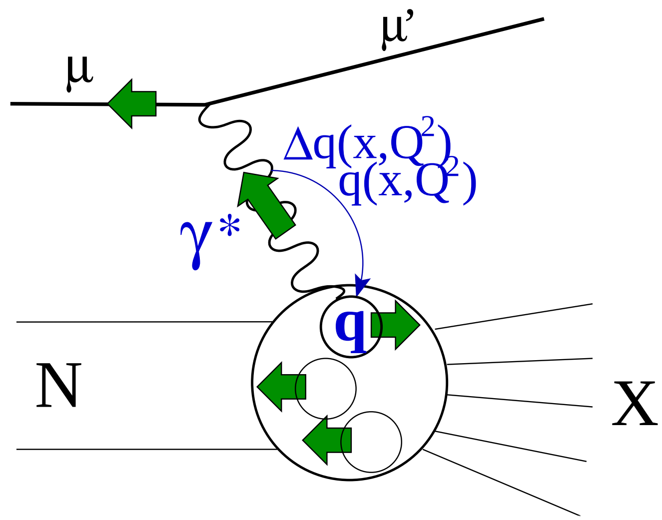
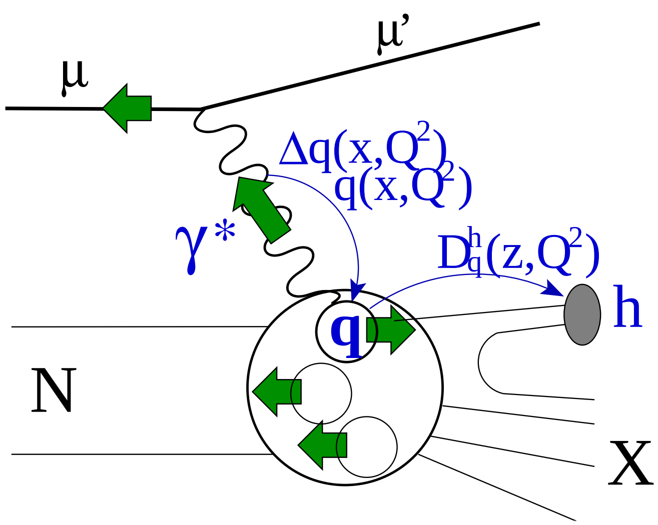
What is detected in final state?

Inclusive DIS



- Detected particle: μ, μ'
- $A_1 = \frac{\sum_q e_q^2 \left[\boldsymbol{\Delta q(x)} + \boldsymbol{\Delta \bar{q}(x)}\right]}{\sum_q e_q^2 \left[q(x) + \bar{q}(x)\right]}$
- only $\Delta q + \Delta \bar{q}$ can be measured



Semi-Inclusive DIS

- Detected particle: μ, μ', h, ...
- $A_1^h = \frac{\sum_q e_q^2 \left[\boldsymbol{\Delta q(x)} \int D_q^h dz + \boldsymbol{\Delta \bar{q}(x)} \int D_{\bar{q}}^h dz\right]}{\sum_q e_q^2 \left[q(x) \int D_q^h dz + \bar{q}(x) \int D_{\bar{q}}^h dz\right]}$
- $D_q^h \neq D_{\bar{q}}^h \Rightarrow$ quarks and anti-quarks separation

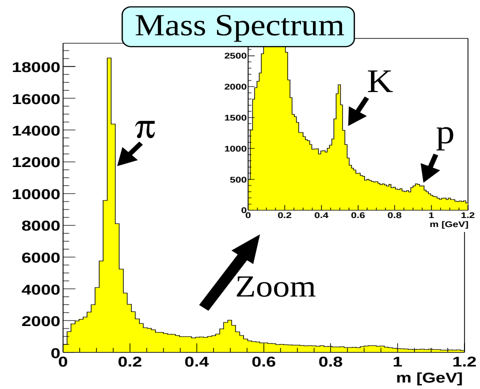
Asymmetries which we measure

$$\vec{A}_1 = \{ A_1, A_1^{h+}, A_1^{h-}, A_1^{K+}, A_1^{K-}, A_1^{K^0_S} \}$$

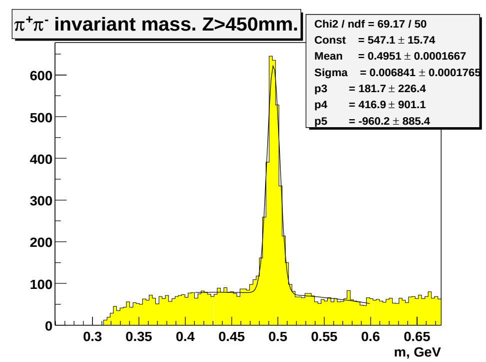
Inclusive Asymmetry

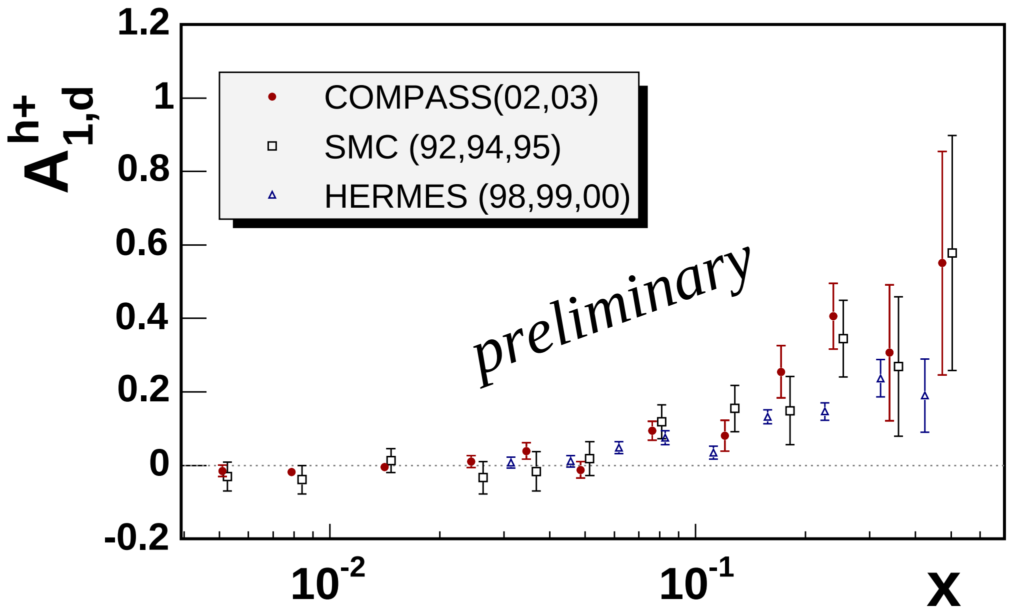
≈90% of hadrons are pions

RICH PID
Threshold: p_K>9 GeV



Secondary vertices produced by track coming from intera−ction point

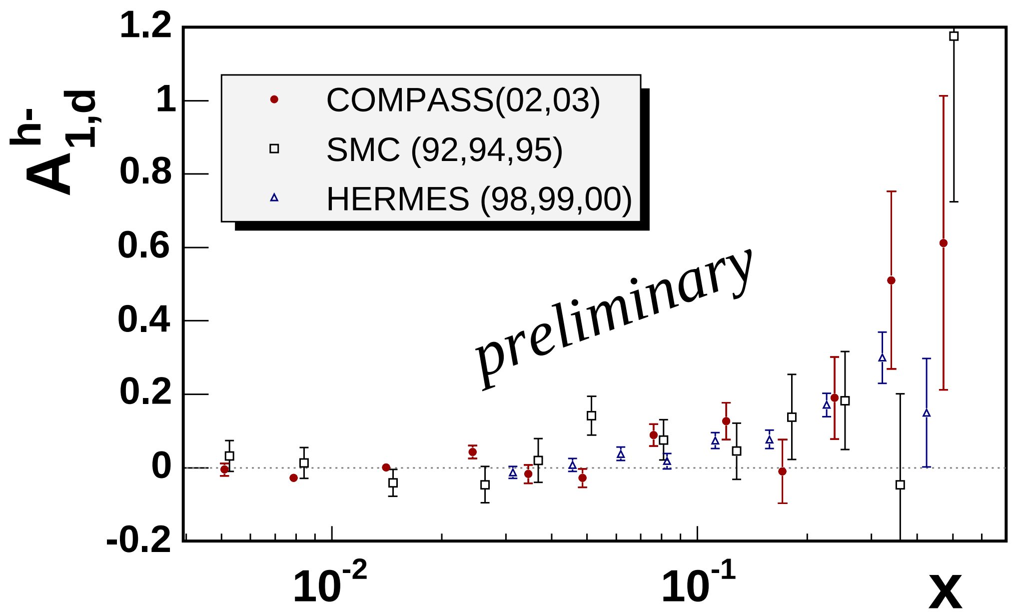




$A^{h+}_{1,d}$
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
COMPASS(02,03)
SMC (92,94,95)
HERMES (98,99,00)
preliminary
10^{-2}
10^{-1}
x

•

•



$A^{h-}_{1,d}$
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
COMPASS(02,03)
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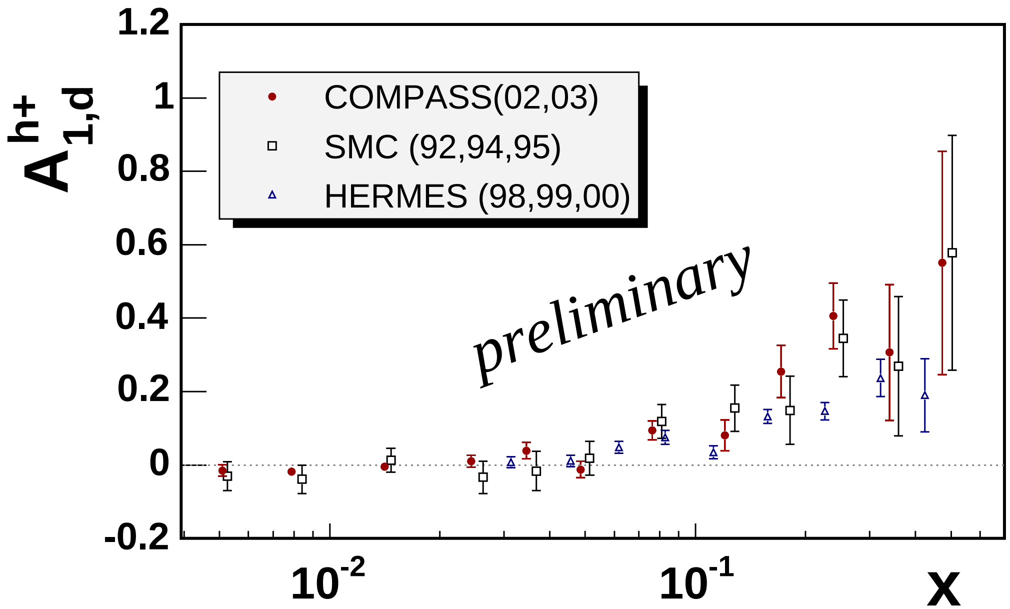
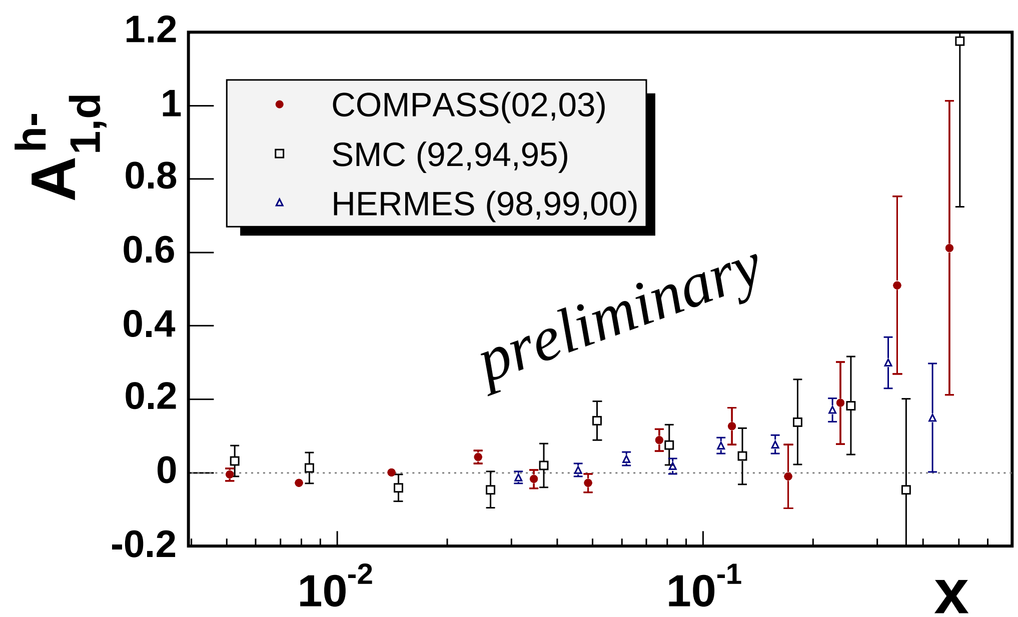


- Agreement with previous experiments

- Significant statistical improvement at low x



Summary

- Analysis of data of 2002 and 2003
- New measurement of A_1^d and g_1^d in DIS region (Q^2>1 GeV^2, 0.004<x<0.7)
  - ◇ Good agreement with results of previous experiments
  - ◇ Improvement in statistical precision factor 2.5 in region $x < 0.03$
  - ◇ Extrapolation improvement of g_1^d toward $x = 0$
  - ◇ With QCD fit ($\overline{MS}$) decrease of error ≈2 for $\Delta\Sigma$
- Hadron asymmetries A_1^{h+} & A_1^{h-} have been shown

Outlook

- Sizable improvement with 2004 data is expected (Calo trigger)
- Kaon asymmetries A_1^{K+}, A_1^{K-}, $A_1^{K_S^0}$ are coming
- Analysis of A_1^d at low x and low Q^2 is going