“Helicity quark distributions from DIS and SIDIS measured in COMPASS”

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JINR, Dubna

on behalf of the COMPASS collaboration

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

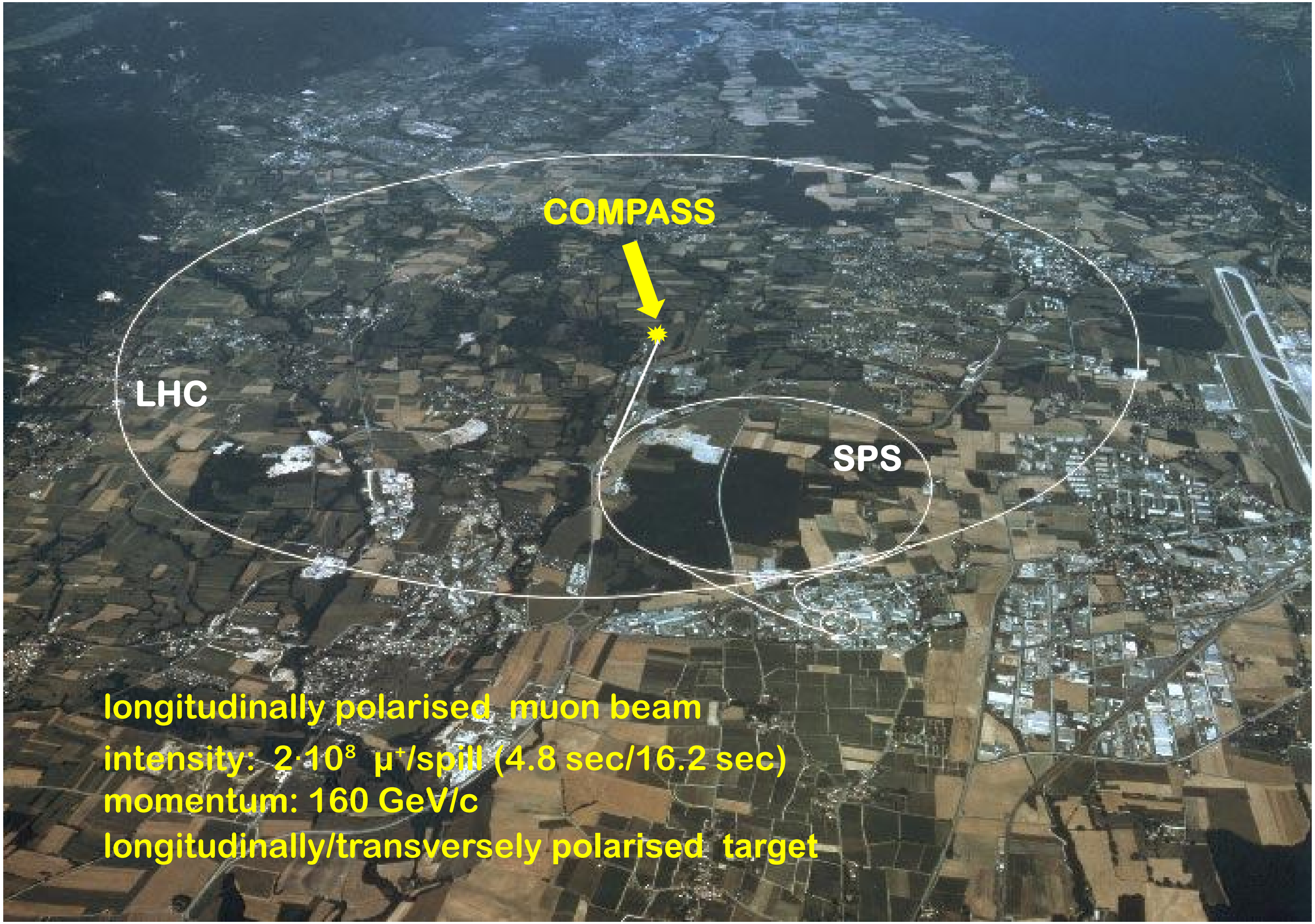
NA58 experiment at CERN

~230 physicists from 11 countries

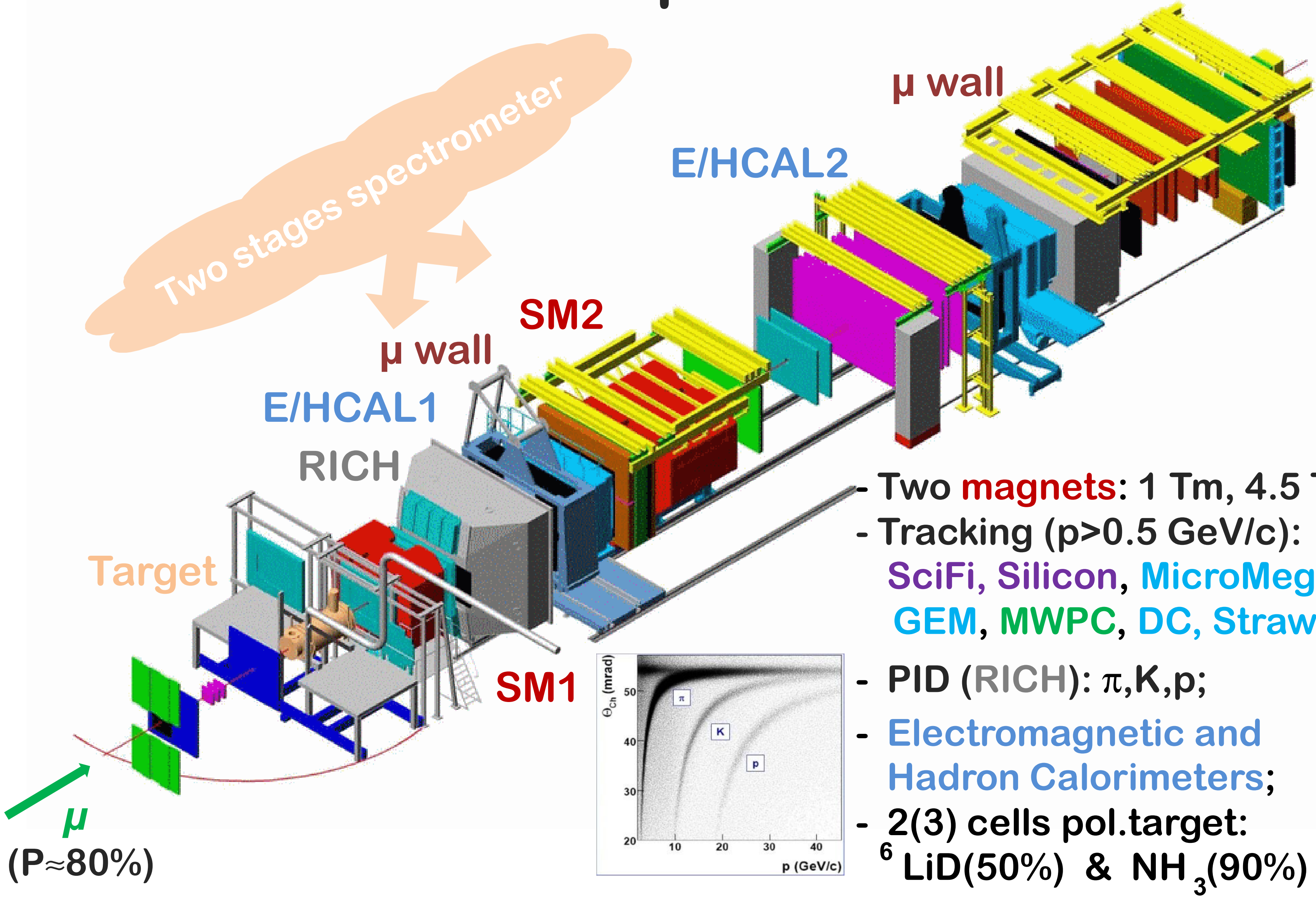
Czech Republic, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Portugal and Russia

- **Muon program (2002-2007)**
  Deep Inelastic Scattering (DIS) of polarized 160 GeV/c muons on polarized deuterons and protons

- **Hadron program (2008-2009)**
  190 GeV/c π, K , p beams search for exotics in diffractive excitation and central production, polarizability of π, K


COMPASS
LHC
SPS
longitudinally polarised muon beam
intensity: 2·10⁸ μ⁺/spill (4.8 sec/16.2 sec)
momentum: 160 GeV/c
longitudinally/transversely polarised target

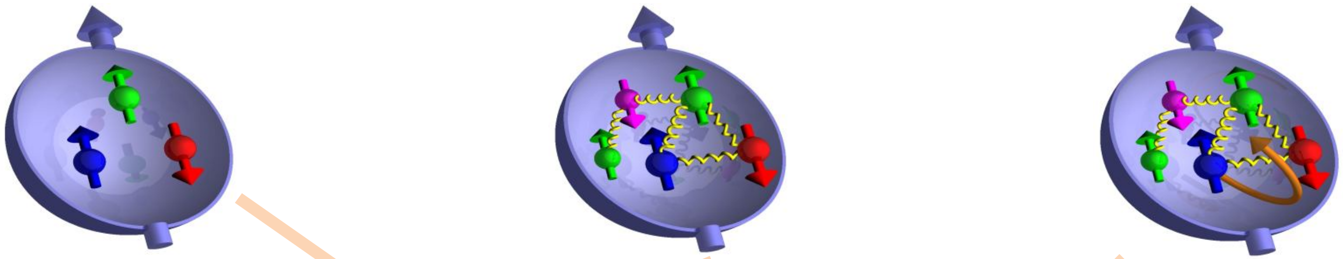
COMPASS spectrometer



- Two magnets: 1 Tm, 4.5 Tm;
- Tracking (p>0.5 GeV/c):
  SciFi, Silicon, MicroMega,
  GEM, MWPC, DC, Straw;

- PID (RICH): π,K,p;
- Electromagnetic and Hadron Calorimeters;
- 2(3) cells pol.target: ^{6}LiD(50%) & NH_3(90%)

Spin of the nucleon



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

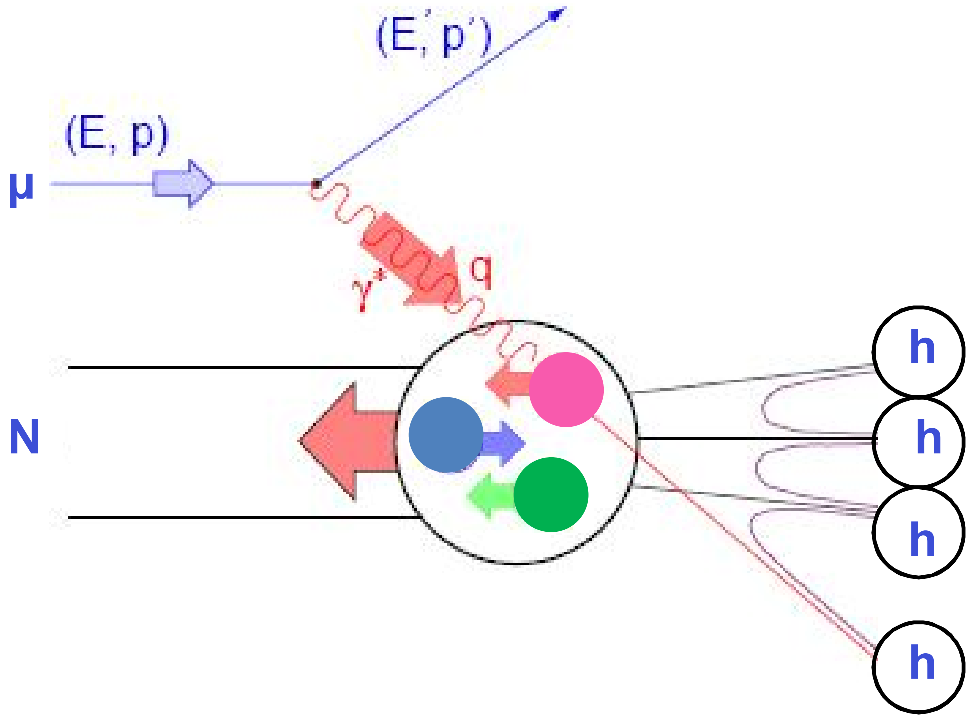
Naive view:

$\Delta\Sigma = \Delta u_v + \Delta d_v = 1$

Complete description :

- $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ (for q and $\bar{q}$)
- ΔG
- orbital angular momenta

Deep inelastic scattering



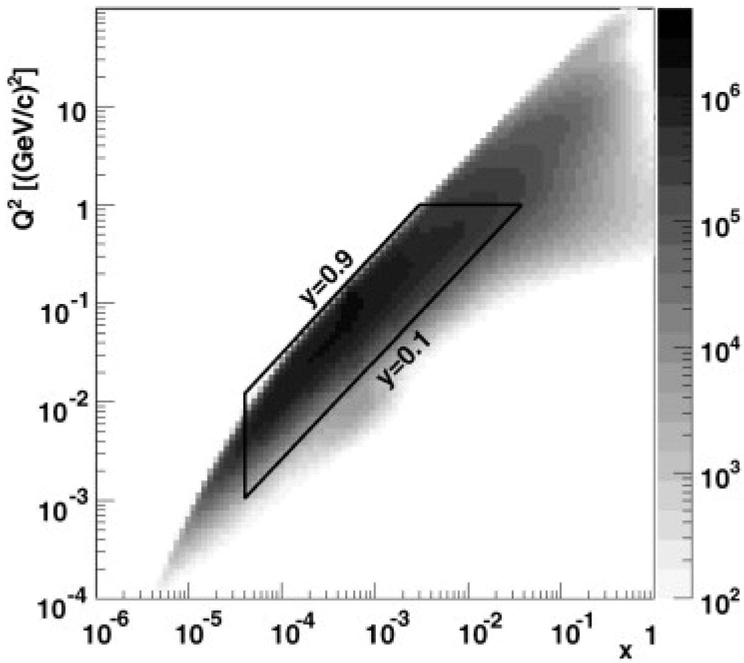
Kinematical variables:

$Q^2 = -q^2$

$x = Q^2/2M\nu$

$\nu = E - E'$

$y = \nu/E$

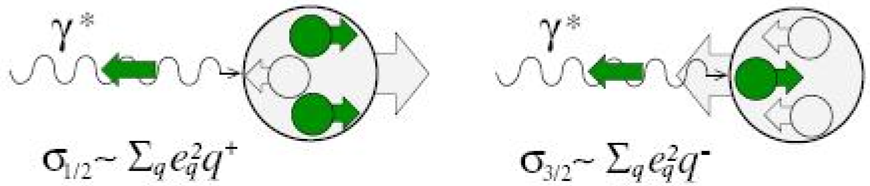


Deep inelastic scattering

- quark densities in QPM:

$$q(x) = q^{+}(x) + q^{-}(x)$$

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



- Longitudinal double-spin asymmetry:

$$A^{\gamma N} \equiv A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\sum_q e_q^2 \Delta q}{\sum_q e_q^2 q}$$

- Longitudinal spin asymmetry μN:

$$A^{\mu N} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = \frac{\Delta\sigma}{\bar{\sigma}} \simeq DA_1$$

D – depolarization factor of γ

- Cross-sections

  and

  Structure functions:

$$\bar{\sigma}(x, Q^2) = aF_1(x, Q^2) + bF_2(x, Q^2)$$
$$\Delta\sigma(x, Q^2) = \alpha g_1(x, Q^2) + \beta g_2(x, Q^2)$$

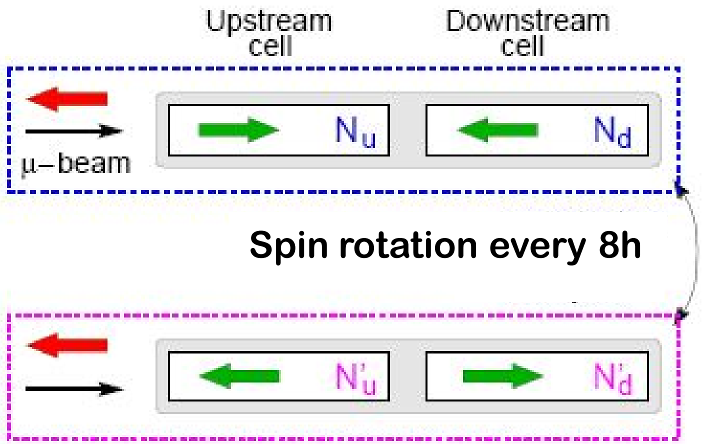
- Structure functions and PDF:

$$F_1 = \frac{1}{2} \sum_q e_q^2 \, (q + \bar{q}), \quad g_1 = \frac{1}{2} \sum_q e_q^2 \, (\Delta q + \Delta \bar{q})$$

- Asymmetry A_1 and structure function g_1: $g_1 \approx A_1 \cdot F_1$

Asymmetry measurement

- to be measured: $A_{\parallel} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$
- measured values: N_u, N_d, N'_u, N'_d
- flux normalization: $\frac{\Phi_u}{\Phi_d} = 1$
- acceptance: (constant ratio) $\frac{a'_d}{a'_u} = 1$



- double ratio method: $\delta = \frac{N_u \cdot N'_d}{N'_u \cdot N_d}$

  $\Rightarrow$ solve for A_{exp} (2^{nd} order equation)

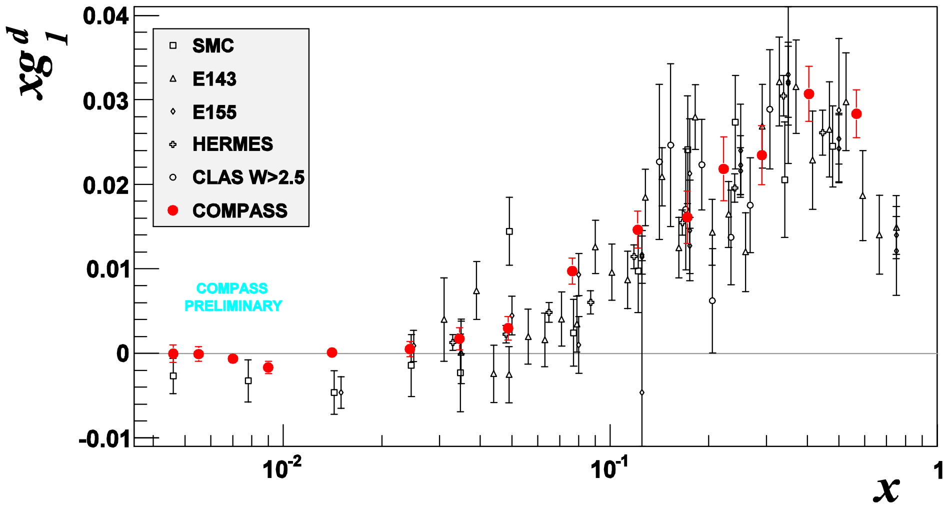
  $\Rightarrow$ minimization of bias

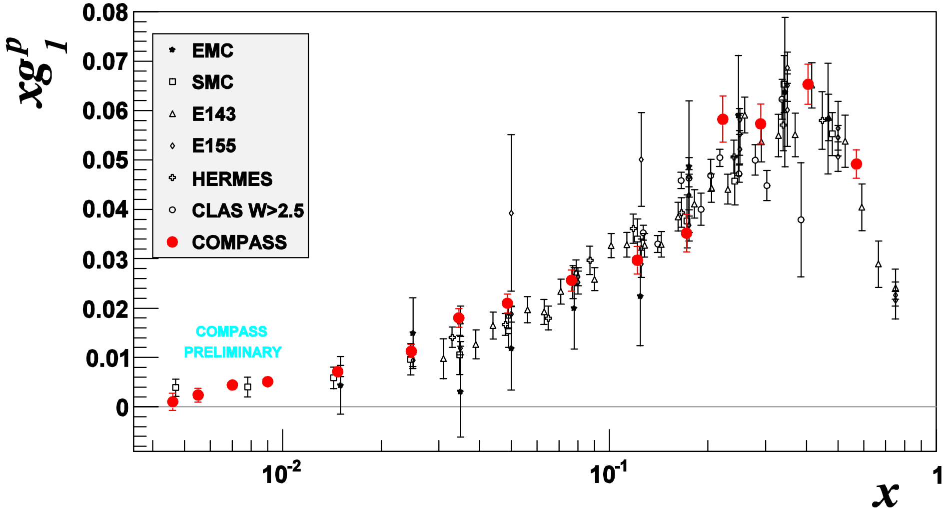
- experimental asymmetry: $A_{exp} = p_\mu \; p_T \, f \; A_{\parallel}$

  p_μ, p_T - beam and target polarization

  f - dilution factor

Structure functions g_1^d and g_1^p





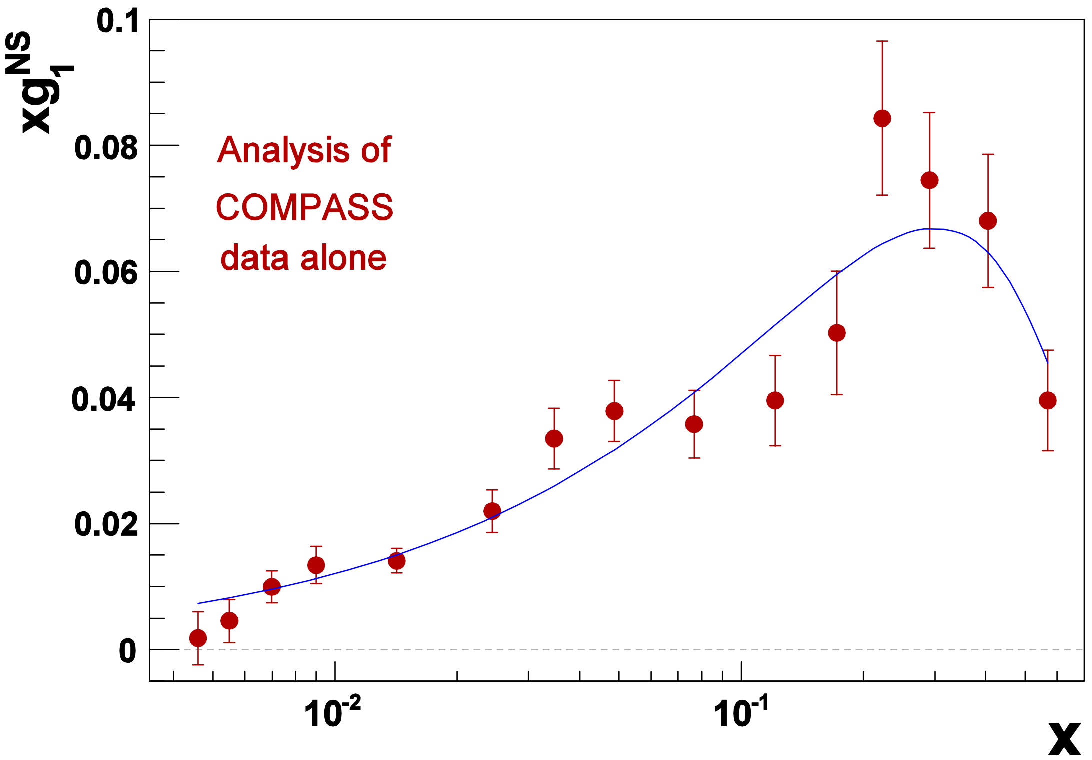
- The non-singlet spin structure function $g_1^{NS}(x)$ can be evaluated

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

- First moments provide a test of the Bjorken sum rule, a fundamental result of QCD derived using current algebra:

$$\Gamma_1^{NS} = \Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C^{NS} \qquad \text{or} \qquad \Delta u - \Delta d = \left|\frac{g_A}{g_V}\right|$$

Structure functions g_1^{NS}



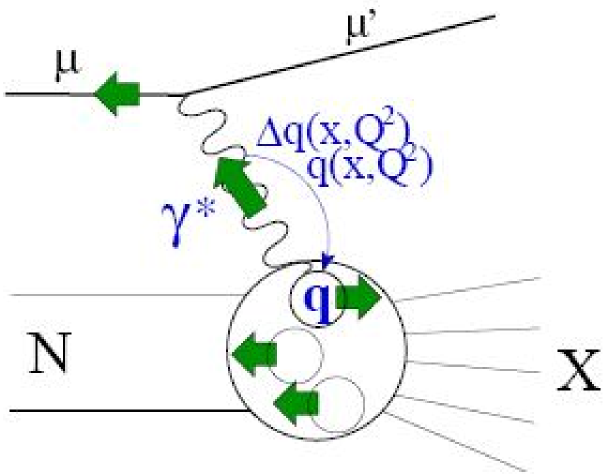
$$g_A/g_V = 1.30 \pm 0.07(stat) \pm 0.10(syst)$$

$$g_A/g_V^{PDG} = 1.269 \pm 0.003$$

Systematic error:

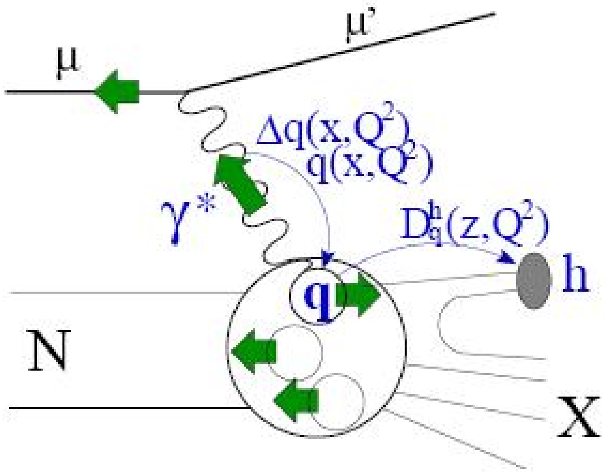
- $\delta(P_b)$ is dominant : 5% → ±0.065
- ^{6}LiD: 7% due to *f* and P_t → ±0.041
- NH_3 : 3% due to *f* and P_t →±0.056

Full flavor separation analysis with LO QCD fit



Inclusive DIS

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



Semi-Inclusive DIS

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

- LO QCD analysis (independent quark fragmentation)

$$A_{1,d} = \frac{5(\mathbf{\Delta u}+\mathbf{\Delta d})+5(\mathbf{\Delta\bar{u}}+\mathbf{\Delta\bar{d}})+4\mathbf{\Delta s}}{5(u+d)+5(\bar{u}+\bar{d})+2(s+\bar{s})}$$

$$A_d^h = \frac{(4D_u^h+D_d^h)(\mathbf{\Delta u}+\mathbf{\Delta d})+(4D_{\bar{u}}^h+D_{\bar{d}}^h)(\mathbf{\Delta\bar{u}}+\mathbf{\Delta\bar{d}})+2(D_s^h+D_{\bar{s}}^h)\mathbf{\Delta s}}{(4D_u^h+D_d^h)(u+d)+(4D_{\bar{u}}^h+D_{\bar{d}}^h)(\bar{u}+\bar{d})+2(D_s^h s+D_{\bar{s}}^h\bar{s})}$$

$$A_{1,p} = \frac{4(\mathbf{\Delta u}+\mathbf{\Delta\bar{u}})+(\mathbf{\Delta d}+\mathbf{\Delta\bar{d}})+2\mathbf{\Delta s}}{4(u+\bar{u})+(d+\bar{d})+(s+\bar{s})}$$

$$A_{1,p}^h = \frac{4(D_u^h\mathbf{\Delta u}+D_{\bar{u}}^h\mathbf{\Delta\bar{u}})+(D_d^h\mathbf{\Delta d}+D_{\bar{d}}^h\mathbf{\Delta\bar{d}})+(D_s^h+D_{\bar{s}}^h)\mathbf{\Delta s}}{4(D_u^h u+D_{\bar{u}}^h\bar{u})+(D_d^h d+D_{\bar{d}}^h\bar{d})+(D_s^h s+D_{\bar{s}}^h\bar{s})}$$

- Matrix form. 10 equations with 5 unknowns

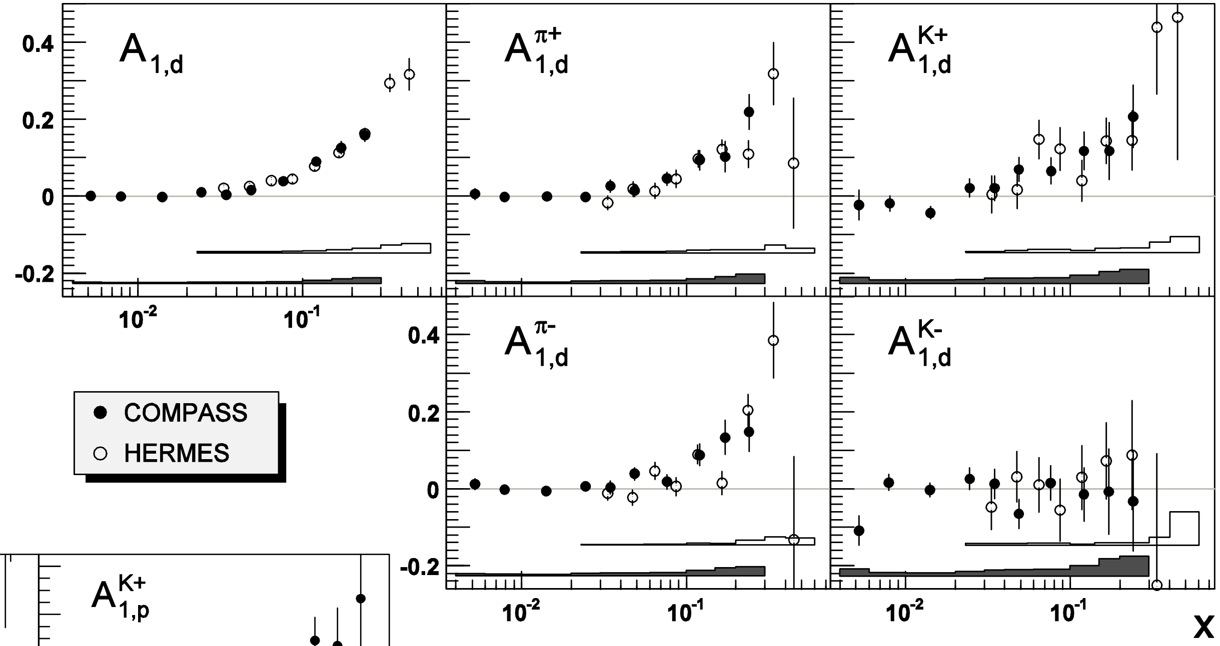
$$\vec{A} = \mathsf{B}\,\Delta\vec{q}, \quad \text{where} \quad \begin{cases} \vec{A} = (A_1^d, A_d^{\pi+}, A_d^{\pi-}, A_d^{K+}, A_d^{K-},\ A_1^p, A_p^{\pi+}, A_p^{\pi-}, A_p^{K+}, A_p^{K-}) \\ \Delta\vec{q} = (\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s) \end{cases}$$

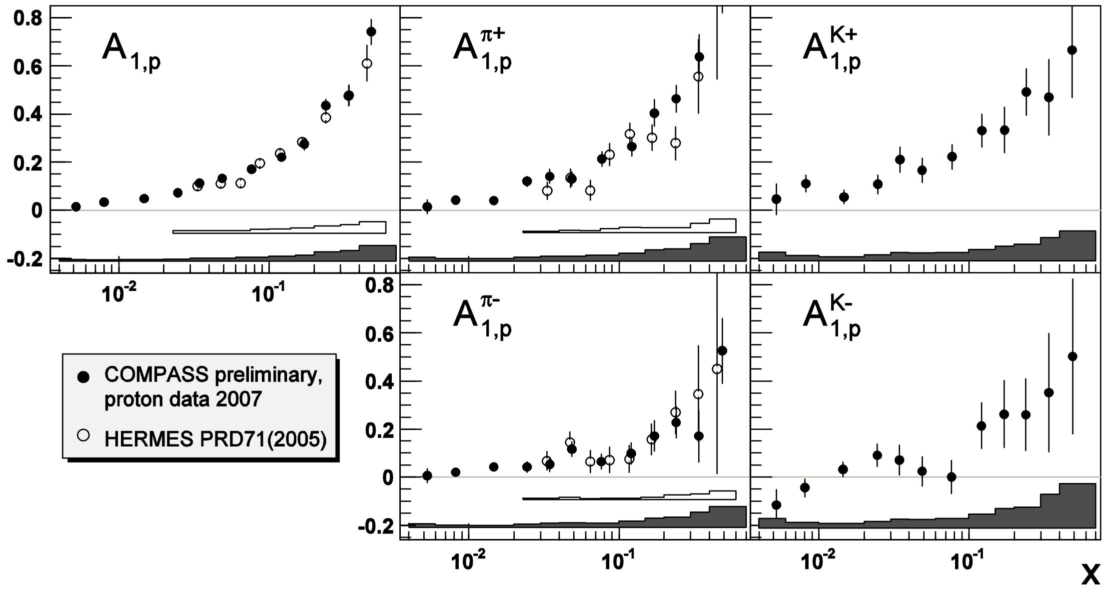
- LS estimation: uniqueness, unbiasedness and minimum variance of the solution

$$\chi^2 = (\vec{A} - \mathsf{B}\Delta\vec{q})^T \,\mathsf{Cov}_A^{-1}(\vec{A} - \mathsf{B}\Delta\vec{q}).$$

Proton and deuteron asymmetries A_1

- **Kinematic**
  $Q^2 > 1\ \mathrm{GeV}^2$
  $0.1 < y < 0.9$
  $0.004 < x < 0.7$





- **Asymmetries of identified hadrons were measured only by COMPASS and HERMES**

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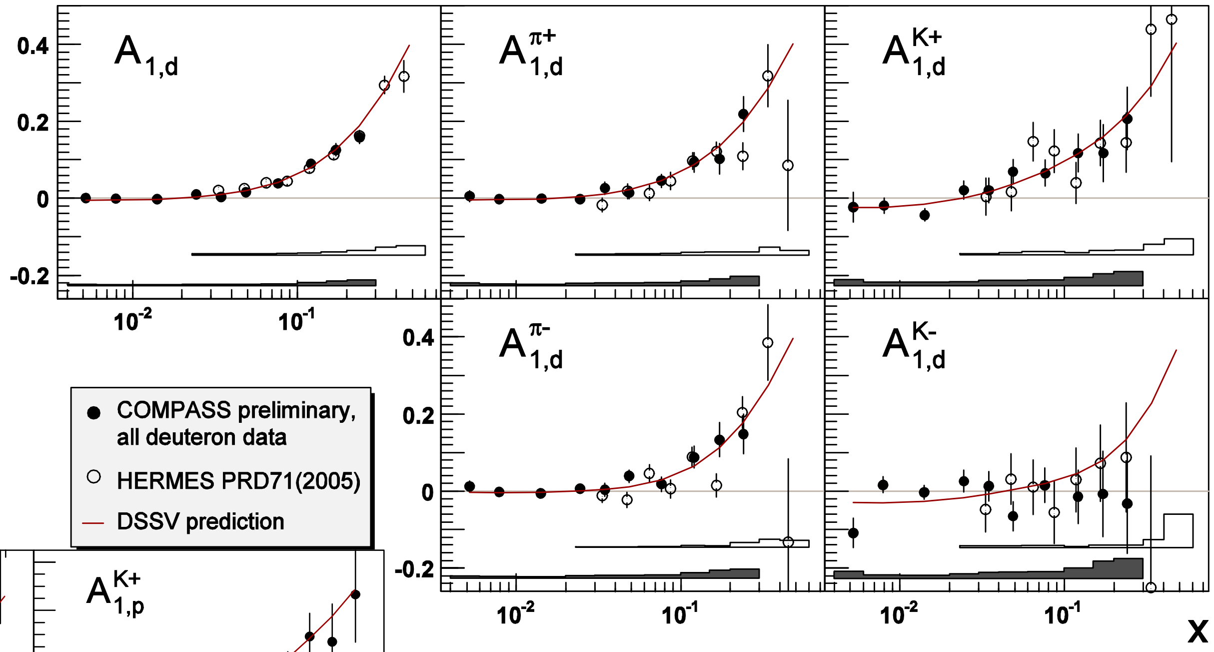

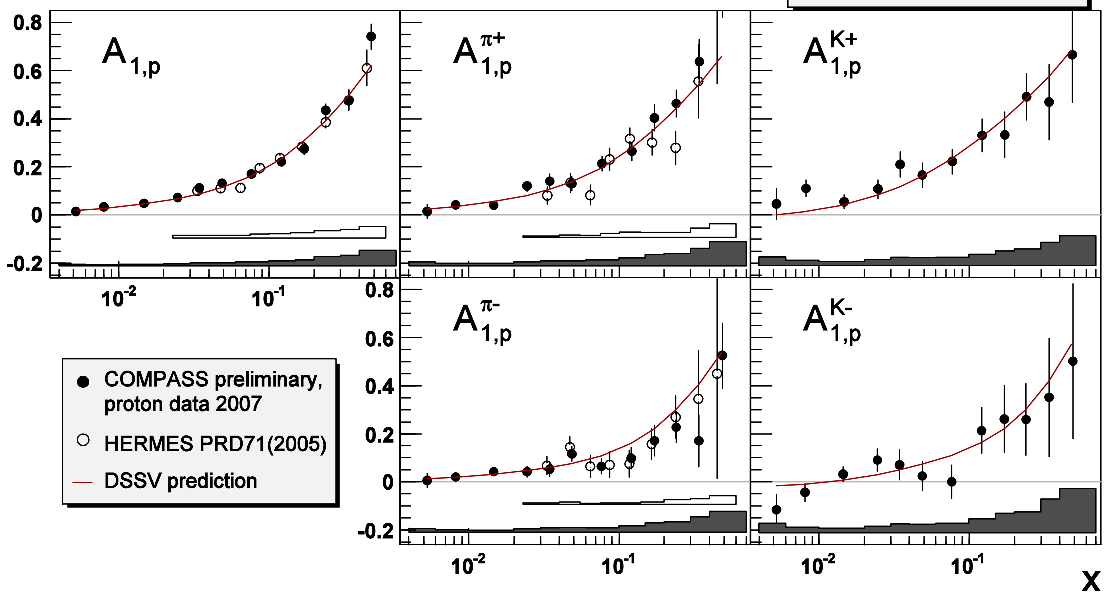

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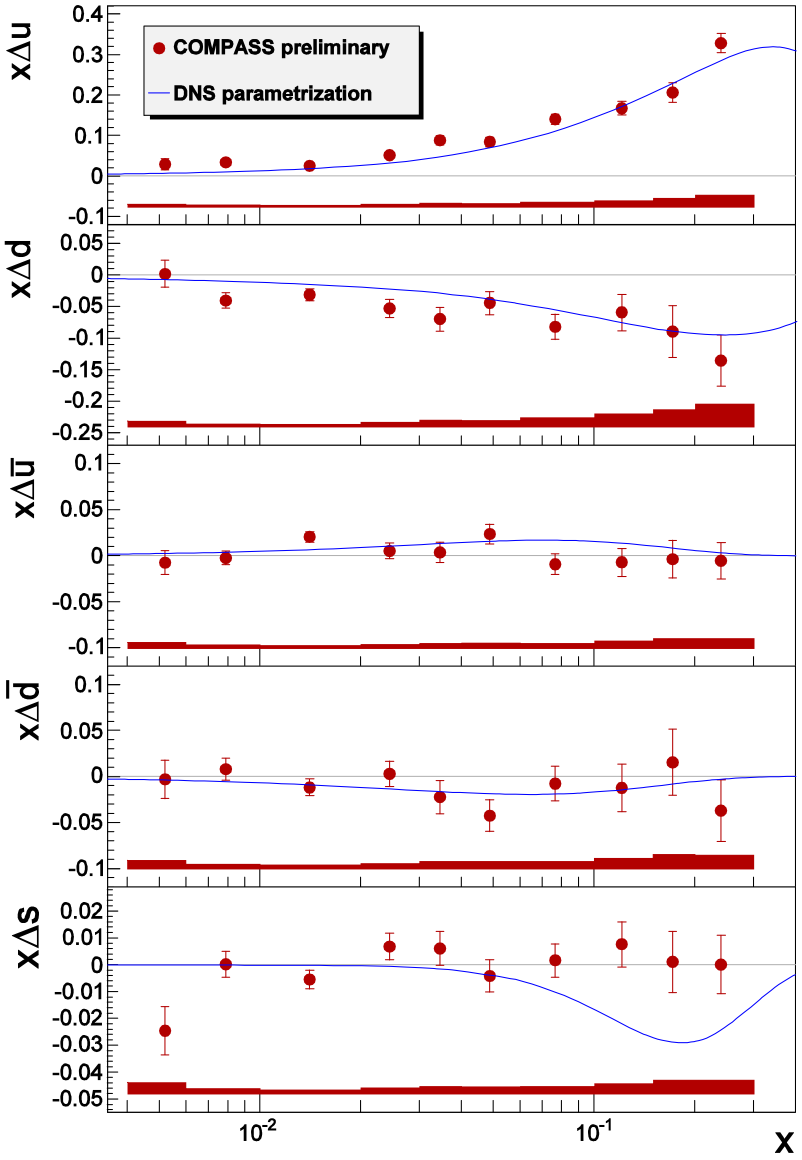


- MRST04 (for unpol.PDFs) and DSS (for FFs);
- Good agreement with global fit exept Δs

Statistic ($\cdot 10^6$)

	Proton	deuteron
Incl	92,5	135,1
π^+	13,3	22,8
π^-	11,8	20,5
K^+	3,9	4,8
K^-	2,6	3,3

- Asymmetry between the unpolarized $\bar{u}$ and $\bar{d}$ distrib. is well established experimental fact

Experiment	$\langle Q^2 \rangle$ [GeV^2]	$\int_0^1 [\bar{u} - \bar{d}] dx$	Reference
NMC/DIS	4	0.147 ± 0.039	M.Arneodo et al., Phys.Rev.D55(1994)R1
HERMES/SIDIS	2.3	0.16 ± 0.03	K.Ackerstaff et al., Phys.Rev.Lett.81(1998)5519
FNAL E866/DY	54	0.118 ± 0.012	R.S.Towell et al., Phys.Rev.D64(2001)052002

- Many non-perturbative models predicts a sizable asymmetry of the helicity densities

	Model	$\int_0^1 [\Delta\bar{u} - \Delta\bar{d}] dx$	Reference
Meson cloud	π-meson	0	A.W.Thomas, Phys.Lett.B126(1983)97
	ρ-meson	$\simeq$ -0.0007 to -0.027	R.J.Fries,A.Schafer, Phys.Lett.B443(1998)40
	π-ρ interf.	$=-6\int_0^1 g^p(x)dx \simeq -0.7$	K.G.Boreskov, A.B.Kaidalov, Eur.Phys.J.C10(1999)143
	ρ and π-ρ interf.	$\simeq$ -0.004 to -0.033	F.G.Cao, A.I.Signal, Eur.Phys.J.C21(2001)105
	ρ-meson	< 0	S.Kumano, M.Miyama, Phys.Rev.D65(2002)034012
	π-σ interf.	$\simeq 0.12$	R.J.Fries,A.Schafer,C.Weiss, hep-ph/0204060
Pauli-blocking	bag model	$\simeq 0.09$	F.G.Cao, A.I.Signal, Eur.Phys.J.C21(2001)105
	ansatz	$\simeq 0.3$	M.Gluck at al., Phys.Rev.D63(2001)094005
		$= \frac{5}{3}\int_0^1 [\bar{d} - \bar{u}] dx \simeq 0.2$	F.M.Steffens, Phys.Lett.B541(2002)346
Chiral-quark soliton		0.31	B.Dressler et al., hep-ph/9809487
		$\simeq \int_0^1 2x^{0.12} [\bar{d} - \bar{u}] dx$	M.Wakamatsu, T.Watabe, Phys.Rev.D62(2000)017506
Instanton		$\frac{5}{3}\int_0^1 [\bar{d} - \bar{u}] dx \simeq 0.2$	Dorokhov, hep-ph/0112332
Statistical		$\simeq \int_0^1 [\bar{d} - \bar{u}] dx \simeq 0.12$	C.Bourrely,J.Soffer,F.Buccella, Eur.Ph.J.C23(2002)487
		$> \int_0^1 [\bar{d} - \bar{u}] dx > 0.12$	R.S.Bhalerao, Phys.Rev.C63(2001)025208

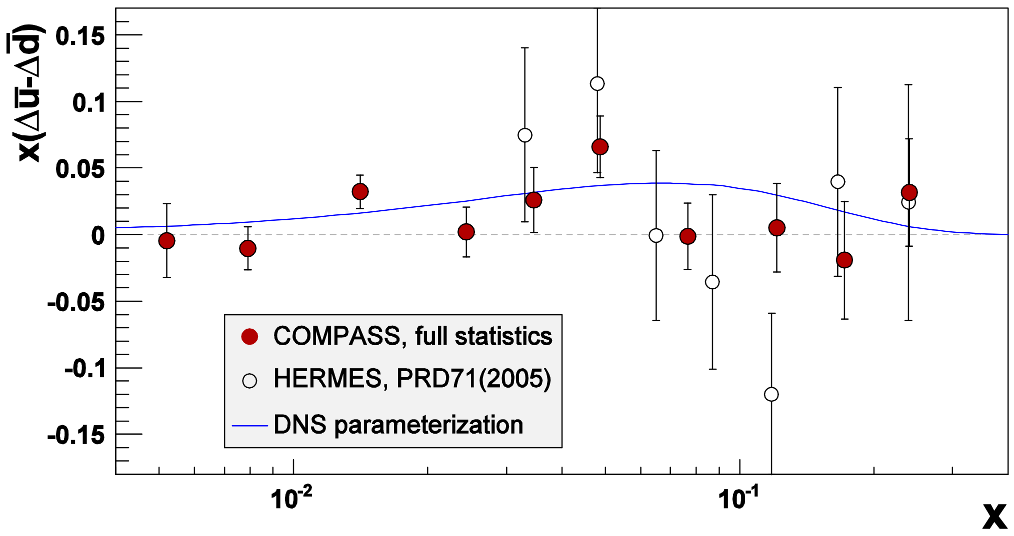
taken from J.C.Peng "Flavor Structure of the nucleon sea", hep-ph/0301053

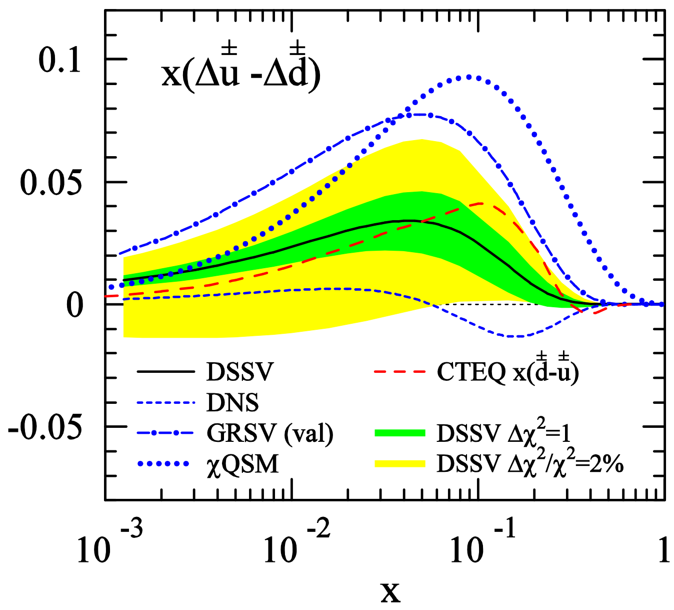
Flavor symmetry breaking of the light sea

Presently $\Delta\bar{u} - \Delta\bar{d}$ is accessible only via SIDIS processes

HERMES : $\int_{0.023}^{0.3} (\Delta\bar{u} - \Delta\bar{d}) dx = 0.048 \pm 0.057(stat) \pm 0.028(syst)$

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





Conclusion

- All COMPASS data with deuteron(2002-2006) and proton(2007) targets have been processed and analyzed;
- g_1^{NS} was obtained from combined analysis of proton and deuteron data

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

  confirm the validity of Bjorken sum rule;
- Full flavor separation analysis with LO QCD fit was done:
    - Good agreement of non-strange PDFs with results of previous QCD fits;
    - Shape of $\Delta s(x)$ disagree significantly with previous fits;
    - Flavor asymmetry of the light sea quarks is observed.

Spin budget of the nucleon

- Contribution of quarks to the nucleon spin $\Delta\Sigma$ is well fixed by inclusive data $\Delta\Sigma = 0.30 \pm 0.01 \pm 0.02$ (Q^2=3 GeV^2);
- QCD fit provides indirect way to determine ΔG: $|\Delta G| < 0.2 \div 0.3$

Spires

The year-by-year statistics (in millions)

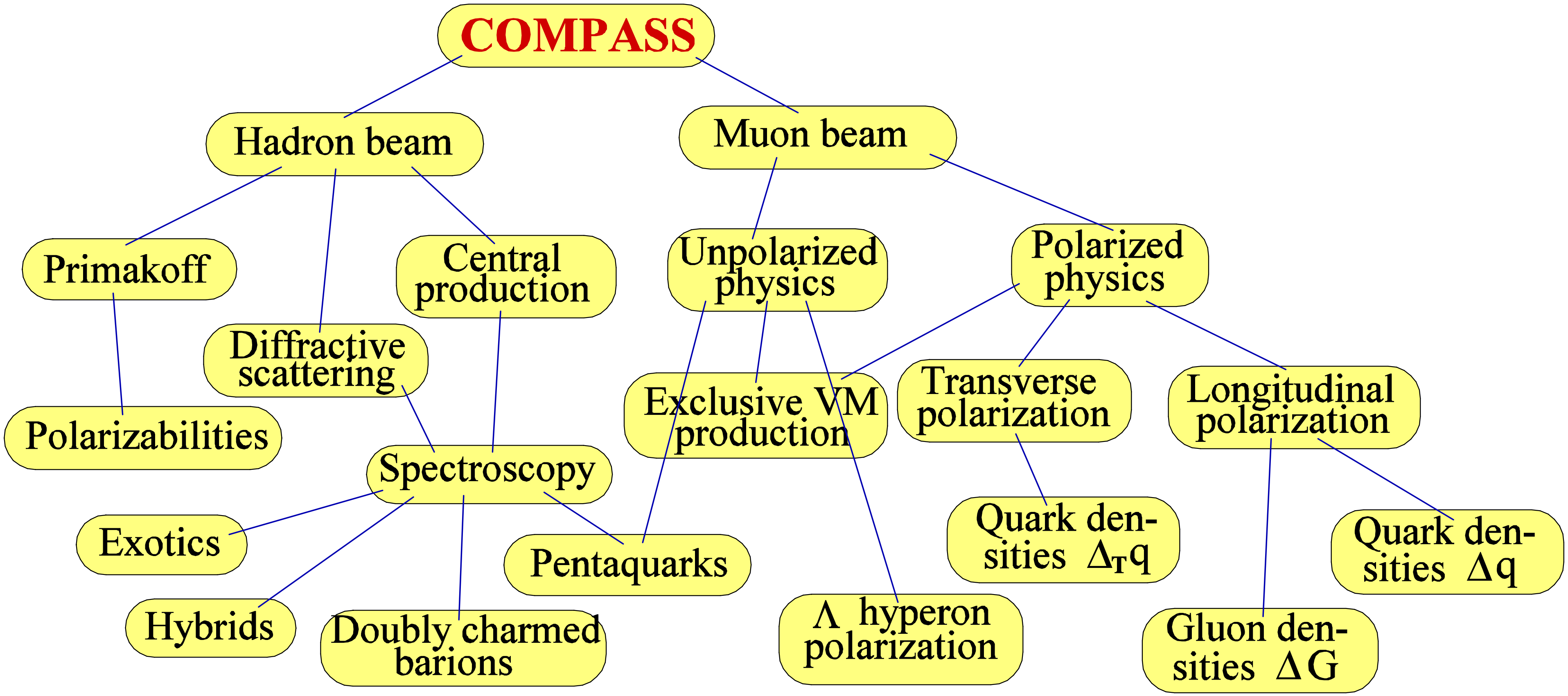
	Proton target	Deuteron target				
	2007	2002	2003	2004	2006	Total
Incl.	92.5	10.3	31.4	58.3	35.1	135.1
π^+	13.3	1.7	5.4	9.8	6.0	22.8
π^-	11.8	1.5	4.8	8.8	5.4	20.5
K^+	3.9	0.2	1.0	1.9	1.7	4.8
K^-	2.6	0.2	0.7	1.3	1.1	3.3

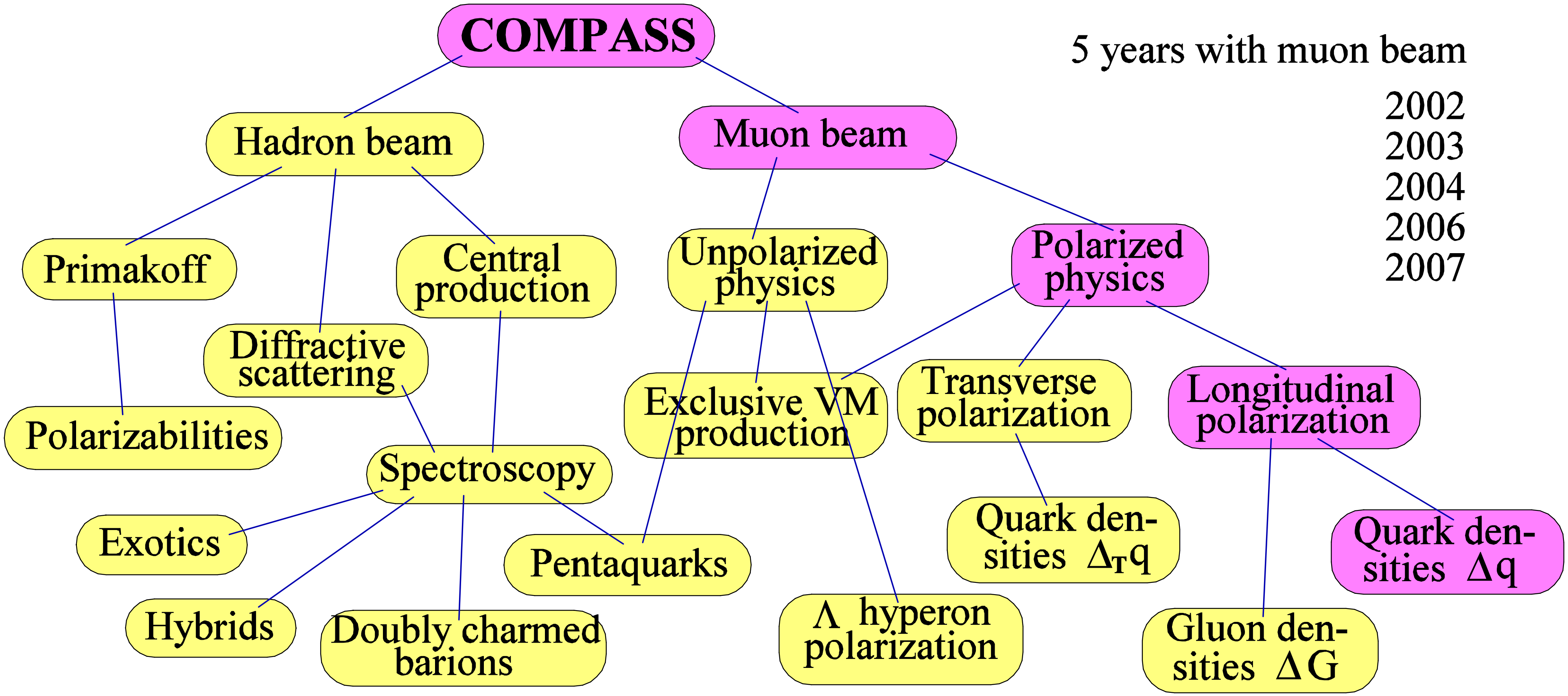
- Statistics of proton and deuteron data looks comparable. However:

	$\bar{f}$	$\bar{P}_t$	$\bar{f} \times \bar{P}_t$
NH_3	0.14	0.87	0.12
^{6}LiD	0.37	0.5	0.19

- Statistical error of the proton data is a factor 2 larger

$$\frac{\delta A_d}{\delta A_p} = \frac{0.12}{0.19}\sqrt{\frac{92.5}{135.1}} = 0.52$$


COMPASS
Hadron beam
Muon beam
Primakoff
Central production
Unpolarized physics
Polarized physics
Diffractive scattering
Polarizabilities
Exclusive VM production
Transverse polarization
Longitudinal polarization
Spectroscopy
Exotics
Pentaquarks
Quark densities $\Delta_T q$
Quark densities Δq
Hybrids
Doubly charmed barions
Λ hyperon polarization
Gluon densities ΔG



5 years with muon beam

2002
2003
2004
2006
2007

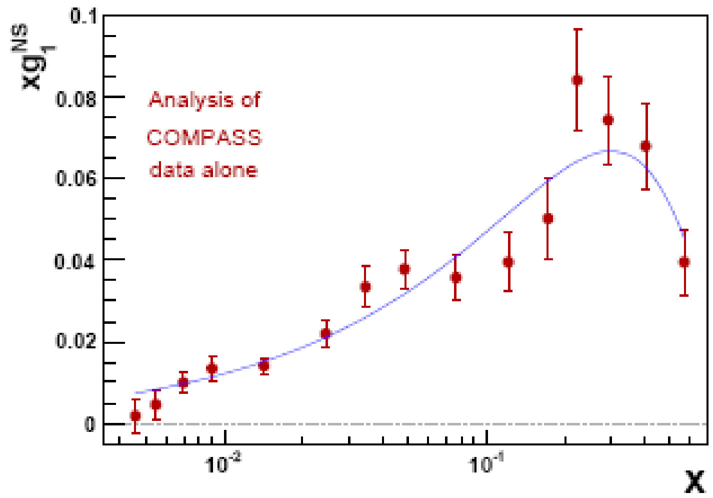
- Evolution of non-singlet distribution is decoupled from $\Delta\Sigma$ and ΔG

$$\frac{d}{dt}\Delta q^{NS} = \frac{\alpha_s(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q^{NS}$$

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

- Parametrization of $\Delta q_3(x)$: $\Delta q_3(x) = \left|\frac{g_A}{g_V}\right| x^\alpha (1-x)^\beta$

g_A/g_V	α	β
1.30 ± 0.07	-0.24 ± 0.07	2.3 ± 0.4

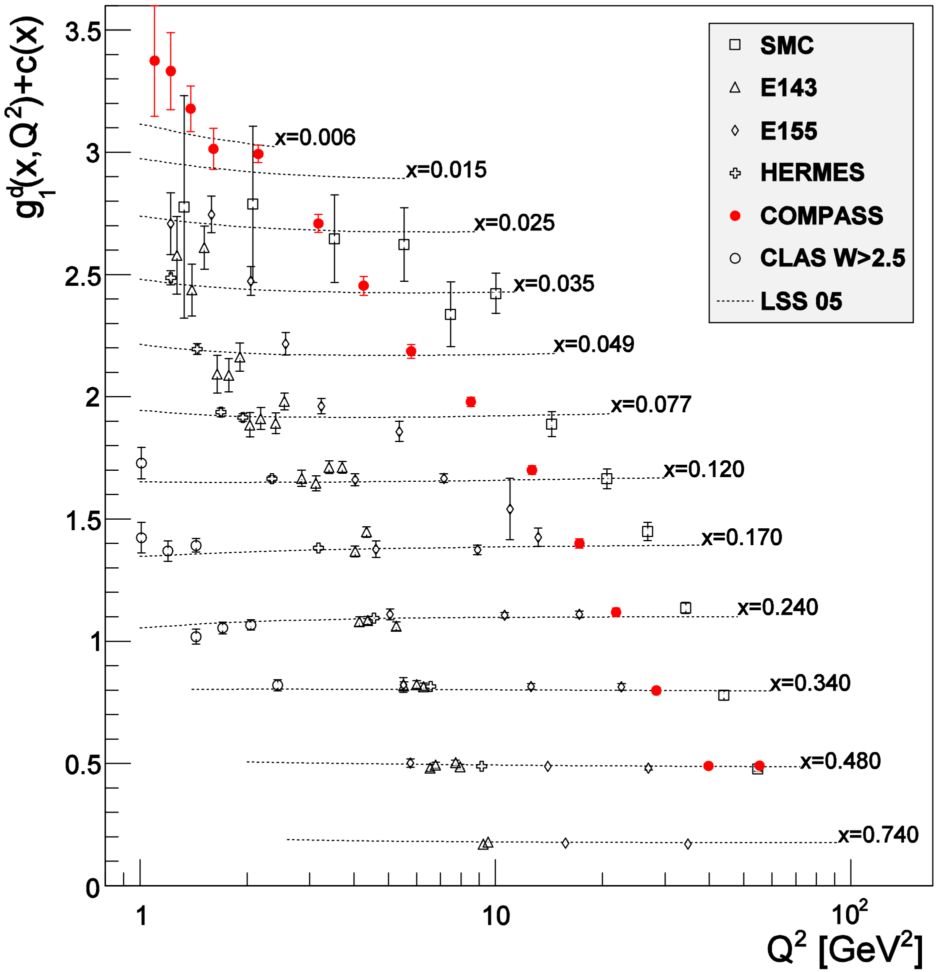


Systematic error

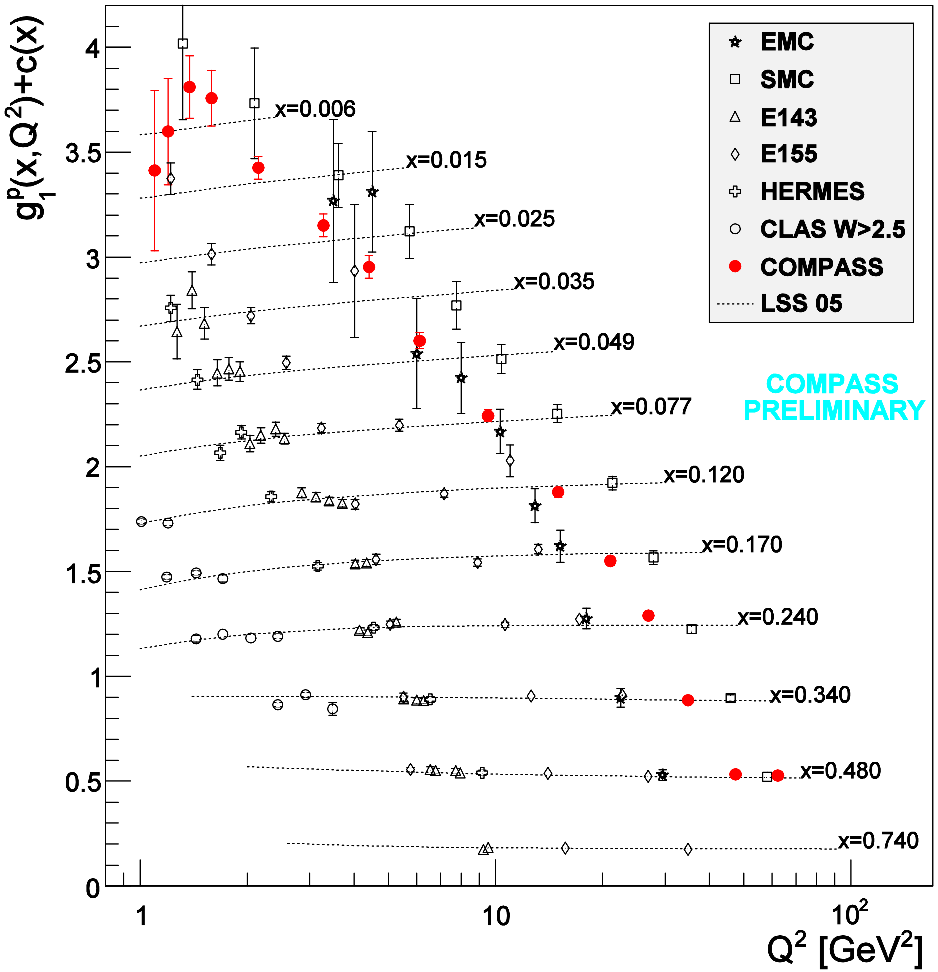
- $\delta(P_b)$ is the dominant error: $5\% \Rightarrow \pm 0.065$
- ^{6}LiD: 7% due to f and P_t: $\Rightarrow \pm 0.041$
- NH_3: 3% due to f and P_t: $\Rightarrow \pm 0.056$

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

$$\boxed{g_A/g_V^{PDG} = 1.269 \pm 0.003}$$



$g_1^d(x,Q^2)+c(x)$
x=0.006
x=0.015
x=0.025
x=0.035
x=0.049
x=0.077
x=0.120
x=0.170
x=0.240
x=0.340
x=0.480
x=0.740
SMC
E143
E155
HERMES
COMPASS
CLAS W>2.5
LSS 05
Q^2 [GeV^2]



$g_1^p(x,Q^2)+c(x)$
x=0.006
x=0.015
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x=0.049
x=0.077
x=0.120
x=0.170
x=0.240
x=0.340
x=0.480
x=0.740
EMC
SMC
E143
E155
HERMES
CLAS W>2.5
COMPASS
LSS 05
COMPASS PRELIMINARY
Q^2 [GeV^2]