Measurement of the longitudinal spin structure of proton by COMPASS

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on behalf of the COMPASS collaboration

August 31, 2009

1. COMPASS experiment
2. DIS and SIDIS asymmetries with deuteron (2002-2006) proton (2007) data
3. Non-singlet structure function g_1^{NS} and Bjorken sum rule
4. Full flavor separation analysis with LO QCD fit

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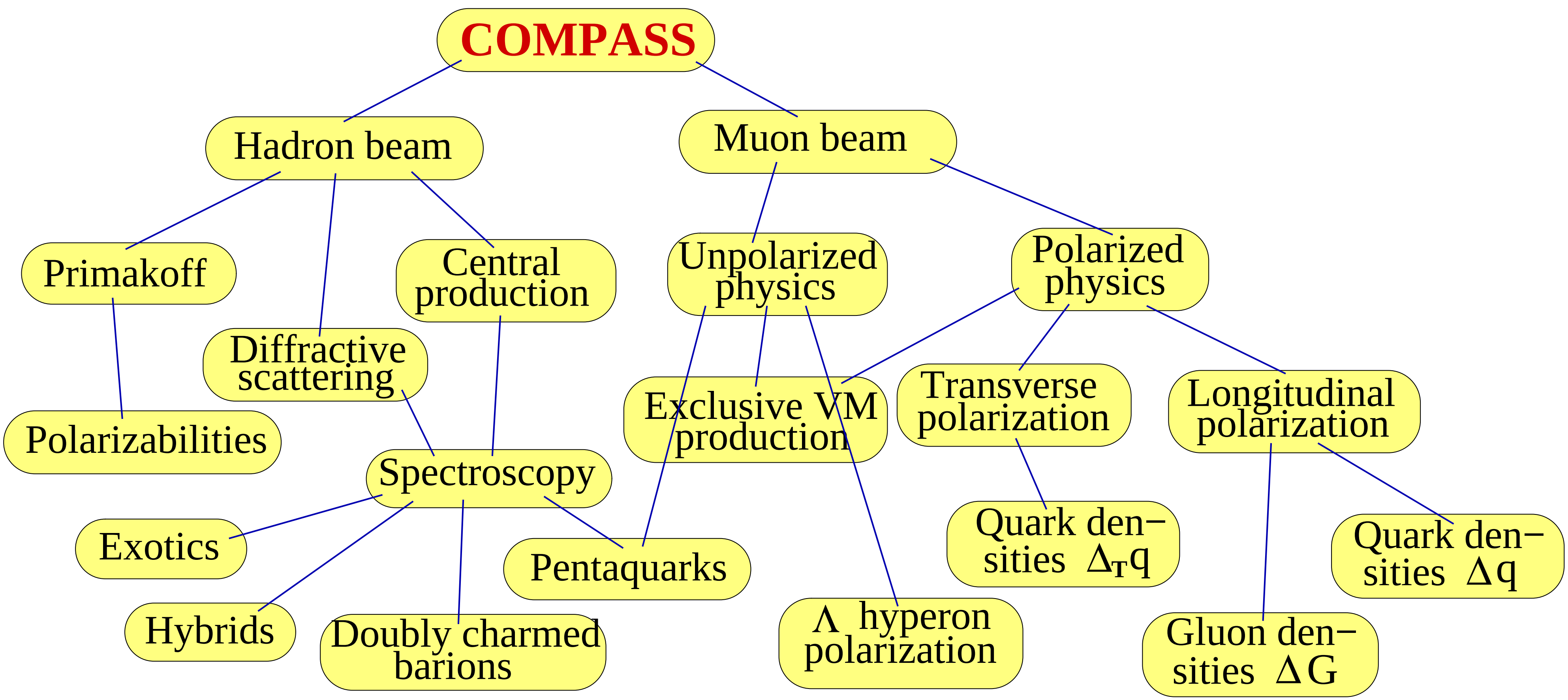
COMPASS experiment

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

More than 220 physicists from 30 institutes



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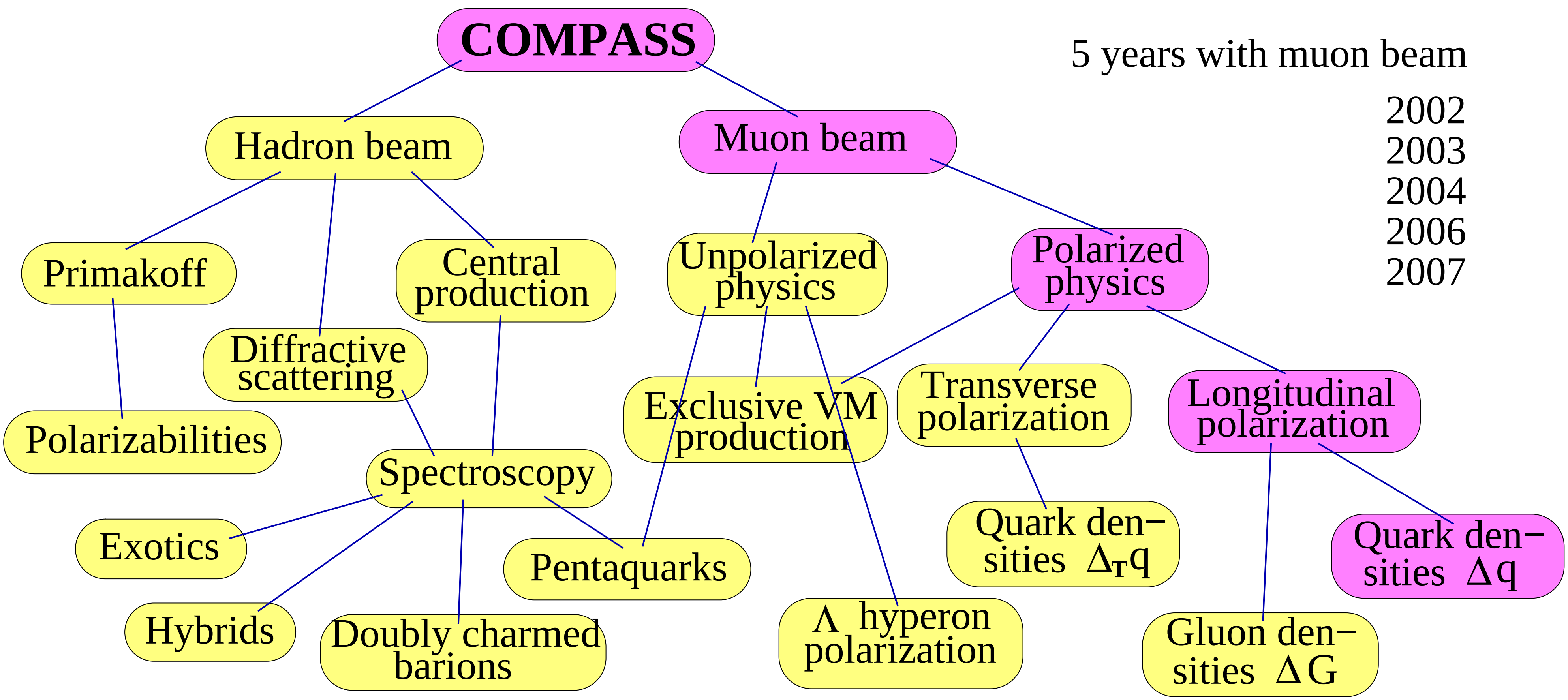
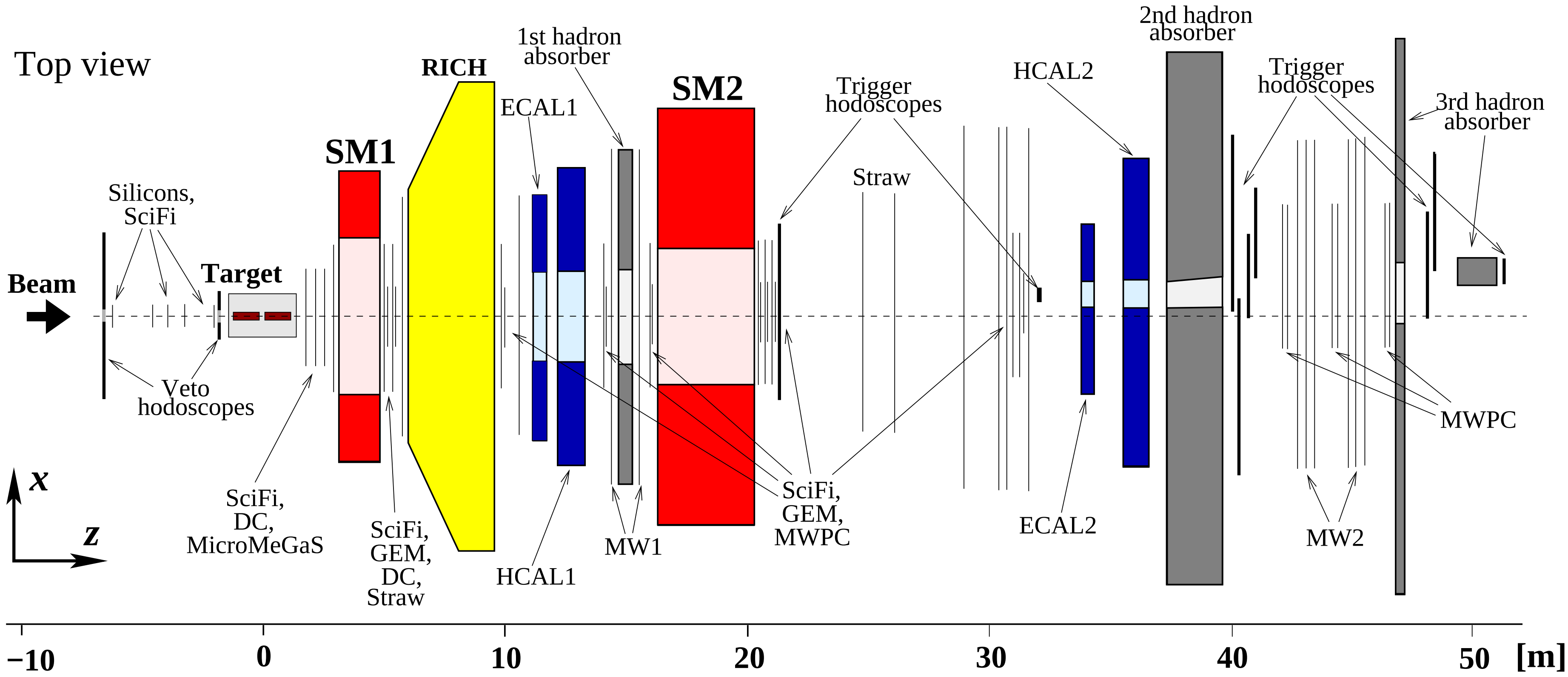


5 years with muon beam

2002
2003
2004
2006
2007

Experimental setup



- Polarized beam μ^+ (-80%), E_b=160 GeV
- 2(3) cells polarized target ^{6}LiD (50%) and NH_3 (90%)
- Two stages spectrometer
- Tracking detectors of different types
- Identification: HCALs, ECALs, RICH, muon walls

Double-spin asymmetries from DIS and SIDIS reactions

Introduction

- Naive view: 3 valence quarks with spin 1/2 $\Rightarrow$ nucleon spin is 1/2.
- Decomposition of nucleon spin:

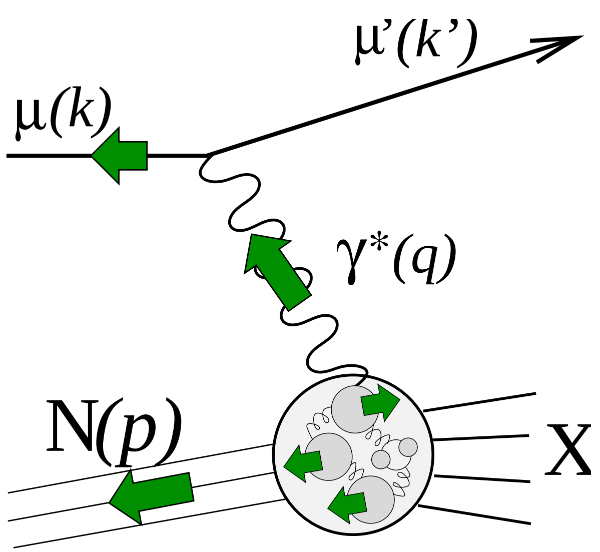
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_G), \quad \text{Jaffe \& Manohar}$$
$$\frac{1}{2} = \quad (\frac{1}{2}\Delta\Sigma + L_q) + J_G, \quad \text{Ji}$$
$$\frac{1}{2} = \quad \ldots \quad \text{other decompositions}$$

- Non-relativistic $SU(6) = SU_f(3) \times SU_S(2)$ quark model
  - ◇ classification of $J^P = \frac{1}{2}^+$ octet of barions
  - ◇ successful to predict magnetic moments of barions
  - ◇ $\Delta\Sigma = 0.58 \pm 0.03$, where $\Delta s \equiv 0$
- Relativistic models of constituent quarks ($m_{u,d} \approx 330\,\text{MeV}$)

$$\Delta\Sigma \approx 0.6 \qquad L_q \approx 0.4$$

- Measurement of EMC (1988): $\Delta\Sigma = 0.12 \pm 0.09 \pm 0.04 \Rightarrow$ "spin crisis"
- Recent evaluation from COMPASS (2007): $\Delta\Sigma = 0.30 \pm 0.01 \pm 0.02$

Deep-Inelastic Scattering (1)

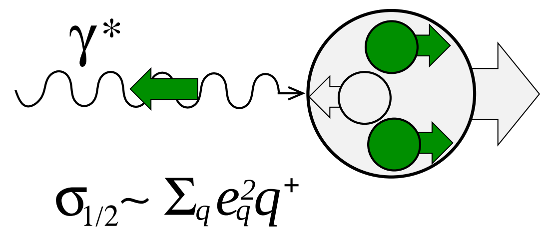


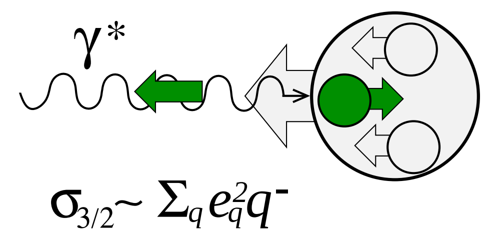
$k = (E, \vec{k})$	4-momentum of beam μ
$k' = (E', \vec{k}')$	4-momentum of scattered μ
$p = (M, \vec{0})$	4-momentum of nucleon
$q = k - k'$	4-momentum of γ^*
$-Q^2 = q^2$	Virtuality of γ^*
$\nu = E - E'$	Energy of γ^* in lab. system
$y = \nu / E$	Fraction of energy of the beam μ taken by γ^*
$x = \dfrac{Q^2}{2M\nu}$	Bjorken scaling variable

Quark-parton model

- Quark densities:

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





- Double-spin asymmetry: $A^{\gamma N} \equiv A_1 = \dfrac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \dfrac{\sum_q e_q^2 \Delta q}{\sum_q e_q^2 q}$

Deep-Inelastic Scattering (2)

- DIS cross-section in approximation of one photon exchange:

$$\sigma = \bar{\sigma} \pm \Delta\sigma$$

- Structure functions $F_{1,2}$ and $g_{1,2}$

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

- Double-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

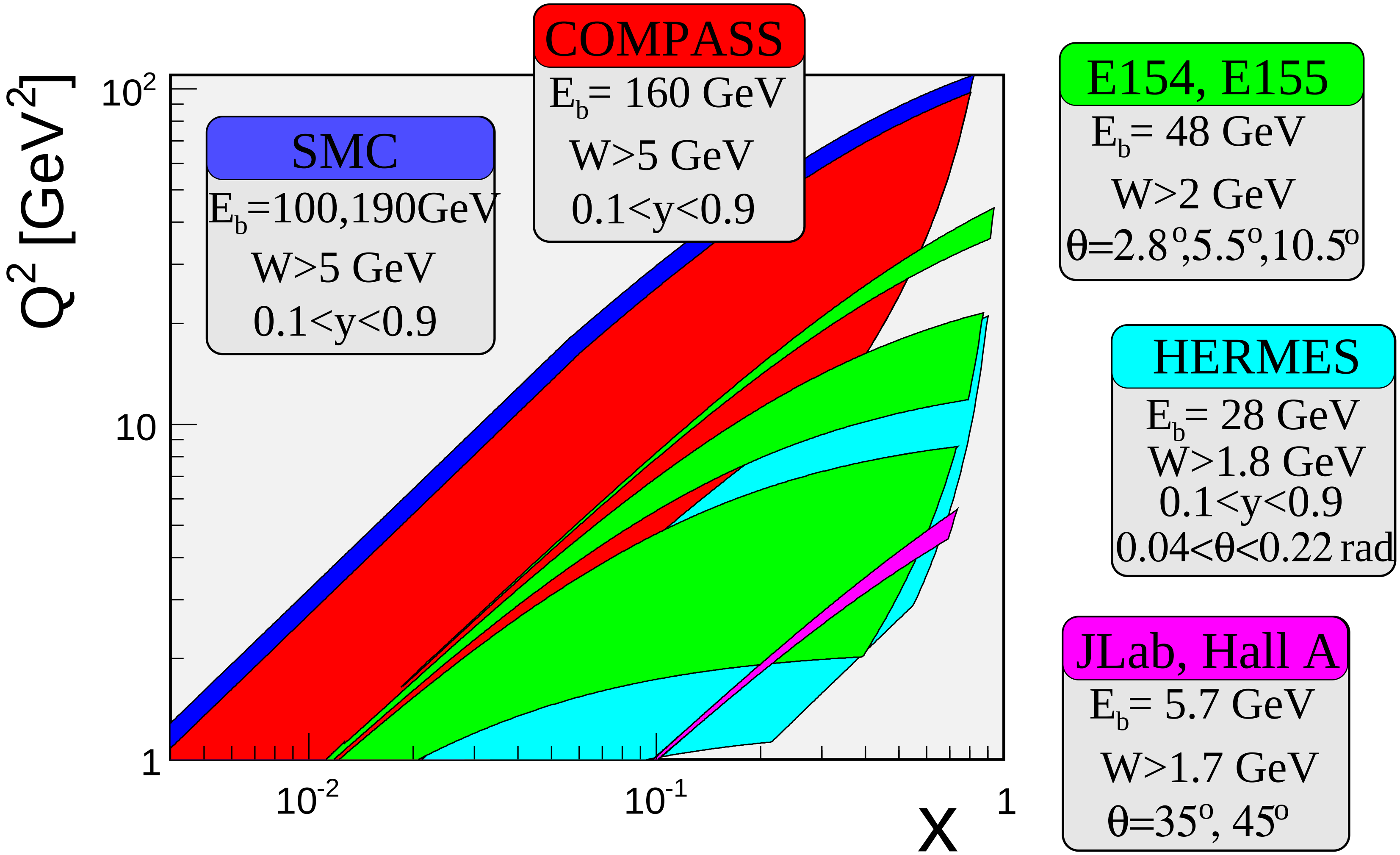
- Relation of structure functions to parton densities in QPM and/or LO QCD:

$$\begin{aligned} F_1 &= \tfrac{1}{2} \textstyle\sum_q e_q^2 \, (q + \bar{q}) \\ g_1 &= \tfrac{1}{2} \textstyle\sum_q e_q^2 \, (\Delta q + \Delta\bar{q}) \end{aligned}$$

- Spin-independent $F_{1,2}$ are well measured in a wide range of (x, Q^2)
- Objective of study:

$$g_1 \simeq A_1 \cdot F_1$$

Kinematic acceptance of typical pDIS experiments

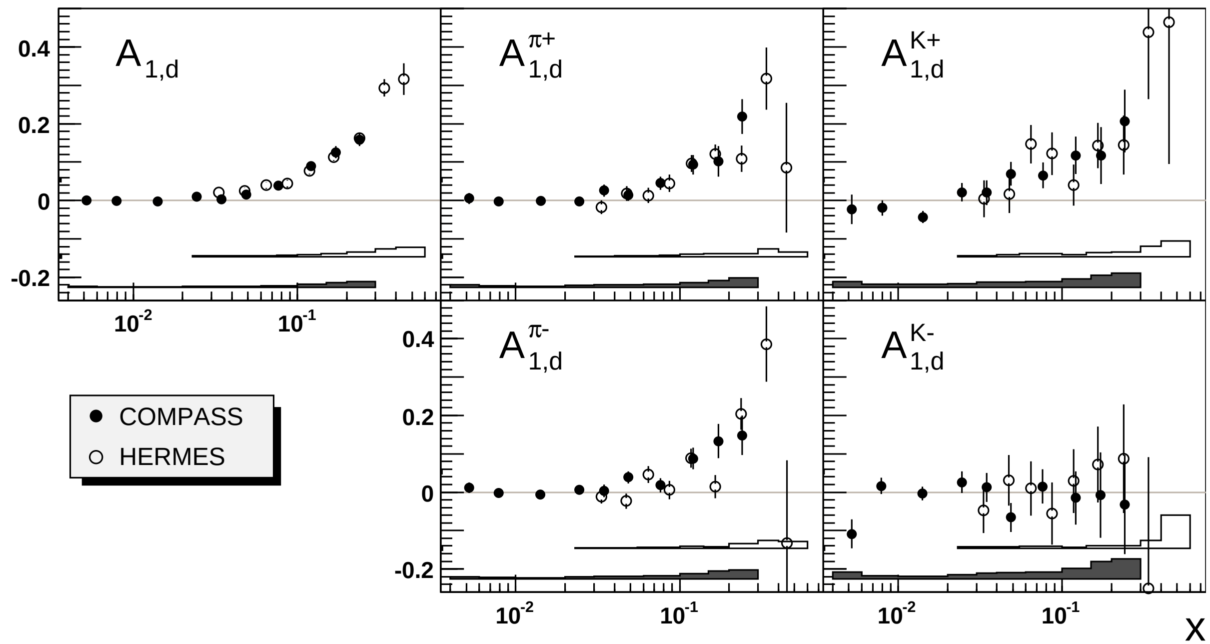


Advantage of COMPASS: access to low x!

Proton and deuteron asymmetries of COMPASS

- Kinematic domain:

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



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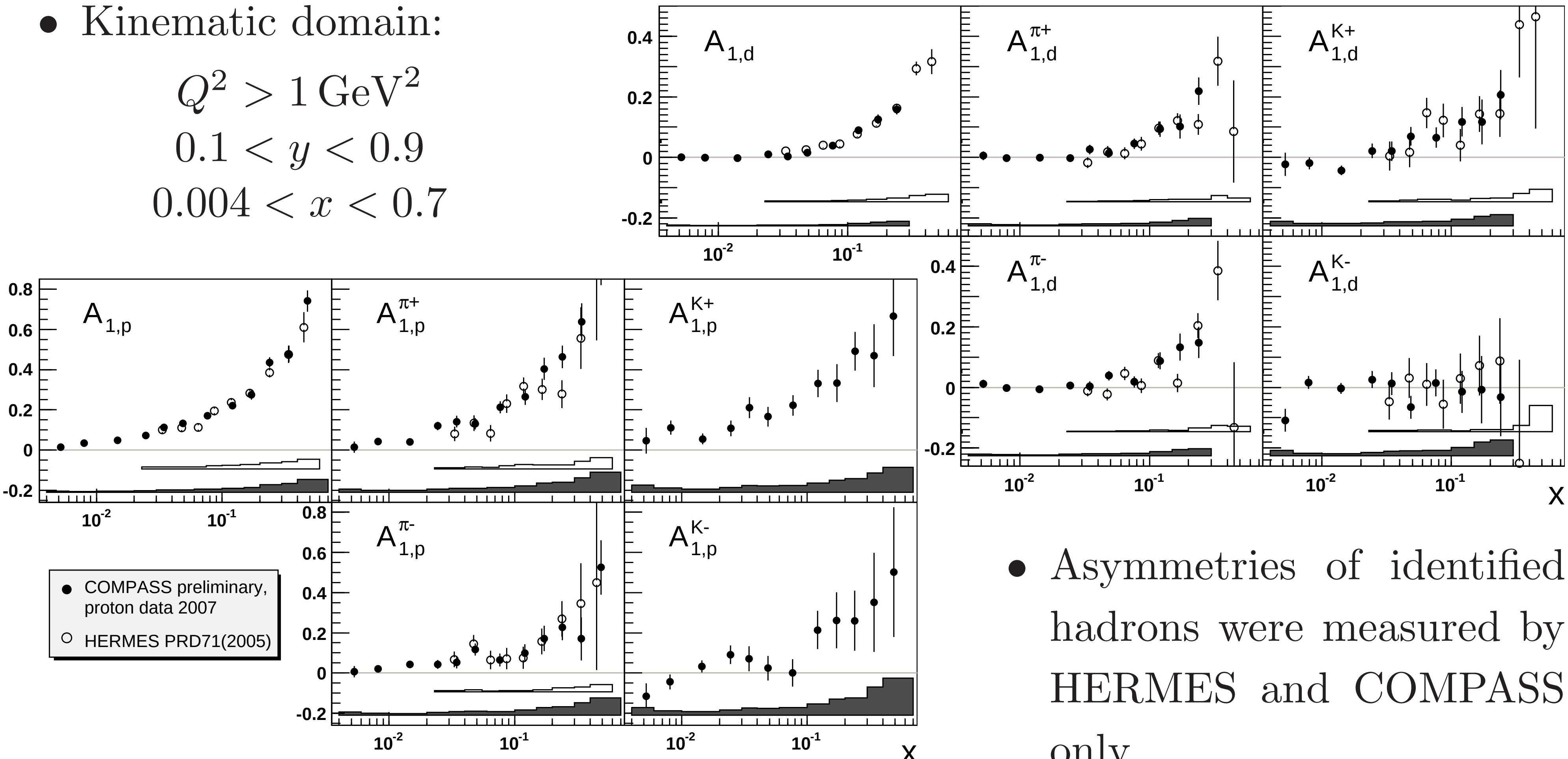
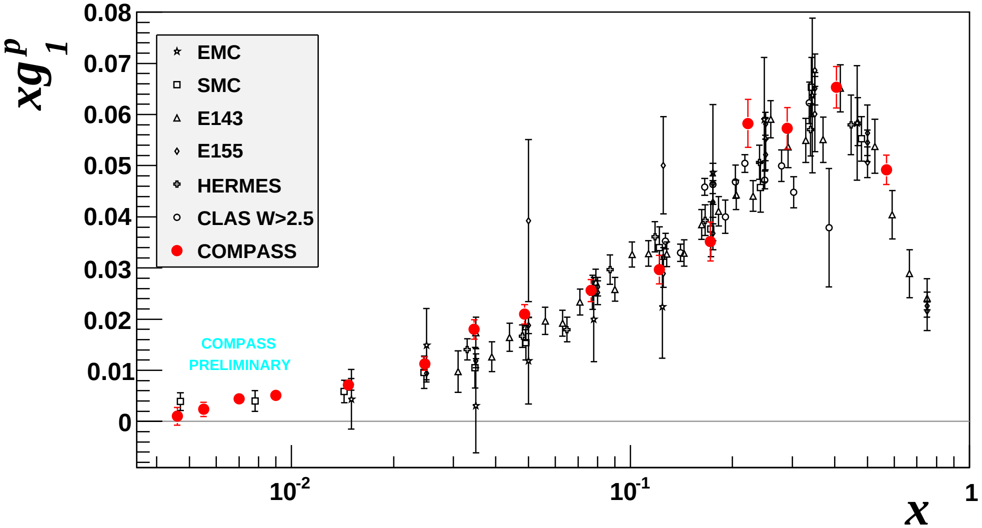
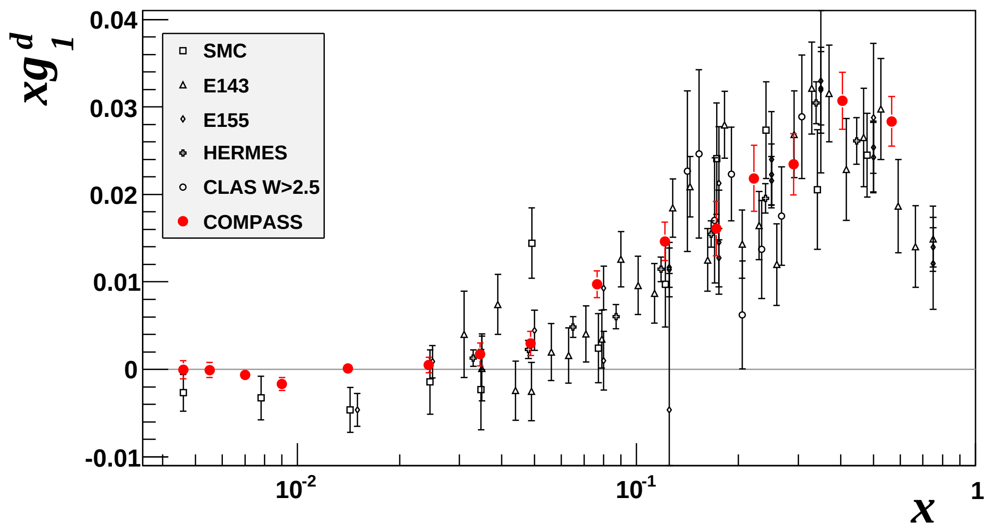


- Asymmetries of identified hadrons were measured by HERMES and COMPASS only

Non-singlet structure function g_1^{NS} and Bjorken sum rule

Structure functions g_1^p and g_1^d





- 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:

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

Fit of COMPASS data alone

- 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

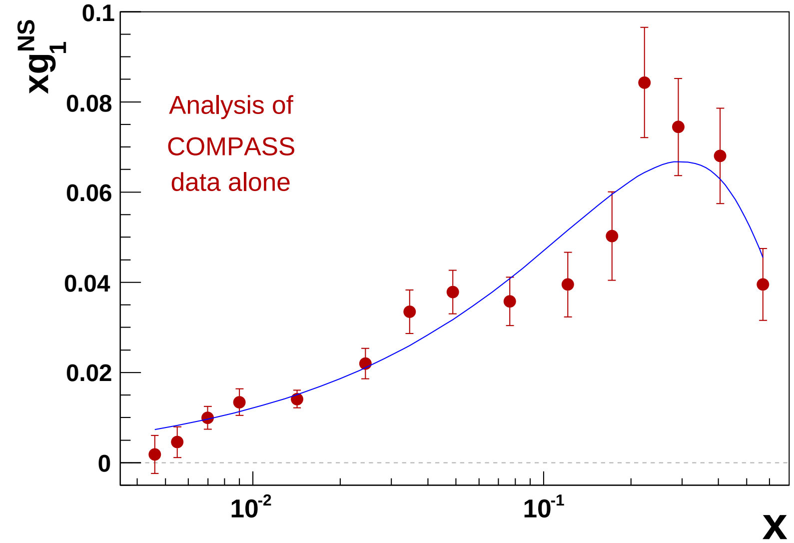
Systematic error

◇ $\delta(P_b)$ is the dominant error: $5\% \Rightarrow \pm 0.065$

◇ ^{6}LiD: 7% due to f and P_t: $\Rightarrow \pm 0.041$

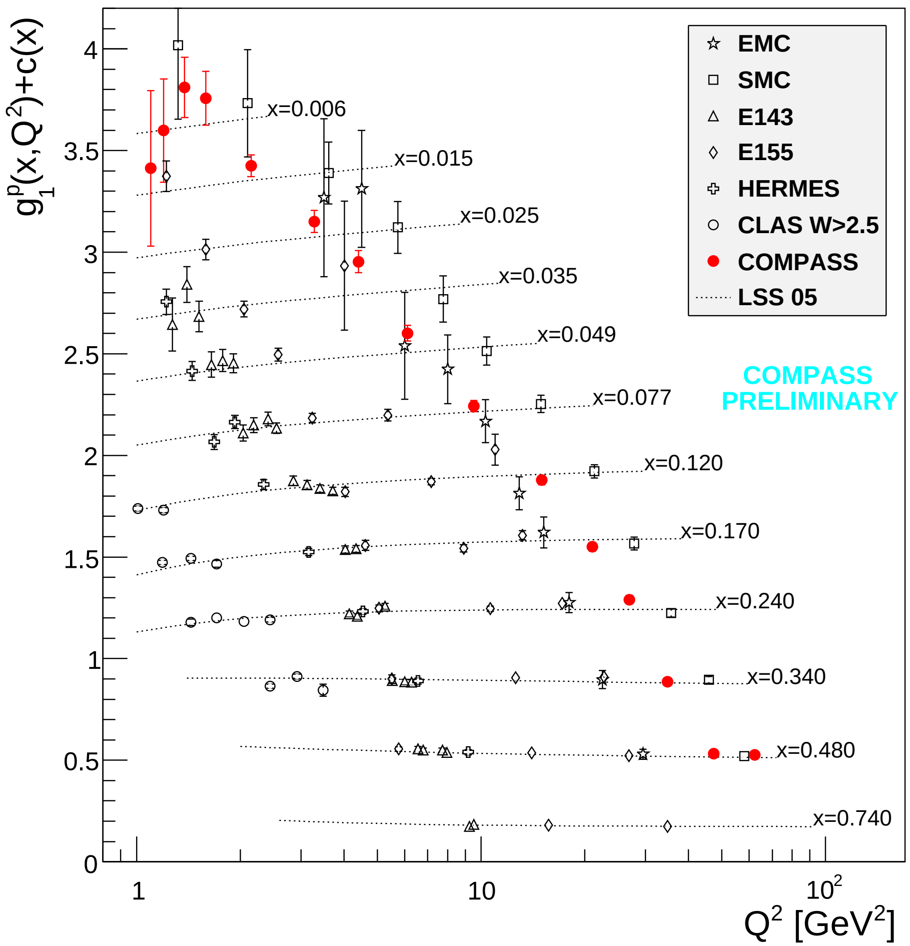
◇ NH_3: 3% due to f and P_t: $\Rightarrow \pm 0.056$

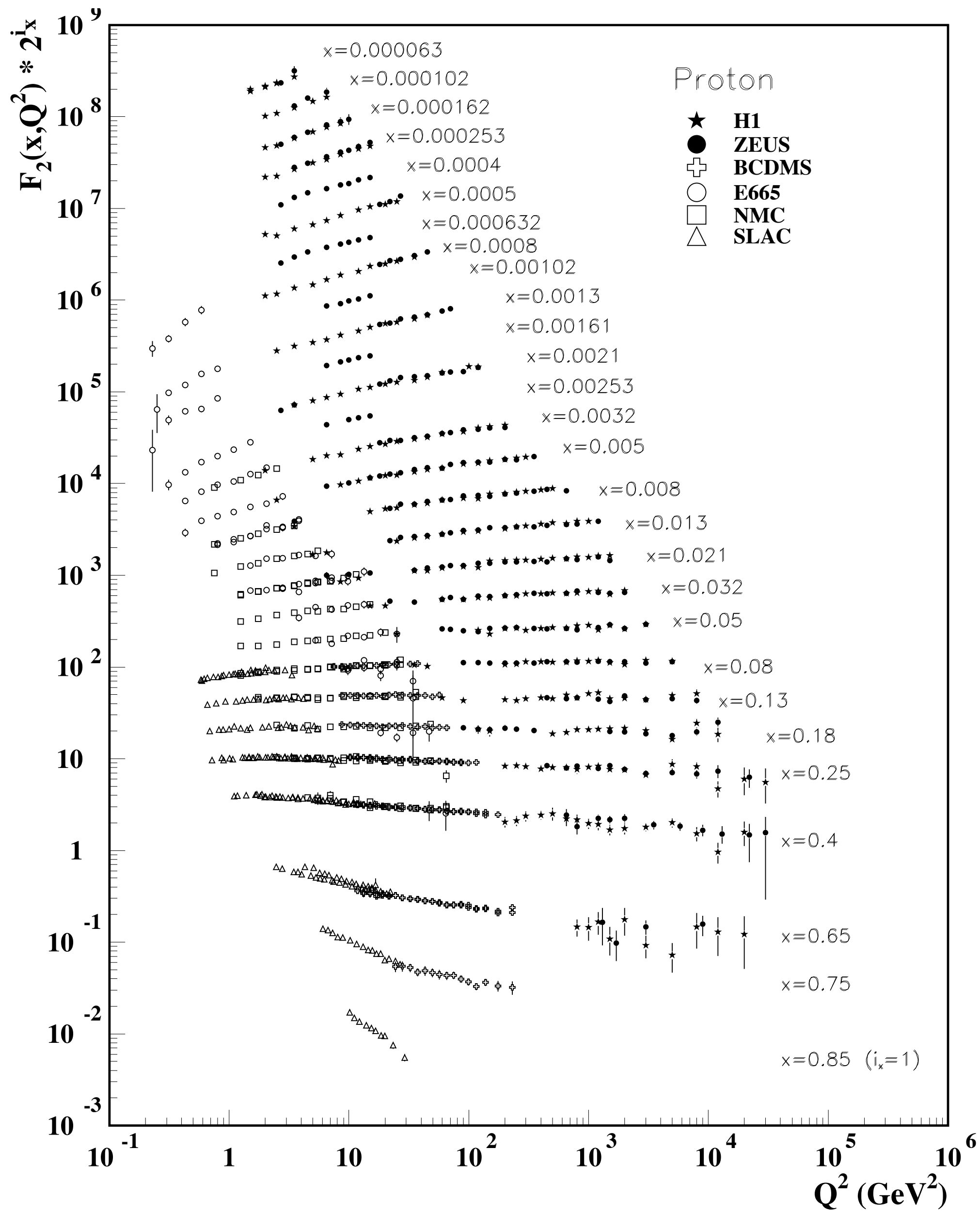
$$g_A/g_V = 1.30 \pm 0.07(stat) \pm 0.10(syst)$$



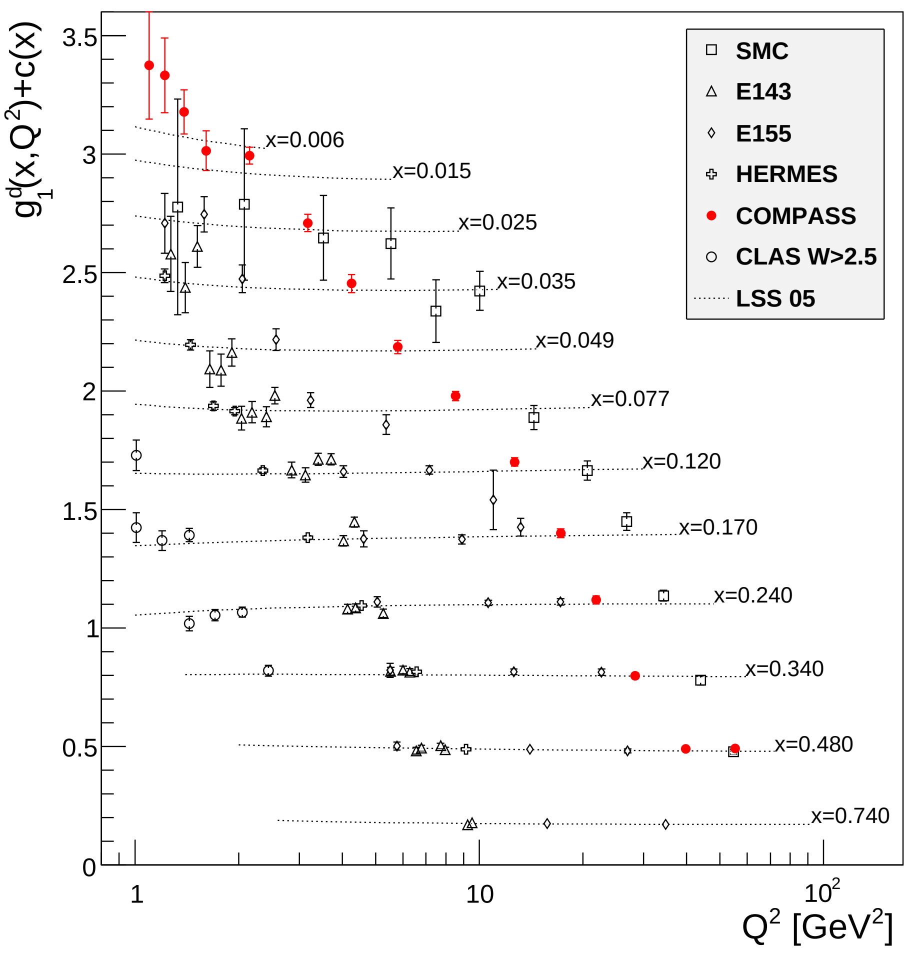
$$g_A/g_V{}^{PDG} = 1.269 \pm 0.003$$

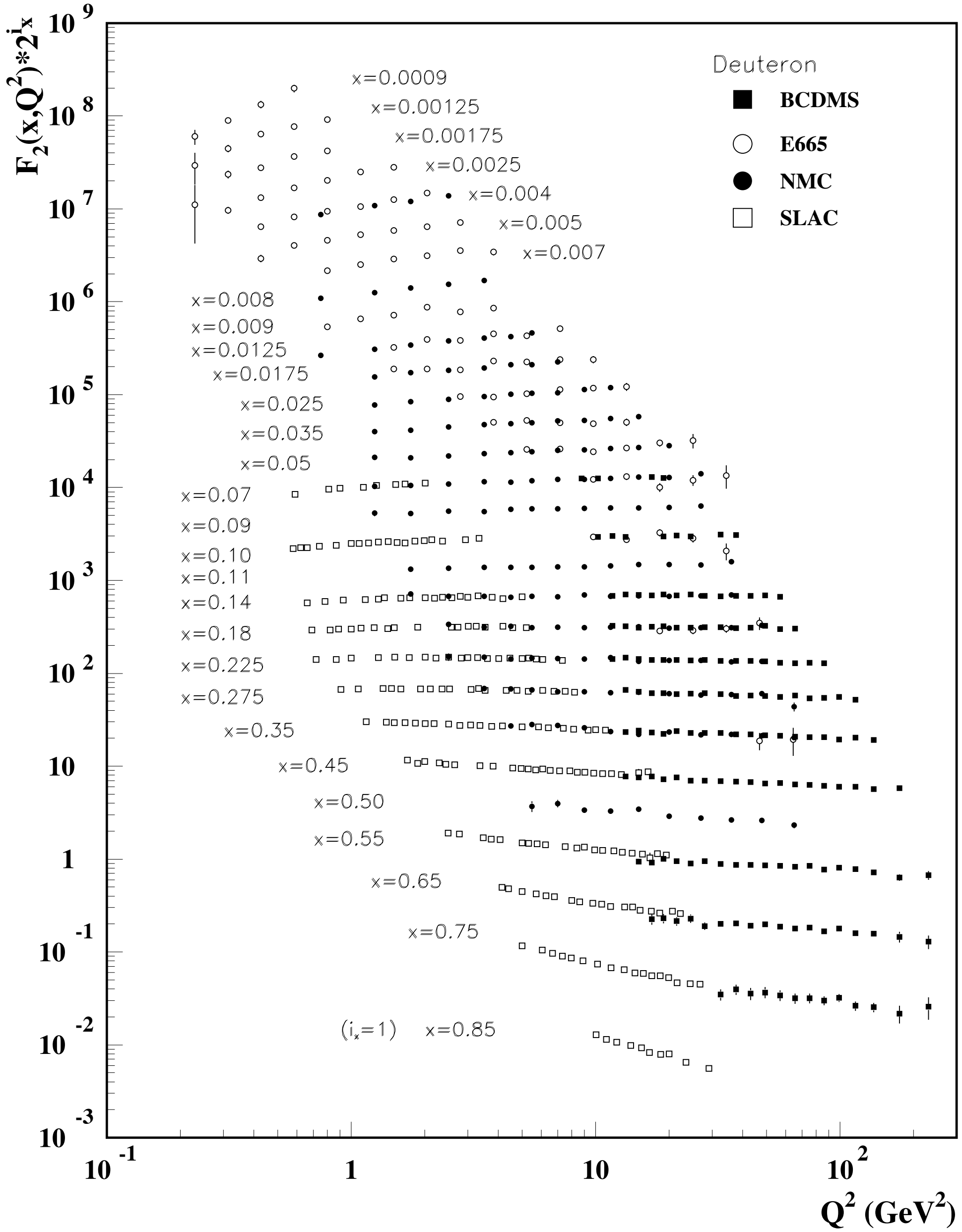
Polarized and unpolarized proton World's data





Polarized and unpolarized <u>deuteron</u> World's data

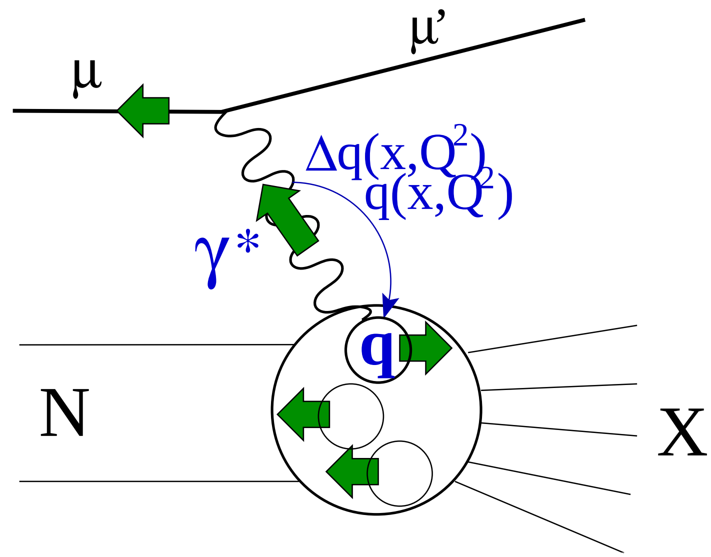


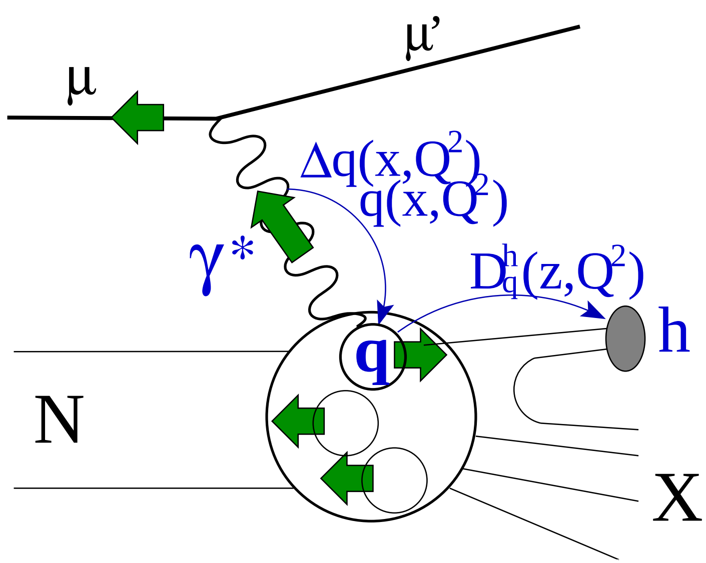


Full flavor separation analysis with LO QCD fit

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

Extraction of parton densities

- 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

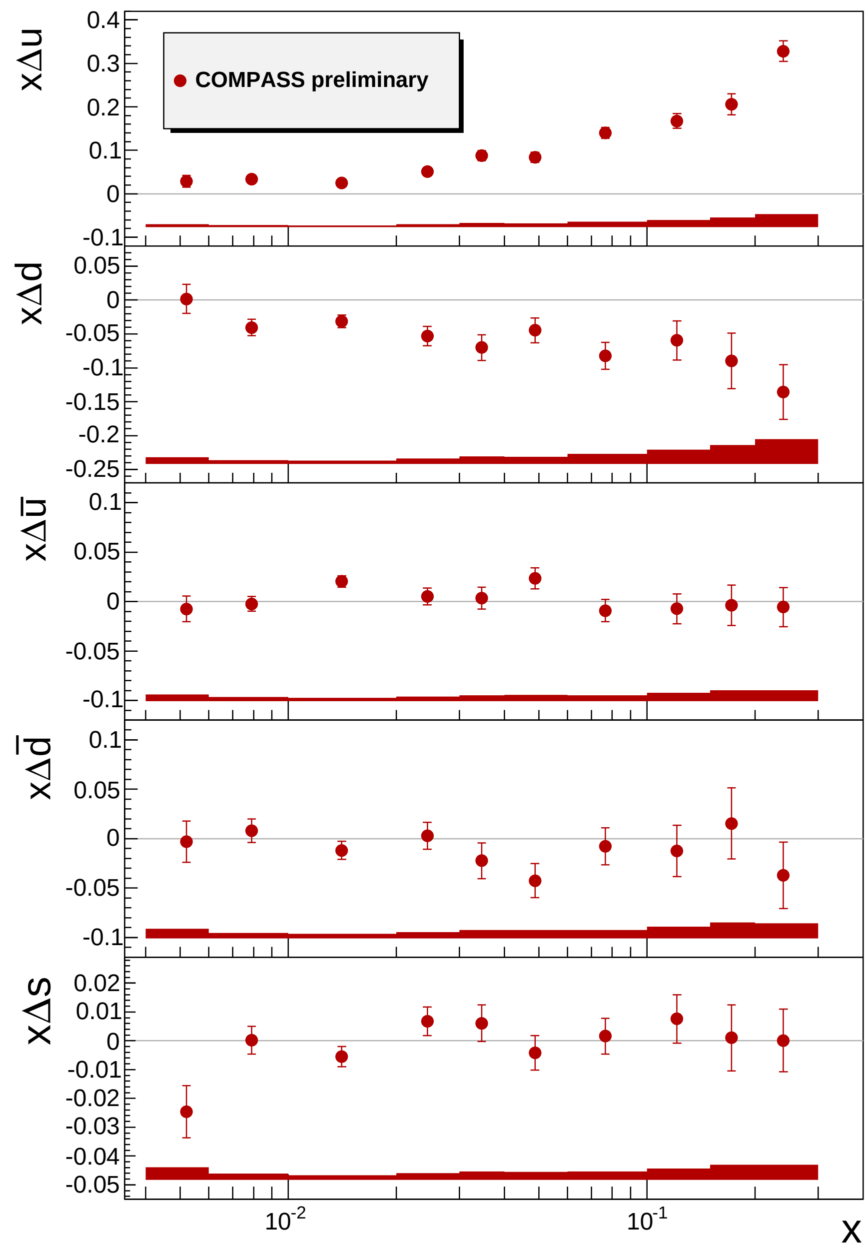
$$\vec{A} = \mathsf{B}\,\Delta\vec{q}, \quad \text{where} \quad \begin{cases} \vec{A} = (A_1^d, A_d^{\pi+}, A_d^{\pi-}, A_d^{K+}, A_d^{K-},\ A_1^p, A_p^{\pi+}, A_p^{\pi-}, A_p^{K+}, A_p^{K-}) \\ \Delta\vec{q} = (\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s), \quad \Delta s \equiv \Delta\bar{s}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

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

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

Results of the fit (Q^2=3 GeV^2)

- **MRST04** parametrization is used for unpolarized PDFs
- **DSS** parametrization is used for FFs: pQCD analysis of electron-positron annihilation, lepton-nucleon DIS and **SIDIS**, hadron-hadron collision data
- All sea-quark distributions are compatible with zero
- Good agreement of Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$ with global fit
- Typical $x\Delta s(x)$ distribution obtained from QCD fits of $g_1(x, Q^2)$ data has minimum at $x \approx 0.2$ $\Rightarrow$ significant discrepancy is observed



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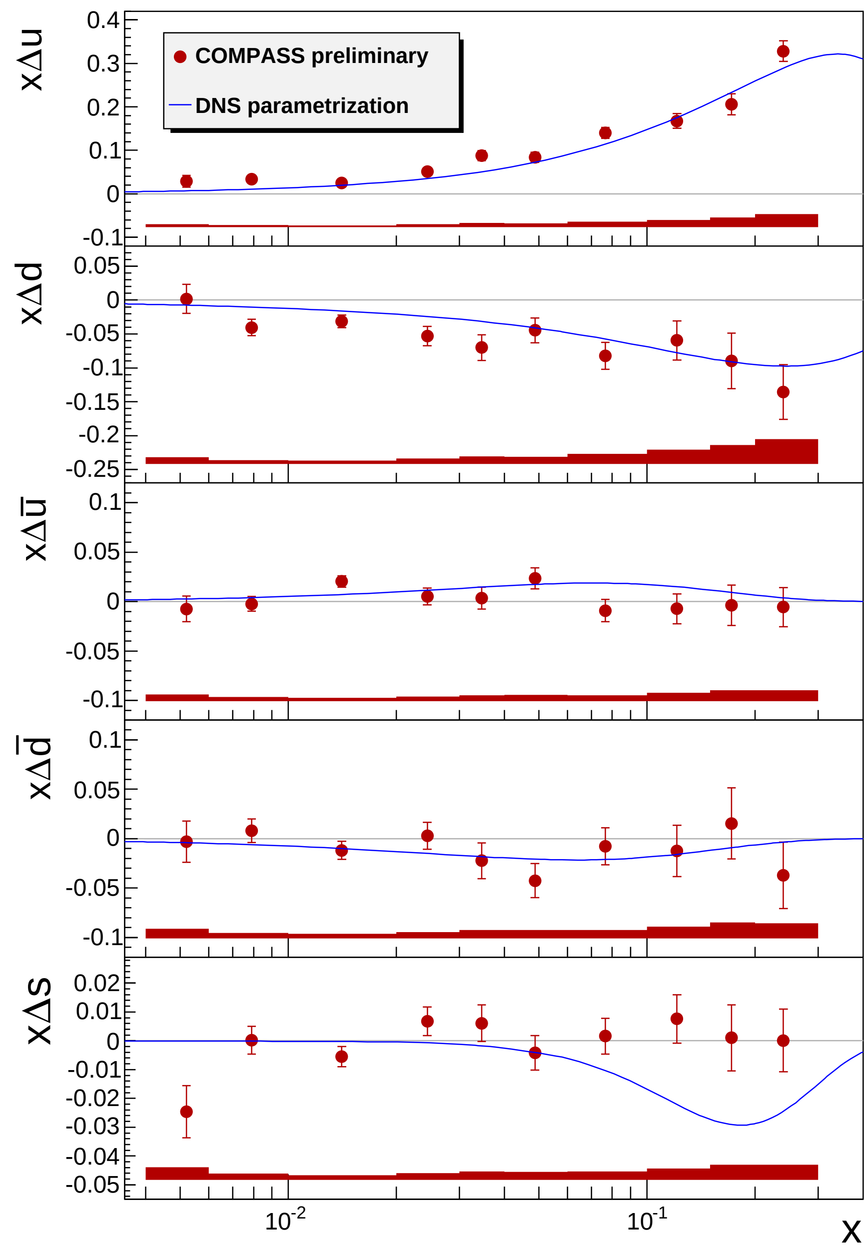


Flavor symmetry breaking of the light sea

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

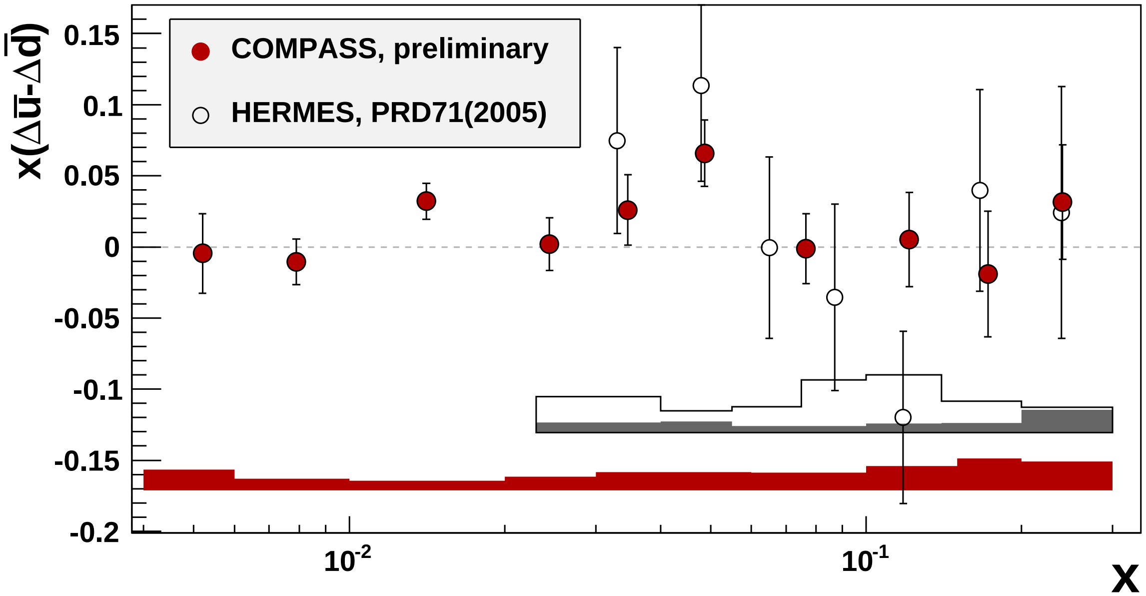
Experiment	$\langle Q^2 \rangle$ [GeV^2]	$\int_0^1 [\bar{u} - \bar{d}]dx$	Reference
NMC/DIS	4	0.147 ± 0.039	M.Arneodo et al., Phys.Rev.D55(1994)R1
HERMES/SIDIS	2.3	0.16 ± 0.03	K.Ackerstaff et al., Phys.Rev.Lett.81(1998)5519
FNAL E866/DY	54	0.118 ± 0.012	R.S.Towell et al., Phys.Rev.D64(2001)052002

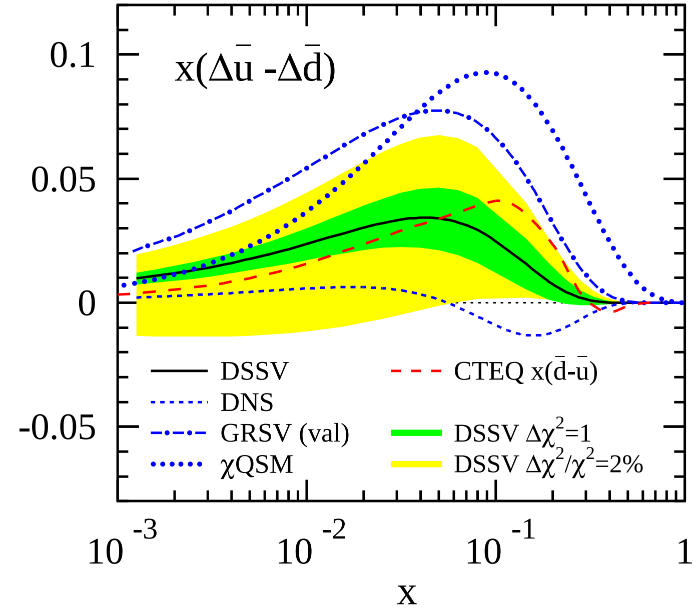
- Many non-perturbative models predicts a sizable asymmetry of the helicity densities

	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

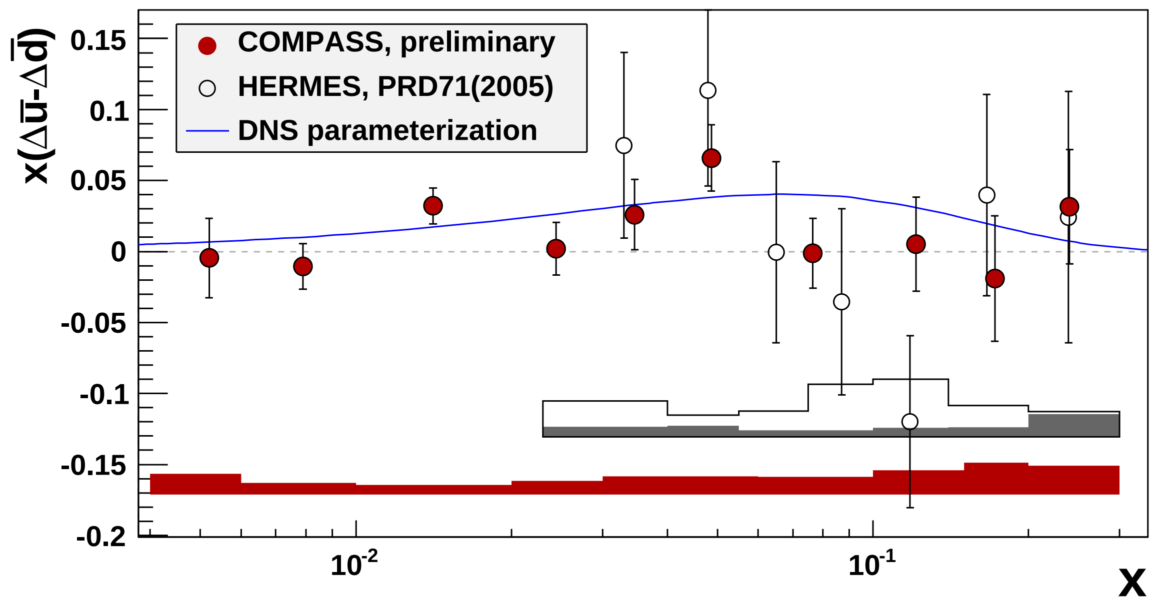
HERMES$(Q^2 = 2.5\,\mathrm{GeV}^2)$: $\int_{0.023}^{0.3}(\Delta\bar{u} - \Delta\bar{d})dx = 0.048 \pm 0.057(stat) \pm 0.028(syst)$

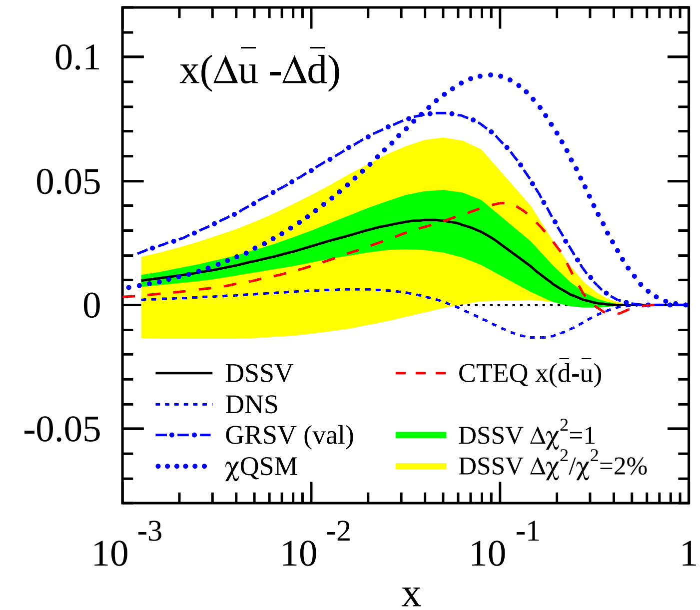
COMPASS$(Q^2 = 3\,\mathrm{GeV}^2)$: $\int_{0.004}^{0.3}(\Delta\bar{u} - \Delta\bar{d})dx = 0.052 \pm 0.035(stat) \pm 0.013(syst)$

- Present analysis: no estimation of systematics coming from uncertainties of FF
- Strength of the effect is comparable to the one observed in unpolarized case

$$\int_0^1(\bar{u} - \bar{d})dx = 0.118 \pm 0.012$$

Flavor symmetry breaking of the light sea





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

$$\text{HERMES}(Q^2 = 2.5\,\text{GeV}^2): \quad \int_{0.023}^{0.3} (\Delta\bar{u} - \Delta\bar{d})dx = 0.048 \pm 0.057(stat) \pm 0.028(syst)$$

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$$\int_0^1 (\bar{u} - \bar{d})dx = 0.118 \pm 0.012$$

Summary

- All COMPASS data with deuteron (2002-2006) and proton (2007) targets have been processed and analyzed
- Combined analysis of proton and deuteron data
  - ◇ Non-singlet structure function g_1^{NS} and Bjorken sum rule

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

  - ◇ Full flavor separation analysis with LO QCD fit
    - ∗ Good agreement of non-strange PDFs with results of previous QCD fits
    - ∗ Shape of $\Delta s(x)$ disagrees significantly with previous fits
    - ∗ Flavor asymmetry of the light sea quarks have been observed $\Delta\bar{u} \gtrsim \Delta\bar{d}$
- Proposal for a one more year (2011) with longitudinally polarized proton target has been submitted for SPSC