Nucleon spin in perspective

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Introduction

A Beautiful Spin (after X. Ji)

- Born with troubles (Stern & Gerlach (1922) vs Goudsmit & Uhlenbeck (1925))
- Is due to space–time symmetry
- Fundamental concept
- Laboratory to explore physics beyond the SM, e.g.:
  - Muon "$g-2$" experiment @ BNL
  - Proton weak charge (Qweak exp @ JLAB)
  - Neutron EDM measurement ...

  Tool to measure observables hard to obtain otherwise, e.g:
  - Strangeness content of the nucleon from polarised parity–violating e–p scattering
  - Electromagnetic form factors of the nucleon from the recoil polarisation
  - Neutron density in large nuclei from parity–violating electron scattering
- and...

A Beautiful Spin (after X. Ji)...cont'd

- Probe to unravel the nonperturbative QCD dynamics, e.g.:
  - Nucleon spin–dependent structure functions, g_1 and $g-2$
  - Quark helicity ($\Delta q(x)$) and transversity ($\Delta_T q(x)$) distributions
  - Gluon polarisation, $\Delta g(x)$
  - Generalised Parton Distributions, GPD
  - Semi–Inclusive Deep Inelastic Scattering, SIDIS
  - (Generalised) Drell–Hearn–Gerasimov–... sum rule
  - Single spin asymmetries

Cross section asymmetries $\Longrightarrow$ structure functions

- In a full analogy to spin–averaged DIS where

$$\sigma \sim F_1(x) = \frac{1}{2}\sum_f e_f^2 q_f(x) \quad \text{and} \quad F_2(x) \approx 2xF_1$$

we now have: $\Delta\sigma = \sigma_{\rightleftarrows} - \sigma_{\rightrightarrows} \sim g_1(x) = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x)$ and $g_2(x)$

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

- A direct observable, μ–p cross section asymmetry, $A^{\mu p}$:

$$A^{\mu d} = \frac{1}{f P_T P_B}\left(\frac{N_{\rightleftarrows} - N_{\rightrightarrows}}{N_{\rightleftarrows} + N_{\rightrightarrows}}\right); \quad f \sim 0.2, \quad P_T \sim 0.9, \quad P_B \sim -0.8$$

- is related to the longitudinal and transverse $\gamma^* p$ asymmetries:

$$\frac{A^{\mu p}}{D} = A_1^p + \eta A_2^p$$

- Longitudinal spin–dependent structure function:

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

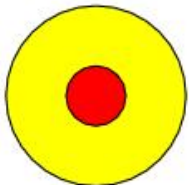
Cross section asymmetries $\Longrightarrow$ structure functions ...

- SIDIS asymmetry, e.g. A^-:

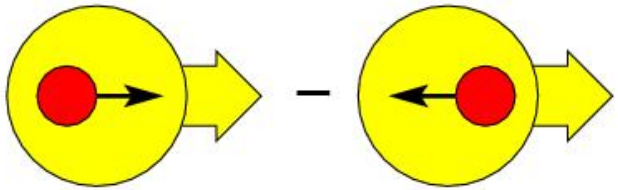
$$A^- = \frac{N^{h^-}_{\rightleftarrows} - N^{h^-}_{\leftrightarrows}}{N^{h^-}_{\rightleftarrows} + N^{h^-}_{\leftrightarrows}} \qquad \text{and} \qquad A_1^h = \frac{\sum_q e_q^2 \left(\Delta q D_q^h + \Delta\bar{q} D_{\bar{q}}^h\right)}{\sum_q e_q^2 \left(q D_q^h + \bar{q} D_{\bar{q}}^h\right)}$$

Partonic structure of the nucleon; distribution functions

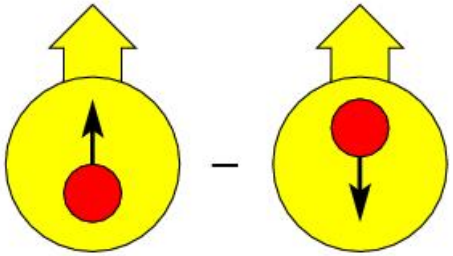
Three species of twist-two quark distributions in QCD (after integrating over the quark intrinsic k_t):

$q(x) =$ 

Quark momentum DF;
well known (unpolarised DIS $\longrightarrow F_{1,2}(x)$).

$\Delta q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin;
known, helicity (polarised DIS $\longrightarrow g_1(x)$).

$\Delta_T q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in the transversely polarised nucleon;
unknown, transversity (polaris. SIDIS $\longrightarrow A_{Collins}$)

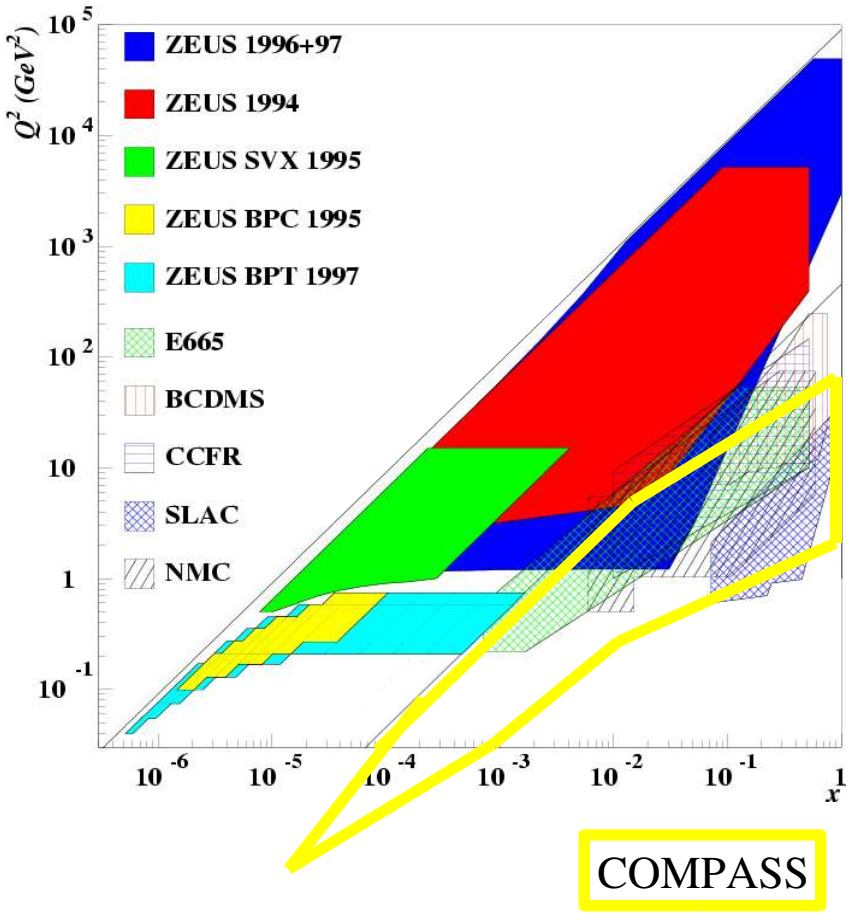
In the nonrelativistic approach $\Delta_T q(x)$ identical with $\Delta q(x)$.
$\Delta_T q(x)$ are C-odd and chiral-odd; may only be measured as $\Delta_T q(x) \otimes \Delta_T D_q^q$.

If the k_t taken into account $\Longrightarrow$ 8 TMD appear; one, $f_{1T}^{\perp}$ accessible through "Sivers asymmetry".

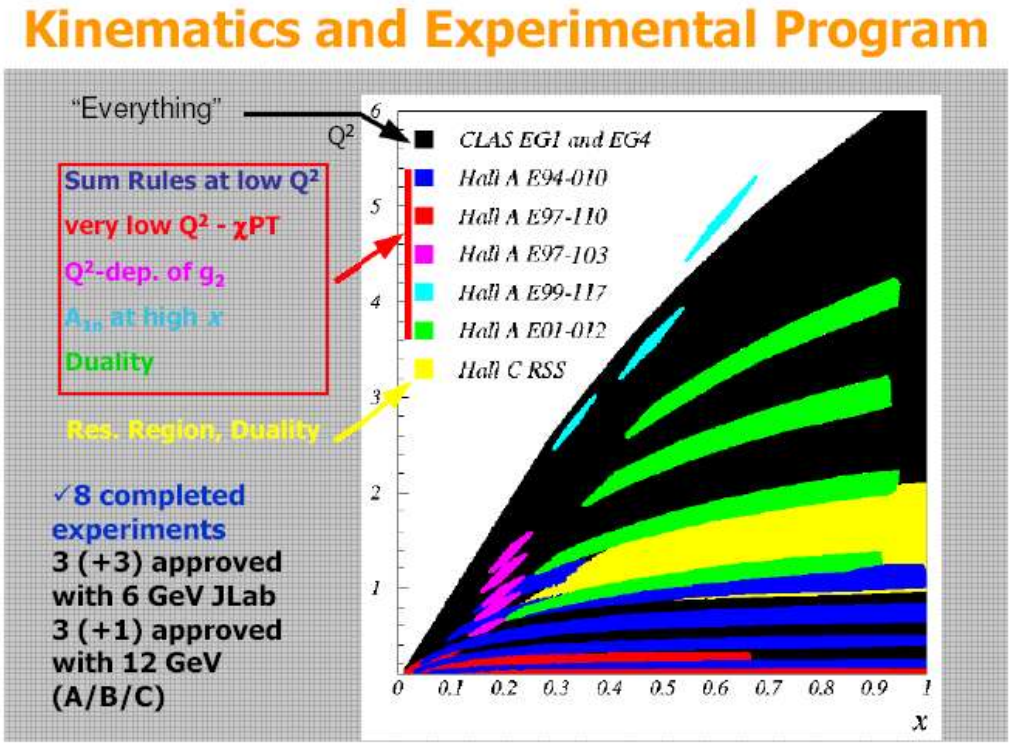
Recent and ongoing spin experiments

- CERN: EMC, SMC, COMPASS
- DESY: HERMES
- SLAC (completed): E142, E143, E154, E155, E156
- BNL (RHIC): STAR, PHENIX, BRAHMS

Acceptance of electroproduction experiments



COMPASS



JLAB

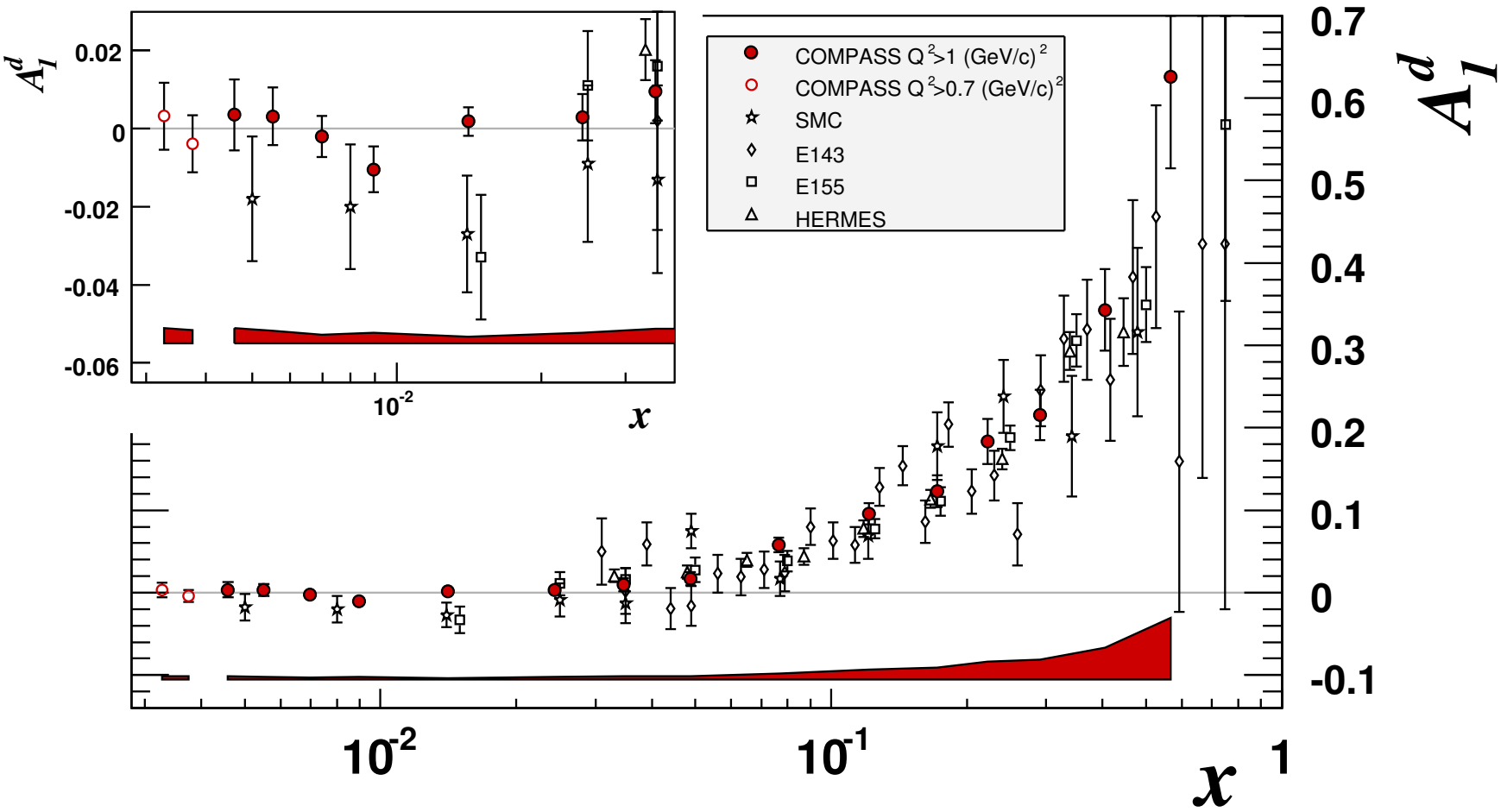
Figure from: N. D'Hose, Villars 2004

Figure from: R. Carlini

Longitudinal spin structure

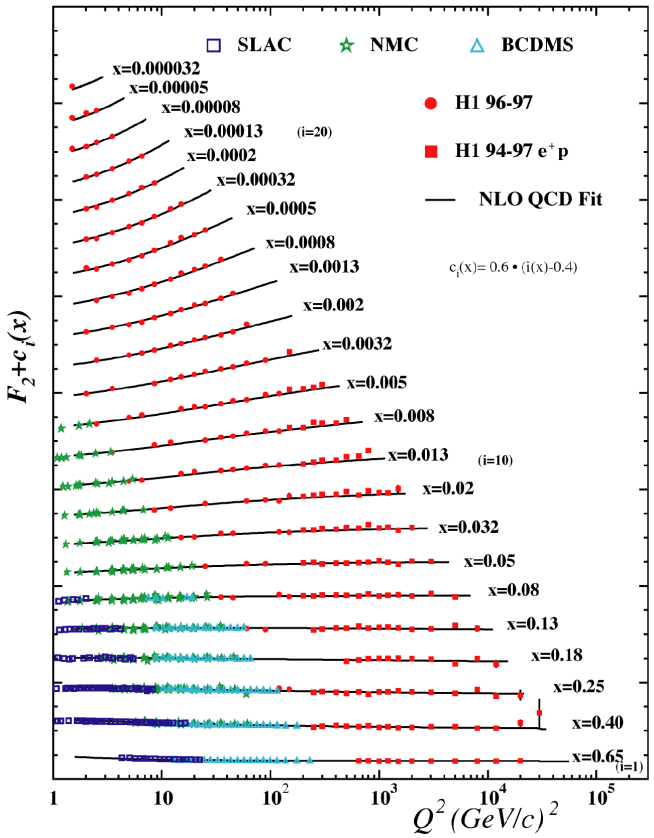
World data on $A_1^d(x)$

V.Yu. Alexakhin (COMPASS) *et al.* Phys. Lett. B **647** (2007) 8



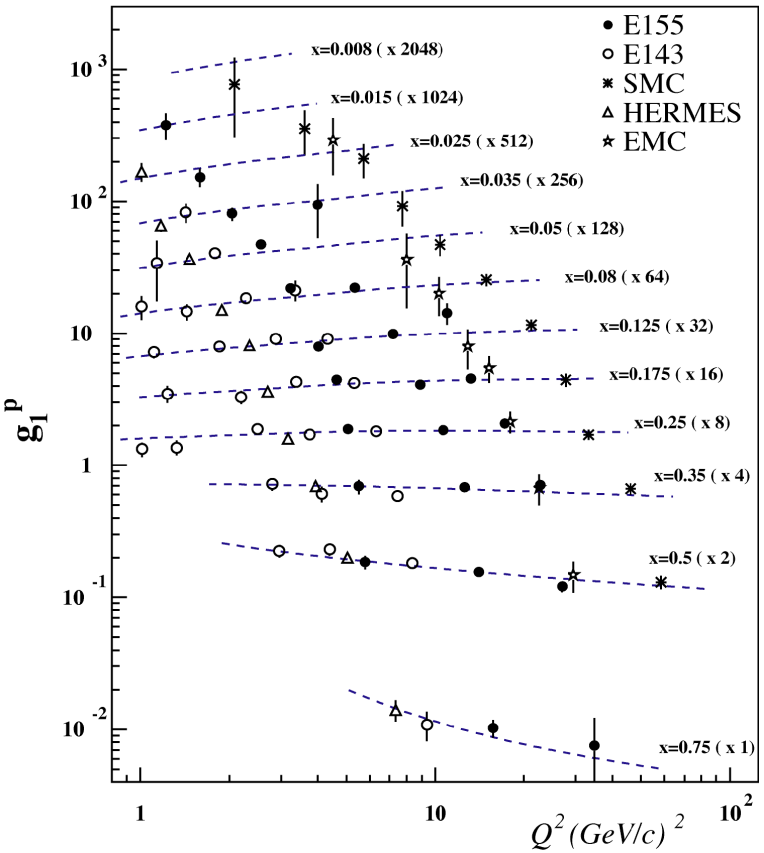
World data on the g_1^p (high energy experiments...)

World data on F_2^p



→ *50% of momentum carried by gluons*

World data on g_1^p



→ *20% of proton spin carried by quark spin*

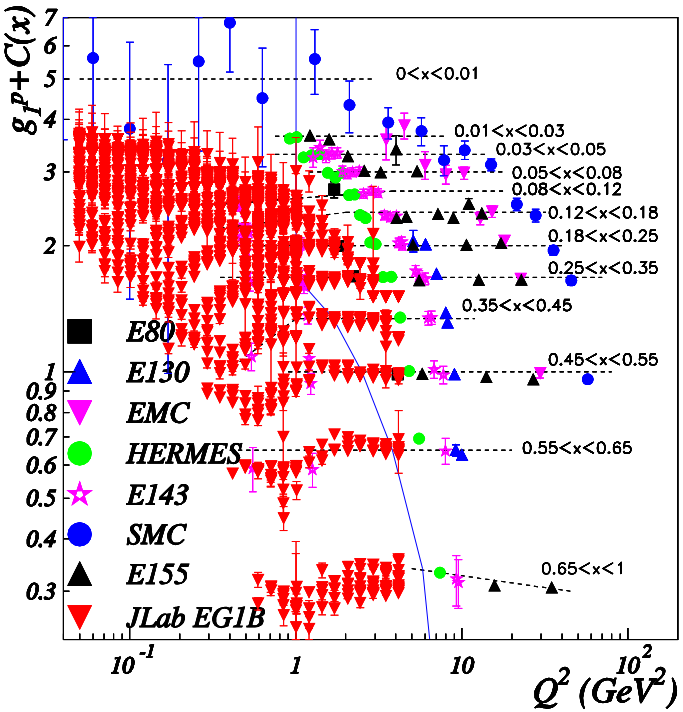
Figure from R.Ent, DIS2006

World data on the g_1^p (...and JLAB)

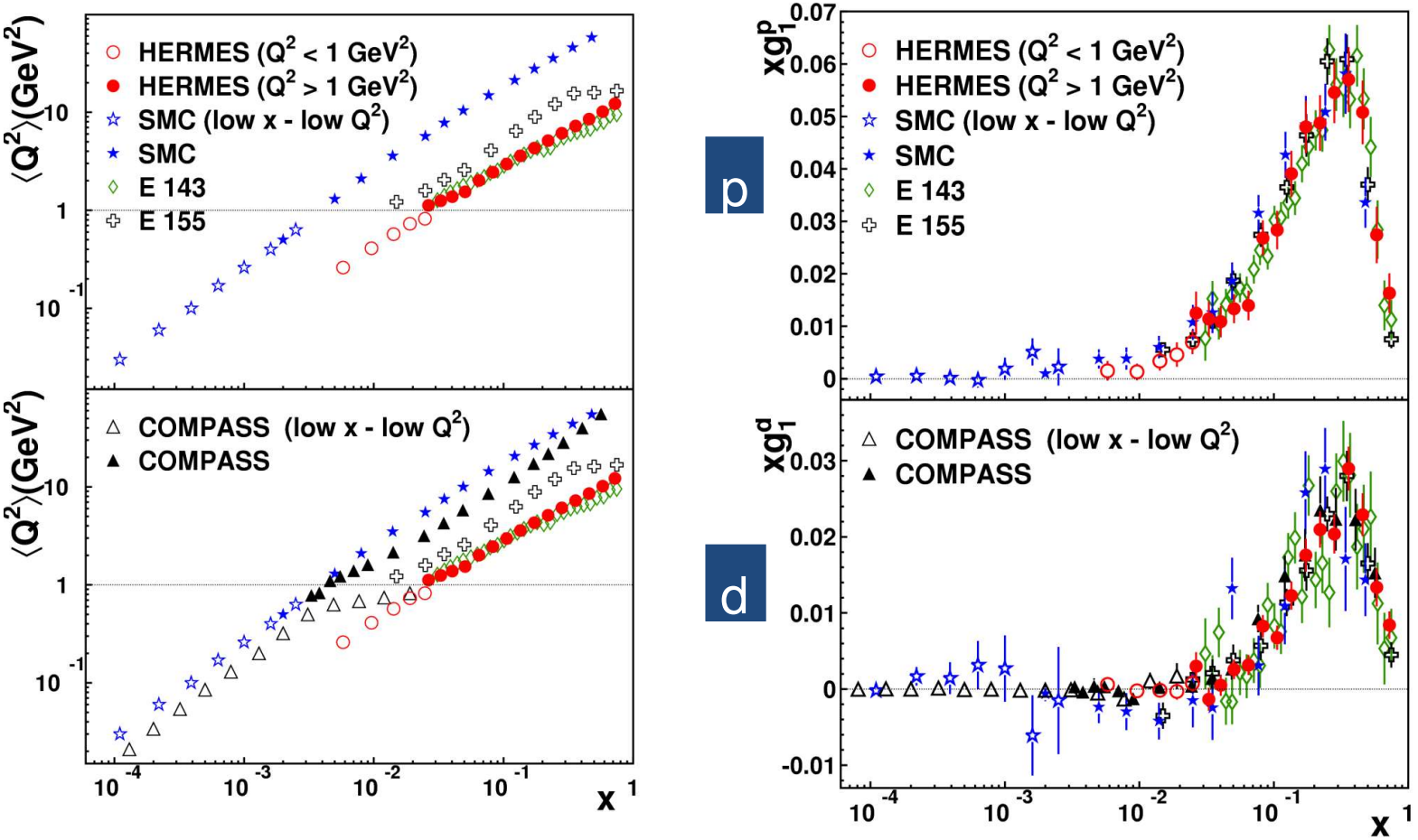
World data on polarized structure function $g_{1p}(x,Q^2)$

CLAS provides a large body of precise g_1 data in the DIS and transition regions that can be used to improve knowledge of twist-2 PDFs.

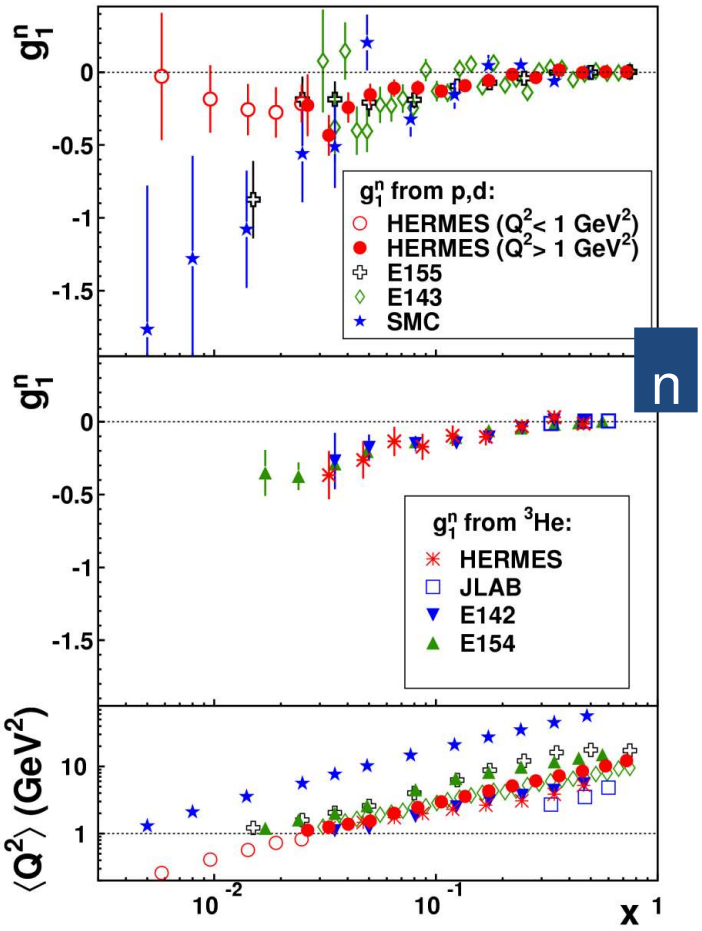
Phys. Rev.C75:035203, 2007
Phys. Lett. B 641, 11 (2006)



World data on the nucleon g_1



World data on the nucleon g_1...cont'd



from p and d

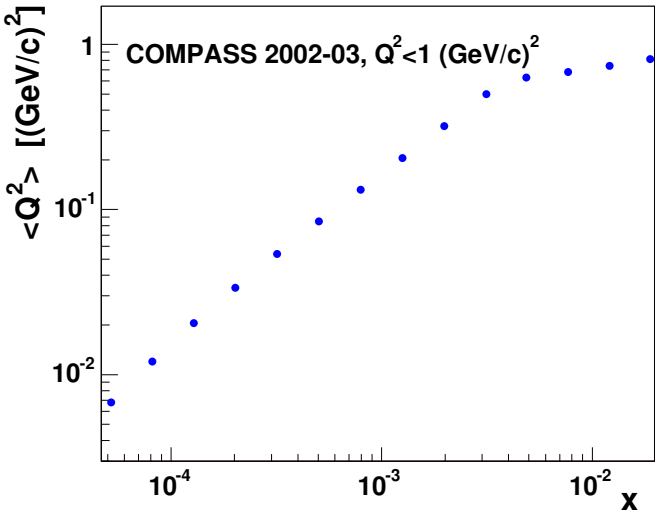
$$g_1^n = \frac{2}{1 - \frac{3}{2}\omega_D} g_1^d - g_1^p$$

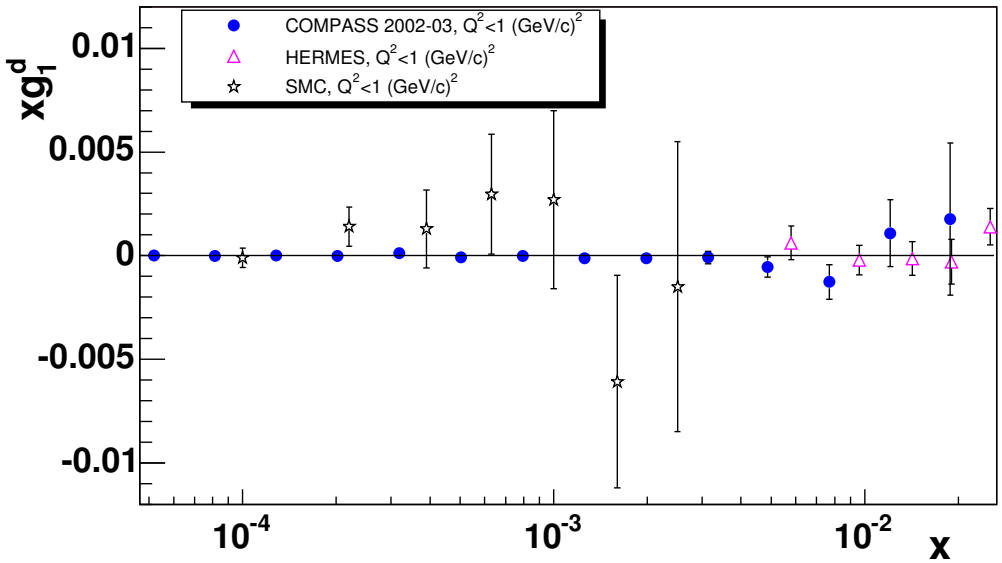
from ^{3}He

G. Mallot, APS, May 2008

g_1^d in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)

V.Yu. Alexakhin (COMPASS) *et al.* Phys. Lett. B **647** (2007) 330



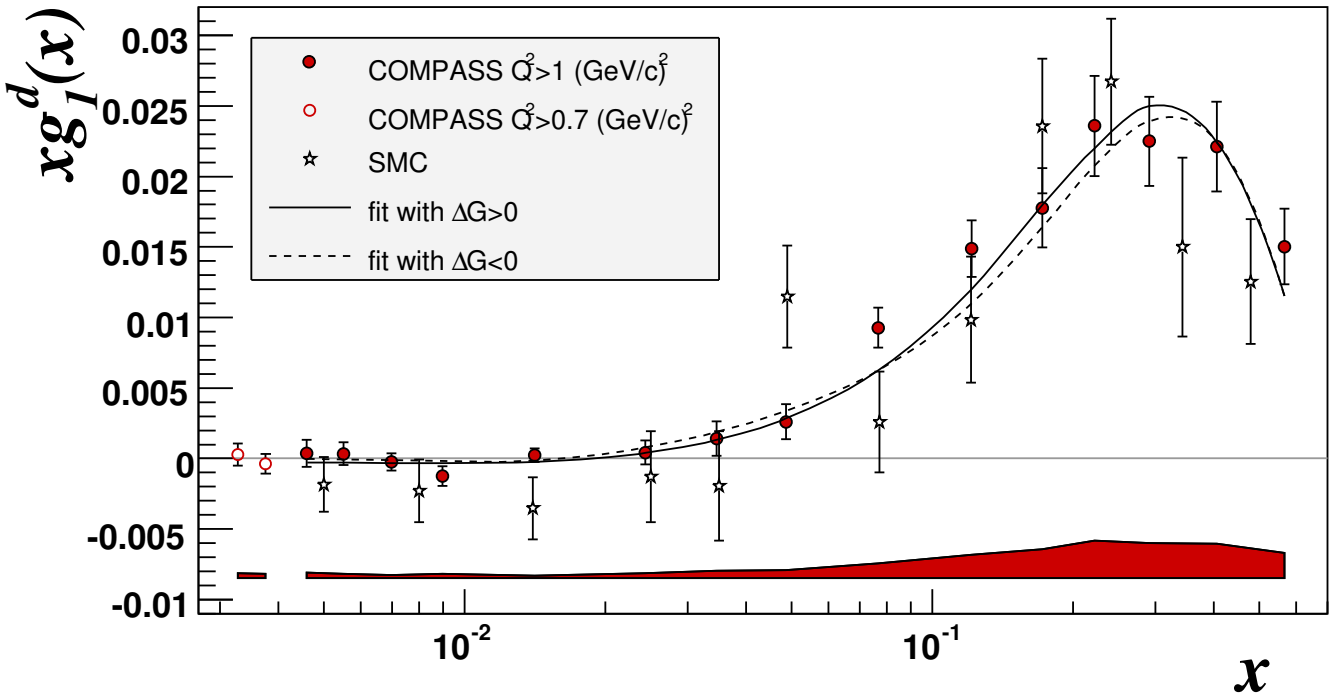


- Order of magnitude improvement over the statistical precision of the SMC.
- Interplay between perturbative and nonperturbative mechanisms.
- Spin effects in g_1^d at low x and Q^2 absent ?

COMPASS QCD analysis of inclusive g_1^d

V.Yu. Alexakhin (COMPASS) *et al.* Phys Lett B**647** (2007) 8

- Two programs: DGLAP evolution of structure functions and evolutions of moments
- NLO $\overline{MS}$ scheme
- World data: 9 experiments, 230 data points (43 from COMPASS)
- Two solutions, $\Delta G > 0$ and $\Delta G < 0$ describe data equally well.

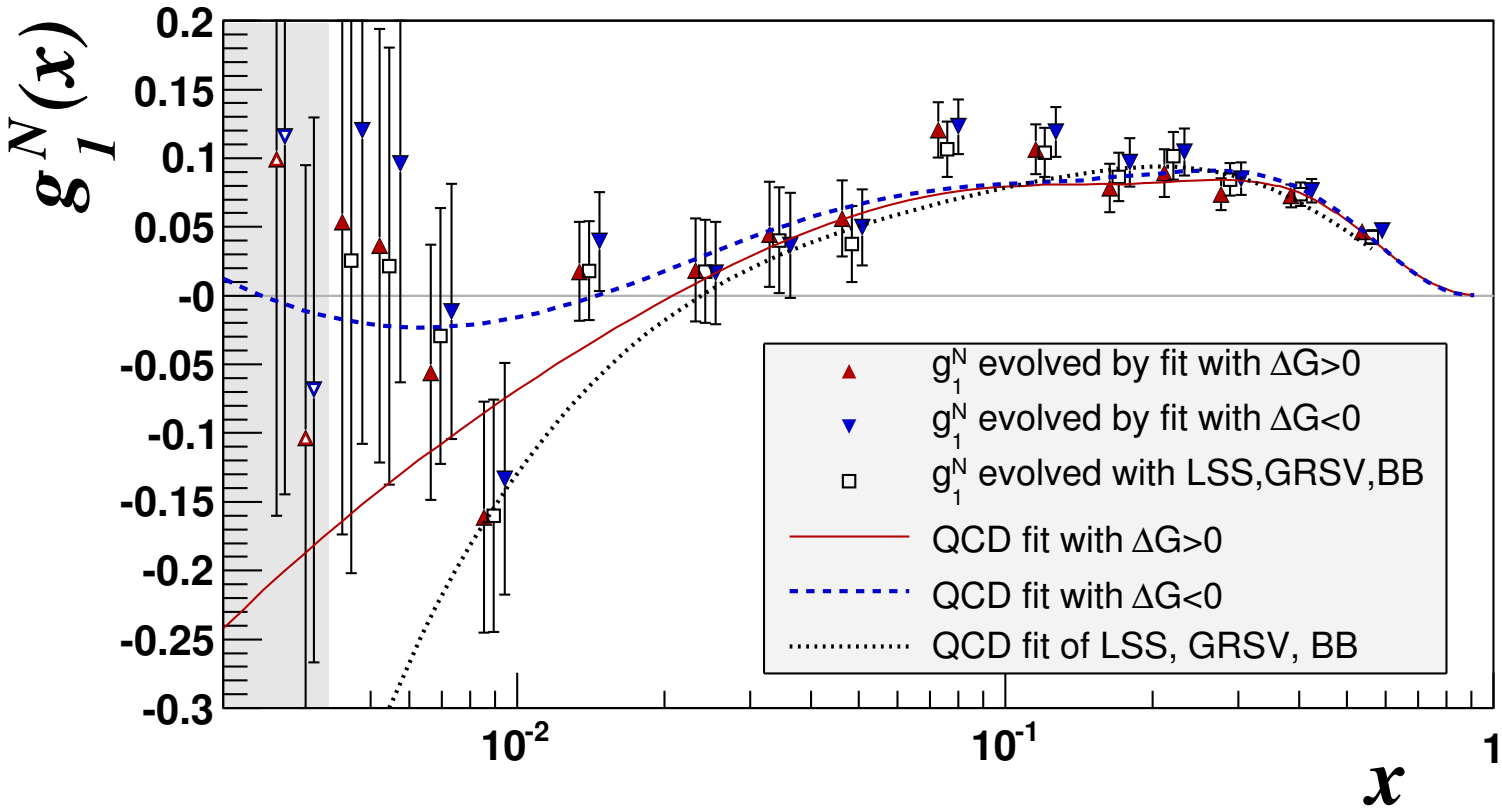


Quark polarisation from COMPASS data only (@ Q^2 = 3 GeV^2):

$a_0 = 0.35 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst.})$ and gluon polarisation: $|\Delta G| \approx 0.2 - 0.3$

COMPASS QCD analysis of g_1^d...cont'd

V.Yu. Alexakhin (COMPASS) *et al.* Phys Lett B**647** (2007) 8



COMPASS g_1^N evolved to $Q^2 = 3$ GeV^2; LSS, GRSV, BB are NLO fits to world (but no COMPASS) data.

Low x data prefer $\Delta G < 0$??? Sign of ΔG not fixed by the g_1 measurements...

Gluon polarisation from QCD evolution

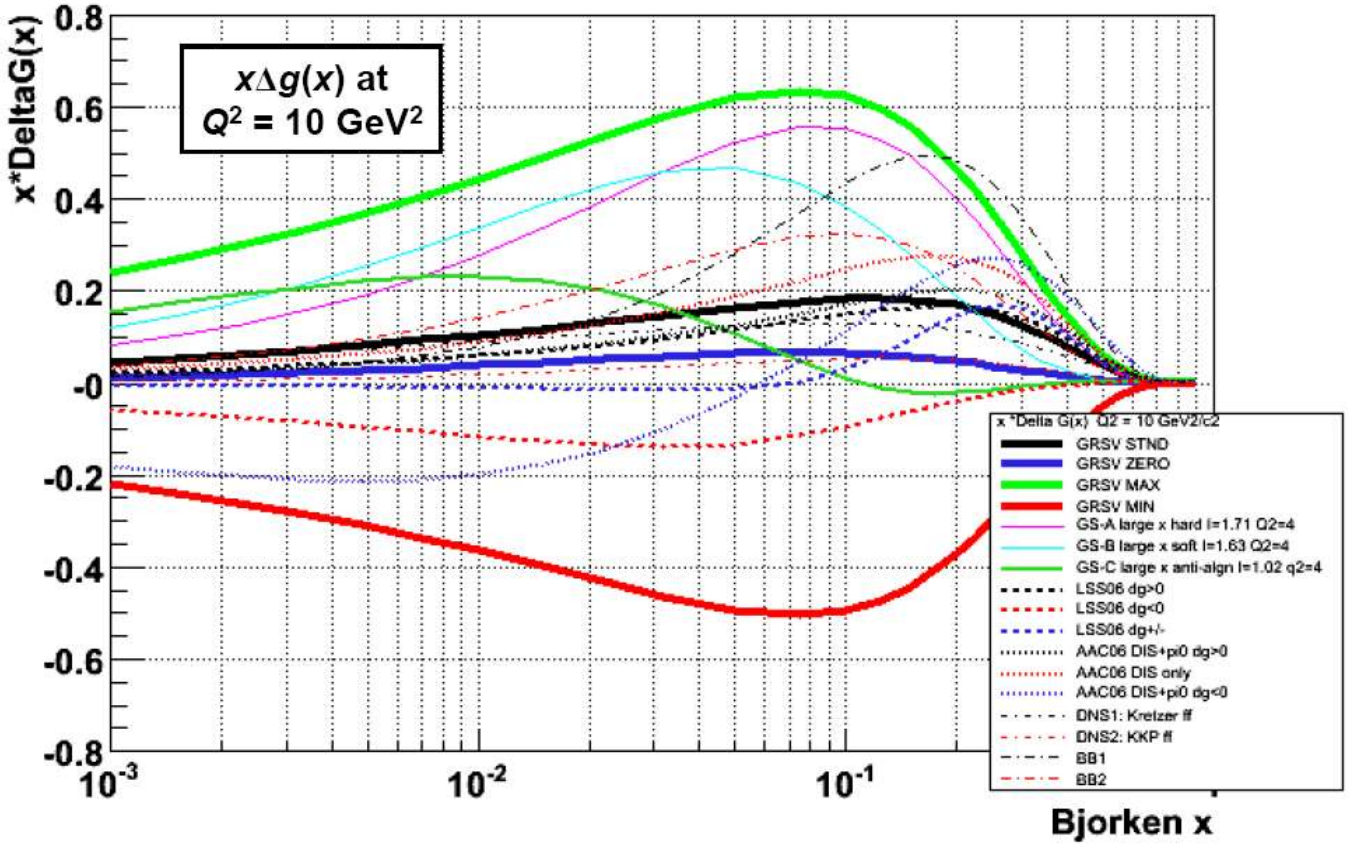


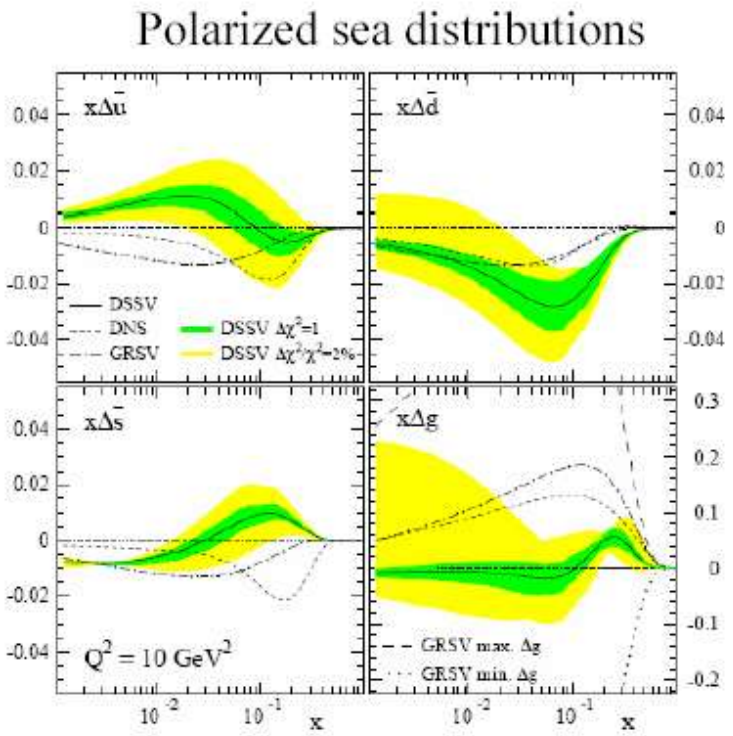
Figure from C. Gagliardi, DIS2008

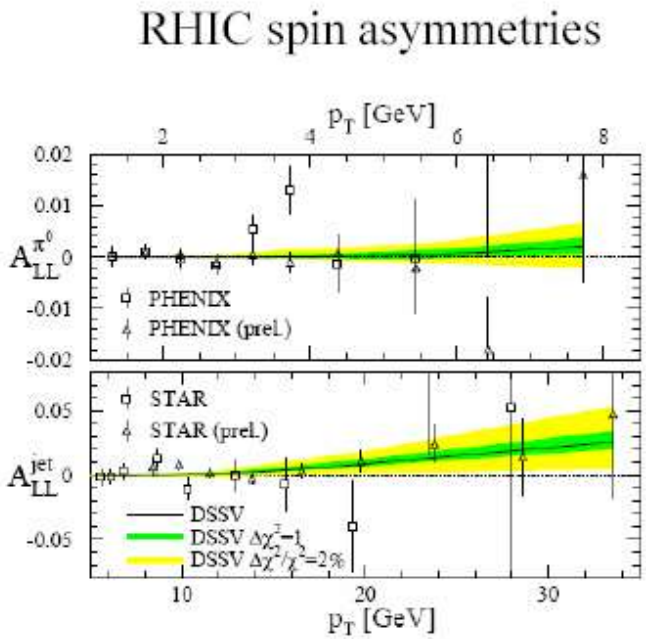
Carl Gagliardi – DIS2008 – Jets in pp at RHIC

NLO QCD analysis of world data

Analysis of worls data by several groups, e.g. the recent ones:

- Leader–Sidorov–Stamenov, LSS06, including COMPASS g_1^d
- De Florian–Sassot–Stratmann-Vogelsang, DSSV08, including RHIC $\vec{p}\vec{p} \rightarrow$jets+... data





NLO QCD analysis of world data...cont'd

TABLE II: First moments $\Delta f_j^{1,[x_{\min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

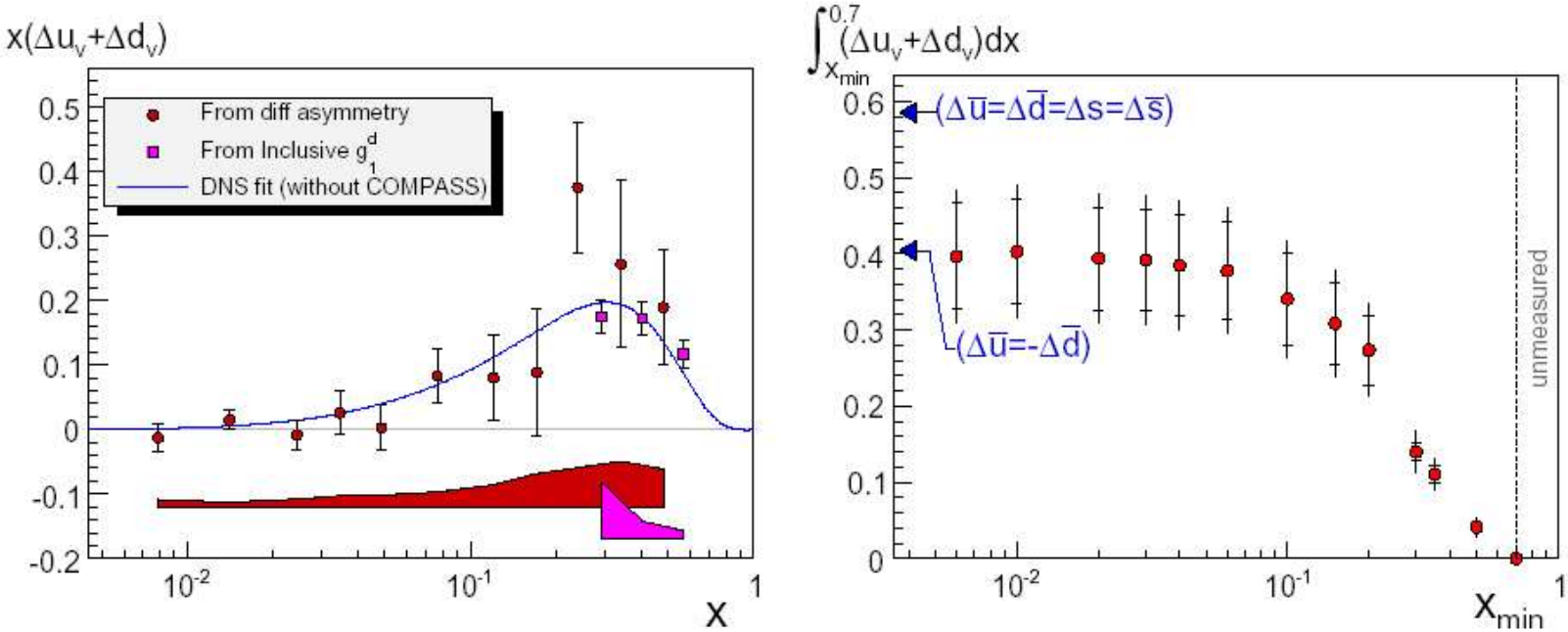
	$x_{\min} = 0$	$x_{\min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

- First moment of the singlet distribution $\sim$0.25 !
- Gluon polarisation small (with lare errors!)

Sea quark polarisation

M. Alekseev *et al.* (COMPASS), Phys. Lett. **B660** (2008) 458.

- Difference asymmetry: $A^{h^+-h^-}$: $A_d^{\pi^+-\pi^-} = A_d^{K^+-K^-}$
- At LO, the fragmentation functions drop out



$$\int_{0.006}^{0.7} (\Delta u_V + \Delta d_V)\mathrm{d}x = 0.40 \pm 0.07 \pm 0.05$$

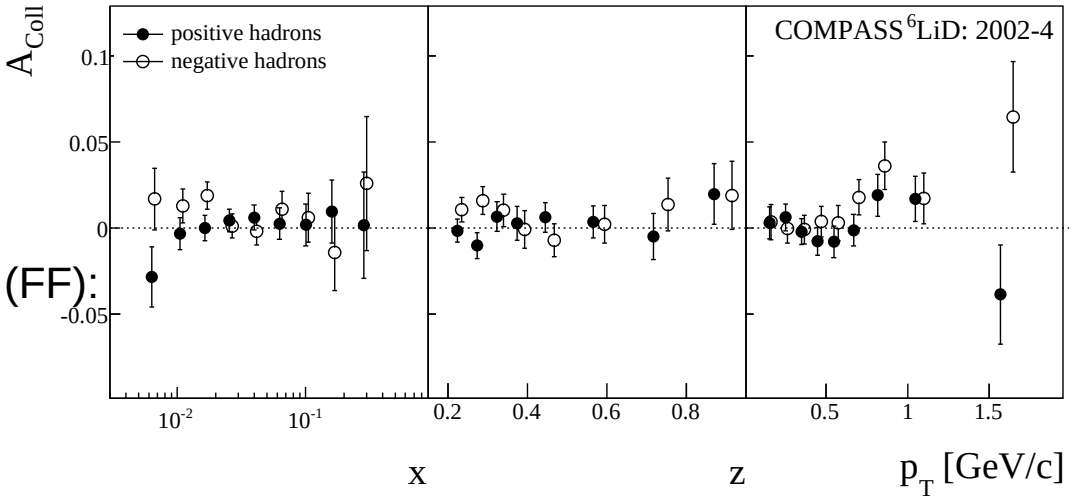
- Unmeasured regions contribute neligibly.
- Non-symmetric sea preferred ?
- Next step: determine Δs from $K^{\pm}$ asymmetries.

Transversity

Results for the Collins and Sivers asymmetries

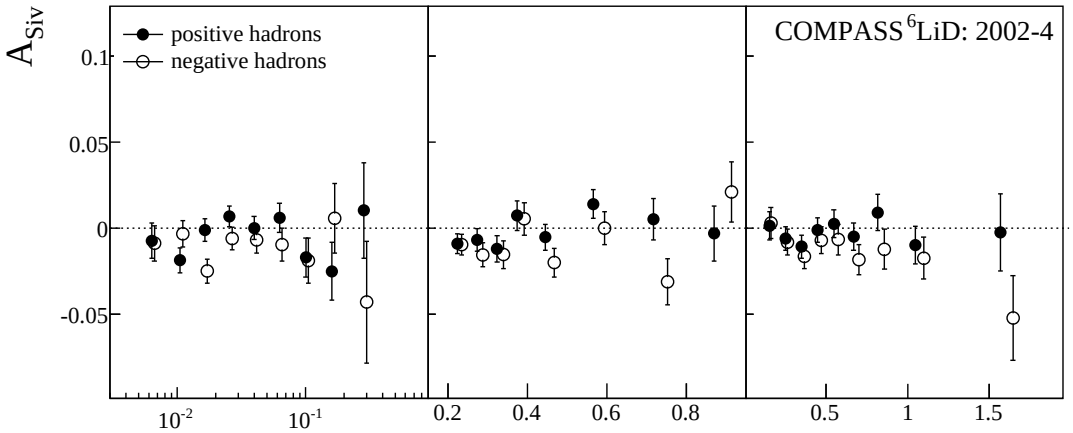
Deuteron target; all hadrons: positive and negative

E.S. Ageev *et al.* (COMPASS) Nucl.Phys.B **765**(2007) 31



Collins asymmetries very small.
These data + Hermes + Belle

$$\Longrightarrow \Delta_T u + \Delta_T d \sim 0$$

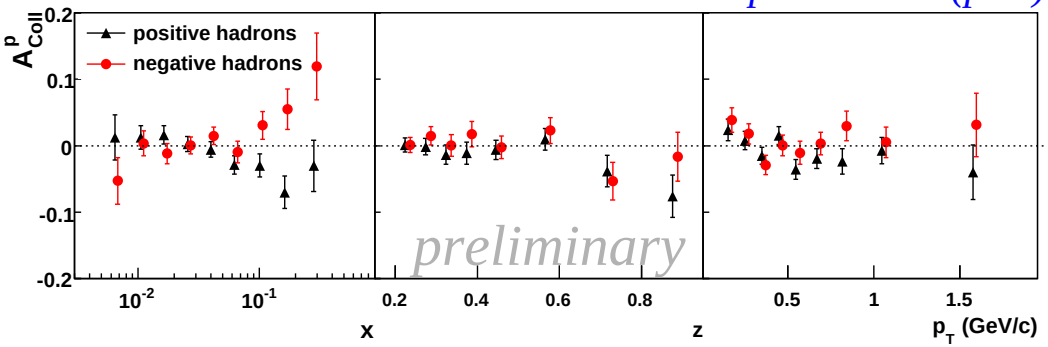


Sivers asymmetries very small.
S.Brodsky & S. Gardner (2006): no gluon orbital angular momentum in the nucleon?

Results for the Collins and Sivers asymmetries...cont'd

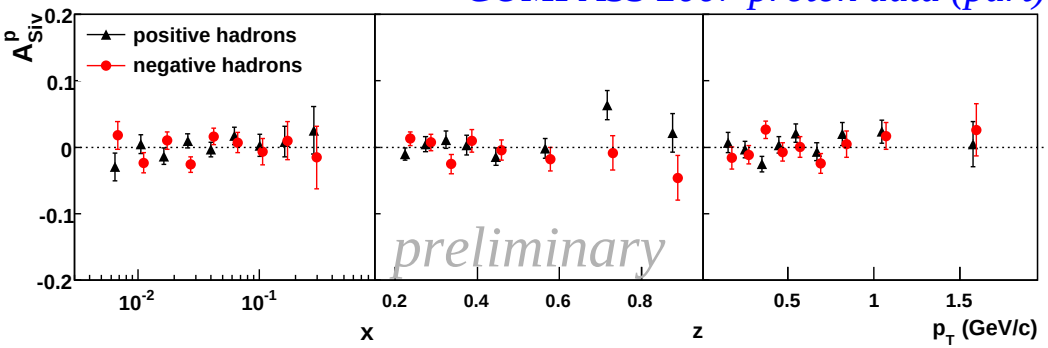
Proton target; all hadrons: positive and negative

COMPASS 2007 proton data (part)



Asymmetries nonzero at $x \gtrsim 0.1$.

COMPASS 2007 proton data (part)



Sivers asymmetries very small.

Gluon polarisation

Nucleon spin decomposition

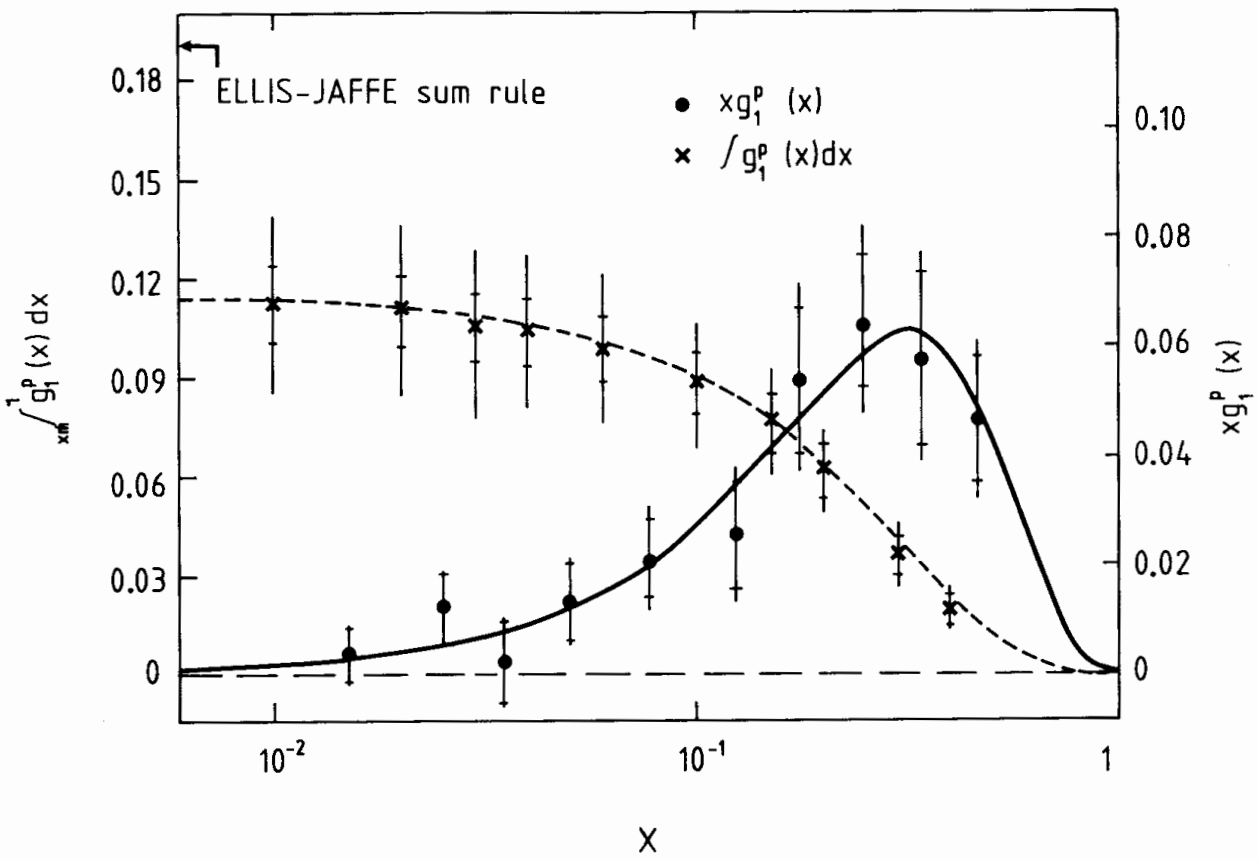
$$\frac{\hbar}{2} = J_q + J_g = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + \left(\Delta G + L_g\right)$$

- Observe! each term is μ^2 dependent;
  decomposition $J_g = \Delta G + L_g$ is NOT gauge–invariant.
- EMC (1988): $a_0 = \Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$ (expected: ~ 0.6 if $\Delta s = 0$).
  Here $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ and $\Delta q = \int \Delta q(x)dx$, $\Delta G = \int \Delta G(x)dx$
- COMPASS @ 3 GeV^2: $a_0 = 0.35 \pm 0.03 \pm 0.05$
- But as a consequence of the "axial anomaly" (axial vector current not conserved) the measured quantity is:

  $$a_0(Q^2) = \Delta\Sigma^{AB} - \left(\frac{n_f \alpha_s}{2\pi}\right)\Delta G(Q^2)$$

  and the "spin crisis" can be solved ($\Delta\Sigma \sim 0.6$) if $\Delta G \sim 2.2$ (and $L \sim -2$) at $Q^2 = 3$ GeV^2.
- Impressive spin-off since 1988: SLAC (E142, E143, E155, E156), SMC, HERMES, JLAB, COMPASS, RHIC Spin.
- Need to measure ΔG (and L)!

“Spin puzzle”: 20 years



European Muon Collaboration, J.Ashman *et al.* Phys. Lett. **B206** (1988) 364

$\Gamma_1^p = 0.123 \pm 0.013 \pm 0.019$ $\qquad$ $\Delta\Sigma = a_0 = 0.12 \pm 0.17$

Ways of measuring the ΔG

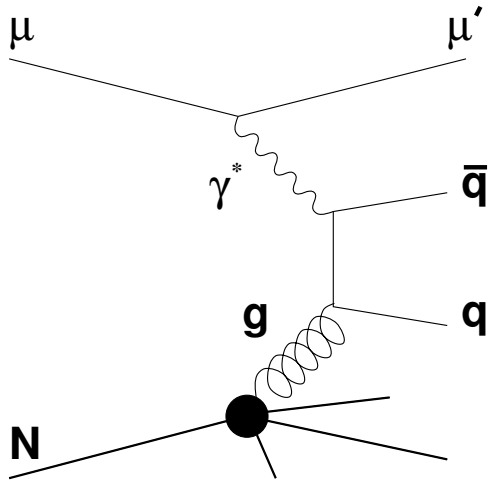
- Scaling violation of g_1 (QCD fits, world data).
- Direct measurements
  - Cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into the charm mesons (max. @ low Q^2, perturbative scale: e.g. mass of the charm quark).
  - Cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into a pair of hadrons of large p_T, separately for low- and high Q^2 (perturbative scale: e.g. p_T).

Direct $\Delta G/G$ measurements

Mechanism employed: photon–gluon fusion. Observable: asymmetry in the hadron production

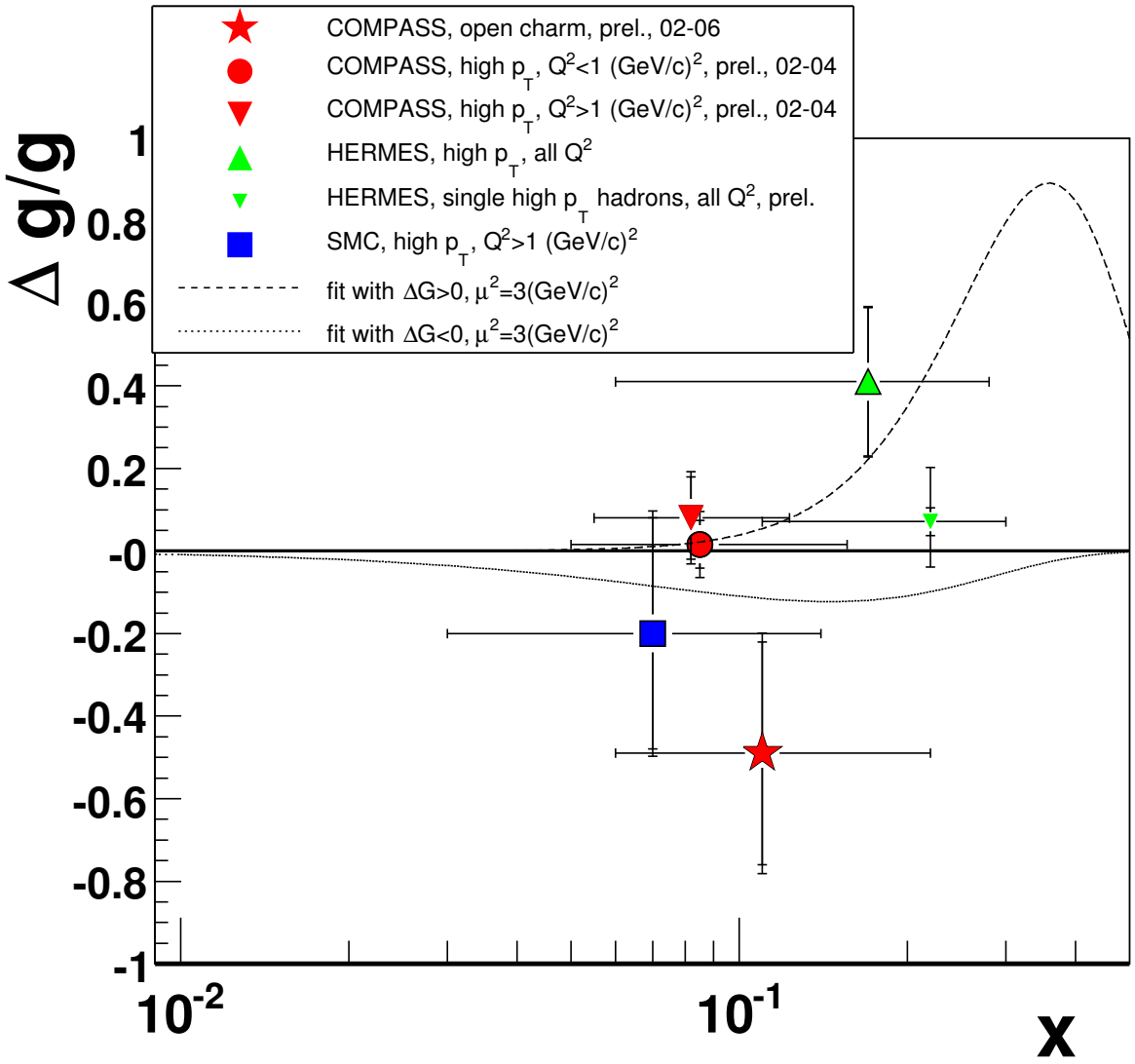
$$A_{\gamma N}^{PGF} = \frac{\int d\hat{s} \Delta\sigma^{PGF} \Delta G(x_g, \hat{s})}{\int d\hat{s} \sigma^{PGF} G(x_g, \hat{s})}$$

$$\approx \langle a_{LL}^{PGF} \rangle \frac{\Delta G}{G}$$



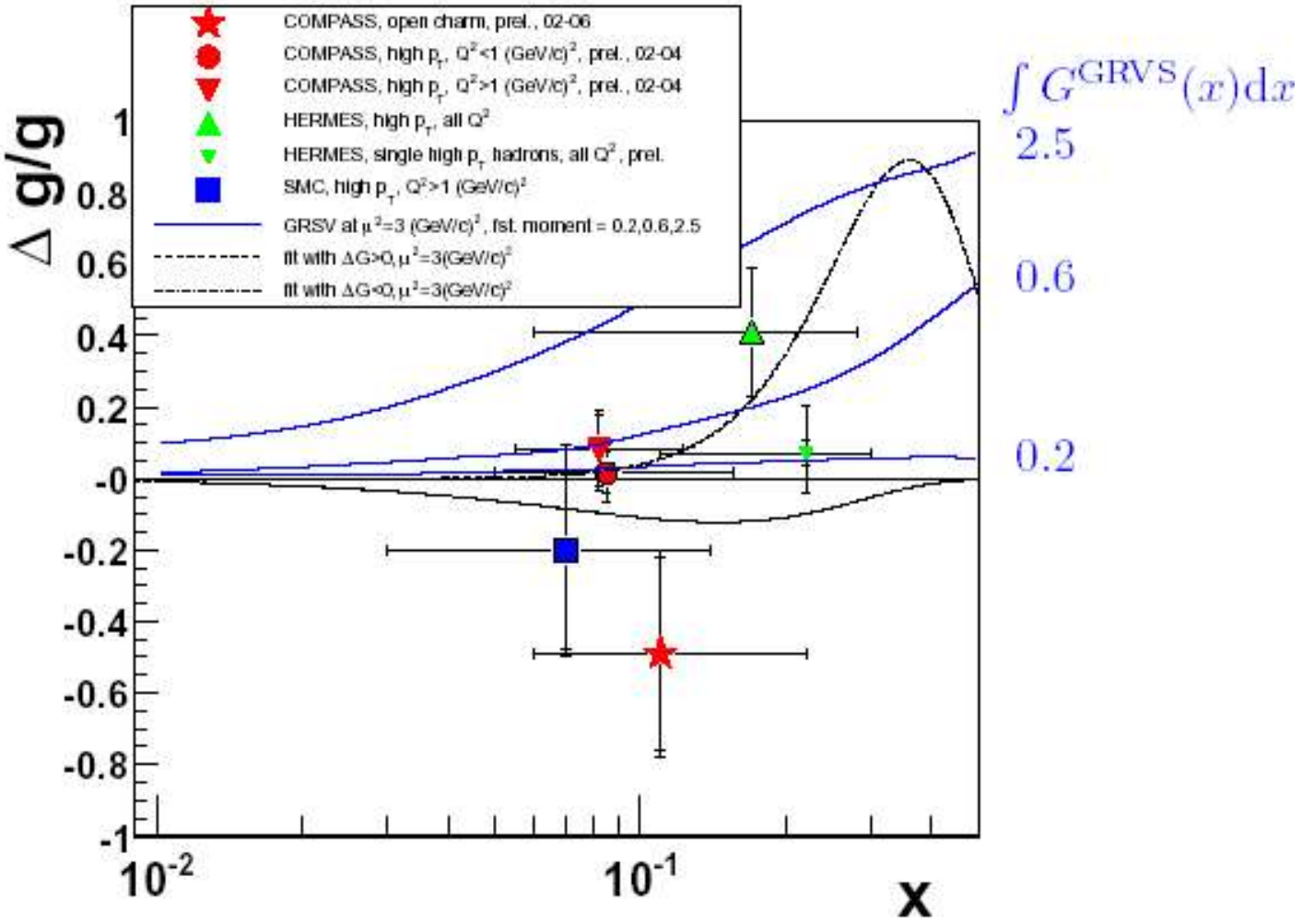
- If q≡ c $\Longrightarrow$ a pair of charmed mesons (we demand only one) in the final state;
  - measurement difficult (low statistics),
  - NLO corrections may be important.
- If q≡ u,d,s $\Longrightarrow$ a pair of jets or (in COMPASS) of high-p_T hadrons;
  - measurement simple (high statistics),
  - strong physics background, MC – dependence.

Summary of the gluon polarisation measurements



At $x_g \sim 0.1$, $\Delta G/G$ is compatible with zero! Qualitative agreement with RHIC results.

Summary of the gluon polarisation measurements



- Restoration of $\Delta\Sigma$=0.6 via the axial anomaly improbable.
- Independent measurement of orbital momentum necessary!

Orbital angular momentum in the proton

Ways of constraining the orbital angular momentum

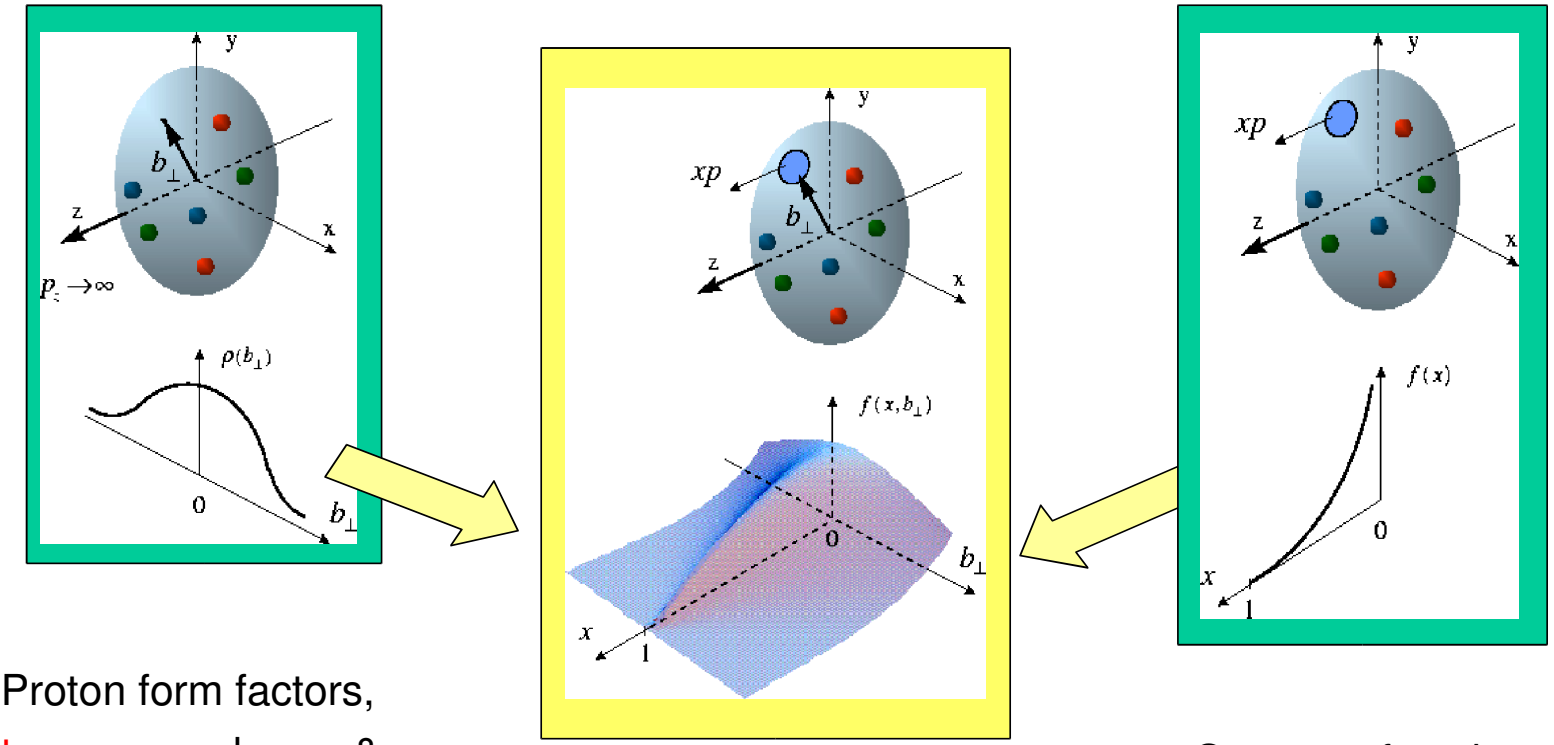
- Extract from the full, 3D decription of the proton $\Longrightarrow$ GPDs
- Measurement of asymmetries sensitive to e.g. the k_T of the partons (Sievers, Cahn ???)
- QCD calculations on the lattice
- X. Ji: evolution equations for J_q and J_g give the asymptotic solutions:

$$J_q(\mu^2 \to \infty) = \frac{1}{2}\frac{3n_f}{16+3n_f}, \qquad J_g(\mu^2 \to \infty) = \frac{1}{2}\frac{16}{16+3n_f}$$

L cannot be negligible!

3D picturing of the proton *via* GPD

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Slide from V.D. Volker, LANL 2007

Access GPD through the DVCS mechanism

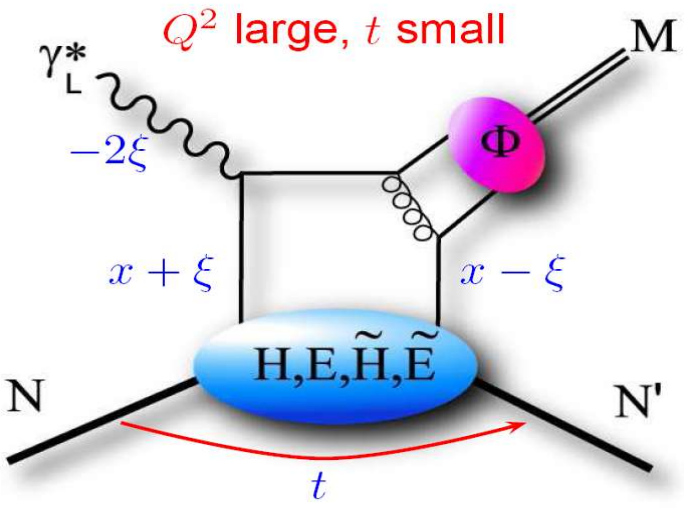


Figure from A. Sandacz, EINN, 2007

- Four GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons
- Factorisation proven for σ_L only
- All depend on 3 variables: x, ξ, t; DIS @ $\xi = t = 0$
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
- $H^q(x,0,0) = q(x)$, $\widetilde{H}^q(x,0,0) = \Delta q(x)$
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions

- H, E accessed in vector meson production *via* A_{UT} asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* A_{UT} asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over x give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors resp.
- Important: $J^q_z = \frac{1}{2}\int dx\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = \frac{1}{2}\Delta\Sigma + L^q_z$ (X. Ji)

DVCS data taken or expected soon; future projects

- Data being analysed:
  - Z1 and ZEUS: cross section for ρ^0, ϕ, J/ψ, Υ production
  - HERMES: cross section for ρ^0, ϕ, BCA, BSA, TSA (π^+)
  - CLAS: cross section for $\rho^+, \phi, \pi^+, \pi^0, \eta$
- Data taken or expected
  - DVCS Coll. (JLAB, Hall A): cross section for π^0 (2009)
  - CLAS: BSA, TSA (2009)
  - COMPASS: muoproduction of ρ^0 on the proton (2007 data)
- Future
  - COMPASS upgrade for DVCS, DVMP ($\sim$ 2010)
  - JLAB 12 GeV upgrade ($\gtrsim$ 2014)
  - PANDA @ FAIR ($\gtrsim$ 2014)
  - EIC/ELIC ($\gtrsim$??)
- First results constraining E and H (and thus orbital momentum) and DVMP models; L_q close to zero ?

Orbital angular momentum in the proton: results from lattice QCD

- In the sum rule: $\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$

- total spin: $J_q^u = 0.22 \pm 0.02, \qquad J_q^d = 0.00 \pm 0.02$
- *OAM* : $L^u = 0.20 \pm 0.04, \qquad L^d = -0.20 \pm 0.04$

$$\Longrightarrow \quad L_q = 0 \ ?$$

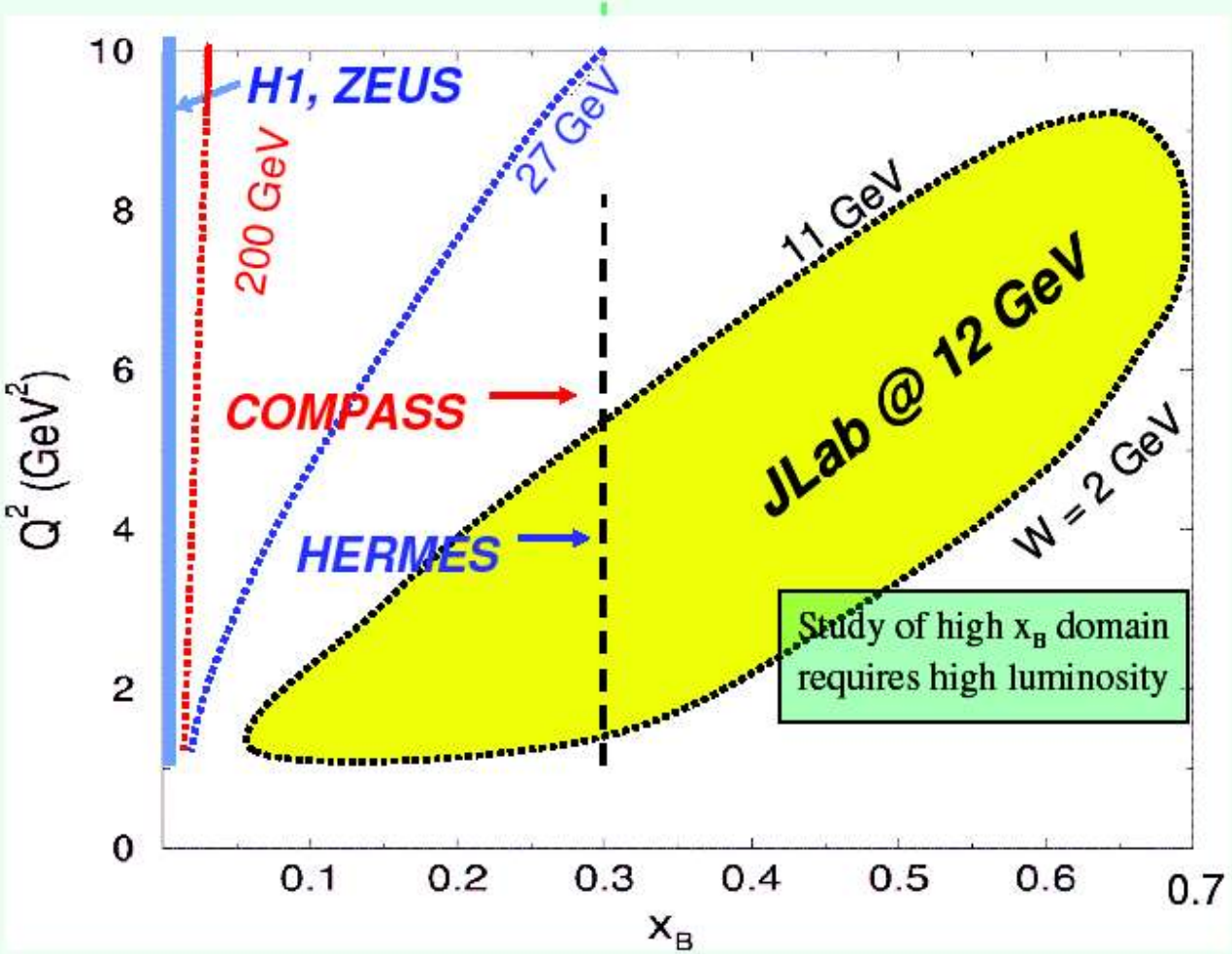
- Errors do not contain the systematic part (hard to estimate) !
- Results on L_q in line with the DVCS results of HERMES, JLAB.

P. Hägler, DIS2008

Future

CEBAF 12 GeV upgrade

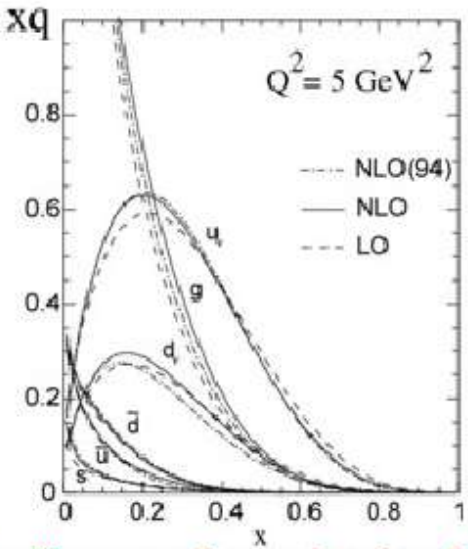
Deeply Virtual Exclusive Processes -
Kinematics Coverage of the 12 GeV Upgrade



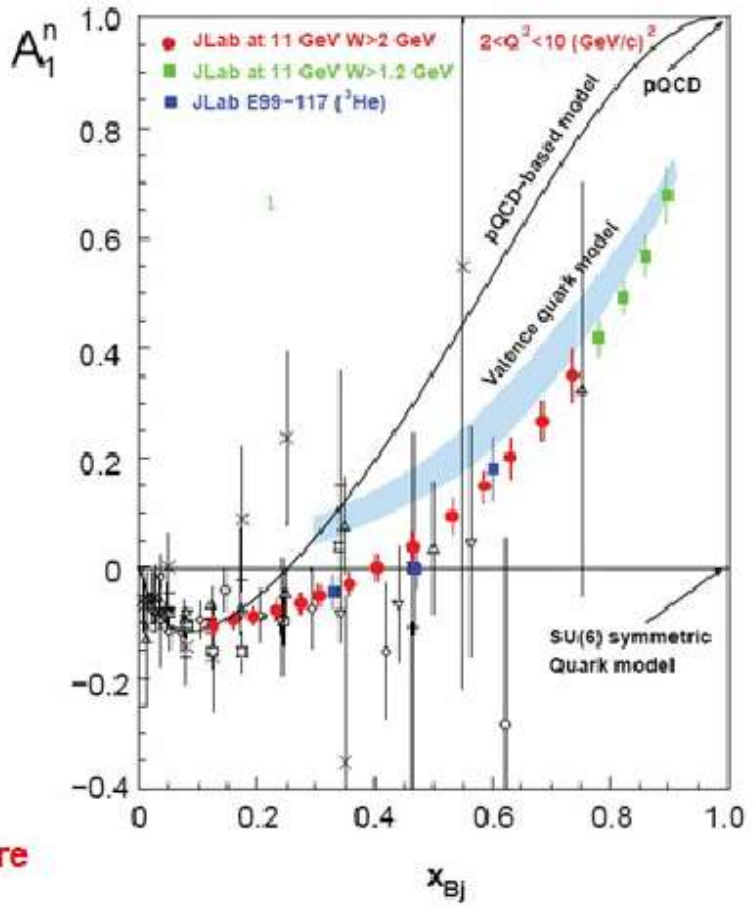
Future: high x structure functions at JLAB 12 GeV

REQUIRES:

- High beam polarization
- High electron current
- High target polarization
- Large solid angle spectrometers



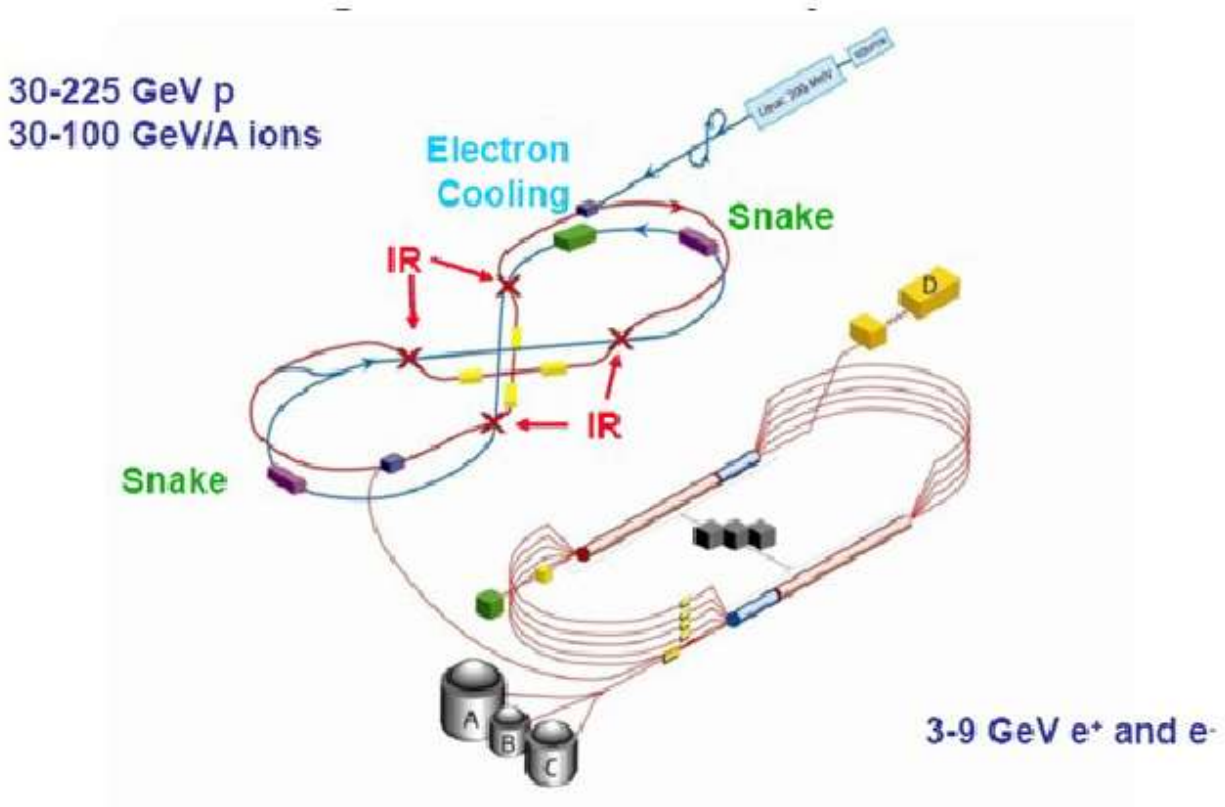
12 GeV will access the regime (x > 0.3), where valence quarks dominate



Slide from H. Montgomery, SPIN 2008

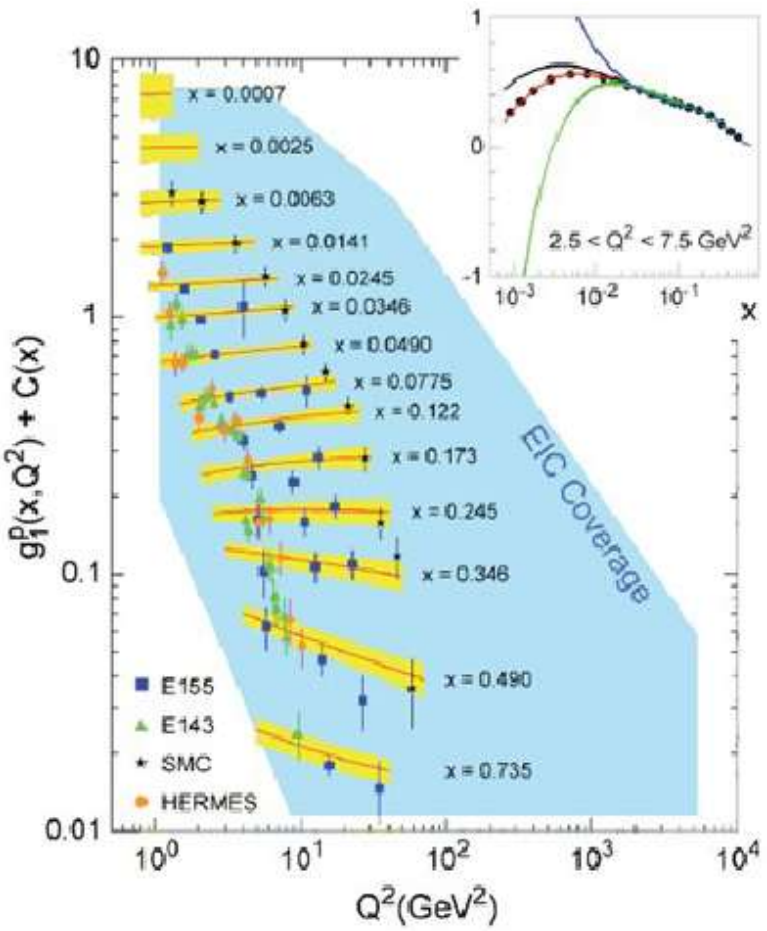
Future: Electron–Ion Collider, EIC

- LHeC @ CERN
- eRHIC @ BNL
- ELIC @ JLAB
- MANUEL @ FAIR (GSI)



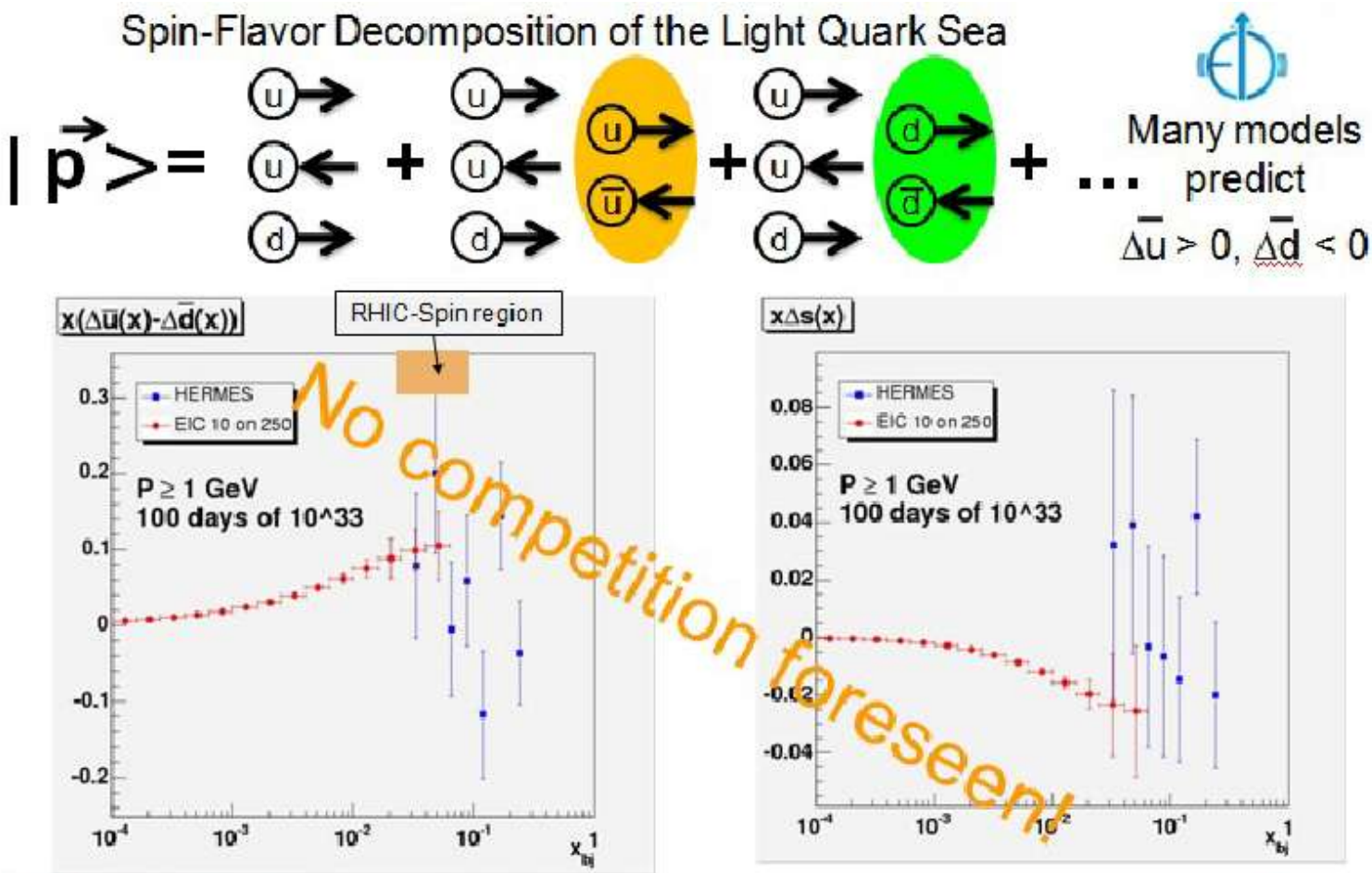
Slide from H. Montgomery, SPIN 2008

Future: Electron–Ion Collider, EIC,...cont'd



Slide from H. Montgomery, SPIN 2008

Future: Electron–Ion Collider, EIC,...cont'd



Slide from H. Montgomery, SPIN 2008

Outline

Outlook

- We have learned a lot about the polarised PDFs (helicity, transversity) in the last 20 years.
- “Spin puzzle”: restoration of $\Delta\Sigma = 0.6$ via the axial anomaly improbable. Significant orbital angular momentum in the proton expected; must find a way to expose it $\Longrightarrow$ DVCS!
- Much experimental and theoretical progress in analysing the physics mechanism of the Single–Spin–Asymmtries.
- More data await analysis (HERMES, COMPASS, RHIC, JLAB); new data come (COMPASS, RHIC); new experiments soon (COMPASS II (2010), JLAB 12 (2014)).
- Polarised EIC badly needed!

THANKS, Jan!