

Longitudinal Spin Structure of The Nucleon

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- Nucleon spin
- Gluon polarization : direct measurements
evaluation from QCD g_1 analysis
- Polarized quark distributions

Nucleon Spin $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$
 quark gluon orbital momenta

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$$\Delta q = \vec{q} - \vec{\bar{q}}$$

$\Delta\Sigma$ Predictions:

- Naive quark parton model + relativistic corr. $\Delta\Sigma \sim 0.75$
- QCD ; Ellis- Jaffe assuming $\Delta s = 0$, $\Delta\Sigma \sim 0.60$

$\Delta\Sigma$ Measurements:

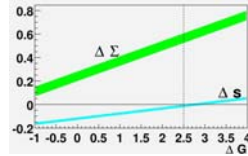
Polarized DIS $\vec{l} \vec{N}$ spin asymmetry $A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1}{F_1}$

$\int_0^1 g_1 dx$ + neutron and hyperon decay measurements
 to determine a_0 , singlet axial matrix element,
 related to $\Delta\Sigma$

Quark contribution to Nucleon Spin

World data on $g_1 \rightarrow a_0 \sim 0.2 - 0.3$

- Quark Parton Model, $a_0 = \Delta\Sigma$
- QCD (AB scheme) $a_0 = \Delta\Sigma - n_f (\alpha_s/2\pi) \Delta G$



For $a_0 = 0.3$, need large $\Delta G \sim 2.5$ (and $L_z \sim -2.3$)
to restore $\Delta\Sigma \sim 0.6$

→ motivated direct measurements of ΔG

How to extract ΔG ?

- Polarized Lepton Nucleon Scattering

HERMES, (SMC), COMPASS

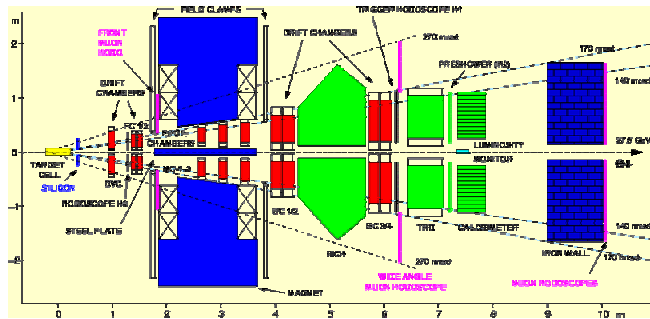
- Polarized pp collisions PHENIX, STAR

- QCD fits : Q^2 evolution of g_1

HERMES

Beam: 27.5 GeV e^\pm ; $\langle 50 \rangle\%$ polarization

Target: (un)-polarized gas targets; $\langle 85 \rangle\%$ polarization



ΔG , Δq all flavors, transversity, GPDs, ...

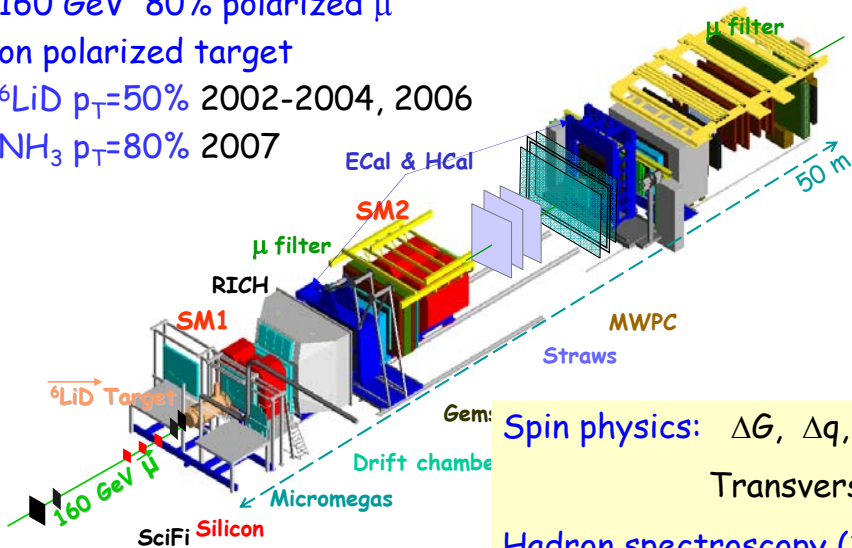
COMPASS

160 GeV 80% polarized μ

on polarized target

${}^6\text{LiD}$ $p_T=50\%$ 2002-2004, 2006

NH_3 $p_T=80\%$ 2007



Gem: Spin physics: ΔG , Δq , g_1 , ...

Transversity...

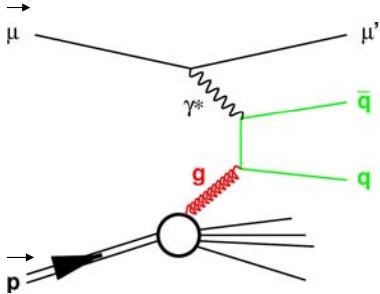
Hadron spectroscopy (2008)

GPDs (2010)...

$\Delta G/G$ from Polarized Lepton Nucleon Scattering

$\Delta G/G$ measurement

Photon gluon fusion $\gamma g \rightarrow q\bar{q}$



• charm $c \rightarrow D^0 \rightarrow K \pi$

scale $\mu^2 = 4 m_c^2$

theory understood, but:

combinatorial background & limited stat:

$\sigma = 100 \text{nb}$, BR = 4%, kaon identification

COMPASS

• high p_T hadron pair $q\bar{q} \rightarrow h h$

• scale $\mu^2 = Q^2$ or Σp_T^2

large statistics

but physical background

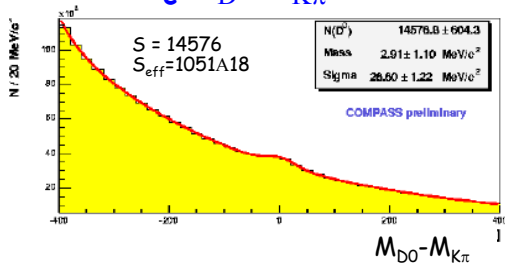
HERMES +
COMPASS

COMPASS open charm

See talk by S.Koblitz

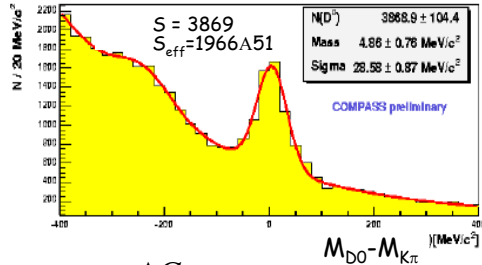
D^0

$c \rightarrow D^0 \rightarrow K\pi$



D^0 tagged by D^*

$c \rightarrow D^* \rightarrow D^0 \pi_s \rightarrow K\pi\pi_s$



$$\langle A_{LL} / D \rangle = \frac{S}{S+B} \langle a_{LL} / D \rangle \frac{\Delta G}{G}(x_g)$$

2002-2004 data, d target

$$\Delta G/G = -0.57 \pm 0.41$$

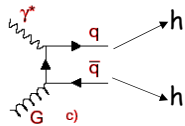
$$\langle x_g \rangle = 0.15 \quad \text{scale } \mu^2 = 13 \text{ GeV}^2$$

2006 data to come...

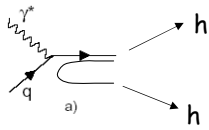
$\Delta G/G$ from high p_T hadron pairs

- $Q^2 > 1 \text{ GeV}/c^2$ COMPASS
- $Q^2 < 1 \text{ GeV}/c^2$ } HERMES +
- 1 hadron } COMPASS

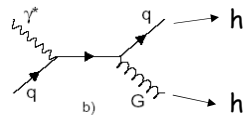
COMPASS $\Delta G/G$, high p_T hadron pairs $Q^2 > 1 \text{ GeV}^2/c^2$



Photon Gluon Fusion (PGF)



Leading process



Gluon radiation

PGF $\sim 33\%$ (Lepto MC)

$$\frac{A_{||}}{D} = R_{pgf} \left\langle \frac{\hat{a}_{pgf}}{D} \right\rangle \left(\frac{\Delta G}{G} \right)^d + \dots \quad \left\{ \begin{array}{l} \Sigma p_T^2 > 2.5 \text{ GeV}^2 \text{ (LO suppr)} \\ x_{Bj} < 0.01 \quad \quad \quad (A_1 \text{ small}) \end{array} \right.$$

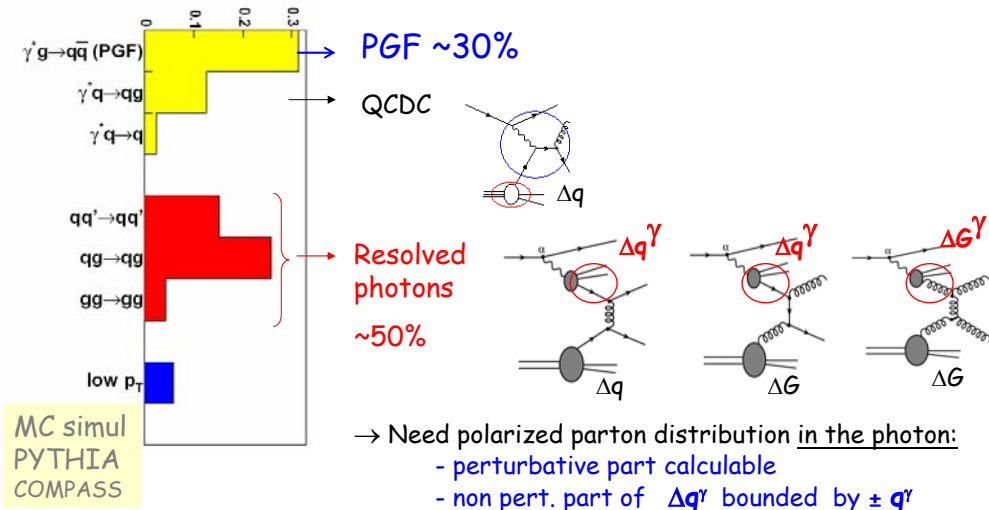
COMPASS 2002-2003 data:

$$\Delta G/G = 0.06 \pm 0.31 \text{ (stat)} \pm 0.06 \text{ (syst)} \quad \langle x_g \rangle \sim 0.13$$

Value compatible with 0. Systematics small

COMPASS $\Delta G/G$, high p_T hadron pairs $Q^2 < 1 \text{ GeV}^2/c^2$

$Q^2 < 1$ 10 times more data, but additional background: resolved photon processes



\rightarrow Estimation of the limited theoretical uncertainty for ΔG

COMPASS $\Delta G/G$, high p_T hadron pairs

$Q^2 < 1 \text{ GeV}^2$ $x_g=0.085$, $\mu^2=3 \text{ GeV}^2$ 2002-2004 data

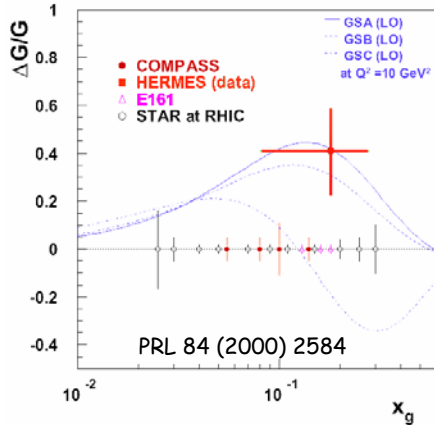
$$\Delta G/G = 0.016 \pm 0.058 \text{ (stat)} \pm 0.055 \text{ (syst)}$$

$\Delta G/G$ compatible with 0. Statistics and systematics small

→ Two independent COMPASS results ($Q^2 < 1$ and $Q^2 > 1$)
consistent with zero

HERMES $\Delta G/G$, high p_T hadron pair all Q^2

2000: 'old' HERMES point shown with 'old' projections



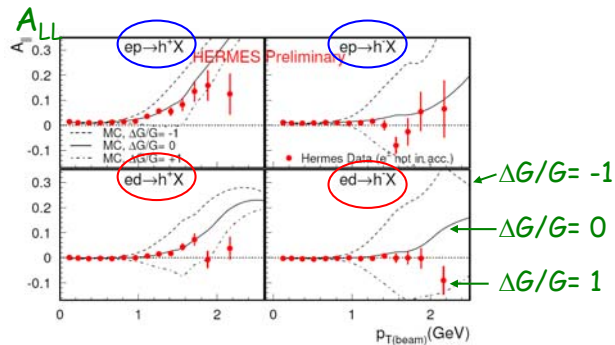
HERMES A_{LL} , high p_T hadrons all Q^2

"New point" :

Spin asymmetry for
various signatures,

p and d targets

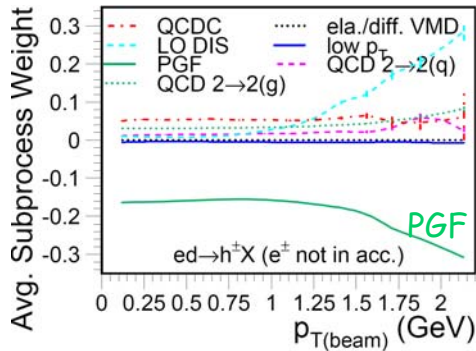
$e d \rightarrow h^+ (h^-) (e')$



HERMES, new point, high p_T hadrons

all Q^2

Competing subprocesses weight



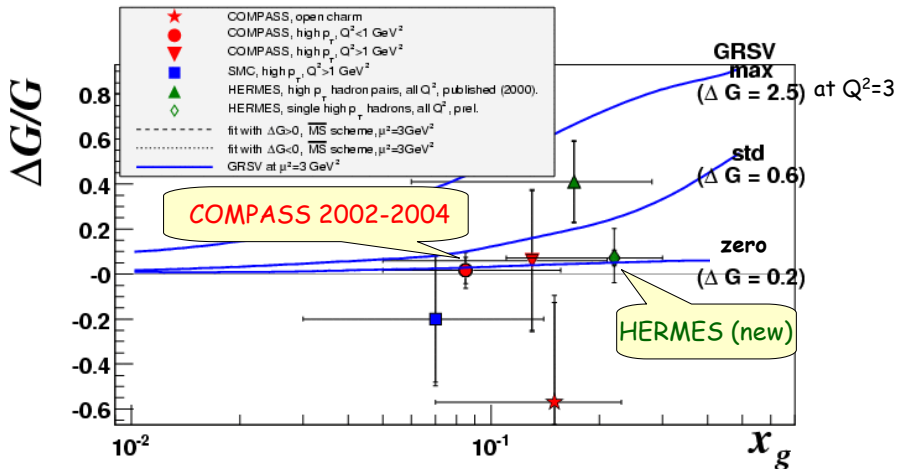
$\langle x_g \rangle = 0.22, \mu^2 = 1.35 \text{ GeV}/c^2$

$$\Delta g/g(x_g, \mu^2) = 0.071 \pm 0.034(\text{stat}) \pm 0.010(\text{sys-exp}) \begin{matrix} -0.127 \\ -0.105 \end{matrix} (\text{sys-model})$$

Syst. model uncertainties still dominating (PDFs, PYTHIA model)

HERMES new result: $\Delta G/G$ is likely small

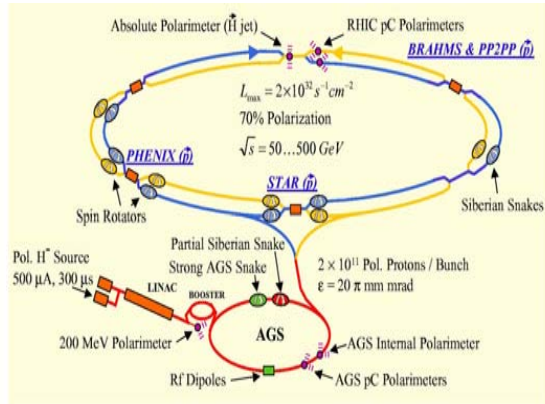
$\Delta G/G$ direct measurements



— GRSV: Gluck, Reya, Stratmann, Vogelsang PRD63 (2002) 094005

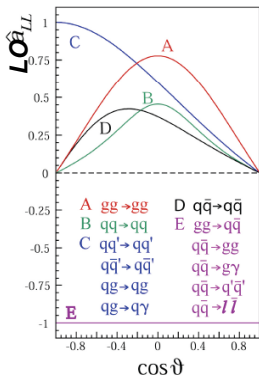
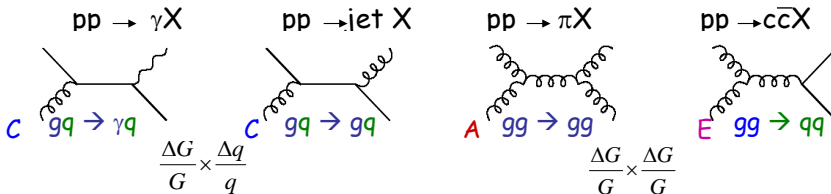
Large ΔG strongly disfavoured

$\Delta G/G$ $\vec{p}\vec{p}$ collisions at RHIC



$\Delta G/G$ $\vec{p}\vec{p}$ collisions PHENIX and STAR

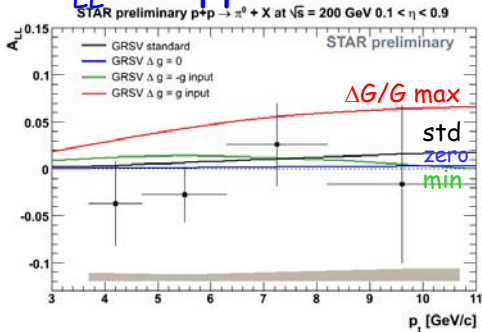
Various channels detected, sensitive to **gluon** at LO:



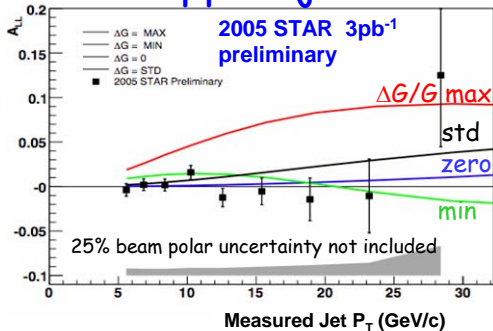
- Different kinematics and systematics
- Beam energies 200 - 500- 64 GeV
 → p_T or x_g range

STAR - A_{LL} results

A_{LL} for $pp \rightarrow \pi^0 X$



$pp \rightarrow \text{jet} + X$

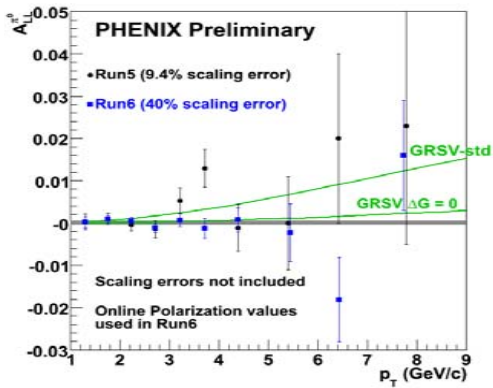


GRSV scenario for ΔG at $Q_0^2 = 1$ (GeV/c)²:

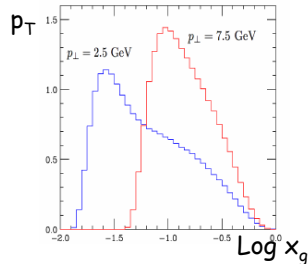
{	max	1.9
	min	-1.8
	Std	0.4
	'zero'	0.1

GRSV max scenario disfavored

PHENIX - A_{LL} for $pp \rightarrow \pi^0$



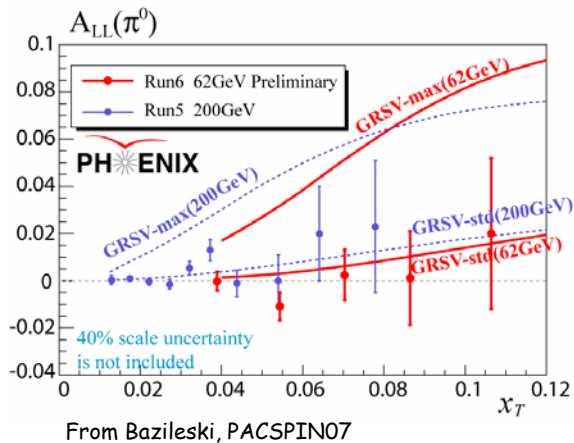
Run3,4,5: PRL 93, 202002; PRD 73, 091102;
hep-ex-0704.3599



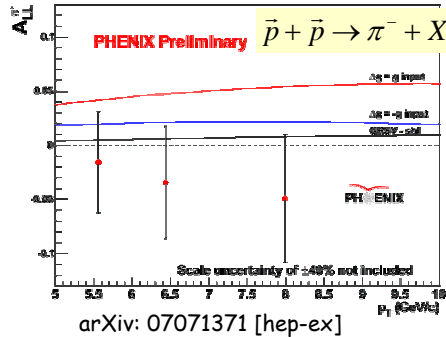
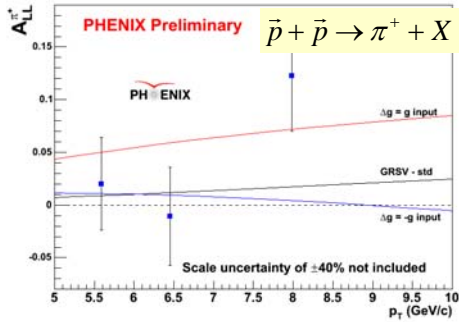
Overlapping p_T bins cover wide range in x_g : $p_T=2-9 \text{ GeV/c} \rightarrow x_g=0.02-0.3$

- GRSV model: $\Delta G(x_g=0.02 \rightarrow 0.3) \sim 0.6 \cdot \Delta G(x_g=0 \rightarrow 1)$
- "GRSV-std" excluded by data on >3 sigma level (Vogelsang and Stratmann, stat. only)

PHENIX 200 & 62 GeV



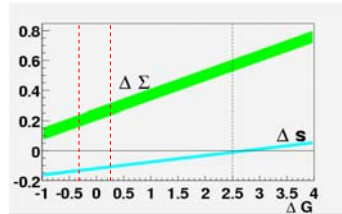
PHENIX π^+ , π^-



- Different sensitivities of charged pions to Δu and $\Delta d \rightarrow$ more sensitivity to sign of ΔG
- Less background than in π^0
- Statistics run05: no constraint on ΔG yet. (2.7 smaller for run06)
- Problem in fragmentation functions?

Gluon polarization and nucleon spin (from direct measurements)

- $\Delta G = \int \Delta G(x) dx$ not large
- $\Rightarrow \Delta \Sigma \sim 0.3$ small (\neq predictions)
- Consequence for spin decomposition



$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$

- possible scenarios:
- $\frac{1}{2} 0.3 + 0.35 + 0.0$
 - $\frac{1}{2} 0.3 + 0.0 + 0.35$
 - ... or even $\Delta G < 0$

$\Delta G/G$ from QCD fits
Global analysis of g_1 world data

Global analysis of g_1 world data

DGLAP evolution equations rule $\partial / \partial \ln Q^2$
dependence of parton distribution functions

Method

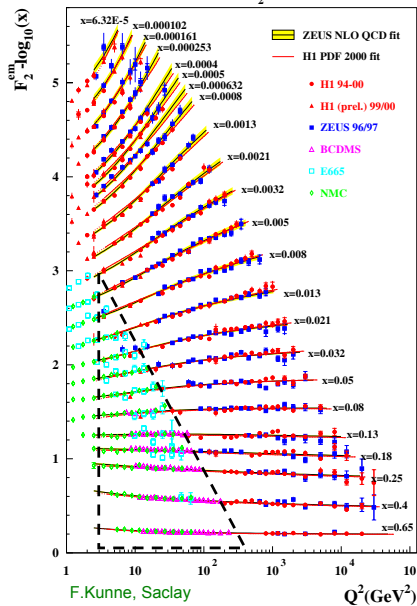
- parameterize parton distributions at Q_0^2
e.g. $\Delta q_i \sim x^{\alpha_i} (1-x)^{\beta_i} (1+\gamma_i x)$
- DGLAP evolution to measured Q^2
- calculate g_1 and fit all g_1 data together

$\Delta\Sigma$ and ΔG coupled in the evolution

→ Indirect determination of $\Delta G(x)$, assuming an initial parameterization

Fonctions de structure du proton (x, Q^2)

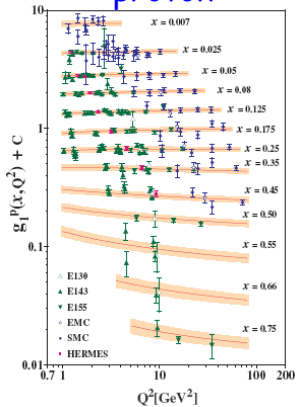
F_2^p unpolarized DIS



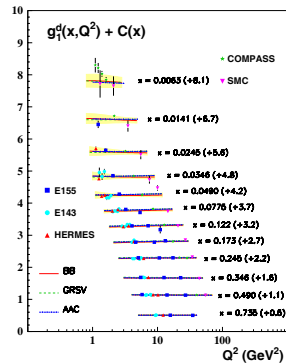
Big lever arm in x and Q^2

→ High precision for g_1^p polarized DIS

proton



deuteron



QCD fits of g_1

Various NLO pQCD global analyses of world data on $g_1^{p,d,n}$ with different parameterizations

Results : Δu Δd well constrained, but ΔG shape unknown

Progress when including new data, e.g.:

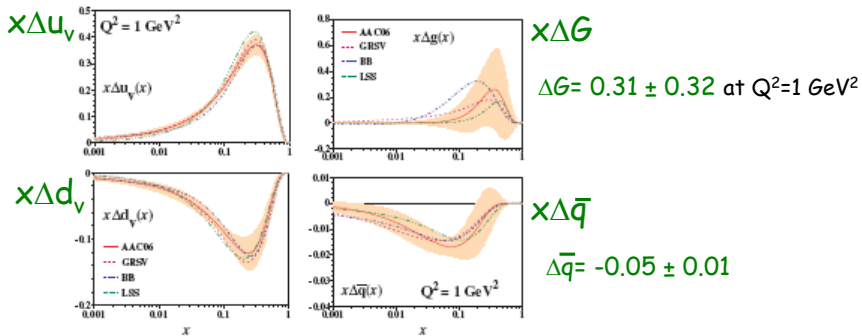
- AAC06 analysis including g_1 new data from HERMES, COMPASS and JLAB + PHENIX $A_{LL} \pi^0$

AAC -hep-ph/0603213

- COMPASS analysis

...

Global QCD analyses: AAC, BB, LSS, GRSV ...

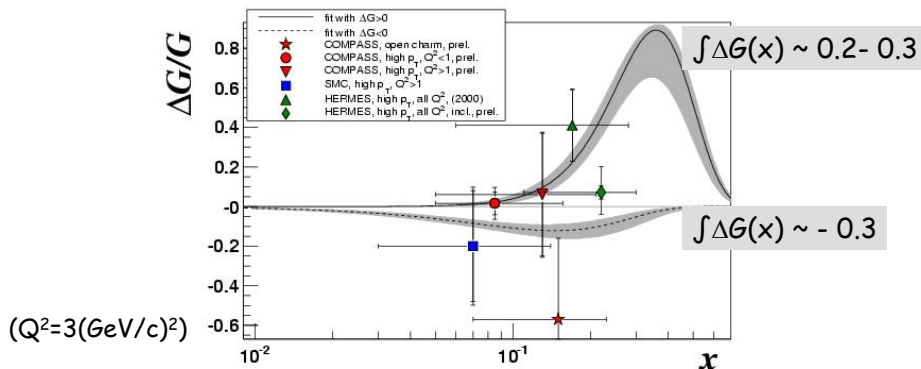


AAC - NLO, hep-ph/0603213

Compared to GRSV, BB and LSS

COMPASS - Global QCD NLO g_1 analysis

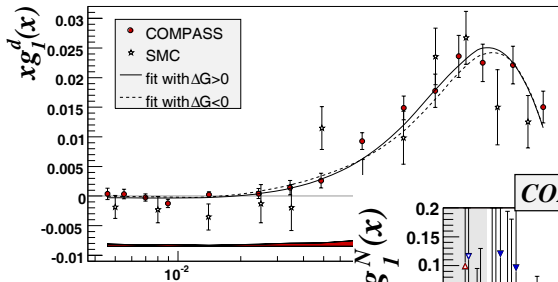
→ two solutions, one with $\Delta G > 0$, the other with $\Delta G < 0$



ΔG measurements not included in fits

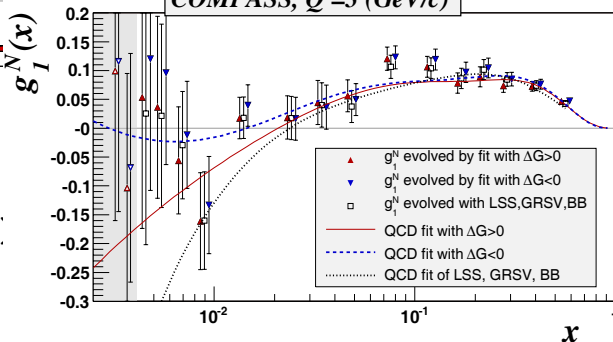
- For both solutions, small first moment $|\Delta G| \sim 0.2 - 0.3$
- $\Delta \Sigma = 0.30 \pm 0.01$ (stat.) ± 0.02 (evol.)
- $\Delta s = -0.08 \pm 0.01 \pm 0.02$ (← COMPASS data alone)

Impact of low x data



$\Gamma_1 = \int g_1(x) dx$:
 only 2% correction from
 unmeasured low x
 (was 50% negative before)

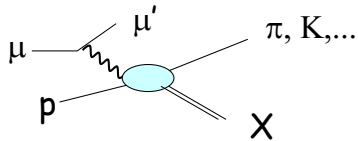
COMPASS, $Q^2=3 (GeV/c)^2$



Disagreement of new data with earlier QCD fits

Flavor separation $\Delta u, \Delta d, \Delta \bar{q}, \Delta s$

Semi-inclusive DIS : $\mu p \rightarrow \mu' h X$



Outgoing hadron
→ quark flavor

Fragmentation
function D_q^h

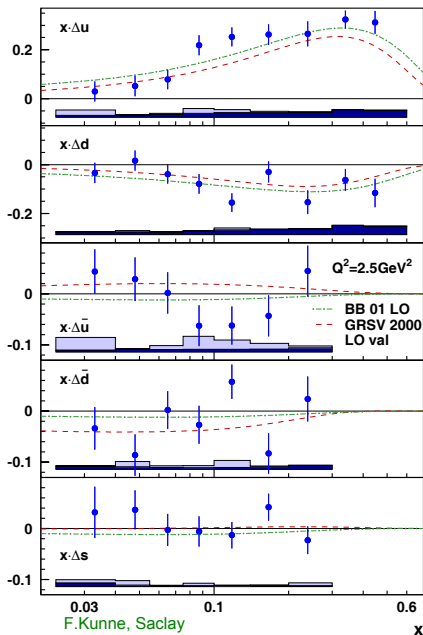
$$A_1^{h(p/d)} = \frac{\sum_q e_q^2 D_q^h \Delta q}{\sum_q e_q^2 D_q^h q}$$

$$D_q^h(z, Q^2)$$

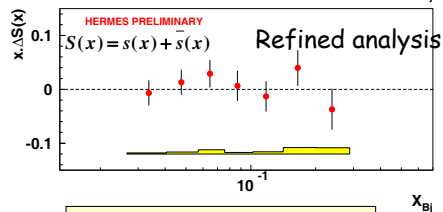
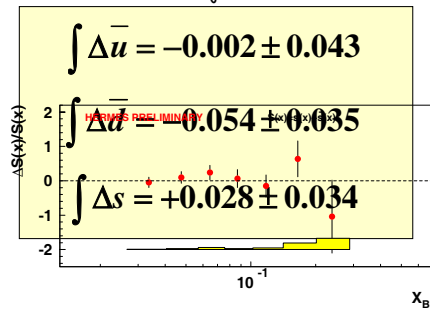
$$z = E_h / \nu$$

deuteron & proton data necessary

HERMES semi inclusive : Δu Δd $\Delta \bar{u}$ $\Delta \bar{d}$ Δs



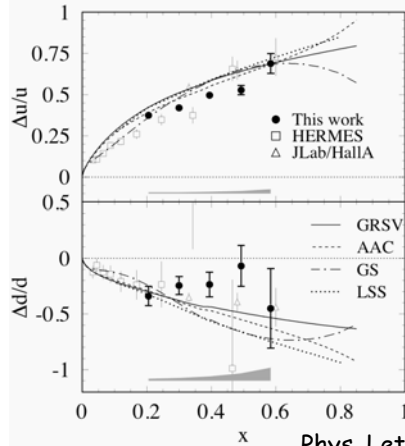
In measured x_{Bj} range (0.023 - 0.6)



$\int_{0.02}^1 \Delta S = 0.006 \pm 0.029 \pm 0.007$

JLab $\Delta q/q$ high x

EG1 collab.
Hall B



Phys. Lett. B 641 (2006) 11

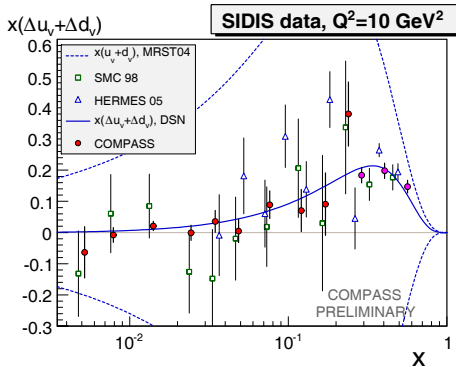
High x data improve NLO PDF fits

COMPASS Semi inclusive : valence/sea

Only deuteron data $\mu d \rightarrow \mu' h X$ $D_q^h \neq D_{\bar{q}}^h \rightarrow$ separate valence and sea
 $u_v = u - \bar{u}$

See talk by W. Wislicki

$$\text{LO: } A^{h^+ - h^-}(x) = \frac{\Delta u_v(x) + \Delta d_v(x)}{u_v(x) + d_v(x)}$$



Integrals:

- $\Delta u_v + \Delta d_v = 0.41 \pm 0.07 \pm 0.05$

- using $\Delta u_v + \Delta d_v$, Γ_1 and a_8 :
 $\Delta \bar{u} + \Delta \bar{d} = 0.00 \pm 0.04 \pm 0.03$

Data favor $\Delta \bar{u} = -\Delta \bar{d}$, in contrast with usual assumption: $\Delta \bar{u} = \Delta \bar{d} = \Delta s = \Delta \bar{s}$, leading to $\Delta u_v + \Delta d_v = a_8 = 0.58$

Summary ...

- ΔG likely below 0.4, direct measurements & g_1 QCD fits
- $\Delta\Sigma \sim a_0$ now established (since ΔG small)

and low x contribution measured

• **Total Nucleon Spin:** $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

Possible scenarios

$$\left\{ \begin{array}{l} \frac{1}{2}0.3 + 0.35 + 0.0 \\ \frac{1}{2}0.3 + 0.0 + 0.35 \\ \dots \quad \text{or even } \Delta G < 0 \end{array} \right.$$

... and Outlook:

COMPASS: 2006+2007 stat., larger acceptance + improved RICH + 3-cell target; proton data. $\Delta G/G$, g_1 , semi-inclusive \rightarrow QCD fits

RHIC: More stat on π channels; new channels: γ +jet...; Δu and Δd

JLab: g_1 and semi-inclusive data \rightarrow QCD fits