Gluon polarisation in the nucleon from COMPASS

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on behalf of the COMPASS Collaboration

DIFFRACTION 2006
International Workshop on Diffraction in High-Energy Physics
5-10 September 2006
Adamantas, Milos, Greece

COmmon Muon Proton Apparatus for Structure and Spectroscopy COMPASS

Bielefeld,Bochum,Bonn,Burdwan/Calculta,CERN,Dubna,Erlangen, Freiburg,Lisbon,Mainz,Moscow,Munich,Nagoya,Prague,Protvino, Saclay,Tel Aviv,Turin,Trieste,Warsaw, ~240 physicists

- Muon beam program:
  - gluon polarisation,
  - polarised quark distributions,
  - polarised fragmentation functions,
  - transversity,
  - Lambda polarisation,
  - vector meson production,
  - DVCS (future)
- Hadron beam program:
  - Primakoff reaction,
  - glueballs,
  - charmed baryons,
  - exotic charm states.

- longitudinally polarised muon beam
- longitudinally or transversely polarised deuteron (^{6}LiD) target
- momentum and calorimetry measurement
- particle identification

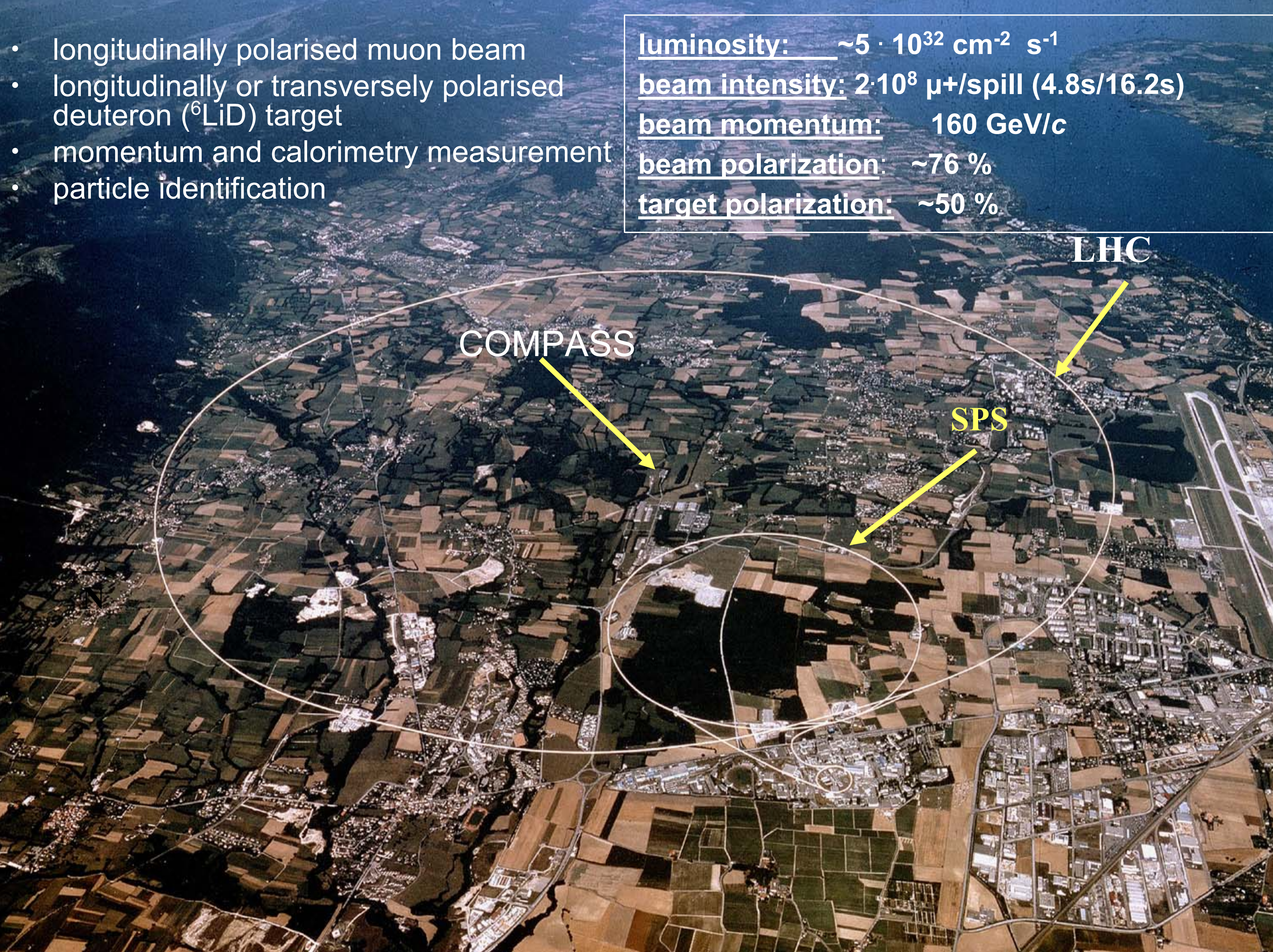
luminosity: ~$5 \cdot 10^{32}$ cm^{-2} s^{-1}

beam intensity: $2 \cdot 10^8$ μ+/spill (4.8s/16.2s)

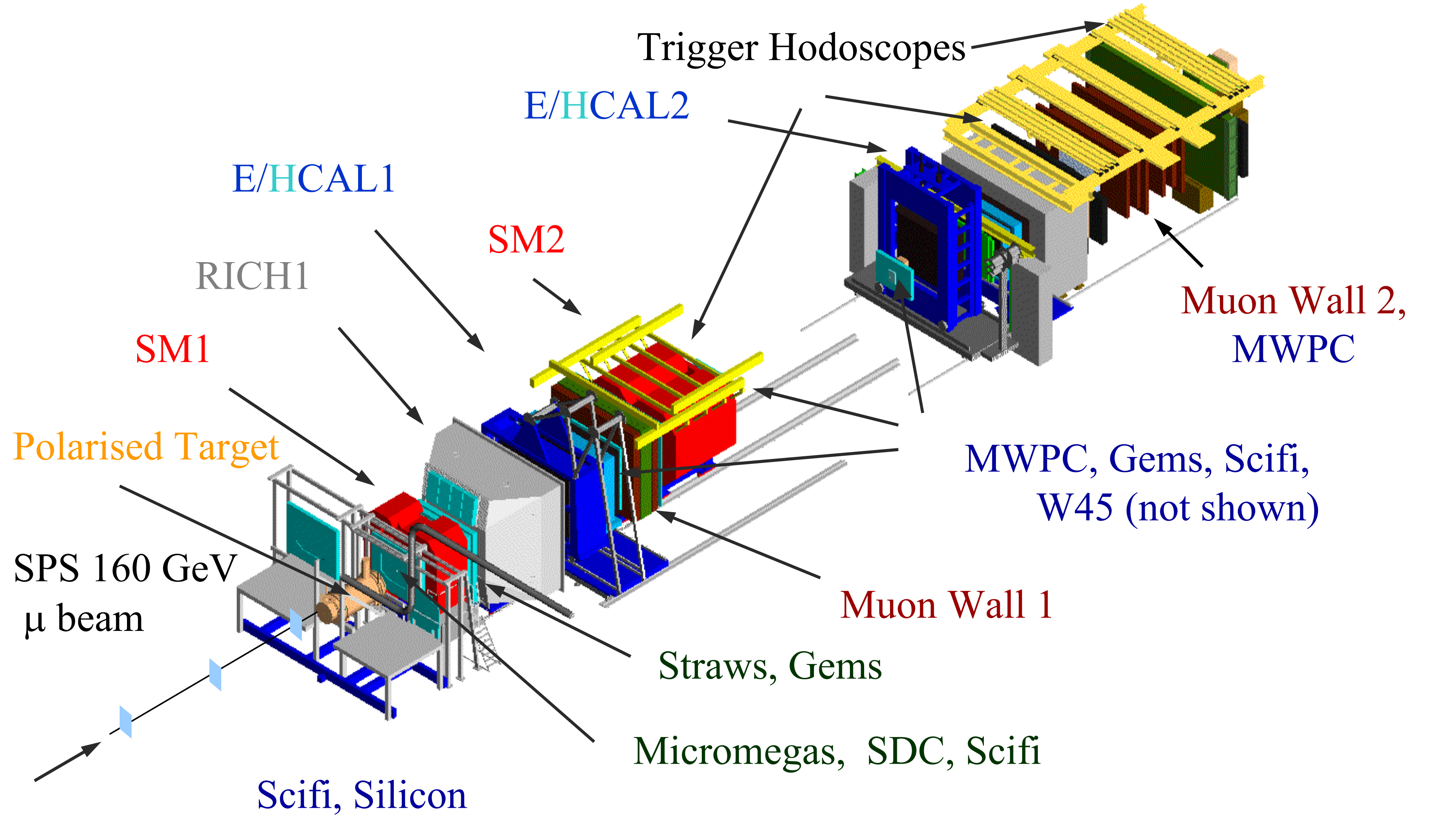
beam momentum: 160 GeV/*c*

beam polarization: ~76 %

target polarization: ~50 %

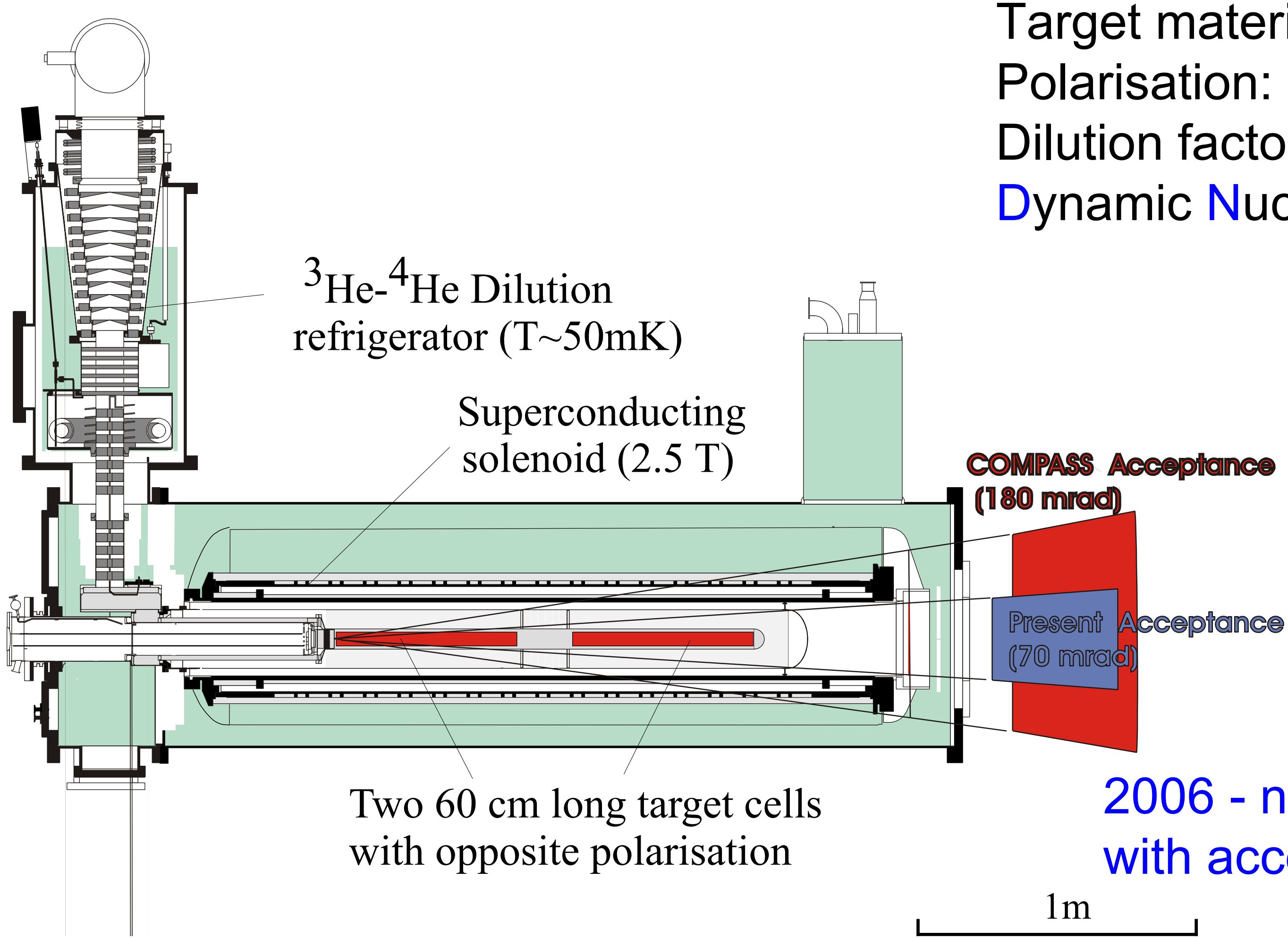


The COMPASS Spectrometer



The COMPASS polarised target

Target material: ^{6}LiD
Polarisation: >50%
Dilution factor: ~0.4
Dynamic Nuclear Polarisation



2006 - new solenoid
with acceptance 180 mrad

Content

- Motivation and Nucleon spin decomposition.
- Inclusive asymmetry A_1^d, structure function g_1^d and QCD analysis for $Q^2 > 1$ GeV^2 (fits).
- Gluon polarisation $\frac{\Delta G}{G}$

Two methods of accessing directly $\frac{\Delta G}{G}$ in Compass.

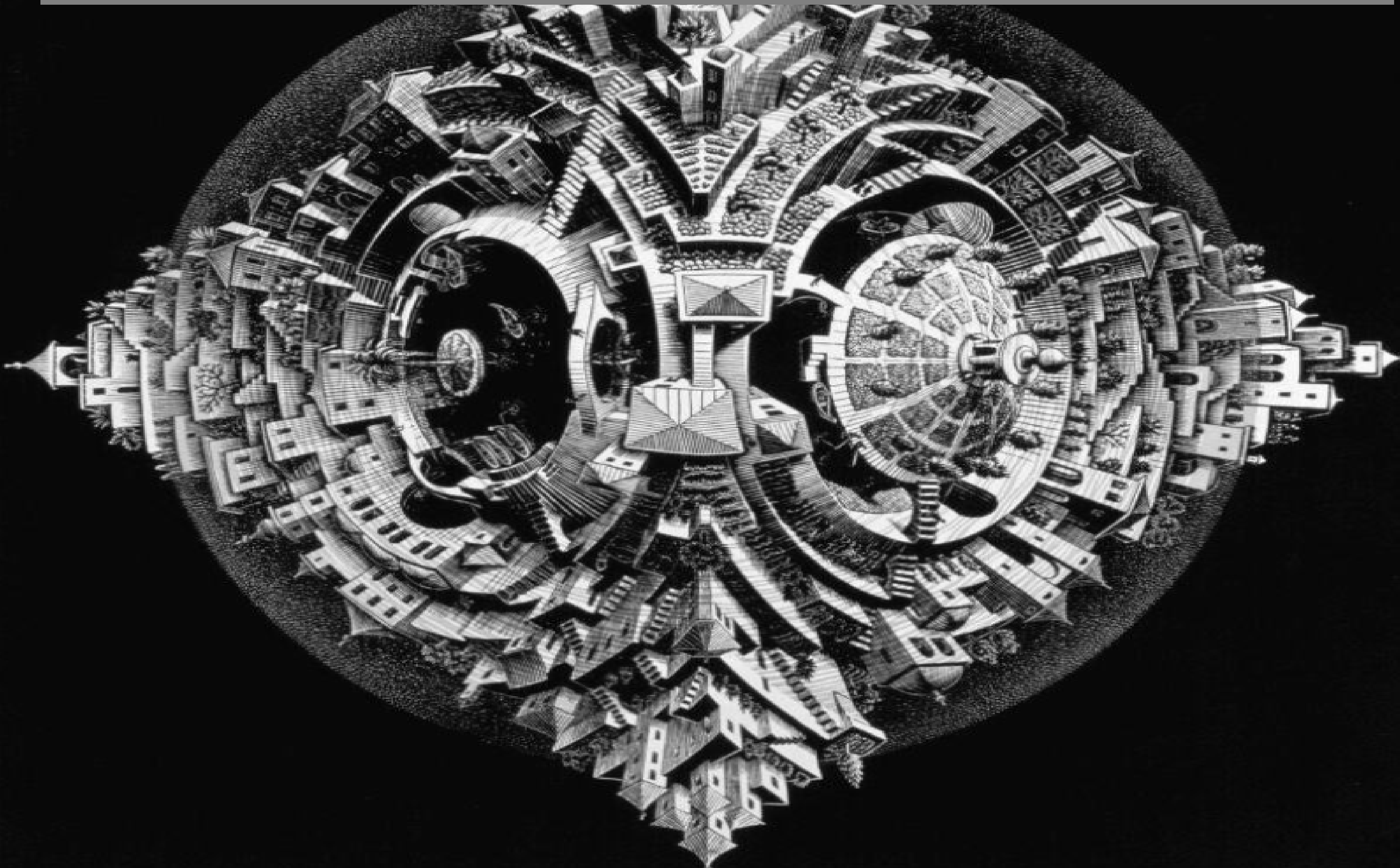
Open charm channel method and results.

High p_T hadron pairs method:

- Results for events with low Q^2.
- Results for events with $Q^2 > 1$ GeV^2.

- Conclusions.

Nucleon spin decomposition



Nucleon spin decomposition

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

- A very small fraction of the proton spin is carried by the spin of the quarks - put the naive but well-accepted quark model into serious questioning!
  (EMC (1988): $a_0 = \Delta\Sigma = 12 \pm 9 \pm 14\%$ while $\approx 60\%$ expected, confirmed by SMC, SLAC and Hermes : $\Delta\Sigma = 20 - 30\%$)
- The possible role of axial anomaly:
  measured quantity $a_0 = \Delta\Sigma - (3\alpha_S/2\pi)\,\Delta G$

- EMC – 1988 – 18 years ago: An impressive follow-ups:
  SLAC E142,E143,E155,E156, SMC, HERMES, JLAB spin physics, COMPASS, RHIC Spin, JLAB12 GeV Upgrade

Nucleon spin decomposition

$g_1(x) = ½\sum e_q^2 \Delta q(x)$ and $\Delta q(x) = q^+(x) - q^-(x)$;

Well defined in terms of quark helicity densities but:

$q+ \sim \Psi\,(1+\gamma_5)\,\gamma_\mu\Psi$, $q- \sim \Psi\,(1-\gamma_5)\gamma_\mu\Psi \Rightarrow \Delta q(x) \sim \Psi\gamma_5\gamma_\mu\Psi$

Axial vector current is not conserved due to

△ Adler-Bell-Jackiw anomaly ;

In a consequence:measured quantity $a_0 = \Delta\Sigma - (3\alpha_S/2\pi)\,\Delta G$.

where $\Delta\Sigma = \Delta u + \Delta d + \Delta s$, $\Delta q = \int \Delta q(x)dx$ and

$\Delta G = \int \Delta G(x)dx$ is a gluon polarization contribution.

Nucleon spin decomposition

$$\Gamma_1 = \int g_1(x)dx$$

$$\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6g_V} C_1^{NS}$$ (Bjorken sum rule)

$$\Gamma_1^{p,n} = \left(\pm a_3 + \frac{a_8}{\sqrt{3}} \right) \frac{C_1^{NS}}{12} + a_0 \frac{C_1^S}{9}$$ (Ellis-Jaffe sum rule)

$a_3, a_8, g_{A,V}$ - hyperon β decay + $SU_f(3)$;

$C_1^{S,NS}$ - calculable in QCD

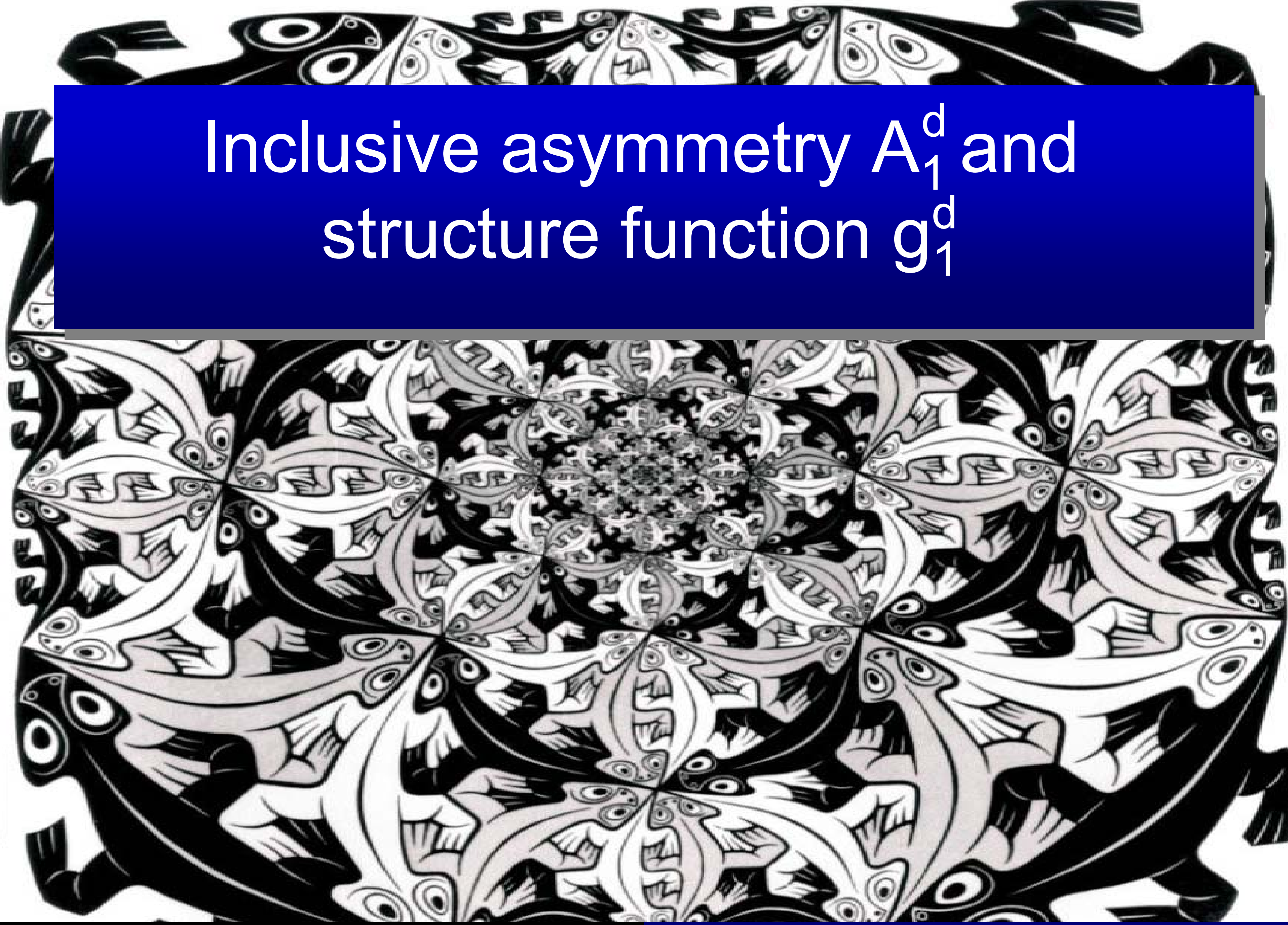
But - due to △ anomaly - $a_0 = \Delta\Sigma - (3\alpha_S/2\pi)\,\Delta G$ and

If $\Delta G \approx 2.5 \rightarrow \Delta\Sigma \approx 0.6 \rightarrow$ can "solve the spin crisis"

$\Downarrow$

Need direct measurement of ΔG

Inclusive asymmetry A_1^d and structure function g_1^d



A_1^d and structure function g_1^d

$$A^{\mu d} = A_{||} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = D\,(A_1^d + \eta\, A_2^d)$$

$|\eta\, A_2^{d,p,n}| \ll |A_1^{d,p,n}|$,

$$A_1^{p,n} = A^{\gamma N} = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}}$$ for nucleon

$$A_1^d = A^{\gamma d} = \frac{\sigma^0 - \sigma^2}{\sigma^0 + \sigma^2}$$ for deuteron

$A_{meas} \sim A^{\mu d} \sim A_1^d$;
Measurement of A_1 gives access to g_1 structure function

$$g_1^d = ½\,(g_1^p + g_1^n)\,(1 - \frac{3}{2}\omega_d) \simeq A_1^d\, F_1^d = A_1^d \frac{F_2^d}{2x(1+R)}$$

A_1^d and structure function g_1^d

- A_1^d and g_1^d for small Q^2 ($Q^2 < 1$ GeV^2):
  physics at small x, parton saturation,
  non-perturbative models (Regge,VDM)
  poorly known (only SMC data)

- A_1^d and g_1^d for high Q^2 ($Q^2 > 1$ GeV^2):
  QCD analysis possible: ΔG estimation

A_1^d and structure function g_1^d

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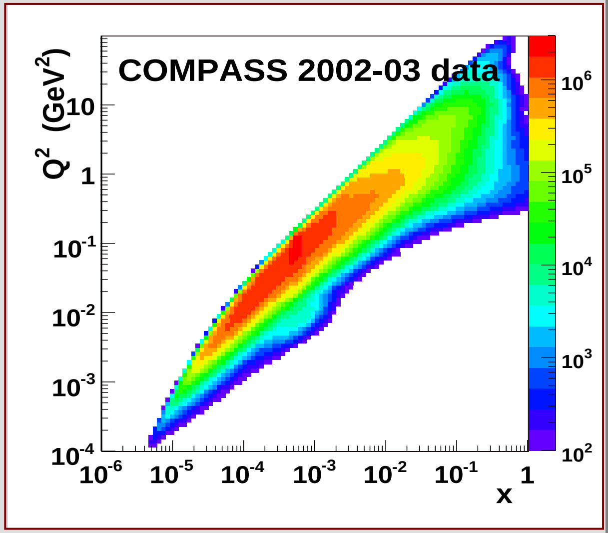
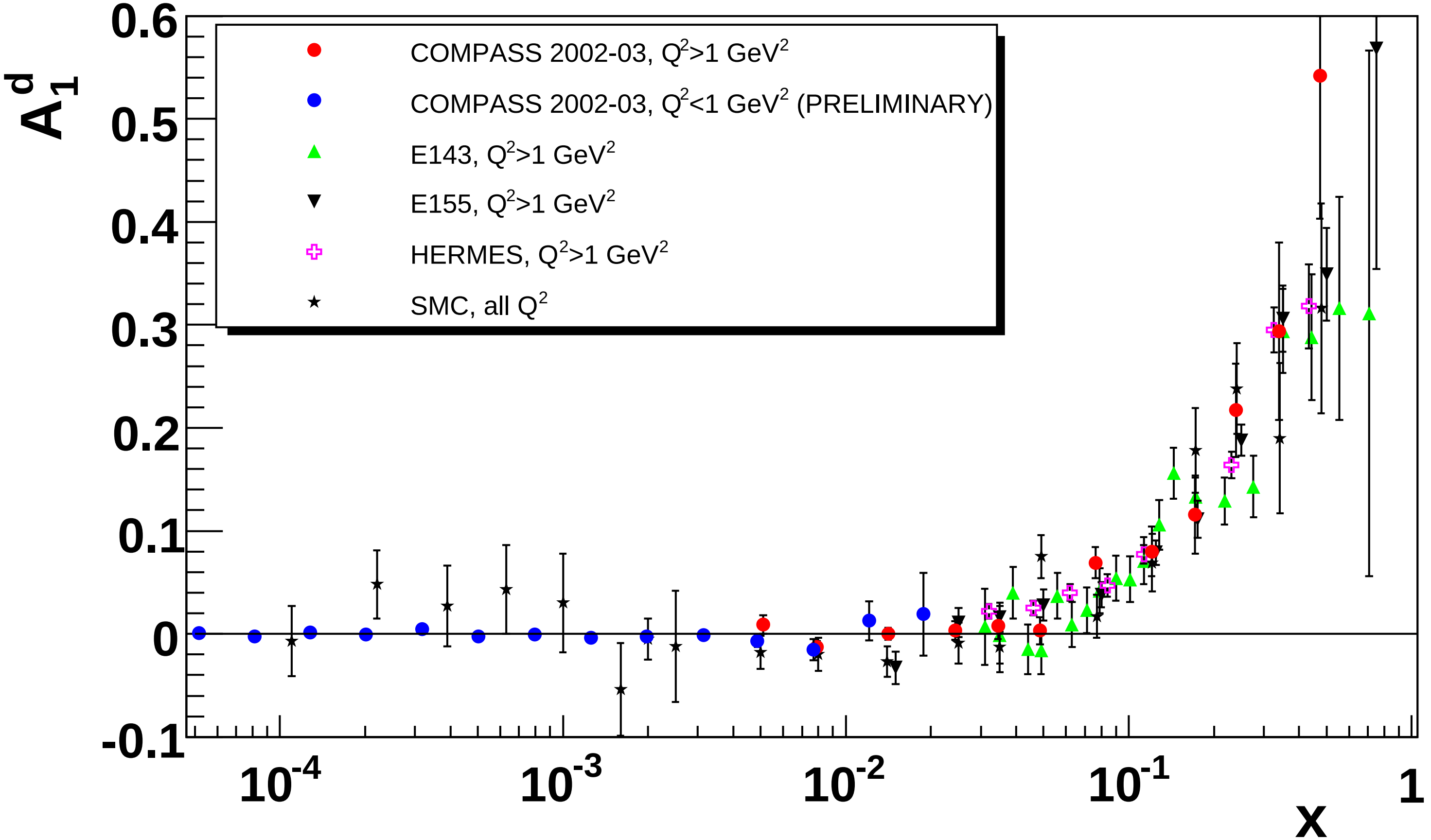


- A_1^d and g_1^d for high Q^2 ($Q^2>1$ GeV^2):
  QCD analysis possible: ΔG estimation

Unfortunately - Q^2 and x are strongly correlated for small Q^2 in COMPASS (fixed target)

A_1^d and structure function g_1^d

blue points – Compass 2002-2003 data for $Q^2 < 1$ GeV^2
10-20 times lower statistical errors compared to SMC



A_1^d and structure function g_1^d

g_1^d - Compass 2002-2003 data for $Q^2 < 1$ GeV^2

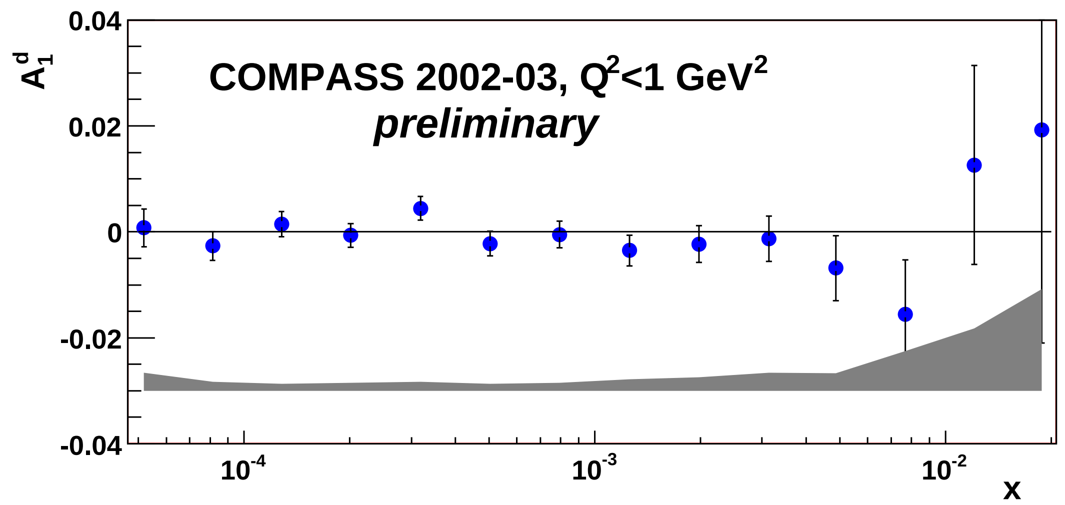
F_2^d taken from SMC param.

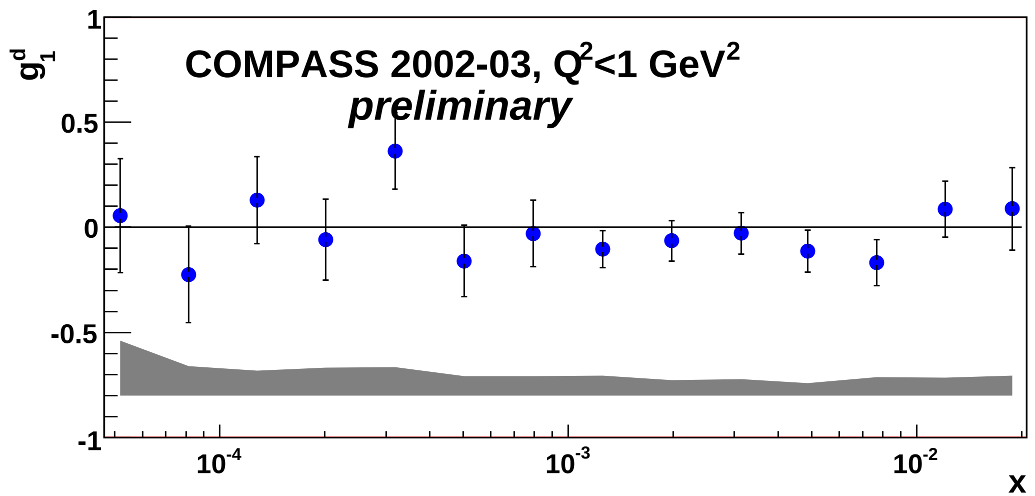
R depends on x: x>0.12

SLAC (Phys.Lett.B250(1990)193, B52(1999)194)

0.003<x<0.12 NMC (unpublished)

x<0.003 ZEUS (Eur.Phys.JC7(1999)609, σ_L, σ_T cross sections param.)

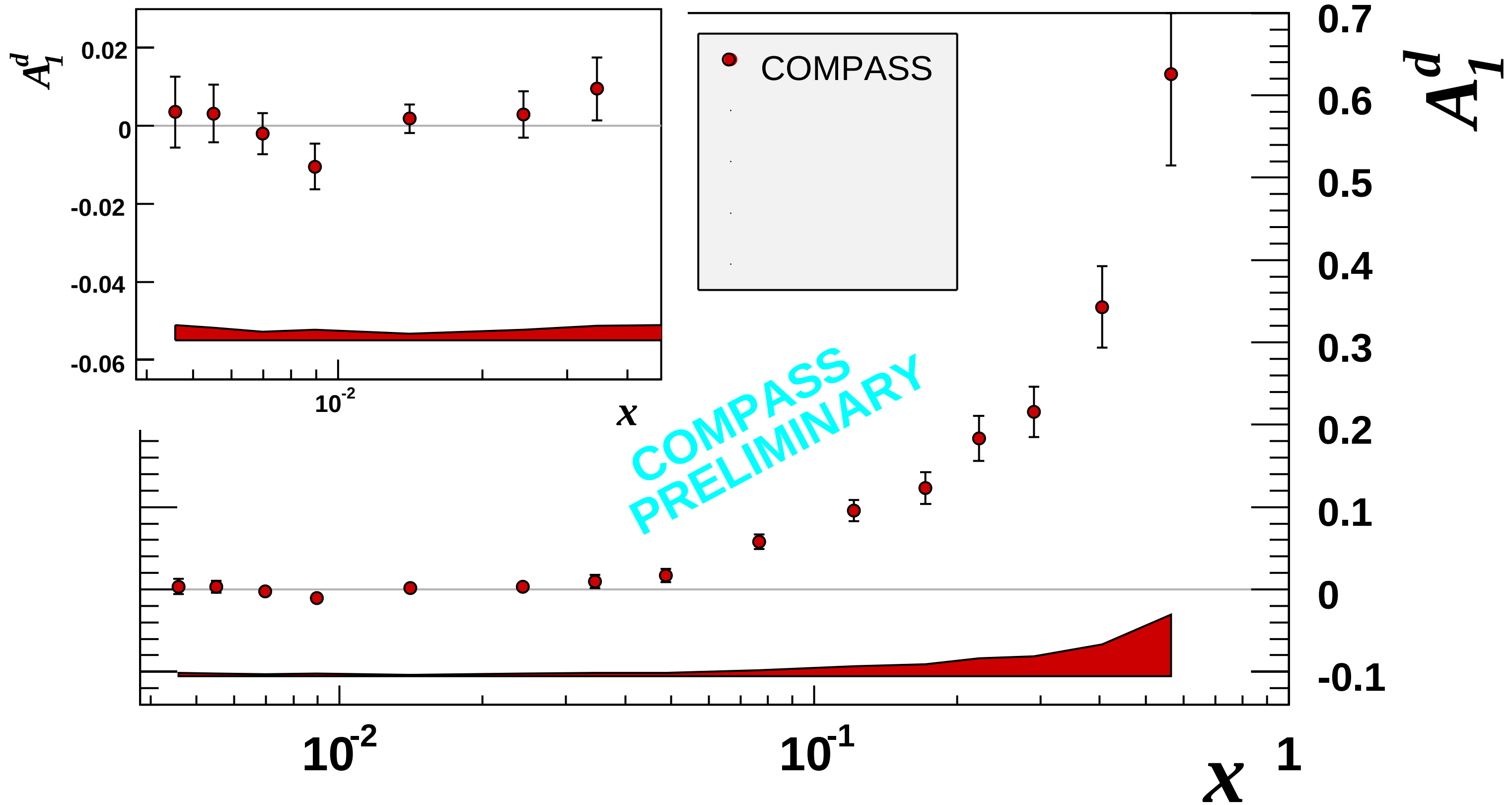




A_1^d and structure function g_1^d

A_1^d - Compass 2002-2004 data for $Q^2 > 1$ GeV^2

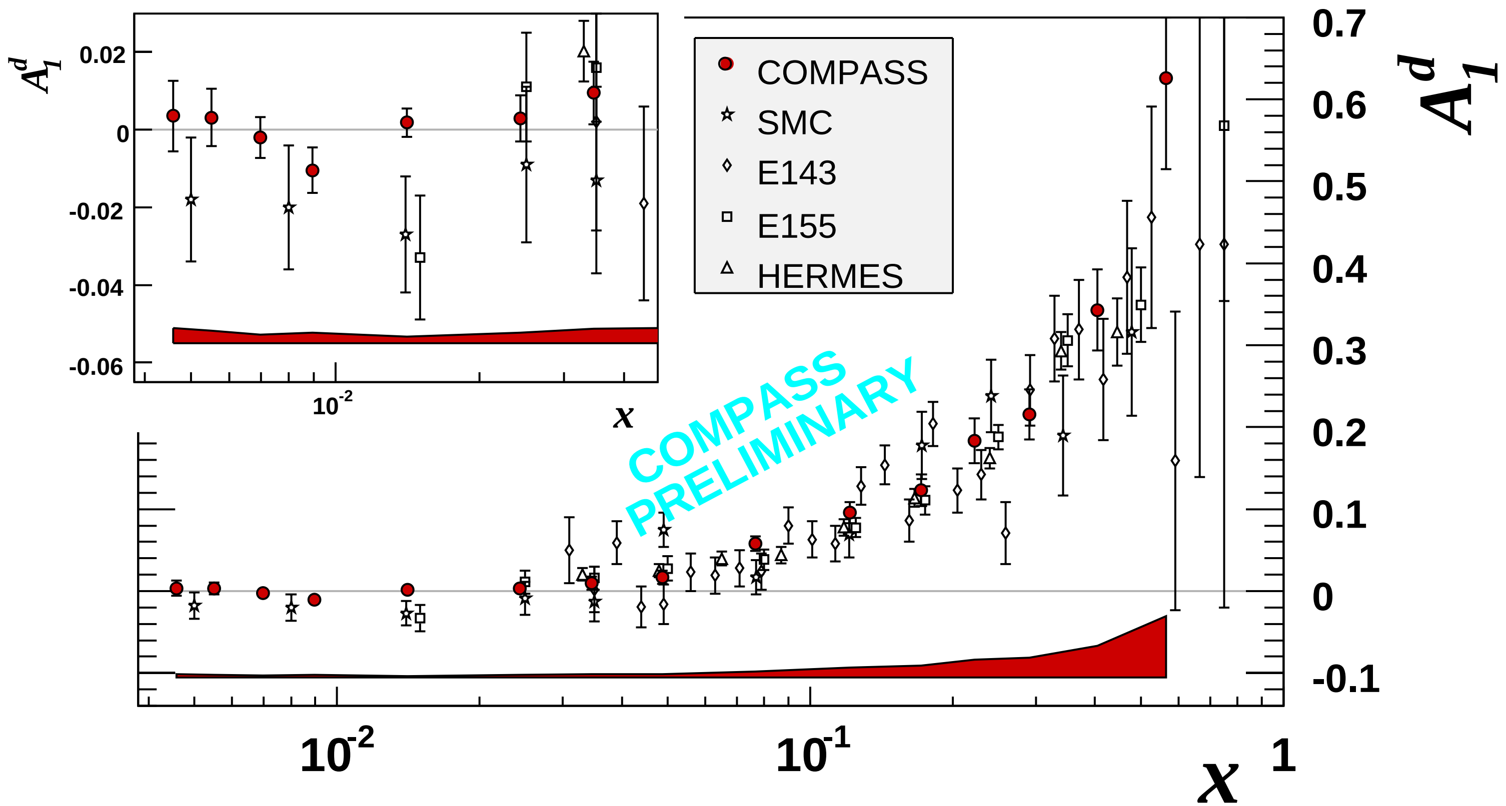
~90 mln events (60 inclusive ones), Q^2 depends on x bins



A_1^d and structure function g_1^d

A_1^d - Compass 2002-2004 data for $Q^2 > 1$ GeV^2

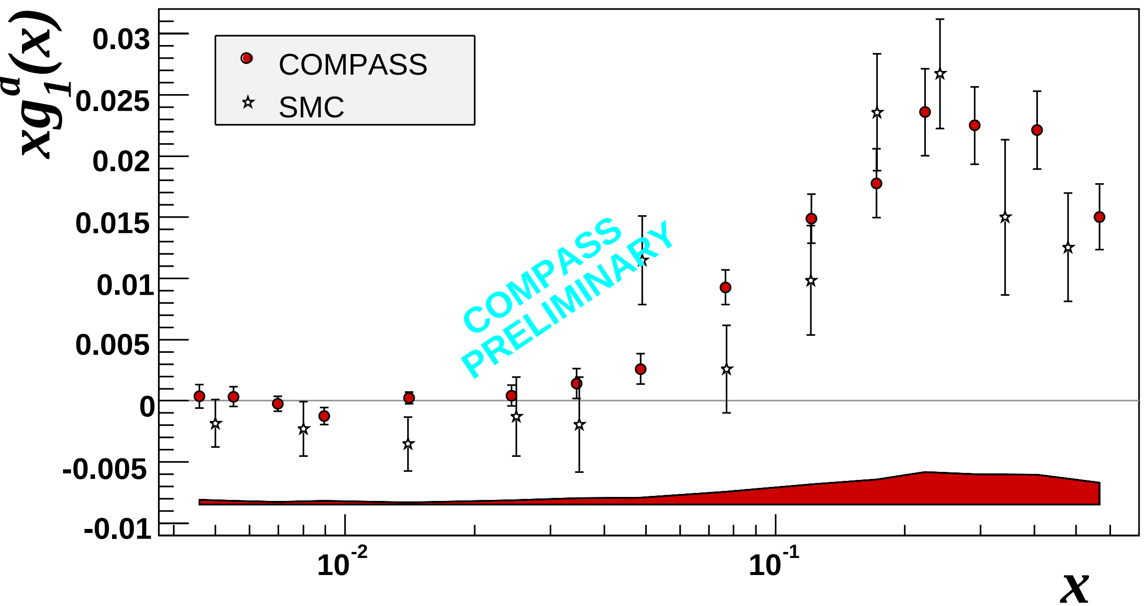
For x<0.03: statistical errors reduced by factor 4;
no tendency toward negative values



A_1^d and structure function g_1^d

g_1^d - Compass 2002-2004 data for $Q^2 > 1$ GeV^2

$$g_1^d = g_1^N \left(1 - \tfrac{3}{2}\omega_d\right) = \frac{F_2^d}{2x(1+R)} A_1^d$$



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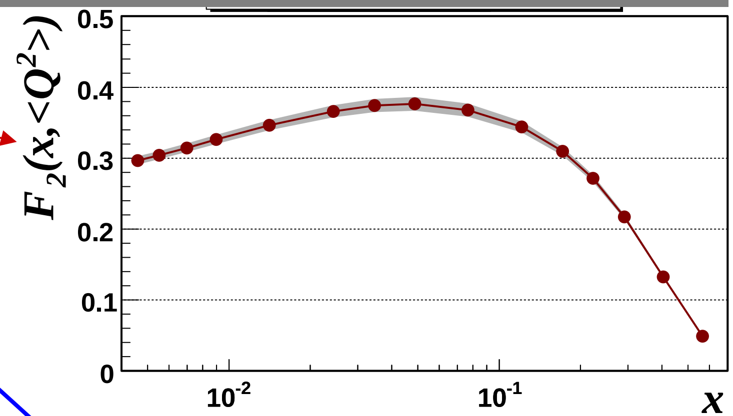
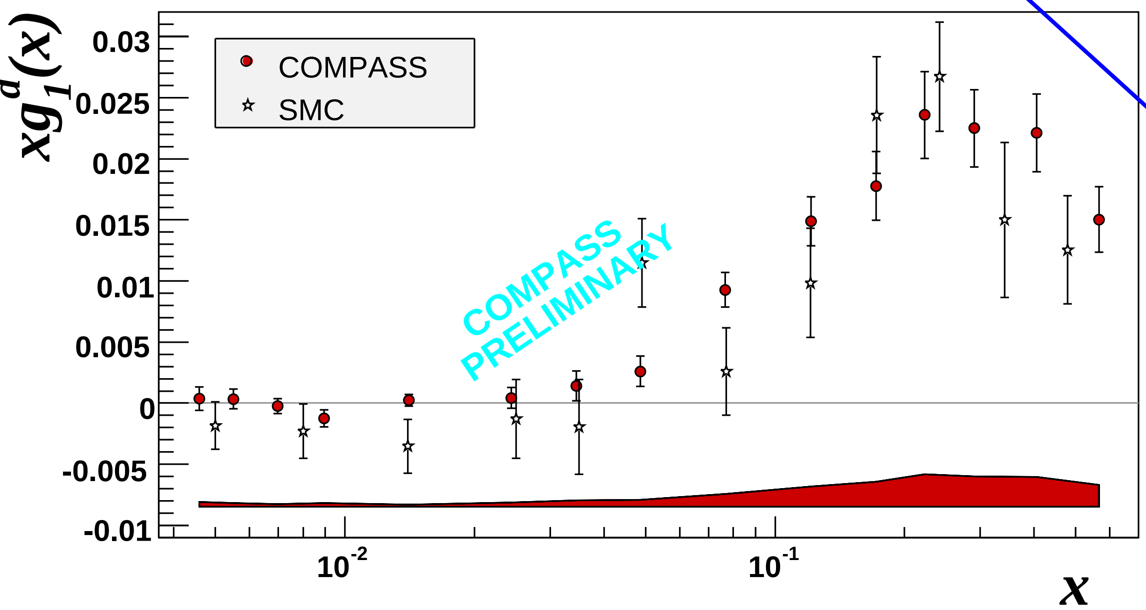
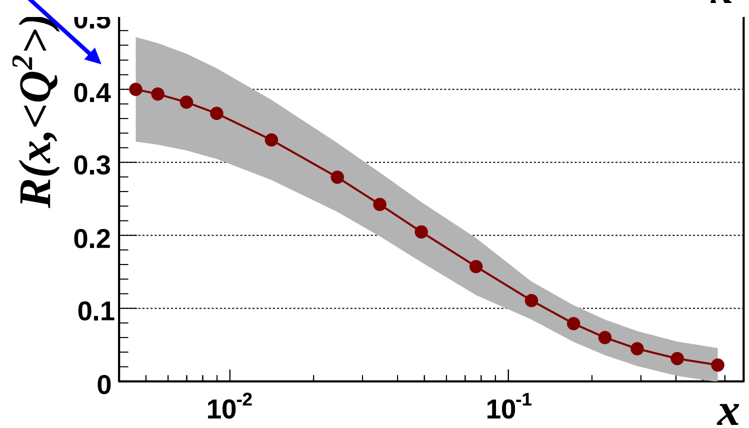






QCD fits

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

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

- DGLAP equations:

$$t = \log\left(\frac{Q^2}{\Lambda^2}\right)$$

$$\begin{cases} \frac{d}{dt}\Delta q^{NS} = \frac{\alpha_S(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q^{NS} \\ \frac{d}{dt}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} = \frac{\alpha_S(t)}{2\pi}\begin{pmatrix} P_{qq}^S & 2n_f P_{qG}^S \\ P_{Gq}^S & P_{GG}^S \end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} \end{cases}$$

- Initial parametrization: x dependence at fixed Q^2

$$\left(\Delta\Sigma, \Delta q_s, \Delta q_8, \Delta G\right) = \eta \frac{x^\alpha (1-x)^\beta (1+\gamma x)}{\int_0^1 x^\alpha (1-x)^\beta (1+\gamma x)\, dx}$$

- Minimization routine

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

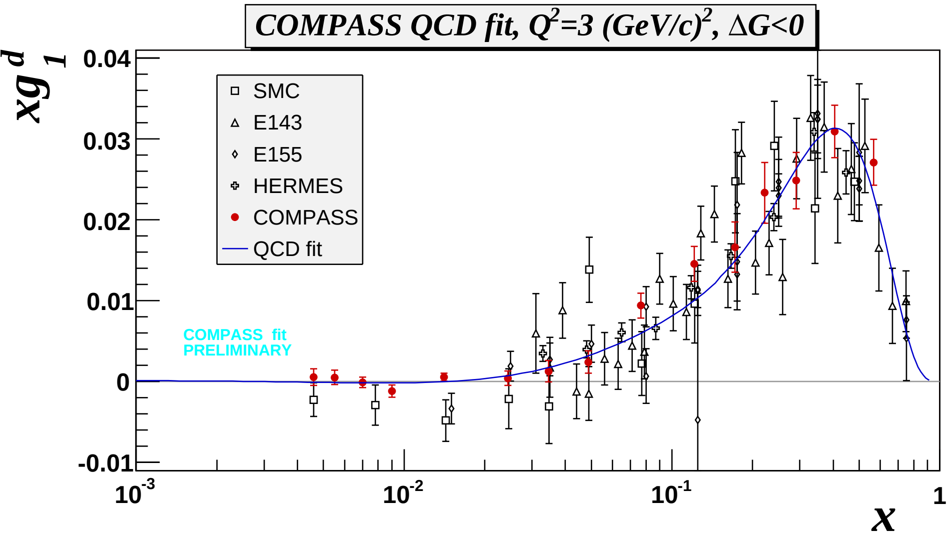
QCD fits

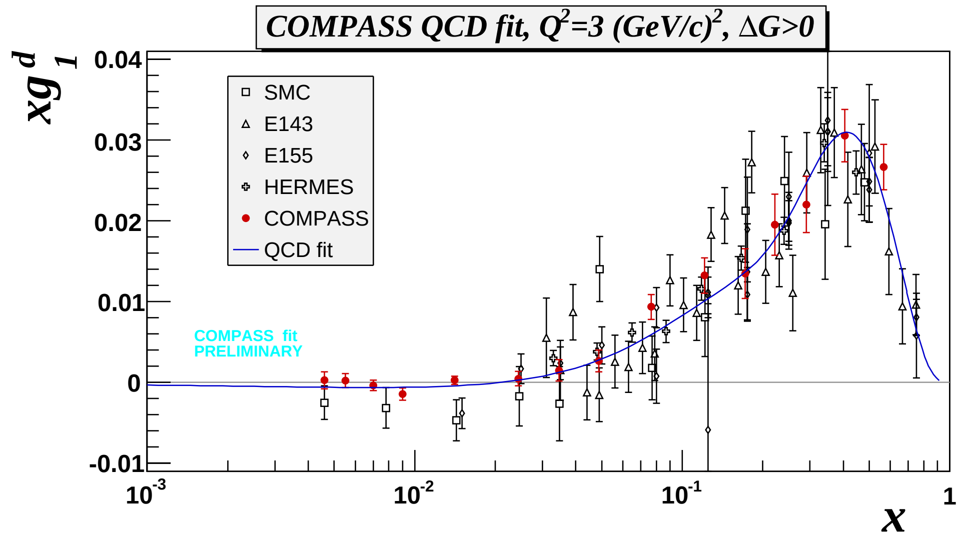
Two different codes in NLO $\overline{\mathrm{MS}}$ scheme used:
- grid in (Q^2,x) space (Phys.Rev.D58(1998)112002)
- Mellin transform + moments space (Phys.Rev.D70(2004)074032)

World data fit: 9 experiments, 230 points

Two solutions describe data equally well: ΔG>0 and ΔG<0, Q^2=3 GeV^2,

$$g_1(x,Q_0^2) = g_1(x,Q_i^2) + \left[g_1^{fit}(x,Q_0^2) - g_1^{fit}(x,Q_i^2)\right]$$

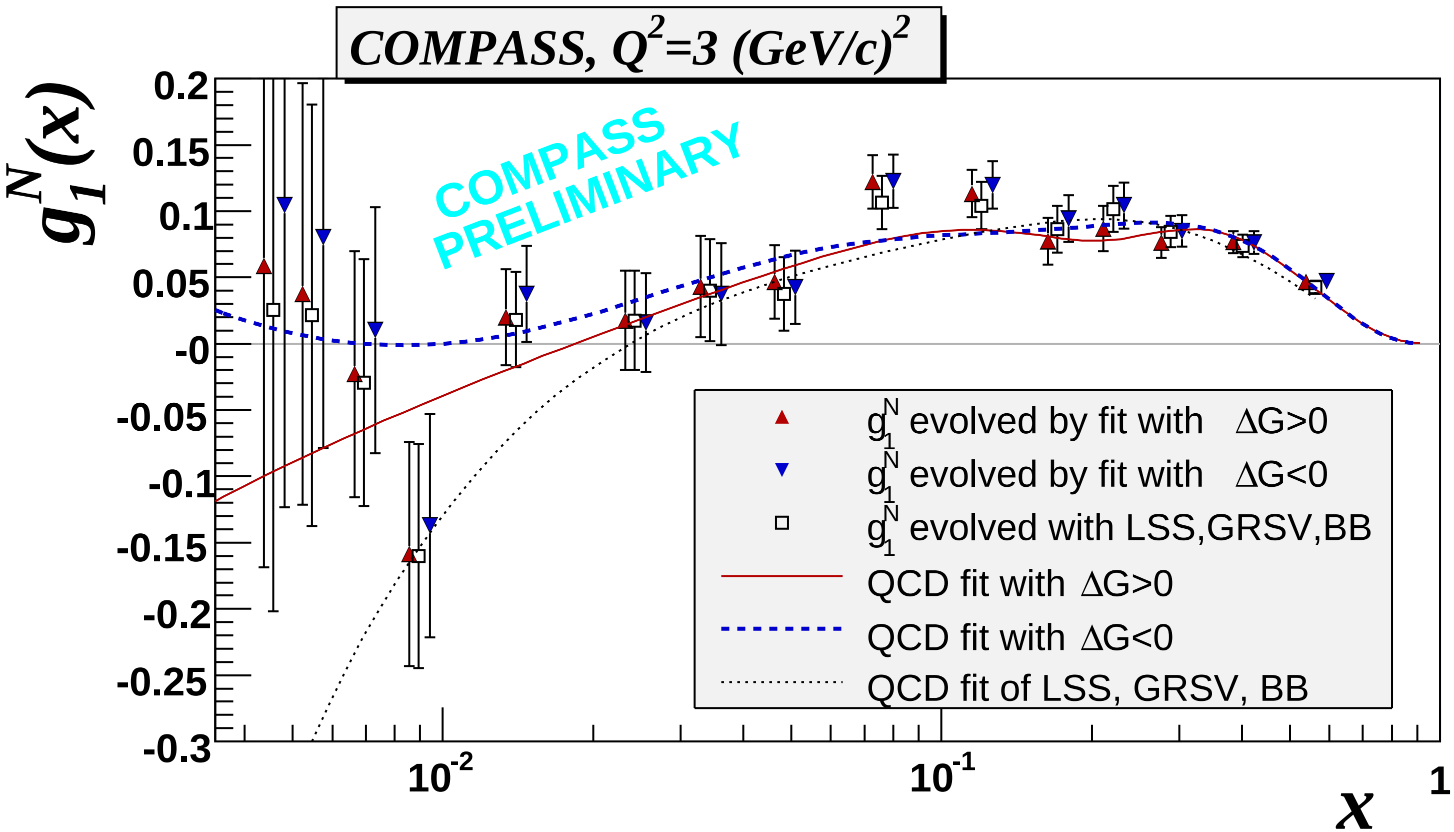




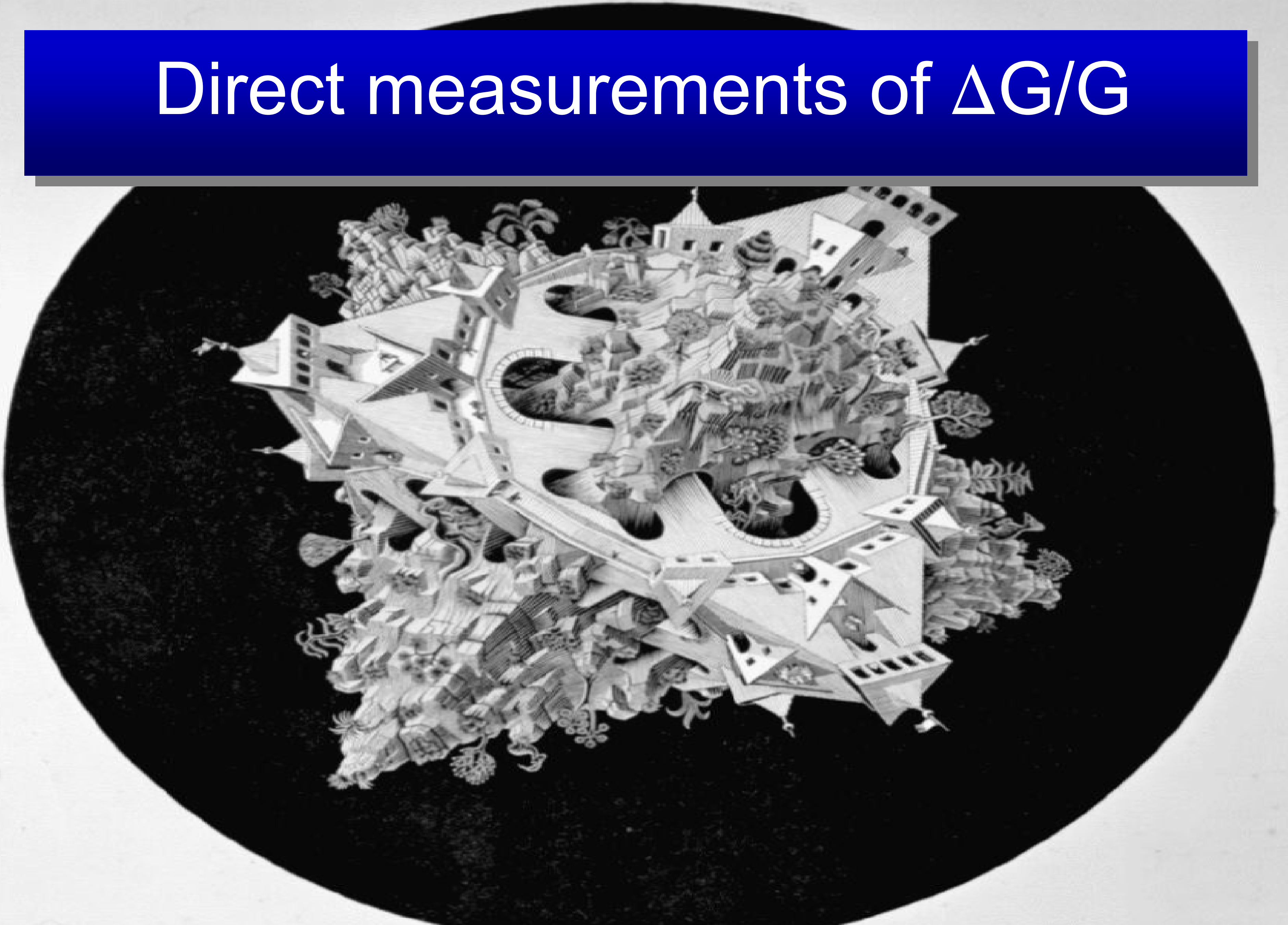
ΔG<0 deuteron ΔG>0

QCD fits

Comparison of fits - disagreement of data with previous QCD fits (LSS05,BB,GRSV)

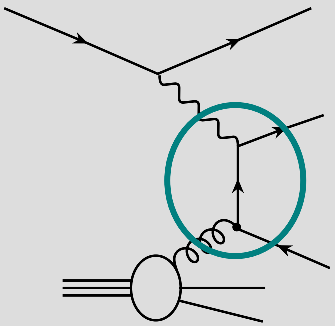


Direct measurements of ΔG/G



Direct measurements of ΔG/G

Photon Gluon Fusion (PGF) probes gluons



$$A_{\parallel} = R_{PGF}\, a_{PGF}^{LL} \frac{\Delta G}{G} + A_{Bkg}$$

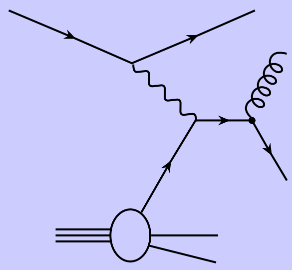
- Open charm „golden channel"
  - ☺ no background asymmetry, less MC dependent.
  - ☹ small statistics, NLO corrections can be important
- 2 high p_T hadrons ($p_T > 0.7$GeV, then selection on Σp_T^2)
  - ☺ Large statistics
  - ☹ physical background: „model" (MC) dependent, requires very good description of data by MC.

Direct measurements of ΔG/G

2 high p_T hadrons:

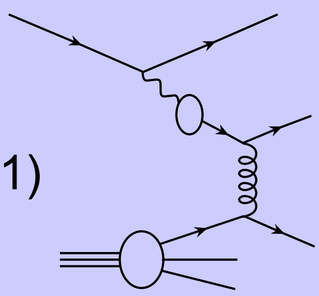
- Low Q^2 analysis ($Q^2<1 GeV^2$): perturbative scale fixed by p_T, complicated physical background e.g. resolved γ,low p_T
- High Q^2 analysis ($Q^2>1 GeV^2$): scale Q^2 ,physical background better controlled in the frame of pQCD.

Physical background:



QCD-Compton

resolved γ ($Q^2<1$)



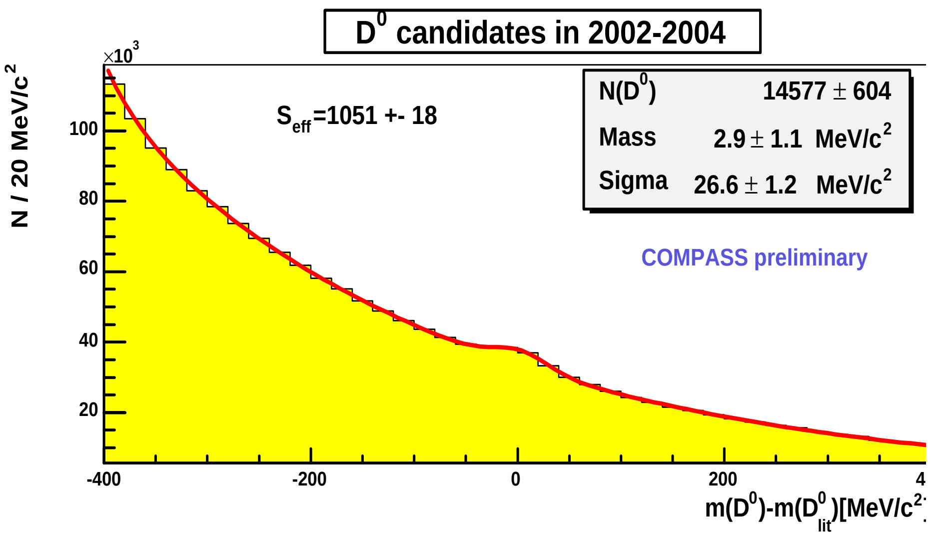
ΔG/G from open charm channel

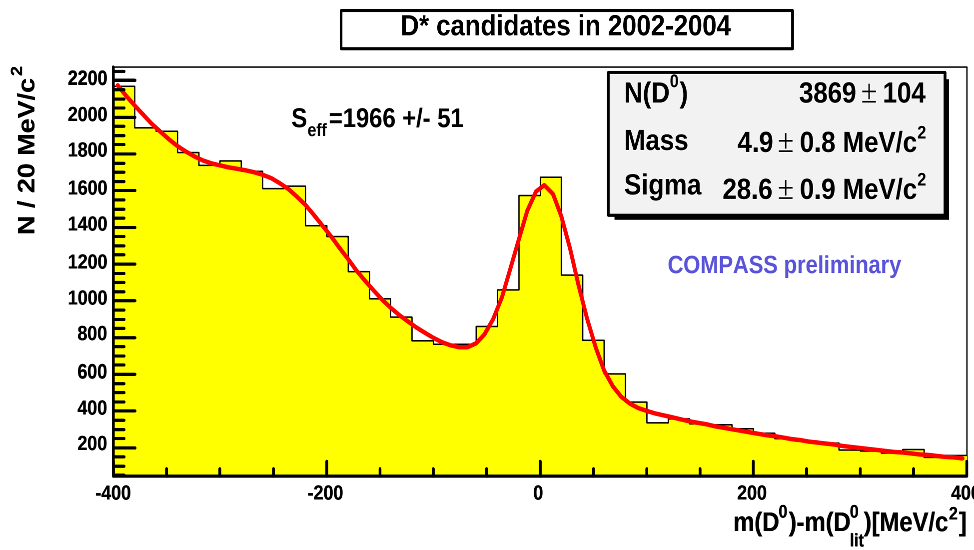
ΔG/G from open charm channel

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

Scale: $\langle Q^2 \rangle \approx 13\ GeV^2$
$\sim 4^*\ m_c^2$

$D^0 \rightarrow K+\ \pi$ (untagged) $D^* \rightarrow D^0 + \pi \rightarrow K+\ \pi+\ \pi$





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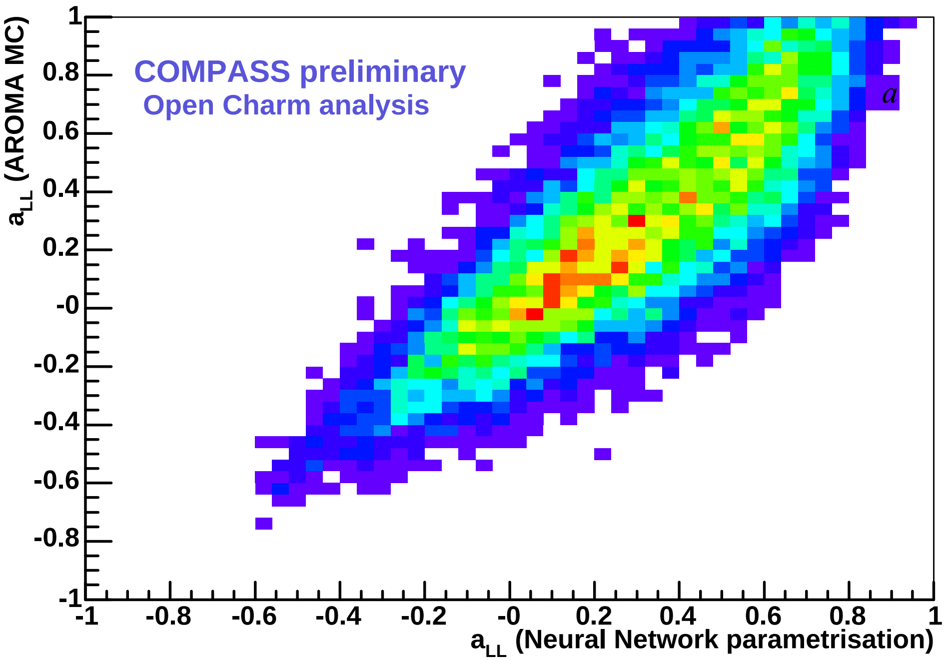


a_{LL} – calculated with help of MC and parametrized by measured quantities (Neural Network used)

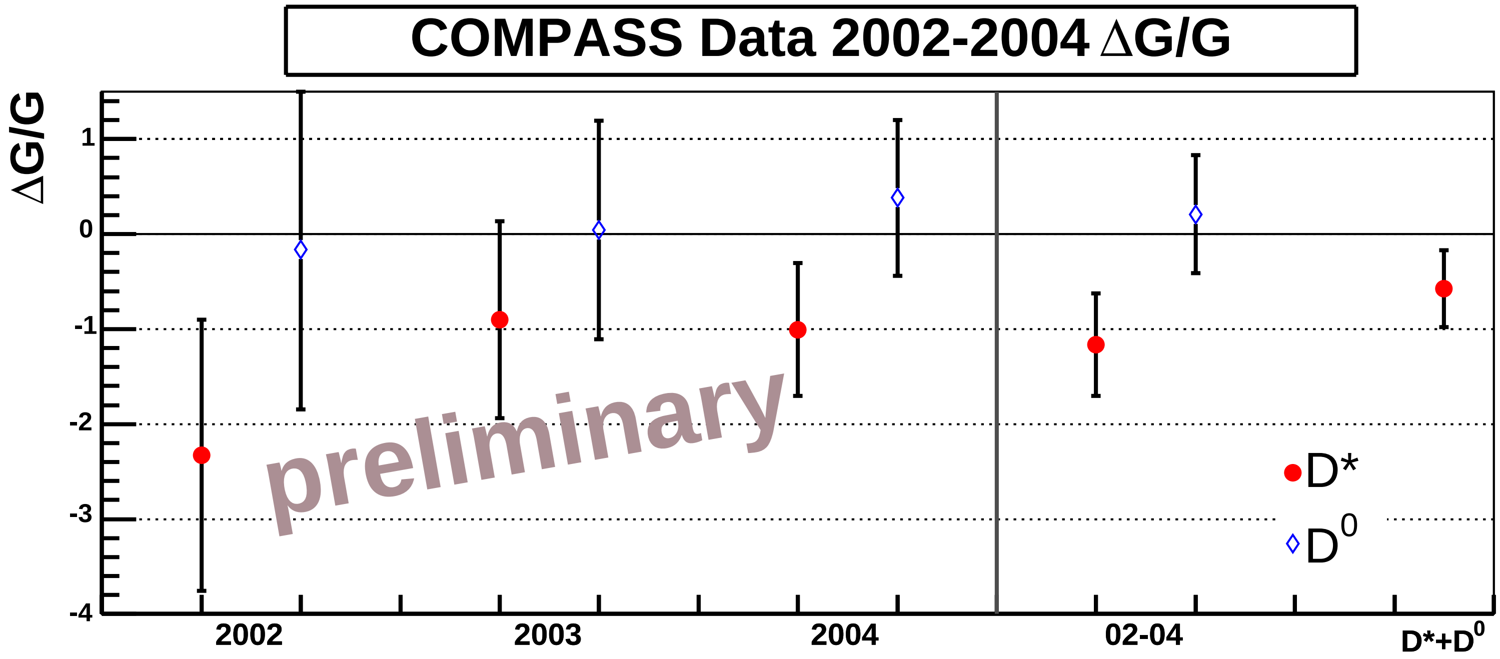
ΔG/G from open charm channel

$D^0 + D^*$ result 2002 – 2004: $\frac{\Delta G}{G} = -0.57 \pm 0.41(\text{stat.})$

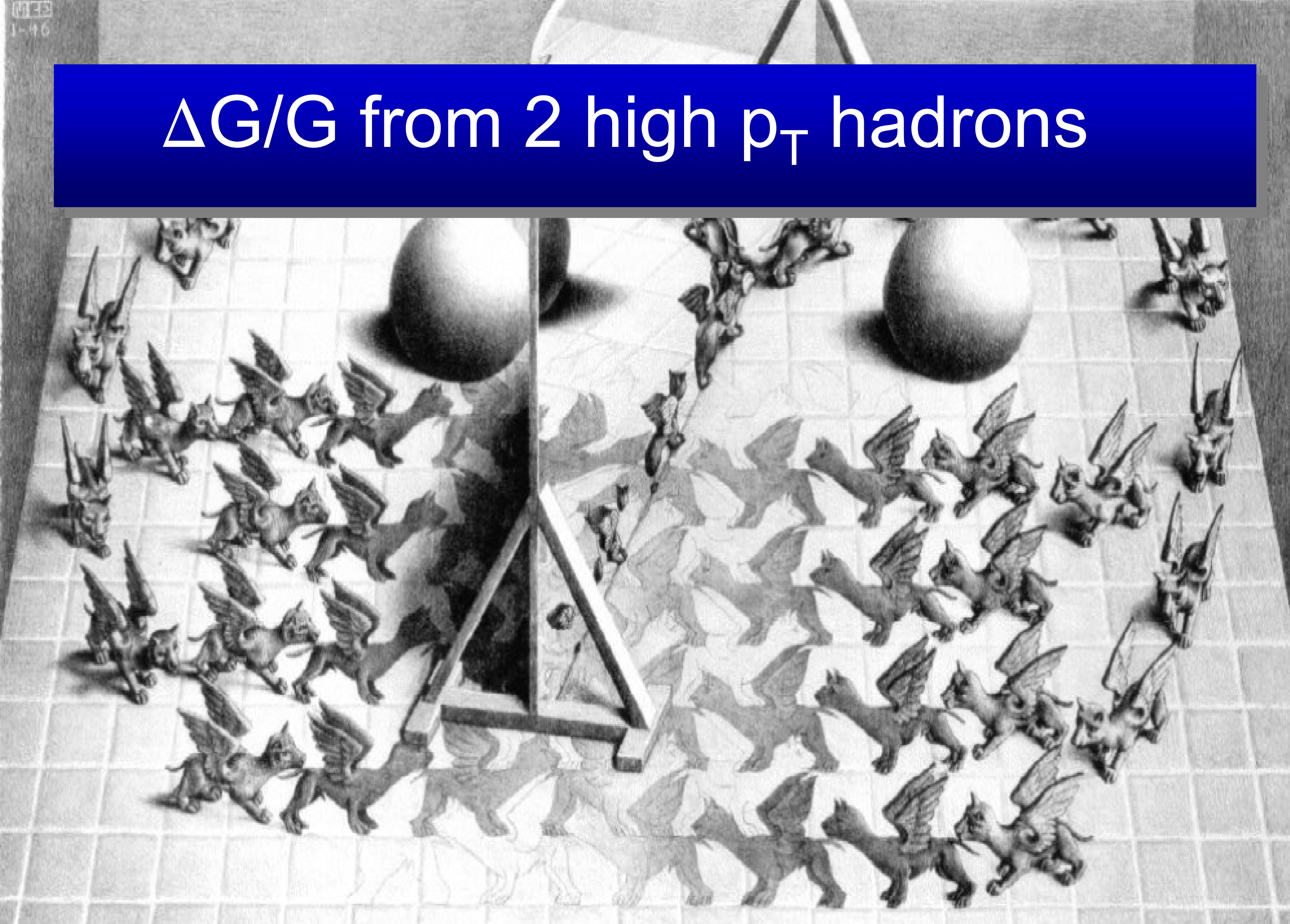
@ $x_g \approx 0.15$,

scale ≈ 13 GeV^2

The studies on the systematical uncertainty are ongoing



$\Delta G/G$ from 2 high p_T hadrons



$\Delta G/G$ from 2 high p_T hadrons (low Q^2)

Low Q^2: $Q^2 < 1$ GeV²

$$A_{LL}/D = R_{pgf}\, \Delta G/G\, a_{LL}^{pgf}$$

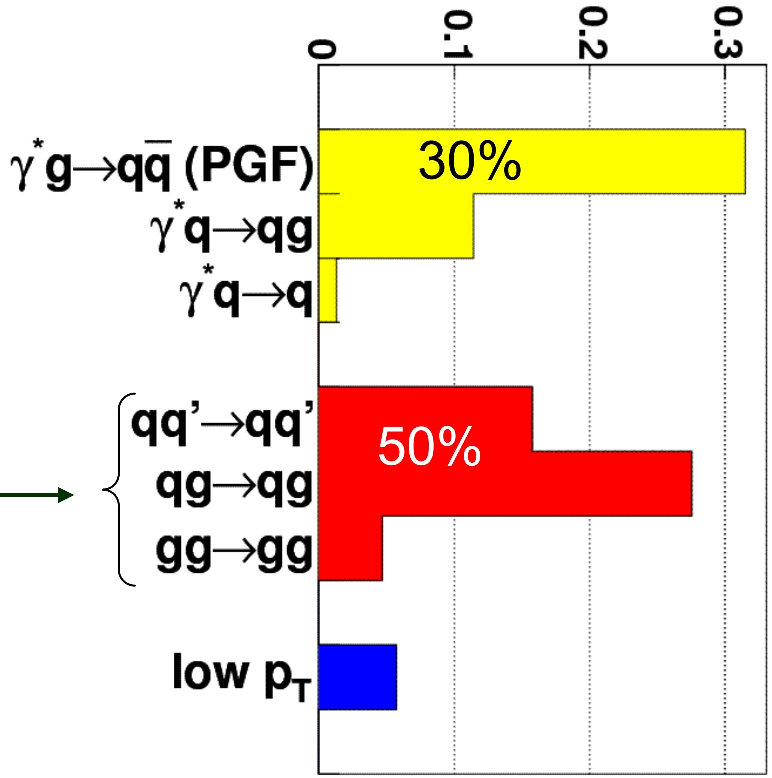
$$+ R_{qcdc}\, \Delta q/q\, a_{LL}^{qcdc}$$

Resolved γ

$$+ R_{qq}\, \Delta q/q\, a_{LL}^{gq}\, (\Delta G/G)^{\gamma}$$

$$+ R_{qg}\, \Delta G/G\, a_{LL}^{qg}\, (\Delta q/q)^{\gamma}$$

$$+ \ldots$$

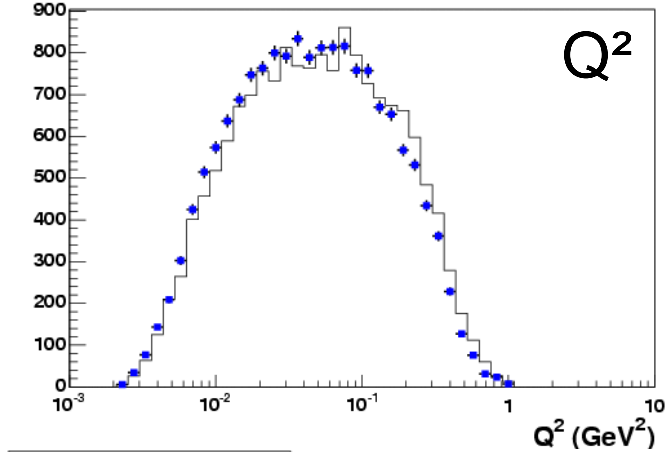


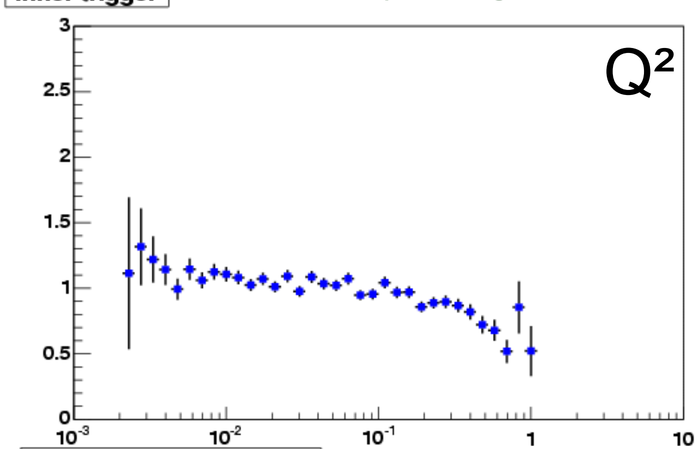
MC event generator *PYTHIA* is used for low Q² analysis

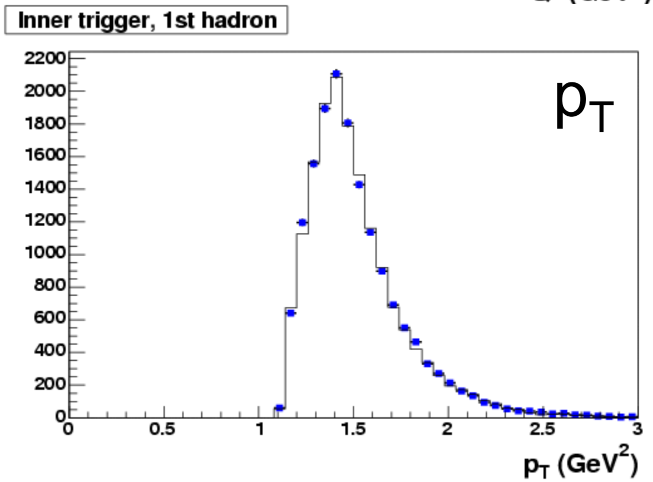
ΔG/G from 2 high p_T hadrons (low Q^2)

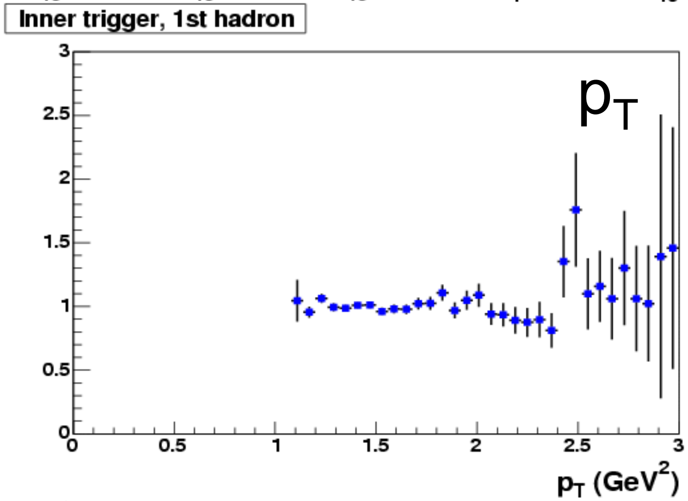
Data & MC

Data/MC









Example of good description of the data by the simulation

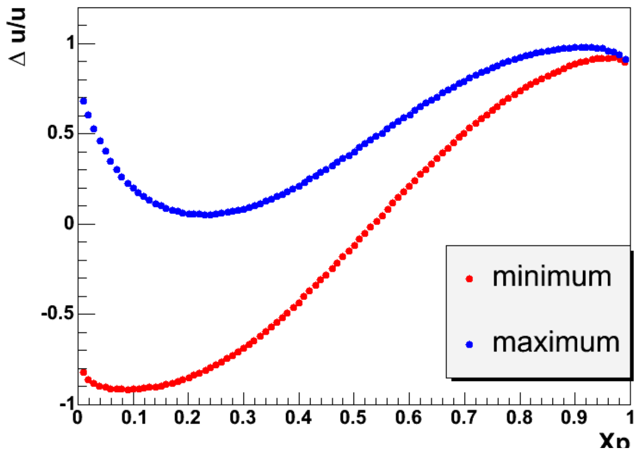
$\Delta G/G$ from 2 high p_T hadrons (low Q^2)

Problem: polarized PDF's of virtual photons not measured!

$\Delta q^{\gamma,pert}(x_p,\mu^2)$ calculable

$$-q^{\gamma,npert}(x_p,\mu_0^2) < \Delta q^{\gamma,npert}(x_p,\mu_0^2) < q^{\gamma,npert}(x_p,\mu_0^2)$$

measured

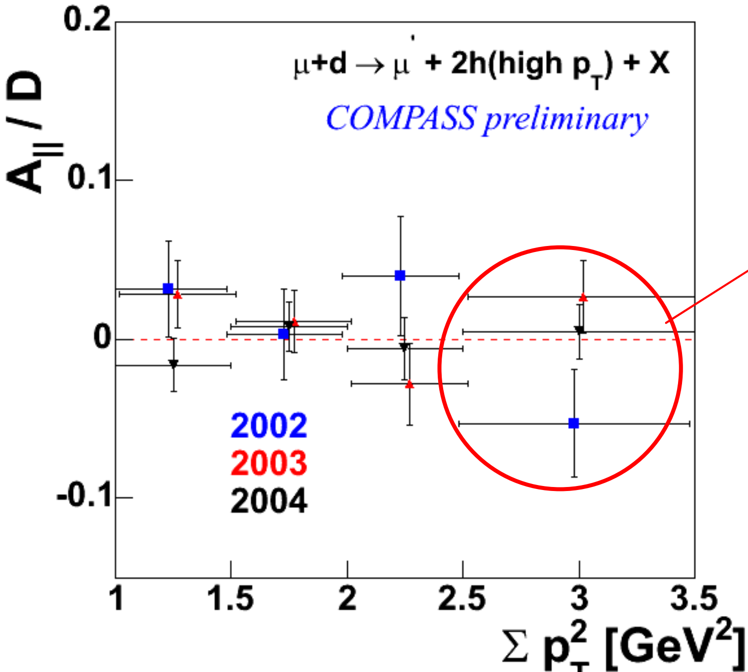


$\Rightarrow$ Allows us to obtain a range for $(\Delta q/q)^\gamma$ and $(\Delta G/G)^\gamma$

$\rightarrow$ Adds a limited uncertainty to the estimation of $(\Delta G/G)(x_g)$

Resolved photon asymmetry

$\Delta G/G$ from 2 high p_T hadrons (low Q^2)



Values used for extraction of $\Delta G/G$

Scale: 3 GeV^2

data	$(\Delta G/G)(x_g)$	stat	exp.syst	MC.syst	γ
02-03	0.024	0.089	0.014	0.052	0.018
02-04	0.016	0.058	0.014	0.052	0.013

$$@\, x_g = 0.085^{+0.071}_{-0.035}$$

2002-2003 published:PLB **633** (2006) 25-32

$\Delta G/G$ from 2 high p_T hadrons ($Q^2>1$)

- Statistics smaller than in low Q^2 analysis (10%)
- Background better controlled – pQCD (QCD-C, LP)
- *LEPTO* MC generator has been used for data description (tunning similar to SMC)
- $\Sigma p_T^2 > 2.5$ GeV^2 used.

Preliminary 2002-2003 data result:

$$\frac{\Delta G}{G} = 0.06 \pm 0.31(\text{stat.}) \pm 0.06(\text{syst.})\ @\ x_g = 0.13 \pm 0.08$$

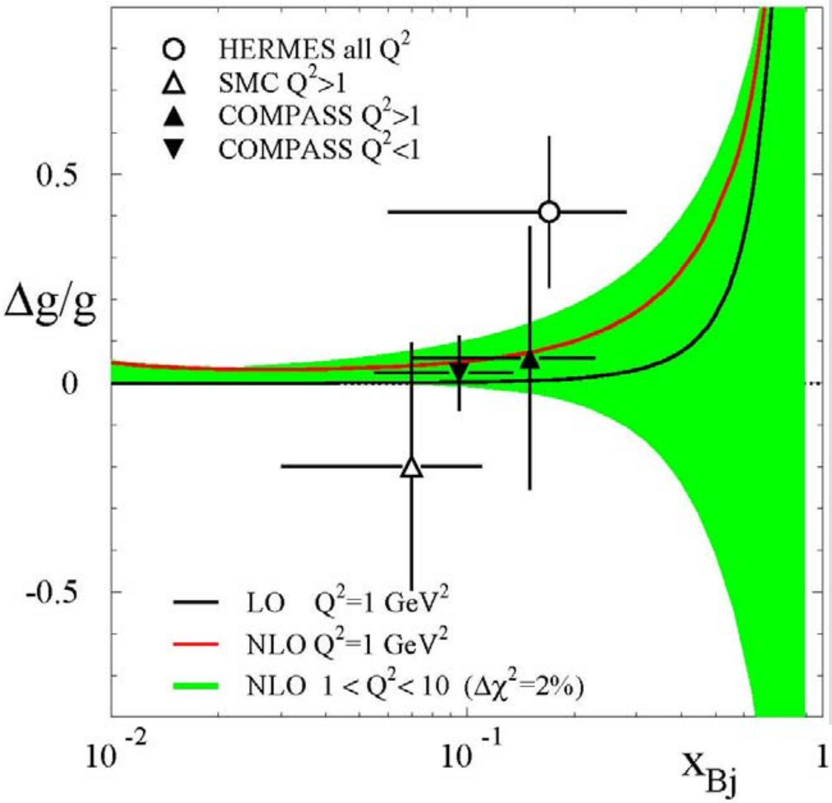
$\Delta G/G$ from 2 high p_T hadrons ($Q^2 > 1$)

- Analysis is ongoing; 2002-2004 results expected soon
- Scale is determined by Q^2 and – in contrast to low Q^2 analysis – the cut $\Sigma p_T^2 > 2.5\ \mathrm{GeV}^2$ can be released to smaller value to optimize „working point"

(question: higher fraction R_{PGF} and small statistics or lower fraction and higher statistics?)

- Neural Network is tested to improve selection of PGF subprocess and optimize „working point".
  The significant improvement is expected.

Comment



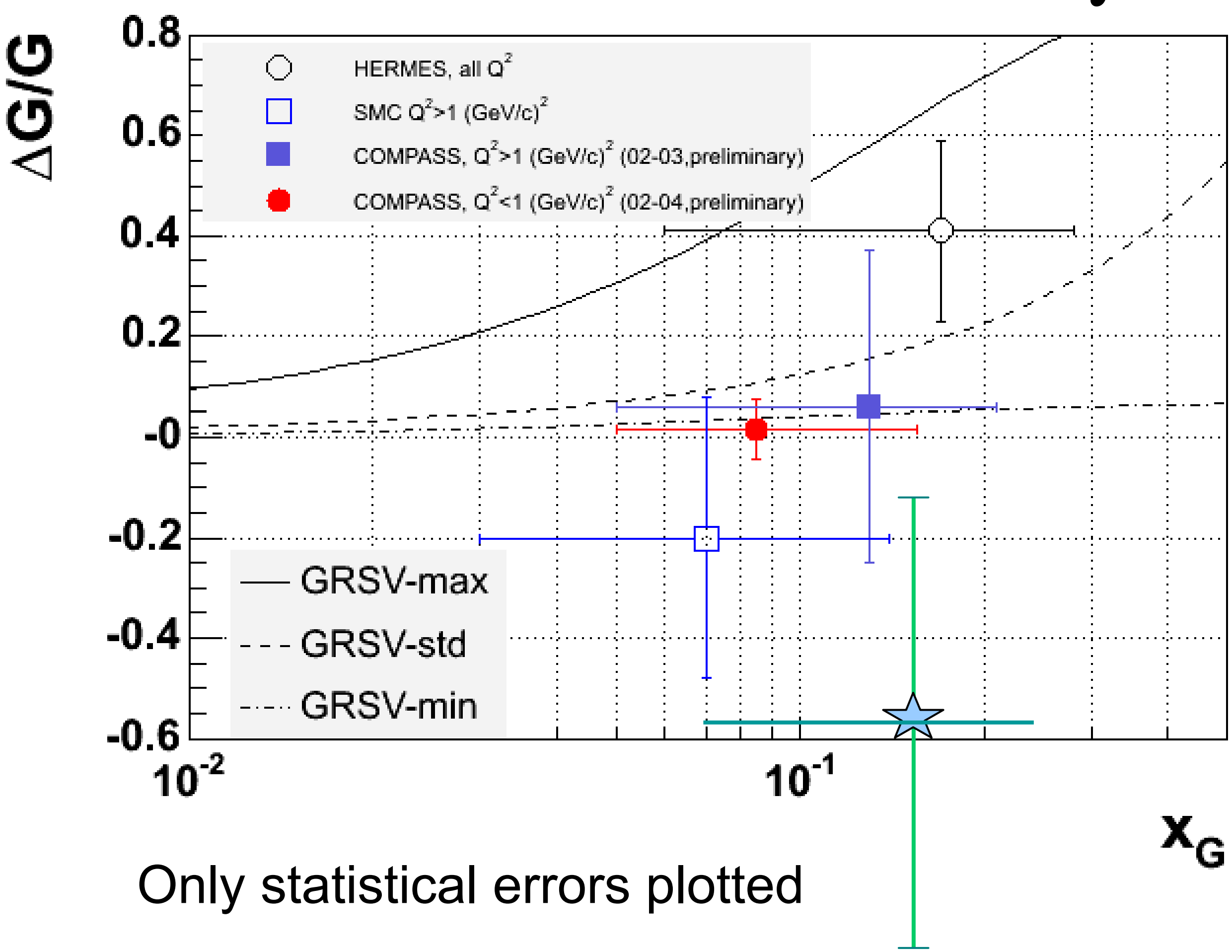
Phys.Rev.D71, 094018 (2005), hep-ph/0602236

MC based high-p_T LO analysis often criticized but:

- NLO corrections partially simulated via so-called parton shower
- Part of the NLO effect taken into account via modification of fragmentation function (internal k_T)
- NLO fit: de Florian, Navarro,Sassot,Jiang; Compass results not taken in the fit!

Results for ΔG/G - summary

$$\int \Delta G(x) = 2.5$$



$$\int \Delta G(x) = 0.62$$

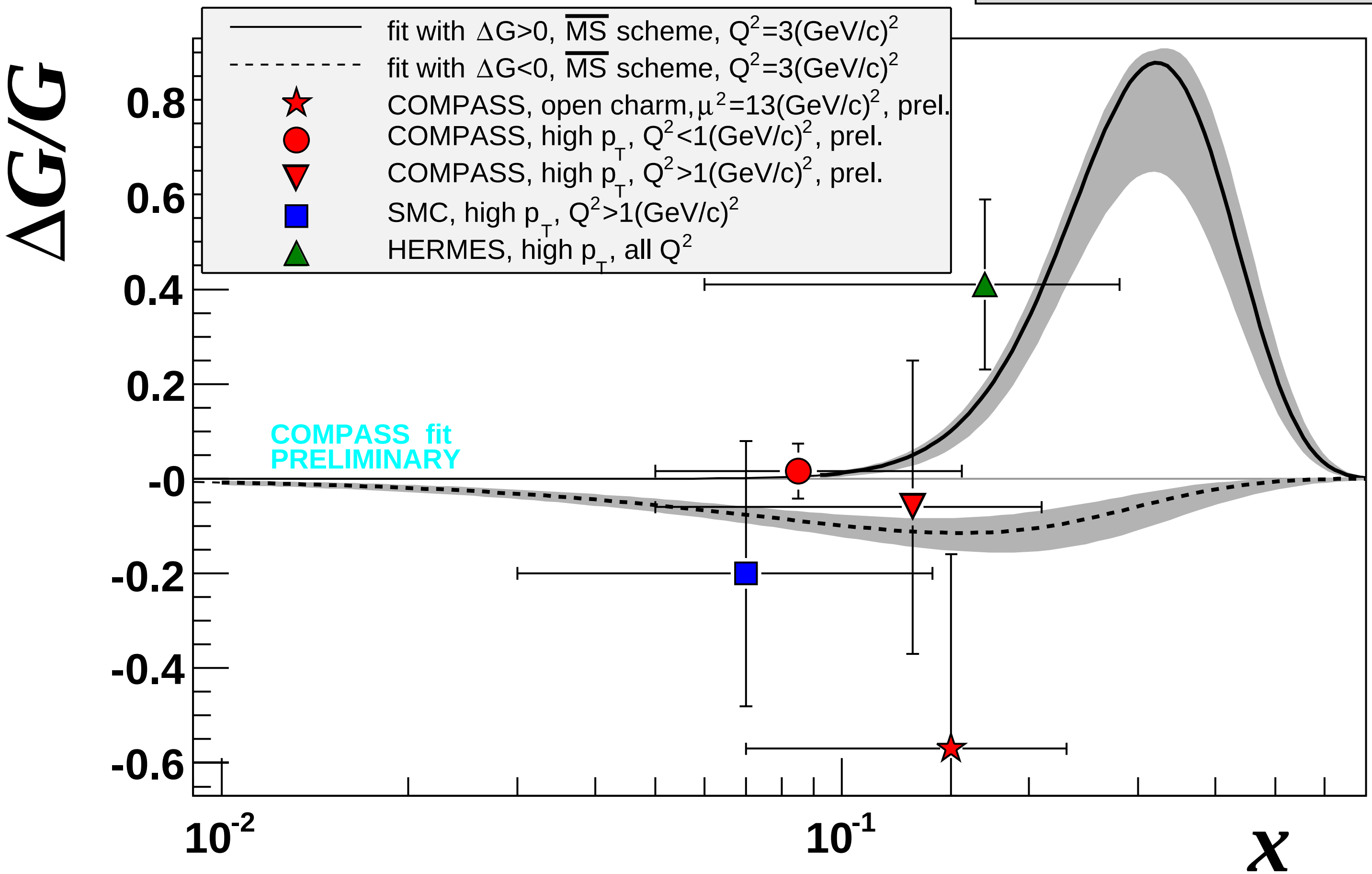
$$\int \Delta G(x) = 0.16$$

☆ Open charm

Only statistical errors plotted

Results for ΔG/G - summary

ΔG/G from QCD fits



Outlook

- More results soon available with 2004 data for $Q^2 > 1$ GeV^2 high p_T events.
- For the future:
  Optimization of event selection with a neural network,
  Bins in x_g (requires improvement of x_g reconstruction),
  NLO + resolved γ in open charm analysis.

- 2006 data with new COMPASS magnet (larger x_g)
- Expected precision with 2006 data (stat.error):
  open charm - 0.28,
  high p_T $Q^2>1$ GeV^2: 0.14,
  high p_T $Q^2<1$ GeV^2: 0.045.

Summary

- New measurements of A_1^d, g_1^d have been presented.
- Good agreement with results from previous experiments in the region of middle and high x.
- Improvement in statistical precision factor 4 for x<0.03.
- No tendency toward negative values at x<0.03.

- Disagreement of data with previous QCD fits (small x)
- Existing QCD parametrization need to be revised.

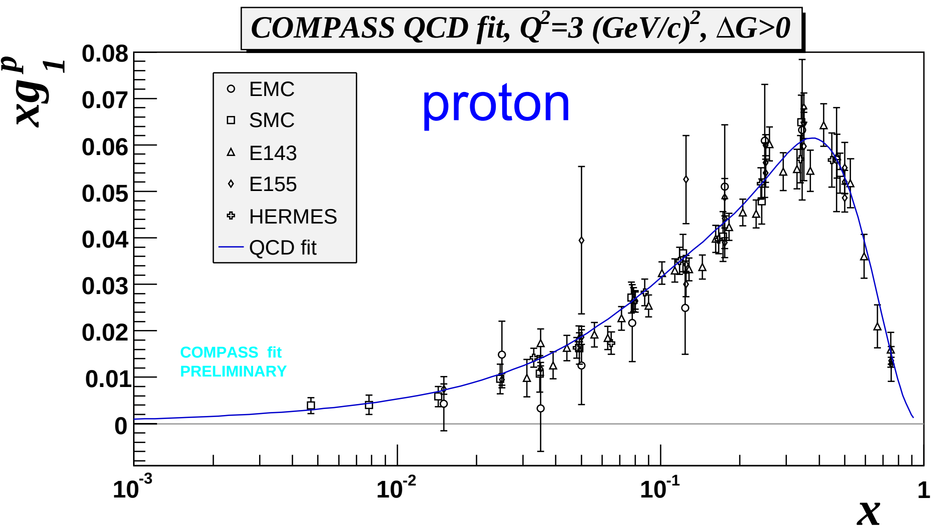
Summary

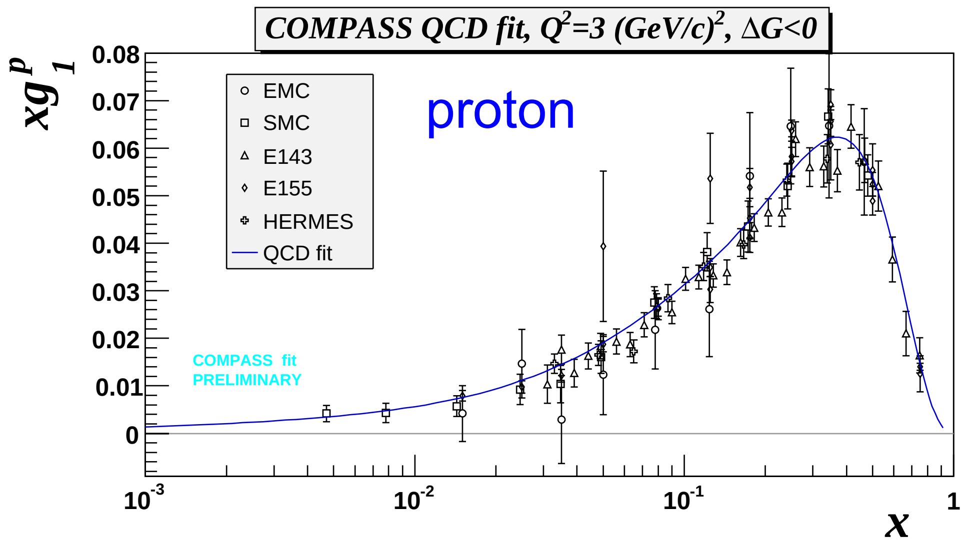
- New measurements of $\Delta G/G$ have been presented.
- Small ΔG is preferred or $\Delta G(x_g)$ has a node around 0.1.
- Ellis-Jaffe sum rule seems to be violated if large ΔG is excluded (axial anomaly).

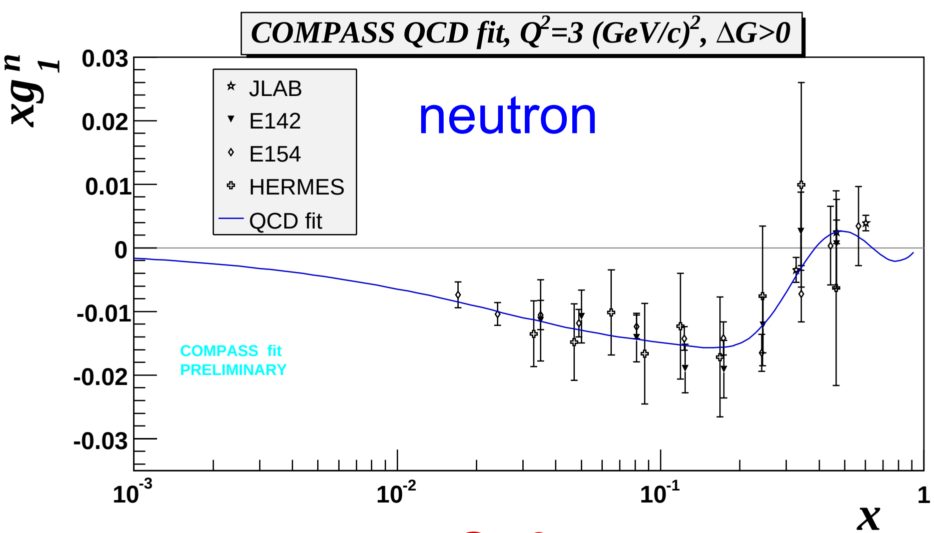
- $\Delta G \approx 0.4$ not excluded and scenario when L is small still possible.
- $\Delta G \approx 0$ indicates the important role of angular orbital momentum in nucleon spin decomposition described in the frame of parton model and pQCD.

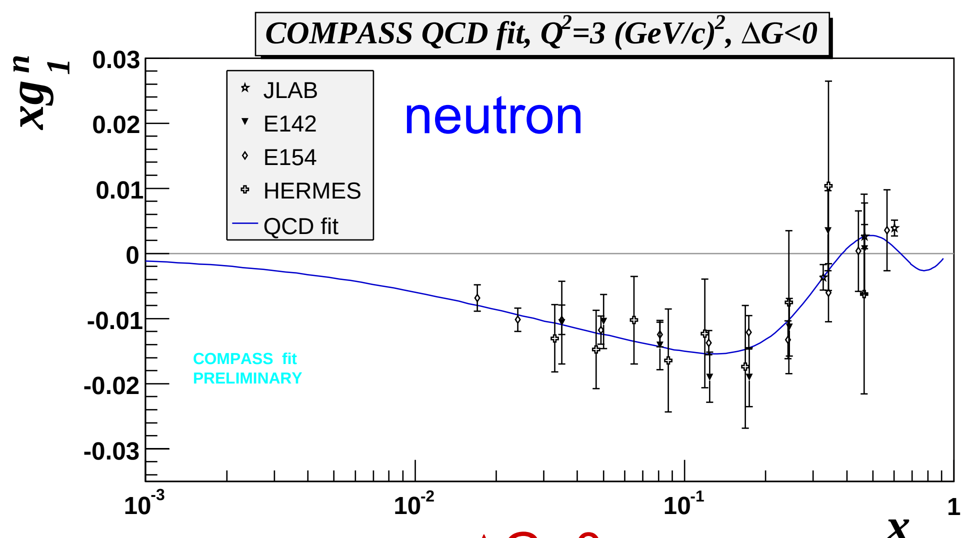
Venus de Milo

Spare 1 – QCD fit









ΔG>0 ΔG<0

Spare 2 – parameters of QCD fit

Quark polarization η_Σ

- Well determined by data (proportional to the $\int_0^1 g_1^d(x,Q^2)dx$)
- No difference between results of two QCD-fit programs and the difference for two solutions ($\eta_G > 0$ and < 0) is also very small

	$\eta_G > 0$	$\eta_G < 0$
η_Σ	0.28 ± 0.01	0.32 ± 0.01

$\Rightarrow$ $\eta_\Sigma = 0.30 \pm 0.01(stat) \pm 0.02(evol)$

Gluon polarization η_G

- Indirect determination (via evolution questions)
- Solutions with $\eta_G > 0$: $\eta_G^{prog\,1} = 0.26 \,^{+\,0.04}_{-\,0.06}$, $\eta_G^{prog\,2} = 0.19 \,^{+\,0.01}_{-\,0.10}$
- Solutions with $\eta_G < 0$: $\eta_G^{prog\,1} = -0.31 \,^{+\,0.1}_{-\,0.1}$, $\eta_G^{prog\,2} = -0.18 \,^{+\,0.04}_{-\,0.03}$

$$|\eta_G| \simeq 0.2 - 0.3$$

Spare 3 – parameters of QCD fit

Quark polarization with COMPASS data only

- The first moment of g_1^d at $Q^2 = 3\,\mathrm{GeV}^2$:

$$\Gamma_1^N = \int_0^1 g_1^N(x, Q^2)dx = 0.0502 \pm 0.0028(stat) \pm 0.0020(evol) \pm 0.0051(syst)$$

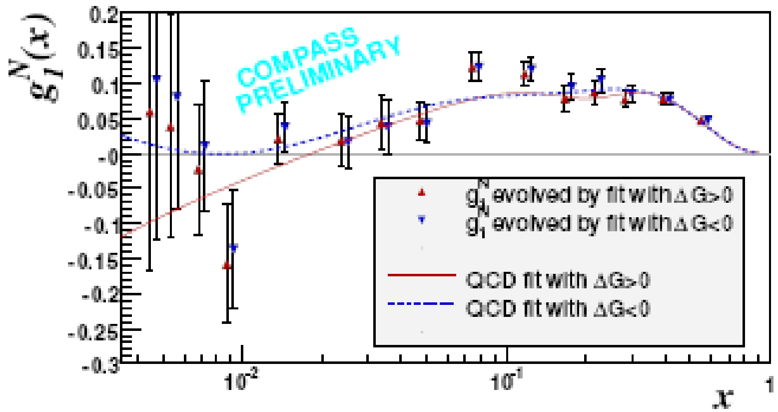
- a_0 can be extracted from the first moment of g_1^N

$$\Gamma_1^N(Q^2)\Big|_{NLO} = \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + \mathcal{O}(\alpha_s^2)\right) \times \left(a_0(Q^2) + \frac{1}{4}a_8\right)$$

- From hyperon β decays assuming $SU(3)_f$:

$$a_8 = 0.585 \pm 0.025$$

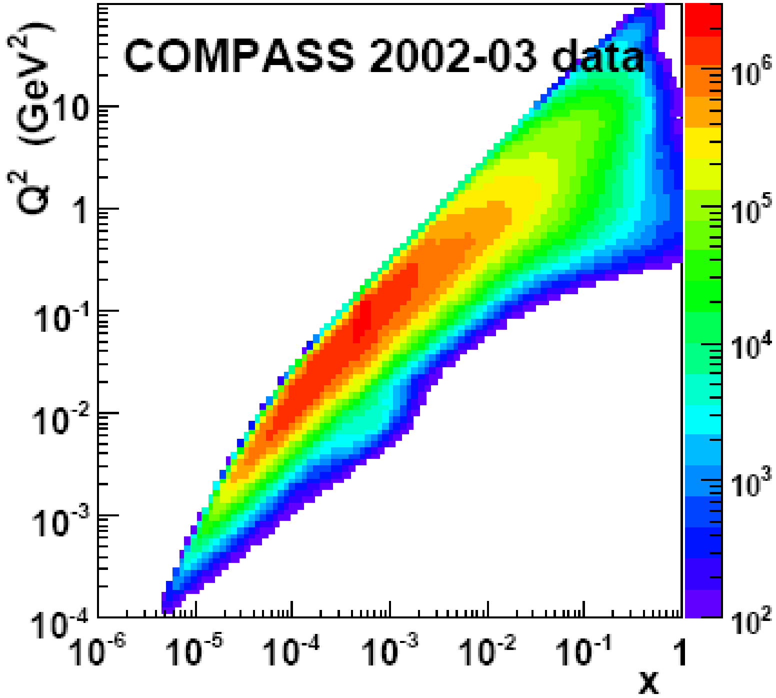
- Contribution from unmeasured x-range is $\approx 4\%$



- Quark polarization at $Q^2 = 3\,\mathrm{GeV}^2$:

$$a_0 = 0.35 \pm 0.03(stat) \pm 0.05(syst)$$
$$\eta_\Sigma = 0.30 \pm 0.01(stat) \pm 0.02(evol)$$

Spare 4 – data taking



Physics topics for longitudinal data

- inclusive asymmetries
- semi-inclusive asymmetries
- open charm production
- high p_T hadrons pairs
- Λ polarisation
- exclusive ρ production
- 20% of time for transverse data taking

	2002	2003	2004
Beam Time	106d	90d	110d
Preparation	30d	7d	3d
Integrated luminosity / fb^{-1}	1	1.2	$\sim$ 2.4

Spare 5 – R for $Q^2<1$ GeV^2

2.1 The R function

The R function which was previously used by the SMC, and it is commonly used by COMPASS [2] is composed of three different parameterizations in different regions of x (see [4] for references and explanations):

- SLAC, $x > 0.12$,
- NMC, $0.003 < x < 0.12$,
- ZEUS, $x < 0.003$.

Values of R have large discontinuities close to the validity limits of the parametrizations, Fig.4. To partially overcome the problem, a new SLAC parametrization was used for $Q^2 > 0.5$ GeV^2, [5]. Below the $Q^2 = 0.5$ GeV^2 the following formula was employed:

$$R(Q^2 < 0.5, x) = R_{SLAC}(0.5, x) \times \beta(1 - exp(-Q^2/\alpha)) \tag{1}$$

where $\alpha = 0.2712$, $\beta = 1/(1 - exp(-0.5/\alpha)) = 1.1880$. At $Q^2 = 0.5$ GeV^2 the function and its first derivative are continuous. In the Q^2=0 limit: $R \sim Q^2$, which is expected from the current conservation. The new R parametrization is shown in the right plot of Fig.4. The error on R, δR, above $Q^2 = 0.5$ GeV^2 was taken from [5] and below $Q^2 = 0.5$ GeV^2 was set to $\delta R = 0.2$. For that value and for the simplest assumption about R for $Q^2 < 0.5$ GeV^2 and any x, e.g. $R = 0.2$, there is an approximate agreement (within 1σ) with the value at the photo-production limit where R=0 and with measurements at higher Q^2 from HERA, where $R \approx 0.4$.