Gluon polarization in the nucleon at COMPASS

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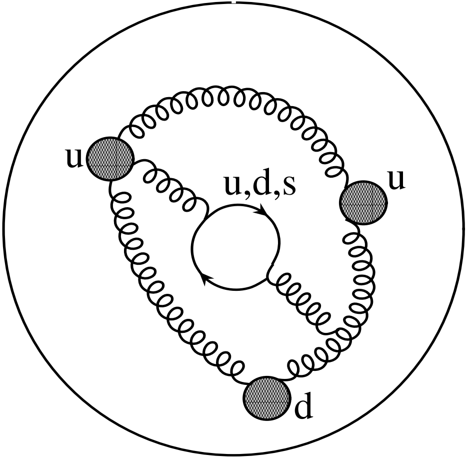
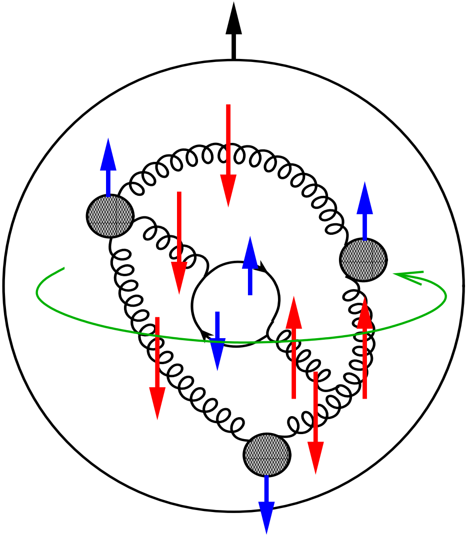
CERN

24th October 2005

The angular momentum sum rule



The angular momentum sum rule



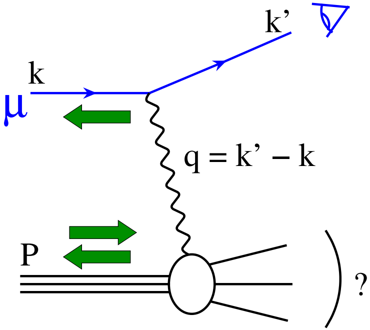
Outline

Introduction: outline

Deep Inelastic Scattering
- Structure functions
- Quark parton model
- QCD

The spin of the nucleon
- The angular momentum sum rule
- Contribution of the quark spin
- Contribution of the gluon spin

lepton–nucleon scattering

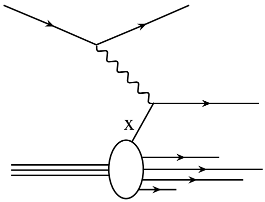


- Inclusive
- 2 independent kinematic variables:

$$Q^2 = -q^2 \ (> 0)$$
$$x_B = \frac{Q^2}{2P \cdot q}$$

- the cross-section is described by structure functions:
  $F_1(x_B, Q^2)$, $F_2(x_B, Q^2)$ unpolarized
  $g_1(x_B, Q^2)$, $g_2(x_B, Q^2)$ polarized

Quark parton model (QPM)



- point–like, collinear, non–interacting partons.
- each parton carries a fraction x of the nucleon momentum
- for the struck quark-parton: $x = x_B$

Quark–parton distribution functions (PDFs):

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

$$F_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 q(x) = \frac{F_2(x)}{2x}$$

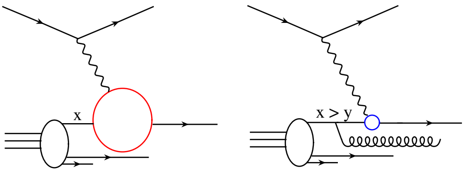
$$g_1(x) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(x)$$

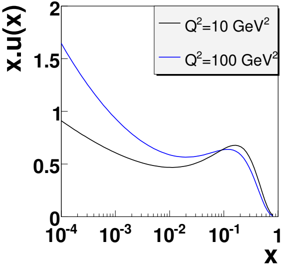
$$g_2(x) = 0$$

QCD improved parton model

- QPM valid for $\alpha_s \to 0$ ($Q^2 \to \infty$)
- At finite Q^2, partons interact
  - $\longrightarrow$ PDFs and structure functions depend on Q^2
  - $\longrightarrow$ Gluons are visible (in the Q^2 dependence)
    new PDFs:

$$G(x, Q^2) = G^+(x, Q^2) + G^-(x, Q^2)$$
$$\Delta G(x, Q^2) = G^+(x, Q^2) - G^-(x, Q^2)$$





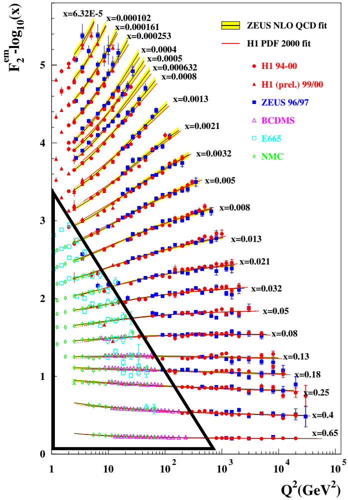
Notations

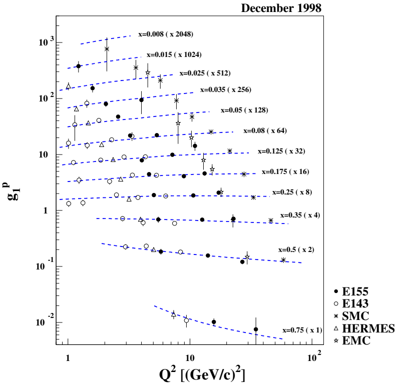
	unpolarized case	polarized case
structure functions	$F_1(x, Q^2), F_2(x, Q^2)$	$g_1(x, Q^2), g_2(x, Q^2)$
quarks PDFs	$q(x, Q^2)$ from F_2	$\Delta q(x, Q^2)$ from g_1
gluons PDFs	$G(x, Q^2)$ from F_2 evolution	$\Delta G(x, Q^2)$ from g_1 evolution

polarization:

$$\frac{\Delta q}{q}(x), \; \frac{\Delta G}{G}(x)$$

Q^2 dependence of the structure functions





$\rightarrow G(x, Q^2)$ $\rightarrow \Delta G(x, Q^2)$

The angular momentum sum rule

Nucleon spin (helicity):

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^{q+g}$$

$\Delta\Sigma = q^+ - q^- = \Delta u + \Delta d + \Delta s$	from the quark spin
$\Delta G = G^+ - G^-$	from the gluon spin
L_z^{q+g}	from orbital momentum

All PDF's integrated over x

Contribution of the quark spin $\Delta\Sigma$

First moment of the spin structure function g_1:

$$g_1(x, Q^2) = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(x, Q^2)$$

$$\int_0^1 g_1(x, Q^2) dx = \frac{1}{2} \sum_{q=u,d,s} e_q^2 \Delta q(Q^2)$$

- charge appears because we use an E.M probe. but we want to determine $\Delta\Sigma = \Delta u + \Delta d + \Delta s$
- instead of $\Delta u, \Delta d, \Delta s$ in the RHS:

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

$$a_3 = \Delta u - \Delta d$$

$$a_8 = \frac{1}{\sqrt{3}}(\Delta u + \Delta d - 2\Delta s)$$

Contribution of the quark spin $\Delta\Sigma$

First moment of the spin structure function g_1:

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$$\int_0^1 g_1(x, Q^2) dx = \frac{1}{12} \left\{ \frac{4}{3} \Delta\Sigma + a_3 + \frac{1}{\sqrt{3}} a_8 \right\}$$

- a_3 was measured in the neutron decay
- a_8 was measured in the decay of strange baryons

- instead of $\Delta u, \Delta d, \Delta s$ in the RHS:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$
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- a_3 was measured in the neutron decay
- a_8 was measured in the decay of strange baryons
- $\Delta s = 0 \rightarrow \Delta\Sigma \simeq 0.6$

- instead of $\Delta u, \Delta d, \Delta s$ in the RHS:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$
$$a_3 = \Delta u - \Delta d$$
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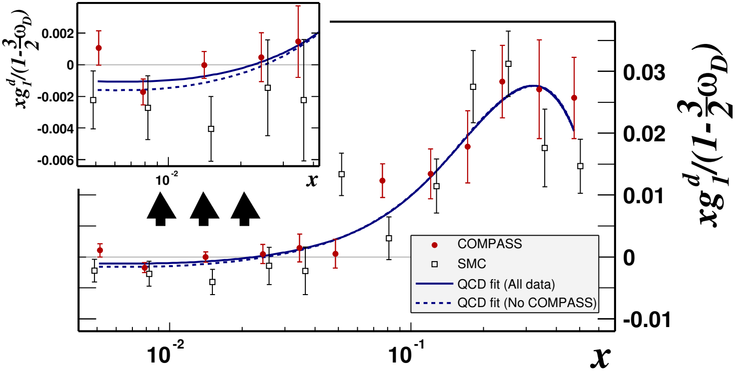
Measurement of g_1 (SMC and COMPASS)



$+$ DESY, SLAC, JLAB

$$\Delta\Sigma = 0.24 \pm 0.03$$

The "spin crisis"

$a_3, \ a_8$
hyp. $\Delta s = 0$

$$\Delta\Sigma \simeq 0.6$$

$a_3, \ a_8$
measurement of $g_1(x)$

$$\Delta\Sigma = 0.24 \pm 0.03$$

Where does the spin of the nucleon comes from?

Contribution of the gluon spin ΔG

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^{q+g}$$

Measuring ΔG is important for 2 reasons:

- $\Delta\Sigma \simeq 0.2$. what is the contribution of the gluon spin ?
- Factorization schemes: ambiguity in the definition of $\Delta\Sigma$...

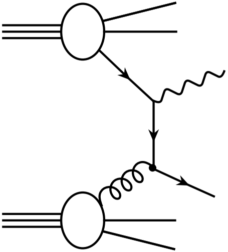
$$\Delta\Sigma - \frac{3\alpha_s}{2\pi}\Delta G \quad ?$$

$\Delta\Sigma$ could be large if ΔG is large.

The experiments

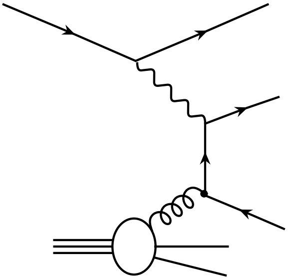
polarized proton–proton collider

- RHIC (PHENIX, STAR)



polarized lepton–nucleon fixed target

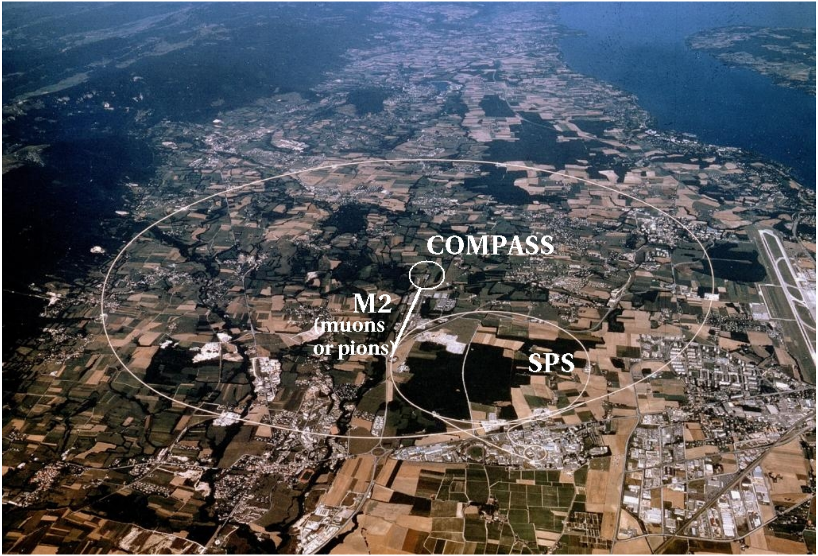
- DESY (HERMES)
- CERN (SMC, COMPASS)



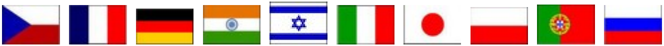
Part II

The COMPASS experiment

SPS, M2 beam line



COMmon aPAratus for Structure and Spectroscopy



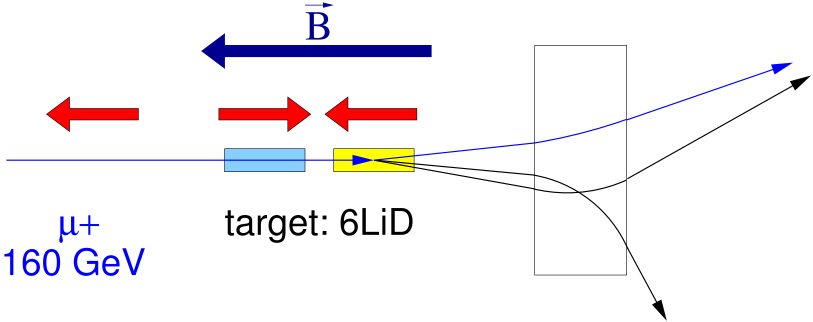
28 institutes from 10 countries

230 physicists

Fixed target experiment, 2 physics programmes:

- pion beam:
  hadron spectroscopy
  - 2004: commissioning
- muon beam:
  longitudinal and transverse spin structure of the nucleon
  - 2001: commissioning
  - 2002, 2003, 2004: data taking

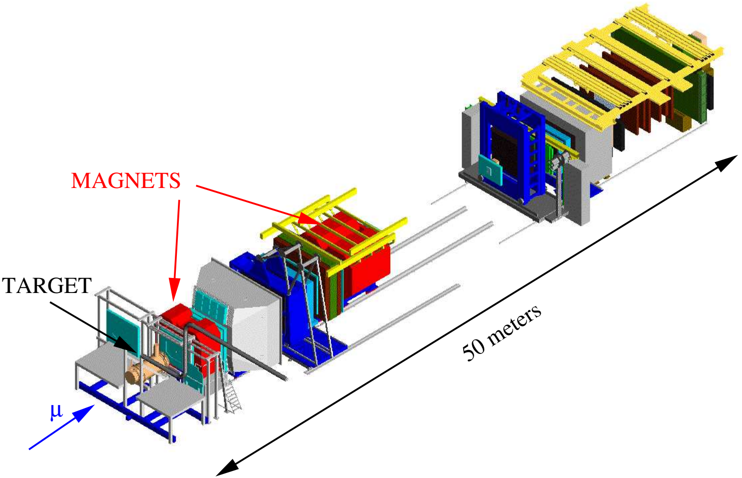
Overview



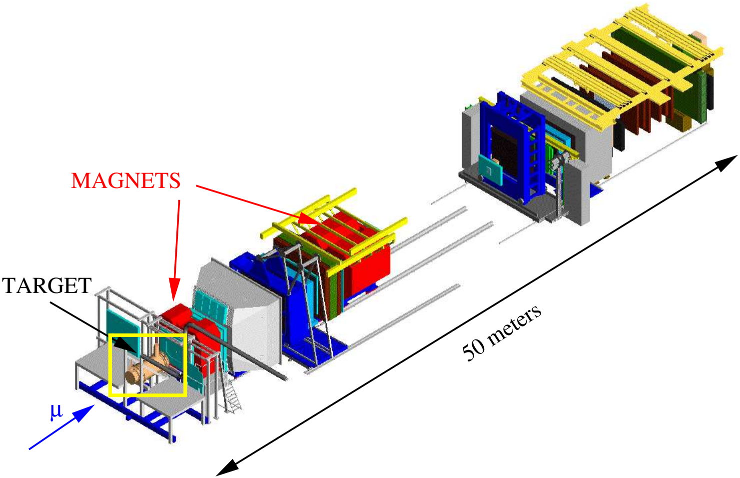
From the counting rate asymmetry between the two target cells, we obtain the cross-section asymmetry:

$$A_{\parallel} \equiv \frac{\sigma^{\leftarrow\Rightarrow} - \sigma^{\leftarrow\Leftarrow}}{\sigma^{\leftarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}}$$

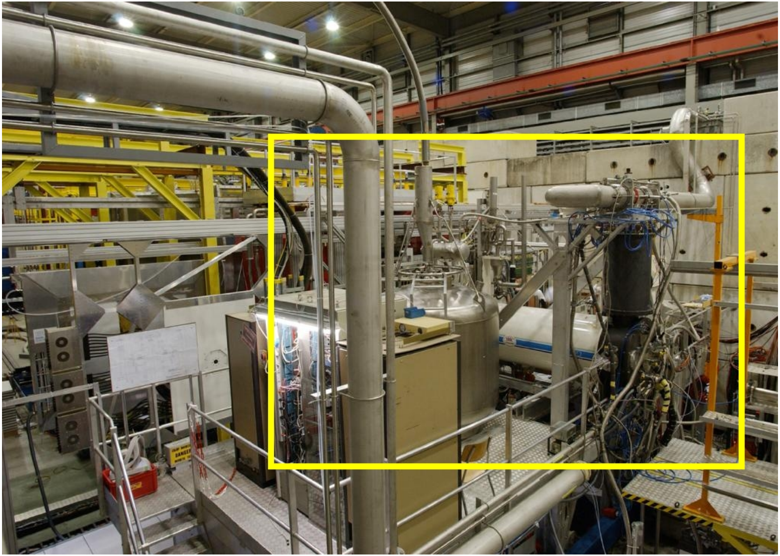
Overview



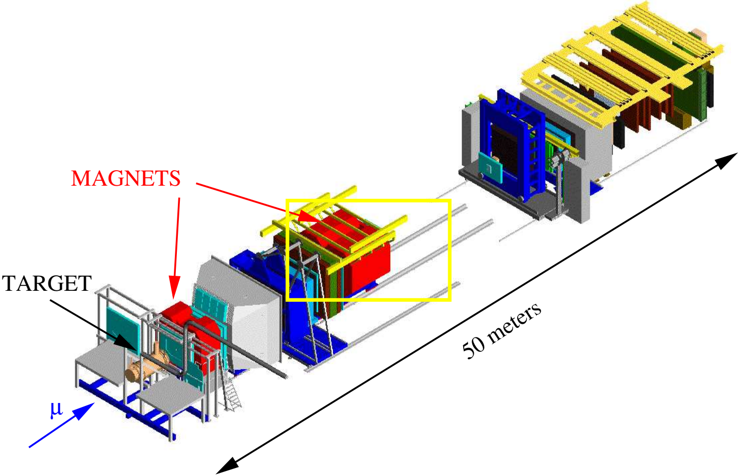
Overview



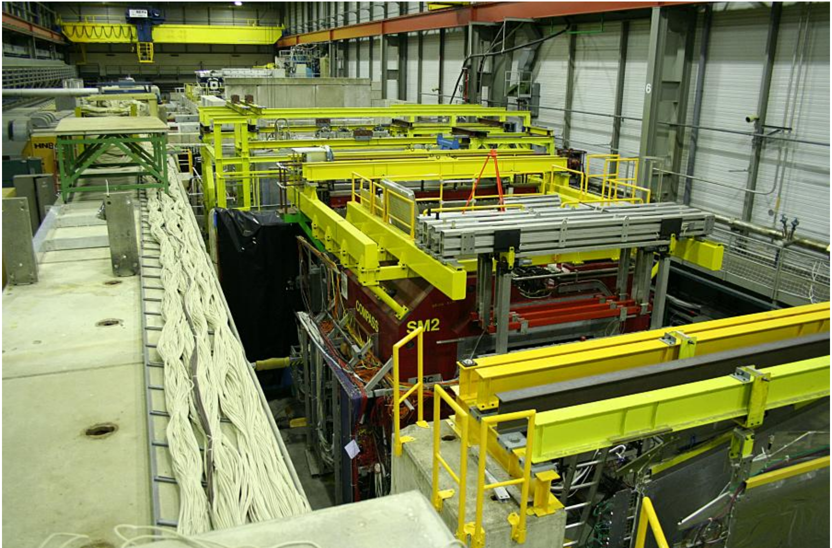
Polarized target



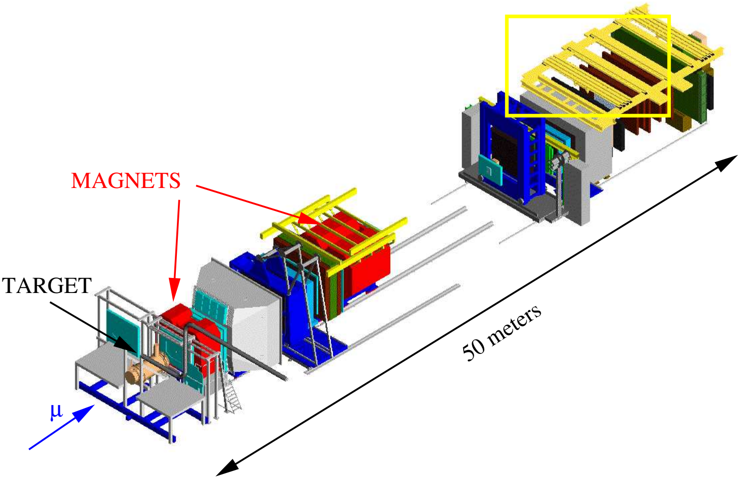
Overview



Second dipole magnet

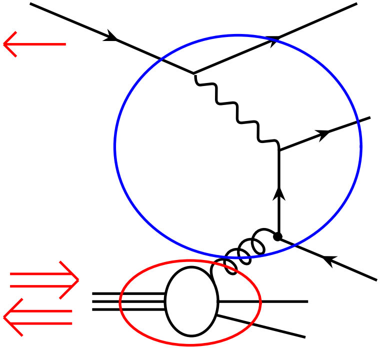


Overview



Hadron absorber

The photon-gluon fusion (pgf)

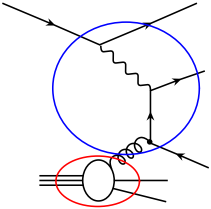


- pgf asymmetry,
  factorization into hard and soft asymmetries.

$$A_{pgf} \equiv \frac{\sigma_{pgf}^{\leftarrow\Rightarrow} - \sigma_{pgf}^{\leftarrow\Leftarrow}}{\sigma_{pgf}^{\leftarrow\Rightarrow} + \sigma_{pgf}^{\leftarrow\Leftarrow}} = \hat{a}_{pgf} \frac{\Delta G}{G}$$

- A hard scale must be present:
  Q^2, p_T^2, m_q^2 ?

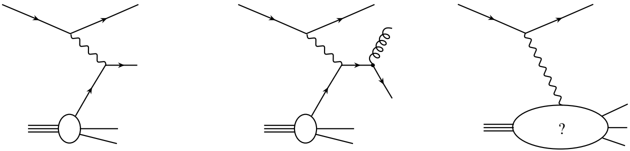
Background processes



$$A_{\parallel} = R_{pgf}\, \hat{a}_{pgf} \frac{\Delta G}{G} + \quad A_{bgd}$$

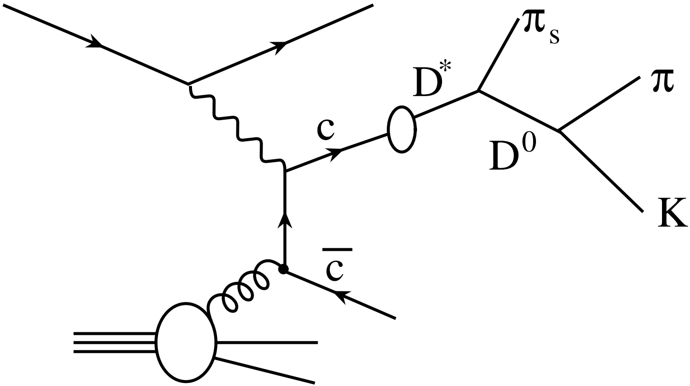
R_{pgf}: fraction of pgf events

Backgrounds

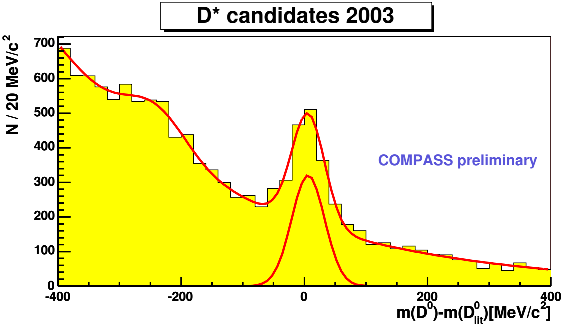


Leading order DIS | QCD Compton scattering | soft processes

Open-charm tagging

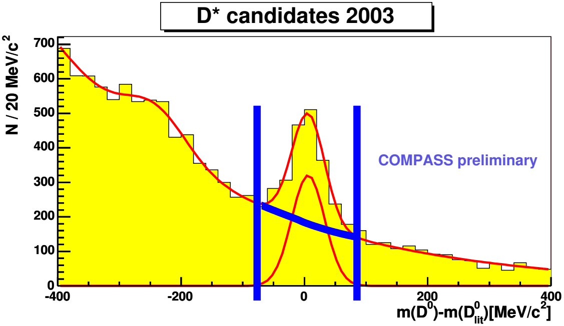


Open-charm tagging (2)



$$A_{\parallel} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} + A_{bgd}$$

Open-charm tagging (2)



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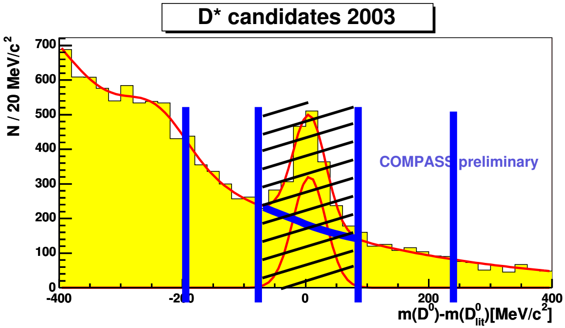


$$A_{\|} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} + A_{bgd}$$

Open-charm tagging, current status

- clean
- low statistics

$\longrightarrow$ small systematics, (still) large statistical error.

2002+2003 COMPASS data:

$$\frac{\Delta G}{G} = -1.08 \pm 0.73$$

Open-charm tagging, current status

- clean
- low statistics

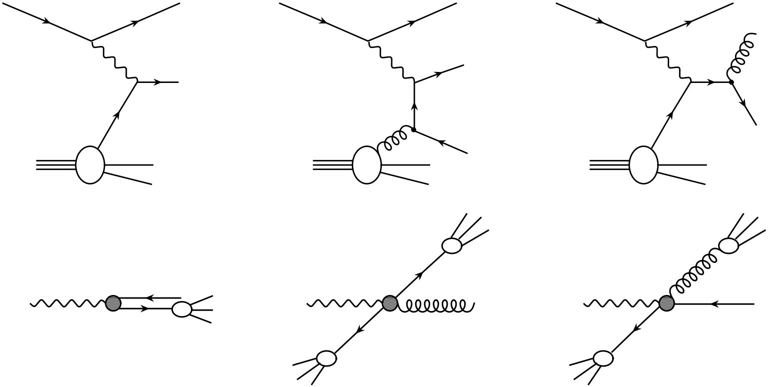
$\longrightarrow$ small systematics, (still) large statistical error.

2002+2003 COMPASS data:

$$\frac{\Delta G}{G} = -1.08 \pm 0.73$$

$$+2004: \quad \pm 0.43$$

High-p_T tagging



leading order DIS (+ soft processes) | photon-gluon fusion | QCD Compton

High-p_T tagging (2)

$$A_{\parallel} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} + A_{bgd}$$

- no need to select c quarks or a particular decay channel
  $\longrightarrow$ high statistics
- No peak $\longrightarrow$ no way to measure R_{pgf} and A_{bgd}
- Estimated by Monte Carlo $\longrightarrow$ model dependence

$\longrightarrow$ good statistical accuracy, large systematics.

Part III

Determination of the gluon polarization

Outline

$$A_{\parallel} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} + A_{bgd}$$

The high p_T asymmetry

PYTHIA simulation

Systematics

Result for $\frac{\Delta G}{G}$

Selection of high p_T events

- 2 hadrons with:

$$p_{T,1} \text{ and } p_{T,2} > 0.7\,\text{GeV}$$
$$p_{T,1}^2 + p_{T,2}^2 > 2.5\,\text{GeV}^2$$
$$\ldots$$

- $Q^2 < 1$ GeV^2 (p_T^2 gives the scale)
- $Q^2 > 1$ GeV^2 data analyzed separately (LEPTO)

The high p_T asymmetry (2002+2003)

$$A_{\parallel} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} \; + \; A_{bgd}.$$

The high p_T asymmetry (2002+2003)

$$A_{\parallel} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} \quad + \quad A_{bgd}.$$

$$\frac{A_{\parallel}}{D} = R_{pgf}\,\frac{\hat{a}_{pgf}}{D}\,\frac{\Delta G}{G} \quad + \quad \frac{A_{bgd}}{D}.$$

The high p_T asymmetry (2002+2003)

$$A_{\parallel} = R_{pgf}\,\hat{a}_{pgf}\,\frac{\Delta G}{G} \quad + \quad A_{bgd}.$$

$$\frac{A_{\parallel}}{D} = R_{pgf}\,\frac{\hat{a}_{pgf}}{D}\,\frac{\Delta G}{G} \quad + \quad \frac{A_{bgd}}{D}.$$

$$= 0.002 \pm 0.019(stat) \pm 0.003(exp.syst).$$

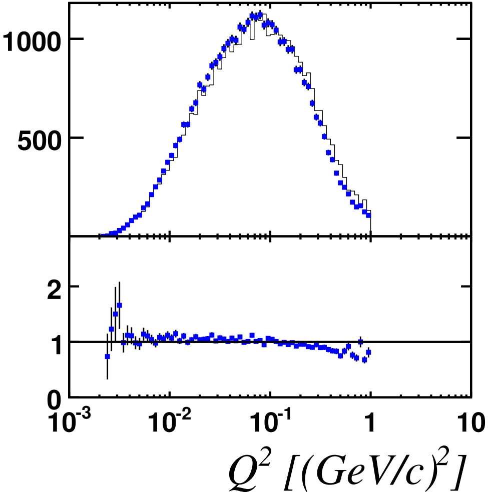
Simulation

- PYTHIA 6.2
- GEANT 3
- same reconstruction program as for real data
- same selection of high p_T events

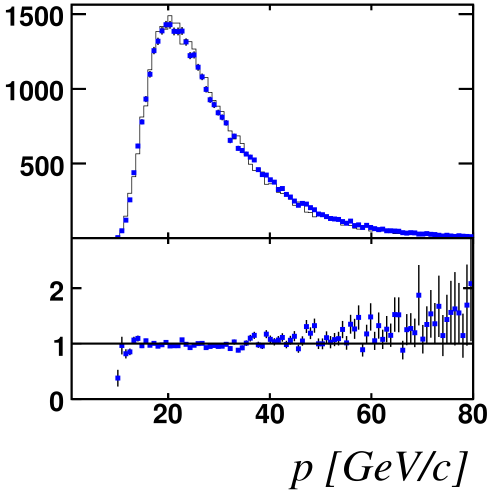
$$\frac{A_{\parallel}}{D} = R_{pgf}\,\frac{\hat{a}_{pgf}}{D}\,\frac{\Delta G}{G} \quad + \quad \frac{A_{bgd}}{D}$$

The simulation has to reproduce the data!

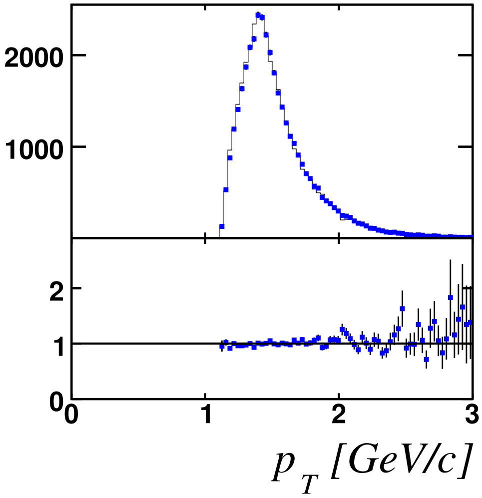
Data / Monte Carlo comparisons: Q^2



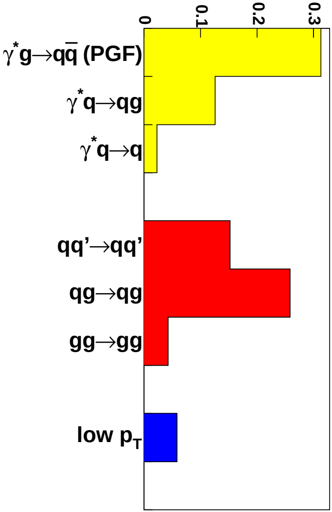
Data / Monte Carlo comparisons: p first hadron

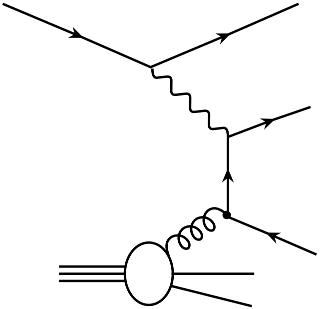


Data / Monte Carlo comparisons: p_T first hadron



The PYTHIA subprocesses





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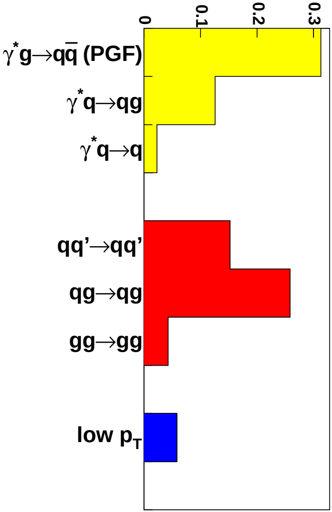

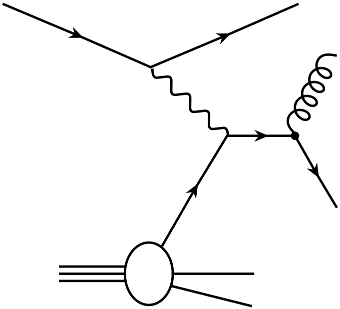

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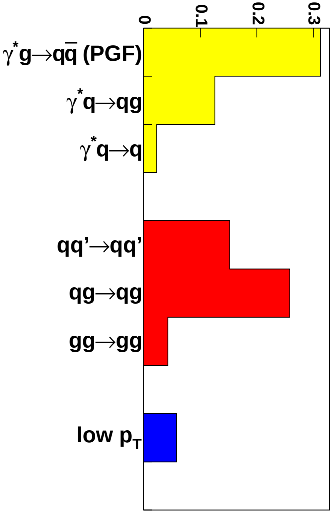

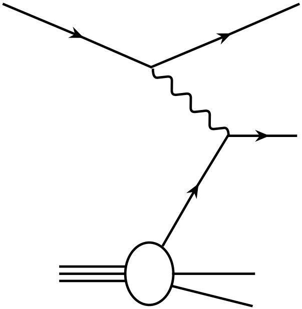

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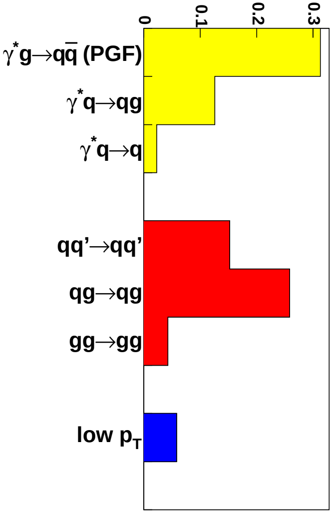

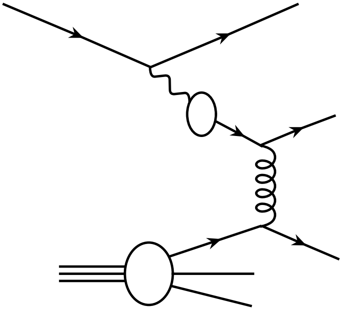

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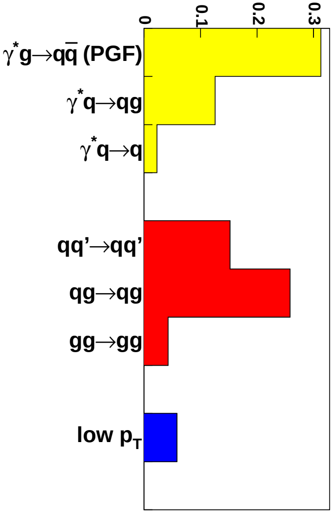

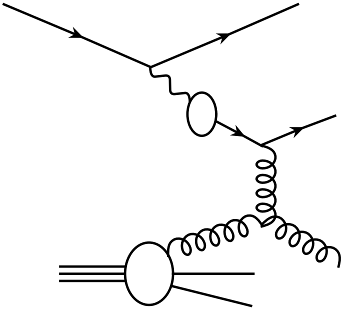

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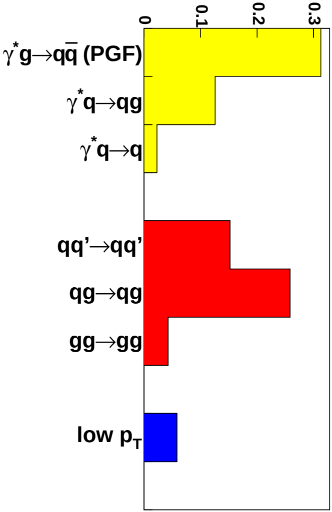
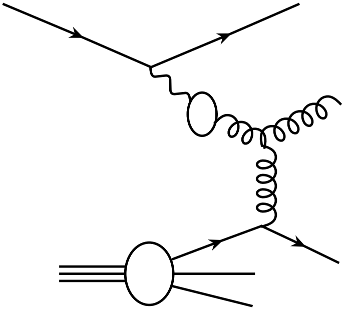
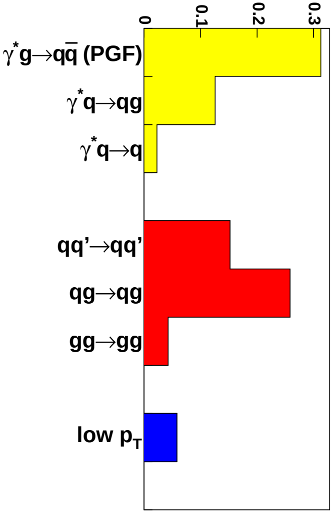
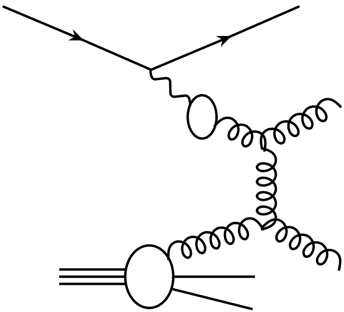


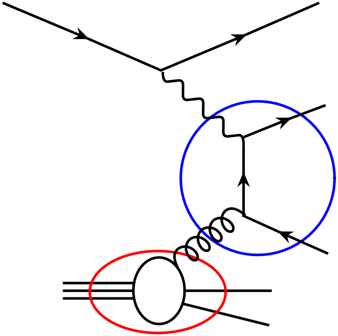


The PYTHIA subprocesses



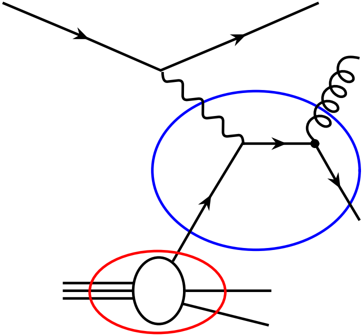


Contributions to the asymmetry



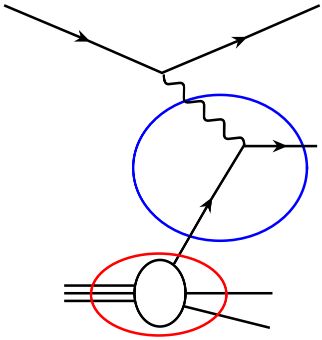
$$\frac{A_{\parallel}}{D} = R_{pgf} \frac{\hat{a}_{pgf}}{D} \left(\frac{\Delta G}{G} \right)^N$$

Contributions to the asymmetry



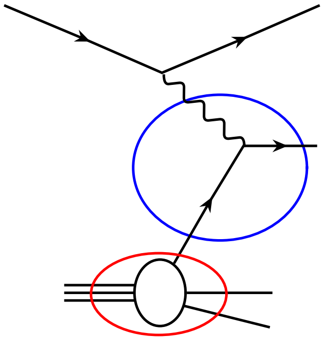
$$\frac{A_{\parallel}}{D} = R_{pgf} \frac{\hat{a}_{pgf}}{D} \left(\frac{\Delta G}{G} \right)^N + R_{qcdc} \frac{\hat{a}_{qcdc}}{D} \left(\frac{\Delta q}{q} \right)^N$$

Contributions to the asymmetry



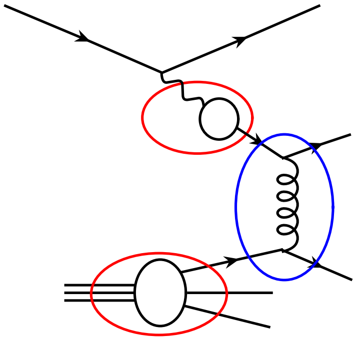
$$\frac{A_{\parallel}}{D} = R_{pgf}\frac{\hat{a}_{pgf}}{D}\left(\frac{\Delta G}{G}\right)^N + R_{qcdc}\frac{\hat{a}_{qcdc}}{D}\left(\frac{\Delta q}{q}\right)^N + R_{lodis}\frac{\hat{a}_{lodis}}{D}\left(\frac{\Delta q}{q}\right)^N$$

Contributions to the asymmetry



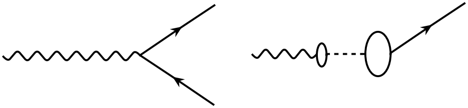
$$\frac{A_{\parallel}}{D} = R_{pgf}\frac{\hat{a}_{pgf}}{D}\left(\frac{\Delta G}{G}\right)^{N} + R_{qcdc}\frac{\hat{a}_{qcdc}}{D}\left(\frac{\Delta q}{q}\right)^{N}$$

Contributions to the asymmetry



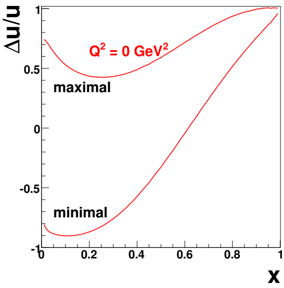
$$\frac{A_{\parallel}}{D} = R_{pgf}\frac{\hat{a}_{pgf}}{D}\left(\frac{\Delta G}{G}\right)^{N} + R_{qcdc}\frac{\hat{a}_{qcdc}}{D}\left(\frac{\Delta q}{q}\right)^{N} + R_{qq'}\hat{a}_{qq'}\left(\frac{\Delta q}{q}\right)^{N}\left(\frac{\Delta q'}{q'}\right)^{\gamma} + \ldots$$

Quark polarization in the photon $\left(\frac{\Delta q}{q}\right)^{\gamma}$



$$\Delta q^{\gamma} = \Delta q^{\gamma}_{q\bar{q}} + \Delta q^{\gamma}_{VMD}$$

- $\Delta q^{\gamma}_{q\bar{q}}$: QED+QCD
- min and max scenarios:
  $-q^{\gamma}_{VMD} \leq \Delta q^{\gamma}_{VMD} \leq q^{\gamma}_{VMD}$



(Glück, Reya, Sieg)

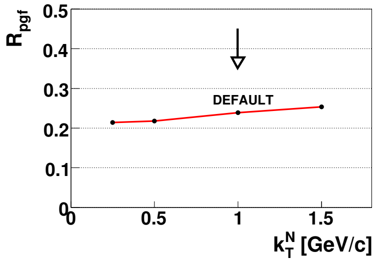
Systematic error associated to the Monte Carlo

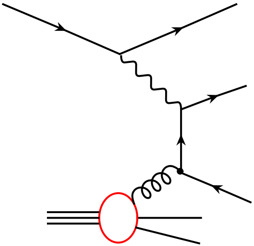
$$\frac{A_{\parallel}}{D} = 0.002 \pm 0.019(stat) \pm 0.003(exp.syst)$$
$$= R_{pgf} \frac{\hat{a}_{pgf}}{D} \frac{\Delta G}{G} + \frac{A_{bgd}}{D}.$$

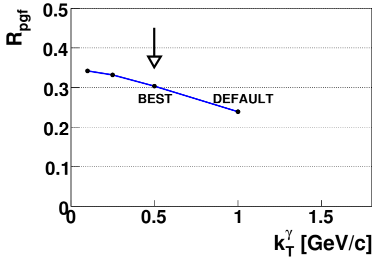
Scan of the PYTHIA parameters

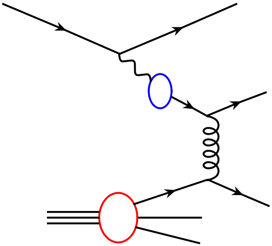
- related to next-to-leading orders:
  - Renormalization/factorization scale,
  - "Parton Showers".
- acting on p_T:
  - parton fragmentation,
  - primordial transverse momentum of the partons in the nucleon and in the photon.

Systematics: k_T^N et k_T^γ









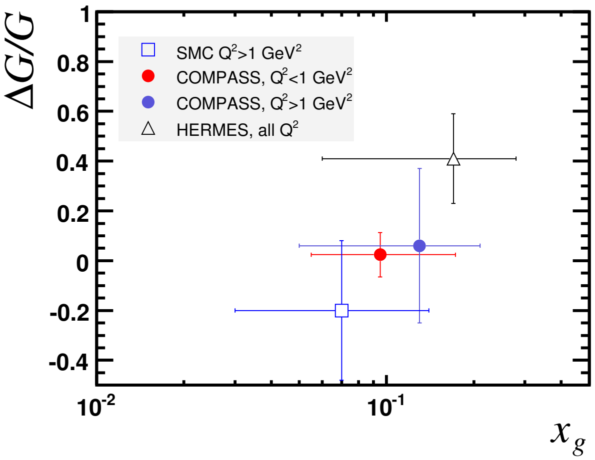
$\frac{\Delta G}{G}$, 2002+2003

$$\left(\frac{\Delta G}{G}\right)_{min} = 0.016 \pm 0.068(stat) \pm 0.011(exp.syst) \pm 0.018(MC.syst)$$

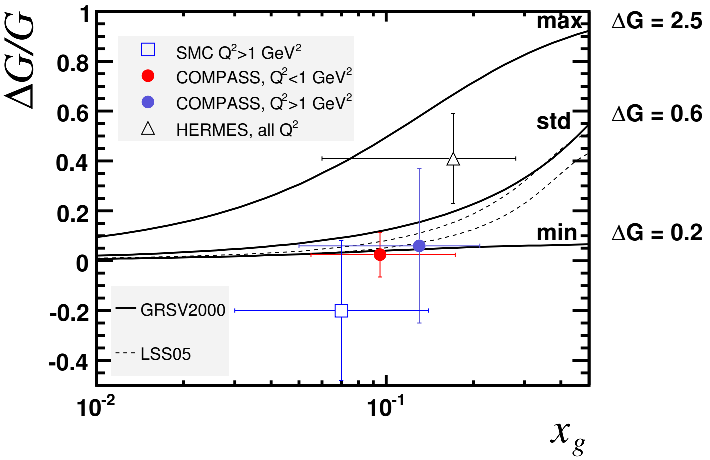
$$\left(\frac{\Delta G}{G}\right)_{max} = 0.031 \pm 0.089(stat) \pm 0.014(exp.syst) \pm 0.052(MC.syst)$$

$$\rightarrow \quad \frac{\Delta G}{G} = 0.024 \pm 0.089(stat.) \pm 0.057(syst.).$$

2002+2003 data



2002+2003 data



Conclusion

2002+2003

$Q^2 < 1\ \mathrm{GeV}^2$	$\frac{\Delta G}{G} = 0.024 \pm 0.089 \pm 0.057$
$Q^2 > 1\ \mathrm{GeV}^2$	$\frac{\Delta G}{G} = 0.06 \pm 0.31 \pm 0.06$
charm	$\frac{\Delta G}{G} = -1.08 \pm 0.73$

Conclusion

	2002+2003	+2004 (proj.)
$Q^2 < 1\ \mathrm{GeV}^2$	$\frac{\Delta G}{G} = 0.024 \pm \underline{0.089} \pm 0.057$	$\pm\underline{0.065}$
$Q^2 > 1\ \mathrm{GeV}^2$	$\frac{\Delta G}{G} = 0.06 \pm \underline{0.31} \pm 0.06$	$\pm\underline{0.22}$
charm	$\frac{\Delta G}{G} = -1.08 \pm \underline{0.73}$	$\pm\underline{0.43}$

Conclusion

	2002+2003	+2004 (proj.)
$Q^2 < 1\ \mathrm{GeV}^2$	$\frac{\Delta G}{G} = 0.024 \pm \underline{0.089} \pm 0.057$	$\pm\underline{0.065}$
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charm	$\frac{\Delta G}{G} = -1.08 \pm \underline{0.73}$	$\pm\underline{0.43}$

- only one point cannot a priori rule out large values of ΔG
- looking at QCD fits of g_1 data, our results favor $\Delta G < 0.5$

Conclusion (2)

- Spin crisis: measured $\Delta\Sigma = 0.2$ instead of 0.6
  Ambiguity in the definition of $\Delta\Sigma$...

$$\Delta\Sigma - \frac{3\alpha_s}{2\pi}\Delta G \quad ?$$

  $\Delta G \simeq 3$ necessary to solve the spin crisis.
  unlikely $\longrightarrow$ still in crisis...

- NB: this is a model dependent analysis
- a paper is about to be submitted