

# Gluon and Spin



- Introduction
- $\Delta G$  from scaling violations
- $\Delta G/G$  from hadron production
  - Open charm
  - Hadron pairs
  - Single hadrons
- $\Delta G$  in pp RHIC

G. Mallot  
CERN/COMPASS

# How it all began



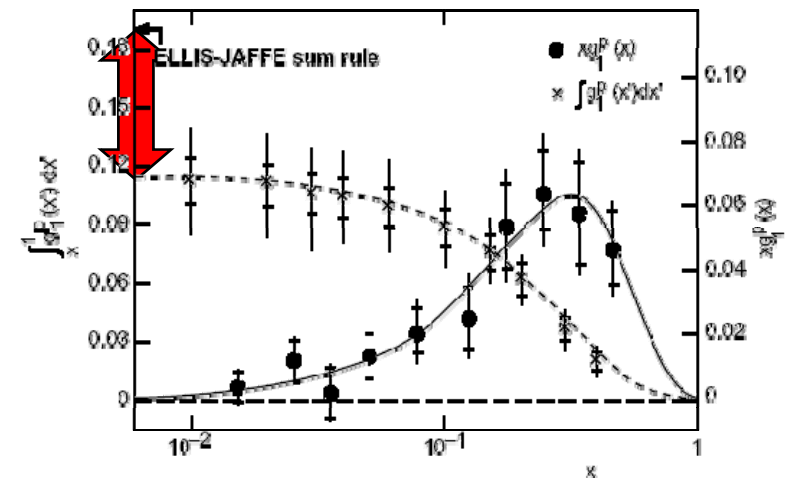
All started 1987 with the discovery by the EMC

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

$$\Delta\Sigma = 0.12 \pm 0.17$$

$$\Delta s = -0.19 \pm 0.06$$

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



- Ellis-Jaffe sum rule violated
- Quark spin contribute little to nucleon spin
- Where is the nucleon spin?

# Theory Input 1988



## Spin Content of the Proton

F. E. Close

*Department, University of Tennessee, Knoxville*

and **PRI**

## CHIRAL SYMMETRY AND THE SPIN OF THE PROTON \*

Stanley J. BRODSKY<sup>a</sup>, John ELLIS<sup>a,b1</sup> and Marek KARLINER<sup>a</sup>

<sup>a</sup> *Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA*

<sup>b</sup> *CERN, CH-1211 Geneva 23, Switzerland*

**PLB 206 (1988) 309**

## A crisis in the parton model: where, oh where is the proton's spin?

E. Leader<sup>1</sup> and M. Anselmino<sup>2</sup>

*Birkbeck College, University of London, London, UK*

*Dipartimento di Fisica Teorica, Università di Torino, I-10125 Torino, Italy*

Received 18 March 1988

**ZPC 41 (1988) 239**

**E2-88-287**

**A.V.Efremov, O.V.Teryaev\***

## SPIN STRUCTURE OF THE NUCLEON AND TRIANGLE ANOMALY

## THE ANOMALOUS GLUON CONTRIBUTION TO POLARIZED LEPTOPRODUCTION

G. ALTARELLI and G.G. ROSS<sup>1</sup>

*CERN, CH-1211 Geneva 23, Switzerland*

Received 29 June 1988

**PLB 212 (1988) 391**

# Considered Options



- Small- $x$  extrapolation? (CR)
- Skyrmions:  $\Delta G = 0$  possibly (BEK)
- Bjorken sum rule broken? (only proton data at that time)  
Measurement wrong? (LA)
- Large  $\Delta G \sim 2-3$  at EMC  $Q^2$  could mask quark spin via axial anomaly (ET, AR)

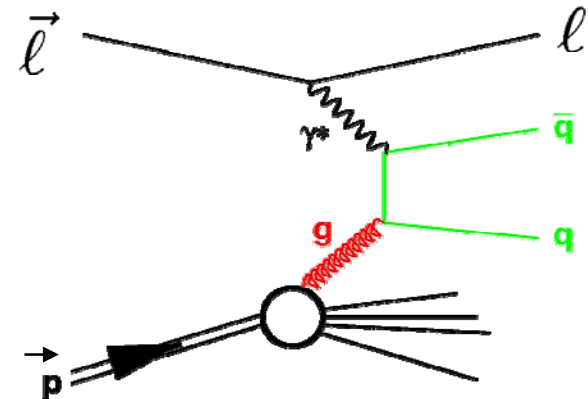
requires fine tuning of cancelation of  $\Delta G$  and orbital angular momentum

# How to measure $\Delta G/G$



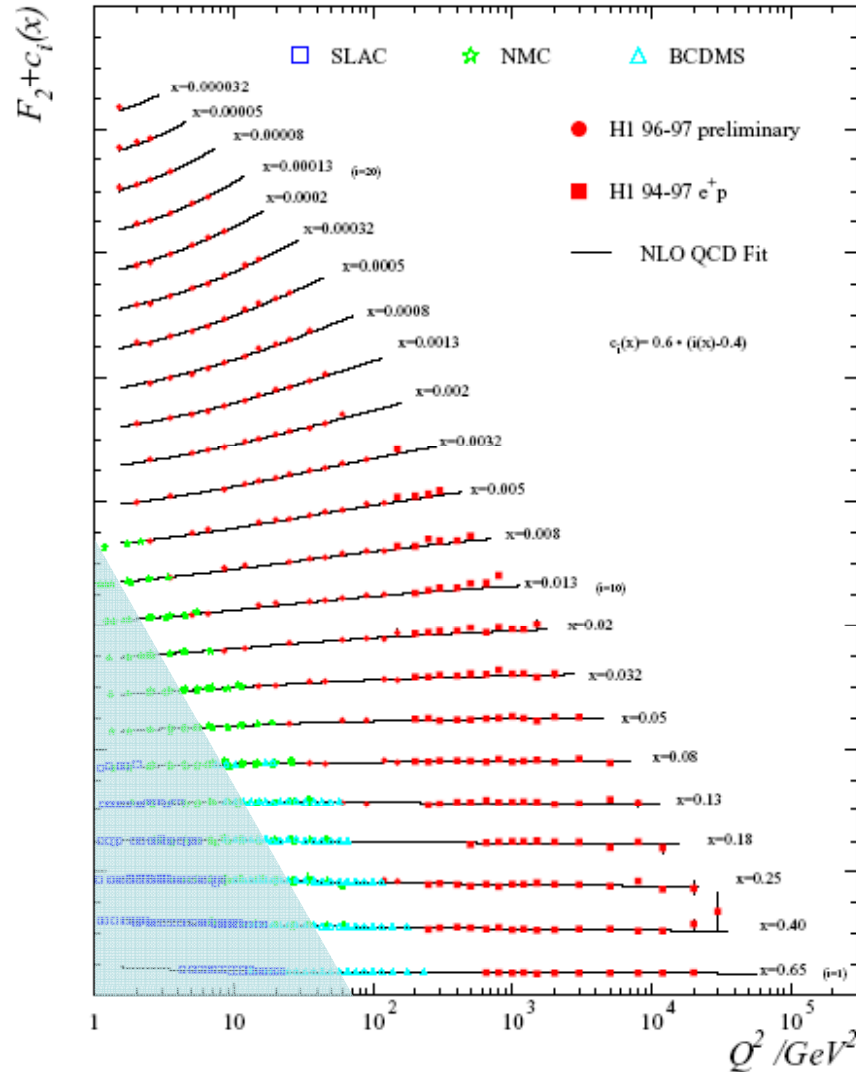
First step: Is  $\Delta G$  indeed in the order  $2-3 \hbar$  ?

- Scaling violations in  $g_1$ , however no polarised ep collider!
- Longitudinal double-spin asymmetries in hadron production via photon-gluon fusion (**Hendlmeier**)
- LDSA in pp collisions at RHIC (**Aidala**)

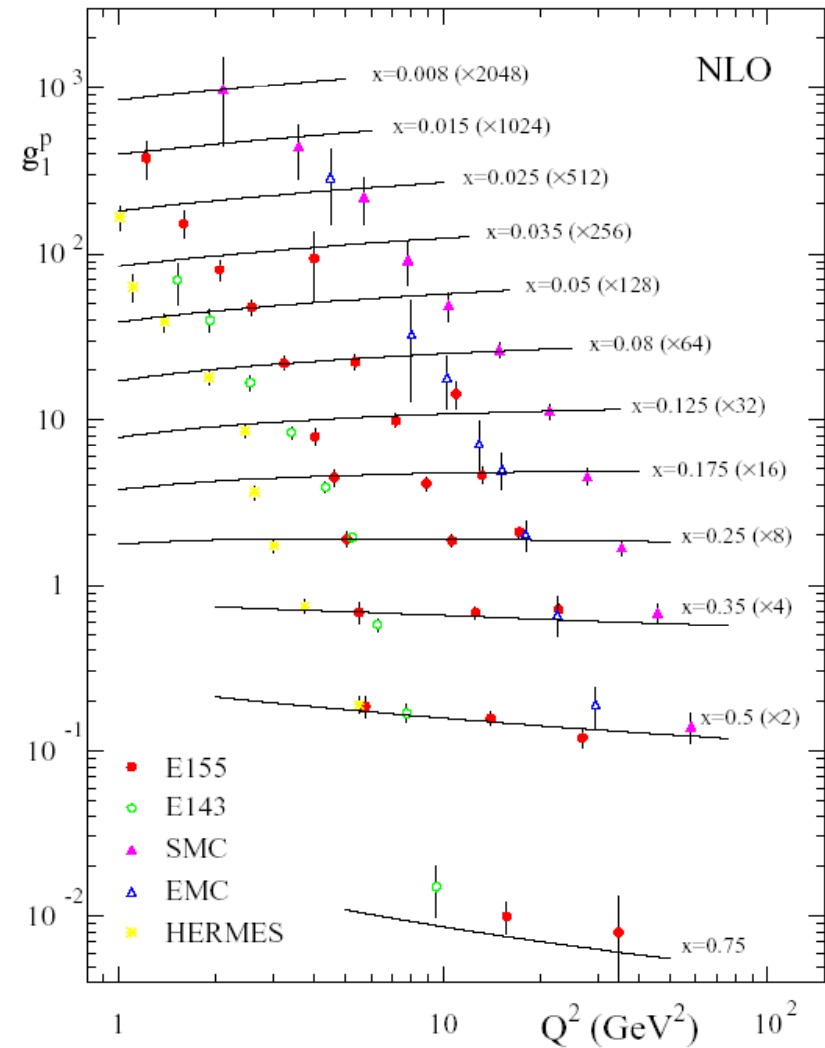


$$F_2(x, Q^2)$$

$$g_1(x, Q^2)$$



Int. Workshop on Structure and Spectroscopy



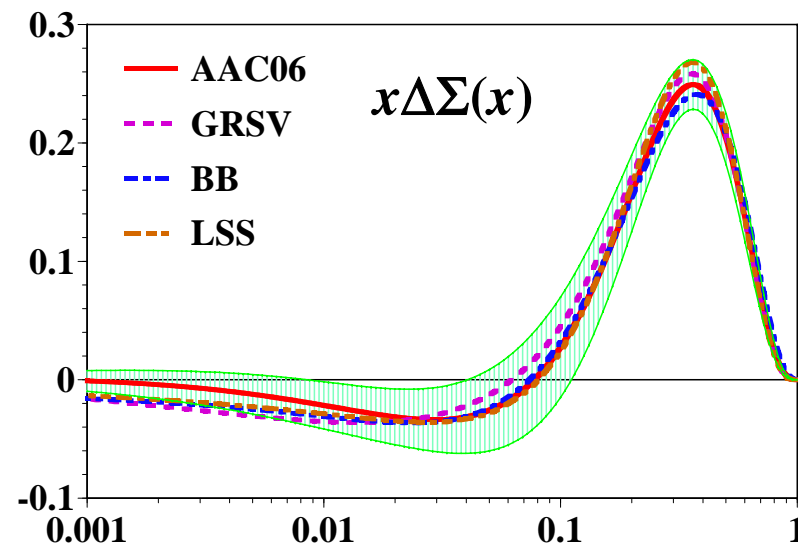
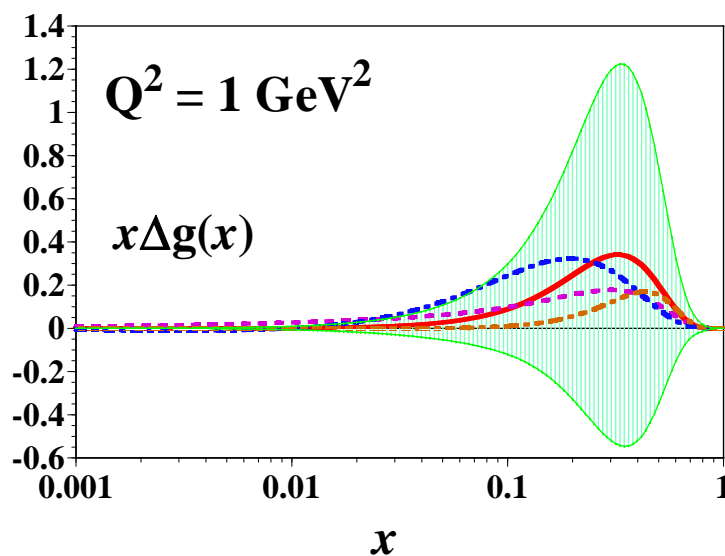
Freiburg March 2007

G. Mallot/CERN

# NLO QCD fits



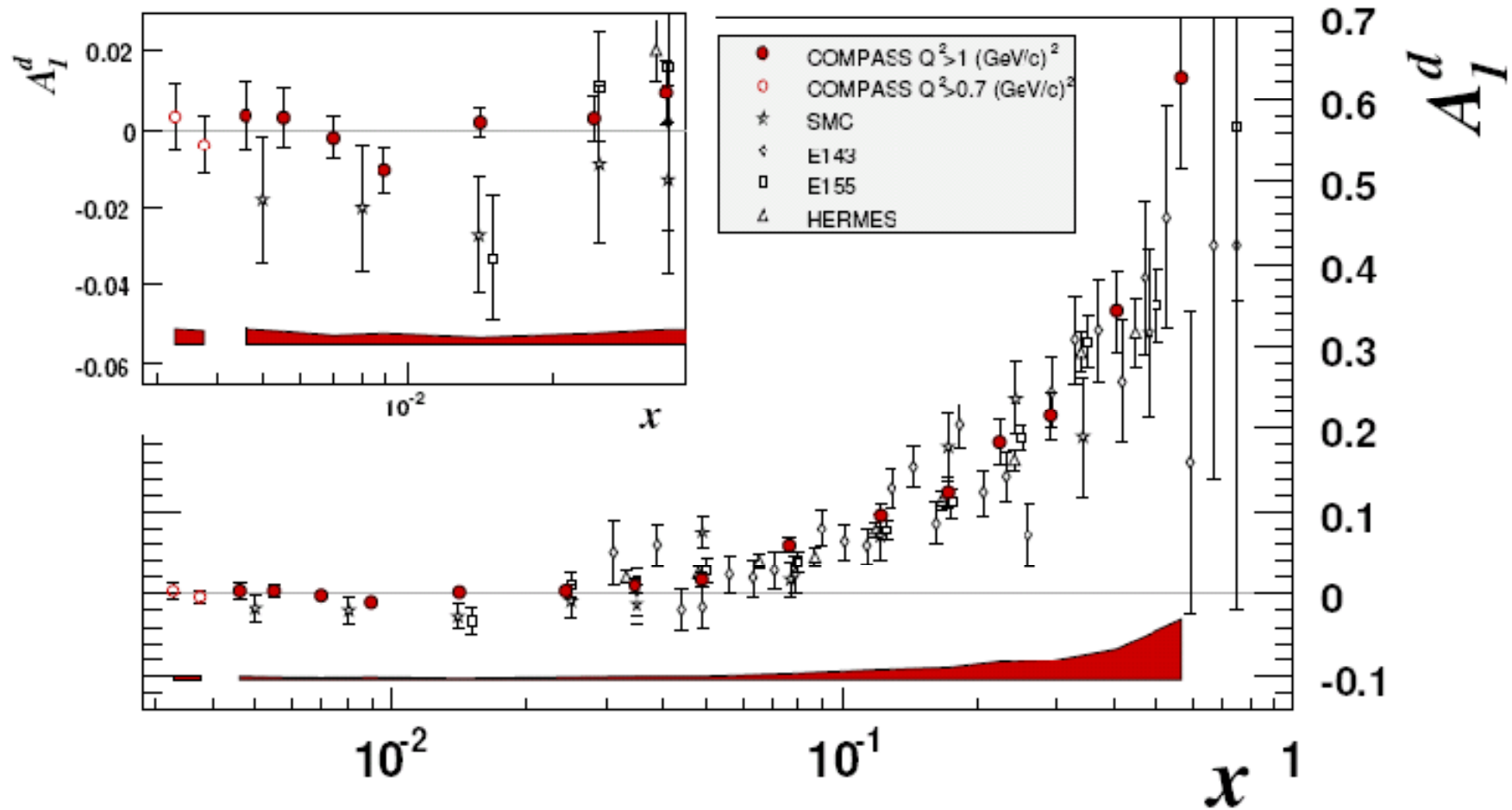
- Several groups performing World Data fits
- Example AAC, new fit 2006
- Still large uncertainty in  $\Delta G$ , even sign not determined
- Extra difficulties in polarized case
  - No positivity condition
  - No momentum sum rule



# New COMPASS $A_1^d$ data



PLB647 (2007) 8







# COMPASS NLO QCD fit

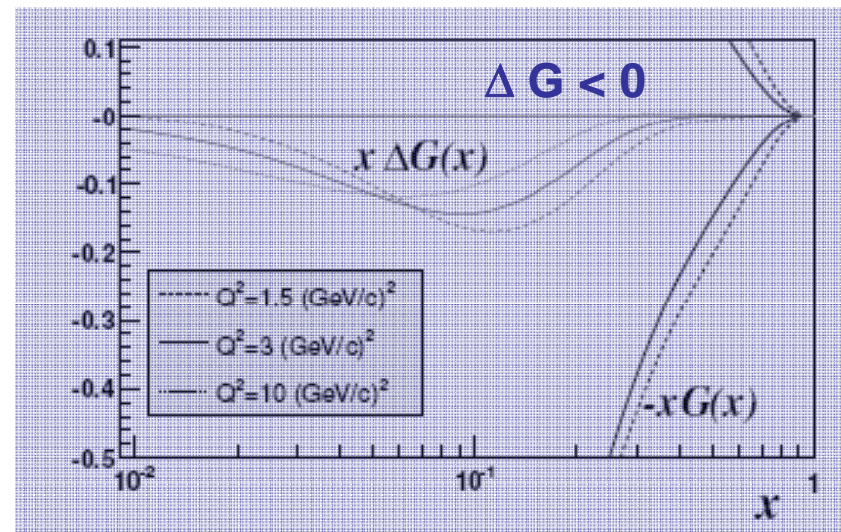
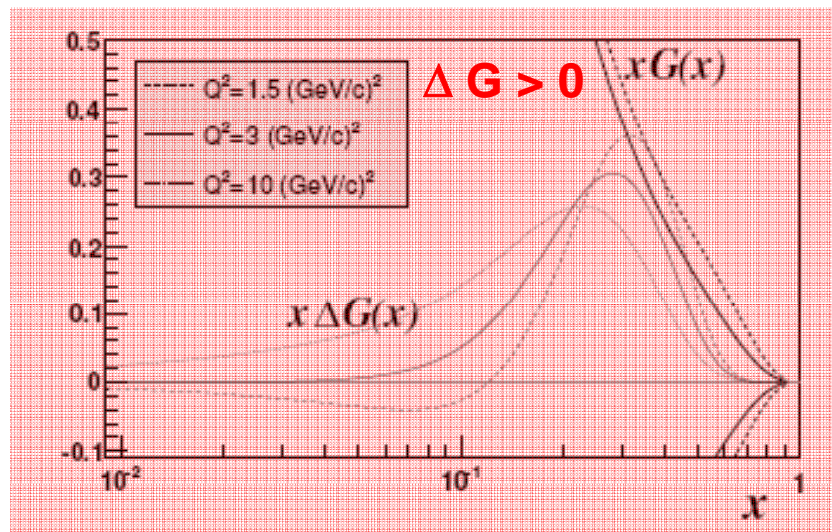


- New  $g_1^d$  data + world data
- $\Delta G > 0$  and  $\Delta G < 0$
- $|\Delta G|' 0.2-0.3$
- $a_0 = 0.33 \pm 0.03 \pm 0.05$
- $\Delta s = -0.08 \pm 0.01 \pm 0.02$

cf.: New Hermes Fit:

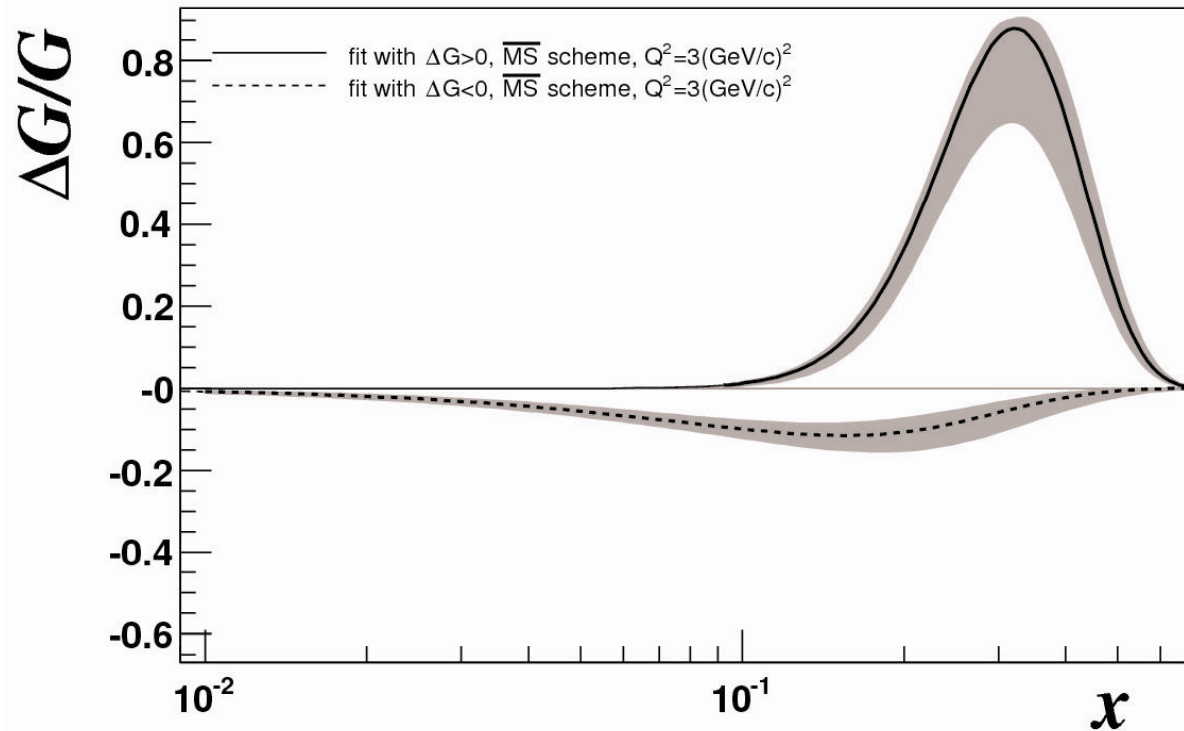
$$a_0 = 0.330 \pm 0.011 \pm 0.025 \\ \pm 0.028 \text{ (evol)}$$

$$\Delta s = -0.085 \pm 0.013 \pm 0.08 \pm 0.09$$



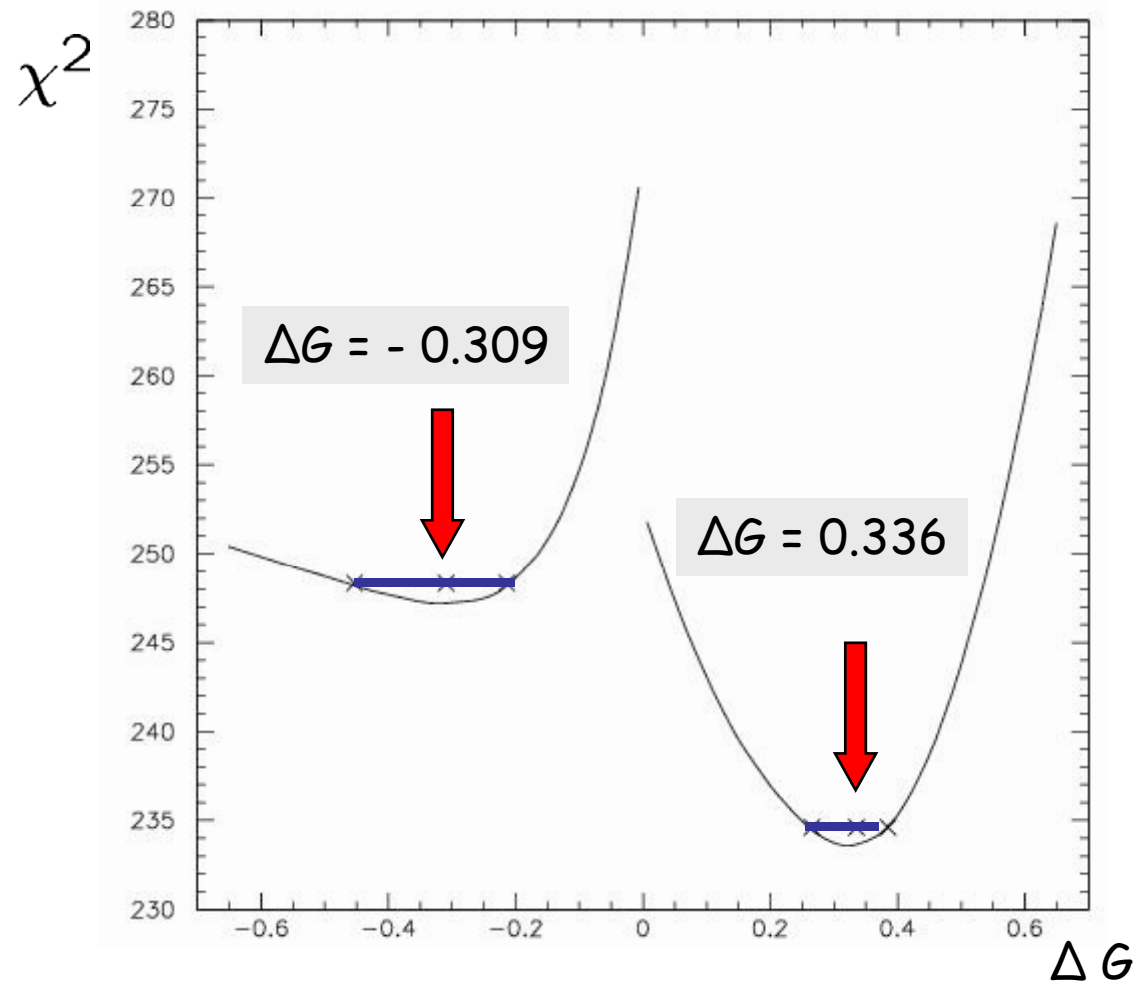


# COMPASS QCD fit



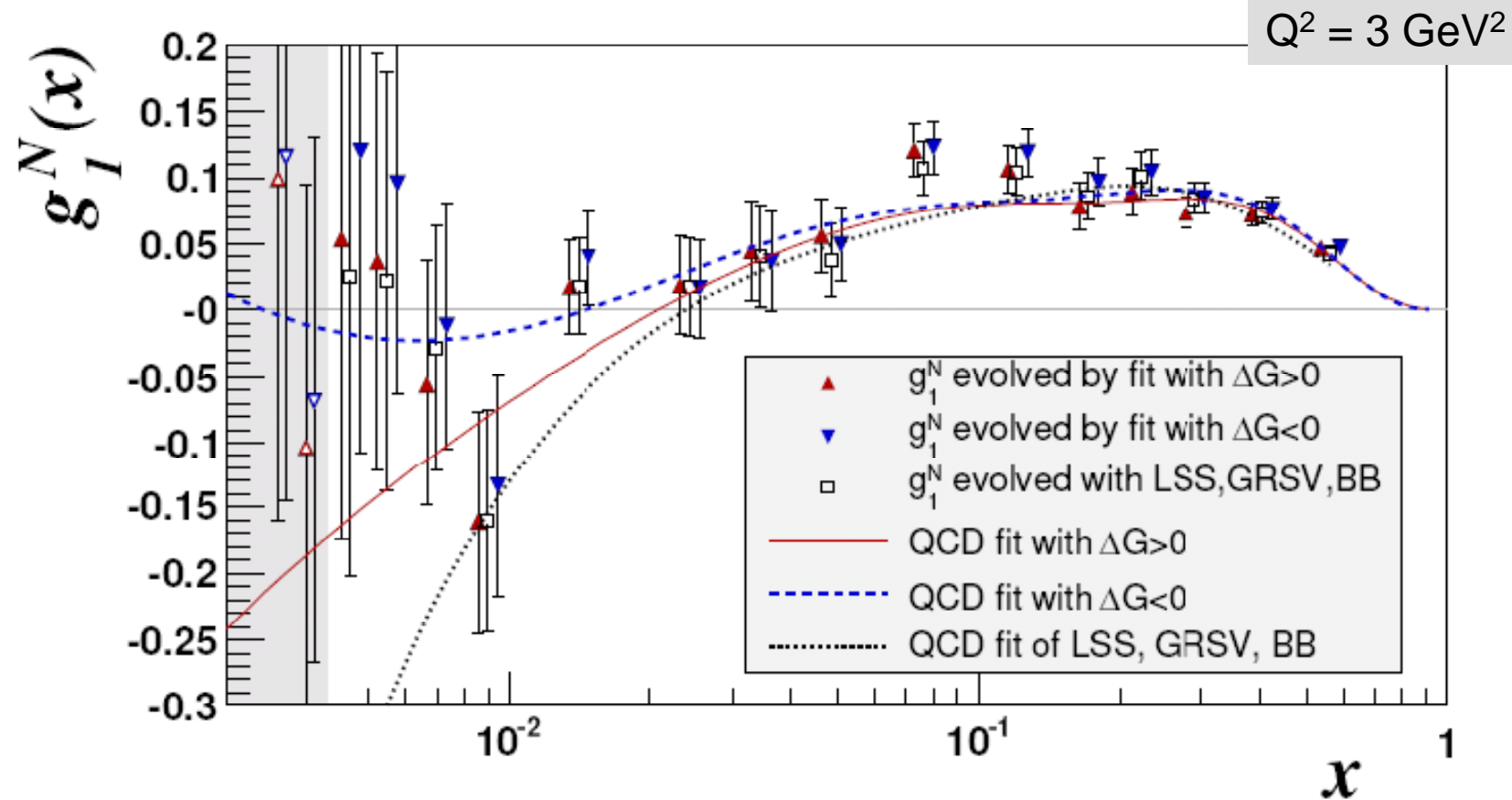
- Not yet included in fits: final Hermes  $g_1^d$
- Uncertainty due to parametrisation not included

# $\chi^2$ as Function of $\Delta G$



- Two distinct solutions
- $\Delta G > 0$  preferred
- $\Delta G < 0$  preferred by small- $x$  points

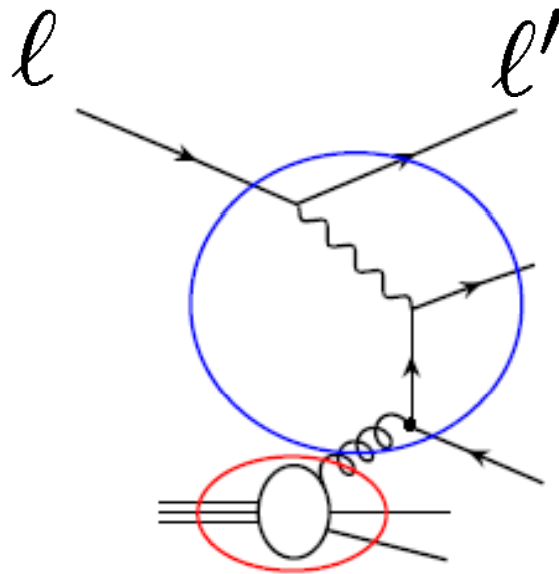
# QCD fit



# Photon-gluon fusion (PGF)



- Gluon polarisation is measurable in PGF



$$A_{||} = R_{pgf} \langle \hat{a}_{pgf} \rangle \frac{\Delta G}{G}$$

- measure  $A_{||}$
- calculate  $R_{pgf}$  and  $\langle \hat{a}_{pgf} \rangle$

using Monte Carlo

# Hadron production



- LO analysis of hadron-pair asymmetries:
  - open charm: single  $D$  meson  
cleanest process wrt physics background
  - high- $p_T$  hadron pairs with  $Q^2 > 1 \text{ GeV}^2$
  - high- $p_T$  hadron pairs with  $Q^2 < 1 \text{ GeV}^2$

AROMA, RAPGAP

LEPTO

PYTHIA

- NLO (photo production)
  - open charm
  - single incl. high- $p_T$  hadron
  - hadron pairs: LO done,
  - NLO underway

Bojak, Stratmann

Jaeger, Stratmann, Vogelsang

Hendlmeier, Stratmann, Schäfer

- All analyses up to now in LO (plus parton showers)

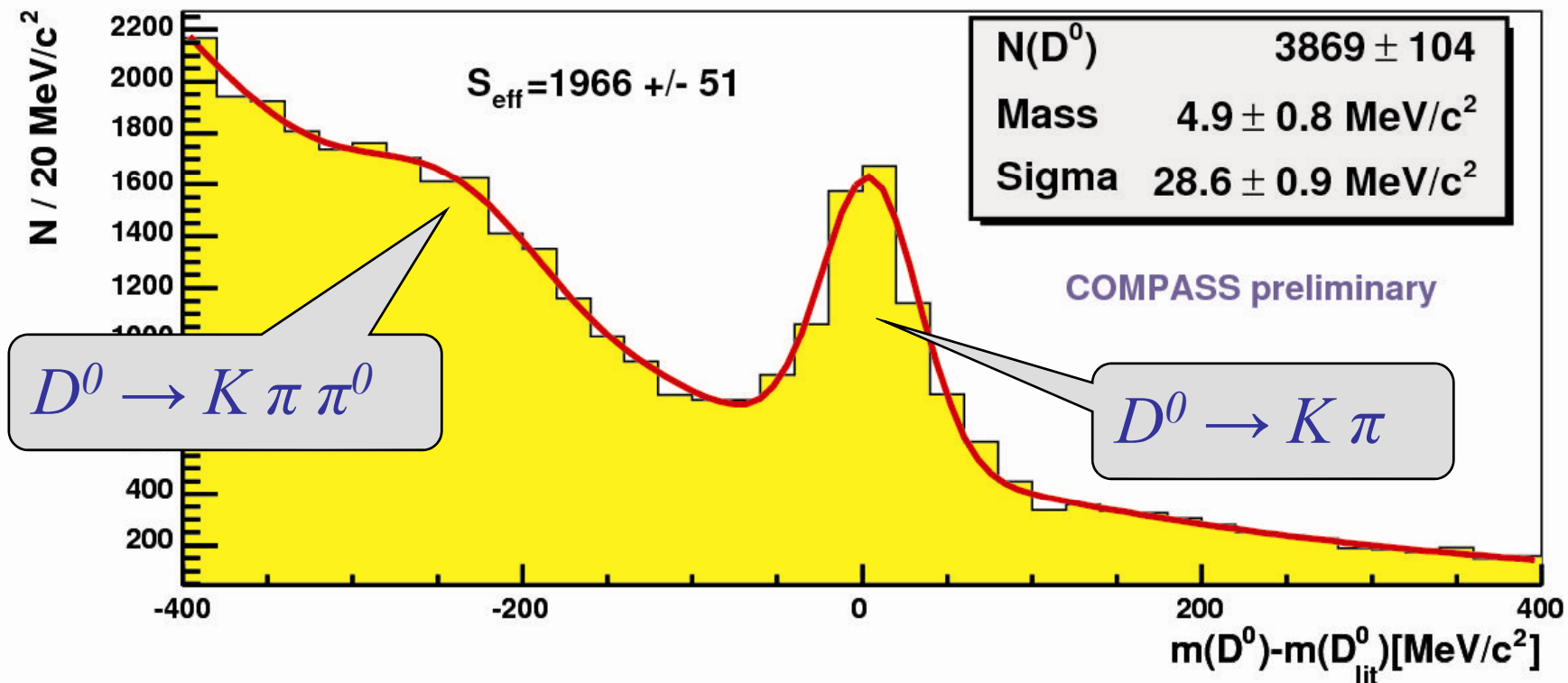


# Open Charm: $D$ 's from $D^*$ 's



$D^* \rightarrow D \pi_s \rightarrow K \pi \pi_s$  slow pion required

2002–2004

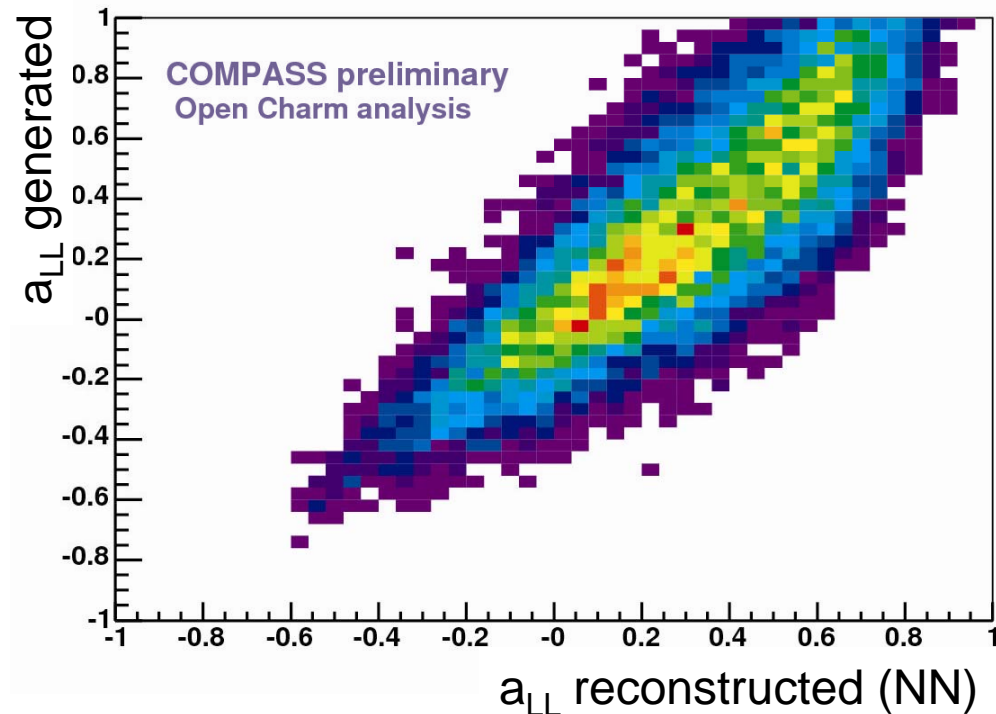




# Open charm: MC



- analysis uses event  $a_{LL}$  weighting,
- $a_{LL}$  estimated with NN from event kinematics
- 
- indispensable due to large variation of  $a_{LL}$
- good correlation of 0.82 between *generated* and *reconstructed*  $a_{LL}$



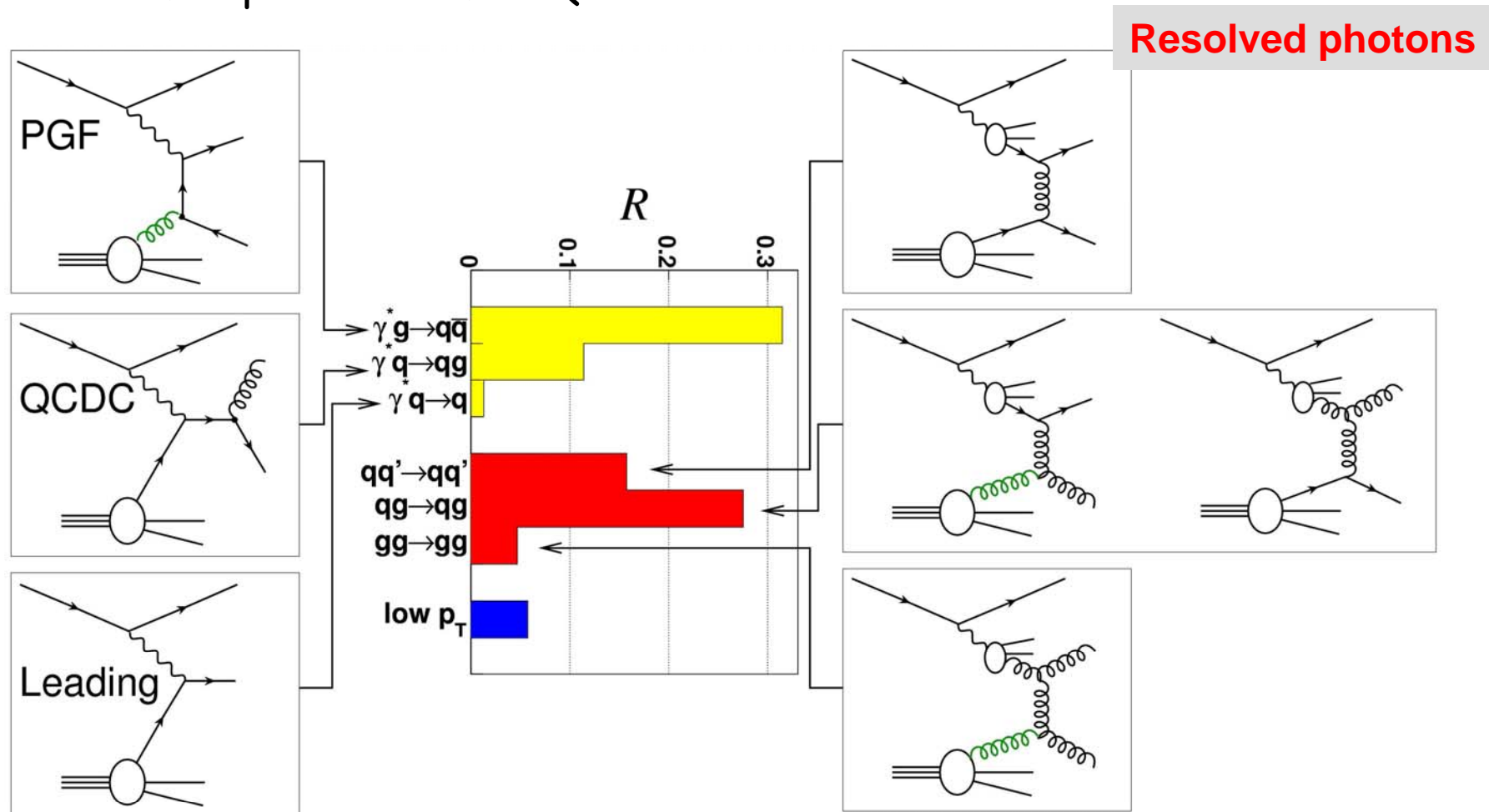




# Light hadron production



Ratios for processes for  $Q^2 < 1$





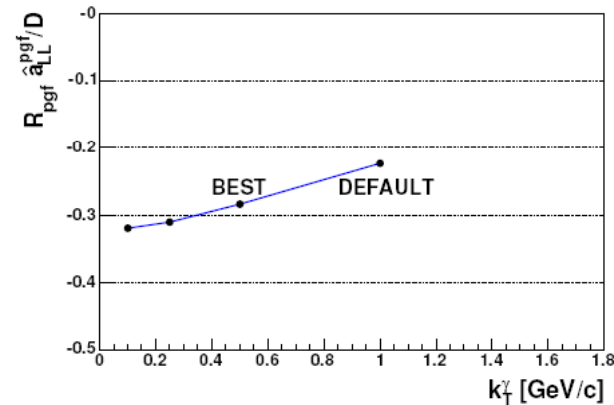
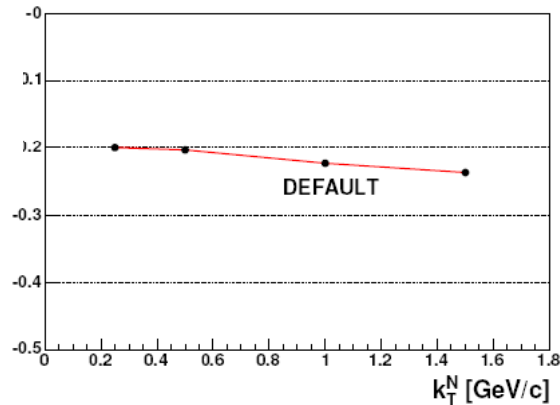
# Example: $k_T$ -tuning



nucleon

photon

$$R_{\text{pgf}} \left\langle \frac{\hat{a}_{\text{pgf}}}{D} \right\rangle$$

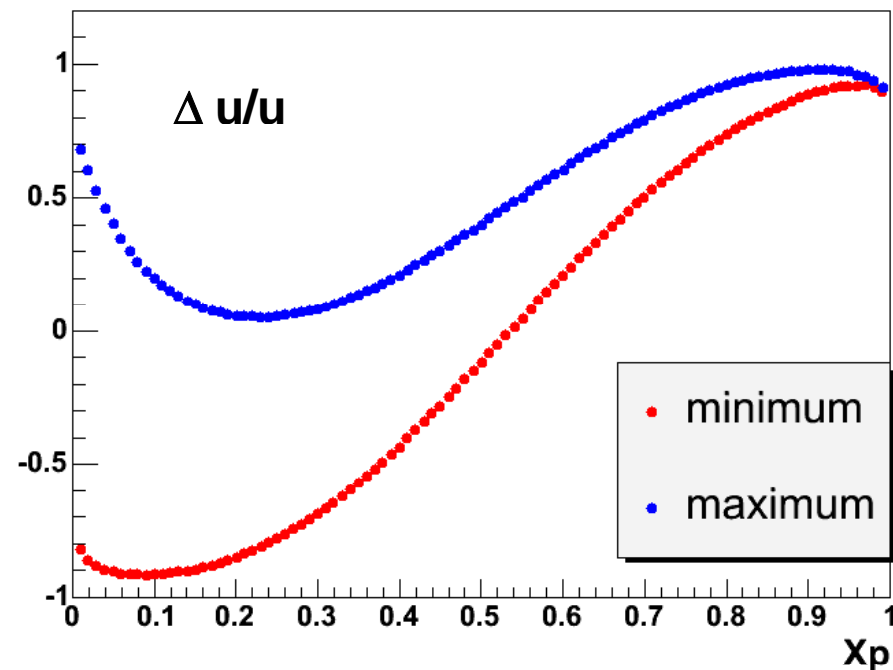


- systematic error:
  - determined using 15 independent MC simulations
  - exploring the parameter space
    - in  $k_T$  of nucleon and photon
    - fragmentation functions
    - parton shower on/off,
    - renormalisation scale

# Resolved photons



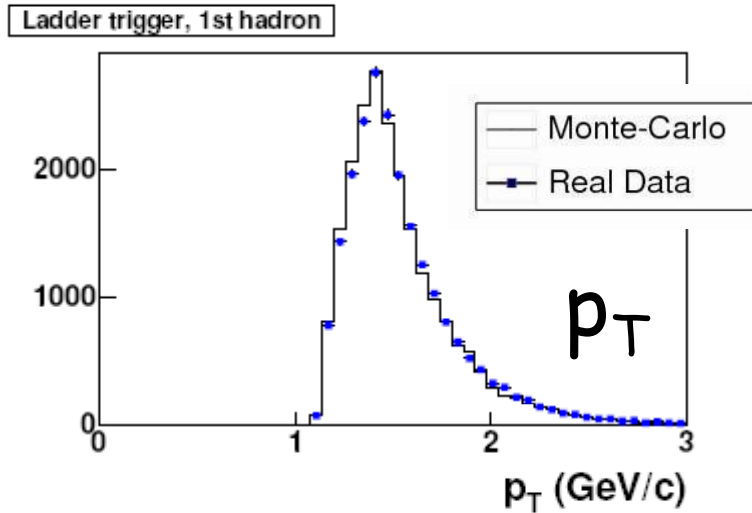
- More than 50%, however assuming a min and max scenario, shows little difference.
- Probing photon at large  $x$ , where photon PDF rather well determined



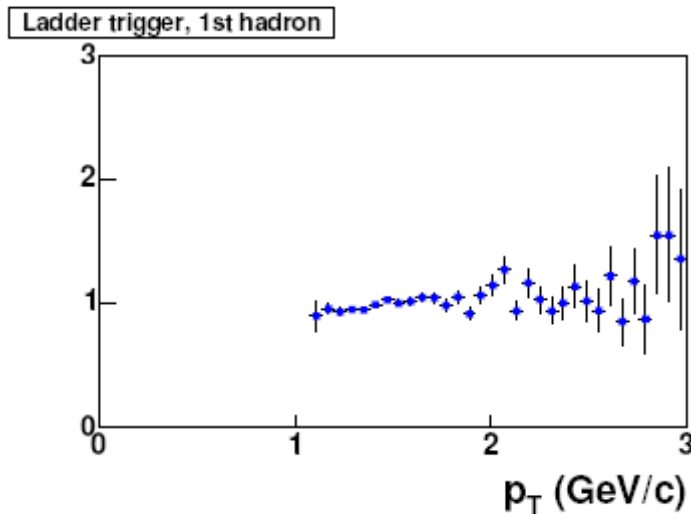
Glück, Reya, Sieg

Freiburg March 2007

# Data versus MC



- excellent to good agreement for all kinematics variables





# Gluon polarisation



high-pT pairs;  $Q^2 > 1 \text{ GeV}^2$ :

$$\frac{\Delta G}{G} = 0.06 \pm 0.31(\text{stat.}) \pm 0.06(\text{syst.}) \quad \langle x_g \rangle = 0.13 \quad 2002\text{--}2003$$

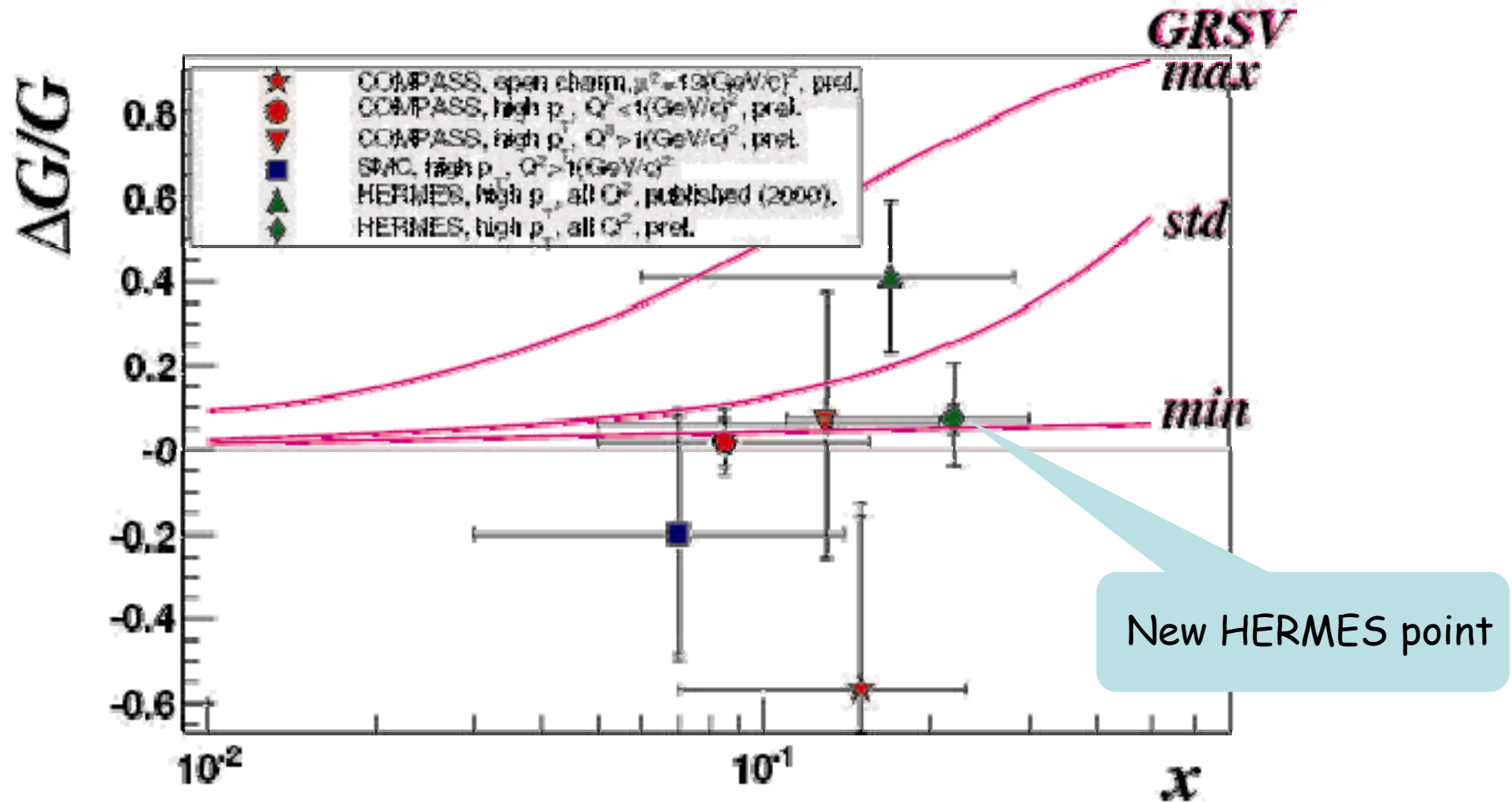
high-pT pairs;  $Q^2 < 1 \text{ GeV}^2$ :

$$\frac{\Delta G}{G} = 0.016 \pm 0.058(\text{stat.}) \pm 0.055(\text{syst.}) \quad 2002\text{--}2004$$
$$\langle x_g \rangle = 0.085 \quad \langle \mu^2 \rangle = 3 \text{ GeV}^2$$

Open charm:

$$\frac{\Delta G}{G} = -0.57 \pm 0.41(\text{stat.}) \pm 0.17(\text{syst.})$$
$$\langle x_g \rangle = 0.15 \quad \langle \mu^2 \rangle = 13 \text{ GeV}^2$$

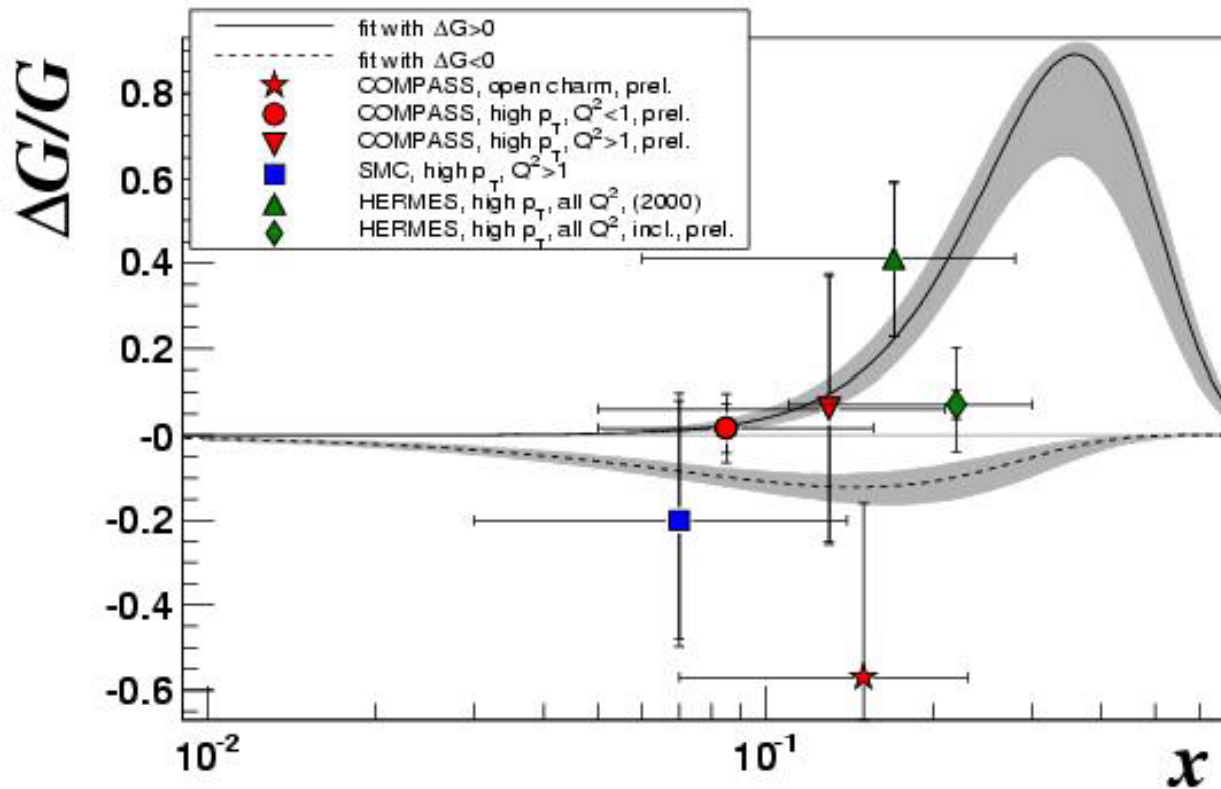
# $\Delta G/G$ from high- $p_T$ pairs



- GRSV-max strongly disfavoured



# COMPASS QCD fit

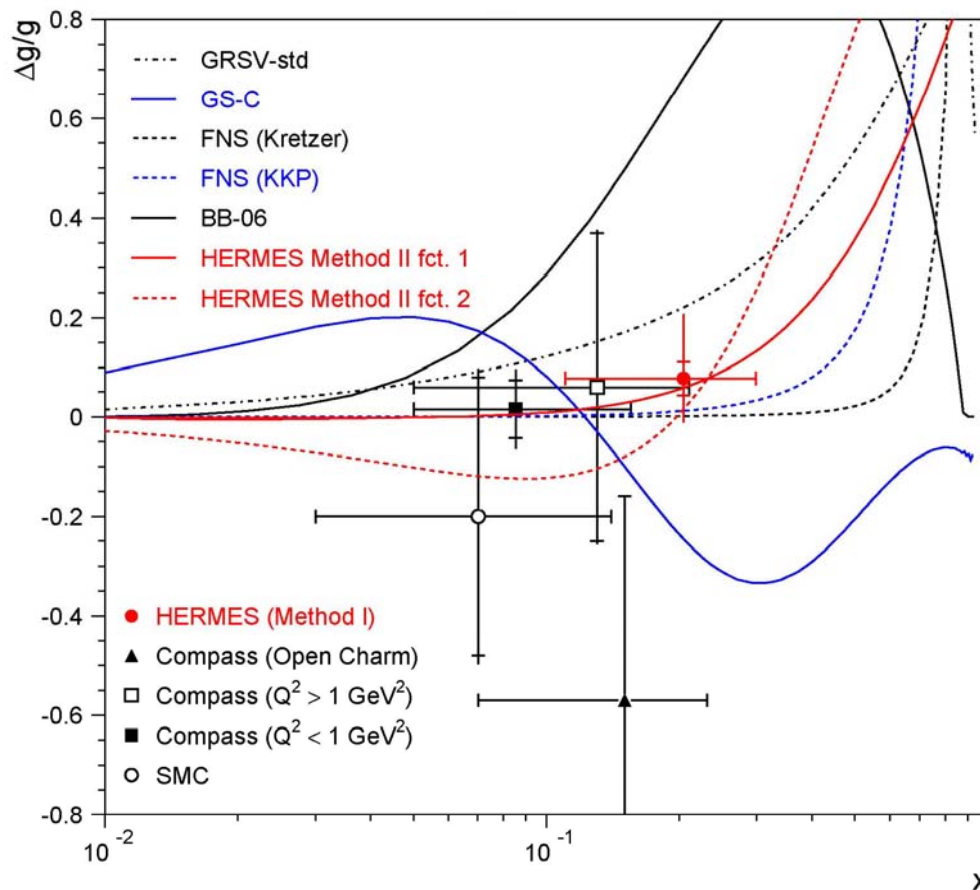


- Note NLO fits, LO data

# New Hermes analysis



## Single inclusive hadrons



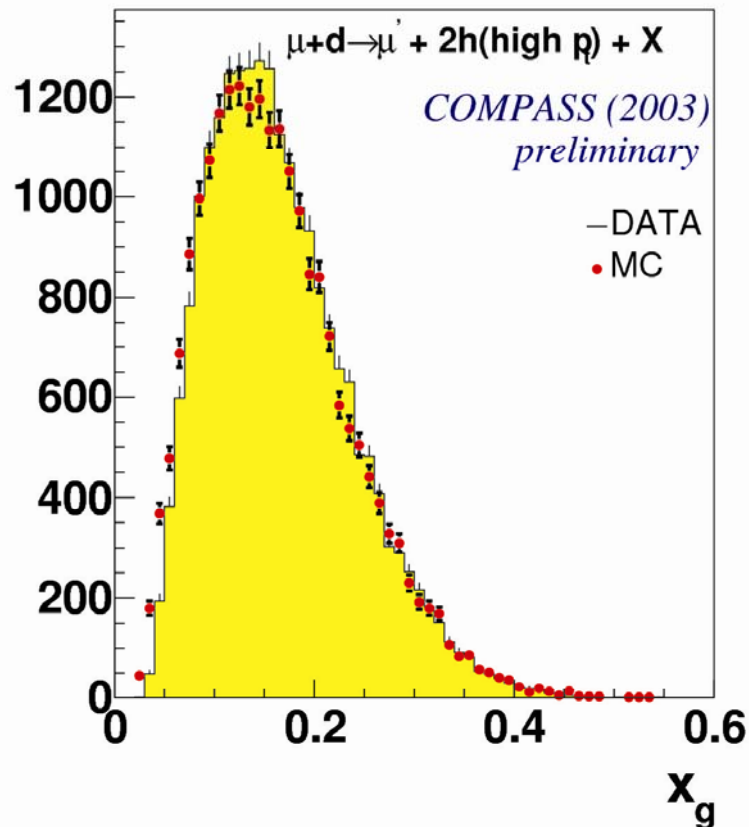
P. Liebing at spin 2006



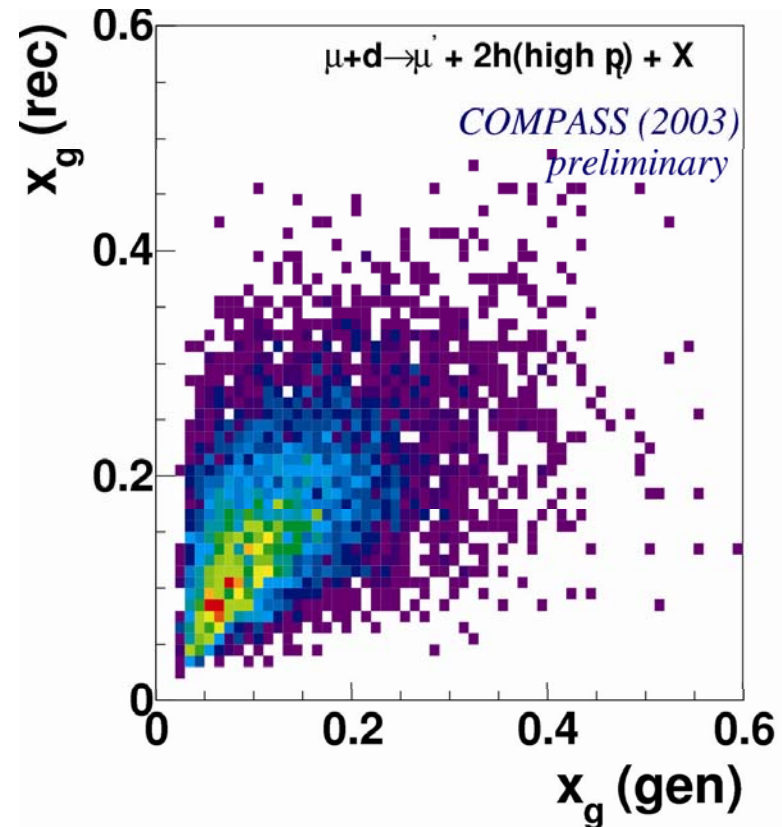
# Can we learn more about $x$ ?



here Lepto and  $Q^2 > 1$

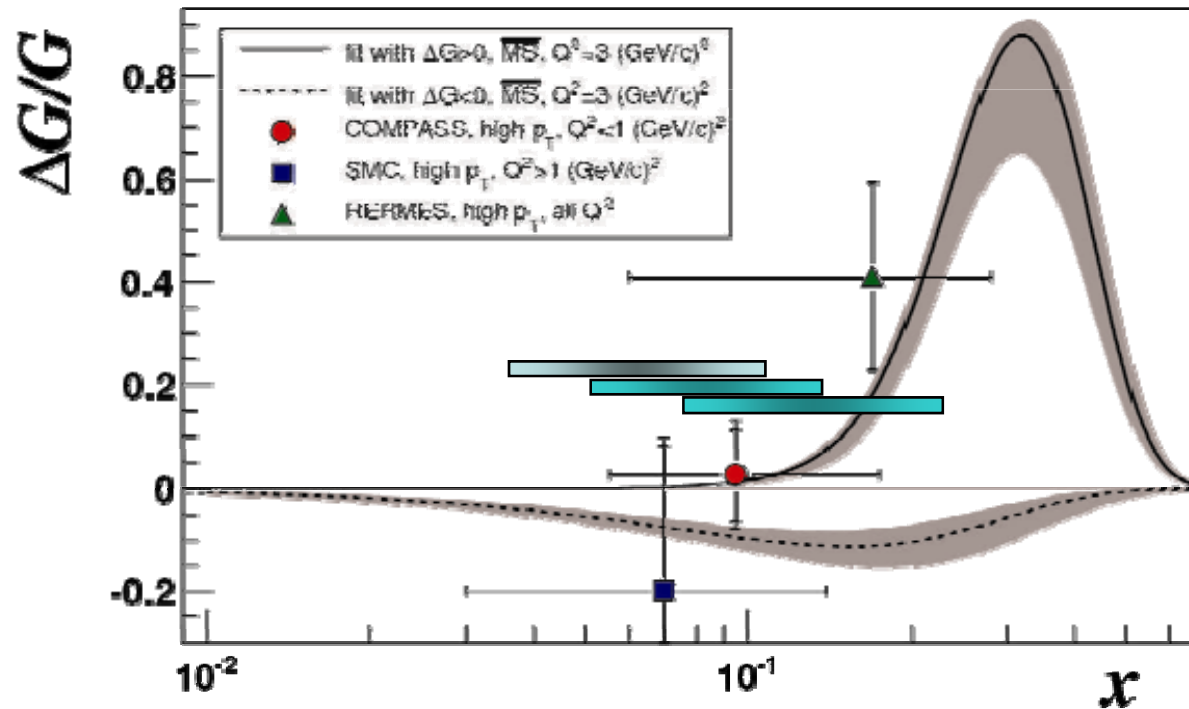


All processes



PGF events (MC)

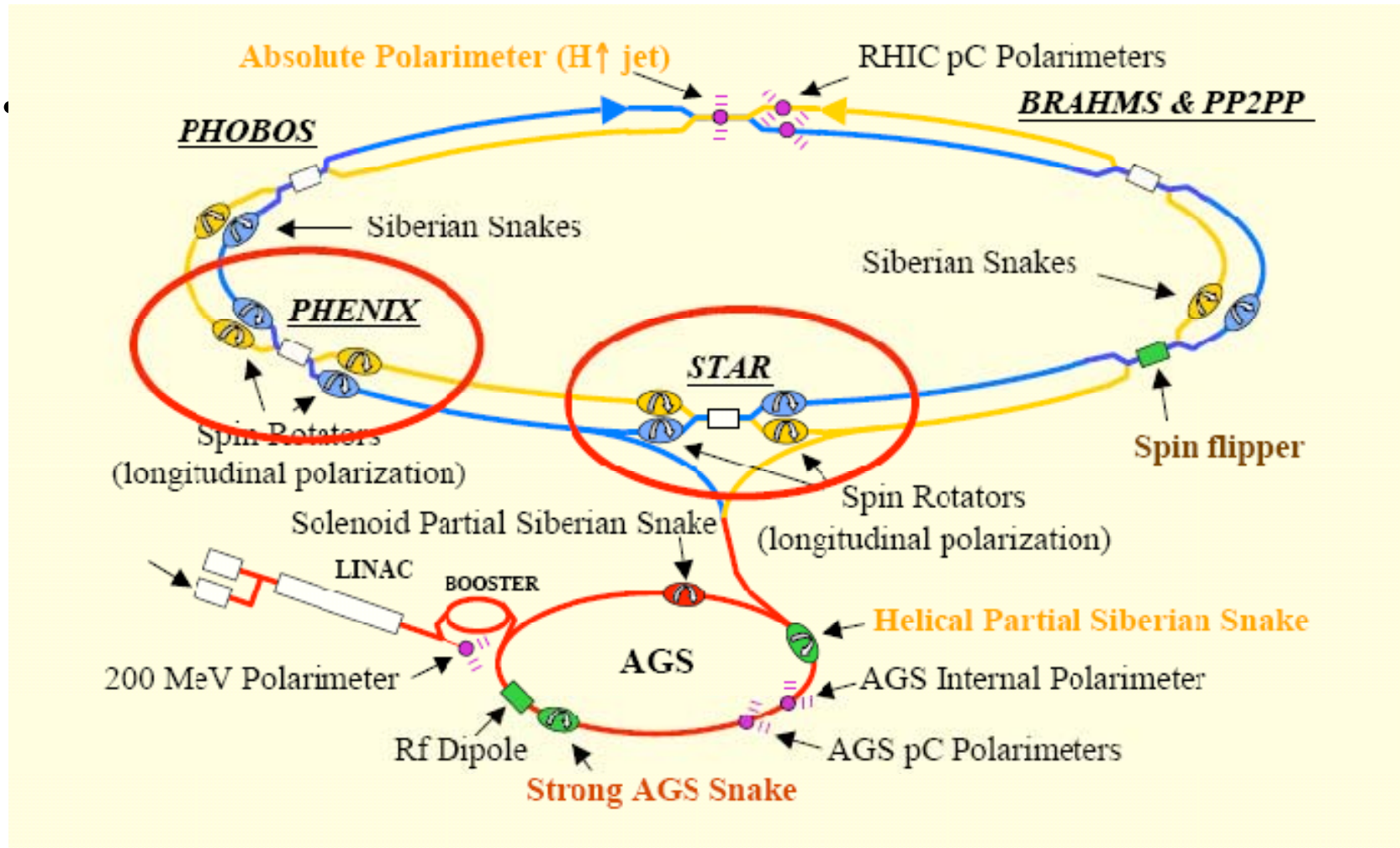
# Splitting in $x_g$ bins?



Compass

- Splitting of high- $p_T$ ,  $Q^2 < 1$  data in 3  $x_g$  bins under study
- Optimizing correlation of rec. and 'true'  $x_g$  (NN)
- More significant with 2006 data

# RHIC: polarised pp



# pp: NLO Calculations



In much better shape:

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \rightarrow \pi + X$ [61, 62]	$\vec{g}\vec{g} \rightarrow gg$ $\vec{q}\vec{q} \rightarrow qg$	$\Delta g$	
$\vec{p}\vec{p} \rightarrow \text{jet}(s) + X$ [71, 72]	$\vec{g}\vec{g} \rightarrow gg$ $\vec{q}\vec{q} \rightarrow qg$	$\Delta g$	(as above)
$\vec{p}\vec{p} \rightarrow \gamma + X$ $\vec{p}\vec{p} \rightarrow \gamma + \text{jet} + X$ $\vec{p}\vec{p} \rightarrow \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{q} \rightarrow \gamma q$ $\vec{q}\vec{q} \rightarrow \gamma q$ $\vec{q}\vec{q} \rightarrow \gamma\gamma$	$\Delta g$ $\Delta g$ $\Delta q, \Delta \bar{q}$	
$\vec{p}\vec{p} \rightarrow DX, BX$ [77]	$\vec{g}\vec{g} \rightarrow c\bar{c}, b\bar{b}$	$\Delta g$	

Jäger, Schäfer, Stratmann,  
Vogelsang; de Florian

Jäger, Stratmann, Vogelsang;  
Signer et al.

Gordon, Vogelsang;  
Contogouris et al.;  
Gordon, Coriano

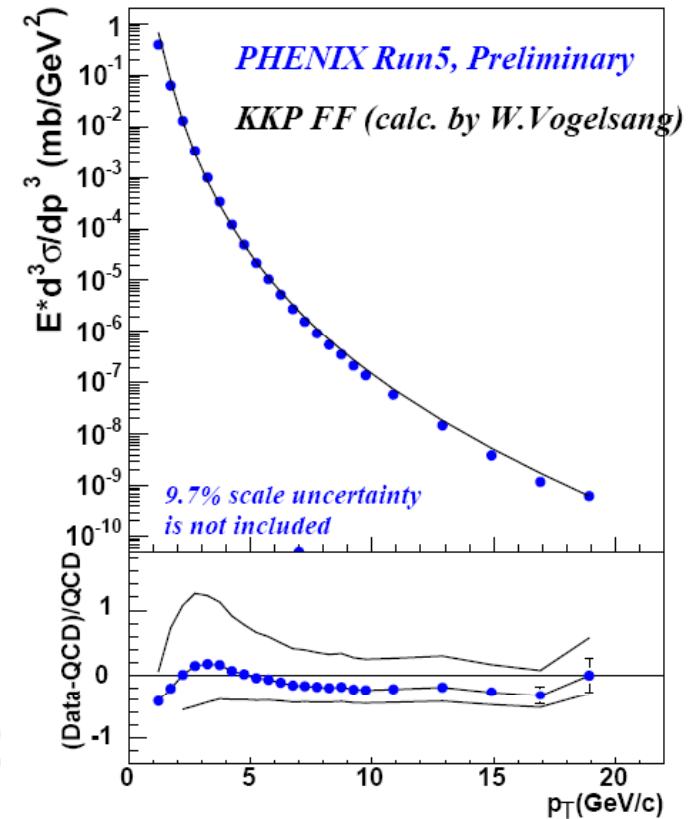
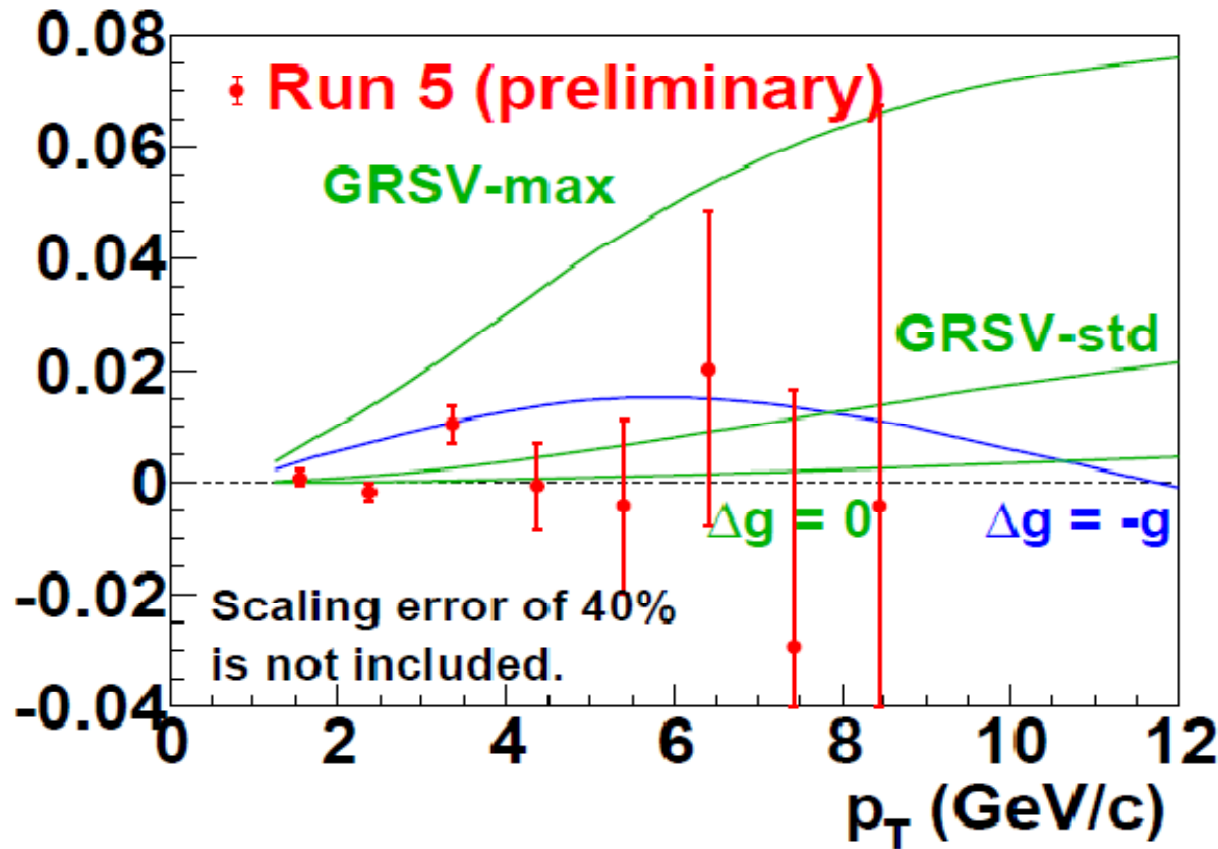
Bojak, Stratmann

Summary by Stratmann, DIS2006

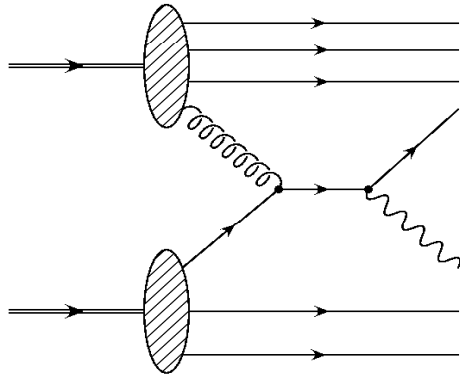
# $\pi^0$ production at RHIC



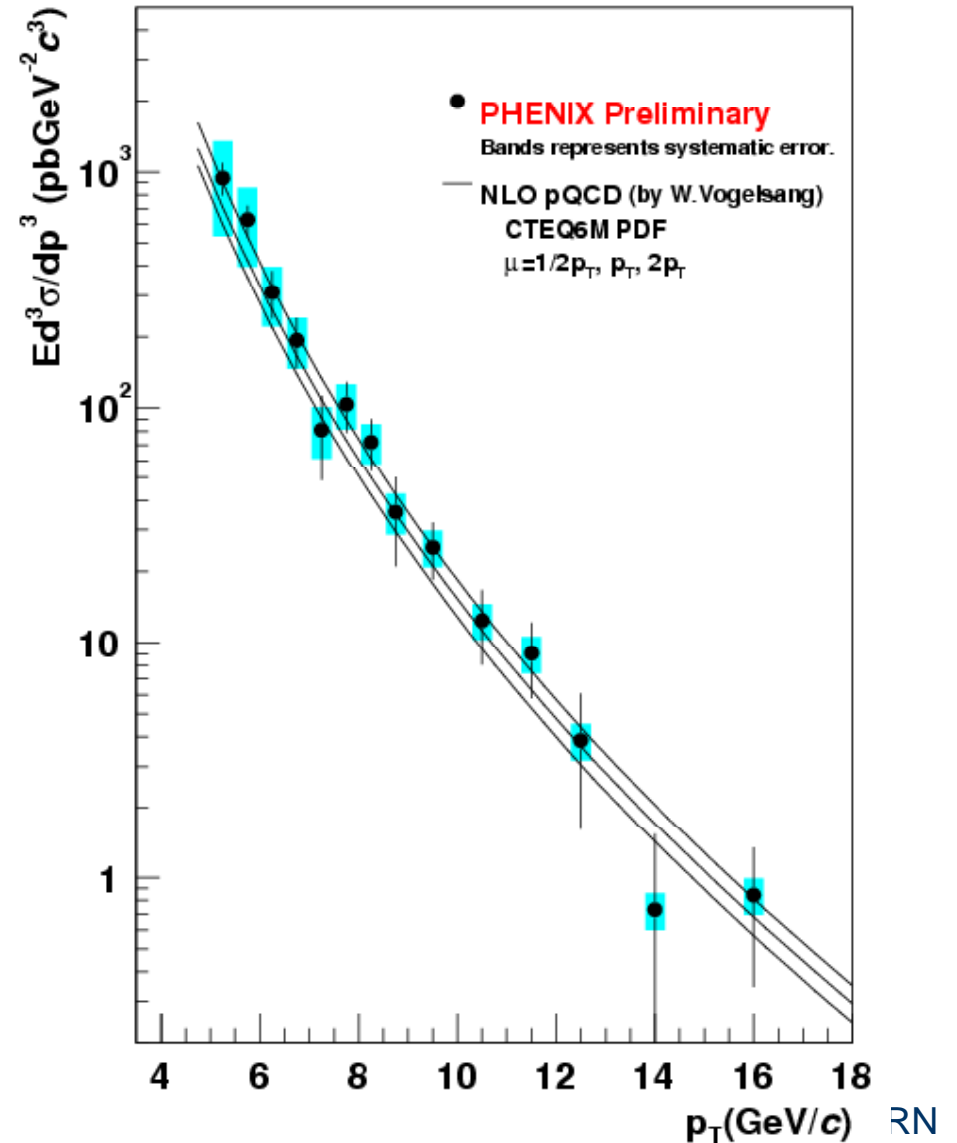
- Phenix



# Direct photons



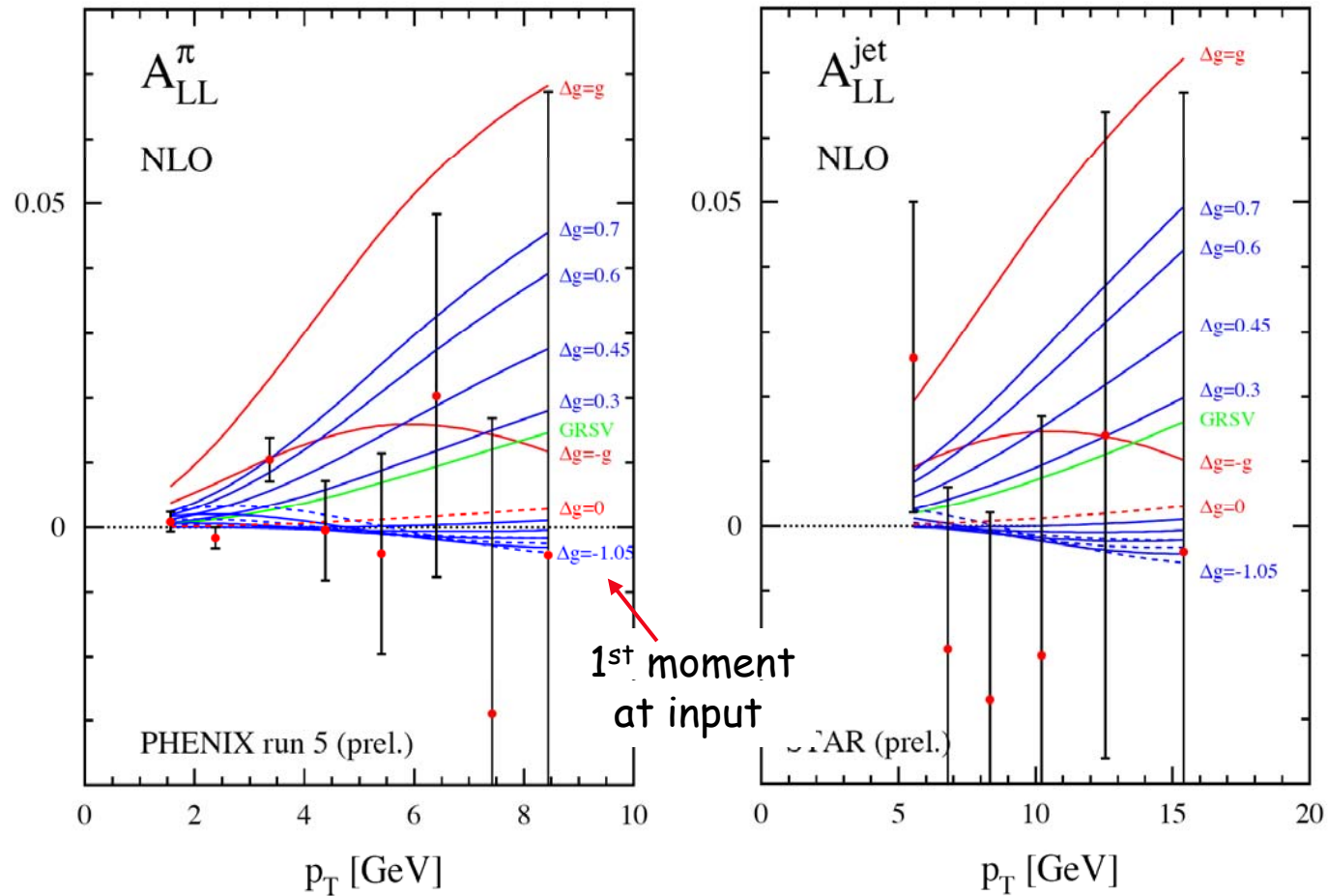
- good agreement of calc. and data at collider energies



# Towards a global analysis



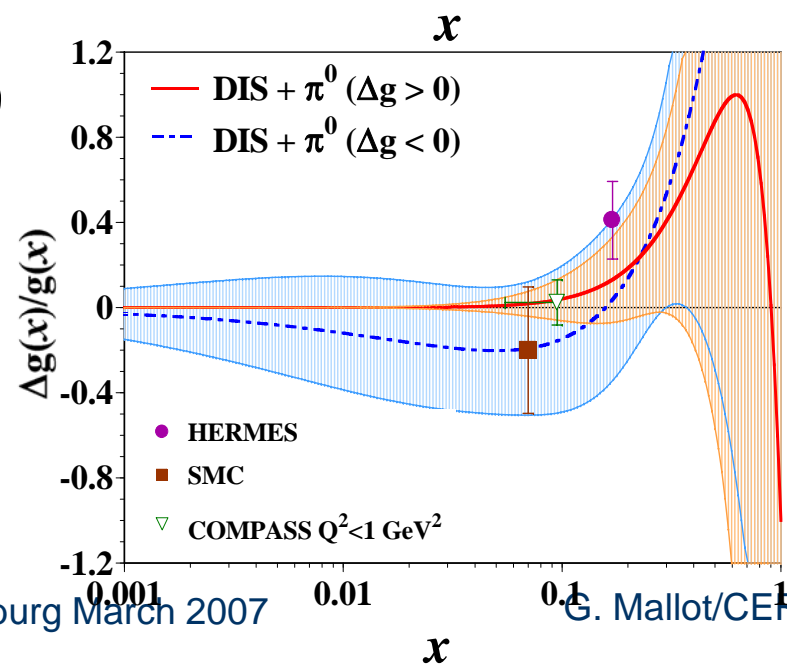
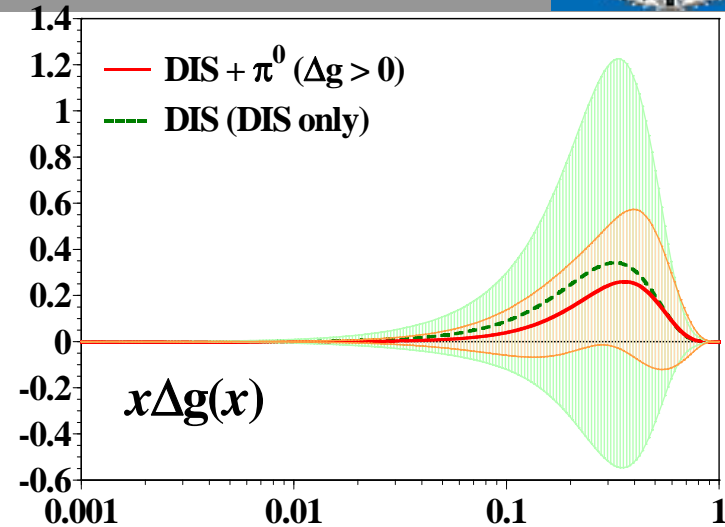
W. Vogelsang, M. Stratmann (DIS2006, work in progress)





# $\Delta g$ from $\pi^0$ production (RUN05)

- 1<sup>st</sup> moment  $\Delta g$ 
  - $0.31 \pm 0.32$  (DIS+ $\pi^0$ )
  - $0.47 \pm 1.08$  (DIS only)
- Significant reduction of the  $\Delta g$  uncertainty
- Sign problem
  - gg process dominates
    - $\Delta\sigma \propto [\Delta g(x)]^2$
    - Positive or negative  $\Delta g$ ?
    - $\chi^2_{\pi^0}$ : 11.18( $\Delta g > 0$ ) vs. 11.05 ( $\Delta g < 0$ ) (8 data points)
- Consistent results
  - 1<sup>st</sup> moment ( $0.1 < x_{Bj} < 1$ )
    - $\Delta g > 0$ :  $0.30 \pm 0.30$
    - $\Delta g < 0$ :  $0.32 \pm 0.42$
  - Large- $x$  is positive

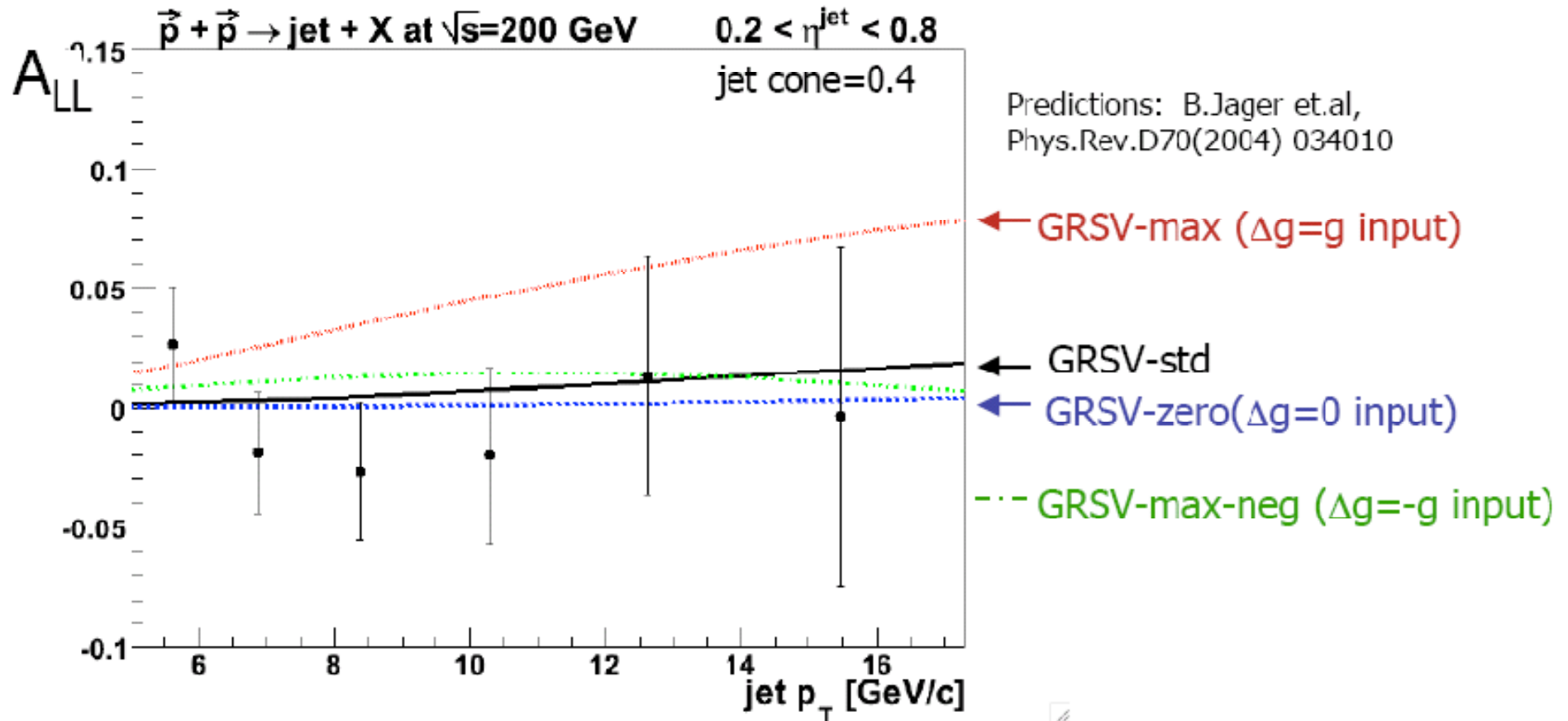




# Inclusive jets at STAR



from Kiryluk, DIS2006



# Summary



- all results indicate  $\Delta G$  small compared to anomaly inspired hypotheses
- sign still undefined
- $\Delta G$  still could carry most of the nucleon's spin
- need data on  $x_g$ -dependence to pin down the shape
- need to include COMPASS and HERMES high-pT data in starting global analyses (NLO calculations)
- looking forward to 500 GeV/c at RHIC