

# Polarised DIS Experiment

## Lecture II

Gerhard Mallot



**1st Summer School on QCD Spin Physics**

The school will give a pedagogical introduction to the field and to the existing research program underway at RHIC. It is intended for graduate students and beginning postdoctoral researchers in theory and experiment. Full and partial scholarships are available.

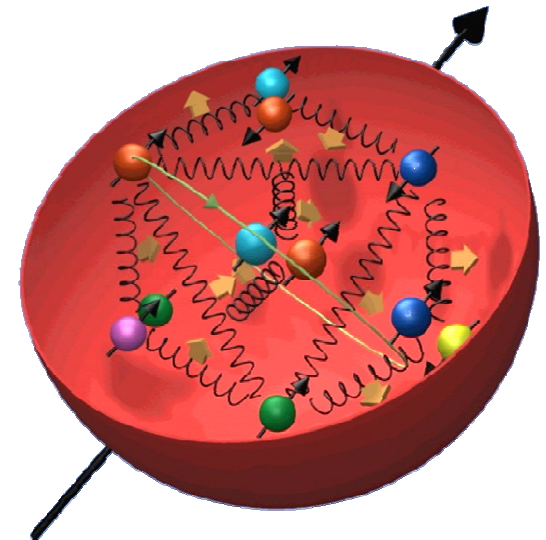
|                                   |   |
|-----------------------------------|---|
| <b>faculty members</b>            | <b>lecturers</b>                            |
| Tamara A. M. de Groot/RBRC        | Introduction to perturbative QCD            |
| Markus Diehl/EPJ                  | Introduction to spin in QCD                 |
| Xiangdong Ji/Princeton            | Theory of polarized ion collisions          |
| William Melby/BNL                 | Polarized deep inelastic scattering         |
| Gerhard Mallot/EPJ                | PHIC spin experiments                       |
| James D. Jones/BNL                | Structure from helicity                     |
| Joseph T. Sully/CPI/Massachusetts | Transverse spin                             |
| Daniel Soper/Oregon               | Polarized beams, polarizing                 |
| Harold Stenlund/Princeton         | Constrained parton distributions            |
| Markus Strohmaier/Princeton       | QCD angular momentum                        |
| Christian Weiss/Princeton         | Fields and strings                          |
| <b>organizers</b>                 | Comprehensive spin in structure's structure |
| Lorenz Von Smolcsanyi             | Spin and nucleon physics                    |
| Alfred W. Schreiber               | Future of spin physics                      |
| <b>support</b>                    |   |
| Joseph Brodsky/RBRC               |   |
| Douglas Bond/Fairfax/RBRC         |   |
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**June 5-12, 2004**

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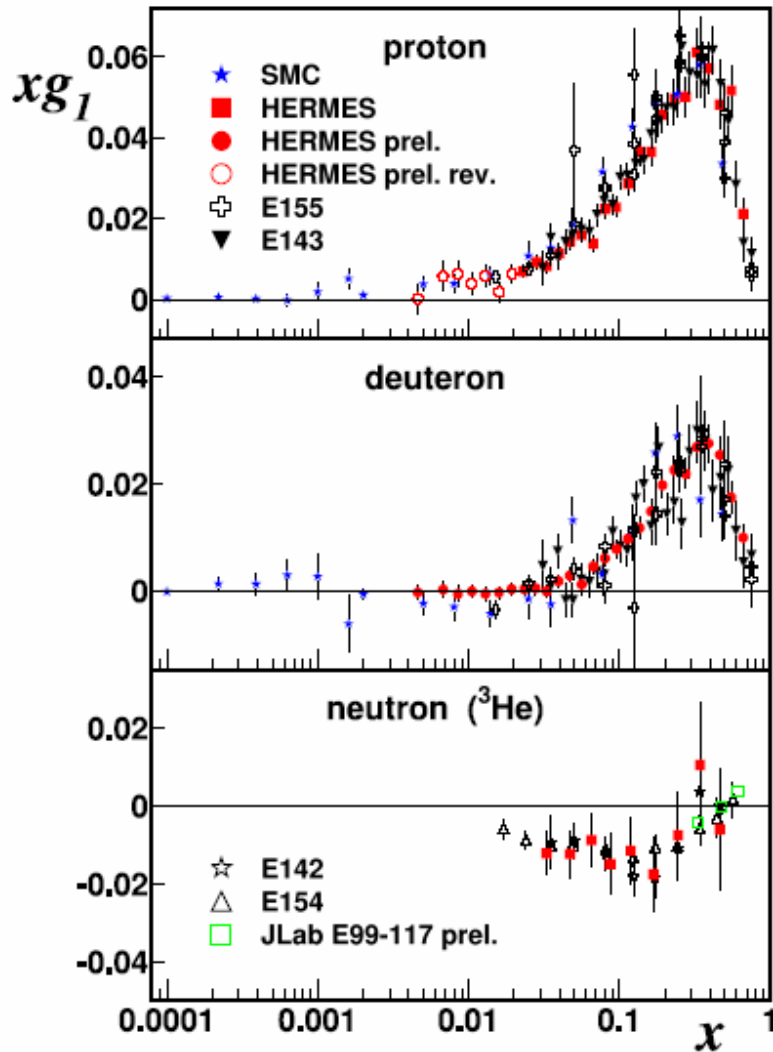
Photo by William Melby/BNL



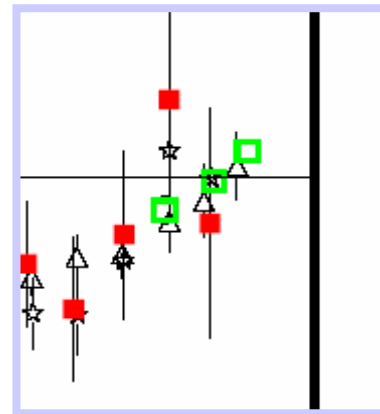
# Plan

- QCD analysis of  $g_1(x, Q^2)$  and PDFs
- status of  $g_2$
- semi-inclusive scattering and flavour decomposition
- transversity  $h_1$  and Collins asymmetry
- the hunt for  $\Delta G$ 
  - *high- $p_T$*  hadron pairs
  - *open charm* production
- summary

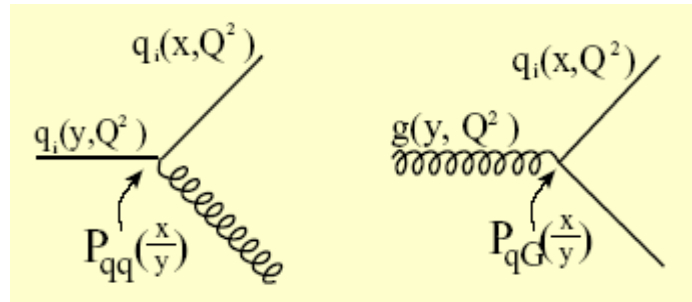
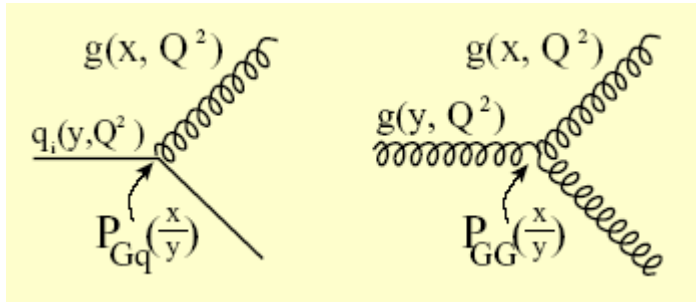
# Status of $g_1$



- Wealth of data  $g_1$  data for p, n and d
- Data taken at different  $Q^2$
- Only weak  $Q^2$ -dependence in overlap region
- Interesting data from JLAB at large  $x$  for neutron:  $g_1^n > 0$



# $Q^2$ Evolution



splitting functions

non-singlet quark distribution

$$\Delta q^{\text{ns}}(x, Q^2) = \sum_{i=1}^{n_f} \left( \frac{e_i^2}{\langle e^2 \rangle} - 1 \right) \Delta q_i(x, Q^2)$$

singlet quark distribution

$$\Delta \Sigma(x, Q^2) = \sum_{i=1}^{n_f} \Delta q_i(x, Q^2)$$

$$\frac{d}{d \ln Q^2} \Delta q^{\text{ns}} = \frac{\alpha_s}{2\pi} \Delta P_{qq}^{\text{ns}} \otimes \Delta q^{\text{ns}}$$

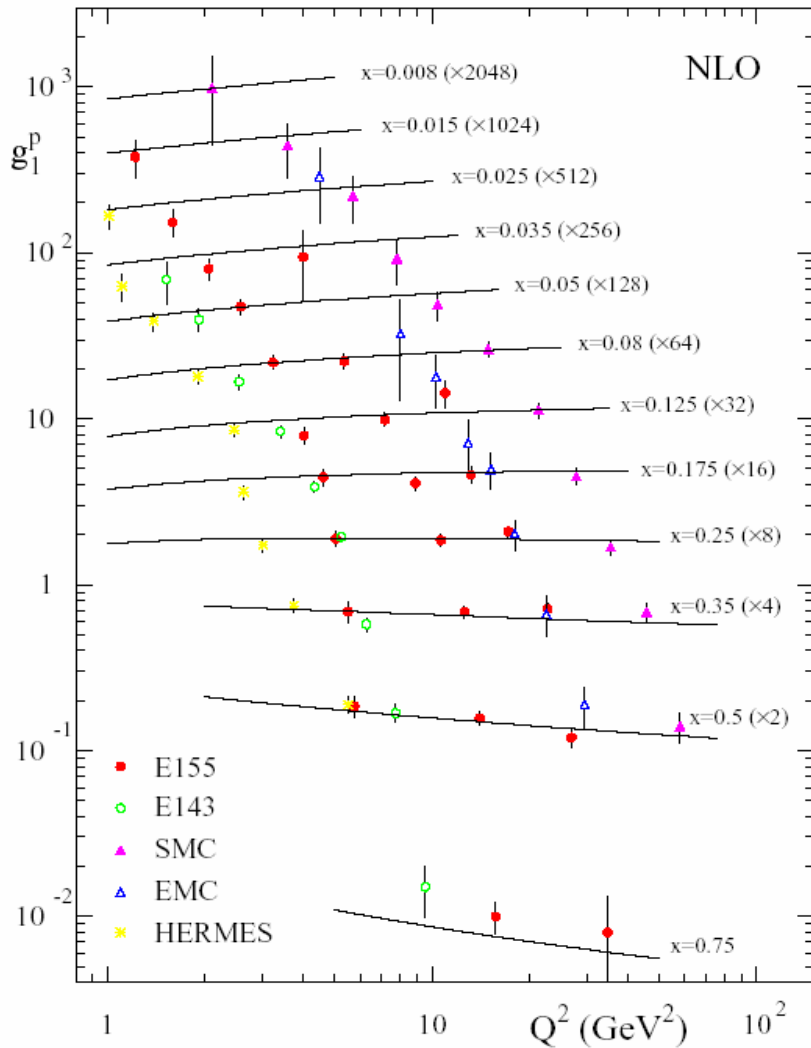
DGLAP evolution

$$\frac{d}{d \ln Q^2} \begin{pmatrix} \Delta \Sigma \\ \Delta g \end{pmatrix} = \frac{\alpha_s}{2\pi} \begin{pmatrix} \Delta P_{qq}^{\text{S}} & 2n_f \Delta P_{qg}^{\text{S}} \\ \Delta P_{gq}^{\text{S}} & \Delta P_{gg}^{\text{S}} \end{pmatrix} \otimes \begin{pmatrix} \Delta \Sigma \\ \Delta g \end{pmatrix}$$

# $Q^2$ Evolution

- non-singlet decouples from gluon evolution, moments  $Q^2$ -independent, like  $\Delta u - \Delta d = g_a$
- Evolution of singlet and gluon coupled, moments  $\Delta\Sigma$  and  $\Delta G$  evolve with  $Q^2$
- In principle  $\Delta G$  can be determined from the  $Q^2$  evolution of  $g_1(x, Q^2)$
- Need reasonable range  $Q^2$  at fixed  $x$
- We have some  $Q^2$  range, but not much, important large  $Q^2$  at small  $x$

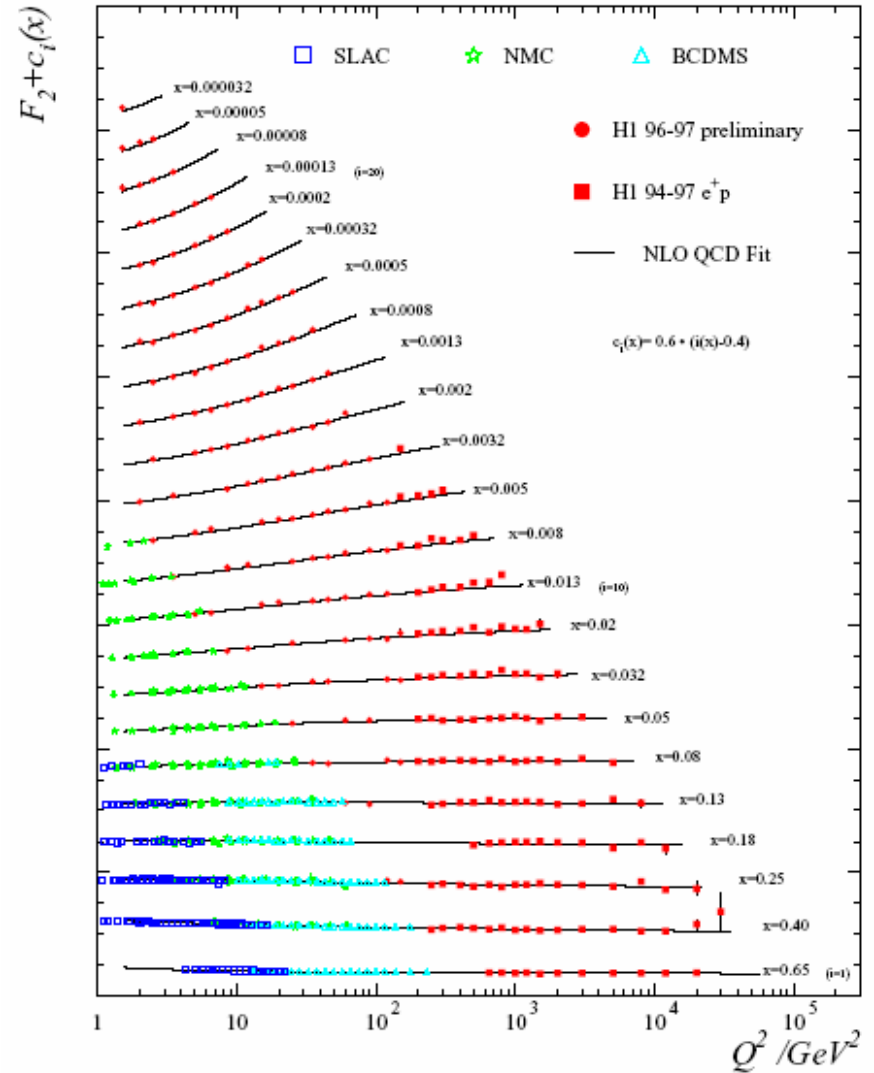
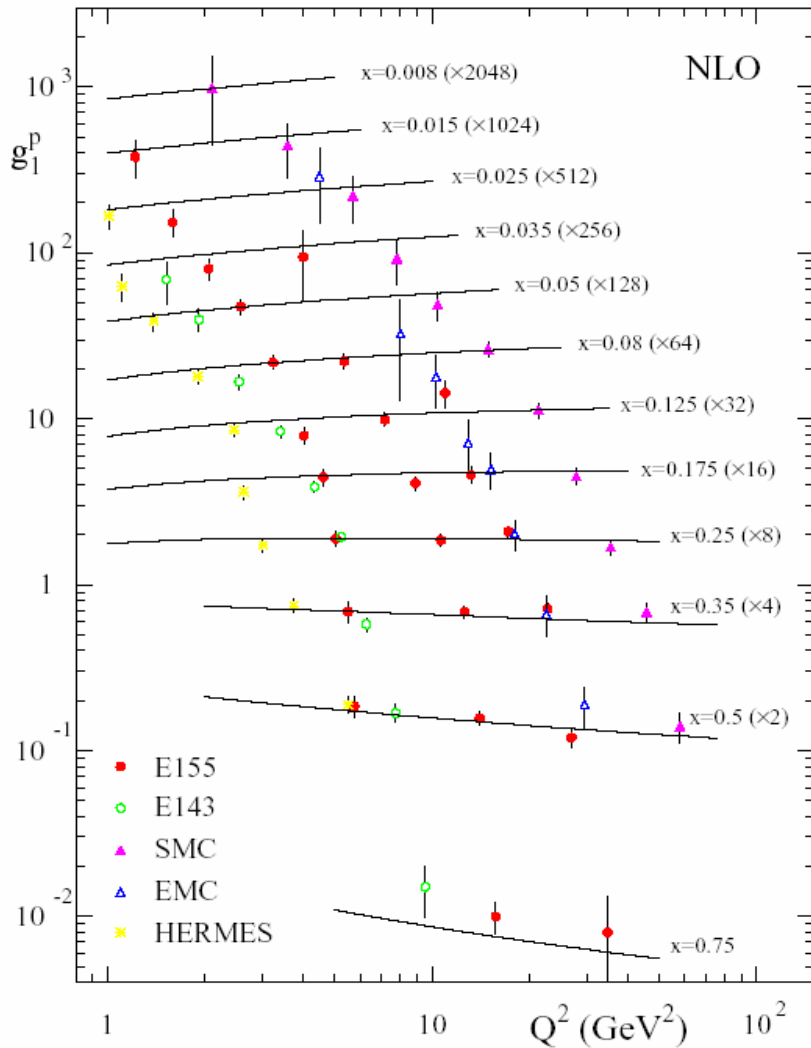
# $g_1(x, Q^2)$



Looks quite nice, but...

# $g_1(x, Q^2)$

# $F_2(x, Q^2)$



# NLO QCD Fits

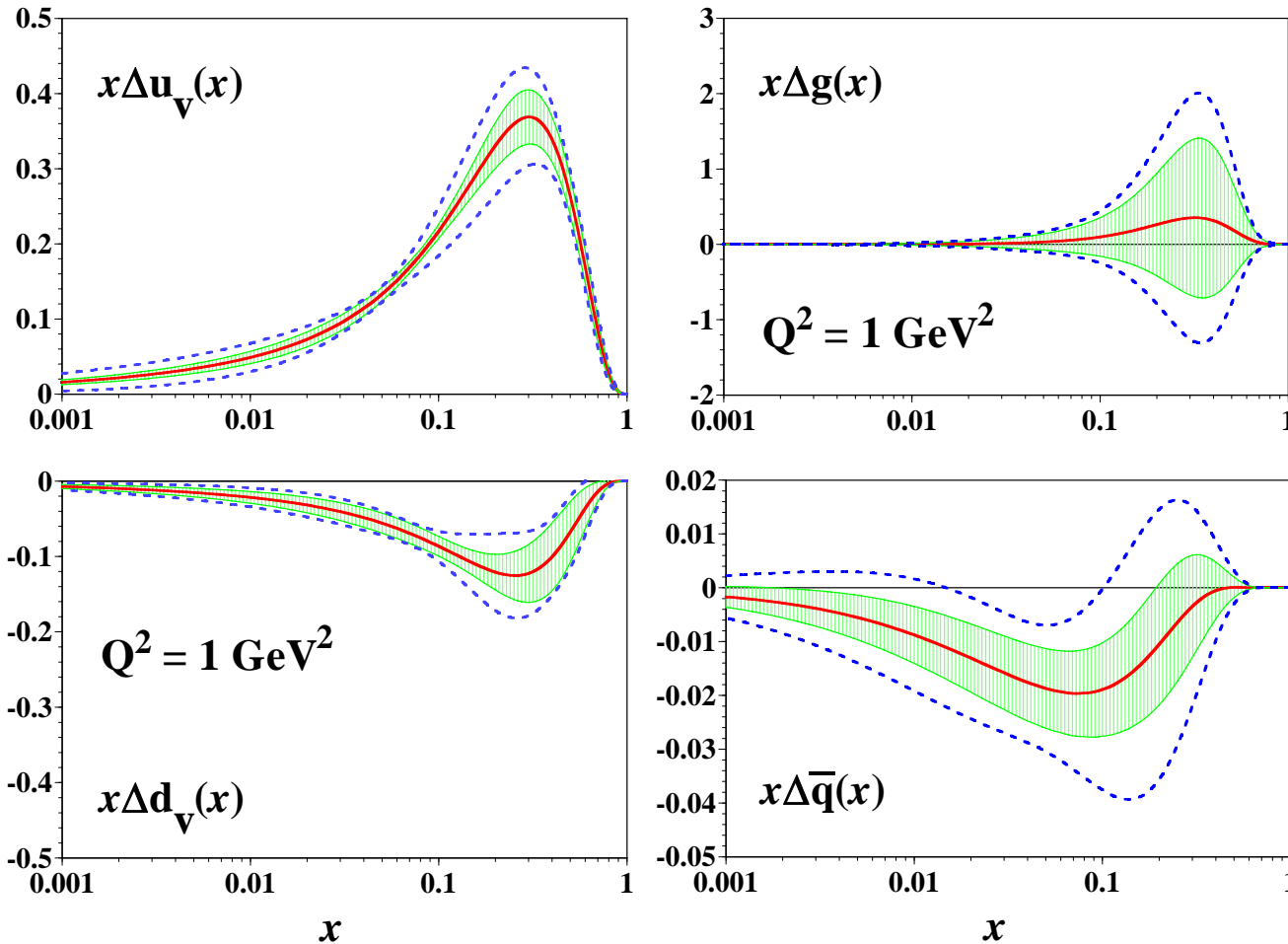
- choose scheme, usually  $\overline{\text{MS}}$
- choose start value for evolution,  $Q^2_0$
- choose parametrisations for
$$\Delta\Sigma, \Delta G, \Delta q^{ns}(x, Q^2_0)$$
- fit parameters of these parametrisations using the DLGAP equations (NLO)
- many groups, an example...

– AAC03

Kumano DIS2004



# AAC03 Fit

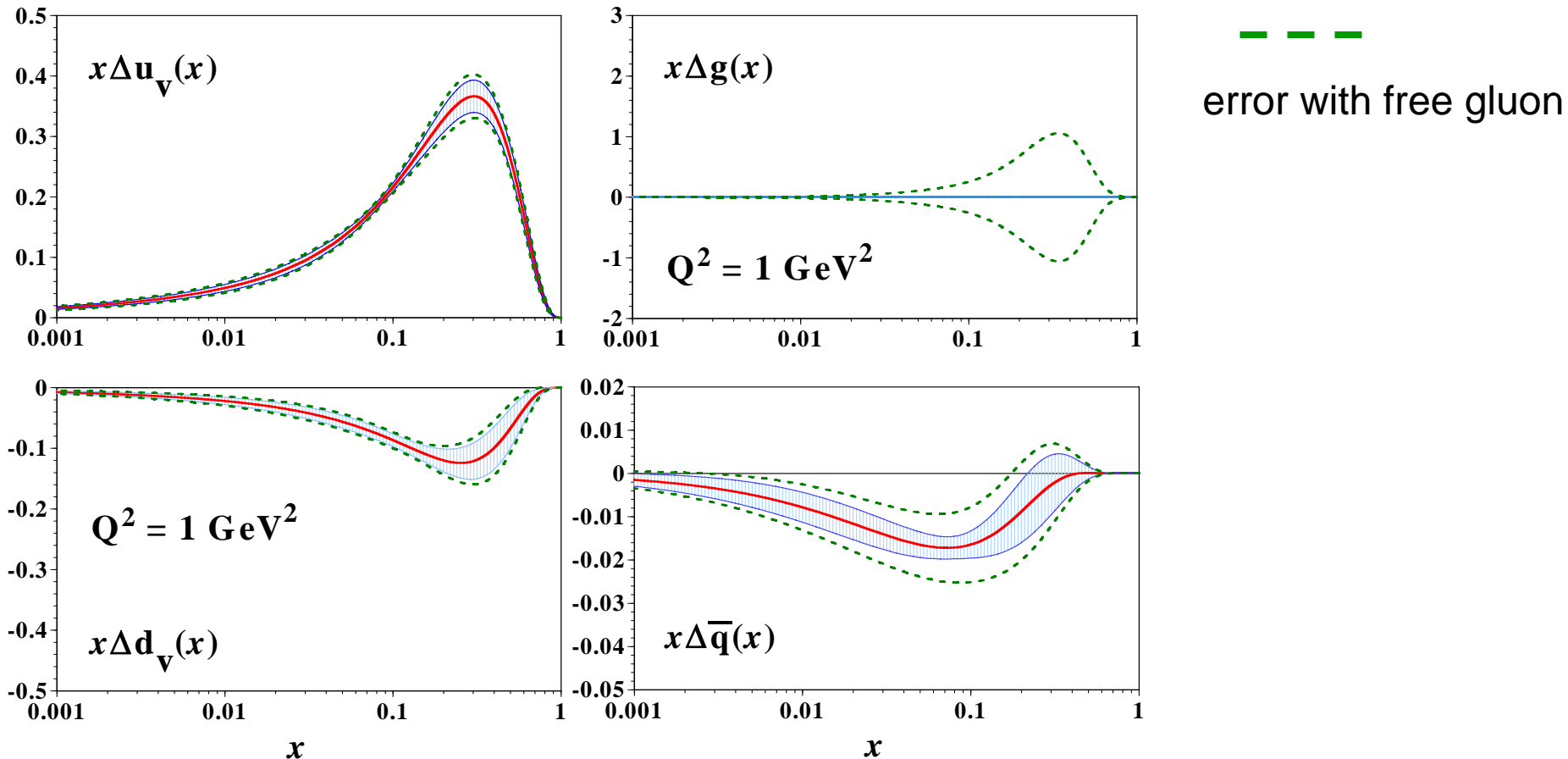


  
 error of AAC00

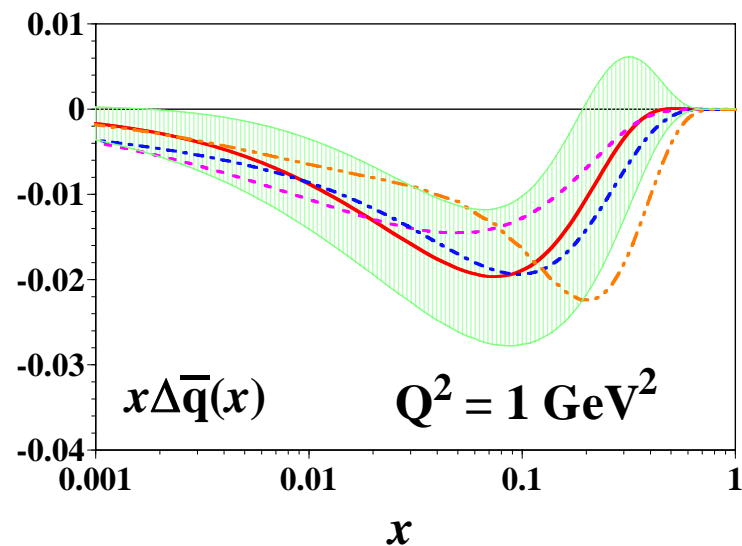
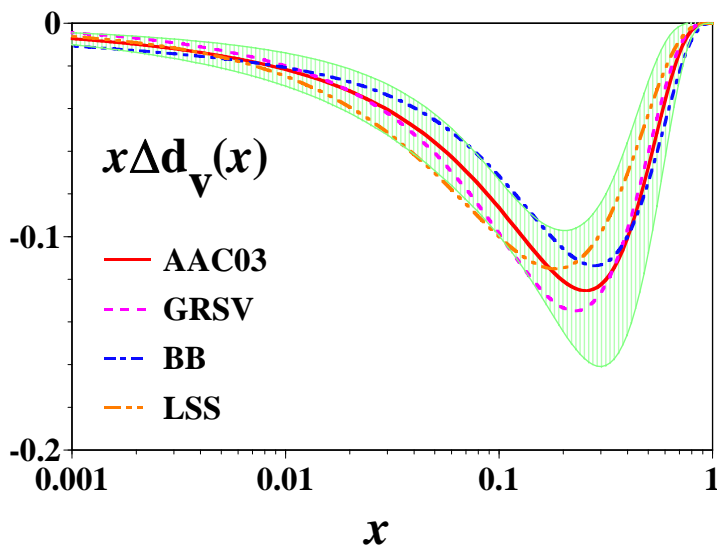
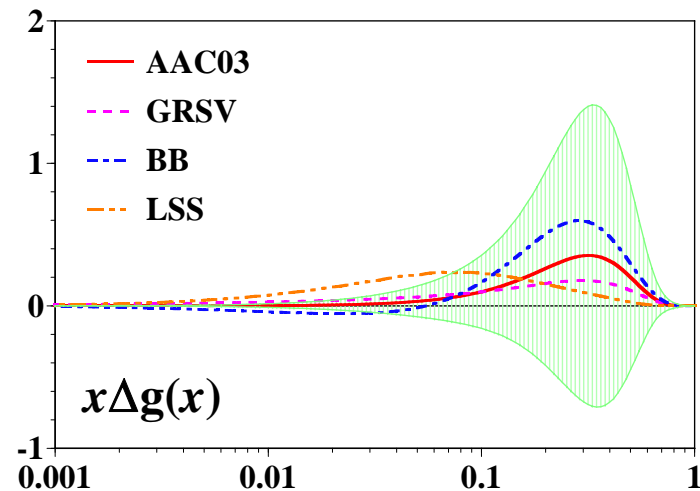
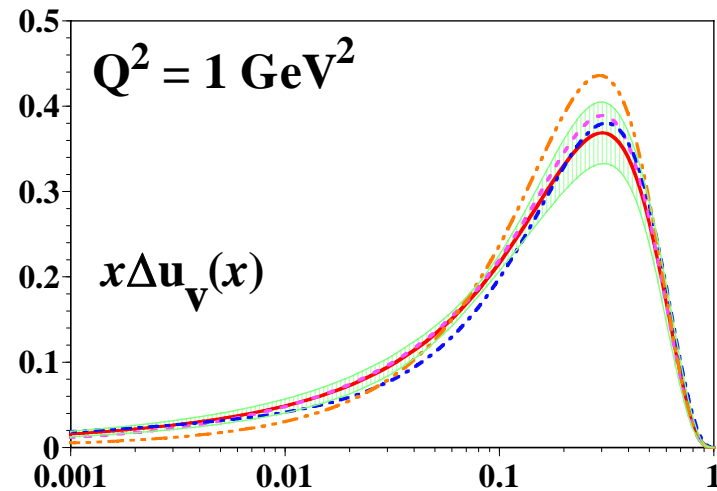
valence well fixed  
 gluon undetermined  
 sea quarks negative

# AAC03 with zero gluon at $Q^2_0$

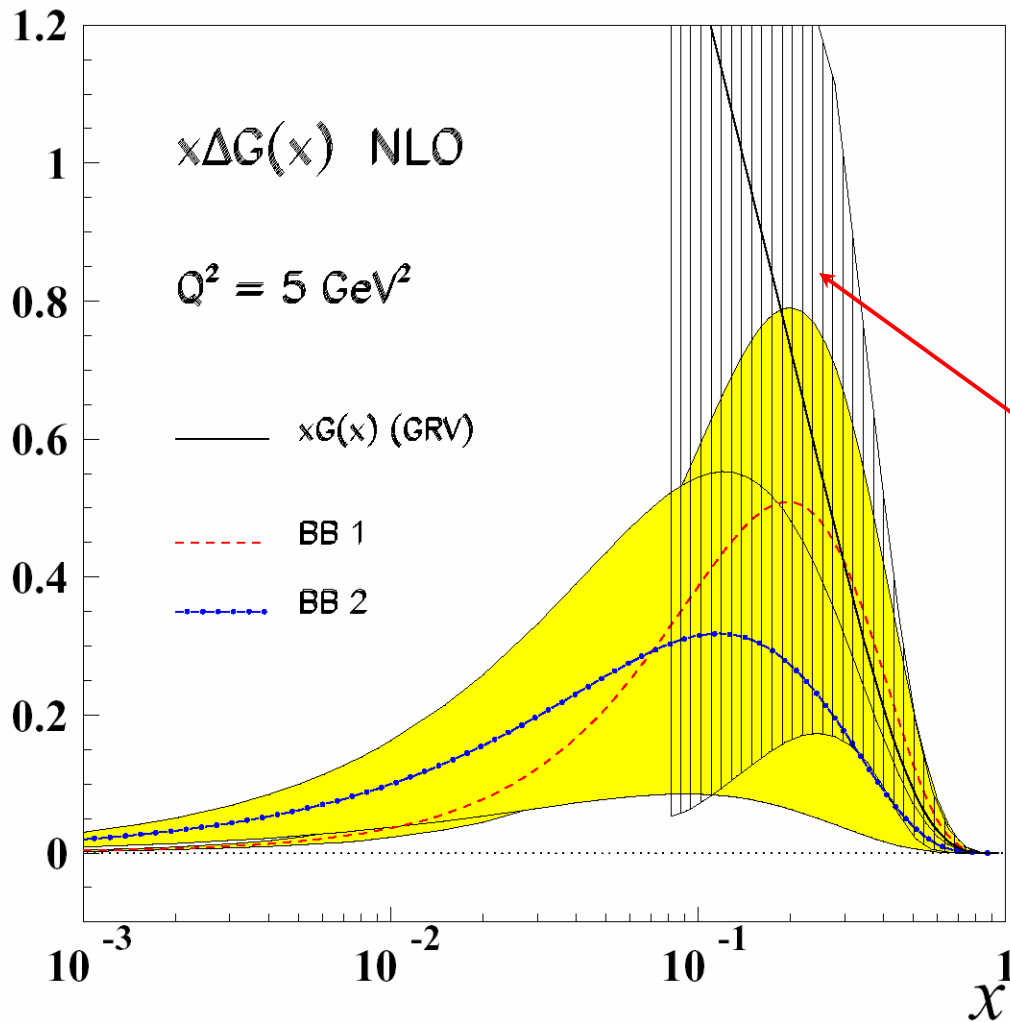
$\chi^2/\text{d.o.f.} = 0.915$



# Comparison of PDF Fits



# BB Fit



slightly positive gluon pol.  
at  $Q^2=5 \text{ GeV}^2$

unpolarised gluon

Blümlein & Böttcher

# First moments

$$Q^2 = 1 \text{ GeV}^2$$

|        | $\Delta g$        | $\Delta\Sigma$    |
|--------|-------------------|-------------------|
| AAC03  | $0.499 \pm 1.268$ | $0.213 \pm 0.138$ |
| GRSV01 | 0.420             | 0.204             |
| LSS    | 0.680             | 0.210             |
| BB     | 1.026             | 0.138             |

Kumano DIS2004

- GRSV01 [ Phys. Rev. D63 (2001) 094005 ]
- LSS01 [ Eur.Phys.J. C23 (2002) 479 ]
- BB02 [ Nucl. Phys. B636 (2002) 225 ]

# $g_2$

$$g_2(x, Q^2) = g_2^{\text{WW}} + \bar{g}_2(x, Q^2)$$
$$g_2^{\text{WW}}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{g_1(y, Q^2)}{y} dy$$

- **twist-3** term  $\bar{g}_2$ , matrix element  $d_2$

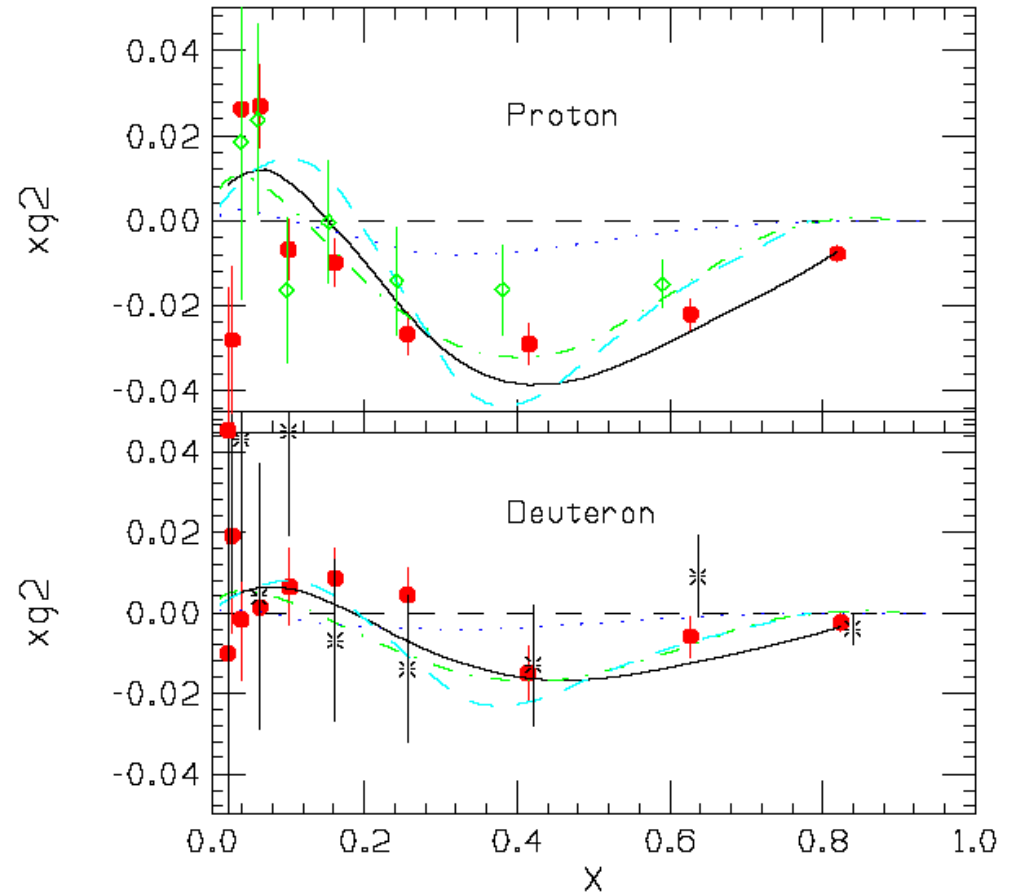
$$d_2 = 3 \int_0^1 x^2 \bar{g}_2(x, Q^2) dx$$

# $g_2$

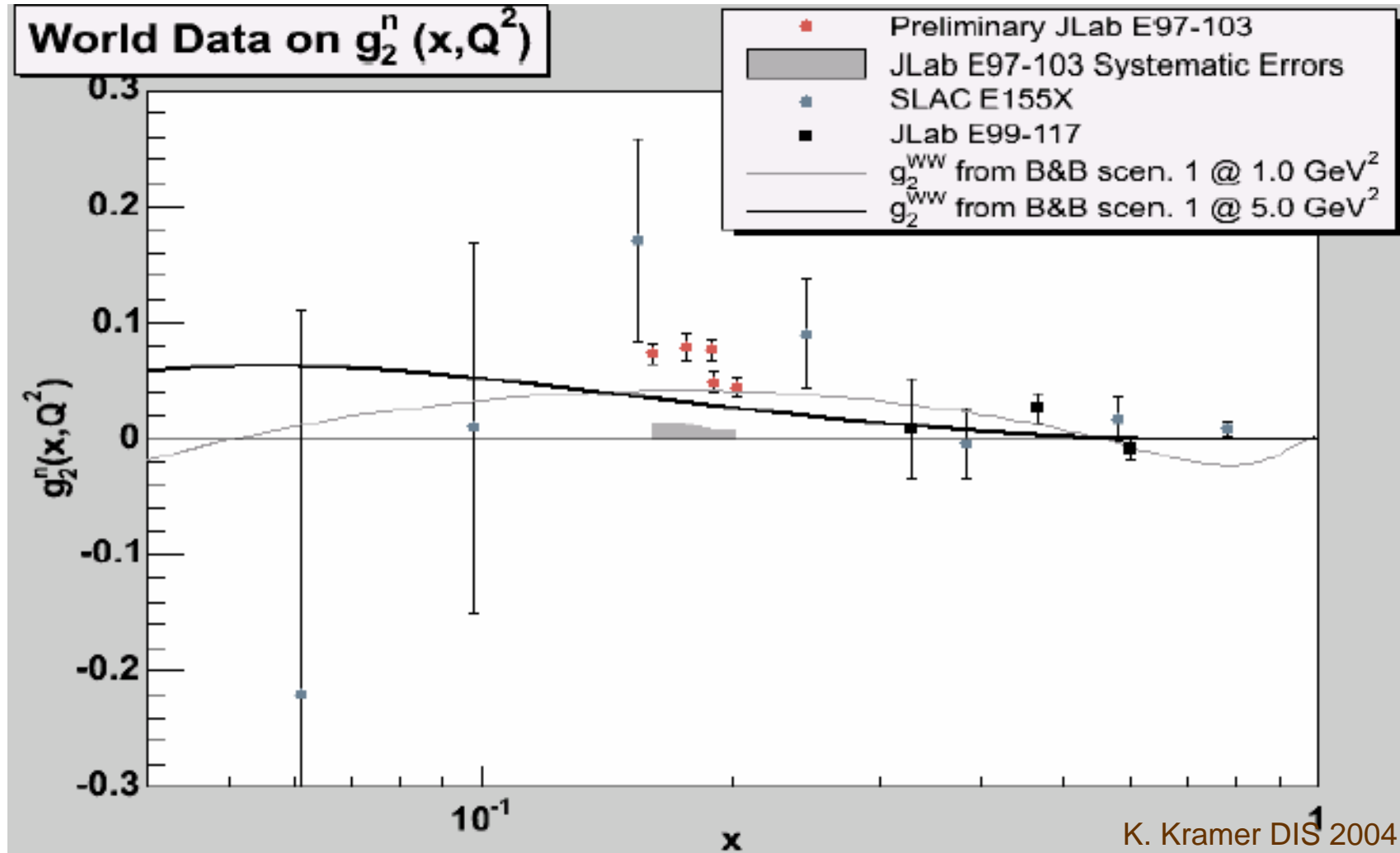
- — twist-2 term:  $g_2^{WW}$
- - - - bag model calculations

● E155X PRELIMINARY  
 ⊕ E143 AVERAGE 29 GeV  
 ※ E155 AVERAGE 38 GeV

$xg_2^{WW}$  solid  
 Stratmann: dot  
 Song: dot  
 Weigel: DASH

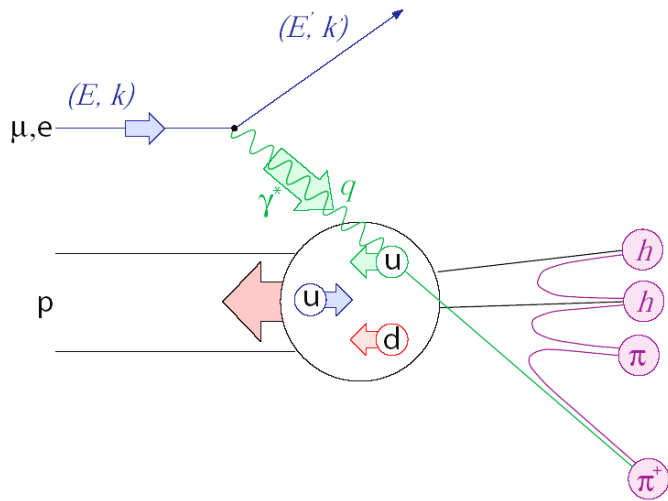


# Neutron $g_2$ from JLAB

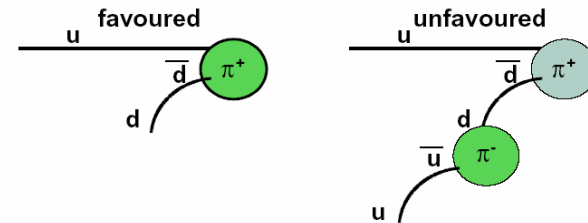




# Fragmentation Function $D_f^h(z, Q^2)$



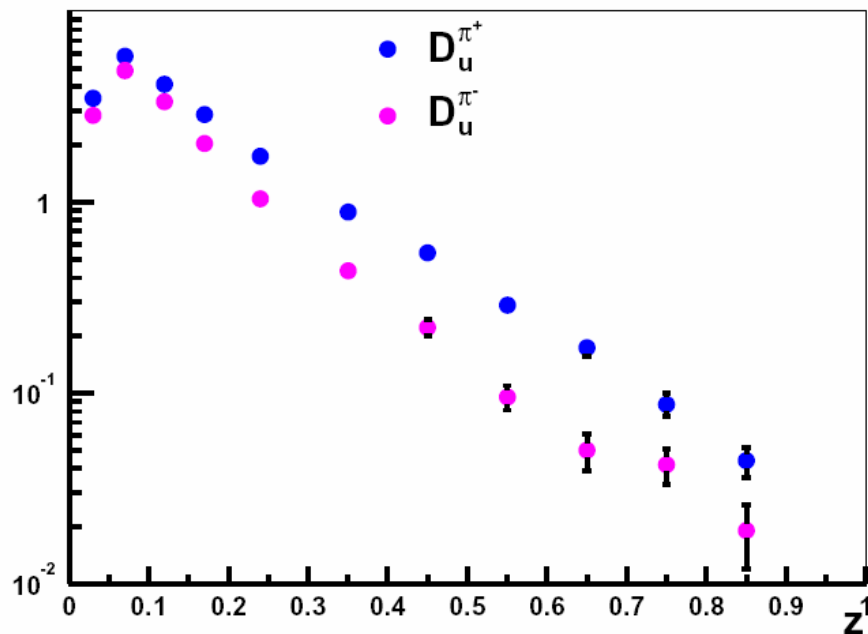
$D_q^h$  from quark  $q$  into hadron  $h$   
 $z = \frac{E_h}{\nu}$  energy fraction carried by  $h$



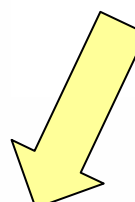
$$\begin{array}{ccccccc}
 D_u^{\pi^+} & \stackrel{=}{=} & D_{\bar{u}}^{\pi^-} & \stackrel{=}{=} & D_{\bar{d}}^{\pi^+} & \stackrel{=}{=} & D_d^{\pi^-} \\
 & \text{CC} & & \text{IS} & & \text{CC} & \\
 D_d^{\pi^+} & \stackrel{=}{=} & D_{\bar{d}}^{\pi^-} & \stackrel{=}{=} & D_{\bar{u}}^{\pi^+} & \stackrel{=}{=} & D_u^{\pi^-}
 \end{array}$$

$$\frac{1}{\sigma_0} \frac{d\sigma^h}{dz} = \frac{\sum_f e_f^2 q_f(\mathbf{x}, Q^2) \cdot D_f^h(z, Q^2)}{\sum_f e_f^2 q_f(\mathbf{x}, Q^2)}$$

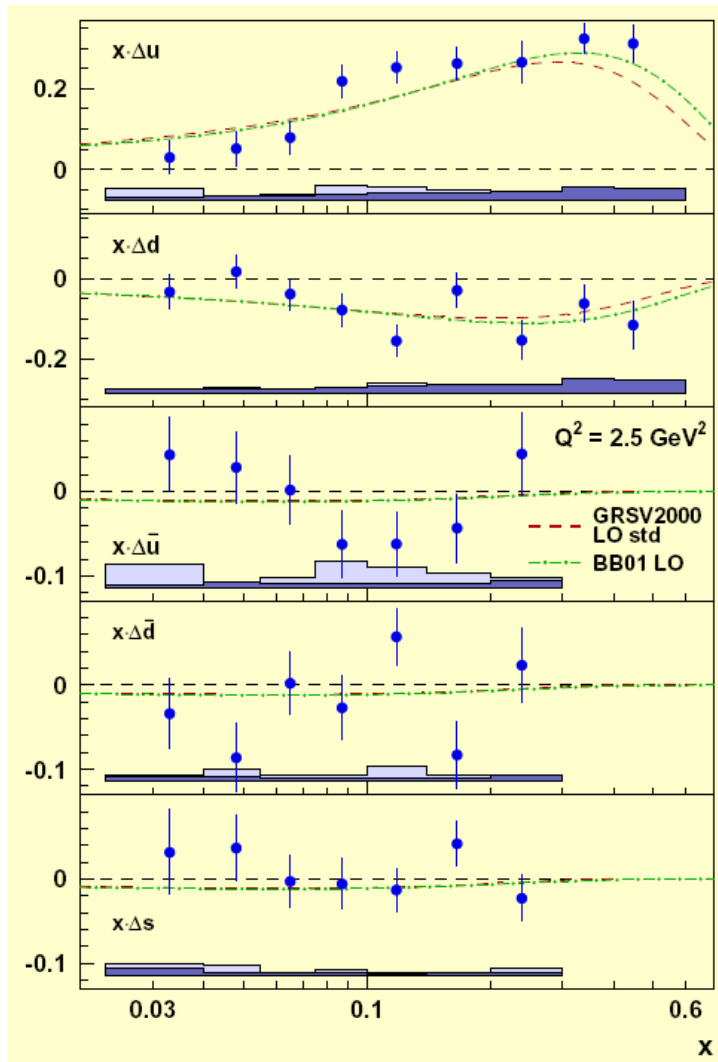
# Semi-inclusive DIS



final hadron “remembers”  
flavour of initially struck!


$$A_1^h(x, Q^2) = \frac{\int dz \sum_f e_f^2 \Delta q_f(x, Q^2) \cdot D_f^h(z, Q^2)}{\int dz \sum_f e_f^2 q_f(x, Q^2) \cdot D_f^h(z, Q^2)}$$

# Flavour separated polarisation



Asymmetries can in LO be related to  $\Delta q$  by

$$\vec{A} = \mathcal{P} \vec{Q}$$

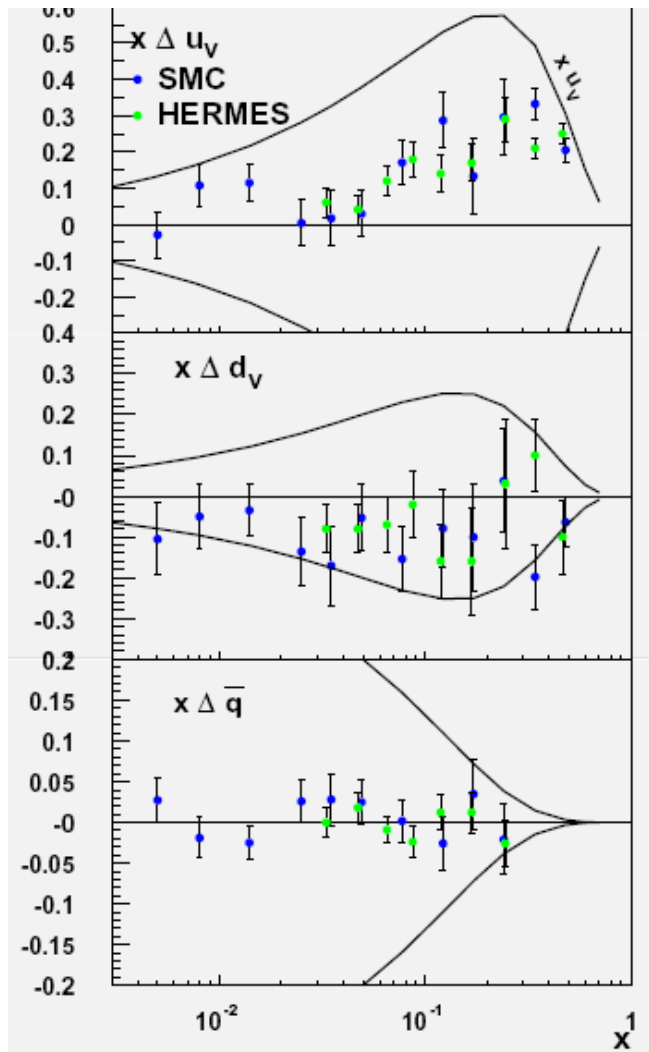
where

$$\vec{A} = (A_{1,t}^h, \dots)$$

$$\vec{Q} = (\Delta q_f, \dots)$$

$$\mathcal{P}_f^h = \frac{e_f^2 q_f(x) \int dz D_f^h}{\sum_i e_i^2 q_i(x) \int dz D_i^h(z)}$$

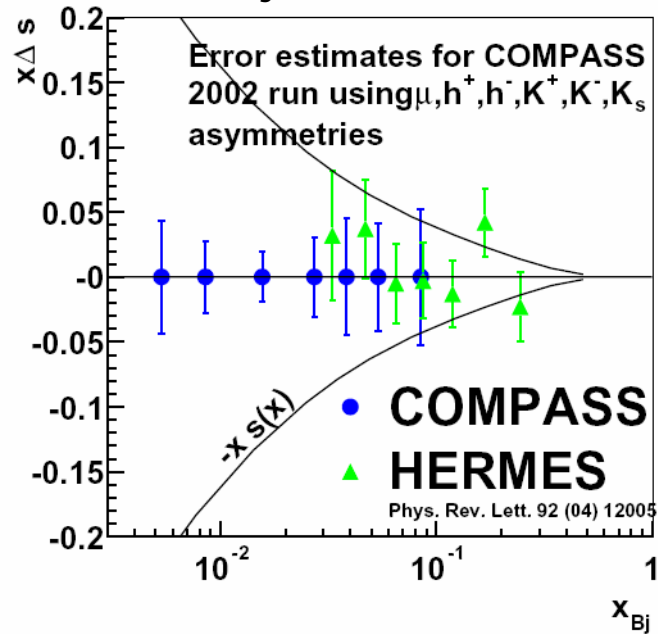
# more data



SMC and COMPASS have more small  $x$  data.

Will help to clarify  $\Delta s$

## Projection for $\Delta s$ (2002 data)



# Transversity $h_1$

$$q(x) = f_1(x) =$$



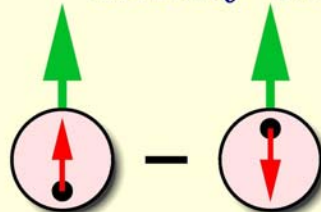
momentum distribution

$$\Delta q(x) = g_1(x) =$$

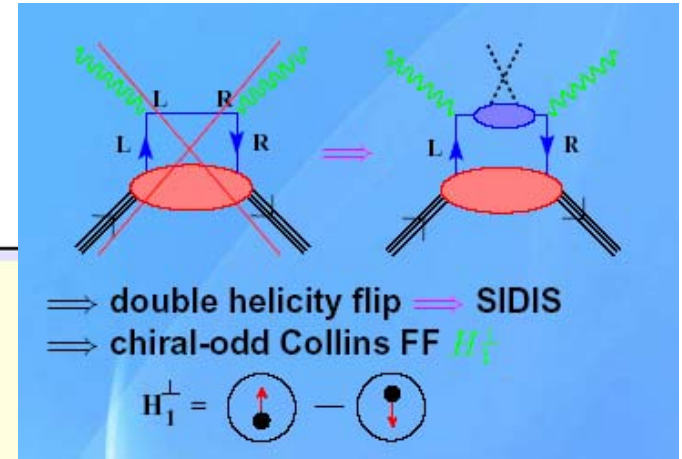


helicity distribution

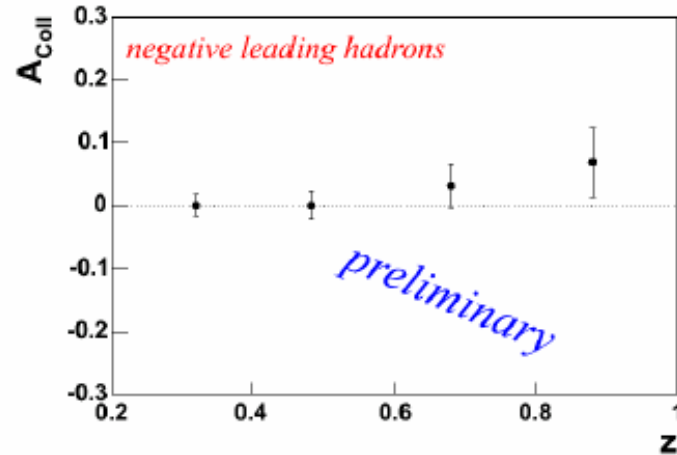
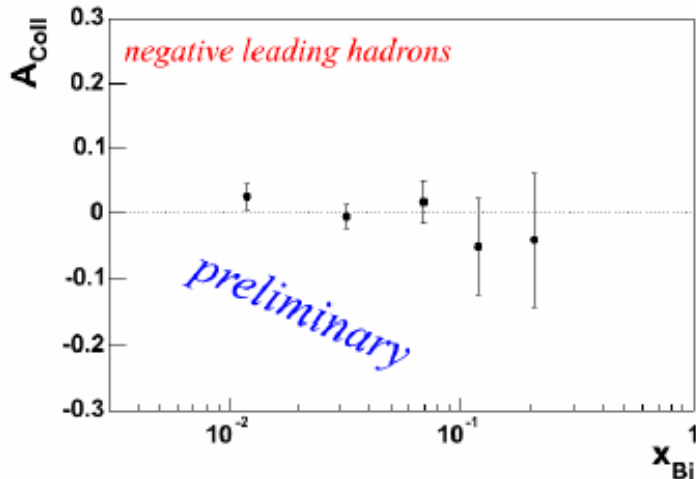
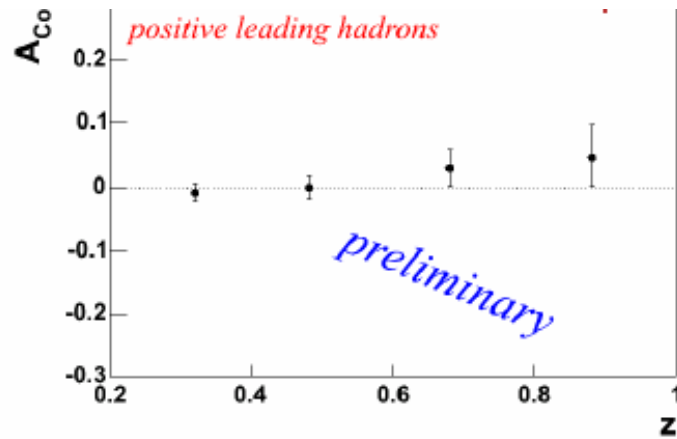
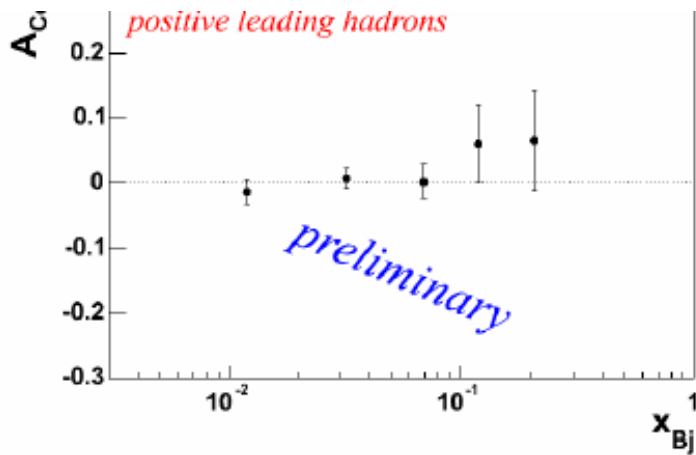
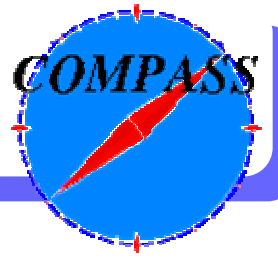
$$\delta q(x) = h_1(x) =$$



transversity distribution

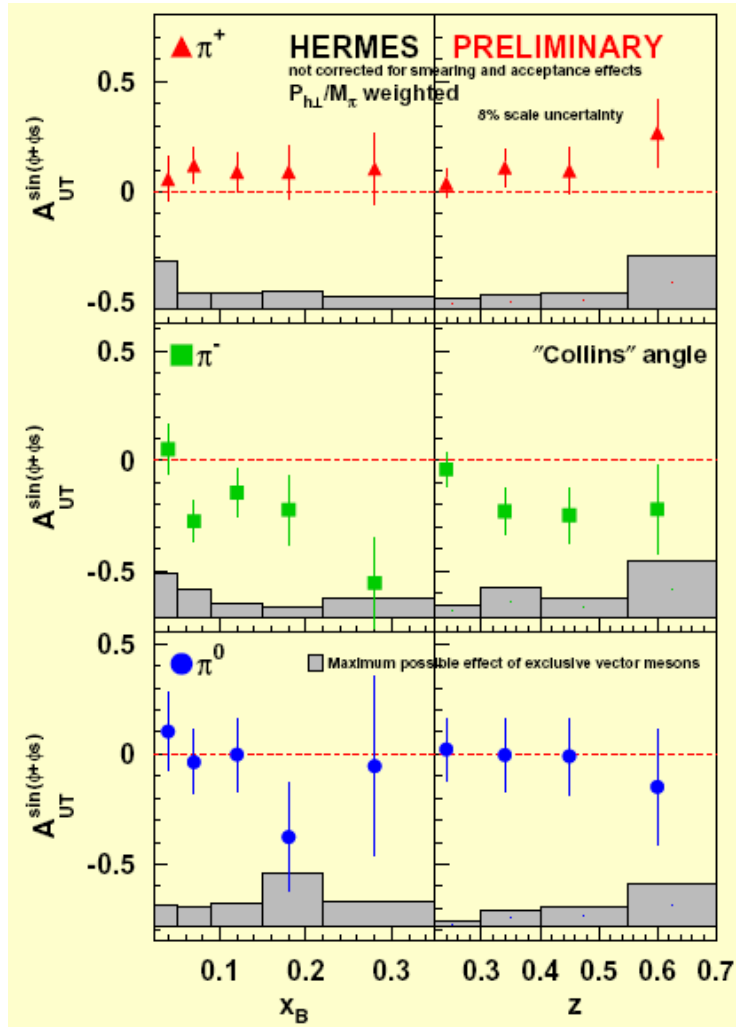


# Collins asymmetries 2002



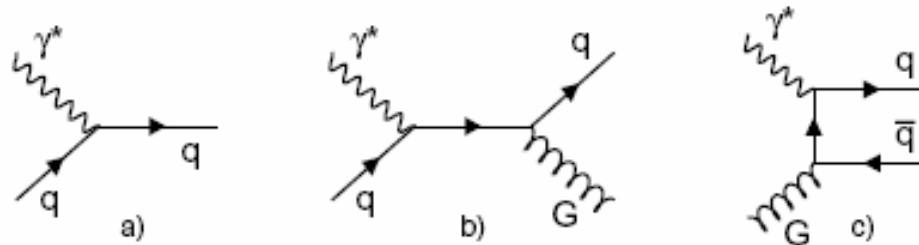
Deuteron

# Hermes Collins asymmetry



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

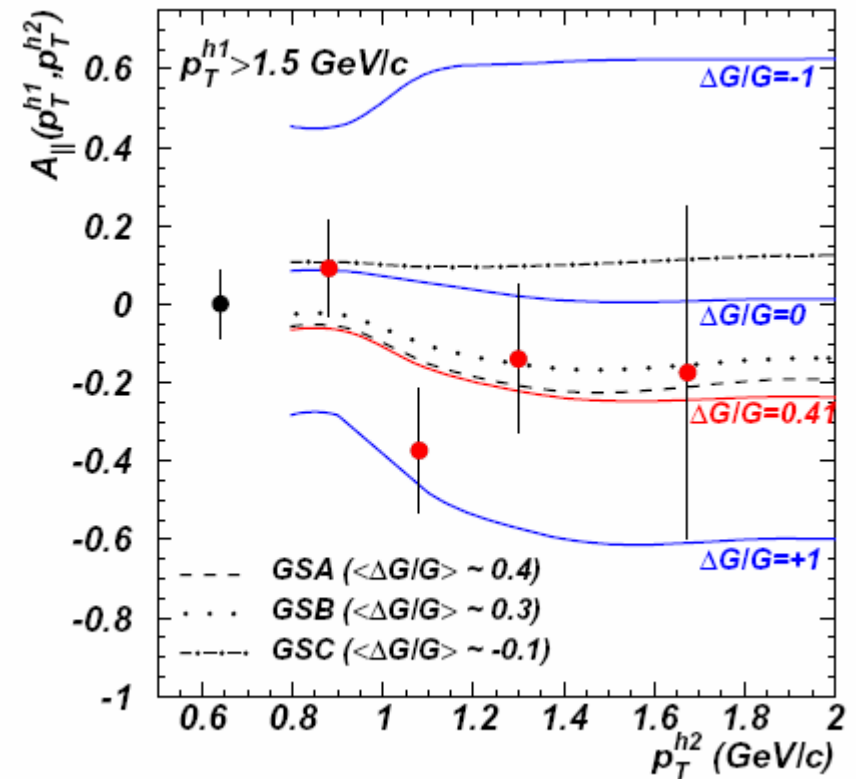
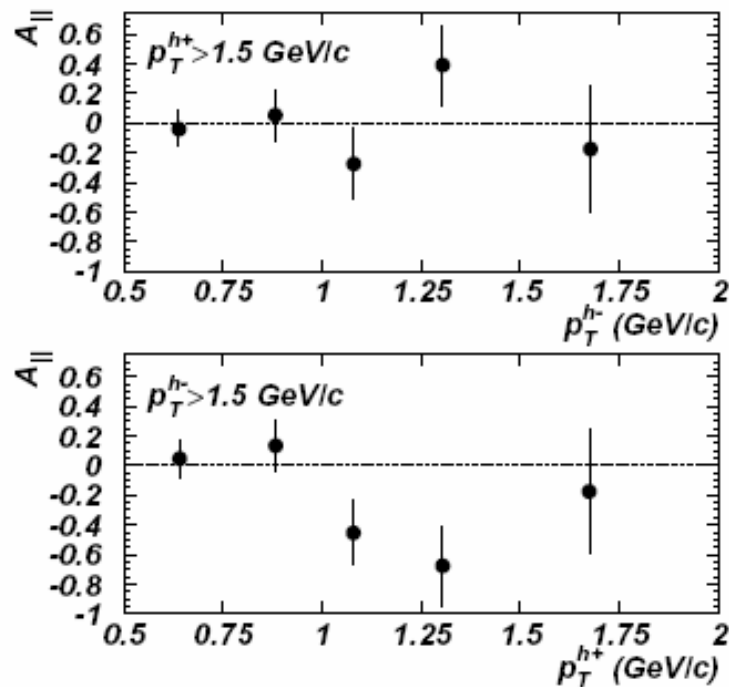
- Contributions: a) LO      b) QCD Compton      c) PGF



$$A_{LL}^{\ell N} \simeq \langle \hat{a}_{LL}^{\gamma g \rightarrow qg} \rangle \frac{\Delta q}{q} + \langle \hat{a}_{LL}^{\gamma g \rightarrow q\bar{q}} \rangle \frac{\Delta g}{g}$$



# Hermes high- $p_T$ pairs



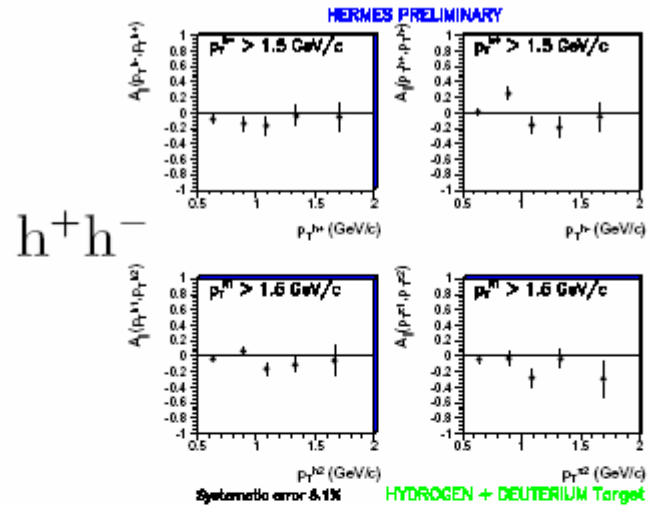
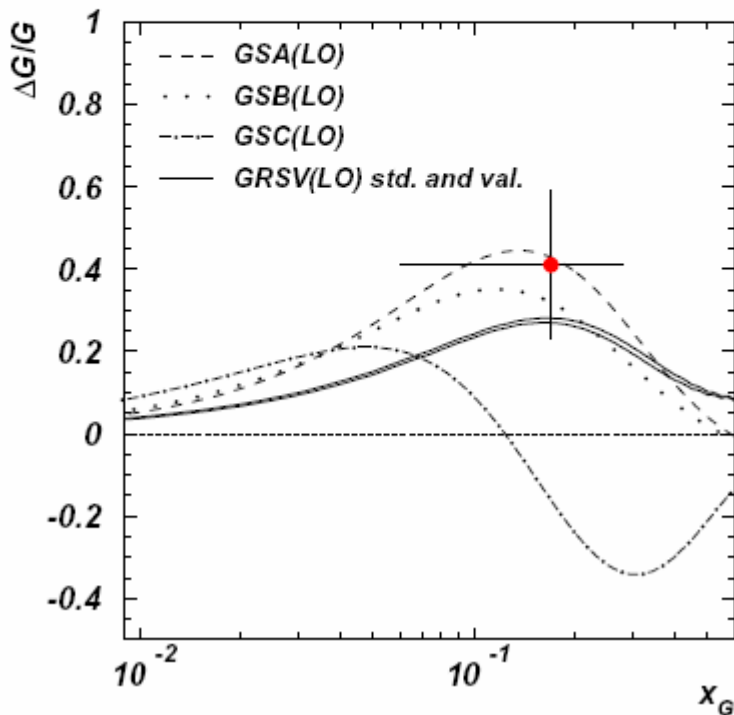
# Hermes high- $p_T$ pairs

- Hermes conclusion:**

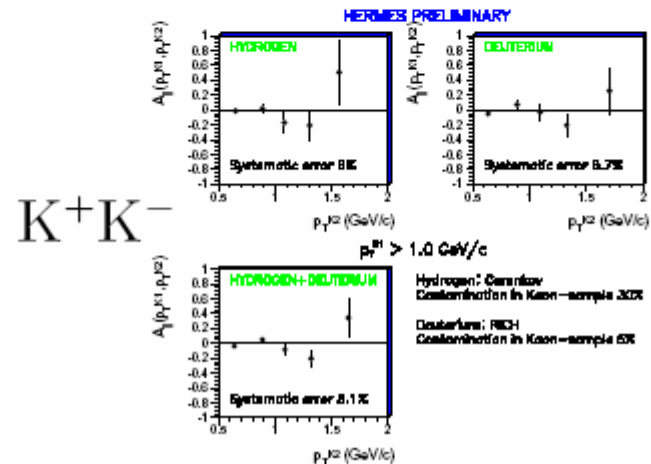
$$\Delta g/g = 0.41 \pm 0.18(\text{stat}) \pm 0.03(\text{syst exp})$$

$$\langle x_g \rangle = 0.17; \langle p_T^2 \rangle = 2.1 \text{ GeV}^2$$

$$\int_{0.06}^{0.028} \frac{\Delta g}{g} g(x) dx \approx 0.6$$

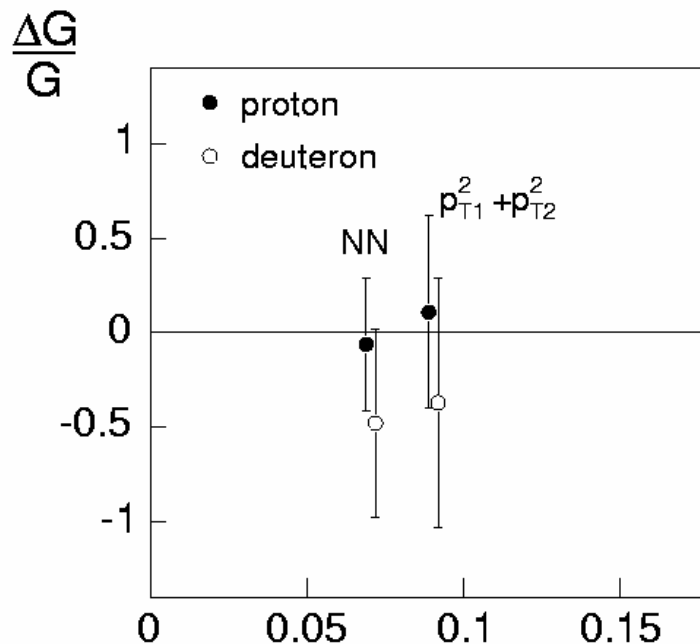


$\pi^+ \pi^-$



# SMC high- $p_T$ analysis

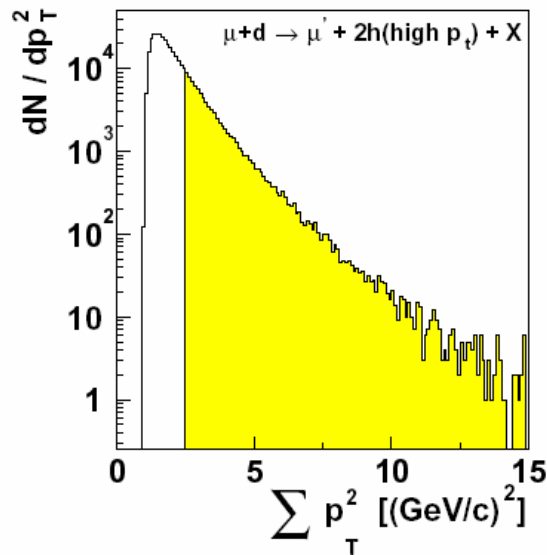
- **Hermes**:  $Q^2$  not reconstructed for high- $p_T$
- **SMC**: cut on  $Q^2 > 1 \text{ GeV}^2$ , theoretical description more sound, limited statistics



| Selection                          | $\Delta G/G \pm \delta(\Delta G/G)_{\text{stat}}$ | $\langle X_g \rangle_{\text{genPGF}}$ |
|------------------------------------|---|---------------------------------------|
| $\Sigma p_T^2 > 2.5 \text{ GeV}^2$ | $-0.07 \pm 0.40$                                  | 0.09                                  |
| NN > 0.26                          | $-0.20 \pm 0.28$                                  | 0.07                                  |

$\langle \eta \rangle$

# COMPASS high- $p_T$ hadron pairs



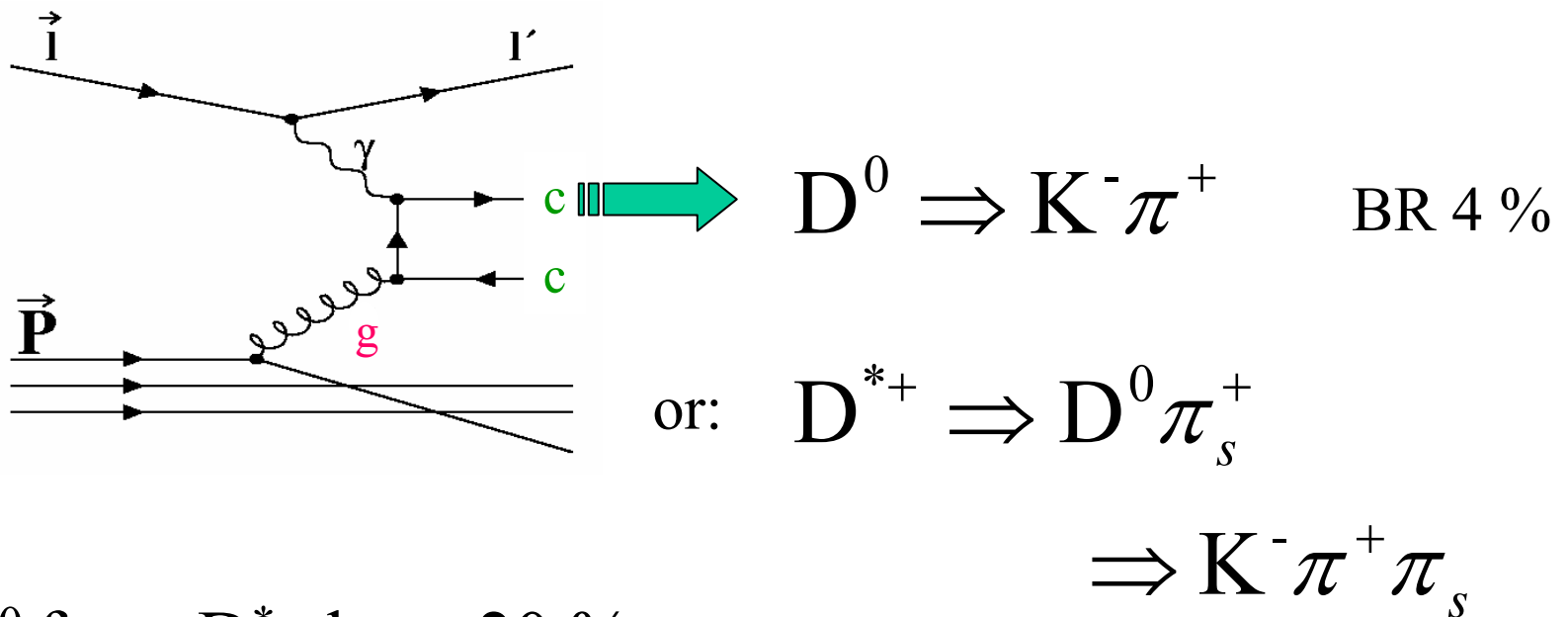
2002 data only, all  $Q^2$ , 75000 events

- High  $p_T$  cut
  - $p_{T1}, p_{T2} > 0.7 \text{ GeV}/c$
  - $p_{T1}^2 + p_{T2}^2 > 2.5 \text{ GeV}^2/c^2$
- Vector mesons are removed
  - $m(h_1 h_2) > 1.5 \text{ GeV}/c^2$
- Products of the target fragmentation are removed
  - $x_F > 0.1$
  - $z > 0.1$

$$\left(\frac{A_{\parallel}}{D}\right)^{\mu d \rightarrow hh} = -0.065 \pm 0.036(\text{stat.}) \pm 0.01(\text{syst.})$$

# Open charm at COMPASS

- Photon-gluon fusion: 1.2  $D^0$  per PGF  $c\bar{c}$  event



$D^0$  from  $D^*$  about 20 %

# Open charm, cuts

- most of 2002 data, prel. RICH and tracking
- $z_D > 0.2$  (background reduction)
- $|\cos(\theta^*)| < 0.85$  (background reduction)
- $10 < p_K < 35 \text{ GeV}/c$  (Rich  $\pi K$  sep.)
- define:

$$\Delta M_{K\pi\pi} = M_{K\pi\pi_s} - (M_{K\pi} + M_{\pi_s})$$

$$M(D^*) - [M(D^0) + M(\pi)]$$

# $D^{*+} \rightarrow D^0 \pi_s^+$ tagging

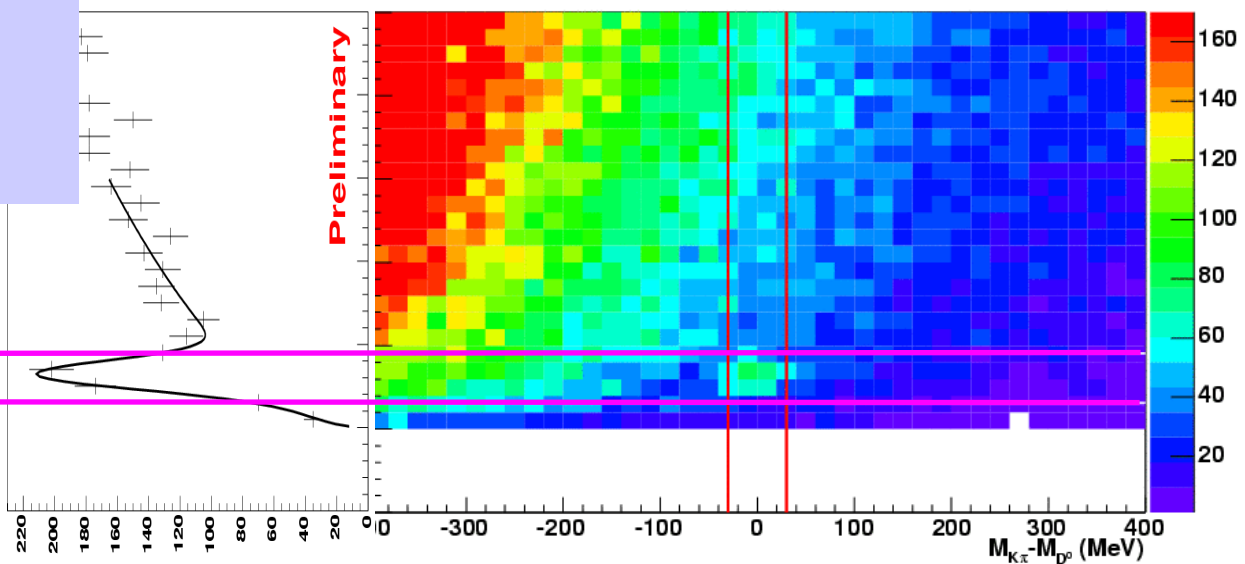
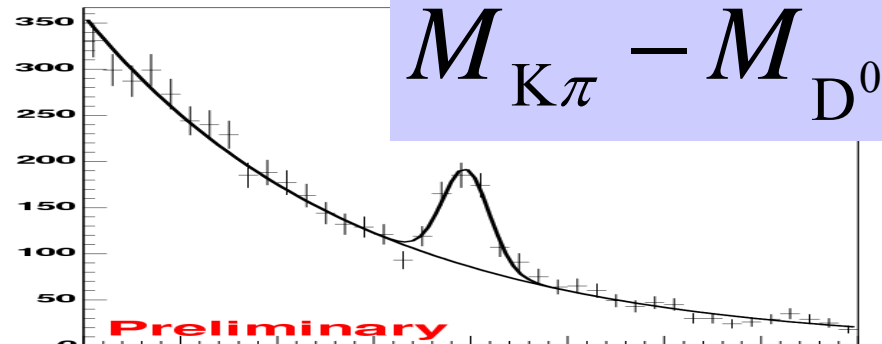
$$D^* \rightarrow D^0 \pi_s$$

$$\rightarrow K \pi \pi_s \quad (+ cc)$$

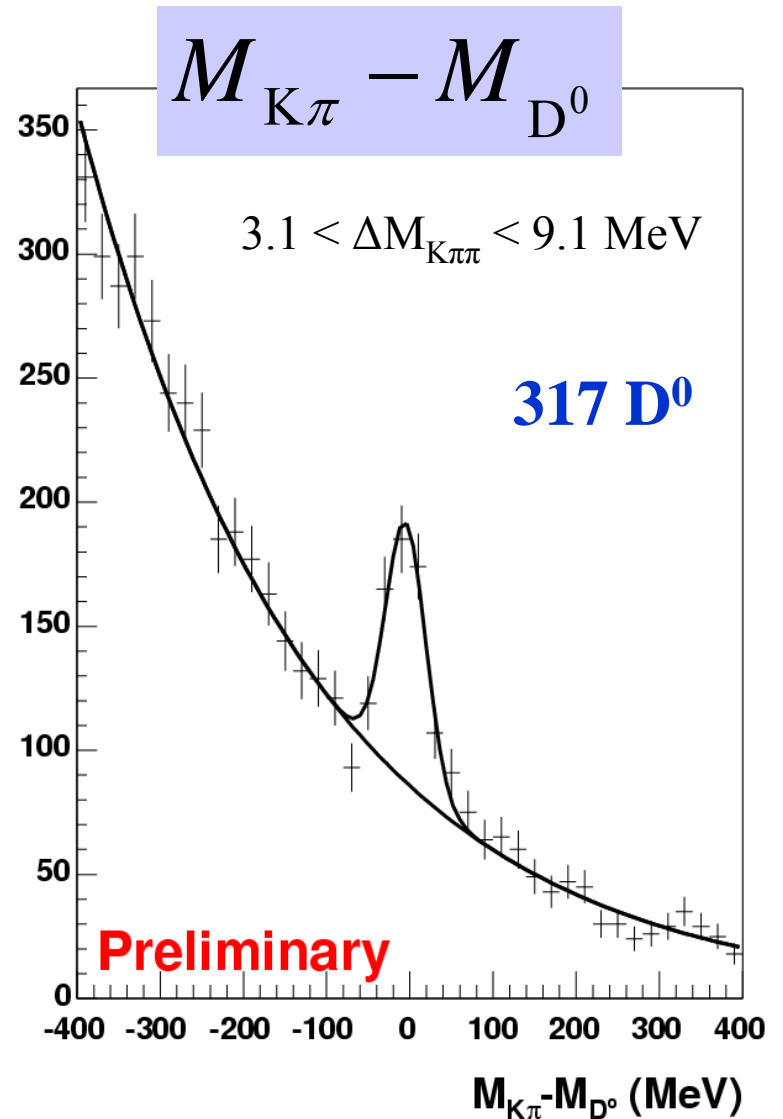
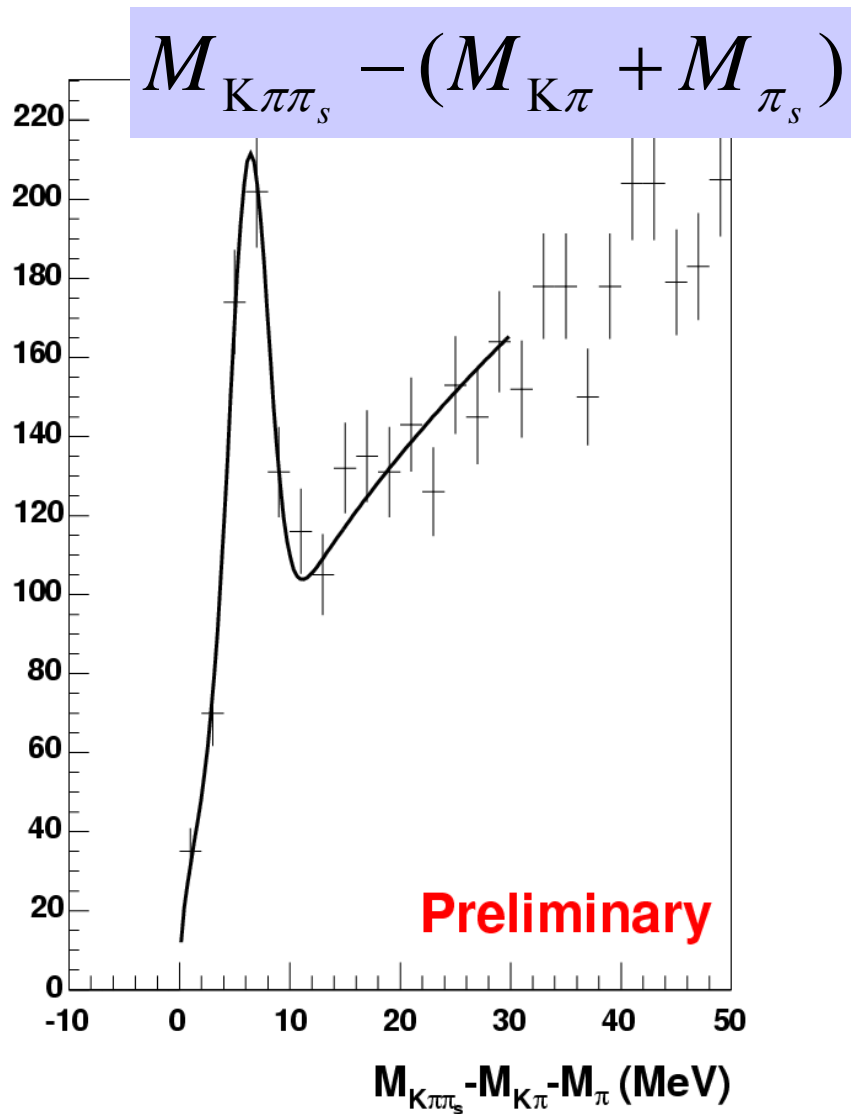
$$\Delta M_{K\pi\pi} = M_{K\pi\pi_s} - (M_{K\pi} + M_{\pi_s})$$

Choose:

$$3.1 < \Delta M_{K\pi\pi} < 9.1 \text{ MeV}$$

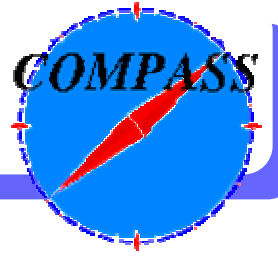


# $D^{*+} \rightarrow D^0 \pi_s^+$ tagging





# Projected precision for $\Delta G/G$



- 2002 – 2004 data:

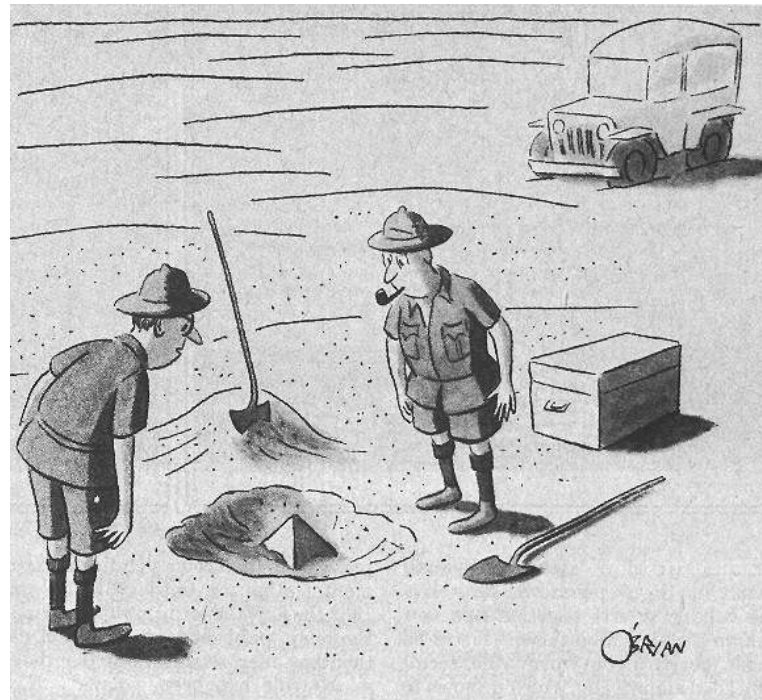
- from high- $p_T$ : (*all*  $Q^2$ )  $\delta(\Delta G / G) = 0.05$
- from high- $p_T$ : ( $Q^2 > 1$ )  $\delta(\Delta G / G) = 0.16$
- from open charm:  $\delta(\Delta G / G) = 0.24$

No systematic error included yet  
(not too big, apart from possible theoretical uncertainties)

# Summary

- Lots to come from:
  - Hermes
  - COMPASS
  - RHIC

- It seems SPIN goes down very far ...



*"This could be the discovery of the century. Depending, of course, on how far down it goes."*