Spin structure of the nucleon studied with muon and electron beams

G. K. Mallot
CERN/PH

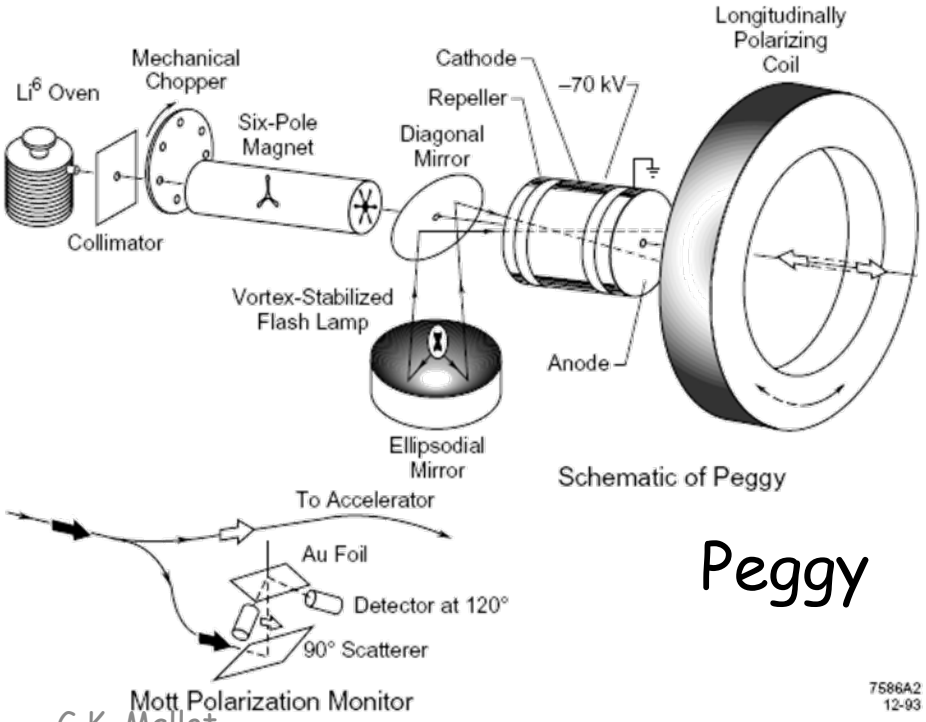
JPS Autumn Meeting,
Yamagata, Japan, September 23 , 2008

Zao Okama Crater Lake

The early days

SLAC-Yale E80 (1975):

- beam:
  10-16 GeV e^- ,
  85% pol from pol. ^{6}Li
- target:
  butanol 60% pol

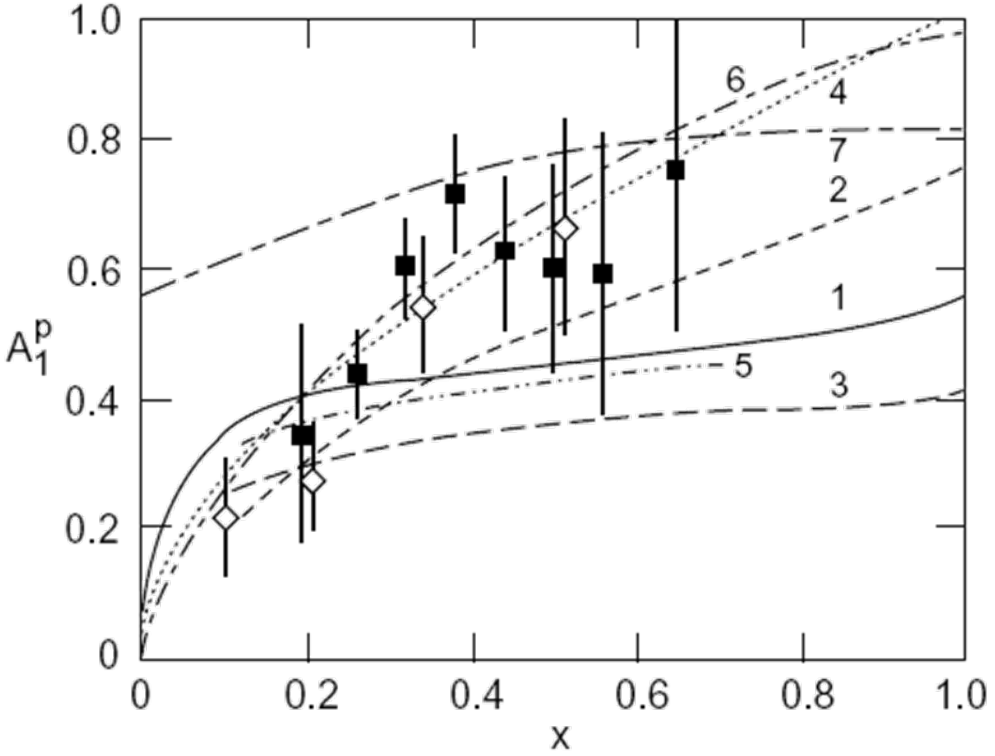


Peggy

Support for the QPM

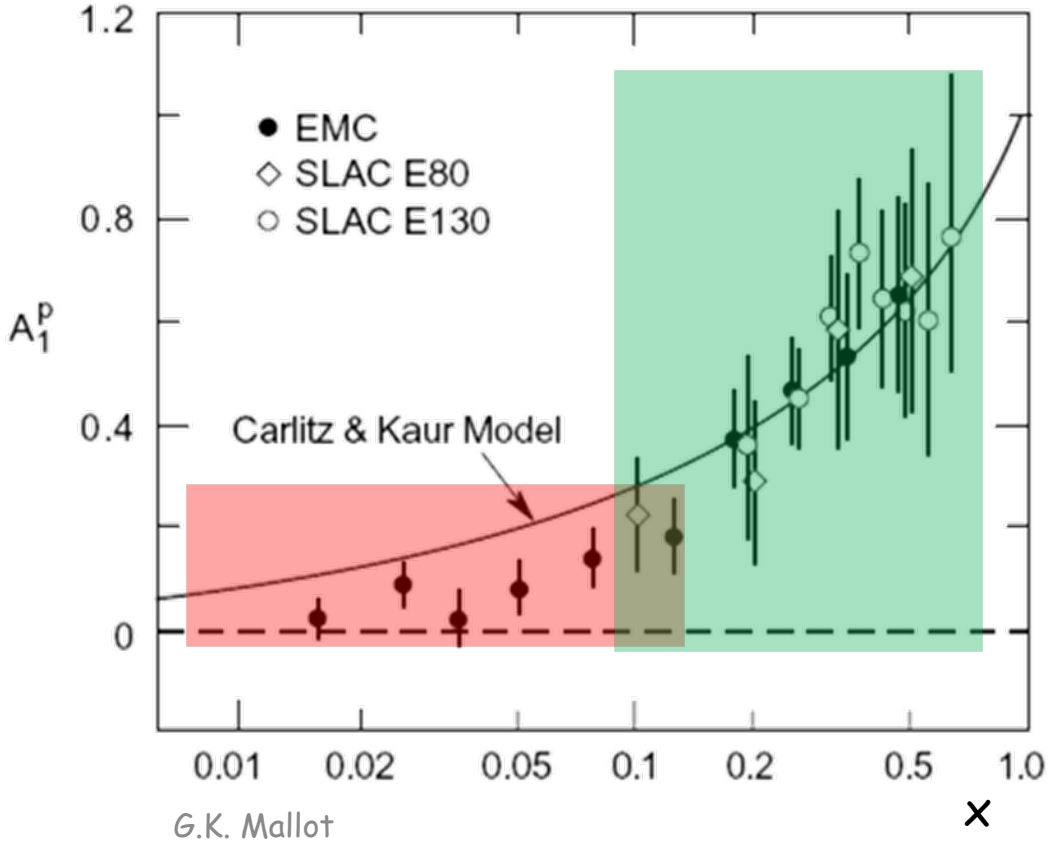
- large longitudinal double spin asymmetries at large x_{Bj}
- predicted by Bjorken from the Quark Parton Model

E80 (◊)
E130 (▪)

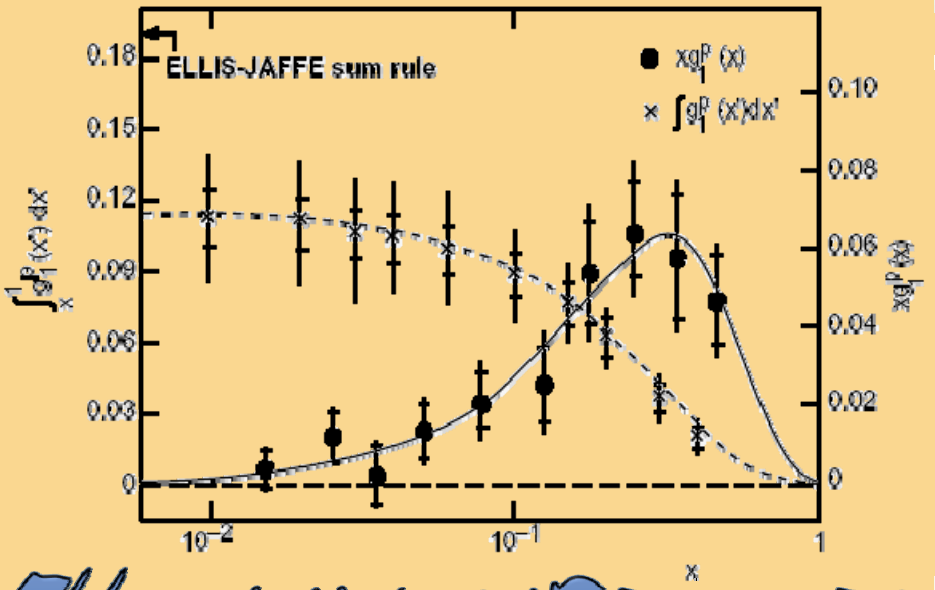


The shock 1987/88

- European Muon Collaboration (EMC) at CERN
- beam: 100 – 280 GeV, muons, pol. 80%
- target: ammonia, 80% pol.
- models wrong below x < 0.1
- unmeasured by E80 & E130



EMC 1987/88



20TH ANNIVERSARY

Implications of the EMC result

- The Ellis-Jaffe sum rule for the proton is violated
- The fundamental Bjorken sum rule can only be valid, if the EJ sum rule for the neutron is violated by the same amount

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_a$$

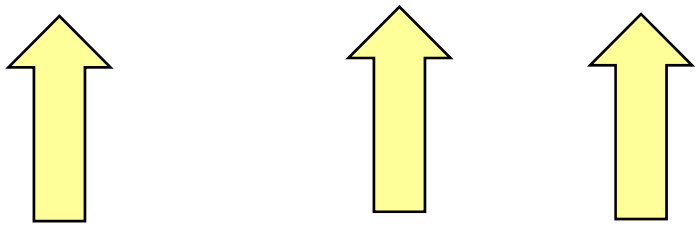
"if wrong, QCD is wrong"

- The strange quark polarization Δs does not vanish
- The quark spins contribute little to the proton spin

Where, oh where is the proton spin?

Elliot Leader

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



small

poorly known
certainly not 6

unknown

Theory Input 1988

CHIRAL SYMMETRY AND THE SPIN OF THE PROTON ☆

Stanley J. BRODSKY [a], John ELLIS [a,b] and Marek KARLINER [a]
[a] *Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA*
[b] *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[1] and M. Anselmino[2]
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 [1]
CERN, CH-1211 Geneva 23, Switzerland

PLB 212 (1988) 391

Received 29 June 1988

Considered Options

- Skyrmions: model, all orbital angl. mom. (BEK) — maybe
- Bjorken sum rule broken? Measurement wrong? (LA) — no!
- Large ΔG ~ 2-3-6 at EMC Q^2 could mask quark spin via axial anomaly (ET, AR) — measure gluon pol!

  requires fine tuning of cancelation of ΔG and orbital angular momentum (orb. ang. mom. is generated at gluon emission)

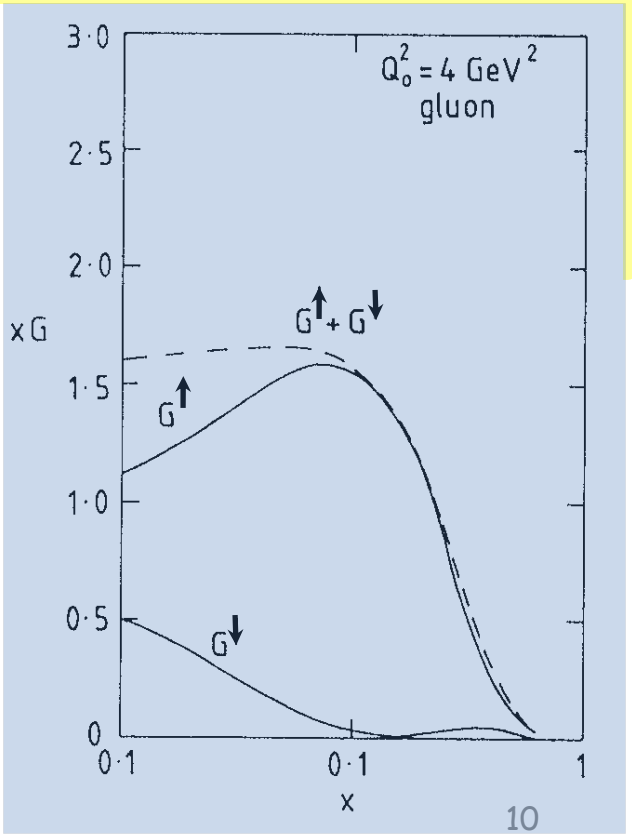
Lepton-Photon 1989

To summarise, let us return to the fit of Fig. 7 and 8. At $Q^2=10GeV^2$ this corresponds to $\Delta g=6.3$ and so the proton helicity is given by

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta g + L_z$$

$$= 0.35 + 6.3 - 6.15$$

G. Ross 1989



possible scenario:

$\Delta G \approx 6$ $(Q^2=10\ GeV^2)$

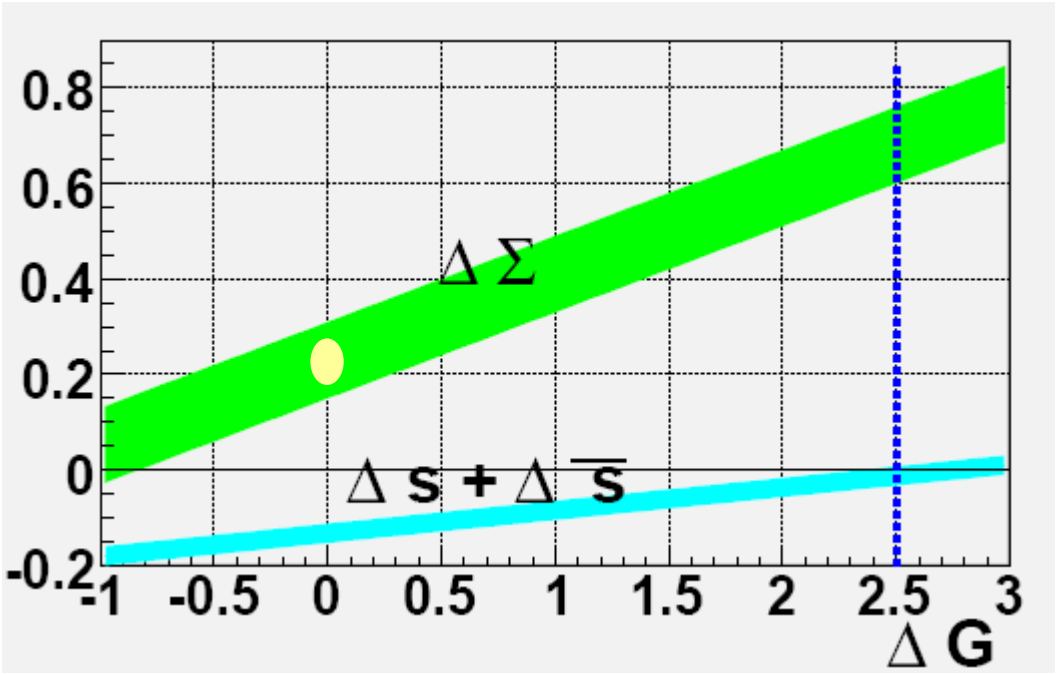
$\Delta g/g(x) = 1$ for $x_g > 0.1$

ΔG and ΔΣ in AB/jet scheme

$$\Delta\Sigma \leftarrow a_0 + \frac{3\alpha_s}{2\pi}\Delta G$$

$$\Delta s \leftarrow \Delta s + \frac{3\alpha_s}{2\pi}\Delta G$$

α_s strong coupling constant



Now:

$a_0 \simeq 0.3$

Need:

$\Delta G \simeq 2.5$

Priorities in 1988

Vernon W Hughes,
1921 – 2003,
E80, E130,
EMC, SMC

- repeat EMC meas. with higher precision and
- measure BJ sum rule (neutron experiment)
- gluon polarization (longer term)

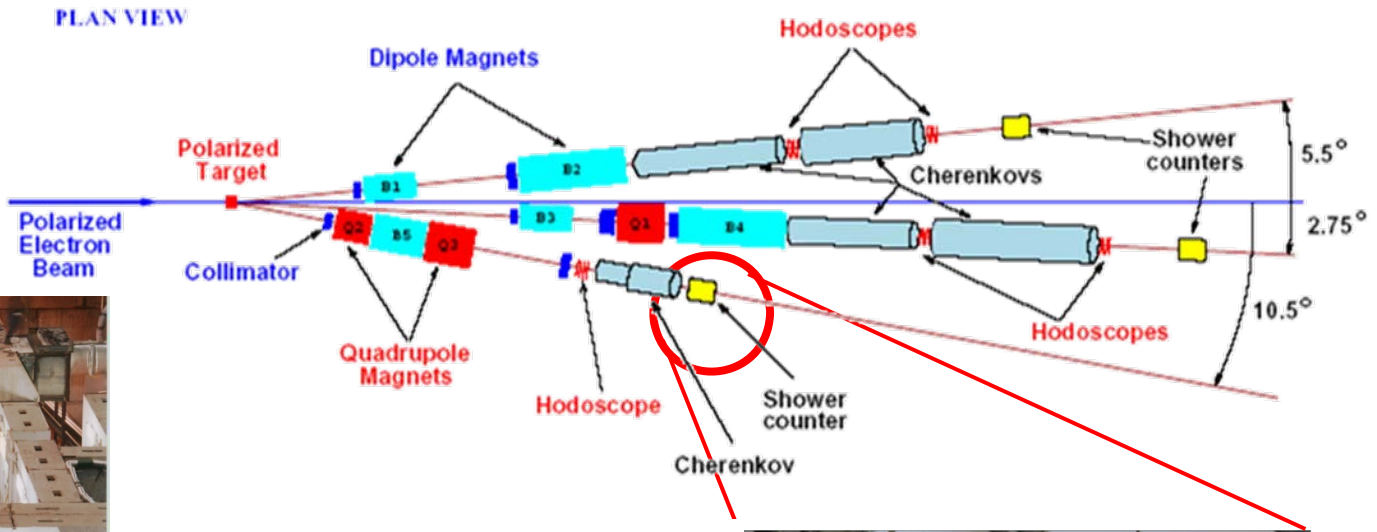
Third generation experiments:

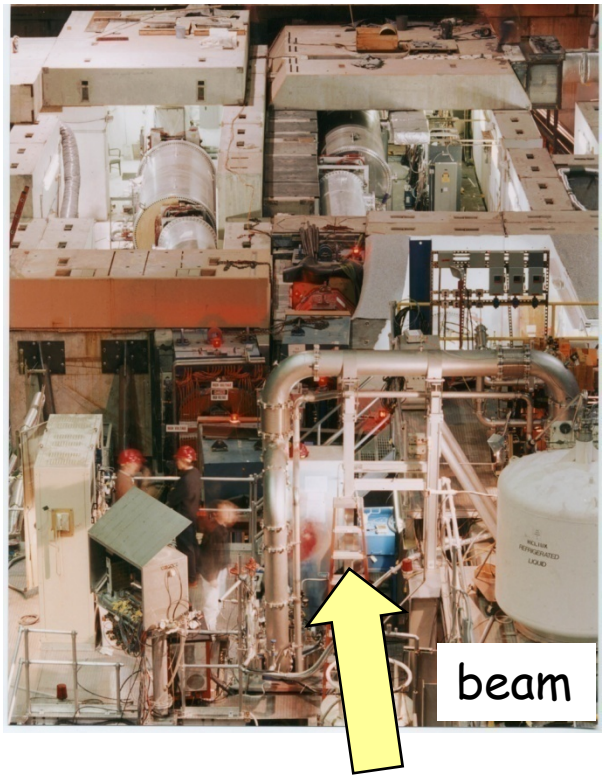
- SMC @CERN
- Hermes @ DESY (delayed)
- E142/43, E154/155, E155x at SLAC

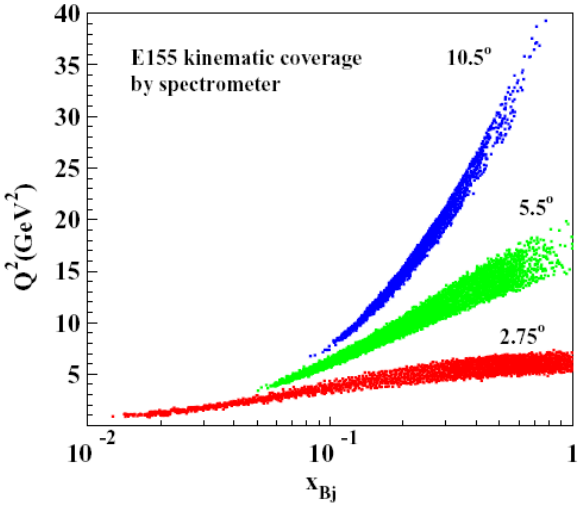
Forth generation experiments:

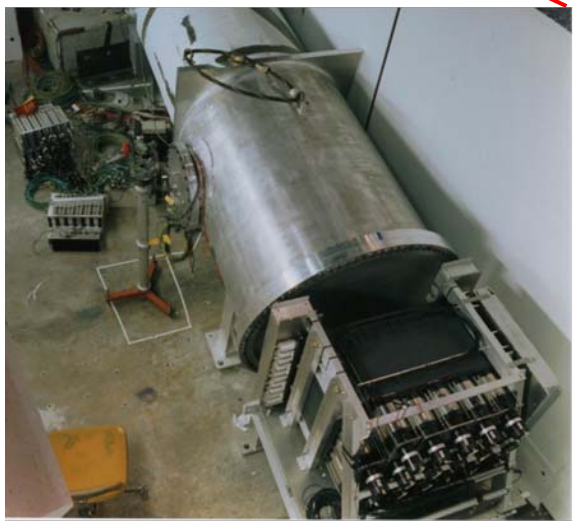
- COMPASS @CERN
- E99-117,… Jefferson Lab
- PHENIX & STAR @ RHIC

SLAC E155 Spectrometer

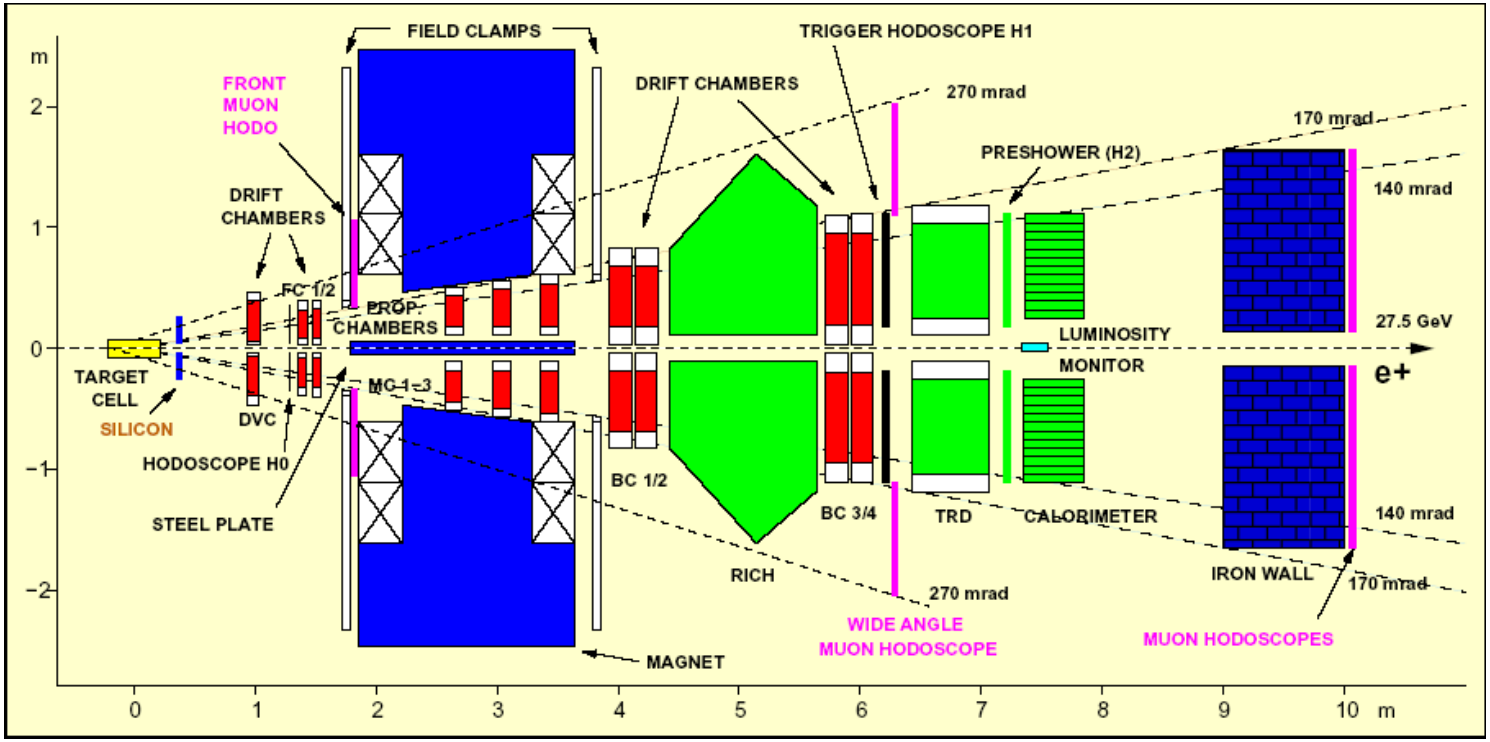








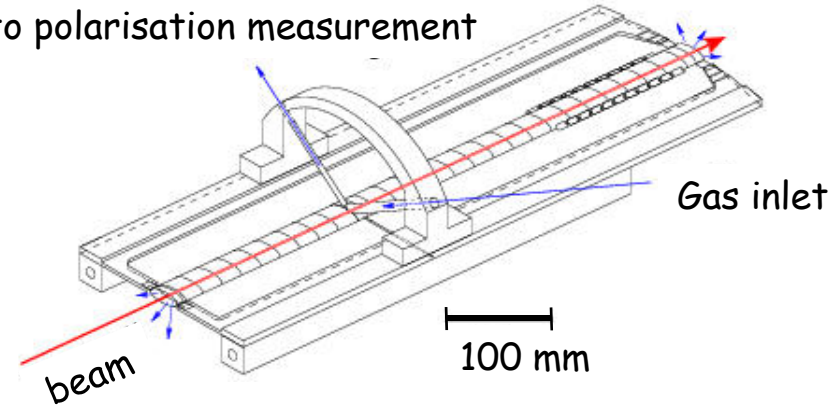
HERMES

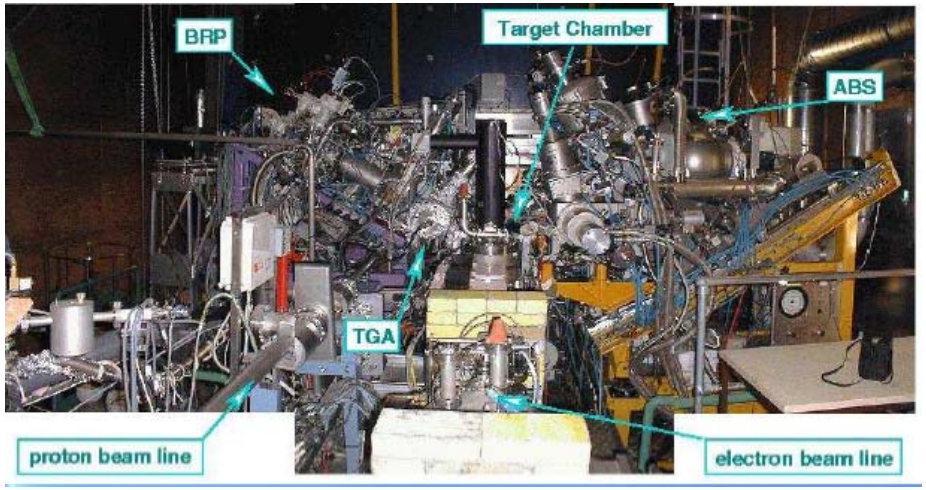

FIELD CLAMPS
TRIGGER HODOSCOPE H1
FRONT MUON HODO
DRIFT CHAMBERS
270 mrad
170 mrad
PRESHOWER (H2)
DRIFT CHAMBERS
140 mrad
FC 1/2
PROP. CHAMBERS
27.5 GeV
LUMINOSITY MONITOR
e+
TARGET CELL
SILICON
DVC
MC 1-3
HODOSCOPE H0
STEEL PLATE
BC 1/2
BC 3/4
TRD
CALORIMETER
RICH
IRON WALL
140 mrad
170 mrad
270 mrad
WIDE ANGLE MUON HODOSCOPE
MUON HODOSCOPES
MAGNET
m
2
1
0
-1
-2
0
1
2
3
4
5
6
7
8
9
10
m

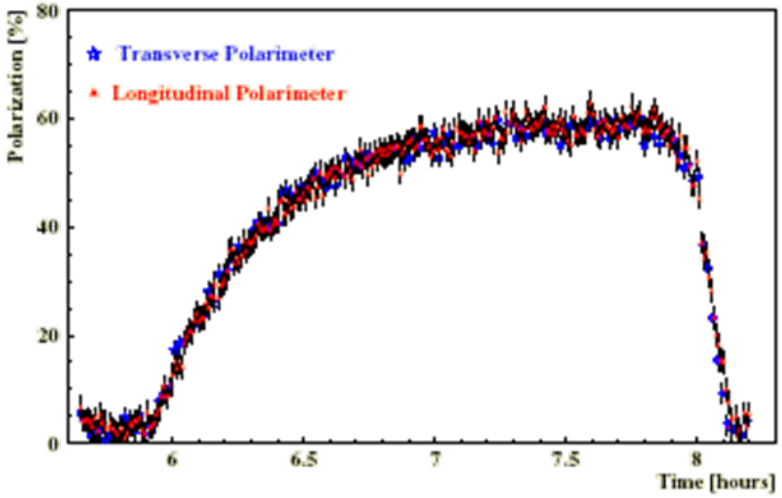
HERMES

Target cell

Gas to polarisation measurement

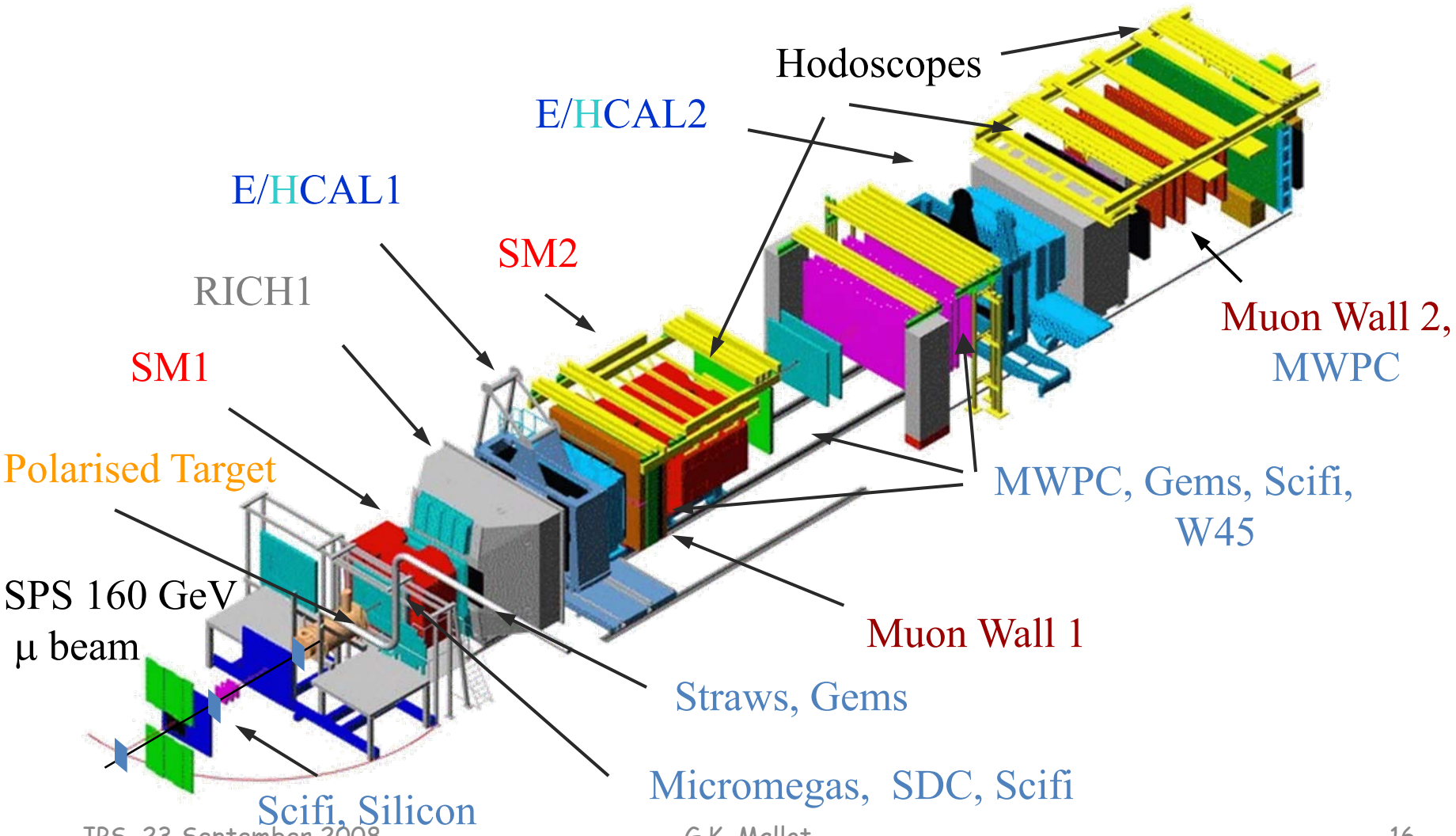






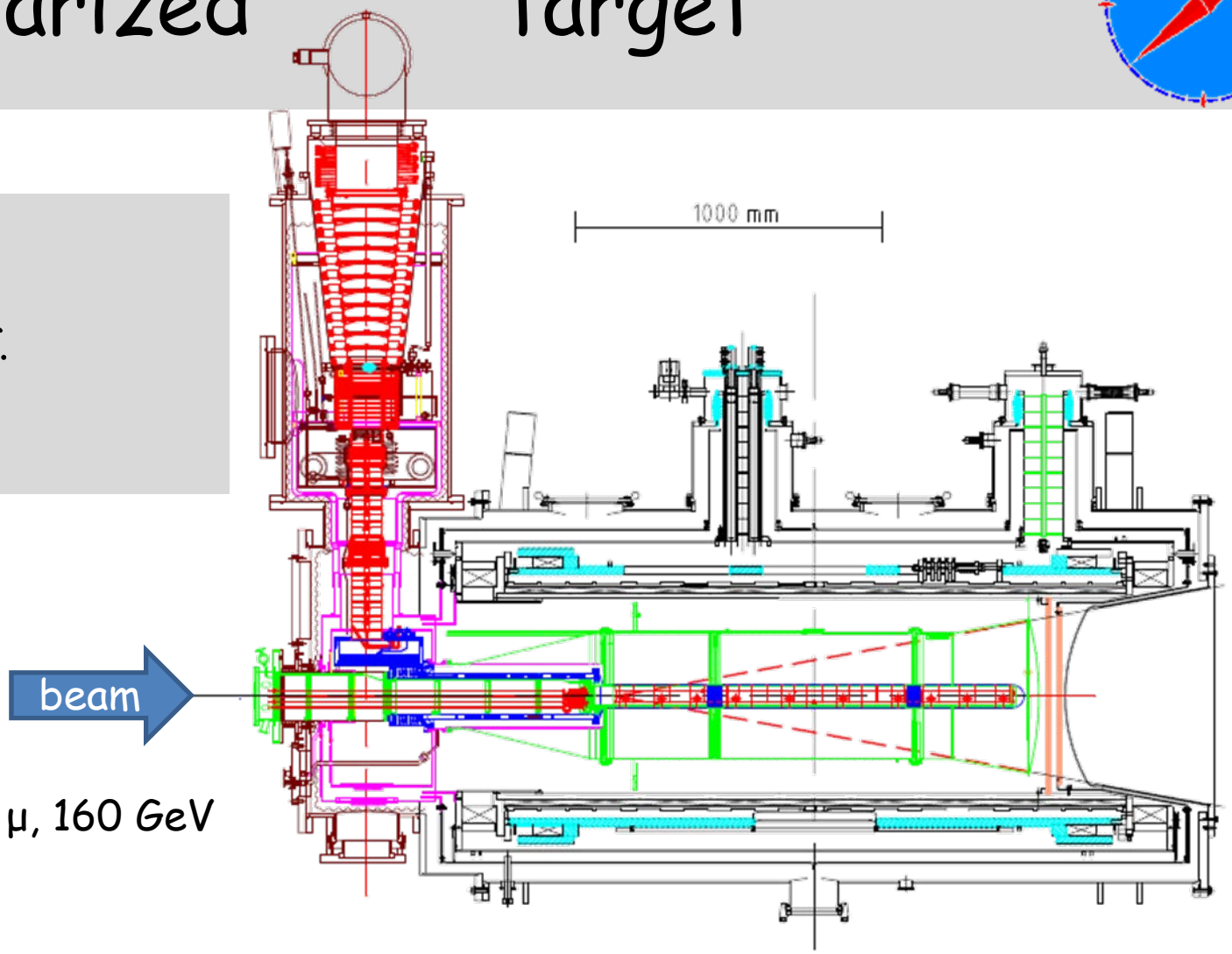
beam polarisation built-up

The COMPASS Spectrometer



Polarized target

- $^6LiD/NH_3$
- 50/90% pol.
- 40/16% dil. f.
- 2.5 T
- 50 mK

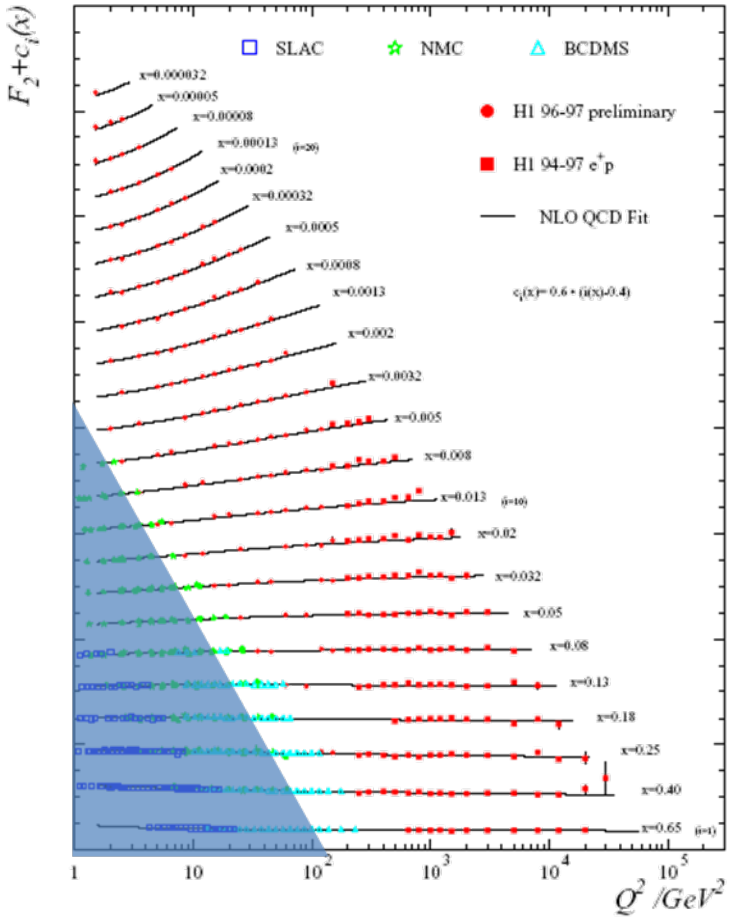


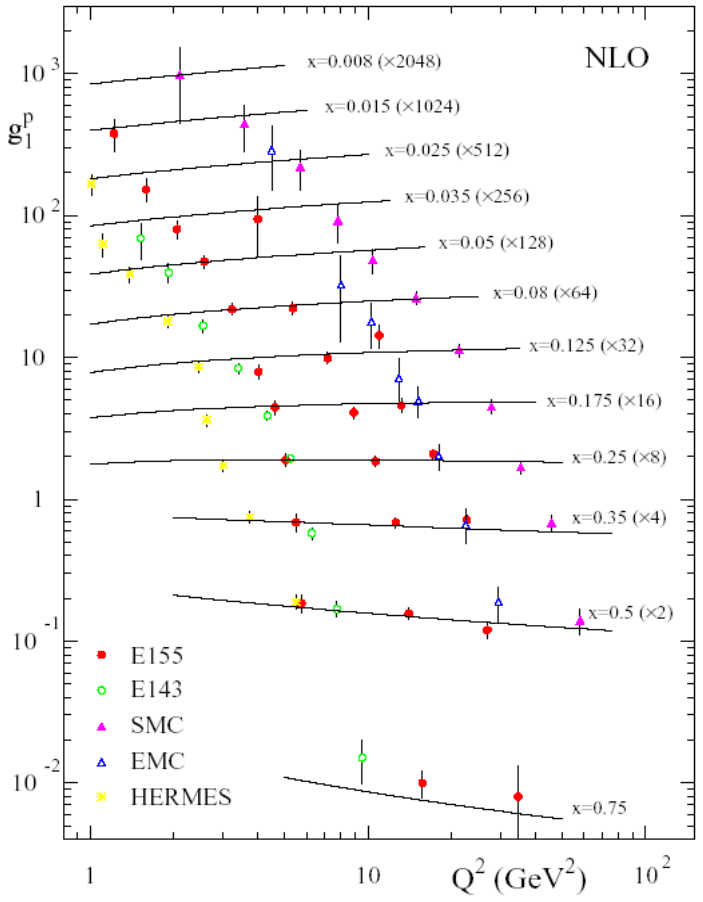
Structure Functions

$F_2(x,Q^2)$

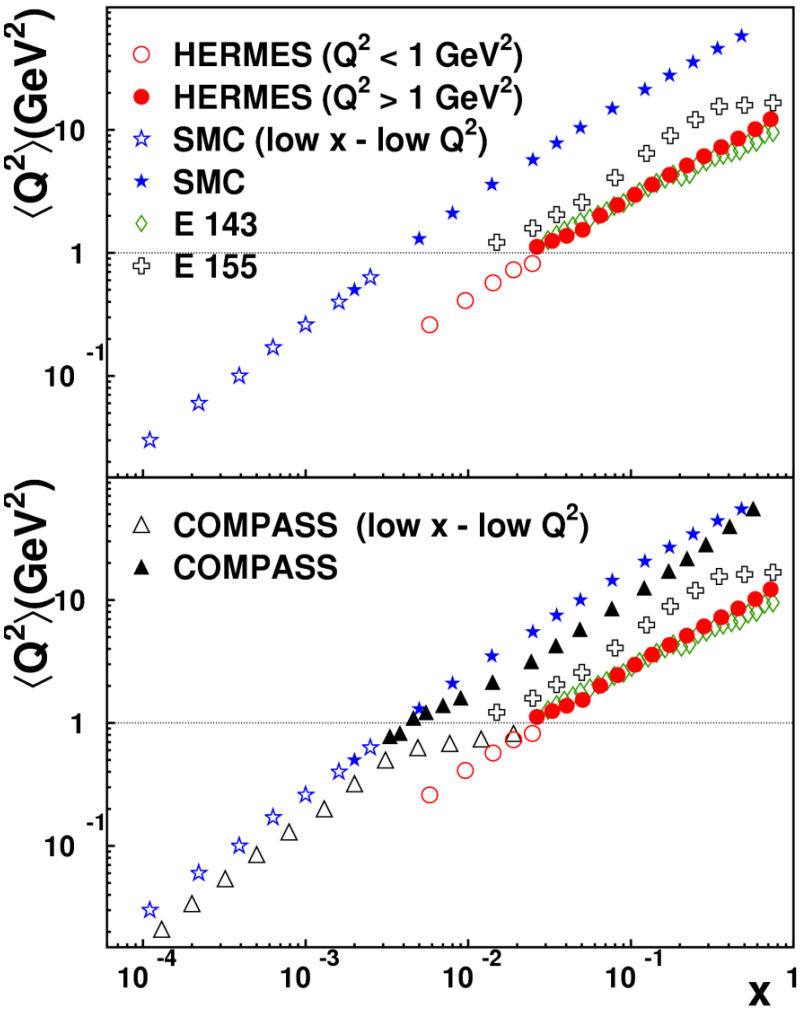
proton

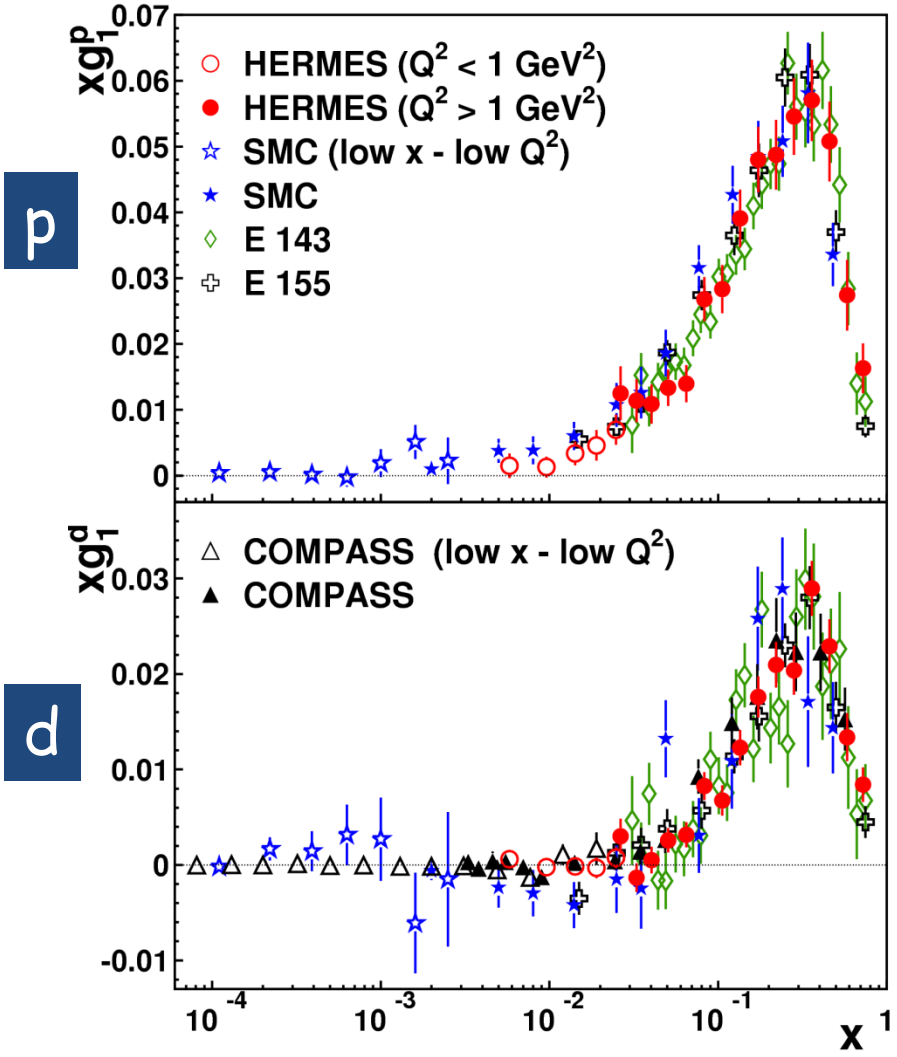
$g_1(x,Q^2)$



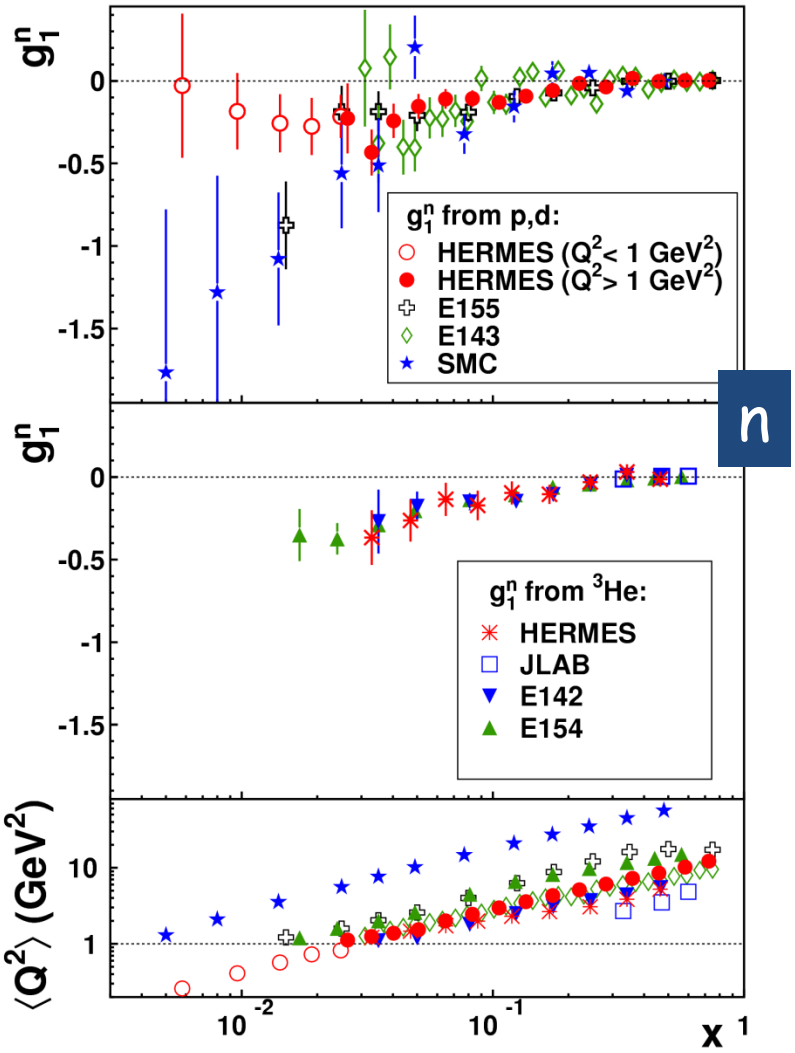


World data on $xg_1(x,Q^2)$





World data on neutron g_1



n

from p and d

$$g_1^n = \frac{2}{1 - \frac{3}{2}\omega_D} g_1^d - g_1^p$$

from ^{3}He

Scaling violations: QCD fits

NLO DGLAP:

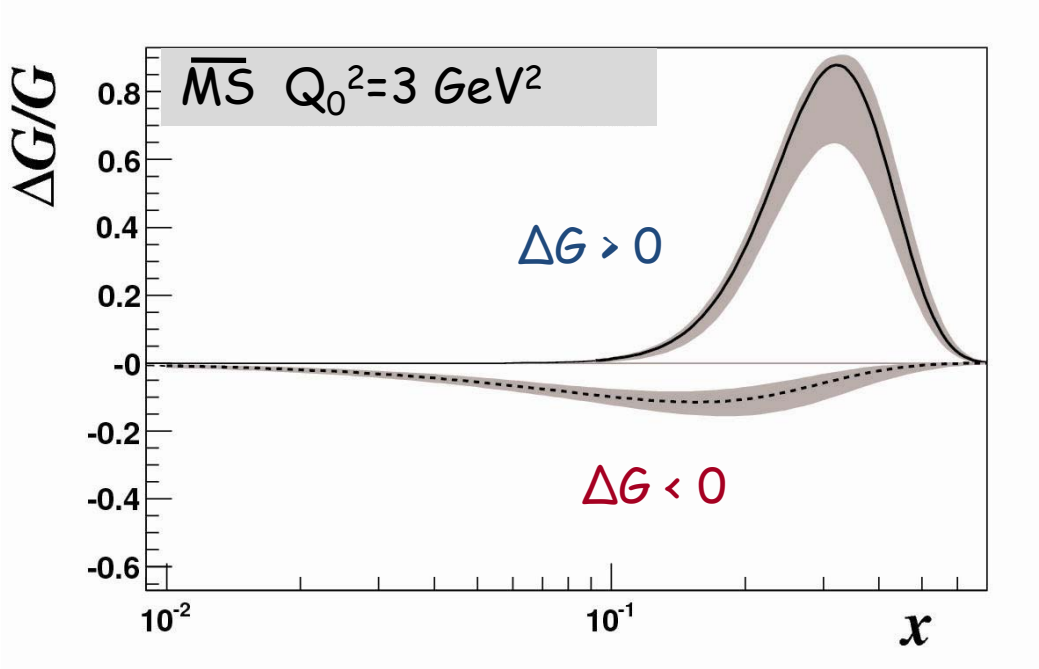
$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\Delta q^{\mathrm{ns}} = \Delta\mathcal{P}^{\mathrm{ns}}_{qq} \otimes \Delta q^{\mathrm{ns}}$$

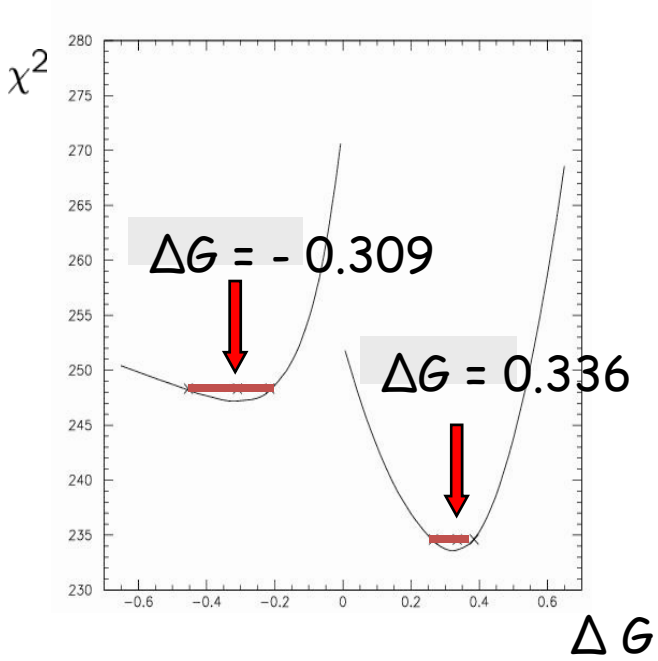
$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\begin{pmatrix} \Delta q^{\mathrm{s}} \\ \Delta g \end{pmatrix} = \begin{pmatrix} \Delta\mathcal{P}^{\mathrm{s}}_{qq} & \Delta\mathcal{P}^{\mathrm{s}}_{qg} \\ \Delta\mathcal{P}^{\mathrm{s}}_{gq} & \Delta\mathcal{P}^{\mathrm{s}}_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Delta q^{\mathrm{s}} \\ \Delta g \end{pmatrix}$$

- choose scheme ($\overline{\mathrm{MS}}$, AB, jet) and Q_0^2
- optionally fix ns moments from hyperon decays (a_3, a_8)
- fit PDFs for quark non-singlet and singlet and gluon to g_1 data
- functional form of PDFs biases error band
- extra problems in polarized case:
  - no positivity condition, no momentum sum rule
- higher twist, …

COMPASS QCD Fit

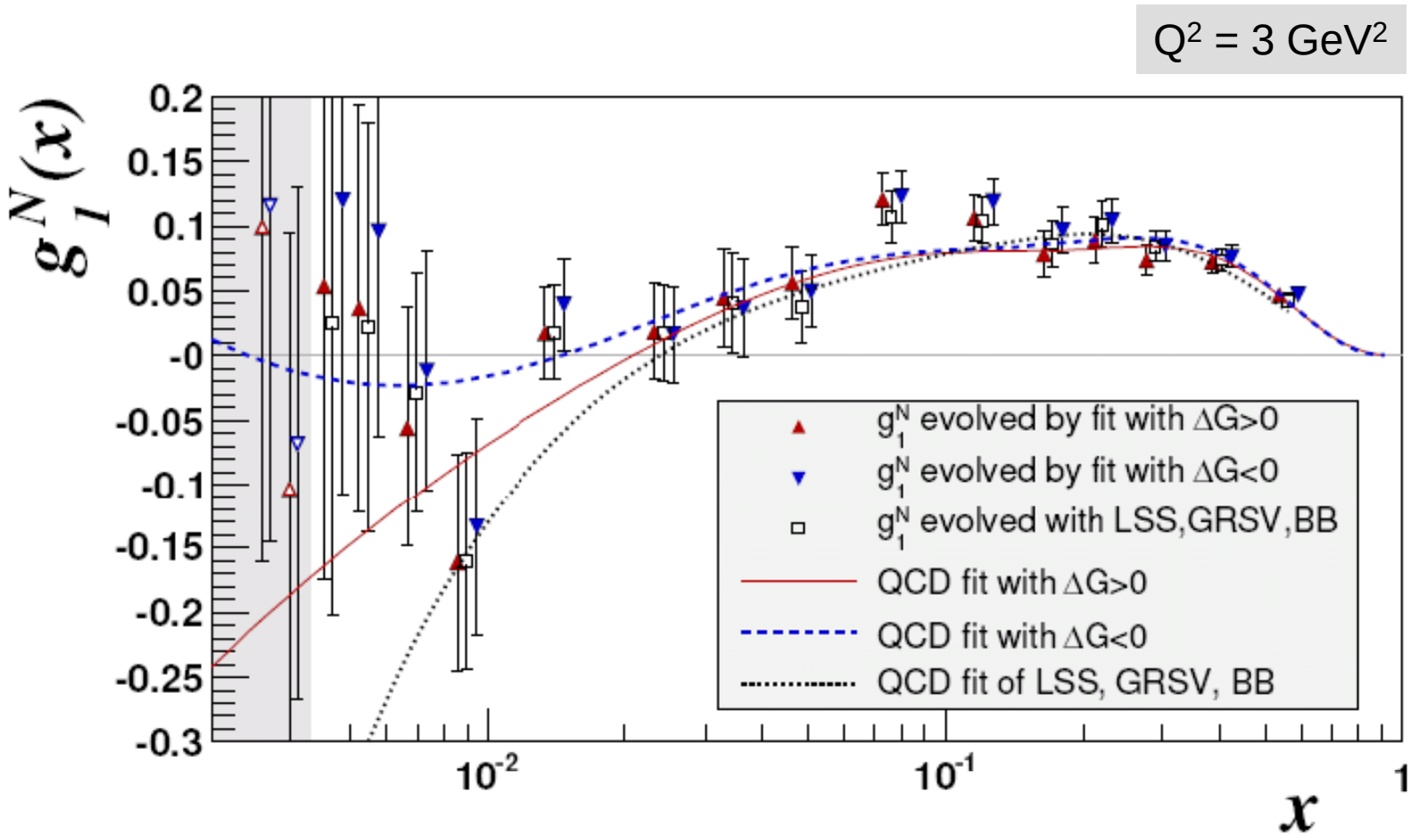
- two solutions with $\Delta G > 0$ and $\Delta G < 0$
- uncertainty due to parametrization not included





PLB 647 (2007) 8-17

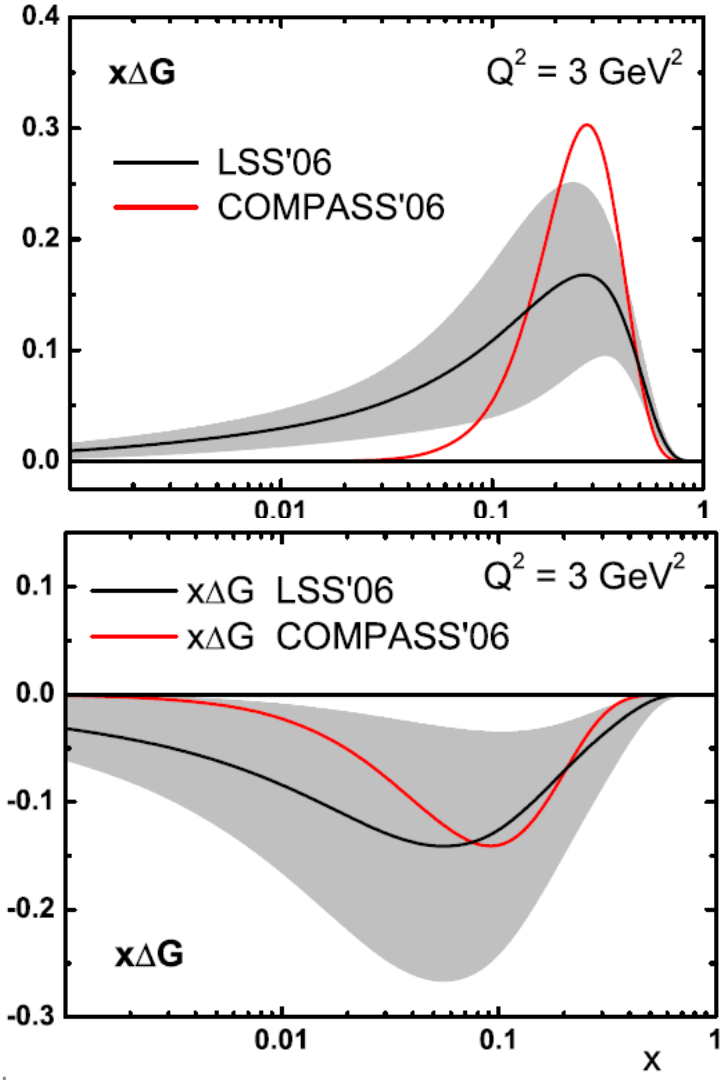
COMPASS deuteron g_1



QCD Fit: LSS06 / COMPASS06

- LSS06 also finds two solutions with small $\Delta G > 0$ and $\Delta G < 0$
- includes HT and Clas data

- How to tell sign of ΔG?



$\Delta G > 0$

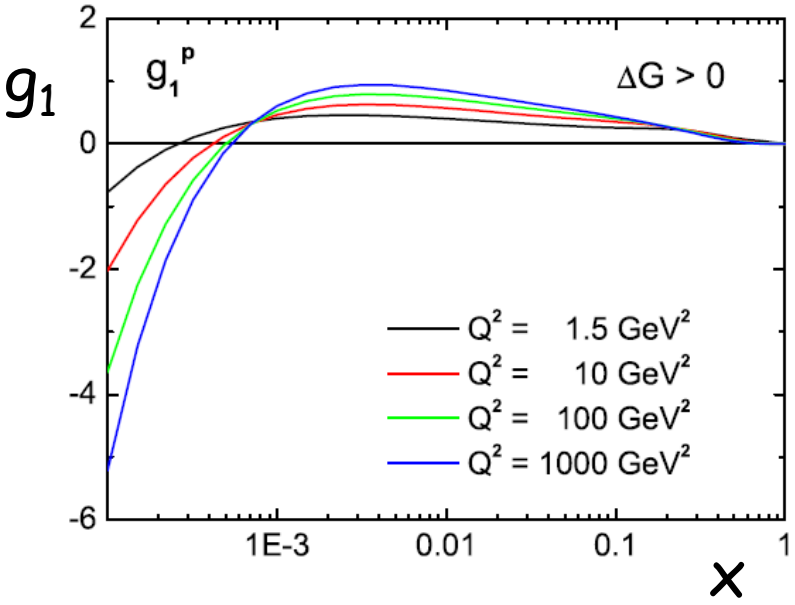
$\Delta G < 0$

Sign of ΔG and low g_1 at small x

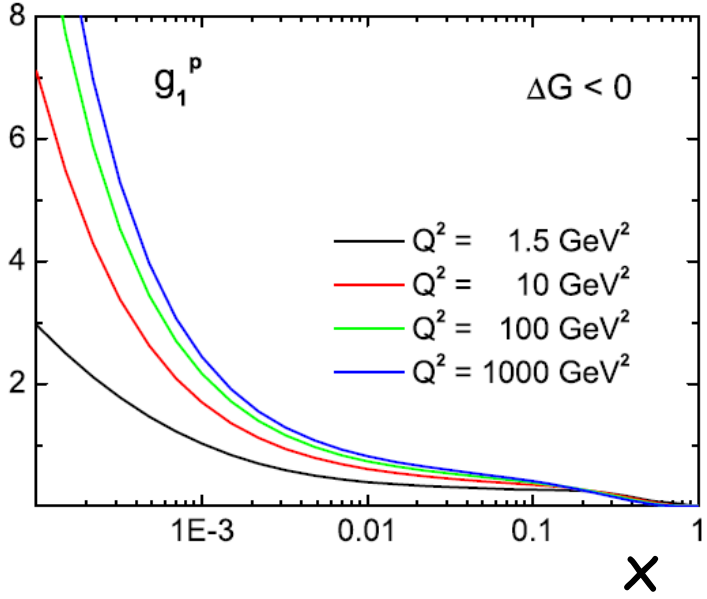
$\Delta G > 0$

$\Delta G < 0$

LSS06



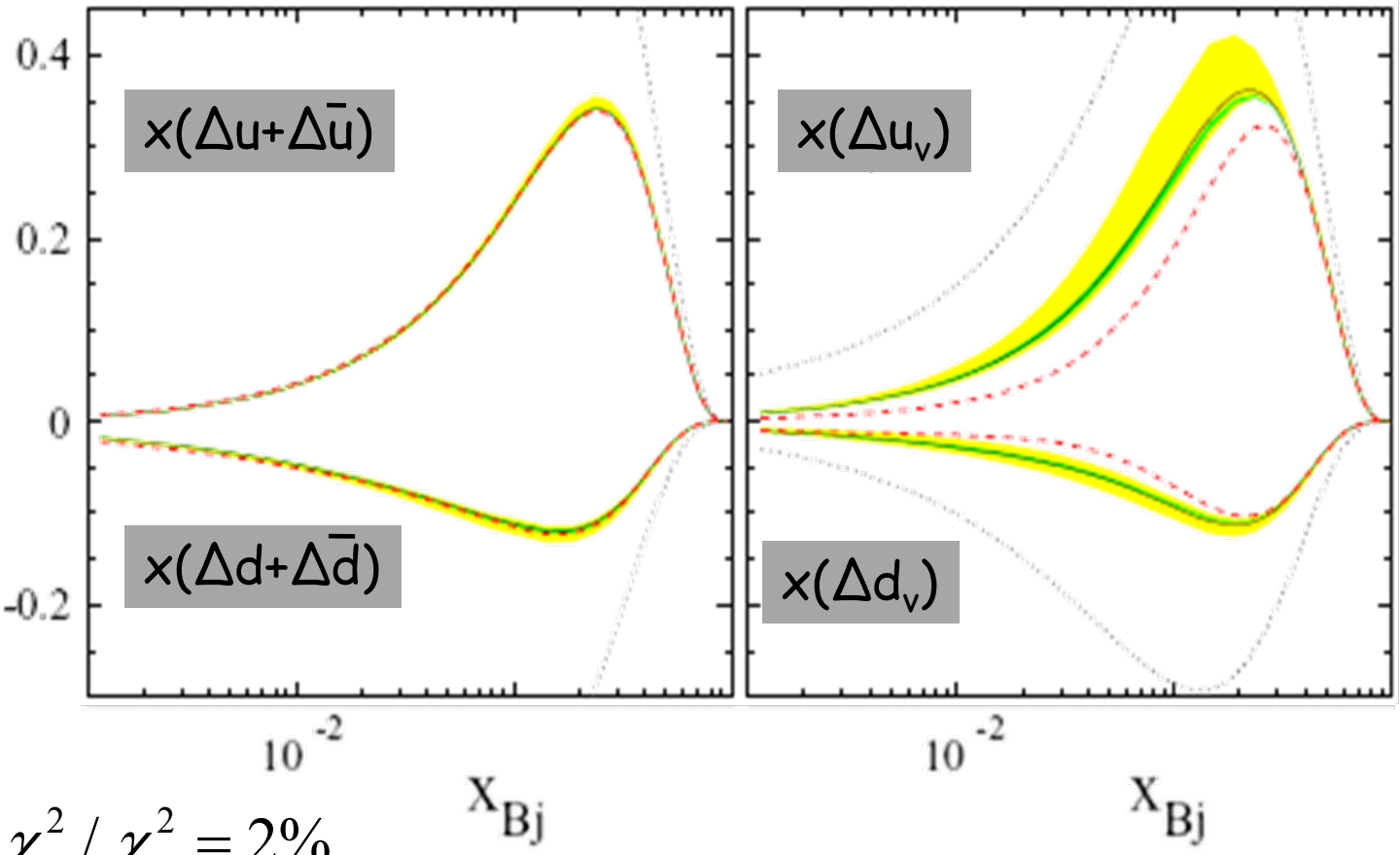
p



Leader, DIS2008

measurable at a polarized ep collider (EIC)

QCD Fit: DNS05/DSSV08



$\Delta\chi^2 / \chi^2 = 2\%$

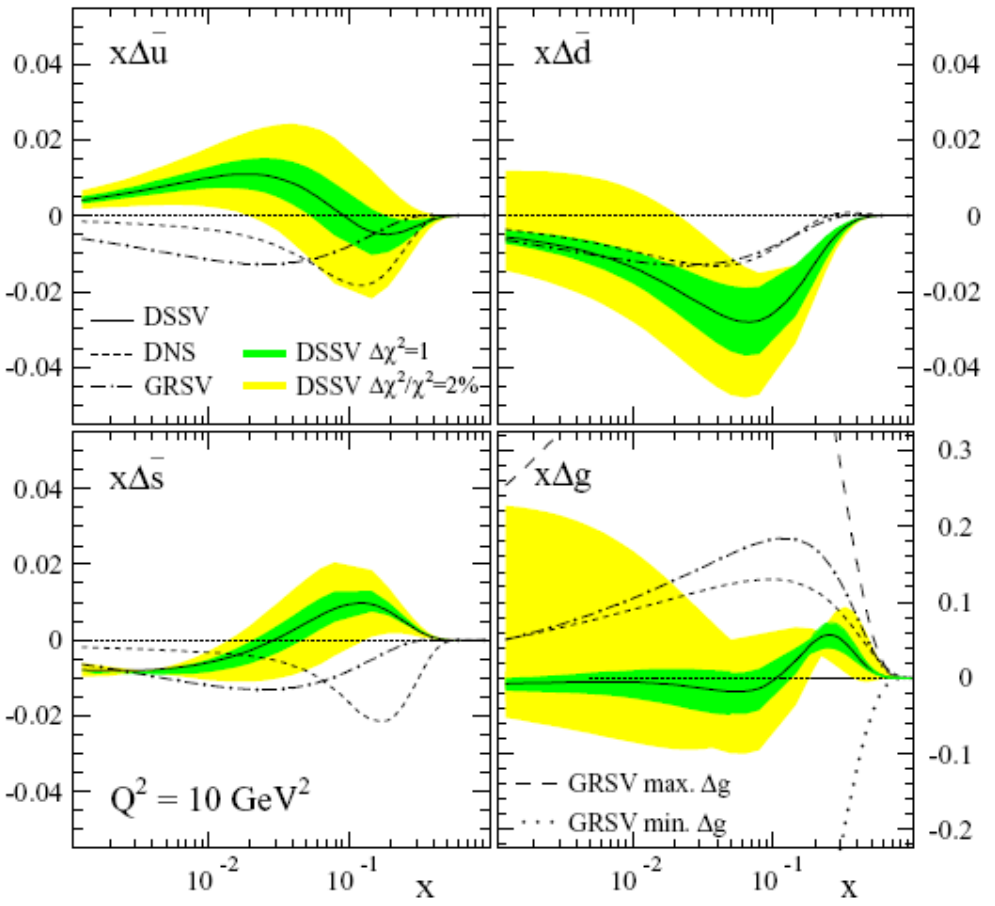
$\Delta\chi^2 = 1$

Q^2=10 GeV^2

de Florian,Navarro, Sassot PRD71:094018

QCD Fit: DSSV08

- include semi-inclusive data
- includes pp data from Phenix and Star
- Δg might have a node
- $\Delta s < 0$ for $x < 0.02$
  $\Delta s > 0$ for $x < 0.02$
  forced by HERMES semi-inclusive data



de Florian, Sassot, Stratmann, Vogelsang
PRL101:072001

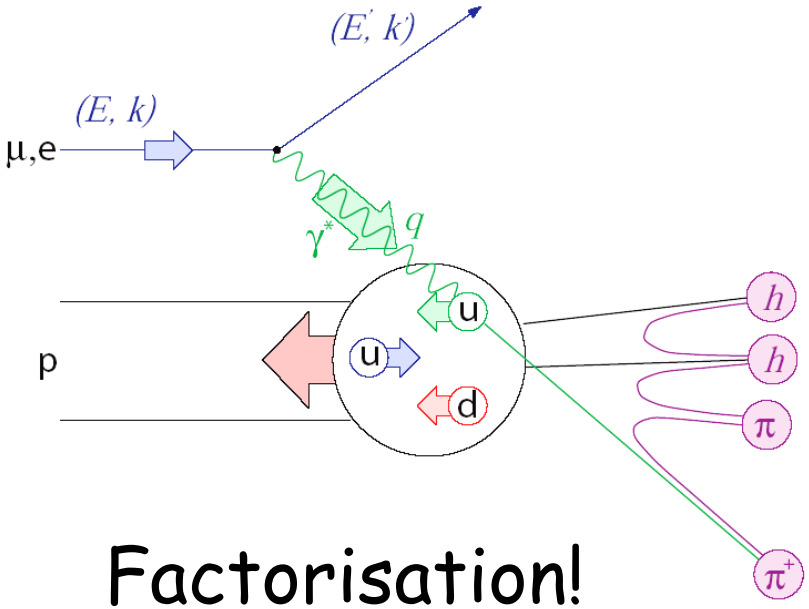
DSSV08

	$x_{\min} = 0$	$x_{\min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

at $Q^2 = 10\ GeV^2$

de Florian, Sassot, Stratmann, Vogelsang
PRL101:07200.

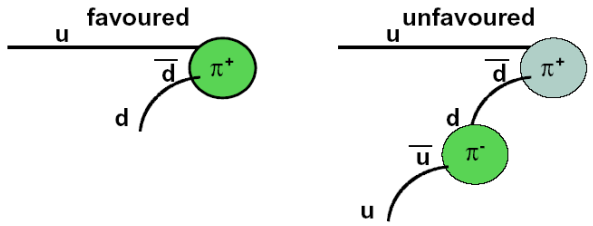
Semi-inclusive DIS



Factorisation!

D_q^h from quark q into hadron h

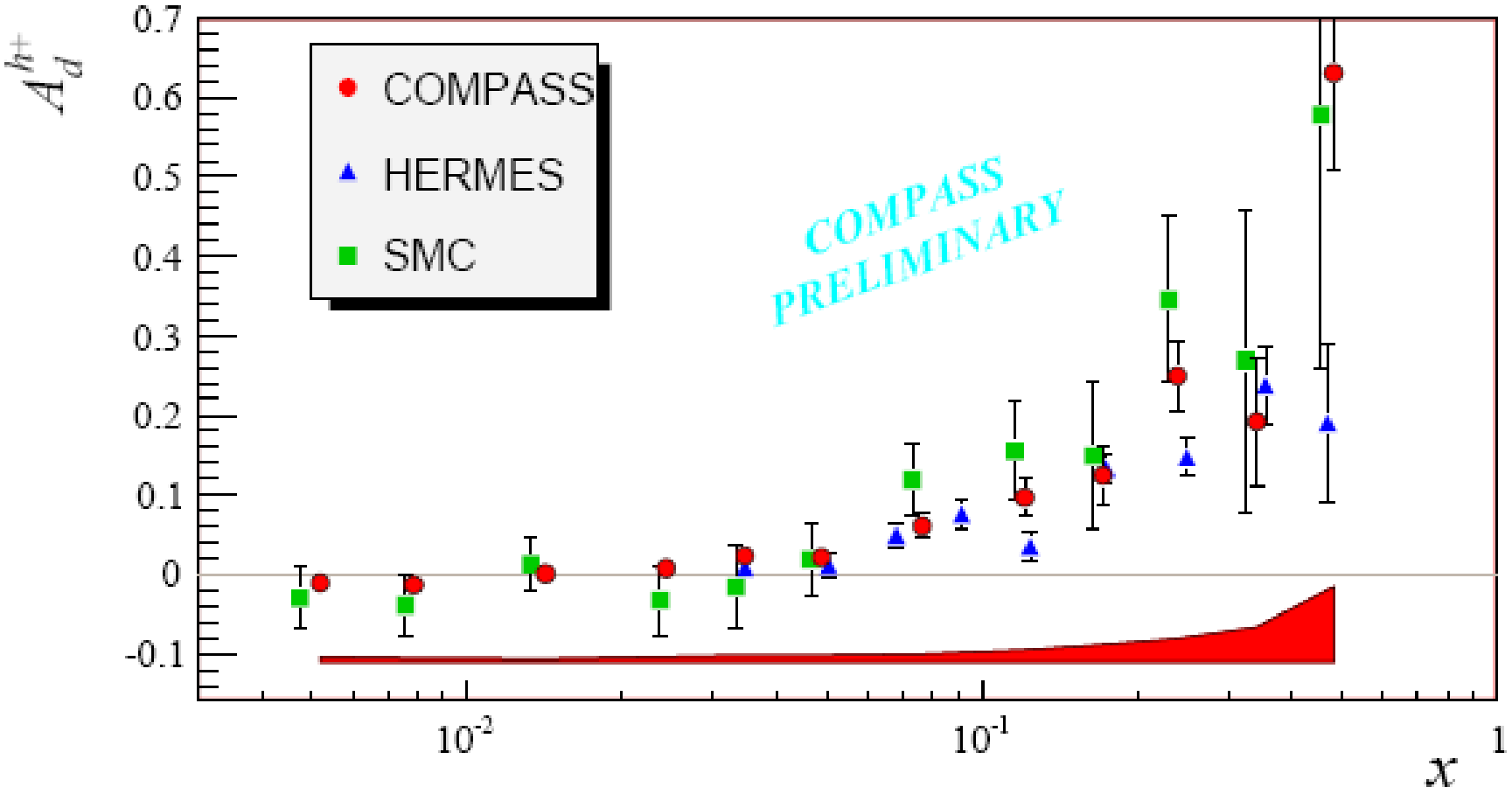
$z = \frac{E_h}{\nu}$ energy fraction carried by h



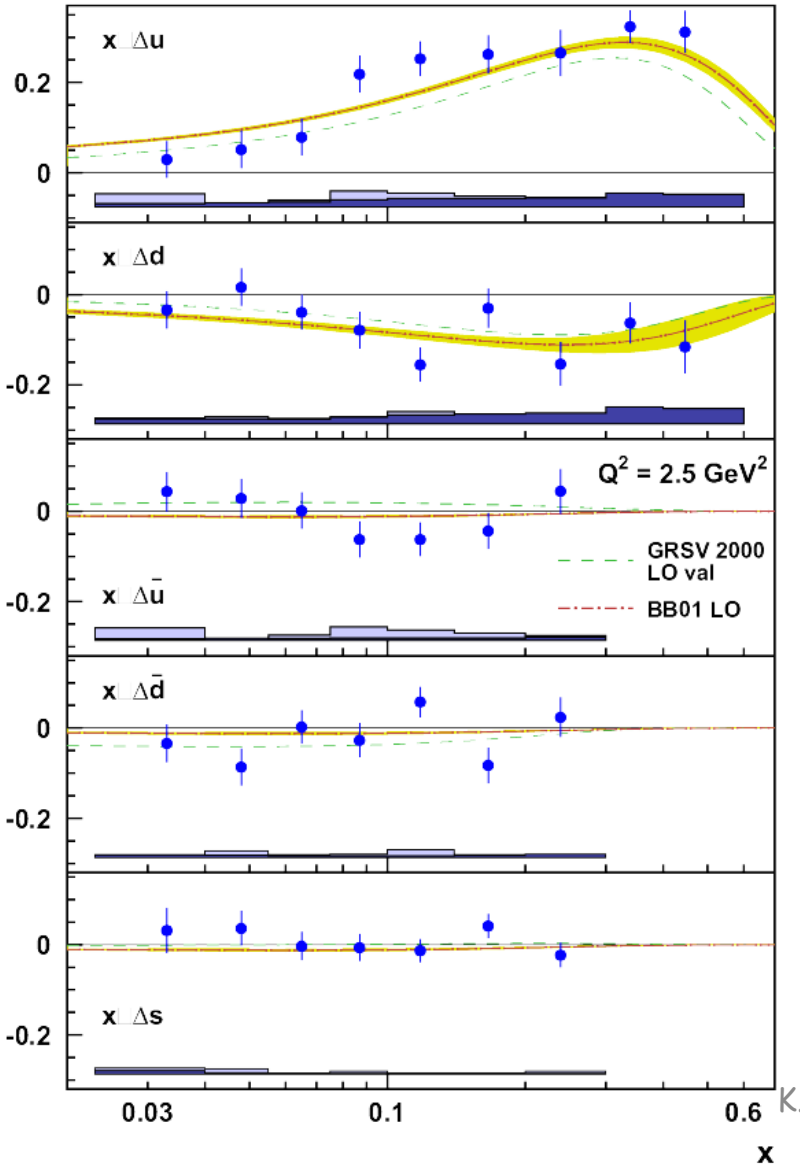
$$D_u^{\pi^+} = D_{\bar{u}}^{\pi^-} \underset{\text{CC}}{=} D_{\bar{d}}^{\pi^+} = D_d^{\pi^-} \qquad D_d^{\pi^+} = D_{\bar{d}}^{\pi^-} \underset{\text{IS}}{=} D_{\bar{u}}^{\pi^+} = D_u^{\pi^-}$$

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

Semi-inclusive asymmetries



Flavour separated polarization



Asymmetries can in LO be related to Δq by

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

where

$$\vec{\mathcal{A}} = (A_{1,t}^{h}, \ldots)$$
$$\vec{\mathcal{Q}} = (\Delta q_f, \ldots)$$

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

Alternative: difference asymmetries

Semi-inclusive asymmetries

$$A^+ = \frac{\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h+}_{\uparrow\uparrow}}{\sigma^{h+}_{\uparrow\downarrow} + \sigma^{h+}_{\uparrow\uparrow}} \qquad A^- = \frac{\sigma^{h-}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\uparrow}}{\sigma^{h-}_{\uparrow\downarrow} + \sigma^{h-}_{\uparrow\uparrow}}$$

$$A_1^h(x) = \frac{\sum_q e_q^2(\Delta q(x) D_q^h + \Delta\bar{q}(x) D_{\bar{q}}^h)}{\sum_q e_q^2(q(x) D_q^h + \bar{q}(x) D_{\bar{q}}^h)}$$

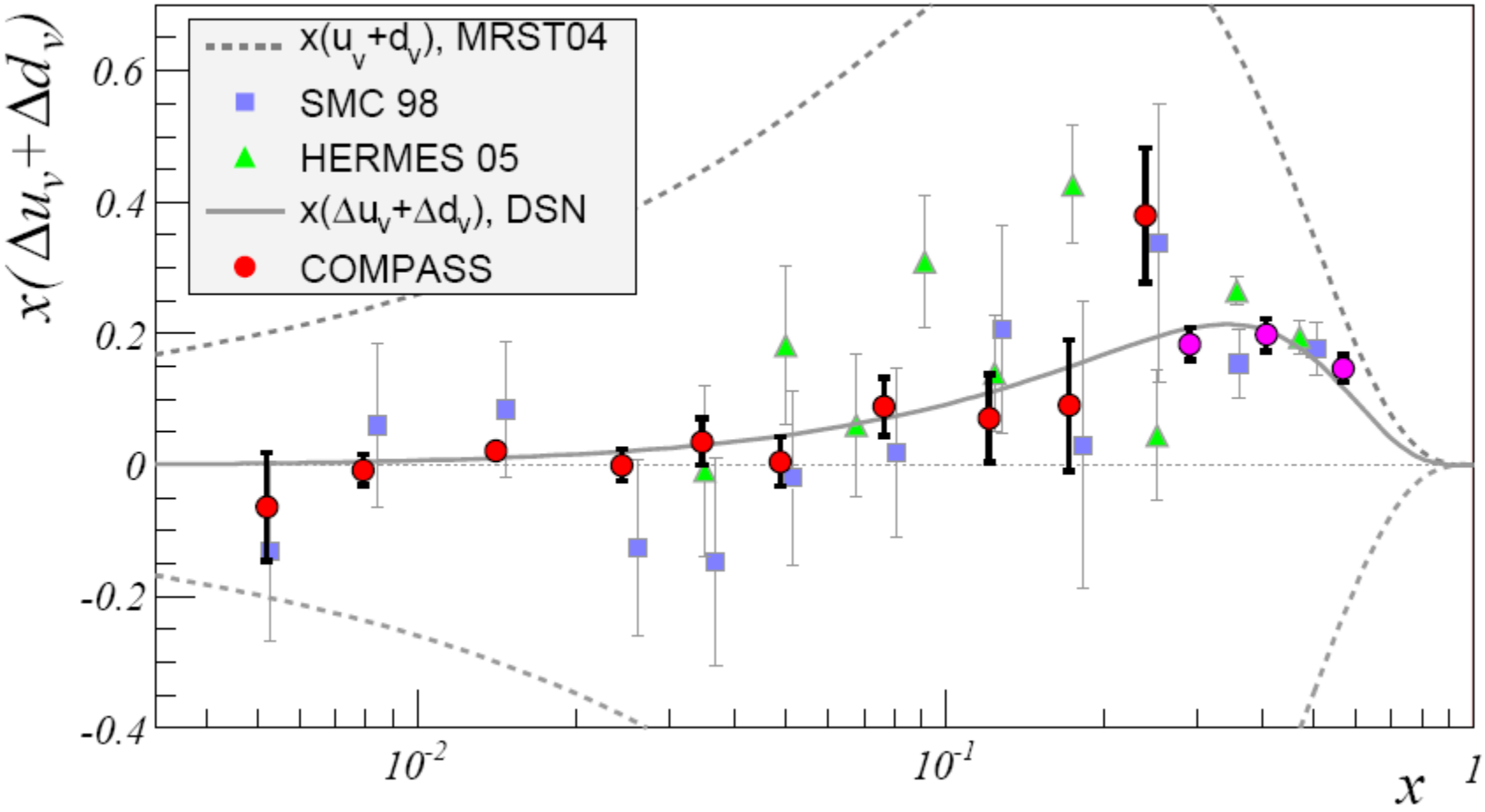
Difference asymmetry

$$A^{+-} = \frac{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) - (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) + (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}$$

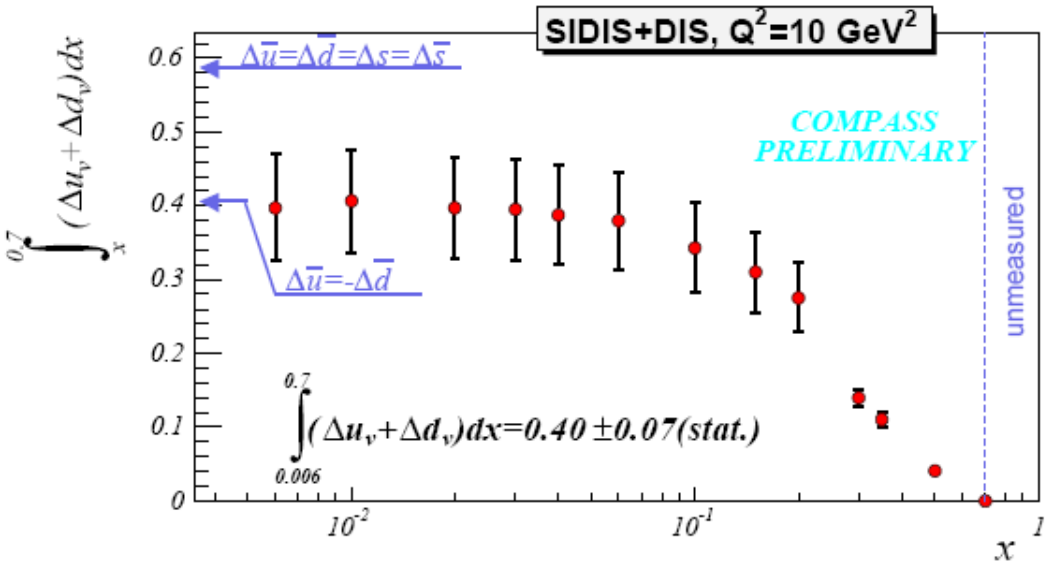
$$A_d^{\pi^+-\pi^-}(x) = A_d^{K^+-K^-}(x) = \frac{\Delta u_v(x) + \Delta d_v(x)}{u_v(x) + d_v(x)}$$

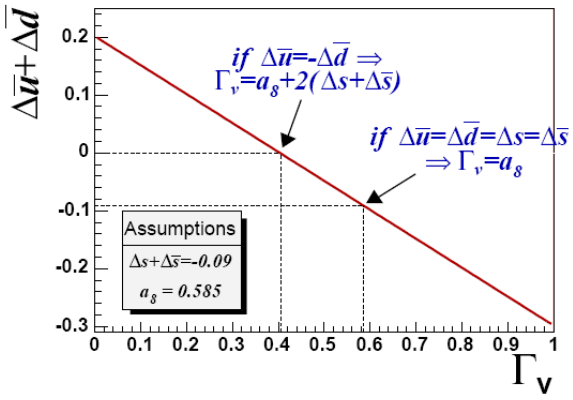
Valence quark polarisation without fragmentations function

Valence polarization



Valence quark polarisation



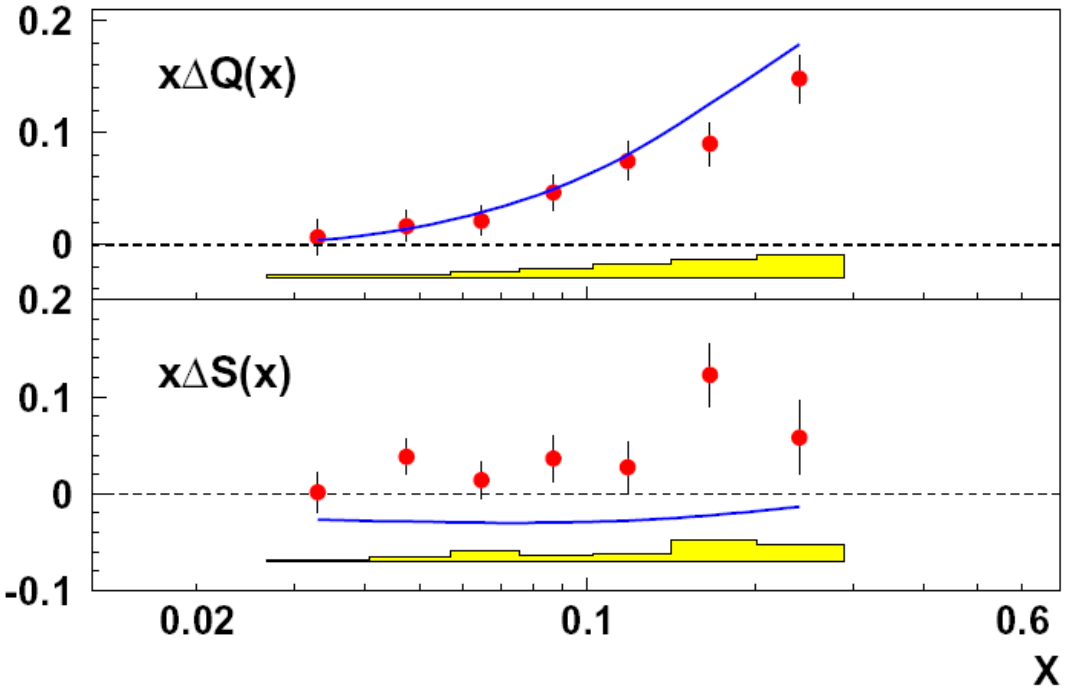


	x-range	Q^2 GeV^2	$\Delta u_v+\Delta d_v$ measurem.	$\Delta u_v+\Delta d_v$ DNS	$\Delta\bar{u}+\Delta\bar{d}$ measurem.	$\Delta\bar{u}+\Delta\bar{d}$ DNS
SMC 98	0.003–0.7	10	$0.26\pm0.21\pm0.11$	0.386	$0.02\pm0.08\pm0.06$	−0.009
HERMES 05	0.023–0.6	2.5	$0.43\pm0.07\pm0.06$	0.363	$-0.06\pm0.04\pm0.03$	−0.005
COMPASS	0.006–0.7	10	$0.40\pm0.07\pm0.05$	0.385	$0.0\pm0.04\pm0.03$	−0.007

Strange quark sea

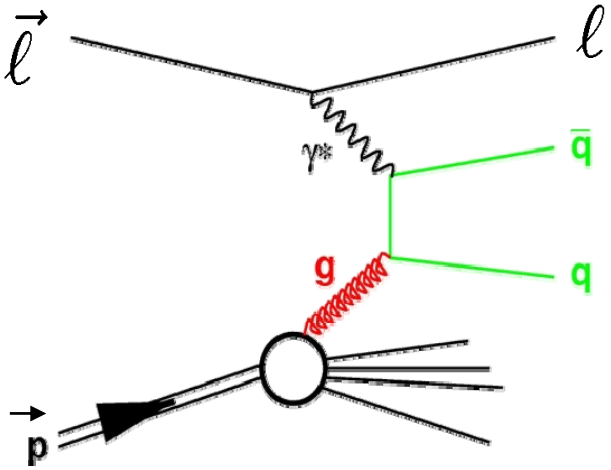
- semi-inclusive data incl. kaon $A_{\parallel,d}^{K\pm}(x)$
- $\Delta Q = \Delta q + \Delta\bar{q}$
- $\Delta S = 0.037 \pm 0.019 \pm 0.027$
- $\Delta S < 0$ expected from incl. data
- results from COMPASS at Spin 2008

$Q^2 = 2.5\ GeV^2$



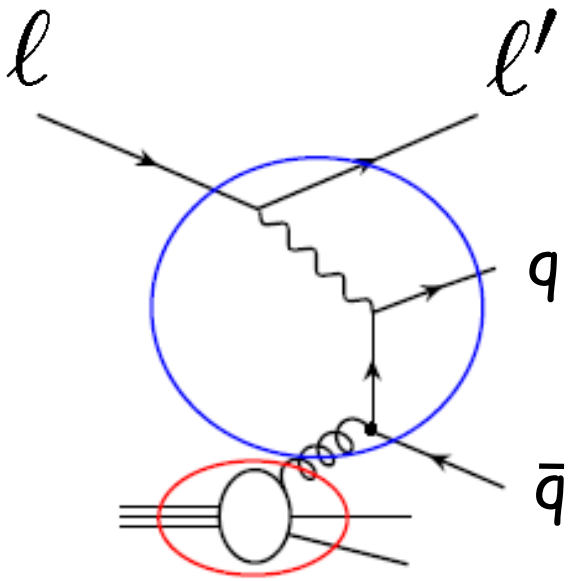
$\Delta g/g$ from hadron production

Photon-gluon fusion



Hadron production in DIS via PGF

Principle: Gluon polarization enters via photon-gluon fusion (PGF)



$$A_{\parallel} = R_{pgf} \langle \hat{a}_{pdf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle$$

- measure $A_{\parallel}$
- calculate R_{pgf}, $\langle \hat{a}_{pgf} \rangle$ and background by Monte Carlo

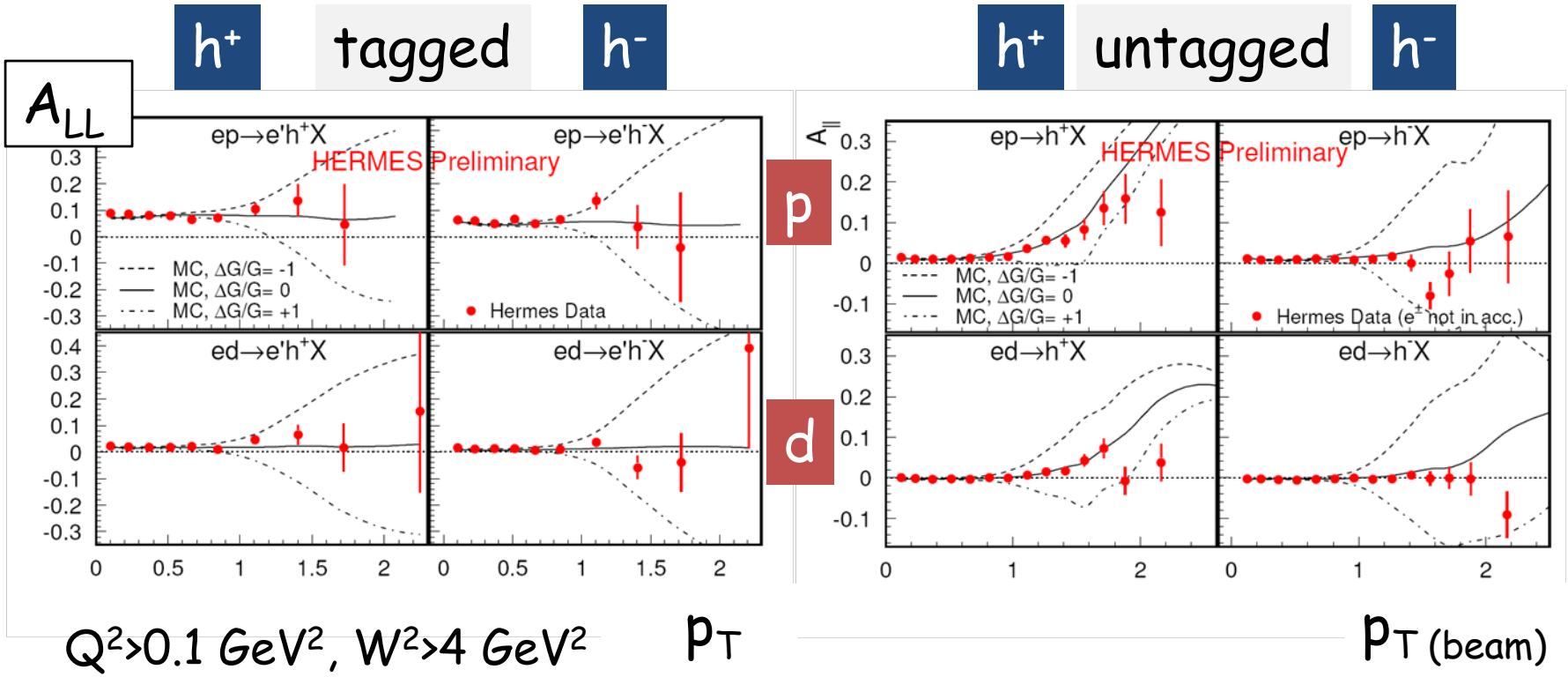
Analyzed channels for $\Delta g/g$

analysed data sets:

- high-p_T hadron pairs (no ID, pions/kaons)
  - $Q^2 > 1\ GeV^2$ — LEPTO
  - $Q^2 < 1\ GeV^2$ or unmeasured "untagged" — PYTHIA
- high-p_T single hadron
  - small Q^2 or unmeasured "untagged" — PYTHIA
- single charmed meson
  - quasi-real photons — AROMA, RAPGAP

All analyses in LO till now (plus parton showers)

A_{LL} for single hadrons



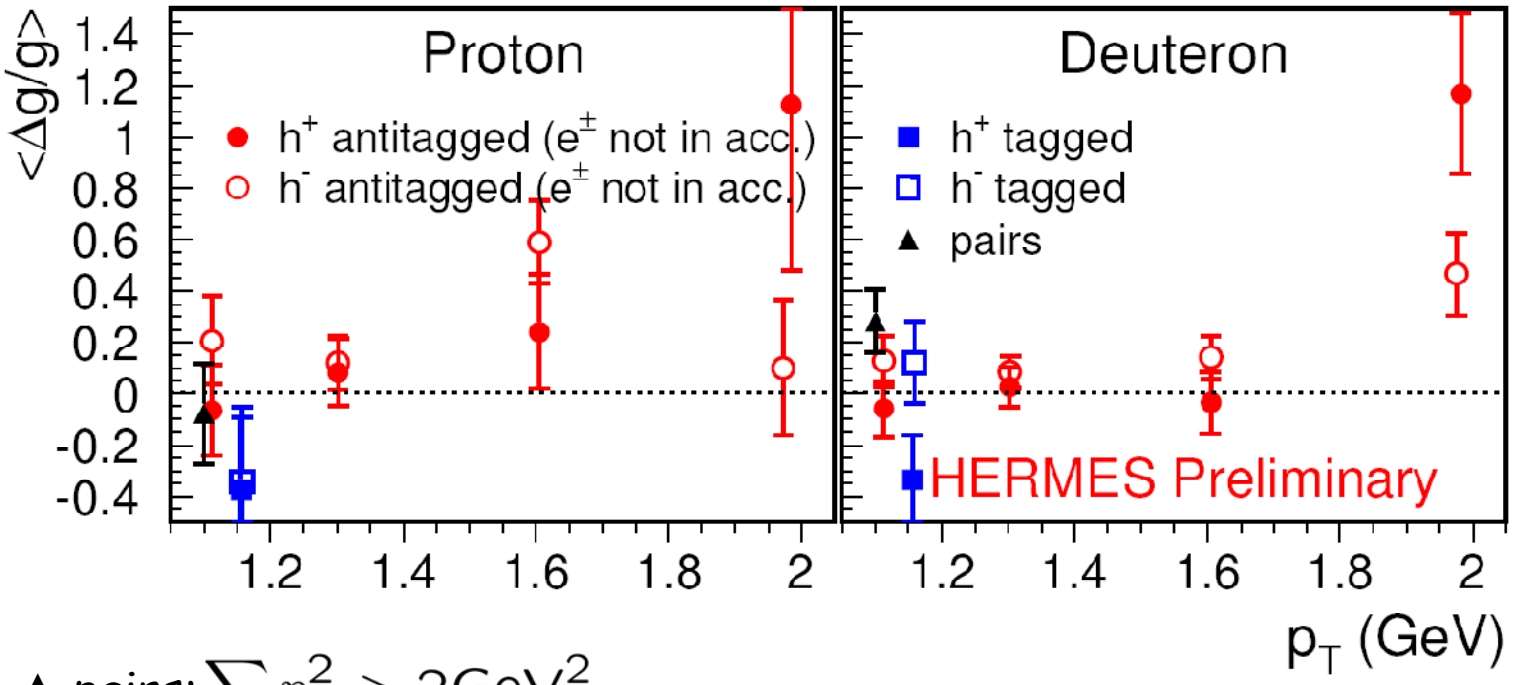
MC plus asymmetry model with $\Delta g/g(x) = -1, 0, 1$ for upper, middle and lower curve

Direct Method (I)

$$\left\langle \frac{\Delta g}{g} \right\rangle = \frac{1}{R_{sig}\langle \hat{a} \rangle} \left\{ A_{\parallel}^{meas} - R_{bg} A_{bg} \right\}$$

from Monte Carlo

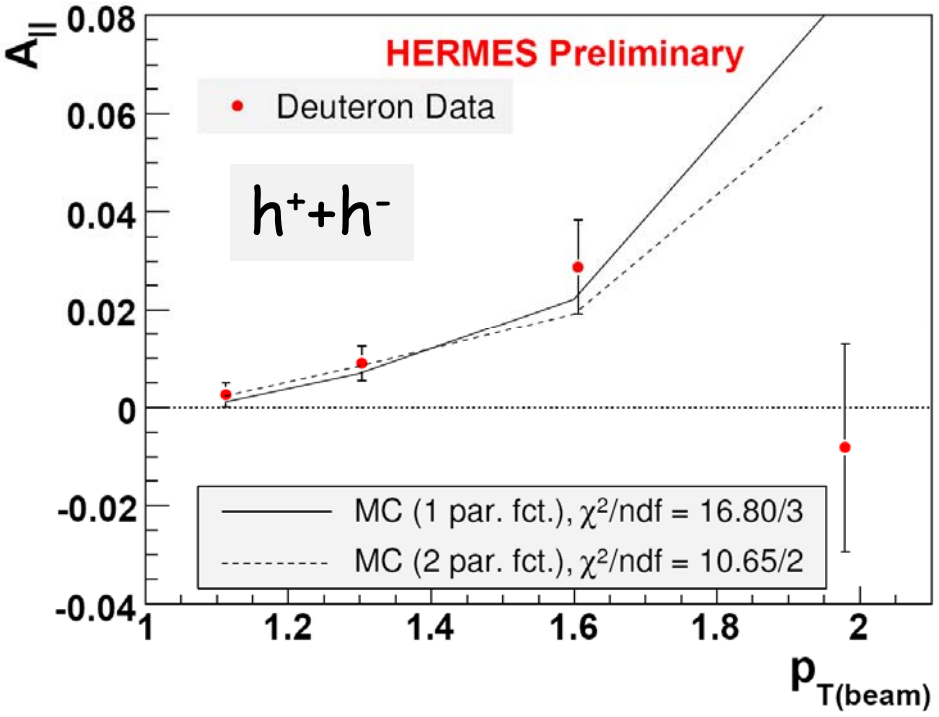
statistical errors only

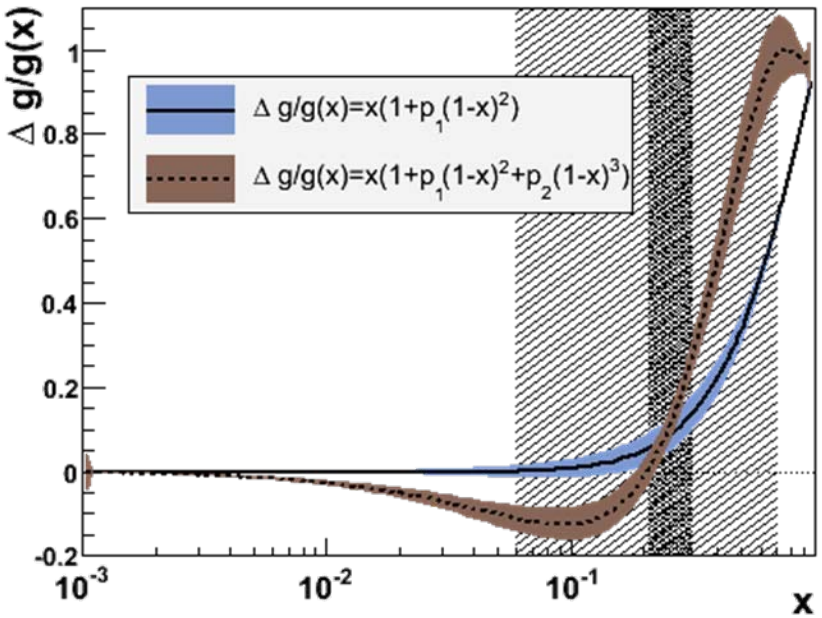


▲ pairs: $\sum p_T^2 > 2\text{GeV}^2$

Indirect Method (II)

Fit parameters of polynomial function to $A_{\parallel}$ using MC

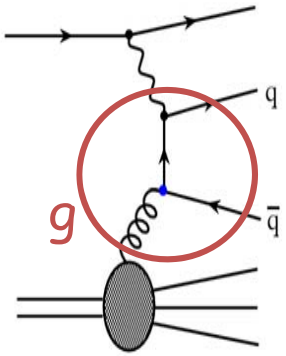




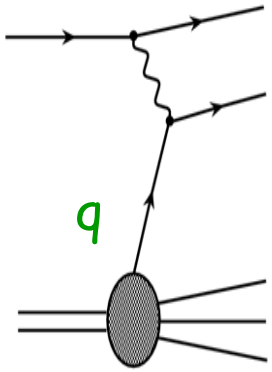
data

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

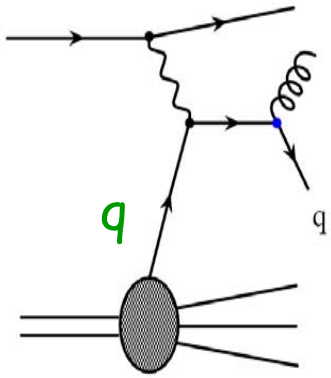
all Q^2



Photon Gluon Fusion ~ 30%



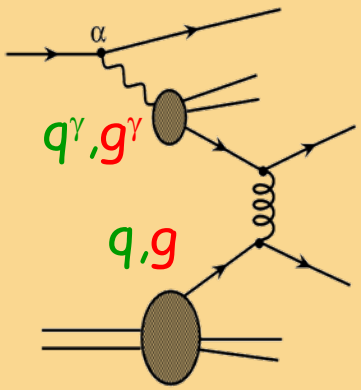
Leading Order



QCD Compton

+

$Q^2 < 1\ GeV^2$



Resolved γ ~50%

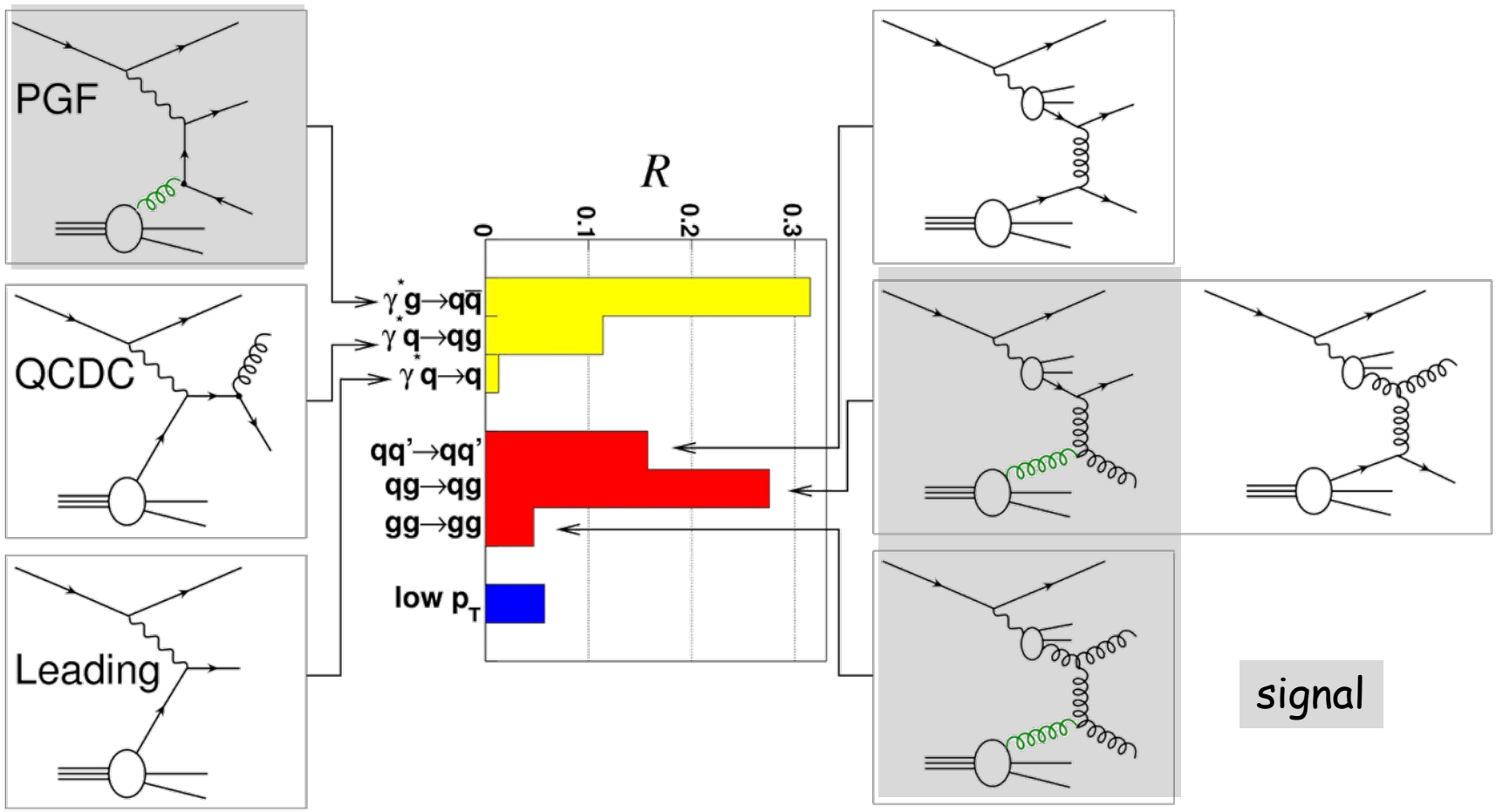
$$A_{LL}^{2h} = R_{pgf} a_{LL}^{pgf} \frac{\Delta g}{g}(x_g) + R_{LO} D A_1^{LO}(x_{Bj}) + R_C a_{LL}^C A_1^{LO}(x_C)$$

use also inclusive A_{LL}

High-p_T pairs, low Q^2

Ratios for hadron pairs with for $Q^2 < 1$

Resolved photons



High-p_T pairs, $Q^2 > 1$ GeV^2

$$A_{LL}^{2h} = R_{pgf} a_{LL}^{pgf} \frac{\Delta g}{g}(x_g) + R_{LO} D A_1^{LO}(x_{Bj}) + R_C a_{LL}^C A_1^{LO}(x_C)$$

- tune MC (Lepto) to reproduce data
- estimate relative fractions R on event-by-event basis using NN trained with MC events (kin. variables)
- use in NN output as event weight
- looser cuts possible
  - $Q^2 > 1$ GeV^2
  - $p_{T1,2} > 0.7$ GeV
  - $x_F > 0$, inv. mass 2h > 1.5 GeV^2

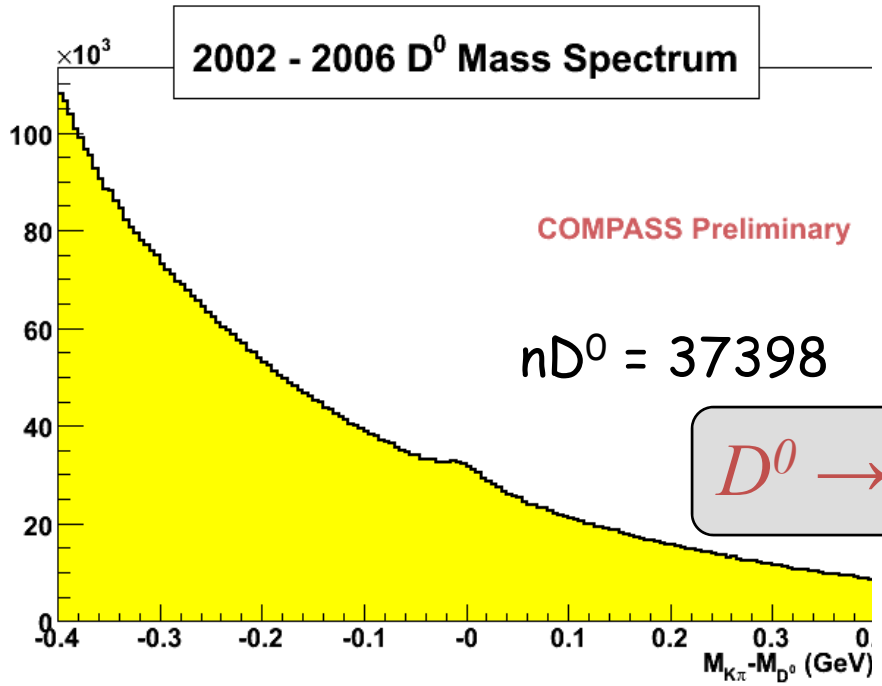
Δg/g from open charm

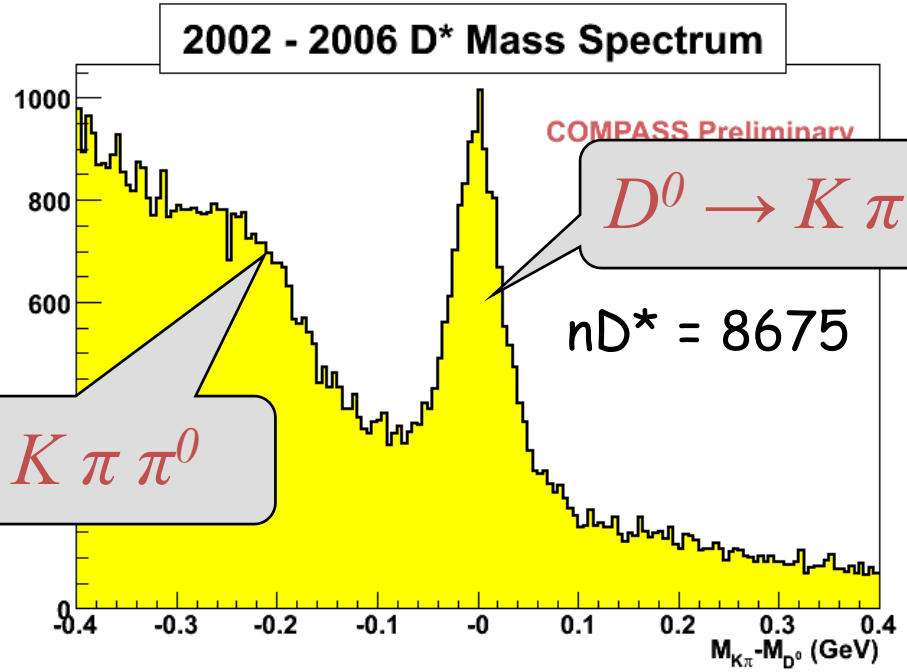
- cleanest process ("golden channel")
  - no or little physics background (LO, QCDC)
- observe asymmetry in D meson production
  - strongly statistics limited
  - only one D meson via $D \rightarrow \pi K$ (BR ~ 4%)
  - combinatorial background large
  - drastically reduced when looking to D* decay in coincidence with slow pion

$$D^* \rightarrow D^0 + \pi_S \rightarrow K + \pi + \pi_s$$

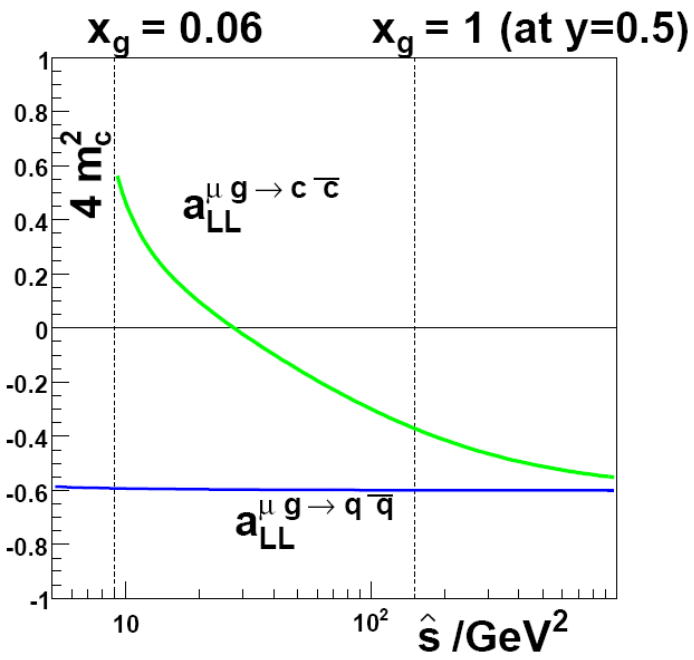
D mass spectra

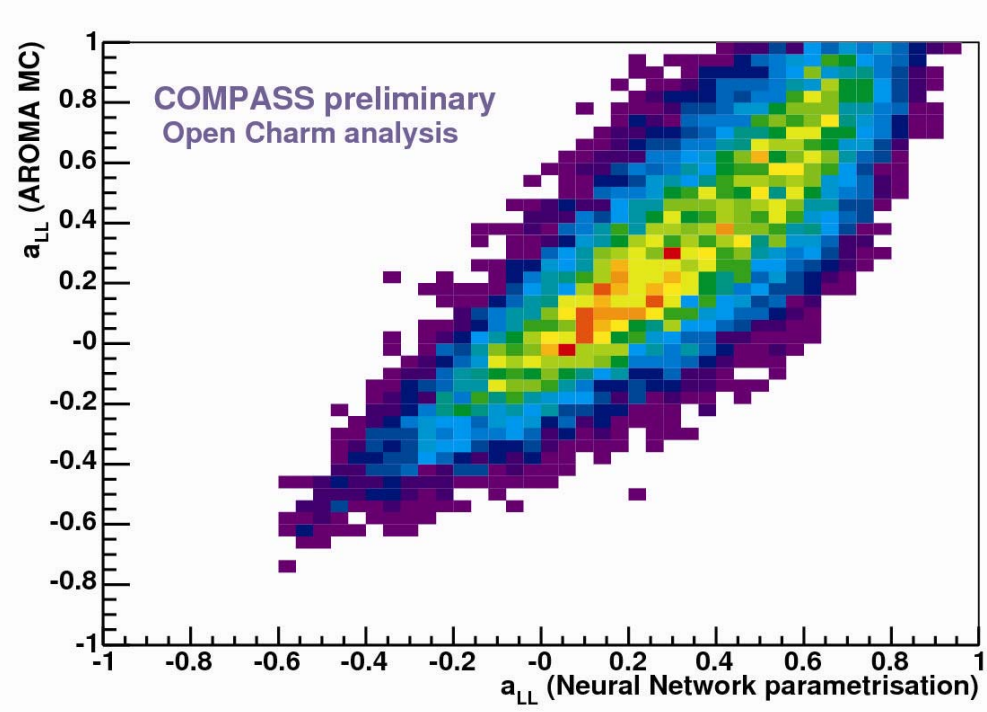
$$D^0 \to K + \pi \qquad D^* \to D^0 + \pi_s \to K + \pi + \pi_s$$



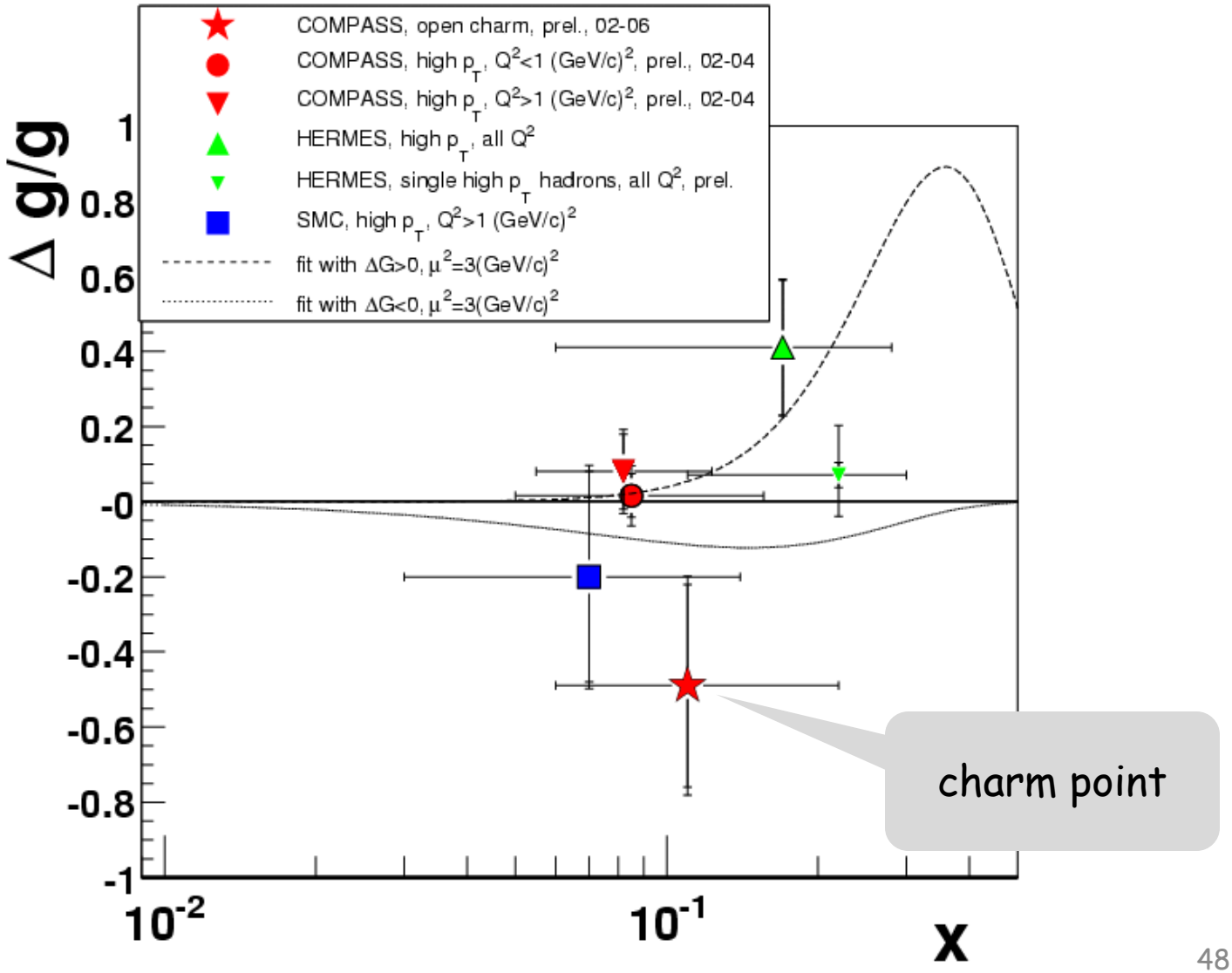


a_{LL} variation





Summary of results on Δg/g

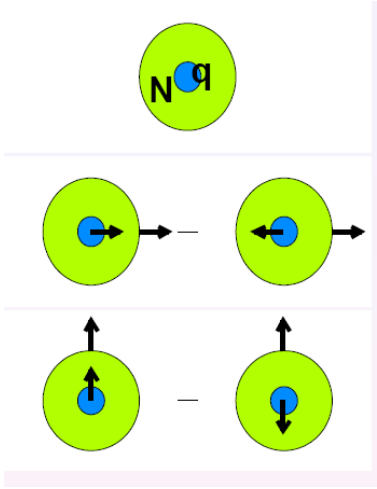


Transversity

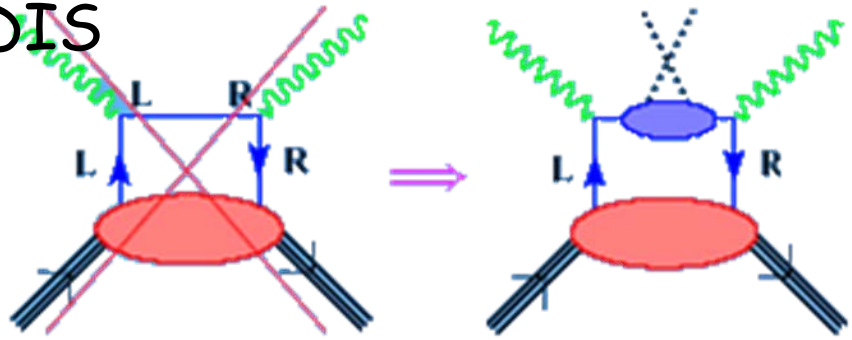
q, g — momentum

$\Delta q, \Delta g$ — helicity

$\Delta_T q$ — transversity (alias h_1)



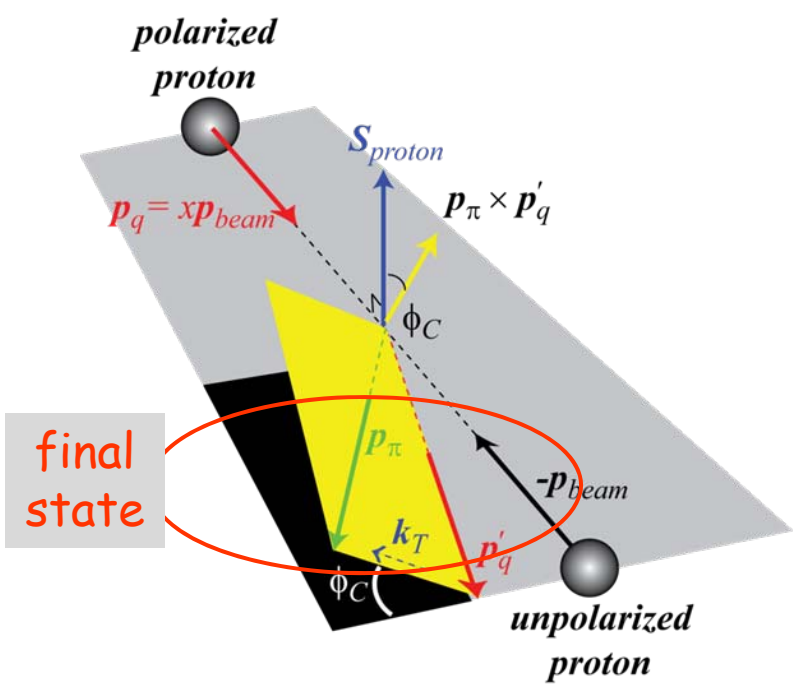
- 3 fundamental twist-2 PDFs, new transversity $\Delta_T q(x)$
- non-relativisic $\Delta_T q = g_1$
- chiral-odd PDF → not seen in DIS
- semi-inclusive DIS allowed if coupled to a chiral-odd FF
- Soffer bound: $2|\Delta_T q| \leq q + \Delta q$



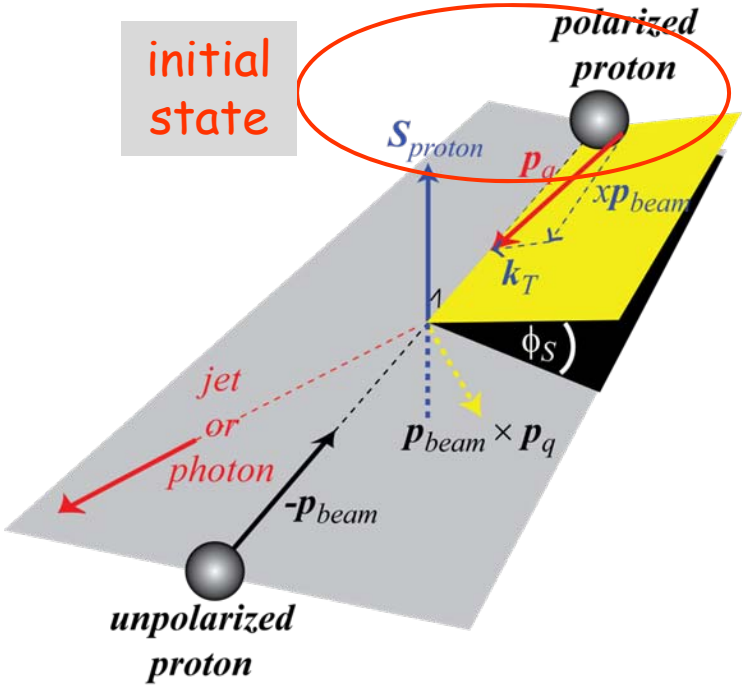
Origin of single-spin asymmetries

from L. Bland

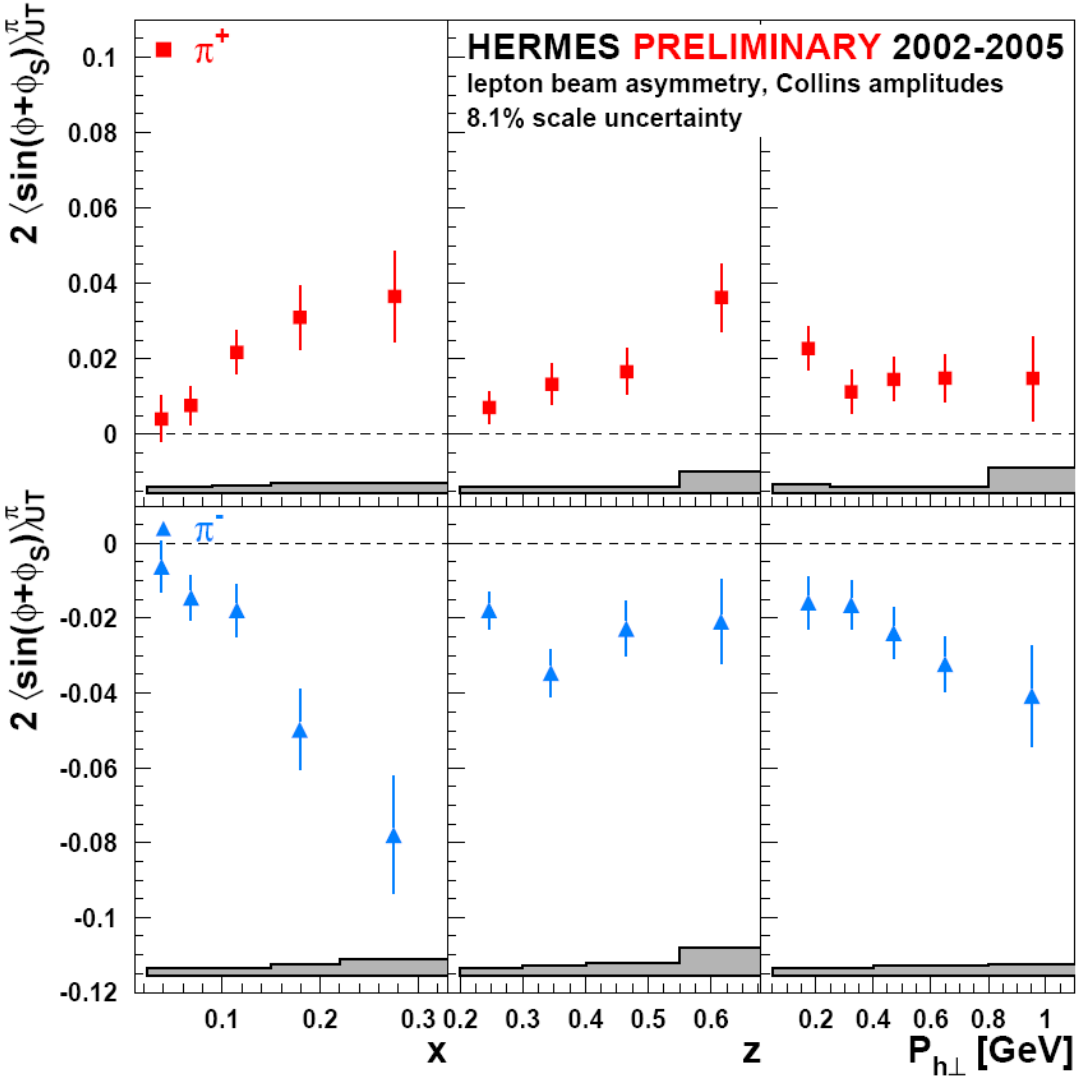
Collins/Heppelmann mechanism requires *transverse quark polarization* and *spin-dependent fragmentation*



Sivers mechanism requires *spin-correlated transverse momentum* k_T in the proton (orbital motion).

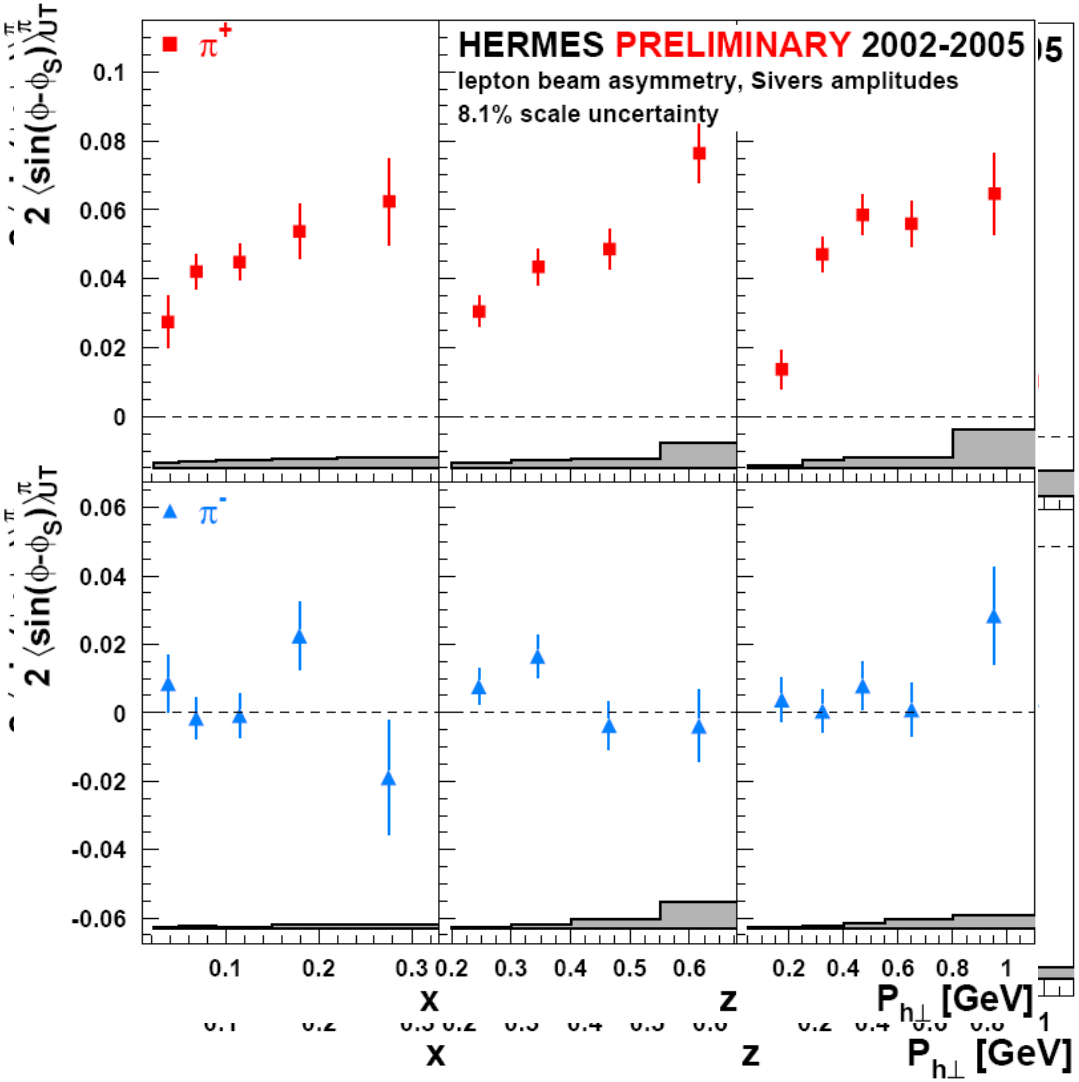


Collins asymmetry (proton)



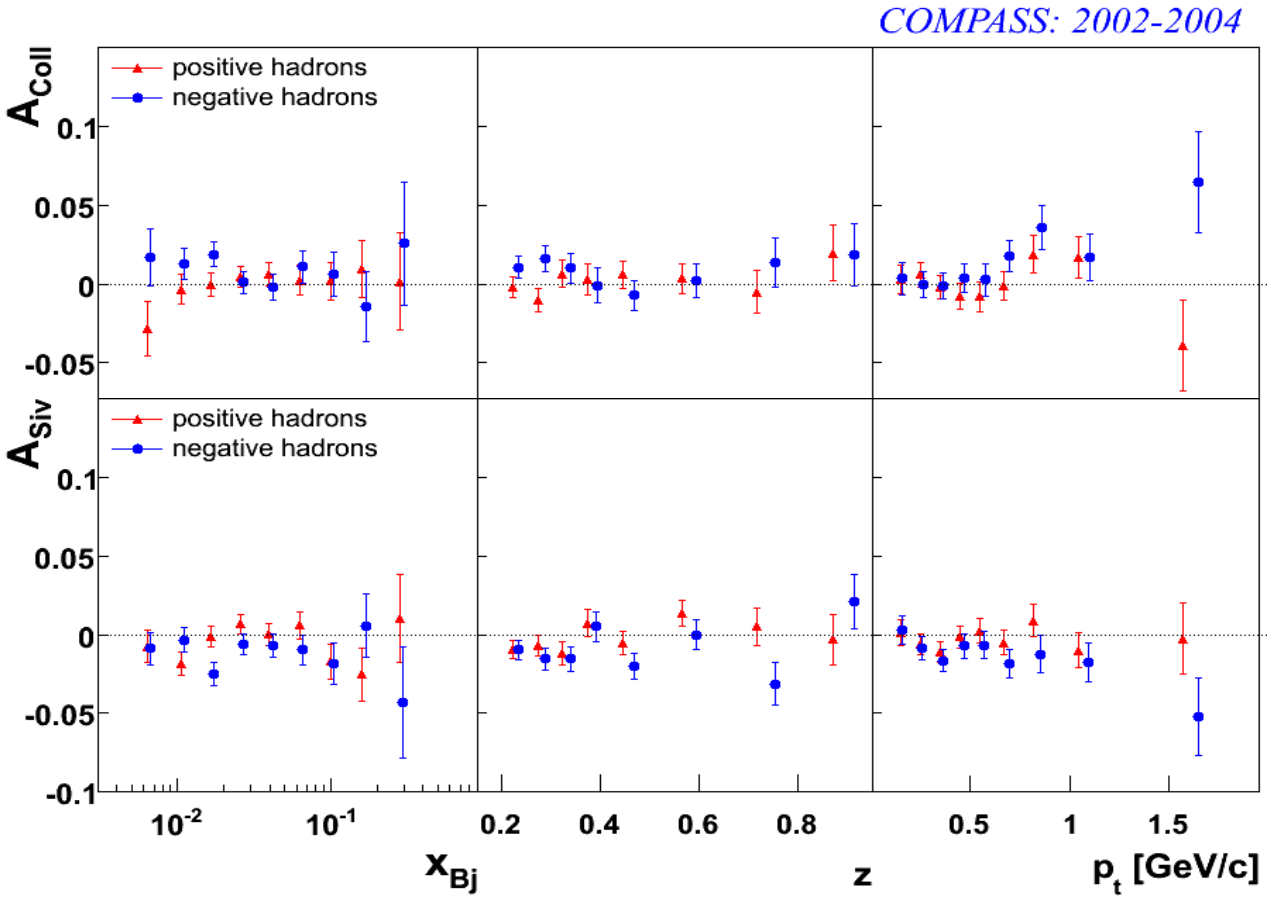
- at large x:
- large and positive for π^+
- large and negtive for π^-

Sivers asymmetry (proton)

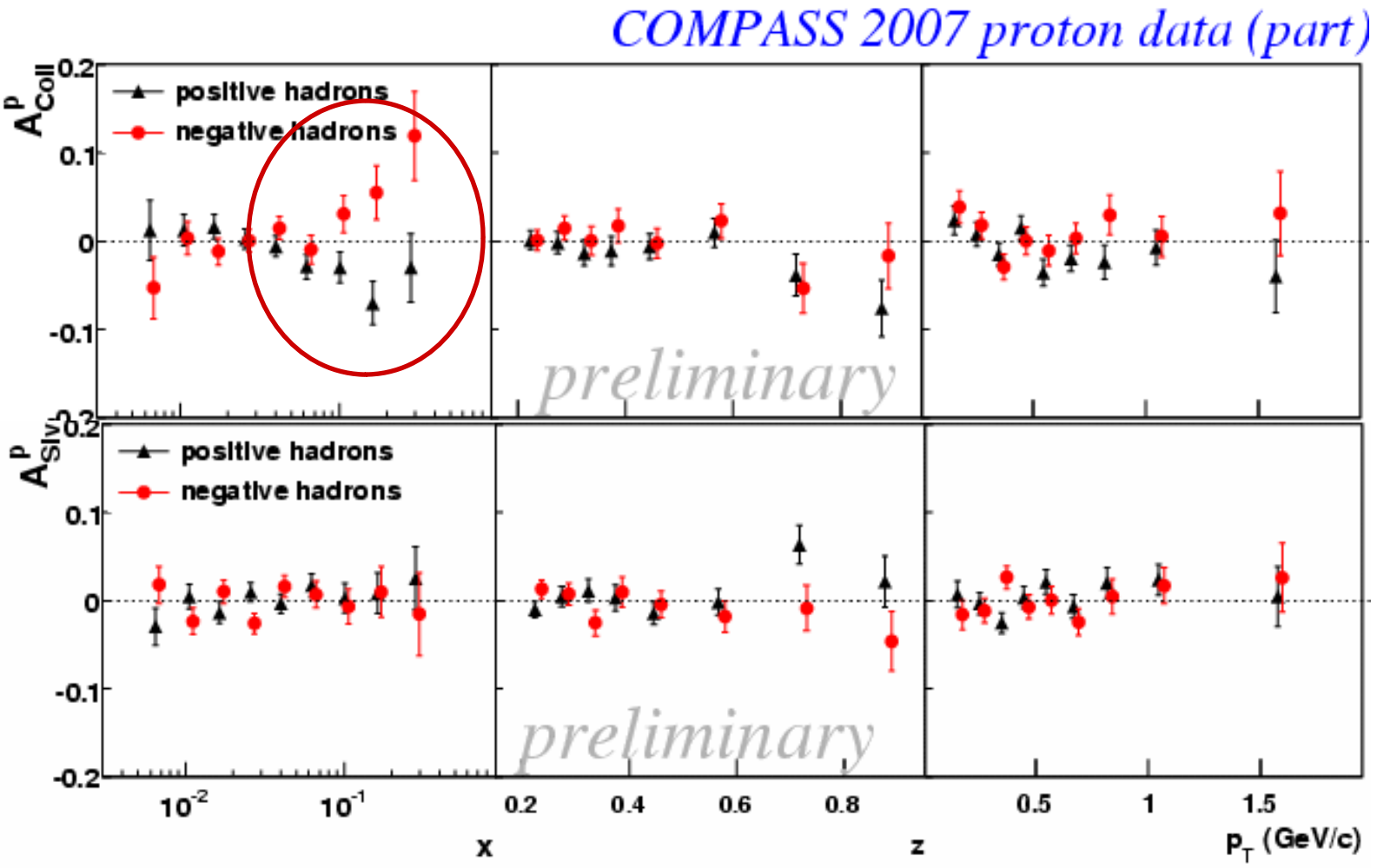


- large and positive for π^+
- small for π^-

Collins & Sivers asymmetries (deut.)

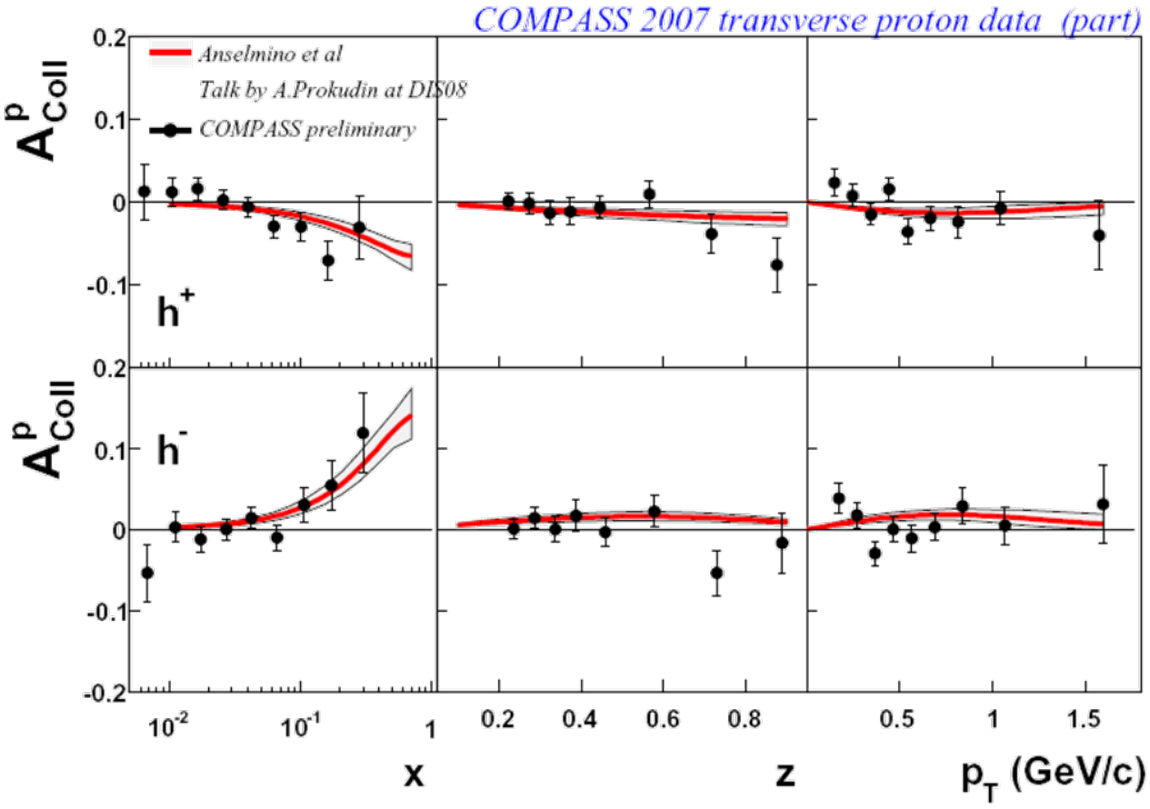


Collins & Sivers asym (proton)



Towards a global fit

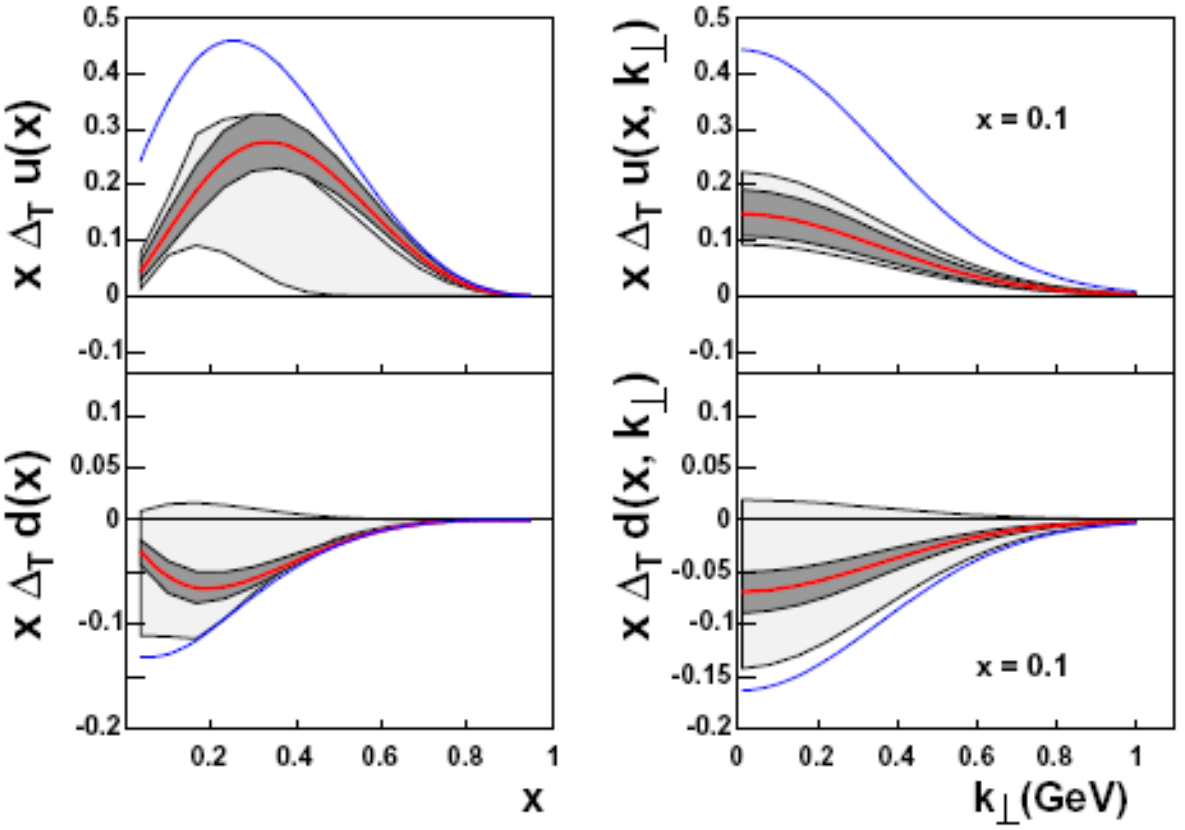
- Data
  - Hermes p
  - COMPASS p,d
  - Belle fragm.



Prokudin et al., DIS2008

A glimpse of transversity

- towards a global analysis



Anselmino et al., DIS2008

Summary & Outlook

Exiciting times behind AND ahead of us:

- Bjorken sum rule confirmed at 10%
- quark polarization are well measured
- anti-quark still need improvement
- first handles on $\Delta g/g$, axial anomaly will not restore quark spin contribution of 0.6
- GPD will be the topic of the next decade