RESULTS ON ΔG FROM

EXPERIMENT @ CERN

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The physics case

Possible ingredients of nucleon's spin

Spin sum rule:

(Jaffe&Manohar, Bashinsky&Jaffe, ...)

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

total spin of quarks	total spin of gluons	total orbital ang. momenta of quarks and gluons

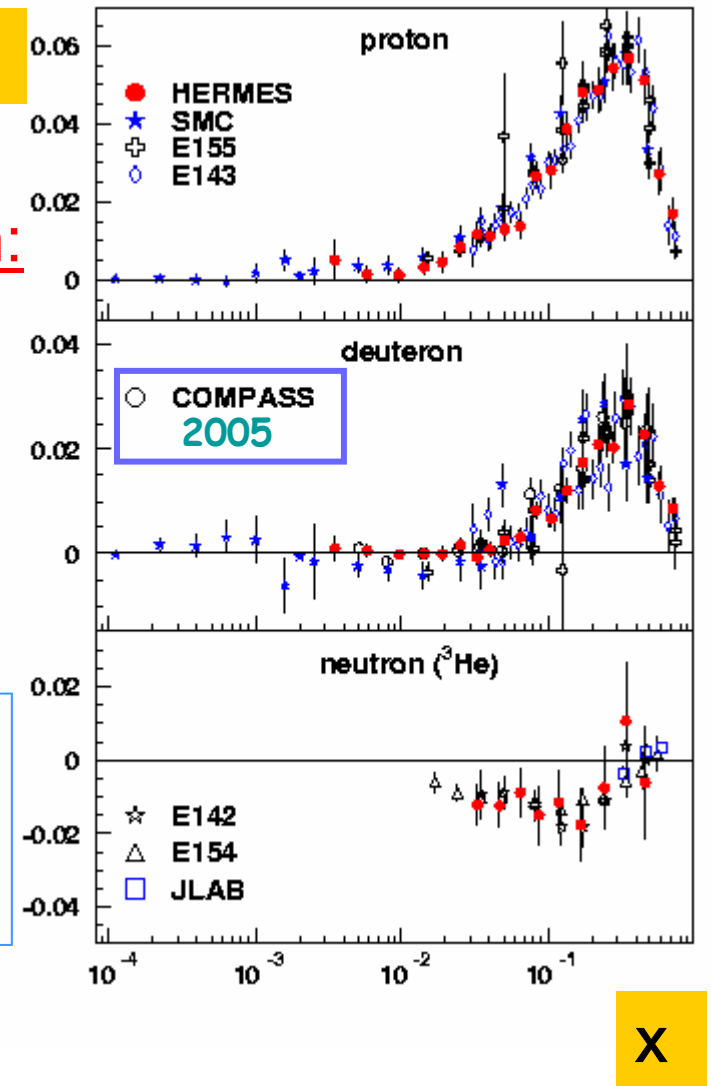
measurable in DIS

Structure function $g_1(x)$

The spin-dependent structure function:

$g_1(x) = \frac{1}{2}\sum e_q^2 \Delta q(x)$ where
$\Delta q(x) = q^+(x) - q^-(x)$ are quark helicity densities

$\Delta q = \int \Delta q(x)dx$
$\Delta\Sigma = \Delta u + \Delta d + \Delta s$: total spin of quarks
$\Delta G = \int \Delta g(x)dx$: total spin of gluons

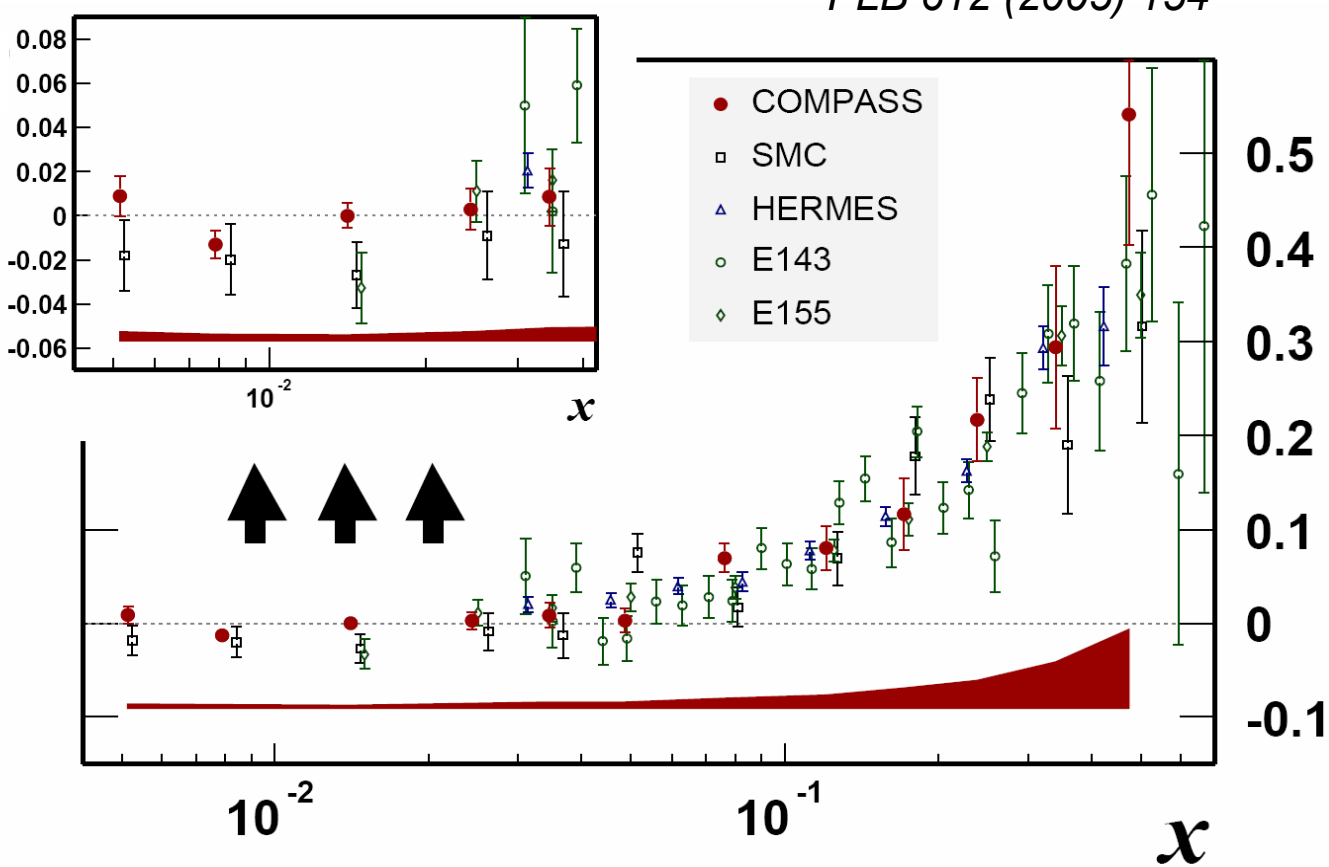


Structure function $g_1(x)$

Recent improvements at small x: COMPASS

PLB 612 (2005) 154

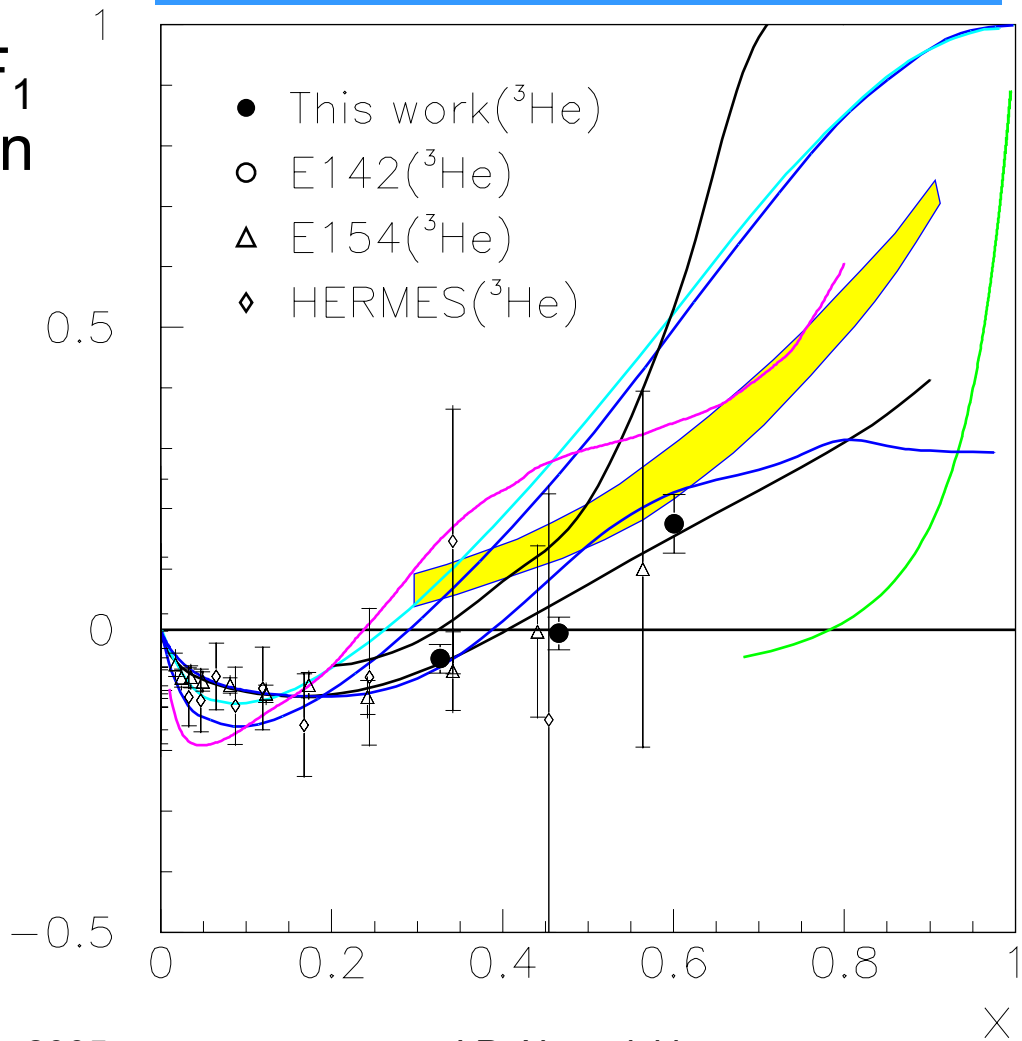
g_1/F_1 deuteron



Structure function $g_1(x)$

Recent improvements at large x: JLAB E99-117

g_1/F_1 neutron



PRL 92 (2004) 012004

Γ_1 - 1st moment of $g_1(x)$

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

Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = (a_3/6)\, C_1^{NS}$

Ellis-Jaffe SR : $\Gamma_1^{p,n} = (\pm a_3 + a_8/\sqrt{3})\, C_1^{NS}/12 + a_0\, C_1^S/9$

a_3, a_8, – from hyperon β decay + $SU_f(3)$; $\begin{cases} a_3 = \Delta u - \Delta d = g_A/g_V \\ a_8 = \Delta u + \Delta d - 2\Delta s \end{cases}$

$C_1^{S,NS}$ – calculable in QCD

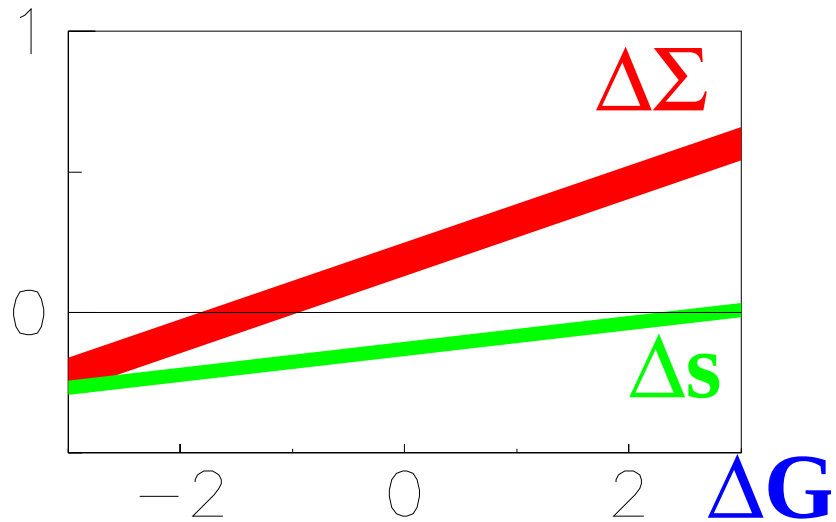
- EMC (1988): $a_0 = 12 \pm 9 \pm 14\%$;
  taking $a_0 = \Delta\Sigma \rightarrow$ "spin crisis"; ~ 60% expected
- One of the 6 most cited exp. papers (SPIRES)
- Confirmed by SMC, SLAC and Hermes : $\Delta\Sigma = 20 - 30\%$

ΔΣ and ΔG

But: $q^+ \sim \Psi\,(1+\gamma_5)\,\gamma_\mu\Psi$, $q^- \sim \Psi\,(1-\gamma_5)\gamma_\mu\Psi$ → $\Delta q(x) \sim \Psi\gamma_5\gamma_\mu\Psi$

... axial vector current is not conserved due to Adler-Bell-Jackiw („trinagle”) anomaly. As a consequence: the measured quantity

$$a_0 = \Delta\Sigma - (3\,\alpha/2\pi)\,\Delta G$$



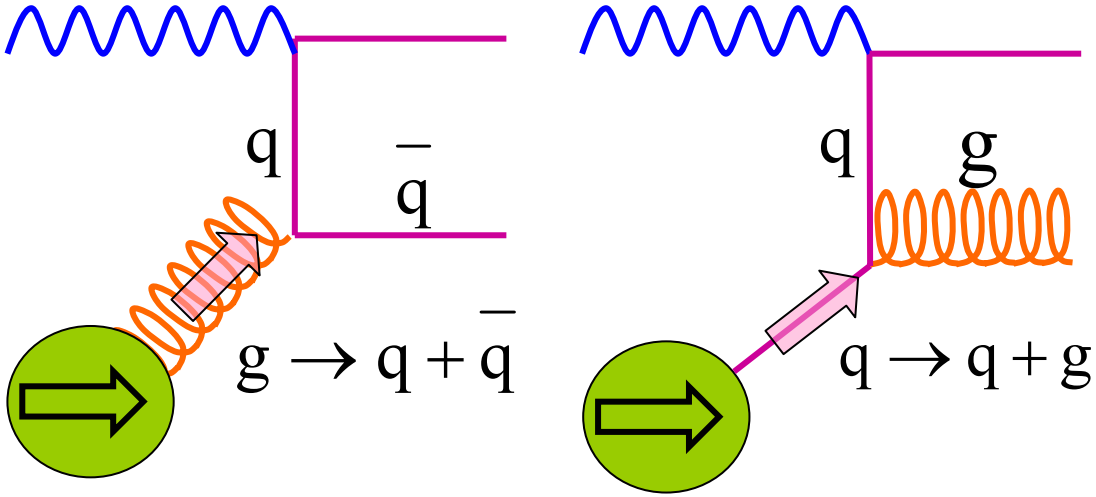
$\Delta G \approx 0$ → $\Delta\Sigma \approx 0.2$ but

$\Delta G \approx 2.5$ → $\Delta\Sigma \approx 0.6$ → can “solve the spin crisis”

Need to determine ΔG

ΔΣ and Δg from NLO QCD

Evolution of g_1 with Q^2 …



… due to:

$g \to q + \bar{q}$ $\quad P_{qg}$

$q \to q + g$ $\quad P_{qq}$

Probabilities

DGLAP evolution equations for quarks and gluons (x, Q^2):

(Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)

Strong coupling constant

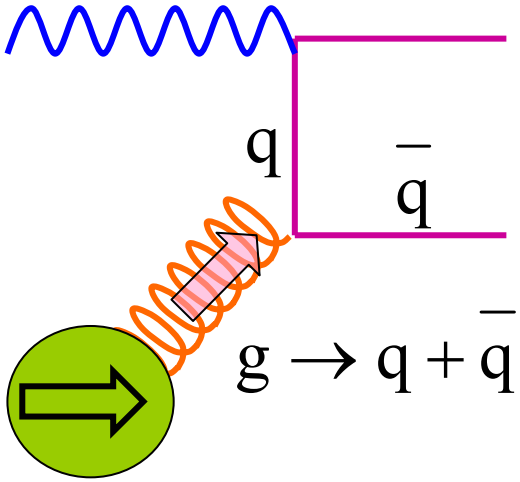
$$\frac{d\,\Delta\Sigma}{d\,\ln Q^2} = \frac{\alpha_s}{2\pi}\left\{\left[P_{qq} \otimes \Delta\Sigma\right] + 6\left[P_{qg} \otimes \Delta g\right]\right\}$$

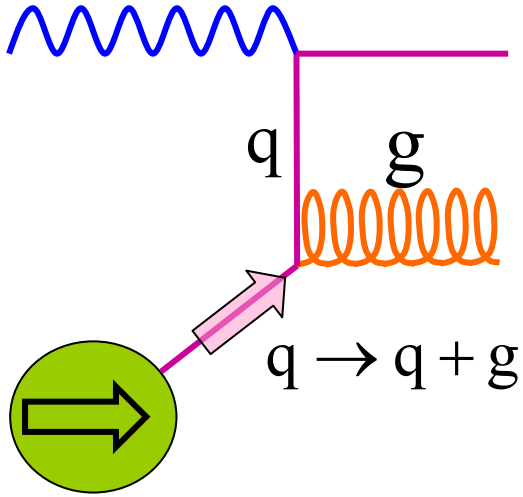
Quark distributions

Gluon distribution

ΔΣ and Δg from NLO QCD

Evolution of g_1 with Q^2 …





… due to:

$g \to q + \bar{q}$ $\quad P_{qg}$

$q \to q + g$ $\quad P_{qq}$

Probabilities

DGLAP evolution equations for quarks and gluons (x, Q^2):

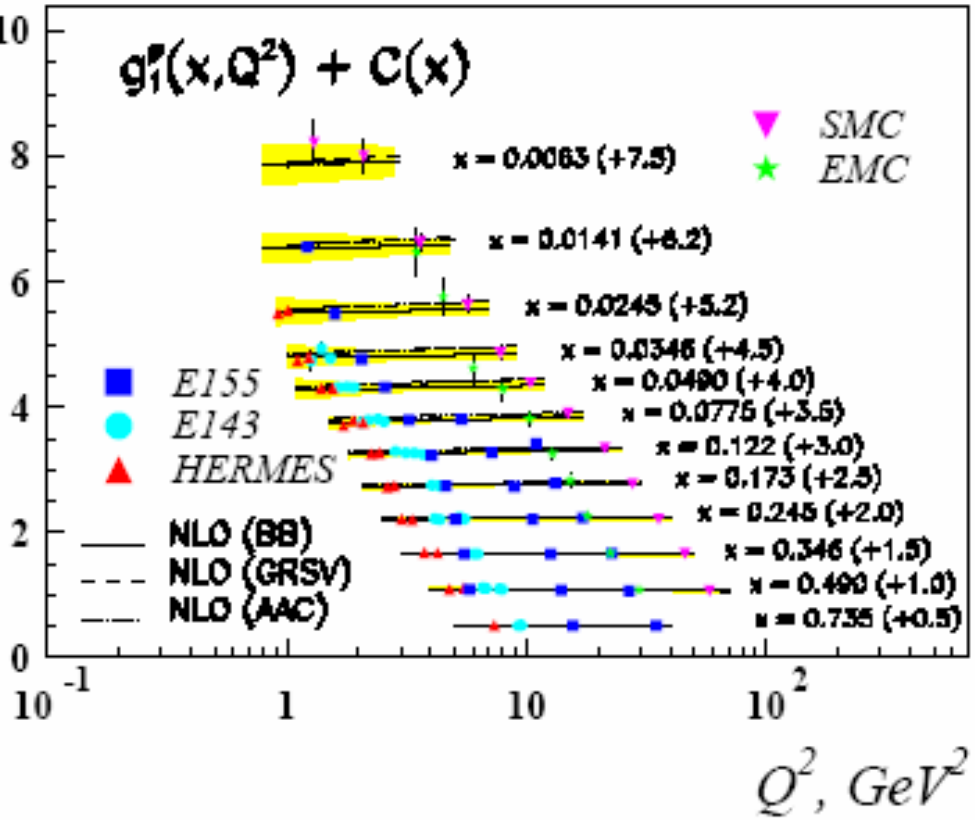
(Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)

… and the corresponding equations for Δq_{NS} and Δg.

ΔΣ and Δg from NLO QCD

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

*J.Blümlein and H.Böttcher, Nucl.Phys.**B636**(2002)225*



$g_1^p(x,Q^2)$ QCD in NLO

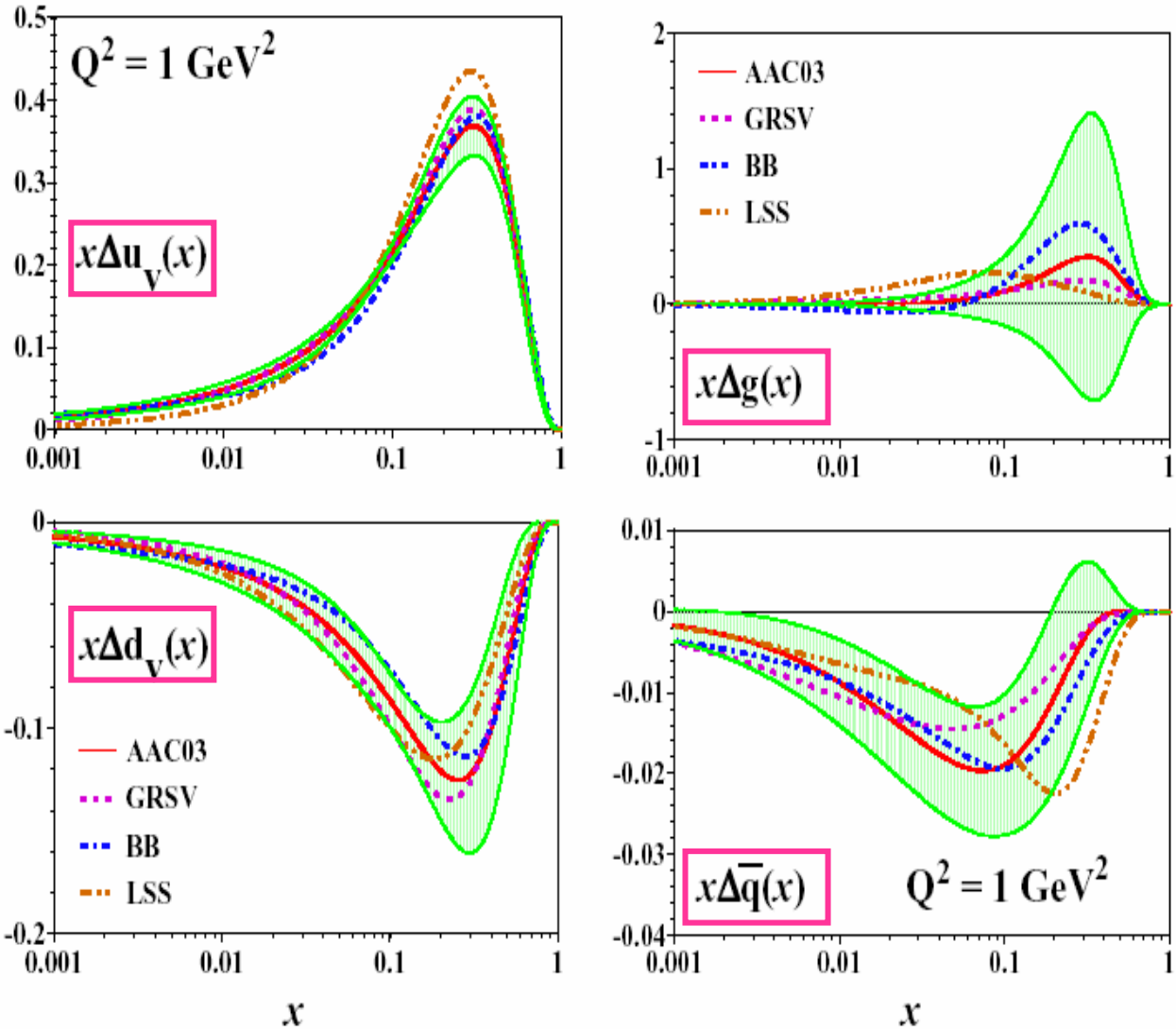
$$g_1^p(x,Q^2) = C_{NS} \otimes \left[\frac{1}{12}(\Delta u - \Delta d) + \frac{1}{36}(\Delta u + \Delta d - 2\Delta s) \right] + C_S \otimes \frac{1}{9}\Delta\Sigma + C_g \otimes 6\,\Delta g$$

(x,Q^2)

Distribution of gluon polarisation

ΔG from QCD fits to g_1 is badly determined

AAC2004: M. Hirai, S. Kumano and N. Saito, Phys.Rev.D (2004)



NLO fits:

Glück, Reya, Stratmann, Vogelsang
Blümlein, Böttcher
Leader, Sidorov, Stamenov

Hirai, Kumano, Saito:

ΔΣ = 0.213 ± 0.138

ΔG = 0.449 ± 1.266
large uncertainty

Use processes where ΔG is probed directly

Status of spin SR using g_1

$Q^2 = 1 \ldots 4\ GeV^2$:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$
$$= 0.14 \ldots 0.24$$

Uncertainty from the sea region

$$\Delta g = 0.4 \ldots 1.3$$

Poorly known

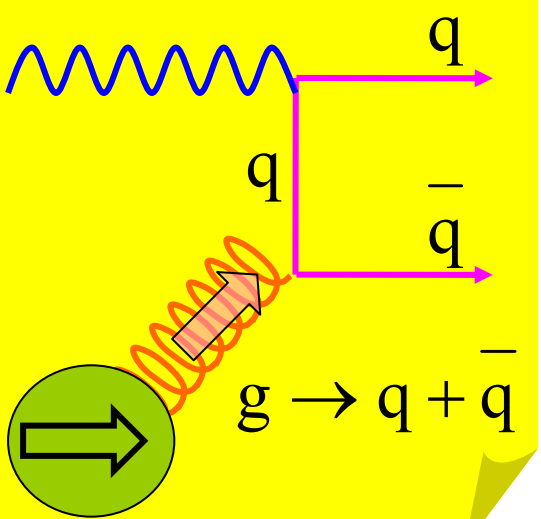
$$\langle L_z \rangle = ?$$

Not known

ΔG
from
Photon-Gluon Fusion

ΔG from Photon-Gluon Fusion (PGF)

Enhance the contribution to the final state from:



$$g \rightarrow q + \bar{q}$$

1)

$u, (\bar{d}, \bar{s}) \rightarrow h^+$

$\bar{u}, (d, s) \rightarrow h^-$

Large p_t hadrons

Hard scale set by p_t

- Large statistics, but ...
- Large background from other processes
- Theoretical uncertainties

2)

$c \rightarrow D^0 \rightarrow K^+ \pi^-$

$\bar{c} \rightarrow \overline{D^0} \rightarrow K^- \pi^+$

also $D^{*\pm} \rightarrow D^0 \pi^\pm$

Hard scale set by m_{charm}

- Clean theory, but ...
- Difficult experimentaly

USE ANY Q^2

ΔG from Photon-Gluon Fusion in COMPASS

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

THE COMPASS COLLABORATION

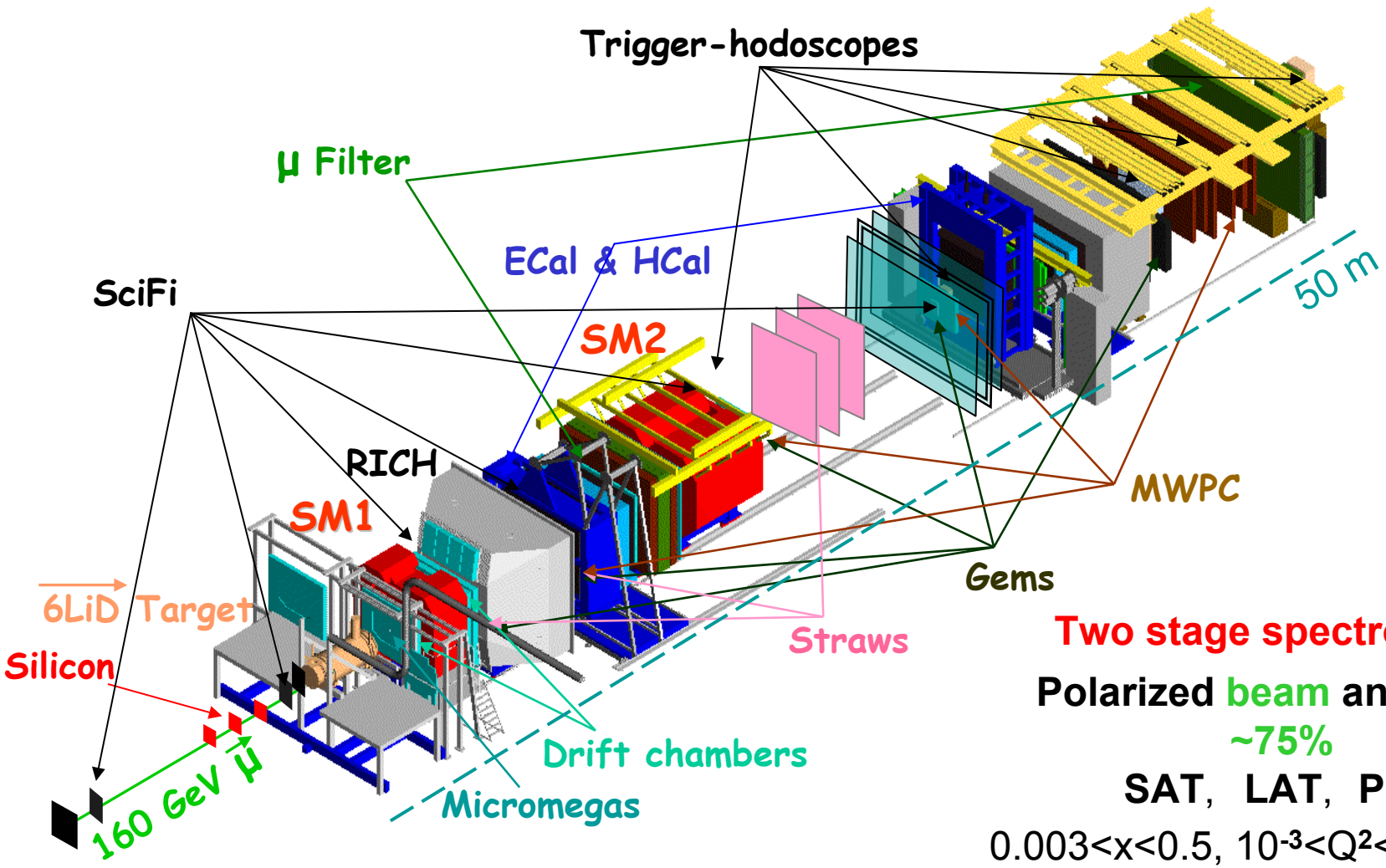
Czech Republic, Finland, France, Germany, India, Israel, Italy, Japan, Poland, Portugal, Russia, Switzerland

Bielefeld, Bochum, Bonn, Burdwan, Calcutta, CERN, Dubna, Erlangen, Freiburg, Heidelberg, Helsinki, Lisbon, Mainz, Miyazaky, Moscow, Munich, Nagoya, Prague, Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw

31 Institutes, more than 270 physicists and students

Beam
momentum 160 GeV
intensity 2.10^8 μ+/spill (4.8s/16.2s)
longitudinal polarization ~ -76%
LHC
COMPASS
SPS
μ+
N
Target
6LiD
longitudinal polarization +53%, -50%

The COMPASS spectrometer



Two stage spectrometer

Polarized beam and target

~75% ≥50%

SAT, LAT, PID

$0.003<x<0.5$, $10^{-3}<Q^2<10$ GeV^2

Data collected

Year	Effective days @ longitudinal polarization	Integrated luminosity (fb^{-1})	Analysed
2002	43	0.45	all
2003	36	0.80	all
2004	54	1.12	~ 50%

More detectors
Improved reconstruction

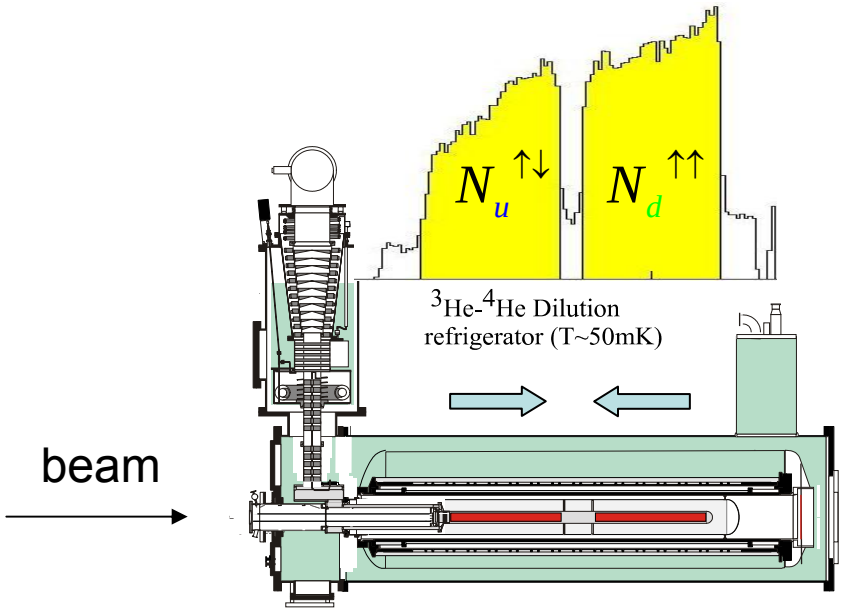
2005: no data taking
2006: taking data with an improved setup

Results shown: from 2002 + 2003 data.

Asymmetry determination

$$A^{measured} = \frac{1}{2}\left(\frac{N_u^{\uparrow\downarrow} - N_d^{\uparrow\uparrow}}{N_u^{\uparrow\downarrow} + N_d^{\uparrow\uparrow}} + \frac{N_d^{\uparrow\downarrow} - N_u^{\uparrow\uparrow}}{N_d^{\uparrow\downarrow} + N_u^{\uparrow\uparrow}} \right)$$

Before reversal — After reversal



TARGET

- Opposite polarizations, $P_t \approx \pm 50\%$
- Polarization reversed
  - by field rotation every ~8 h
  - by microvawes 2-3 times/year
- Dilution factor $\langle f \rangle \approx 0.4$

BEAM
$\langle P_\mu \rangle \approx -76\%$

DEPOLARIZATON F.
$\langle D \rangle \approx 0.6$

$$A_{\parallel} = \frac{A^{measured}}{f \cdot |P_\mu \cdot P_t|}$$

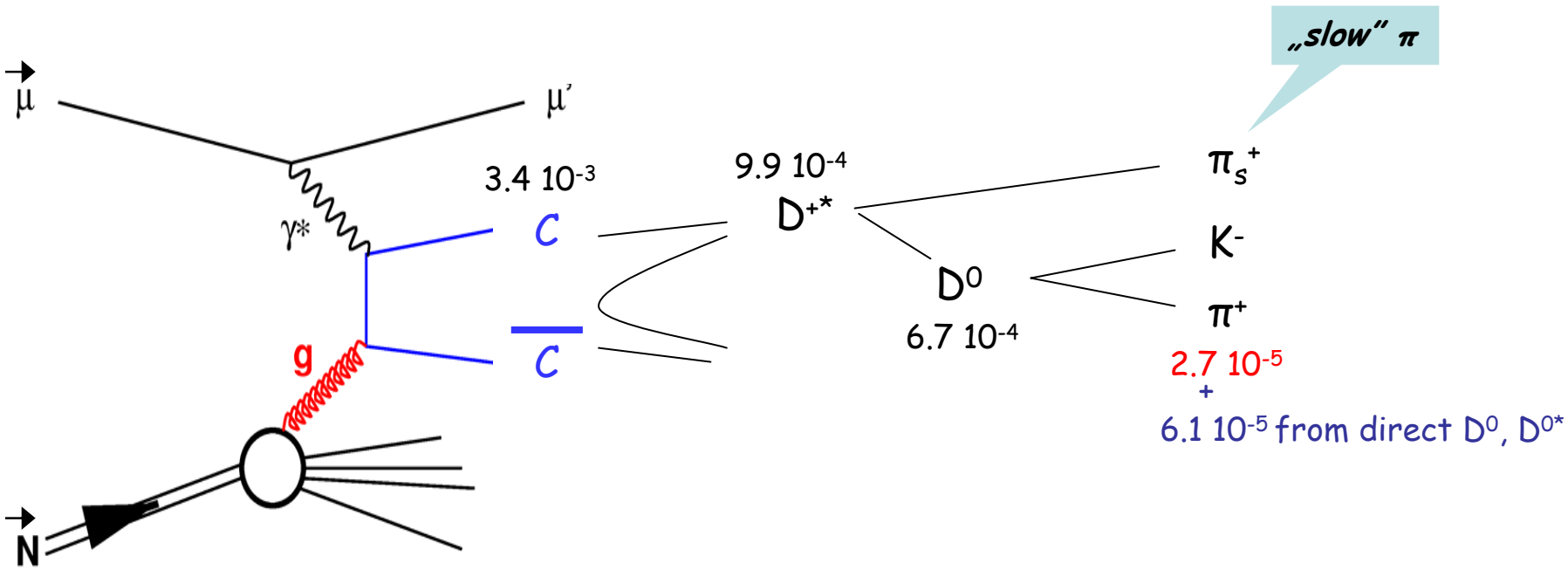
We use event-by-event weighting to optimize determination of ΔG.

$\Delta g(x)$ from charmed mesons:

$$D^0 \rightarrow K\pi$$

$$D^* \rightarrow D^0\pi_s \rightarrow K\pi\,\pi_s$$

Open charm production

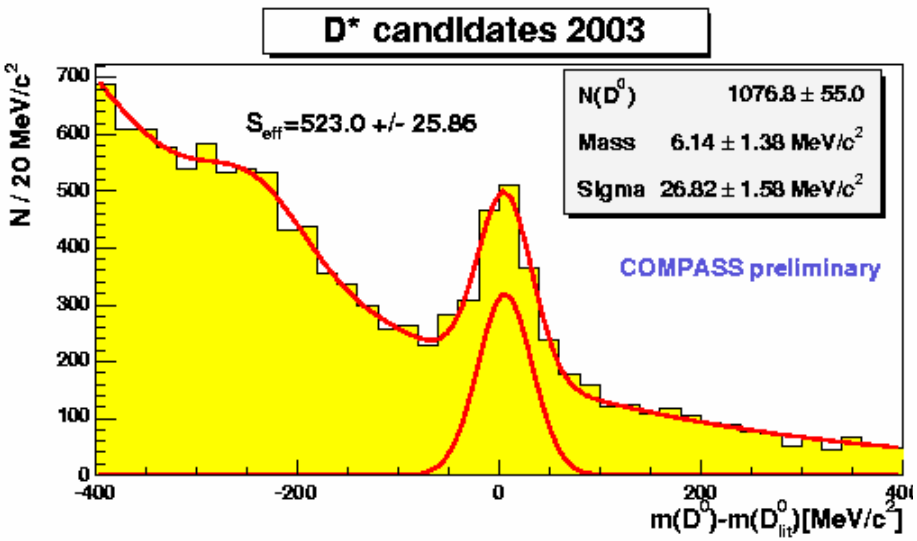


- **Unambiguous signature,**
- **Combinatorial background.**

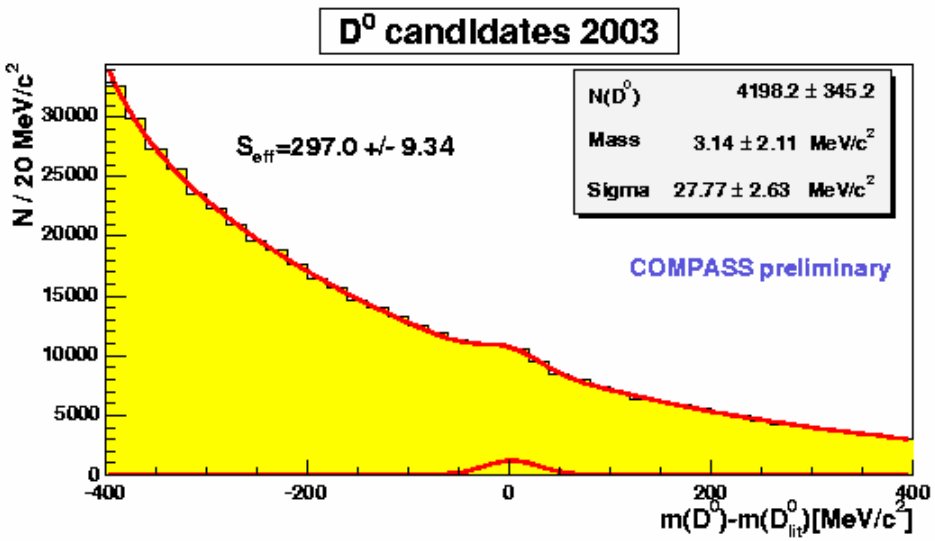
Open charm (D^0) signal

- about 30cm thick ^{6}LiD target cell → No charm decay vertex reconstruction
- K/π identification in RICH important
- use D^* tagging; $D^* \to D^0 \pi_s \to K\pi\, \pi_s$ → Cut on $m(K\pi\pi) - m(K\pi)$.

m_{D0} with D^* tagging

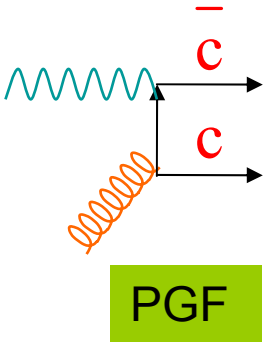


m_{D0} without D^* tagging



Δg from D^* and D^0

- **Dominant contribution:**



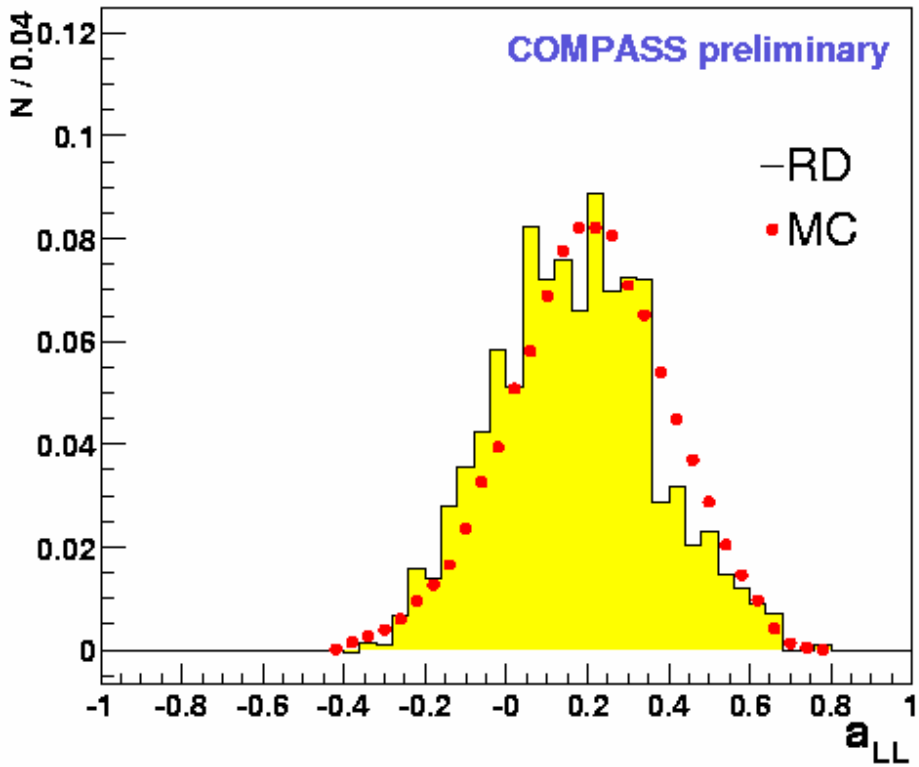
$$A_{\parallel} \approx \left\langle \hat{a}_{LL}^{\gamma g \to c\bar{c}} \right\rangle \frac{\Delta g}{g}$$

- $a_{LL}(y, p_{tD}, z_D)$ **parametrisation determined using MC (Aroma)**

- **Use event weighting to calculate** $A_{\parallel}$ **:** $w = fP_{\mu} a_{LL} \dfrac{S}{S+B}$

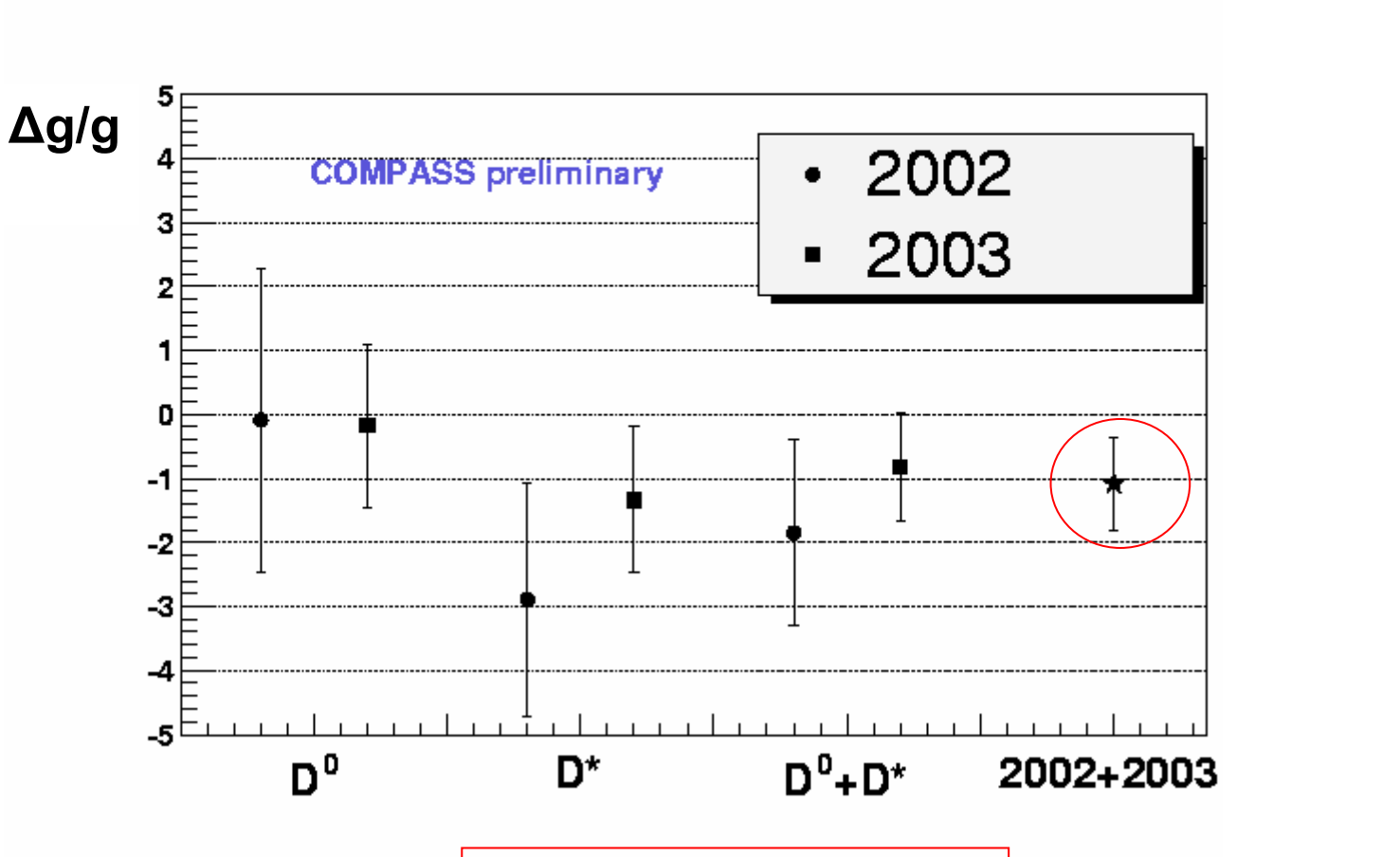
  taking into account correlation between $(fP_{\mu} a_{LL})$ **and** $\dfrac{S}{S+B}$

a_{LL} parametrisation



Background substracted signal region

Δg from D* and D0



$$\frac{\Delta g}{g} = -1.08 \pm 0.73(stat.)$$

$$\langle x_g \rangle = 0.15 \pm 0.08\,(rms)$$

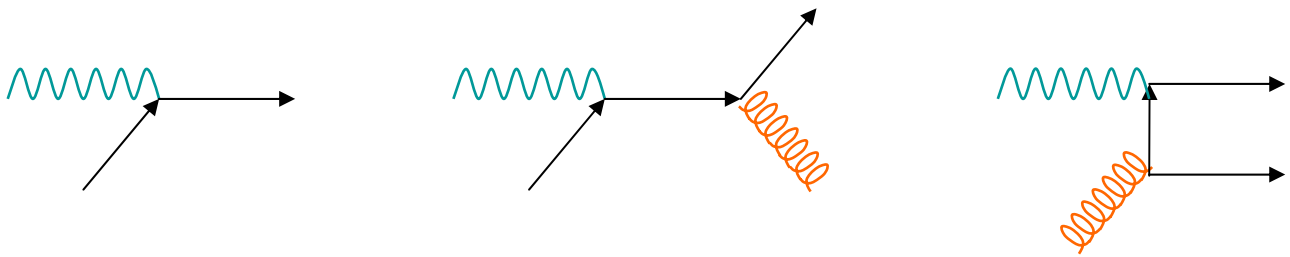
COMPASS preliminary

$\Delta g(x)$ from large p_t hadrons

- Two hadrons at large p_t: $p_{t,1(2)} > 0.7$GeV, $(p_{t,1})^2 + (p_{t,2})^2 > 2.5\text{GeV}^2$
- Exclude resonance region: $M_{1,2} > 1.5$GeV
- Supress contribution from the target fragmentation region: x_F, $z > 0.1$
- Consistent LO analysis:
  - PDF,
  - a_{LL},
  - parton showers OFF in JETSET.

Contributions to the asymmetry at large p_t

LO + QCD Compton + PGF + Resolved photon processes



$$A_{\parallel} = R_{LP}\left\langle \hat{a}_{LL}^{\gamma q\to q}\right\rangle A_1^d + R_{QCD\text{-}C}\left\langle \hat{a}_{LL}^{\gamma q\to qg}\right\rangle A_1^d + R_{PGF}\left\langle \hat{a}_{LL}^{\gamma g\to q\bar{q}}\right\rangle \frac{\Delta g}{g} + A_{res.phot.}$$

$$R_i = \frac{\sigma_i}{\sigma_{tot}}$$

small at small x

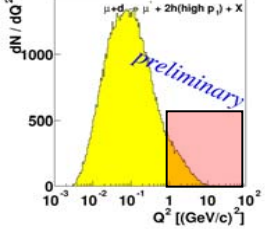
small at large Q^2

Q^2 >1GeV^2 , x<0.05: **ONLY PGF** CONTRIBUTING TO THE ASYMMETRY

Q^2 < 1GeV^2: **ALL PROCESSES** CONTRIBUTING TO THE ASYMMETRY

Q^2 **bigger** then 1 GeV^2

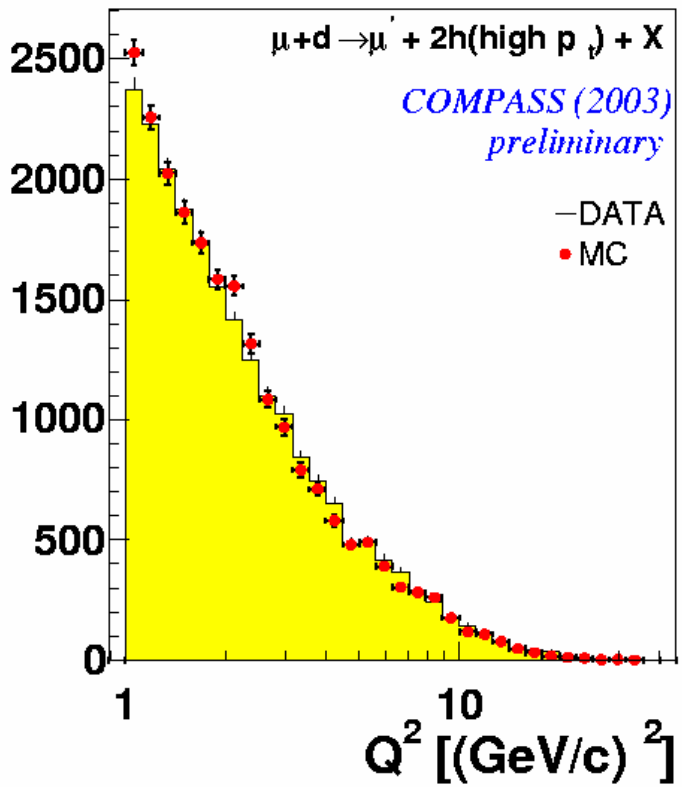
Δg from large p_t: $Q^2 > 1$ GeV^2

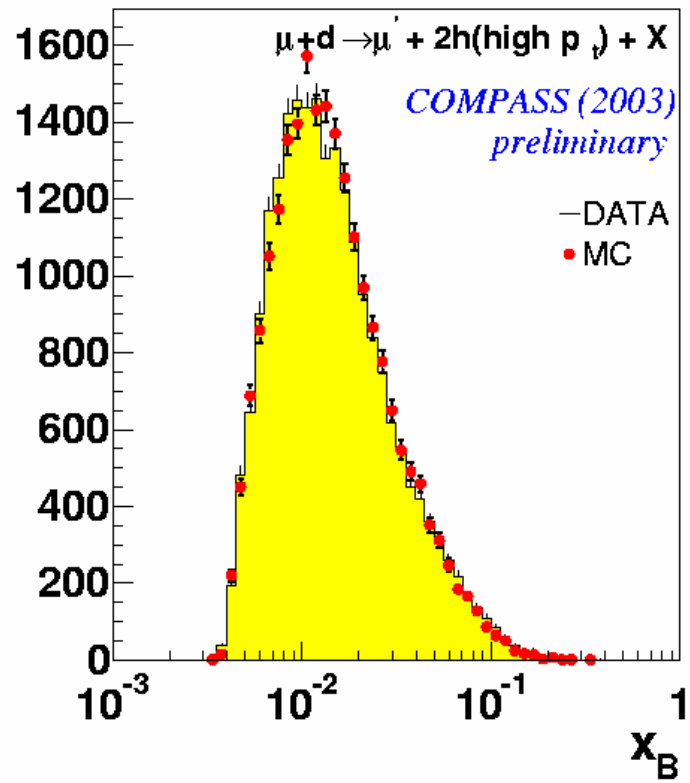


10% of data

- **LEPTO tuned to reproduce the data ...**

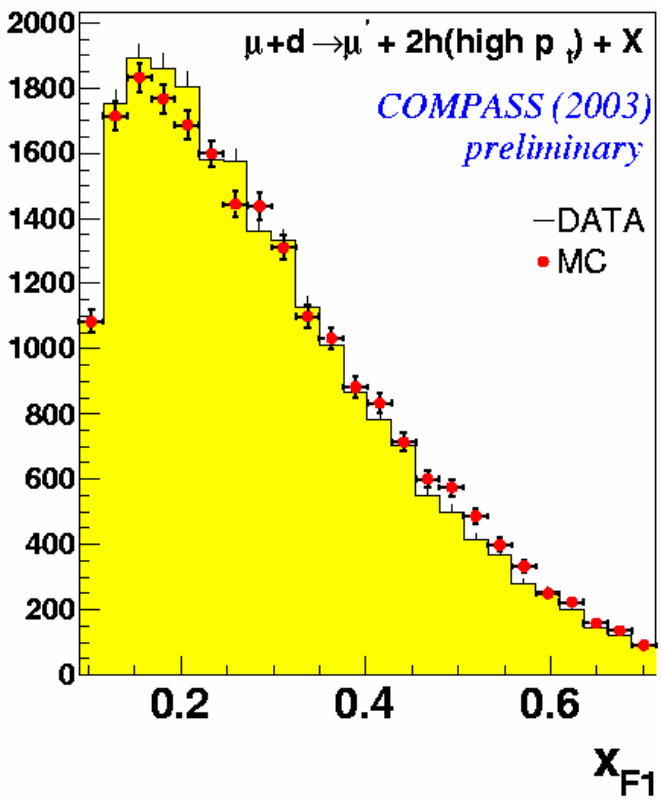
Data vs. Monte Carlo for muon variables

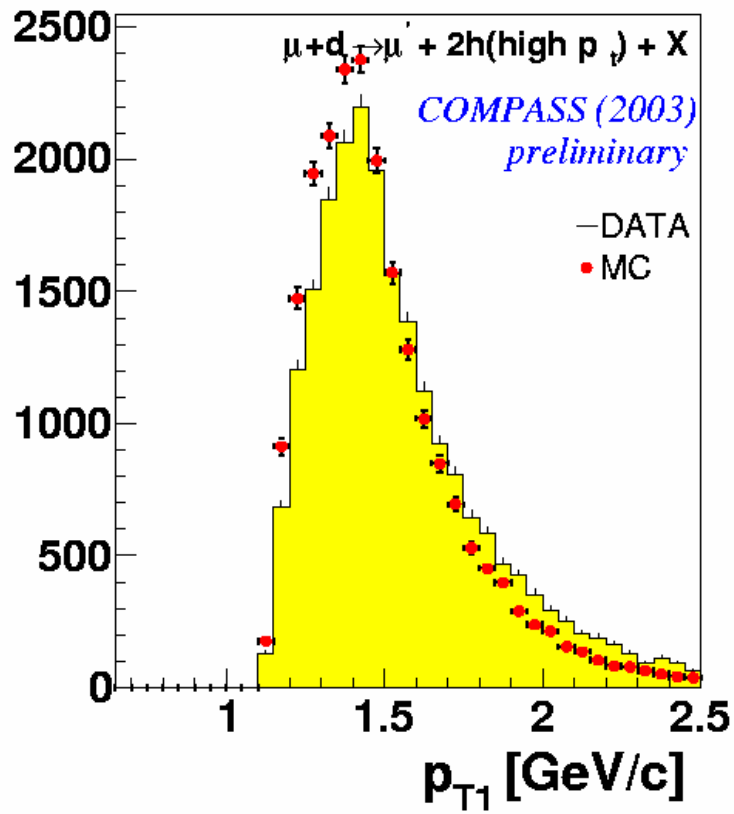




Δg from large p_t: $Q^2 > 1\ GeV^2$

Data vs. Monte Carlo for hadron variables





Δg from large p_t: $Q^2 > 1$ GeV^2

- **Use event weighting to calculate** $A_{\parallel}$: $w = fDP_{\mu}$

$$\frac{A_{\parallel}}{D} = -0.015 \pm 0.089(stat.) \pm 0.013(syst.)$$

COMPASS preliminary

- **Only PGF contributing to the asymmetry:**

$$\frac{\Delta g}{g} = \frac{A_{\parallel}}{D} \cdot \frac{1}{\langle a_{LL}/D \rangle \cdot R_{PGF}}$$

-0.75±0.15 *0.34±0.07* ← **From LEPTO**

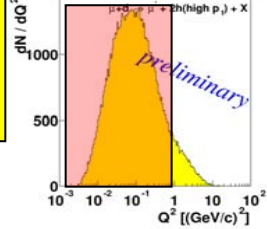
$$\frac{\Delta g}{g} = 0.06 \pm 0.31(stat.) \pm 0.06(syst.)$$

$$\langle x_g \rangle = 0.13 \pm 0.08\ (rms)$$

COMPASS preliminary

Q^2 **smaller** then 1 GeV^2

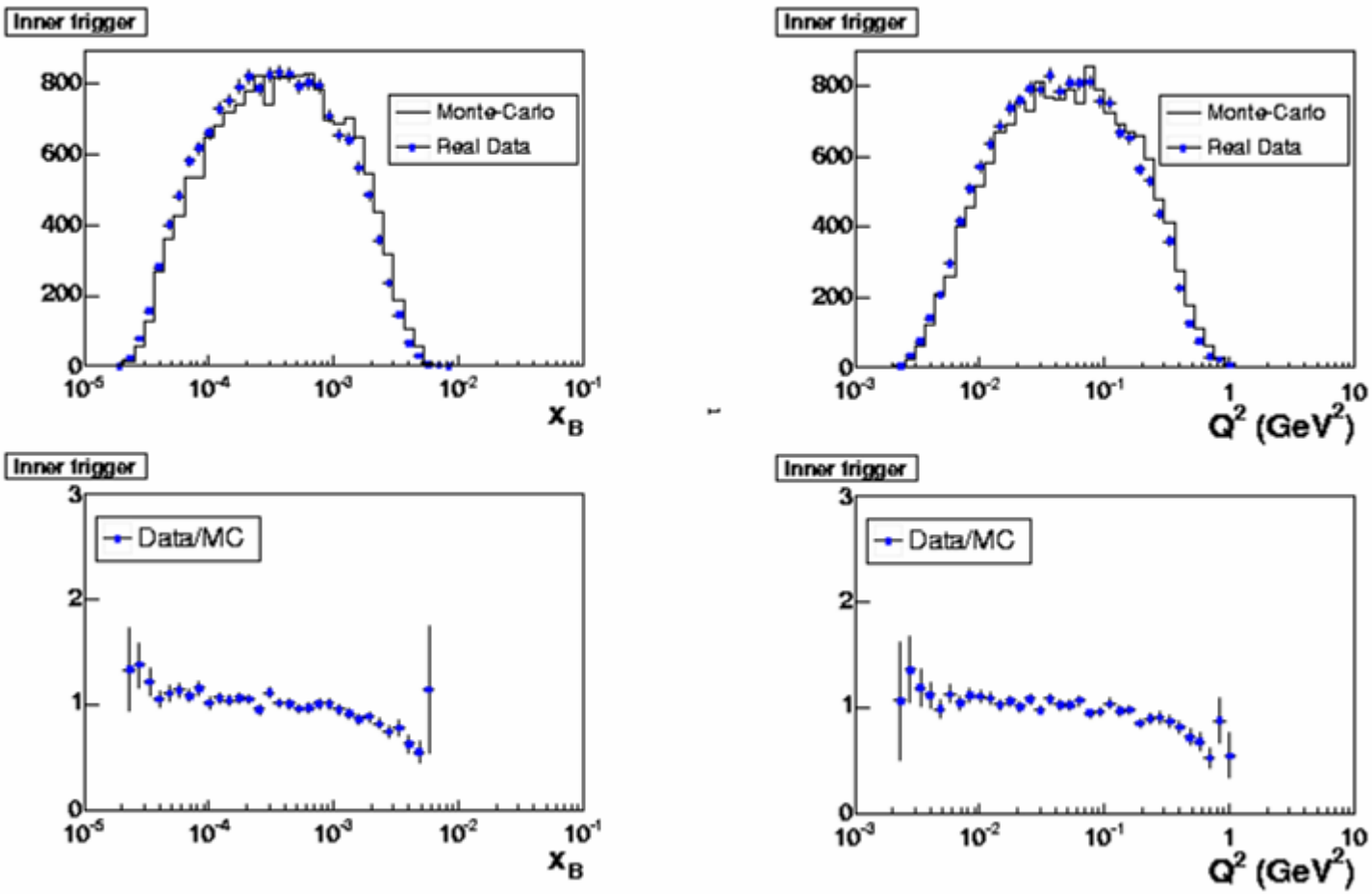
Δg from large p_t: $Q^2 < 1$ GeV^2



90% of data

- **PYTHIA** tuned to reproduce the data

Data vs. Monte Carlo for muon variables

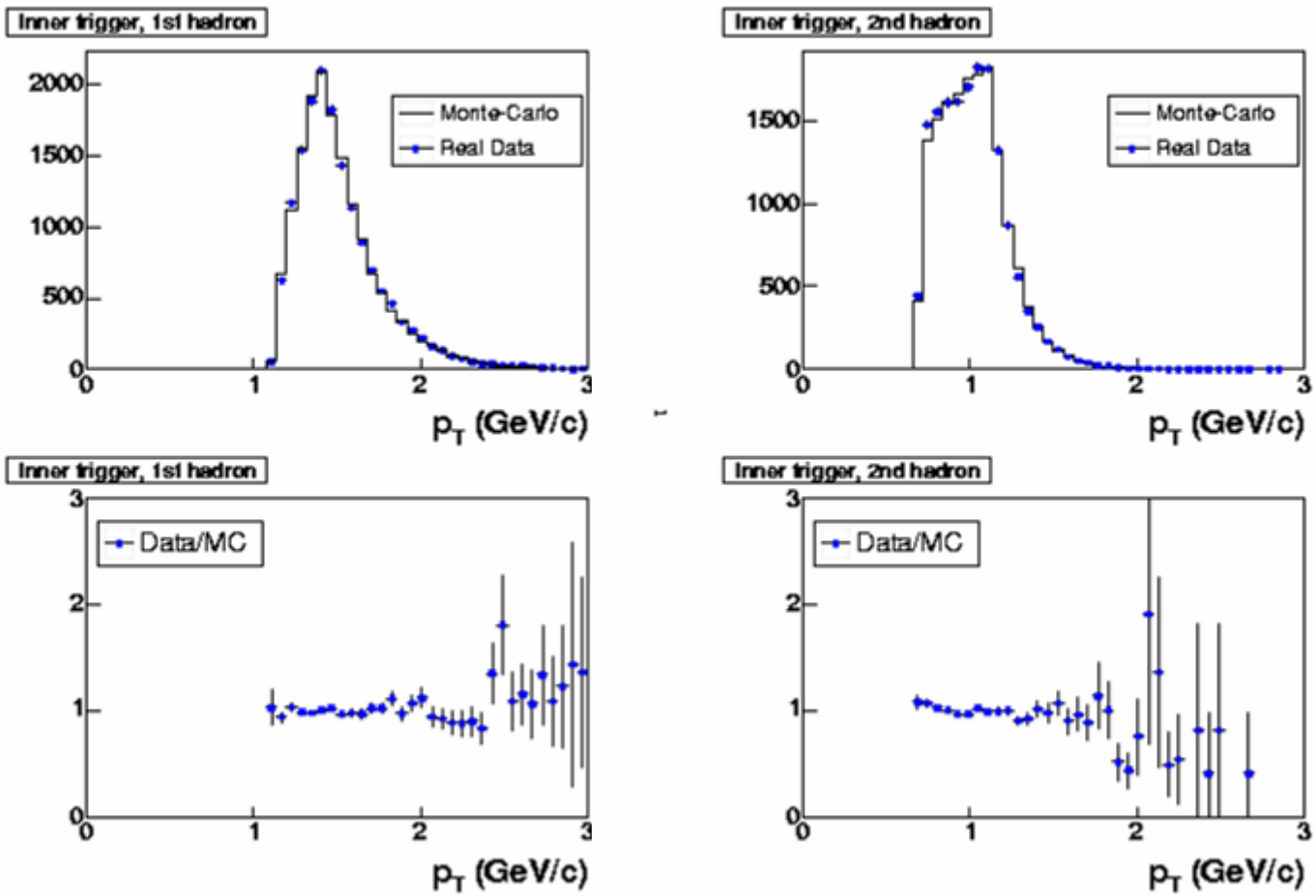


Δg from large p_t: $Q^2 < 1$ GeV^2

Data vs. Monte Carlo for hadron variables

Leading hadron

Next-to-leading hadron

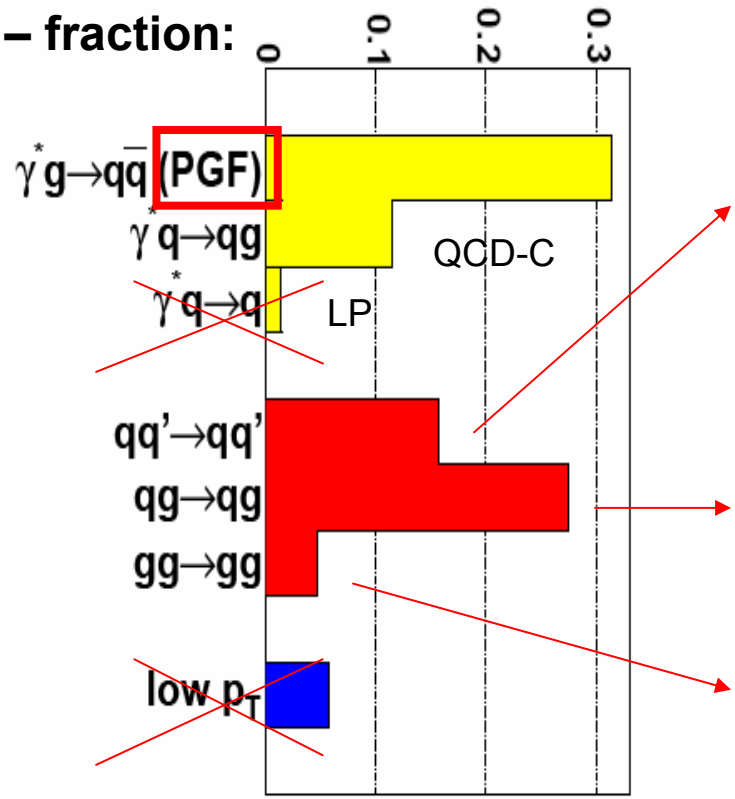


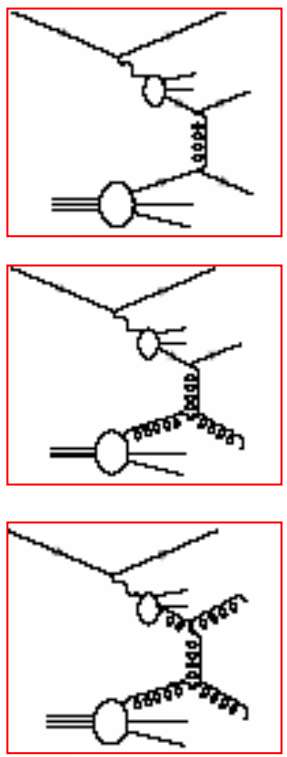
Δg from large p_t: $Q^2 < 1\ GeV^2$

hard | soft: resolved photon | soft: small-p_t

$$A_{\parallel} = R_{PGF} \cdot A_{PGF} + R_{QCD\text{-}C} \cdot A_{QCD\text{-}C} + R_{LP} \cdot A_{LP} + \sum_{q,q'=u,d,s,g,\ldots} R_{f,\gamma} \left\langle a_{LL}^{ff'} \frac{\Delta q^{\gamma}}{q} \frac{\Delta q'^{N}}{q'} \right\rangle + R_{small\text{-}p_t} \cdot A_{small\text{-}p_t}$$

R – fraction:



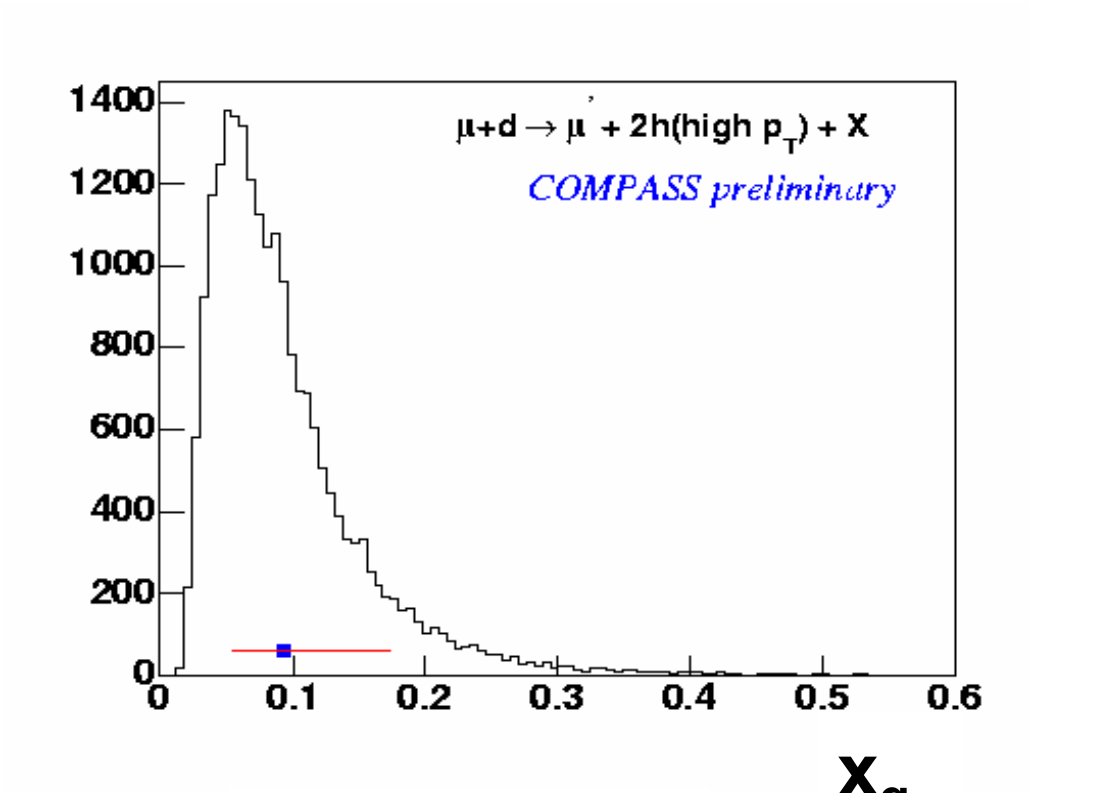


- $(\Delta q'/q')^N$: use parametrisations GRSV2000/GRV2000,
- $(\Delta q/q)^{\gamma}$: assume minimal and maximal scenarios;

  Gluck, Reya, Sieg, EPJC20(2001)271/
  Gluck, Reya, Schienbein, PRD60(1999)054019
- Fractions R_i obtained from PYTHIA,

Δg from large p_t: $Q^2 < 1$ GeV^2

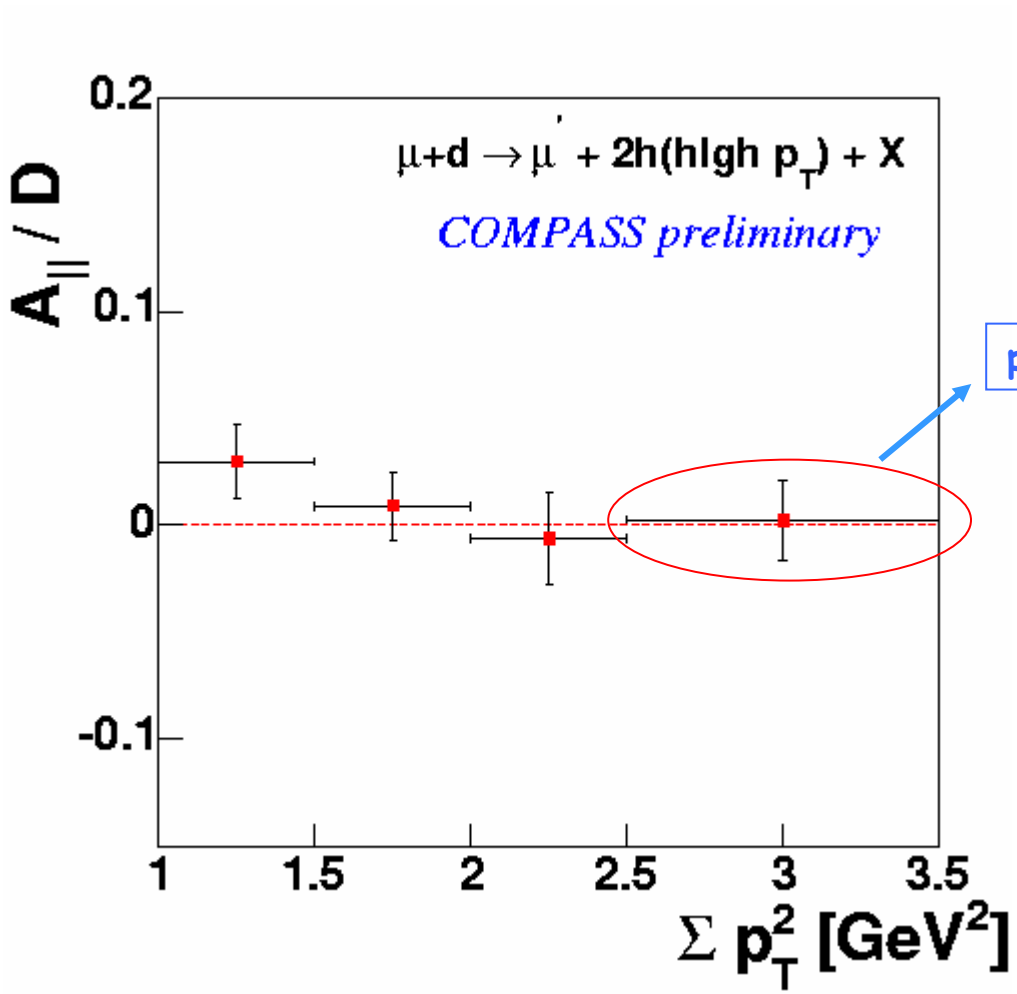
n_g determined from PYTHIA



$$\langle x_g \rangle = 0.095^{+0.078}_{-0.040}$$

Δg from large p_t: $Q^2 < 1$ GeV^2

Measured asymmetry vs. P_t-cut



$p_{t1}^2 + p_{t2}^2 > 2.5$ GeV^2:

Δg from large p_t: $Q^2 < 1$ GeV^2

Systematic errors - experimental:

Dominant contribution: false asymmetries. Estimated using a large sample of events without p_t cut.

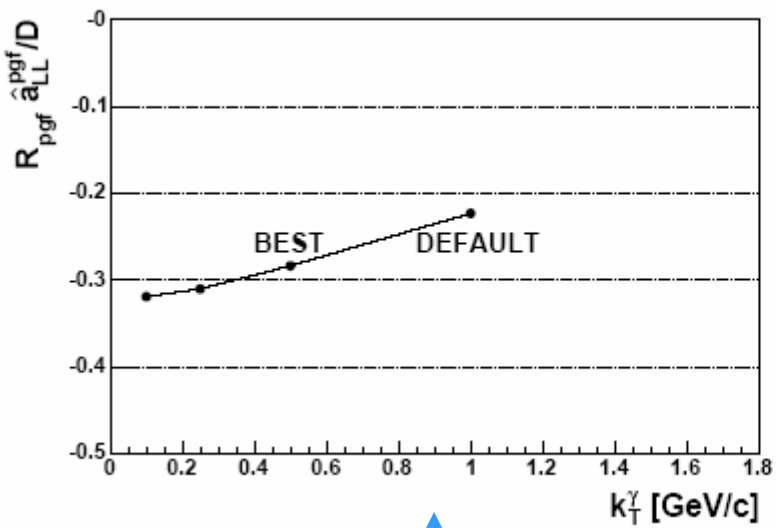
Systematic errors - due to MC:

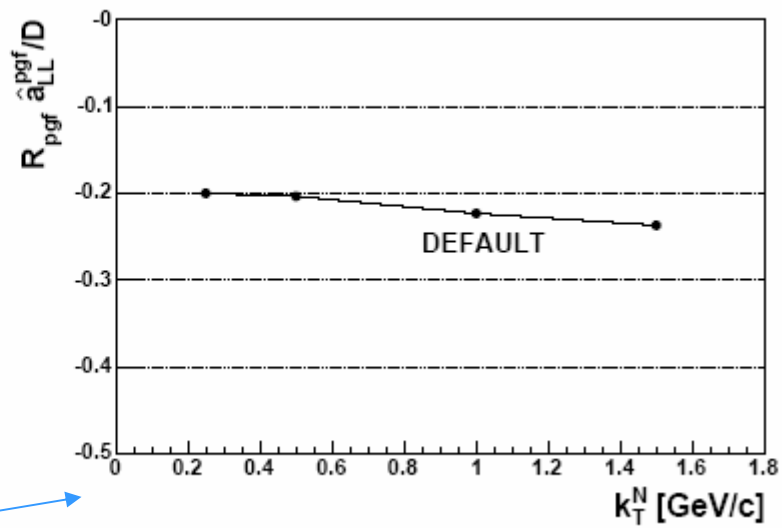
Dependence of $R_{PGF} \frac{a_{LL}^{PGF}}{D}$ on:

- parton fragmentation functions,
- primordial k_T^N, k_t^γ,
- renormalisation and factorisation scales,
- parton showers ON/OFF.

Related to NLO

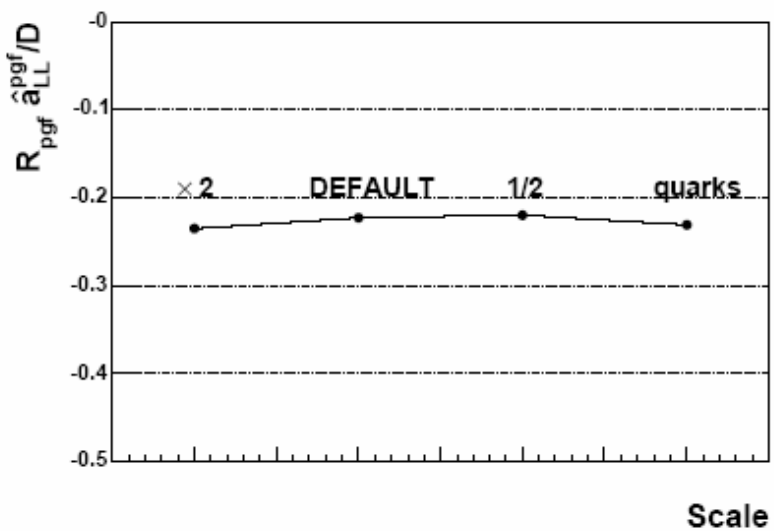
Δg from large p_t: $Q^2 < 1\ GeV^2$





k_T - dependence

scales dependence



Δg from large p_t: $Q^2 < 1\ \mathrm{GeV}^2$

COMPASS preliminary

$A_{\parallel}$

$$\frac{A_{\parallel}}{D} = -0.002 \pm 0.019(stat.) \pm 0.003(syst.), \qquad \langle D \rangle = 0.64$$

$\Delta g/g$

$$\left[\frac{\Delta g}{g}(x_g = 0.09)\right]_{\min} = 0.016 \pm 0.068(stat.) \pm 0.011(\exp.syst.) \pm 0.018(\mathrm{MC}syst.)$$

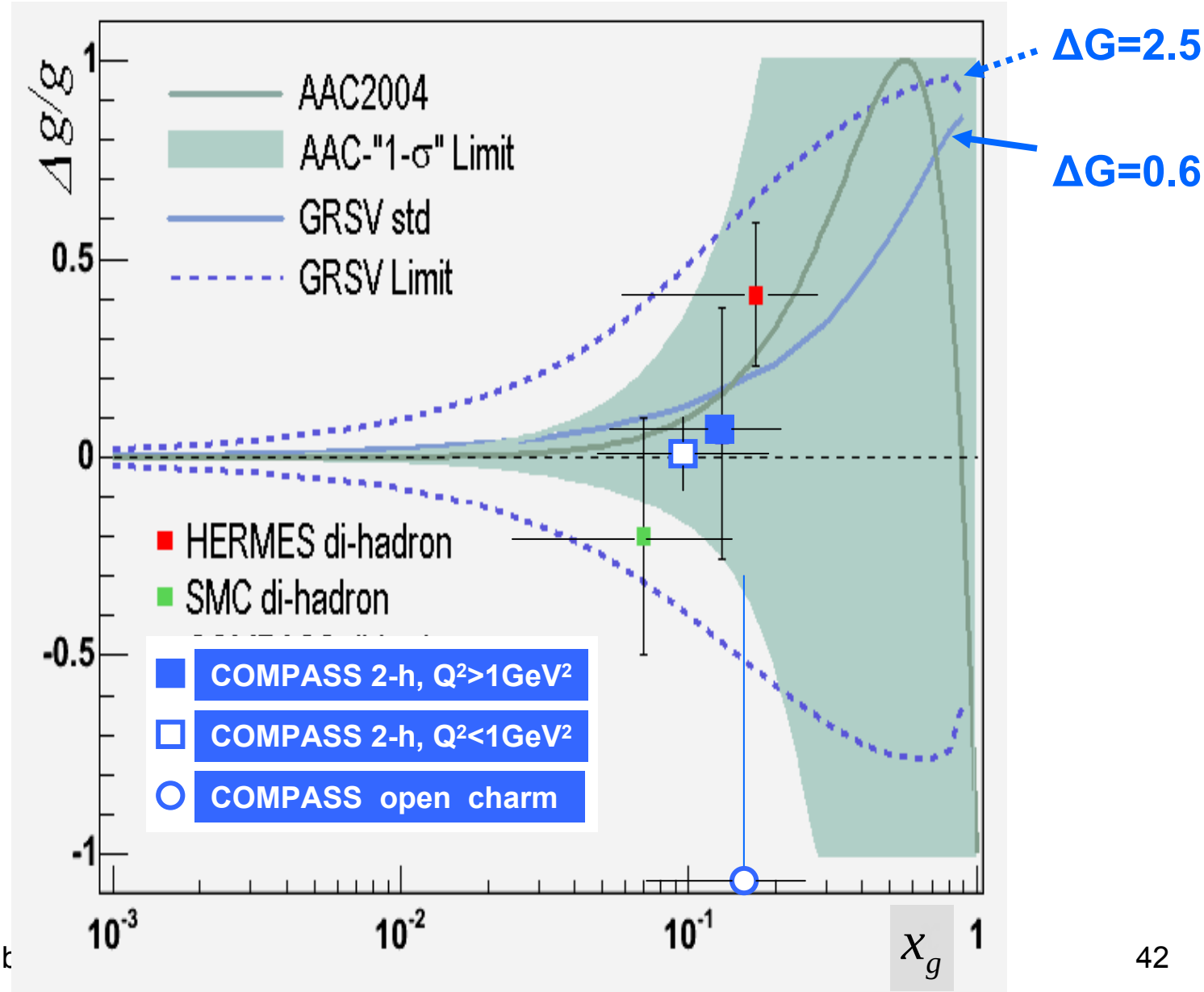
$$\left[\frac{\Delta g}{g}(x_g = 0.10)\right]_{\max} = 0.031 \pm 0.089(stat.) \pm 0.014(\exp.syst.) \pm 0.052(\mathrm{MC}syst.)$$

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

$$\langle x_g \rangle = 0.095^{+0.078}_{-0.040}, \qquad \mu^2 \simeq 3\,\mathrm{GeV}^2$$

assuming PYTHIA!

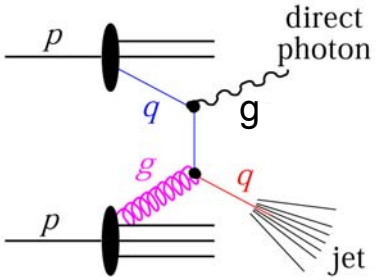
Results on Δg



Results from RHIC

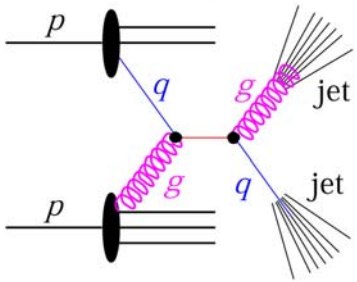
Reactions sensitive to Δg at RHIC

J.Sowinski, SPIN04



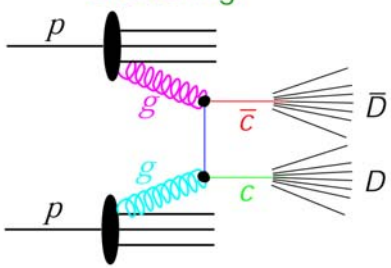
Quark - Gluon Compton Scattering

Direct photons - „golden channel”
RARE



Quark - Gluon (also Gluon - Gluon) Elastic Scattering

Jets and π^0



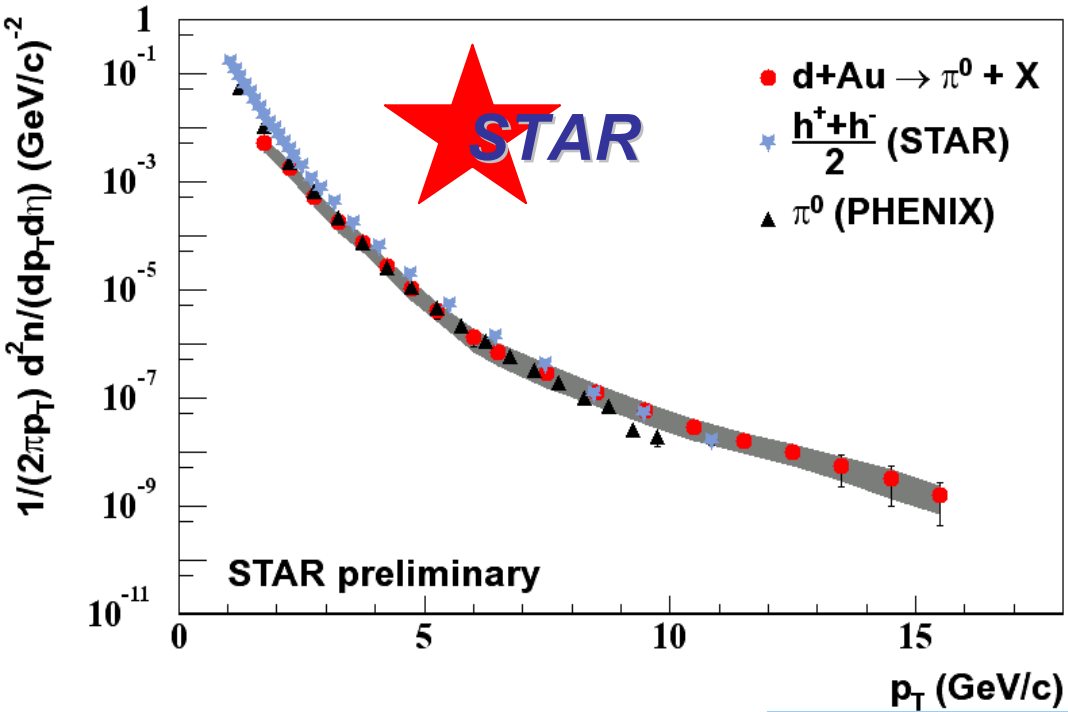
Gluon - Gluon Fusion

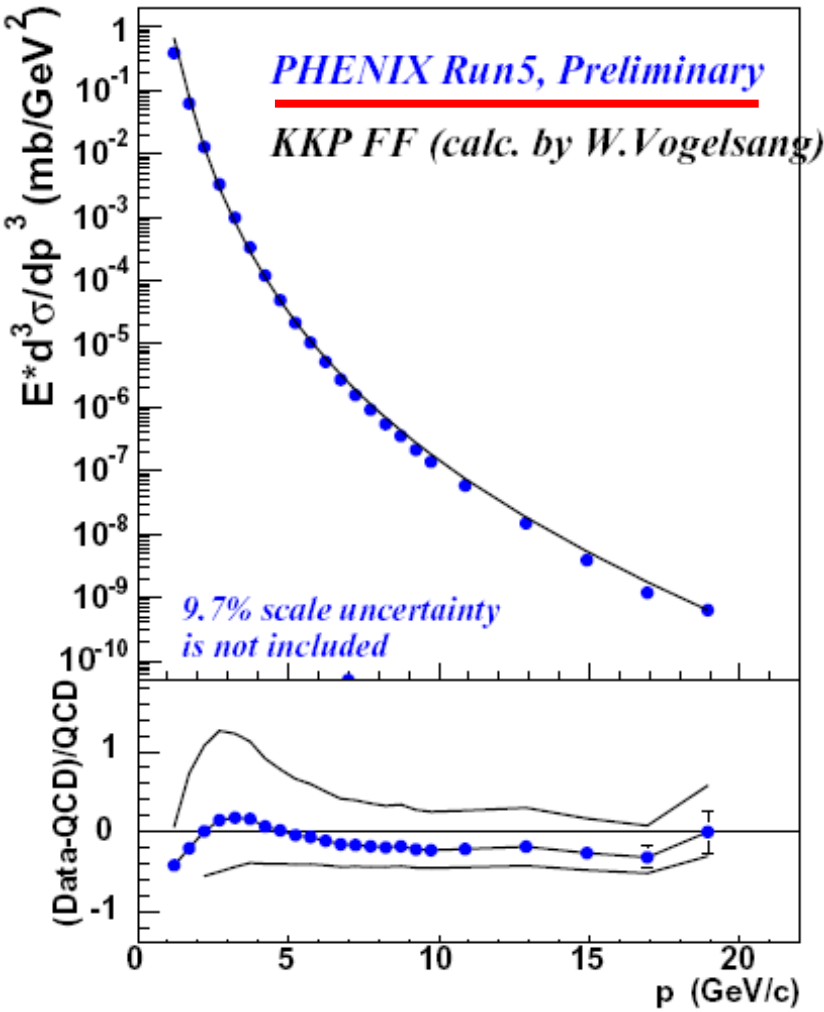
Heavy flavor
RARE

Inclusive π^0

K.Boyle, PANIC05

PHENIX: p p → π^0 X
STAR : d Au → π^0 X
200 GeV

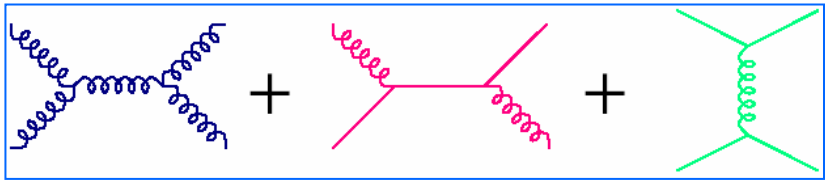




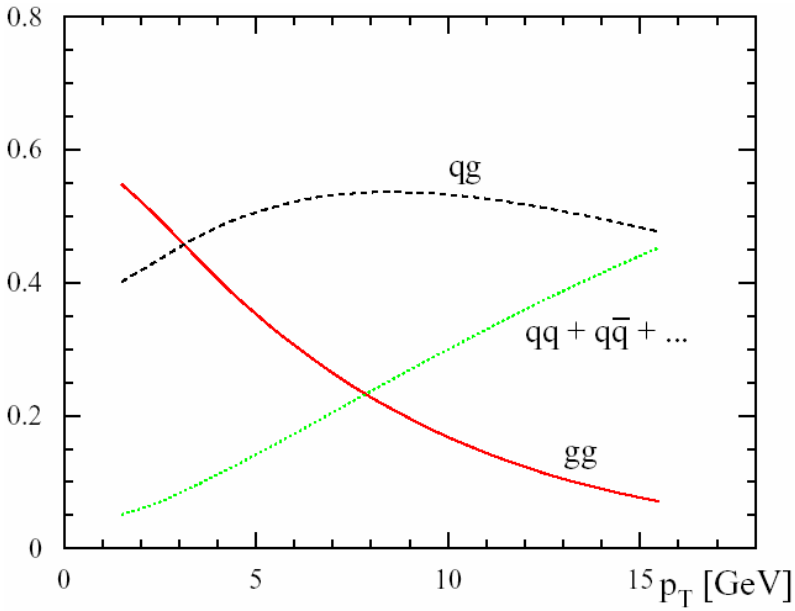
Good agreement with NLO QCD

A_{LL} of π^0

A_{LL} of π^0 has contributions from $\Delta g \cdot \Delta g$, $\Delta g \cdot \Delta q$, and $\Delta q \cdot \Delta q$:



Fractional contributions:

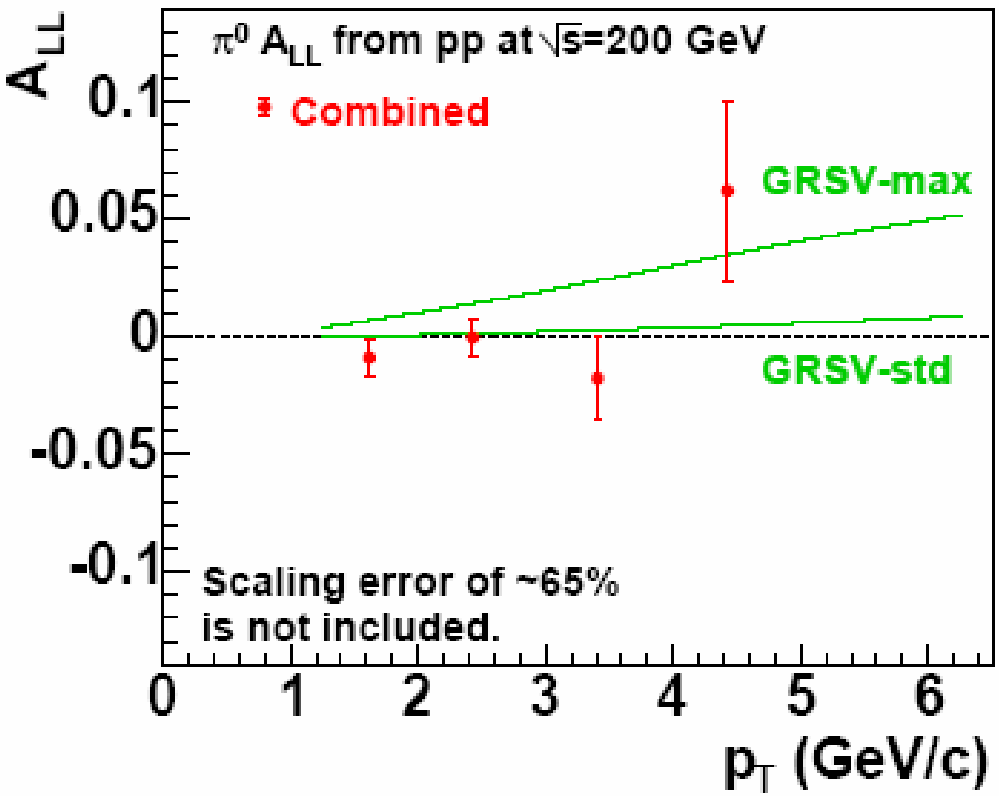


- At small p_T, A_{LL} depends on $(\Delta g)^2$
- At lager p_T, $(\Delta g \cdot \Delta q)$ becomes important

A_{LL} of π^0: PHENIX, run 3+4

PHENIX

RUN 3+4



$$A_{LL} \sim$$

$$R_{gg} \quad a_{LL}(gg \to gg) \quad \left(\frac{\Delta g}{g}(x)\right)^2$$

$$+R_{gu} \quad a_{LL}(gu \to gu) \quad \frac{\Delta g}{g}(x)\frac{\Delta u}{u}(x)$$

$$+R_{gd} \quad a_{LL}(gd \to gd) \quad \frac{\Delta g}{g}(x)\frac{\Delta d}{d}(x)$$

$$+R_{uu} \quad a_{LL}(uu \to uu) \quad \left(\frac{\Delta u}{u}(x)\right)^2$$

$$+R_{dd} \quad a_{LL}(dd \to dd) \quad \left(\frac{\Delta d}{d}(x)\right)^2$$

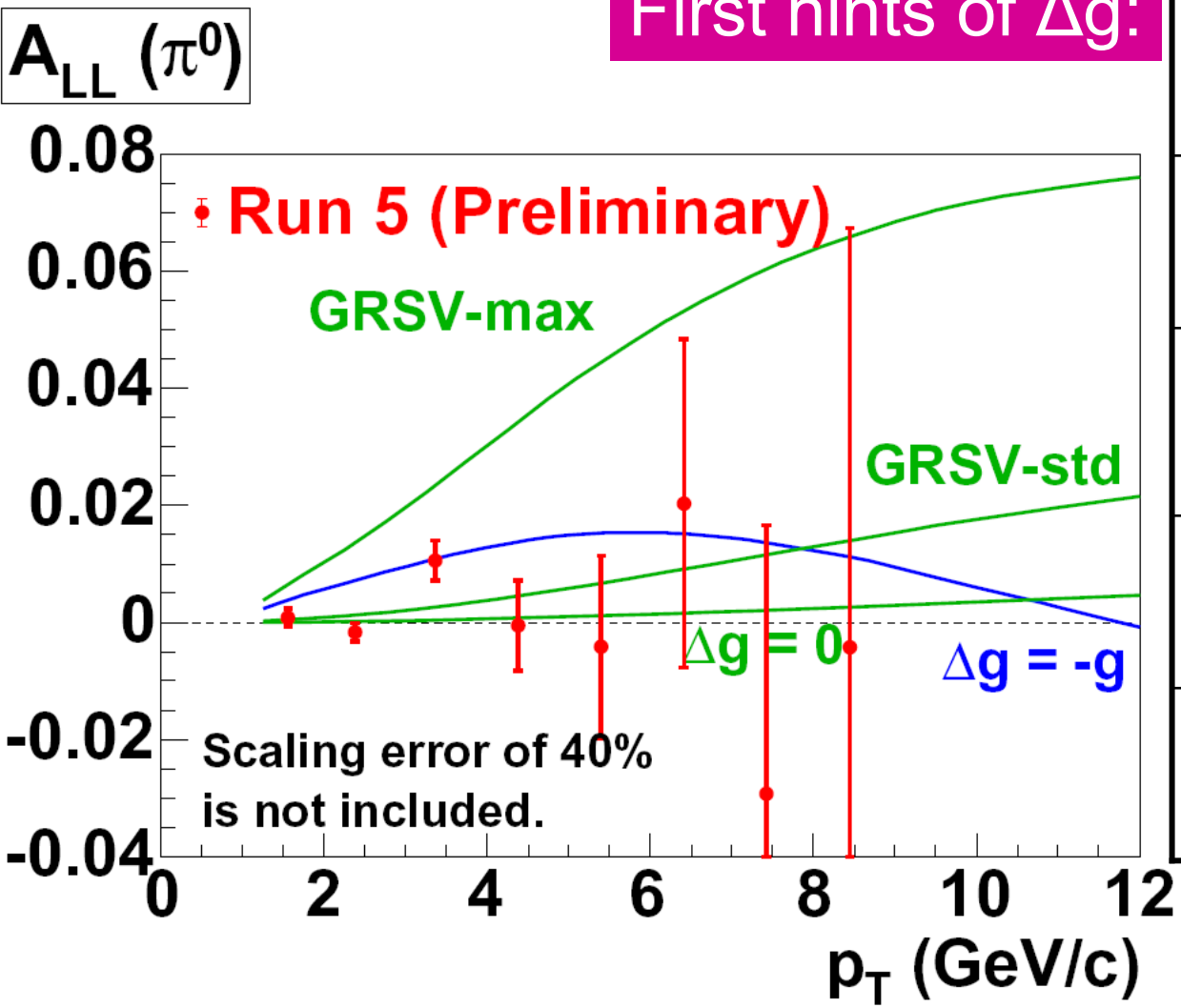
$$+R_{ud} \quad a_{LL}(ud \to ud) \quad \frac{\Delta u}{u}(x)\frac{\Delta d}{d}(x)$$

Δq/q input - from PDF

A_{LL} of π^0: PHENIX, 60% of run 5

K.Boyle, PANIC05

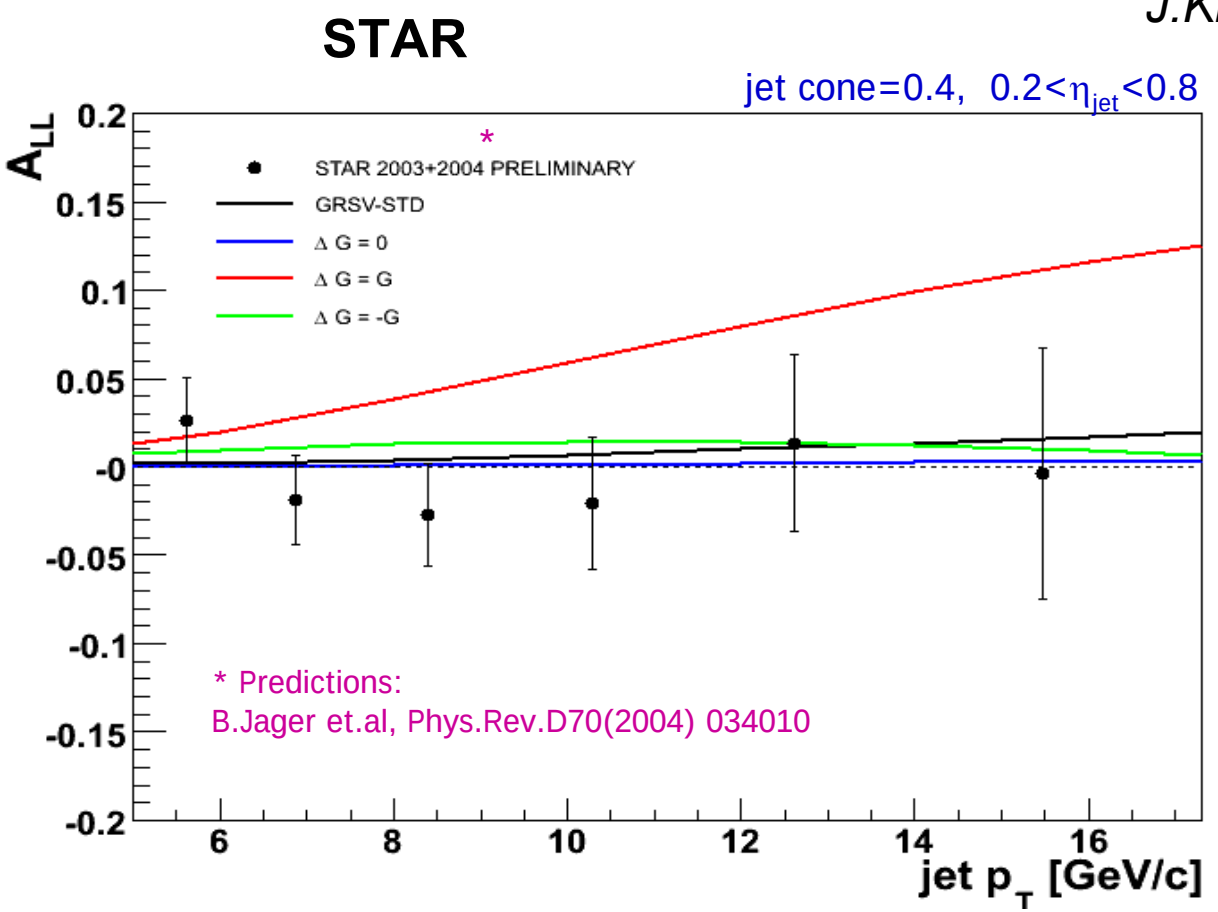
First hints of Δg:



Δg param. $Q^2=4GeV^2$	C.L. (%)
GRSV-std	17.1-21.7
GRSV-max (Δg=g)	0.0-0.0
GRSV-0 (Δg=0)	16.7-18.4
GRSV-min (Δg=−g)	0.0-0.7

A_{LL} of inclusive jets: STAR, run 3+4

J.Kiryluk, DNP2005



RUN 3+4
preliminary

Results limited by statistical precision

Total systematic uncertainty ~0.01 (STAR) + beam pol. (RHIC)

Δg at RHIC: outlook from RUN 5

- RUN 3: $0.2 pb^{-1}$ and 30%
  RUN 4: $0.2 pb^{-1}$ and 40%

- RUN 5 : $3 pb^{-1}$ and 50%.

→ Large increase in figure-of-merrit (x 40) compared to RUN 3+4!

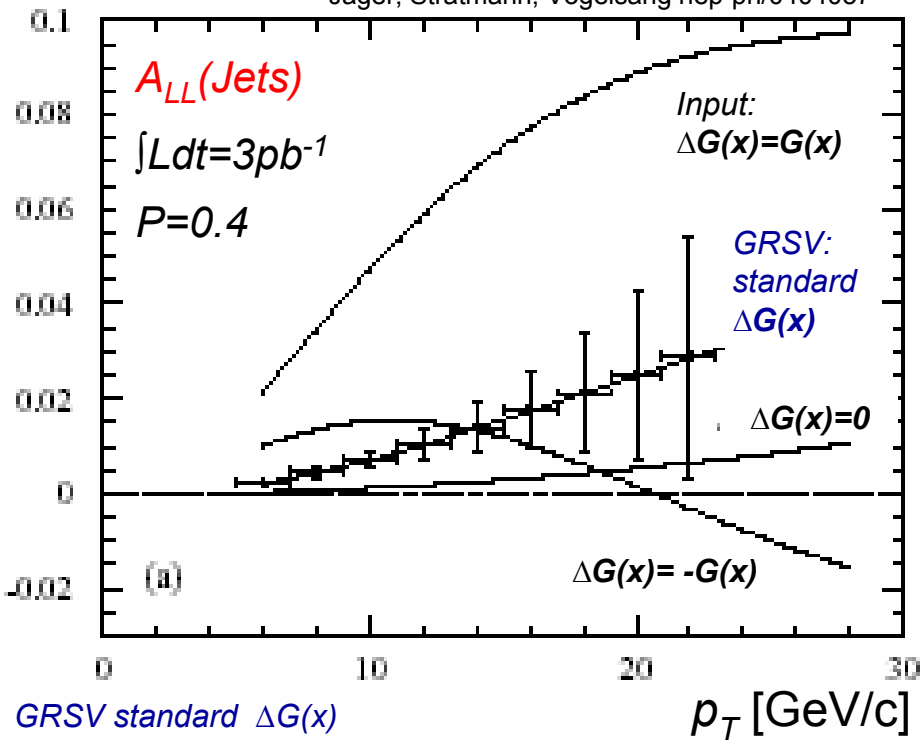
→ Potential to discriminate between the extreme scenarios for the gluon polarization distributions.

Δg at RHIC: outlook from RUN 5

M.Grosse-Perdekamp, Praha2005

A_{LL} in inclusive jet production (STAR)

Jager, Stratmann, Vogelsang hep-ph/0404057

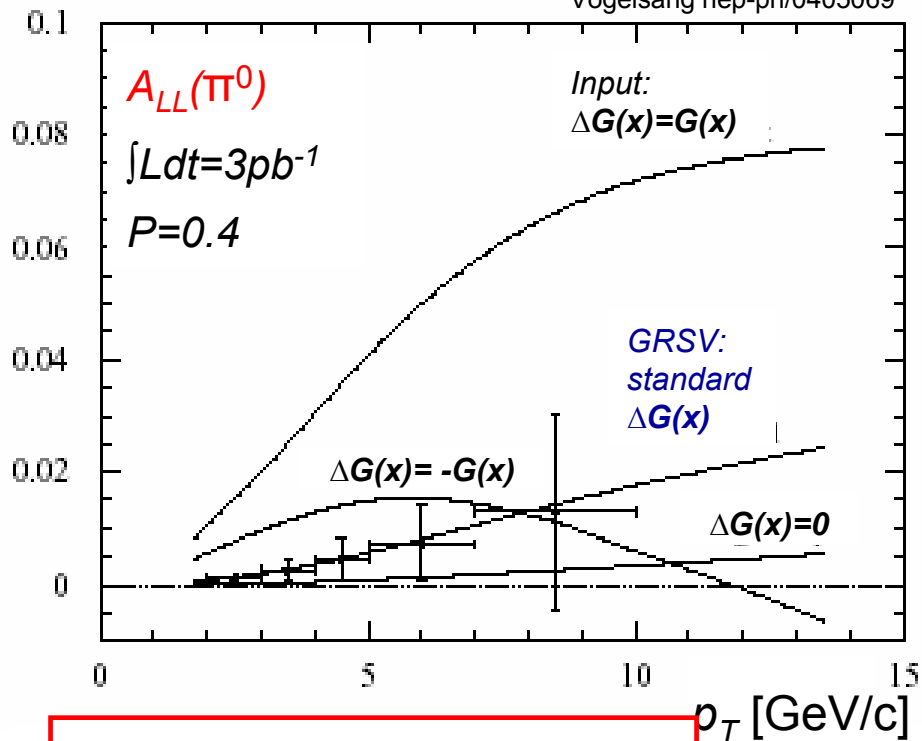


GRSV standard ΔG(x)

➔ Gluon distribution from NLO pQCD fit to DIS data on A_1, Gluck Reya, Stratmann, Vogelsang Phys. Rev. D63:094005, 2001

A_{LL} in inclusive π^0 production (PHENIX)

Vogelsang hep-ph/0405069



run 05: $\int Ldt \sim 3.0\ pb^{-1}$ $P = 0.45$

COMPASS conclusions

- Three independent results from COMPASS indicate that Δg (in LO) is small at $x_g \approx 0.1$
- Open charm result has the smallest theoretical uncertainty but requires more data to be statisticaly significant.
- High p_t, small Q^2 result has the smallest error,

$$\Delta g / g = 0.024 \pm 0.110$$

$$(\Delta g = 0.304 \pm 1.34 \text{ using g from GRV})$$

assuming correct simulation of physics by PYTHIA (in particular at small Q^2).

COMPASS outlook

- Reduction of statistical errors on $\Delta g/g$ by ~30% after including 2004 data:

- Further improvements in the analysis:
  - use Neural Networks to increase R_{PGF},
  - NLO analysis.(?)

- Resuming data taking in 2006 with improved experimental setup:
  - RICH upgrade,
  - larger acceptance of polarized target solenoid,
  - larger acceptance of ECAL, ...

ΔG outlook

- COMPASS will have more precise results from 2002 + 2003 +2004 + 2006 data at $x_g \approx 0.1$,

- STAR and PHENIX will be able to discriminate between different scenarios Δg for $x_g \approx 0.06 - 0.2$,

- HERMES – expect results at $x_g \approx 0.2$ from large p_t data using the deuteron target?

Whatever ΔG,
nucleon spin will remain

½ … ☺