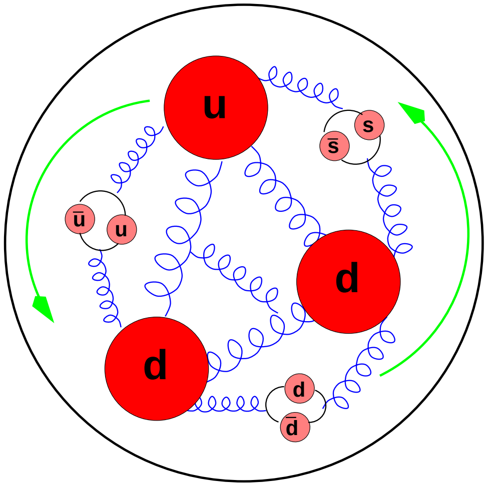
# Gluon polarisation and other polarised lepton scattering physics

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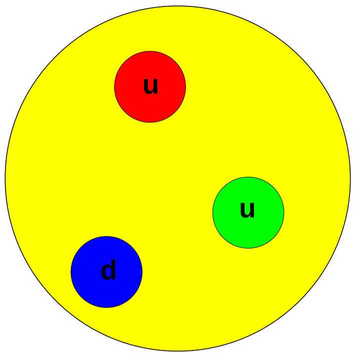
Physics in Collision, Prague 2005

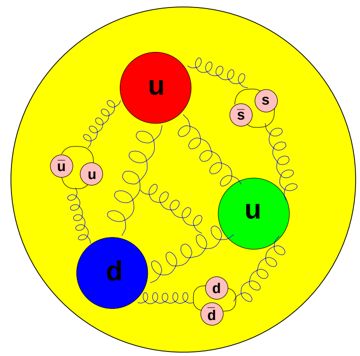
9. Juli 2005

# The spin of the nucleon

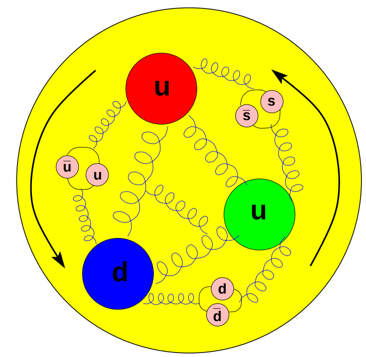



Naive parton model:
$\Rightarrow \Delta\Sigma = \Delta u_v + \Delta d_v = 1$

EMC (1988)
$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$




gluons important in
unpolarized case




complete description:
orbital angular momenta

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

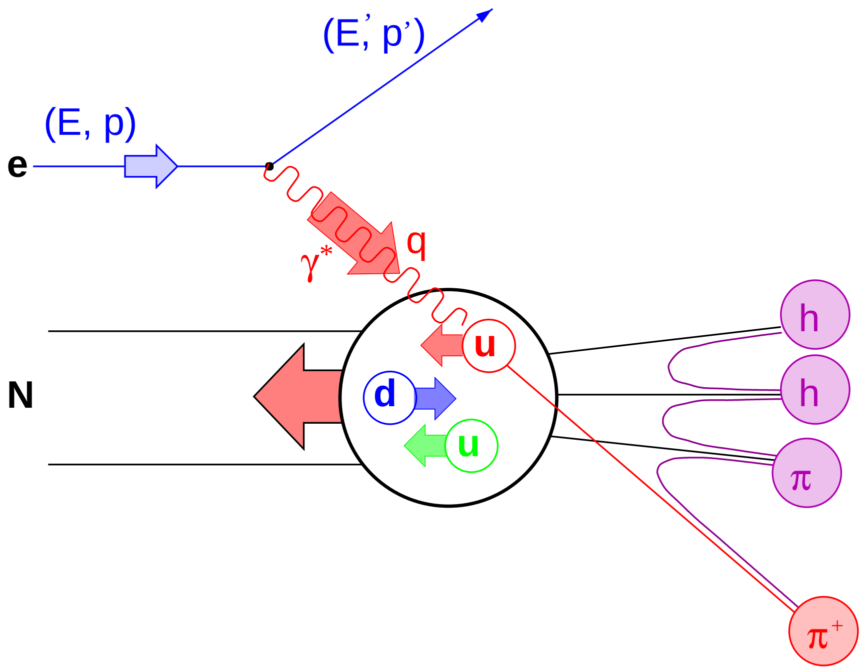
# Overview

- Introduction
- Polarised deep inelastic scattering
- Longitudinal spin structure functions
- Gluon polarisation

  Open Charm production
  High $p_{\mathrm{T}}$ hadron pairs
  $\pi^0$ asymmetries in pp collisions

- Transversity
- Outlook

# Deep inelastic scattering




$Q^2 = -q^2 \qquad x = Q^2/2M\nu$

$\nu = E - E' \qquad y = \nu/E$

$z \; = E_{\mathrm{h}}/\nu$

$p_{\mathrm{T}}$ : hadron transverse momentum

$D_{\mathrm{q}}^{\mathrm{h}}(x)$ : fragmentation function (from quark q into hadron h)

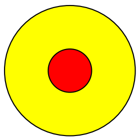
- **Inclusive cross section**

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}E'} \sim \underbrace{c_1 F_1(x,Q^2) + c_2 F_2(x,Q^2)}_{\text{spin independent}} + \underbrace{c_3 g_1(x,Q^2) + c_4 g_2(x,Q^2)}_{\text{spin dependent}}$$

$F_1$, $F_2$, $g_1$, $g_2$ structure functions

# Leading order quark distributions

spin averaged distributions

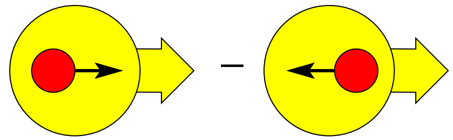
$q(x) =$ 

**unpolarised quark and nucleon**

vector–charge:

$$\langle PS|\overline{\psi}\gamma^{\mu}\psi|PS\rangle = \int_0^1 q(x) - \bar{q}(x)\, dx$$

helicity distributions

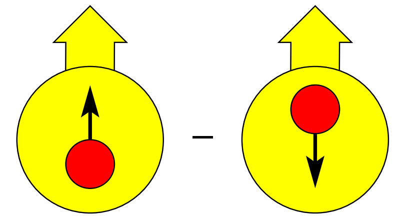
$\Delta q(x) =$ 

**longitudinally polarised quark and nucleon**

axial–charge:

$$\langle PS|\overline{\psi}\gamma^{\mu}\gamma_5\psi|PS\rangle = \int_0^1 \Delta q(x) + \Delta\bar{q}(x)\, dx$$

transverse distributions

$\Delta_T q(x) =$ 

**transversely polarised quark and nucleon**

tensor–charge:

$$\langle PS|\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle = \int_0^1 \Delta_T q(x) - \Delta_T\bar{q}(x)\, dx$$

all three PDFs equally important to describe the nucleon

# Spin averaged distributions

- **structure function $F_2$**

$$F_2(x) = x\Sigma_{\mathrm{q}}^{2N_f}\ e_{\mathrm{q}}^2\ q(x)$$

- **analysis of $Q^2$ dependence**

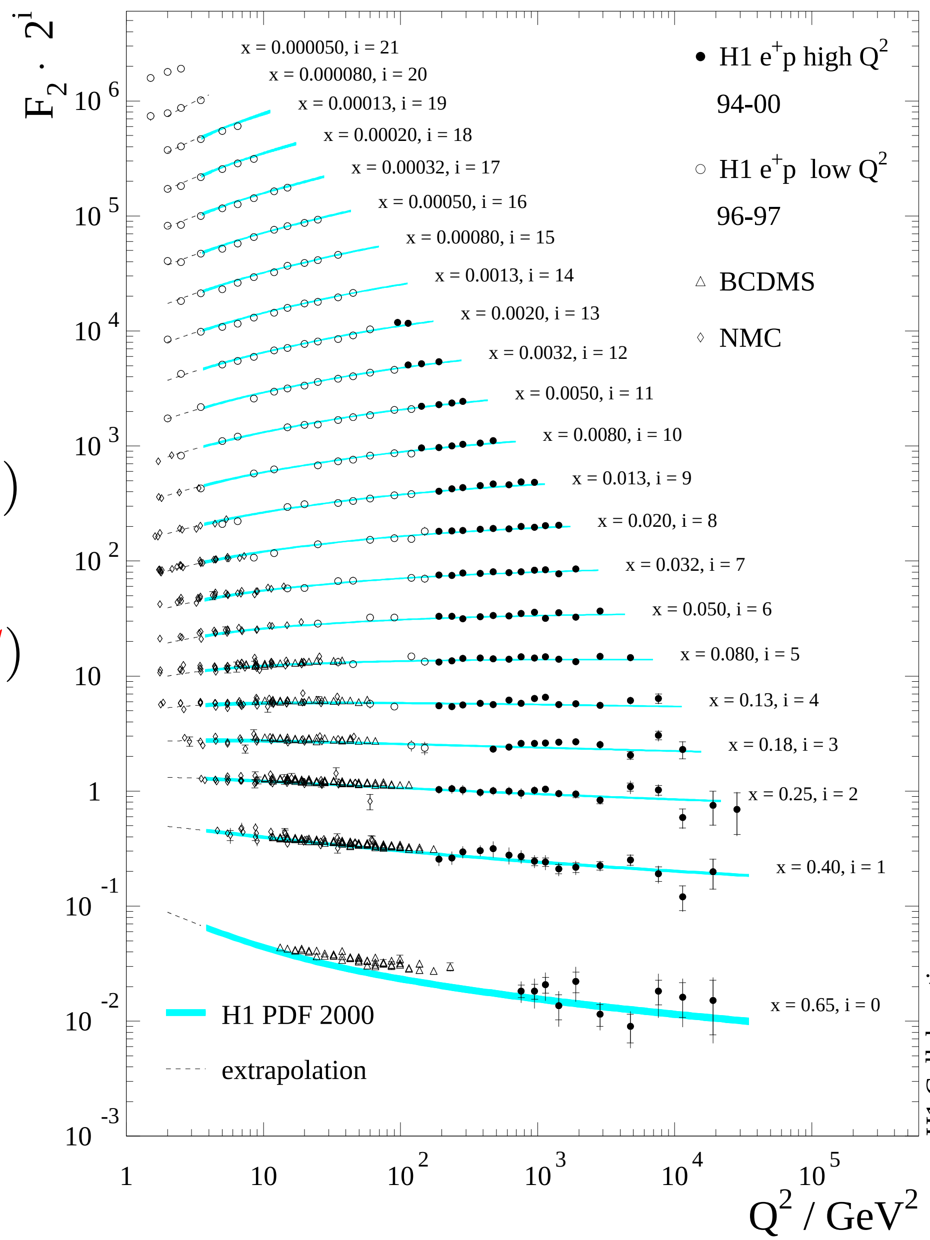
$$\frac{\mathrm{d}q(x,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}(P_{qq}\otimes q + P_{qg}\otimes G)$$

$$\frac{\mathrm{d}G(x,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}(P_{gq}\otimes q + P_{gg}\otimes G)$$

(DGLAP evolution equations)

- **extraction of $q(x)$ and $g(x)$**

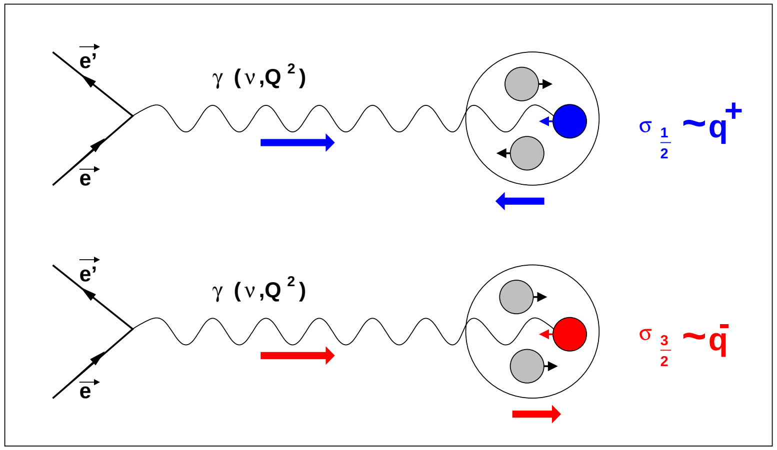
$q(x)$ and $G(x)$ well known



# Polarised deep inelastic scattering

# Polarised deep inelastic scattering

- **absorption of polarised photons (QPM)**




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

$+$ quark $\uparrow\uparrow$ nucleon
$-$ quark $\downarrow\uparrow$ nucleon

- **photon nucleon asymmetry**

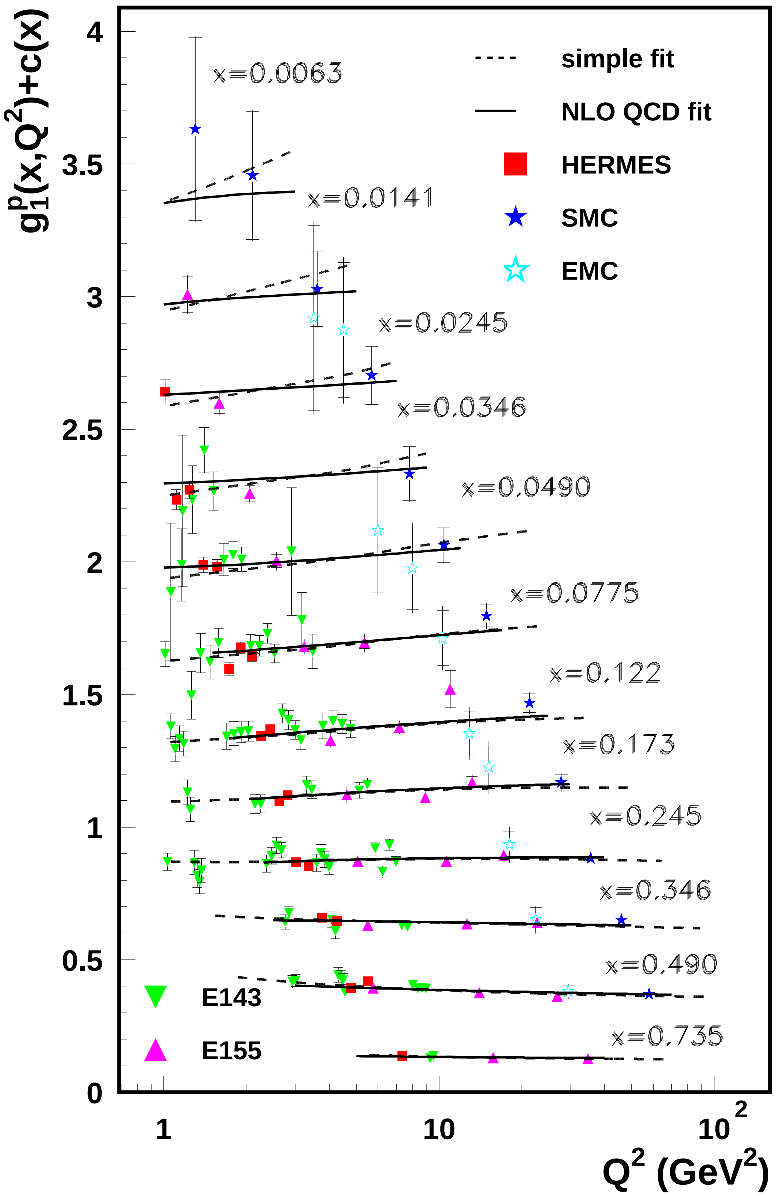
$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\Sigma_q\ e_q^2\ (q(x)^{+} - q(x)^{-})}{\Sigma_q\ e_q^2\ (q(x)^{+} + q(x)^{-})} = \frac{g_1(x)}{F_1(x)}$$

- **experimental asymmetry**

$$A_{\mathrm{exp}} = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$
$$= p_{\mathrm{B}}\ p_{\mathrm{T}}\ f\ A_{\|} \approx p_{\mathrm{B}}\ p_{\mathrm{T}}\ f\ D\ A_1$$

$p_{\mathrm{B}}$, $p_{\mathrm{T}}$ beam and target polarisation
$f$ dilution factor
$D$ polarisation transfer

# Polarised distributions




- **longitudinal spin structure**

$$g_1(x) = \frac{1}{2}\Sigma_{\rm q}^{2N_f}\ e_{\rm q}^2\ \Delta q(x)$$

- **moments**

$a_q = \int_0^1 \Delta q(x) \mathrm{d}x$ contribution of quarks q

$a_0 = a_{\rm u} + a_{\rm d} + a_{\rm s}$ contribution all quarks

- **E155 QCD analysis**

**axial charge $a_0 (= \Delta\Sigma)$**

$$a_0 = 0.23 \pm 0.07\ (\mathrm{sta})\ \pm 0.19\ (\mathrm{sys\&th})$$

**first moment of $\Delta G(x)$**

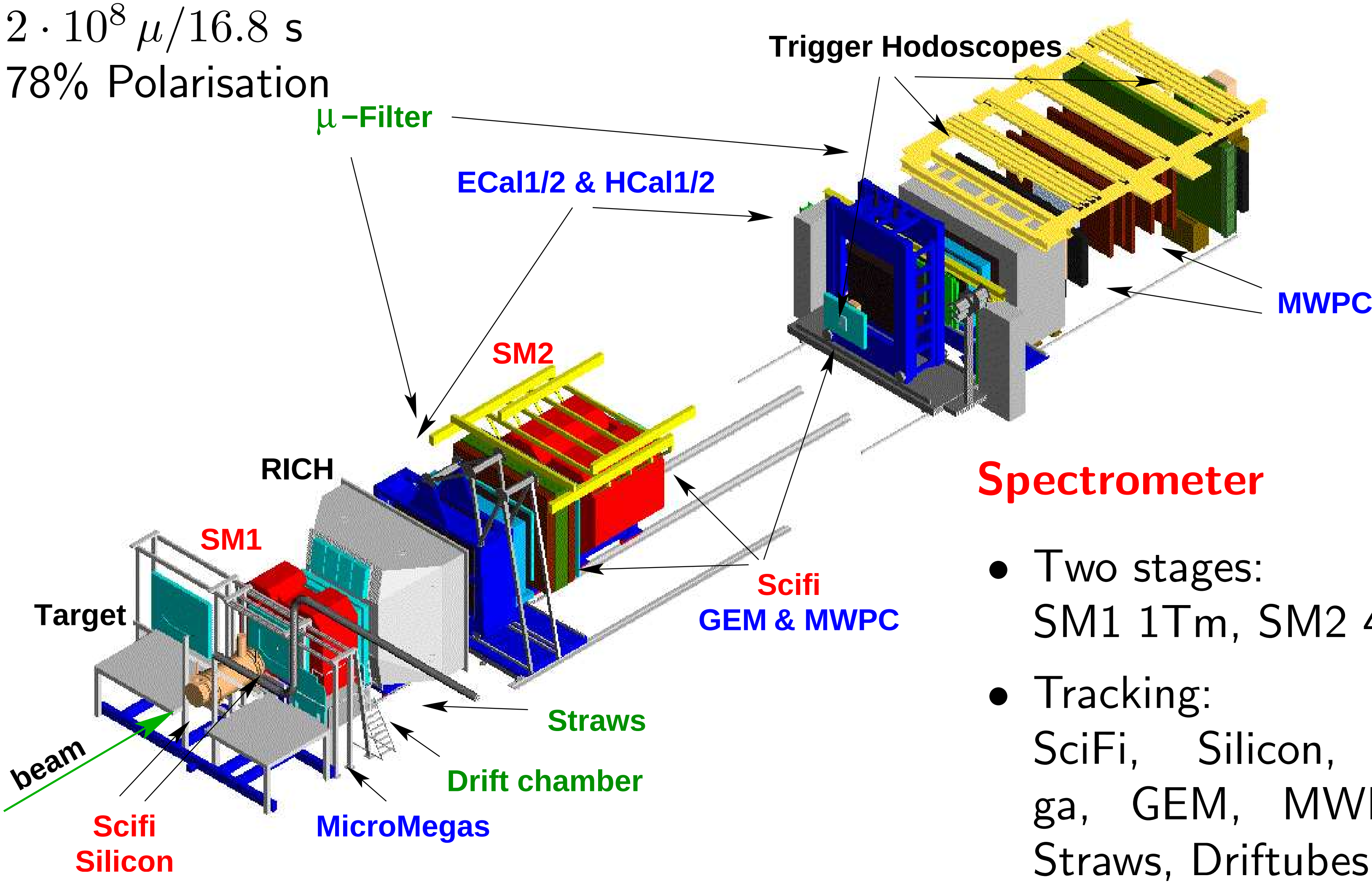
$$a_g = 0.99\ ^{+1.17}_{-0.31}\ (\mathrm{sta})\ ^{+0.42}_{-0.22}\ (\mathrm{sys})\ ^{+1.43}_{-0.45}\ (\mathrm{th})$$

# Experiments

Muon beam

# COMPASS at CERN

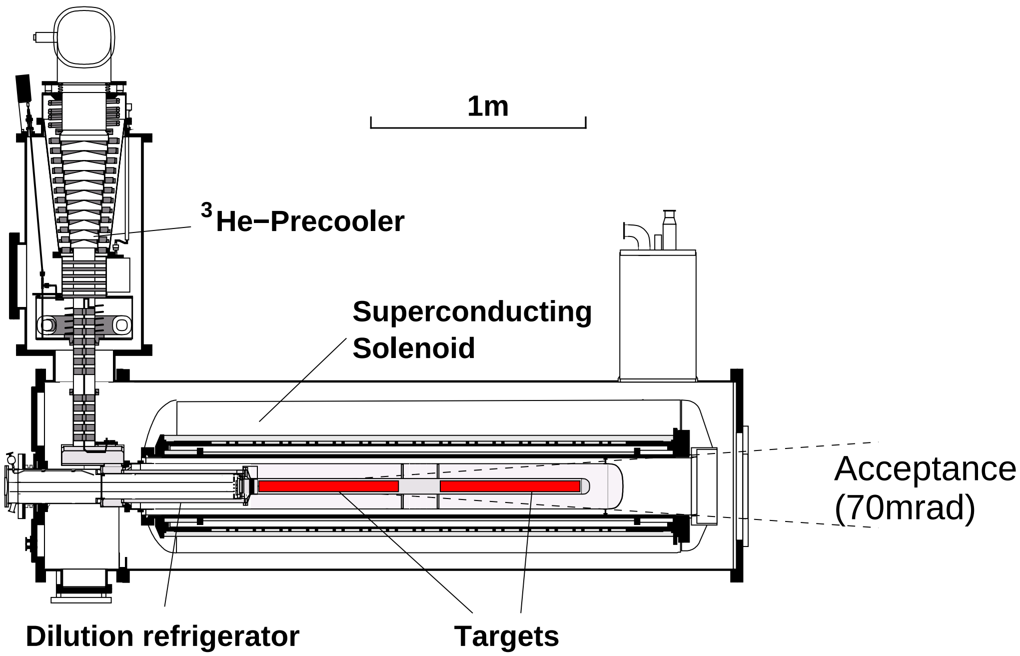
160 GeV/c
$2 \cdot 10^8\, \mu/16.8$ s
78% Polarisation




## Spectrometer

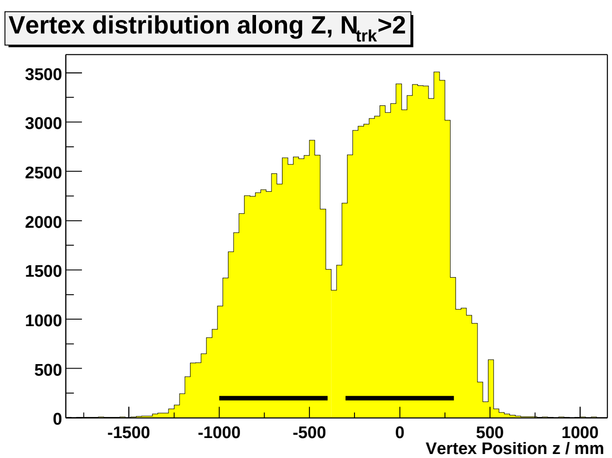
- Two stages:
  SM1 1Tm, SM2 4.5Tm
- Tracking:
  SciFi, Silicon, MicroMega, GEM, MWPC, Drift, Straws, Driftubes
- PID: RICH, ECAL, HCAL, muon filter

# The polarised target



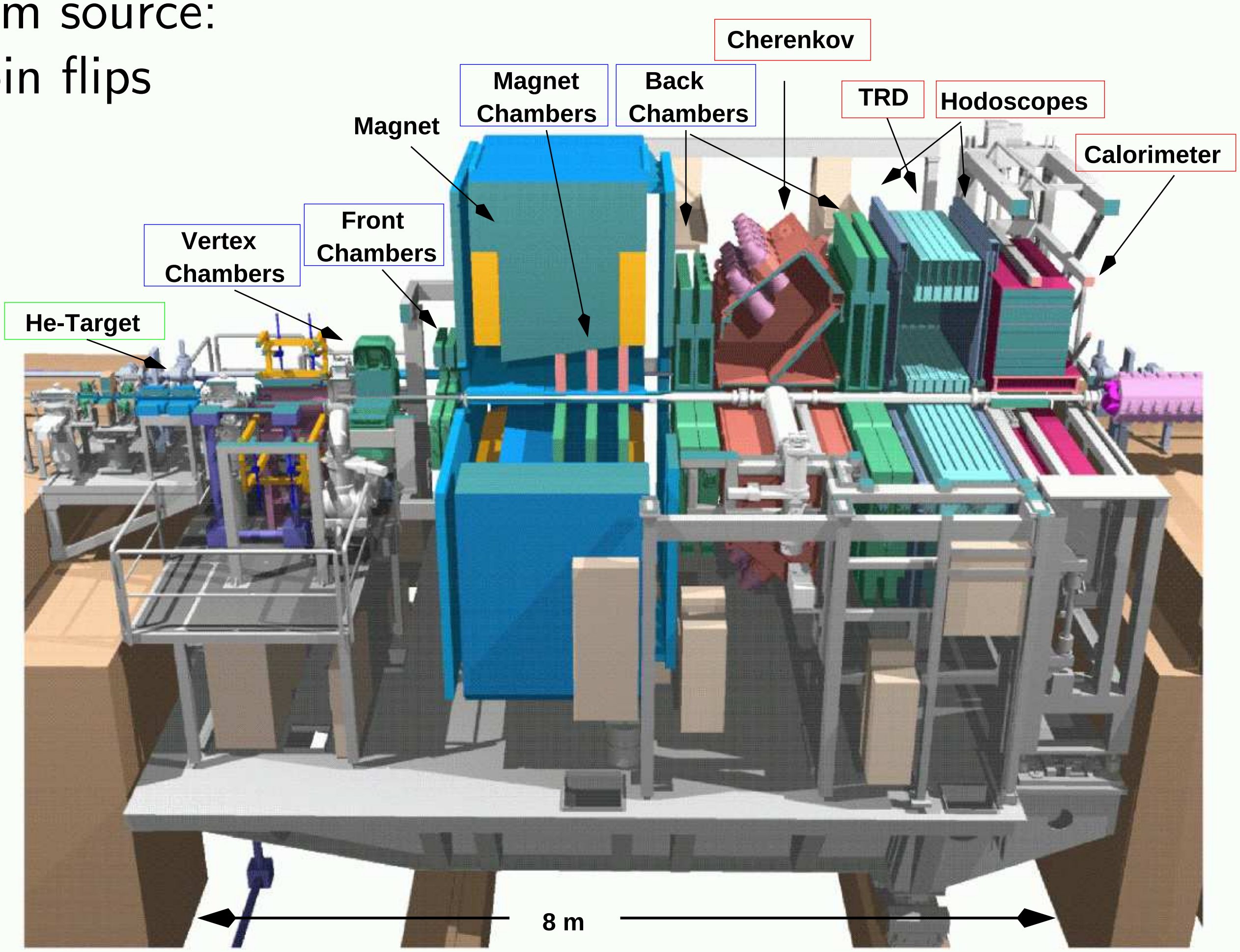

- target material: $^{6}$LiD
- polarisation: $> 50\%$
- dilution factor: $\sim 0.4$
- Dynamic Nuclear Polarization
- solenoid field: 2.5 T
- $^3$He/$^4$He: $T_{min} \approx$ 50 mK
- two 60 cm long target cells with opposite polarisation
- 2006 new solenoid with 180 mrad acceptance

- Reconstructed interaction vertices



# HERMES at DESY

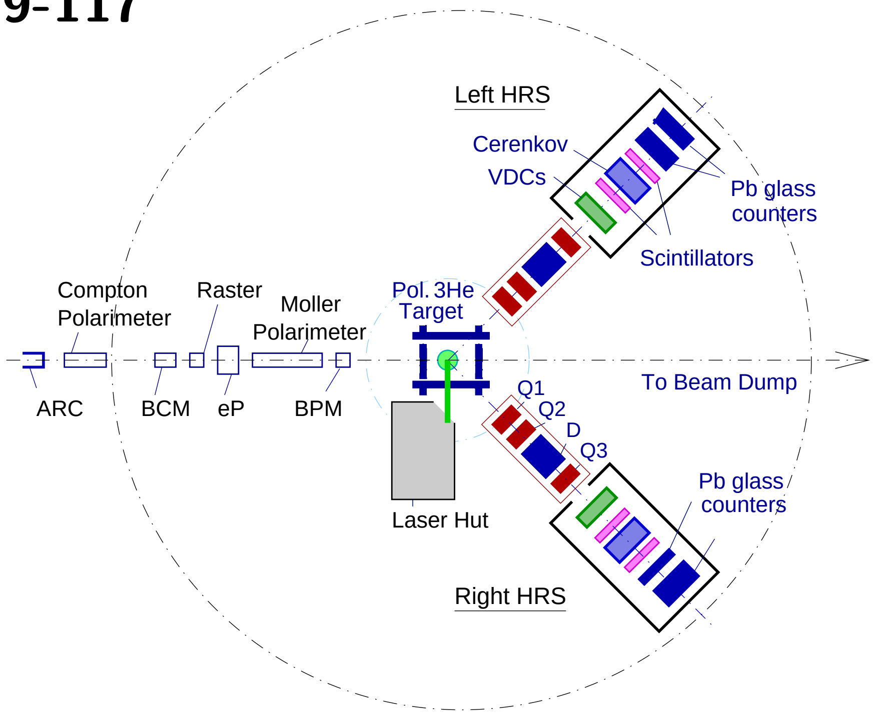
- atomic beam source:
  frequent spin flips




- positron identification: TRD, preshower + calorimeter
- PID: dual radiator RICH for $2 < p < 20$ GeV
- acceptance: $40 < \theta < 220$ mrad

# Experiments at JLAB

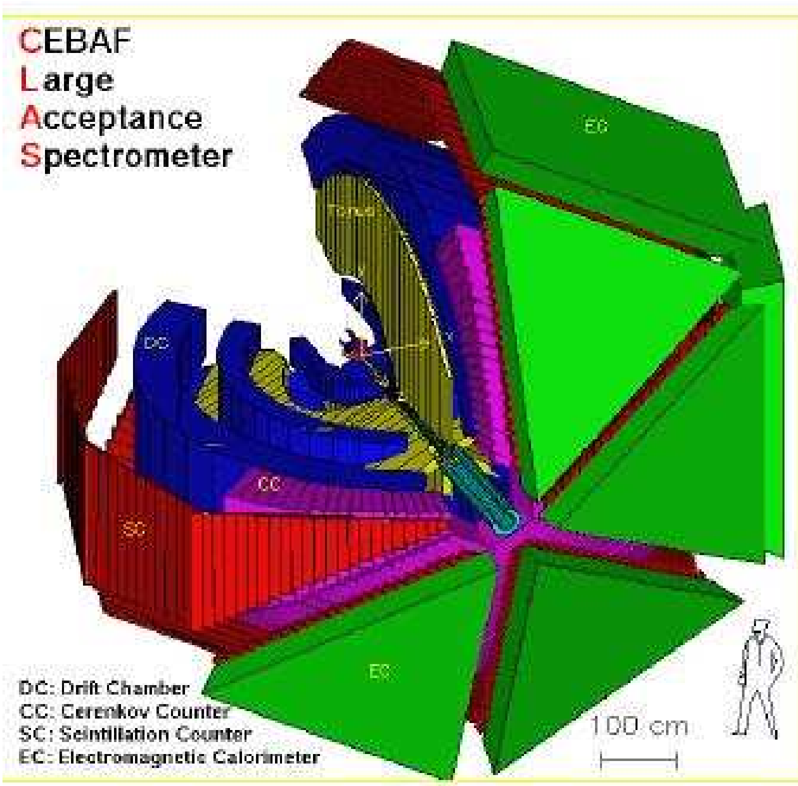
## E99-117



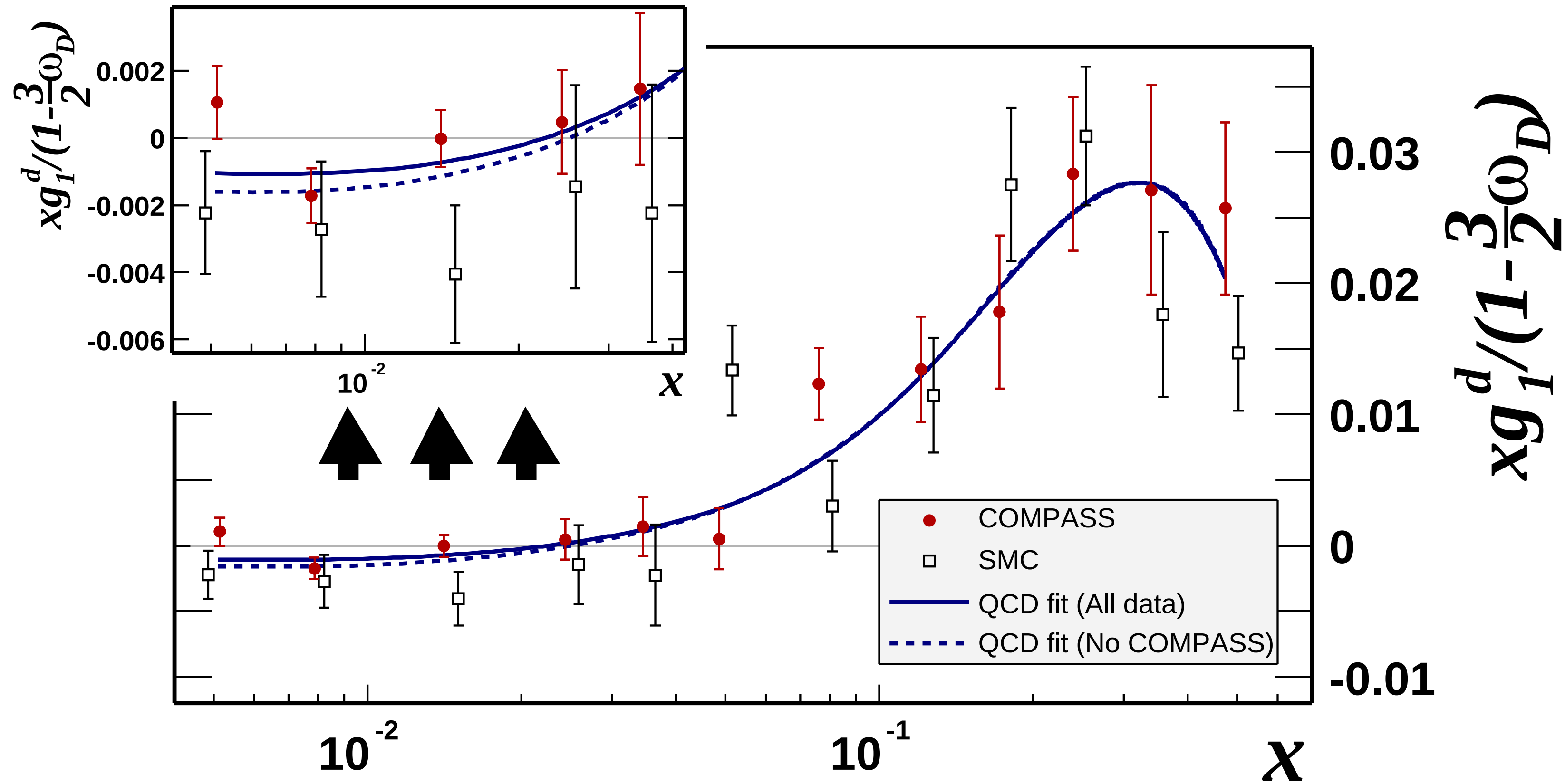

- **electron beam:** 5.7 GeV, 80% polarisation
- **$^3$He target:** 40% polarisation
- **kinematic range:** 2.7 GeV$^2 < Q^2 < 4.8$ GeV$^2$, $W > 2$ GeV

## CLAS

- **measurement** of $A_1^{\mathrm{p}}$ and $A_1^{\mathrm{d}}$ for $0.2 < x < 0.6$
- **kinematic range:** 1.4 GeV$^2 < Q^2 < 4.5$ GeV$^2$, $W > 2$ GeV

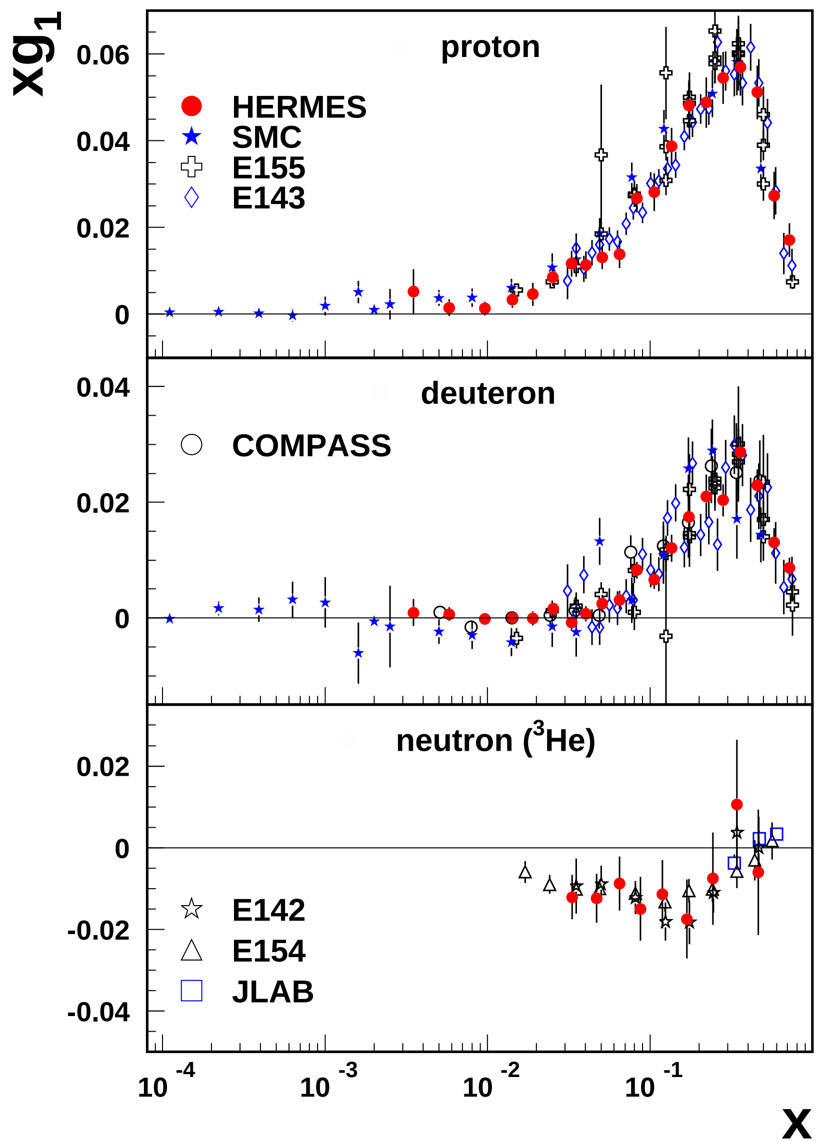


# $g_1$ at low $x$ (COMPASS)




- high statistics $A_1^{\rm d}$ at low $x$ for $Q^2 > 1$ GeV$^2$
- COMPASS systematically above SMC at low $x$
- $xg_1$ points at measured $Q^2$
- QCD fit to world data: $\Delta\Sigma = 0.202^{+0.042}_{-0.077} \longrightarrow 0.237^{+0.024}_{-0.029}$

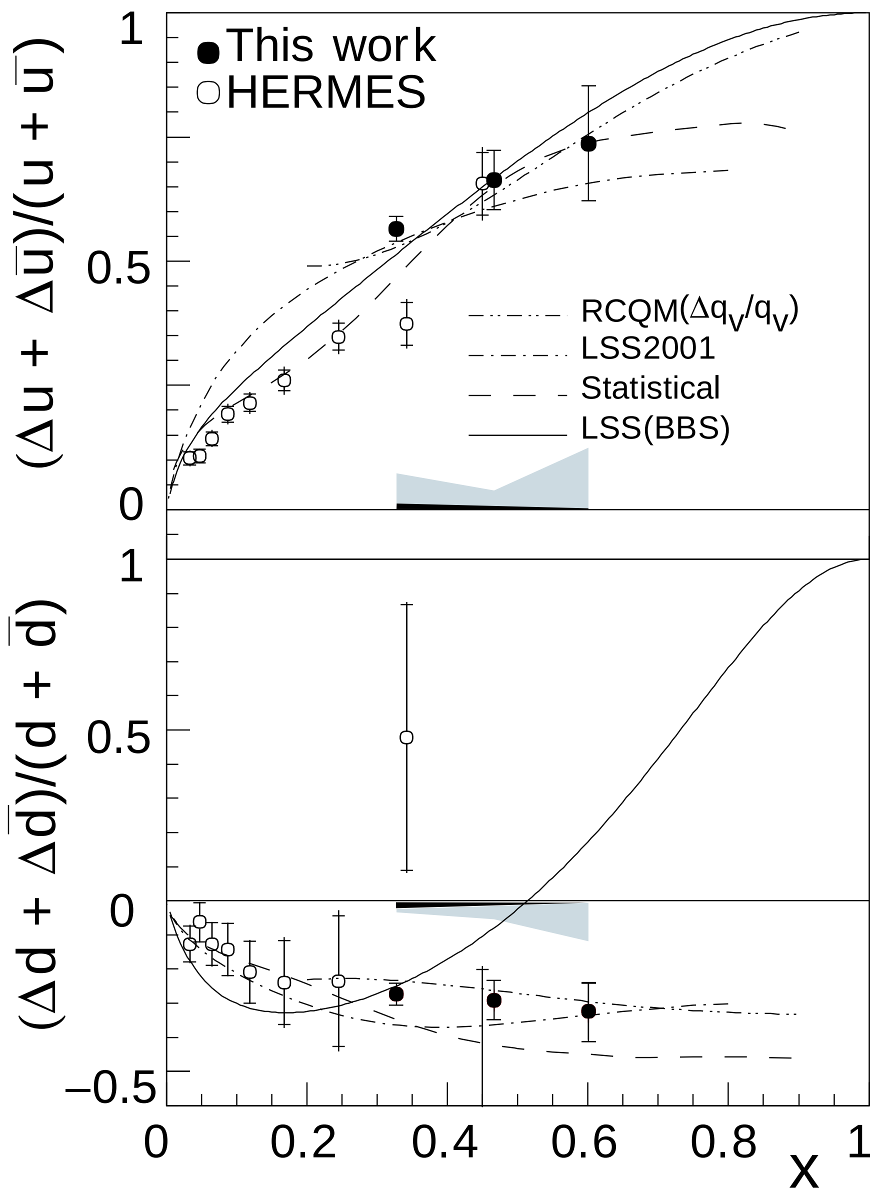
# Final $g_1$ data (HERMES)



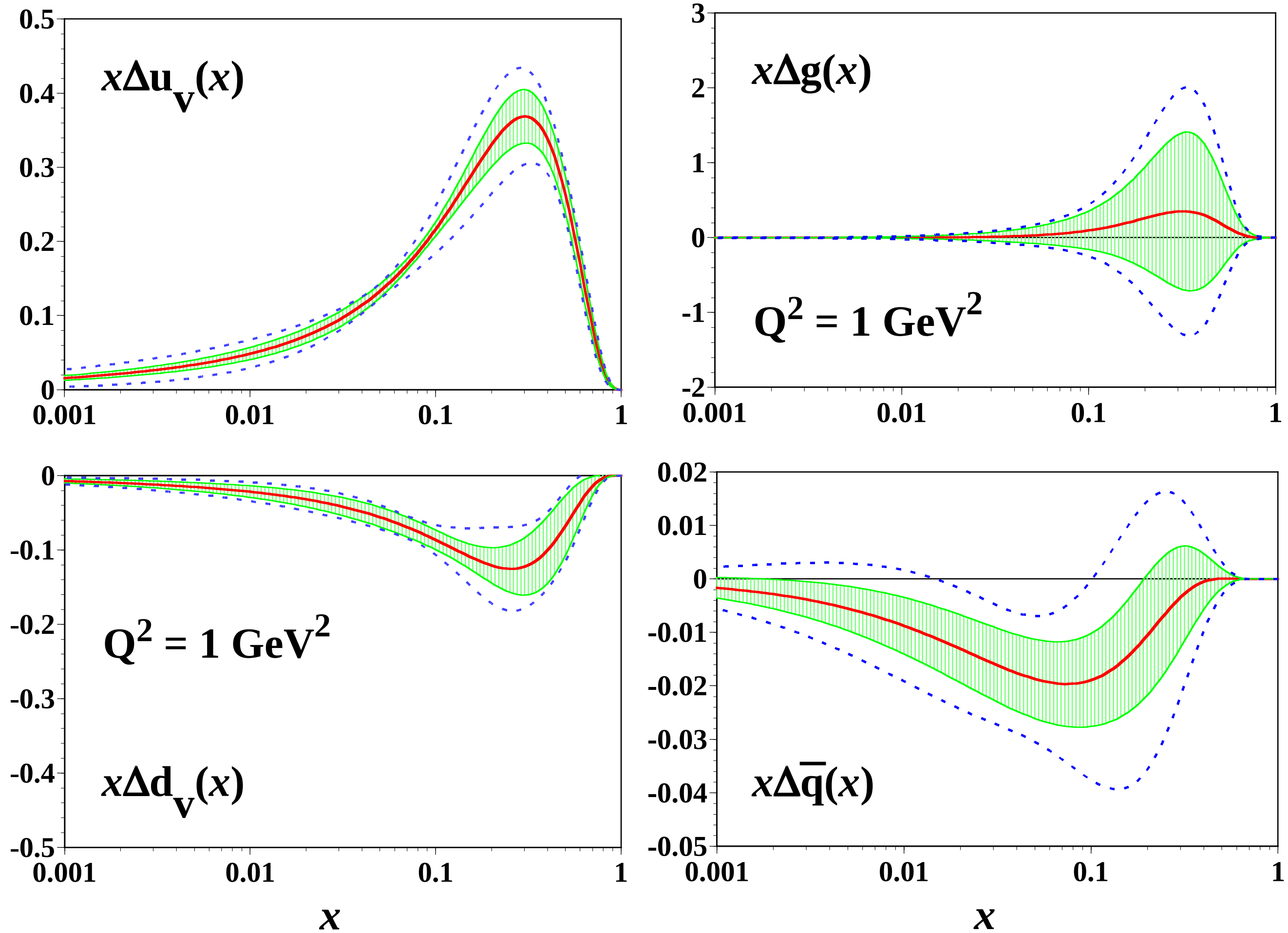

- High statistics measurement of $A_1^{\mathrm{p}}$ and $A_1^{\mathrm{d}}$
- New method for smearing corrections (rad. corr. and resolution)
- Statistical correlations between $x$ bins
- Improvement of integrals in the measured range

# $g_1$ at high $x$ (JLAB)

- E99-117 result for $A_1^n$
- $A_1^n > 0$ at $x > 0.5$
- combining with $A_1^p$ results: $\Delta u/u > 0$, but $\Delta d/d < 0$
- pQCD expectation: $\Delta u/u = \Delta d/d = 1$ at high $x$
- hint for quark orbital angular momentum



# Polarised parton distributions

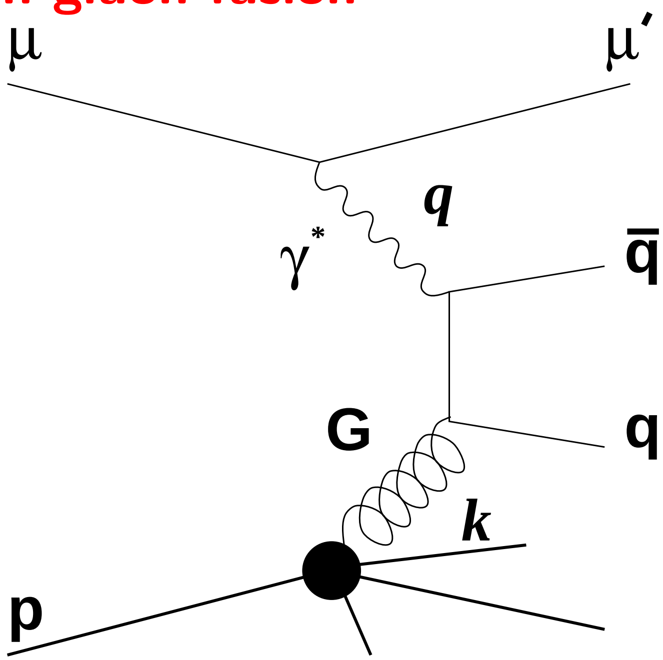



- Recent AAC03 analysis using all published data except final HERMES
- Valence quark distributions well determined, antiquark distribution larger errors
- Polarised gluon distribution not determined

# Gluon polarisation

# $\Delta G/G$ measurement in DIS

- **Photon gluon fusion**




$$A_{\gamma \mathrm{N}}^{\mathrm{PGF}} = \frac{\int \mathrm{d}\hat{s}\, \Delta\sigma^{\mathrm{PGF}} \Delta G(x_{\mathrm{g}}, \hat{s})}{\int \mathrm{d}\hat{s}\, \sigma^{\mathrm{PGF}} G(x_{\mathrm{g}}, \hat{s})}$$

$$\approx \langle a_{\mathrm{LL}}^{\mathrm{PGF}} \rangle \frac{\Delta G}{G}$$

$\langle a_{\mathrm{LL}}^{\mathrm{PGF}} \rangle$ analysing power

- **Methods**
  - **Open charm production**

    $\gamma \mathrm{g} \rightarrow \mathrm{c}\bar{c}$

    $\rightarrow \mathrm{D}^0 \rightarrow \pi \mathrm{K}$ BR: 4%

    scale: $m_{\mathrm{c}}^2$

    clean channel,
    limited staticstics

  - **High $p_{\mathrm{T}}$ hadron pairs**

    $\gamma \mathrm{g} \rightarrow \mathrm{q}\bar{q}$

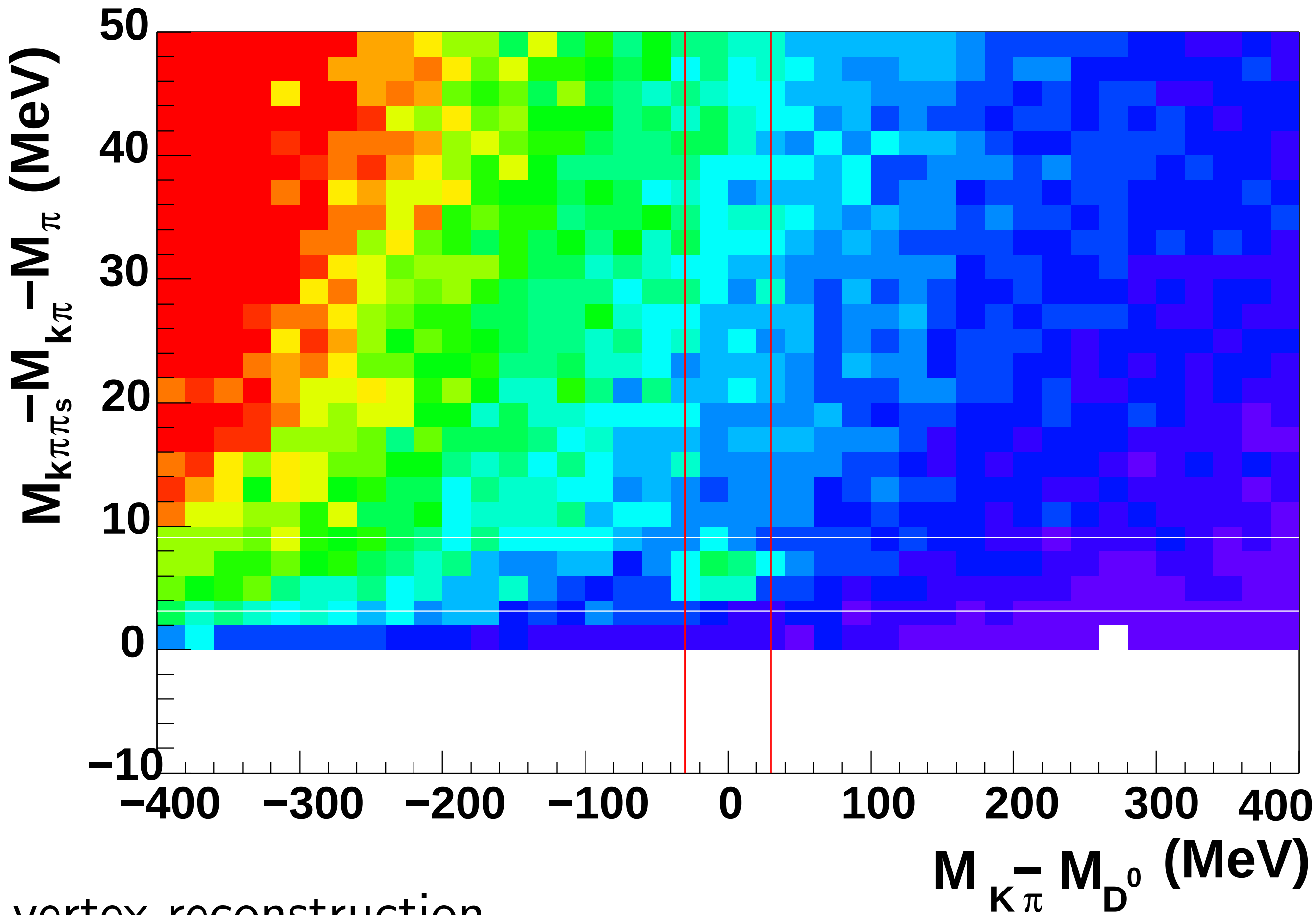
    $\rightarrow$ 2 jets or $\mathrm{H}^+\mathrm{H}^-$

    scale: $Q^2$ or $\Sigma p_{\mathrm{T}}^2$

    oppositely charged hadrons pairs with large $p_{\mathrm{T}}$ und $\Delta\Phi \approx \pi$

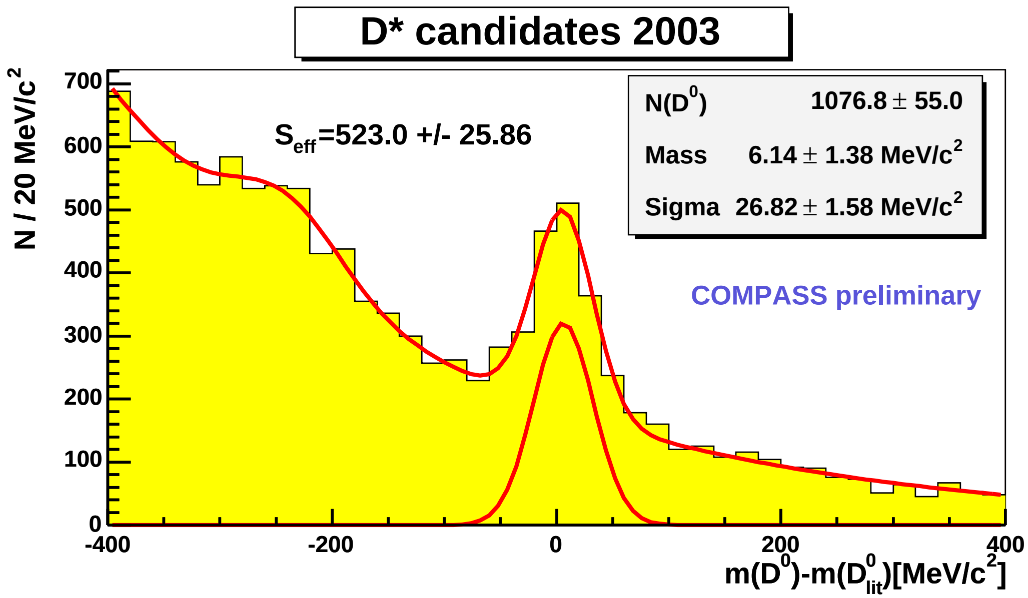
# $\Delta G$ from open charm

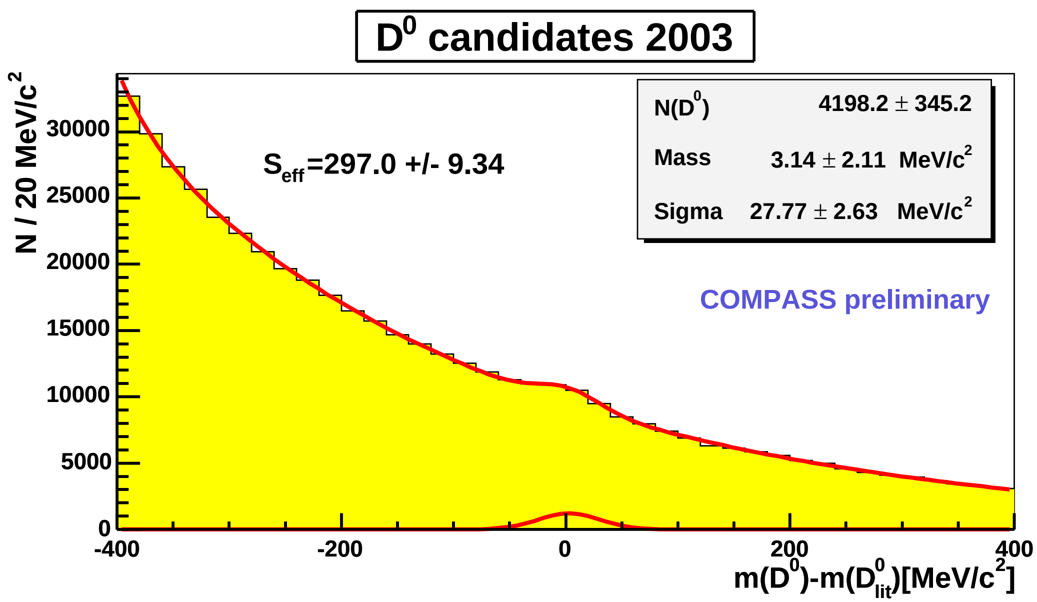
$D^*$ **tagging:** $D^* \longrightarrow D^0\pi_{\text{slow}} \longrightarrow (K\pi)\pi_{\text{slow}}$




- No decay vertex reconstruction
- Kaon identification by RICH essential
- Cut on mass difference $M_{K\pi\pi} - M_{K\pi} - M_\pi$

# Mass spectra




- 1500 $D^0$ from $D^*$
- Effective signal

$$S_{\text{eff}} = \frac{S}{1 + S/B}$$

- Experimental asymmmetry

$$A_{\text{exp}} = p_\mu \, p_{\text{T}} \, f \, a_{\text{LL}} \, \frac{S}{S+B} \, \frac{\Delta G}{G}$$

- No physics background

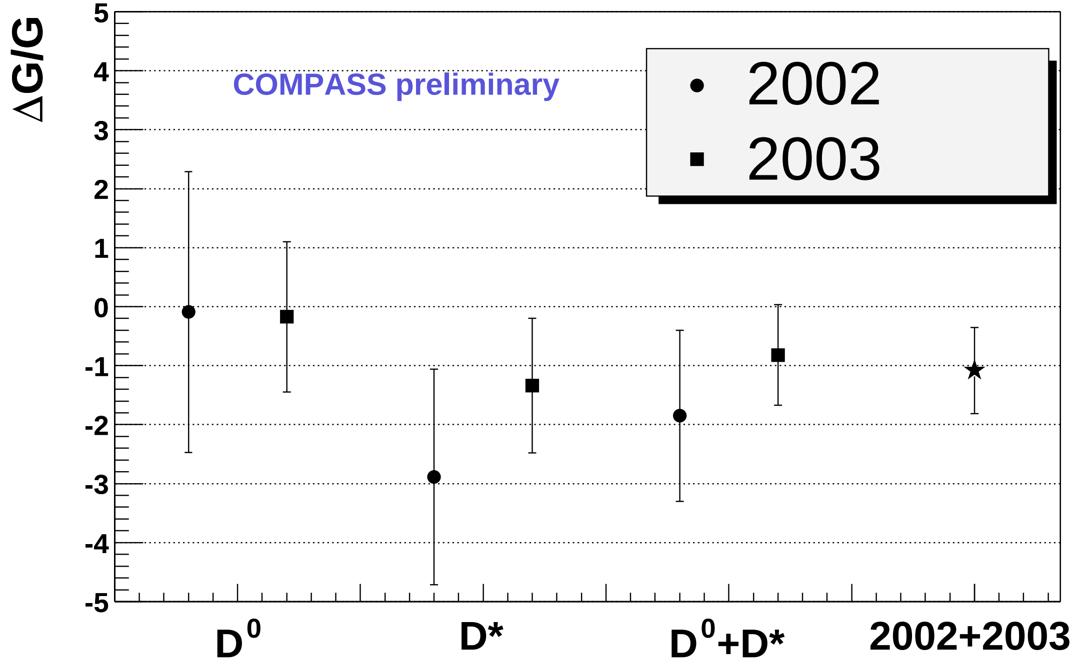
# Extraction of $\Delta G/G$

- needs $\langle a_{\mathrm{LL}}^{\mathrm{PGF}} \rangle$
  calculated from MC

- AROMA generator

- good description of
  data distributions by MC

- preliminary result
  at $\langle x_{\mathrm{g}} \rangle = 0.15$ (RMS 0.08)
  from 2002+2003

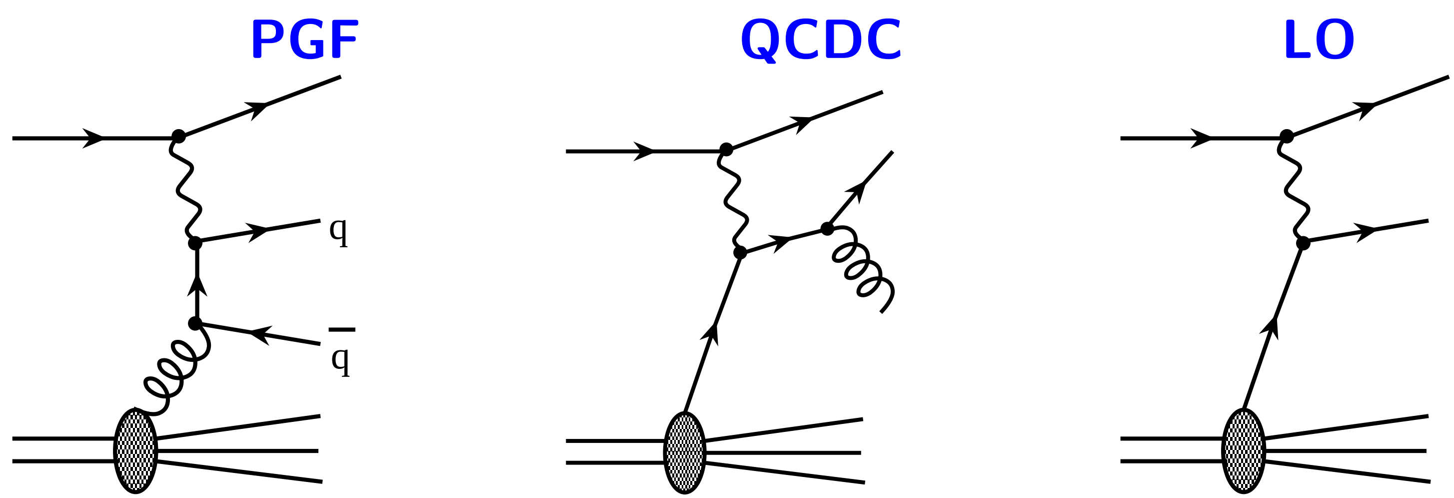



$$\Delta G/G = -1.08 \pm 0.73\,(\text{stat})$$

- improvements with 2004 data
  and additional channels

# High $p_T$ hadron pairs ($Q^2 > 1$ GeV$^2$)

- contributions to experimental asymmetry




$$\frac{A_{\parallel}}{D} = R_{\mathrm{PGF}} \left\langle \frac{A_{LL}^{\mathrm{PGF}}}{D} \right\rangle \frac{\Delta G}{G} + \left( R_{\mathrm{QCDC}} \langle A_{LL}^{\mathrm{QCDC}} \rangle + R_{\mathrm{LO}} \langle A_{LL}^{\mathrm{LO}} \rangle \right) A_1^{\mathrm{d}}$$

- Monte Carlo for $R$, $\langle A_{LL} \rangle$
- data selection

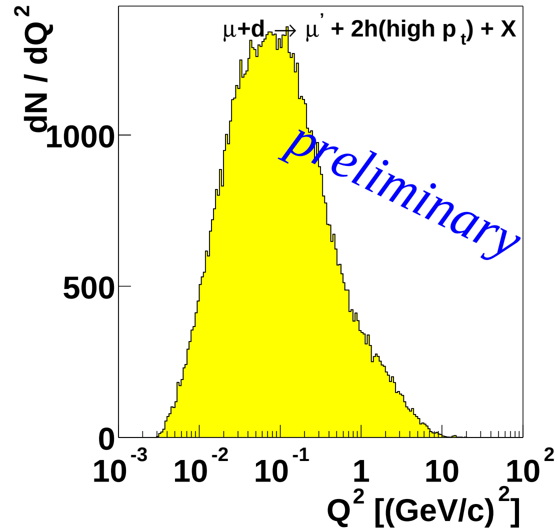
Current fragmentation: $x_F > 0.1$ and $z > 0.1$
Radiative corrections/ photon polarisation: $0.1 < y < 0.9$
High $p_{\mathrm{T}}$: $p_{\mathrm{T},1}, p_{\mathrm{T},2} > 0.7$ GeV and $p_{\mathrm{T},1}^2 + p_{\mathrm{T},2}^2 > 2.5$ GeV$^2$

# $\Delta G/G$ for $Q^2 > 1$ GeV$^2$

- 2002/03 data

$$A_{\|}/D = -0.015 \pm 0.080(\text{stat.}) \pm 0.013(\text{syst.})$$

- Monte Carlo sample generated with LEPTO reasonable agreement with data




- additional $x$ cut $\Rightarrow$ $A_1^{\rm d}$ small, LO and QCDC neglected

- $\langle \frac{A_{LL}^{\rm PGF}}{D} \rangle = -0.75 \pm 0.05$
  $R_{\rm PGF} = 0.33 \pm 0.07$, $\langle x_g \rangle = 0.13$ (RMS 0.08)

$$\Delta G/G = 0.06 \pm 0.31(\text{stat.}) \pm 0.06(\text{syst.})$$

- expectation for 2002-2004: $\delta(\Delta G/G) = 0.22$

- only 10% of statistics at $Q^2 > 1$ GeV$^2$

- single hadron analysis started

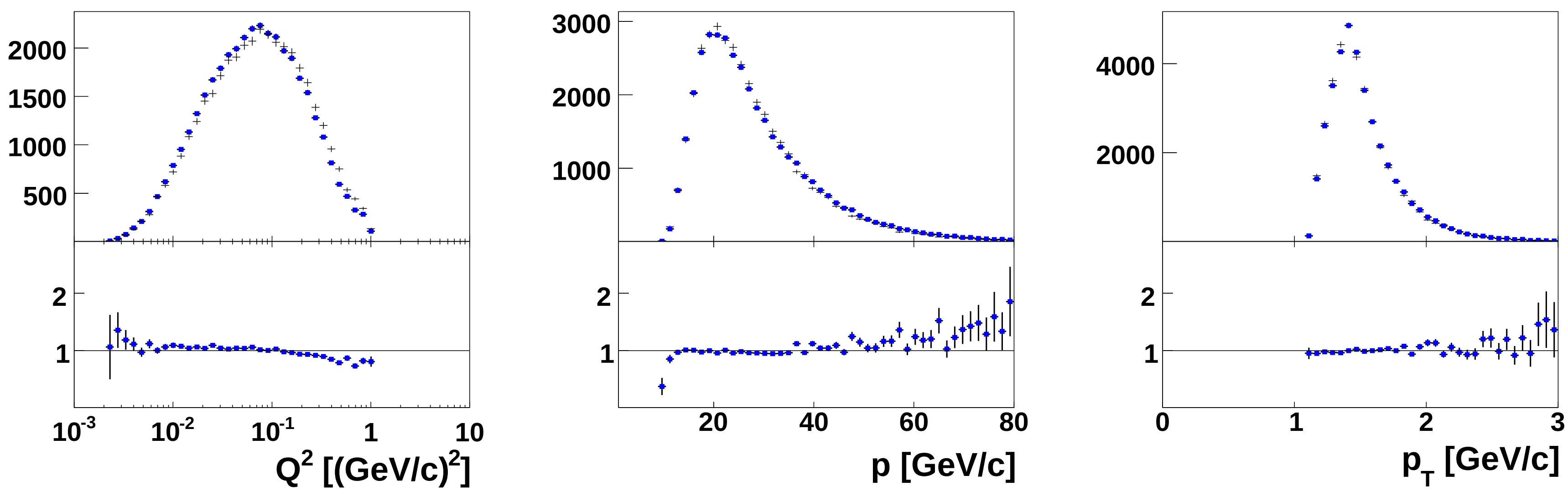
# $\Delta G/G$ for $Q^2 < 1$ GeV$^2$

- Much more statistics
  but additional background from resolved photon processes

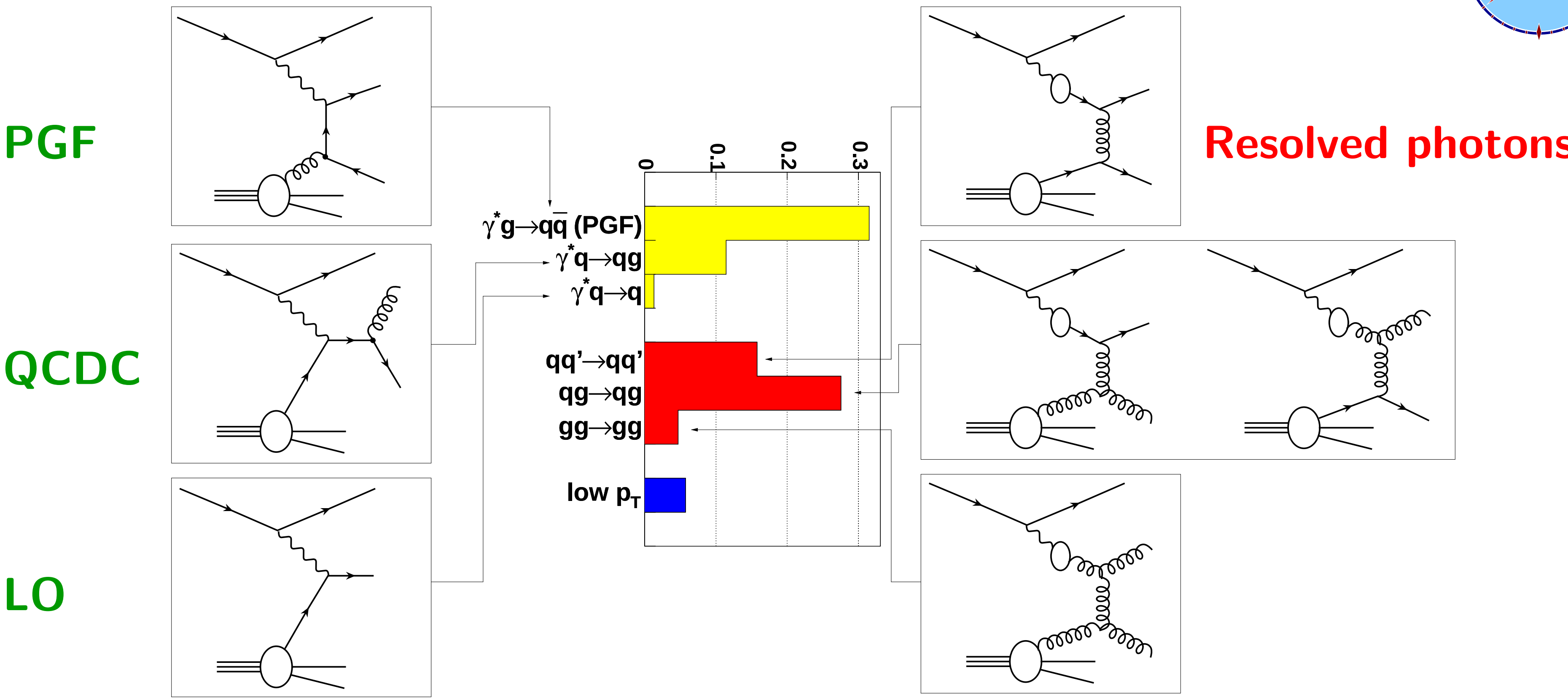
- Data selection same as for large $Q^2$

$$A_{\parallel}/D = 0.002 \pm 0.019(\text{stat.}) \pm 0.003(\text{syst.})$$

- MC simulation with PYTHIA compared to data (blue points)



# Contributions to asymmetry

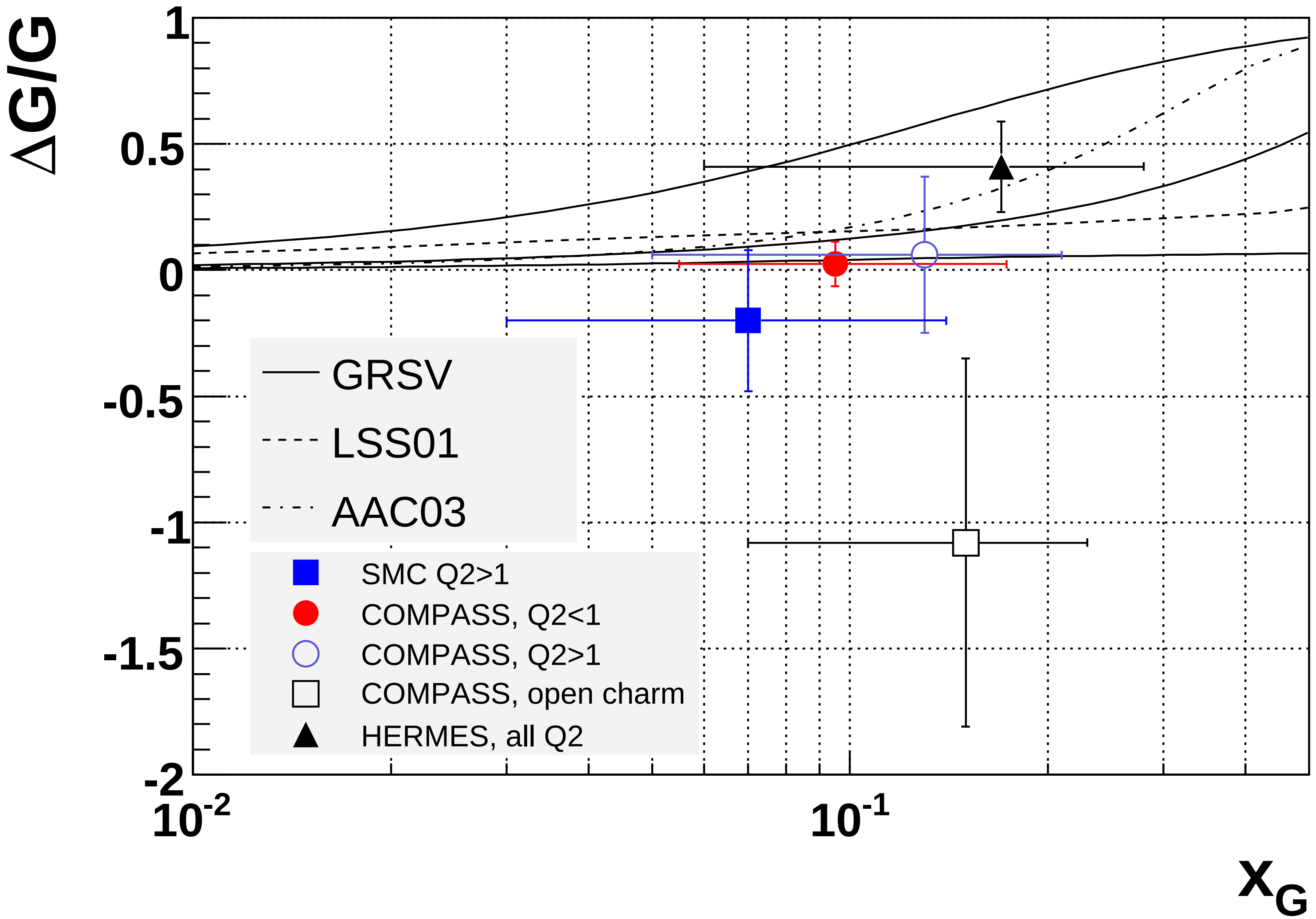



- Resolved photons: polarised PDFs in deuteron and photon needed
- Photon non-perturbative part unknown: estimate using unpolarised contribution

$$\Delta G/G(x_{\rm g} = 0.095^{+0.08}_{-0.04}, \mu^2 = 3\ \text{GeV}^2) = 0.024 \pm 0.089(\text{stat.}) \pm 0.057(\text{syst.})$$

- systematic error includes exp. syst., MC syst. and estimate of photon contribution

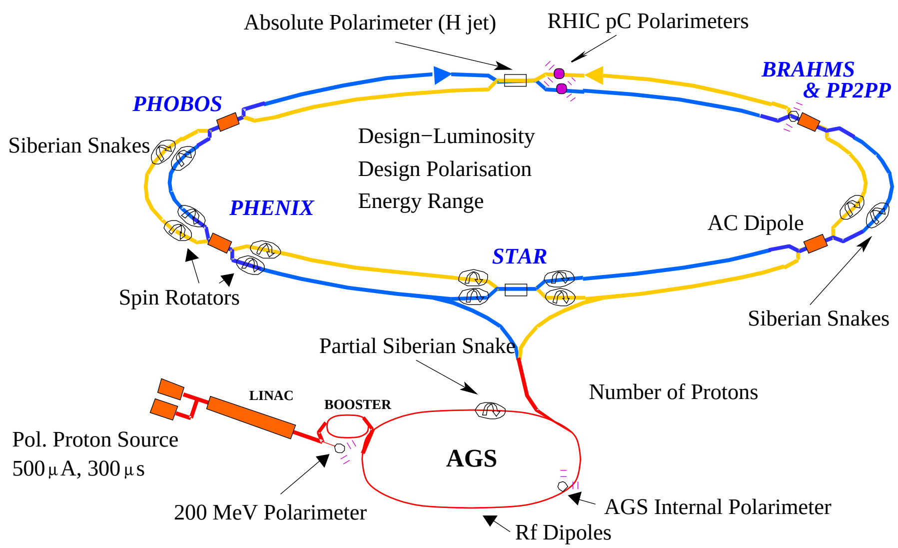
# $\Delta G/G$ measurements in DIS




**$\Delta G/G$ is small or has a node around $x_g \approx 0.1$**

# $\Delta G/G$ from pp collider

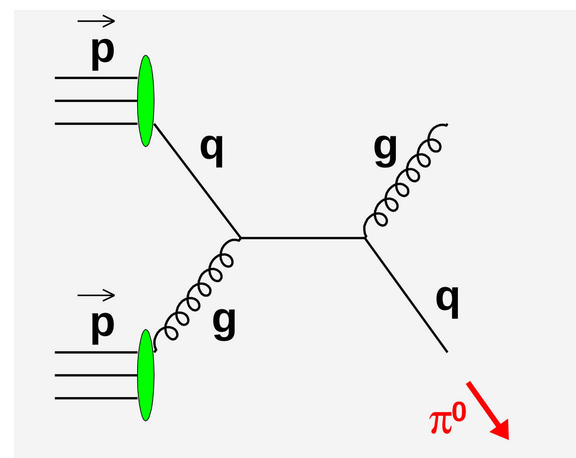
## RHIC: $\vec{p}\vec{p}$ at 200 GeV




- longitudinal and transverse polarisation for PHENIX and STAR
- transverse polarisation for BRAHMS
- run 5 just finished successfully, results from run 3 and 4

## Methods

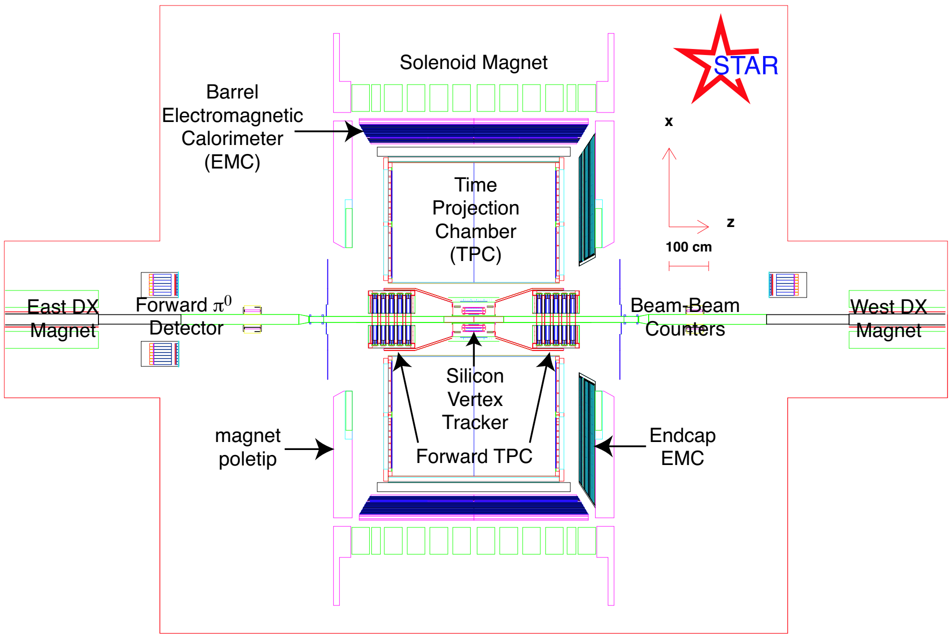
- cleanest channel prompt photons: $qg \longrightarrow q\gamma$
- needs high luminosity
- up to now: $qg \longrightarrow qg$




- pionproduktion, jets
- other contributions:
  $gg \longrightarrow gg$
  $gg \longrightarrow q\bar{q}$

# Experiments

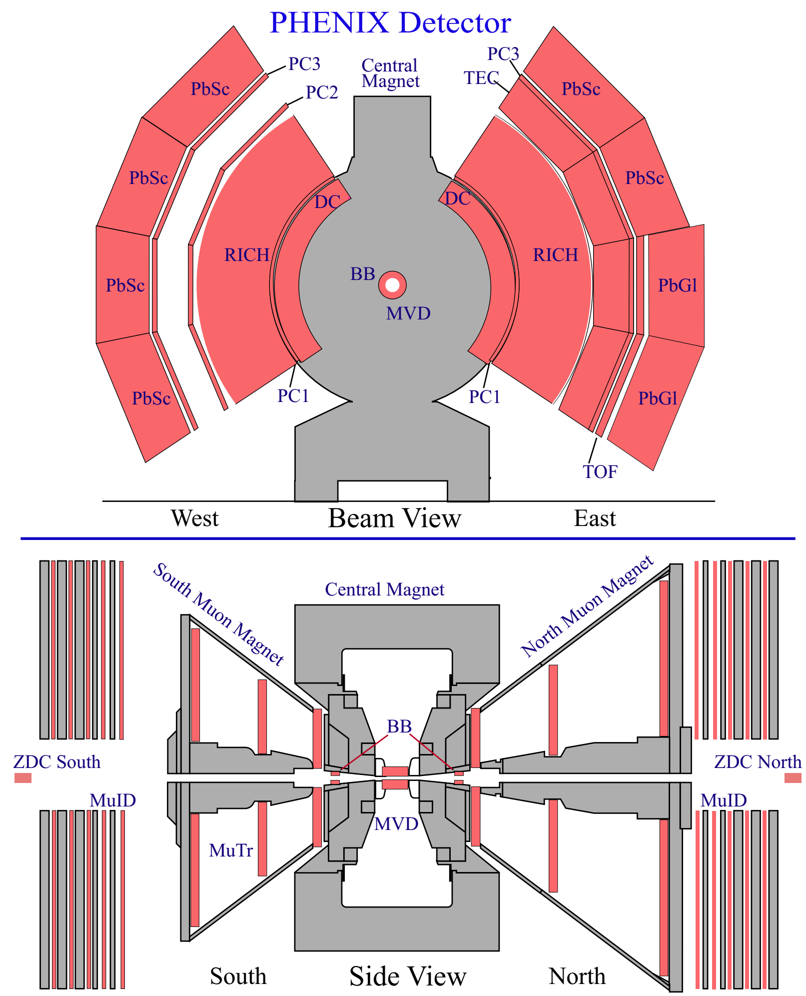
## STAR




- analysis of 2 jet events at mid rapidity

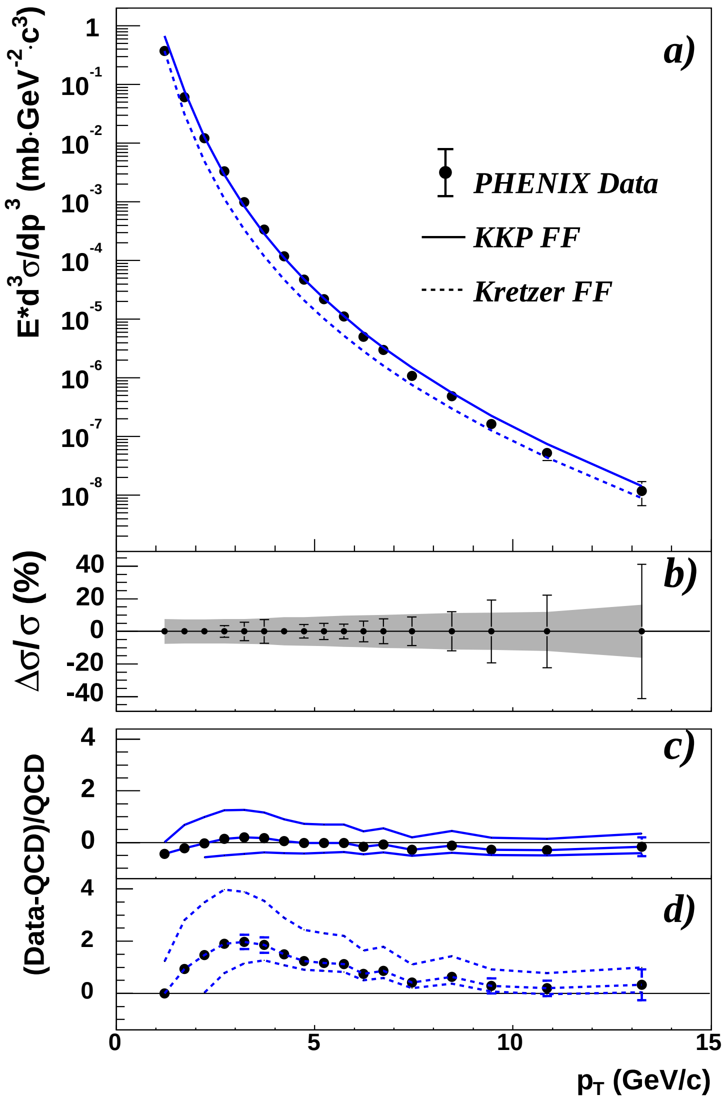
## PHENIX

- analysis of $\pi^0$ production
- first prompt photons

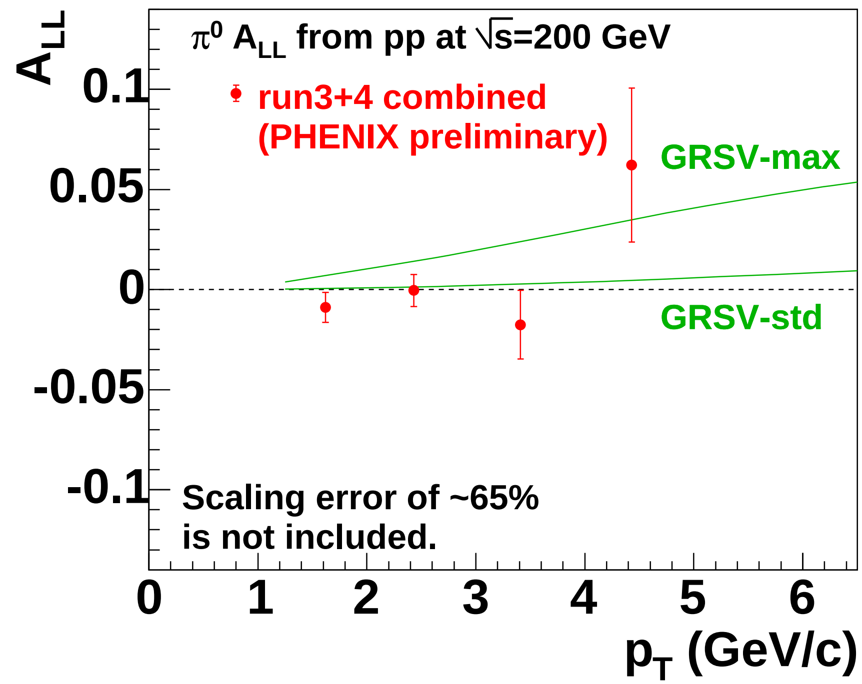


# PHENIX results

## $\pi^0$ production




## $\pi^0$ asymmetries

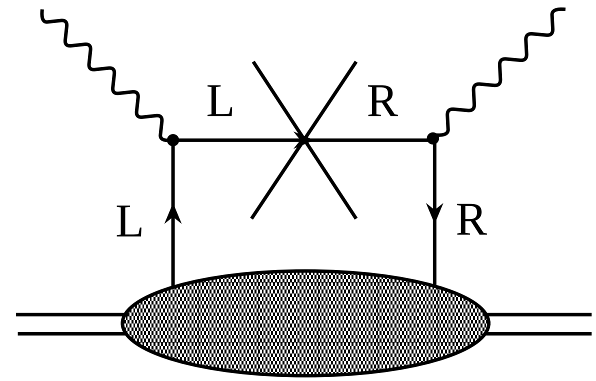



- good description of cross section with NLO QCD
- small asymmetries observed
- favours standard GRSV or smaller gluon distribution

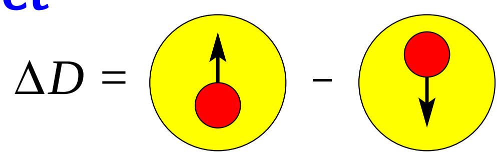
# Transversity

# Transversity

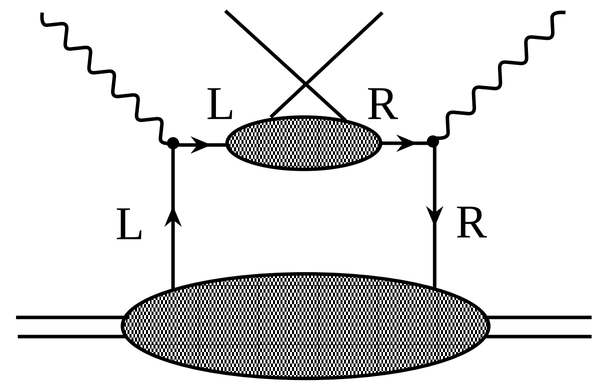
- transversity not measurable in inclusive DIS as quark helicity must flip $\Rightarrow$ SIDIS

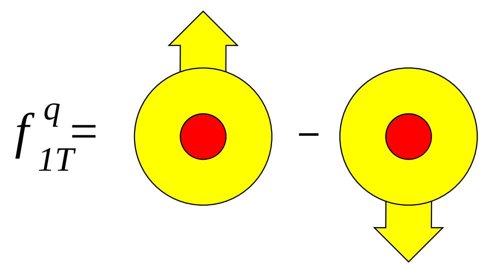



- polarisation of struck quark measured e.g. by azimuthal asymmetry of produced hadrons
  $\Rightarrow$ **Collins–Effect**




- azimuthal asymmetries also due to quark transverse momenta
  $\Rightarrow$ **Sivers–Effect**




- other possibility to measure transversity uses interference in the angle between two hadrons

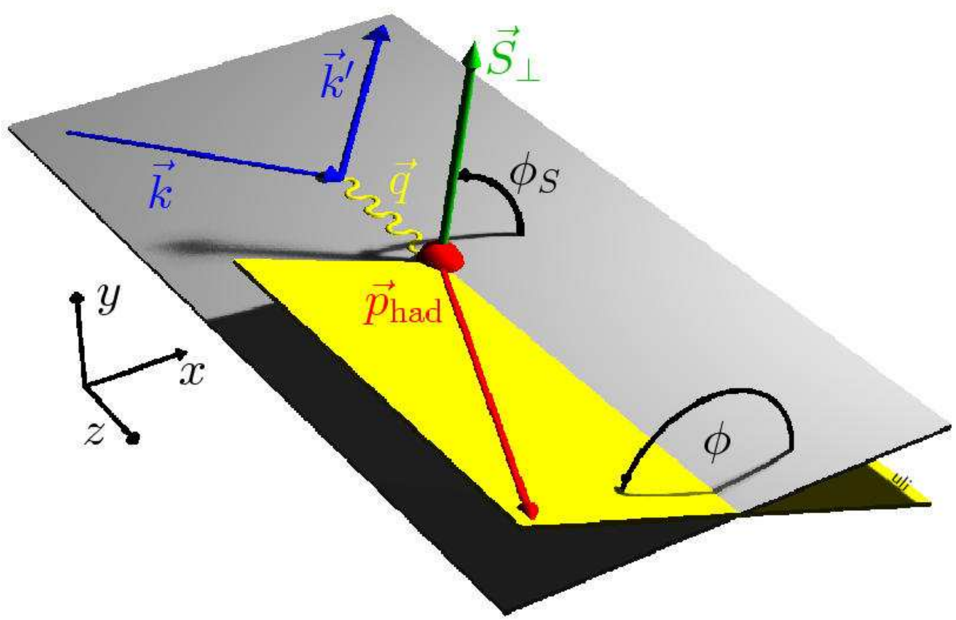
# Collins and Sivers effect

Using a transversely polarized target allows to disentangle Collins and Sivers–Effect.

$$A_T^h = \frac{1}{|S_T|}\frac{\sigma^{\Uparrow} - \sigma^{\Downarrow}}{\sigma^{\Uparrow} + \sigma^{\Downarrow}}$$

$$\sim \ldots \sin(\phi + \phi_s - \pi)\frac{\sum_i e_i^2 \Delta_{\mathrm{T}} q_i(x) \Delta_{\mathrm{T}} D_{q_i}^{\mathrm{h}}(z)}{\sum_i e_i^2 q_i(x) D_{q_i}^{\mathrm{h}}(z)} \qquad \text{Collins–Effect}$$

$$+ \ldots \sin(\phi - \phi_s)\frac{\sum_i e_i^2 f_{1T}^{\perp i}(x) D_{q_i}^{h}(z)}{\sum_i e_i^2 q_i(x) D_{q_i}^{h}(z)} \qquad \text{Sivers–Effect}$$

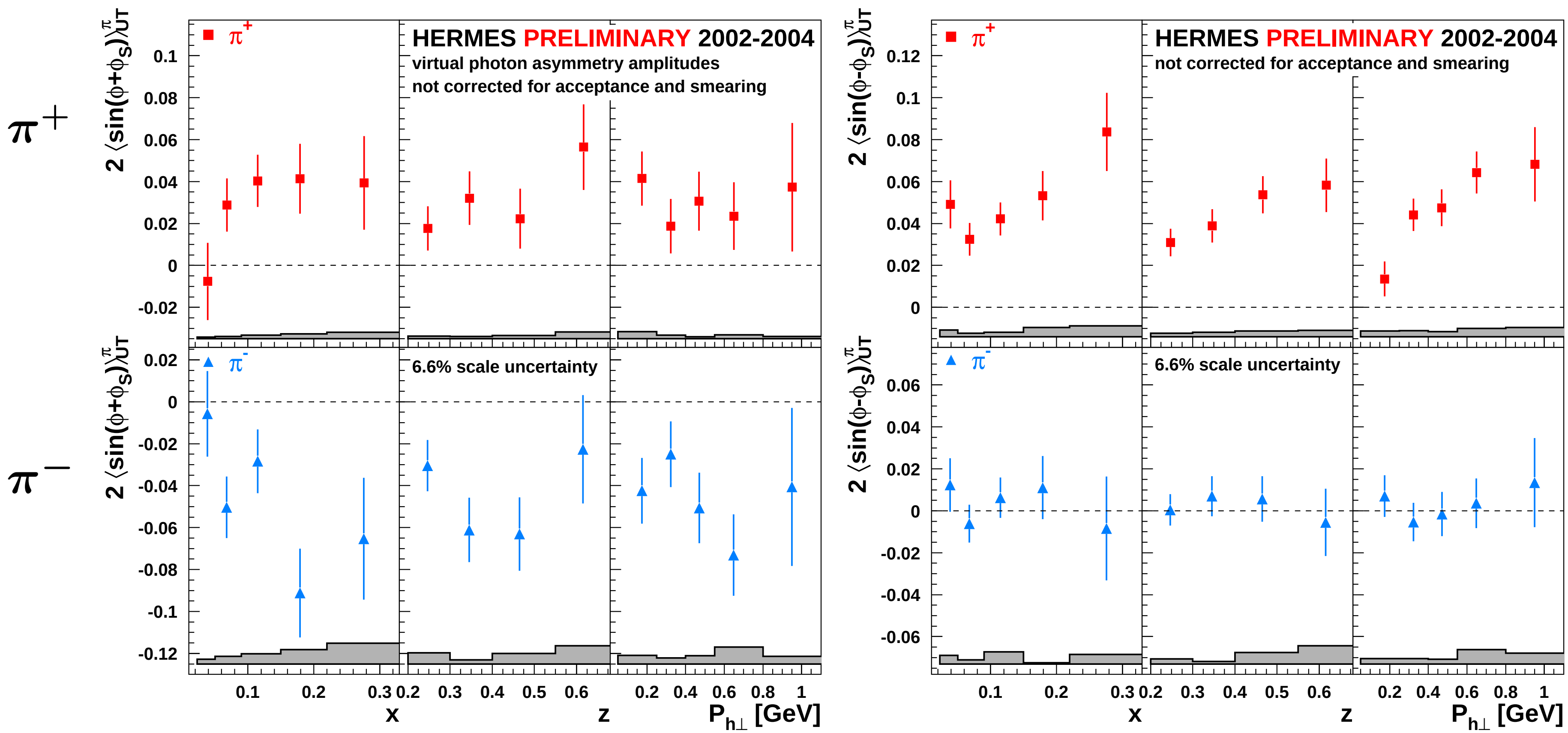



- $\Delta_T q(x)$ transversity DF
- $f_{1\mathrm{T}}^{\perp}(x)$ Sivers DF
- $q(x)$ unpolarized DF

- $\Delta_{\mathrm{T}} D_{\mathrm{q}}^{\mathrm{h}}(z)$ Collins FF
- $D_{\mathrm{q}}^{\mathrm{h}}(z)$ unpolarized FF

# HERMES results

**Collins** **Sivers**



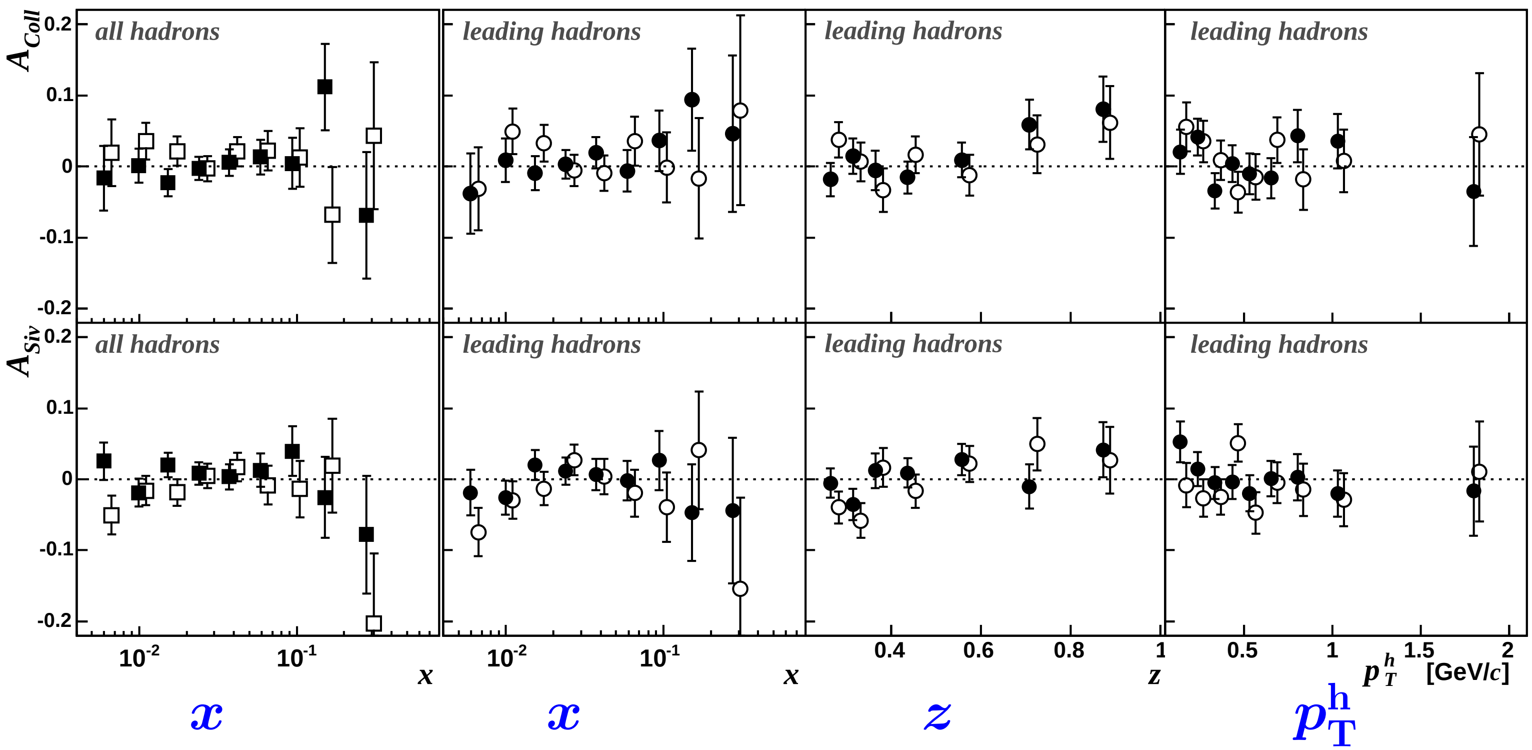

- Collins asymmetries positive for $\pi^+$, negative for $\pi^-$ $\Longrightarrow$ unexpected for $\pi^-$
- Sivers asymmetries postive for $\pi^+$ and zero for $\pi^-$ $\Longrightarrow$ hint for $L_z$

# COMPASS results

**All Hadrons** **Leading hadrons**

**Collins**

**Sivers**




- Collins and Sivers asymmetries
  for positive hadrons (closed symbols) and negative hadrons (open symbols)
- asymmetries small: cancellation in deuteron?
- more statistics from 2003 and 2004, proton target ($NH_3$) in 2006

# Measurement of Collins fragmentation function

- **Access to $\Delta D_{q}^{h}(z)$ in $e^{+}e^{-}$ collisions**
- **Method: Hadrons pairs in opposite jets**

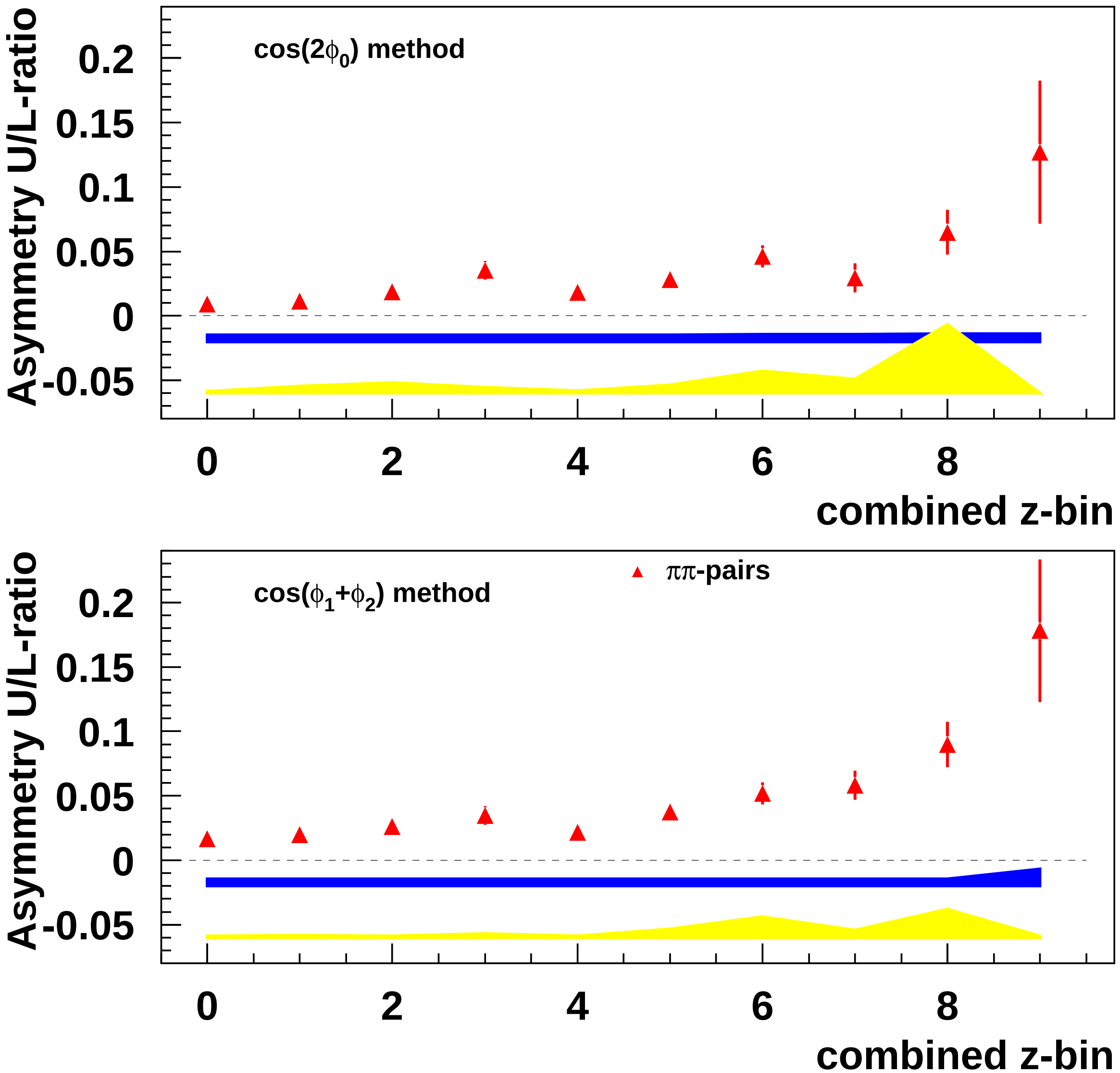
$$\sigma \sim A \cdot \Sigma D_{q}^{h1}(z_1) D_{q}^{h2}(z_2)$$

- **Transverse momenta included**

$$\sigma \sim ..... + B \cdot \cos(\phi_1 + \phi_2) \Delta_T D_{q}^{h1}(z_1) \Delta_T D_{q}^{h2}(z_2)$$

- **BELLE: 8 GeV $e^{-}$ + 3.5 GeV $e^{+}$**
- **Off resonance data:** $e^{+}e^{-} \longrightarrow q\bar{q}$ **q=(u,d,s,c)**
- **Use unlike and like sign $\pi\pi$ pairs**
- **Determination of double ratios $\Longrightarrow$ cancellation of acceptance**

# Asymmetries from BELLE

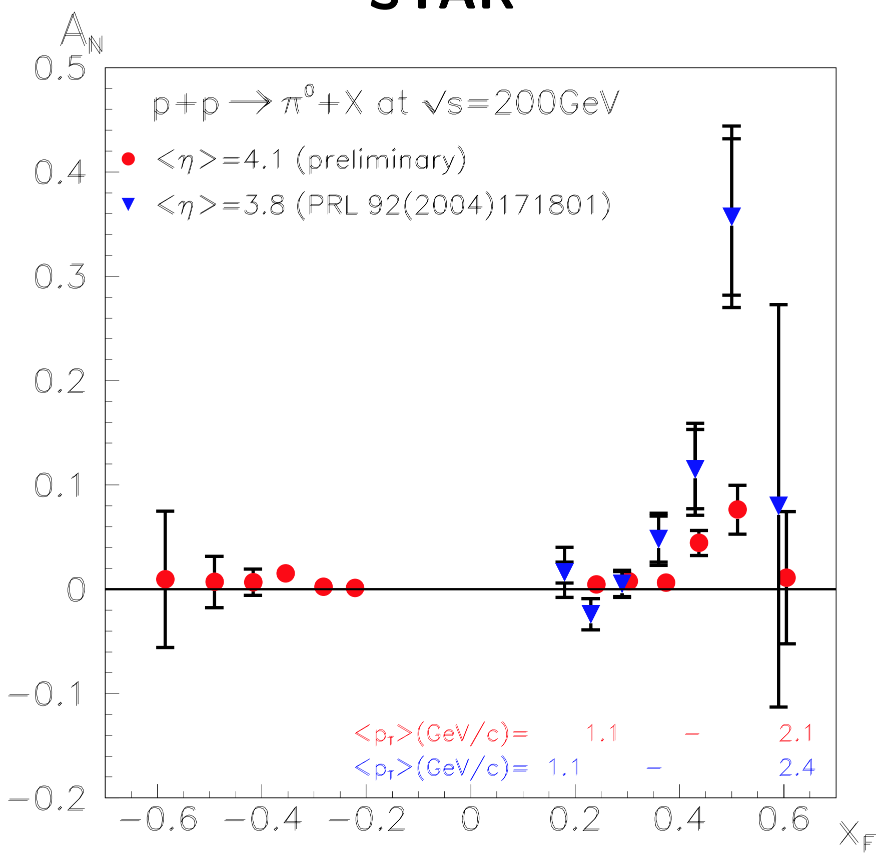



- Two different methods used
- Significant asymmetry rising with $z$ $\Longrightarrow$ observation of Collins FF

# Single spin asymmetries from RHIC

- Collins and Sivers not distinguishable

**STAR**

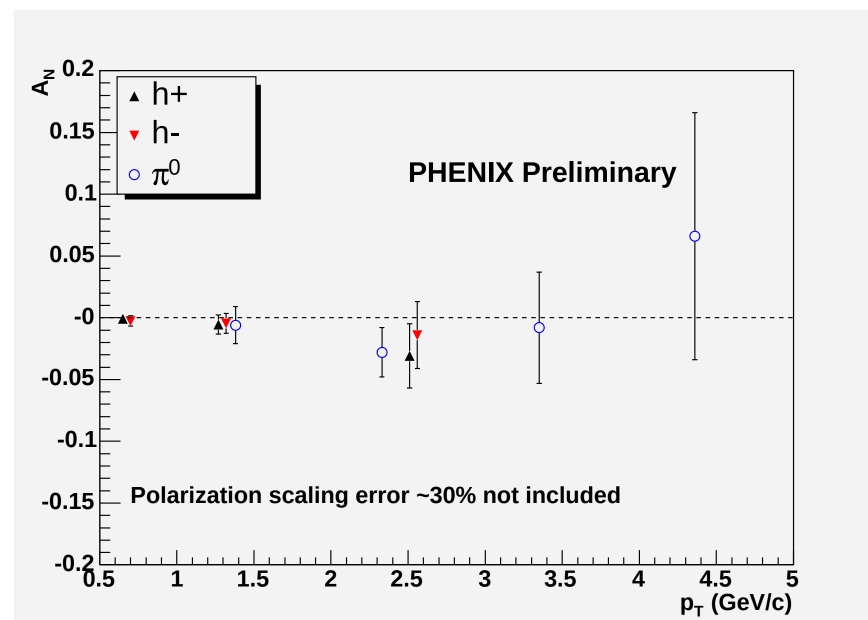



$A(\pi_0) > 0$ at $x_F > 0$

$A(\pi_0) = 0$ at $x_F < 0$

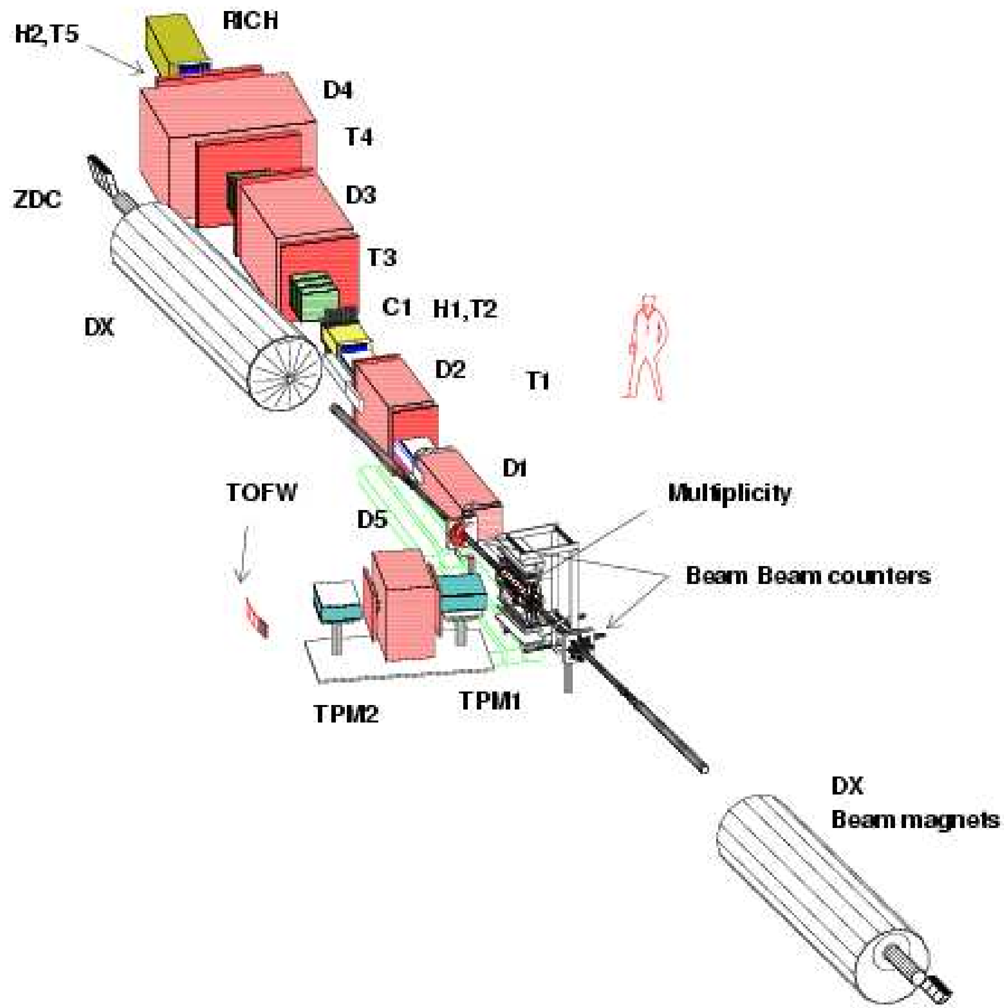
**PHENIX**

$\pi^0$, $h^+$, $h^-$

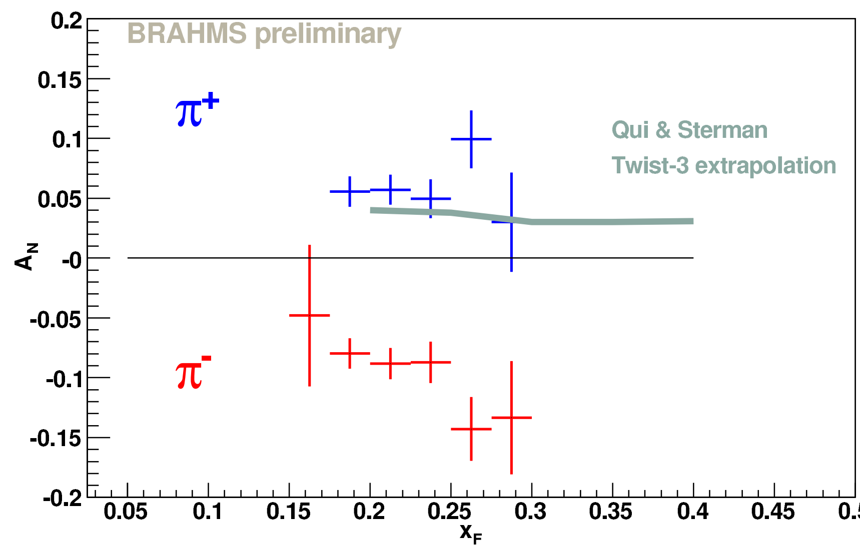



$A = 0$ for $x_F \approx 0$

# Results from Brahms




- Results for pions and protons




$A(\pi^+) > 0,\ A(\pi^-) < 0$ at $x_F > 0$

$A(\pi^-) \approx 0$ at $x_F < 0$

$A(p) \approx 0$

# Summary

- Spin physics is a very active field
- Many new results from COMPASS, HERMES, JLAB, RHIC and BELLE
- Gluon polarisation measured with several methods
  $\Rightarrow$ more statistics needed
- New precise data for the longitudinal spin structure functions
  $\Rightarrow$ improvement of polarised PDFs
- New puzzling results from all experiments on transversity
- Many more results on semi-inclusive DIS, single spin asymmetries, $\rho$ meson production, $\Lambda$ polarisation ...
- Plans:
  - COMPASS: more data from 2004, data taking continues on 2006
  - RHIC: run 5 just finished
  - HERMES: more data from 2005, measurements of GPDS e.g. via DVCS 2006/2007