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# The Spin Structure of the Nucleon

– part 2 –

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Spin and Symmetries – Praha 2004

6.7.2002

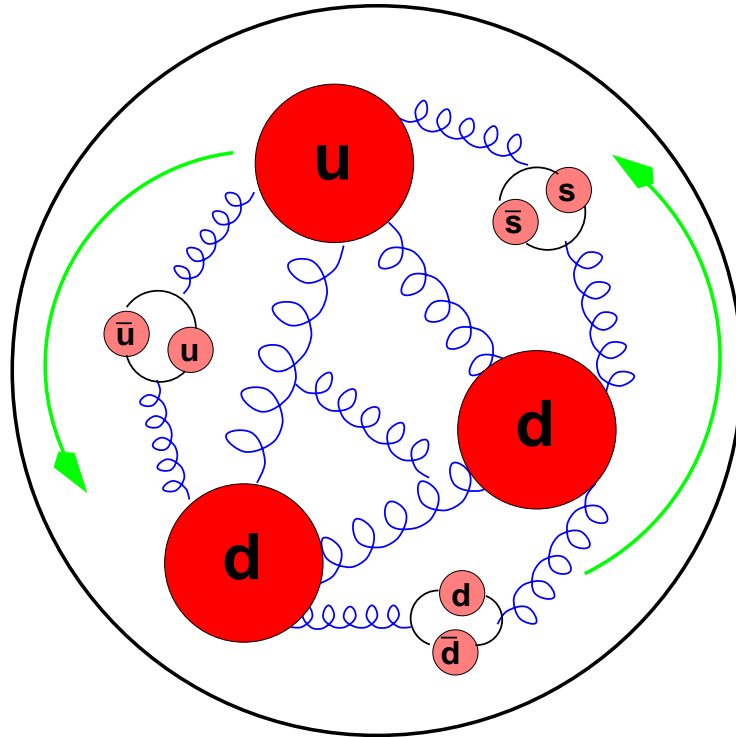
# Contents

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- Semi-inclusive asymmetries
- Flavour separation
- Measurement of  $\Delta G$
- Transversity
- Asymmetries from RHIC

# PROTON SPIN PUZZLE

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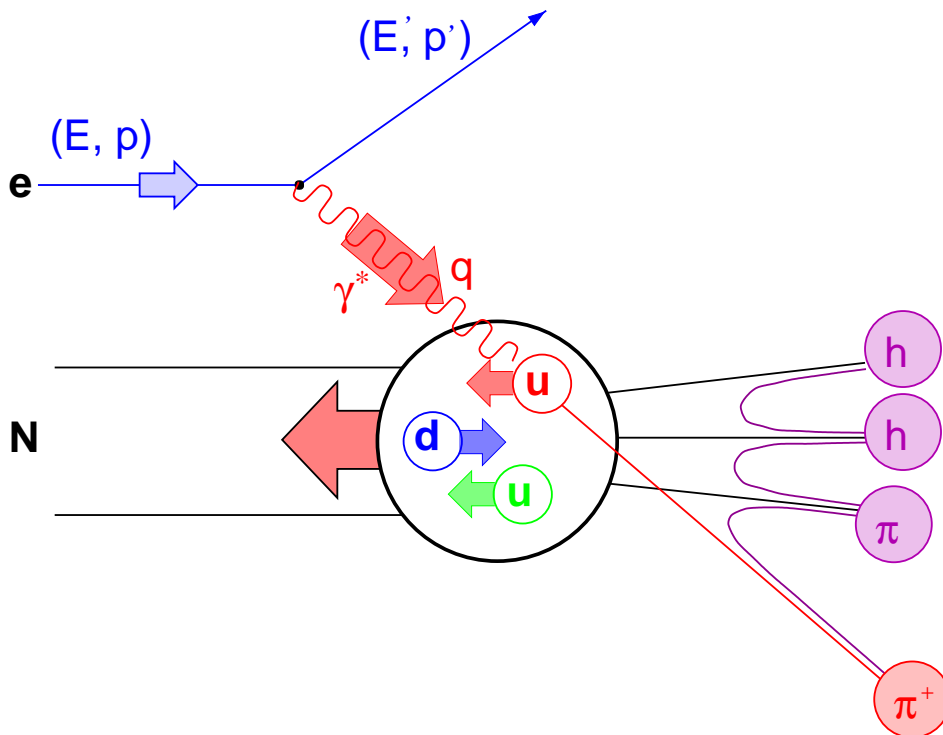


$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$

quarks  
antiquarks
gluons
angular-  
momentum

- Inclusive asymmetries: only  $\Delta\Sigma$  studied
- Semi-inclusive asymmetries needed for flavour separation and  $\Delta G$
- Exclusive measurements for total angular moments of quarks  $I_q = S_q + L_q$

# SEMI-INCLUSIVE DIS



- Leading hadron originates with large probability from struck quark

- **Fragmentation function  $D$**

$D_q^h(z)$  from quark  $q$  into hadron  $h$

$z = E_h/\nu$  energy fraction carried by hadron

- **Semi-inclusive asymmetry**

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

- Fragmentation functions from measurements (e.g. EMC) or Monte Carlo

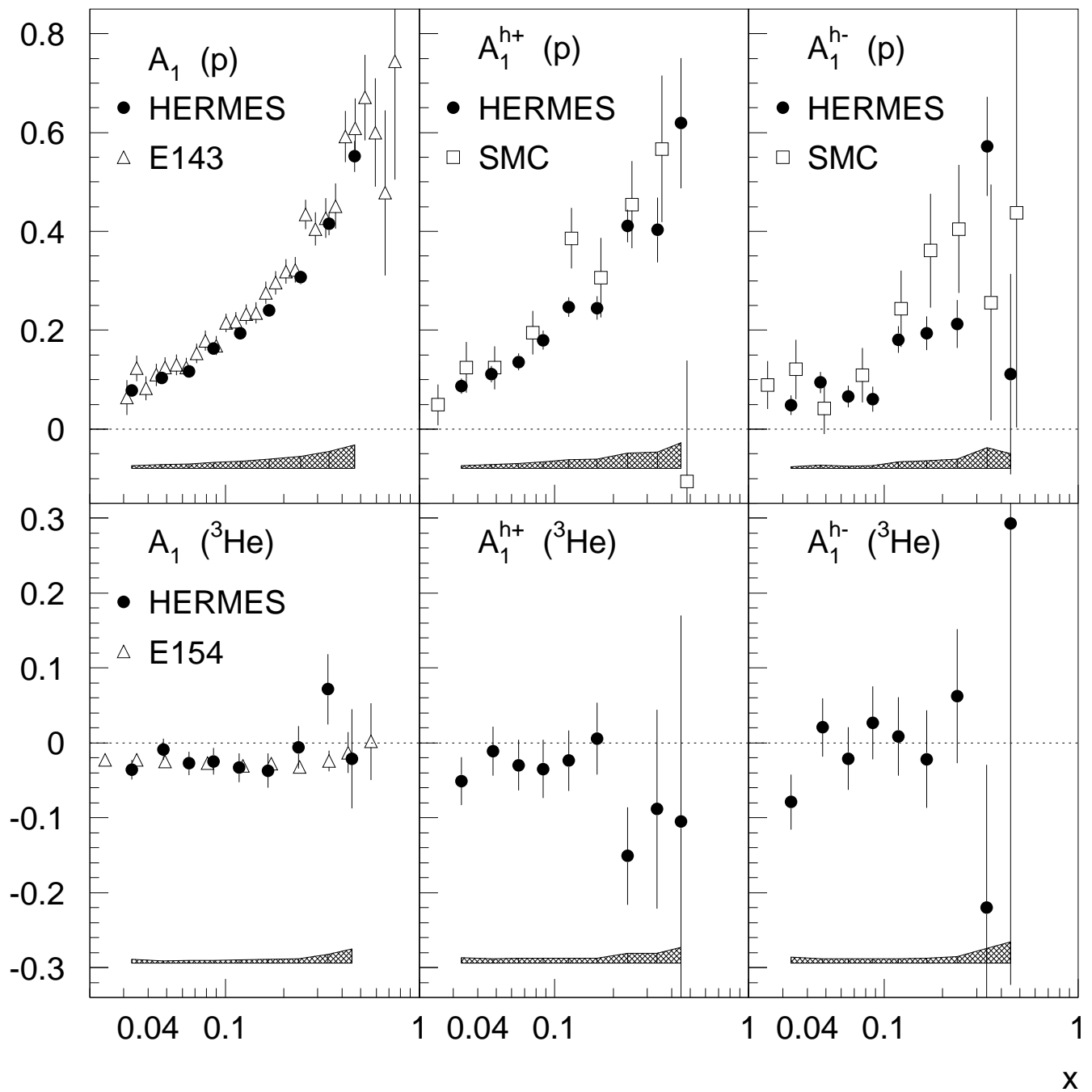
# SEMI-INCLUSIVE ASYMMETRIES

- **Experiments:**

SMC ( $h^\pm$  from p,d)

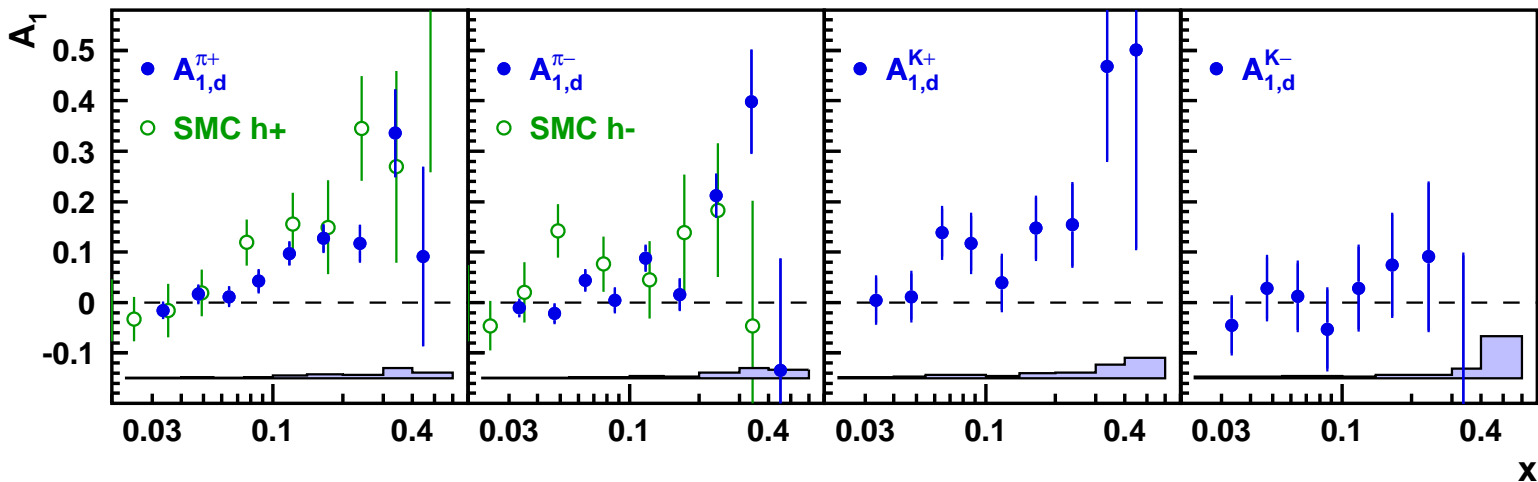
HERMES ( $h^\pm$  from p,n , identified  $\pi^\pm$ ,  $K^\pm$  from d)

- Results from p and  $^3\text{He}$



# SEMI-INCLUSIVE ASYMMETRIES

- Results from d target



## Determination of polarized parton distributions

- HERMES method:

solve linear equation system for quark polarisations  $\vec{Q}$

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

with  $\vec{A} = (A_{1,p}, A_{1,d}, A_{1,p}^{\pi^\pm}, A_{1,d}^{\pi^\pm}, \dots)$

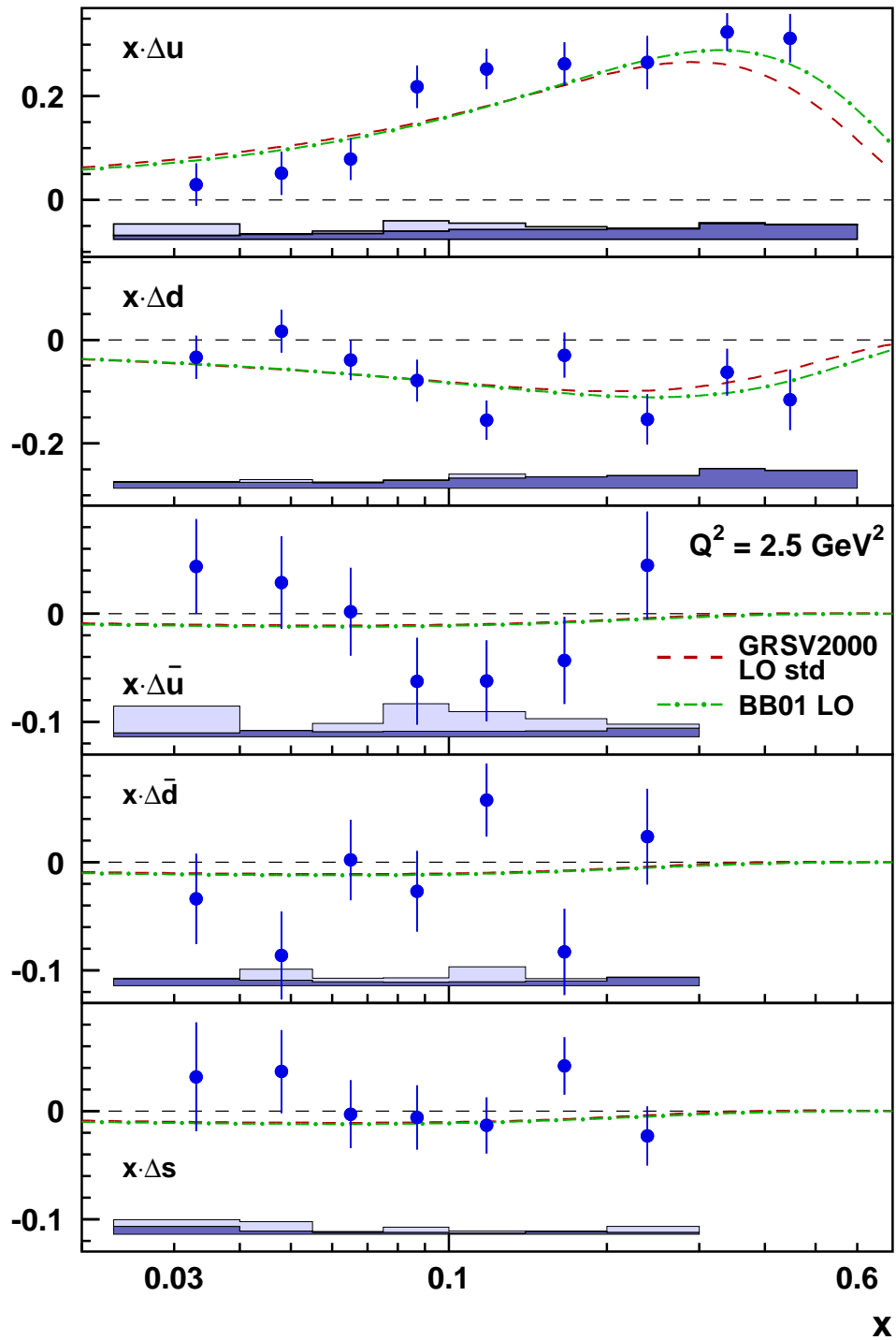
matrix  $P = \left( \frac{e_f^2 q_f(x) \cdot D_f^h(z)}{\sum_{f'} e_{f'}^2 q_{f'}(x) \cdot D_{f'}^h(z)} \right)$

- statistics sufficient for 5 parameter fit

$$\vec{Q}(x) = \left( \frac{\Delta u(x)}{u(x)}, \frac{\Delta d(x)}{d(x)}, \frac{\Delta \bar{u}(x)}{\bar{u}(x)}, \frac{\Delta \bar{d}(x)}{\bar{d}(x)}, \frac{\Delta s(x)}{s(x)} \right)$$

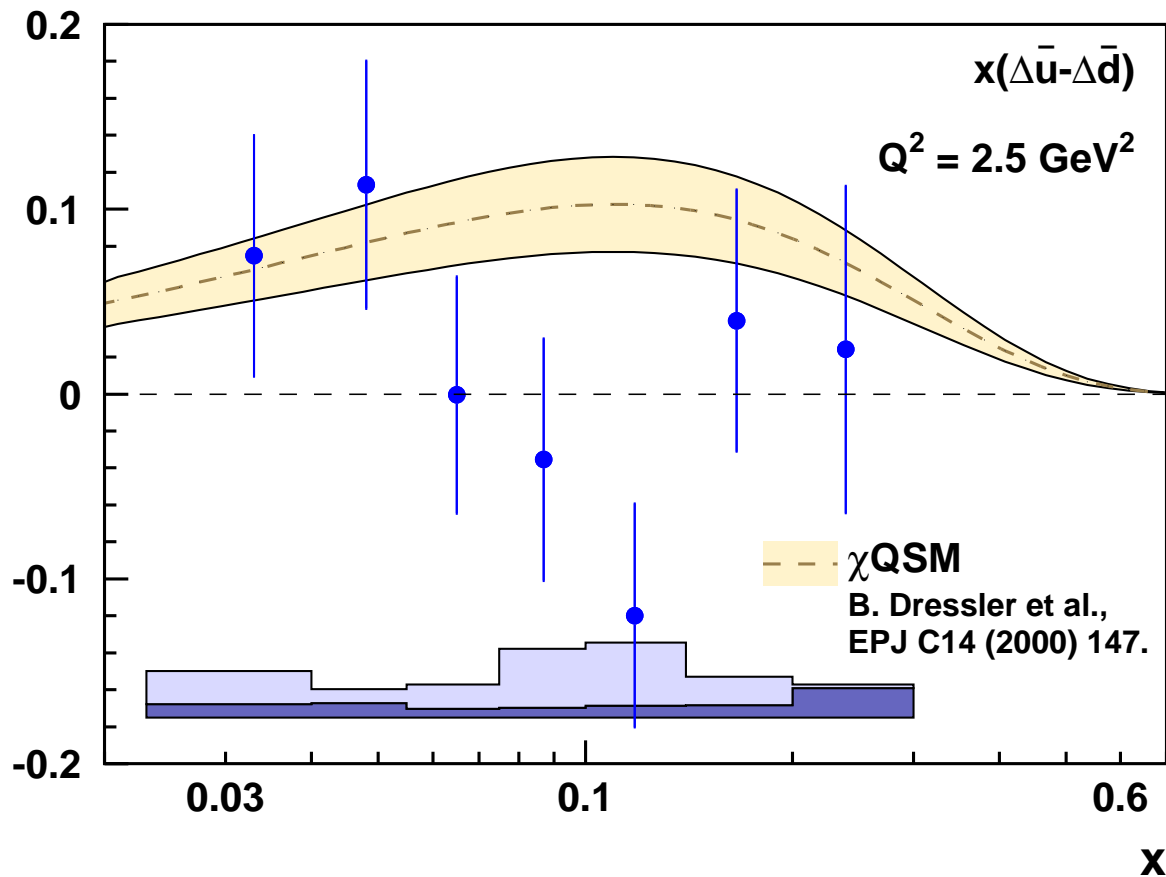
# POLARIZED PDFs

## HERMES results



- $\Delta d(x) \approx -0.4\Delta u(x)$
- $\Delta s$  compatible with 0, not negative

# POLARISED PDFs



- HERMES data consistent with flavor symmetric helicity distributions
- Data with much higher statistics needed  
→ COMPASS:  $h^\pm$ ,  $K^\pm$ ,  $K_S$  asymmetries



# GLUON POLARISATION

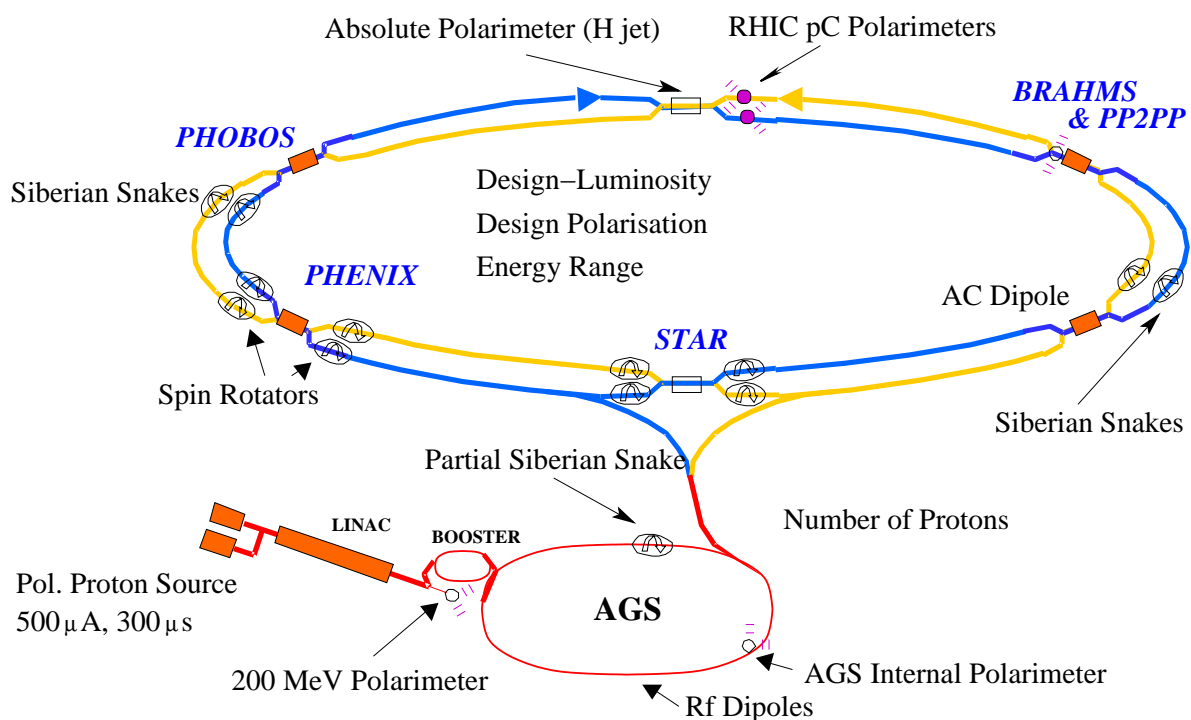
## Experiments

### Fixed target

<b>CERN</b>	<b>SMC</b>	$\vec{\mu} \vec{p}, \vec{d}$	100, 190 GeV
<b>DESY</b>	<b>HERMES</b>	$\vec{e} \vec{p}, \vec{n}, \vec{d}$	27.5 GeV
<b>CERN</b>	<b>COMPASS</b>	$\vec{\mu} \vec{d}$	160 GeV

### Collider

<b>BNL</b>	<b>STAR</b>	$\vec{p} \vec{p}$	200 GeV
<b>BNL</b>	<b>PHENIX</b>	$\vec{p} \vec{p}$	200 GeV

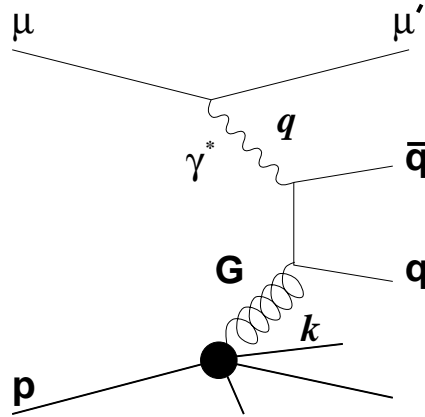


- 2003: longitudinal polarisation of about 30%, luminosity:  $0.2 \text{ pb}^{-1}$

# METHODS (1)

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## DIS: Photon Gluon Fusion



- open charm production

$$\begin{aligned}\gamma g &\longrightarrow c\bar{c} \\ &\longrightarrow D^0 \longrightarrow \pi K \quad \text{BR} : 4\%\end{aligned}$$

hard scale: mass of charm quark

clean channel, but  $D^0$  reconstruction necessary

- high  $p_T$  hadron pairs

$$\begin{aligned}\gamma g &\longrightarrow q\bar{q} \\ &\longrightarrow 2 \text{ jets or } h^+ h^-\end{aligned}$$

detection of 2 hadrons of opposite charge with high  $p_T$   
and  $\Delta\phi \approx \pi$ ,

hard scale:  $p_T$

analysis more involved due to background from leading  
order processes, QCD Compton and resolved photons

# HIGH $p_T$ ASYMMETRIES

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## Results for high $p_T$ hadrons

- SMC p,d (93–96)  $Q^2 > 1 \text{ GeV}^2$  (DIS)

$$A_p^{lN \rightarrow lhhX} = 0.030 \pm 0.057(\text{stat}) \pm 0.010(\text{syst})$$

$$A_d^{lN \rightarrow lhhX} = 0.070 \pm 0.077(\text{stat}) \pm 0.010(\text{syst})$$

- HERMES p (96) all  $Q^2$  (quasireal photons)

$$A_p^{lN \rightarrow lhhX} = -0.28 \pm 0.12(\text{stat}) \pm 0.020(\text{syst})$$

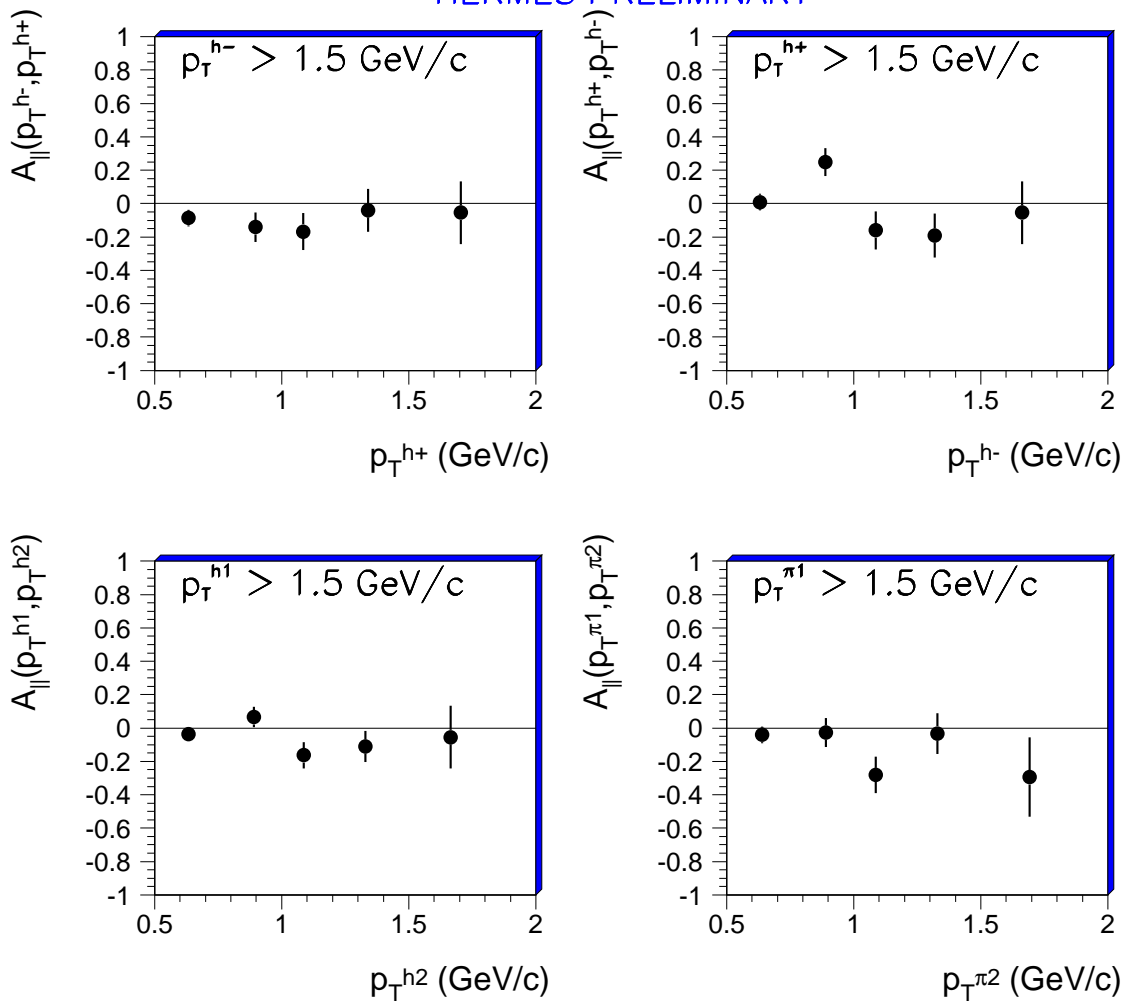
- COMPASS (2002) all  $Q^2$  (quasireal photons)

$$A_d^{\gamma N \rightarrow hhX} = -0.065 \pm 0.036(\text{stat}) \pm 0.010(\text{false})$$

- HERMES p,d all  $Q^2$  (quasireal photons)  $h^+h^-$  and  $K^+K^-$

# HIGH $p_T$ ASYMMETRIES

HERMES PRELIMINARY

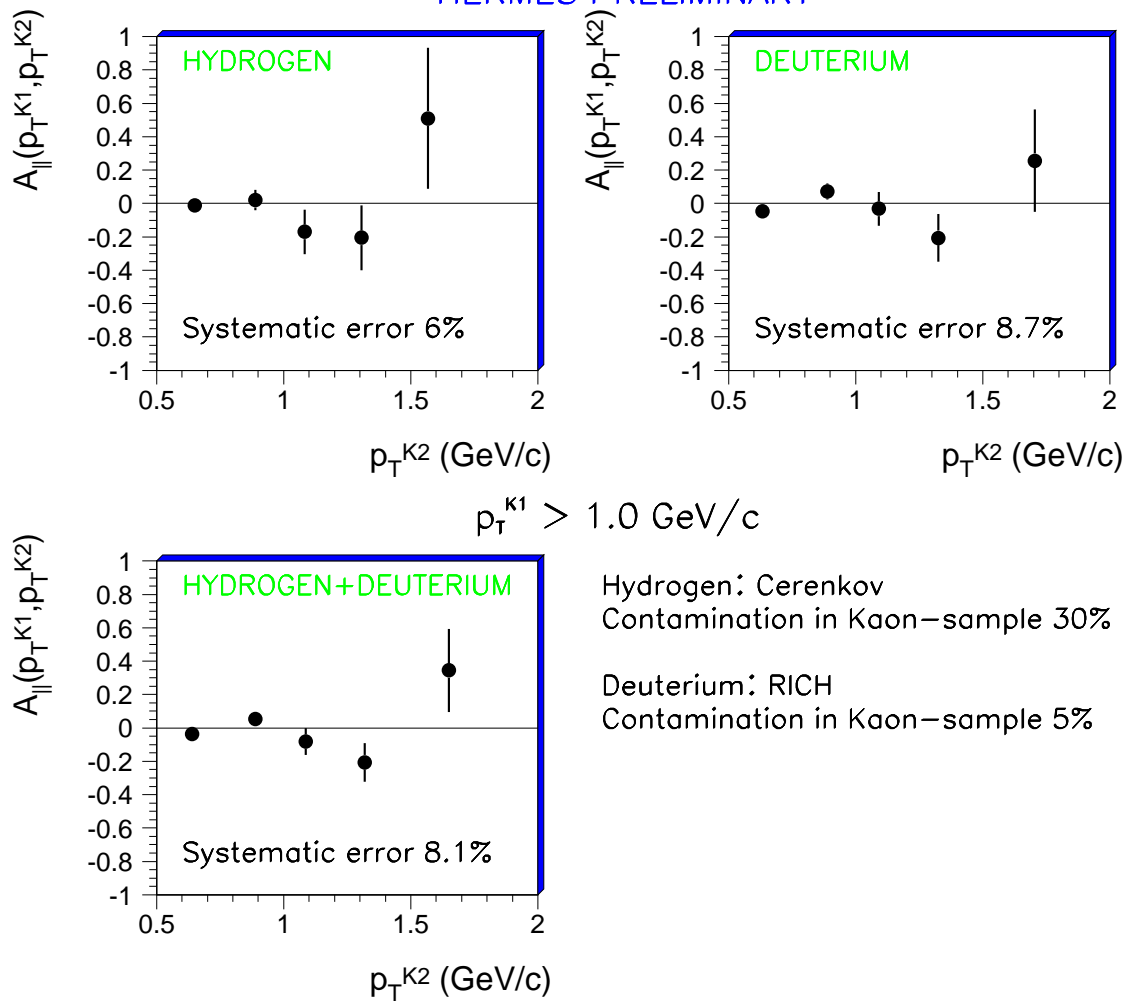


Systematic error 8.1%

HYDROGEN + DEUTERIUM Target

# HIGH $p_T$ ASYMMETRIES

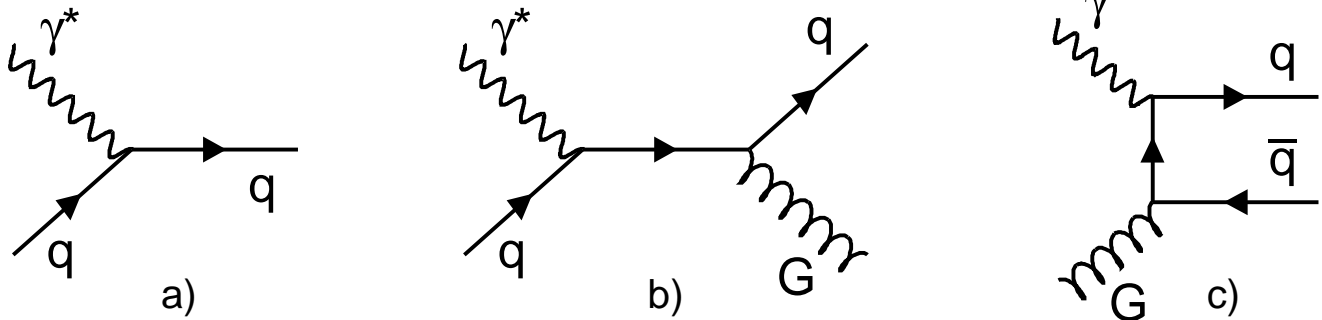
HERMES PRELIMINARY



# GLUON POLARISATION (1)

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## Extraction of $\Delta G/G$



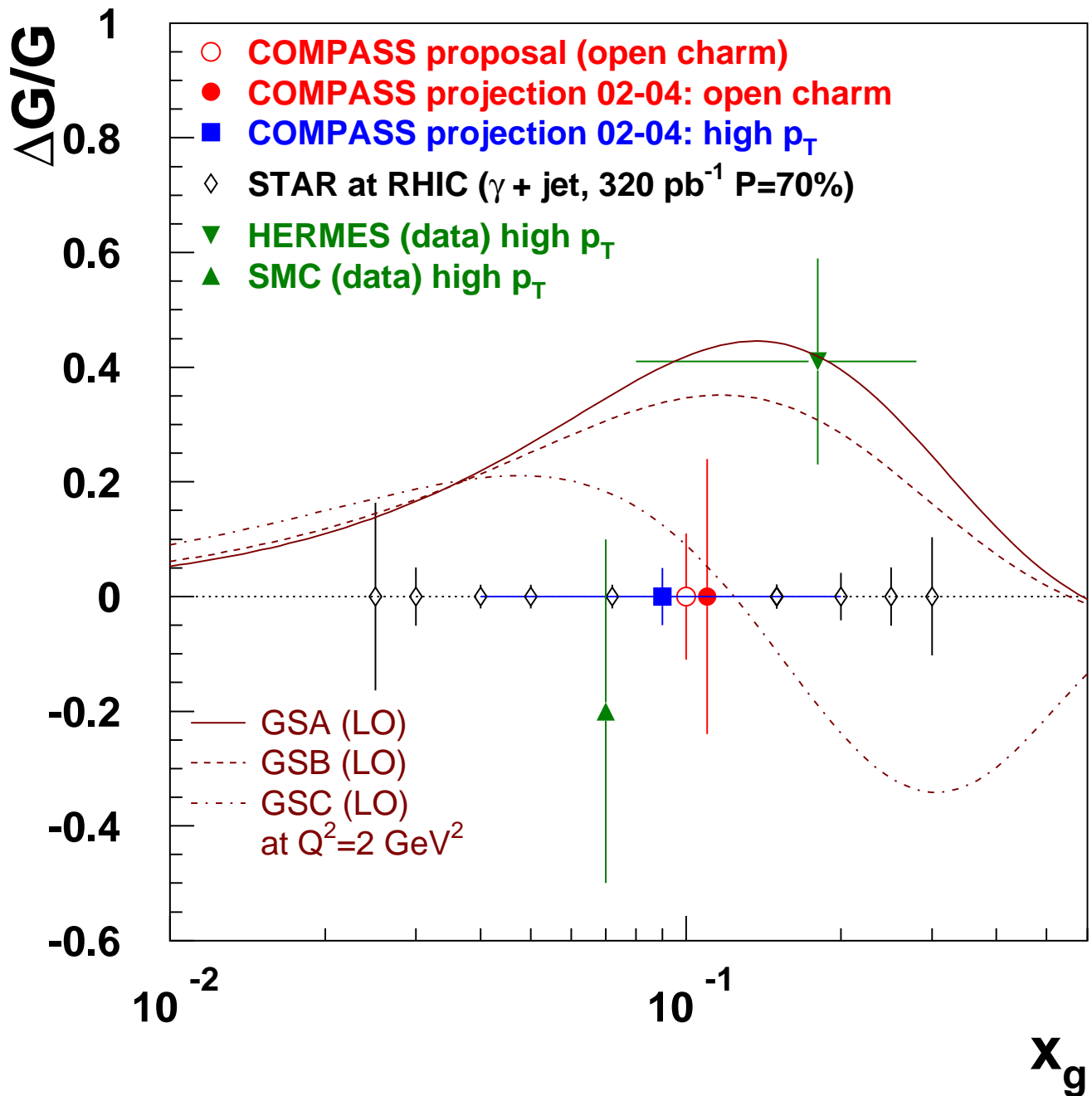
$$A_{LL} \sim \langle a_{LL}^{\gamma g \rightarrow qg} \rangle \frac{\Delta q}{q} + \langle a_{LL}^{\gamma g \rightarrow q\bar{q}} \rangle \frac{\Delta G}{G} \dots$$

- contributions from PDF, QCD Compton, leading order, resolved photons, vector meson production
- Monte Carlo determination of relative contributions (PYTHIA, LEPTO)

## OPEN CHARM PRODUCTION

- COMPASS (2002) d all  $Q^2$
- $D^* \rightarrow D^0 \pi \rightarrow K \pi$
- prospects for 2002 – 2004:  $\delta(\Delta G/G) \approx 0.24$

# EXPECTED RESULTS



# GLUON POLARISATION (2)

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- Quark gluon scattering at pp collider

different channels to look at

cleanest channel:

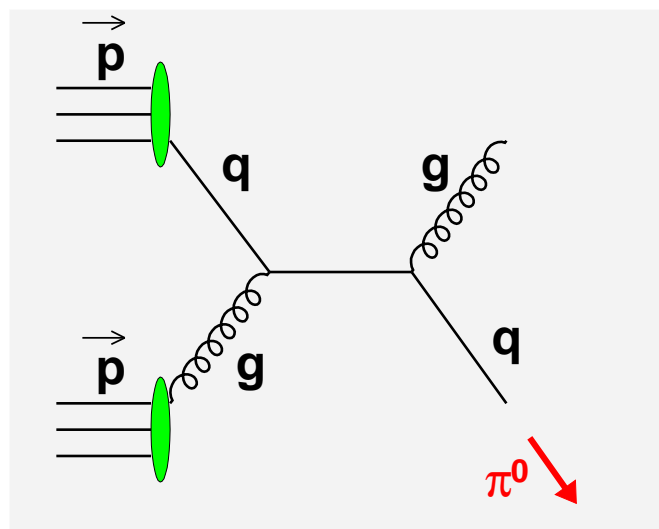
$qg \longrightarrow \gamma q$       prompt photons

needs high luminosity

up to now only other channels studied:

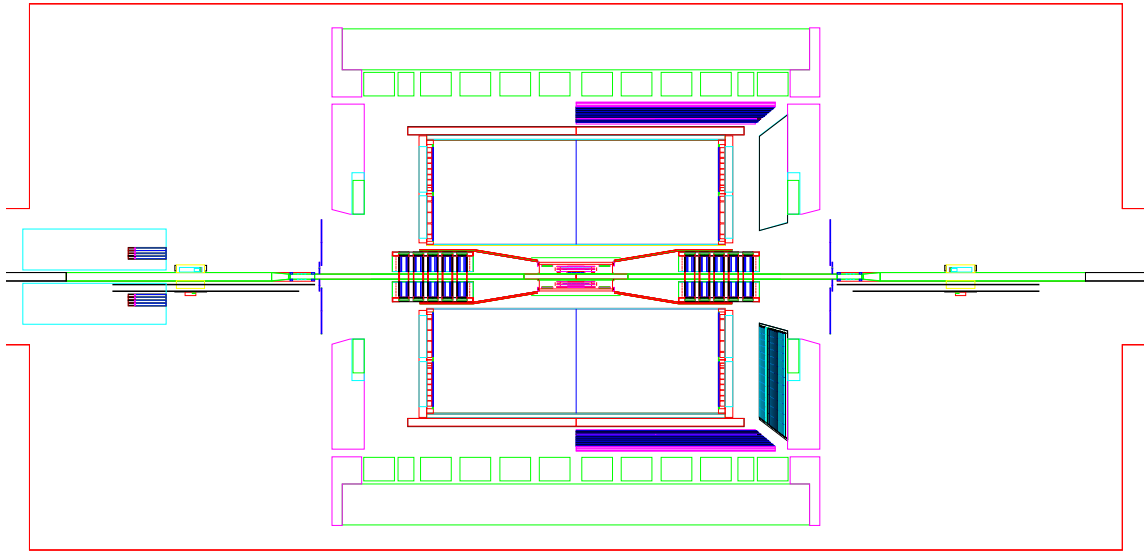
$qg \longrightarrow qg \longrightarrow 2 \text{ jets}$       STAR

$qg \longrightarrow qg \longrightarrow \pi^0 X$       PHENIX

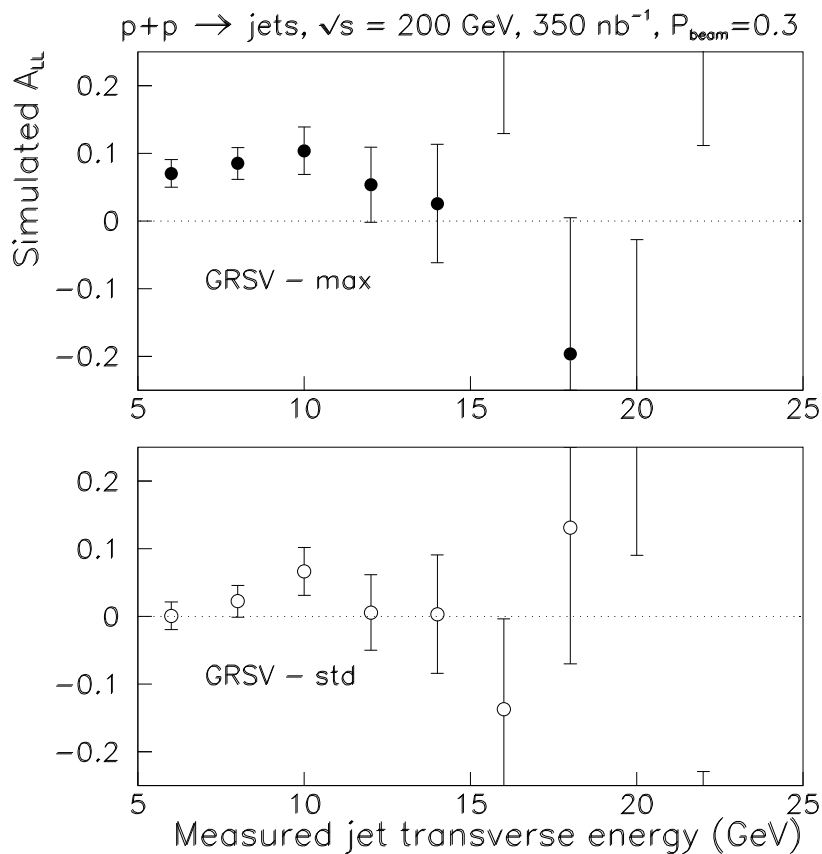




# STAR

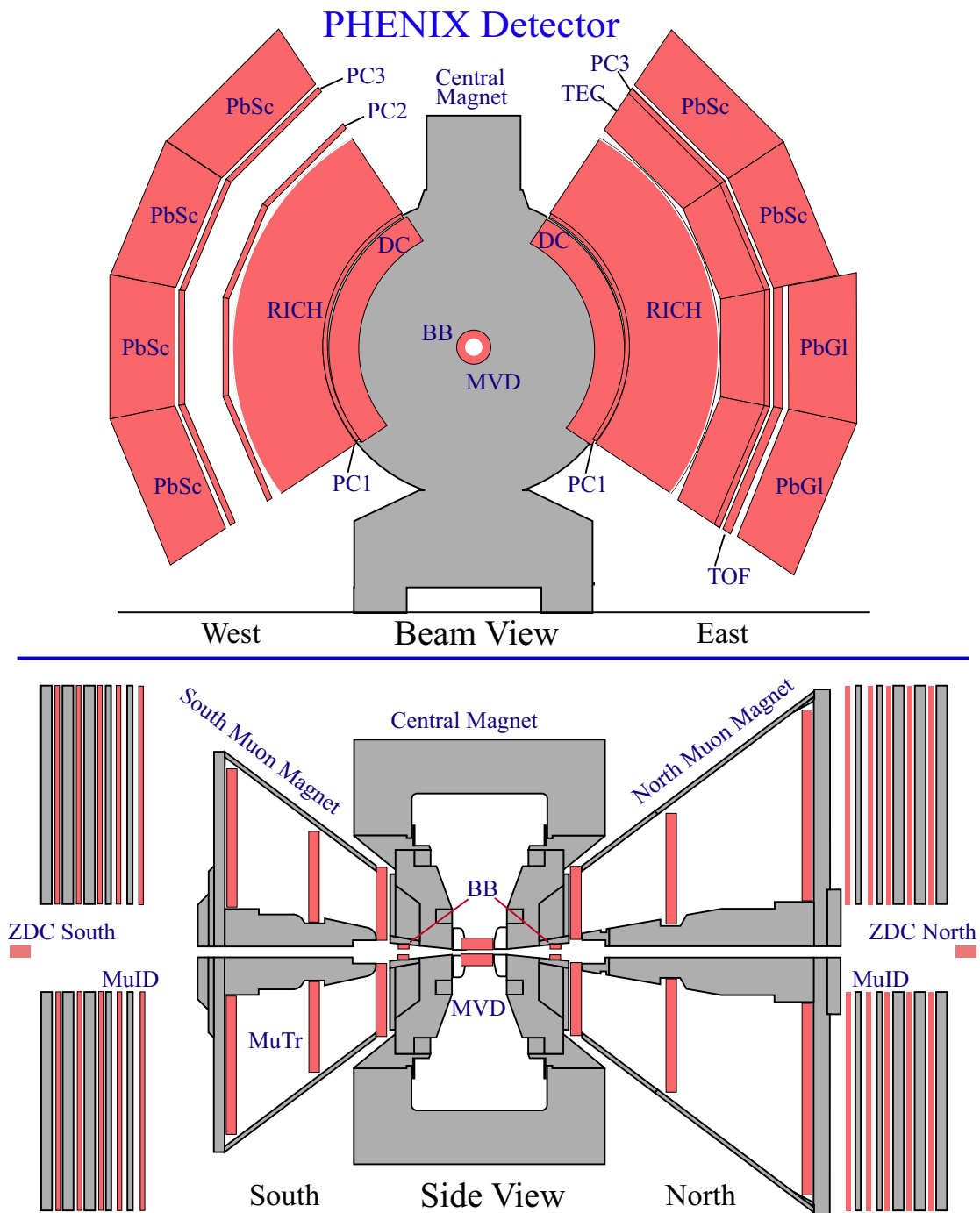


- jets at mid rapidity
- still under analysis
- expected statistical precision for  $A_{LL} \sim 0.030$

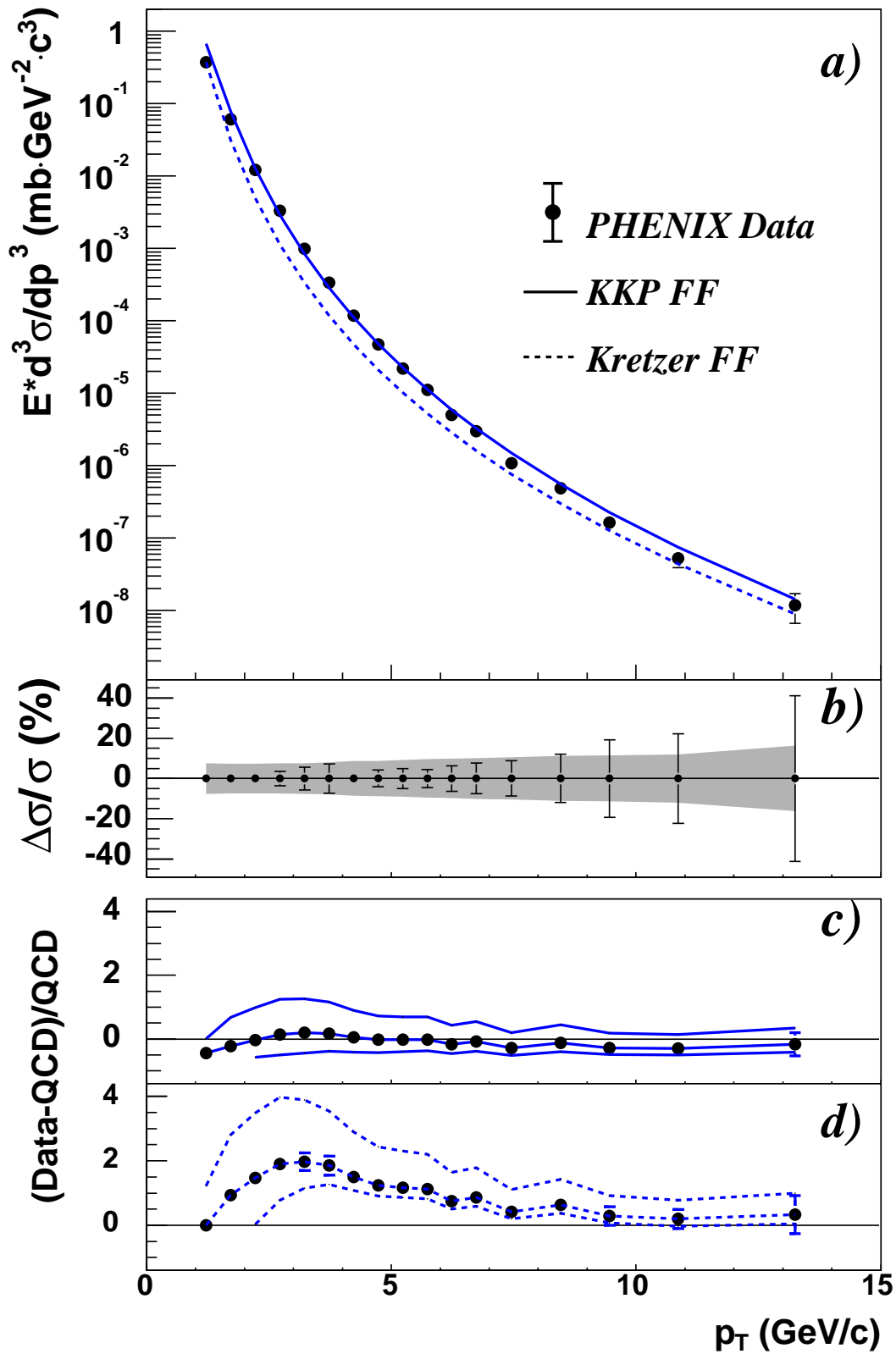


# PHENIX

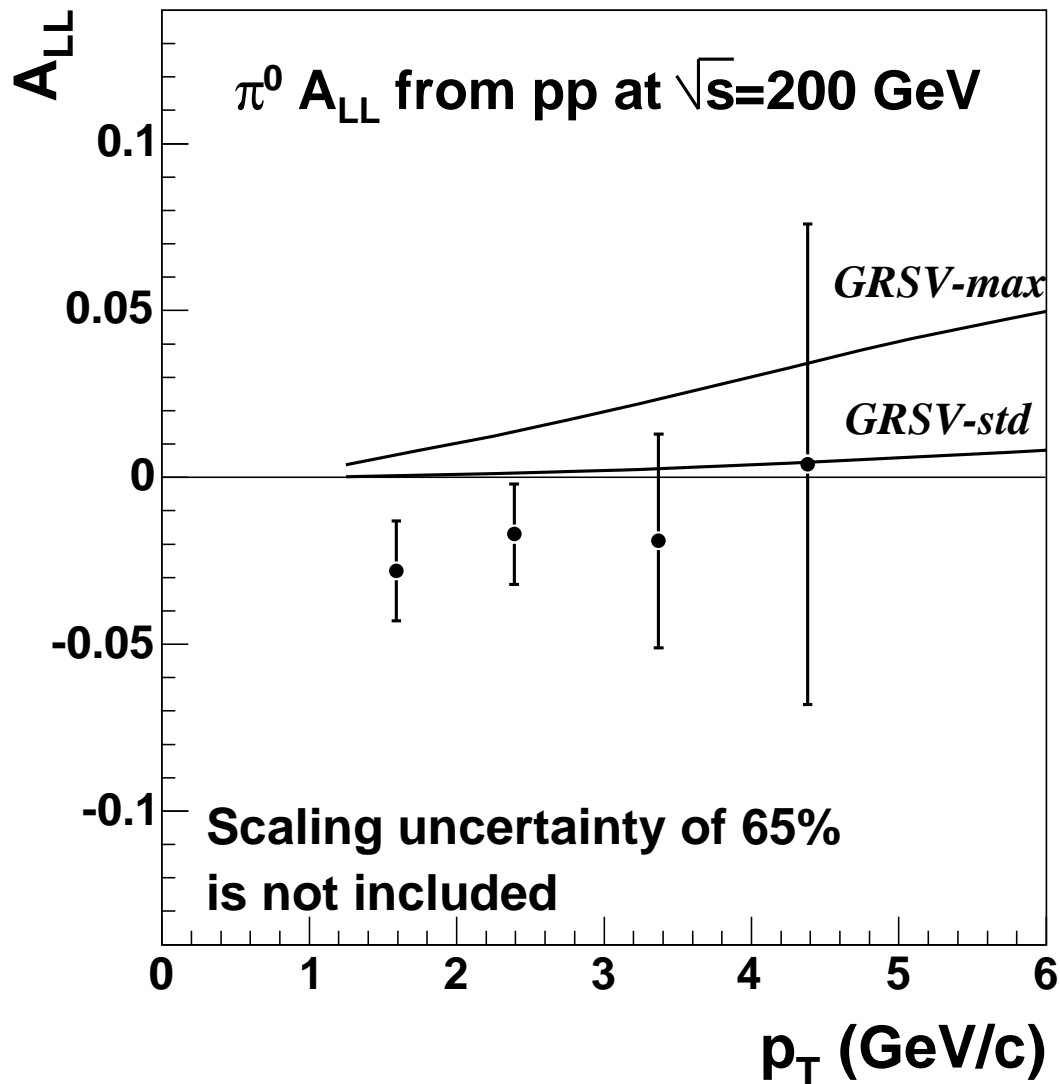
- investigation of  $\pi^0$  production and asymmetries



# RESULTS FOR $\pi_0$

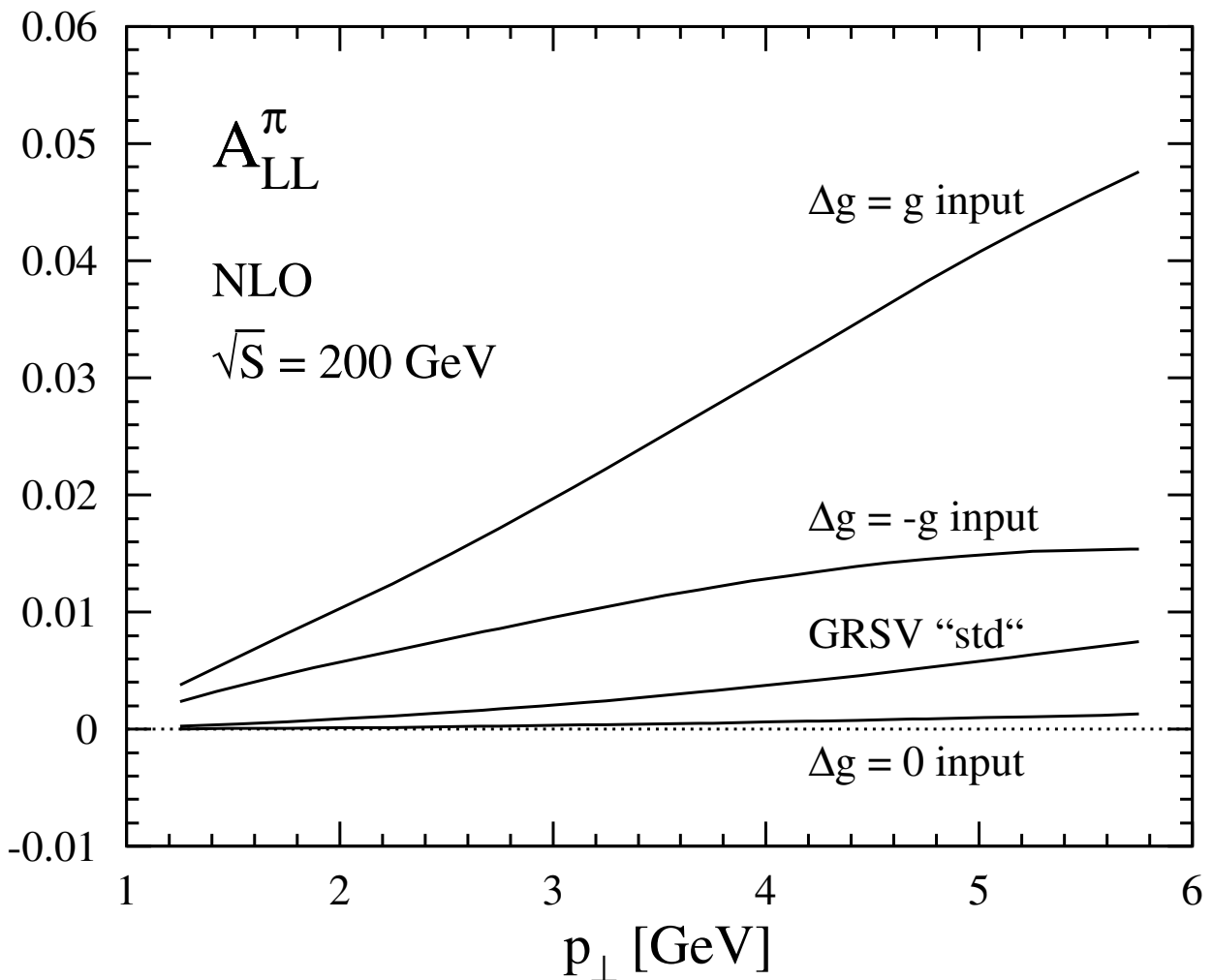


# ASYMMETRY $A_{LL}$



- good description of cross section with NLO QCD
- background decreasing with  $p_T$
- observed asymmetry is small

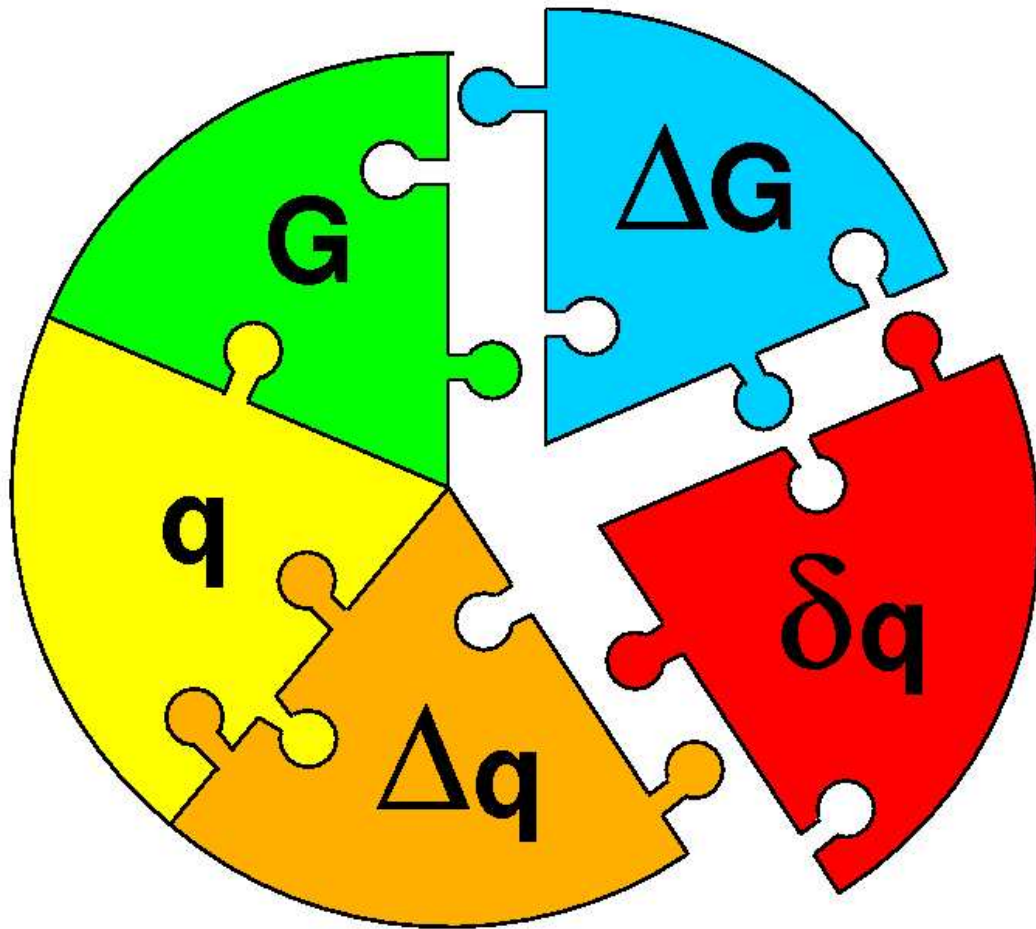
# Interpretation?



- $qg \longrightarrow qgX$  at small  $p_T$   
 $gg \longrightarrow qqX$  at large  $p_T$
- background decreasing with  $p_T$
- pQCD predicts positive asymmetries
- prediction for asymmetries using wide range of input  $\Delta g(x)$
- more precise data needed needed

# TRANSVERSITY

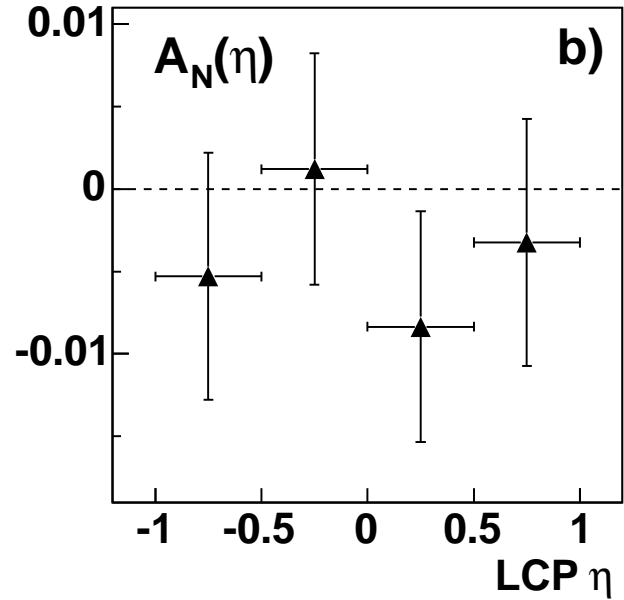
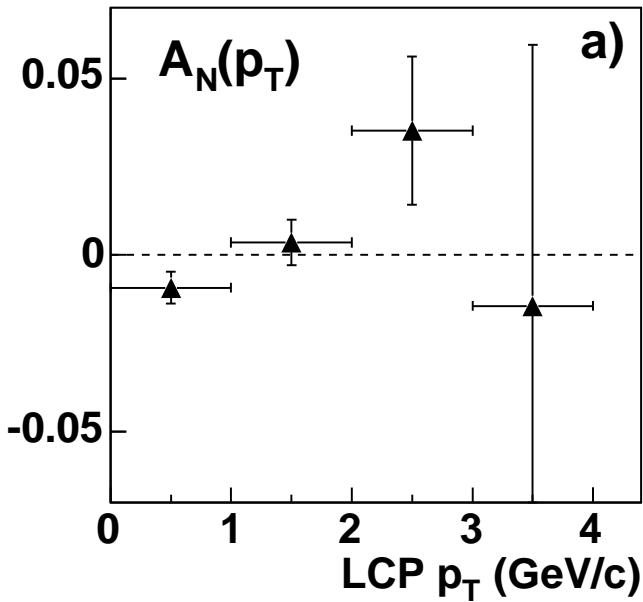
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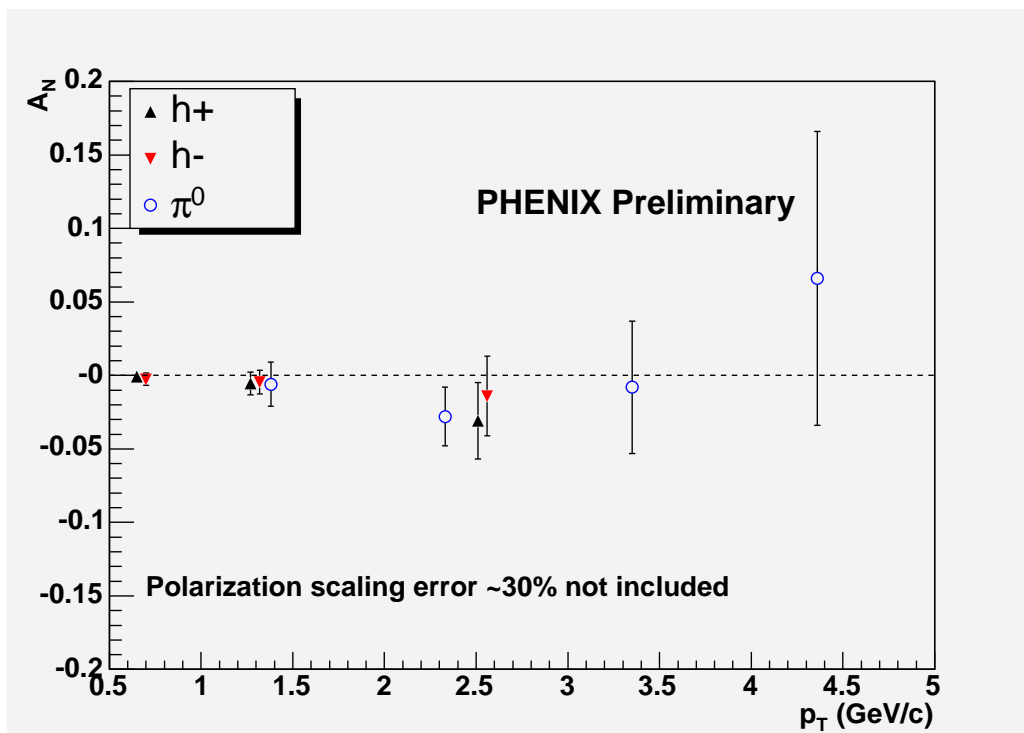
see Klaus Riths talk

# RESULTS FROM RHIC

STAR



PHENIX



# SUMMARY

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- Spin physics is a very active field
- Experiments are concentrating on semi-inclusive (and exclusive) measurements now
- Fixed target and collider experiments
- Flavour separation of polarised PDFs studied
- Measurement of gluon polarisation started
- Additional topics not discussed:  
transversity, DVCS, exclusive meson production
- Many new data to come soon