Spin Structure of the Nucleon

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- Longitudinal spin structure
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- Summary and the future

Topics not covered: GDH sum rule, g_2 (mainly JLAB),
GPD's meas., Belle Collins FF

Introduction

Spin degree of freedom

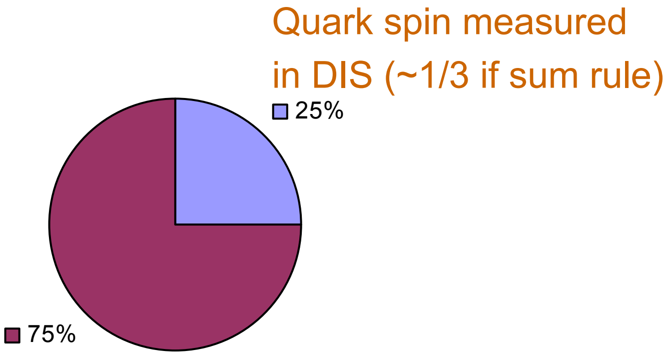
- Spin is a fundamental degree of freedom originated from the space-time symmetry.
- Spin plays a critical role in determining the basic structure of fundamental interactions.
- Test of a theory is not complete without a full test of spin-dependent decays and scattering.

Spin provides a unique opportunity to probe the inner structure of a composite system (such as the proton) and hence testing our ability to understand the working of non-perturbative QCD

- The driving question for QCD spin physics is where the nucleon spin comes from?

X.Ji, DIS2008

Total proton spin = 1/2



“Dark” angular momentum?

Structure functions and anomaly

DIS:

$$\sigma \sim F_1(x) = \tfrac{1}{2}\sum_i e_q^2 q_i(x) \quad \text{and} \quad F_2(x) \approx 2xF_1$$

$$\Delta\sigma = \overset{\leftrightarrows}{\sigma} - \overset{\rightrightarrows}{\sigma} \sim g_1(x) = \tfrac{1}{2}\sum_i e_q^2 \Delta q_i(x) \quad \text{and} \quad g_2$$

where: $\Delta q(x)=q^+(x) - q^-(x)$

„Switching on" spin lead us to two complications:

$q^+ \sim \Psi\,(1+\gamma^5)\,\gamma_\mu\Psi,\quad q^- \sim \Psi\,(1-\gamma^5)\gamma_\mu\Psi \;\Rightarrow \Delta q(x) \sim \Psi\gamma^5\gamma_\mu\Psi$

1. Axial vector current is not conserved – triangle anomaly (Adler-Bell-Jackiw)
2. There is no local and gauge invariant, dimension-3 axial vector operator for gluons in QCD; (local in axial gauge).

solved? See PRL100 (2008),232002-1

However there is a good helicity gluon distribution function defined in axial gauge where QPM is formulated! (infinite momentum frame).

Sum rules

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

$$\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6g_V} C_1^{NS}$$ (Bjorken sum rule)

$$\Gamma_1^{p,n} = \left(\pm a_3 + \frac{a_8}{3}\right)\frac{C_1^{NS}}{12} + a_0 \frac{C_1^S}{9}$$ (Ellis-Jaffe sum rule)

$a_3, a_8, g_{A,V}$ - weak β hyperon decays + $SU_f(3)$;

$C_1^{S,NS}$ - Calculable in pQCD

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

Invariant triangle anomaly term

$$\Gamma_1^{p(n)} = \frac{1}{2}\left(\frac{4\,(1)}{9}\Delta u + \frac{1(4)}{9}\Delta d + \frac{1}{9}\Delta s\right)$$

$$= (-)\frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

Decomposition of the nucleon spin

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L$$

- Naive scenario: $\Delta\Sigma=1$ and the rest 0.(e.g. SU(6) static model)
- Relativistic corrections change this requirement to ~ 0.6!

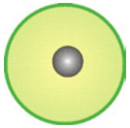
Simple example - MIT Bag model: „bag" with relativistic quarks confined in sphere with radius R.

Lower spinor („p" state) – effectively transfers spin to orbital angular momentum and the contribution to the nucleon „spin" is smaller: ~0.65

$$\Psi = \begin{pmatrix} f \\ i\hat{\sigma}\hat{r}g \end{pmatrix} \rightarrow \begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix} \Rightarrow (f^2 - \tfrac{1}{3}g^2) \quad \sim 0.65$$

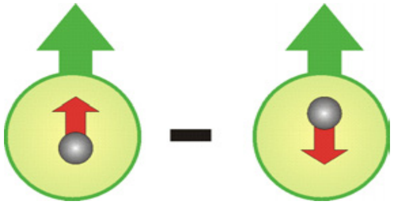
Transversity

- $q(x)$: unpolarized



- $\Delta q(x) = q^{\leftrightarrows} - q^{\rightrightarrows} = q^{+} - q^{-}$: helicity

- $\Delta_T q(x) = q^{\uparrow\uparrow} - q^{\downarrow\uparrow}$: transversity



$\Delta_T q(x)$ is C-odd and chiral odd →not in inclusive DIS

In Drell-Yan: $\Delta_T q(x) \otimes \Delta_T q(x)$

SIDIS (semi-inclusive…): $\Delta_T q(x) \otimes \Delta_T D_q h(z)$

Transversity

Key features of transversity:

- probes relativistic nature of quarks
- no gluon analog for spin-1/2 nucleon
- different Q^2 evolution and sum rule than $\Delta q(x)$
- sensitive to valence quark polarization

- Nonrelativistic quarks – no differences between transversity and helicity – boosts and rotations commute.
- Relativistic quarks gives the difference example - again MIT Bag model:

„renormalization" factor:

$$\Psi = \begin{pmatrix} f \\ i\hat{\sigma}\hat{r}g \end{pmatrix} \rightarrow \begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix} \Rightarrow (f^2 - \tfrac{1}{3}g^2)$$ helicity – 0.65

$$(f^2 + \tfrac{1}{3}g^2)$$ transversity – 0.83

Leader sum rule (04):

$$\frac{1}{2} = \frac{1}{2}\sum_{q,\bar{q}}\int dx \cdot \Delta_T q(x) + \sum_{q,\bar{q},g}\langle L_z\rangle$$

in analogy with:

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

Collins and Sivers effects

Collins effects

$$N_h^{\pm} = N_h^0 \cdot [1 \pm A_1 \cdot \sin\Phi_{Coll}]$$

$$A_1 = f \cdot P_T \cdot D \cdot A_{Coll}$$

$$A_{Coll} = \frac{\Sigma_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\Sigma_q e_q^2 \cdot q \cdot D_q^h}$$

Polarimeter!

$\Delta_T^0 D_q^h$ describes the spin-dependent part of the hadronisation of a transversally polarised quark *q* into a hadron *h*

Sivers effects

$$N_h^{\pm} = N_h^0 \cdot [1 \pm A_1 \cdot \sin\Phi_{Siv}]$$

$$A_1 = f \cdot P_T \cdot D \cdot A_{Siv}$$

$$A_{Siv} = \frac{\Sigma_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\Sigma_q e_q^2 \cdot q \cdot D_q^h}$$

probability of finding unpolarized quarks inside transversally polarized nucleon

Intrinsic $\vec{k}_T$ dependence of the quark distribution

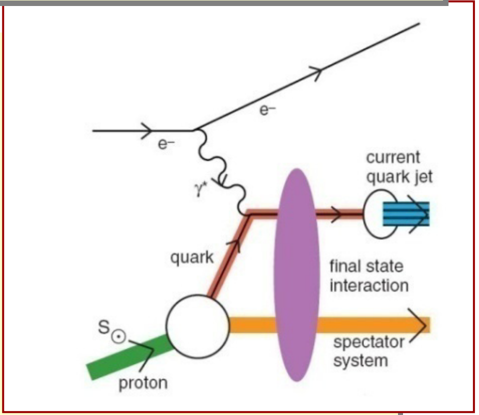
$$q_T(x,\vec{k}_T) = q(x,|\vec{k}_T|^2) + \Delta_0^T q(x,|\vec{k}_T|^2)\sin\Phi_S$$

Measurements: single-spin asymmetry on transversely polarized target

Sivers effect

- Final state interactions generate asymmetry before the active quark fragments – condition: k_T of quark in tranversely polarized nucleon
- Non-integrated distributions (in k_T)
- Chiral-even, T-odd (Collins: chiral-odd, T-even)

- Transverse structure (k_T) – beyond the simple QPM model of paralell stream of partons – connection with orbital angular momentum?



Sivers effect requires:

- Correlation of the two QCD amplitudes
  γ p↑⟶ F i γ p↓⟶ F – where F – same final state
- Boths amplitudes should have different phases (T-odd)
- Amplitudes with two different spin projections $\Longrightarrow$ ΔL=1!
- FSI (dla DIS) i ISI (dla DY) – reason why Sivers is not universal distribution

Longitudinal spin structure

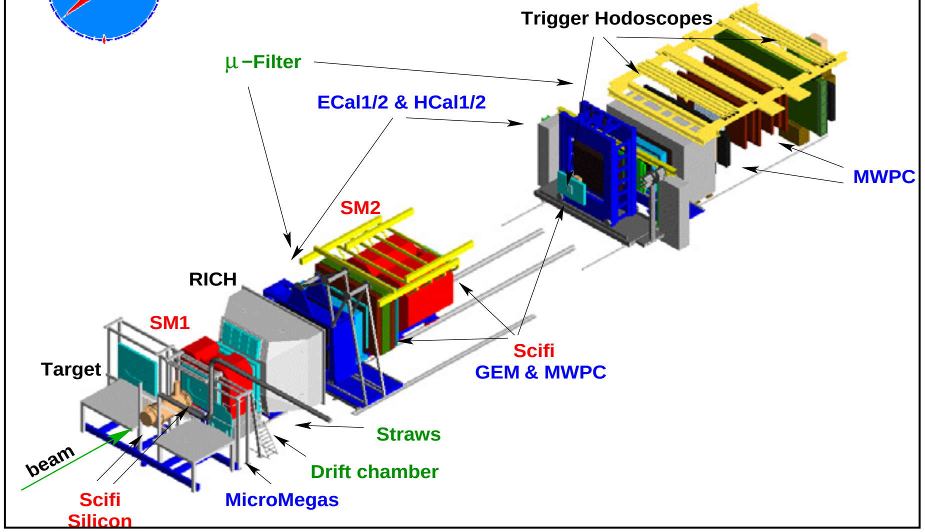
Experiments

Experiments:

- Inclusive spin-dependent DIS
  EMC, SMC, COMPASS (CERN),E142,E143,E154,E156,
  HERMES (DESY) ,JLAB-Hall,A,B(CLAS)
- Semi-inclusive DIS: SMC, COMPASS,HERMES
- Polarized pp collision RHIC,PHENIX & STAR, BRAHMS (Brookhaven)
- ee: BELLE (KEK) (Fragmentation functions)

Beam: 160 GeV ,$P_{beam:}$~75%

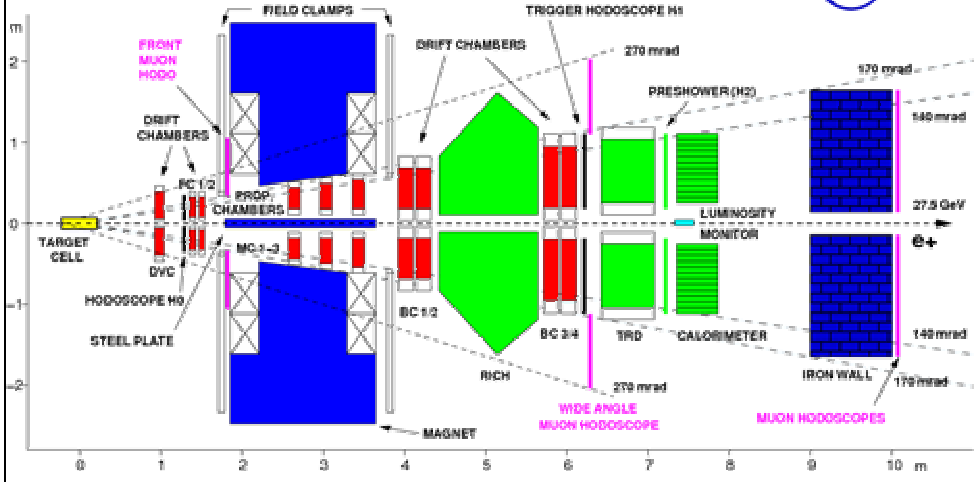
Target: ^{6}LiD; 50% pol, NH_3 (2007)



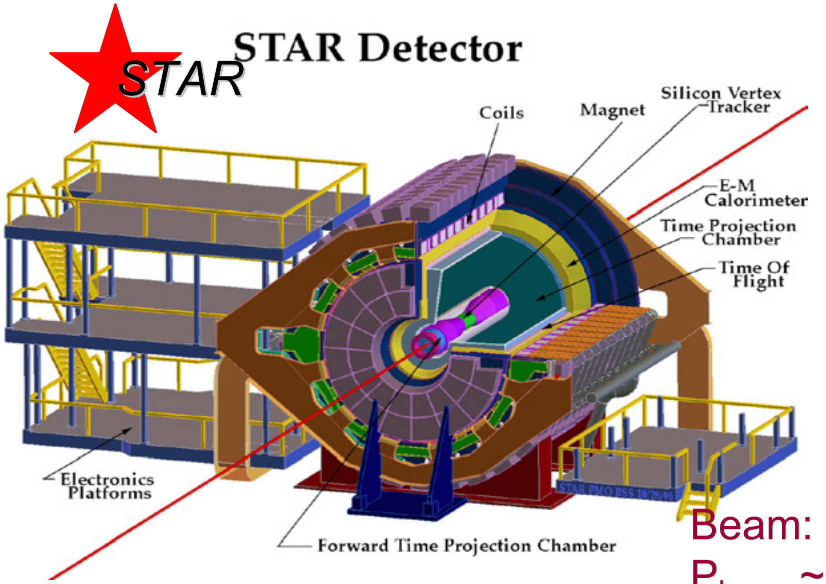
Beam: 27.5 GeV $e^{\pm}$ P_{beam}~(53±1.0)%

Internal Gas Target: pol.: He , H , D

unpol: H_2, D_2, He, N, Ne, Kr, Xe



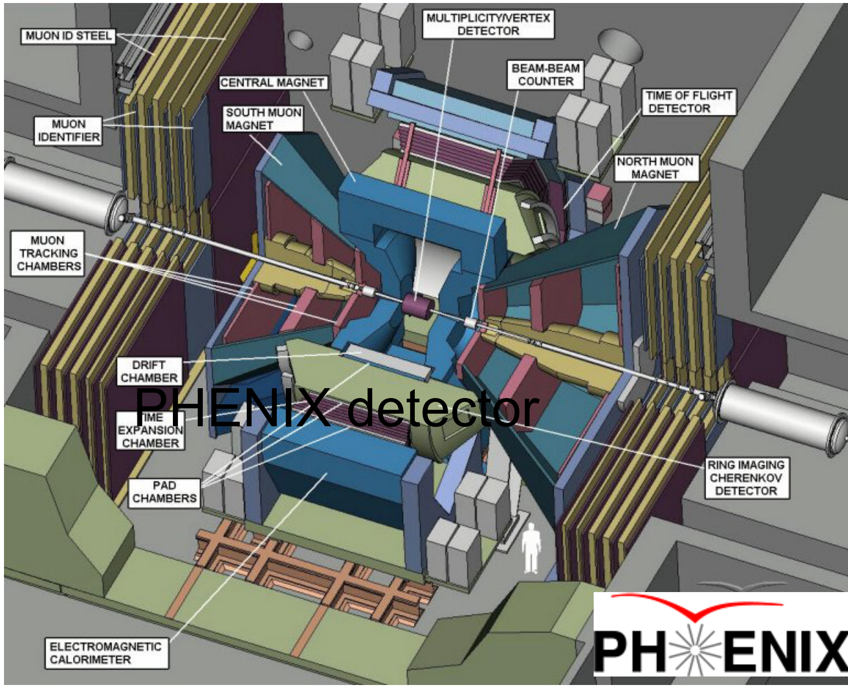
Experiments



RHIC

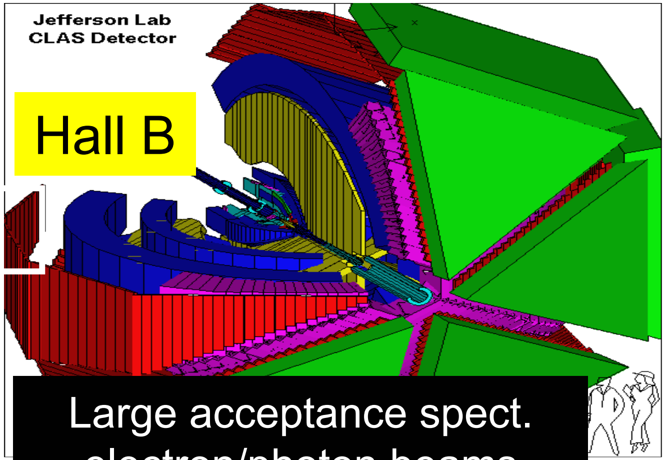
Beam: 200 GeV pp

$P_{beam:}$~60 %



PHENIX detector

JLAB



Hall B

Large acceptance spect.
electron/photon beams

Beam: ≤6 GeV e^-; 85% polarization
Target: polarized targets ^{3}He, ^{6}LiD, NH_3

A_1 and g_1

How to translate measured longitudinal asymmetry to g_1 structure function?

$$A_{||} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = D\,(A_1 + \eta\, A_2\,)$$

$$|\eta\, A_2^{d,p,n}| \ll |A_1^{d,p,n}|\,,$$

$$A_1^{p,n} = A^{\gamma N} = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}}$$ for nucleon

$$A_1^{d} = A^{\gamma d} = \frac{\sigma^{0} - \sigma^{2}}{\sigma^{0} + \sigma^{2}}$$ for deuteron

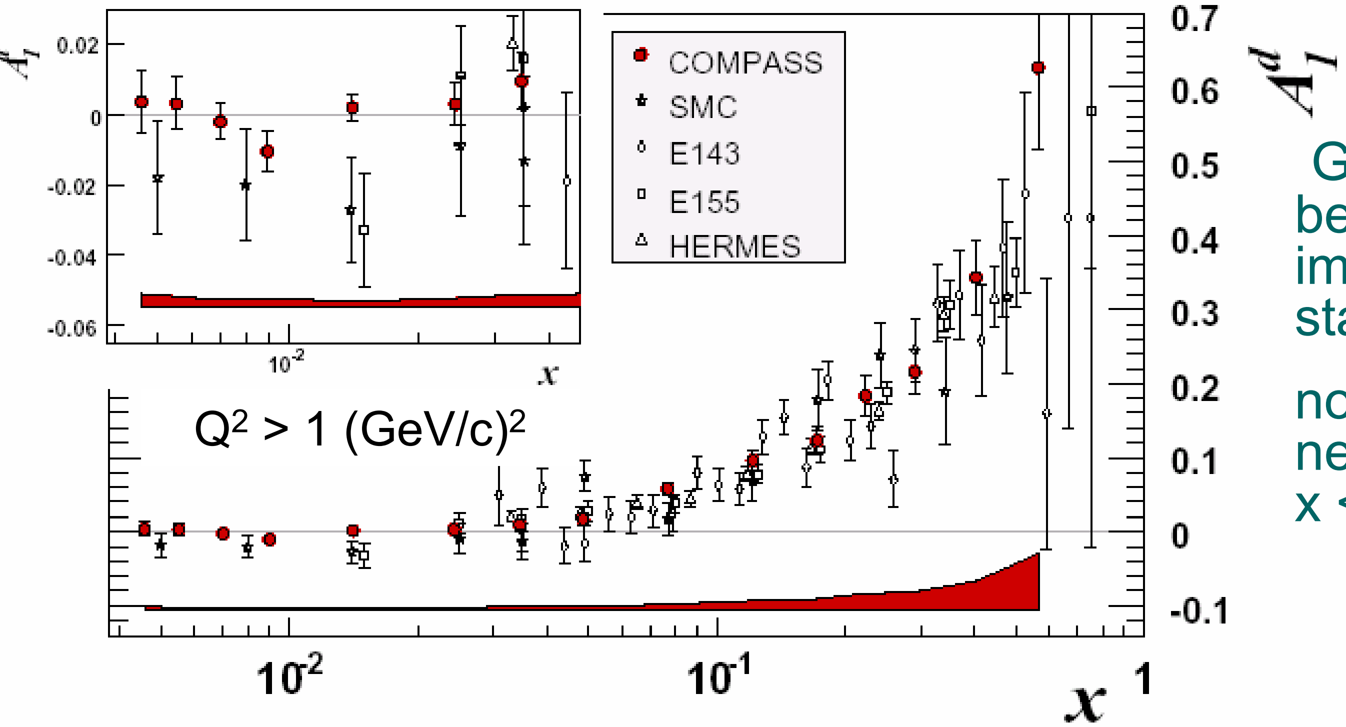
$$A_{meas} \sim A_{||} \sim A_1$$

For deuteron:

$$g_1^d = ½\,(g_1^p + g_1^n)\,(1- \frac{3}{2}\,\omega_d\,) \simeq A_1^d\, F_1^d = A_1^d\, \frac{F_2^d}{2x(1+R)}$$

New results: COMPASS

COMPASS 2002-2004 data ($Q^2>1(GeV/c)^2$) PLB 647 (2007)8



Good agreement between experiments, improved significantly statistics at low x,

no tendency towards negative values at x < 0.03

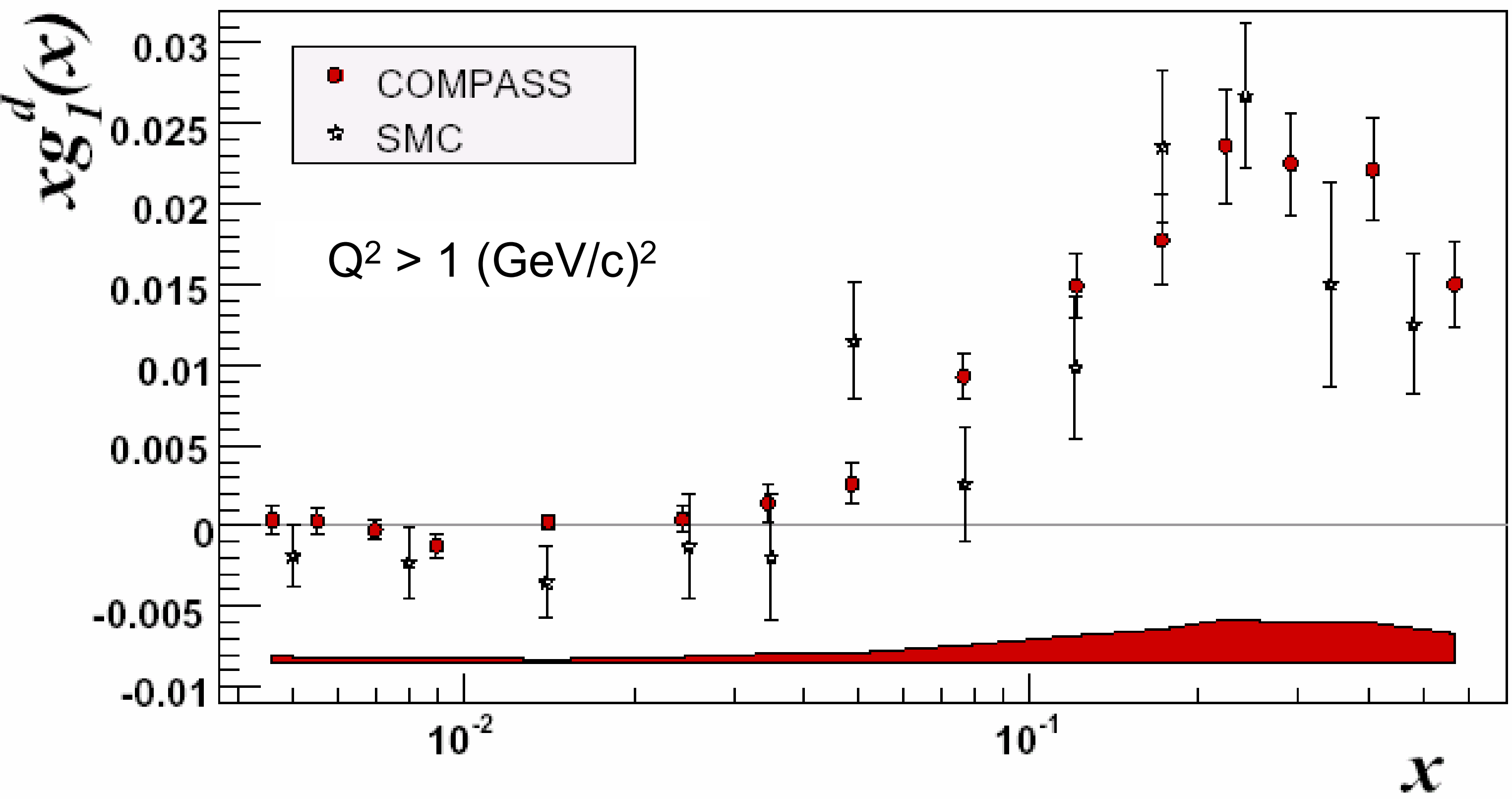
COMPASS 2002-2003 data ($Q^2<1(GeV/c)^2$) PLB 647 (2007)330

10-20 times lower statistical errors compared to SMC- very precise!
The results compatible with zero for small x

New results: COMPASS

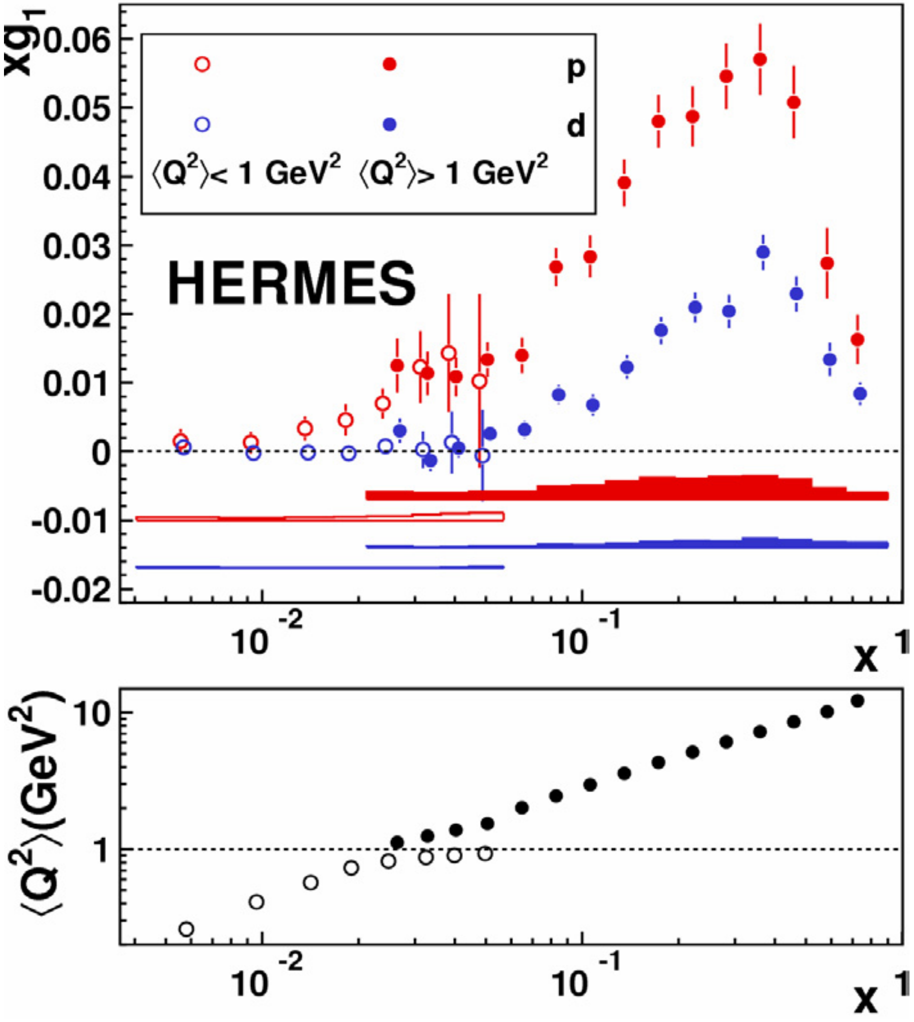
COMPASS 2002-2004 data ($Q^2 > 1 (\mathrm{GeV}/c)^2$)

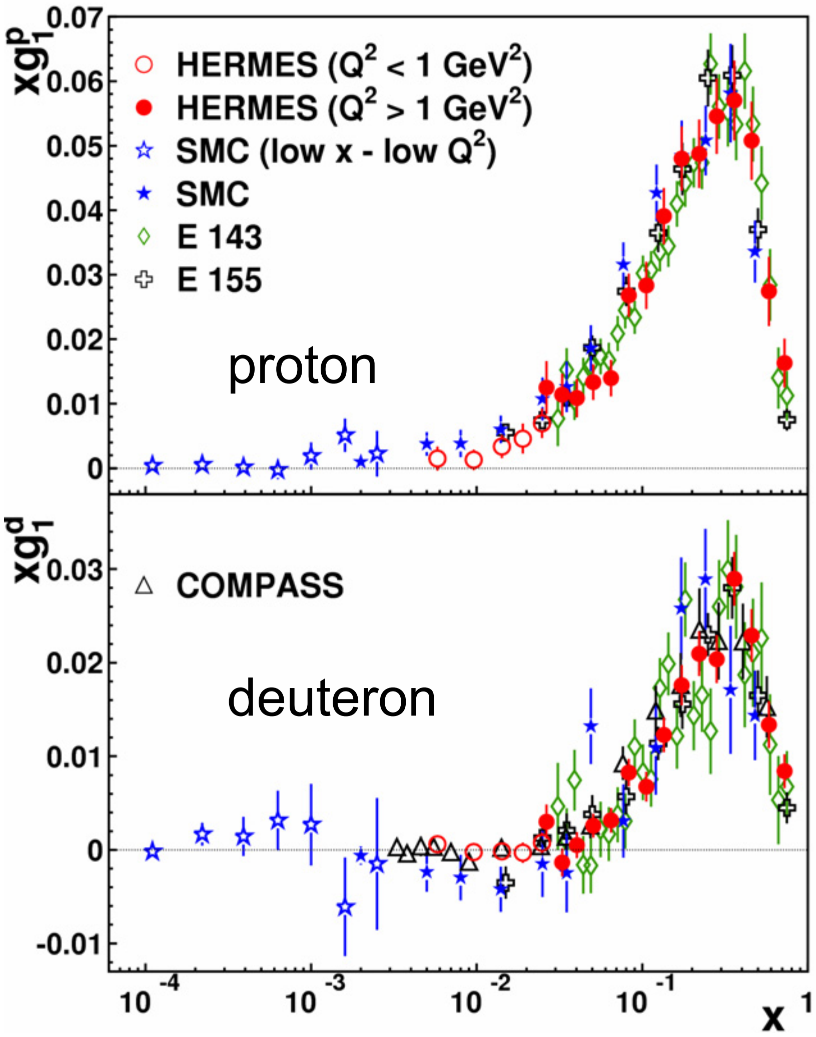
$$g_1^d = g_1^N (1 - \tfrac{3}{2}\omega_d) = \frac{F_2^d}{2x(1+R)} A_1^d$$



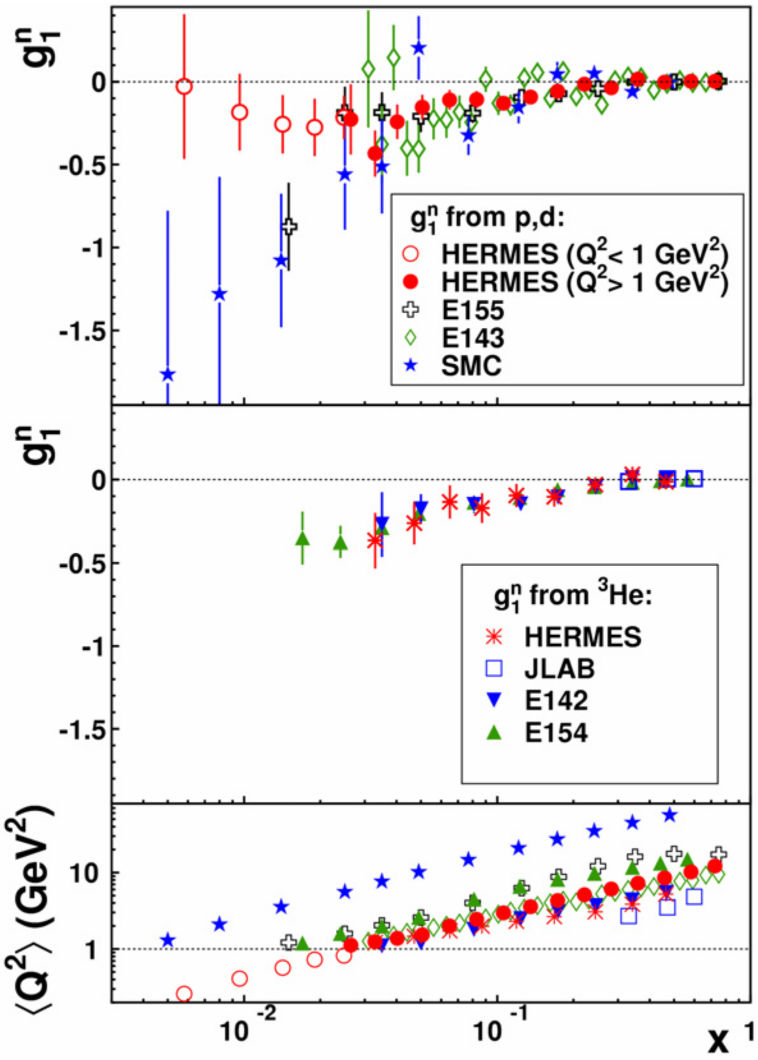
New results: HERMES

PRD 75:012007(2007).





New results: HERMES

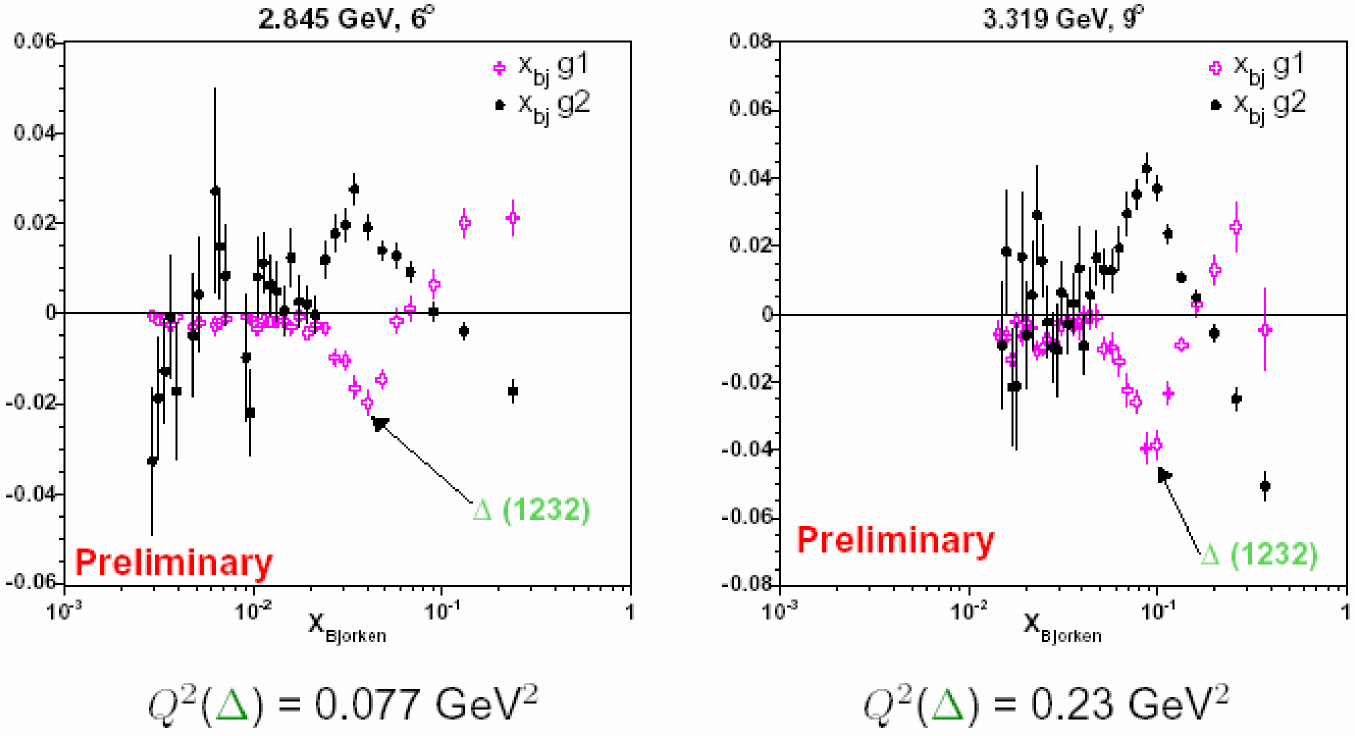


Neutron results

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

- g_1^n negative everywhere except at very high-x
- Low-Q^2 data tends to zero at low-x
  - Does not support earlier conjecture of strong decrease for $x \rightarrow 0$

JLAB Hall B: ^{3}He structure functions („effective neutron”)



$Q^2(\Delta)$ = 0.077 GeV^2

$Q^2(\Delta)$ = 0.23 GeV^2

Small Q^2 !
Note: precision of g_2

JLAB – g_1 for large x – important (CLAS)
PRL92 (2004)012004

Moment of g_1 (COMPASS)

Compass data only

Phys.Lett.B 647(2007)8

$$\Gamma_1^N\left(Q_0^2=3GeV^2\right)=\int_0^1 g_1^N(x)dx=0.050\pm0.003(stat)\pm0.003(evol)\pm0.005(syst)$$

$$\Gamma_1^N\left(Q^2\right)=\frac{1}{9}\left(1-\frac{\alpha_s(Q^2)}{\pi}+O(\alpha_s^2)\right)\left(a_0(Q^2)+\frac{1}{4}a_8\right)$$ (NLO QCD)

a_8 = 0.585 ± 0.025

(Goto *et al*., PRD62 (2000) 034017: SU(3)$_f$ assumed for weak decays)

$$\boxed{a_{0|Q_0^2=3(GeV/c)^2}=0.35\pm0.03(stat)\pm0.05(syst)}$$

Contribution from unmeasured x range ≈ 4%

HERMES: The deuteron integral is observed to saturate
a_0 = 0.330 ± 0.011(theor) ± 0.025 (exp) ± 0.028 (evol) at 5 (GeV/c)^2

Strange sea polarization (HERMES)

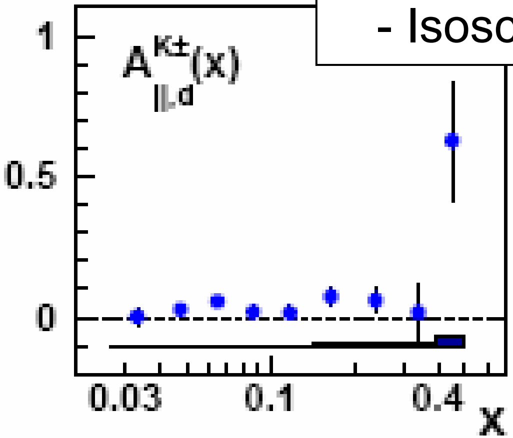
Seminclusive DIS – SIDIS: separation of the flavours.

Example: strange quark sea from HERMES

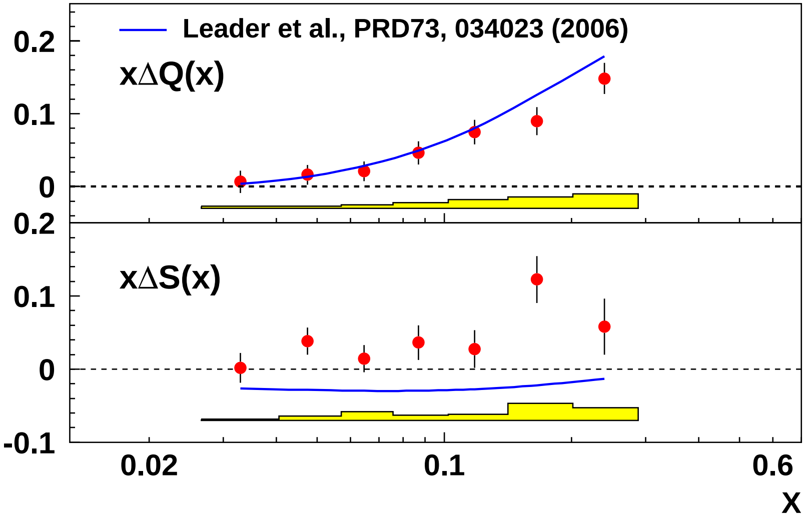
$$\vec{e}+\vec{d}\rightarrow e'K^{\pm}X$$

All needed information can be extracted from HERMES data alone!

- inclusive $A_{1,d}(x,Q^2)$ and kaon $A^K_{1,d}(x,Q^2)$ asym.
- Kaon multiplicities → D_Q^K and D_S^K
- Isoscalar target (deuteron) → fragmentation simplifies



Fit to the x-dependence of multiplicities to get S(x) PDF and Kaon FF



$$\int_{0.02}^{0.6}\Delta Q = 0.359\pm0.026\pm0.018$$

$$\int_{0.02}^{0.6}\Delta S = 0.037\pm0.019\pm0.027$$

COMPASS: $(\Delta s+\Delta\bar{s})=\frac{1}{3}(\hat{a}_0-a_8)=-0.08\pm0.01(stat)\pm0.02(syst)$

Difference asymmetries

Semi-inclusive hadron asymmetries

Idea: PLB 230(1989)141,
SMC:PLB 369(1996)93,

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

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

Difference asymmetry

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

Fragmentation functions cancel out in LO and under the assuption of independent fragmentation.

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

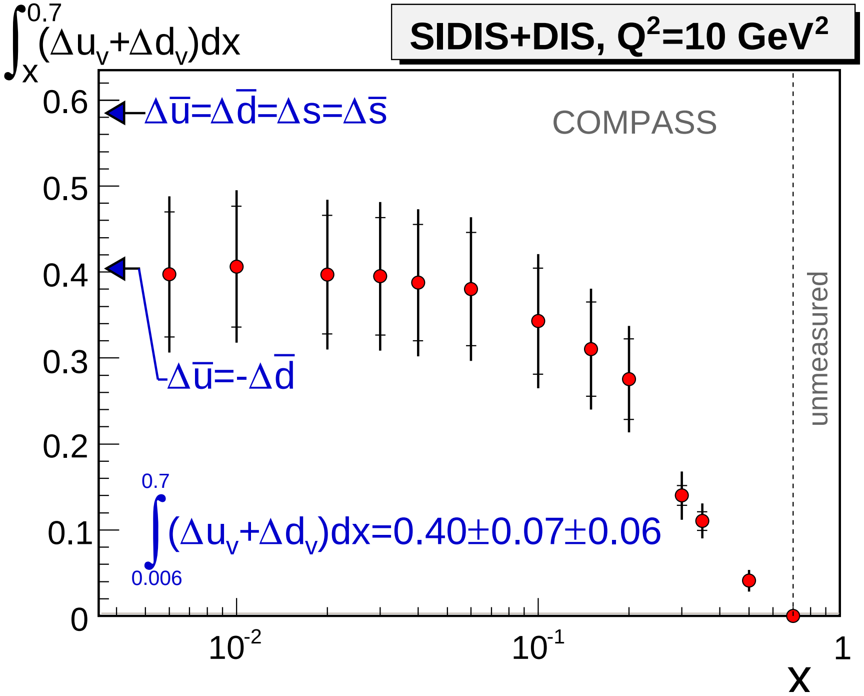
Only valence quarks!

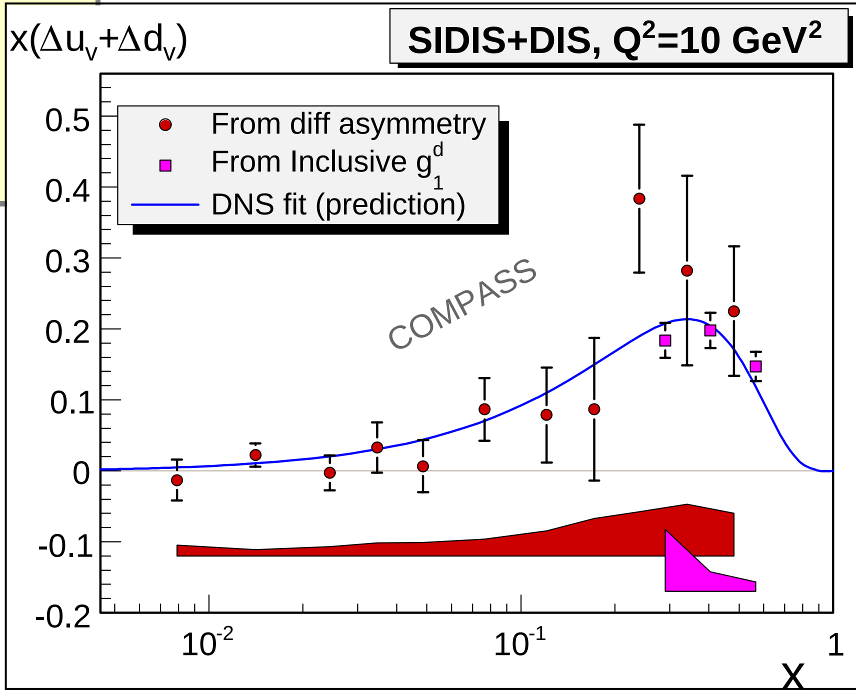
Valence quarks (COMPASS)

$$\Gamma_v = \int_0^1 (\Delta u_v(x) + \Delta d_v(x))dx$$

$$\Delta\bar{u} + \Delta\bar{d} = 3\Gamma_1^N - \tfrac{1}{2}\Gamma_v + \tfrac{1}{12}a_8 = (\Delta s + \Delta\bar{s}) + \tfrac{1}{2}(a_8 - \Gamma_v)$$

$$\left.\begin{array}{ll} \Delta\bar{u} = \Delta\bar{d} = \Delta s = \Delta\bar{s} & \text{symmetric} \\ \Delta\bar{u} = -\Delta\bar{d} & \text{asymmetric} \end{array}\right\} \text{scenario}$$





Data: asymmetric scenario!

PLB 660(2008)458

QCD analysis (fits)

Idea:

- Measured structure function $g_1^{p,n,d}$ (different x and Q²)

$$g_1(x,Q^2)=\tfrac{1}{2}\langle e^2\rangle\left[C_q^s\otimes\Delta\Sigma+C_q^{NS}\otimes\Delta q^{NS}+2n_fC_G\otimes\Delta G\right]$$

- DGLAP equations:

$$t=\log\left(\frac{Q^2}{\Lambda^2}\right)$$

$$\begin{cases}\dfrac{d}{dt}\Delta q^{NS}=\dfrac{\alpha_S(t)}{2\pi}P_{qq}^{NS}\otimes\Delta q^{NS}\\[2ex] \dfrac{d}{dt}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}=\dfrac{\alpha_S(t)}{2\pi}\begin{pmatrix}P_{qq}^S & 2n_fP_{qG}^S\\ P_{Gq}^S & P_{GG}^S\end{pmatrix}\otimes\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}\end{cases}$$

- Initial parametrization:
  x dependence at fixed Q²

($\gamma \neq 0$ for singlet only for $\Delta G > 0$)

$$(\Delta\Sigma,\Delta q_s,\Delta q_8,\Delta G)=\eta\frac{x^\alpha(1-x)^\beta(1+\gamma x)}{\int_0^1 x^\alpha(1-x)^\beta(1+\gamma x)dx}$$

- Minimization routine

$$\chi^2=\sum_{i=1}^{N}\frac{\left[g_1^{calc}(x,Q^2)-g_1^{\exp}(x,Q^2)\right]^2}{\left[\sigma_{stat}^{\exp}(x,Q^2)\right]^2}$$

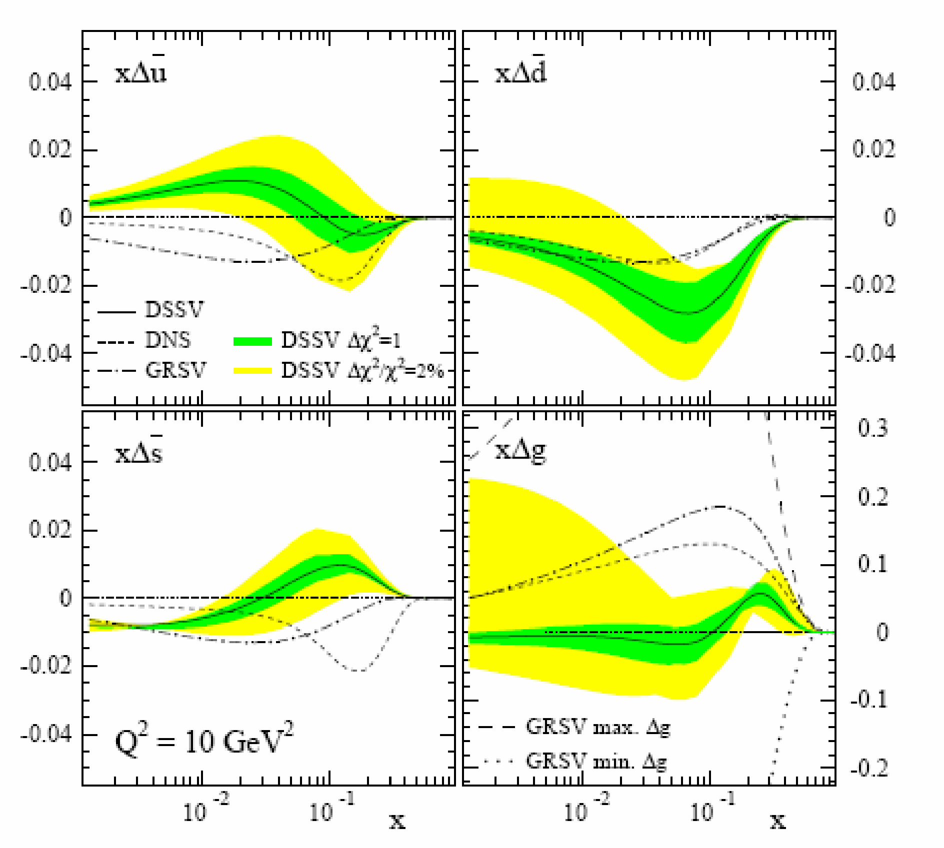
QCD analysis (fits)

- Make some generic assumptions about the functional form with a few parameters fixing by fitting the data
- Many efforts in the past have been made
  - Gluck, Reya, Stratmann, Vogelsang (2001)
  - Blumlein and Bottcher (2003)
  - Leader, Sidorov, Stamenov (2006)
  - Hirai, Kumano, Saito (2006)
  - …..

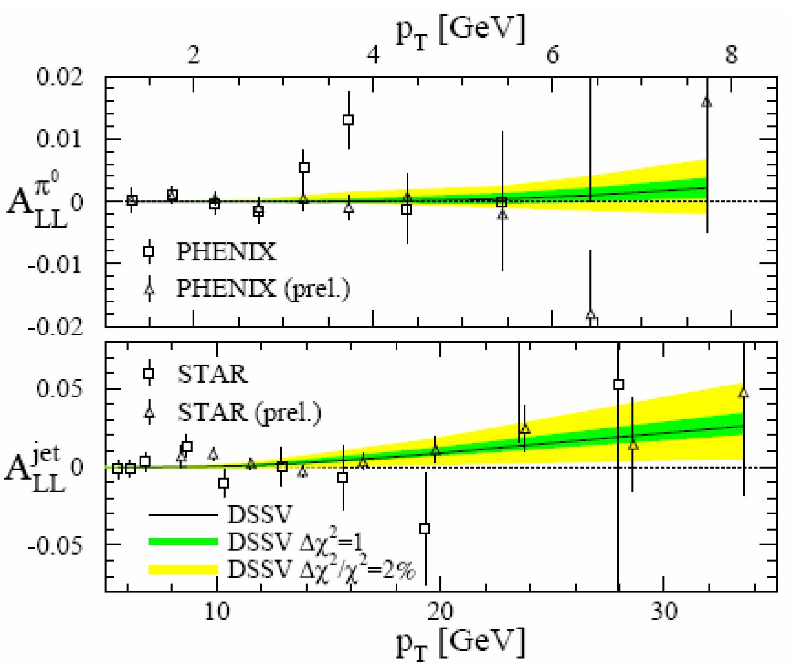
One of the most recent is the NLO fit by de Florian, Sassot, Stratmann and Vogelsang (hep-ph/0804.0422) in which pp collision jet data are first included. (Technically challenging!)

DSSV PDF

Polarized sea distributions



RHIC spin asymmetries



DSSV PDF

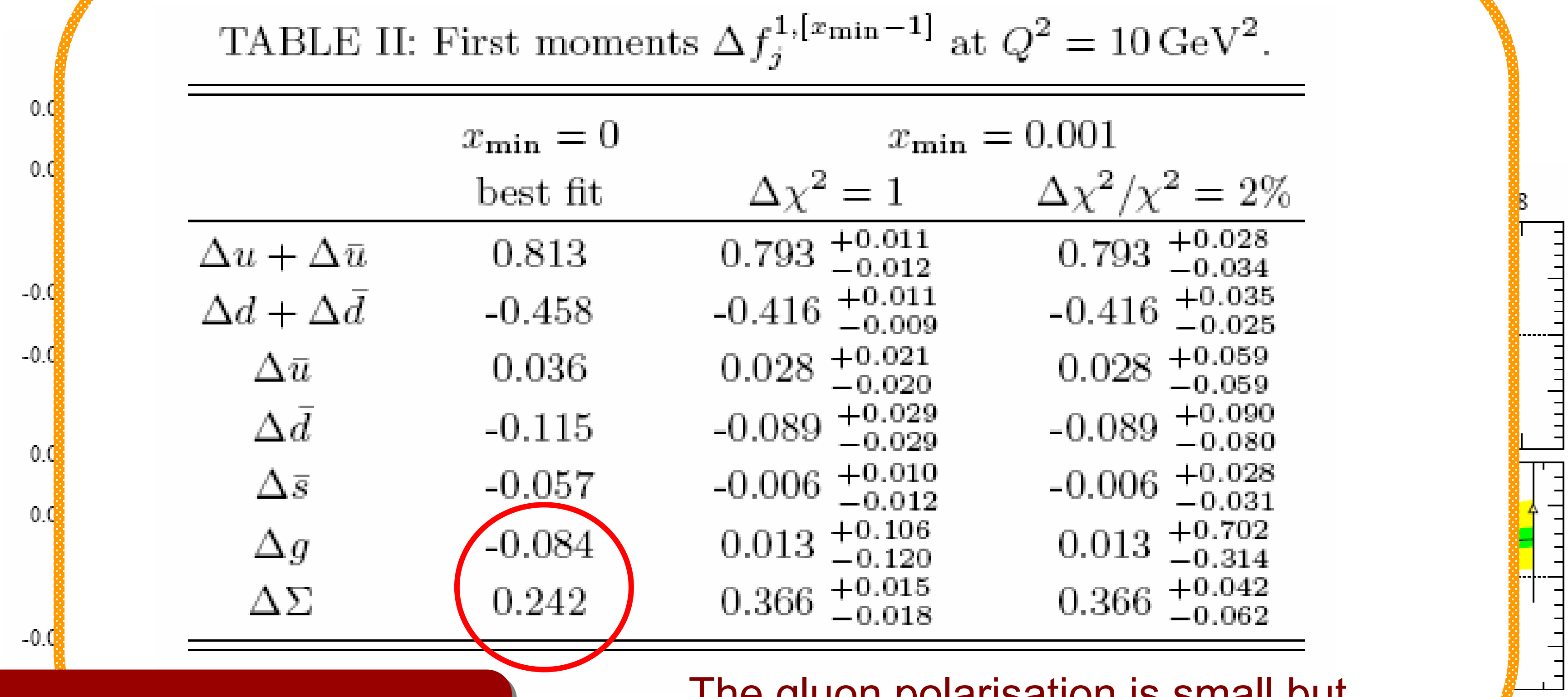


TABLE II: First moments $\Delta f_j^{1,[x_{\rm min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

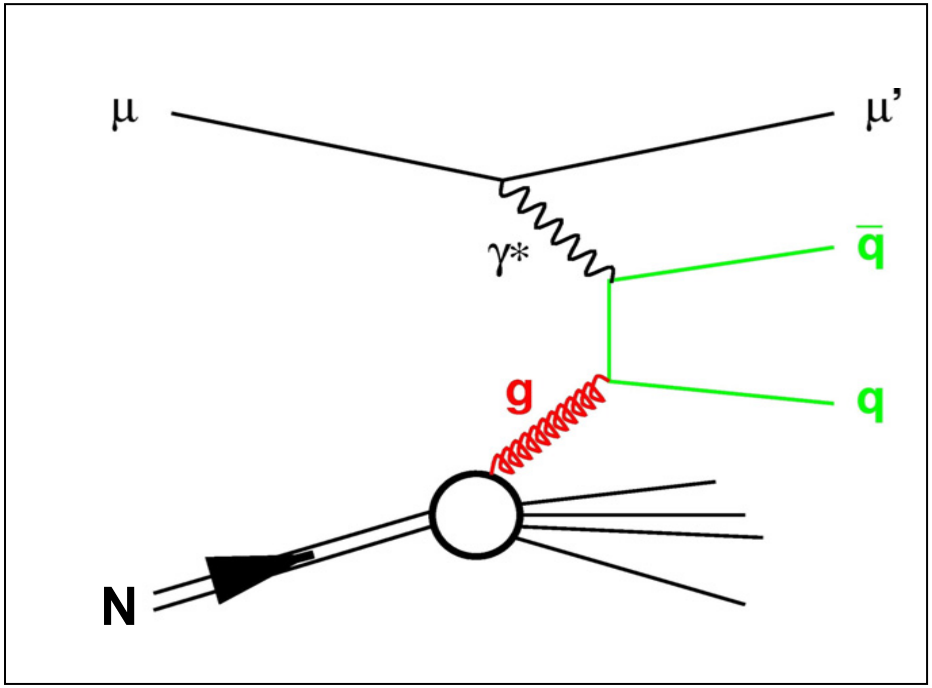
	$x_{\rm min} = 0$	$x_{\rm min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\,^{+0.011}_{-0.012}$	$0.793\,^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\,^{+0.011}_{-0.009}$	$-0.416\,^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\,^{+0.021}_{-0.020}$	$0.028\,^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-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	$0.366\,^{+0.015}_{-0.018}$	$0.366\,^{+0.042}_{-0.062}$

$\Delta\Sigma$ ~from ¼ up to 1/3

The gluon polarisation is small but still with large errors!

Gluon polarization

Photon-Gluon Fusion



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

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

Analysing power Gluon polarization

Open Charm

cross section difference in charmed meson production

$$\gamma^* g \to c\bar{c} \to D^0 X$$

→ clean channel
→ but experimentally difficult
and NLO corr. can be important

High-p_T Hadron Pairs

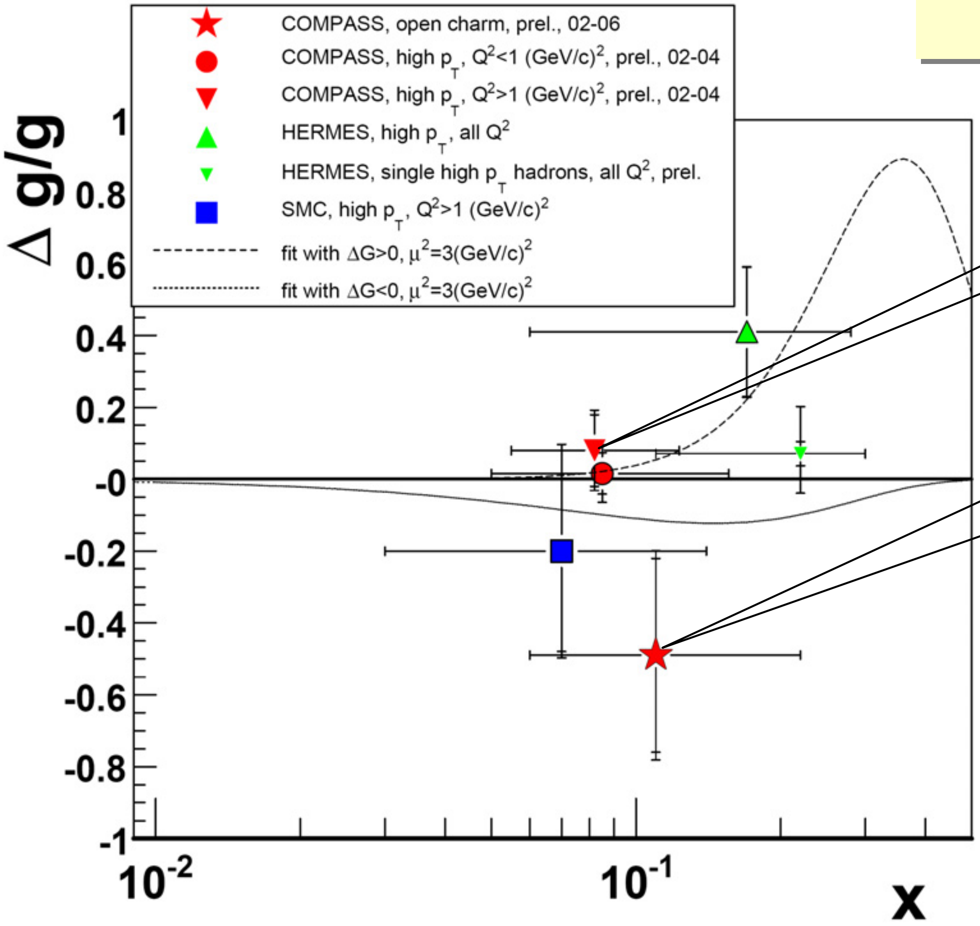
cross section difference in 2 hadrons production

$$\gamma^* g \to q\bar{q} \to h\bar{h}$$

→ large gain in statistics
→ but physical background
and analysis MC dependent

New results: COMPASS ΔG/G measurements summary

ΔG/G measurements



new high p_T point

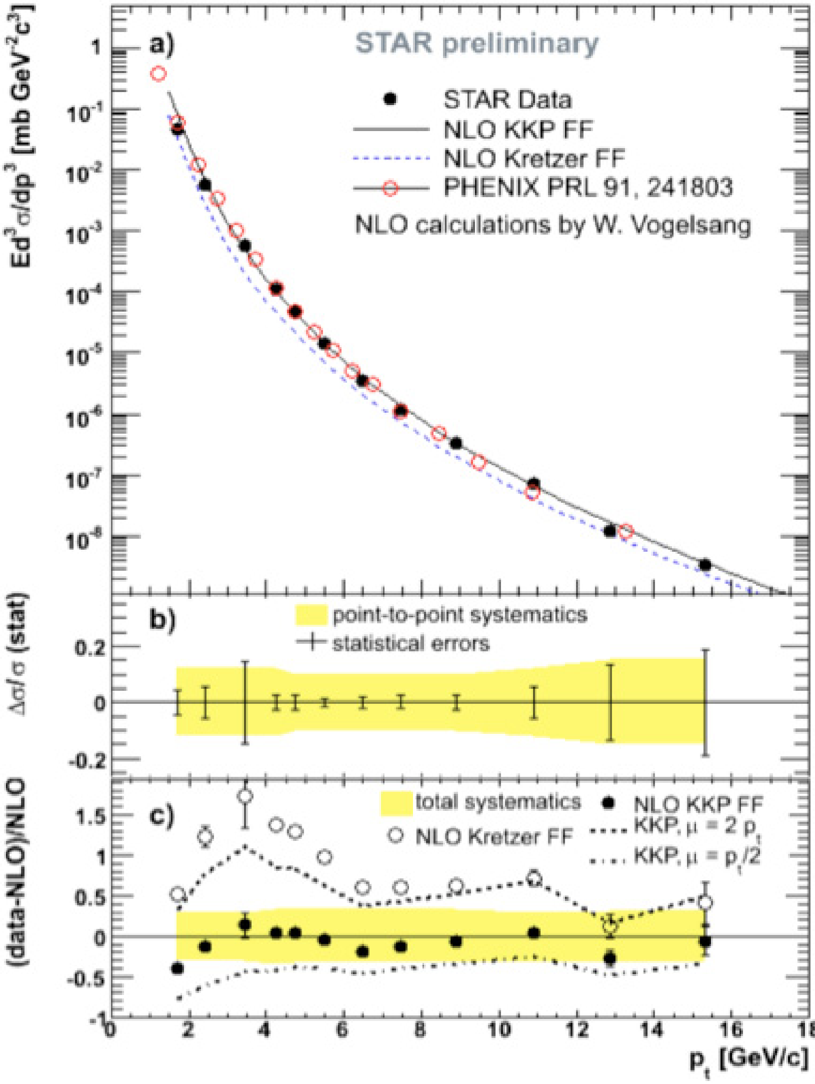
new charm point

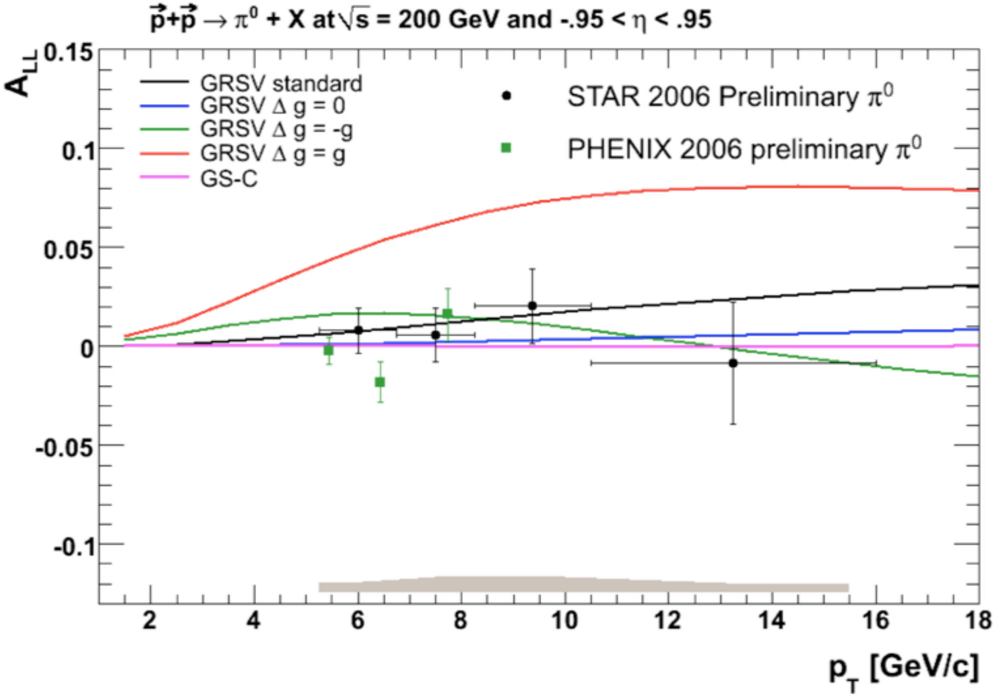
New high-p_T COMPASS result:
Data: 2002−2004 $Q^2>1(GeV/c)^2$
$\Delta G/G=0.08\pm0.1(stat.)\pm0.05(sys.)$

New charm COMPASS result:
Data: 2002−2006
$\Delta G/G=-0.49\pm0.27(stat.)\pm0.11(sys.)$

QCD fits → ΔG ≈| 0.2−0.3| as direct measurements point to a small value of ΔG ….. axial anomaly contribution is small → $a_0 \approx \Delta\Sigma$

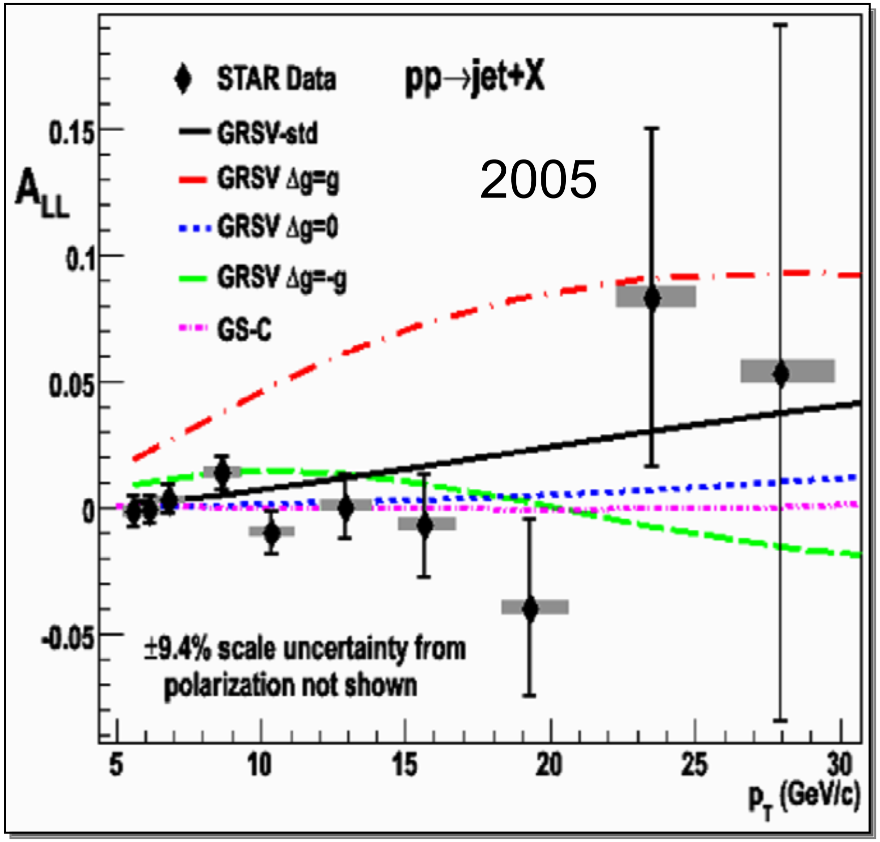
New results: RHIC-STAR π

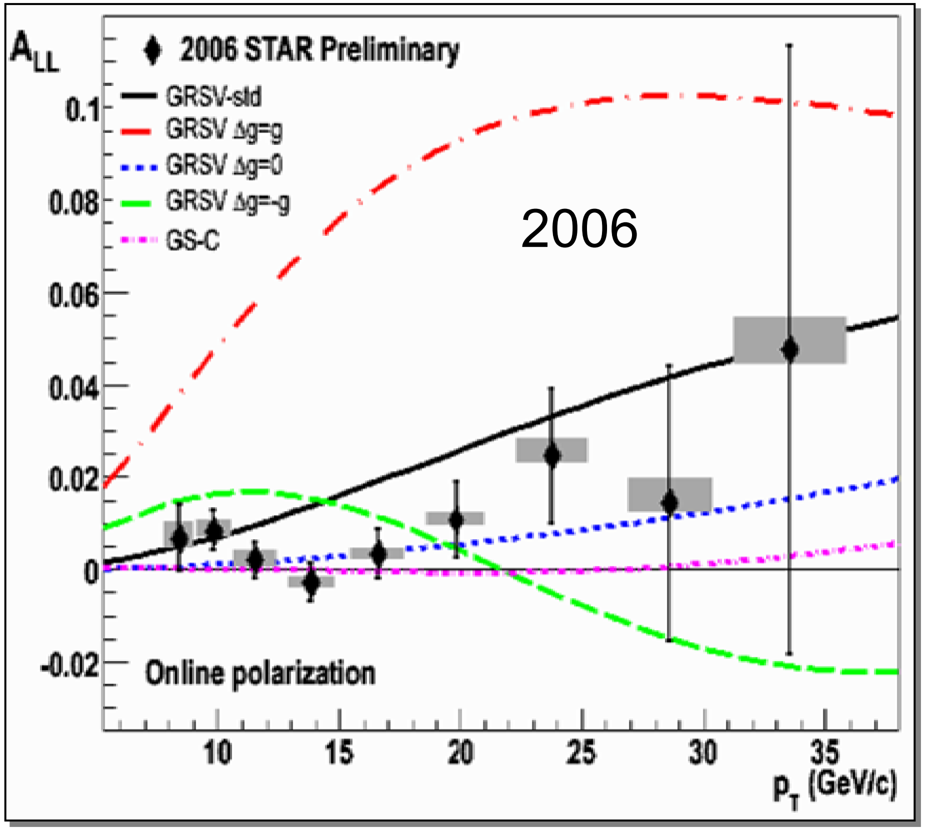




STAR/PHENIX π^0 asymmetries
QCD NLO analysis

New results: STAR inclusive jets



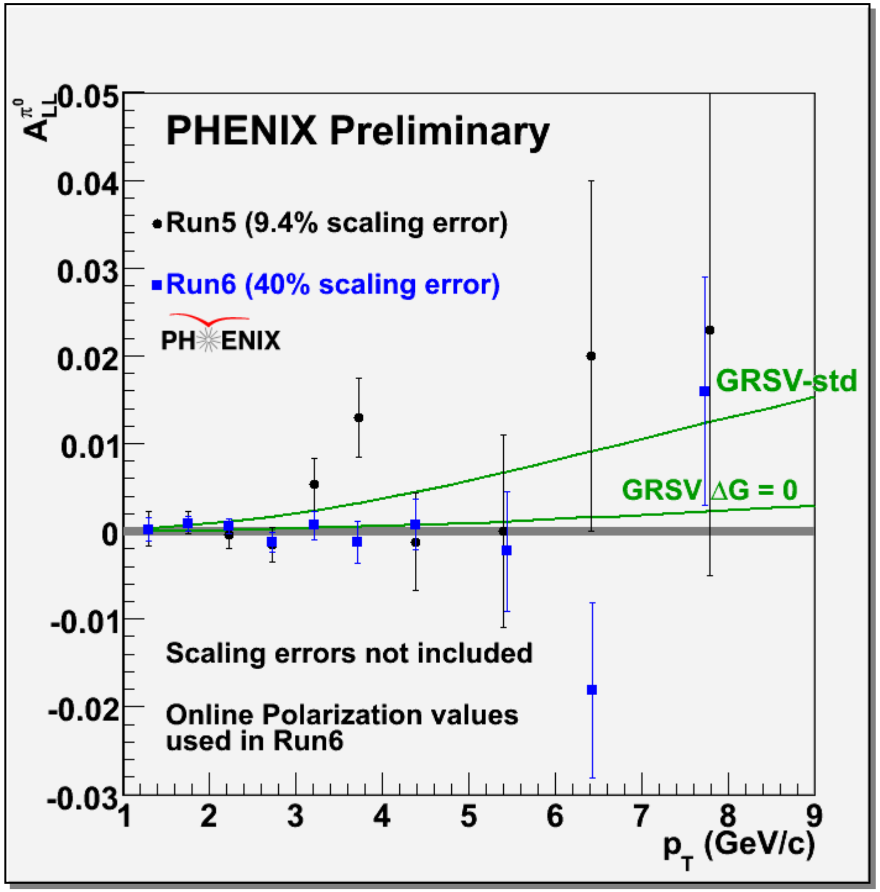


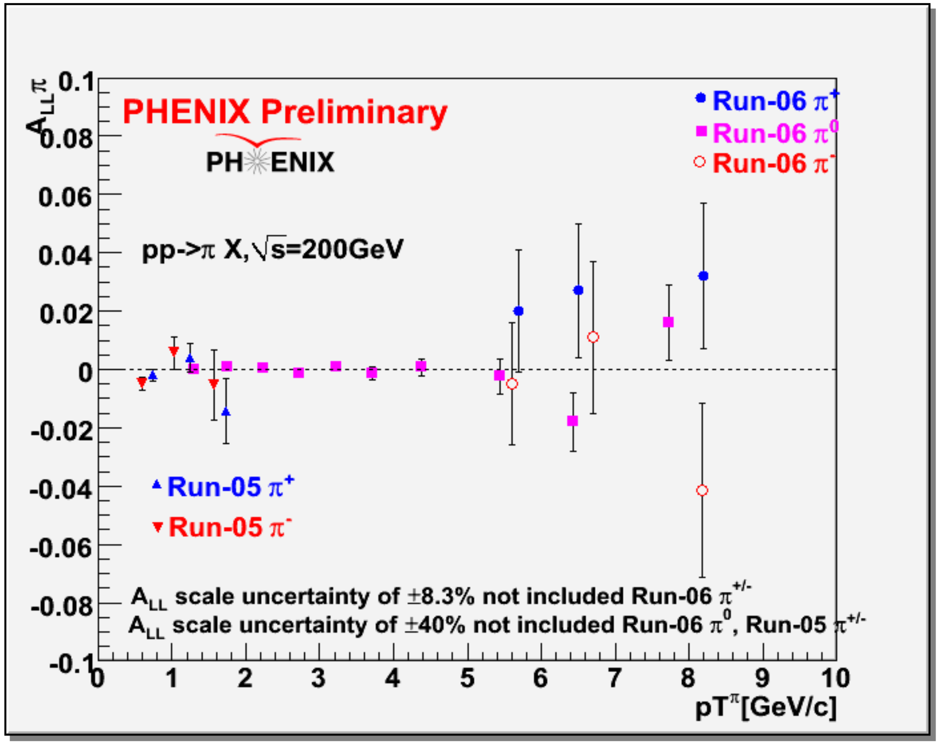
PRL100 (2008)28

Statistical uncertainty are 3-4 times smaller than in 2005 for p_T>13 GeV/c

GRSV-stnd. excluded 99% CL
ΔG<-0.7: 90%

New results: PHENIX, π



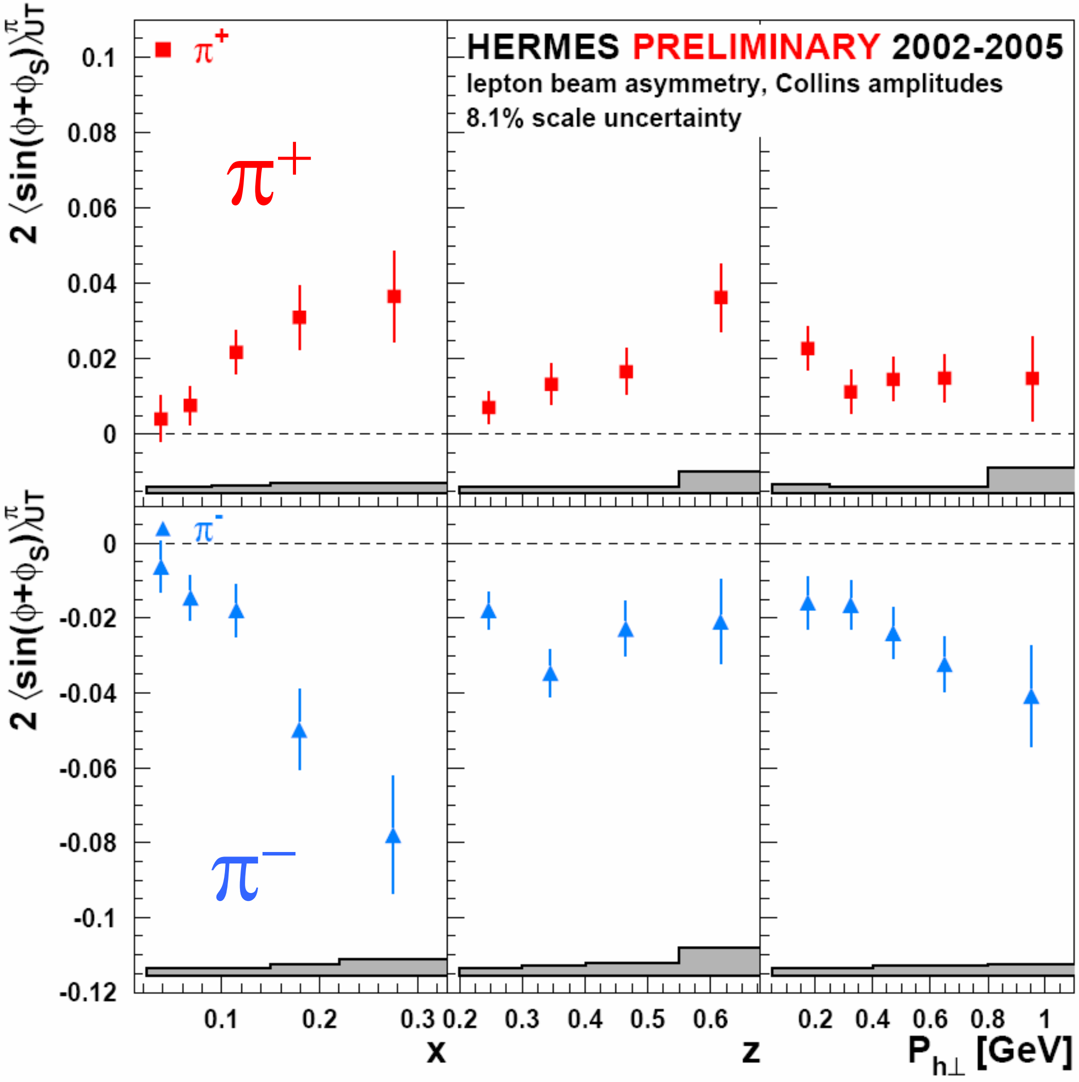


Summary: Gluon polarization rather close to 0 however still ΔG on the level ~0.2-0.3 not excluded! More precise measurements (large x) are needed!

Transversity

Collins asymmetries (HERMES)

$ep^{\uparrow} \rightarrow \pi X$



$$\delta q(x) \otimes H_1^{\perp q}(z)$$

first time: *transversity* & *Collins FF* are **non-zero!**

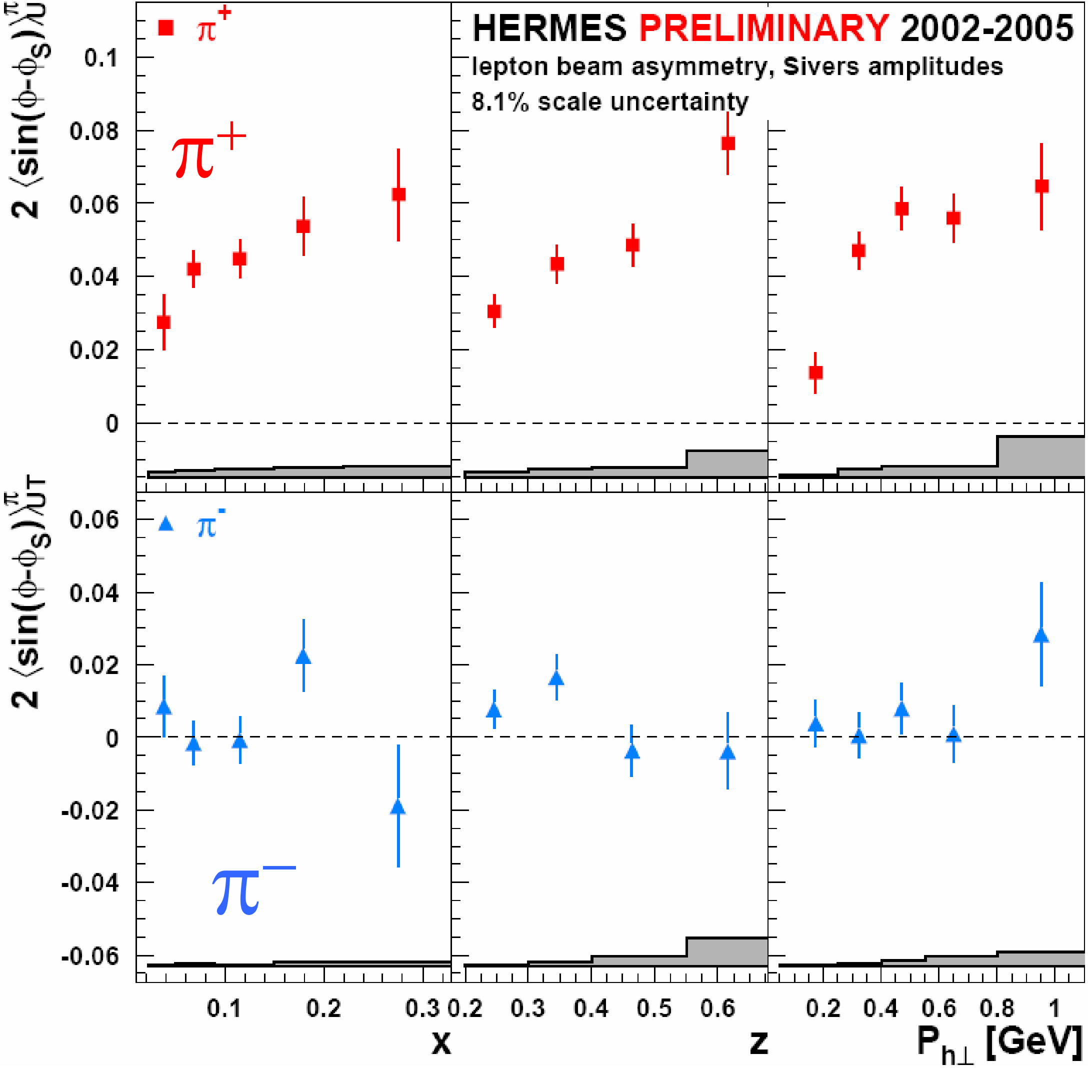
- π^+ asymmetries positive – no surprise: u-quark dominance and expect $\delta q>0$ since $\Delta q>0$

- large negative π^- asymmetries – **ARE** a surprise: suggests the *disfavoured CollinsFF* being large and with oposite sign:

$$H_1^{\perp,\mathrm{disfav}}(z) \boxed{\approx -} H_1^{\perp,\mathrm{fav}}(z)$$

Sivers asymmetries (HERMES)

$ep^{\uparrow} \rightarrow \pi X$



$$f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

π^+ are subtantial and positive:

- first unambiguous evidence for a **non-zero T-odd** distribution function in DIS
- a signature for quark orbital angular momentum !

- SURPRISE:

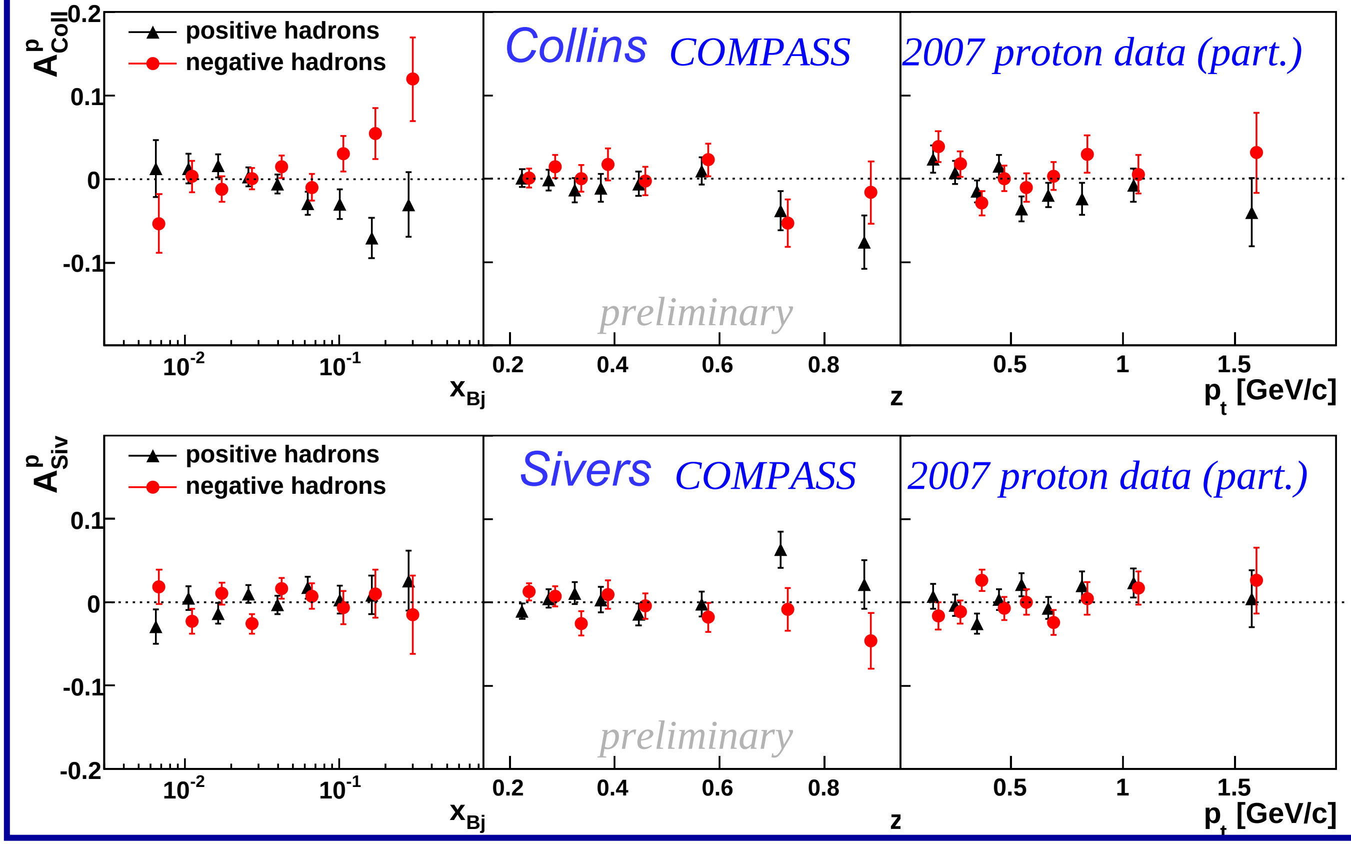
K^+ amplitude 2.3±0.3 times larger than for π^+

→ conflicts with usual expectations based on u-quark dominance

→ suggests substantial magnitude of the Sivers fct. for sea quarks

Collins and Sivers asymmetries new results from COMPASS

Sivers and Collins asymmetries measured by COMPASS on deuteron target are compatible with zero (cancellation?, subm. PLB ,hep-ex/0802.2160)



Proton data:

Non-zero
as in HERMES

Zero!??

Subm. to PRL
arXiv:0801.1078

Star: Di-jet Sivers measurement: 2006 p+p, 11pb^{-1}
A~0 $\longrightarrow$ ISI and FSI cancel? PRL 99(2007)142003,

Orbital angular momentum

Spin in the asymptotic limit

- Scale evolution equation

$$\frac{d}{d\,ln\,\mu^2}\begin{pmatrix}J_q(\mu^2)\\J_g(\mu^2)\end{pmatrix}=\frac{\alpha_s}{2\pi\cdot 9}\begin{pmatrix}-16,3n_f\\16,-3n_f\end{pmatrix}\begin{pmatrix}J_q(\mu^2)\\J_g(\mu^2)\end{pmatrix}$$

- Asymptotic solution

$$J_q(\infty)=\frac{1}{2}\frac{3n_f}{16+3n_f},J_g(\infty)=\frac{1}{2}\frac{16}{16+3n_f}$$

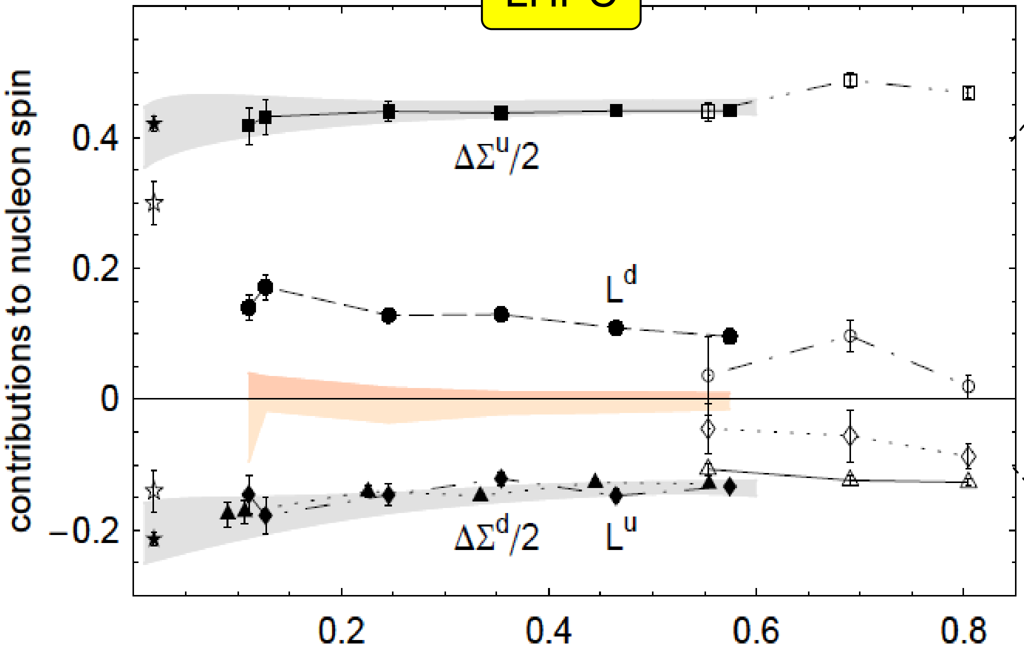
Roughly half of the angular momentum is carried by gluons!

L must be important! (X.Ji)

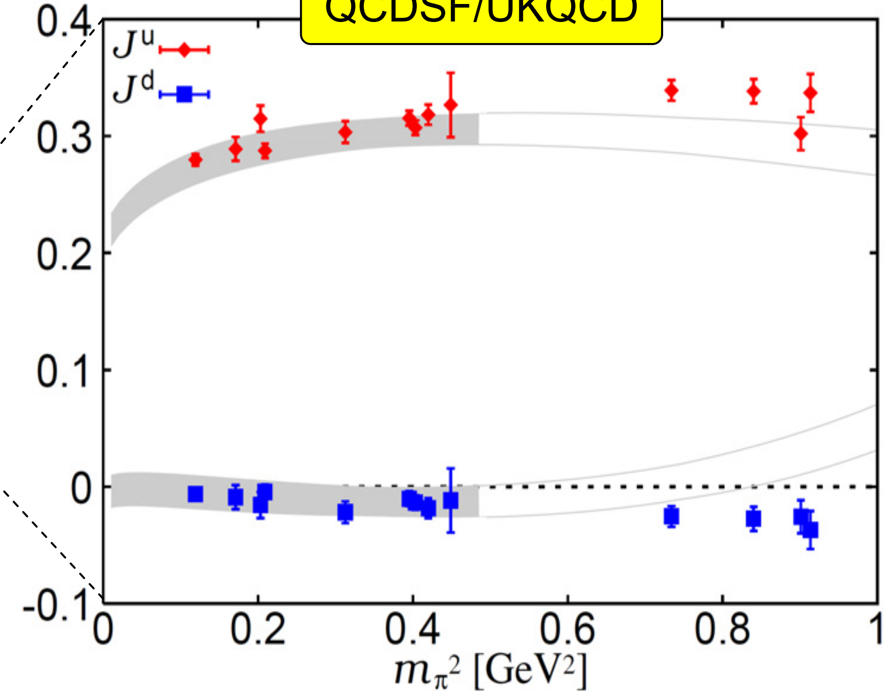
- MIT Bag model – simple but not agrees with DIS measurements
- Nonperturbative QCD on Lattice
- GPD’s – Generalized Parton Distributions
- „room” for L – non-zero internal k_T
- Cahn asymmetry - seen in SIDIS; new COMPASS result : ~10%

Quark spin, OAM and total angular momentum

LHPC



QCDSF/UKQCD



Agrees with GPD's measurements HERMES & JLAB!

overall agreement within errors

$J_\mu \approx 0.22 \pm 0.02 \cong 44\%$ of $1/2$

$J_d \approx 0.00 \pm 0.02$

$L^d \approx -L^u \approx 0.20 \pm 0.04 \cong 40\%$ of $1/2$

$L^{u+d} \approx 0.00 \pm 0.04$

Summary

Summary

- Precise mesurements of the spin structure function g_1 show that quarks contribute only in ~1/3 to the spin of the nucleon. This result is also confirmed by QCD fits and by independent measurement of the valence quark polarization (difference asymmetries) .
- Direct measurements point to a small value of gluon polarization however still 0.2-0.3 is not excluded (QCD fits, $\Delta G/G$ at large x).
- Different types of asymmetries precise measured at RHIC also indicate that large gluon polarization is rather excluded.
- New results from difference asymmetries show that asymmetric scenario is observed: $\Delta\bar{u} = - \Delta\bar{d}$
- Small positive polarization for strange quark polarization have been measuered by HERMES while COMPASS results based on sum rules give small negative polarization of strange sea.

Summary

- Collins asymmetry measured on proton target is non-zero for larger x_{Bjk}.
- Collins and Sivers asymmetries measured by COMPASS on deuteron target are compatible with zero (cancellation in deuteron?).
- Non-zero Sivers asymmetry is observed by HERMES on proton target. Compass results from proton data are compatible with zero!
- Non-zero Sivers asymmetry indicates non-zero orbital angular momentum. The cancellation of the L for quarks is predicted by non-perturbative QCD calculations on lattices (contribution from quark helicity ~40%) New results from DVCS measurements (Hermes, JLab) agree with the Lattice QCD results.

Possible scenarios (quarks ~1/3) :

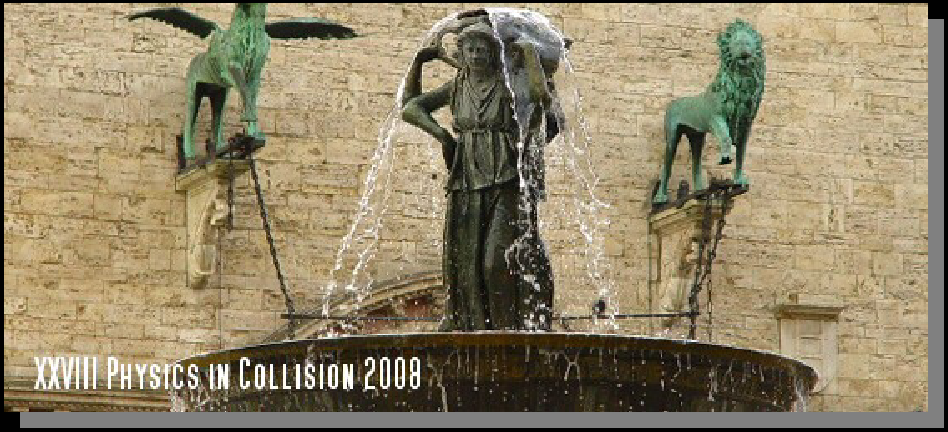
1. Gluon polarization ~0.3 (mainly large x effect) - no needs of L (L=0)
2. Gluon polarization ~0 - significant contribution from L (quarks and gluons)
3. Gluon polarization ~0 and Lattice calcul. – only gluons give L contribution

Future

- New data from RHIC (Star jets, run 2009, beyond 2009 – 500 GeV)
- New results from HERMES and COMPASS (proton data, flavour separation)
- New results from JLAB (g_1 for large x, g_2)
- DVSC + GPD's – future plans for COMPASS, JLAB upgrade
- Lattice QCD – probably the most promising tool to study L

Still a lot of things to do to understand the spin structure of the nucleon – particle from which we are made of ☺

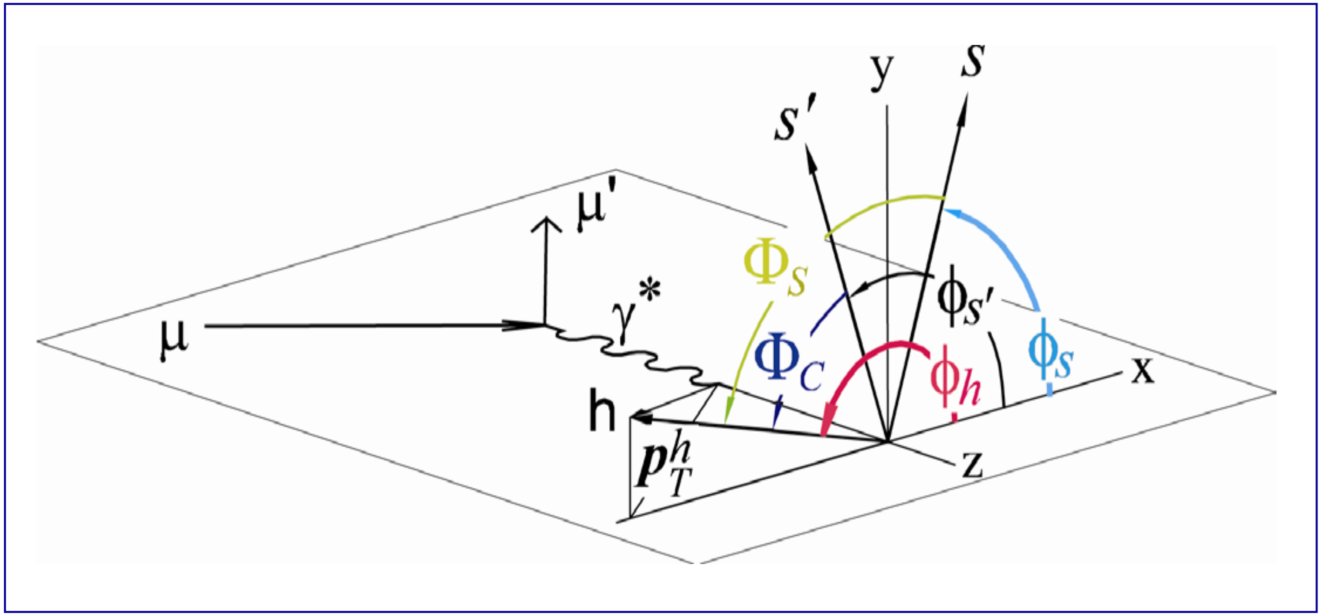
Backup slides



Collins and Sivers angles

$$\Phi_C = \phi_h - \phi_{S'}$$

$$\Phi_S = \phi_h - \phi_S$$



$\phi_{S'}$ **azimuthal angle of spin vector of fragmenting quark ($\phi_{S''} = \pi - \phi_S$)**

ϕ_h **azimuthal angle of hadron momentum**

Compass fit (world data)

Quark polarisation:

Phys.Lett.B 647(2007)8

	$\eta_G > 0$	$\eta_G < 0$
$\eta\Sigma$	0.27 ± 0.01	0.32 ± 0.01

$$\longrightarrow \eta_\Sigma = \mathbf{0.30 \pm 0.01(stat) \pm 0.02(evol)}$$

$$\left(\eta_K = \int_0^1 \Delta \mathbf{k} \, \mathbf{dx} \right)$$

(error ≈ factor 2 larger without COMPASS data)

Gluon polarisation (indirect determination via DGLAP):

- Solutions with $\eta_G > 0$: $\eta_G^{prog1} = 0.34^{+0.05}_{-0.07}, \quad \eta_G^{prog2} = 0.23^{+0.04}_{-0.05}$
- Solutions with $\eta_G < 0$: $\eta_G^{prog1} = -0.31^{+0.10}_{-0.14}, \quad \eta_G^{prog2} = -0.19^{+0.06}_{-0.11}$

$$|\eta_G| \approx \mathbf{0.2 - 0.3}$$

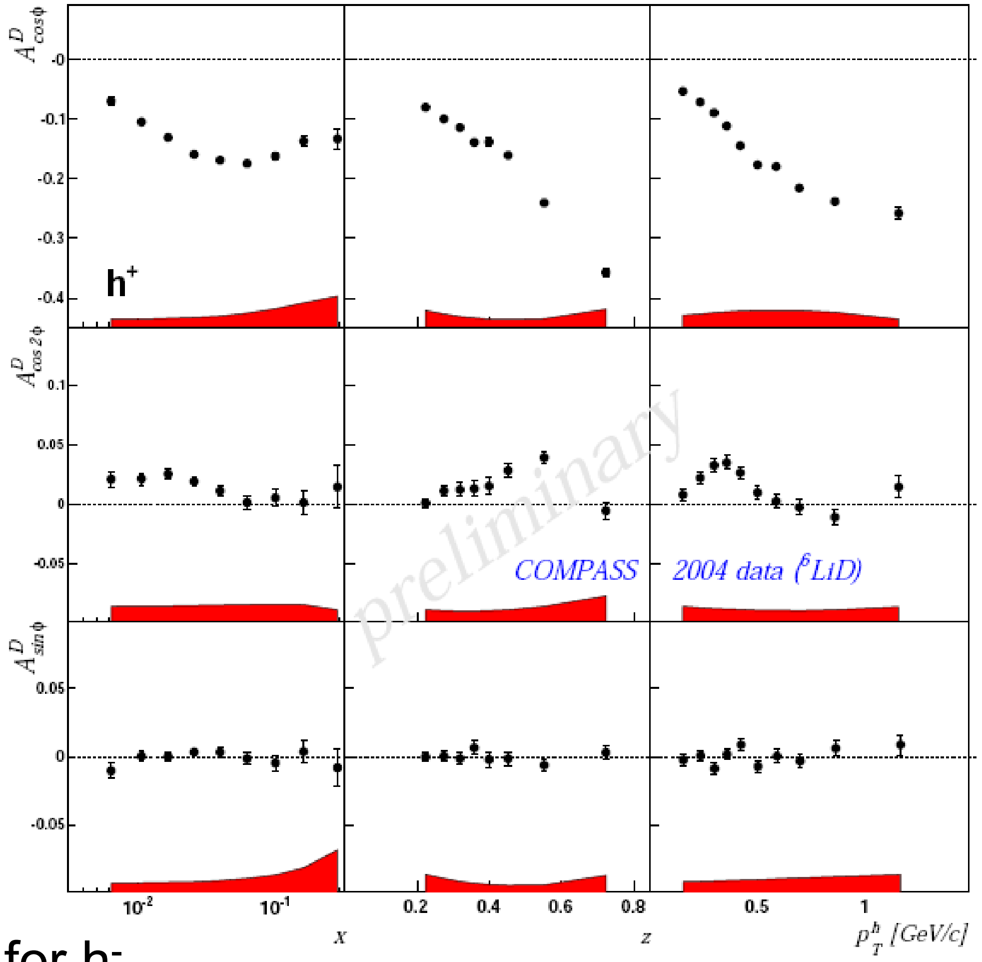
Cahn’s asymmetry (COMPASS)

Unpolarized: „pure” kinematical effect which reflects the fact of existence of internal k_T in the nucleon – potential „room” for L

$\mathrm{Cos}(\phi_h)$

$\mathrm{Cos}(2\phi_h)$

$\mathrm{Sin}(\phi_h)$



Cahn - 10% effect

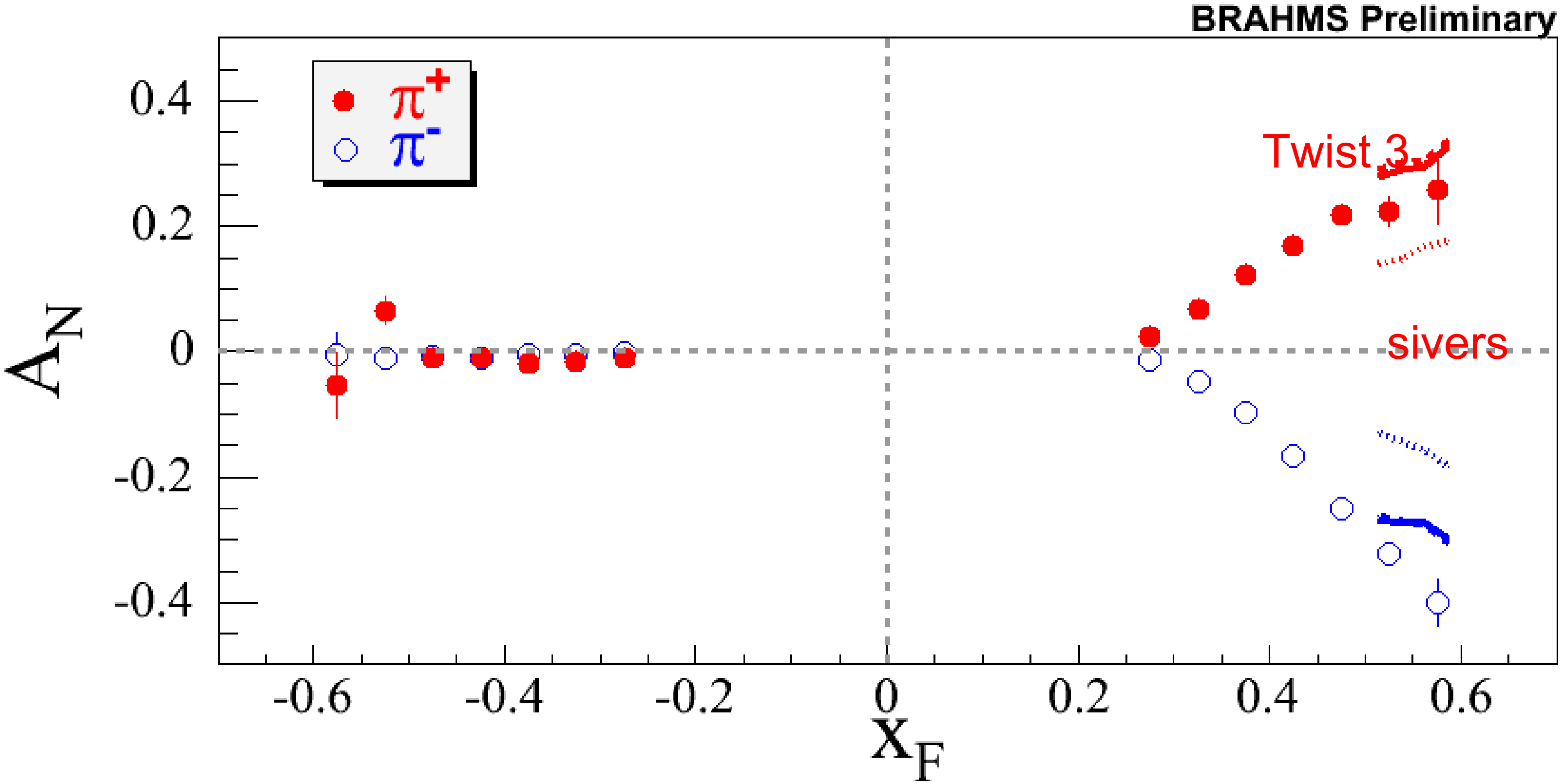
Cahn+
Boer-Mulders

Beam polarization

Similar for h^-

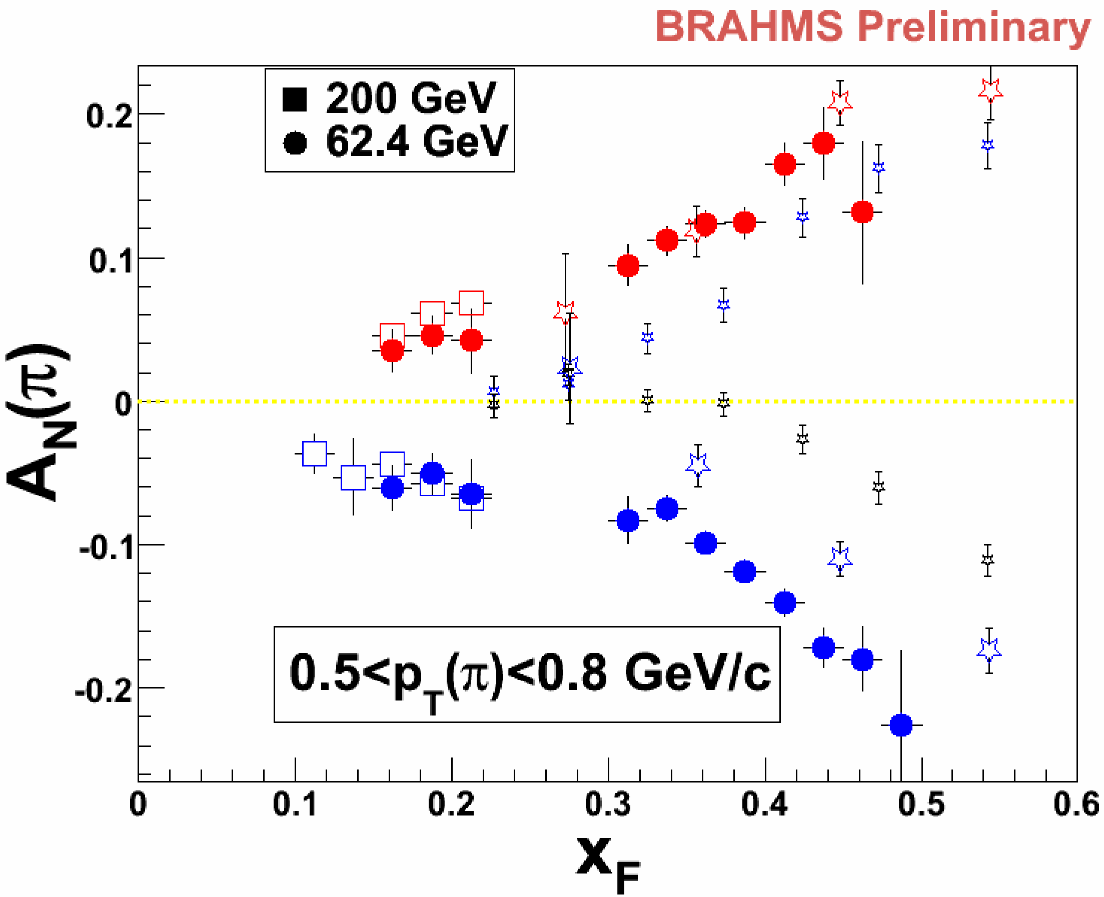
BRAHMS

Submitted to Physical Review Letters
arXiv:0801.1078



- Large $A_N(\pi)$: 0.3-0.4 at x_F~0.6 p_T~1.3 GeV
- Strong x_F -p_T dependence. Though $|A_N(\pi^+)|$ ~ !$A_N(\pi^-)|$ $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with x_F-p_T

Unifying 62 and 200 GeV BRAHMS + E704



E704 data – all pt (small star) pt>0.7 red star.

Lattice QCD

X.Ji spin sum rule →

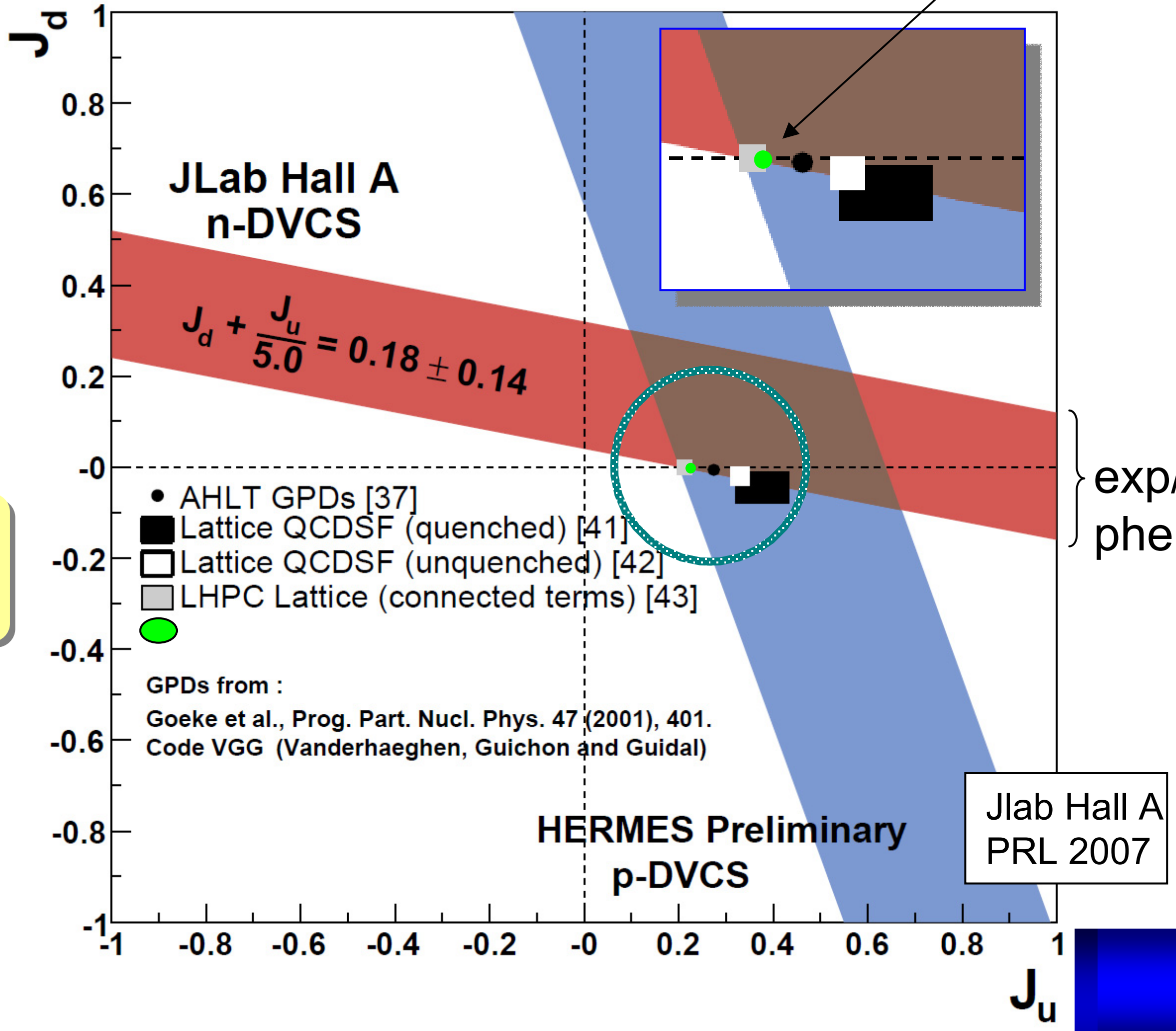
$$\frac{1}{2} = S_z = \underbrace{\frac{1}{2}\Delta\Sigma_q + L_q}_{J_q = \frac{1}{2}(A^q_{20}(0) + B^q_{20}(0))} + \underbrace{\Delta G + L_g}_{J_g}$$

„graviton-like coupling“ in lattice QCD

$J^u \approx 40\%$ of $1/2$

$J^d \approx 0$

be aware of systematic uncertainties of lattice simulations



lattice

exp/ pheno

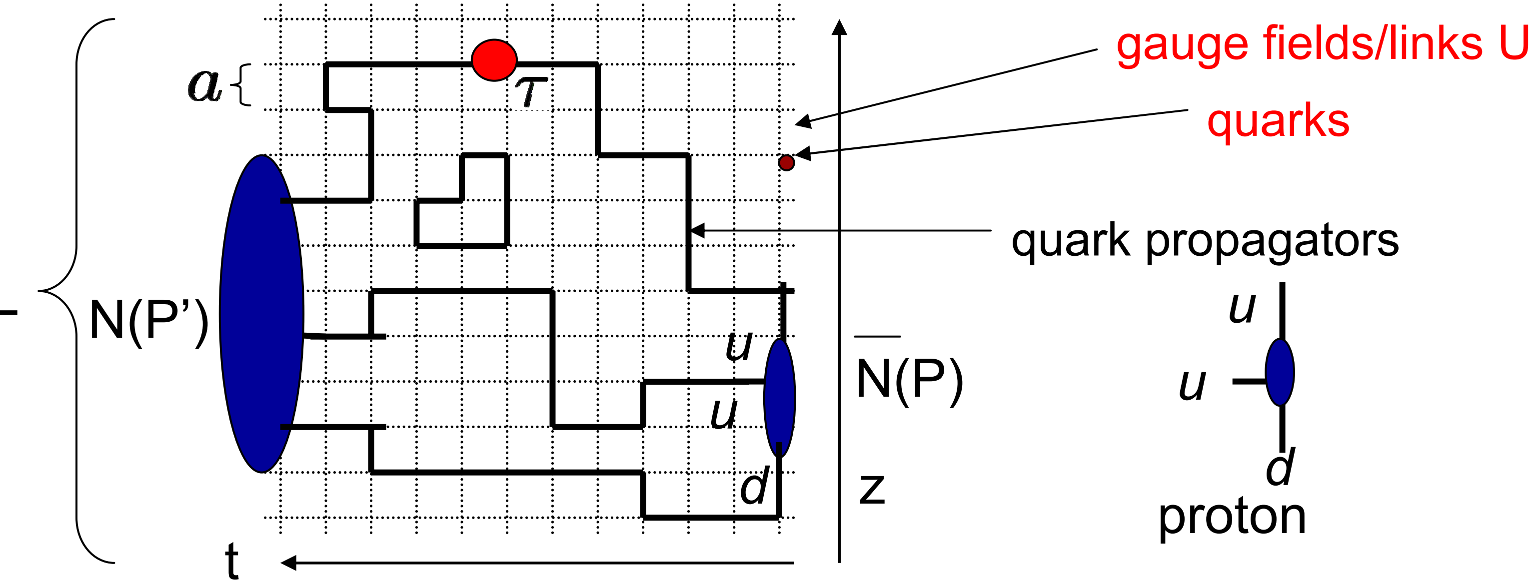
Jlab Hall A PRL 2007

Lattice QCD

$$e^{-E(T-\tau)-E\tau}\langle P',\Lambda'|\overbrace{\bar{q}[\Gamma_{Dirac}D^{\mu_1}D^{\mu_2}\ldots]q}^{\bullet}|P,\Lambda\rangle$$

$$\sim \Delta\Sigma, \delta q(x), F_1(t), A_{20}(t), B_{20}(t)\ldots \qquad t=\Delta^2$$

● = vector-, axialvector-, ***graviton-, quark spin flip-***, „spin-n“ coupling

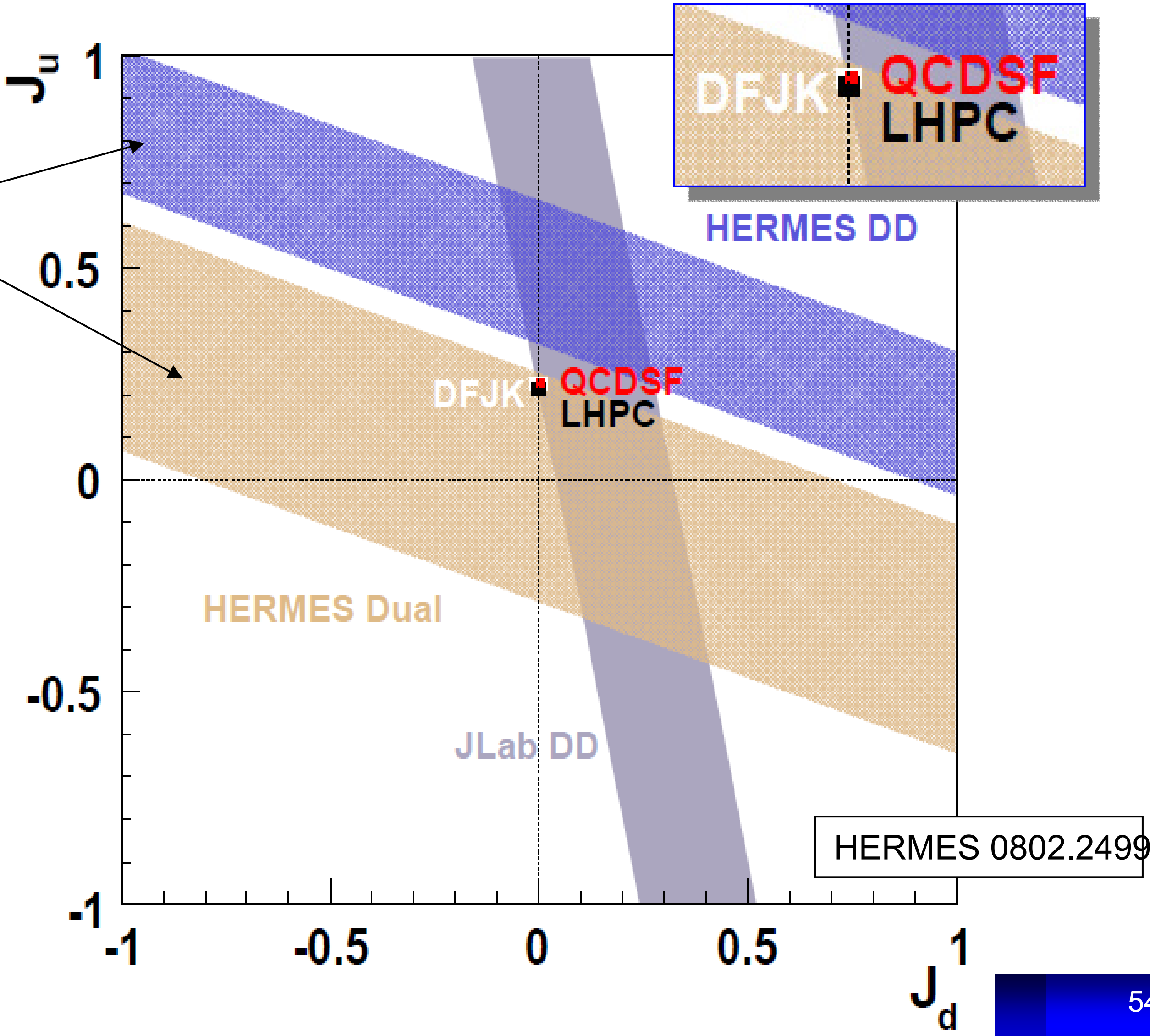


Philipp Hägler
talk on DIS2008

$$\langle q_2|\bar{q}_1\rangle \sim \int DADqD\bar{q}e^{iS[q,\bar{q},A]} \to \left[\int DUe^{-S[U]}\det D[U]\right]D^{-1}_{1\to2}[U]\approx \frac{1}{N}\sum_{i=1}^{N}D^{-1}_{1\to2}[U_i]$$

compute the path-integral numerically

Towards the decomposition of the nucleon spin



HERMES 0802.2499

substantial uncertainties due to model dependence

uncertainties will be reduced in future → more HERMES data, JLab 12 GeV upgrade

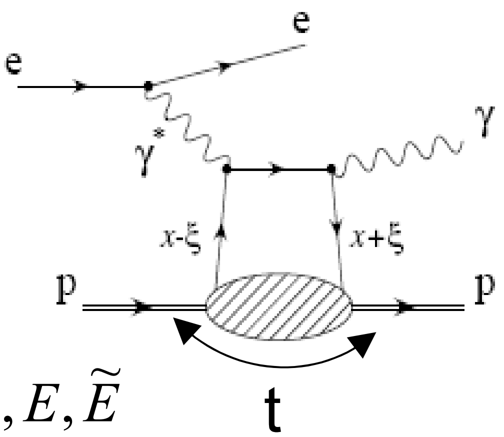
be aware of systematic uncertainties of lattice simulations

GPD's: distributions in quantum phase space

- In the past, we only knows how to imagine quarks either in
  - Coordinate space (form factors)
  - Momentum space (parton distributions)
- GPDs provide correlated distributions of quarks and partons in combined coordinate and momentum (phase) space
  - Wigner distribution in Quantum Mechanics(1932)
  - GPD: Wigner-type quark distributions

Measurements: HERMES, JLAB

DVCS:



$$H(x,\xi,t), \widetilde{H}, E, \widetilde{E}$$

$$H(x,0,0) = q(x)$$

$$\widetilde{H}(x,0,0) = \Delta q(x)$$

$$\int H(x,\xi,t)dx = F(t)$$

H(x,0,t) → 3D view of nucleon (x,$d_\perp$) related to L_z (Ji sum rule)

$$\mathbf{2J_q} = \int x\left(\mathbf{H+E}\right)(x,\xi,0)\,dx$$

A short comment on the frames

GPDs or PDFs (p’=p) defined by the relation:

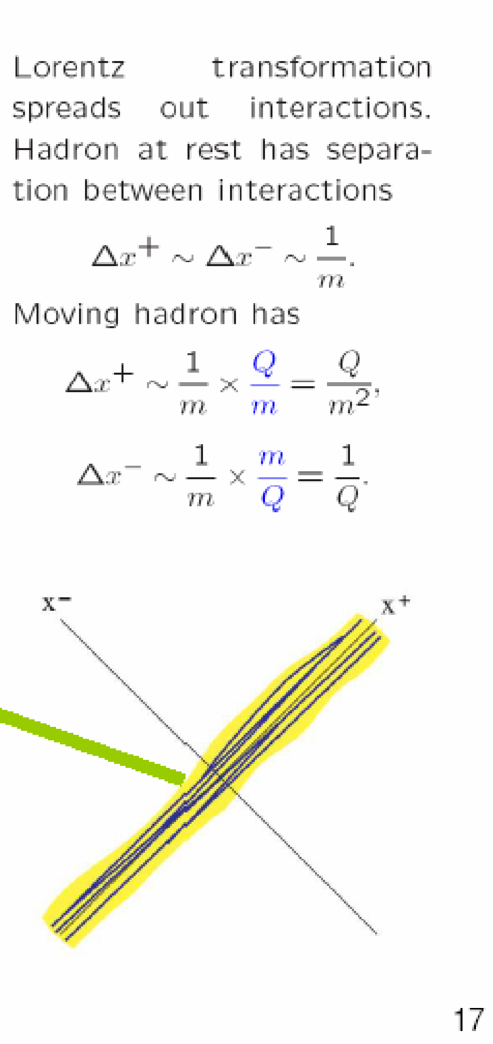
$$\int \frac{dz^-}{4\pi} e^{ik^+z^-} \langle p',s'|\bar{q}(0)\gamma^+ q(z)|p,s\rangle_{z^+=0,z_\perp=0}$$

are valid in all frames =>
Infinite Momentum Frame (IMF)
or Proton Rest Frame (PRF)!

However, the interpretation in term of quark/anti-quarks creation/anihilation is only valid in the IMF: same time (x^-) between the 2 quark fields.

In fact, in the PRF, the left quark field is operating not at the same time as the right one => we loose the simple interpretation…

Then, in the following, when we talk about GPDs, we mean GPDs in the IMF
(even if the experiment is a PRF experiment!)



Lorentz transformation spreads out interactions. Hadron at rest has separation between interactions

$$\Delta x^+ \sim \Delta x^- \sim \frac{1}{m}.$$

Moving hadron has

$$\Delta x^+ \sim \frac{1}{m} \times \frac{Q}{m} = \frac{Q}{m^2},$$

$$\Delta x^- \sim \frac{1}{m} \times \frac{m}{Q} = \frac{1}{Q}.$$

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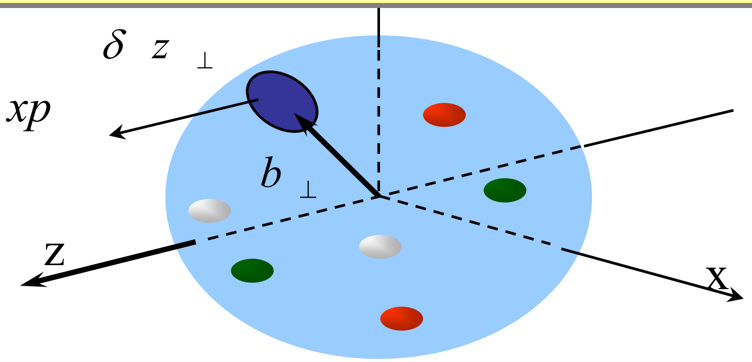
Generalized Parton Distributions



The GPDs contain the information on the longitudinal momentum AND the transverse spatial distributions of the partons in the nucleon