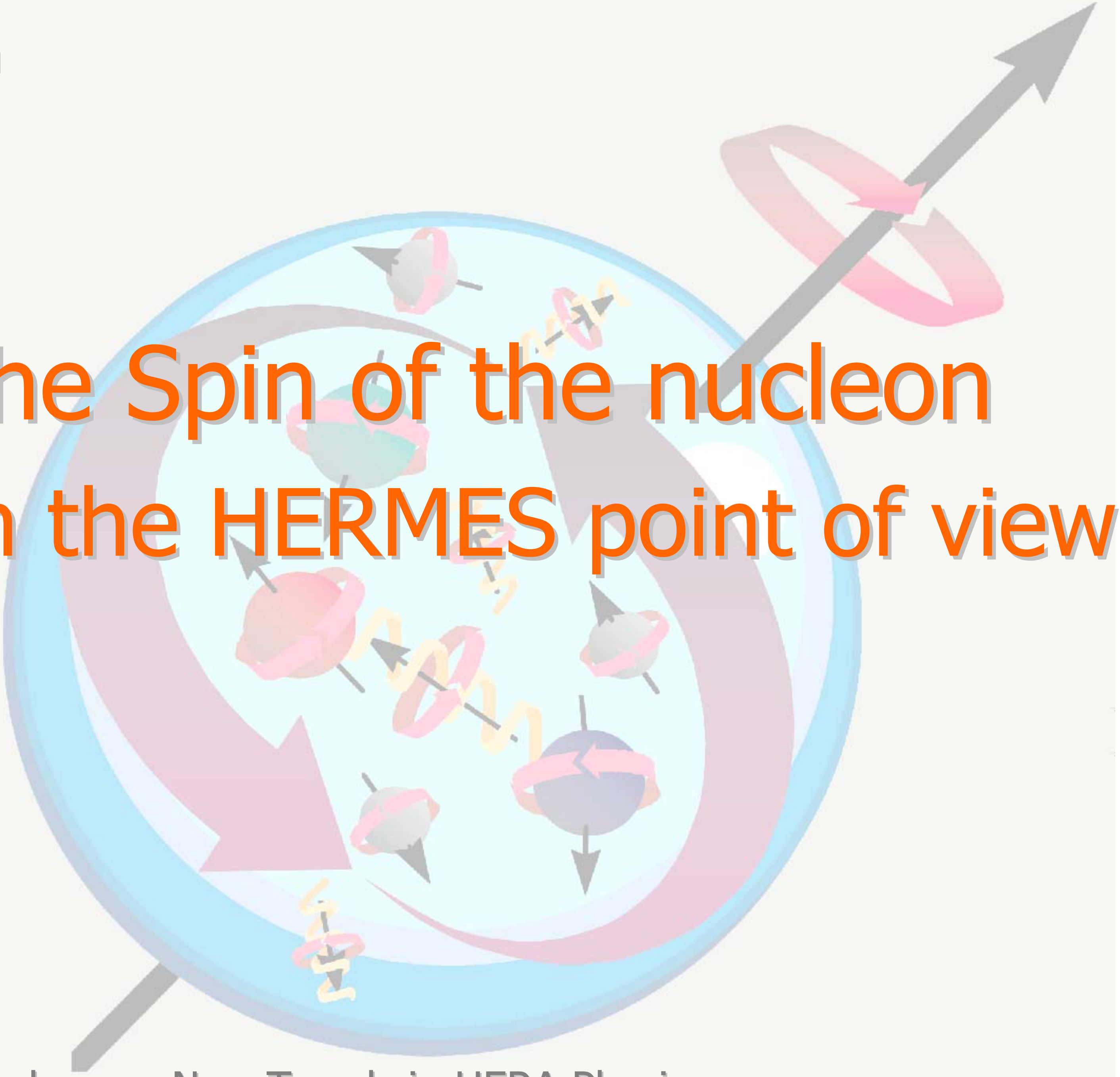
Delia Hasch

INFN
Frascati

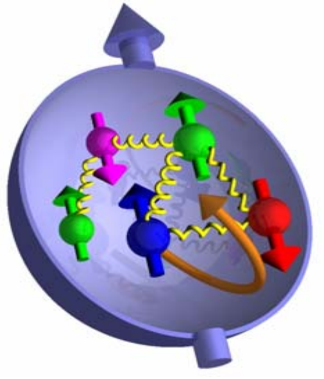


the Spin of the nucleon
-from the HERMES point of view-

Ringberg workshop on New Trends in HERA Physics, Ringberg Castle, October 5-10, 2008

HERa MEasurement of Spin

$$\frac{s_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z^q + \Delta G + L_z^g$$



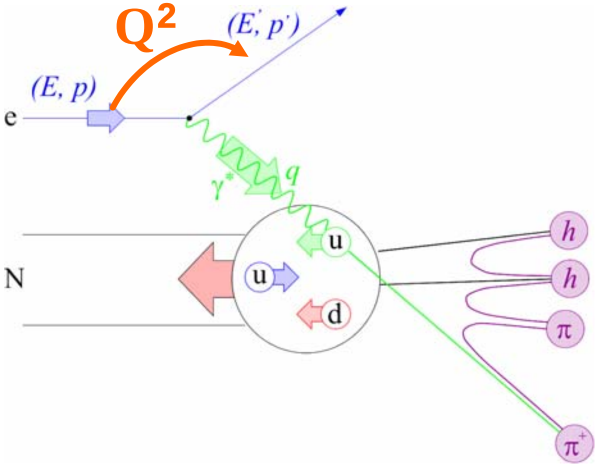
outline:

- prerequisites
- polarisation of quarks: $\Delta\Sigma = \Delta u_v + \Delta d_v + \Delta q_s$
- polarisation of gluons: ΔG

new developments

- hunting for the OAM $L_{q,g}$ **→ talk by M. Düren**
- transverse spin phenomena **→ talk by U. D'Alesio**

polarised deep-inelastic scattering



$$Q^2 = -q^2 \overset{\text{lab}}{=} 2EE'(1\text{-}\cos\theta)$$

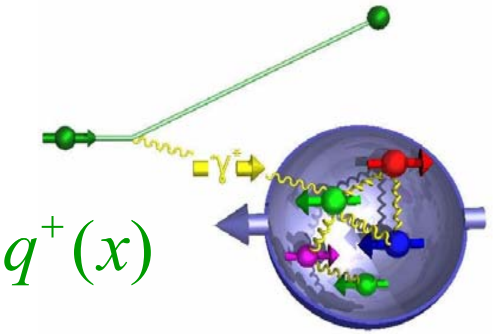
$$x \overset{\text{lab}}{=} \frac{Q^2}{2M\nu}, \qquad x \in [0,1] \qquad \nu \overset{\text{lab}}{=} E - E'$$

$$z \overset{\text{lab}}{=} \frac{E_h}{\nu},$$

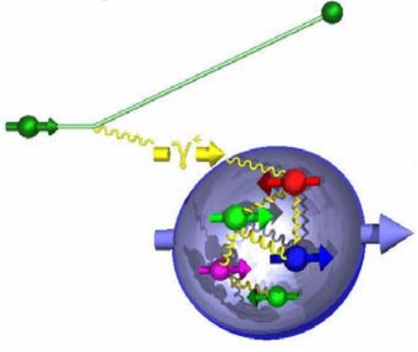
factorisation:

$$\sigma^{h}_{DIS} \propto \sum_f \hat{\sigma}_{part} \otimes pdf(x) \otimes frag^{q,g\to h}(z)$$

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



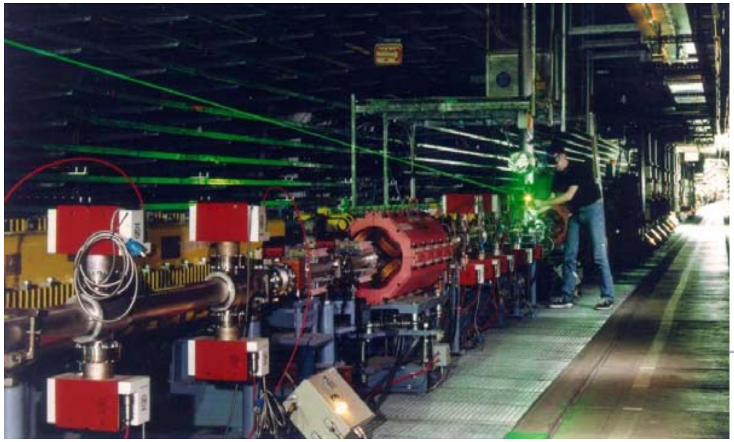
$q^+(x)$



$q^-(x)$

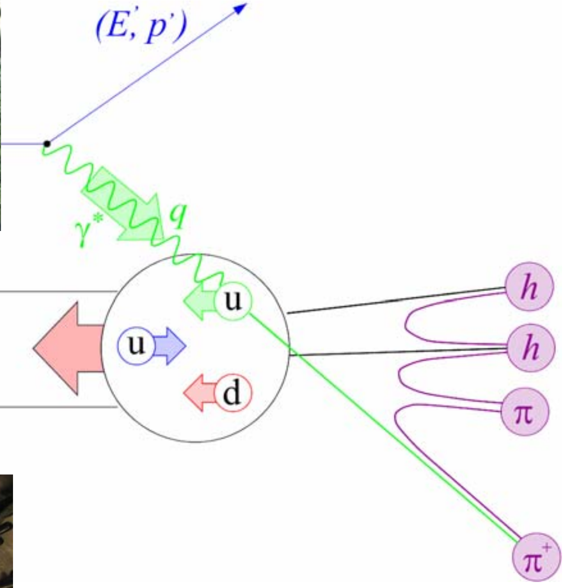
experimental prerequisites

-the 2nd generation-



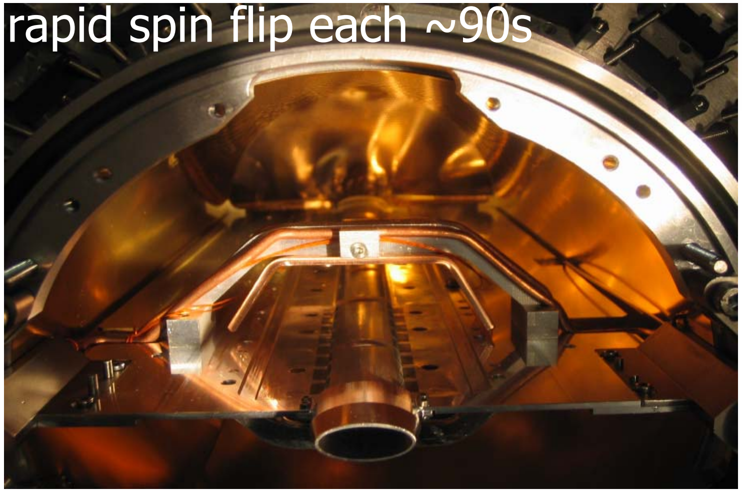
HERA 27.5 GeV (e+/e-)→

$\langle P_b \rangle \sim 53 \pm 2.5$ %



storage cell target: no dilution

rapid spin flip each ~90s



$^1\mathrm{H}^{\rightarrow}$ $\langle |P_t| \rangle \sim 85\%$

$^2\mathrm{H}^{\rightarrow}$ $\langle |P_t| \rangle \sim 84\%$

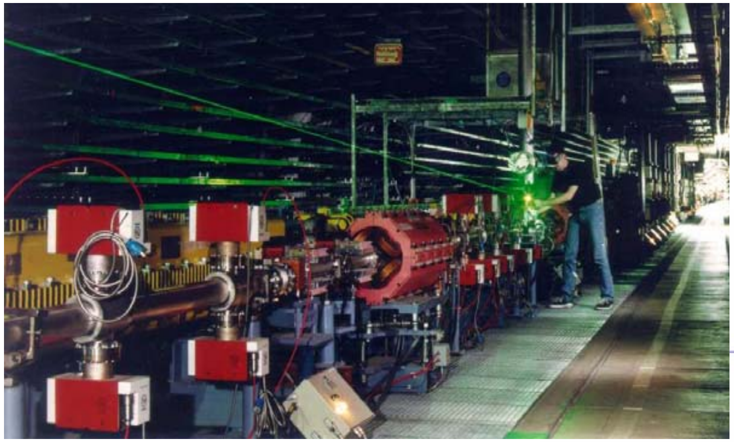
$^1\mathrm{H}^{\uparrow}$ $\langle |P_t| \rangle \sim 74\%$

$$\delta\sigma \propto \frac{1}{P_b P_t f} \cdot \frac{1}{\sqrt{N}}$$

f: target dilution factor

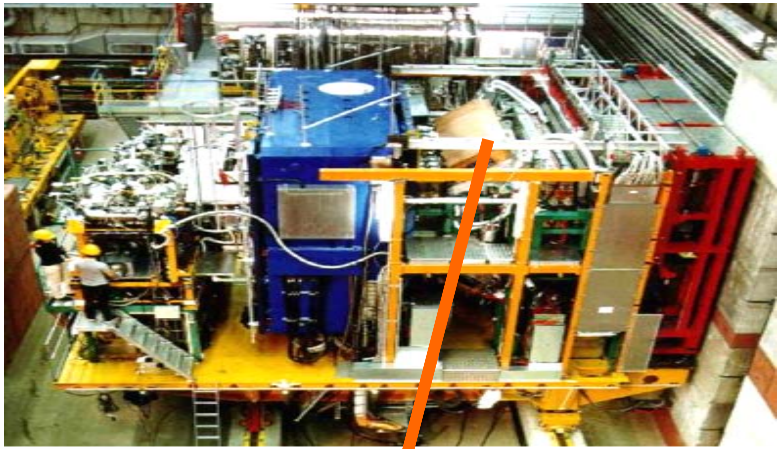
f=1 gas targets, f~0.02 solid targets

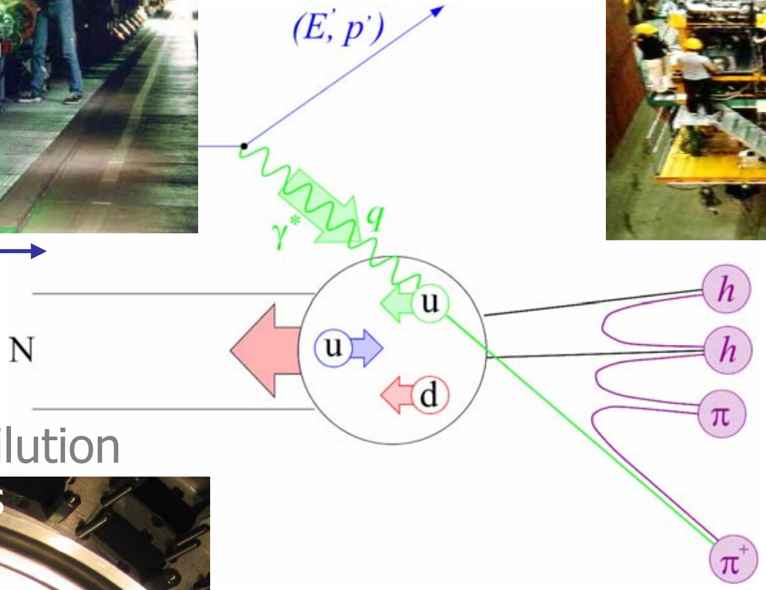
experimental prerequisites
-the 2nd generation-



HERA 27.5 GeV $(e+/e-)^{\longrightarrow}$

$\langle P_b \rangle \sim 53 \pm 2.5\ \%$





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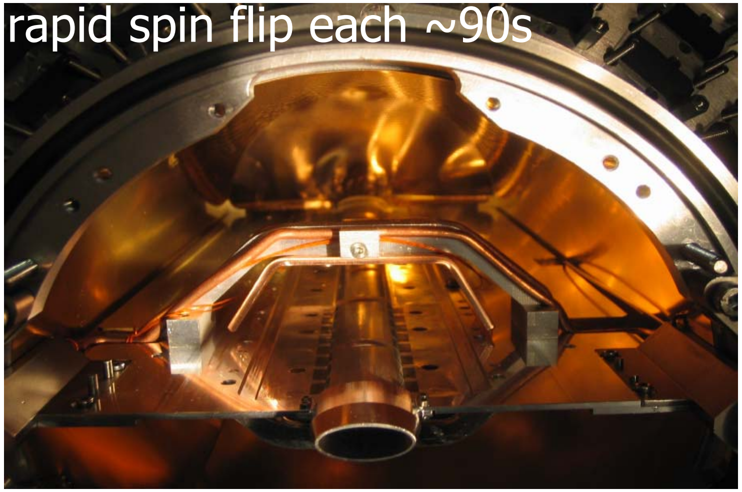

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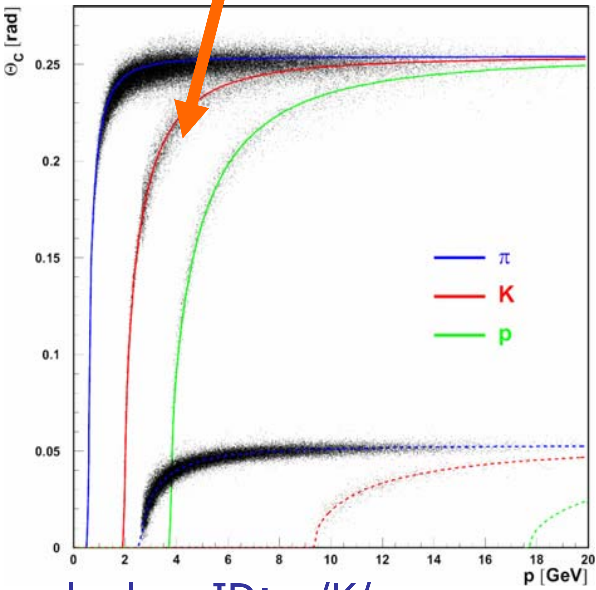
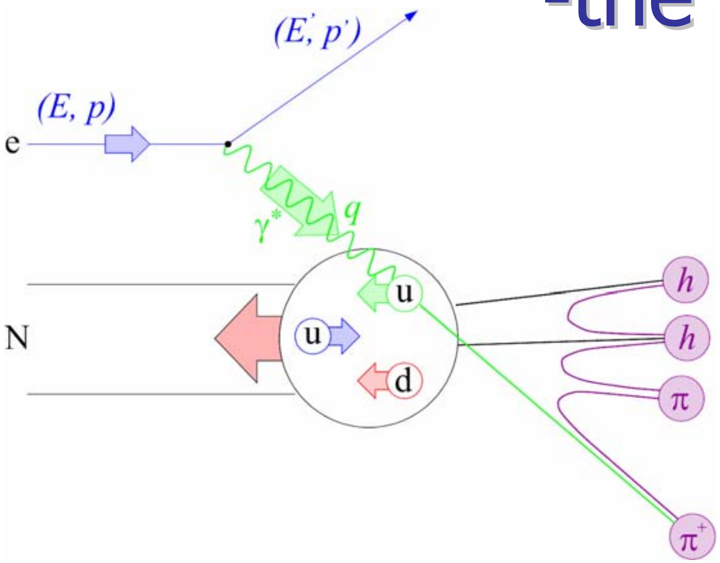


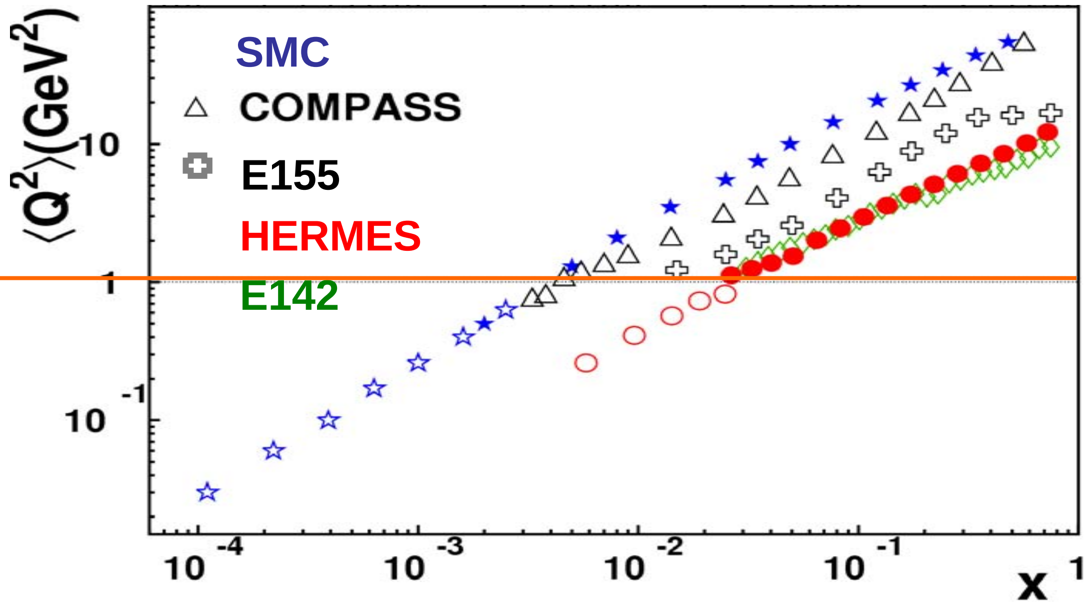
hadron ID: π/K/p

$2 < E_h < 15$ GeV

experimental prerequisites

-the 2nd generation-

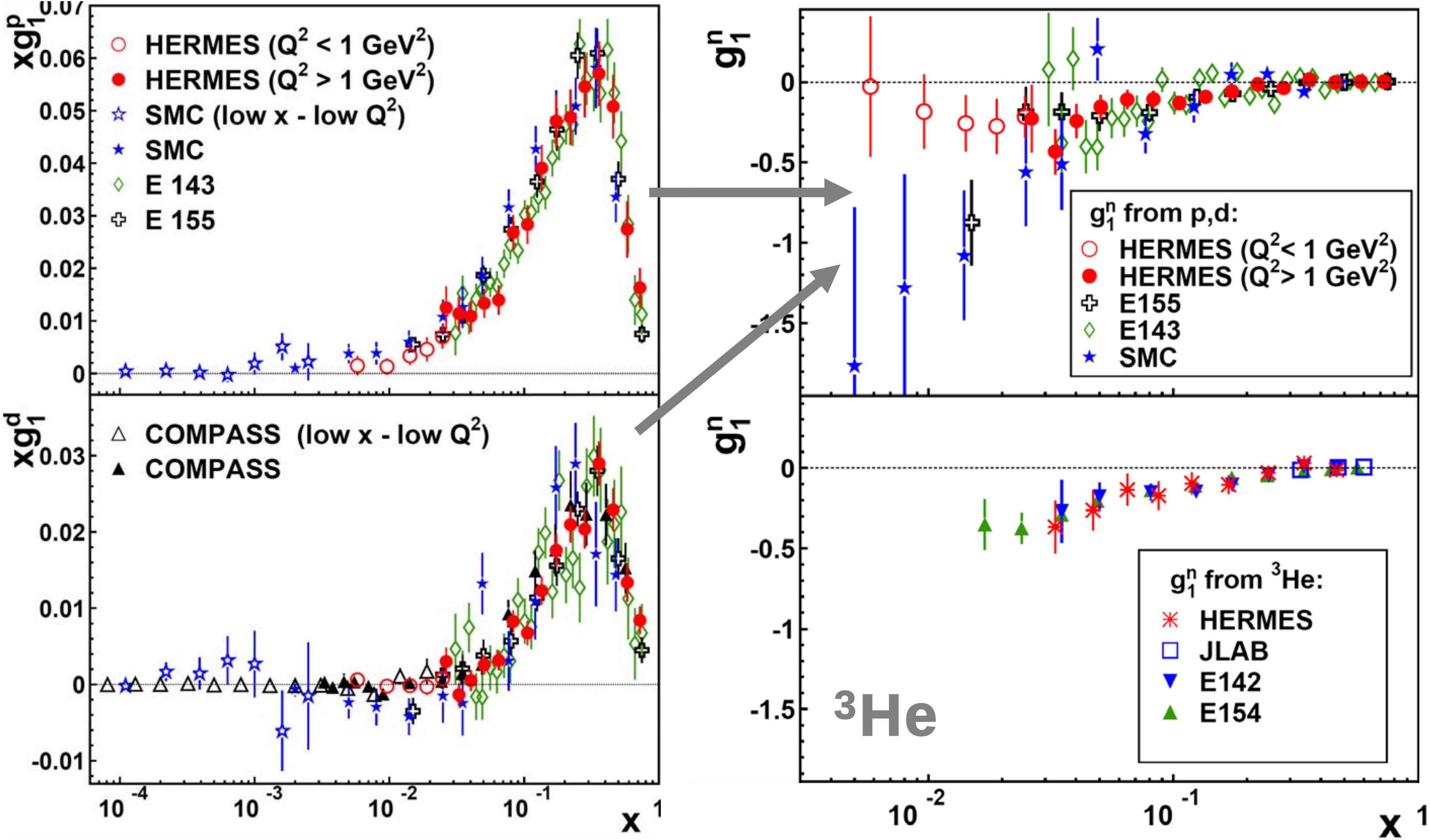




DIS

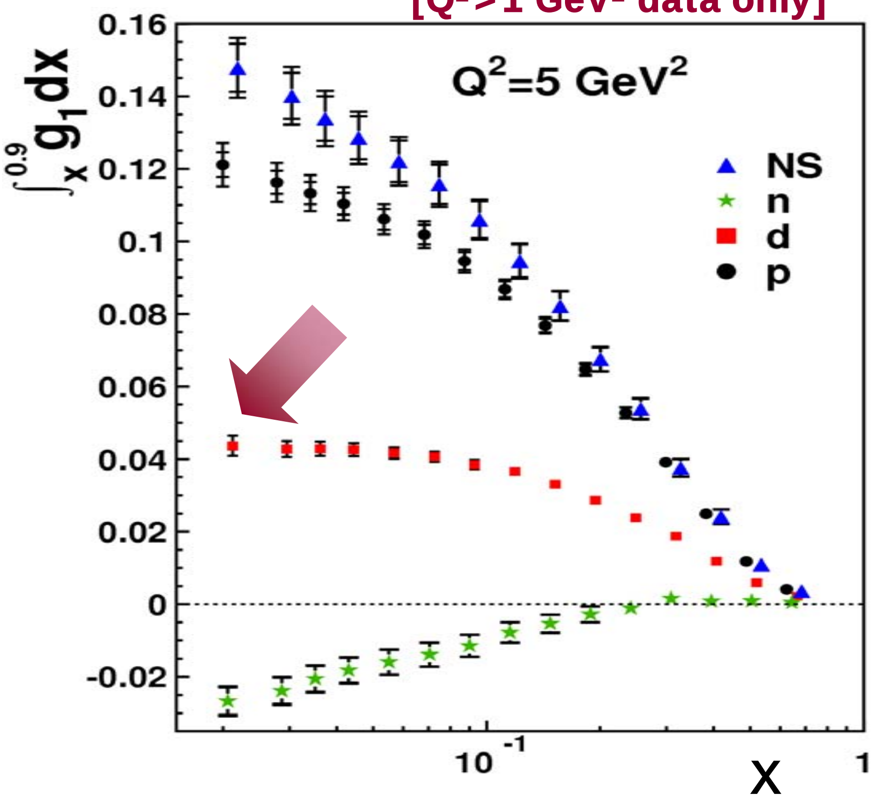
polarised structure function g_1

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\,(\Delta q + \Delta\bar{q})$$



first moment Γ_1^d and $\Delta\Sigma$

[Q² > 1 GeV² data only]



→assume *saturation* of Γ_1^d :

$$a_0^{\overline{MS}} = \Delta\Sigma \propto \frac{1}{\Delta C_s}\left[9\,\Gamma_1^d - \frac{1}{4} a_8 \Delta C_{NS}\right]$$

from theory

from hyperon beta decay

$a_0^{\overline{MS}} = \Delta\Sigma$ (exp) (theory) (evol)

= 0.330 ± 0.025 ± 0.011 ± 0.028

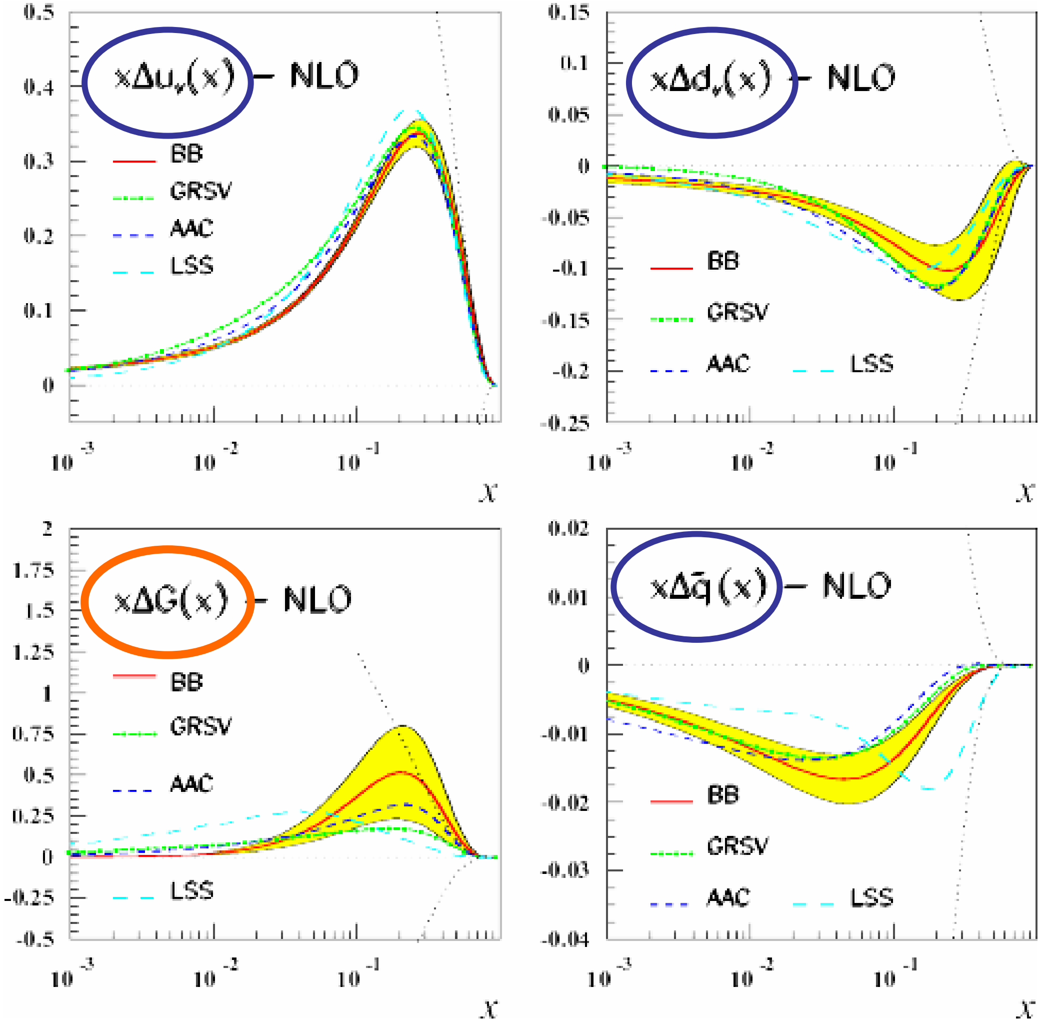
QCD-fit:

$a_0^{\overline{MS}} = \Delta\Sigma$

$= 0.35 \pm 0.03^{(stat)} \pm 0.05^{(sys+evol)}$

Δq and ΔG from inclusive data

$$g_1^{\mathrm{NLO}}(\mathrm{x},\mathrm{Q}^2) = g_1^{\mathrm{LO}} + \frac{1}{2}\langle e^2\rangle \sum_{\mathrm{q}} \mathrm{e}_{\mathrm{q}}^2 [\Delta\mathrm{q}(\mathrm{x},\mathrm{Q}^2)\otimes C_{\mathrm{q}} + \Delta\mathrm{g}(x,\mathrm{Q}^2)\otimes C_{\mathrm{g}}]$$



- valence quarks are well determined:

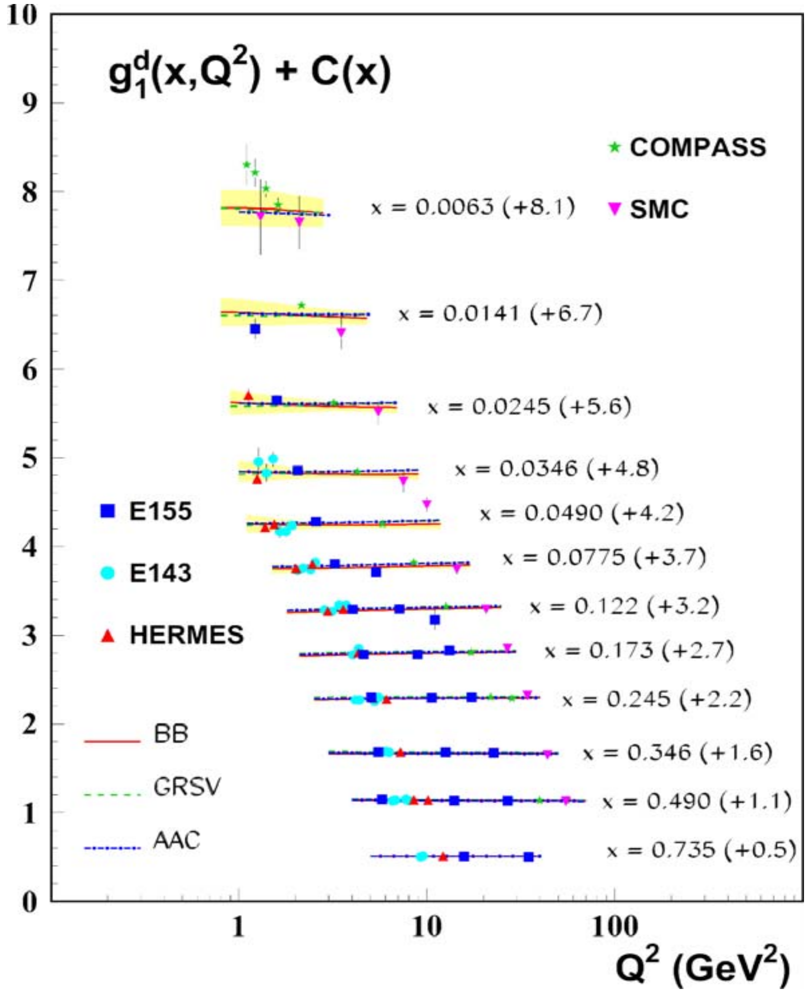
  $\Delta u_v > 0$, $\Delta d_v < 0$

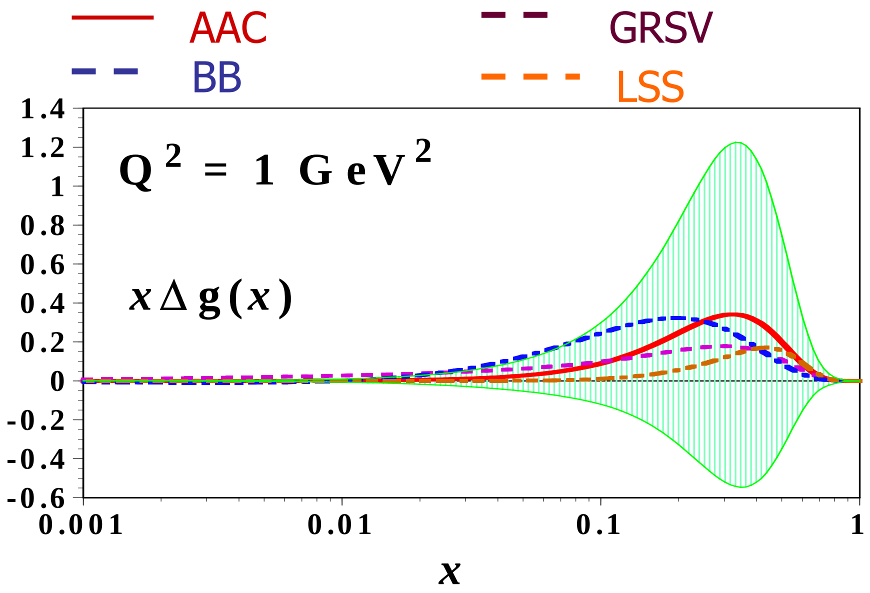
- gluons and sea quarks are poorly constraint by data

$SU(3)_f$ symmetry implicitly assumed

call for more direct probes…

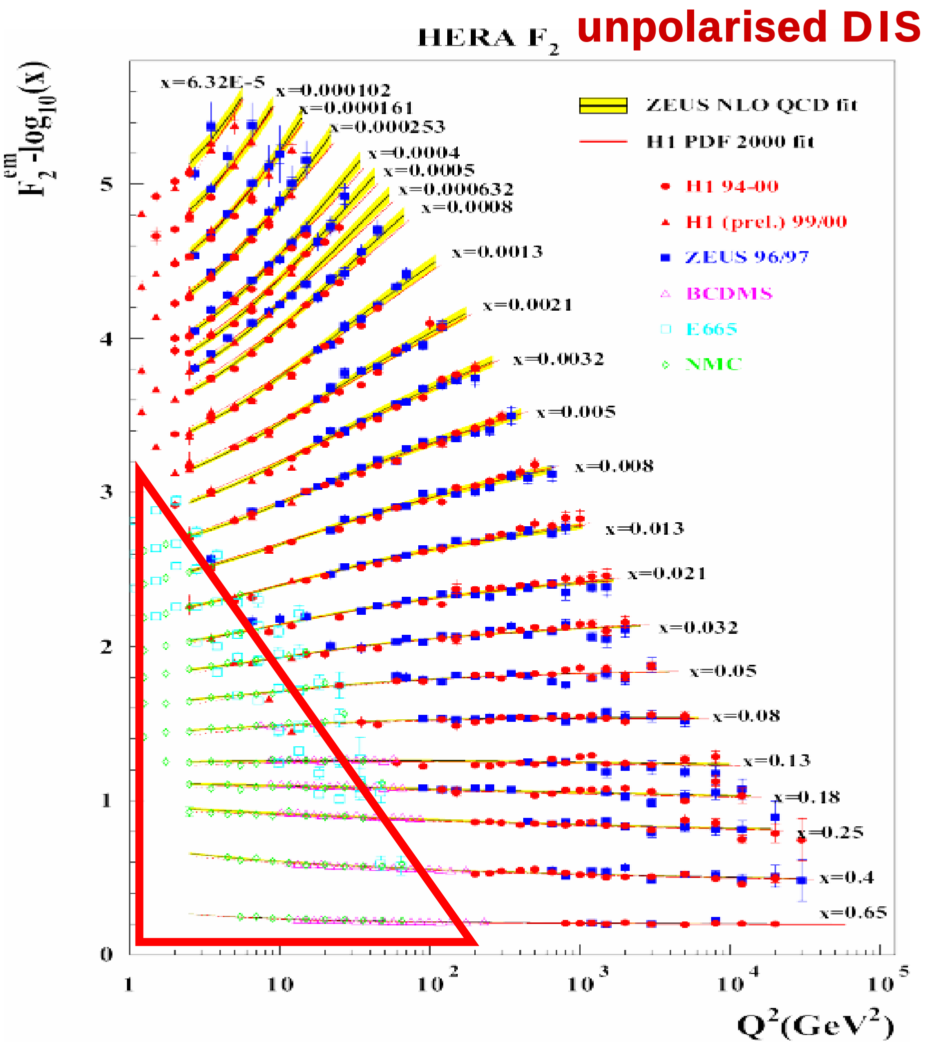
kinematic range of polarised DIS exp:

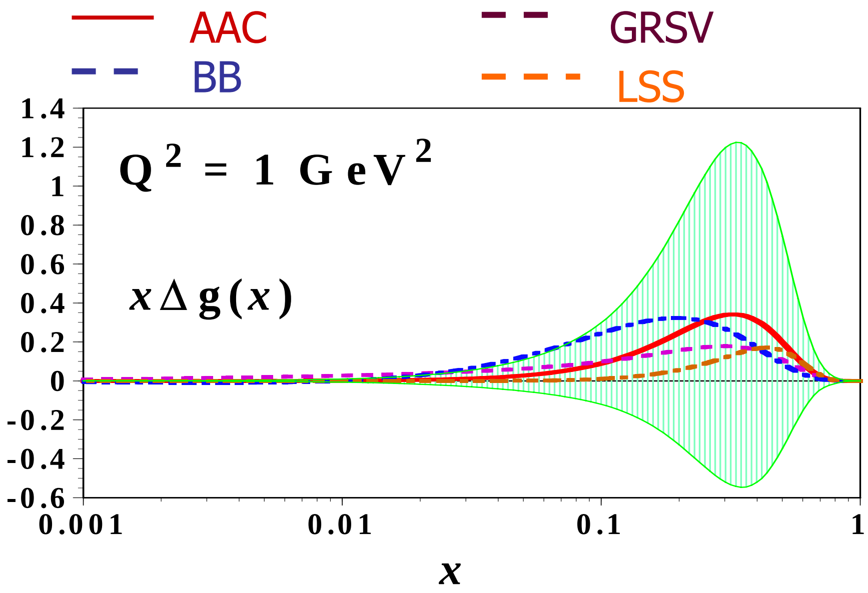




call for more direct probes…

kinematic range of polarised DIS exp:

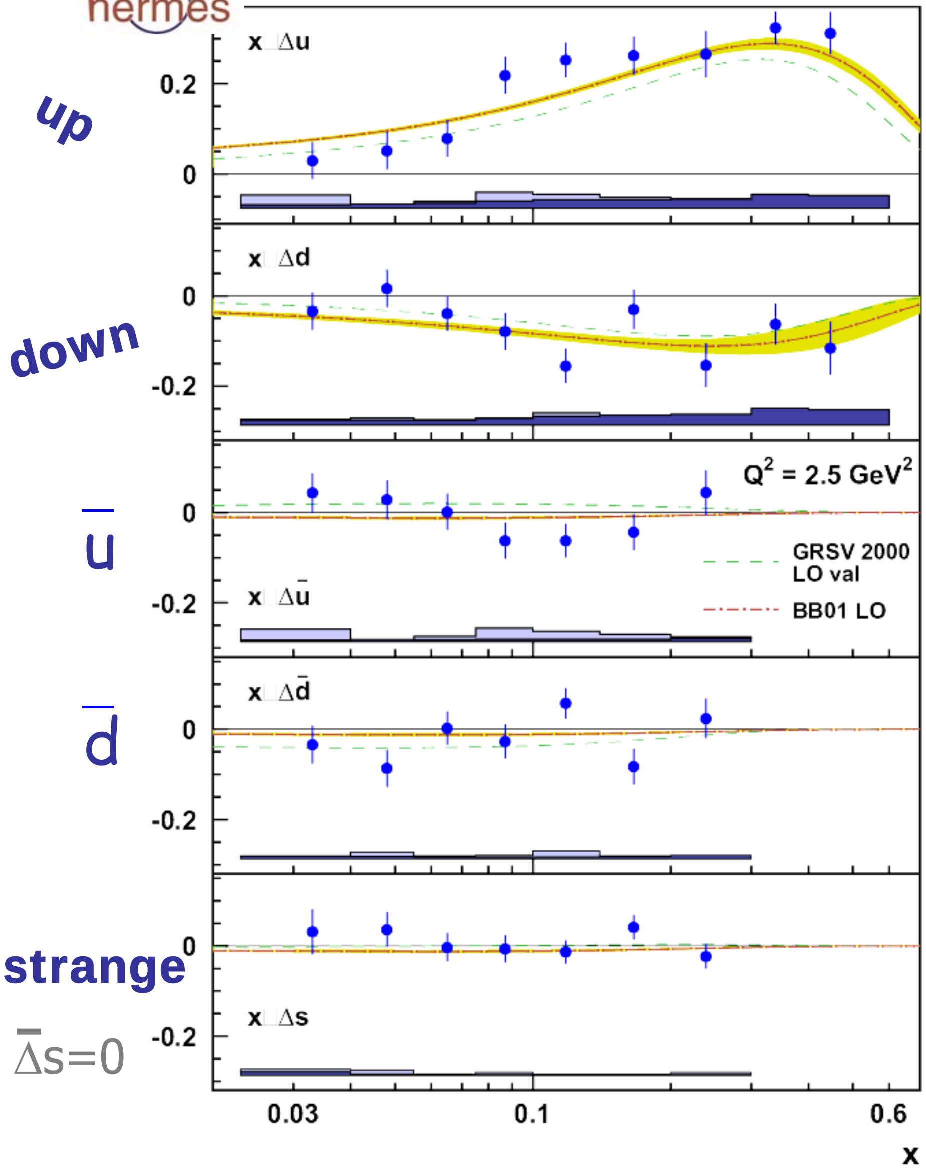




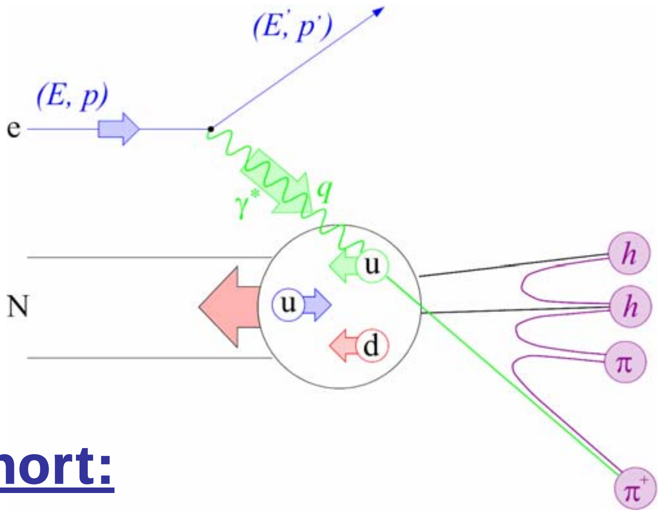
need *polarised collider* to extend kinematic coverage

→need *more direct* probes

flavour tagging: *semi-inclusive* DIS



[PRL92(2004), PRD71(2005)]



in short:

$\Delta u(x) > 0$ and large

$\Delta d(x) < 0$ and smaller

$\Delta s(x) \approx 0$

HERMES: only direct 5-flavour separation of polarised pdfs

more about *strange* quarks

- strange quarks carry no isospin, thus the same in proton and neutron
- → use isoscalar probe and target to extract *strange-quark* distributions

more about *strange* quarks

- strange quarks carry no isospin, thus the same in proton and neutron
- → use isoscalar probe and target to extract *strange-quark* distributions
- needed ingredients: $A_{1,d}(x,Q^2)$, $A_{1,d}^{K^+ + K^-}(x,z,Q^2)$ and $K^+ + K^-$ multiplicities
- *strange-quark* fragmentation function either directly from data or from parametrisations

→ **only assumptions:**

- isospin symmetry between proton and neutron
- charge conjugation invariance in fragmentation

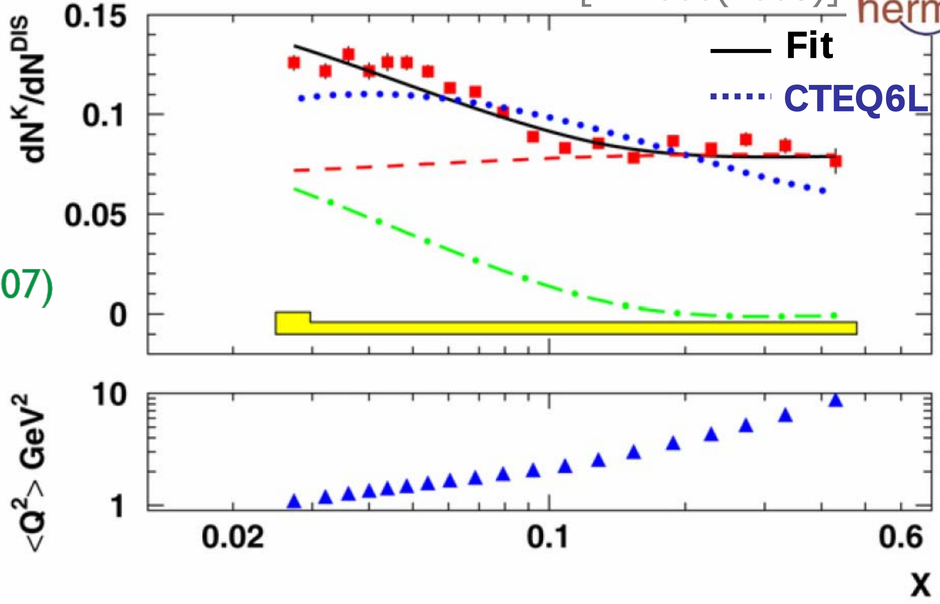
unpolarised *strange* quarks

[PLB666(2008)]

$\mathrm{K}^+ + \mathrm{K}^-$ **multiplicities:**

$$\int_{0.2}^{0.8} D_S^{\mathrm{K}}(z)dz = 1.27 \pm 0.13$$

de Florian et al., PRD75 (2007)



unpolarised *strange* quarks

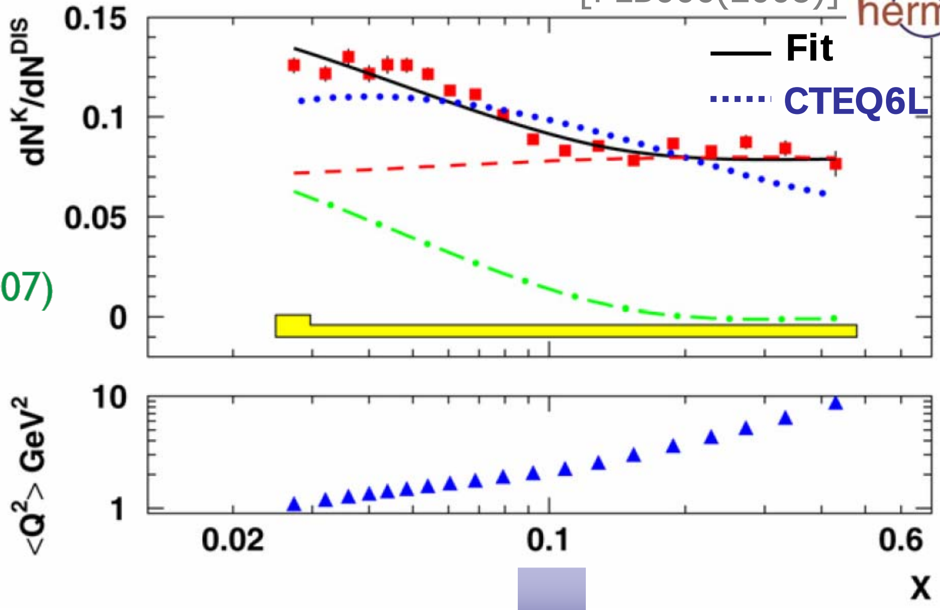
$K^+ + K^-$ multiplicities:

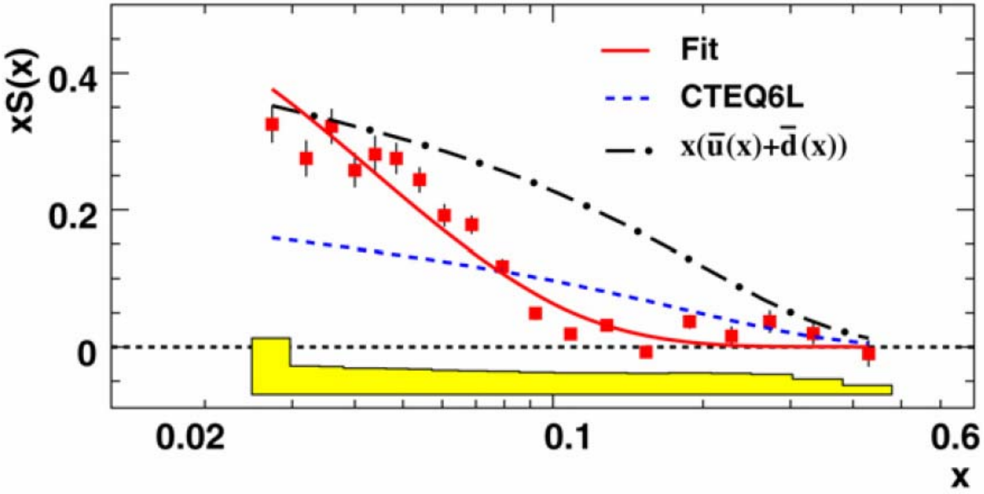
$$\int_{0.2}^{0.8} D_S^{K}(z)dz = 1.27 \pm 0.13$$

de Florian et al., PRD75 (2007)

- S(x) non-zero for x<0.1 vanishes for x>0.1
- apparent discrepancy with CTEQ6L
- S(x) NOT an average of an isoscalar non-strange see

[PLB666(2008)]





polarised *strange* quarks

- results consistent with previous flavour decomposition
- no sizeable negatively polarised strange sea as expected from inclusive DIS results
- sign of violation of SU(3)$_f$ symmetry or of substantial contribution from low-x region

axial charge: $a_8 = \Delta q_8 = \Delta Q - 2\Delta S$

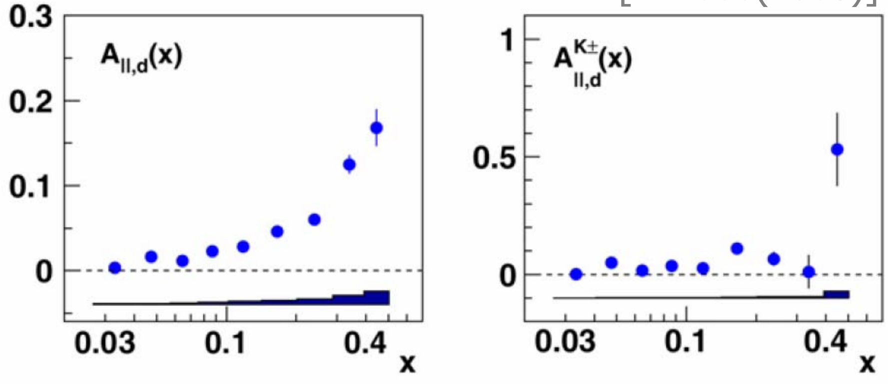
→ HERMES: (0.02<x< 0.6)

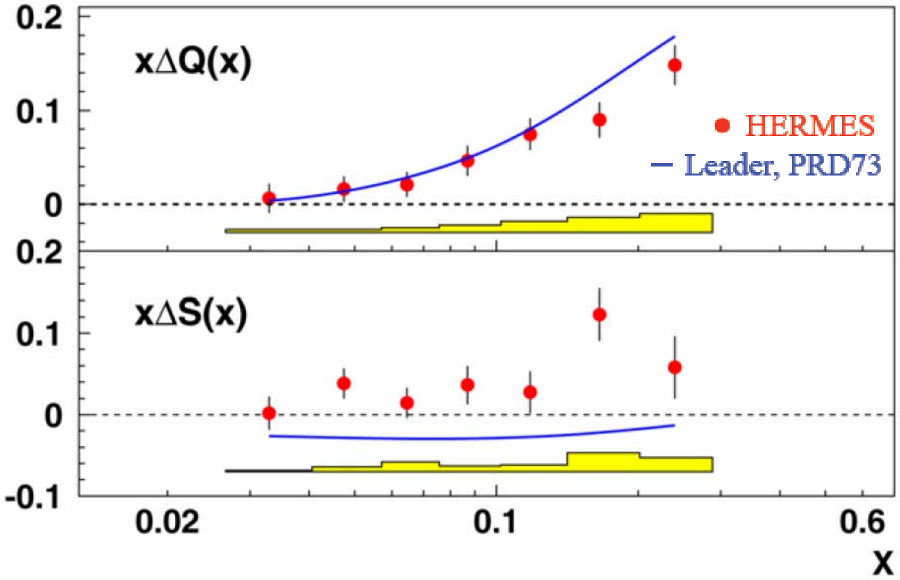
$\Delta q_8 = 0.285 \pm 0.073$

→ hyperon decay constants (SU(3) symm)

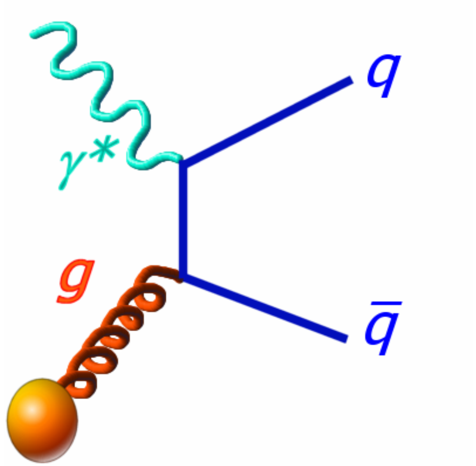
$\Delta q_8 = 0.586 \pm 0.031$

[PLB666(2008)]





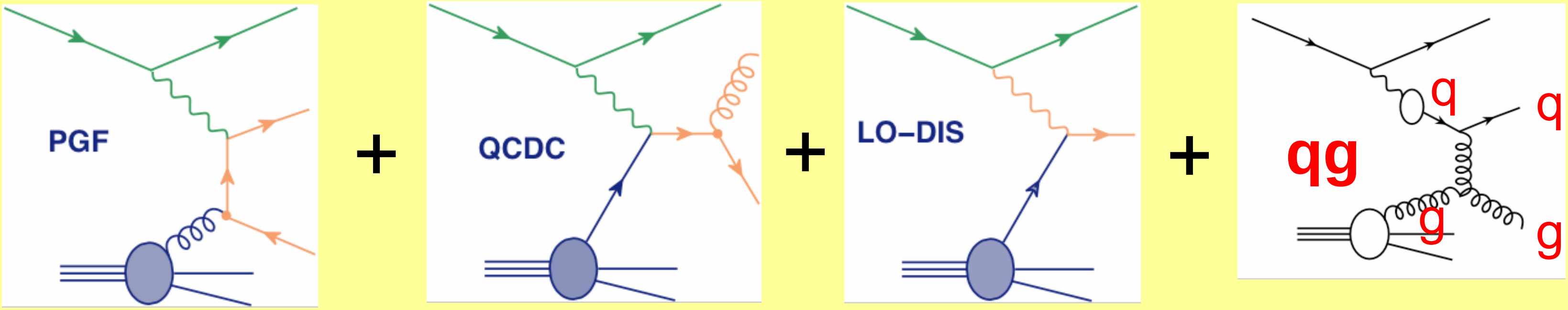
‘direct’ measurement of ΔG



Photon-Gluon Fusion (PGF)

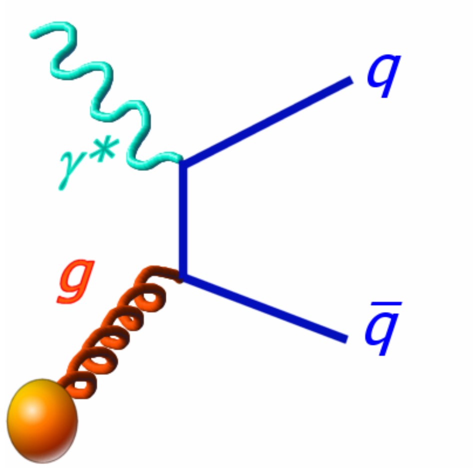
- golden channel: charm production
  - → theoretically very clean
  - → experimentally very challenging
- @HERMES ($\sqrt{s}$=7 GeV):
  hadron production at high P_T
  - → experimentally very clean
  - → highly model dependent
    due to variety of background processes

other sub-processes make life hard:



extraction relies on Monte Carlo description of subprocesses (pythia)

direct measurement of ΔG



- golden channel: charm production
  - → theoretically very clean
  - → experimentally very challenging

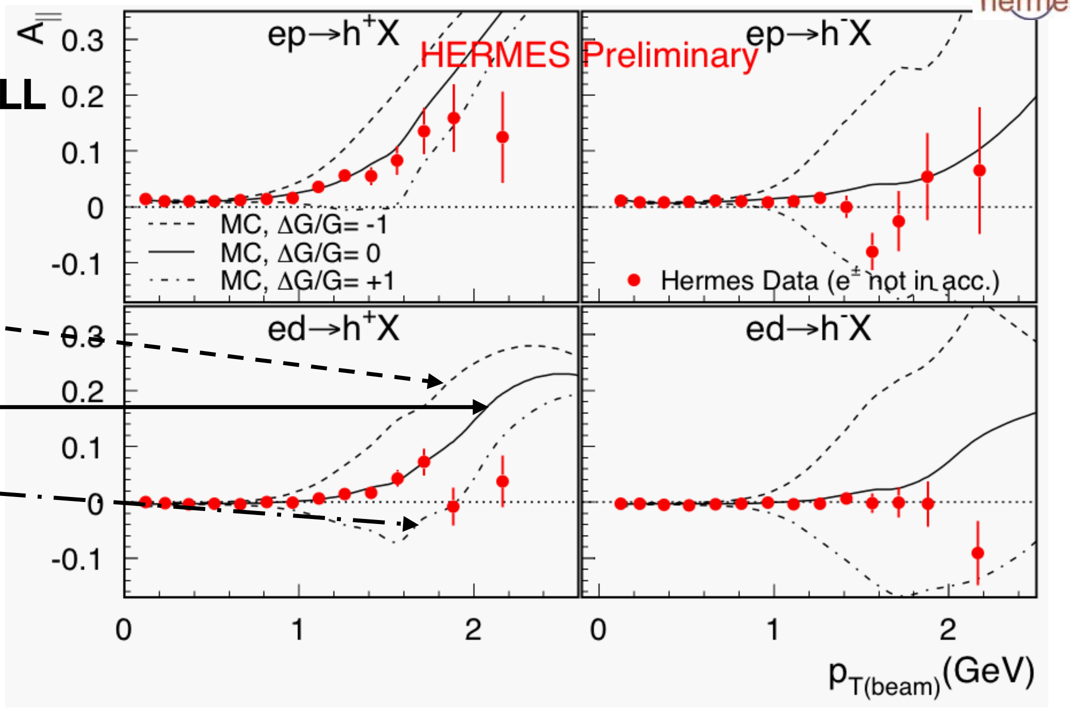
- @HERMES ($\sqrt{s}=7$ GeV):
  hadron production at high P_T

^{Pythia}MC:

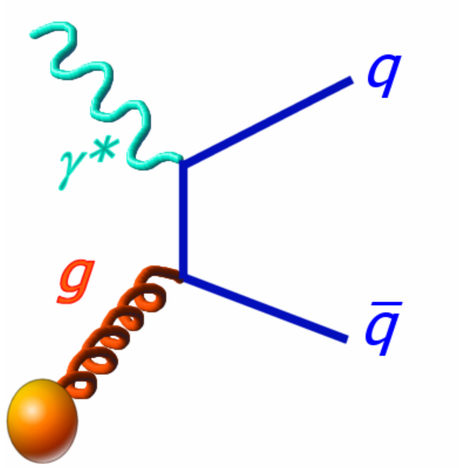
$\Delta g/g = -1$

$\Delta g/g = 0$

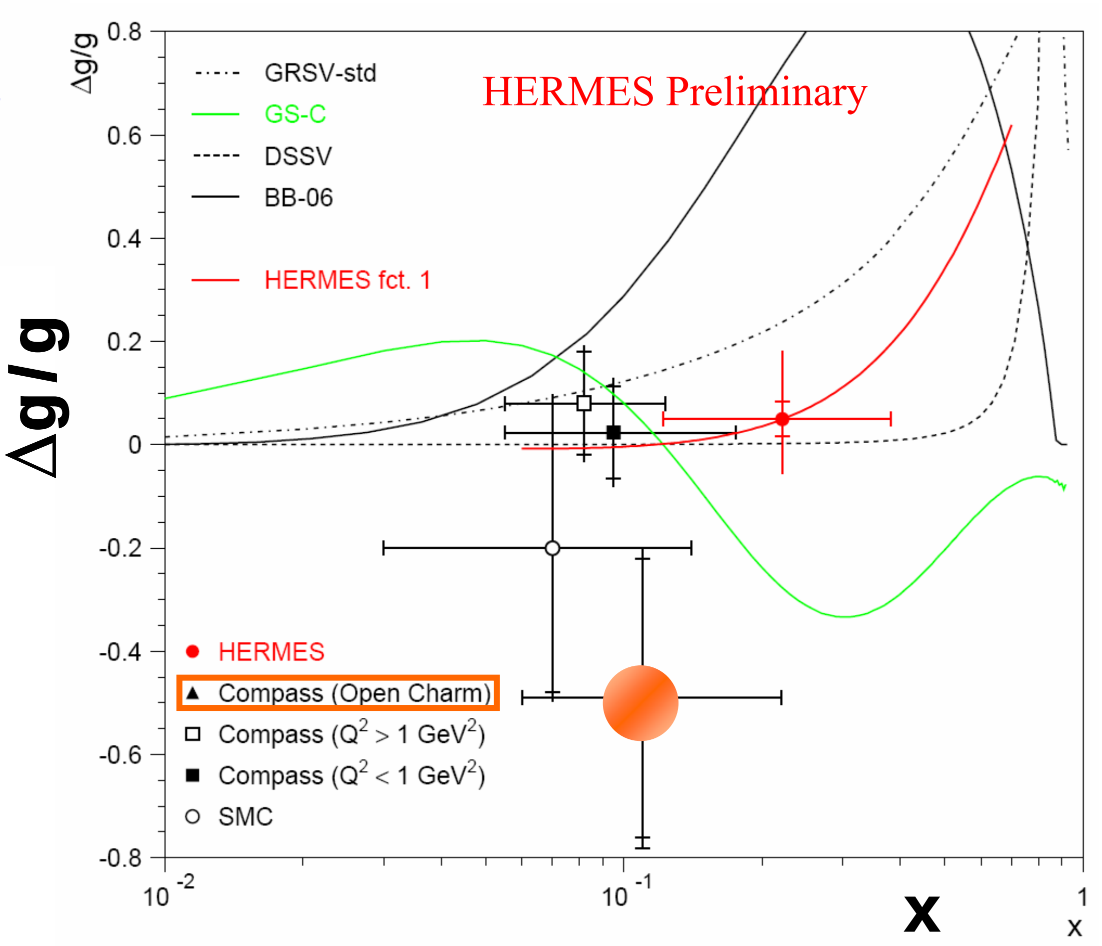
$\Delta g/g = +1$



direct measurement of ΔG



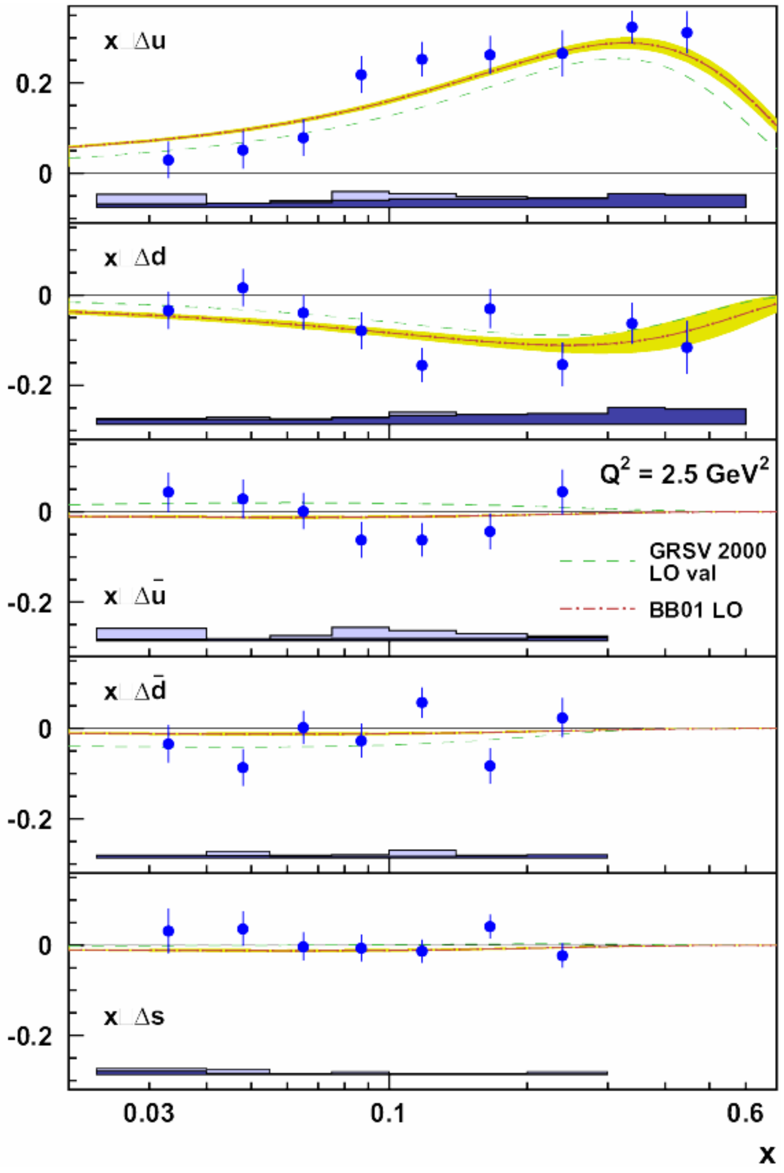
- **golden channel: charm production**
- **hadron production at high P_T**



@**x**[0.06,0.3]

Δg/g ~ zero!

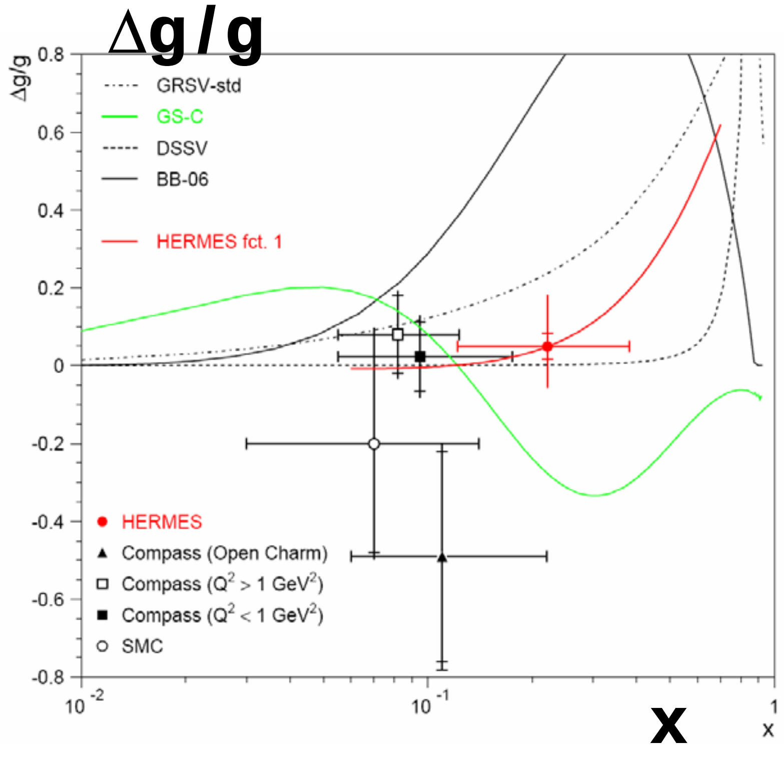
quark and gluon polarisations



ΔΣ ~ 0.3

ΔG ~ 0

→ orbital angular momentum → next talk



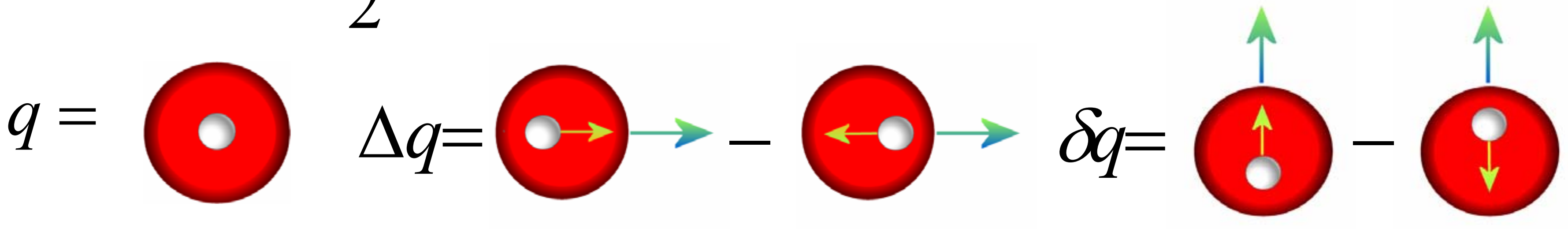
transverse spin phenomena

[courtesy of A. Bacchetta]

beyond collinear approximation

quark structure of the nucleon

$$\Phi^{\mathrm{Tw2}}_{\mathrm{Corr}}(x) = \frac{1}{2}\left\{ q(x) + \mathrm{S}_{\mathrm{L}}\Delta q(x)\gamma_5 + \delta q(x)\gamma_5\gamma^1\mathrm{S}_{\mathrm{T}} \right\} n^+$$



unpolarised quarks
and nucleons

longitudinally polarised
quarks and nucleons

transversely polarised
quarks and nucleons

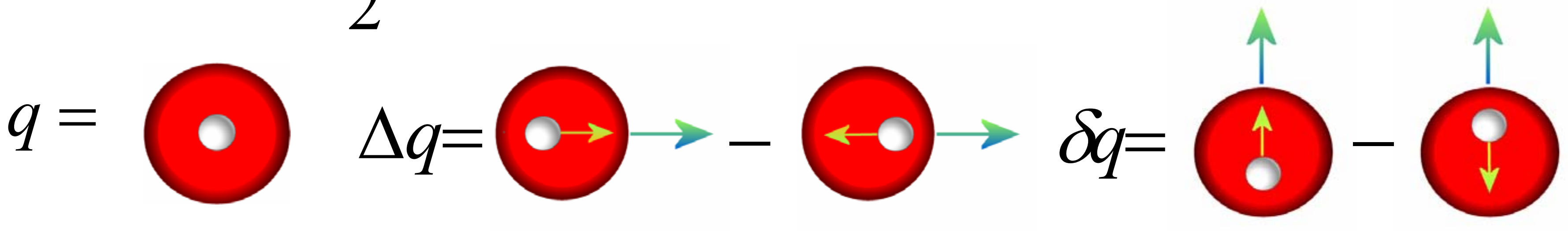
[also: h_1^q, $\Delta_T q$]

Peculiarities of δq

- probes relativistic nature of quarks
  →otherwise $\delta q = \Delta q$
- no gluon analog for spin-1/2 nucleon
  →<u>different Q^2 evolution than Δq</u>
- sensitive to *valence* quark polarisation
- only known way to obtain tensor charge

quark structure of the nucleon

$$\Phi^{\text{Tw2}}_{\text{Corr}}(x) = \frac{1}{2}\left\{ q(x) + S_L \Delta q(x)\gamma_5 + \delta q(x)\gamma_5\gamma^1 S_T \right\} n^+$$



unpolarised quarks
and nucleons

longitudinally polarised
quarks and nucleons

transversely polarised
quarks and nucleons

[also: h_1^q, $\Delta_T q$]

δq: *helicity-flip of both nucleon and quark*

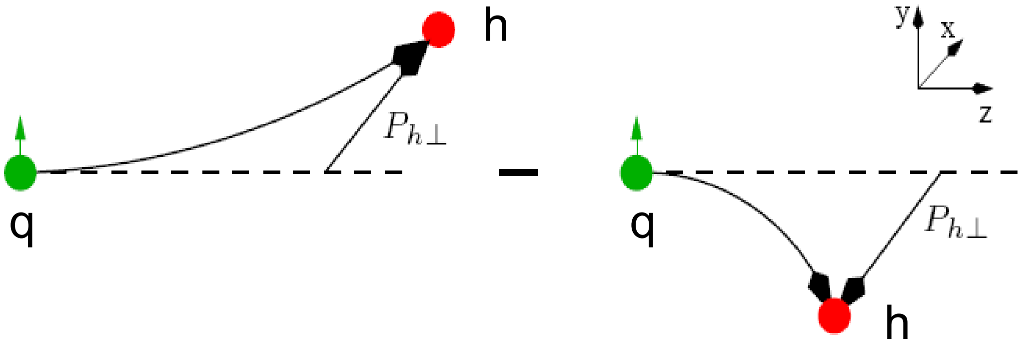
δq is *chiral-odd* → **needs a chiral odd partner:**

SIDIS: $$\sigma^{ep\to ehX} \propto \sum_q \sigma^{eq\to eq} \otimes \underbrace{\underset{\text{chiral-odd PDF}}{\delta q(x)} \otimes \underset{\text{chiral-odd FF}}{FF^{q\to h}(z)}}_{\text{chiral-even}}$$

chiral-odd fragmentation function acts as polarimeter of transverse quark polarisation

"Collins-effect"

- ***Collins FF*** **$H_1^{\perp}(z,k_T^2)$** correlates *transverse spin* of fragmenting quark and *transverse momentum* $P_{h\perp}$ of produced hadron h



→ left-right (azimuthal) asymmetry in the direction of the outgoing hadron

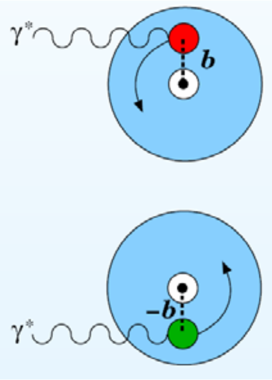
our observable: single-spin azimuthal asymmetry

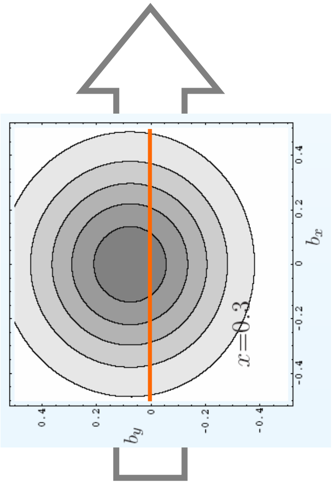
is this observable unique?

“*Sivers-effect*”

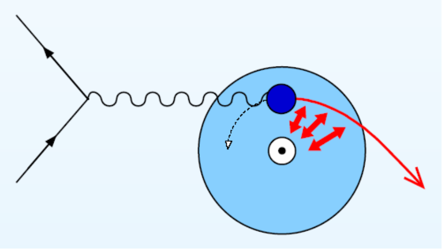
- another mechanism that produces single-spin azimuthal asymmetries:

Sivers distribution function : distribution of unpolarised quarks in a transversely polarised nucleon → describes *spin-orbit correlations*





$u_X\,(x, \boldsymbol{b}_\perp)$



[Matthias Burkardt:
chromodynamic lensing]

a non-zero Sivers fct. requires non-zero orbital angular momentum !

Sivers fct. is (naively) time-reversal *odd* !

polarised DIS^h cross section

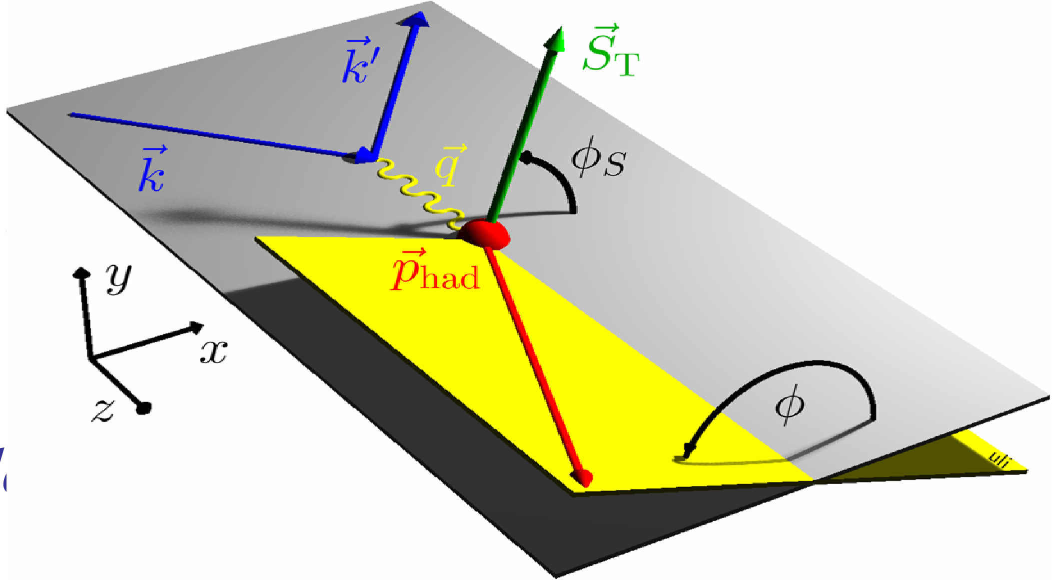
σ_{UU}

$$d\sigma^h(x,y,z,\boxed{P_{h\perp},\phi,...}) =$$

$$\boxed{d\sigma_{UU}} + \cos 2\phi\, d\sigma_{UU} + \frac{1}{Q}$$

q(x)

$$+S_L\Big[\sin 2\phi\, d\sigma_{UL} + \frac{1}{Q}\sin\phi\, d$$

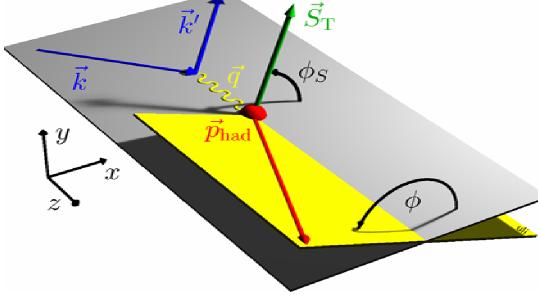


Δq(x)

$$+S_T\Big[\sin(\phi+\phi_S)d\sigma_{UT} + \sin(\phi-\phi_S)d\sigma_{UT} + \sin(3\phi-\phi_S)d\sigma_{UT} + \frac{1}{Q}...\Big]$$

$$+\lambda S_T\Big[\cos(\phi-\phi_S) + \frac{1}{Q}...\Big] + ...$$

polarised DIS^h cross section



$$d\sigma^h(x,y,z,\boxed{P_{h\perp},\phi,\ldots}) =$$

$$d\sigma_{UU} + \cos 2\phi\, d\sigma_{UU} + \frac{1}{Q}\cos\phi\, d\sigma_{UU} + \lambda\frac{1}{Q}\sin\phi\, d\sigma_{LU}$$

q(x)

$$+S_L\left[\sin 2\phi\, d\sigma_{UL} + \frac{1}{Q}\sin\phi\, d\sigma_{UL}\right] + \lambda S_L\left[d\sigma_{LL} + \frac{1}{Q}\cos\phi\, d\sigma_{LL}\right]$$

$\delta q \otimes H_1^{\perp} + f_{1T}^{\perp} \otimes D_1 + h_L \ldots$

$\Delta q(x)$

$$+S_T\left[\sin(\phi+\phi_S)d\sigma_{UT} + \sin(\phi-\phi_S)d\sigma_{UT} + \sin(3\phi-\phi_S)d\sigma_{UT} + \frac{1}{Q}\ldots\right]$$

$\delta q \otimes H_1^{\perp}$

$f_{1T}^{\perp} \otimes D_1$

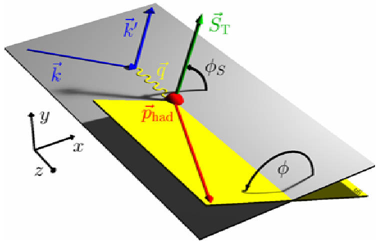
transversity

(Collins effect)

SIDIS with *transversely*
polarised targets but not only…

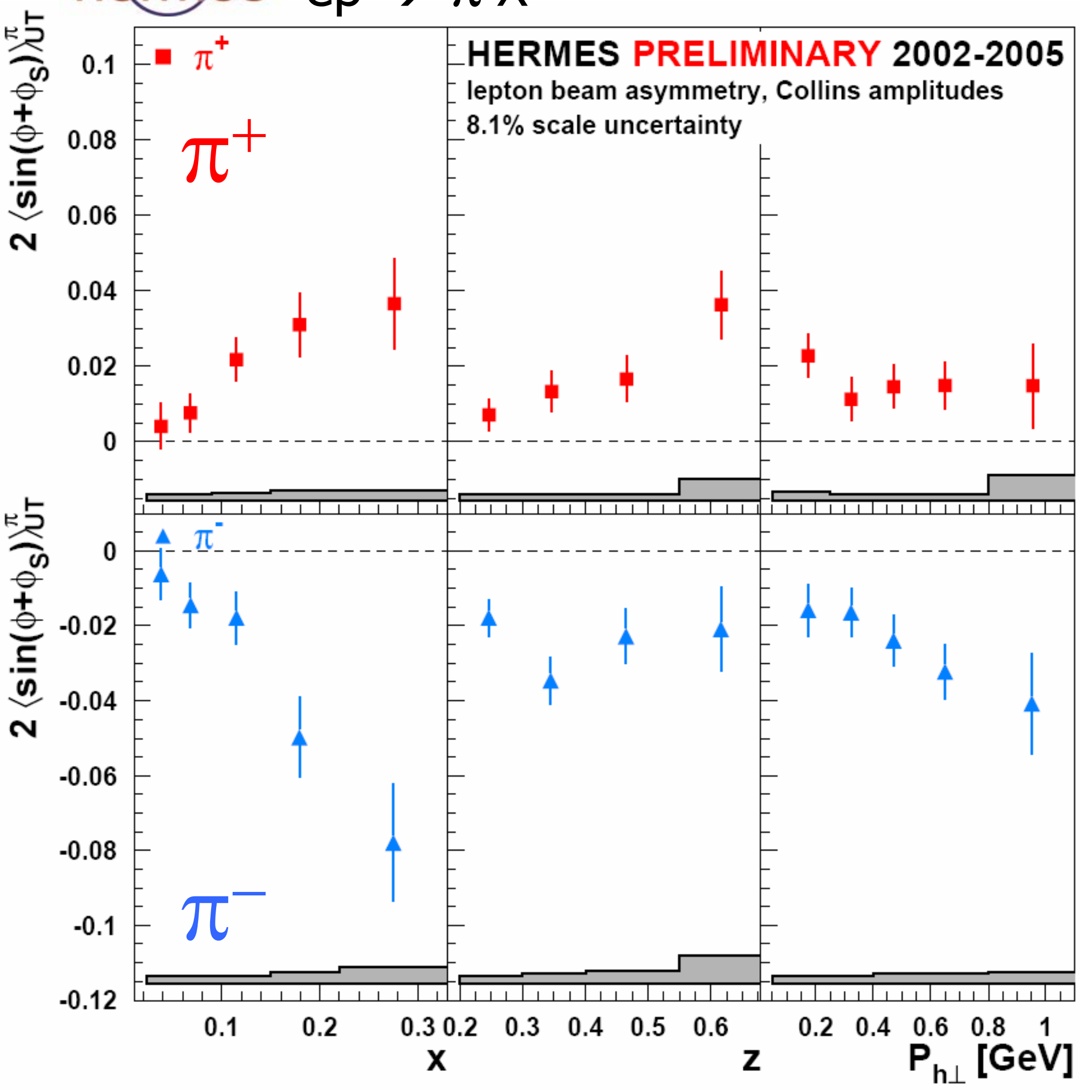
$$-\phi_S) + \frac{1}{Q}\ldots\Big] + \ldots.$$

Collins asymmetries



ep↑→ π X

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



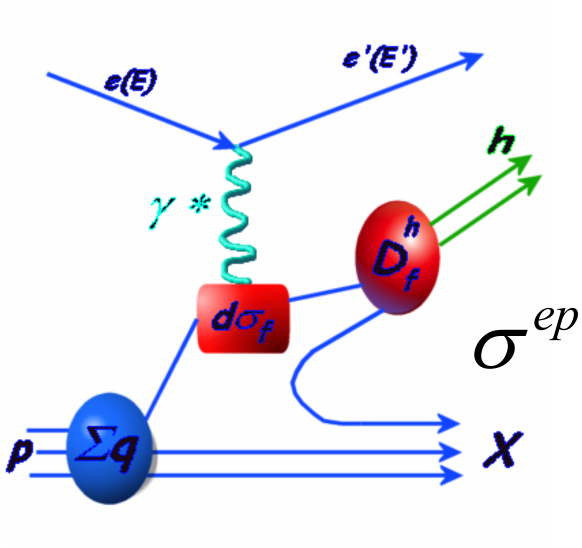
first time: *transversity* & *Collins FF* are **non-zero!**

- 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:

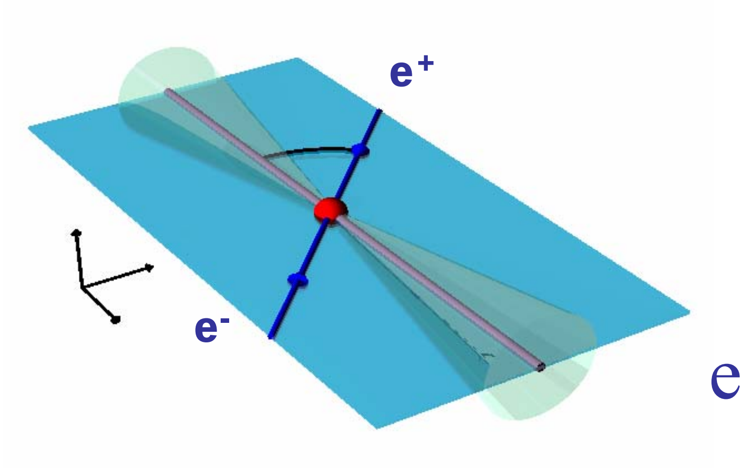
$$H_1^{\perp,\mathrm{disfav}}(z)\boxed{\approx -}H_1^{\perp,\mathrm{fav}}(z)$$

extracting *transversity*



$$\sigma^{ep\to ehX} \propto \sum_q \sigma^{eq\to eq} \otimes \delta q(x) \otimes FF^{q\to h}(z)$$

spin-dependent
fragmentation
function
→
e^+e^-

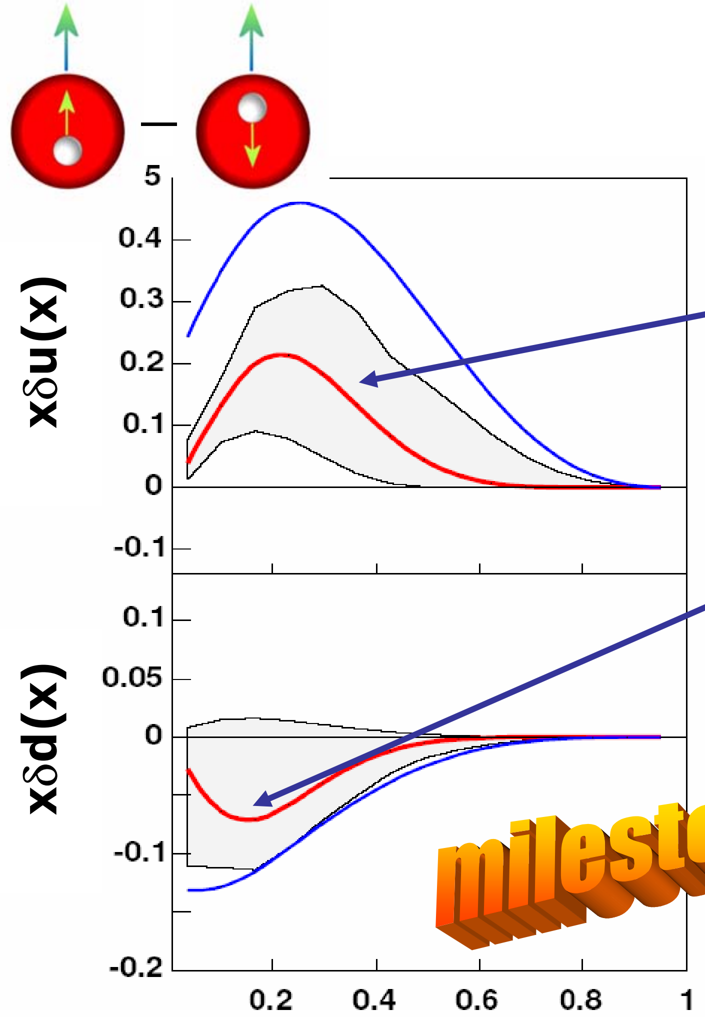


$$\mathrm{e}^+\mathrm{e}^- \to \pi^+_{\mathrm{jet1}}\,\pi^-_{\mathrm{jet2}}\,\mathrm{X}$$

first glimpse of transversity

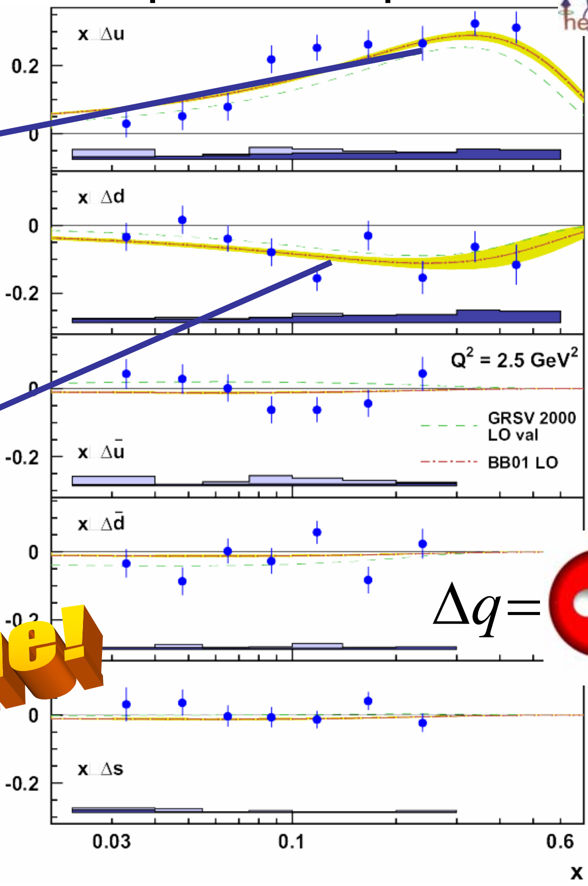
global, simultaneous fit:

$\delta q=$



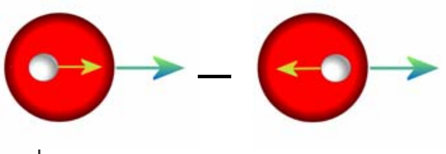
[Anselmino et al. PRD75(2007)]

compare to Δq:



milestone!

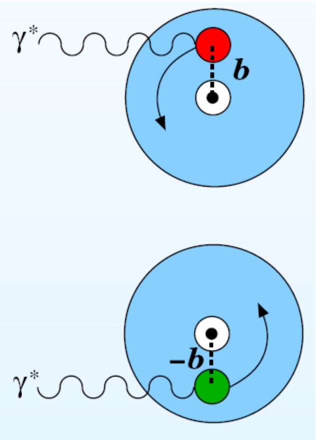
$\Delta q=$

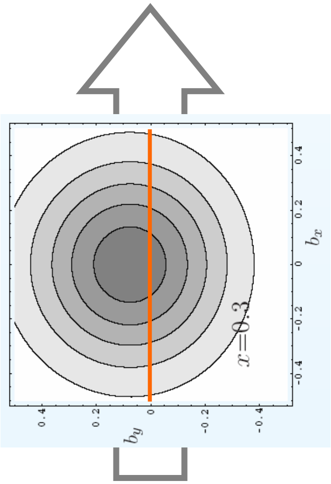


all details:
U. D'Alesio

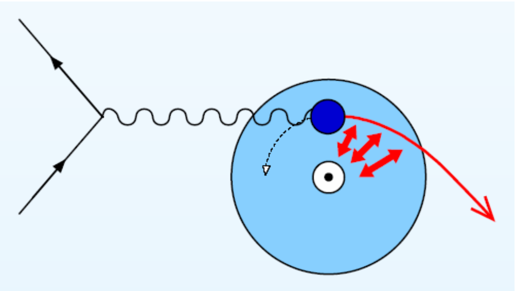
spin-orbit structure

Sivers function:





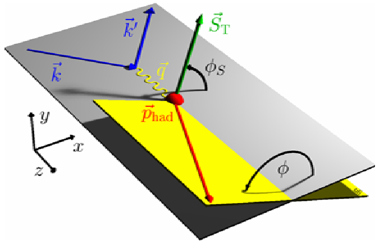
$u_X\,(x,\boldsymbol{b}_\perp)$

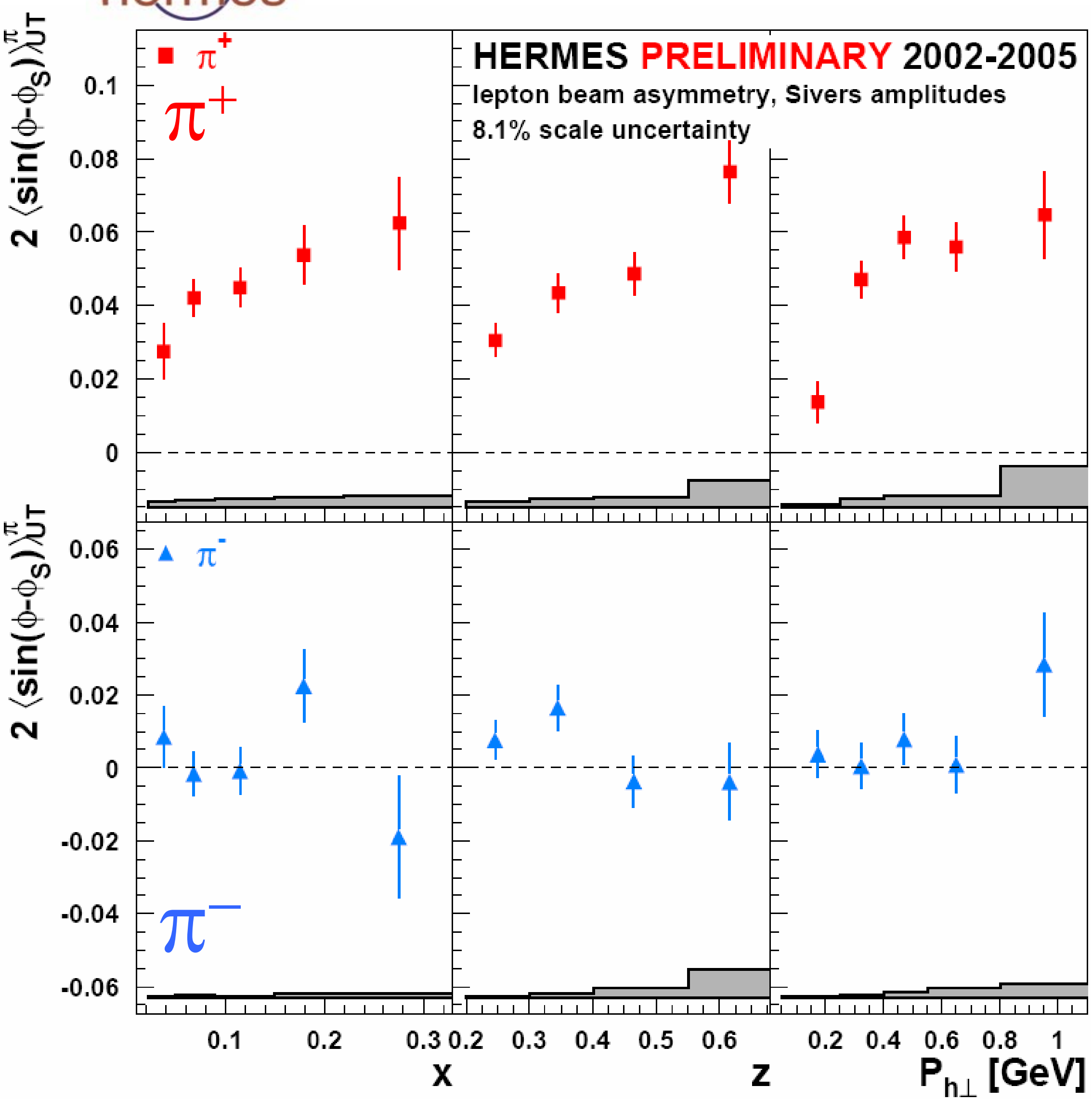


[Matthias Burkardt]

a non-zero Sivers fct. requires non-zero orbital angular momentum !

Sivers asymmetries





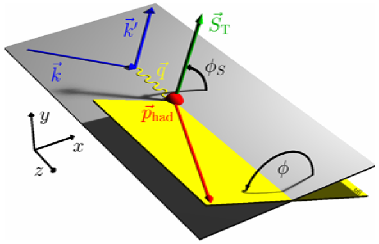
$$f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

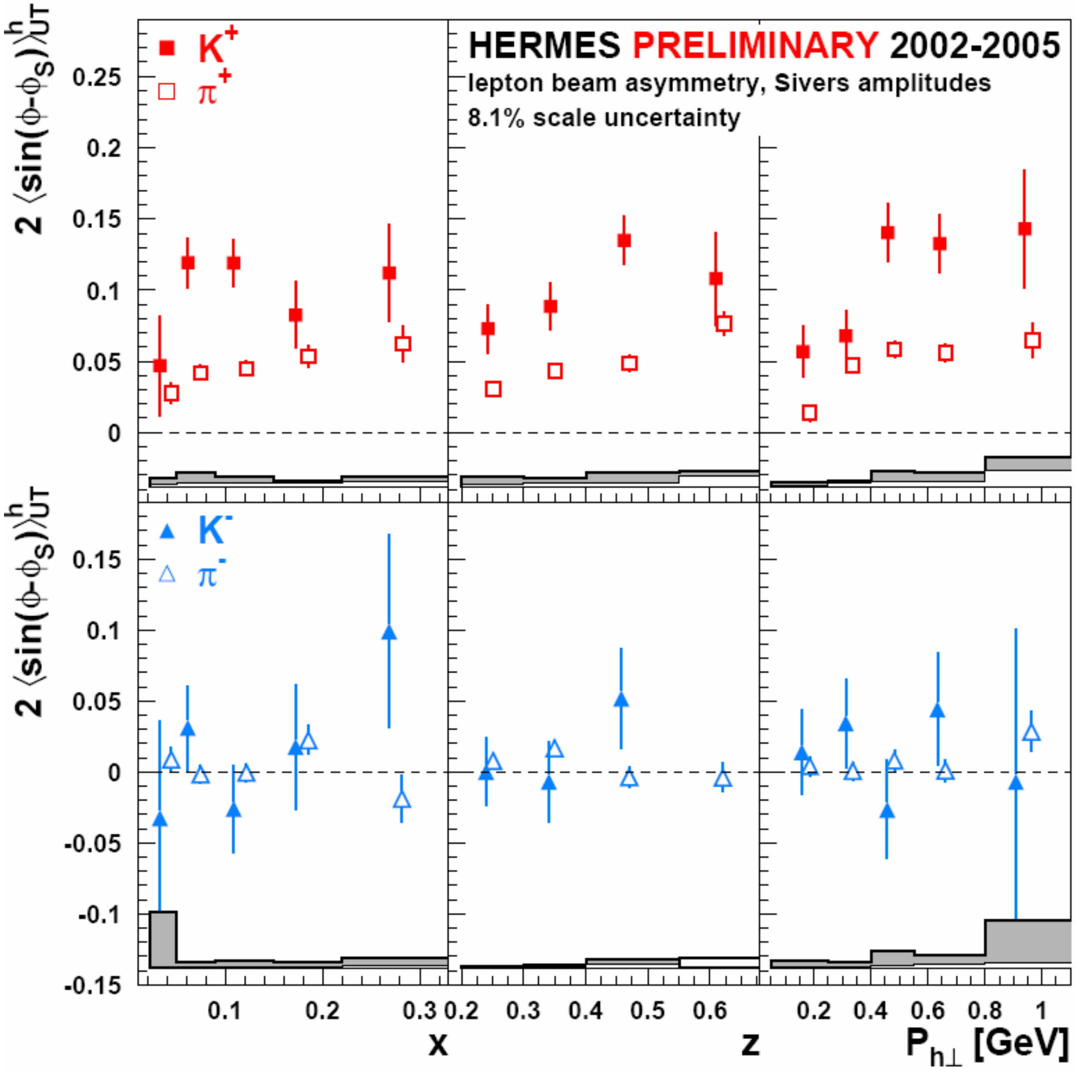
π^+ are subtantial and positive:

- first unambiguous evidence for a **non-zero T-odd** distribution function in DIS

- a signature for quark orbital angular momentum !

Sivers asymmetries





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

- SURPRISE:

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

→ conflicts with usual expectations based on u-quark dominance

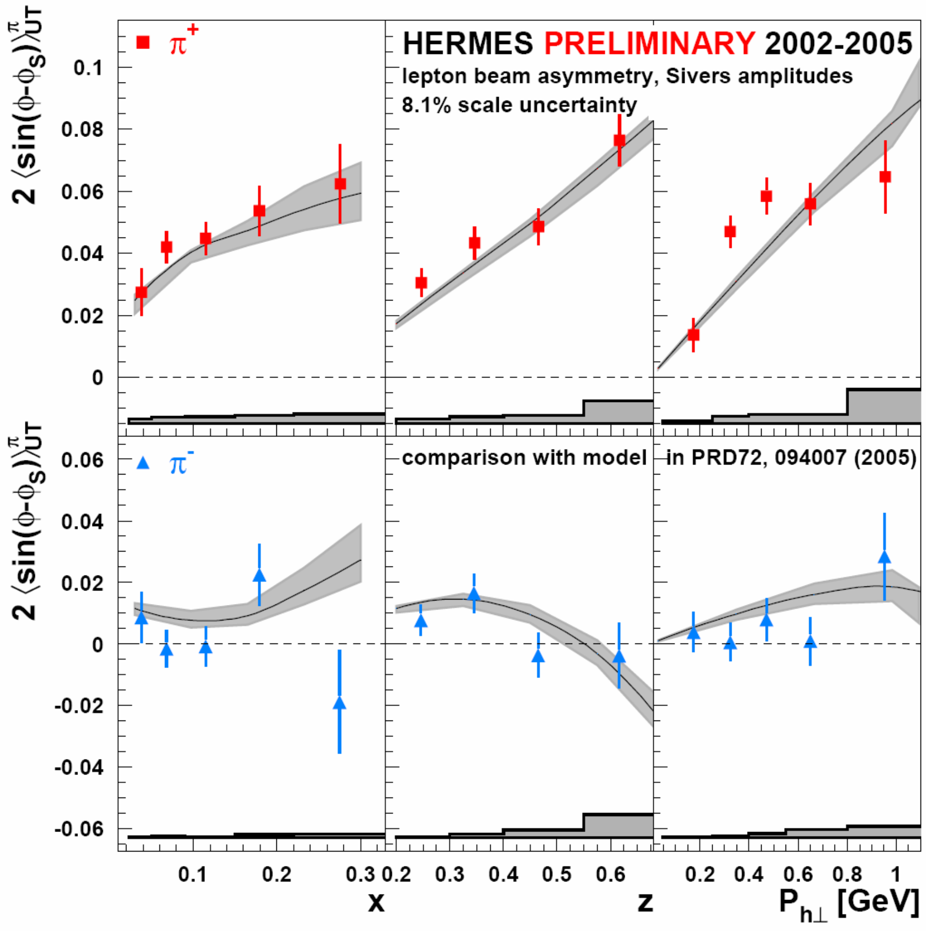
→ suggests substantial magnitude of the Sivers fct. for sea quarks

$$K^+ = \left|u\bar{s}\right\rangle \quad \pi^+ = \left|u\bar{d}\right\rangle$$

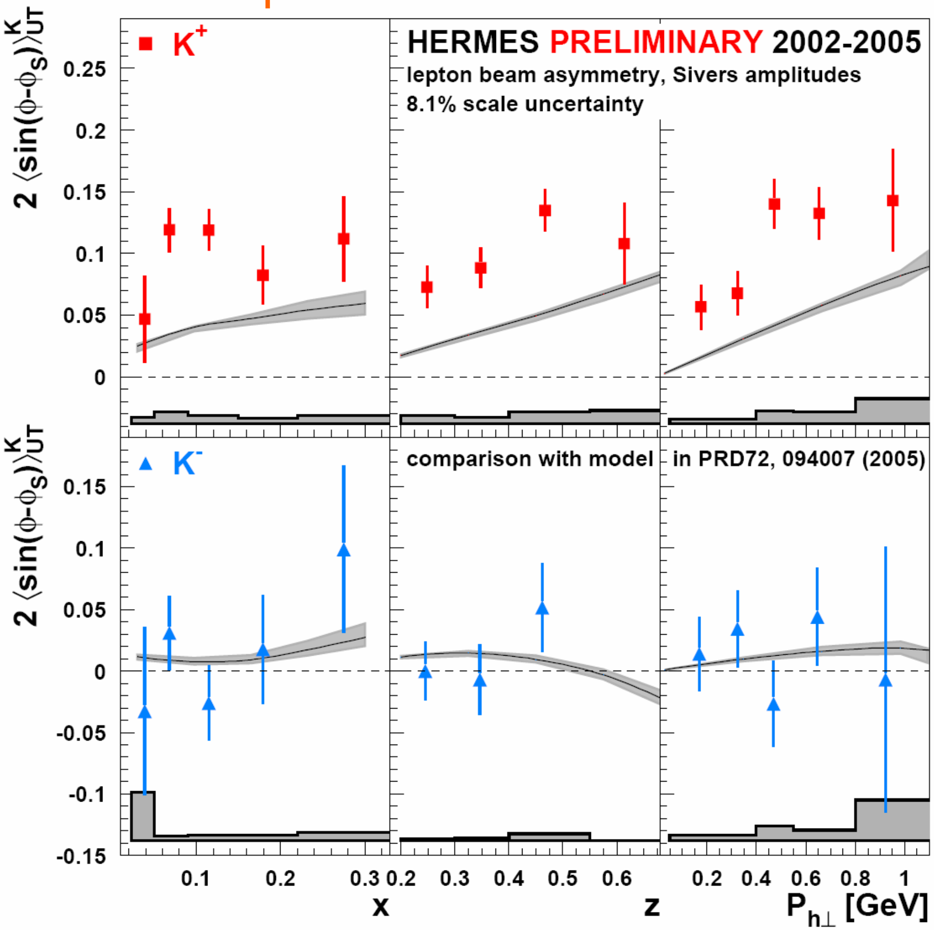
comparison to models

[Anselmino et al. PRD72(2005)]

excellent description of pion data
but: cannot constrain sea



predictions for kaons:



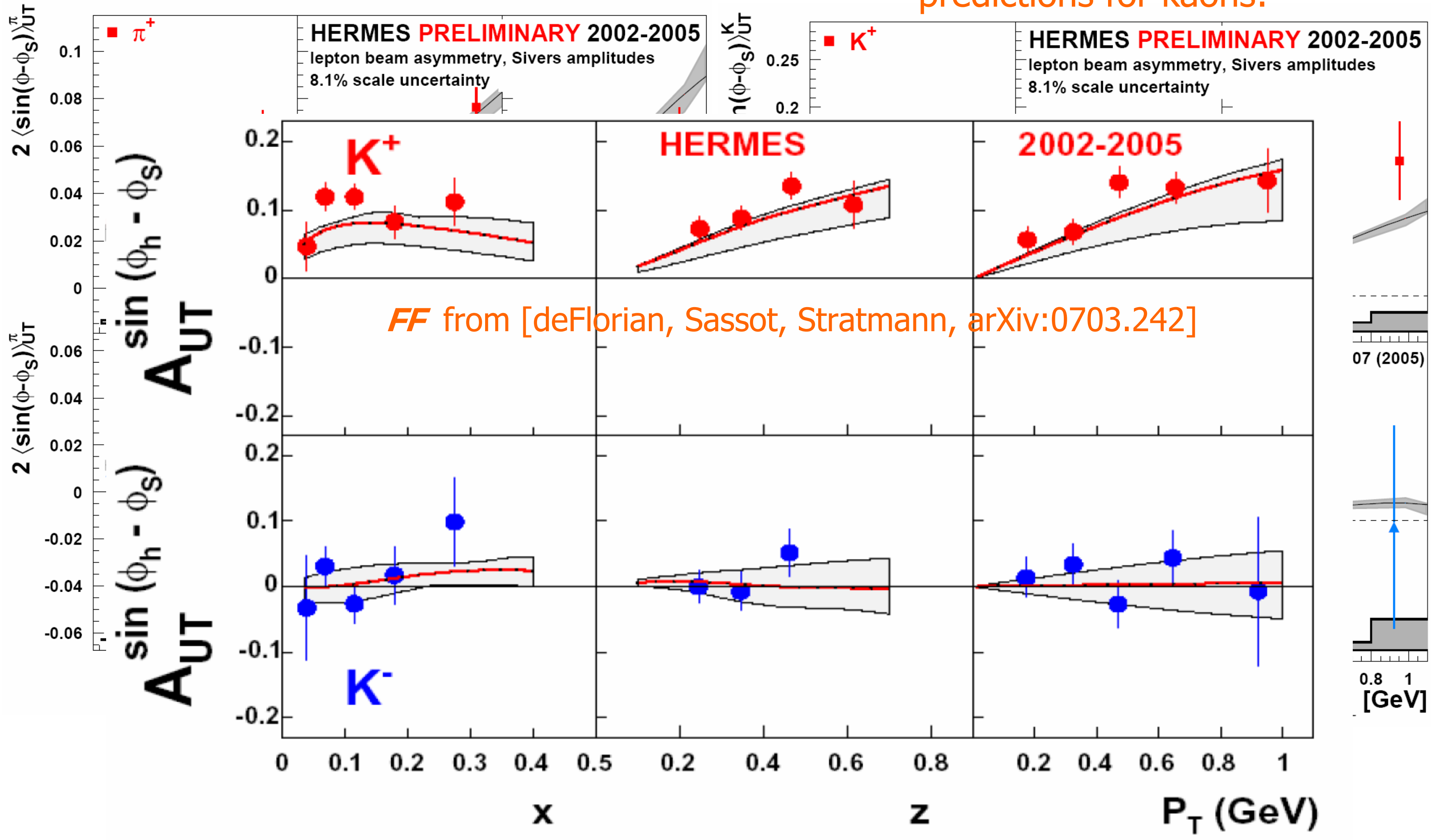
kaon data suggest that sea quark contribution may be significant

comparison to models

[Anselmino et al. PRD72(2005)]

excellent description of pion data
but: cannot constrain sea

predictions for kaons:

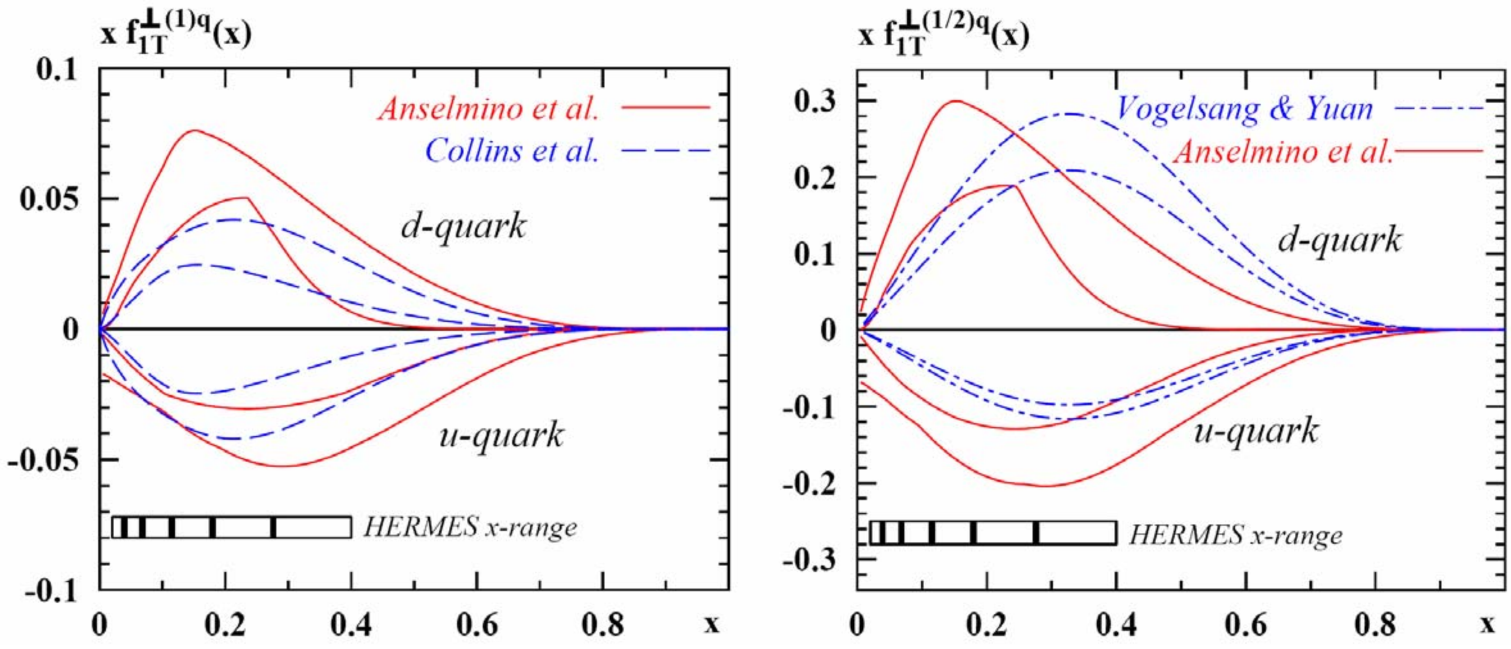


FF from [deFlorian, Sassot, Stratmann, arXiv:0703.242]

extracting the *Sivers* function

$$A_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

usual unpolarised fragmentation function



ToDo:

crucial test of pQCD:

$$(f_{1T}^{\perp q})_{\mathrm{DIS}} \approx -(f_{1T}^{\perp q})_{\mathrm{DY}}$$

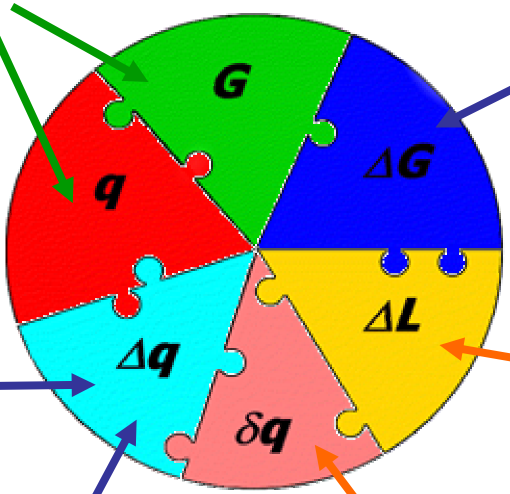
Polarized Antiproton EXperiments

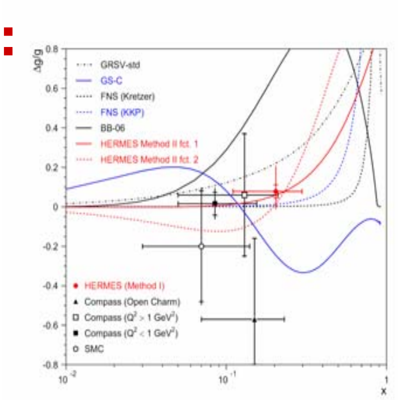
@FAIR (GSI)

structure of the nucleon

from unpolarised DIS

from polarised DIS :

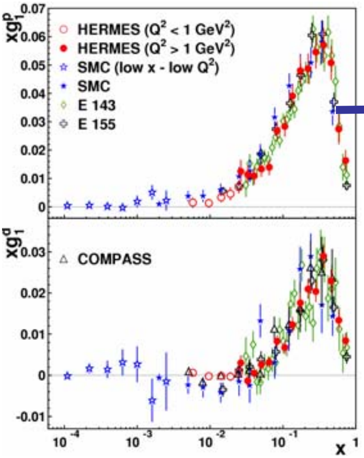




first glimpse

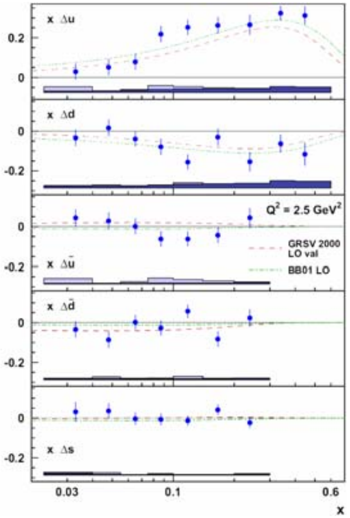
→$a_0 = \Delta\Sigma$

$= 0.330 \pm 0.025^{(exp)}$

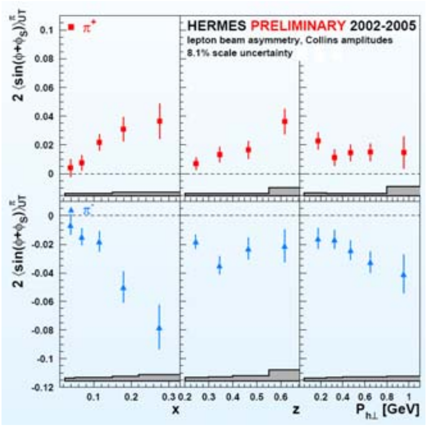


→ first signals of GPDs: $J_u + J_d$

→ **see next talk !**



first extraction of δq , spin-orbit structures & OAM



→direct flavour decomposition

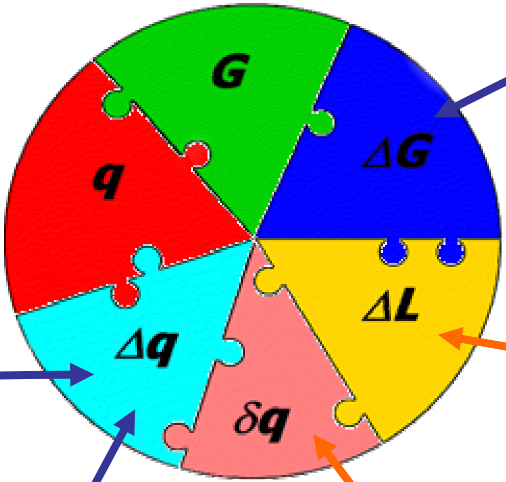
new concepts:

GPDs → 3D picture of the nucleon

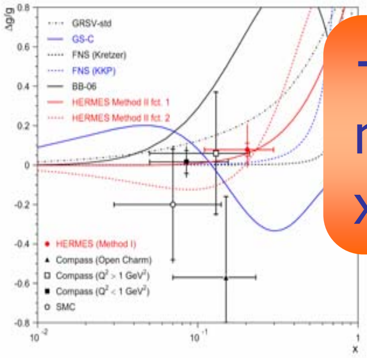
TMDs → beyond collinear approximation

structure of the nucleon

-the open tasks-



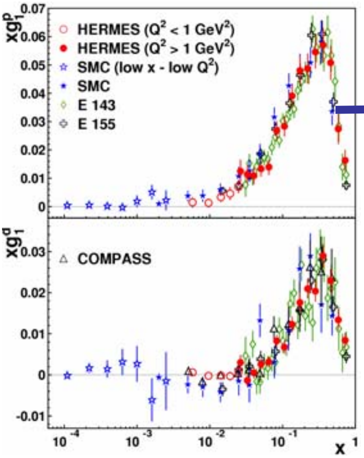
first glimpse



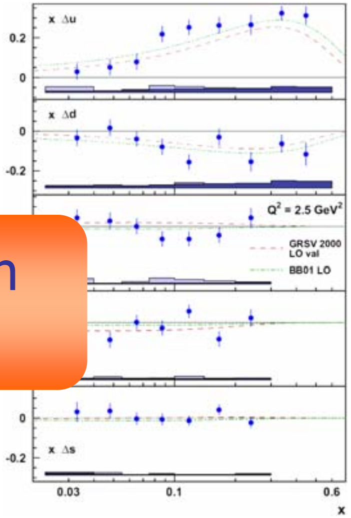
→ detailed measurement of x-dependence

→ first signals of GPDs: $J_u + J_d$

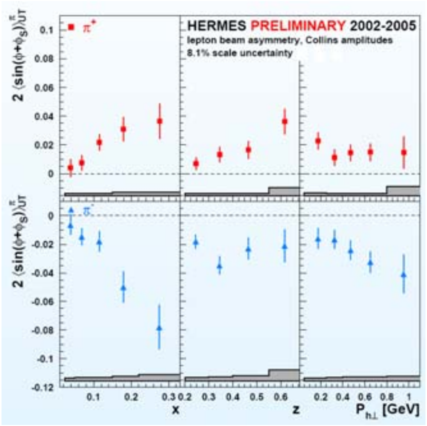
→ **see next talk !**



→ detailed measurement in 3 kine variables



first extraction of δq



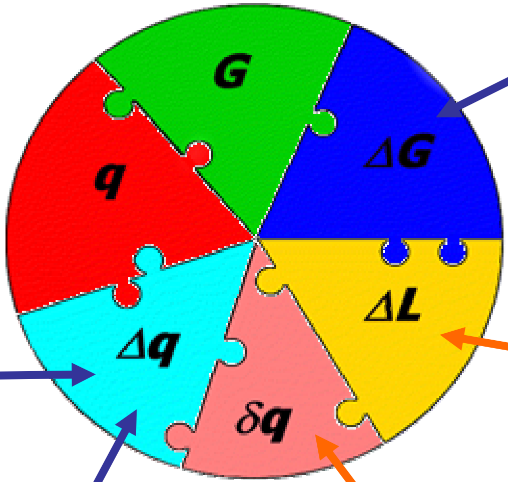
→ extrapolation x→0, x→1

→ detailed measurement in 2 kine variables

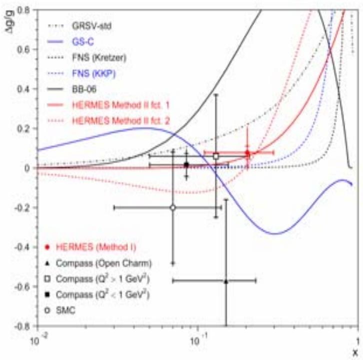
structure of the nucleon

-the future facilities-

RHIC,
EIC,
(JPARC)

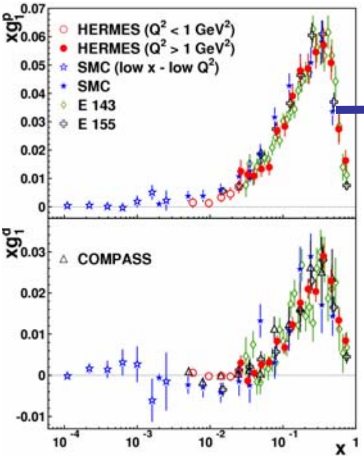


first glimpse



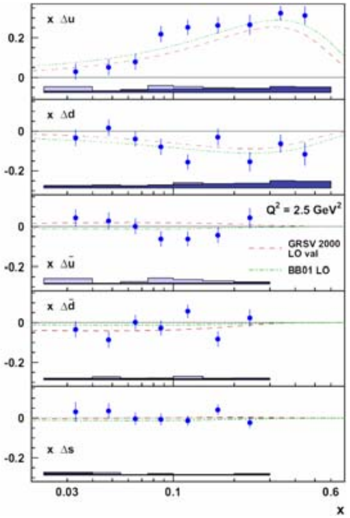
→ first signals of GPDs: $J_u + J_d$

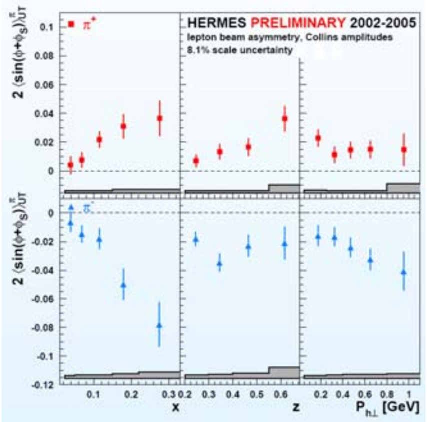
→ **see next talk !**



JLab@12GeV
EIC

first extraction of δq





polarised collider:
EIC

EIC,
FAIR

Backup slides

multiplicities compared to theory

new FF from combined NLO analysis of single-inclusive hadron production in e^+e^-, pp and DIS

[deFlorian,Sassot,Stratmann arXiv:0708.0769]