The (mysterious) Proton Spin

Klaus Rith

University of Erlangen -Nürnberg & DESY

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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSC/74-78
SPSC P.18
1 July 1974

PROPOSED EXPERIMENTS AND EQUIPMENT
FOR A PROGRAMME OF MUON PHYSICS AT THE SPS

by

The European Muon Collaboration

1980-84:
19 joint publications

The European Muon Collaboration

British Participants: R. Clifft, E. Gabathuler, H. Montgomery, P.R. Norton, J.C. Thompson (Daresbury Laboratory), T. Sloan (Lancaster Univ.), G.R. Court, R. Gamet, P. Hayman, J.R. Holt (Liverpool Univ.), W.S. Williams (Oxford Univ.), F. Combley (Sheffield Univ.) and F. Farley (R.M.C. Shrivenham).

CERN Participants: M. Borghini and J.H. Field.

French Participants: J.J. Aubert, C. Broll, X. de Bouard, G. Coignet, J. Favier, H. de Kerrett, L. Massonnet, H. Pessard, F. Vannucci and M. Vivargent (Institut de Physique Nucléaire, Orsay).

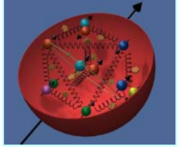
German Participants: H.J. Behrend, F.W. Brasse, W. Flauger, J. Gayler, V. Korbel*, A. Ladage, J. May, P. Söding (Deutsches Elektronen-Synchrotron, Hamburg), U. Hahn, K. Moser, K. Rith, E. Schlösser, H.E. Stier (Freiburg Univ.), O.C. Allkofer (Kiel Univ.), K.H. Becks, J. Drees, U. Opara and H. Wahlen (Wuppertal Univ.).

* Now at CERN.

Italian Participants: P. Dalpiaz, P.F. Dalpiaz, M.I. Ferrero and C. Franzinetti (Turin Univ.).

Contactman: E. Gabathuler - present address NP-Division, CERN.

Spin



- Spin: extremely important quantity in quantum physics with properties of angular momentum

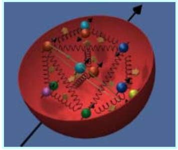
- Spin-1/2 particles:

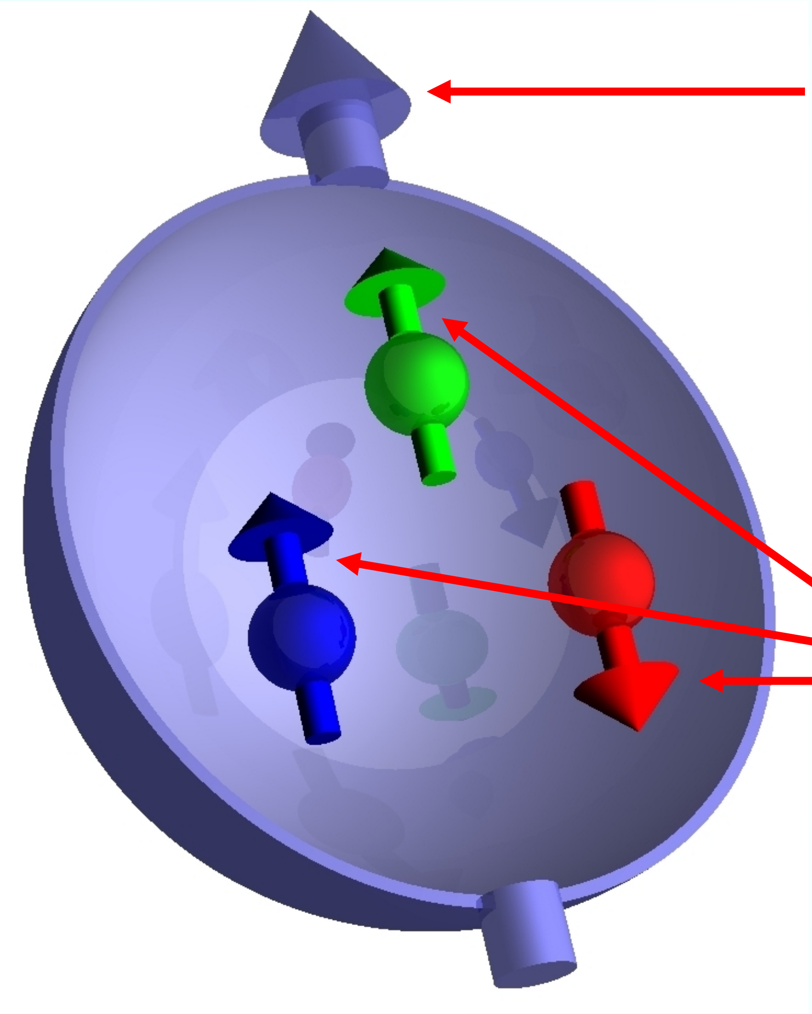
  fundamental constituents [quarks, leptons (e, μ,τ, neutrinos), proton, neutron,...]

- Spin-1/2 responsible for stability of matter (Pauli-principle):

  No two Spin-1/2 particles can occupy a state where all quantum numbers are identical

Nucleon Spin: constituent quark model





Nucleon Spin

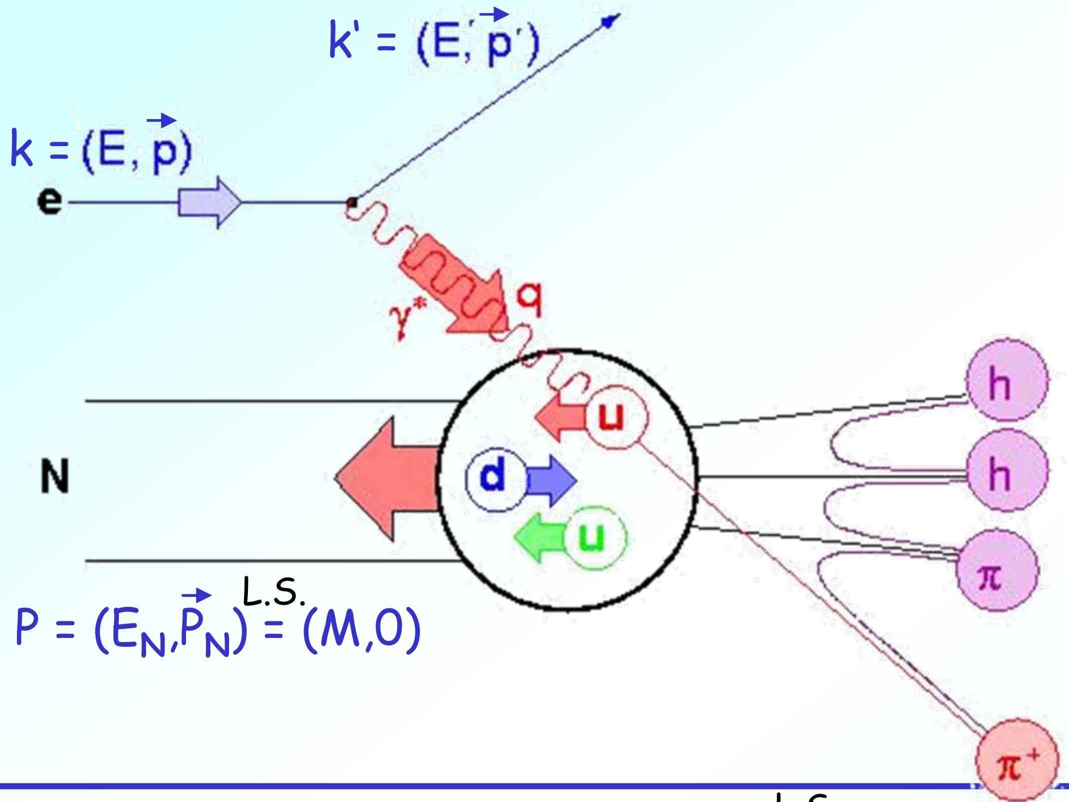
$$\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma$$

Contribution of quark spins:

$$\Delta\Sigma = 1$$

Determination of $\Delta\Sigma$

Polarized deep-inelastic scattering



Asymmetries:

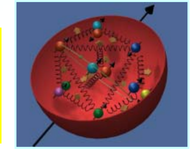
$$A = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

$Q^2 = -q^2 = -(k - k')^2$, $\nu = Pq/M \overset{L.S.}{=} E - E'$,

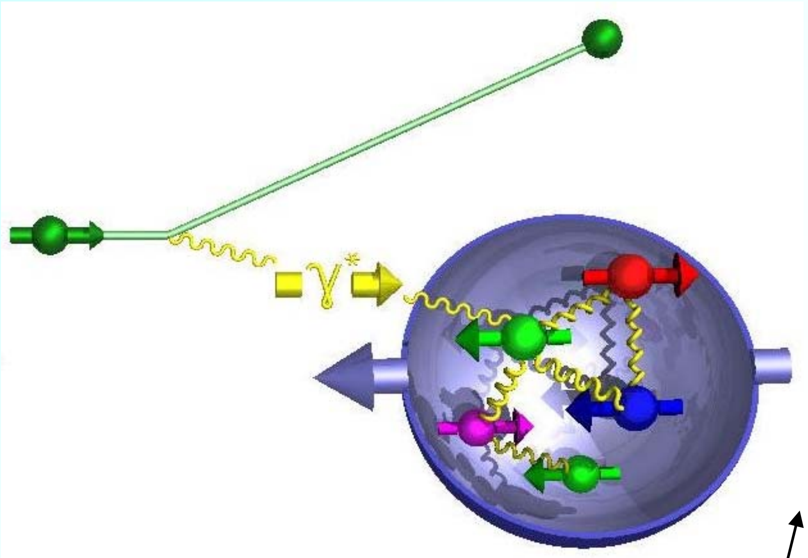
$x = Q^2/(2Pq)$ = fraction of nucleon's longitudinal momentum carried by struck quark

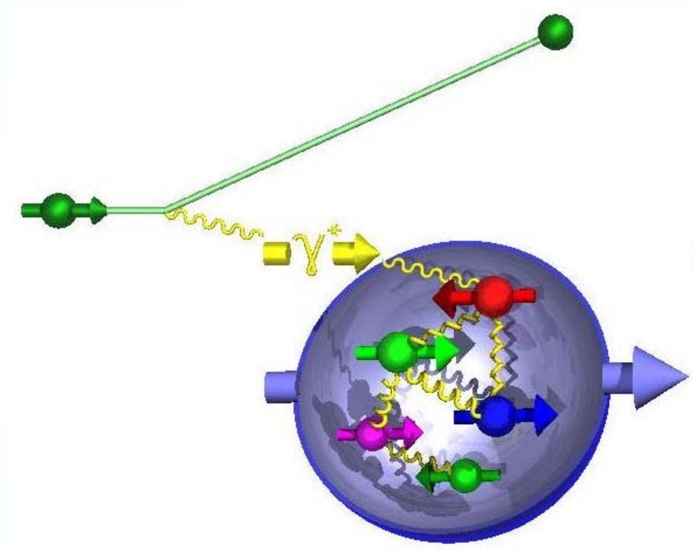
$q(x)$ = quark number density (quark momentum distribution)

Quark helicity distributions $\Delta q(x)$



More precisely: „helicity weighted momentum distributions“





Proton

Quark

$q^{+}(x) = q^{\uparrow\uparrow}$

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

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

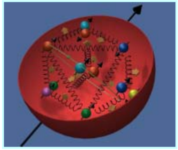
$\Delta q = \int_0^1 \Delta q(x)\, dx$

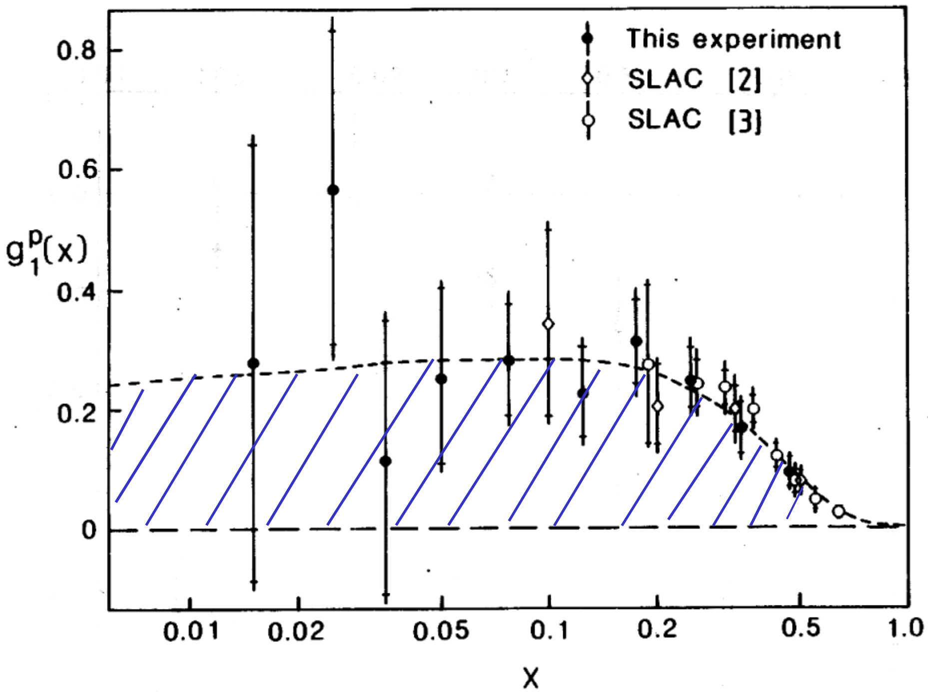
$\Delta\Sigma = \sum_q \Delta q$

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

$\Gamma_1 = \int_0^1 g_1(x)\, dx$

The EMC result for $g_1^p(x)$





Consequence (1987):	QPM:
$\Delta u \cong 0{,}78$	4/3
$\Delta d \cong -0{,}47$	-1/3
$\Delta s \cong -0{,}19$	0

1) Quark-'Sea' is negatively polarised

2) $\Delta\Sigma = \Delta u + \Delta d + \Delta s =$
$= 0{,}12 \pm 0{,}09 \pm 0{,}14$ — QPM: 1

Contribution of Quark Spins to Nucleon-Spin very small

$\Gamma_1^p = 0{,}126 \pm 0{,}010 \pm 0{,}015$

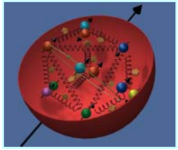
J. Ashman et al., PL B 206 (1988) 364 (1411 Cit.)

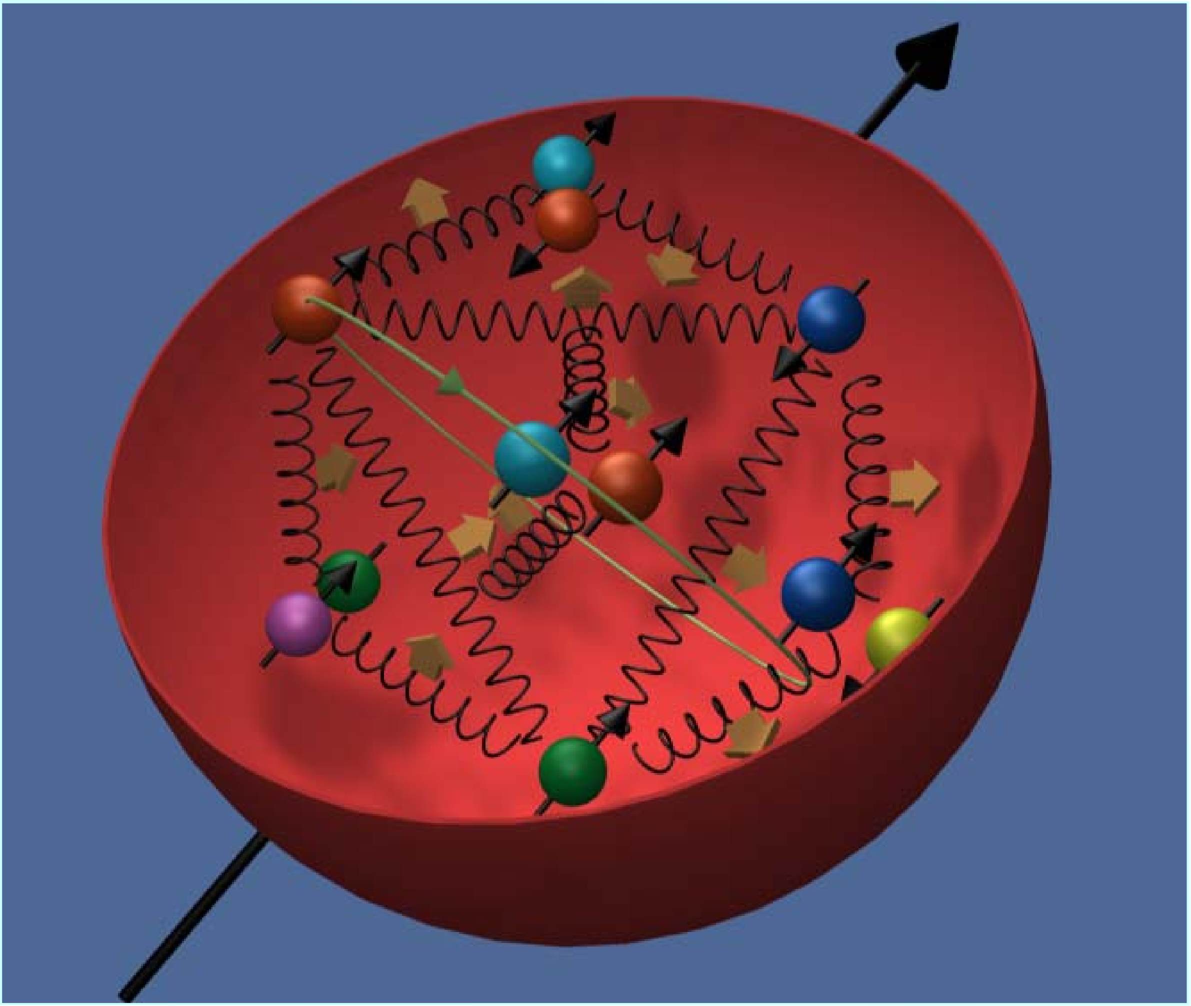
J. Ashman et al. Nucl. Phys. B 328 (1989) 1 (1212 Cit.)

Spin-'crises'

5th most cited paper in experimental accelerator based particle physics

Nucleon Spin: QCD picture





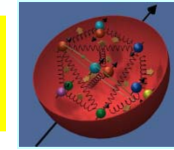
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma \text{ (Quark spins)}$$

$$+ \Delta G \text{ (Gluon spins)}$$

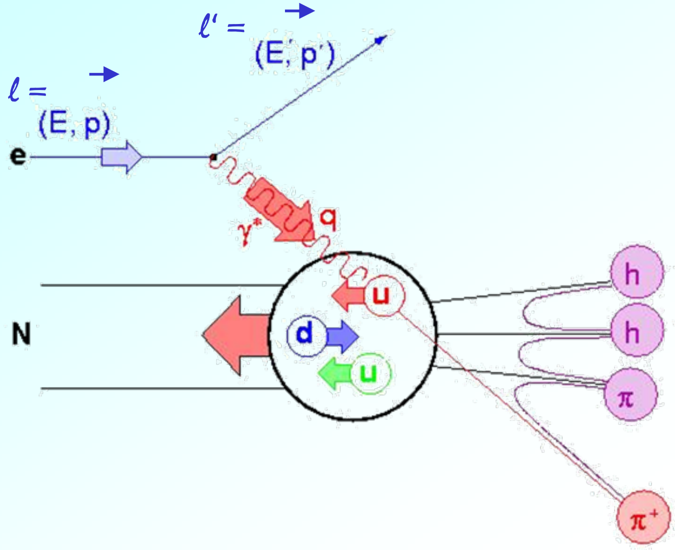
$$+ L_q + L_g$$

(Orbital angular momenta)

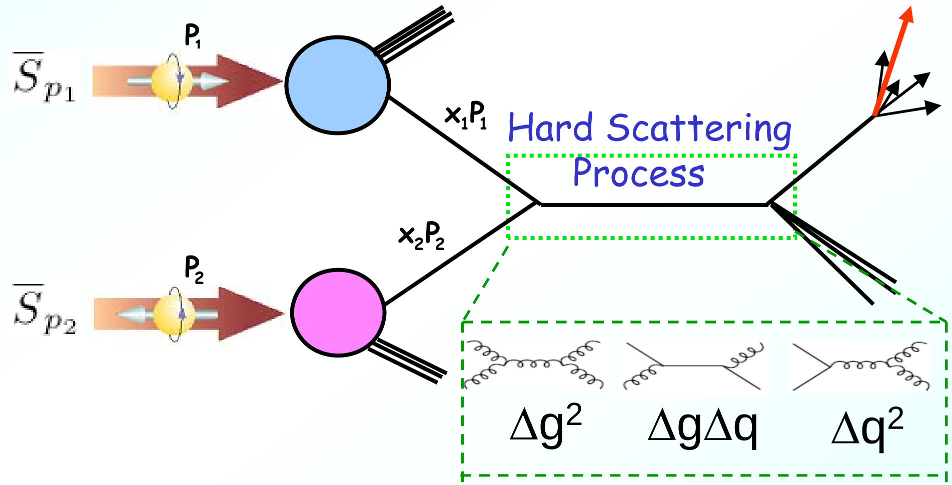
Nucleon Spin - Tools



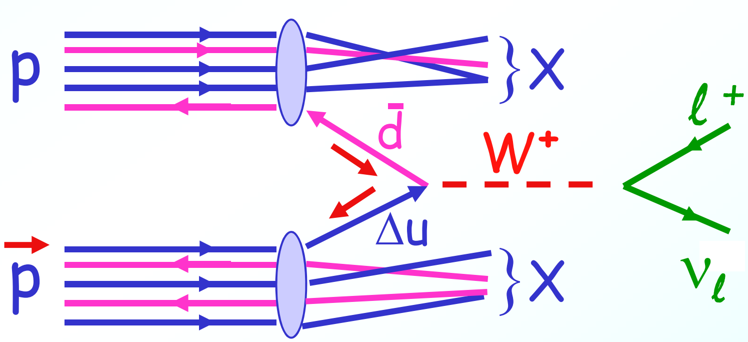
Polarised DIS



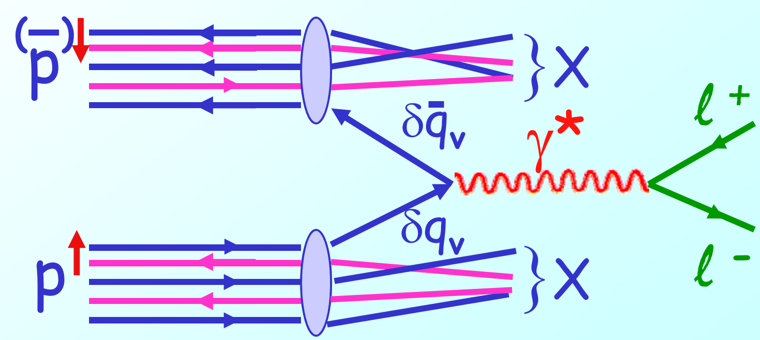
π° or jet production in pp



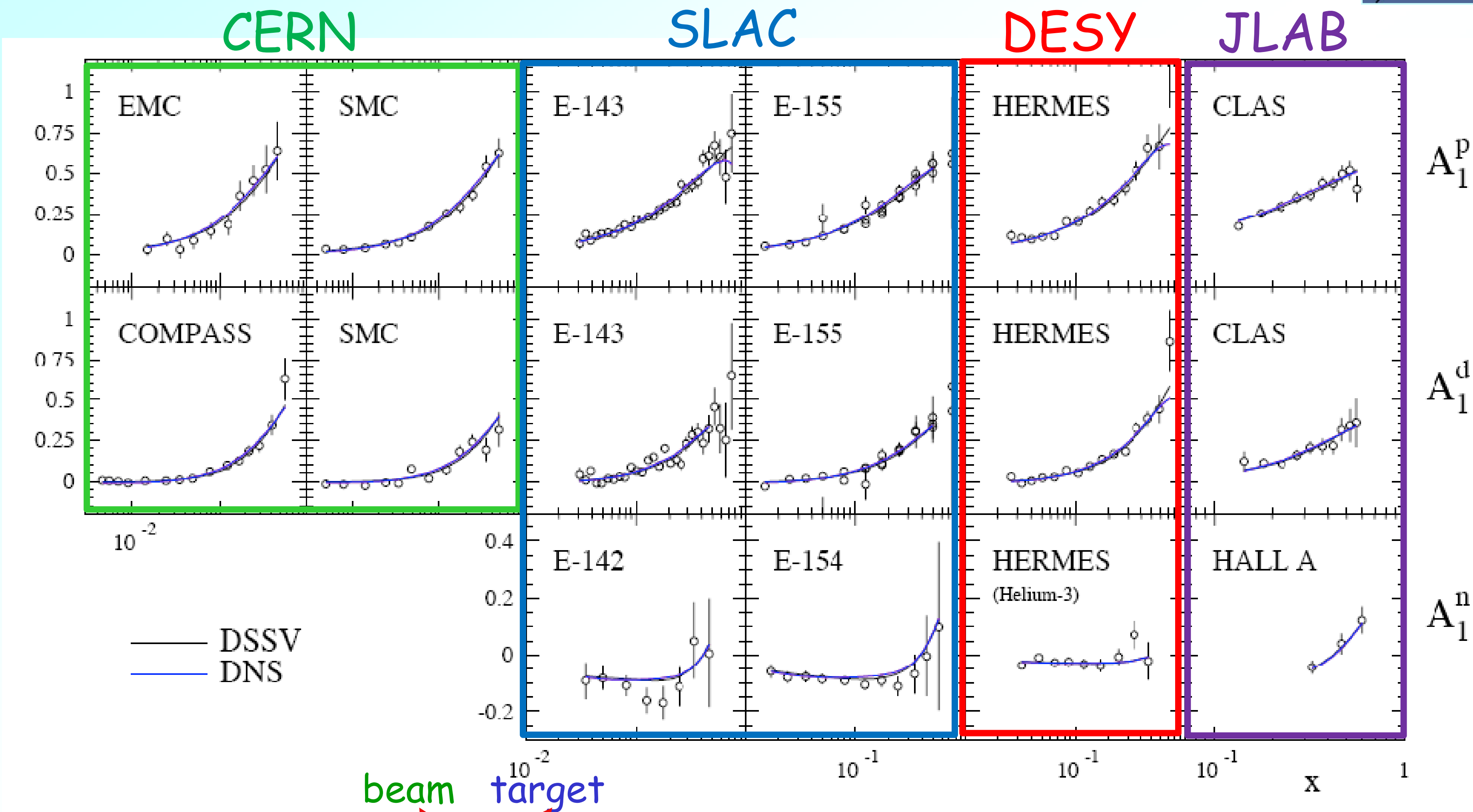
W± -production



Drell-Yan



Asymmetries in polarized DIS



From W. Vogelsang

beam target

$$A_1(x) \cong \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \stackrel{\text{L.O.}}{\cong} \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)} = \frac{g_1(x)}{F_1(x)}$$

HERMES

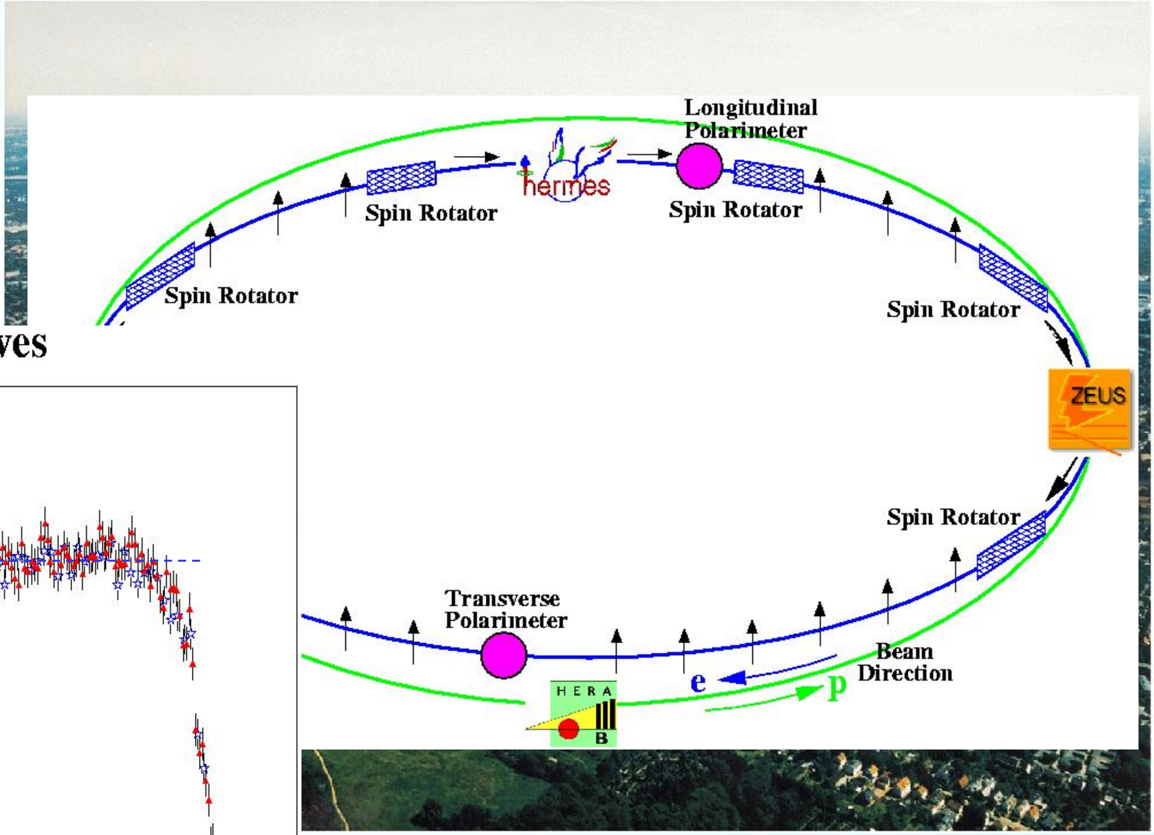
HERA MEasurement of Nucleon Spin

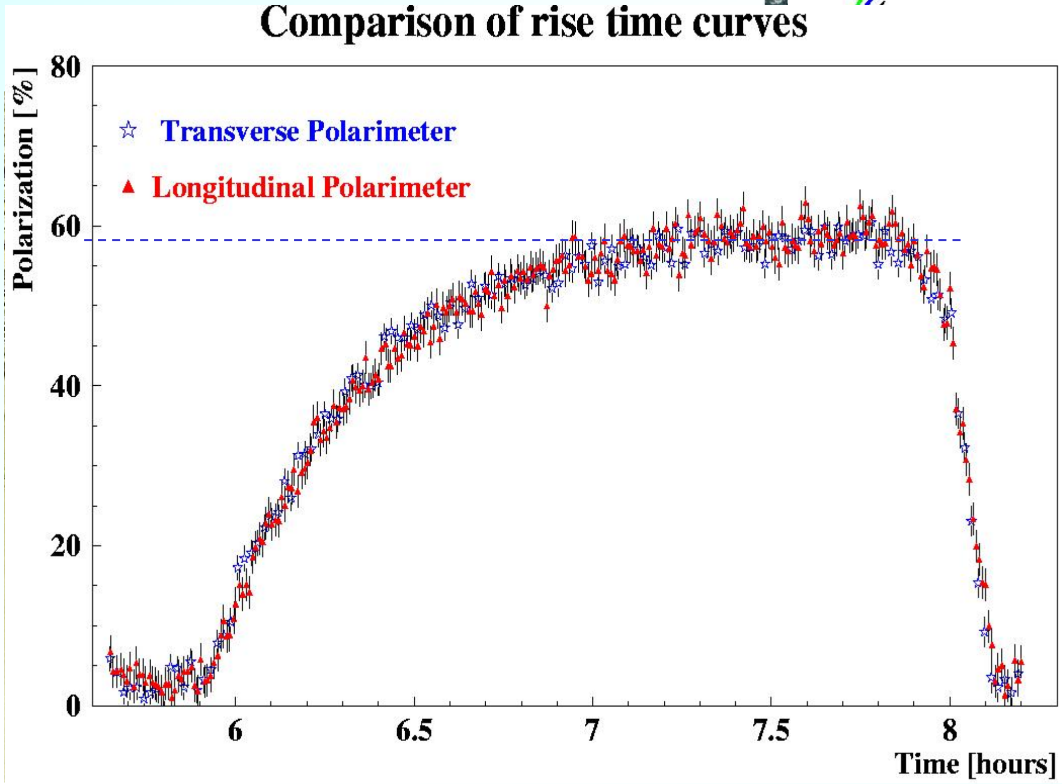
Ferrara group: 20 collaboration members in total

HERA

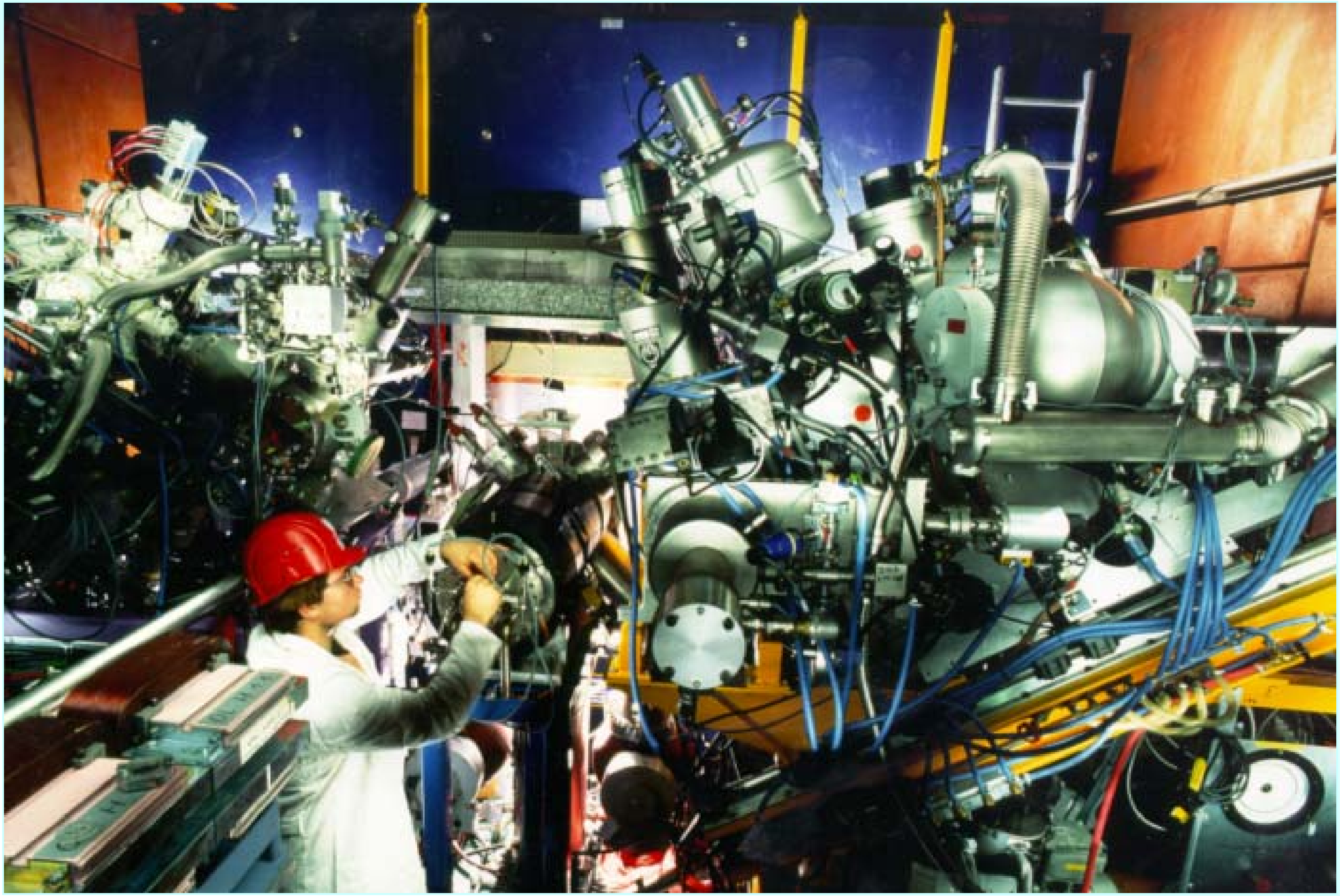
Electron beam:

E = 27.6 GeV, I_e < 50 mA

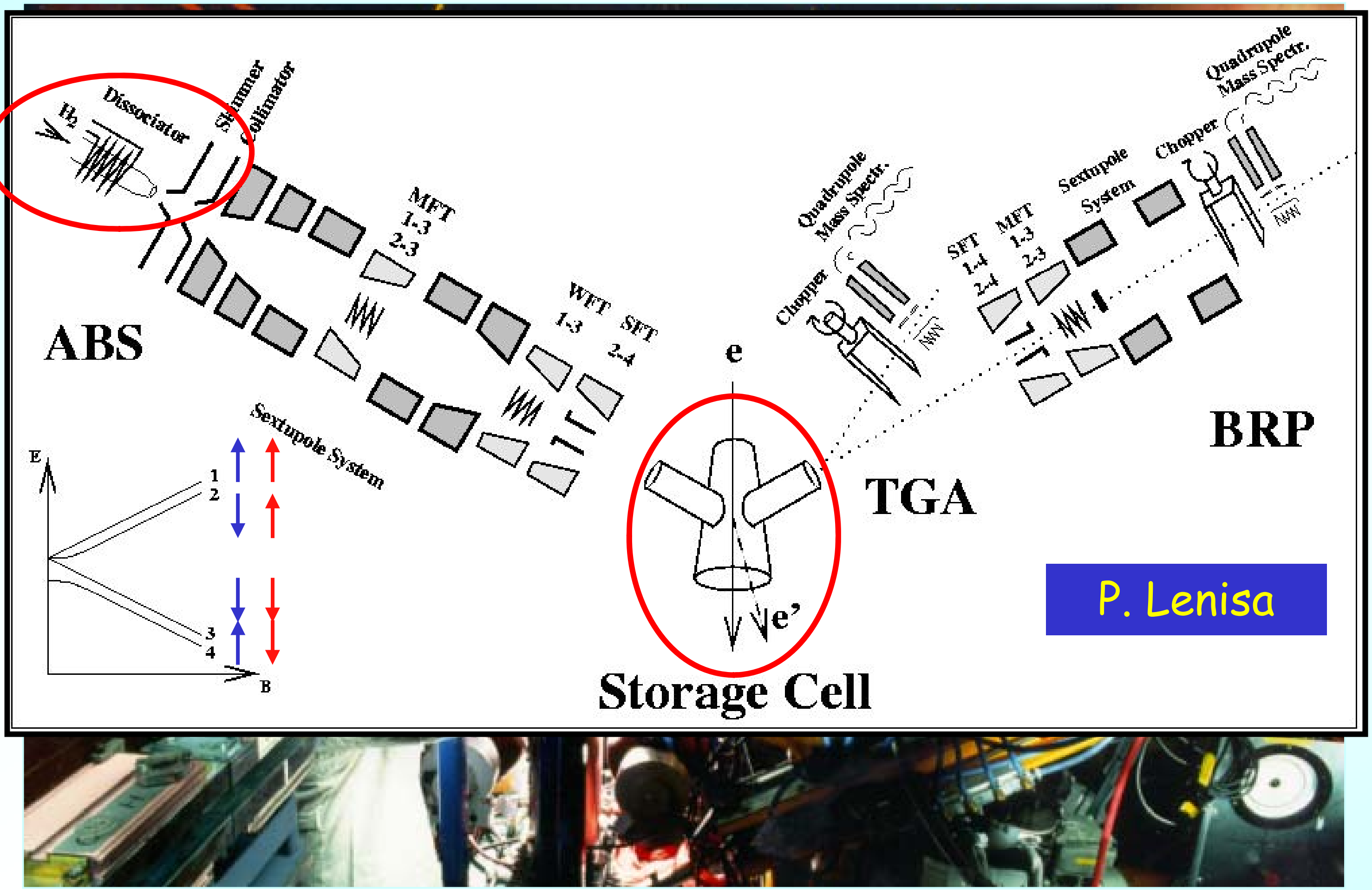




Internal polarized storage-cell gas target



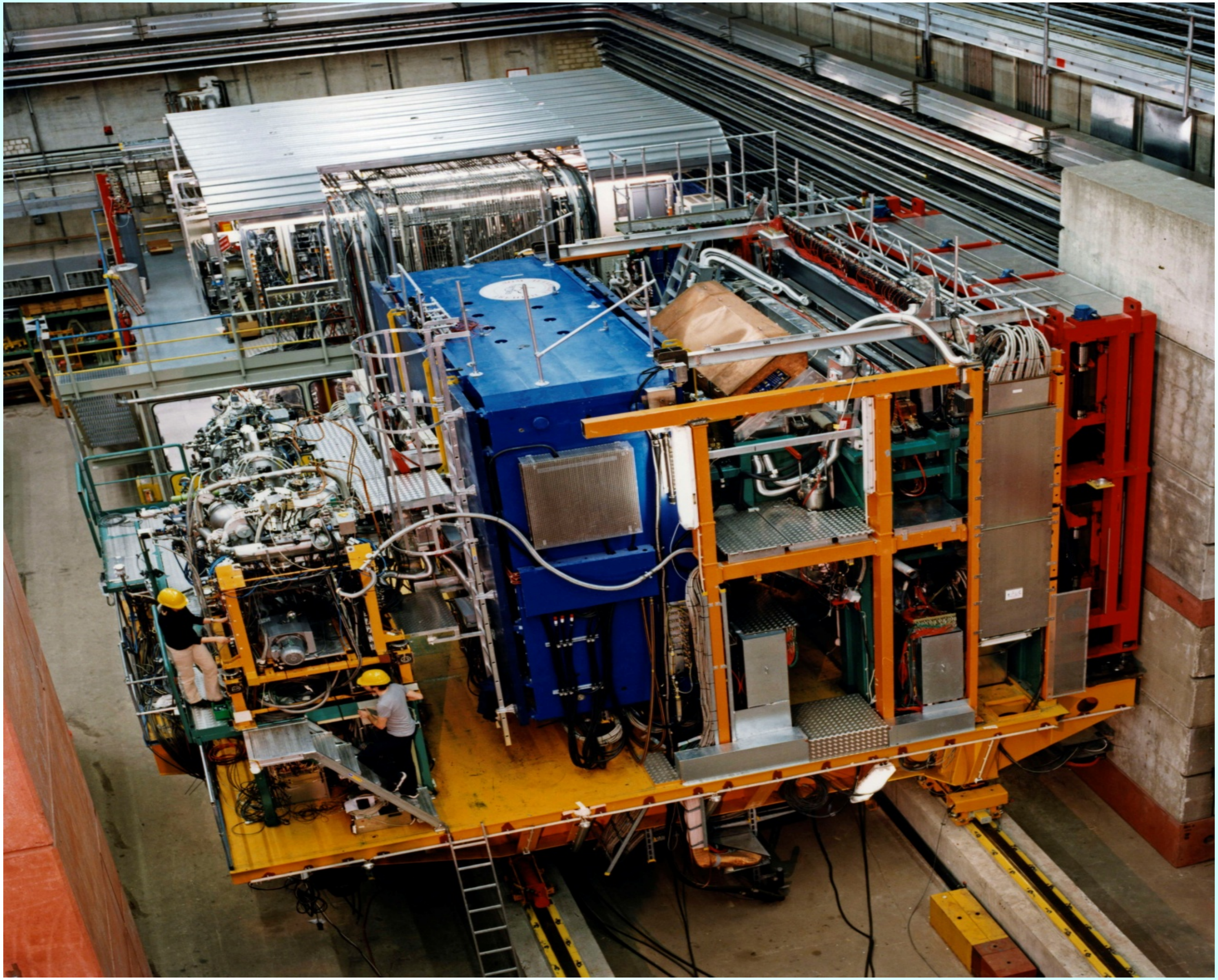
Internal polarized storage-cell gas target



Principle: Stern-Gerlach separation of HF-states + RF-transitions

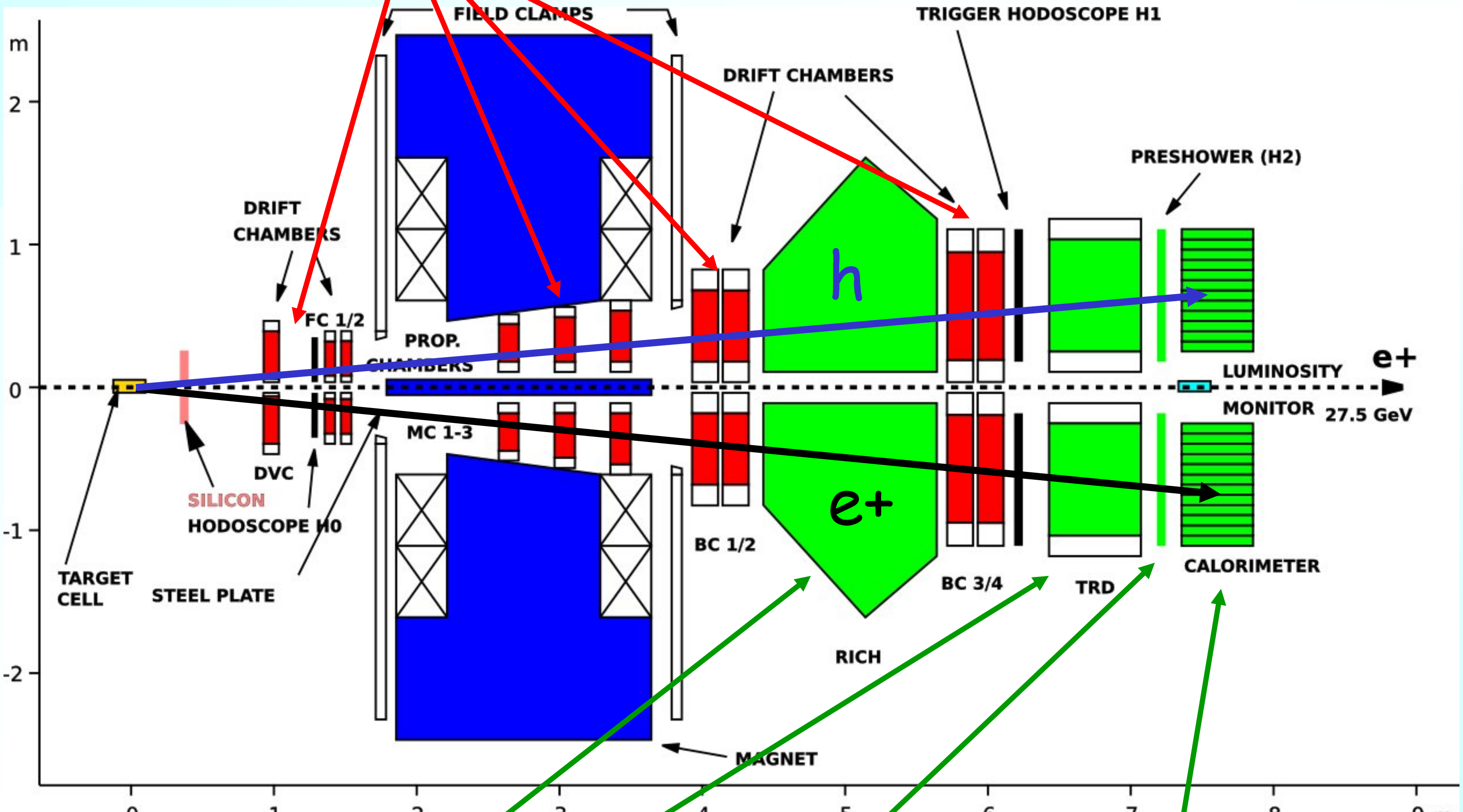
Target polarisation: $P_T \approx 0.85$, Dilution factor: f=1

HERMES Spectrometer



HERMES Spectrometer

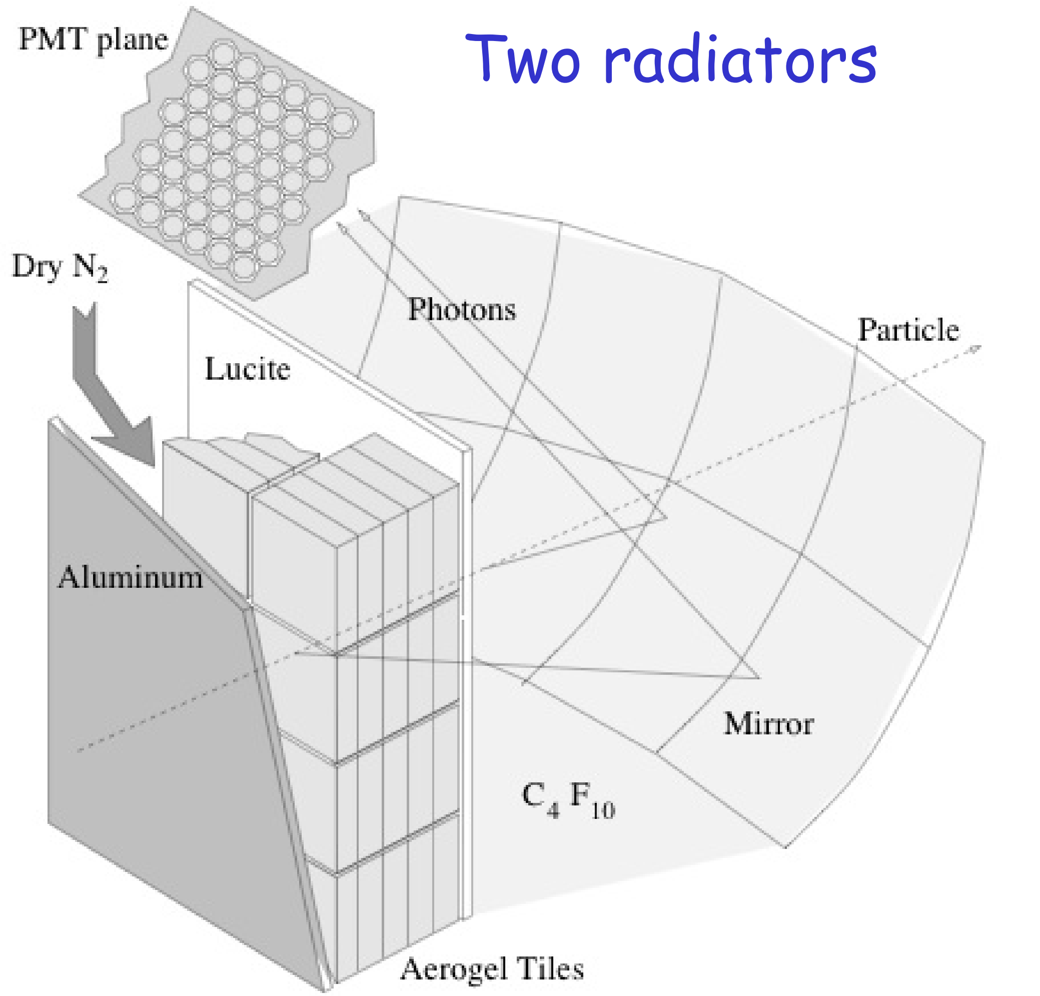
- tracking: δp/p~2%, δΘ<0.6 mrad, 40-220 mrad

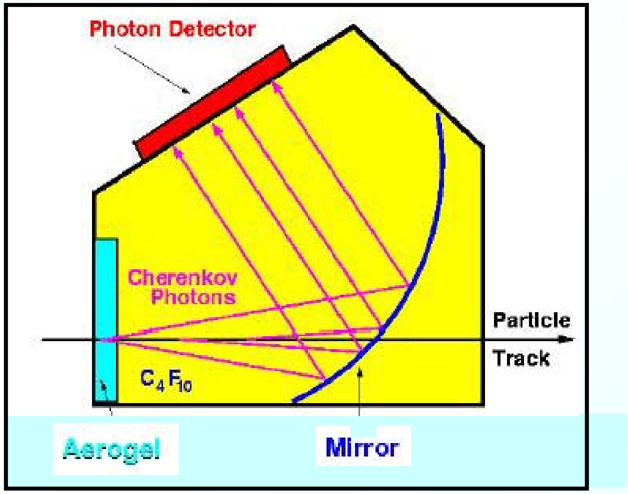


- PID: RICH, TRD, Preshower, Calorimeter
  lepton-hadron separation > 98%

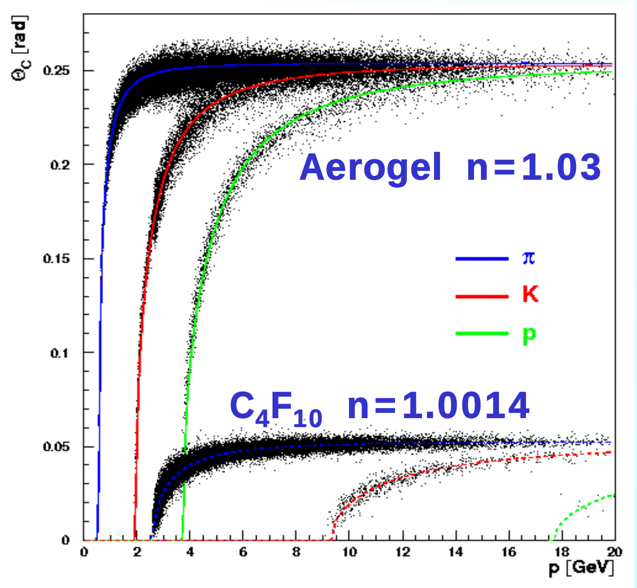
HERMES spectrometer – RICH

Two radiators





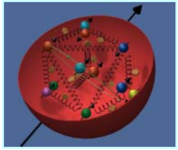
hadron separation



Hadron: π ~ 98%, K ~ 88% , P ~ 85%

hermes

Data taking



1995-2000: Longitudinal target polarisation

(1995: $^{3}\overrightarrow{He}$, 1996-97 $\overrightarrow{H}$, 1998-2000 $\overrightarrow{D}$)

+ unpolarised targets (H_2, D_2, ^{4}He, N_2, ^{20}Ne, ^{84}Kr, ^{131}Xe)

2002-2005: Transverse target polarisation ($H^{\uparrow}$)

+ unpolarised targets

2006-30/06/2007: Recoil detector (H_2, D_2)

exclusive reactions

The Asymmetry $A_1 \cong g_1/F_1$

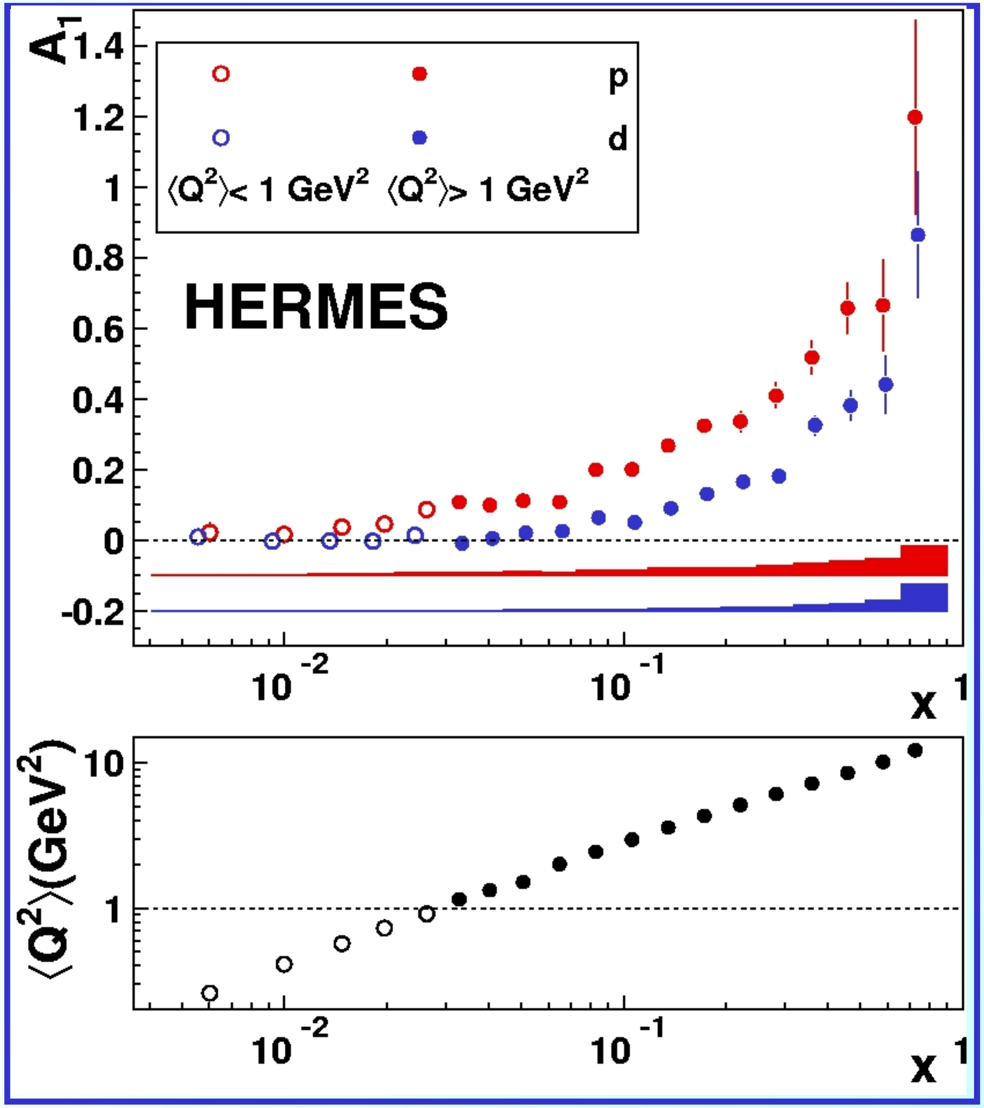
beam target

$$A_1(x) \cong \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}}$$

$$\cong \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)}$$

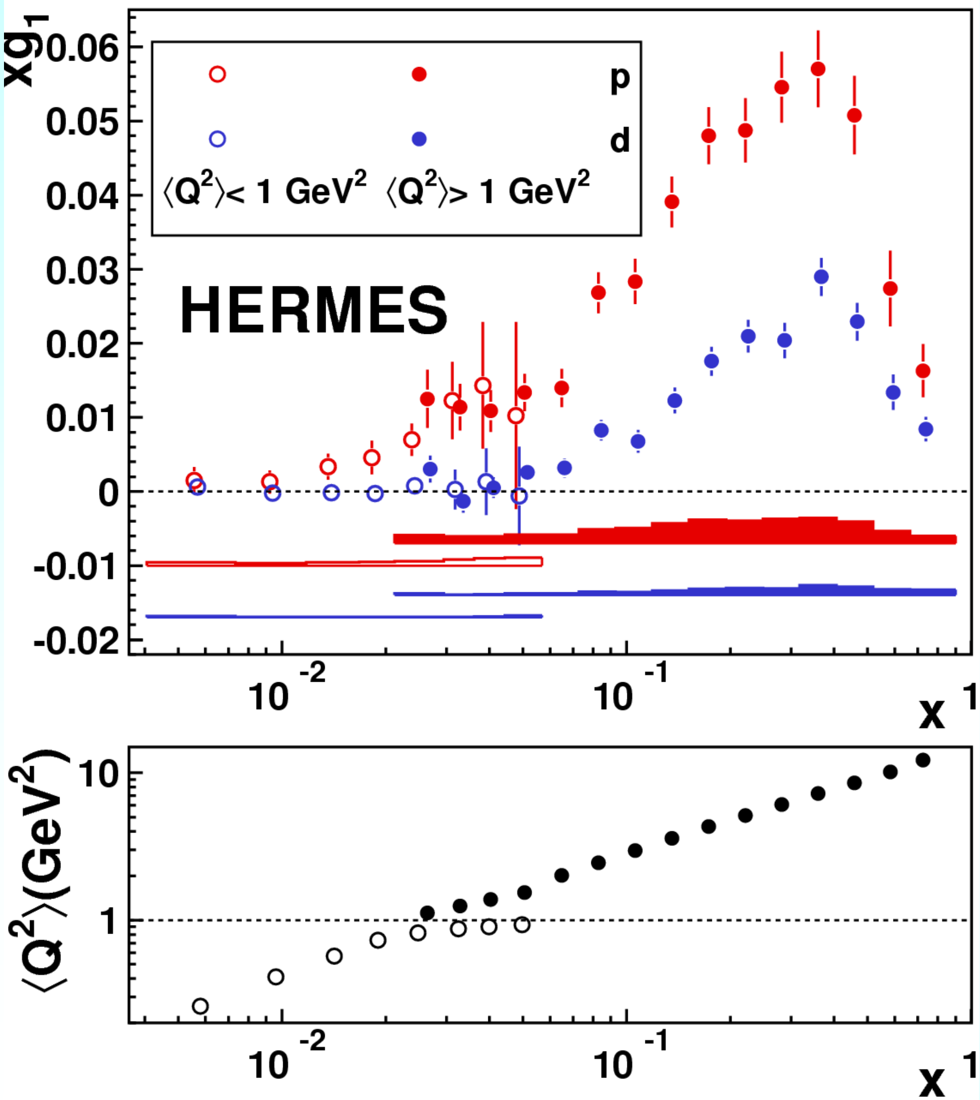
$$= \frac{g_1(x)}{F_1(x)}$$

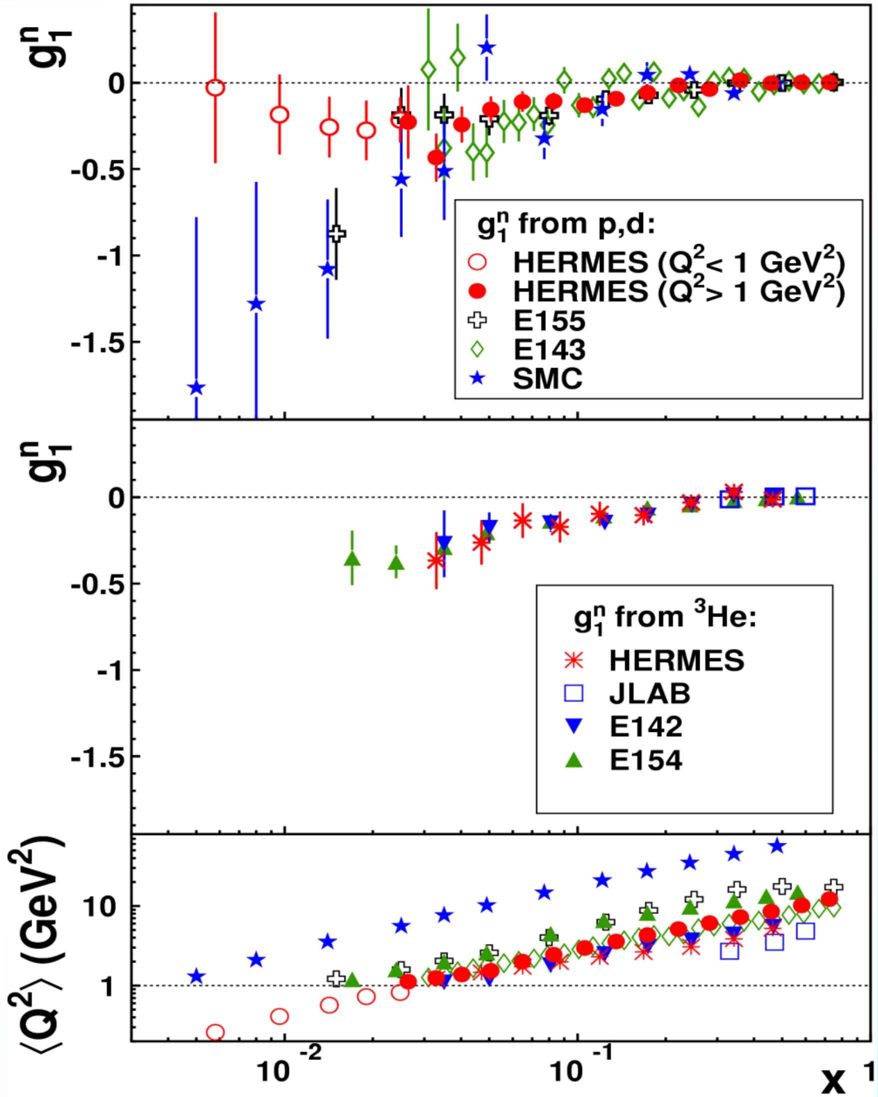
P. R. D 75 (2007) 012007



$g_1(x)$

P. R. D 75 (2007) 012007

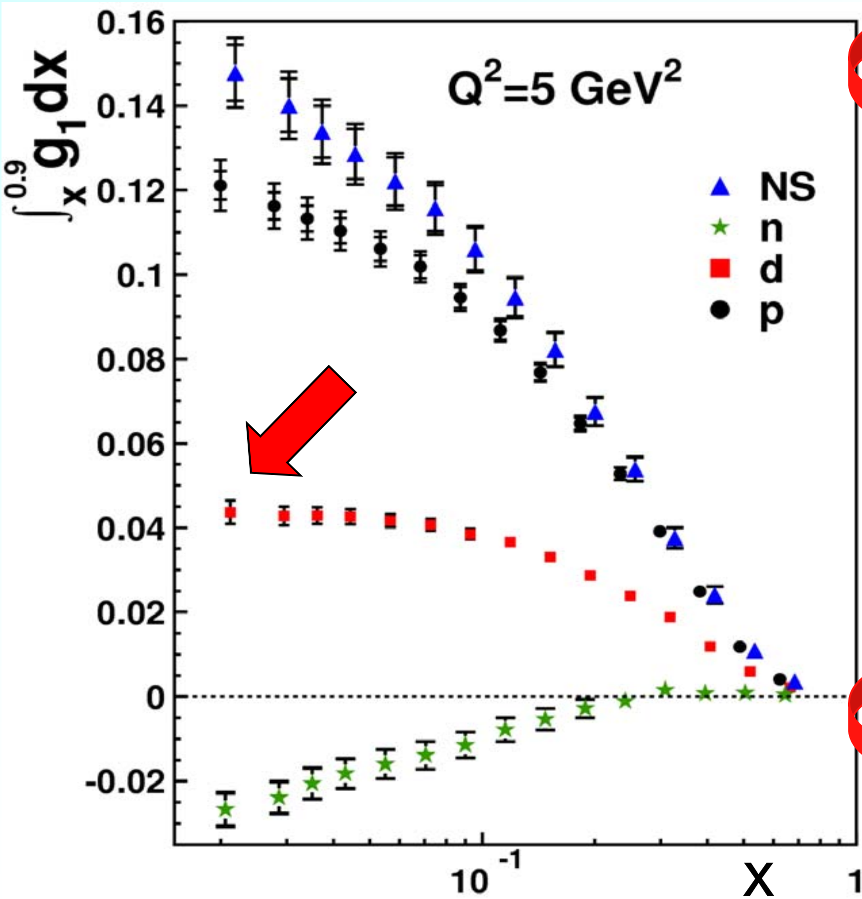




Integrals, $\Delta\Sigma$

Most precise determination of $\Delta\Sigma$

[Q^2>1 GeV^2 data only]



Assumption: Γ_1^d saturates for x<0.05

$\Gamma_1^d = 0{,}042 \pm 0{,}001^{(stat)} \pm 0{,}003^{(sys)}$

QCD

$$\Delta\Sigma = \frac{1}{\Delta C_S}\left[\frac{9\Gamma_1^d}{(1-\frac{3}{2}\omega_D)} - \frac{1}{4}\, a_8\, \Delta C_{NS}\right]$$

D-state probability in deuteron wave function

SU(3)

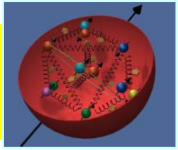
$\overline{\text{MS}}$ (exp) (theory) (evol.)

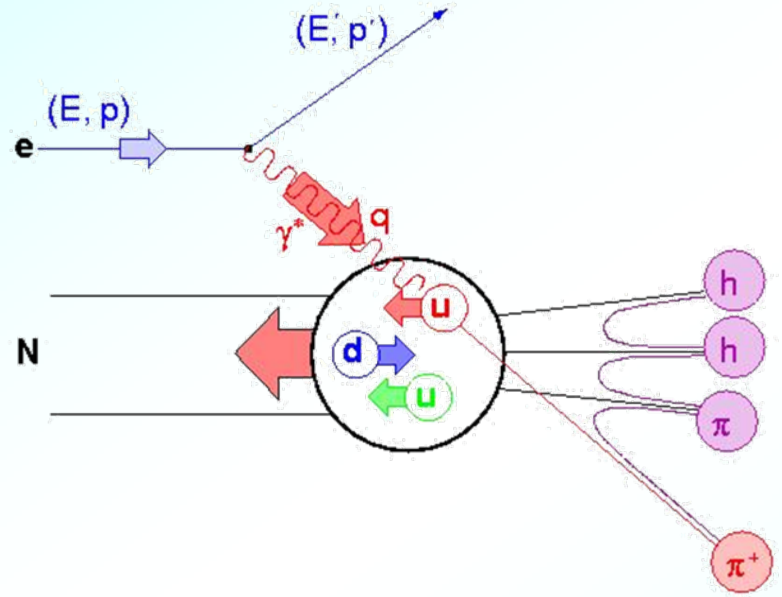
$\Delta\Sigma = 0{,}330 \pm 0{,}025 \pm 0{,}011 \pm 0{,}028$

EMC: $\Delta\Sigma = 0{,}12 \pm 0{,}09 \pm 0{,}14$

M. Contalbrigo

Quark helicity distributions from SIDIS





Leading hadron originates with large probability from struck quark

$D_q^h(z)$:= Fragmentation function (FF)

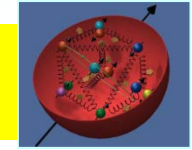
$z = E_h/\nu$

Measure hadron asymmetries

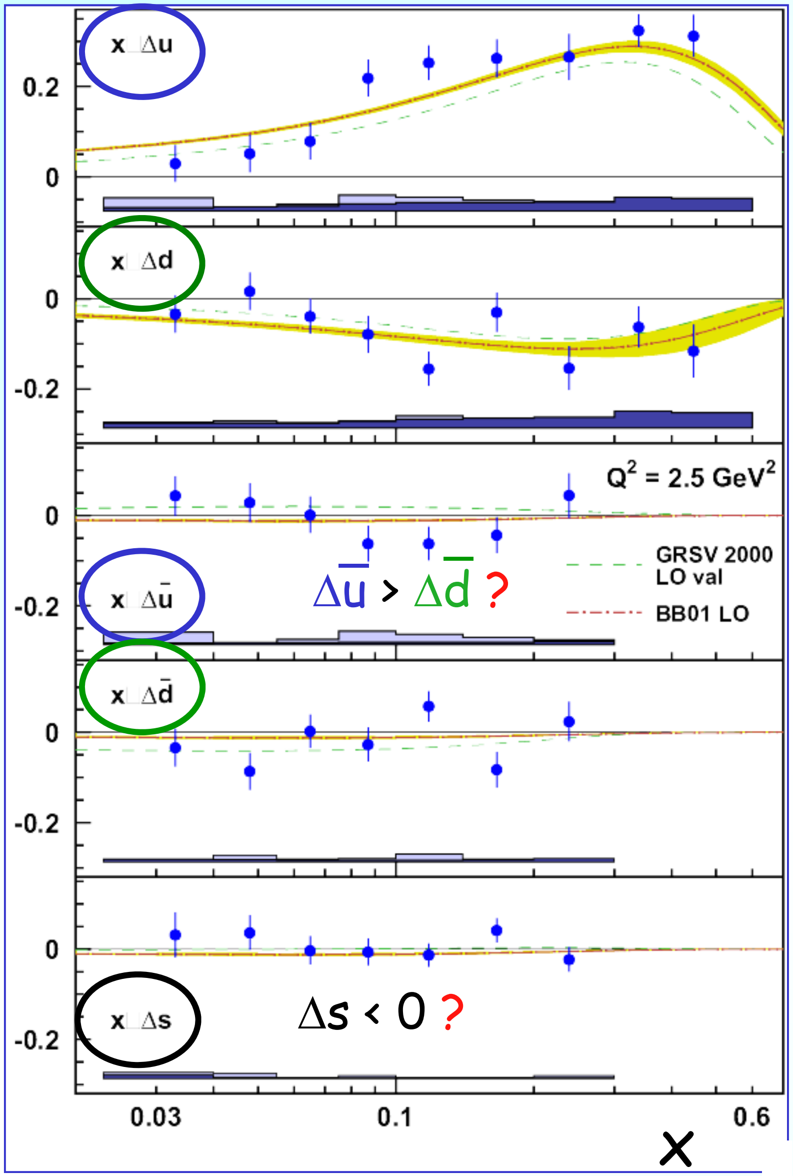
$$A_1^h(x,z) = \frac{\sum_q z_q^2 \Delta q(x) D_q^h(z)}{\sum_q z_q^2 q(x) D_q^h(z)}$$

Targets: $\vec{H}$, $\vec{D}$; $h = \pi^\pm, K^\pm, p$

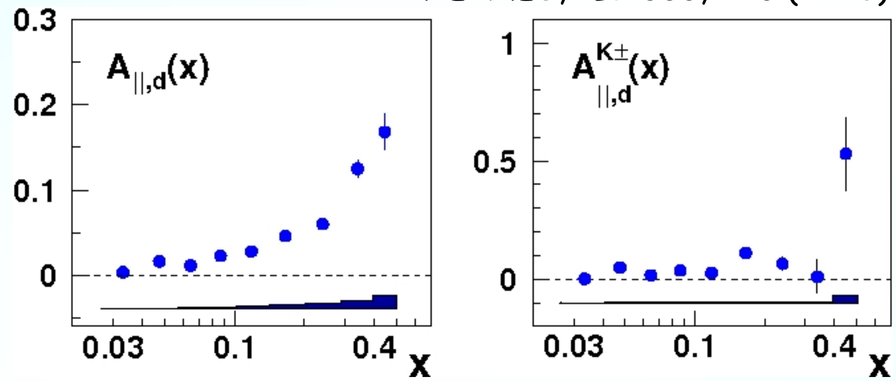
Quark helicity distributions

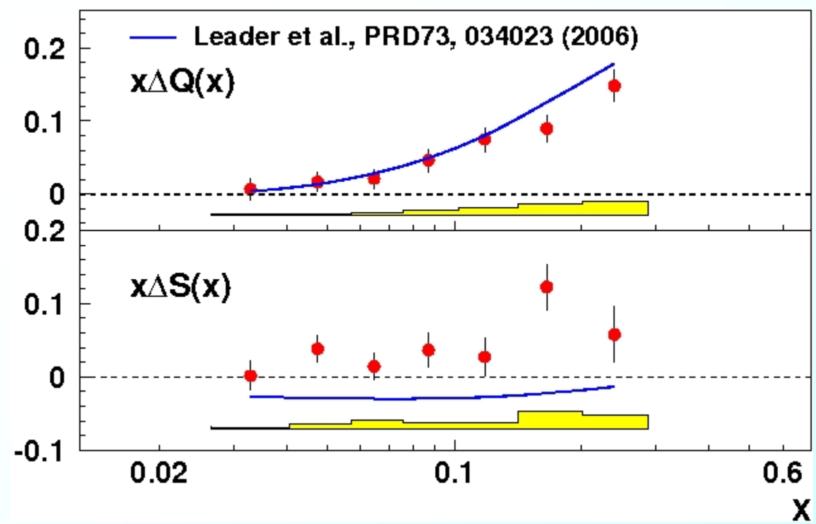


HERMES, PRL 92 (2004) 012005, PRD 71 (2005) 012003



HERMES, PLB 666, 446 (2008)



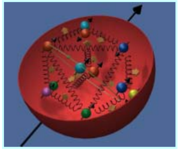


$\Delta S = 0.037 \pm 0.019(\text{stat.}) \pm 0.027(\text{syst.})$

(inclusive data and SU(3):

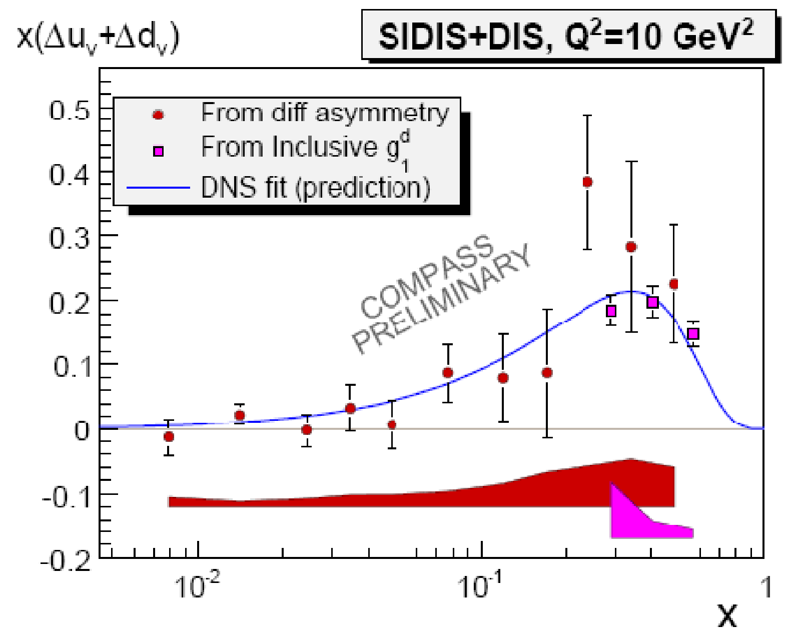
$\Delta S = -\,0.085 \pm 0.013(\text{stat.}) \pm 0.012(\text{syst.})$)

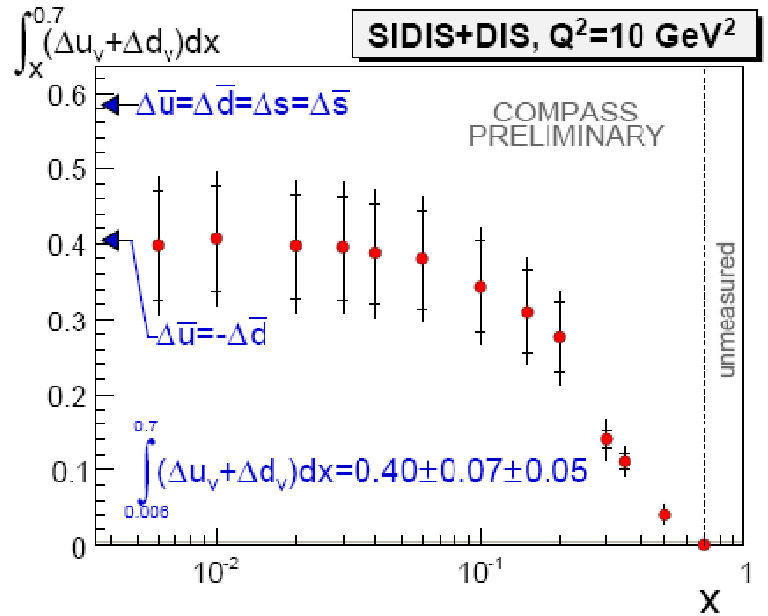
Valence-quark helicity distributions



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

COMPASS, PLB 660 (2008) 458





$$\Delta\bar{u} + \Delta\bar{d} = 3\Gamma_1^N - \tfrac{1}{2}\Gamma_1^V + a_8/12$$

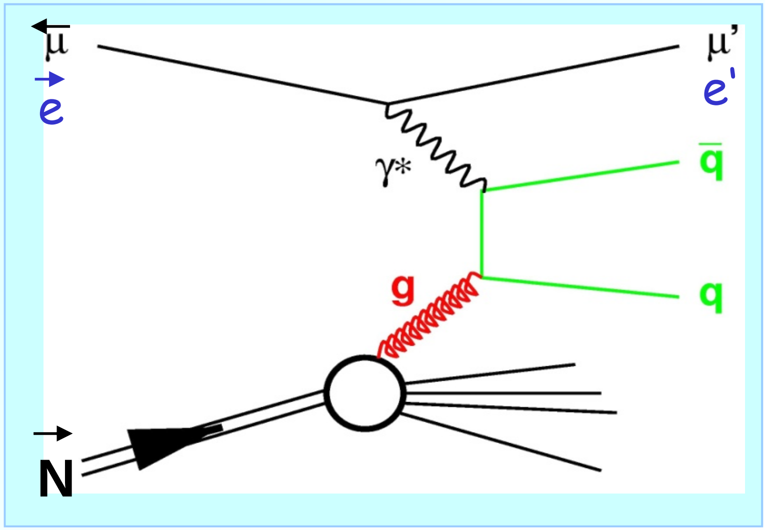
Flavor asymmetric polarized sea ($\Delta\bar{u} = -\Delta\bar{d}$) favoured

Gluon helicity distribution

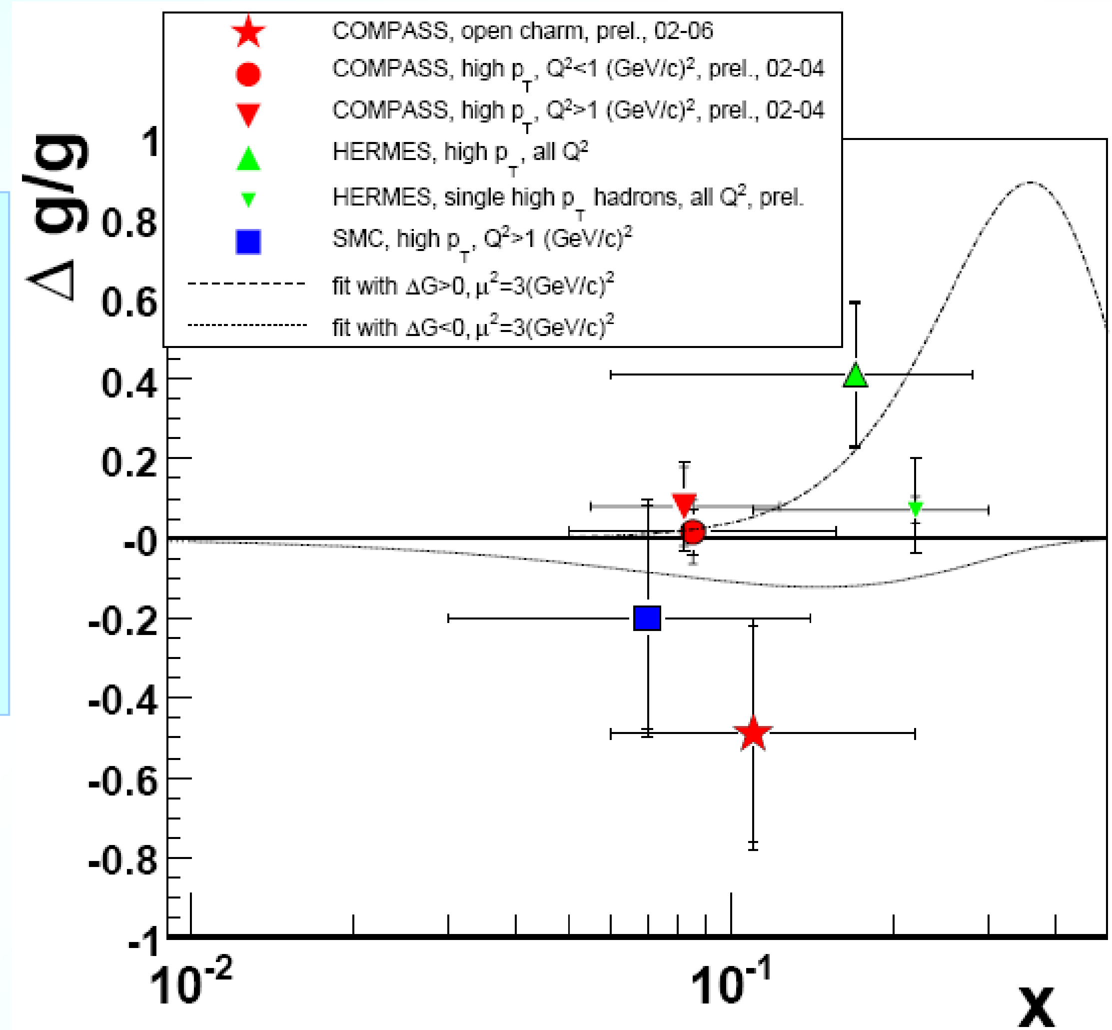
$\Delta g(x)$

Gluon helicity distribution

Photon-gluon fusion



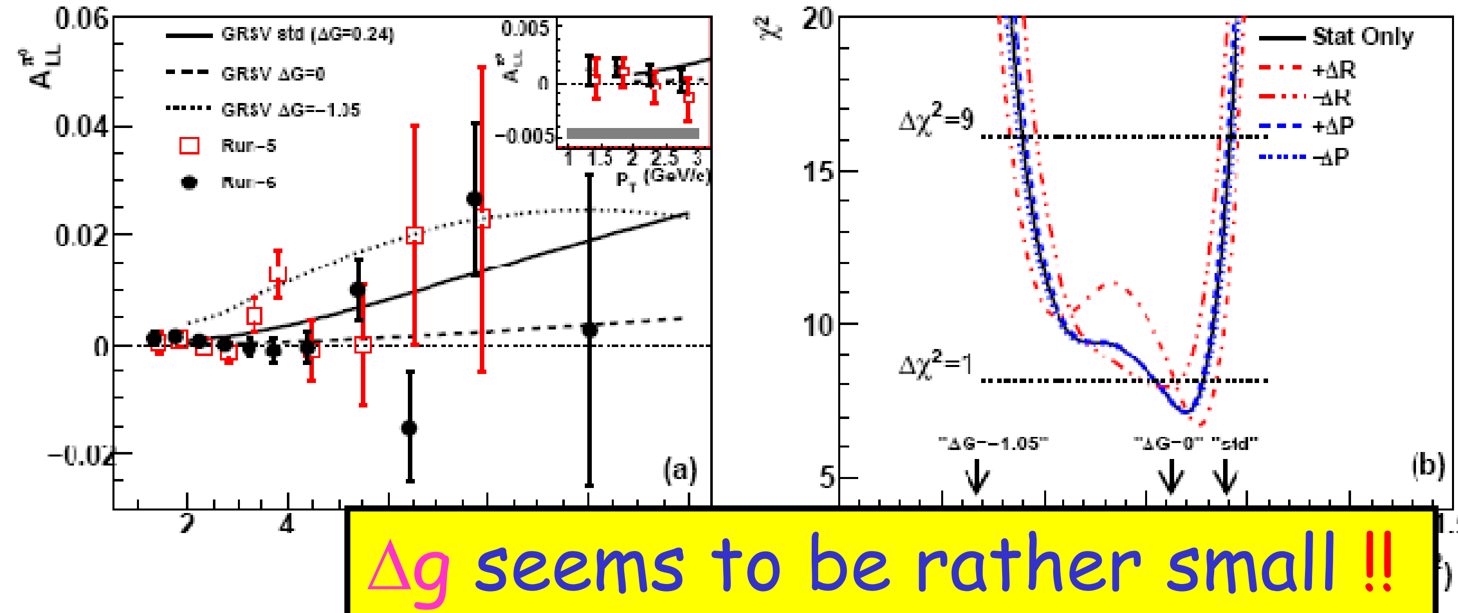
- Charm production
- Hadrons with high pt



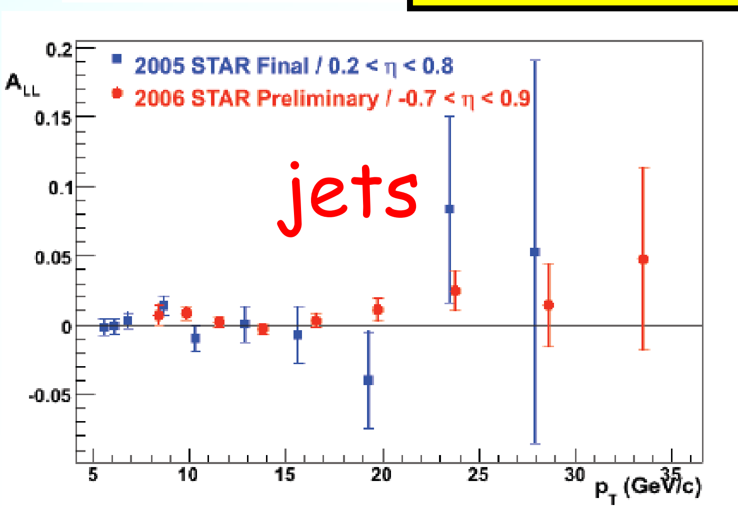
L.O. analyses

ΔG from $\vec{p}\vec{p} \rightarrow \pi^0$ (jet) X

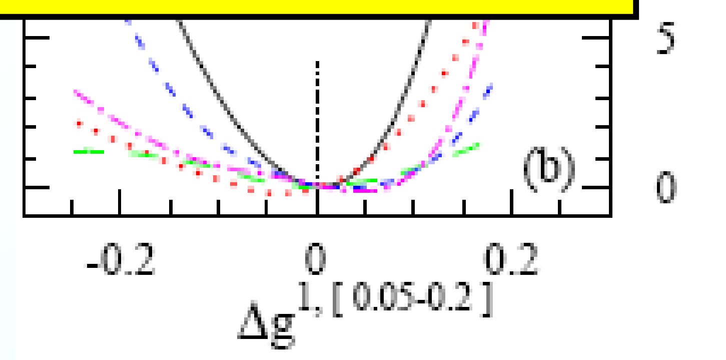
A. Adare et al. (PHENIX); arXiv:0810.0694



Δg seems to be rather small !!

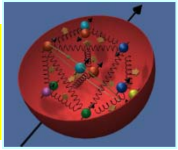


jets



NLO analysis (without data from previous slide)

Spin budget



- Origin of nucleon spin still unclear:

  Where do the missing 65% come from?
  X. Ji: ‚Dark Spin'

- Is there a substantial contribution of Δg and/or $\Delta\bar{q}$ at very low x?

  ➡ EIC

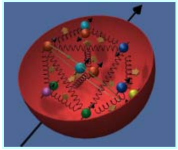
- What is the contribution of orbital angular momenta

  L_q, L_g ???

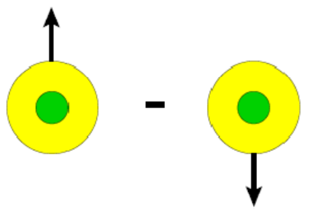
Quark orbital angular momentum

L_q

The Sivers distribution function f_{1T}

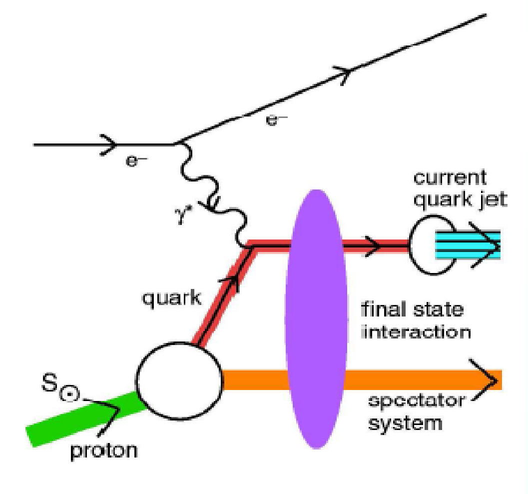


- Describes correlation between intrinsic quark p_T and transverse nucleon spin



- $f_{1T}^{\perp q}(p_T^2)$ describes probability to find an unpolarised quark with transverse momentum in a transversely polarised nucleon

Chiral – even & naïve T - odd

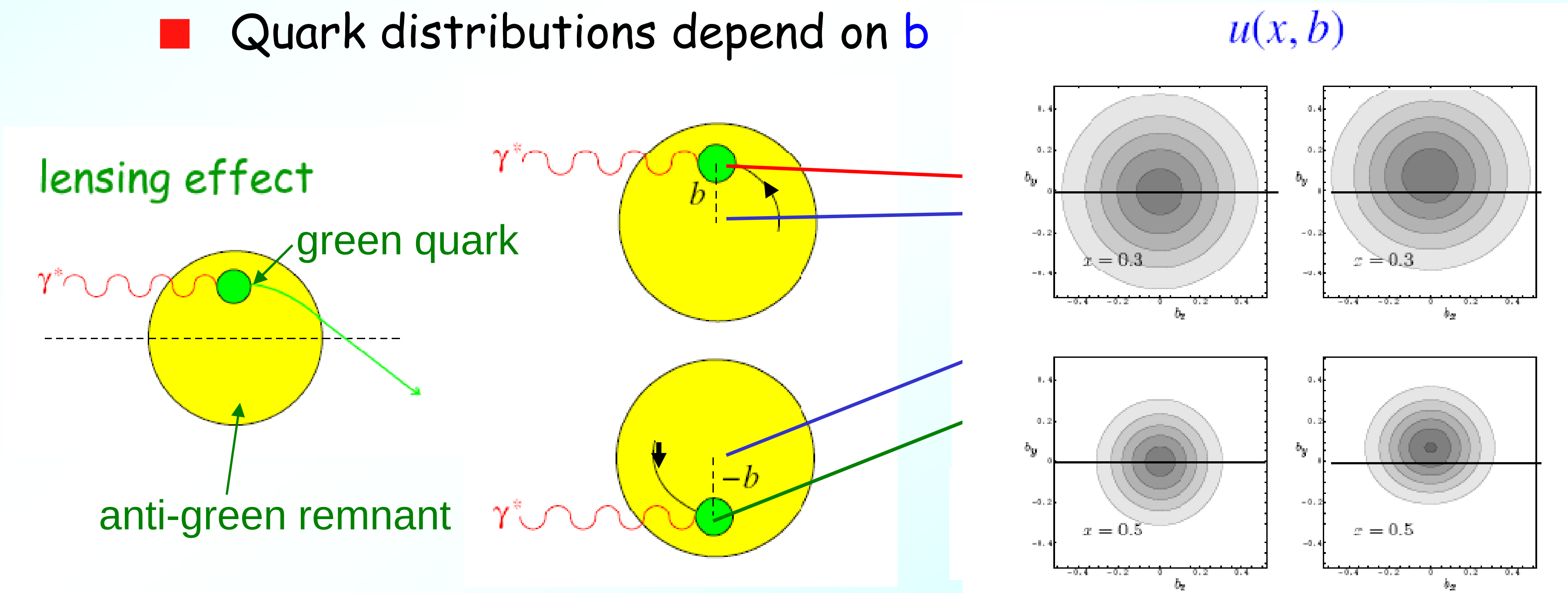


requires a quark rescattering via soft gluon exchange (gauge link) (Brodsky, Hwang, Schmidt)

- Non-zero Sivers DF requires non-vanishing orbital angular momentum in the nucleon wave function

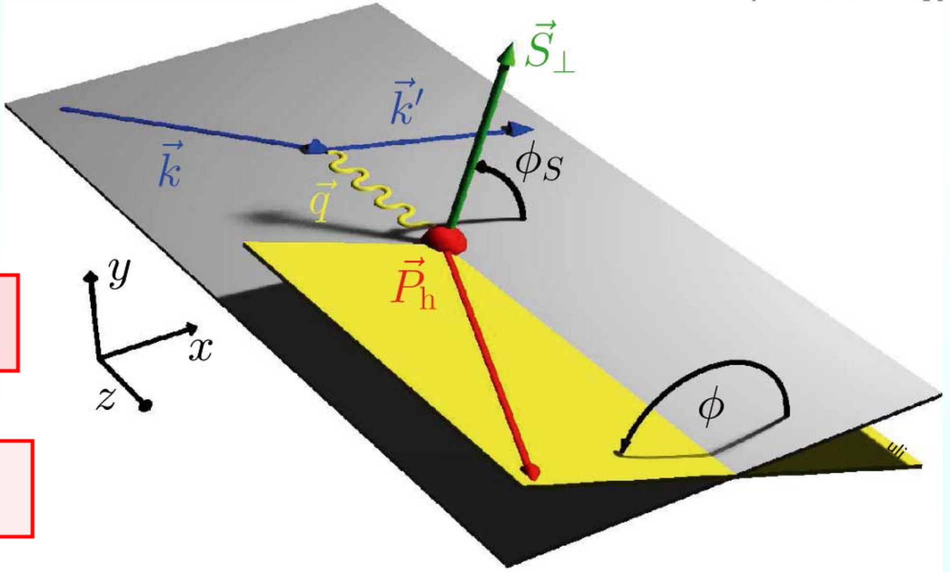
The Sivers effect

- Attractive FSI deflects quark inwards
- Left-right distribution asymmetry is converted into right-left momentum asymmetry
- Impact parameter formalism (M. Burkardt hep-ph/030926)
  - Orbital angular momentum of quarks
    - ➡ Virtual photon sees different x for different b
  - Quark distributions depend on b



Azimuthal angular distributions

Amplitude has 2 components:



Transversity DF

$2\langle\sin(\phi + \phi_S)\rangle^h_{UT} \sim \delta q(x) \cdot H_1^{\perp q}(z)$

Collins Fragmentation Function

U: unpol. e±-beam
T: transv. pol. Target
$z = E_h/\nu$

Unpolarised FF

$2\langle\sin(\phi - \phi_S)\rangle^h_{UT} \sim f_{1T}^{\perp q}(x) \cdot D_1^q(z)$

Sivers DF

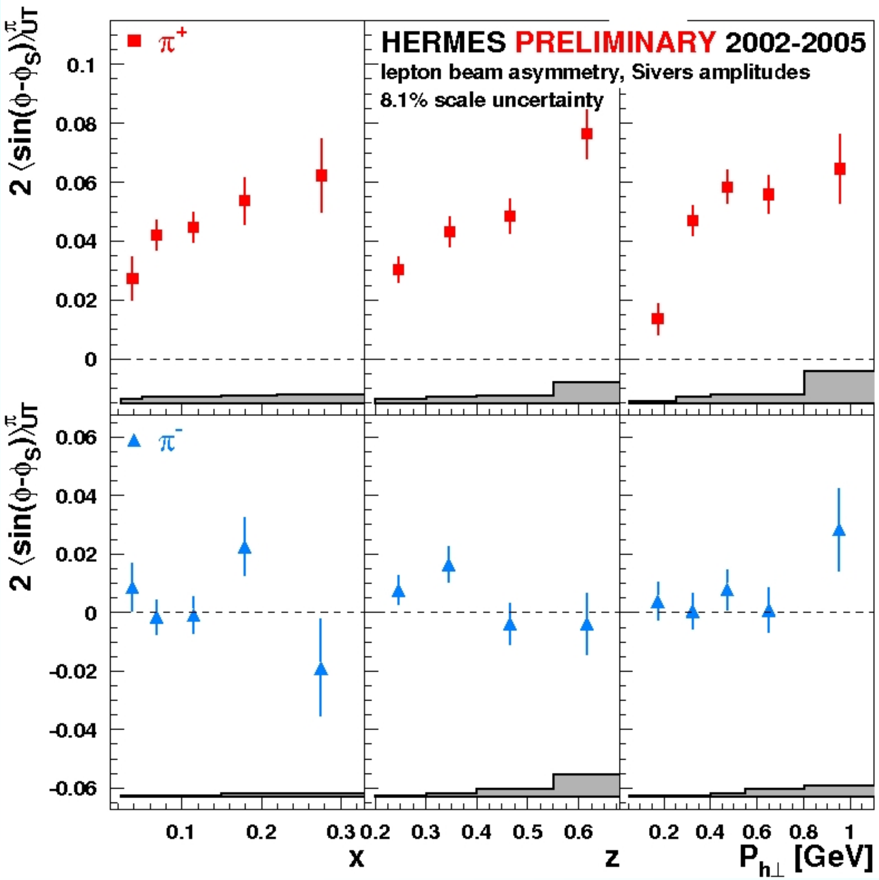
(Requires non-vanishing orbital angular momenta L_q of quarks)

Sivers amplitudes (p)

$$2\langle \sin(\phi - \phi_S)\rangle^{h}_{UT} \sim f_{1T}^{\perp q}(x) \otimes D_1^q(z)$$

M. Diefenthaler @ DIS07, hep-ex 0706.2242

(also HERMES, P. R. L. 94 (2005) 012002)



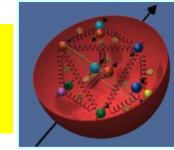
- First observation of non-zero Sivers distribution function in DIS

→ Experimental evidence for orbital angular momentum L_q of quarks

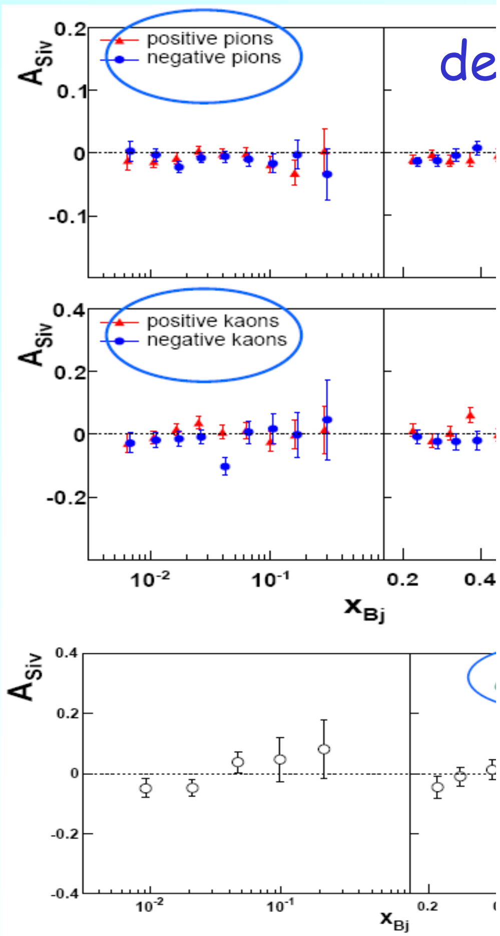
But: Quantitative contribution of L_q to nucleon spin still unclear

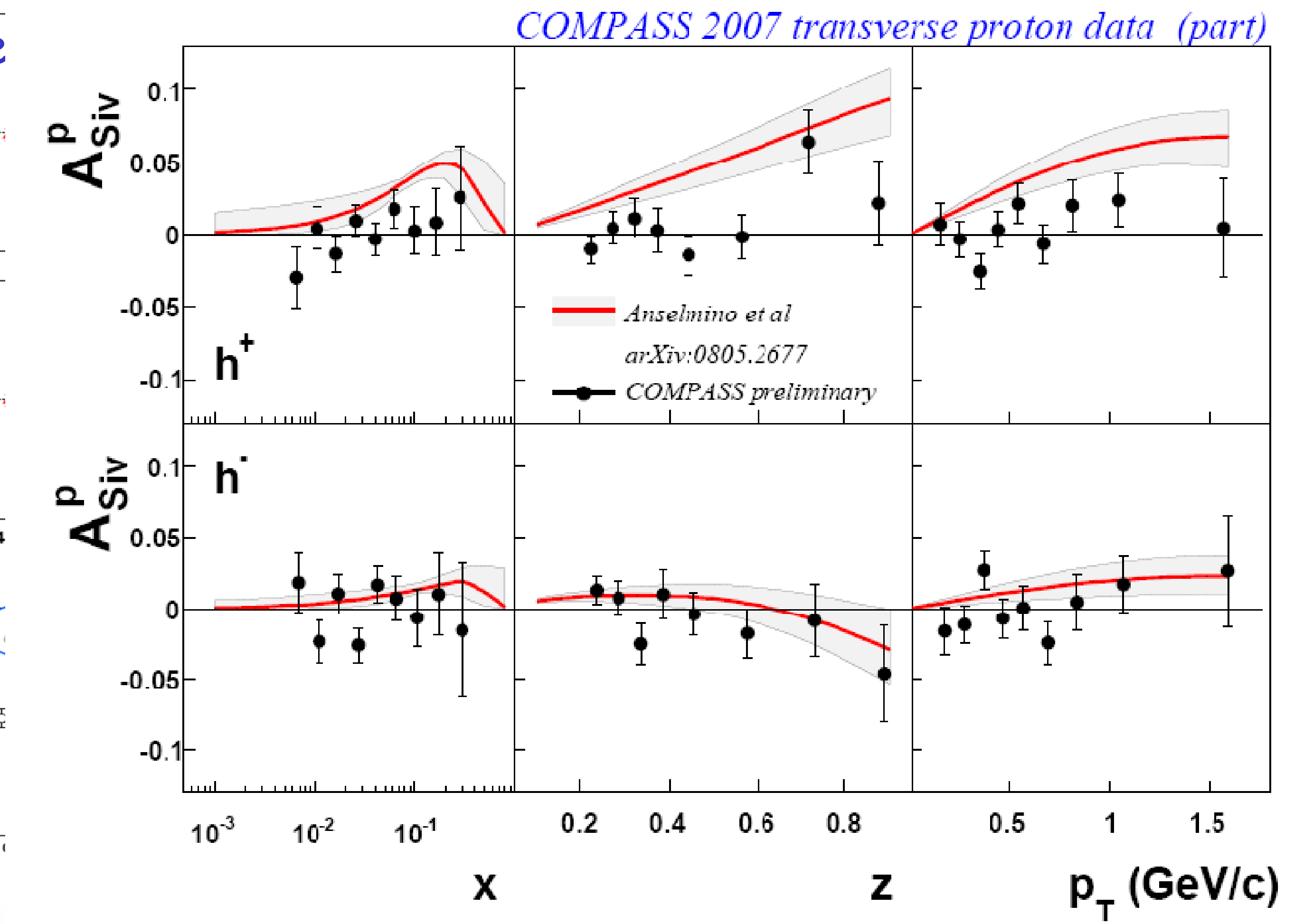
L. Pappalardo

Sivers ampl. (d +p)



COMPASS, hep-ex/0802.2160

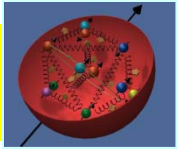




Compatible with zero

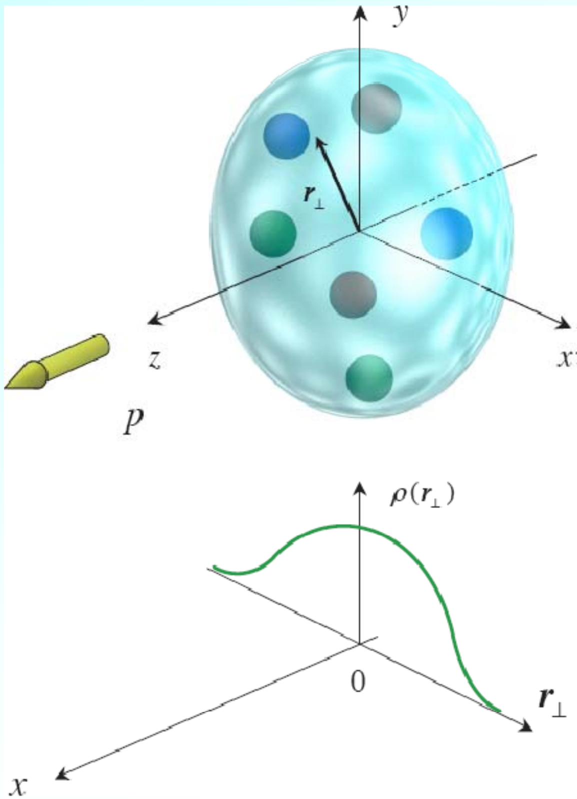
Still compatible with zero

Determination of L_q - GPDs



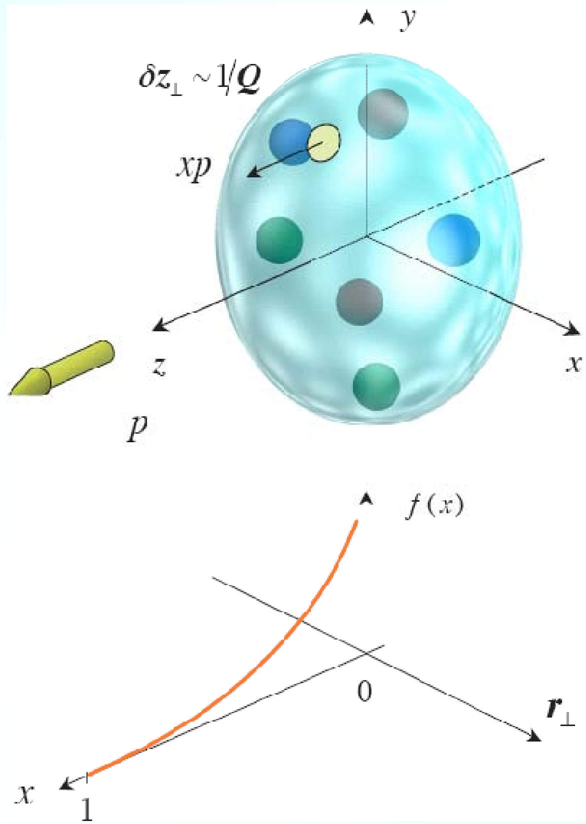
Tool: Generalised Parton Distributions

Formfactors:



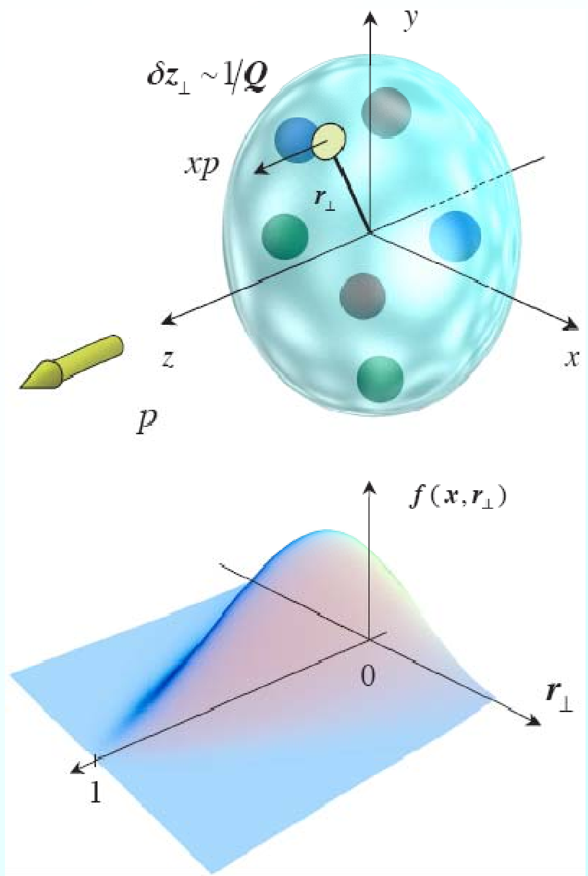
Fouriertransform of e.g. a radial charge distribution

PDFs:



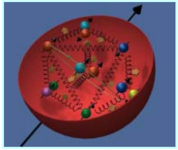
Number density of quarks with longitudinal momentum fraction x

GPDs:



Generalised description in 2+ 1 dimensions

Determination of L_q

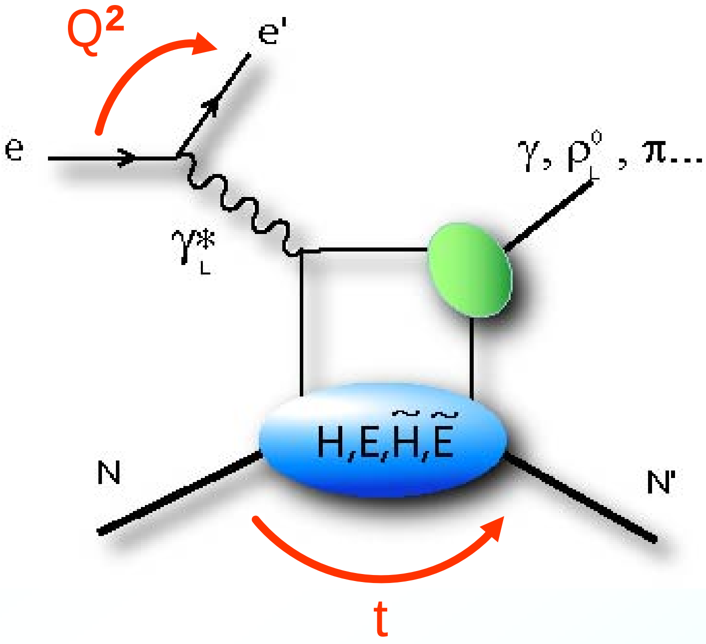


Ji relation:

$$J_q = 1/2\Delta\Sigma + L_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x\, [H(x,\zeta,t) + E(x,\zeta,t)]$$

$H(x,\zeta,t)$, $E(x,\zeta,t)$: Generalised Parton Distributions (GPDs)

Access: *exclusive processes*

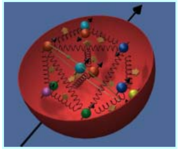


Final state sensitive to different GPDs

Vector mesons (ρ, ω, ϕ) H, E

Pseudoscalar mesons(π,η) $\tilde{H}$, $\tilde{E}$

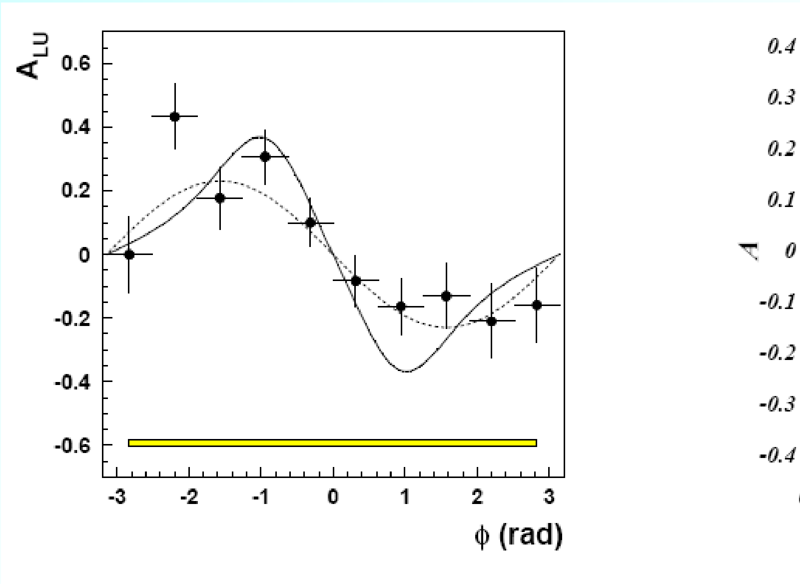
DVCS (γ) H, E, $\tilde{H}$, $\tilde{E}$



Azimuthal asymmetries

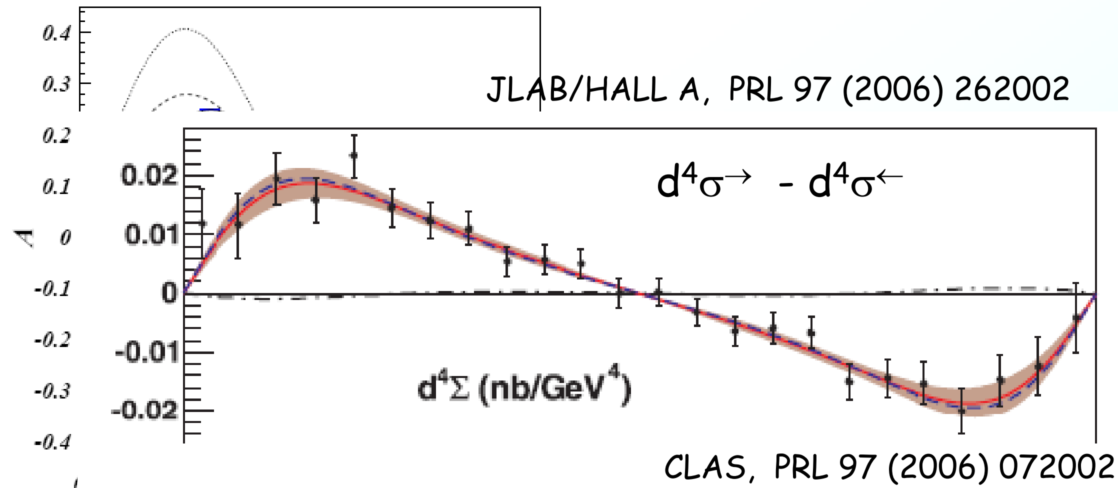
DVCS: Beam-spin asymmetry

HERMES, PRL 87 (2001) 182001

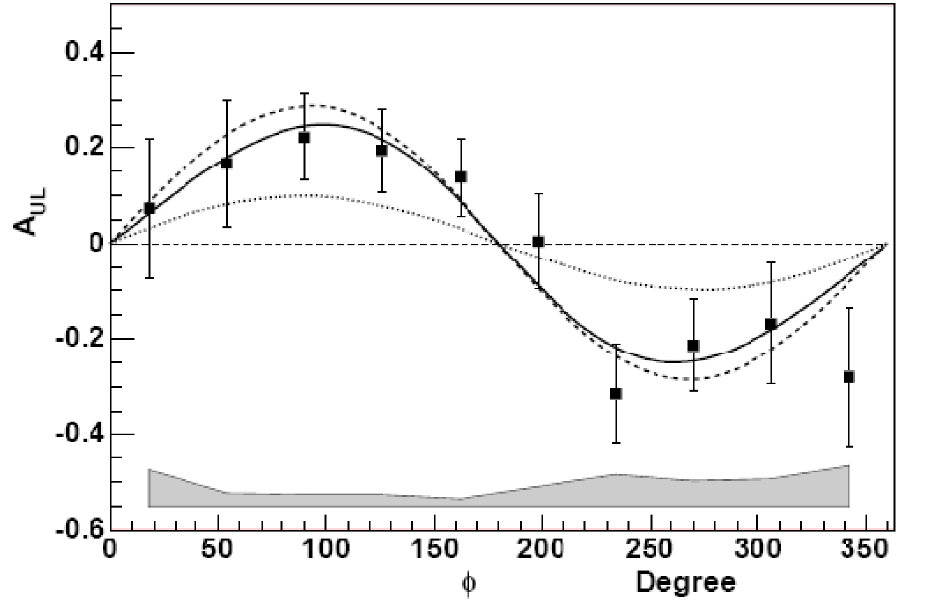


CLAS, PRL 87 (2001) 182002

JLAB/HALL A, PRL 97 (2006) 262002

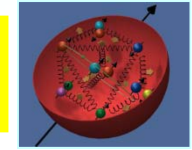


CLAS, PRL 97 (2006) 072002



DVCS: Longitudinal target-spin asymmetry

Hard exclusive processes - L_q



Pioneer measurements

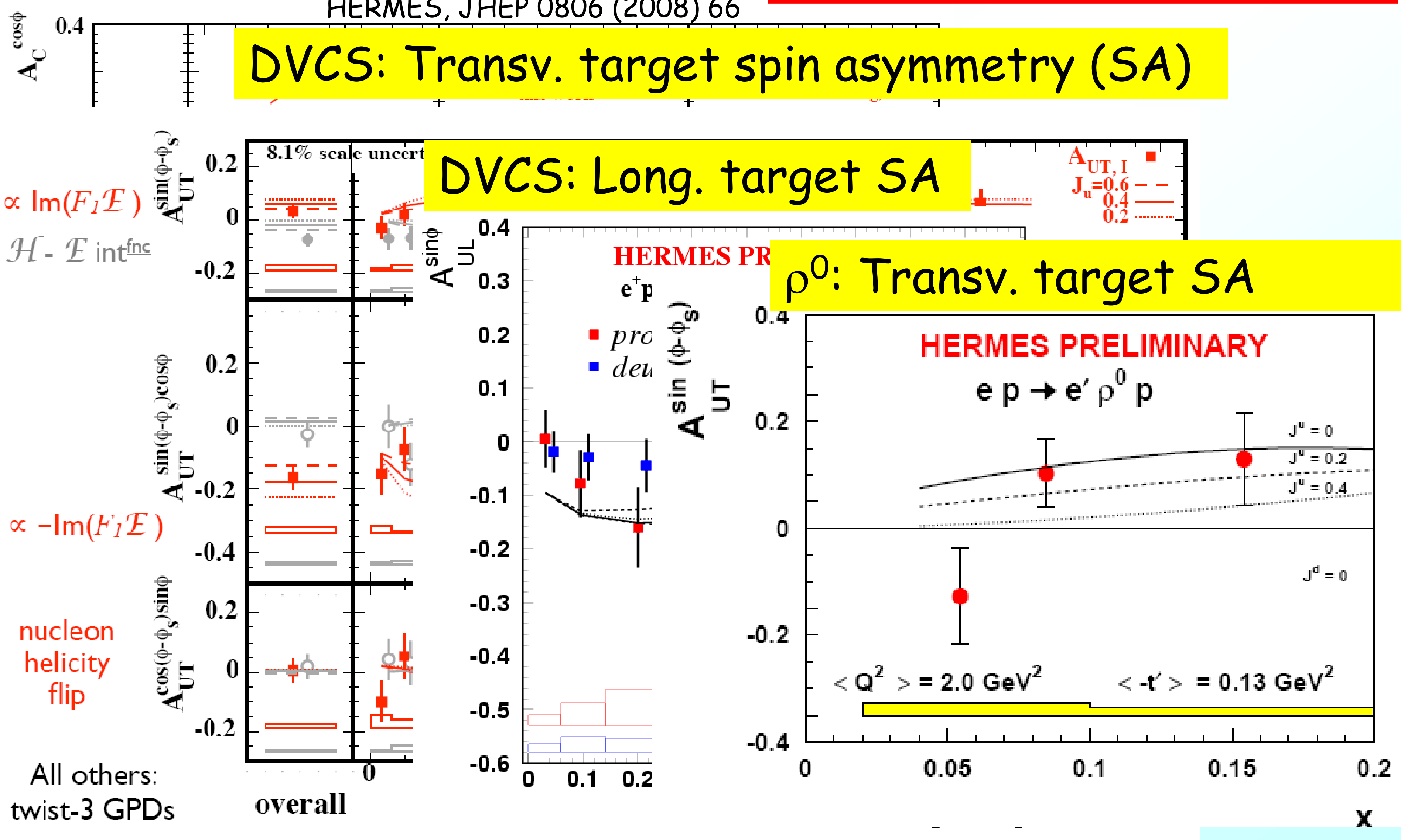
DVCS: Beam charge asymmetry

HERMES, JHEP 0806 (2008) 66

DVCS: Transv. target spin asymmetry (SA)

DVCS: Long. target SA

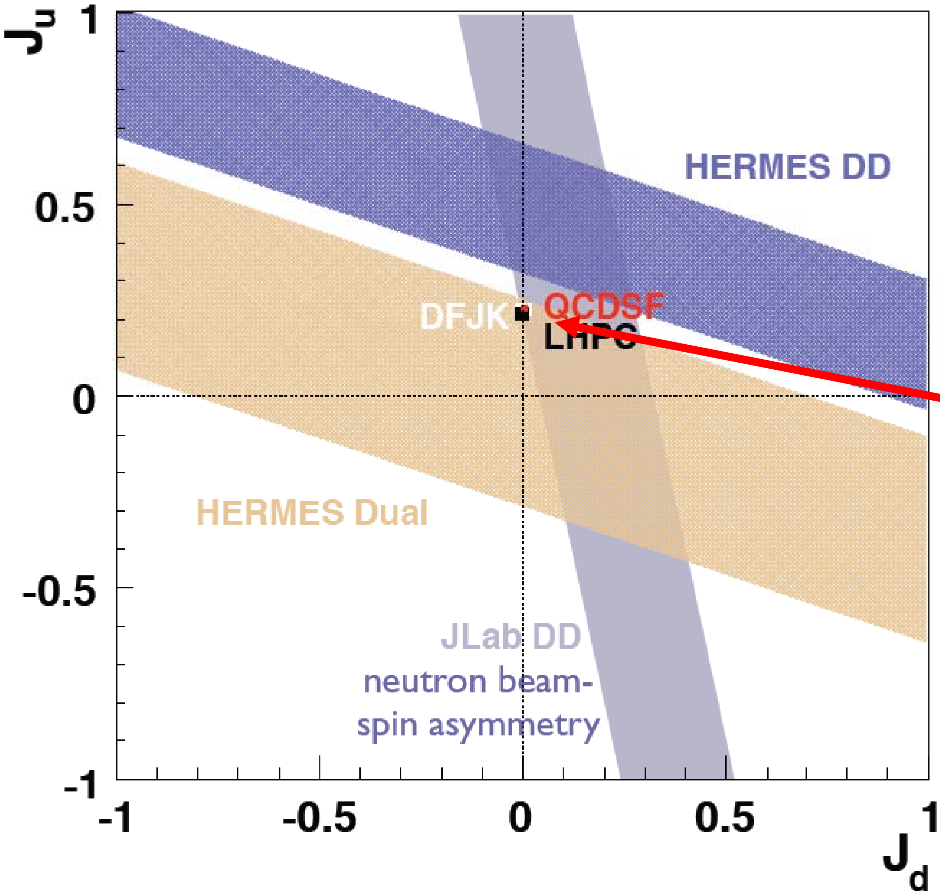
ρ^0: Transv. target SA

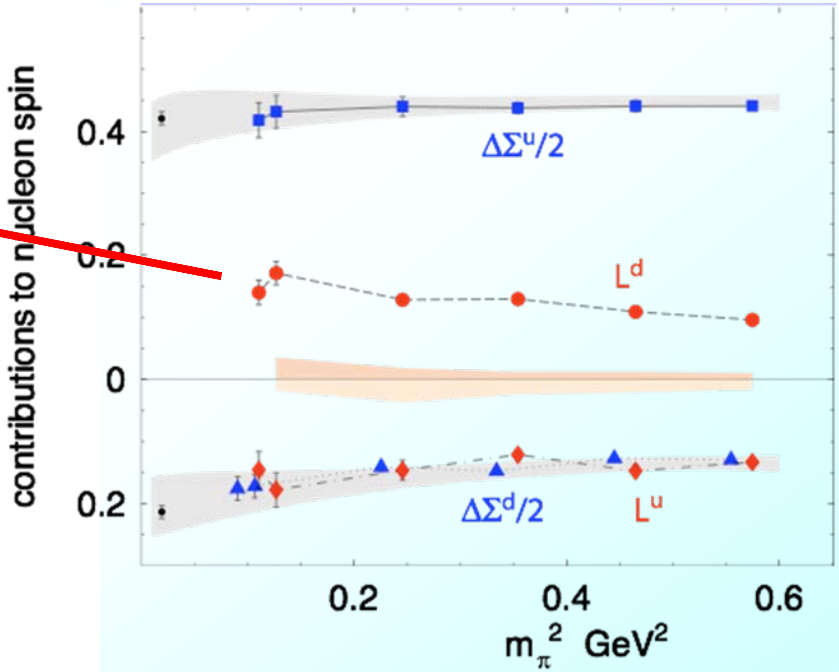


Determination of J_q

First model dependent attempt:

HERMES, JHEP 06 (2008) 066;
JLAB/HALL A, PRL 99 (2007) 242501





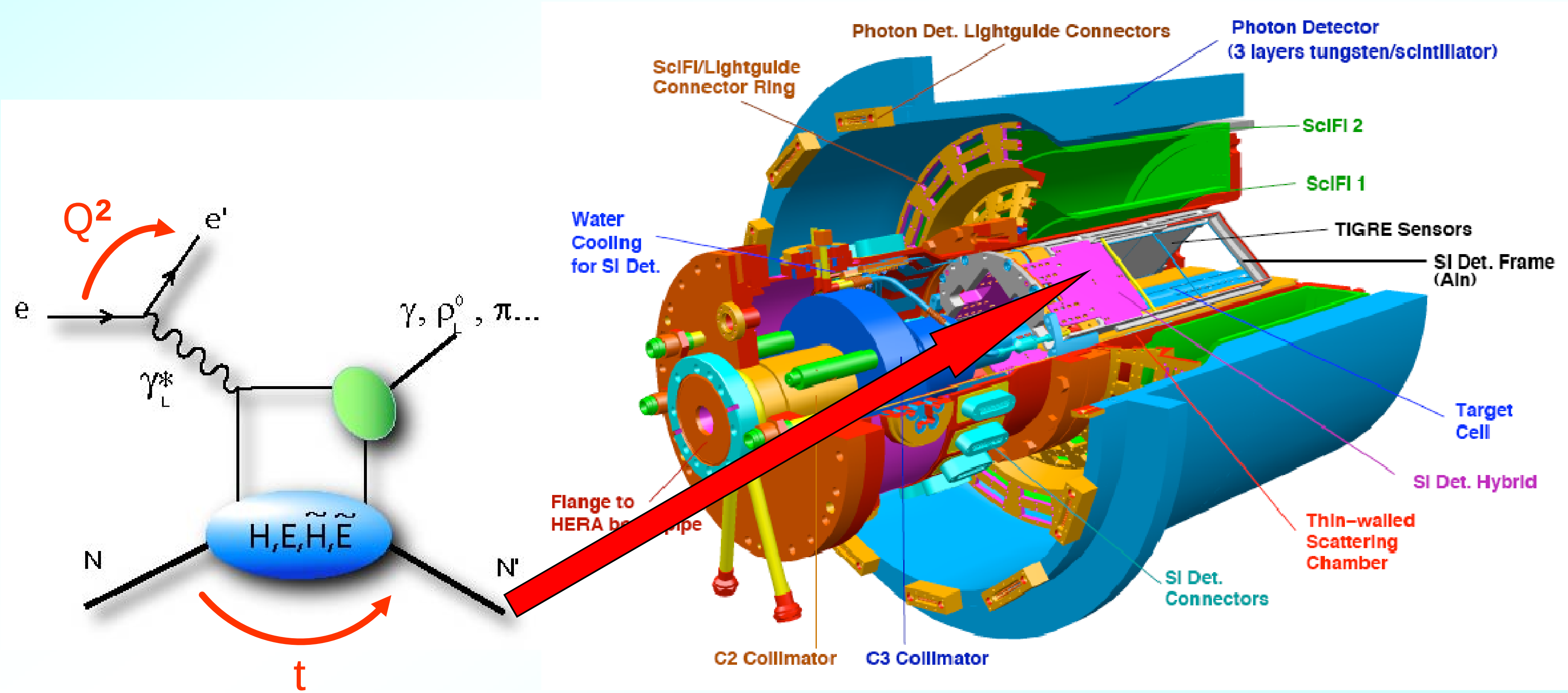
Lattice: $L_d \approx -L_u \approx 0.2$

$L_d + \Delta d/2 \approx 0$!??

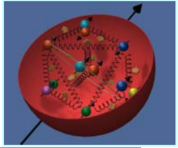
Determination of L_q

2006 - 2007:

Detailed study of exclusive processes with Recoil-Detector:

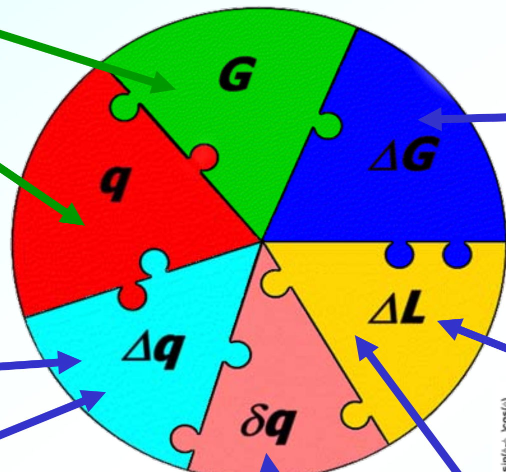


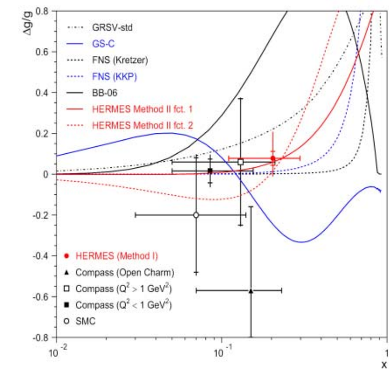
Nucleon Spin Structure & HERMES



Unpolarised DIS
SLAC, BCDMS, NMC, HERA…

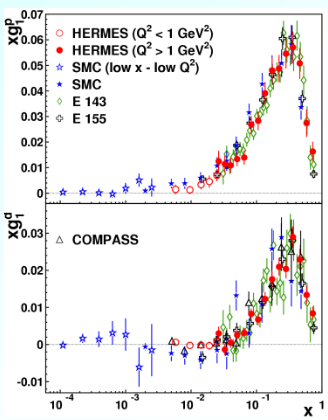
→ $\Delta g/g$
$= 0.071 \pm 0.035(\text{exp})$

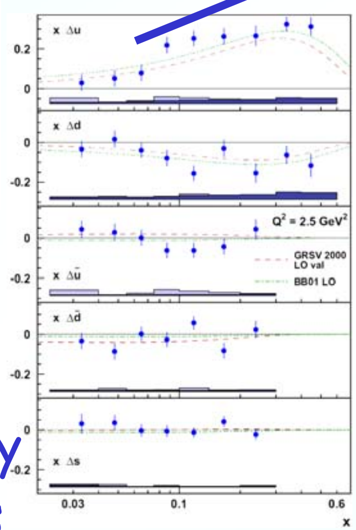


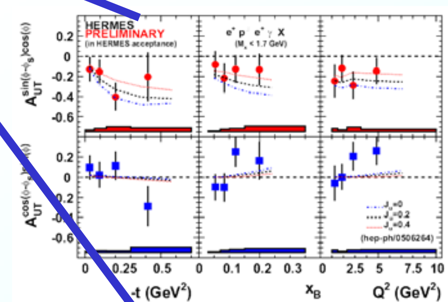


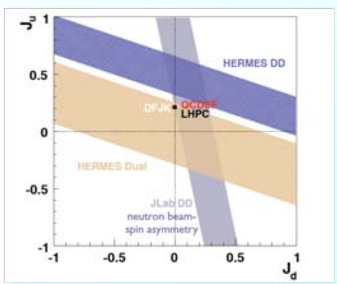
→ $\Delta\Sigma$
$= 0.330 \pm 0.025^{(\text{exp})}$

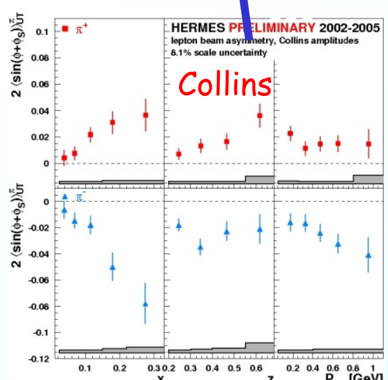
→ Signals for GPDs → $J_u + J_d$

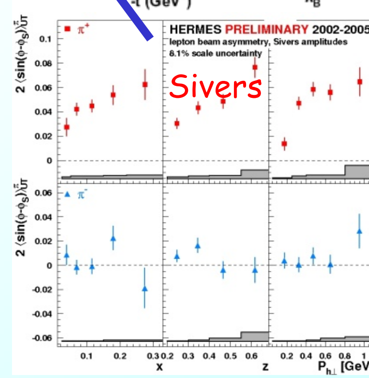












→ individual quark helicity distributions

→ $\delta q(x) \neq 0$

→ $L_q \neq 0$

After Delia Hasch, Spin06, Kyoto