Physics at hermes

Selected highlights

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& DESY

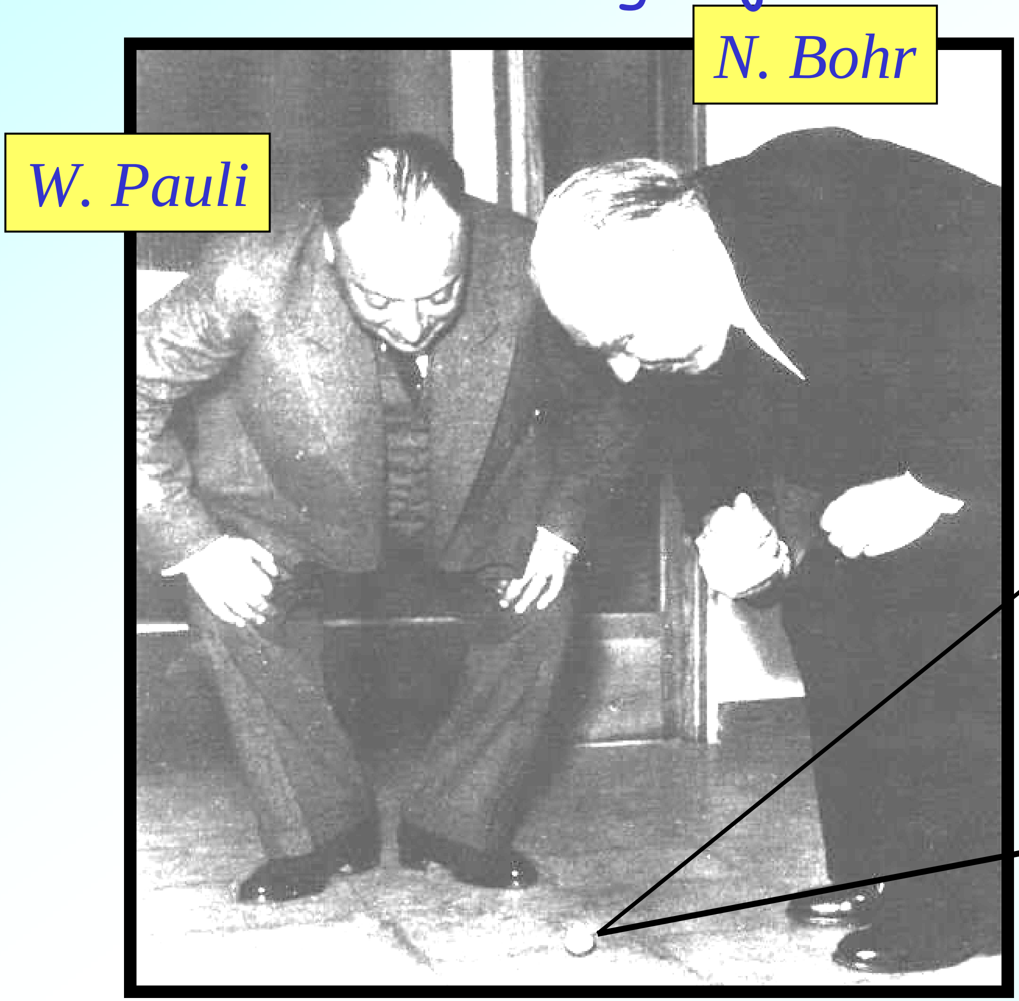
Overview

- Introduction – Nucleon Spin
- HERMES
- Determination of $\Delta\Sigma$
- The quark helicity distributions $\Delta q(x)$
- The gluon helicity distribution $\Delta g(x)$
- Transverse spin physics: transversity $\delta q(x)$, Collins FF, Sivers DF
- Quark orbital angular momenta L_q, GPDs
- Summary and outlook

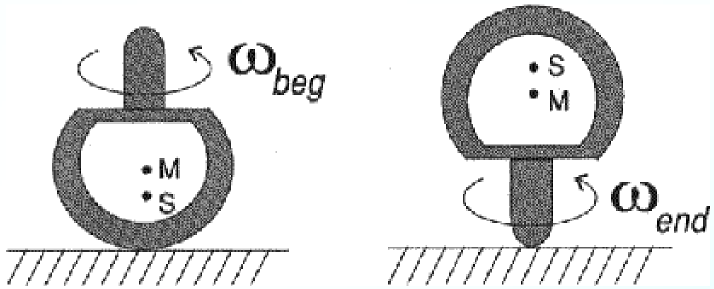
Introduction and Motivation

Main research topic: nucleon spin

Fascinating object



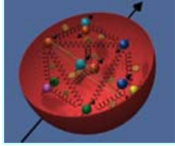
University of Lund, 31.5.1951



tippe-top

Stehauf-Kreisel

Spin



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

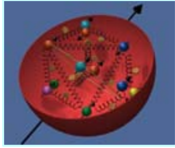
- Spin-1/2 particles (Fermions):

  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"

Spin and magnetic moment



Magnetic moment $\vec{\mu} = g(e/2M)\vec{s}$

Pointlike fundamental fermions: $s = \frac{1}{2}$, $g=2$, $\langle\mu_F\rangle = (e_F/2m_F)\,\hbar$

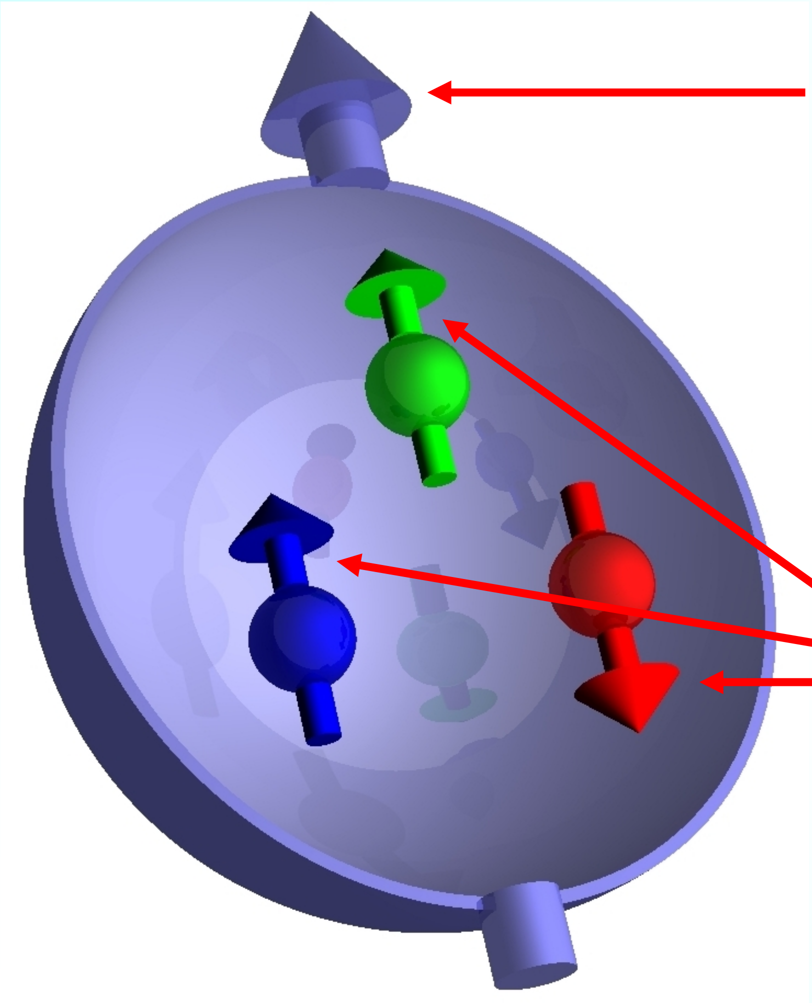
Proton p: $s = \frac{1}{2}$, $g^p = 5{,}46$

Neutron n: $s = \frac{1}{2}$, $g^n = -3{,}82$

$g^{p,\,n} \neq 2$, $\langle\mu^n\rangle \neq 0$

- p, n are not fundamental and pointlike
  $\sqrt{\langle r^2\rangle} \cong 0{,}84 \cdot 10^{-15}$ m
- p, n are composite systems

Nucleon Spin: constituent quark model



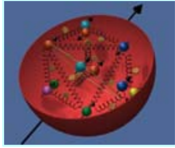
Nucleon Spin

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

Contribution of quark spins:

$$\Delta\Sigma = 1$$

Nucleon Spin: constituent quark model



$|p\rangle = |uud\rangle$, $e_u = 2/3$

$|n\rangle = |ddu\rangle$, $e_d = -1/3$

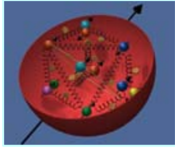
$$\chi_p(J=\tfrac{1}{2}, m_J=\tfrac{1}{2}) = \sqrt{2/3}\,\chi_{uu}(1,1)\chi_d(\tfrac{1}{2},-\tfrac{1}{2}) - \sqrt{1/3}\,\chi_{uu}(1,0)\chi_d(\tfrac{1}{2},\tfrac{1}{2})$$

$$|p^\uparrow\rangle = \{2|u^\uparrow u^\uparrow d^\downarrow\rangle - |u^\uparrow u^\downarrow d^\uparrow\rangle - |u^\downarrow u^\uparrow d^\uparrow\rangle + 2|u^\uparrow d^\downarrow u^\uparrow\rangle - \ldots\ldots + 2|d^\downarrow u^\uparrow u^\uparrow\rangle - \ldots\ldots\}/\sqrt{18}$$

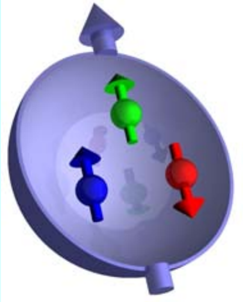
- $u^{\uparrow\uparrow} = u^+ = 5/3$; $u^{\uparrow\downarrow} = u^- = 1/3$; $u = u^+ + u^- = 2$; $\Delta u = u^+ - u^- = 4/3$

  $d^{\uparrow\uparrow} = d^+ = 1/3$; $d^{\uparrow\downarrow} = d^- = 2/3$; $d = d^+ + d^- = 1$; $\Delta d = d^+ - d^- = -1/3$

$$\Delta\Sigma = \Delta u + \Delta d = 1$$



Magn. moment: constituent quark model



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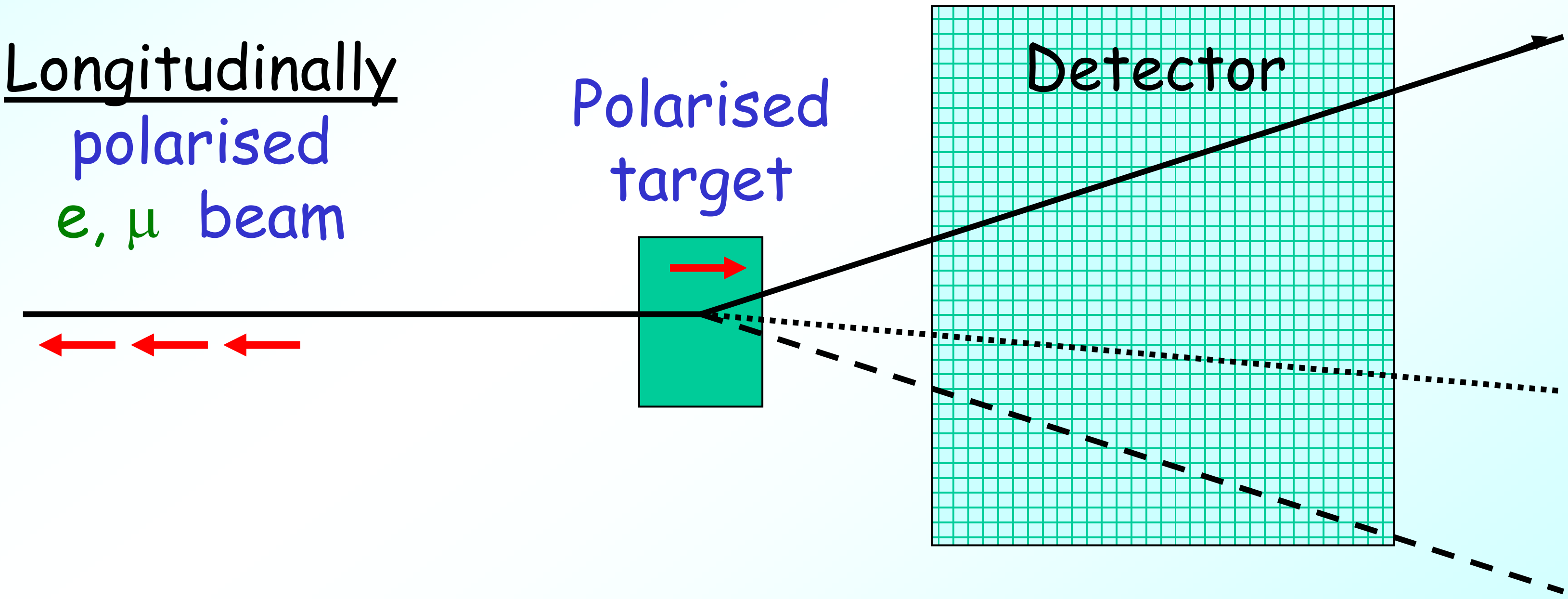
- $\langle\mu^p\rangle = \langle p^\uparrow|\vec{\mu}\,|p^\uparrow\rangle = 1/3\{4\langle\mu^u\rangle - \langle\mu^d\rangle\}$;
- $\langle\mu^n\rangle = 1/3\{4\langle\mu^d\rangle - \langle\mu^u\rangle\}$;

$\langle\mu^n\rangle/\langle\mu^p\rangle = -2/3 \cong -1{,}91/2{,}73$ with $m_u = m_d = m_q \cong M_p/2.73$

Experimental tool

Polarised Deep-Inelastic lepton (e,μ) - nucleon Scattering (DIS)



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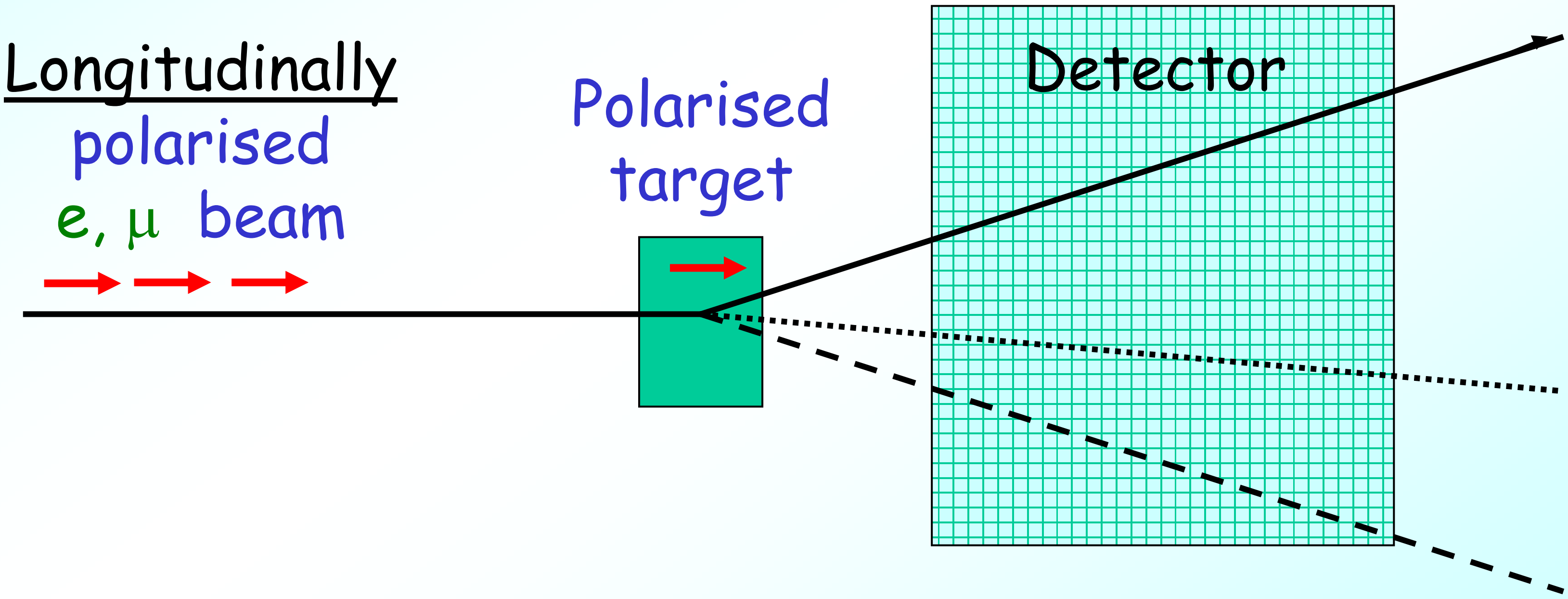

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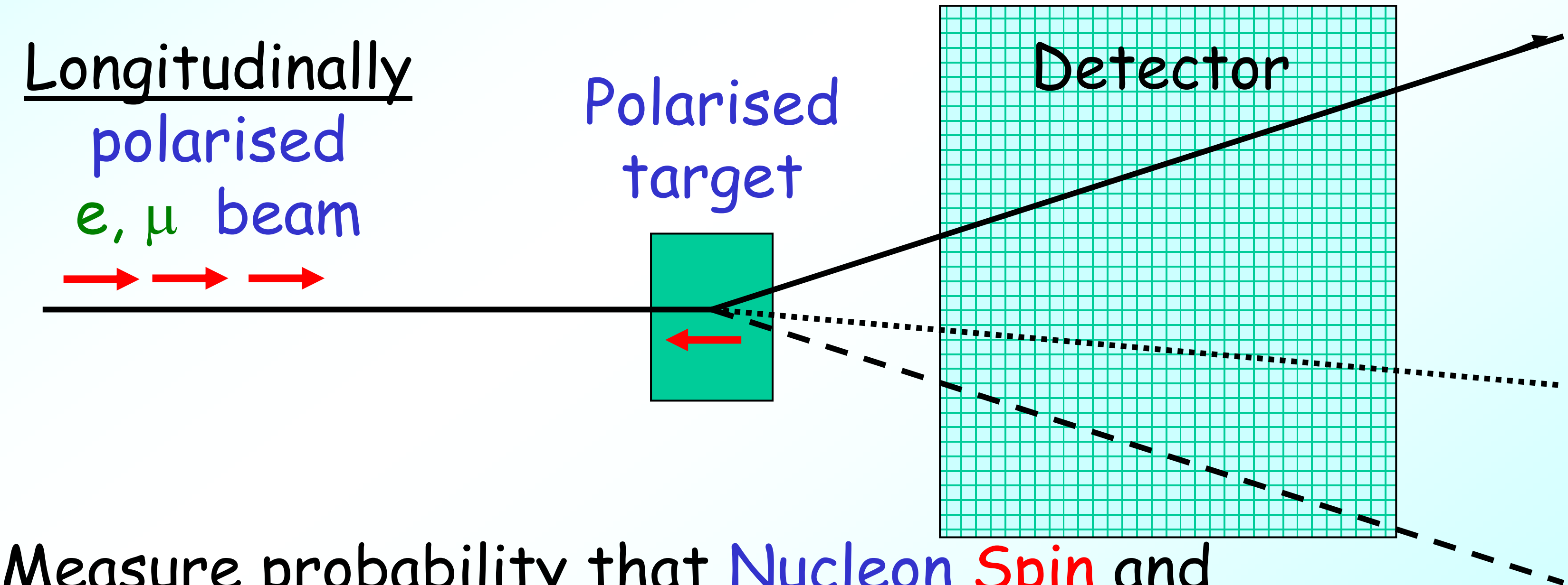
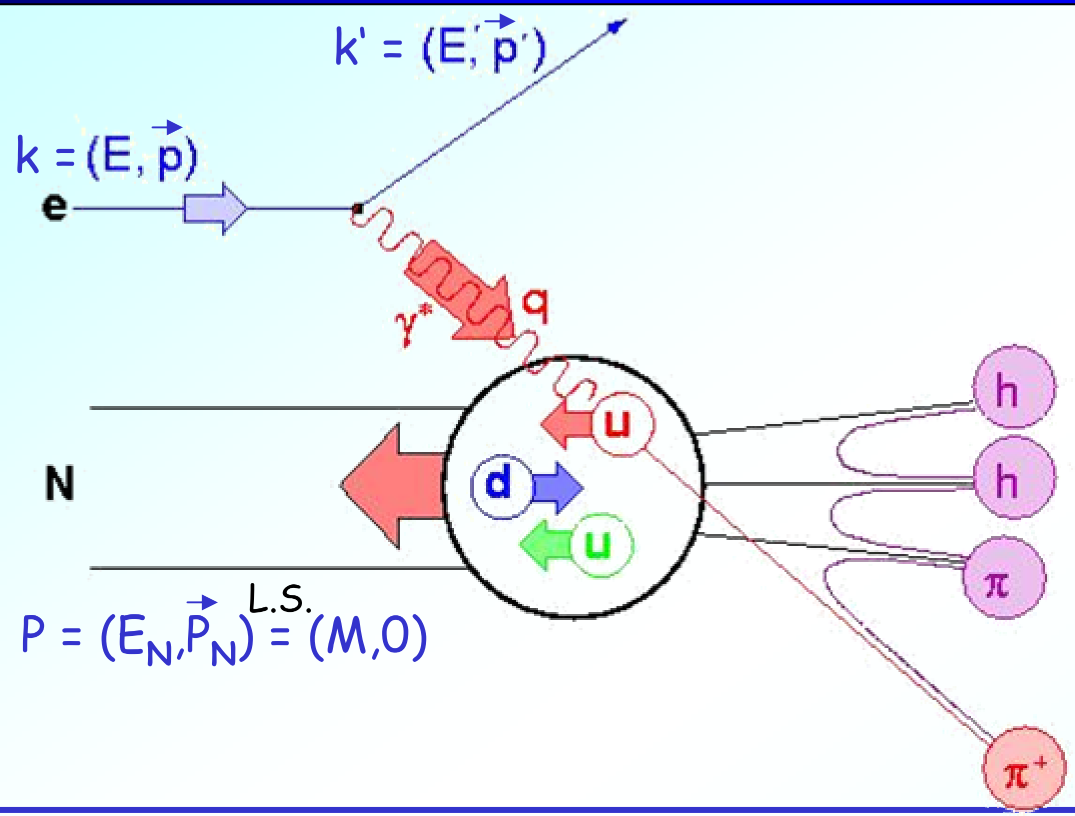


Measure probability that Nucleon Spin and
Quark Spin ↑↓ or ↑↑,
Spin-dependent structure function $g_1^{p,n}(x,Q^2)$

Polarized deep-inelastic scattering



Asymmetries:

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

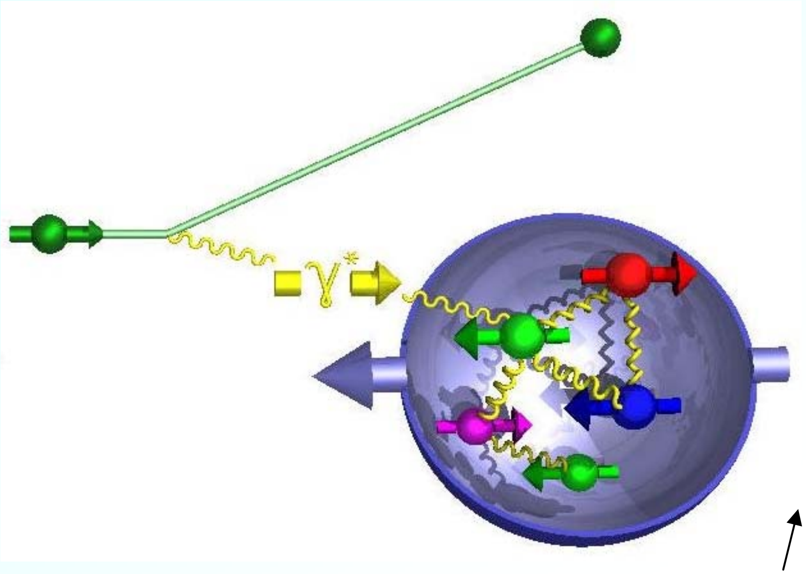
$Q^2 = -q^2 = -(k - k')^2$, $\nu = Pq/M \overset{L.S.}{=} E - E'$,

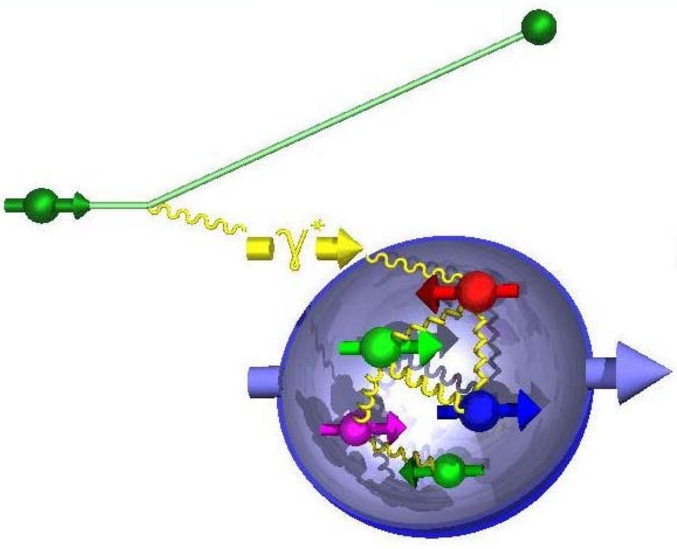
$x = Q^2/(2Pq)$ = fraction of nucleon's longitudinal momentum carried by struck quark

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

Quark helicity distributions $\Delta q(x)$

More precisely: „helicity weighted momentum distributions"





Proton

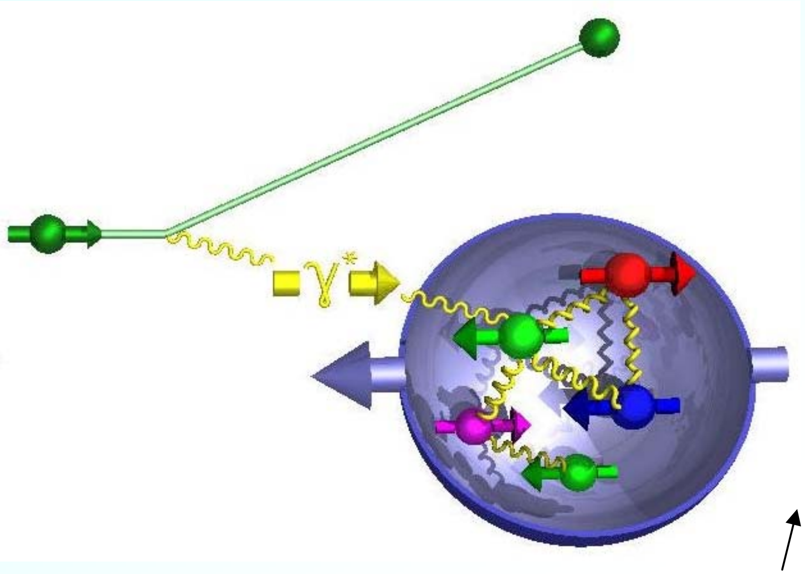
Quark

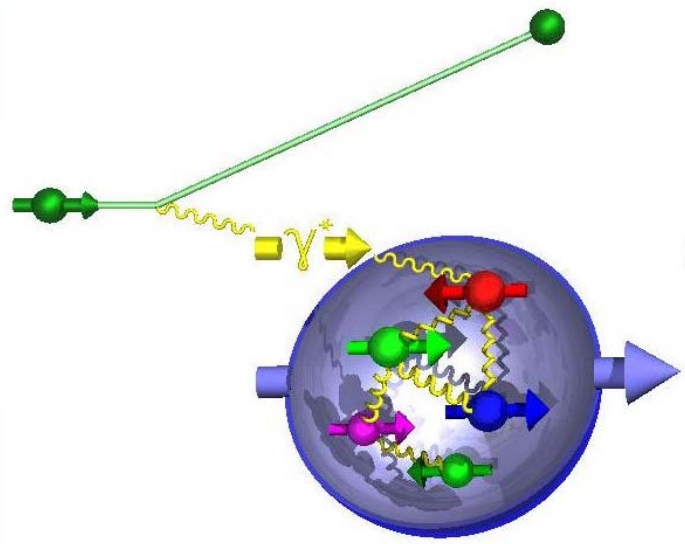
$q^{+}(x) = q^{\uparrow\uparrow}$

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

Quark helicity distributions $\Delta q(x)$

More precisely: „helicity weighted momentum distributions“





Proton

Quark

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

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

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

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

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

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

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

Integrals and sum rules

- $\Gamma_1 := \int_0^1 g_1(x)dx;$
- $9\,\Gamma_1^{p,(n)} = 4(1)\Delta u + 1(4)\Delta d + \Delta s$

SU(3): 2 relations

- $a_3 = \Delta u - \Delta d \quad = g_A/g_V = 1{,}269 \pm 0.003$ Neutron decay
- $a_8 = \Delta u + \Delta d - 2\Delta s \quad = 0{,}586 \pm 0.031$ Λ,Σ decay
- $a_0 \overset{\overline{MS}}{=} \Delta\Sigma = \Delta u + \Delta d + \Delta s = ?$

QCD

$\overline{MS}$ scheme: =0

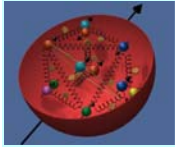
$$36\,\Gamma_1^{p,(n)}(Q^2) = [\pm 3a_3 + a_8]\,\Delta C_{NS}(Q^2) + 4\Delta\Sigma\,\Delta C_S(Q^2) + 8n_f\,\Delta G\,\Delta C_G(Q^2)$$

$$\Delta\Sigma \overset{\overline{MS}}{=} a_0 = \frac{1}{\Delta C_S}\left[\frac{9\Gamma_1^d}{(1-\frac{3}{2}\omega_D)} - \frac{1}{4}a_8\,\Delta C_{NS}\right]$$

$\omega_D = 0.05 \pm 0.05$

D-state probability in deuteron wave function

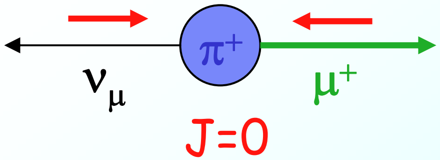
The EMC experiment at CERN (1984-85)



- Myon beam: 100, 120 and 200 GeV

  $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

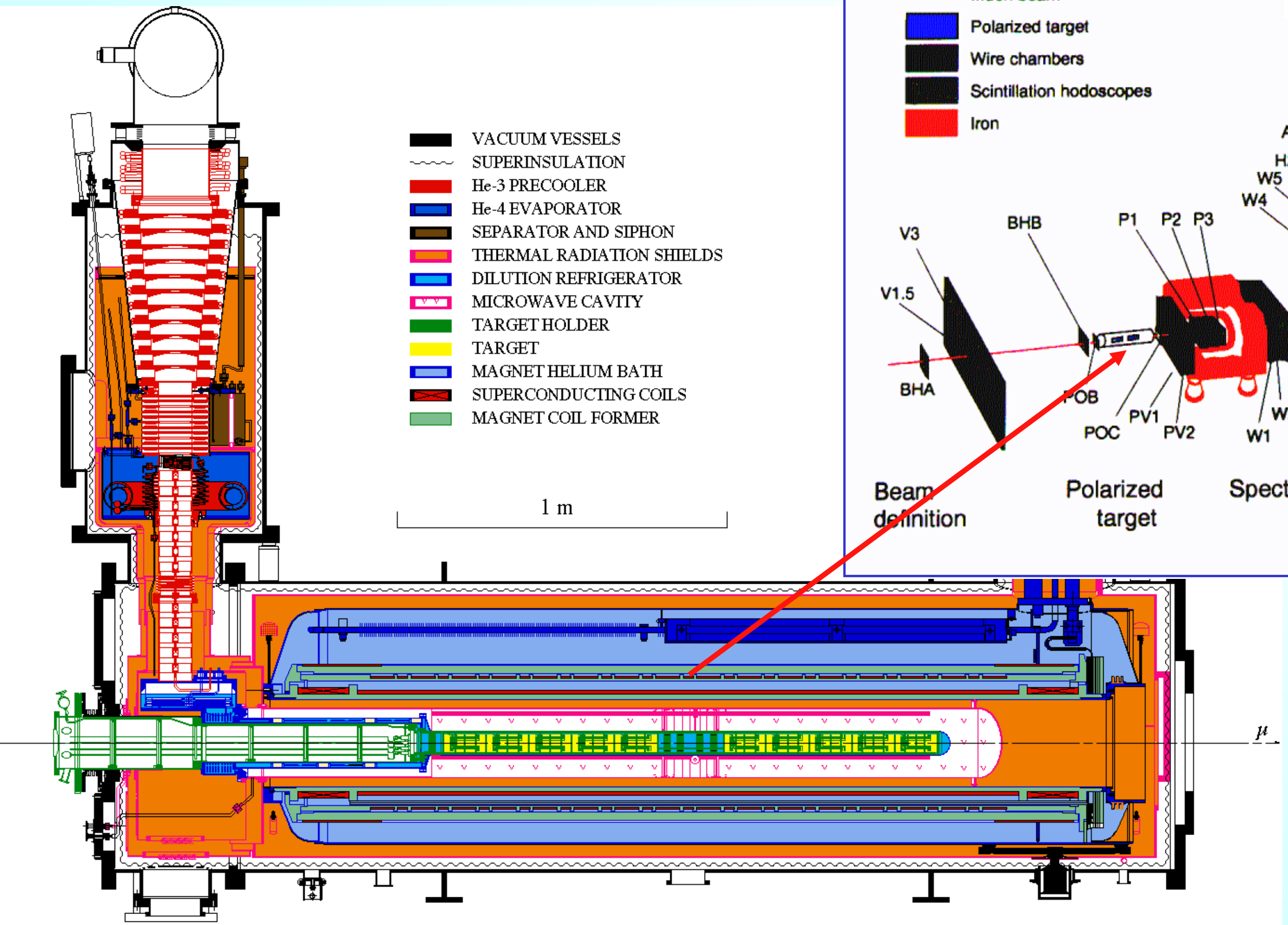
- 'Natural' beam polarisation:

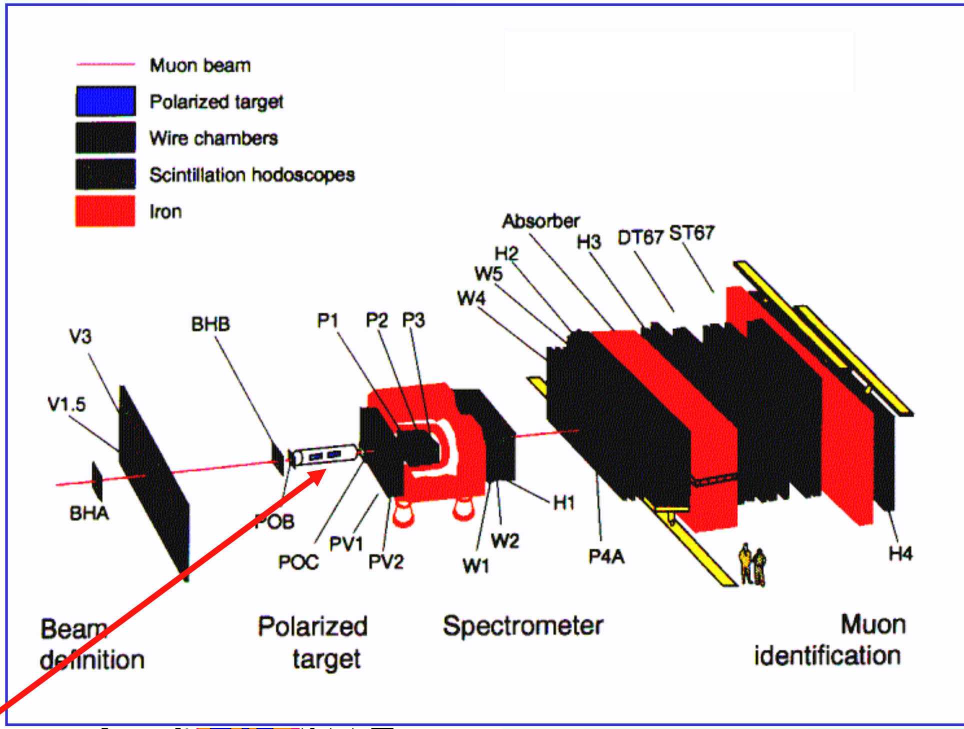


- Polarised NH_3-Target, T = 0,5 K, B = 2.5 T,

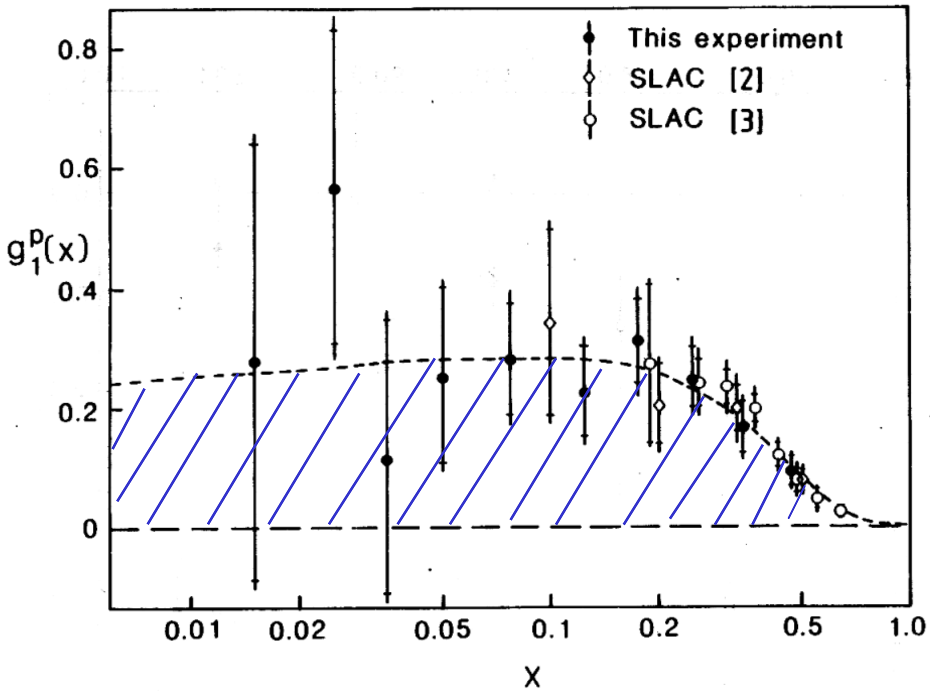
  Fraction of polarisable protons: $f \cong 3/17$

The EMC experiment at CERN





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



Γ_1^p =0,126 ± 0,010 ± 0,015

J. Ashman et al., PL B 206 (1988) 364 (1403 Cit.)

J. Ashman et al. Nucl. Phys. B 328 (1989) 1 (1207 Cit.)

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

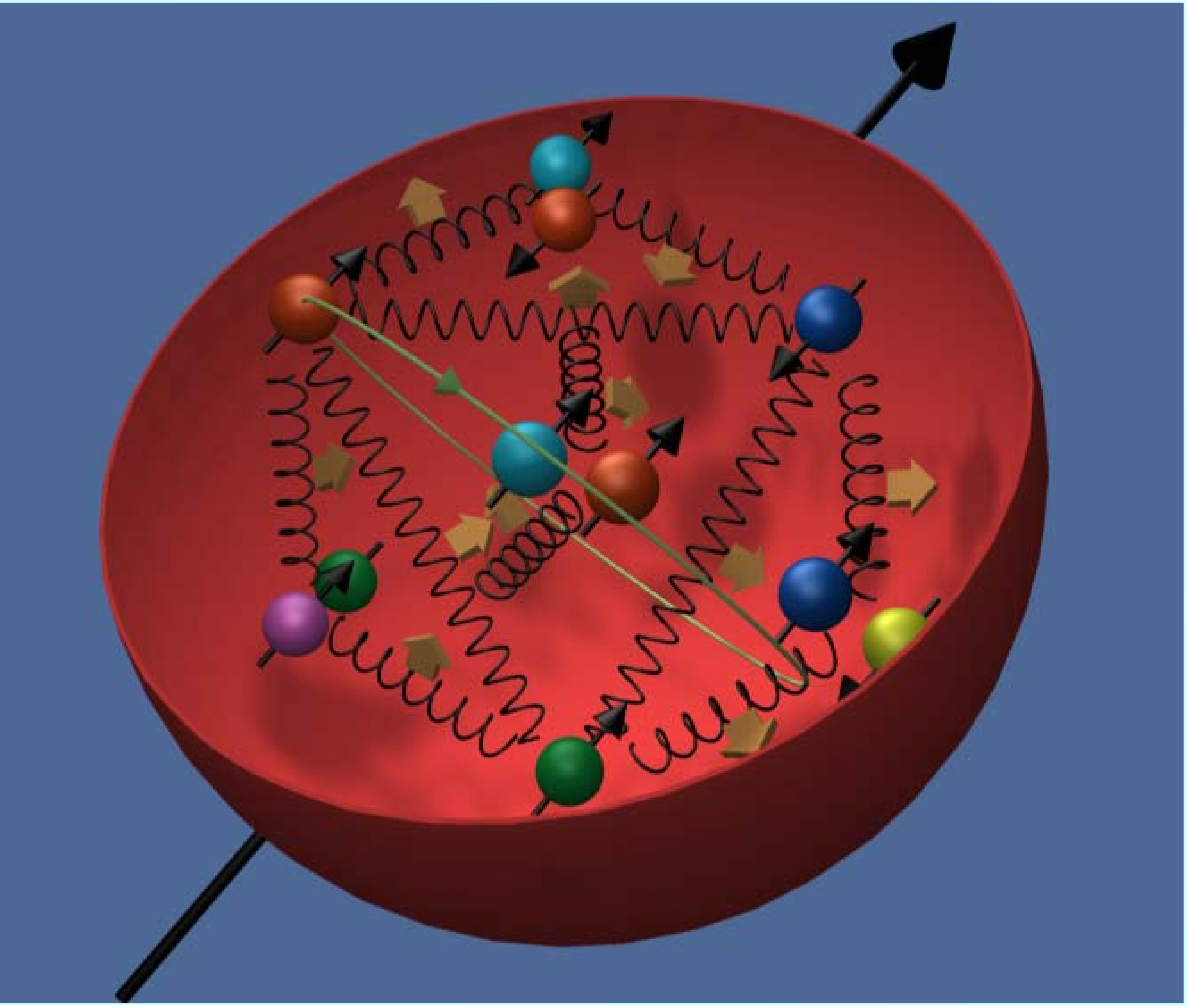
2) $\Delta\Sigma = \Delta u + \Delta d + \Delta s =$
$= 0,12 \pm 0,09 \pm 0,14$ (QPM: 1)

Contribution of Quark Spins to Nucleon-Spin very small

Spin-'crises'

5th most cited paper in experimental accelerator based particle physics

Nucleon Spin: QCD picture



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

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

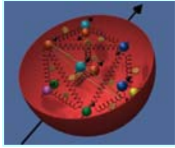
$$+\ L_q + L_g$$

(Orbital angular momenta)

HERMES

HERA MEasurement of Nucleon Spin

The HERMES experiment at HERA



Idea (1987):

Use

- polarized electron beam of HERA
- gas targets with high polarisation and low dilution
- storage cell target internal to HERA e-ring

Conditions (1988) for approval (1992/93)

- High flux of highly polarised atoms from polarized sources

Performance exceeds design values by about a factor of 2 ✓

- Experimental demonstration of storage cell technique

Verified by pioneer experiments at Heidelberg TSR and Novosibirsk e-storage ring ✓

- Experimental demonstration of high longitudinal electron beam polarisation

?

Electron beam polarisation

Mechanism: Spin flip by emission of synchrotron radiation

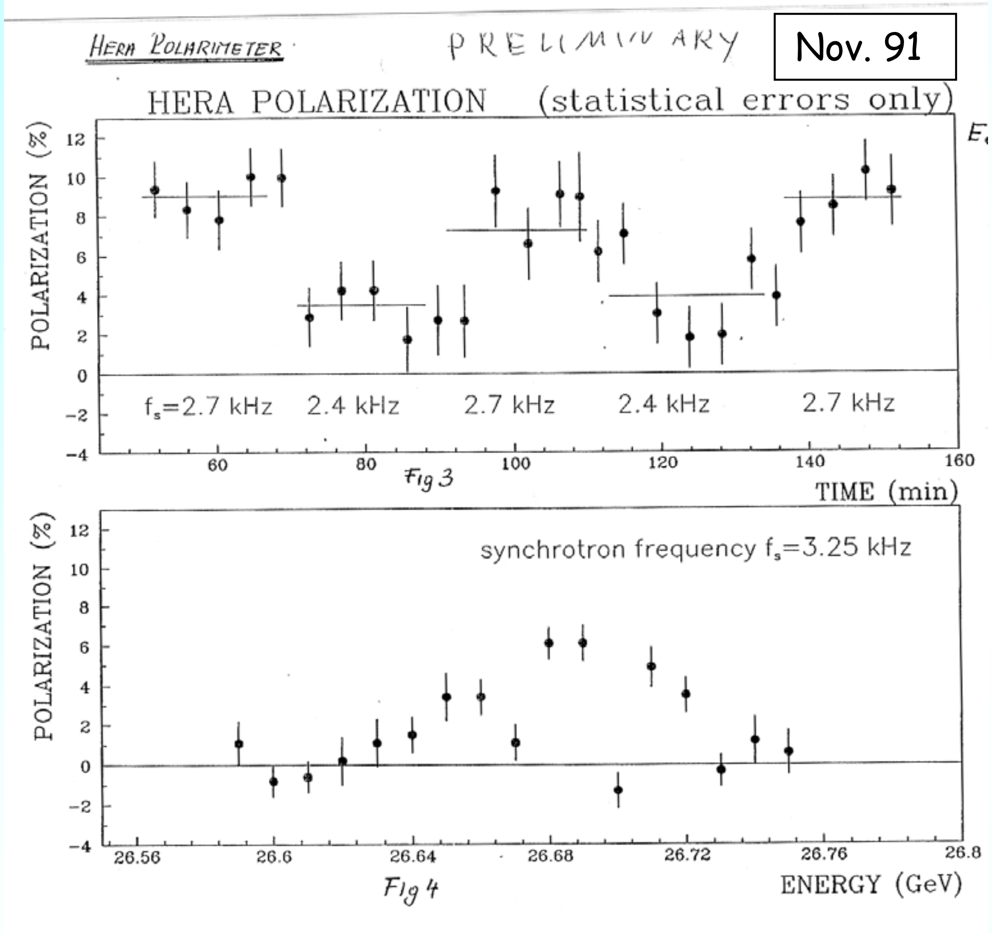
$\approx$ 1 / 10^{11} emissions

Degree of polarisation: depends critically on machine energy and magnet alignement

Longitudinal polarisation: requires spin rotators

- 6-7/91: first attempt
- 11/91: $P_T \approx$ 8-10 % (realignment of several magnets)
- 4-7/92: $P_T \approx$ 15-20 % (normal HERA running)
- 9/92: $P_T \approx$ 60 % (dedicated running) ➡ approval
- Winter 93/94: installation of spin rotators
- 5/94: $P_L \approx$ 60 %

Electron beam polarisation



Electron beam polarisation

HERA POLARIMETER PRELIMINARY Nov. 91

HERA POLARIZATION (statistical errors only)

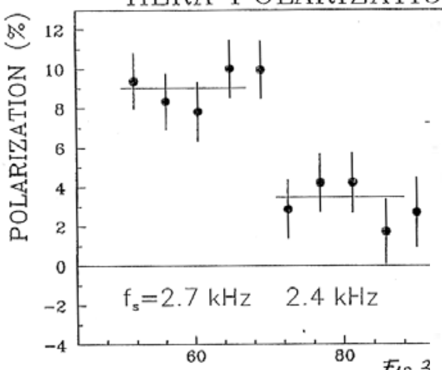


Fig 3

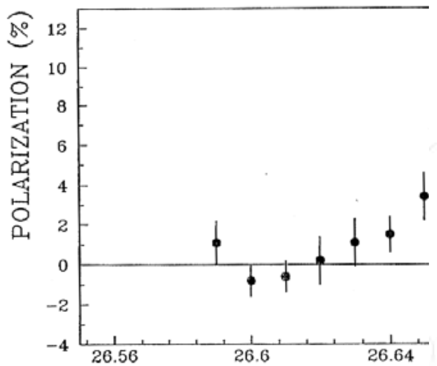


Fig 4

Nov. 91

DESY

DESY TELEGRAMM

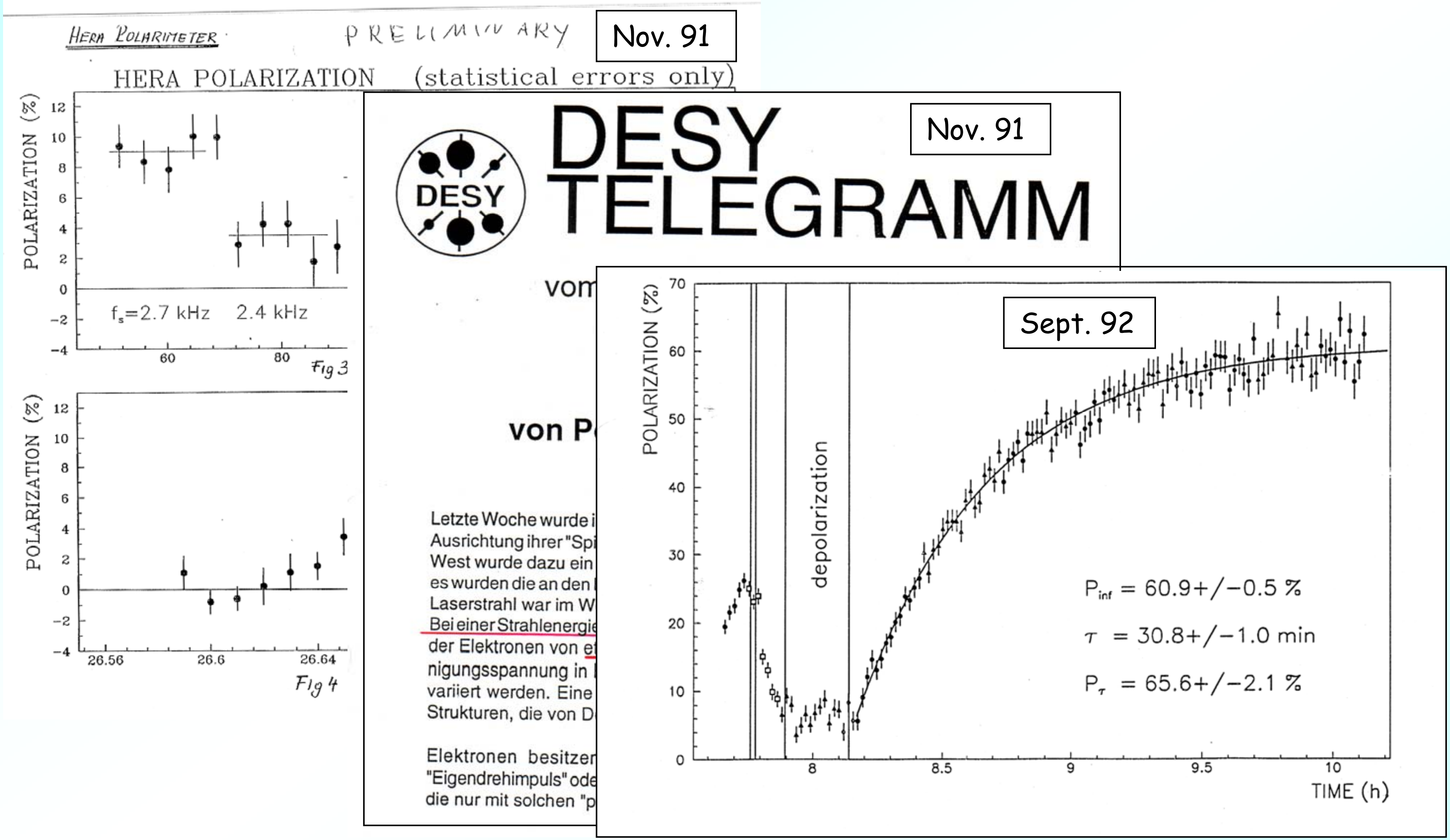
vom 24. November 1991

Erste Messung von Polarisation der Elektronen in HERA

Letzte Woche wurde in HERA zum ersten Mal die Polarisation von Elektronen, die Ausrichtung ihrer "Spins", beobachtet. Im Bereich des geraden Abschnitts HERA-West wurde dazu ein Laserstrahl auf die umlaufenden Elektronen gerichtet, und es wurden die an den Elektronen zurückgestreuten Photonen nachgewiesen. Der Laserstrahl war im Wechsel (90mal in der Sekunde) links und rechts polarisiert. Bei einer Strahlenergie von 26,67 GeV wurde auf diese Weise ein Polarisationsgrad der Elektronen von etwa 8% gemessen. Durch die Veränderung der Beschleunigungsspannung in HERA konnte ihre Polarisation gezielt und reproduzierbar variiert werden. Eine in 10MeV-Energieschritten durchgeführte Messung zeigt Strukturen, die von Depolarisationsresonanzen herrühren.

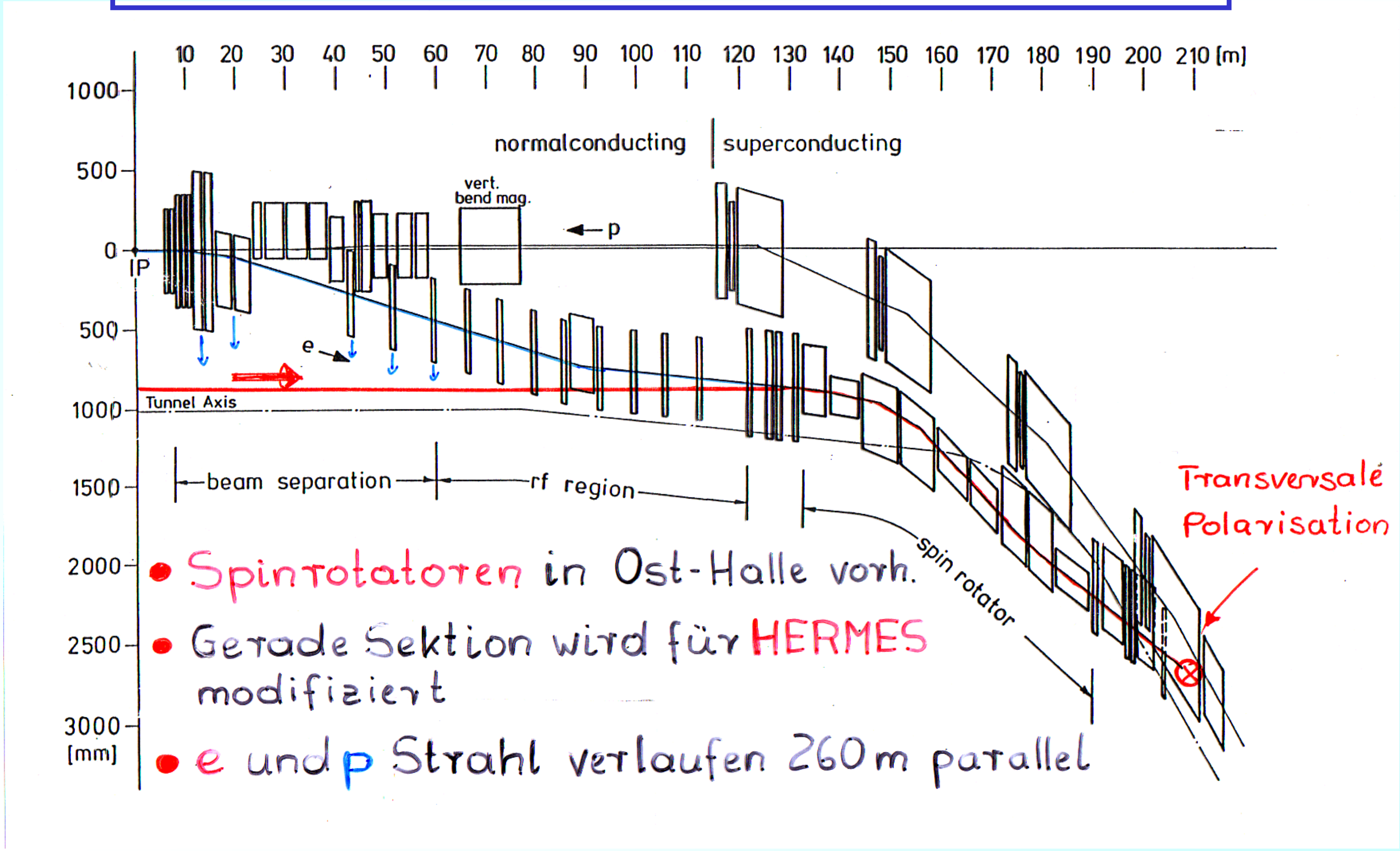
Elektronen besitzen die Eigenschaft kleiner Kreisel, sie haben einen "Eigendrehimpuls" oder "Spin". In der Teilchenphysik gibt es einige Fragestellungen, die nur mit solchen "polarisierten" Elektronen untersucht werden können.

Electron beam polarisation



Longitudinal e polarisation

Installation of Spinrotators: winter 1993/94



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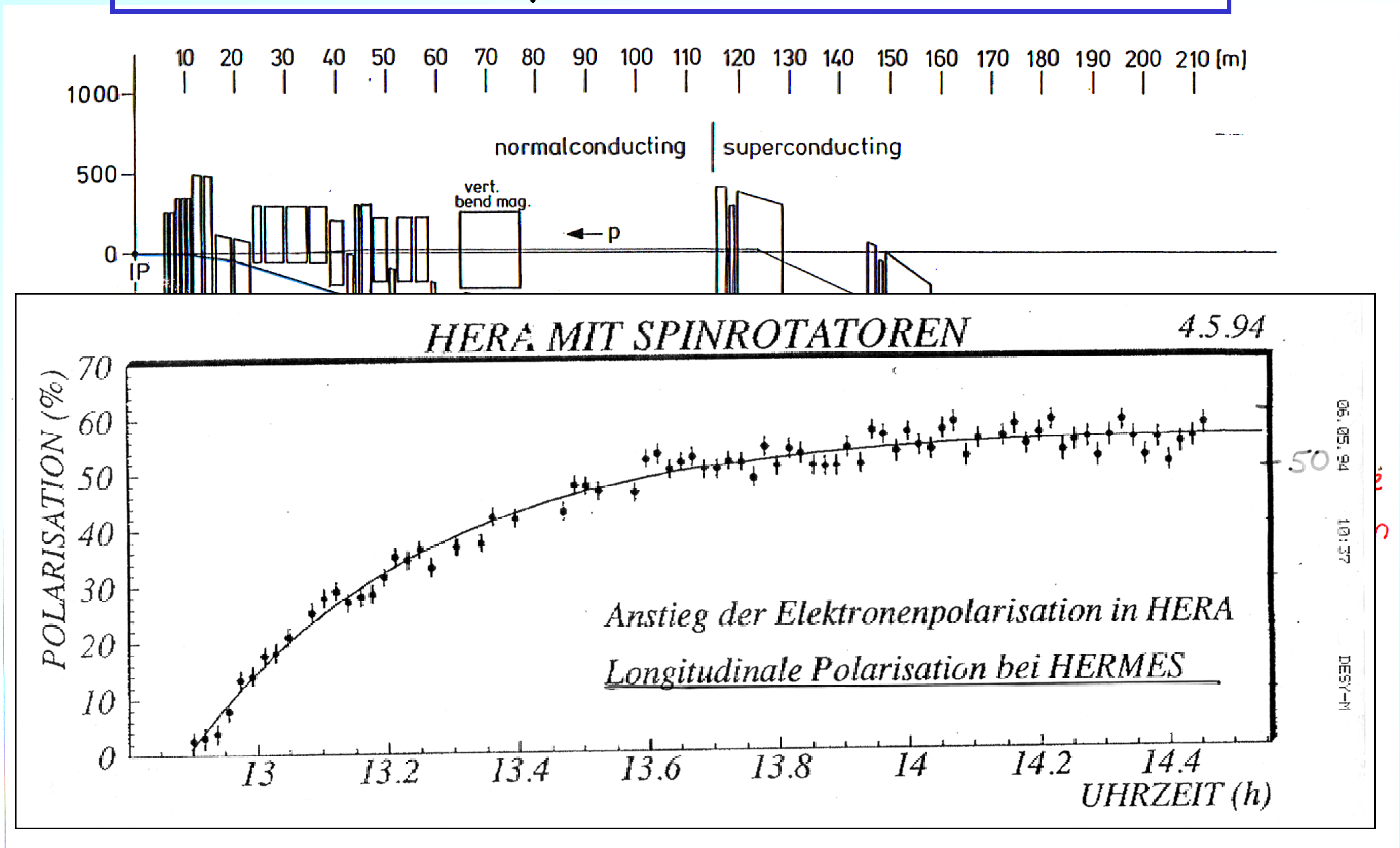
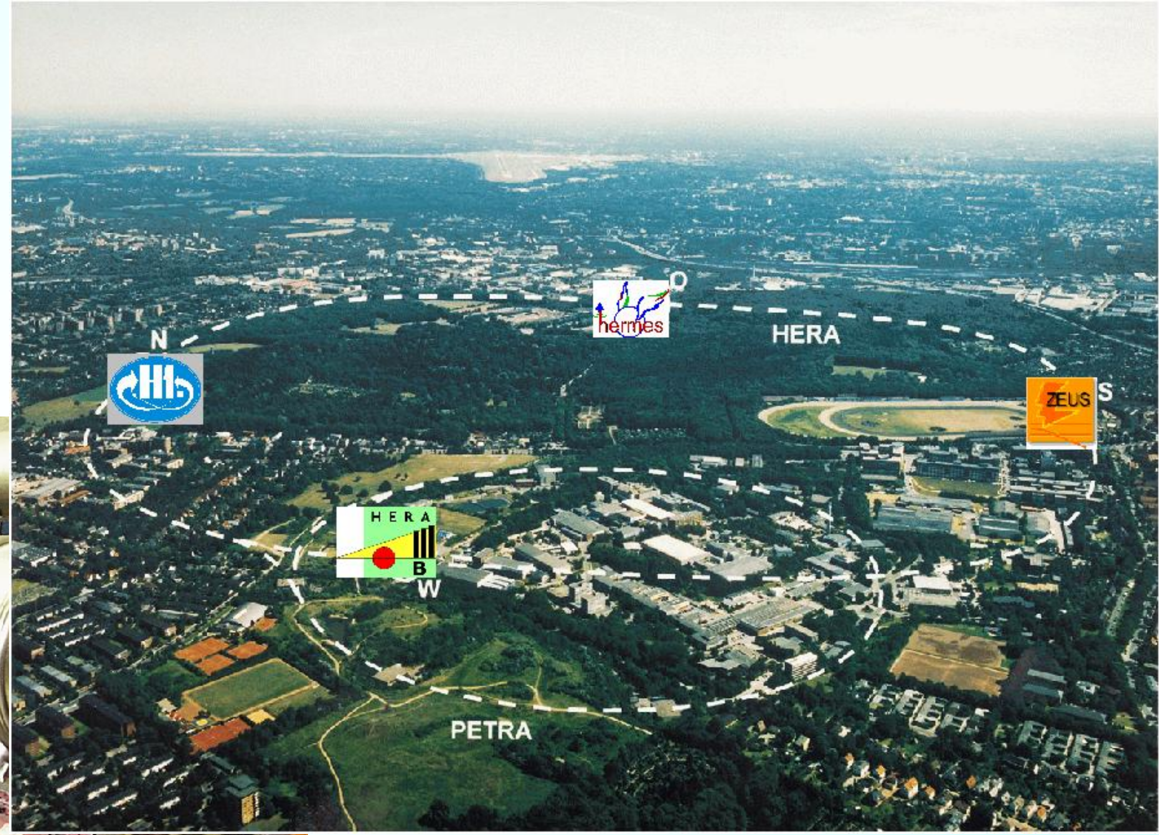
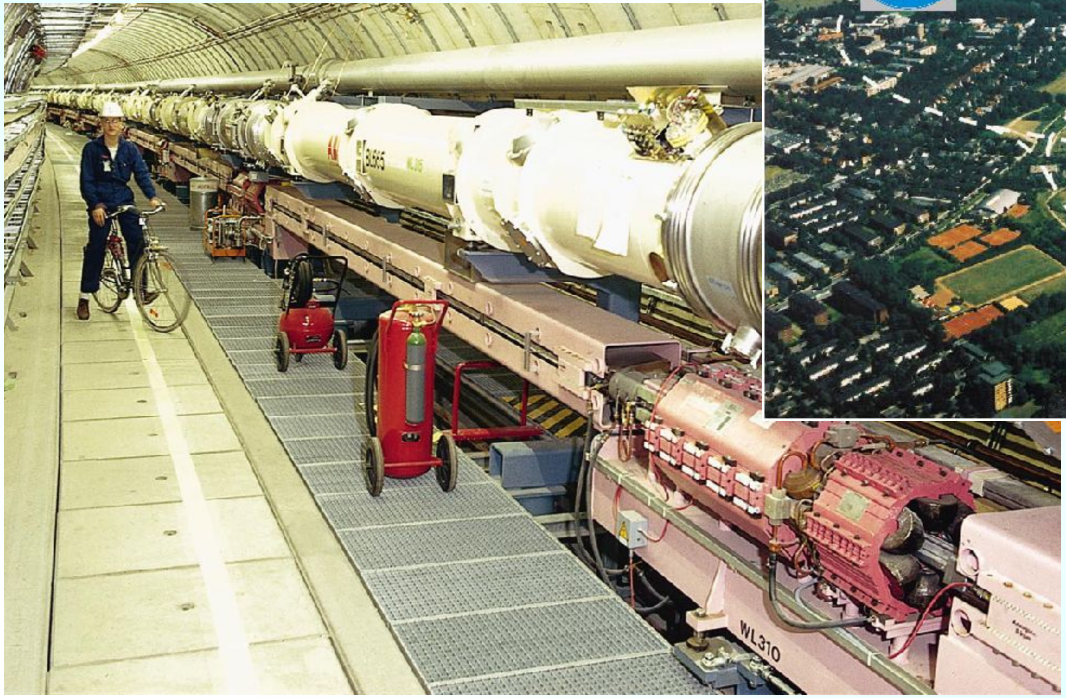


Electron beam:

E = 27.6 GeV, I_e < 50 mA





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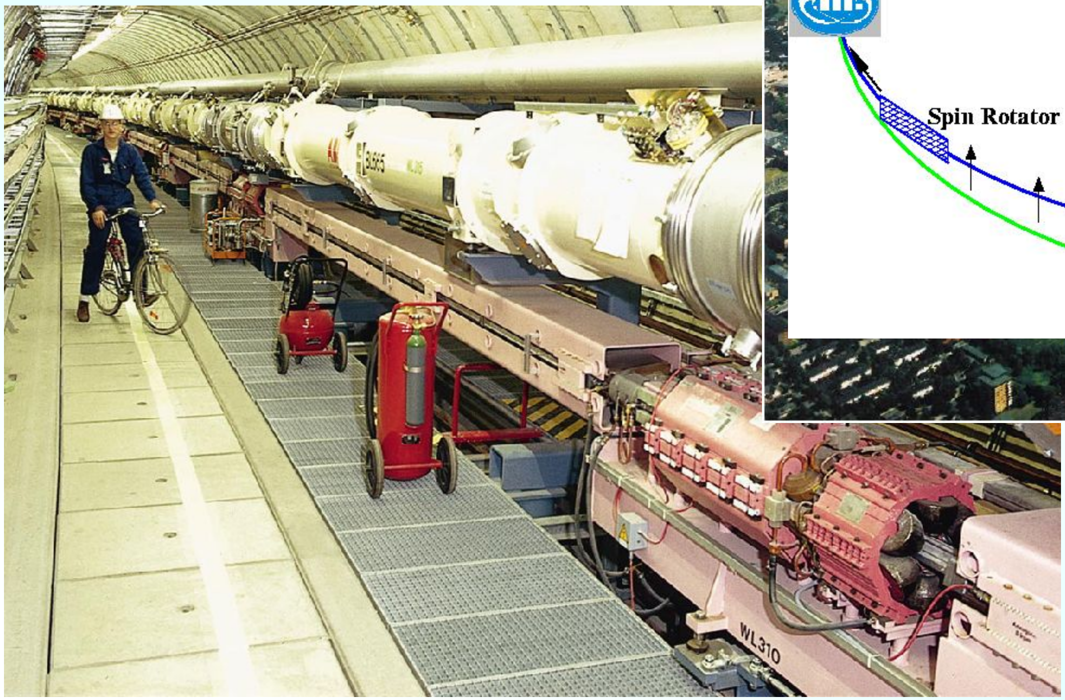

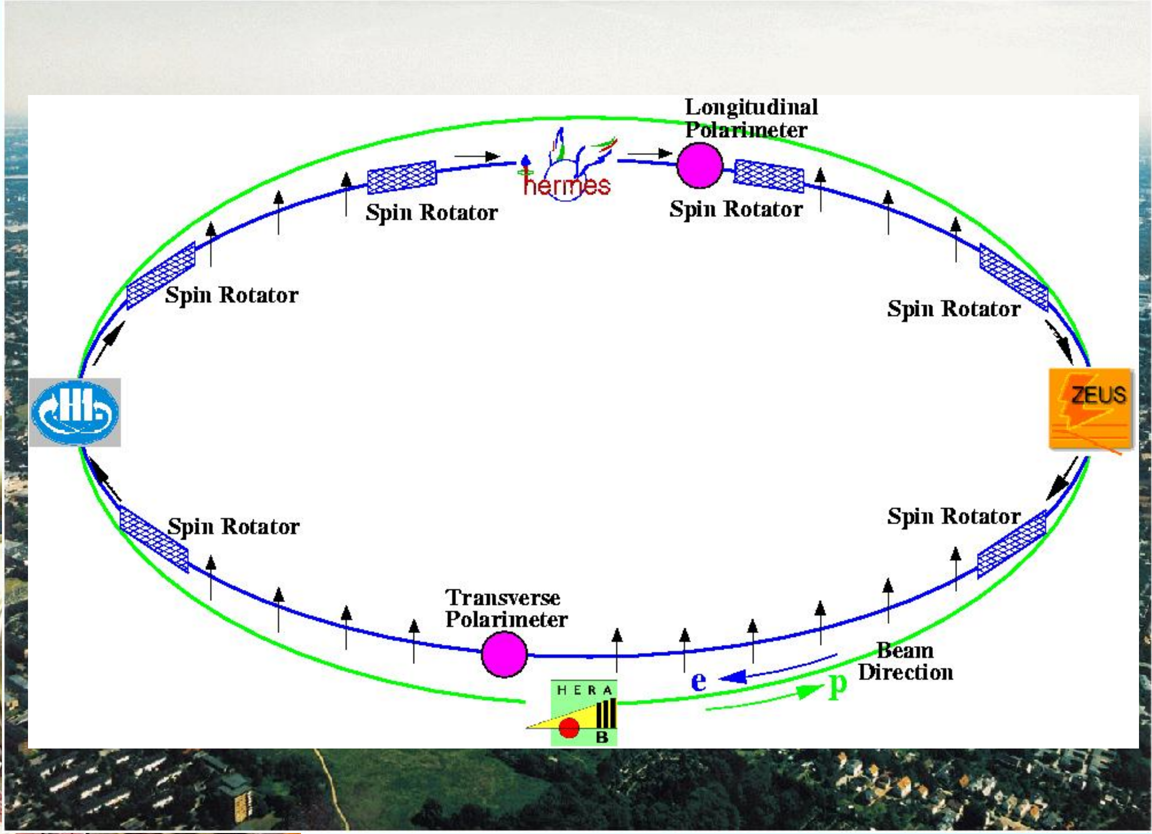

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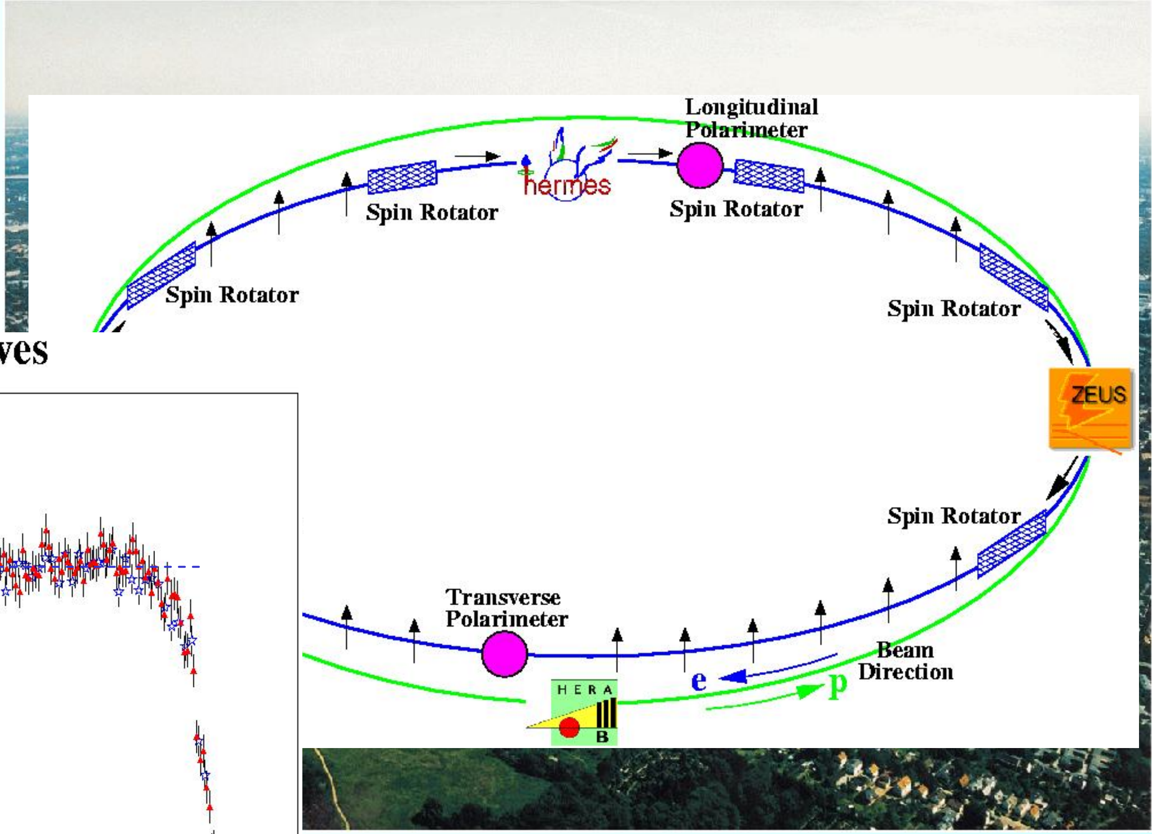
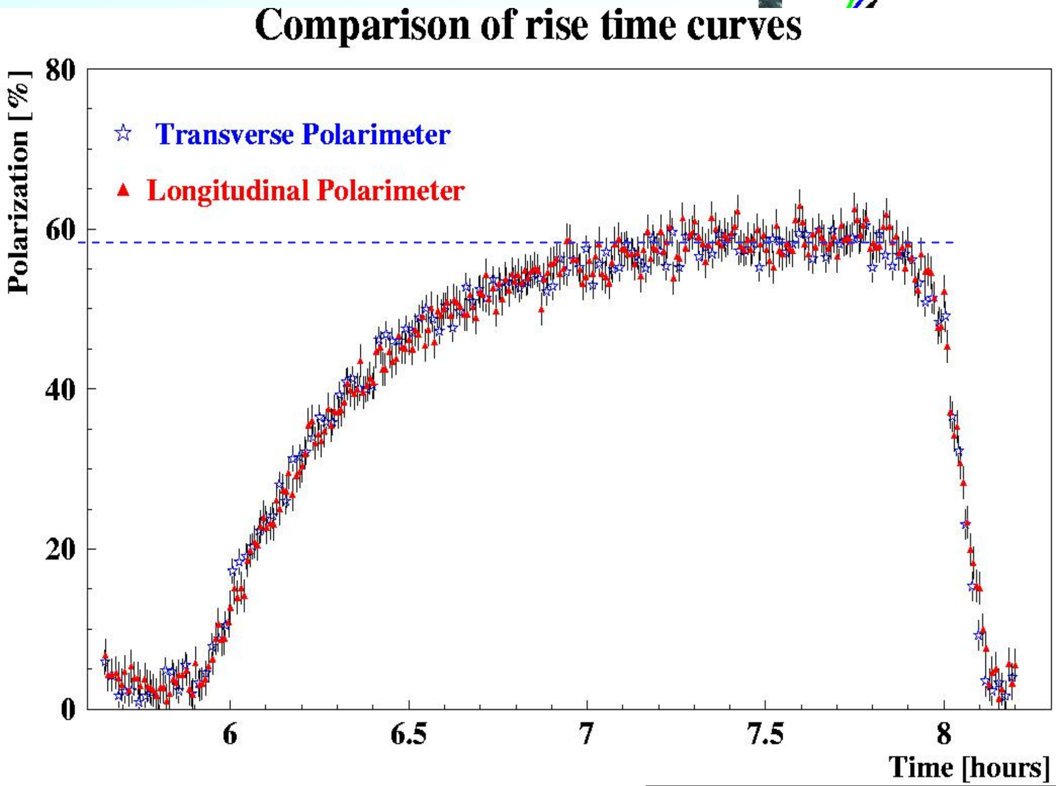
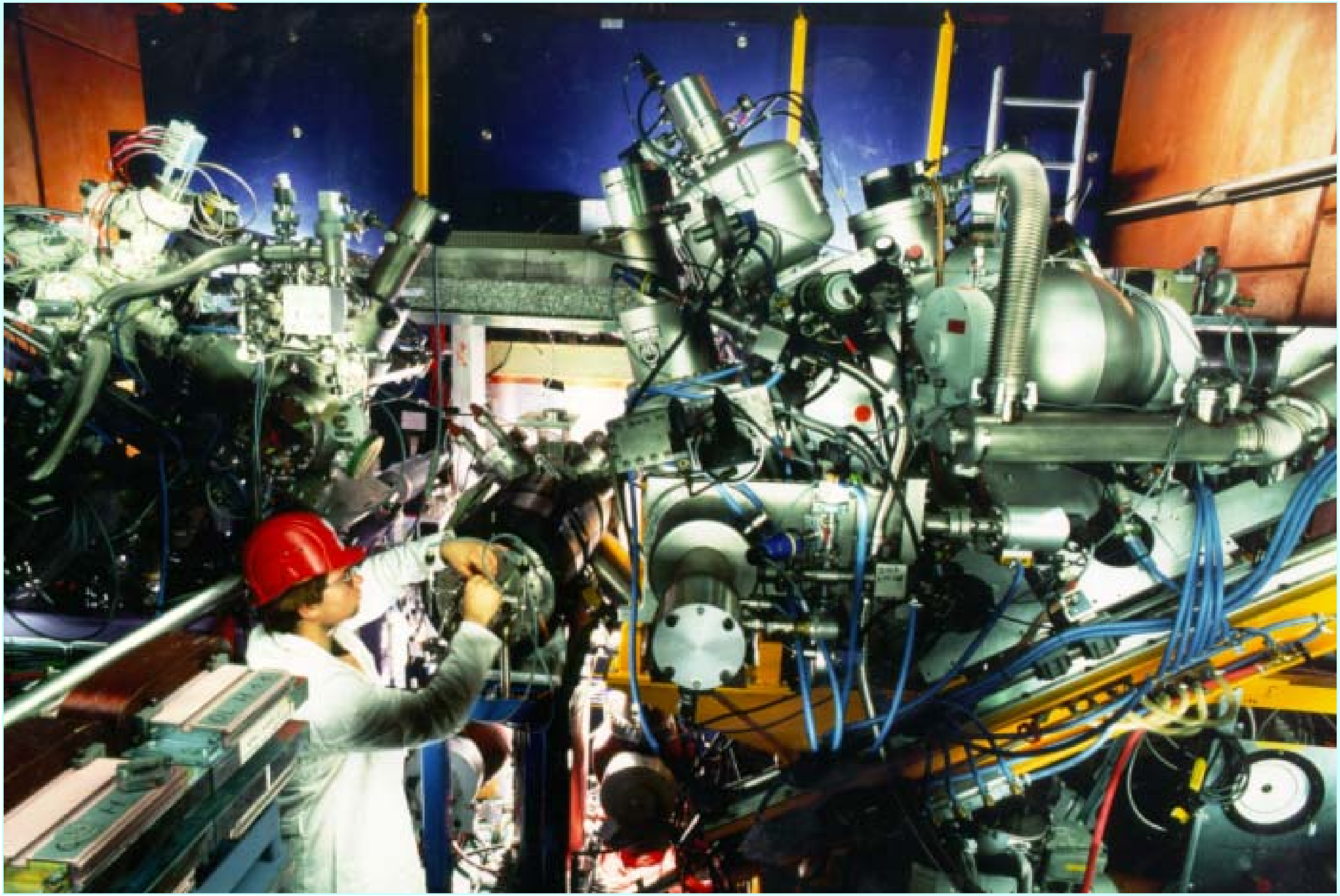


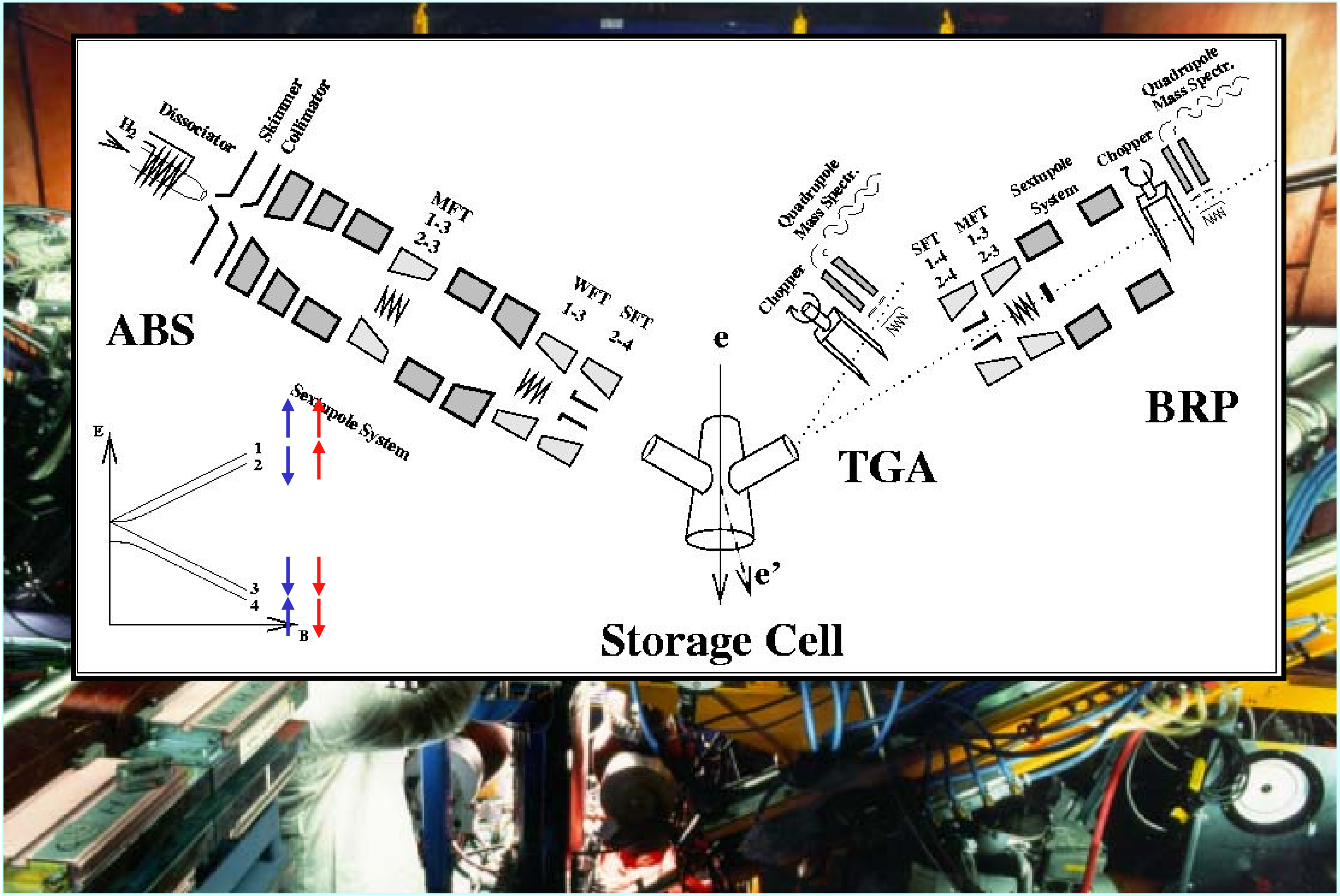


The polarised atomic gas target



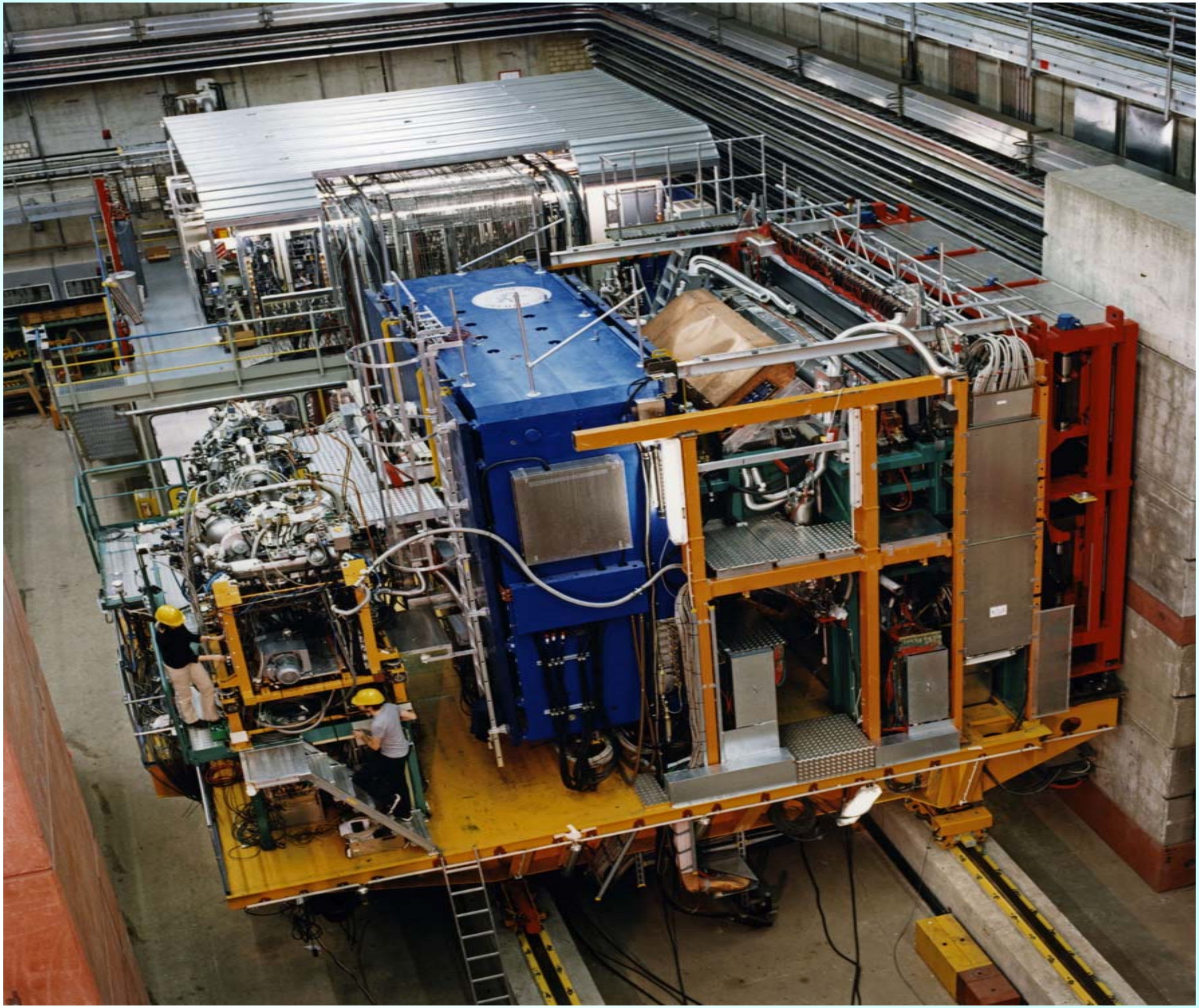
Target polarisation: $P_T \approx 0.85$

The polarised atomic gas target



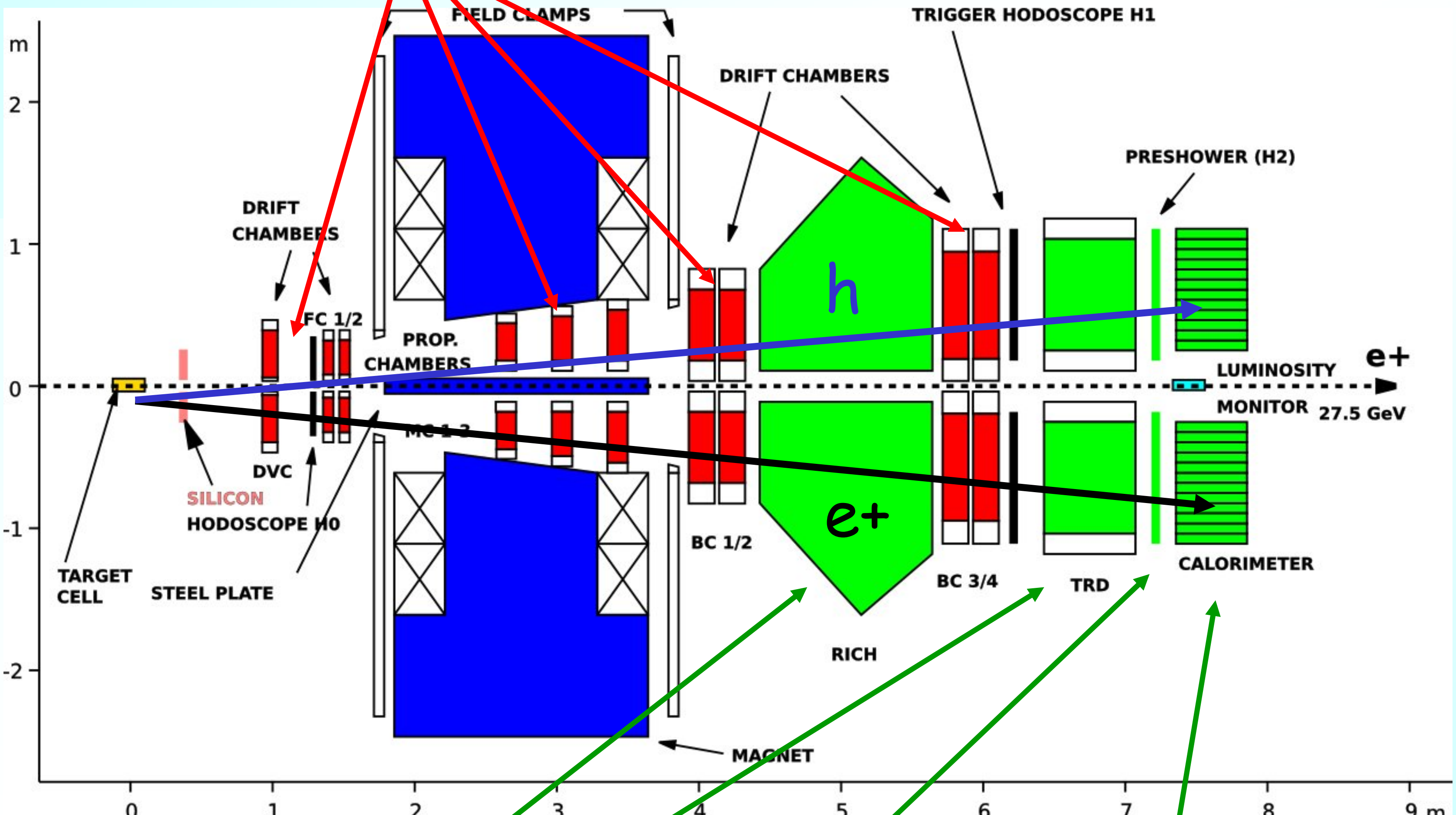
Target polarisation: $P_T \approx 0.85$

HERMES Spectrometer

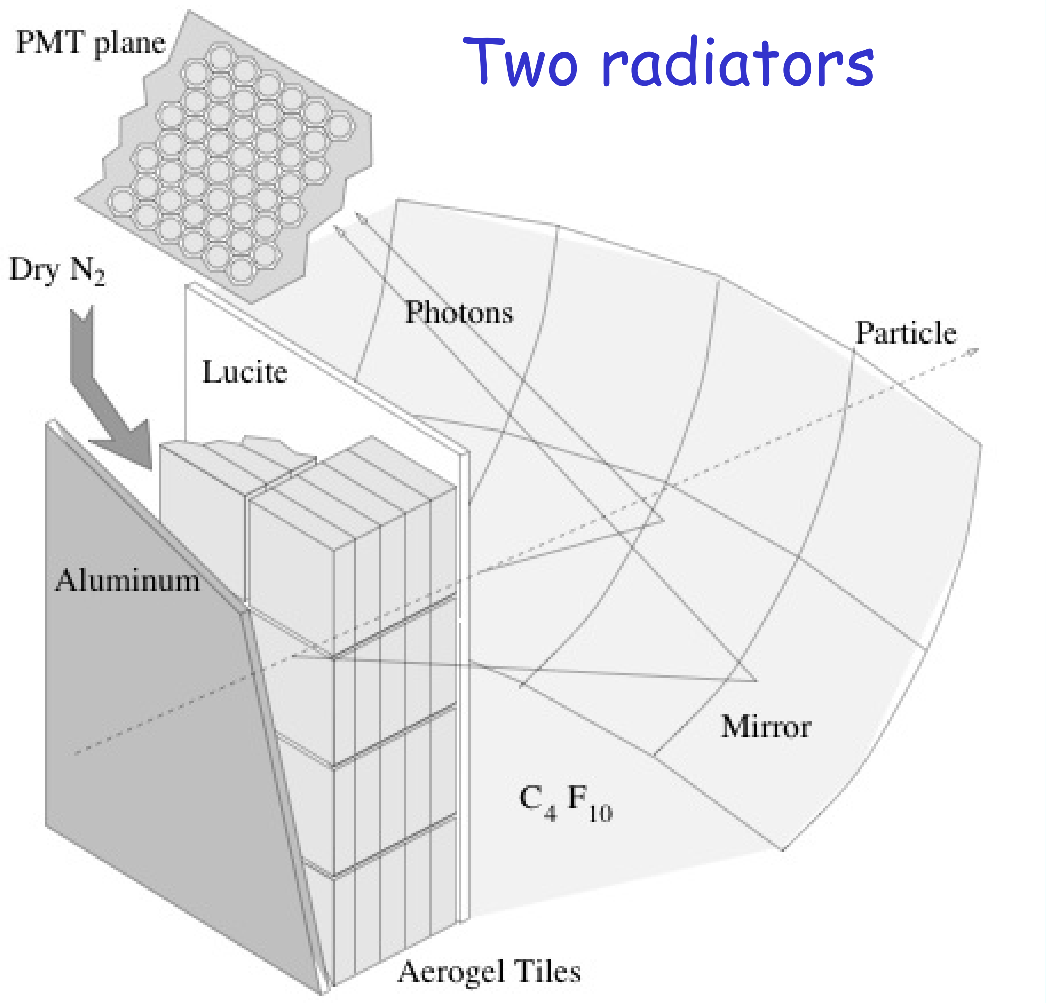


HERMES spectrometer

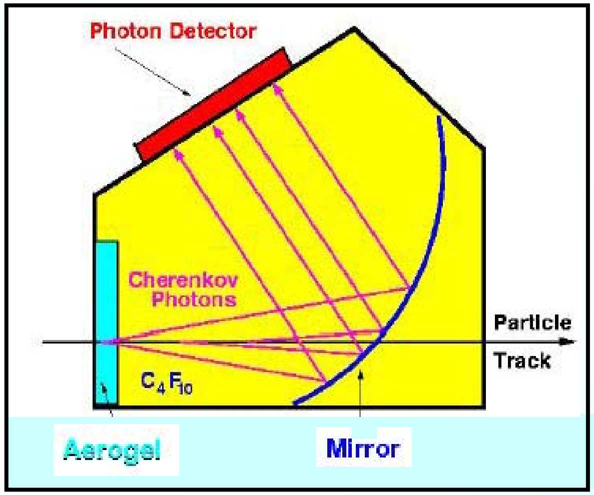
- tracking: δp/p~2%, δΘ<0.6 mrad, 40-220 mrad



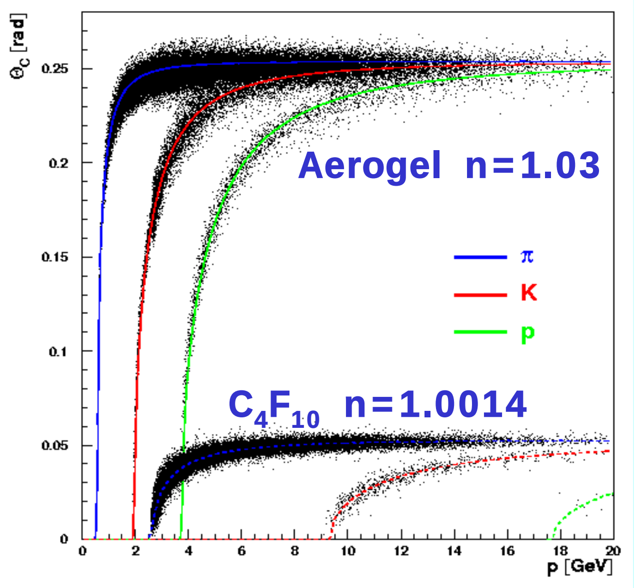
- PID: RICH, TRD, Preshower, Calorimeter
  lepton-hadron separation > 98%



Two radiators



hadron separation



Hadron: π ~ 98%, K ~ 88% , P ~ 85%

Data taking

1995-2000: Longitudinal target polarisation

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

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

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

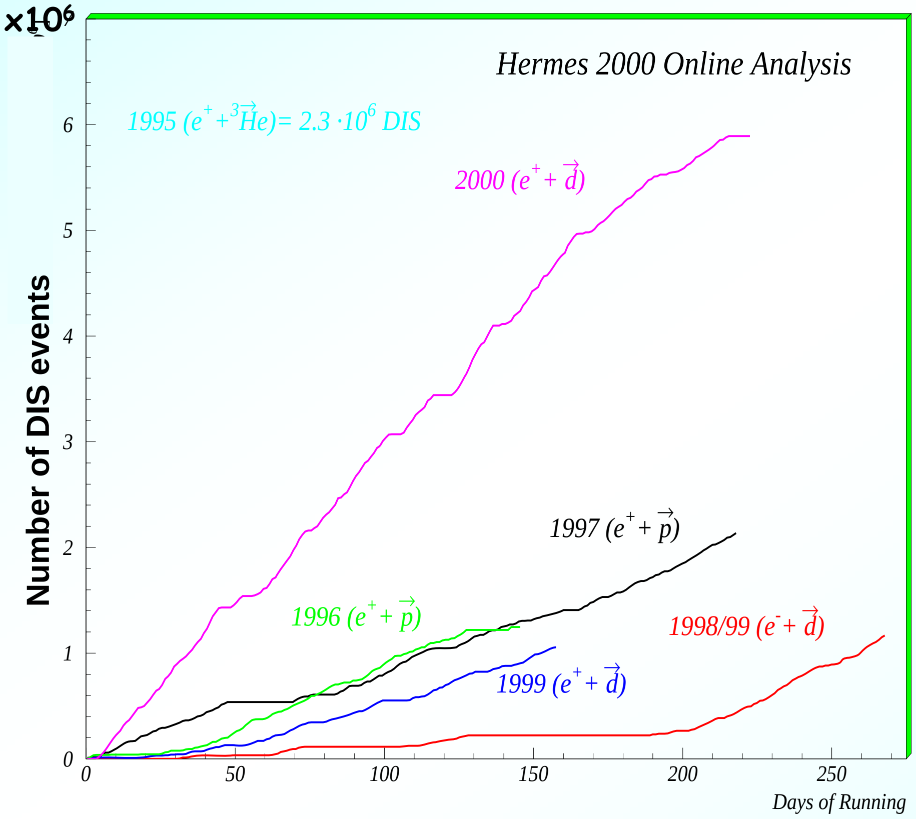
+ unpolarised targets

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

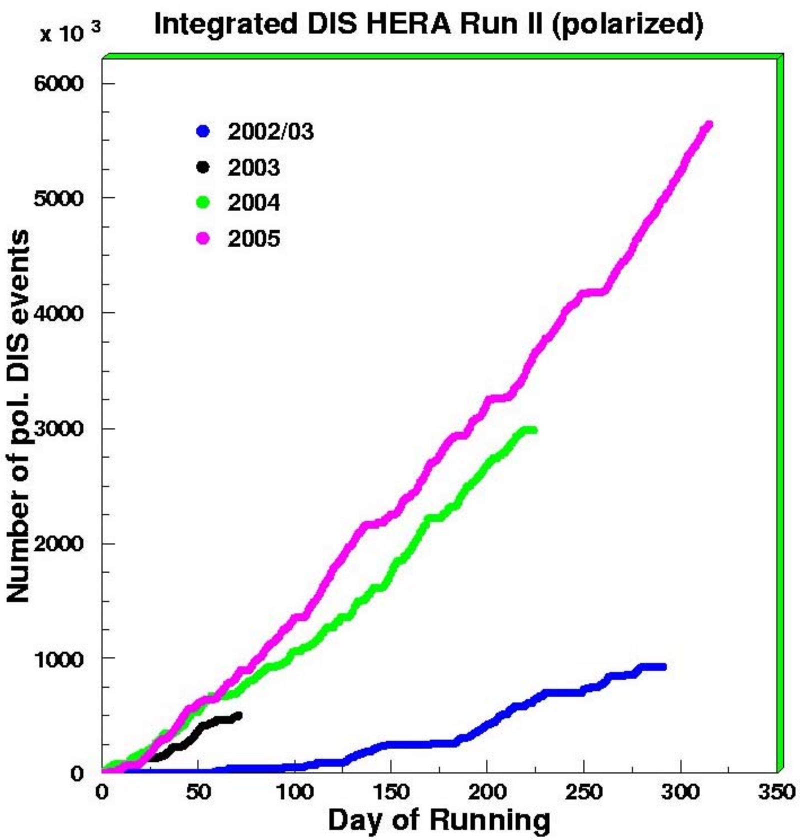
exclusive reactions

Data taking with polarised targets

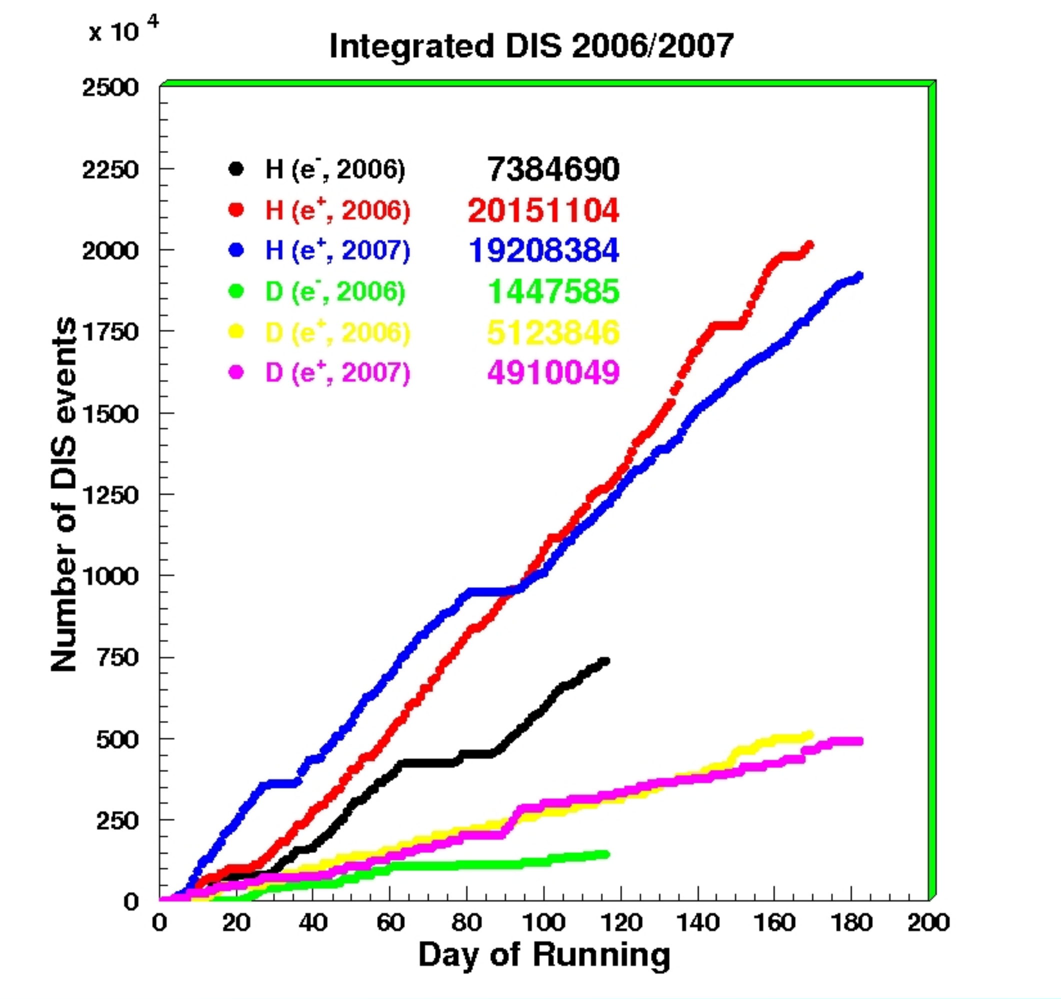
- Longitudinal target polarisation (1995-2000)



- Transverse target polarisation (2002-2005)



Data taking with recoil detector



Determination of $\Delta\Sigma$

The Asymmetry $A_1 \cong g_1/F_1$

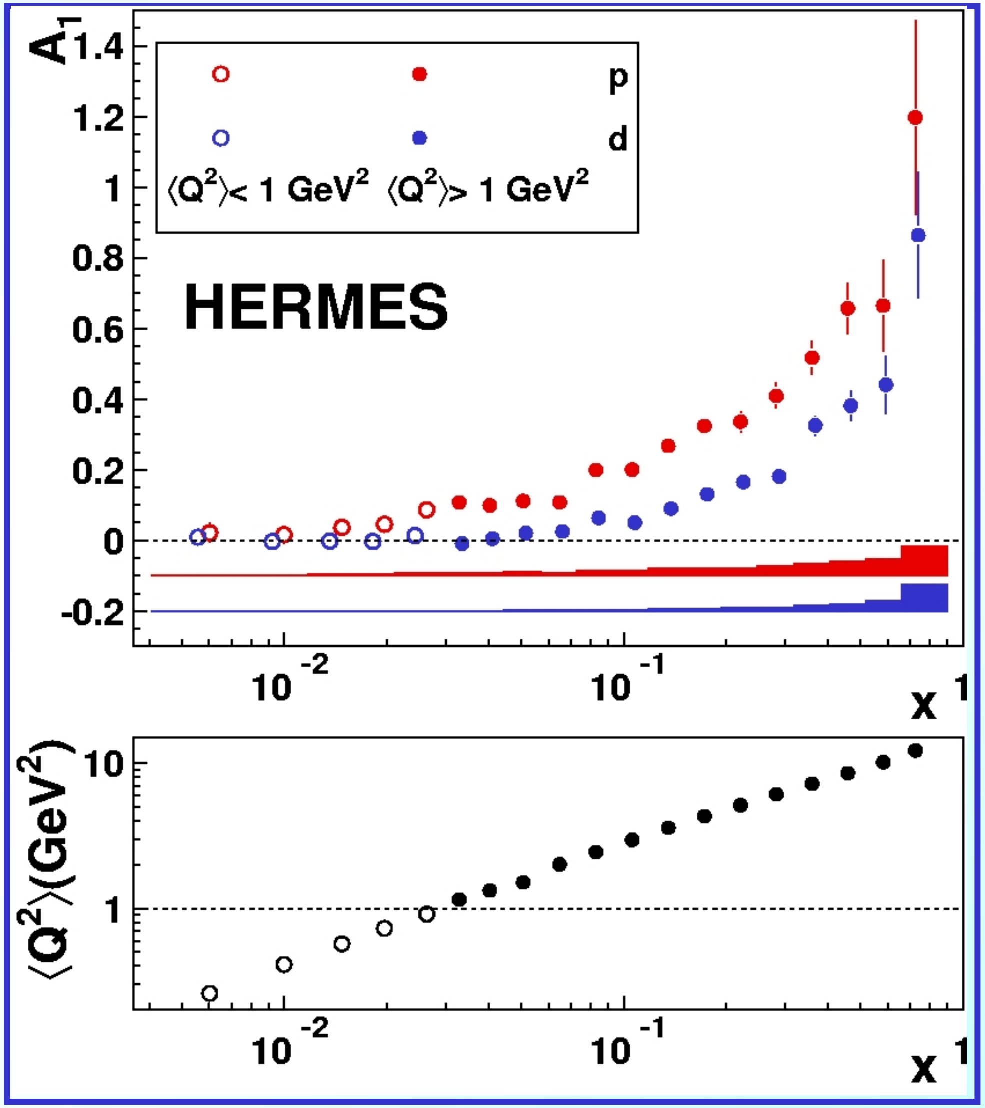
beam target

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

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

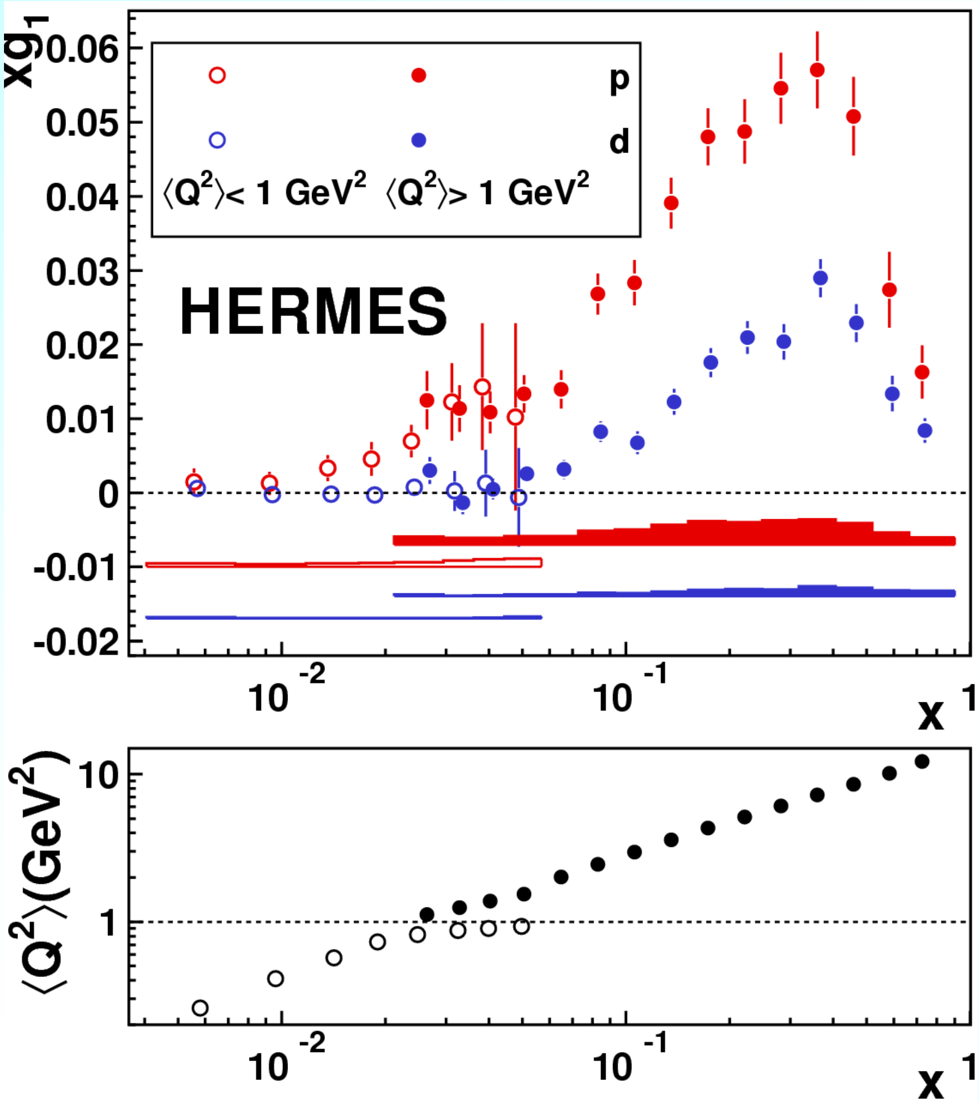
$$= \frac{g_1(x)}{F_1(x)}$$

P. R. D 75 (2007) 012007



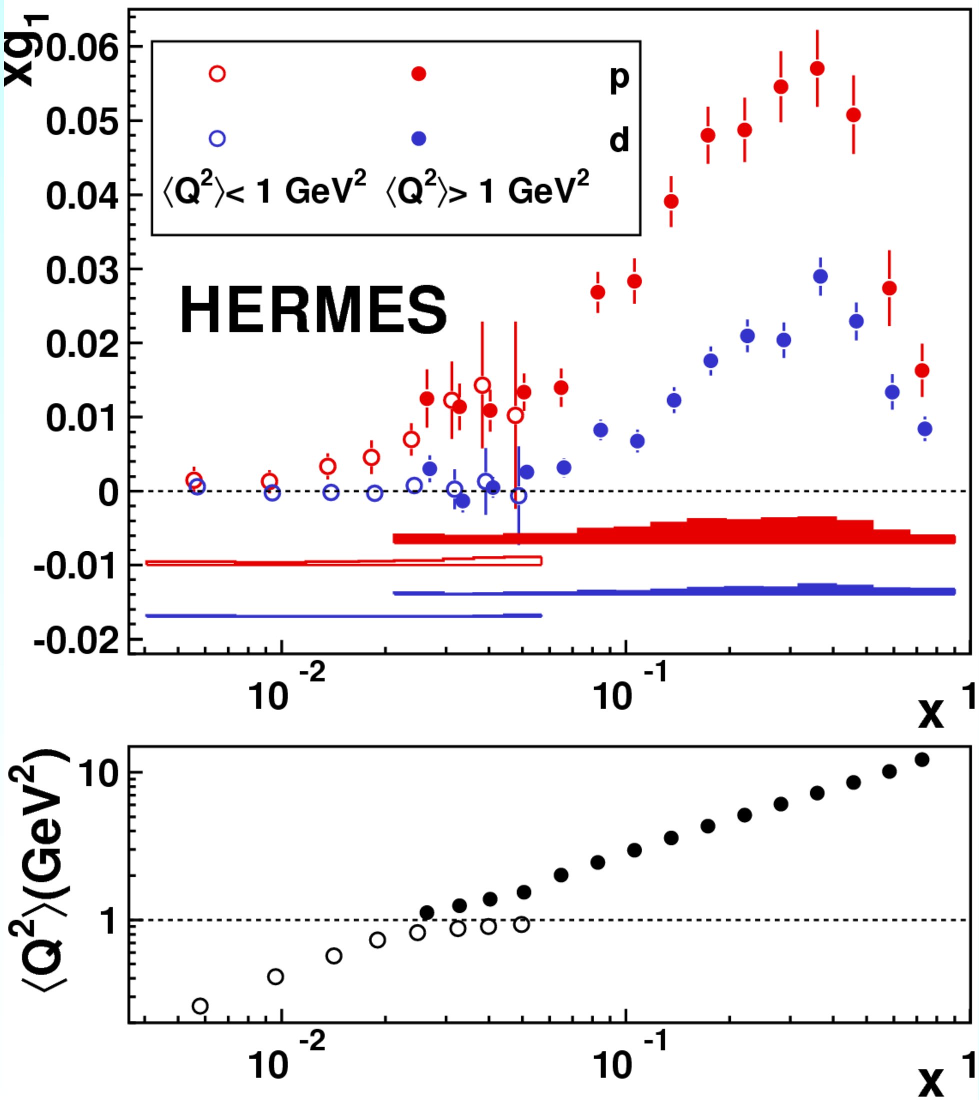
$g_1(x)$

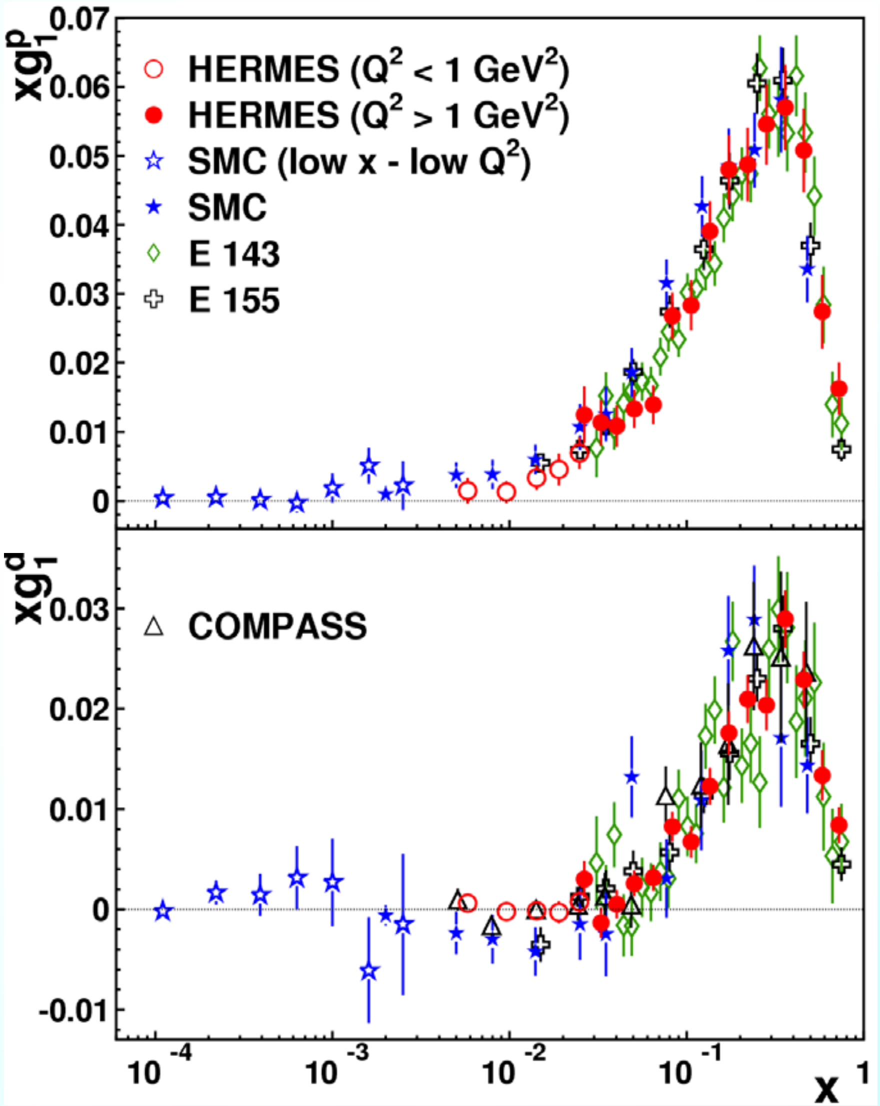
P. R. D 75 (2007) 012007



$g_1(x)$

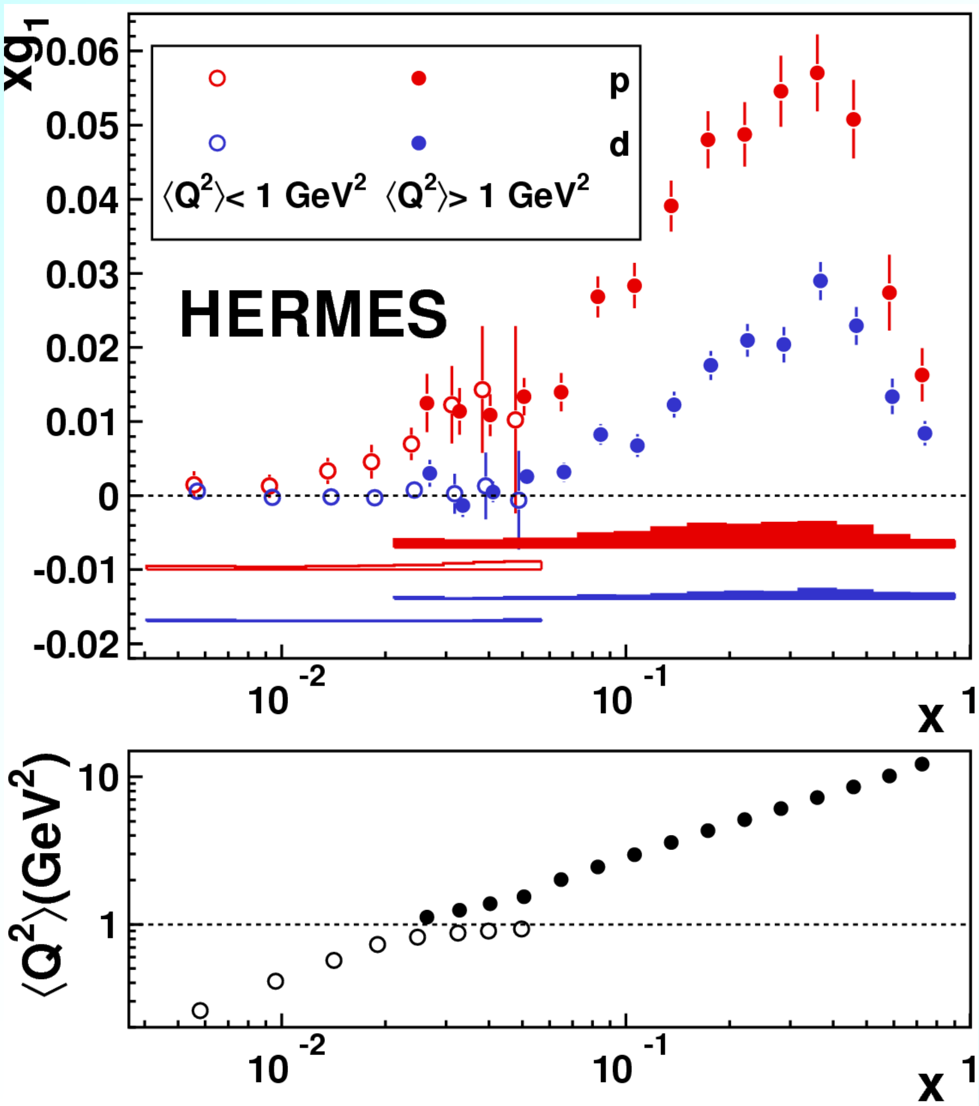
P. R. D 75 (2007) 012007

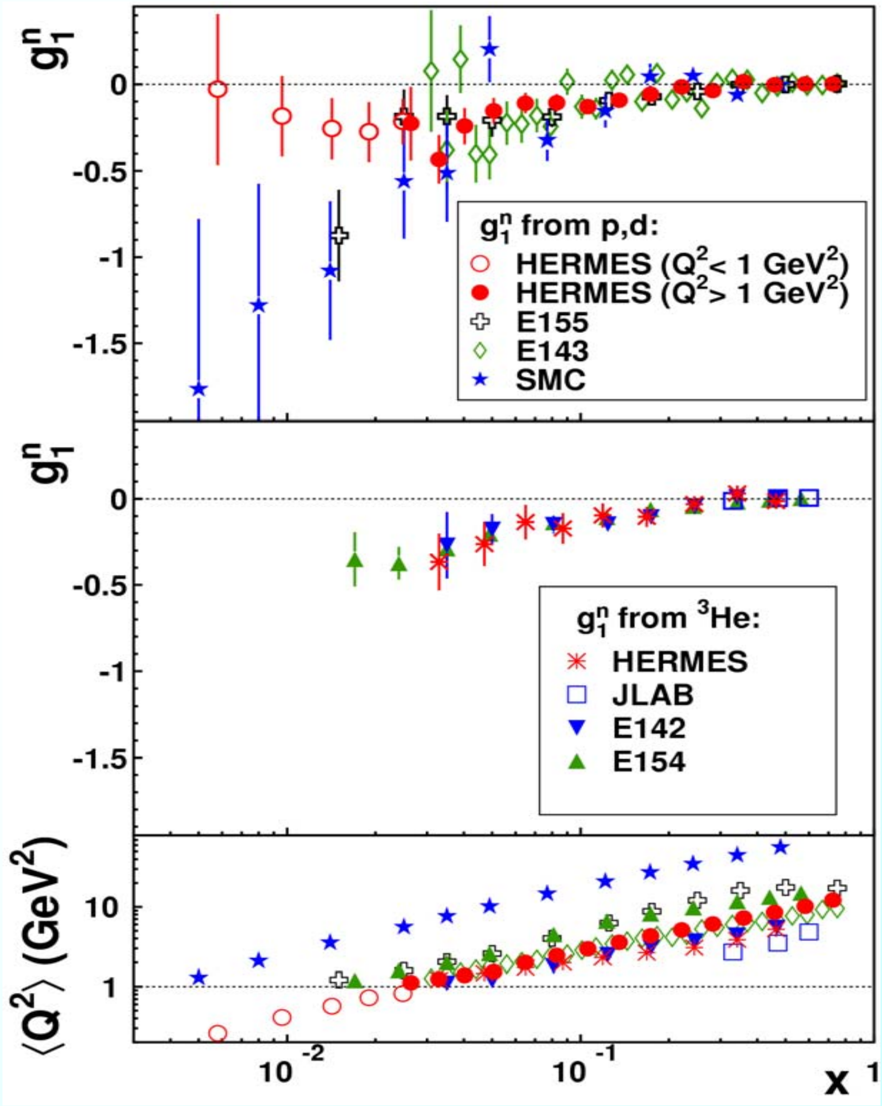




$g_1(x)$

P. R. D 75 (2007) 012007



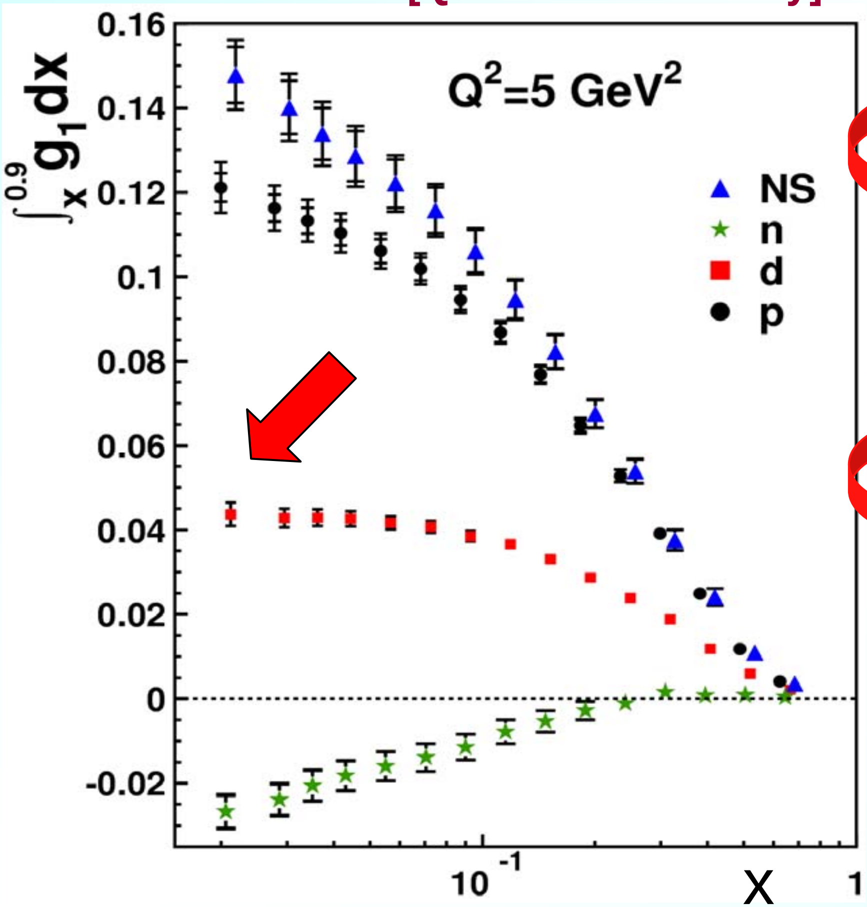


Integrals, $\Delta\Sigma$

Most precise determination of $\Delta\Sigma$

P. R. D 75 (2007) 012007

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



Assumption: Γ_1^d saturates for $x<0.05$

(supported by COMPASS data at lower x)

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

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

$$\Delta\Sigma^{\overline{MS}} = 0{,}330 \pm 0{,}025^{(exp)} \pm 0{,}011^{(theory)} \pm 0{,}028^{(evol.)}$$

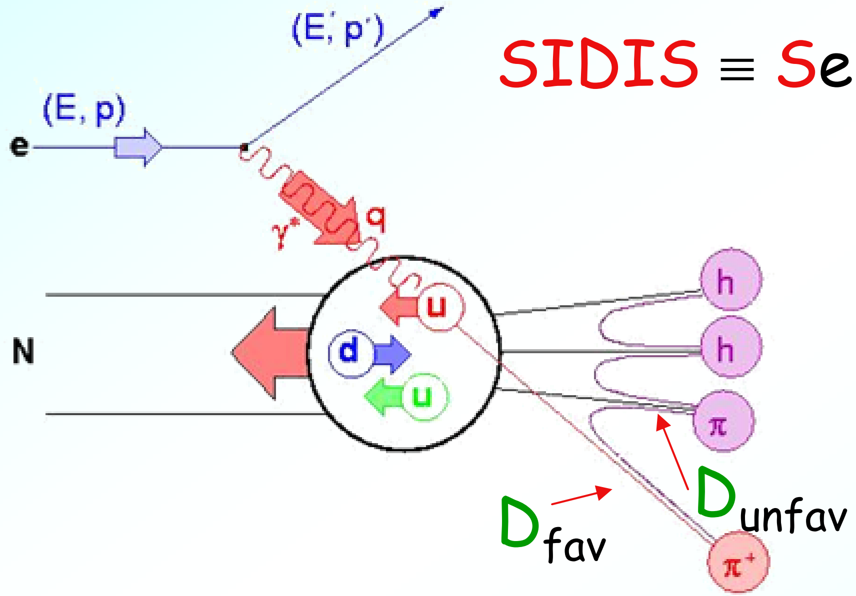
remember:

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

Quark helicity distributions

$\Delta q(x)$

$\Delta q(x)$ from SIDIS



SIDIS ≡ Semi-Inclusive DIS

Leading hadron originates with large probability from struck quark

$D_q^h(z)$:= Fragmentation function (FF) $z \overset{L.S.}{=} E_h/\nu$

Measure hadron asymmetries

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

Targets: $\vec{H}$, $\vec{D}$; h = $\pi^\pm$, $K^\pm$, p (identified with RICH)

Semi-inclusive asymmetries

In leading order QCD:

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

$$= \sum_q \frac{e_q^2 q(x)\, D_q^h(z)}{\sum_{q'} e_{q'}^2 q'(x)\, D_{q'}^h(z)} \frac{\Delta q(x)}{q(x)}$$

Quark-'Purity' P^h_q

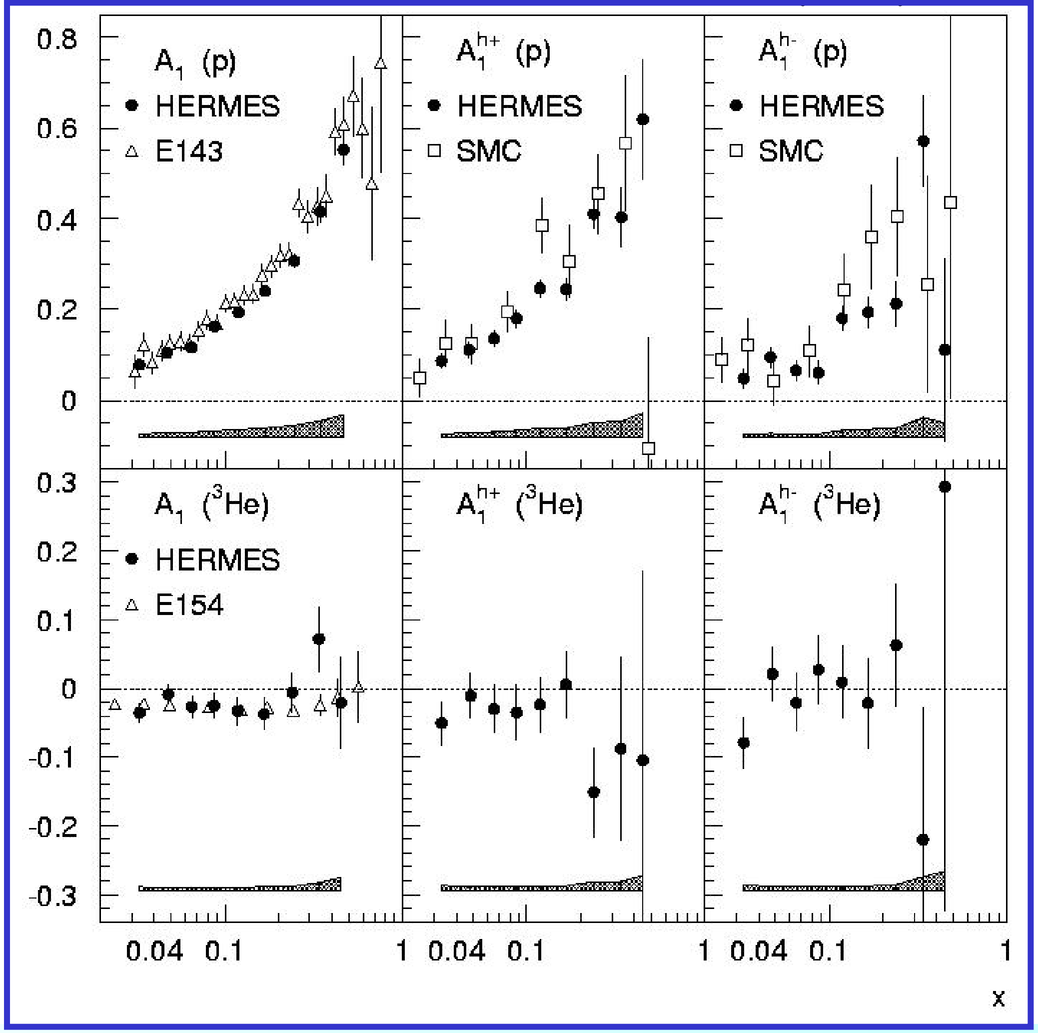
Different targets and hadrons h:

Solve linear system for $\vec{Q}$ with

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

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

P.L. B 464 (1999) 123

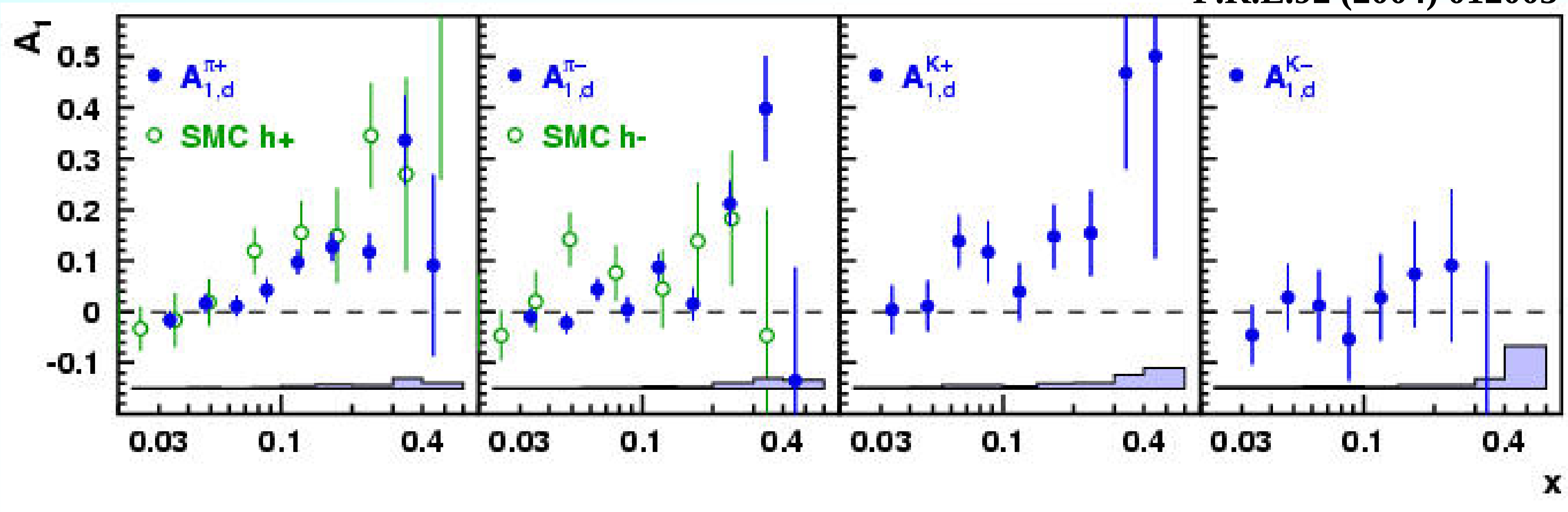


Semi-inclusive asymmetries

- π, K, p asymmetries identified with RICH

Pions | Kaons

P.R.L.92 (2004) 012005



- Statistics sufficient for 5-parameter-fit

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

PURITIES

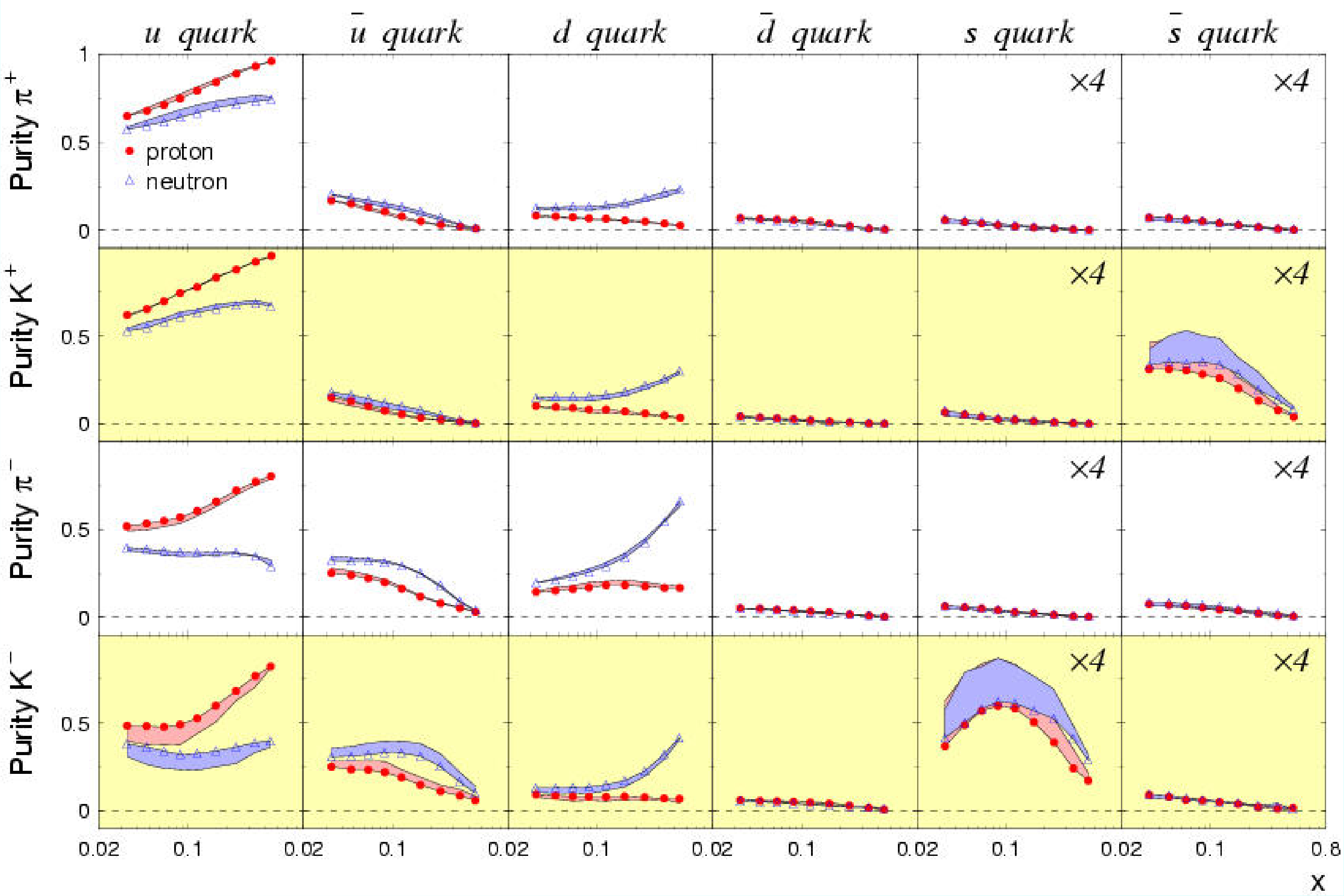
(Probability that observed hadron originates from quark of type q)

$\pi+ \equiv (u\bar{d})$

$K+ \equiv (u\bar{s})$

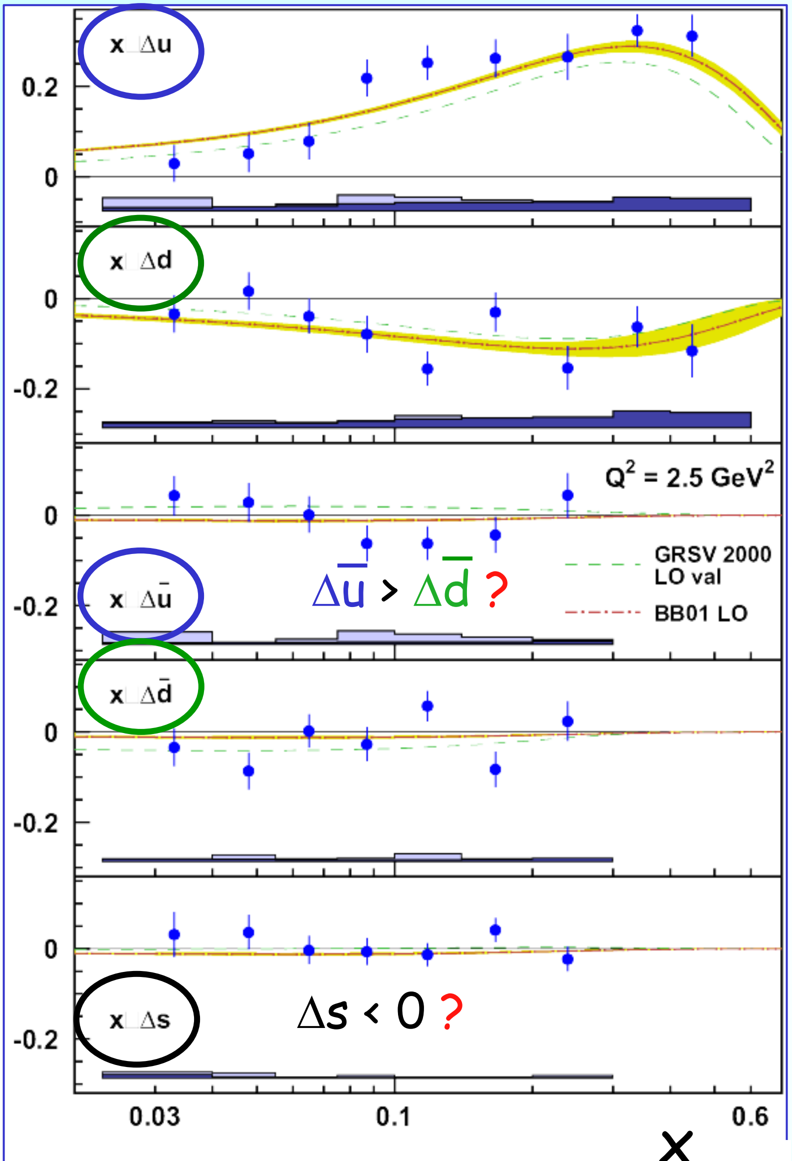
$\pi- \equiv (d\bar{u})$

$K- \equiv (s\bar{u})$



Quark helicity distributions

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



- u quarks: large positive polarisation
- d quarks: negative polarisation

  $\Delta d(x) \cong -\ 0.4\ \Delta u(x)$ (!?)

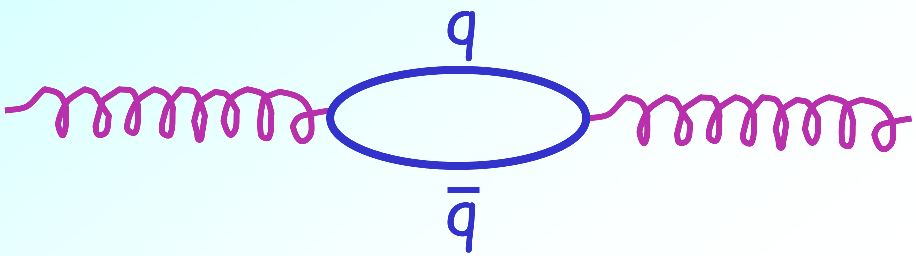
- Sea quarks ($\bar{u}$, $\bar{d}$, s): polarisation compatible with 0.

Gluon helicity distribution

$\Delta g(x)$

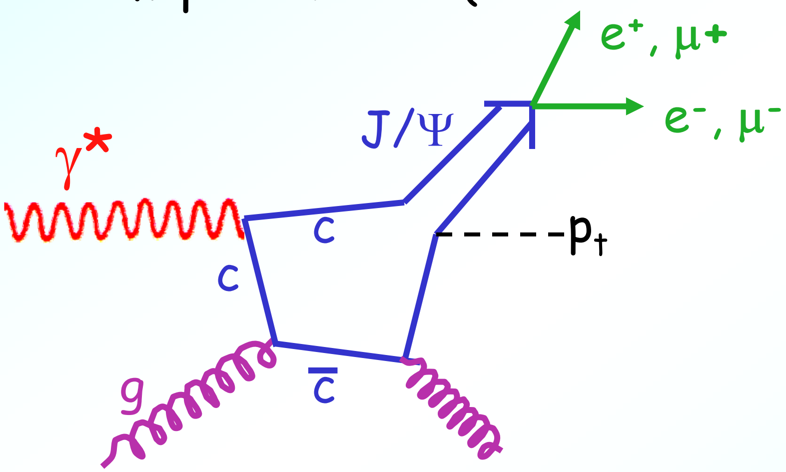
Direct determination of $\Delta g/g$

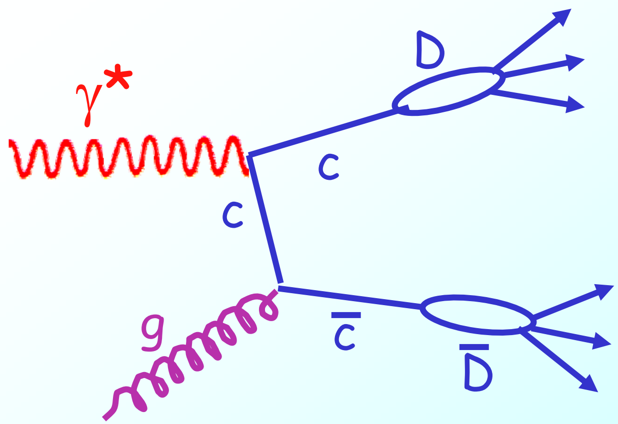
Method: Photon-Gluon-Fusion



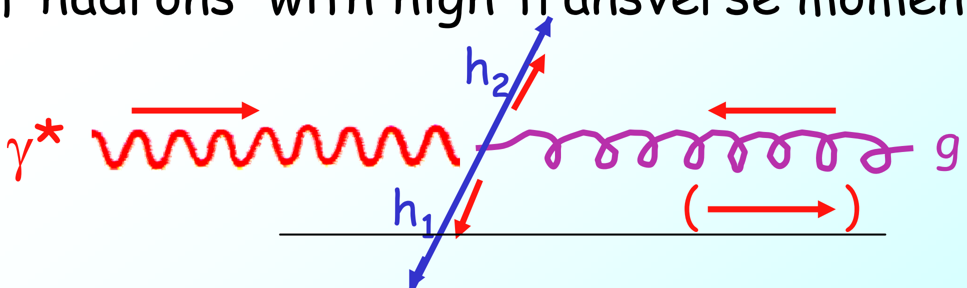
$\Delta t \sim \hbar/2m_q$

- Charm-production (Hard scale: mass of c-Quarks)





- (Pairs) of hadrons with high transverse momenta (Hard scale: p_t)



Direct determination of $\Delta g/g$

Data: Deuteron target

- Single hadron with high transverse momentum
- No scattered electron in acceptance

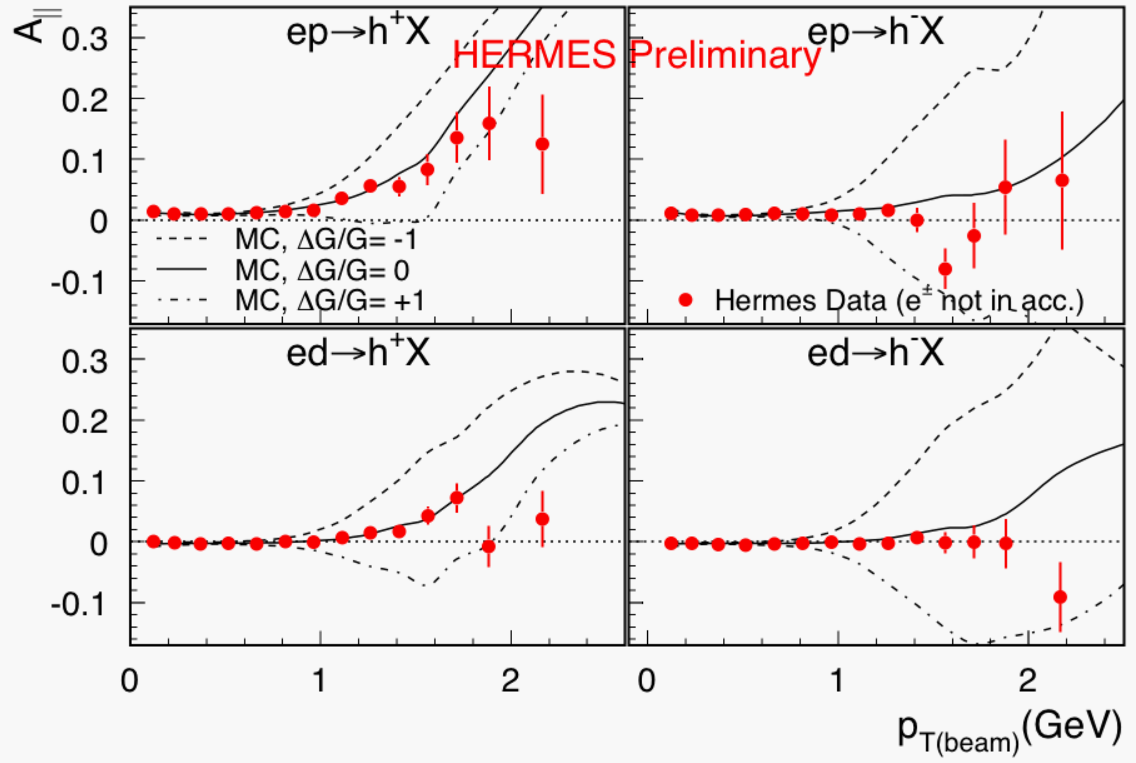
MC: PYTHIA 6.2

- Simulation of total ep cross section
- Determination of relative contributions R of sub-processes

  - Vector mesons
  - anomalous ($\gamma^* \rightarrow \bar{q}q$) processes
  - direct photon processes (PGF, QCDC)
  - LO DIS (γ^* q$\rightarrow$ q)

  and their asymmetries

Measured asymmetries



Comparison of measured asymmetries with those from MC for:

$\Delta g/g = 0$ (middle curve) (contribution of quarks)
$\Delta g/g = -1$ (upper curve)
$\Delta g/g = +1$ (lower curve)

Determination of $\Delta g/g$:

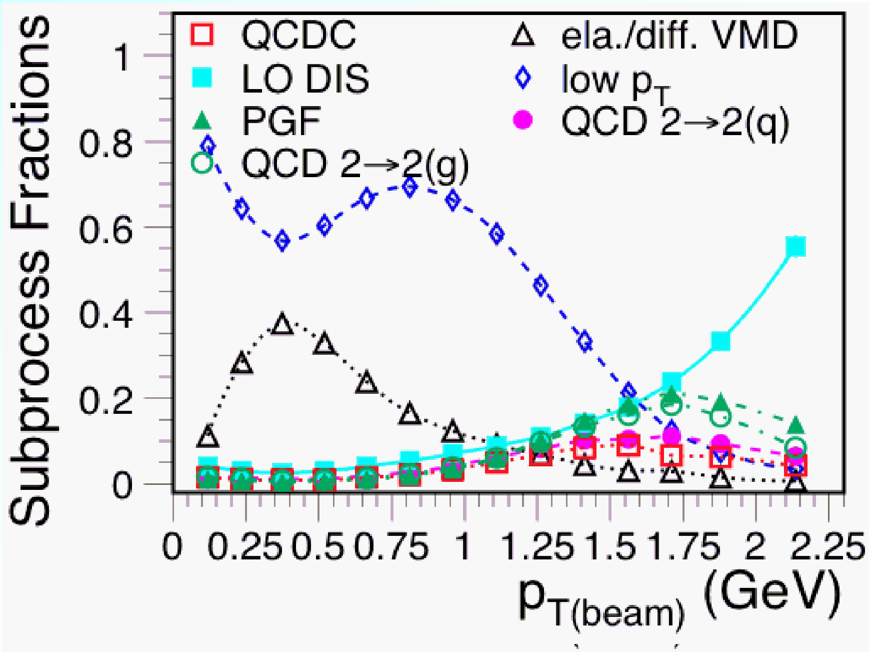
$$A_{\parallel}^{sig} \approx \langle \hat{a} \rangle (p_T) \left\langle \frac{\Delta g}{g} \right\rangle (p_T)$$

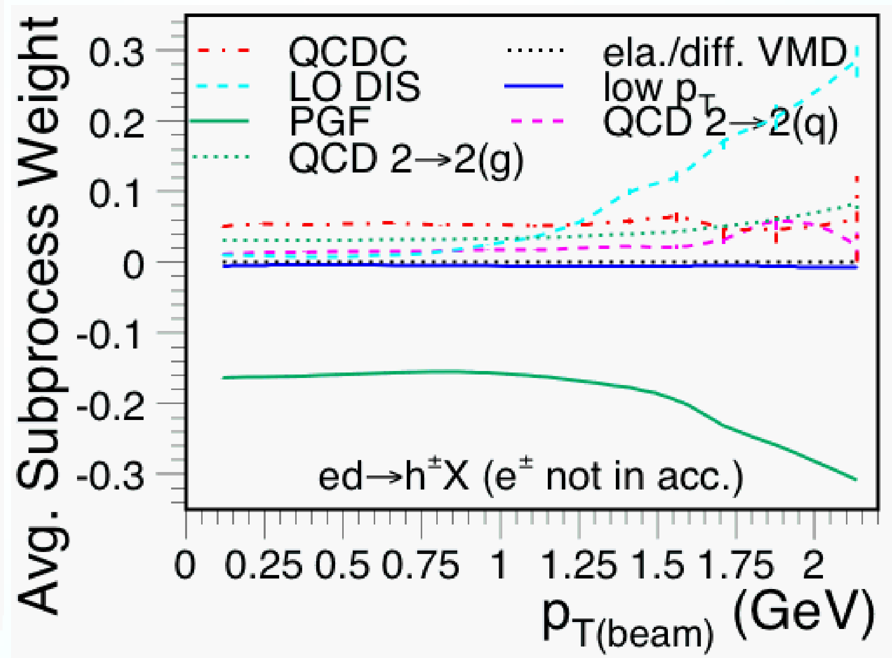
$$\left\langle \frac{\Delta g}{g} \right\rangle (p_T) = \frac{A_{\parallel}^{meas} - R_{BG} A_{BG}}{R_{sig} \langle \hat{a} \rangle}$$

Sub-processes

sub-process contributions R

sub-process asymmetries (with GRSV std.)

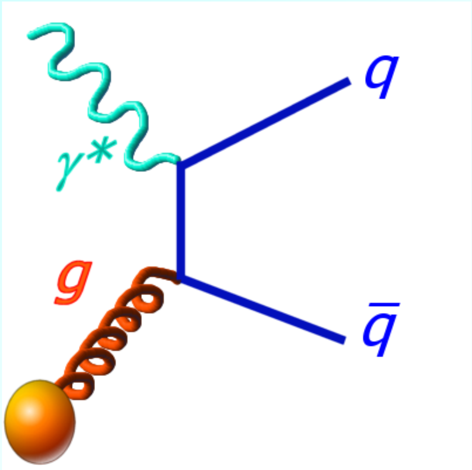


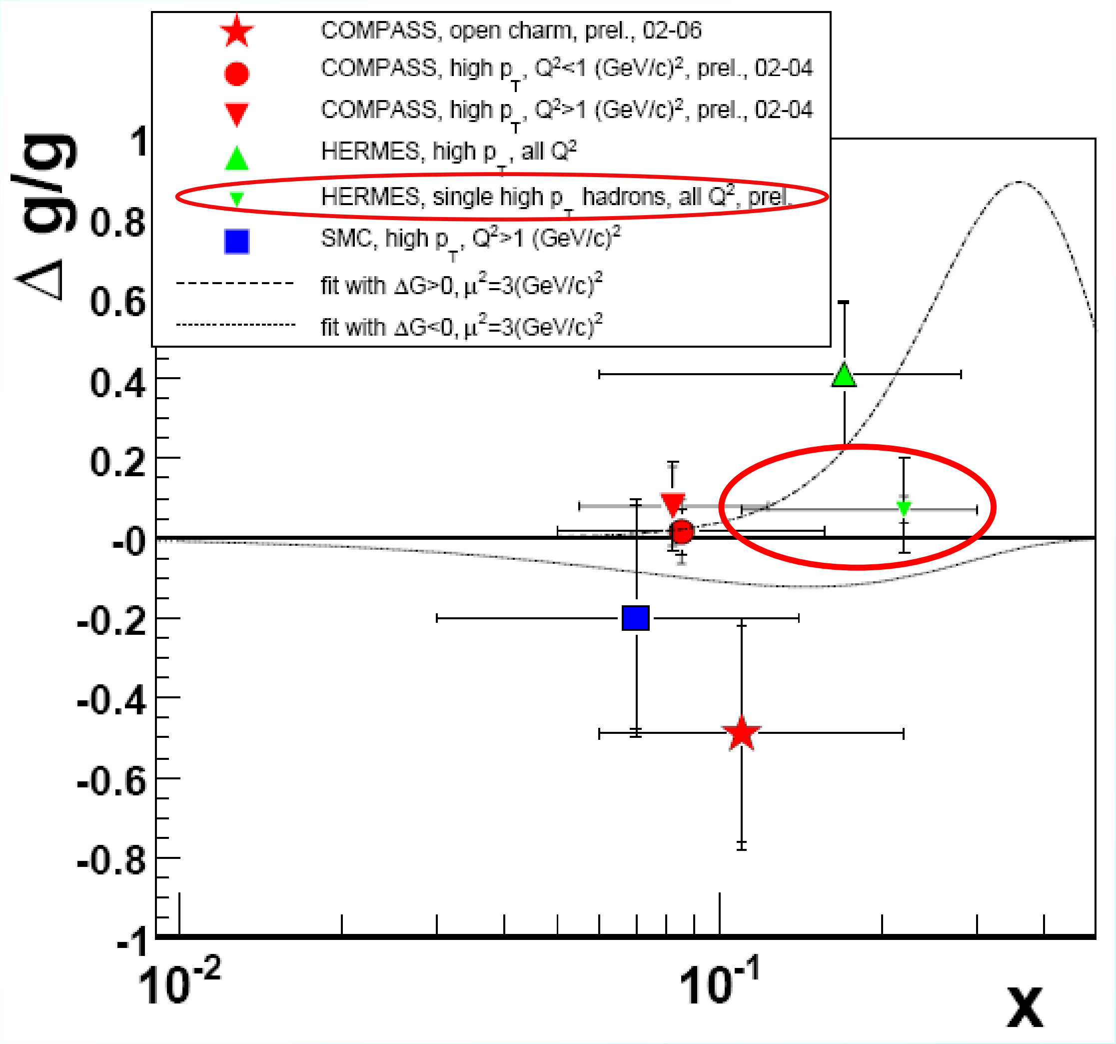


- VMD decreases with p_T
- DIS increases with p_T
- Hard QCD2->2(q) small contrib.
- Signal processes PGF&QCD2->2(g) are about the same size

- DIS increases with p_T (x) - positiv
- |PGF| increases with p_T - negativ
- Alle others flat and small, but:
- important for background-asymmetry!

Direct determination of $\Delta g/g$



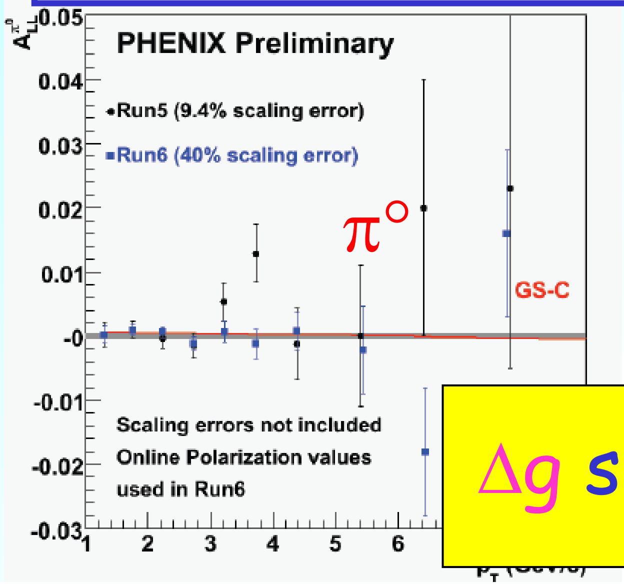


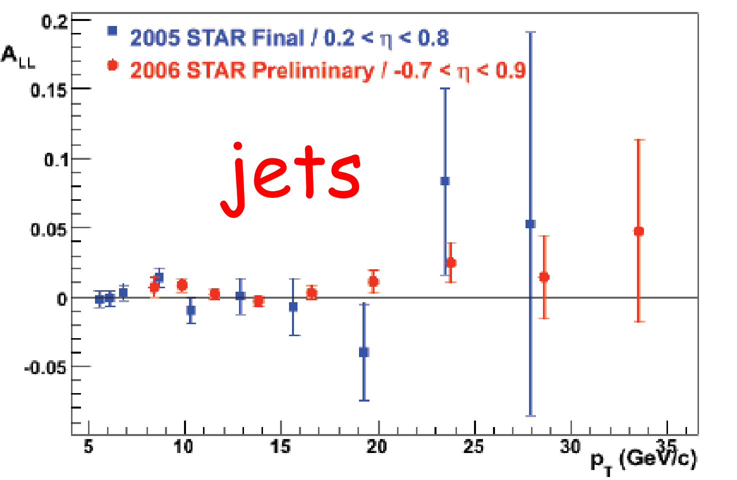
$\langle\mu^2\rangle = 1.35\ \text{GeV}^2$

$$\Delta g/g(x,\mu^2) = 0.071 \pm 0.034^{(stat)} \pm 0.010^{(sys\text{-}exp)}\ {}^{+0.127}_{-0.105}\ (sys\text{-}model)$$

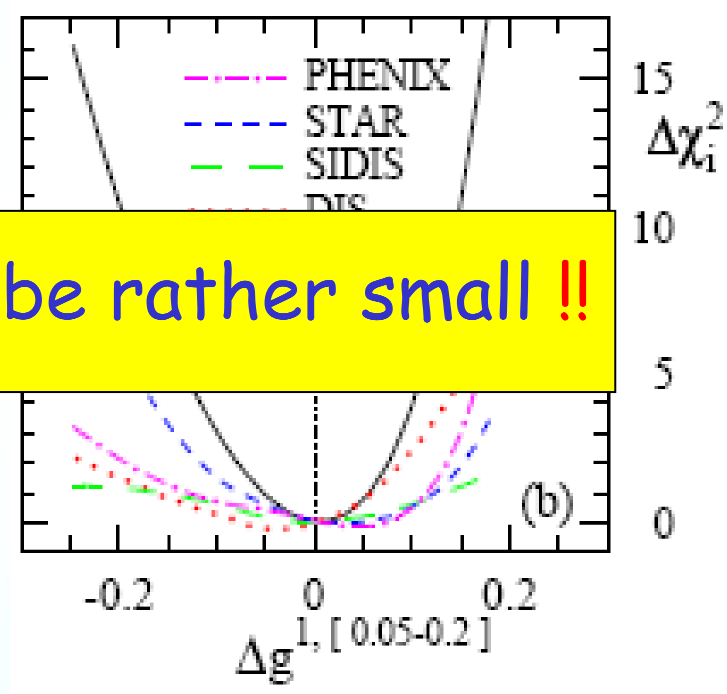
Gluon polarisation

RHIC: $\vec{p}\,\vec{p} \rightarrow \pi^{\circ}$ (jet) X





De Florian et al.: hep-ph/0804.0422



Δg seems to be rather small !!

- 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?

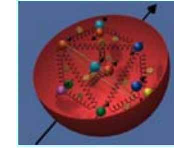
  ➡ EIC

- What is the contribution of orbital angular momenta

  L_q, L_g ???

Transverse spin physics

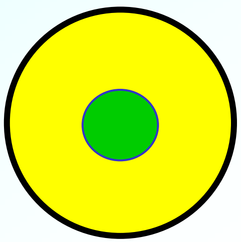
Transversity $\delta q(x)$



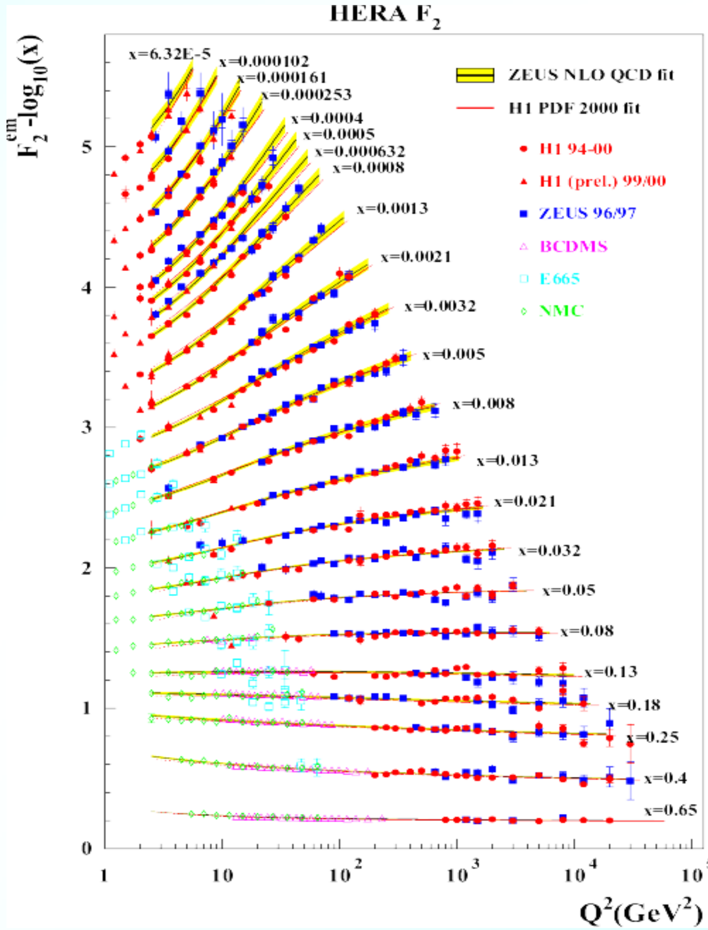
For a complete description of momentum and spin distribution of the nucleon at leading-twist: 3 distribution functions (DF)

Unpolarised DF

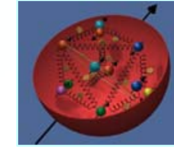
$q(x)$



well known

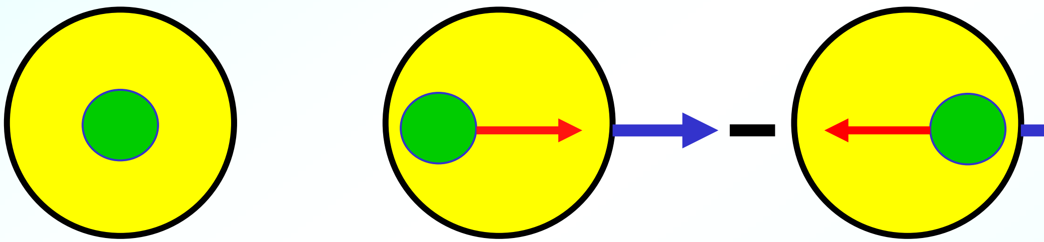


Transversity $\delta q(x)$

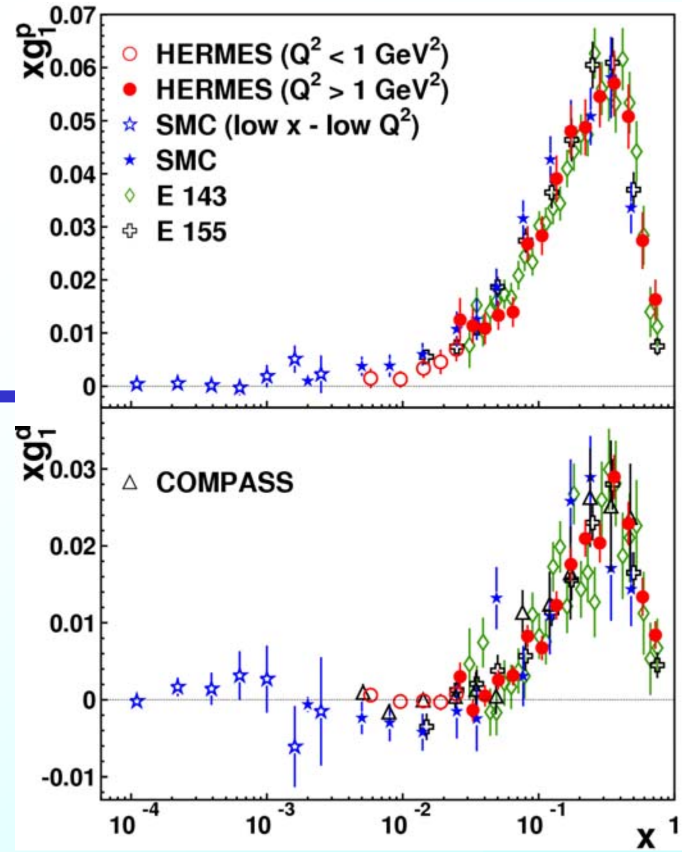


For a complete description of momentum and spin distribution of the nucleon at leading-twist: 3 distribution functions (DF)

Unpolarised DF	Helicity DF
$q(x)$	$\Delta q(x)$



well known | known

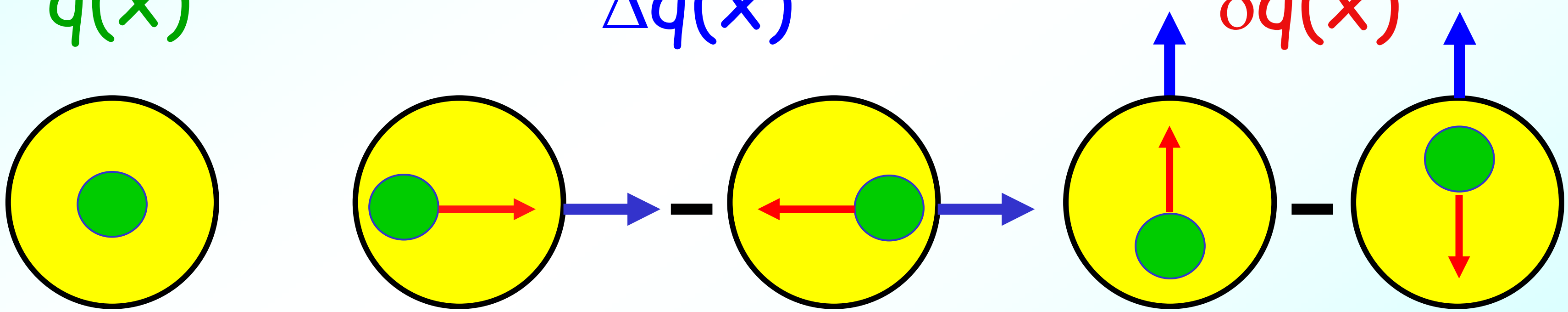


HERMES 1995-2000

Transversity $\delta q(x)$

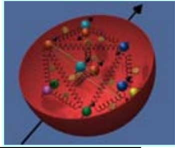
For a complete description of momentum and spin distribution of the nucleon at leading-twist: 3 distribution functions (DF)

Unpolarised DF	Helicity DF	Transversity DF
$q(x)$	$\Delta q(x)$	$\delta q(x)$



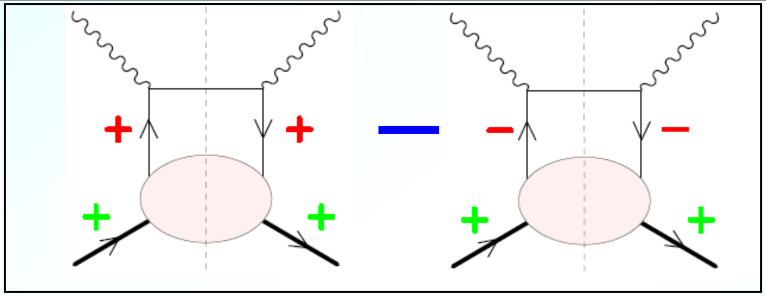
well known	known	unknown before HERMES
	HERMES 1995-2000	HERMES 2002-2005

The transversity distribution



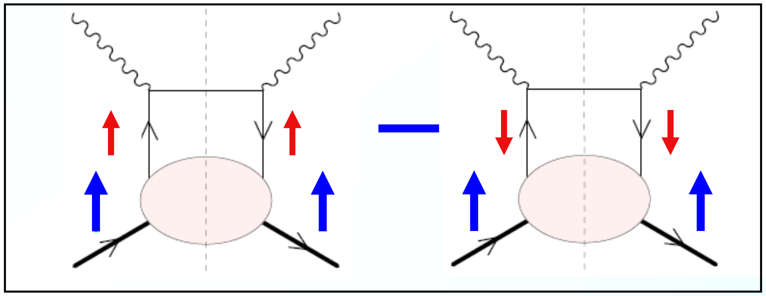
$\Delta q(x,Q^2)$

Helicity basis: $|+\rangle, |-\rangle$



$\delta q(x,Q^2)$

Transverse Spin basis: $|\uparrow\rangle, |\downarrow\rangle$

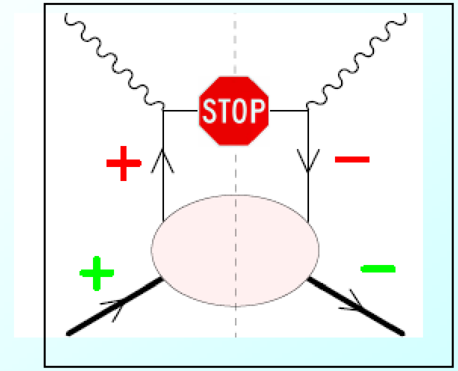


δq is chiral-odd

associated with helicity flip of struck quark

δq in helicity basis:

$$|\uparrow,\downarrow\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle \pm i|-\rangle\right)$$

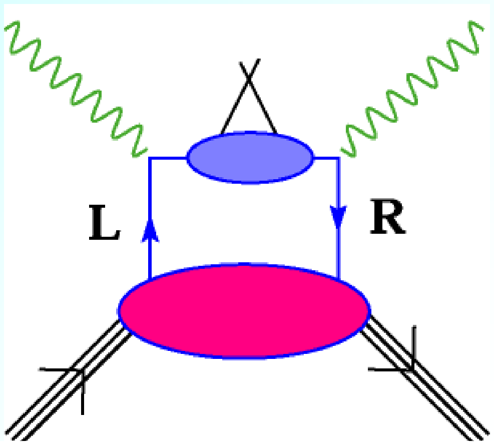


Hard EM and strong interactions cannot flip the chirality of the probed quark

δq is not accessible in inclusive DIS

How to measure transversity

Need another chiral-odd object! ⇒ Semi-Inclusive DIS



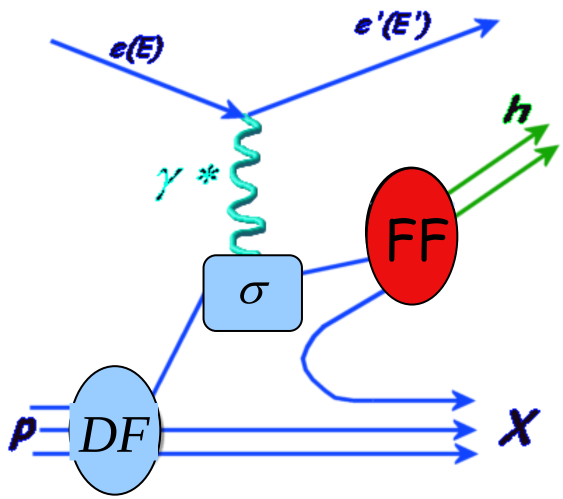
one hadron in the initial state and at least one in the final state (semi-inclusive leptoproduction)

$$\sigma^{ep\to ehX} = \sum_q \delta q \quad \sigma^{eq\to eq} \otimes FF^{q\to h}$$

⇓ **chiral-odd DF**

⇓ **chiral-odd FF**

CHIRAL EVEN

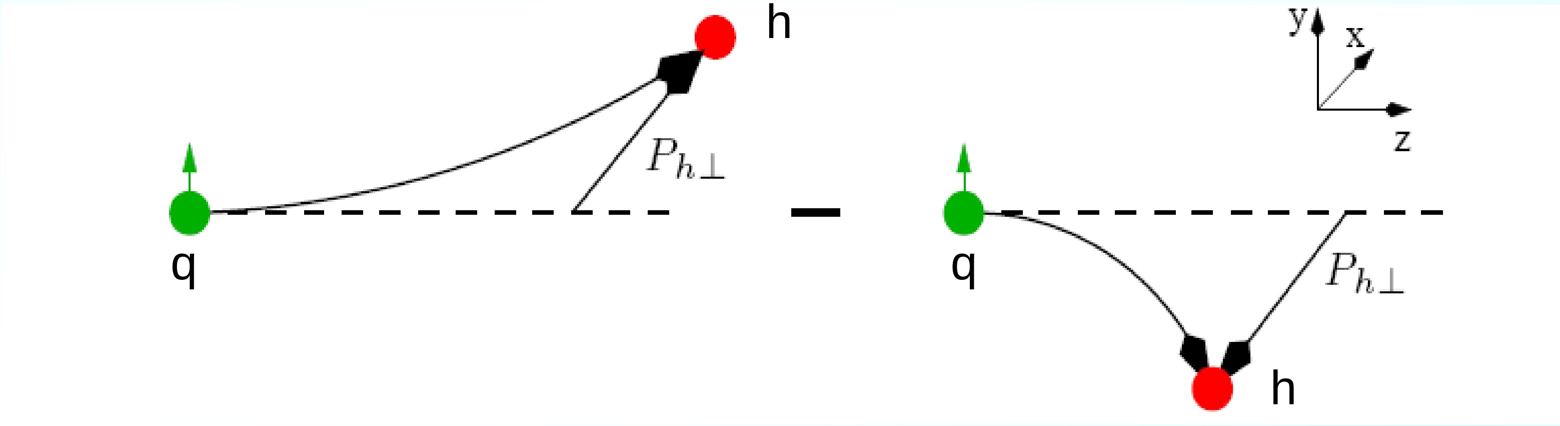


The Collins fragmentation function

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

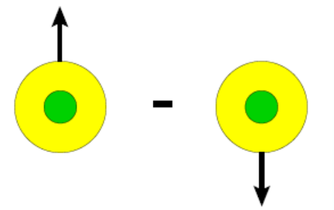
Chiral – odd & naïve T – odd

produces left-right asymmetry in the direction of the outgoing hadron



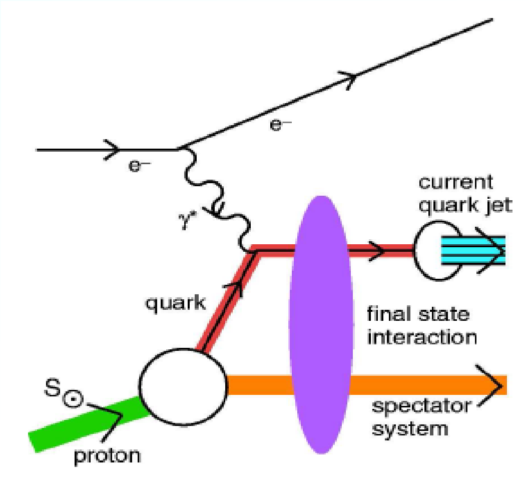
The Sivers distribution function f_{1T}

- 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

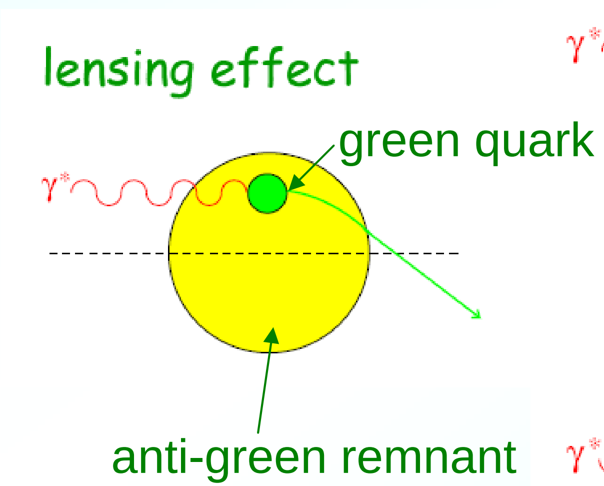


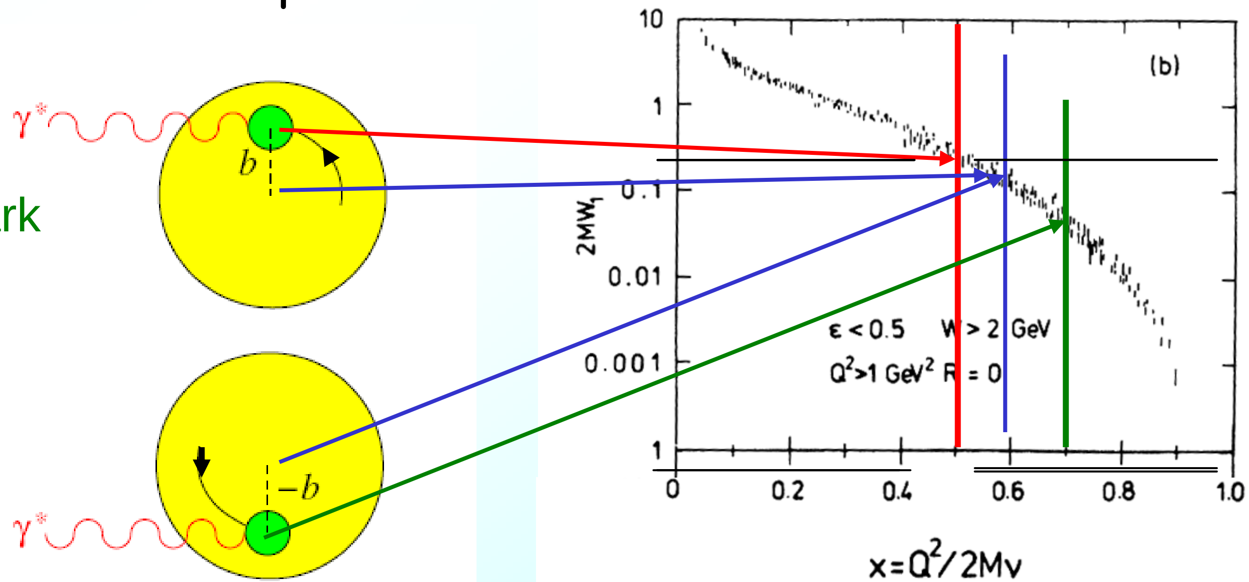
requires a quark rescattering via soft gluon exchange (gauge link) (Brodsky, Hwang, Schmidt)

- 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





The Sivers effect

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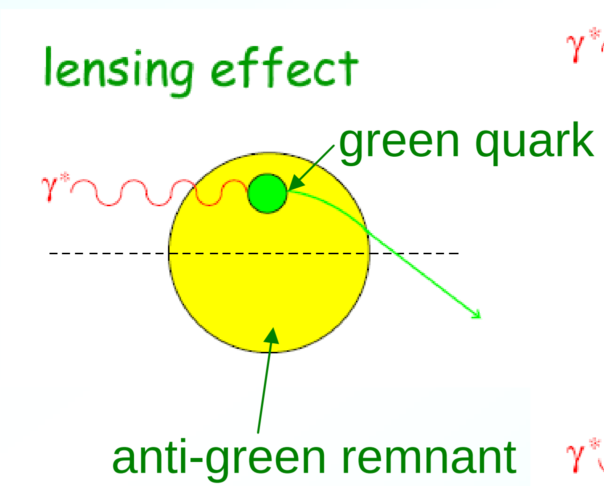
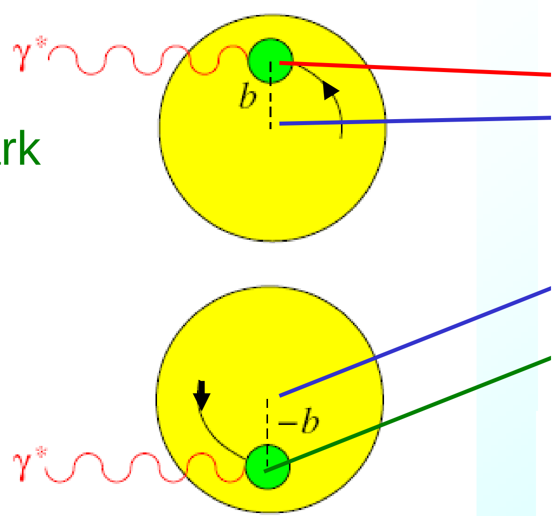
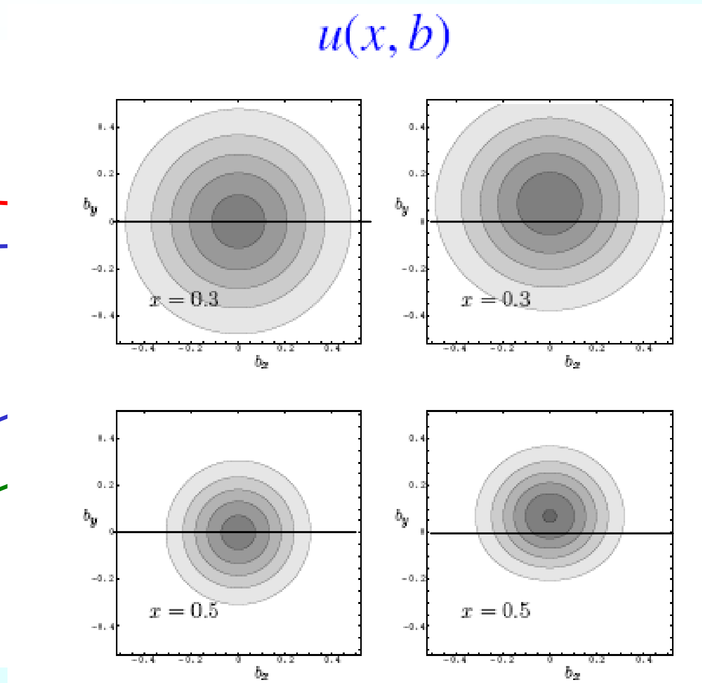


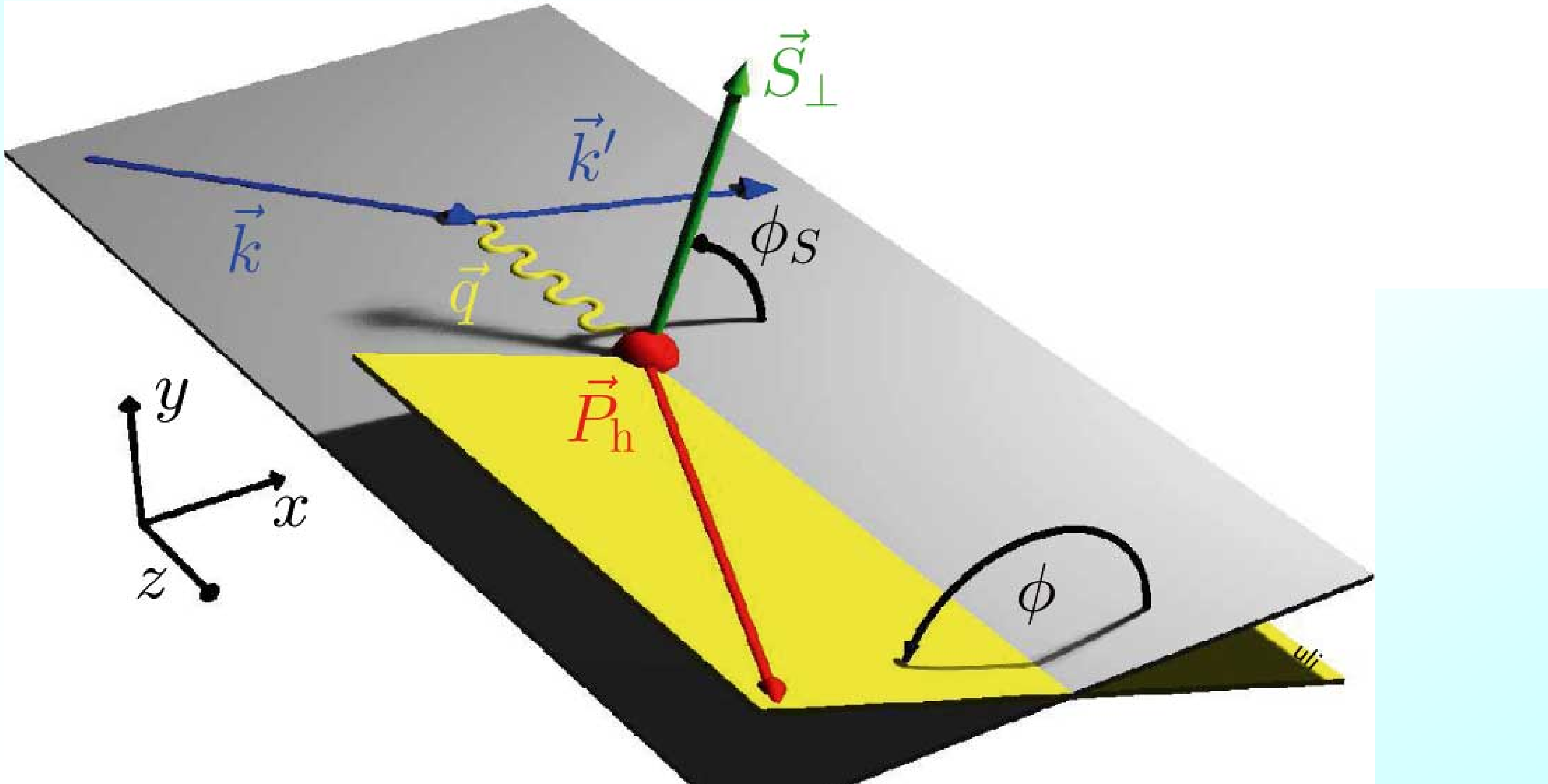




Angular distributions in SIDIS

ϕ: angle between lepton scattering plane and hadron production plane

ϕ_S: angle between lepton scattering plane and transverse spin component $S_\perp$ of target nucleon



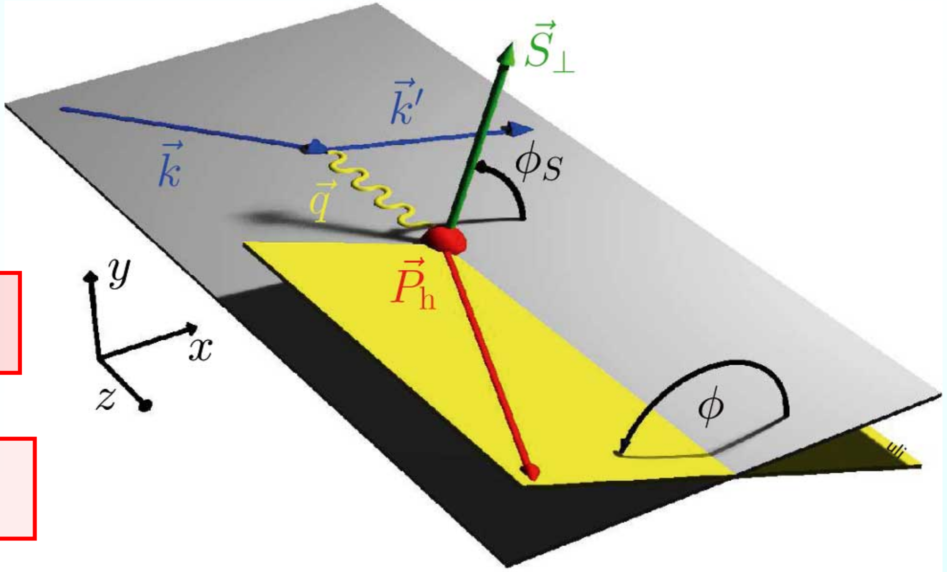
Azimuthal angular distributions

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

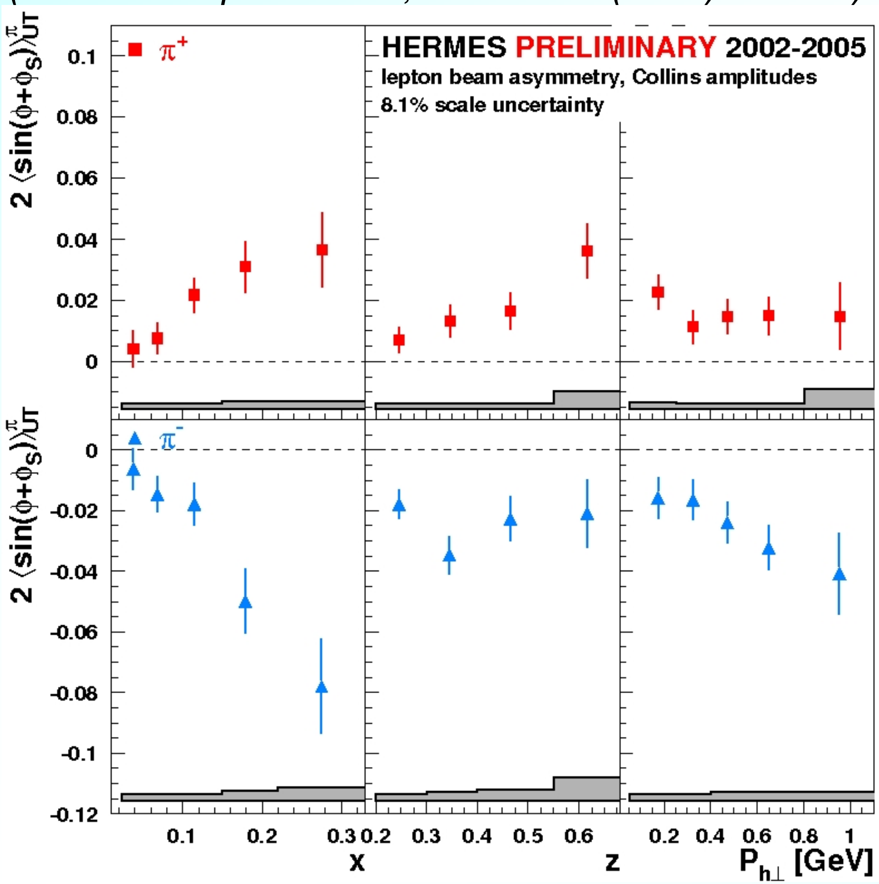
(Requires non-vanishing orbital angular momenta L_q of quarks)

Collins amplitudes (proton target)

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

M. Diefenthaler @ DIS07, hep-ex 0707.0222

(also: A. Airapetian et al, P. R. L. 94 (2005) 012002)

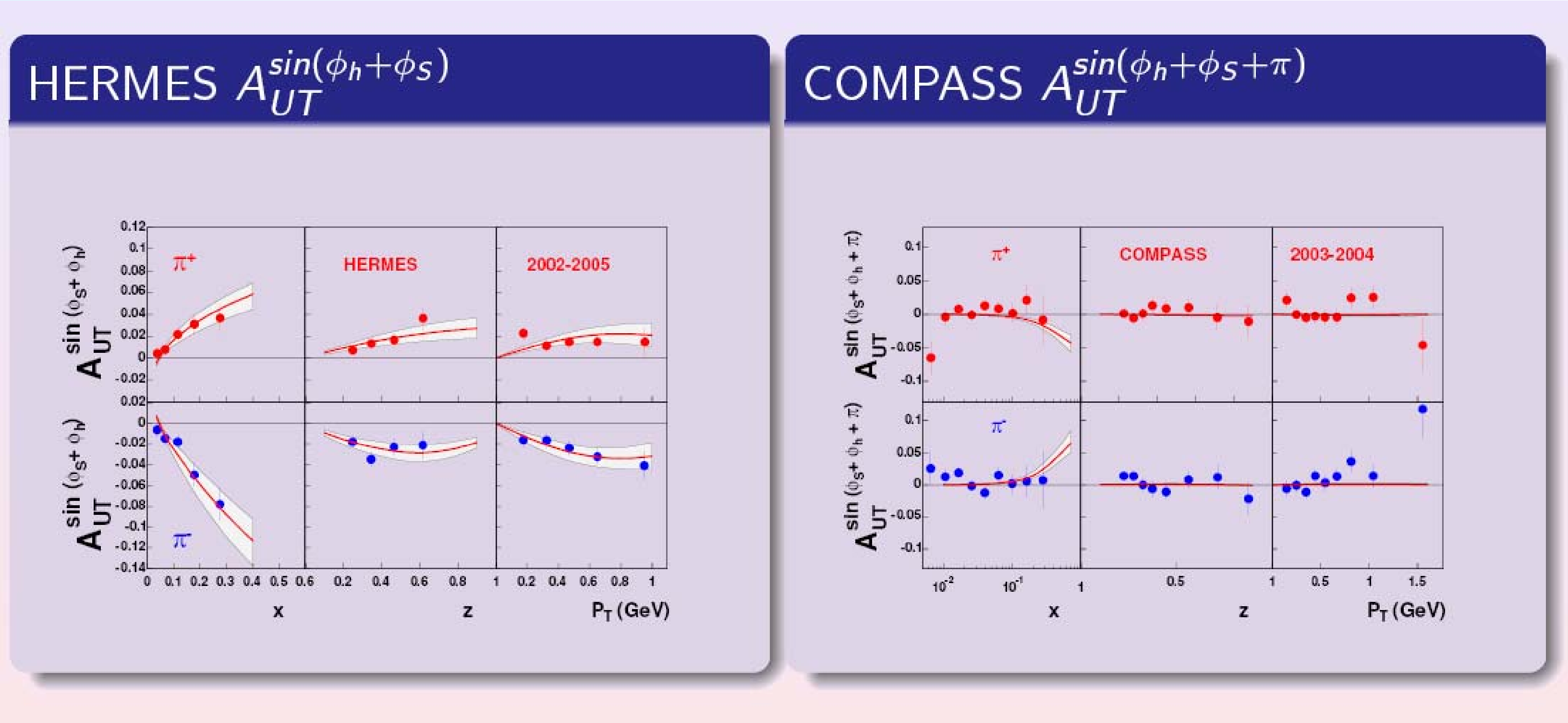


- First measurement of non-zero Collins effect
- Both Collins fragmentation function and transversity distribution function are sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation, i.e. $u \rightarrow \pi^-$

$$H_{1,disf} \approx - H_{1,fav}$$

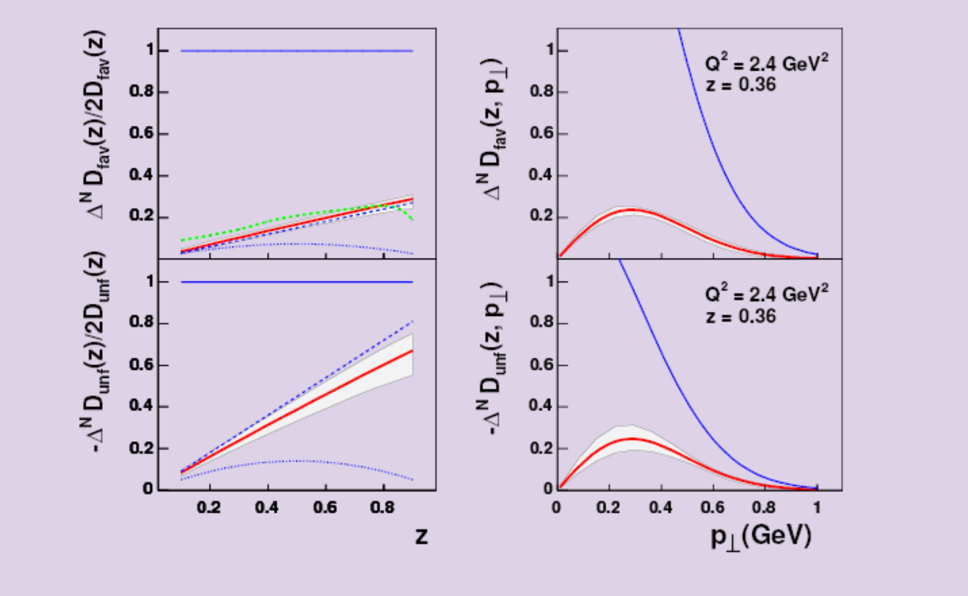
Collins amplitudes for $\pi^{+/-}$ und $K^{+/-}$

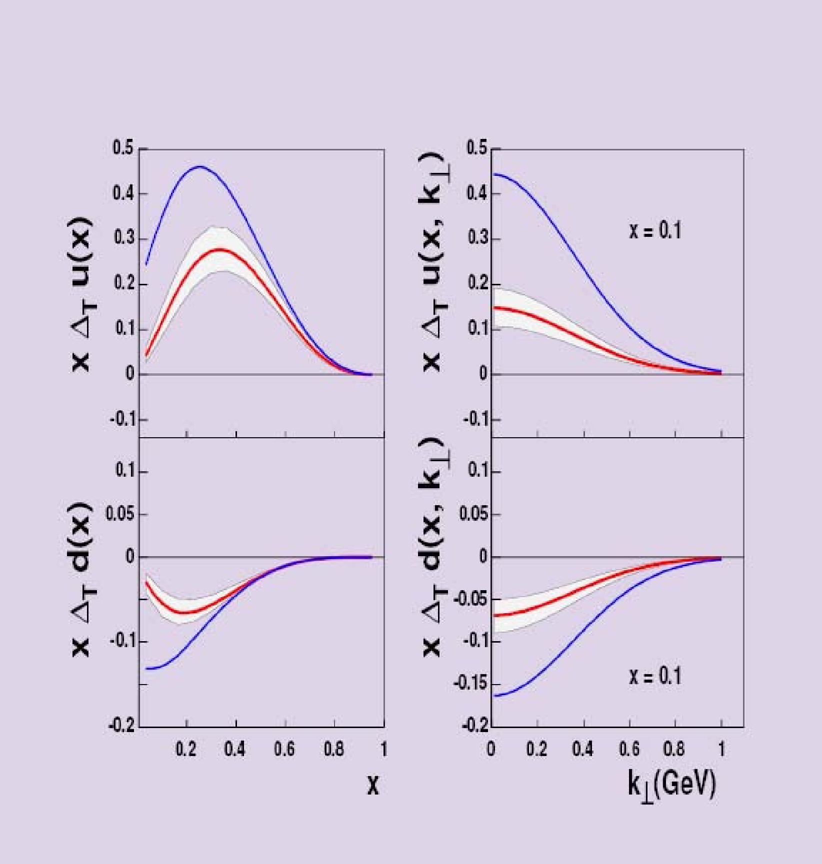
Fits of HERMES (p), COMPASS (d) and BELLE data
by Anselmino et al. (from A. Prokudin @ DIS2008)



Collins FF and Transversity

Fits of HERMES (p), COMPASS (d) and BELLE data
by Anselmino et al. (from A. Prokudin @ DIS2008)



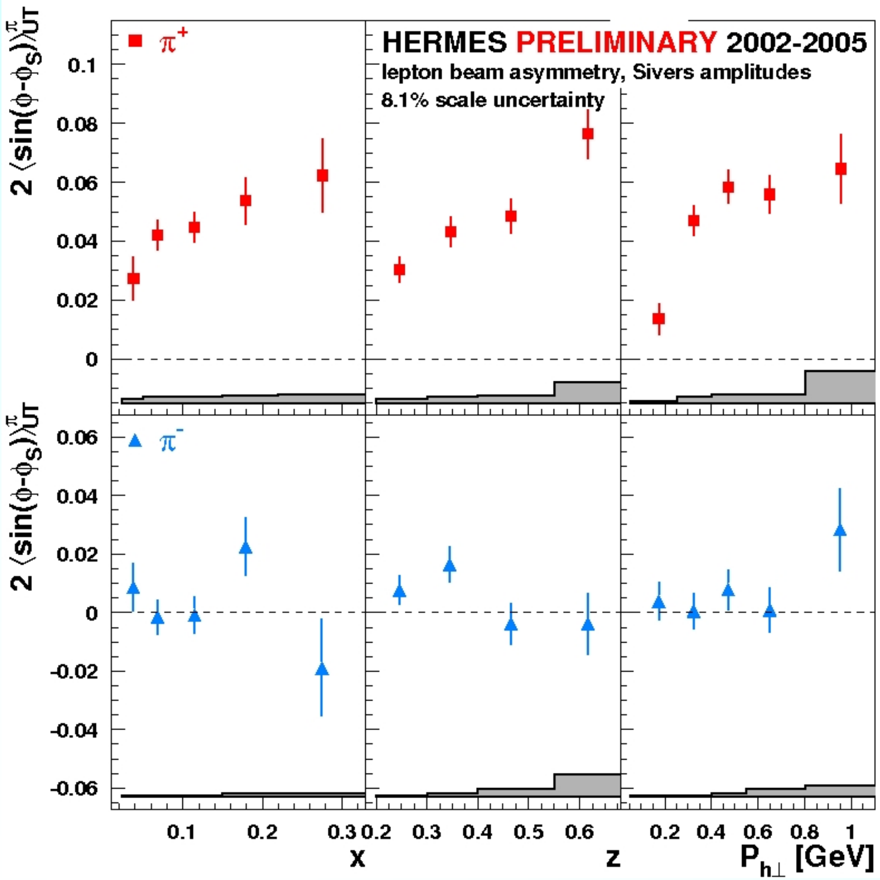


Sivers amplitudes (proton target)

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

M. Diefenthaler @ DIS07, hep-ex 0706.2242

(also: A. Airapetian et al, P. R. L. 94 (2005) 012002)

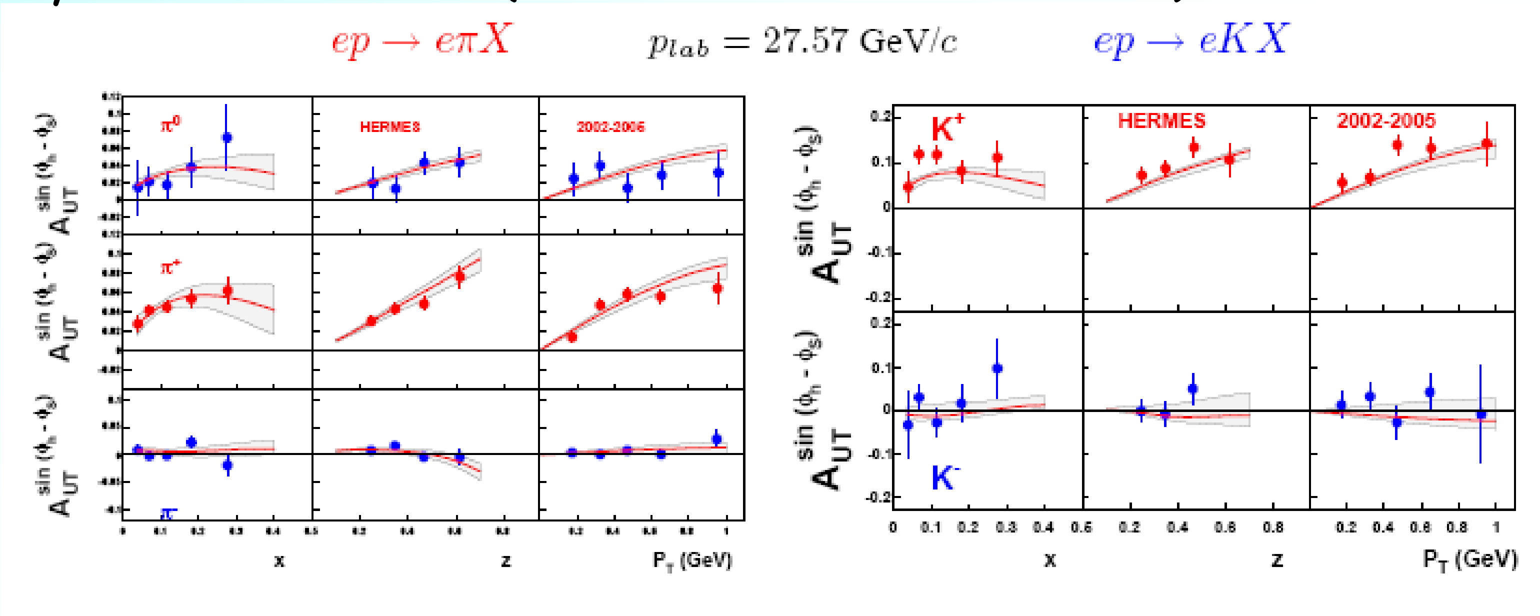


- First observation of non-zero Sivers distribution function in DIS

→ Experimental evidence for orbital angular momentum L_q of quarks

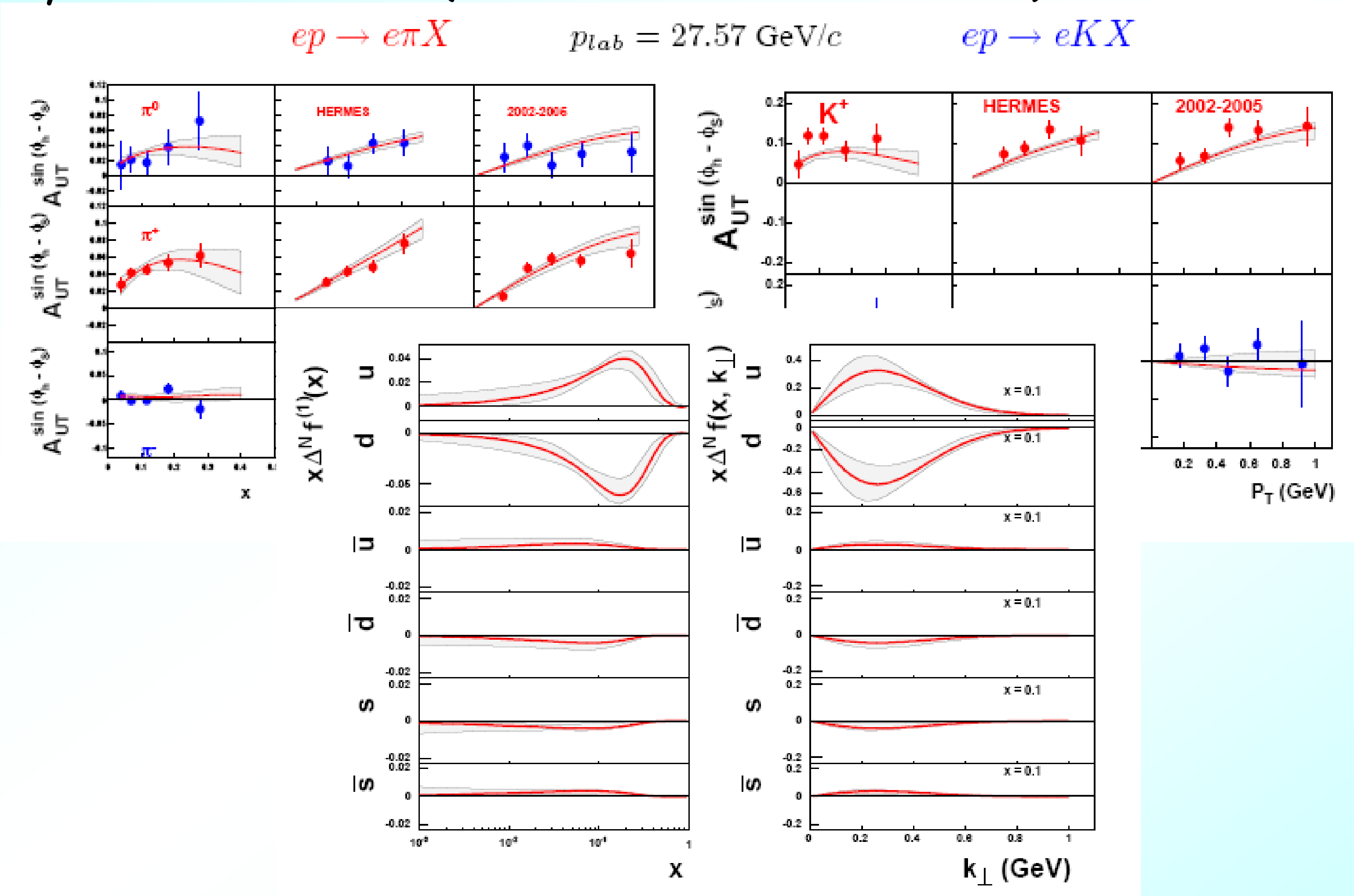
But: Quantitative contribution of L_q to nucleon spin still unclear

Fits of HERMES (p) and COMPASS (d) data
by Anselmino et al. (from S. Melis @ DIS2008)



Sivers distribution

Fits of HERMES (p) and COMPASS (d) data
by Anselmino et al. (from S. Melis @ DIS2008)

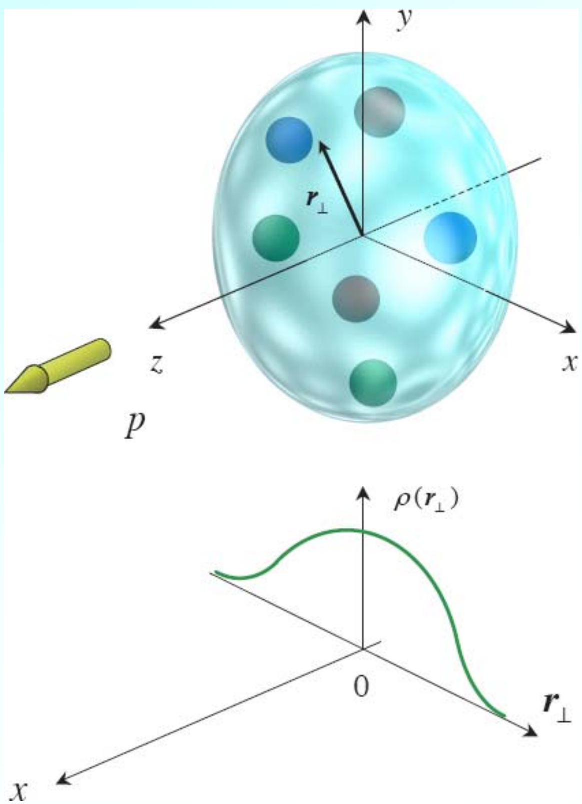


Quark orbital angular momentum

L_q

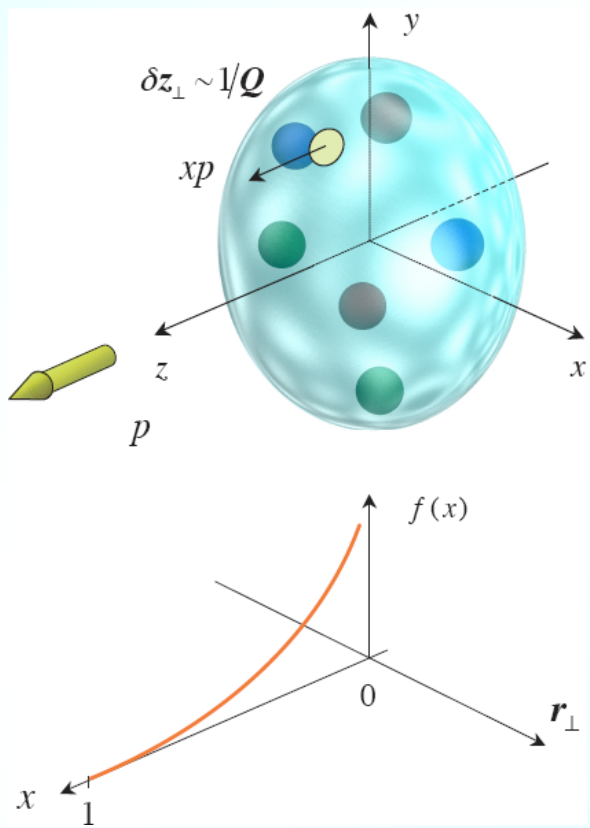
Tool: Generalised Parton Distributions

Formfactors:



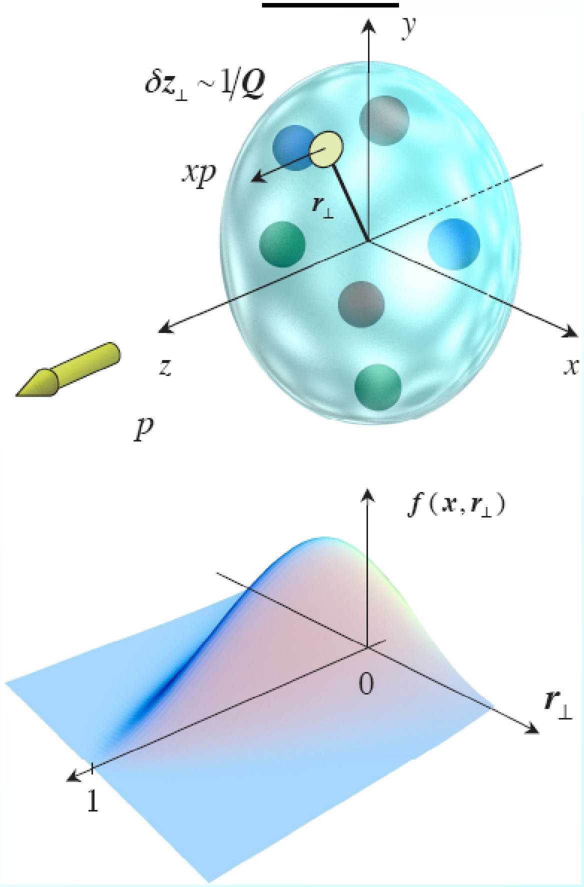
Fouriertransform of e.g. a radial charge distribution

PDFs:



Number density of quarks with longitudinal momentum fraction x

GPDs:



Generalised description in 2+ 1 dimensions

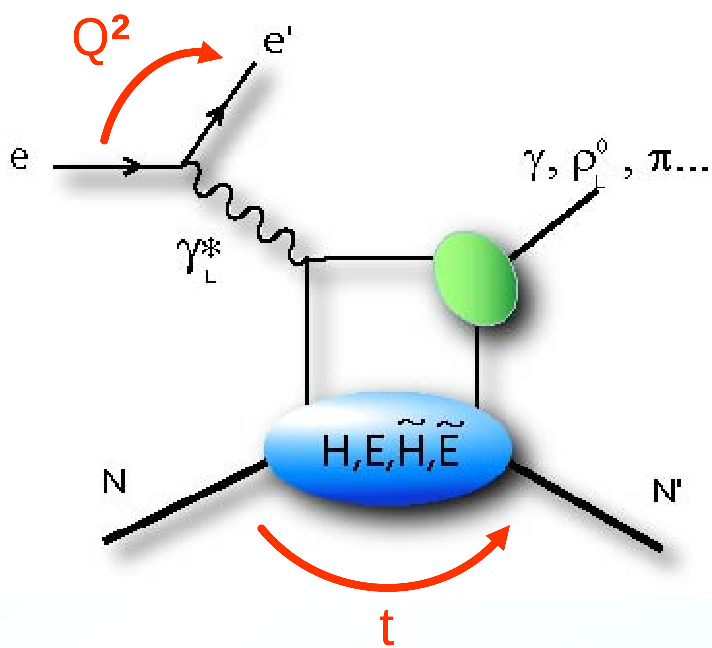
Determination of L_q

Ji sum rule:

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

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

Access: *exclusive processes*



Final state sensitive to different GPDs

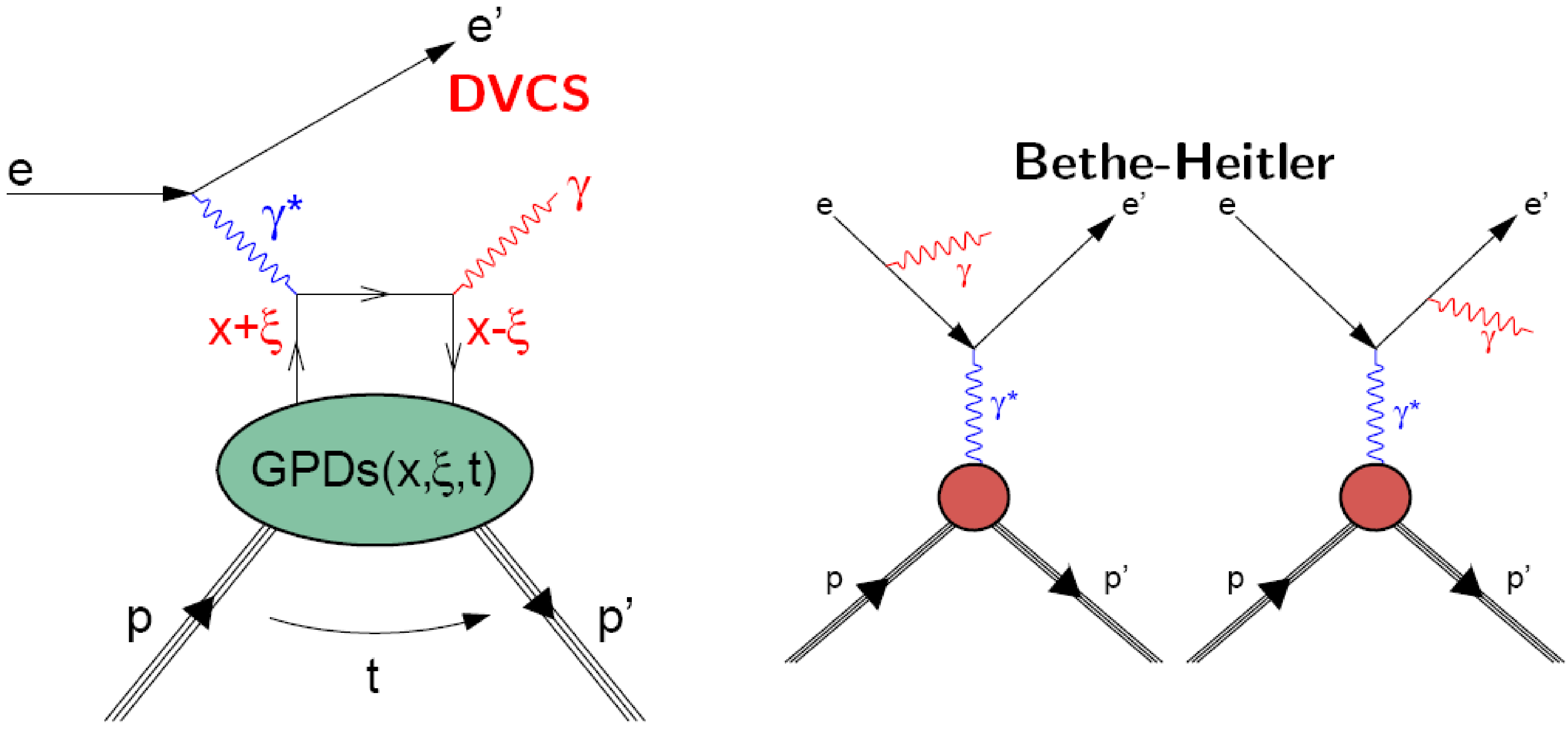
Vector mesons (ρ, ω, ϕ) H, E

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

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

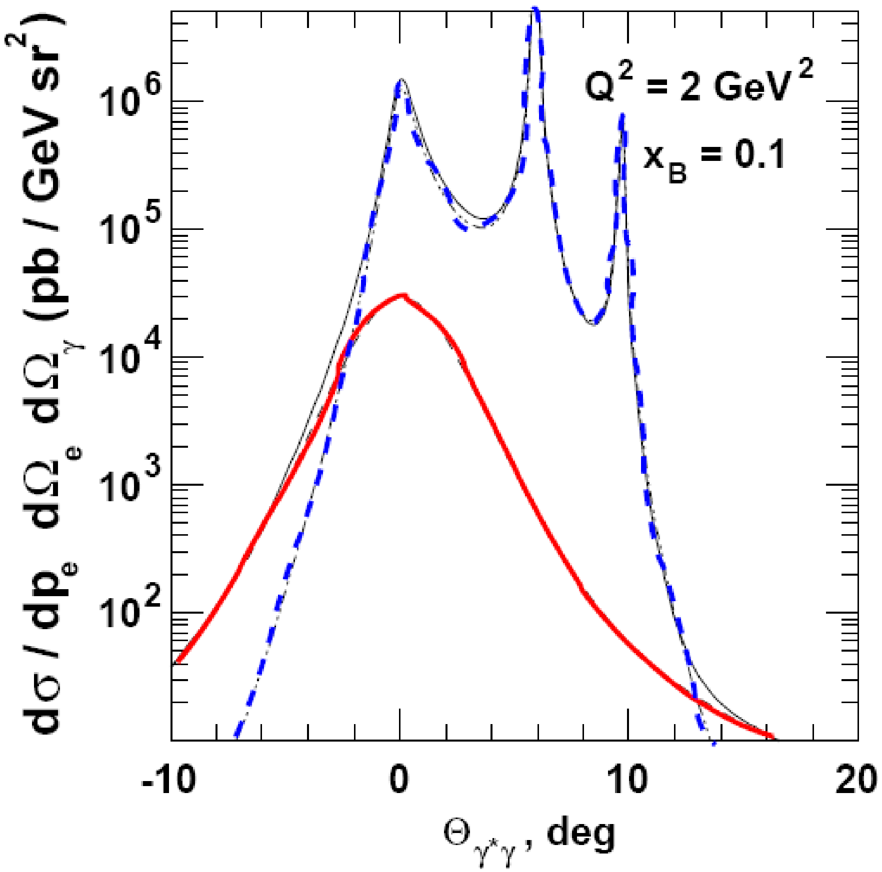
Example: DVCS

DVCS ≡ Deeply Virtual Compton Scattering



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{y^2 x_B}{32(2\pi)^4 Q^4 \sqrt{1+\frac{4M^2x_B^2}{Q^2}}} \left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I} \right)$$

Example: DVCS



At HERMES kinematics:

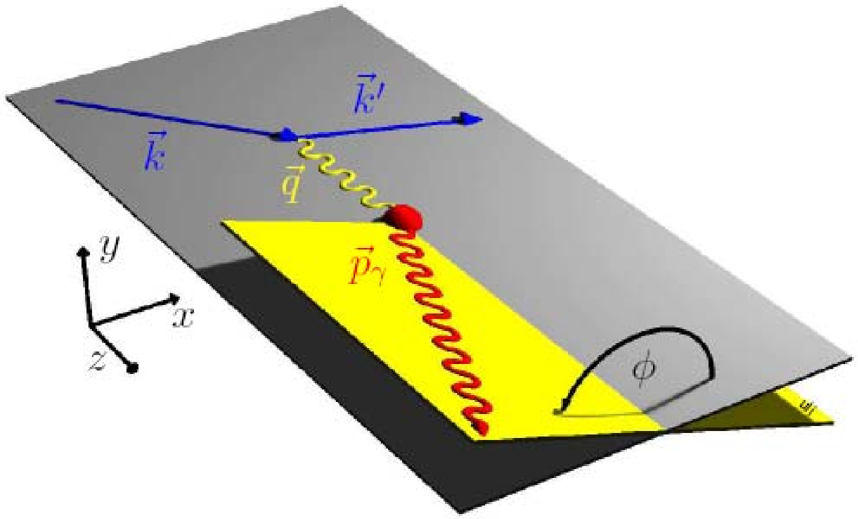
$$|\mathcal{T}_{\mathrm{DVCS}}|^2 < |\mathcal{T}_{\mathrm{BH}}|^2$$

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}Q^2\mathrm{d}x_B\mathrm{d}t\mathrm{d}\phi} = \frac{y^2 x_B}{32(2\pi)^4 Q^4 \sqrt{1+\frac{4M^2x_B^2}{Q^2}}} \left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

Example: DVCS

Fourier expansion in ϕ for

- **beam polarization P_B**
- **beam charge C_B**
- **unpolarized target:**



$$|\mathcal{T}_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\rm BH} \cos(n\phi)$$

$$|\mathcal{T}_{\rm DVCS}|^2 = K_{\rm DVCS} \left[\sum_{n=0}^{2} c_n^{\rm DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\rm DVCS} \sin(n\phi) \right]$$

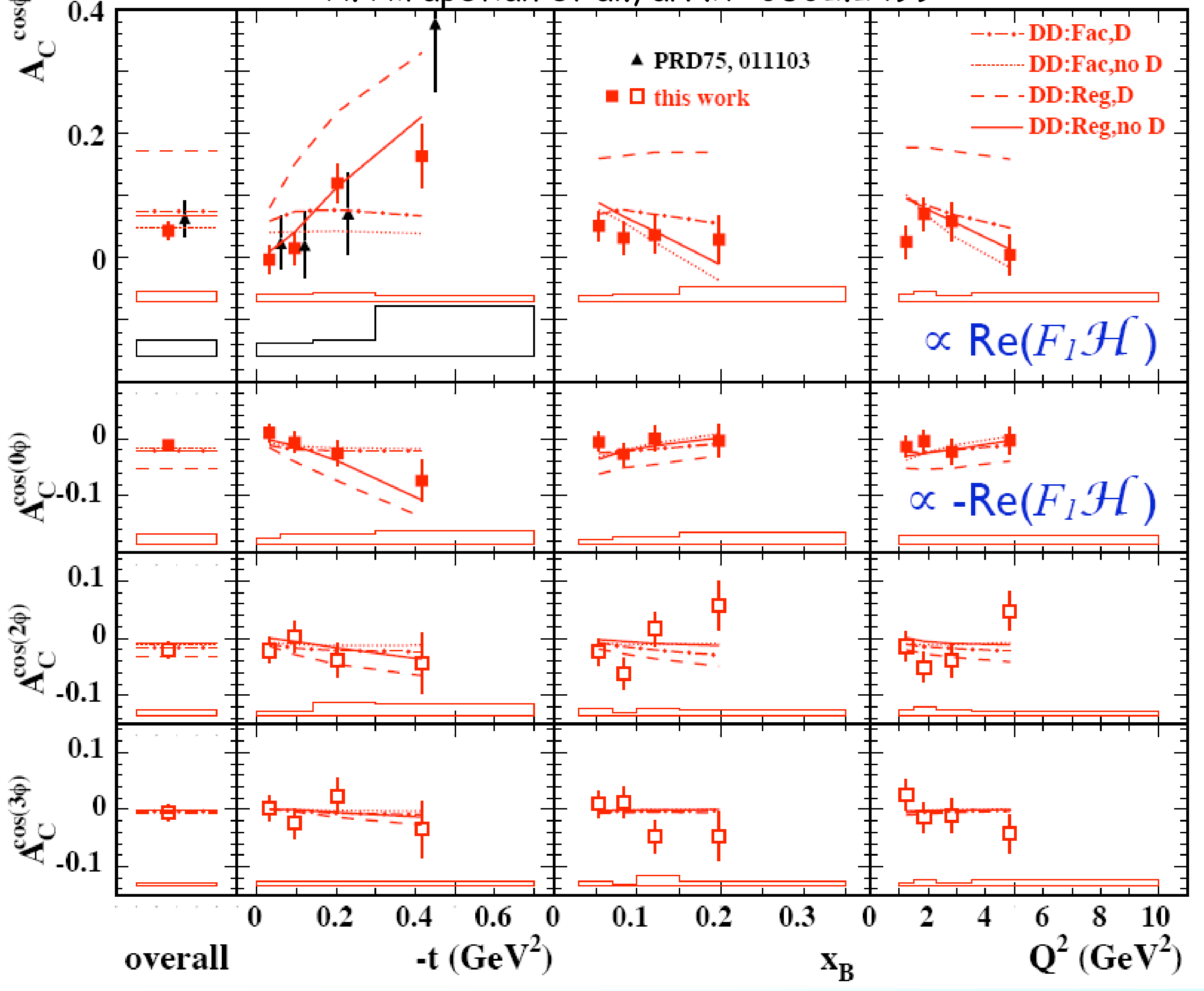
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Determination of L_q

DVCS: Beam charge asymmetry

Pioneer measurements

A. Airapetian et al., arXiv: 0802.2499



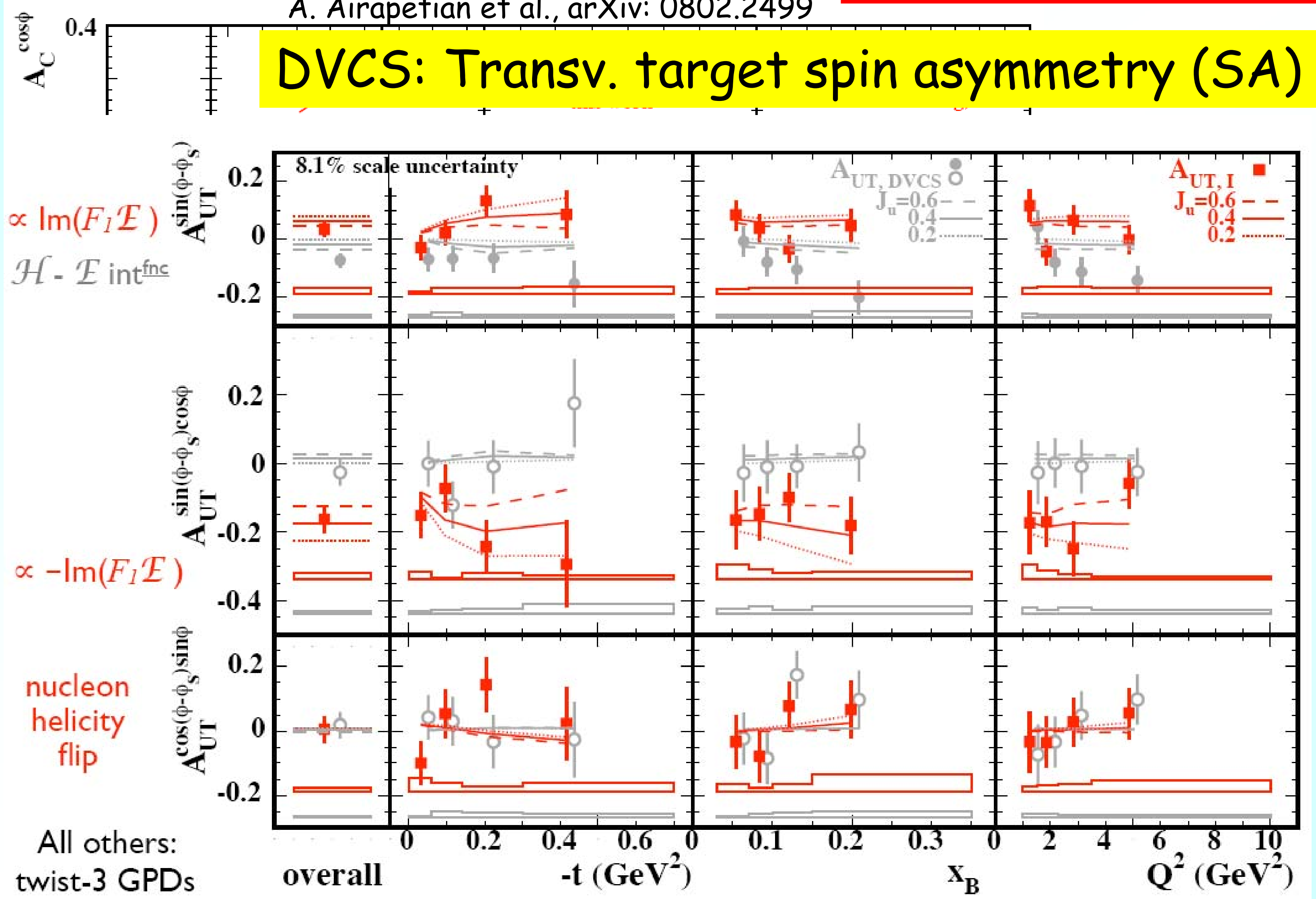
Determination of L_q

DVCS: Beam charge asymmetry

Pioneer measurements

A. Airapetian et al., arXiv: 0802.2499

DVCS: Transv. target spin asymmetry (SA)



Determination of L_q

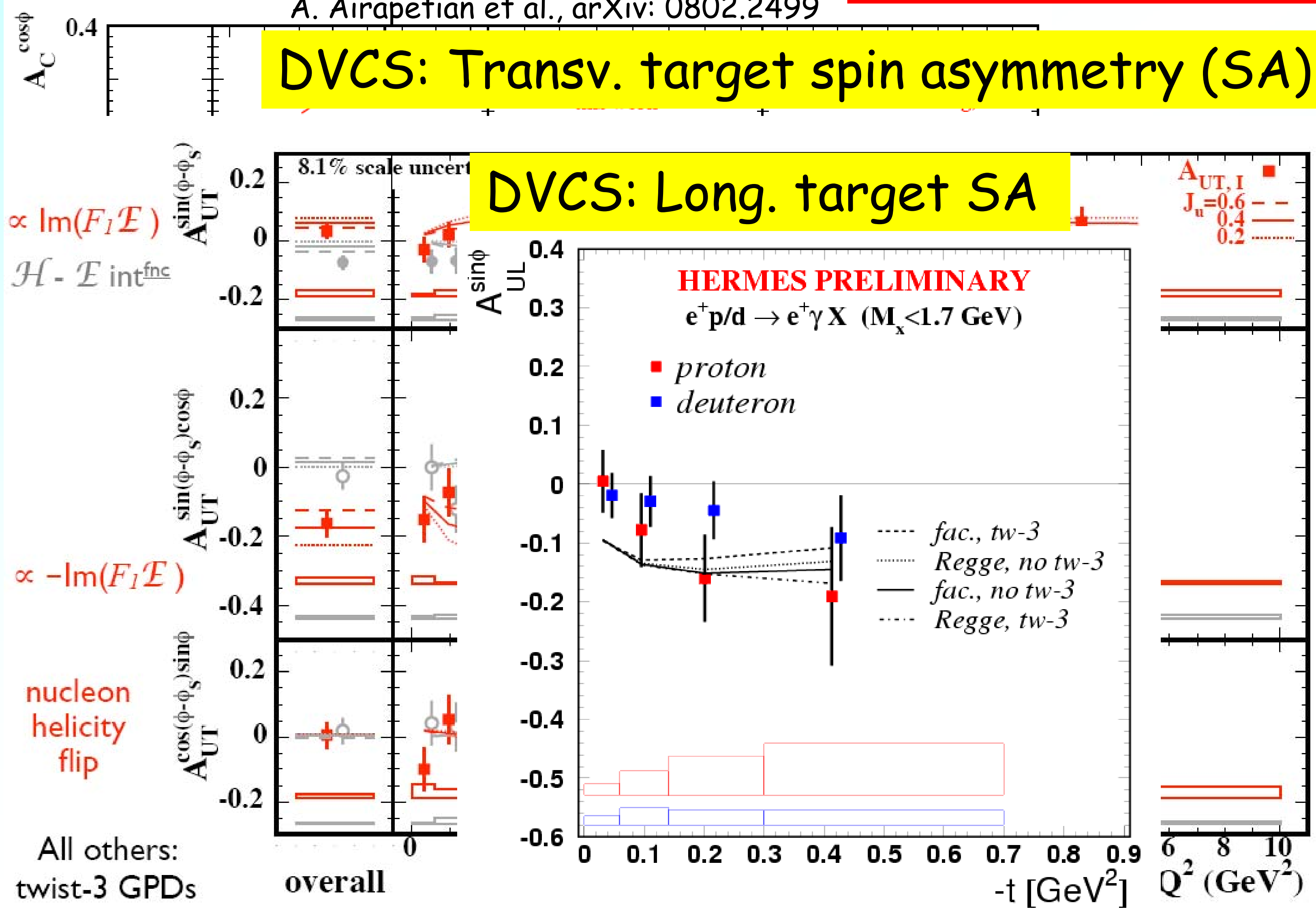
DVCS: Beam charge asymmetry

Pioneer measurements

A. Airapetian et al., arXiv: 0802.2499

DVCS: Transv. target spin asymmetry (SA)

DVCS: Long. target SA



Determination of L_q

DVCS: Beam charge asymmetry

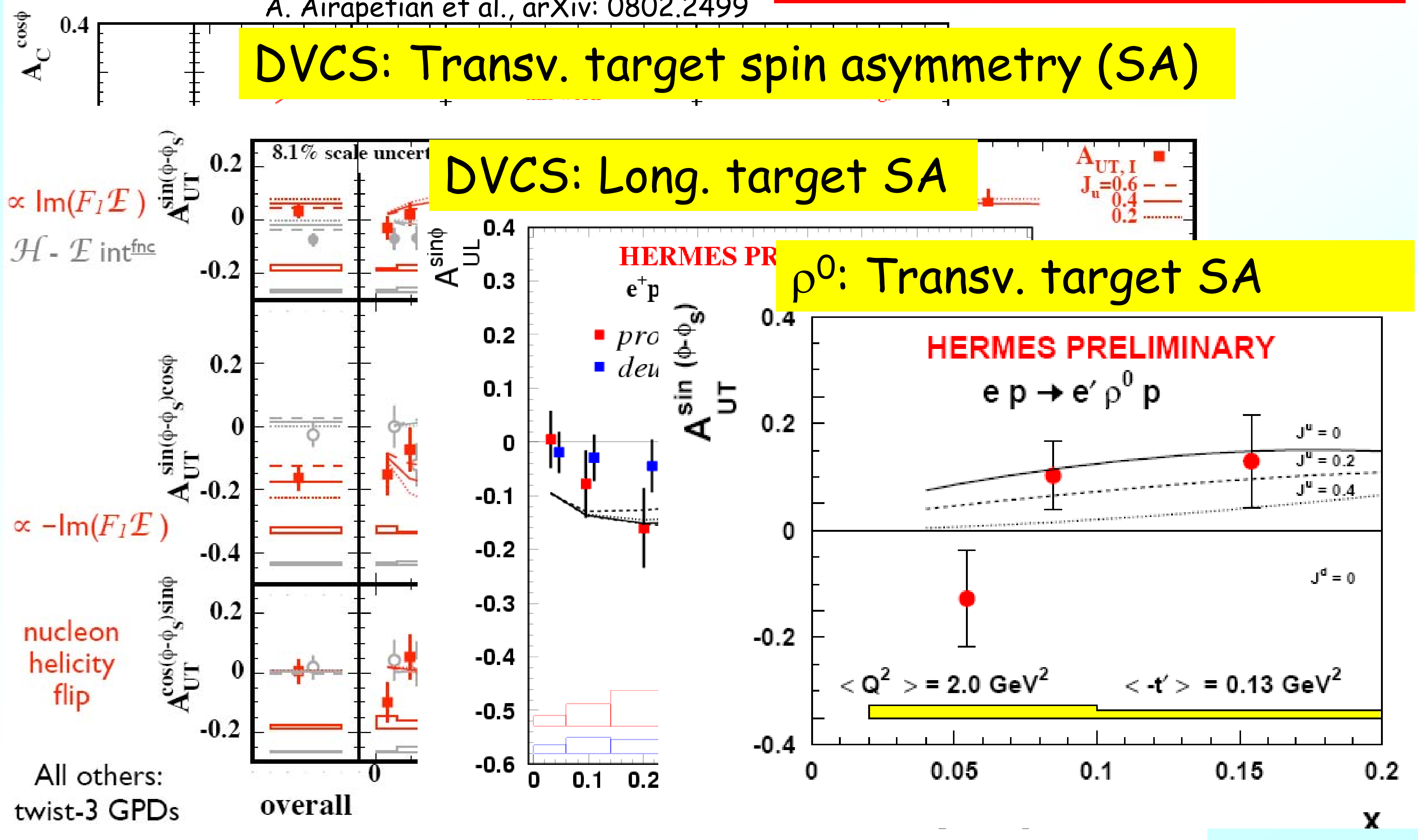
Pioneer measurements

A. Airapetian et al., arXiv: 0802.2499

DVCS: Transv. target spin asymmetry (SA)

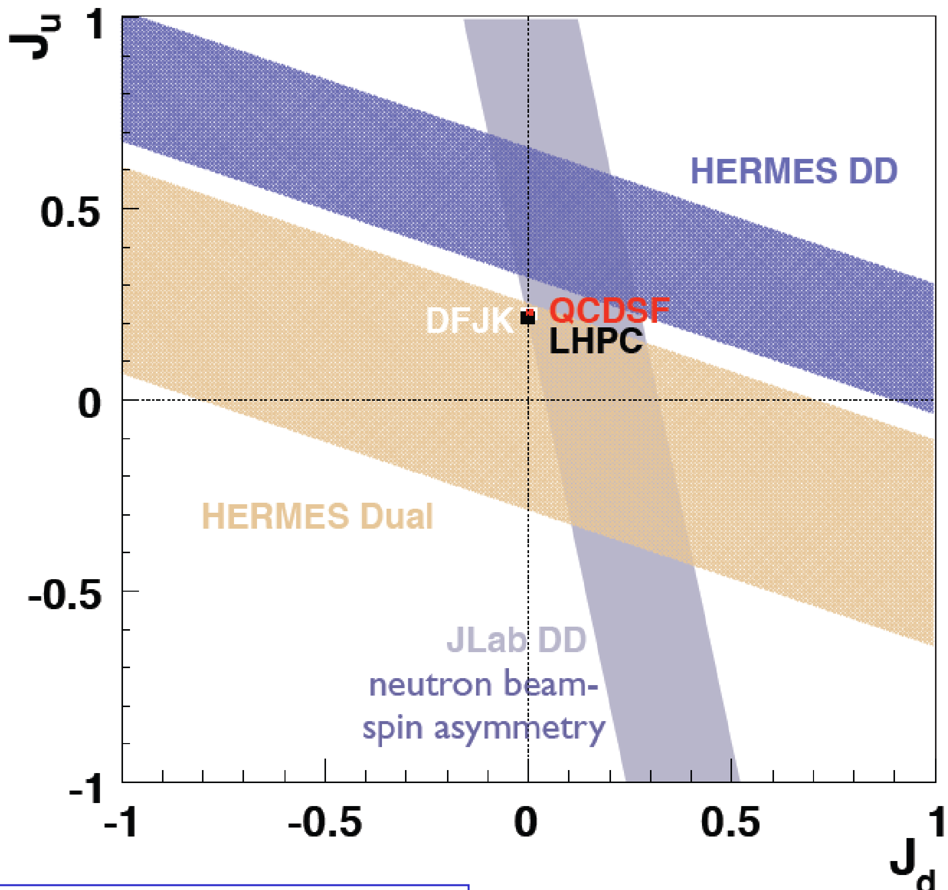
DVCS: Long. target SA

ρ^0: Transv. target SA



Determination of L_q

A. Airapetian et al., JHEP 0806 (2008) 66

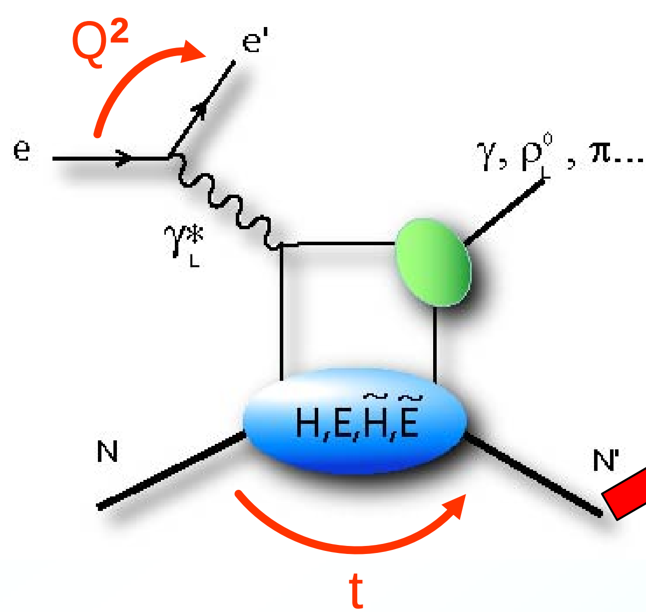


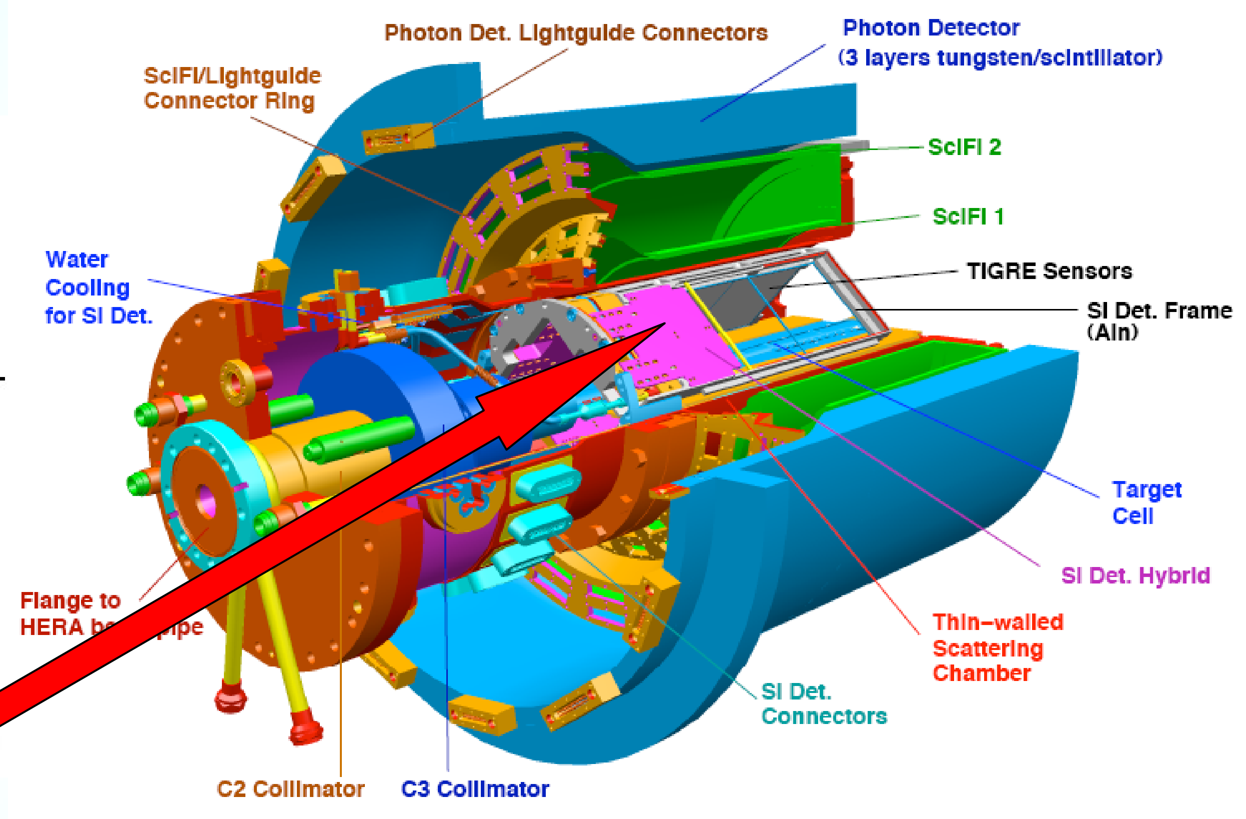
Lattice: $L_u \approx -L_d \approx 0.2$!??

Determination of L_q

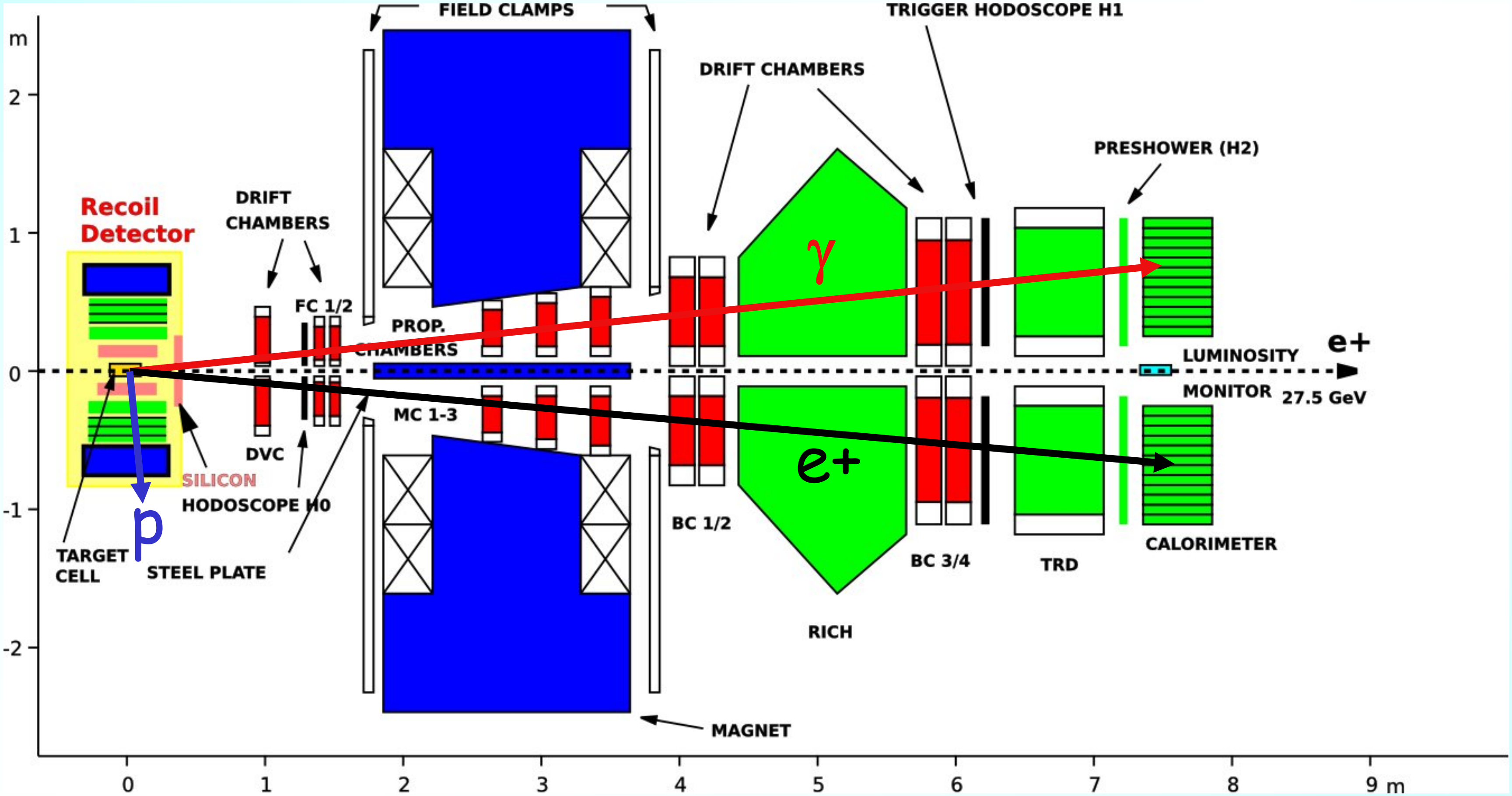
Program until June 30th 2007:

Detailed study of exclusive processes with Recoil-Detector:



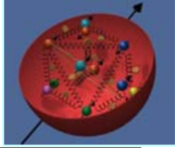


Determination of L_q – Recoil Detector



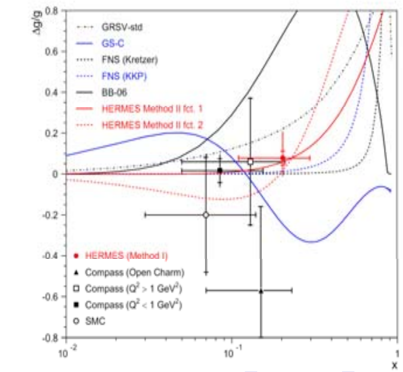
Summer students: Hanna, Cory, Falk

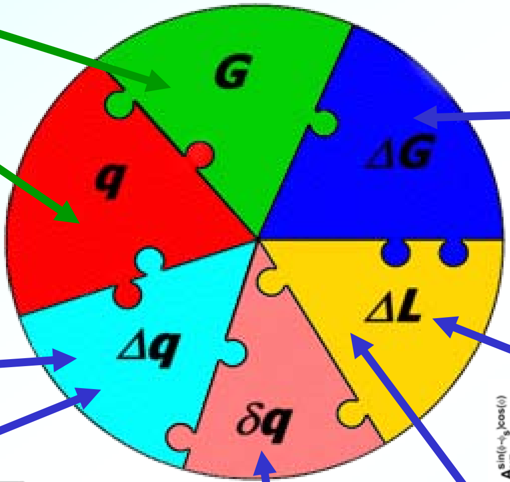
Nucleon Spin Structure & HERMES



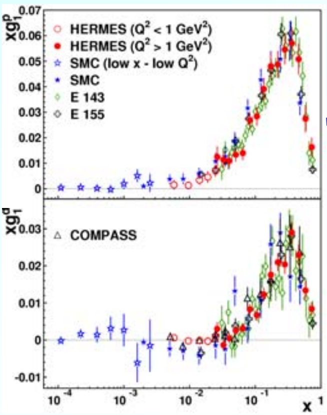
Unpolarised DIS
SLAC, BCDMS, NMC, HERA…

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

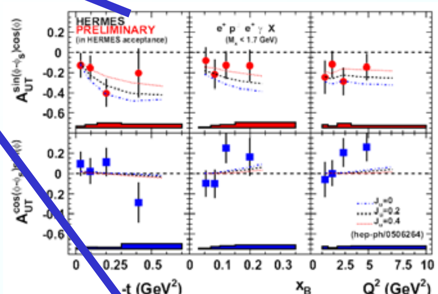


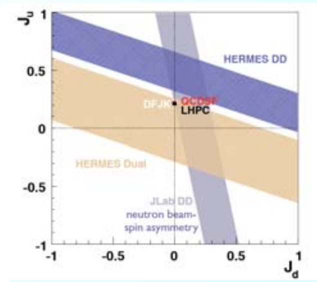


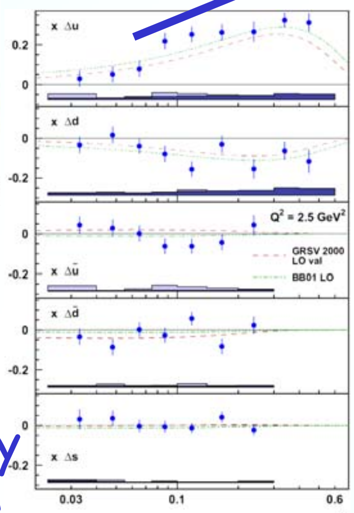
→$\Delta\Sigma$
$= 0.330 \pm 0.025^{(\text{exp})}$

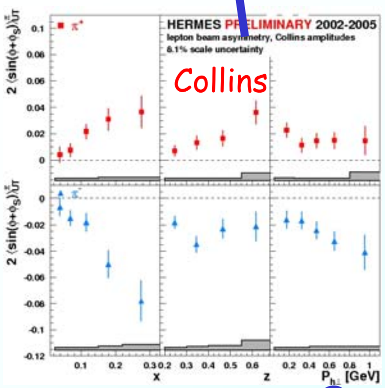


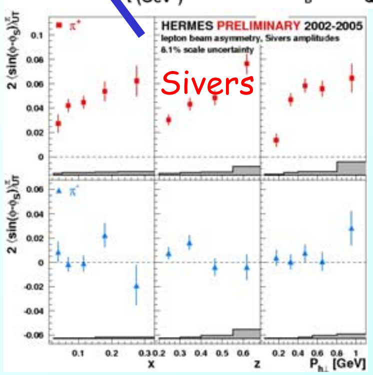
→ Signals for GPDs → $J_u + J_d$











→individual quark helicity distributions

→$\delta q(x) \neq 0$

→$L_q \neq 0$

After Delia Hasch, Spin06, Kyoto

Further results - Outlook

Many more results on various subjects: at present >50 publications with in average 60 citations each

Examples:

- hadron multiplicities and fragmentation functions
- SSA for inclusive and exclusive π production
- vector meson production
- DSA for exclusive VM production
- DIS on nuclear targets
- Nuclear attenuation of coherent and incoherent ρ's (coherence length, colour transparency)
- longitudinal and transverse Λ polarisation
- .....

Still much more to come !!