Physics at HERMES

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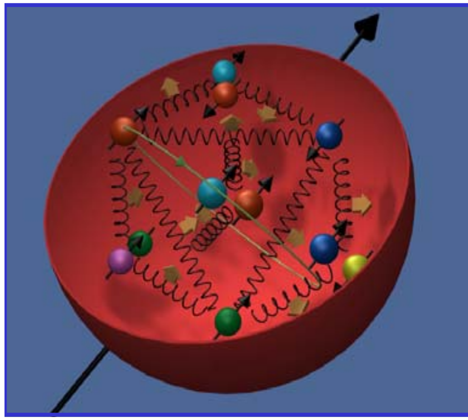
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Outline

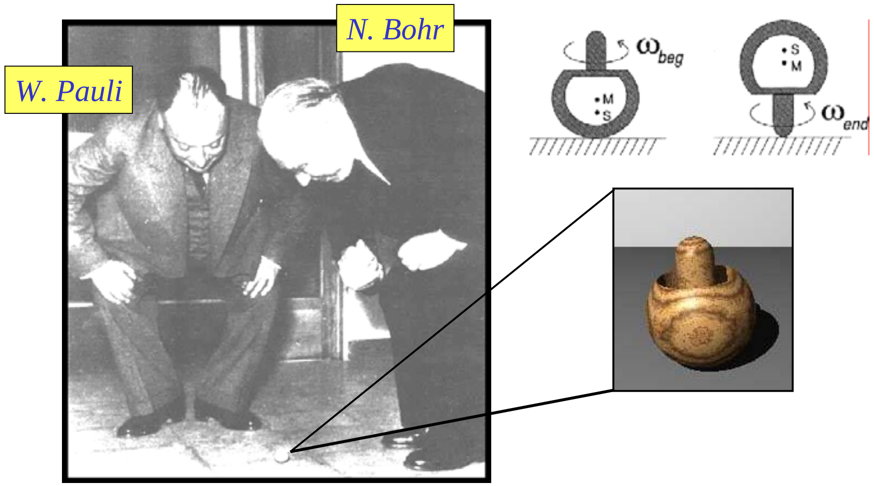


- The spin puzzle
  Introduction to spin physics
- HERMES physics:
  Modest aims and rich harvest
- HERMES technology:
  Polarization and novel techniques
- Physics results in more detail:
  - Spin structure of the nucleon
  - Hard exclusive reactions
  - Quarks in nuclei
- Conclusions

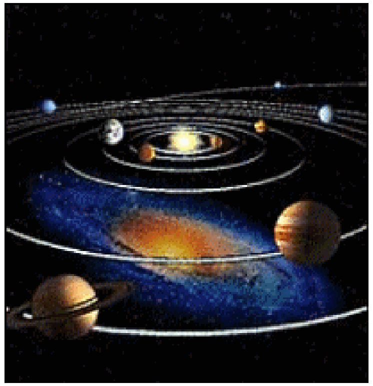
Some transparencies are stolen from
Aschenauer, di Nezza, Hasch, Nowak, Ji, …

Fascinating by spin …

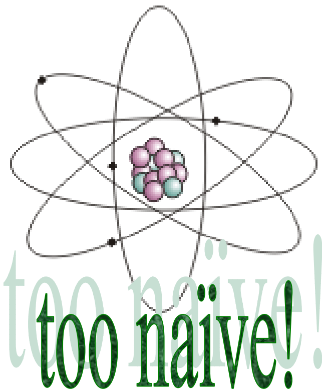
"You think you understand something? Now add spin..." -- R. Jaffe



Fascinating by spin … an analogy



Planets have an orbital angular momentum around the sun and a spin angluar momentum around their own axis...

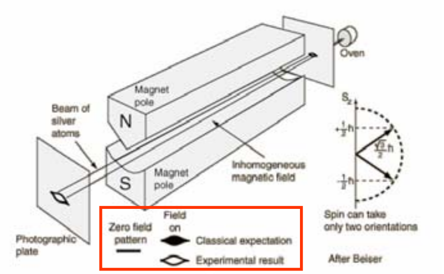


Just like electrons in an atomic orbit!??

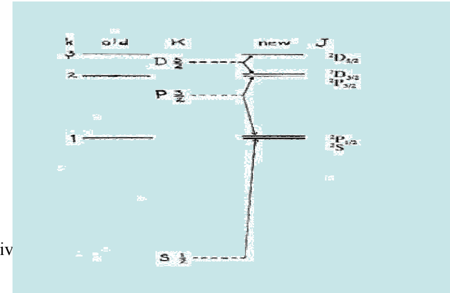
What is Spin ?

[http://www.markusehrenfried.de/science/physics/hermes/whatisspin.html

- Stern-Gerlach (1921):



- Uhlenbeck, Goudsmit: (1925)
  explanation of atomic spectra
  quantum number: m_s=1/2



What is Spin ?

Spin and Symmetry: [S.Hawkins: A brief history of time]

spin: 2

180°

spin: 1

360°

spin: $\frac{1}{2}$?

math: antisymmetric wave function

2x360°

Is spin important ?

Pauli principle ...

half integer SPIN

→ obey Pauli principle
→ antisymmetric under exchange of identical particles
→ Fermi-Dirac statistics: *Fermions*

integer SPIN

→ don't care for Pauli principle
→ symmetric
→ Bose-Einstein statistics: *Bosons*

Is spin important ?

Pauli principle ...

half integer SPIN

MATTER

integer SPIN

FORCES

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

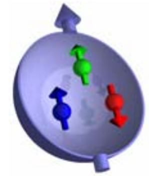
BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c²	Electric charge
g gluon	0	0

The proton spin structure

The proton spin structure … (1987)



Quark parton model

$$\frac{1}{2}=\frac{1}{2}\underbrace{(\Delta u_v+\Delta d_v+\Delta q_s)}_{\Delta\Sigma=1}$$

Prediction by Ellis and Jaffe
(based on $SU(3)_f$ and
the assumption that strange quarks
do not play an important role)

$$\Delta\Sigma = 3F - D = 0.58$$

The quarks carry 58% of the proton spin!

Measurement by the
European Muon Collaboration (CERN) '87

$$\Delta\Sigma = 0.123 \pm \ldots$$

The quarks do not dominate the proton spin!

Spin Puzzle

The proton spin structure … today

QPM:

$$\frac{1}{2}=\frac{1}{2}\underbrace{(\Delta u_v+\Delta d_v+\Delta q_s)}_{\Delta\Sigma=1}$$

Spin Puzzle

→SLAC, CERN, DESY: 0.2-0.4

gluons are important !

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

don't forget the orbital angular momentum!

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

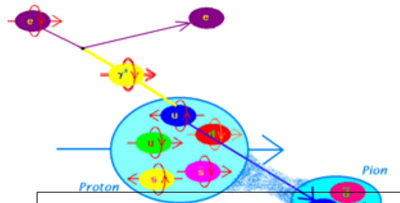
Proton spin; quark spin; quark orb. angular mom.; gluon spin; gluon orb. angular mom.

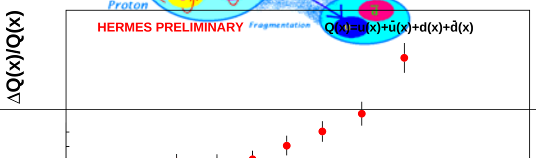
HERMES physics

Why HERMES?
A historical review

- In 1987 EMC discovered the "spin puzzle":
  - Violation of the Ellis Jaffe sum rule
  - A large negative strange sea polarization

  Both results were based on inclusive DIS data and validity of $SU(3)_f$





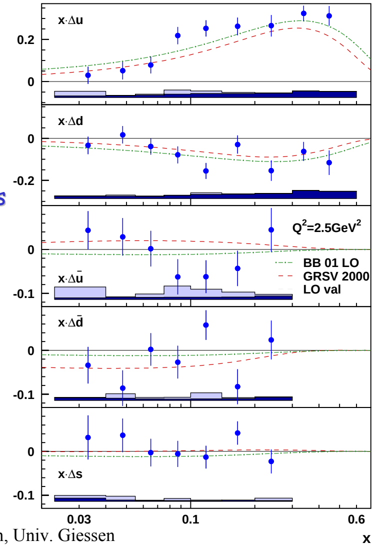
Original physics program of HERMES:

- In 1989 we decided to solve the "spin puzzle" with a semi-inclusive DIS experiment doing a flavor decomposition of the quark spin
- Re-measure inclusive polarized DIS on proton and neutron:
  - Ellis-Jaffe sum rule
  - Bjorken sum rule
  - g_1, g_2
- Measure semi-inclusive polarized DIS on p and n:
  - $\Delta u(x)$, $\Delta d(x)$, $\Delta s(x)$

Why HERMES?
A historical review

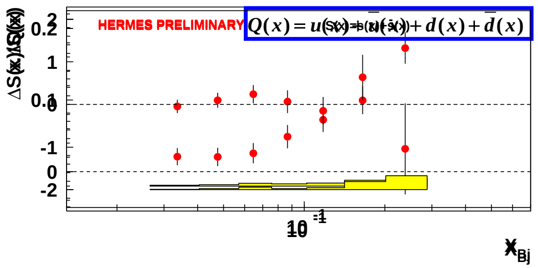
Results (in short):

- Ellis-Jaffe sum rule: is really broken
- Bjorken sum rule: is fine (fortunately)
- g_1, g_2 are well known nowadays
- $\Delta u(x)$ is large and positive
- $\Delta d(x)$ is smaller and negative
- $\Delta s(x)$ is approx. zero i.e.
  - $SU(3)_f$ is (probably) broken and
  - only ~30% of the spin of the nucleon is due to the spin of the quarks



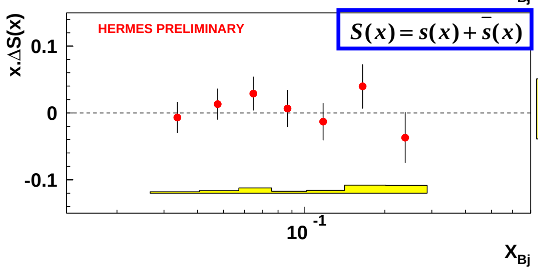
Spin of the nucleon

Latest results!



$$\int_{0.02}^{1} \Delta Q \, dx = 0.29 \pm 0.03 \pm 0.01$$

~30% up and down quark contribution in valence region



$$\int_{0.02}^{1} \Delta S \, dx = 0.006 \pm 0.029 \pm 0.007$$

<3% strange quark contribution

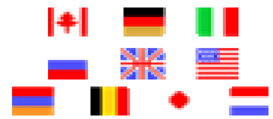
Physics program at HERMES today:

- Flavor decomposition of quark spin (done)
- Gluon spin contribution (first result but large errors)
- Transversity, Collins and Sivers functions (first non-zero results)
- Orbital angular momentum of quarks (first results, but model dependent)
- Generalized parton distributions (first results on BCA, BSA, TTSA,…)
- Fragmentation process in vacuum and nuclear medium
- Spin matrix elements of vector meson production
- Positive Pentaquark signal
- …

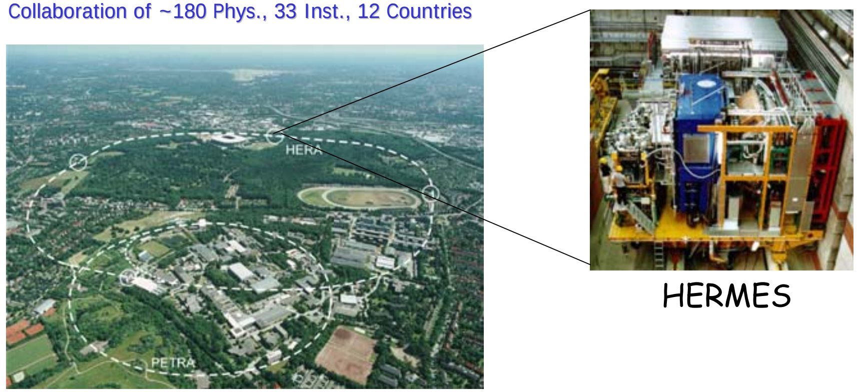
In many areas HERMES contributed as a pioneering experiment

HERMES technology

HERa MEasurement of Spin



Collaboration of ~180 Phys., 33 Inst., 12 Countries



Polarization and novel techniques

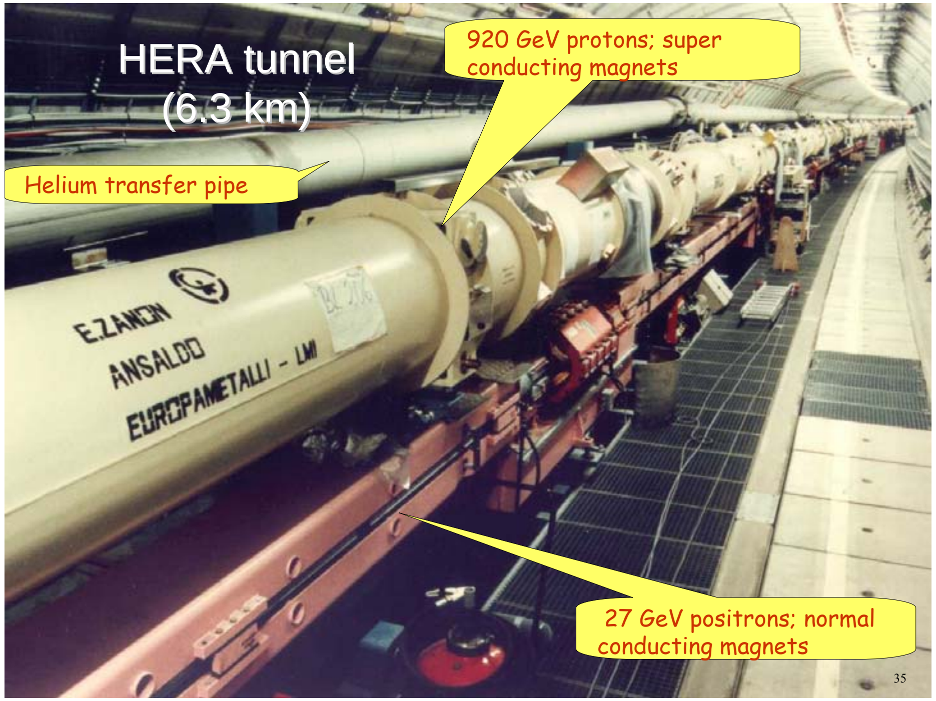
HERMES requires:

- Large polarization of beam and target; pure target
- Relatively large luminosity (Much larger than EMC)
- Relatively high beam energy (Q^2>1 GeV^2; larger than Jlab)
- Relatively large acceptance (Much larger than SLAC)
- Strangeness identification (kaons)
- Recoil protons (for exclusive reactions)

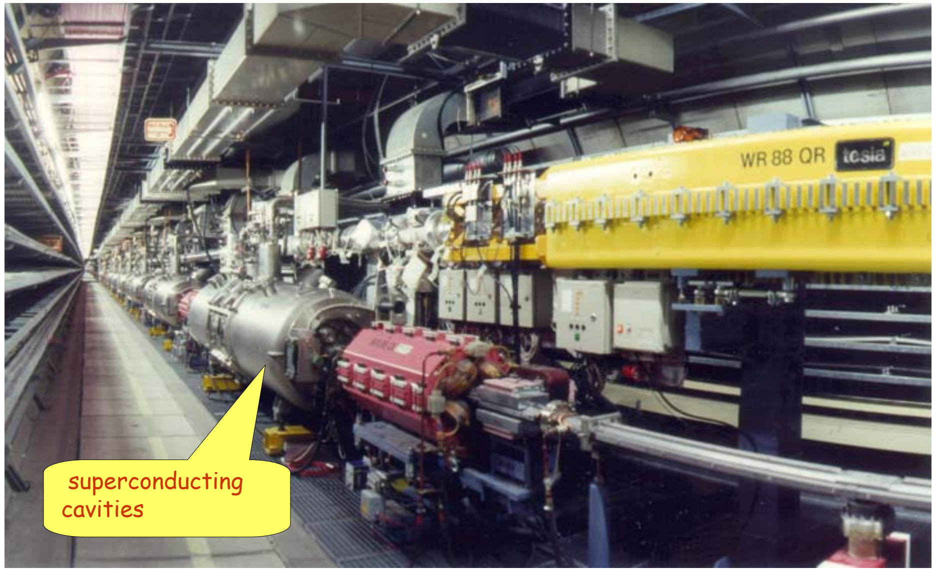
Solution:

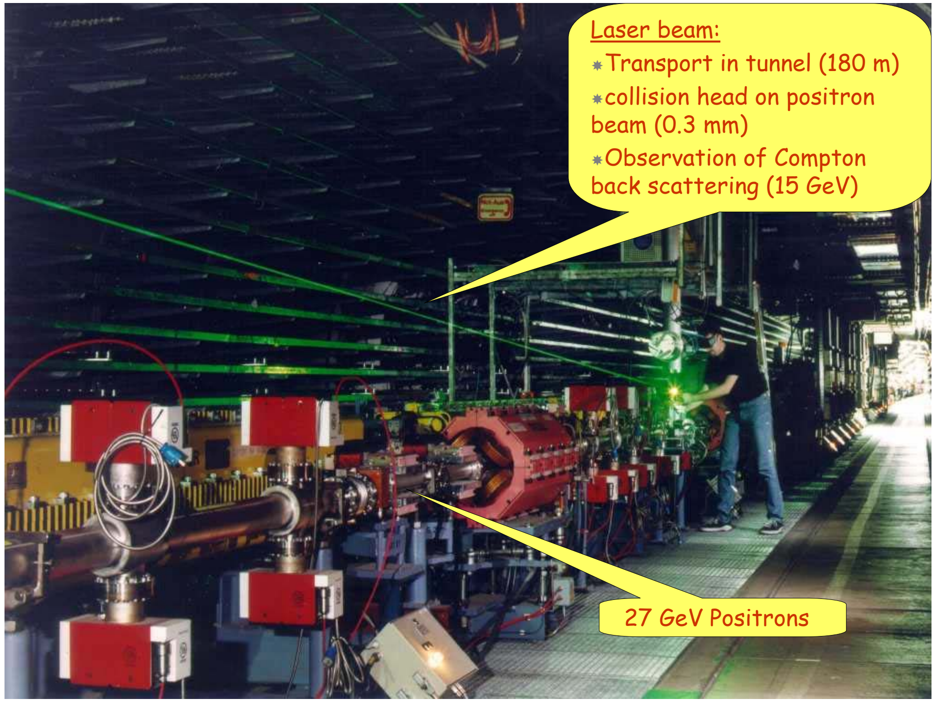
- High HERA beam polarization (pushed by HERMES) and ABS
- Storage cell technique (new at that time)
- HERA fixed target
- Standard open spectrometer
- RICH upgrade in 2000 (well working RICH)
- Recoil upgrade in 2006 (for GPD program)

Beam polarization

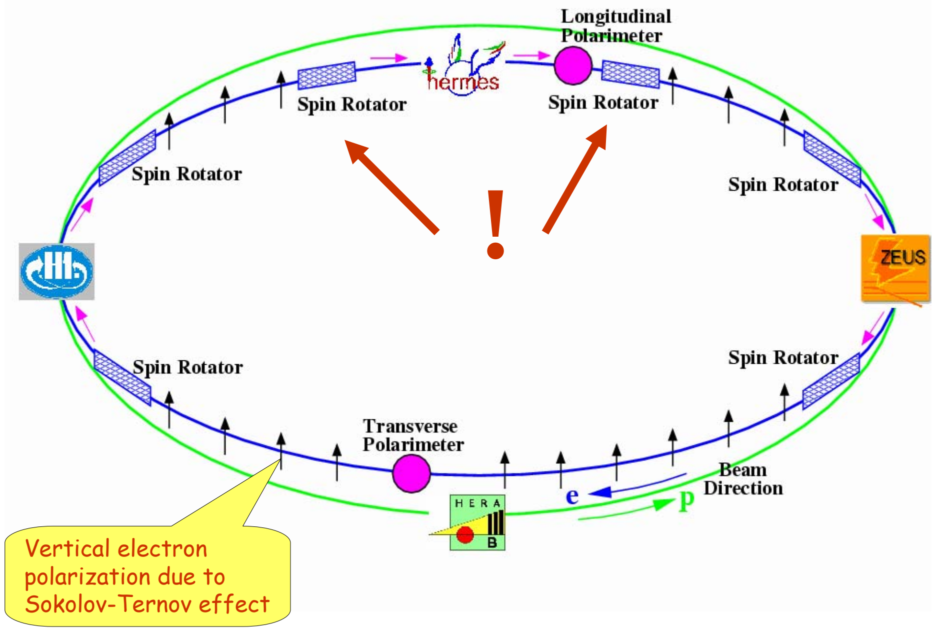


HERA



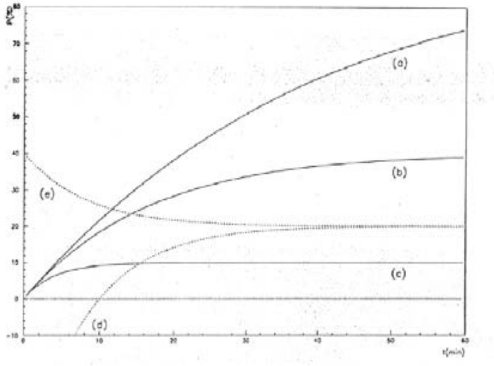


Polarization at HERA

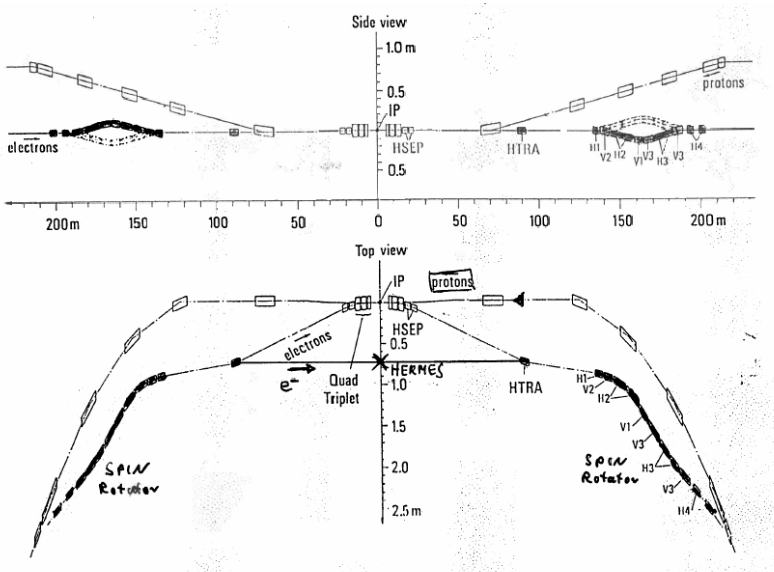


Polarization at HERA

- Sokolov Ternov effect: emission of synchrotron radiation leads to electron polarization
- Probability for a spin flip of the electron during the emission of a synchrotron photon is 10^{-11}
- The probability to flip the spin parallel or antiparallel to the magnetic field is different (96:4)
- The polarization will slowly increase according to an exponential curve with an initial slope of 2.5%/min at 27.5 GeV
- This is a very slow process compared to betatron oscillations or even to the revolution time of 21 μs.
- The equilibrium polarization is 92.38%
- Depolarizing resonances will usually reduce the equilibrium polarization significantly (e.g. the quardupole fields precess the electron spin direction)
- Many complicated schemes have been invented to compensate the resonances (e.g. the harmonic bumps are tuned to compensate individual harmonics of depolarizing frequencies)

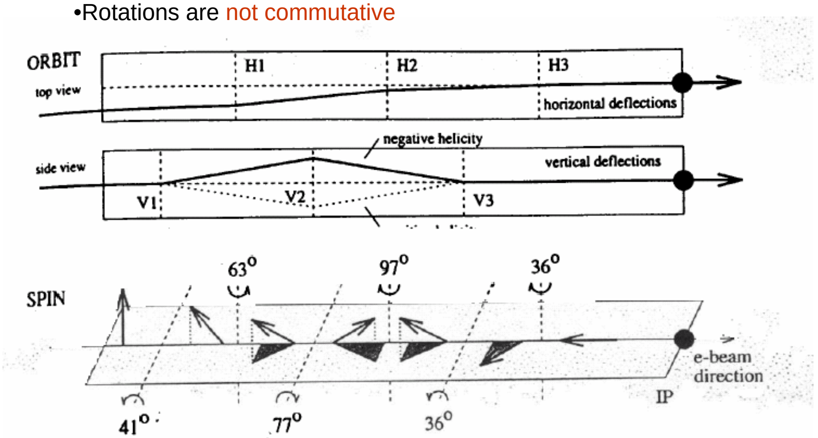


Spin rotator at HERA



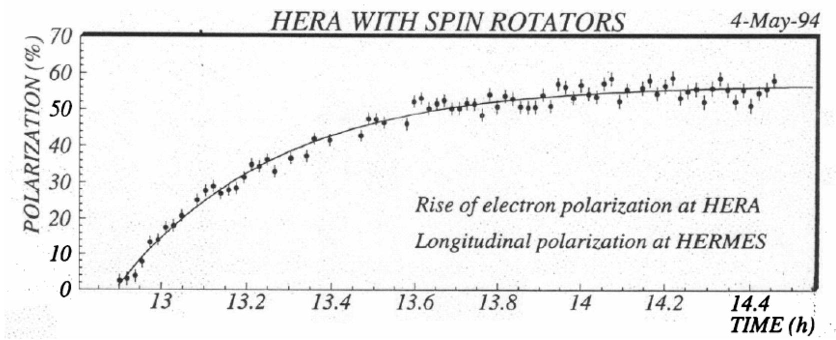
Spin rotator

- The spin precesses in the magnetic field of the dipole magnets
- Only the vertical direction is stable due to the dipole magnets of the storage ring
- To obtain longitudinal polarization one needs spin rotators
- The spin rotator is based on two effects:
  - The spin precession angle is larger by a factor 62.5 compared to the beam deflection (depends on the energy and the anomalous magn. moment)
  - Rotations are not commutative

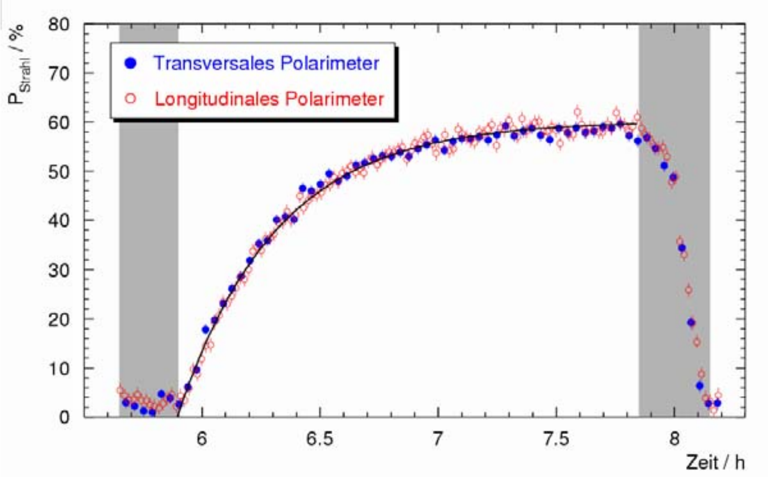


HERA polarization

- World premiere in May '94:

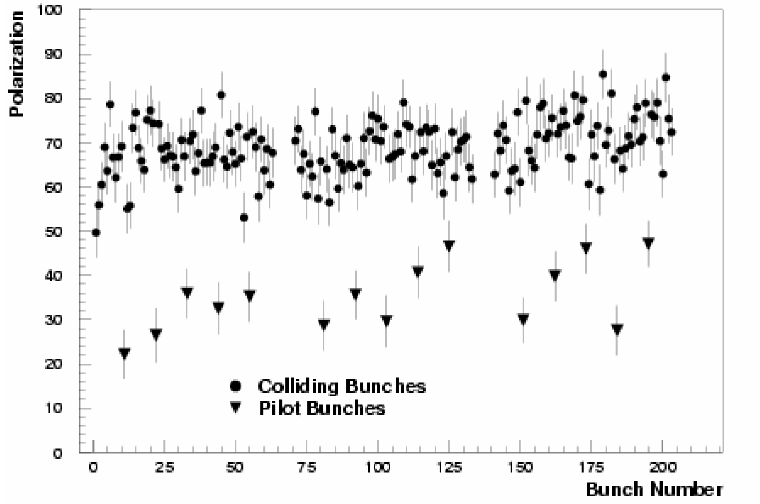


Polarization at HERA

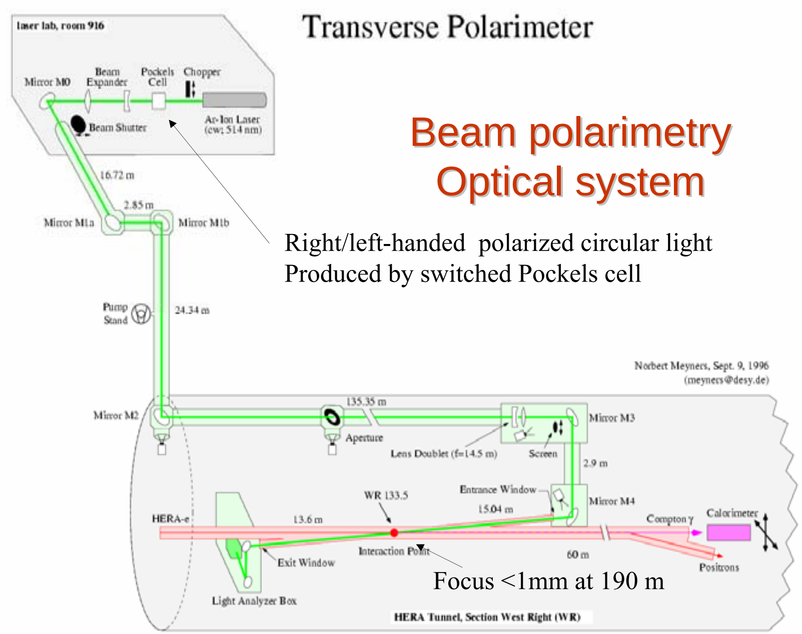


- Mittl. Strahlpolarisation $\langle P_B \rangle \sim 55\%$
- $\delta P_B / P_B = 1.8 \ldots 3.4\%$

Bunch dependence of polarization

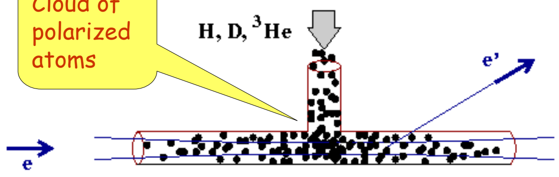


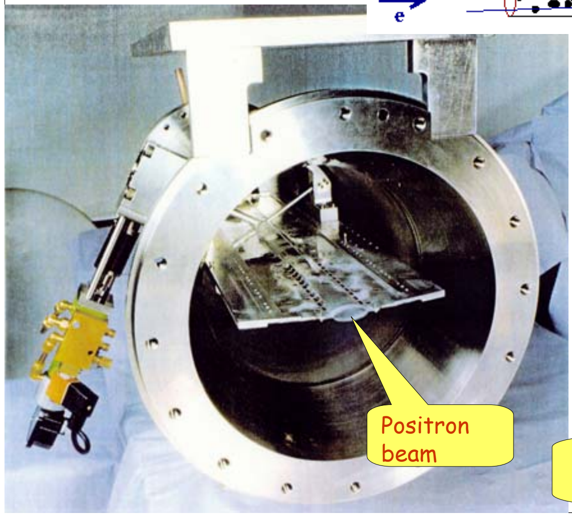
Beam polarimetry
Optical system



Target polarization

The HERMES Target: a storage cell





Semi-inclusive and exclusive physics!

Low density:
no external rad. corrections,
no rescattering of hadronic final state

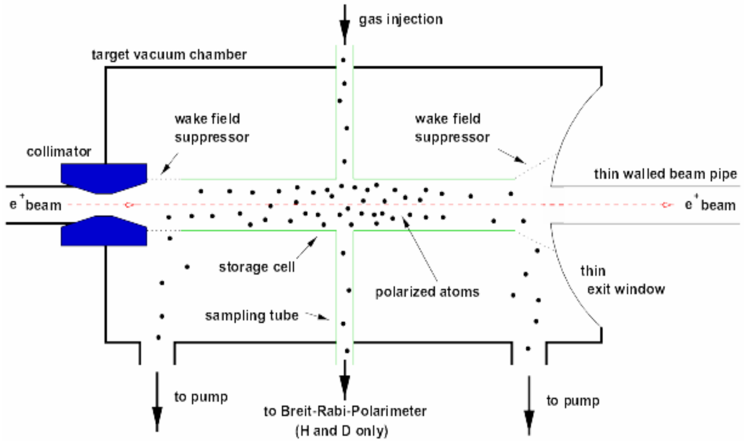
No dilution, high polarization:
50% (^{3}He) - 95% (H, D)

Nuclear targets: H, D, ^{3}He, N, Ne, Kr (13 Mio DIS in 2000)

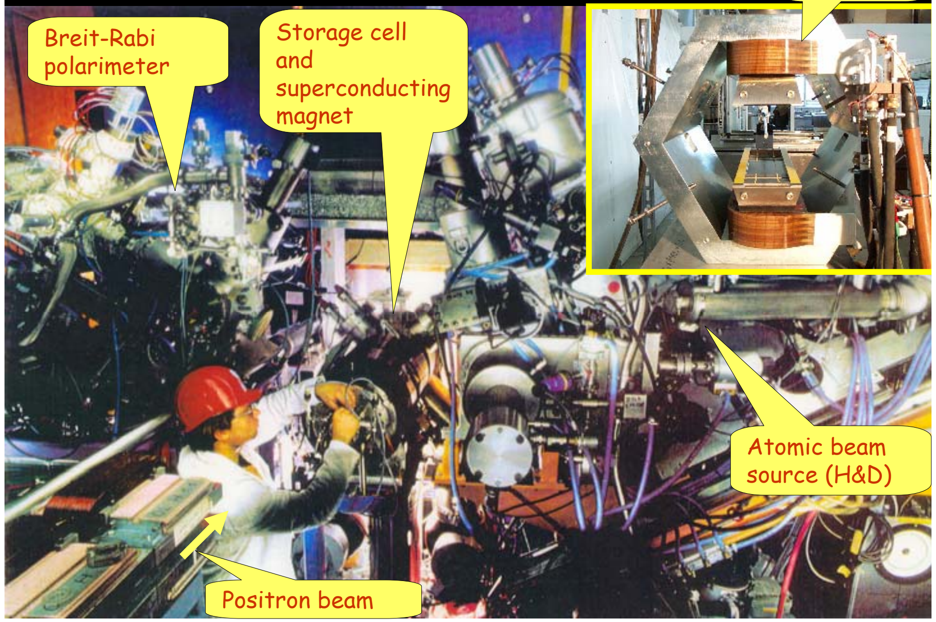
Unpolarized targets at high lumi:
$5*10^{33}$/s cm^2

End-of-fill running: Killing the HERA beam in a gas cloud

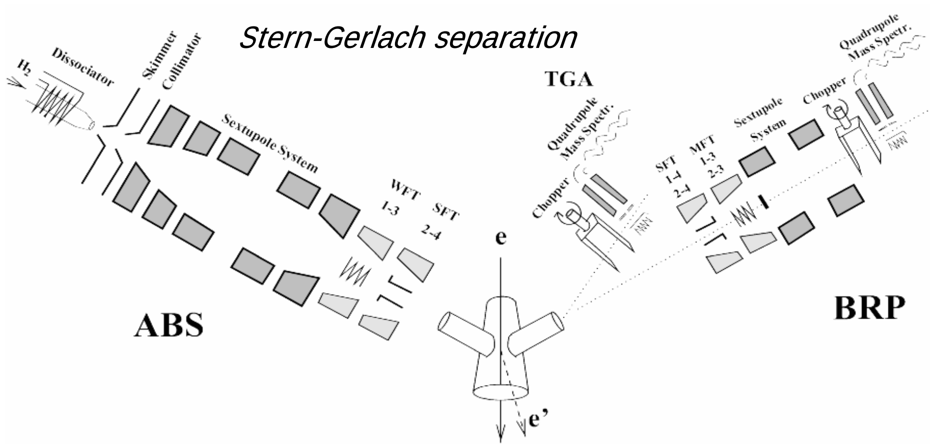
Target region



The source of atoms



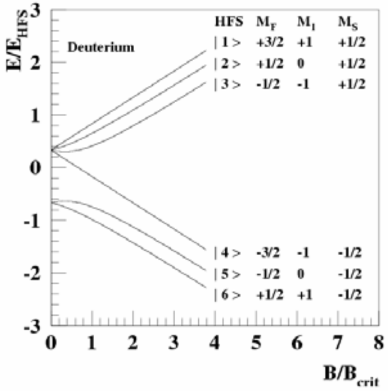
Atomic beam source



The Storage Cell and Target Holding Field Magnet

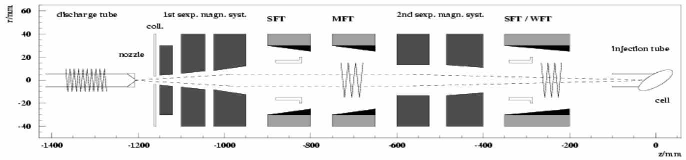
- Cell walls made out of 75 μm thick aluminum (hadrons detectable).
- Drifilm coating to minimize wall depolarization and recombination.
- Helium cooled cell - temperature range of $34 \ldots 300\,K$.
- Holding field range $0 \ldots 350\,mT$.

Select indvidual hyperfine states



The Atomic Beam Source (ABS)

ABS

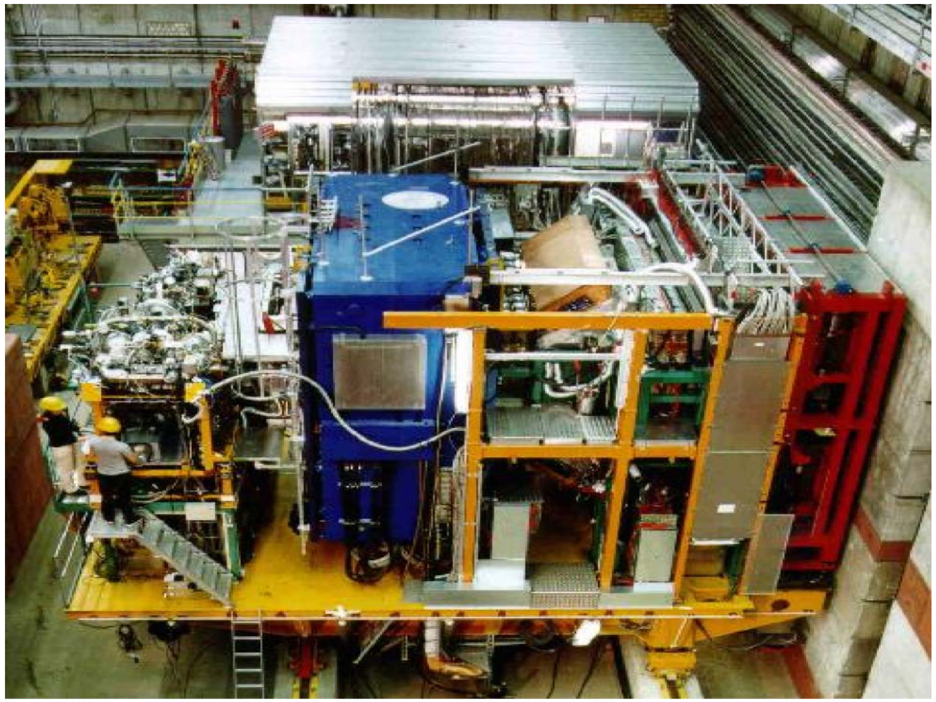


- RF dissociator with $\simeq 80\%$ degree of dissociation.
- 5 (tapered) magnets in 2 subsystems.
- 4 transition units, 3 of them independently operational.
- $\vec{D}$ beam intensity $\sim 3.5 \cdot 10^{16}\,nuc\,s^{-1}$ (3 hyperfine states).

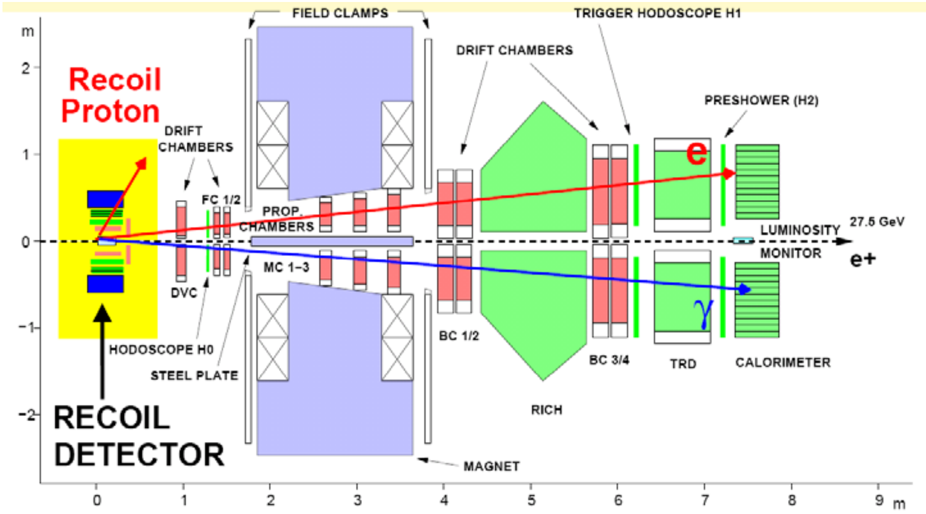
Default Injection Modes:

Pol.	Inj. HFS	high frequency transitions	
		appendix	between sextupole subsystems
P_e	$\|1\rangle, \|2\rangle, \|3\rangle$	OFF	OFF
P_{z+}	$\|1\rangle, \|6\rangle$	SFT 2-6 (**s26**)	SFT 3-5 (**t35**)
P_{z-}	$\|3\rangle, \|4\rangle$	WFT 1-4/2-3 (**w14**)	SFT 3-5 (**t35**)
P_{zz+}	$\|3\rangle, \|6\rangle$	SFT 2-6 (**s26**)	MFT 1-4 (**m14**)
P_{zz-}	$\|2\rangle, \|5\rangle$	SFT 3-5 (**s35**)	MFT 1-4 (**m14**)
P_{e+}, P_{z+}	$\|1\rangle$	OFF	MFT 3-4 (**m34**), SFT 2-6 (**t26**)
P_{e+}, P_{zz-}	$\|2\rangle$	OFF	WFT 1-4/2-3 (**v14**), SFT 2-6 (**t26**)
P_{e+}, P_{z-}	$\|3\rangle$	OFF	WFT 1-4/2-3 (**v14**), SFT 3-5 (**t35**)
P_{e-}, P_{z-}	$\|4\rangle$	WFT 1-4/2-3 (**w14**)	MFT 3-4 (**m34**), SFT 2-6 (**t26**)
P_{e-}, P_{zz-}	$\|5\rangle$	SFT 3-5 (**s35**)	WFT 1-4/2-3 (**v14**), SFT 2-6 (**t26**)
P_{e-}, P_{z+}	$\|6\rangle$	SFT 2-6 (**s26**)	WFT 1-4/2-3 (**v14**), SFT 3-5 (**t35**)

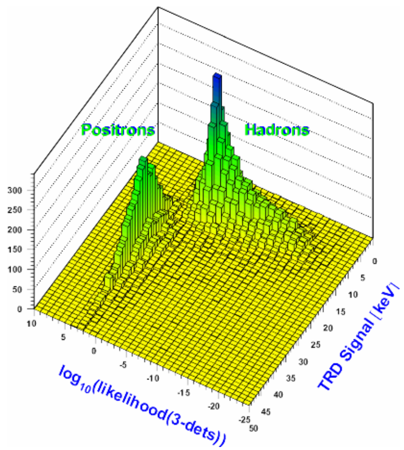
The HERMES detector



The spectrometer



Particle identification

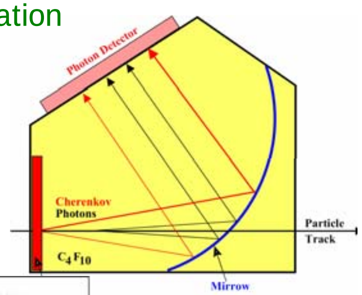


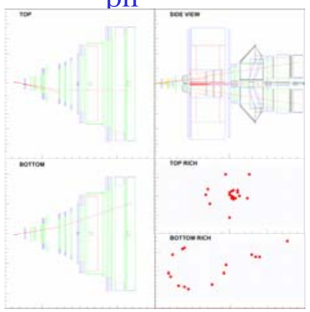
Particle identification

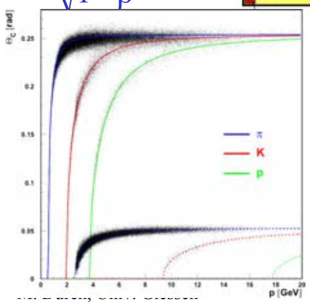
double radiator RICH for π / K / p separation
aerogel: n=1.03
C_4F_{10}: n=1.0014

Cherenkov light emission:

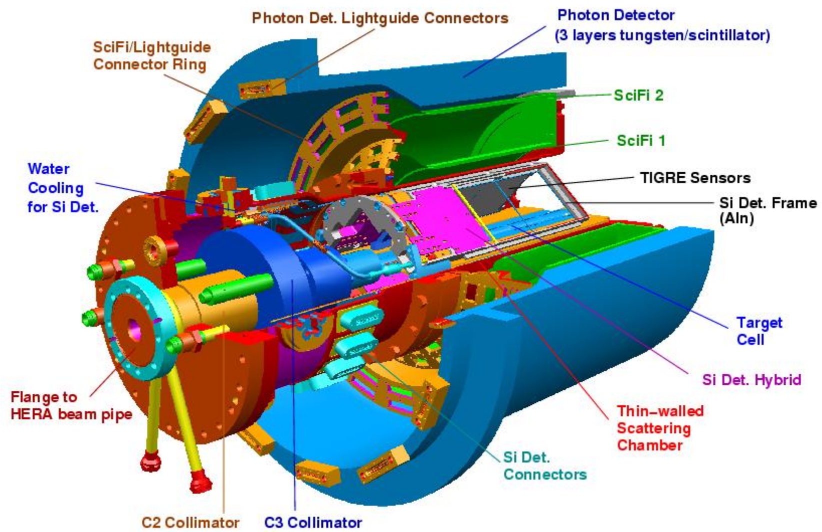
$$\cos\vartheta_c = \frac{1}{\beta n} \quad \Rightarrow \quad p = \frac{mc\beta}{\sqrt{1-\beta^2}}$$



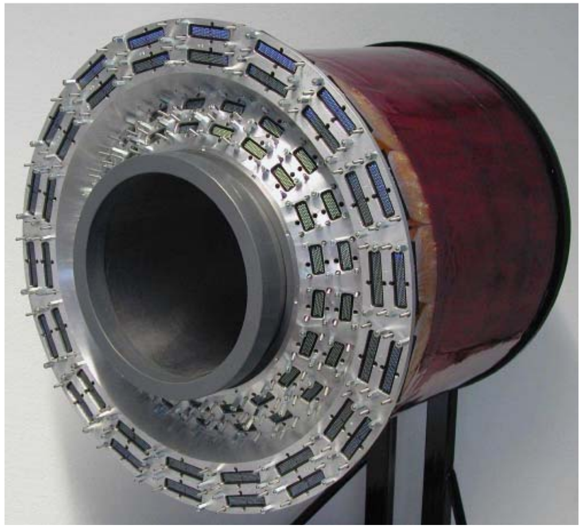




Recoil detector



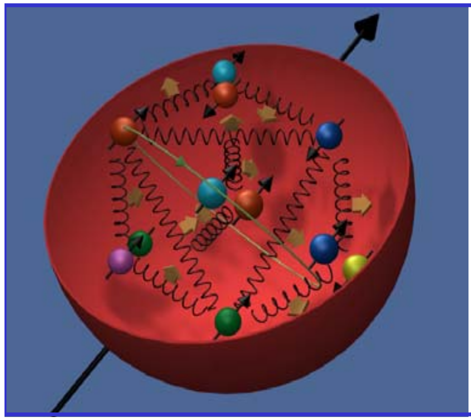
Scintillating fiber detector



HERMES' guide to success:

- Novel technologies (at time of proposal)
- Unique facility (energy, luminosity, precision, …)
- Polarization (that is where one can falsify models)
- Flexibility for upgrades

Outline



- The spin puzzle
  Introduction to spin physics
- HERMES physics:
  Modest aims and rich harvest
- HERMES technology:
  Polarization and novel techniques
- Physics results in more detail:
  - Spin structure of the nucleon
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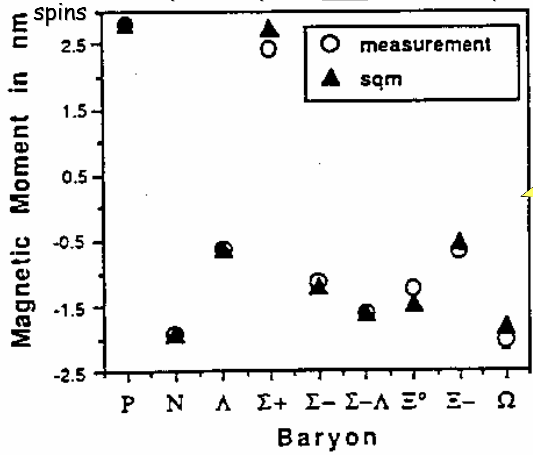
The spin crisis (1987)

- We measured the quark spin distributions in the EMC experiment
- The results violated naive expectations (Ellis Jaffe sum rule)
- Most of the proton spin is not due to the quark spins



Comment by Bjorken:
If my sum rule is wrong then QCD is wrong as well

Comment by Frank Close:
If the violation would have been discovered in the sixties, the quark model would have been discarded

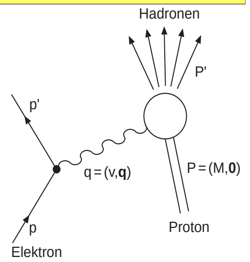
Today we do not understand any more why the magnetic moments come out so well in the naive quark model

Magnetic moments:
Great success of the quark model!

Unpolarized structure functions

$$F_2^p(x,Q^2) = x\sum_i e_i^2 q_i(x)$$

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4}\cdot\left[F_1(x,Q^2)\cdot y^2 + \frac{F_2(x,Q^2)}{x}\cdot\left(1-y-\frac{Mxy}{2E}\right)\right]$$



for longitudinally (σ_L) and transversely (σ_T) polarised photons:

$$\frac{d^2\sigma}{dxdQ^2} = \Gamma(\sigma_T + \epsilon\sigma_L).$$

Γ describes the flux of virtual photons and ϵ is the degree of transverse polarisation of the virtual photon:

$$\epsilon = \frac{1-y}{1-y+y^2/2}. \qquad (2.23)$$

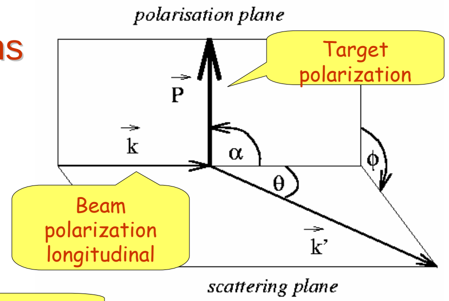
The ratio $R = \sigma_L/\sigma_T$ of the longitudinal and transverse cross sections is related to the structure functions by the following equation:

$$R(x,Q^2) = \frac{(1+4M^2x^2/Q^2)F_2(x,Q^2) - 2xF_1(x,Q^2)}{2xF_1(x,Q^2)}. \qquad (2.24)$$

$2xF_1(x) \neq F_2(x)$

Callan-Gross-relation holds only approximately: $R(x,Q^2)$ small but not equal to zero in QCD

Polarized structure functions



Cross section is as usual the product of a leptonic and a hadronic tensor:

$$\frac{d^3\sigma}{d\cos\theta\, d\phi\, dE'} = \frac{\alpha^2 E'}{Q^4 E} L^{\mu\nu} W_{\mu\nu}$$

leptonic tensor

lepton spin vector

$$L^{\mu\nu} = 2\left[k'^\mu k^\nu + k^\mu k'^\nu - k\cdot k' g^{\mu\nu} - i\epsilon^{\mu\nu\alpha\beta} q_\alpha s_{l\beta}\right]$$

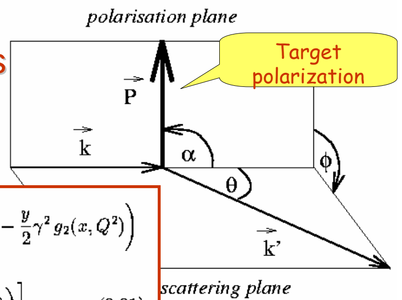
hadronic tensor

$$\begin{aligned} W_{\mu\nu} &= -\frac{F_1(Q^2,\nu)}{M} g_{\mu\nu} \\ &+ \frac{F_2(Q^2,\nu)}{Mp\cdot q} p_\mu p_\nu \\ &+ \frac{ig_1(Q^2,\nu)}{M\nu}\epsilon_{\mu\nu\lambda\sigma} q^\lambda s_h^\sigma \\ &+ \frac{ig_2(Q^2,\nu)}{M^2\nu^2}\epsilon_{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s_h^\sigma - s_h\cdot q p^\sigma). \end{aligned}$$

Unpolarized structure functions (first two terms)

Polarized structure functions (last two terms)

Polarized structure functions



Polarized part of cross section

$$\frac{d^3(\sigma(\alpha)-\sigma(\pi+\alpha))}{dx\,dy\,d\phi} = \frac{e^4}{4\pi^2Q^2}\left[\cos\alpha\left(\left[1-\frac{y}{2}-\frac{y^2}{4}\gamma^2\right] g_1(x,Q^2) - \frac{y}{2}\gamma^2 g_2(x,Q^2)\right) - \sin\alpha\cos\phi\sqrt{\gamma^2\left[1-y-\frac{y^2}{4}\gamma^2\right]}\left(\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right)\right]. \qquad (2.31)$$

Experimentally, asymmetries are measured:

$$A_\parallel = \frac{\sigma^{\uparrow\downarrow}-\sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow}+\sigma^{\uparrow\uparrow}}; \qquad A_\perp = \frac{\sigma^{\uparrow\rightarrow}-\sigma^{\uparrow\leftarrow}}{\sigma^{\uparrow\rightarrow}+\sigma^{\uparrow\leftarrow}}$$

Interpretation of structure functions in the simple quark model:

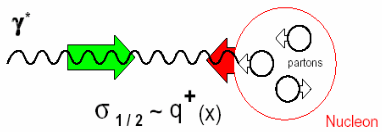
$$\begin{aligned} F_1(x,Q^2) &= \sum_f \frac{e_f^2}{2}\left(q_f^+(x)+q_f^-(x)\right) \\ F_2(x,Q^2) &= 2xF_1(x) \\ g_1(x,Q^2) &= \sum_f \frac{e_f^2}{2}\left(q_f^+(x)-q_f^-(x)\right) \\ g_2(x,Q^2) &= 0 \end{aligned}$$

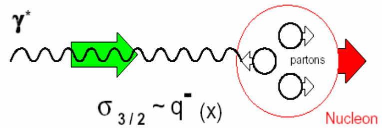
Quark distribution with quark spin parallel to proton spin

ditto, but anti-parallel

Helicity distribution $q_f^+ - q_f^- = \Delta q_f$

Partonic Interpretation





QPM:

$$\begin{aligned} q(x) &= q^+(x) + q^-(x) \\ F_1(x) &= \frac{1}{2}\sum_f e_f^2 q_f(x) \\ F_2 &= 2xF_1 \\ \Delta q(x) &= q^+(x) - q^-(x) \\ g_1(x) &= \frac{1}{2}\sum_f e_f^2 \Delta q_f(x) \\ g_2 &= 0 \end{aligned}$$

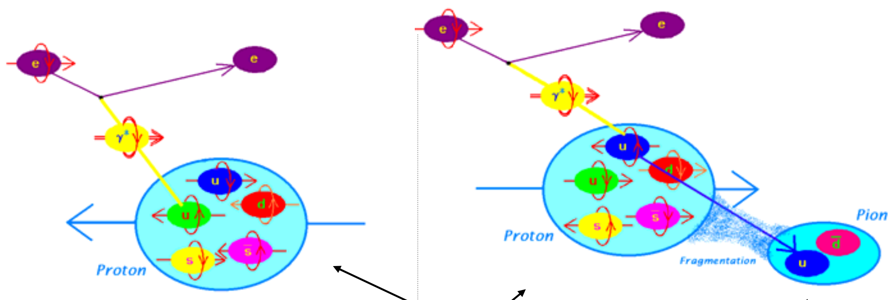
simple physical interpretation of g_1 in terms of quark helicity distributions $\Delta q_f(x)$

BUT no simple partonic picture for g_2

g_2 is NOT zero. Moments of g_2 can be calculated in QCD

How are spin distributions of quarks measured?

Principle: Helicity conservation in polarized DIS



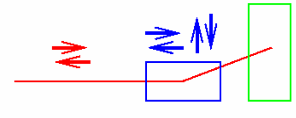
- Polarized beam
- Exchanged photon (spin 1) is polarized
- It is absorbed by quark (spin$\frac{1}{2}$) with opposite spin

- Target spin is flipped experimentally
- Measured asymmetry is related to quark polarization

Hadron tagging selects quark flavor

Spin Structure Functions in DIS

form cross section asymmetries w.r.t. orientations of beam and target spins



measured asymmetries:

$$A_{||} = \frac{\sigma^{\rightleftarrows} - \sigma^{\rightrightarrows}}{\sigma^{\rightleftarrows} + \sigma^{\rightrightarrows}} \qquad A_{\perp} = \frac{\sigma^{\Downarrow\rightarrow} - \sigma^{\Uparrow\rightarrow}}{\sigma^{\Downarrow\rightarrow} + \sigma^{\Uparrow\rightarrow}}$$

relation to virtual photon asymmetries A_1 and A_2:

$$A_{||} = D(A_1 + \eta A_2) \qquad A_{\perp} = d(\zeta A_1 + A_2)$$

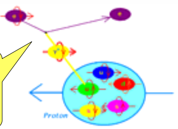
relation to spin structure functions g_1 and g_2:

$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1} \approx \frac{g_1}{F_1} \qquad A_2 = \gamma\frac{(g_1 + g_2)}{F_1}$$

D, d : photon depolarization factors ($D \approx y$)

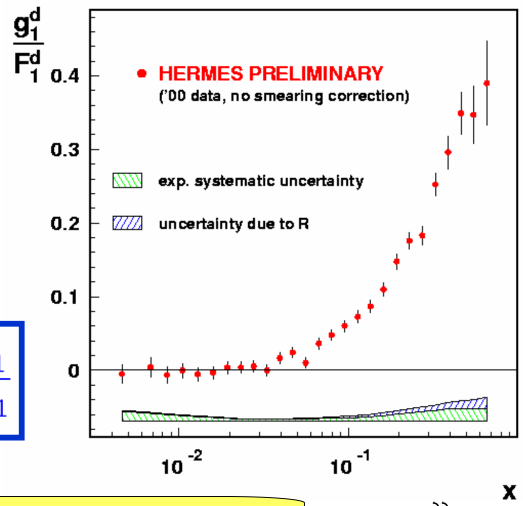
η, γ, ζ : kinematic factors ($\eta \approx \gamma \xrightarrow{Q^2 \gg M^2} 0$)

These relations take the non-zero angles into account



The spin structure function

$$g_1^d(x) = \tfrac{5}{36}\left(\Delta u(x) + \Delta d(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x)\right) + \tfrac{1}{18}\left(\Delta s(x) + \Delta\bar{s}(x)\right)$$



$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1} \approx \frac{g_1}{F_1}$$

HERMES is a precision experiment

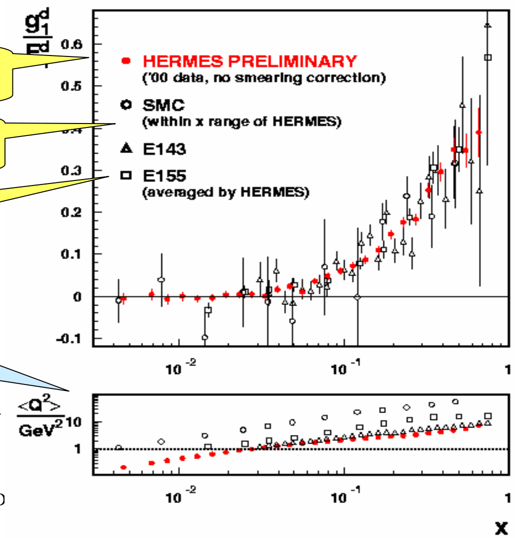
The spin structure function

$$g_1^d(x) = \tfrac{5}{36}\left(\Delta u(x) + \Delta d(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x)\right) + \tfrac{1}{18}\left(\Delta s(x) + \Delta\bar{s}(x)\right)$$

HERMES/DESY: electron/positron scattering off a polarized gas target

SMC/CERN: muon scattering off a polarized solid state target

SLAC: electron scattering off a polarized solid state target

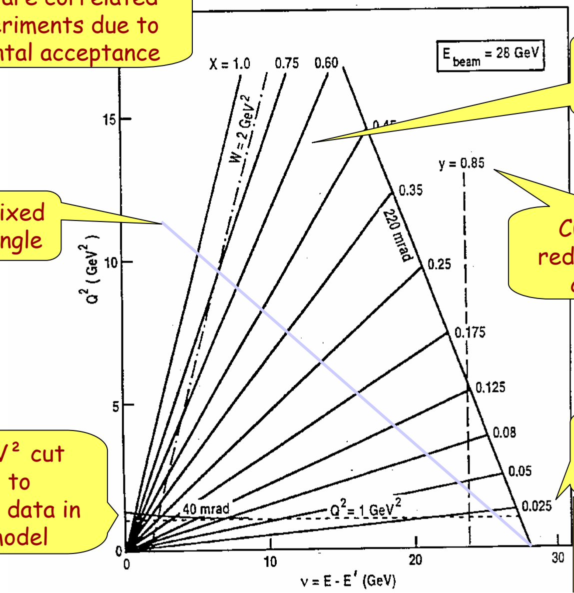


$\langle Q^2 \rangle$ differs by factor 10 between SMC and HERMES

$\langle x \rangle$ and $\langle Q^2 \rangle$ are correlated in all experiments due to experimental acceptance

Kinematics and cuts in DIS

x and Q^2 are correlated in all experiments due to experimental acceptance



At large Q^2 the number of events dies out

Fixed angle

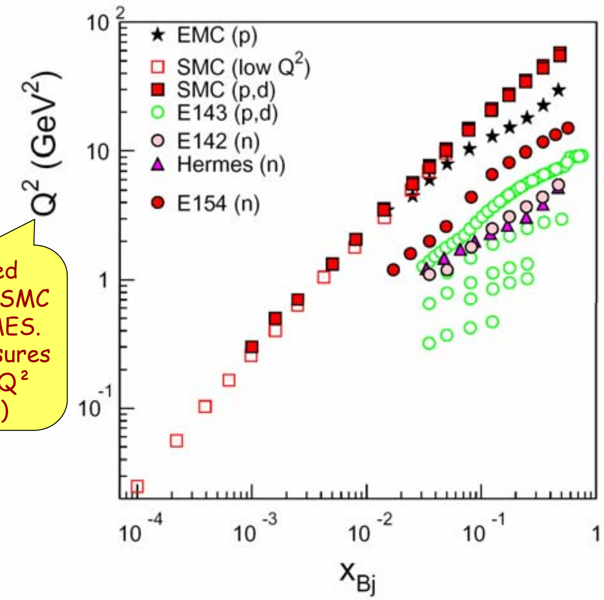
Cut at large y reduces radiative corrections

Q^2>1 GeV^2 cut allows to interprete data in quark model

beam energy defines smallest possible x

$$x=\frac{Q^2}{2M\nu}>\frac{1\,\text{GeV}}{2\cdot 0.938\cdot E}\approx 0.02$$

Kinematics and cuts in DIS

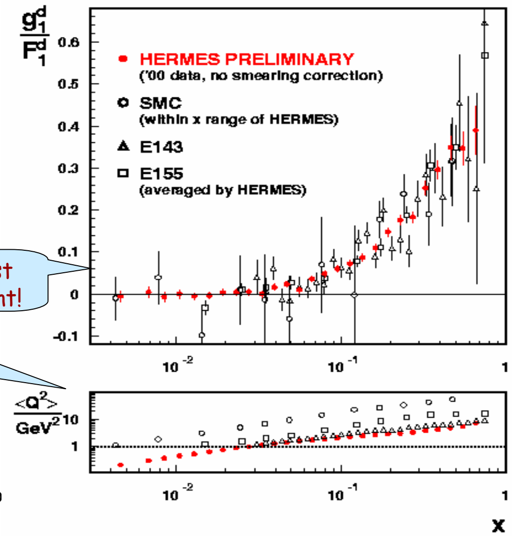


Averaged values for SMC and HERMES. SLAC measures at fixed Q^2 (angles)

The spin structure function

$$g_1^d(x)=\frac{5}{36}\left(\Delta u(x)+\Delta d(x)+\Delta\bar{u}(x)+\Delta\bar{d}(x)\right)+\frac{1}{18}\left(\Delta s(x)+\Delta\bar{s}(x)\right)$$

- F_1 varies with Q^2 according to DGLAP equations
- g_1 has a similar Q^2 dependence as F_1
- Q^2 evolution for g_1 can be calculated in QCD in a similar way as for F_1



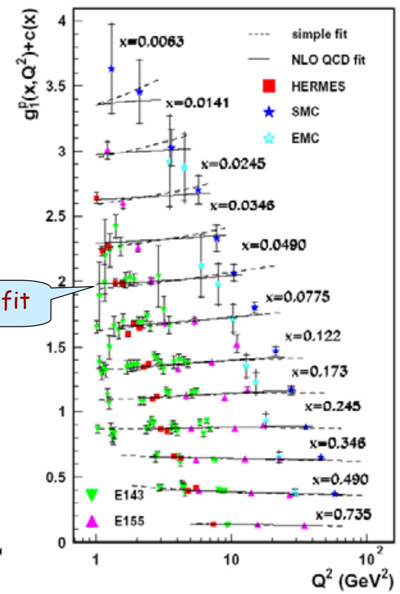
g_1/F_1 is almost Q^2 independent!

$\langle Q^2\rangle$ differs by factor 10 between SMC and HERMES

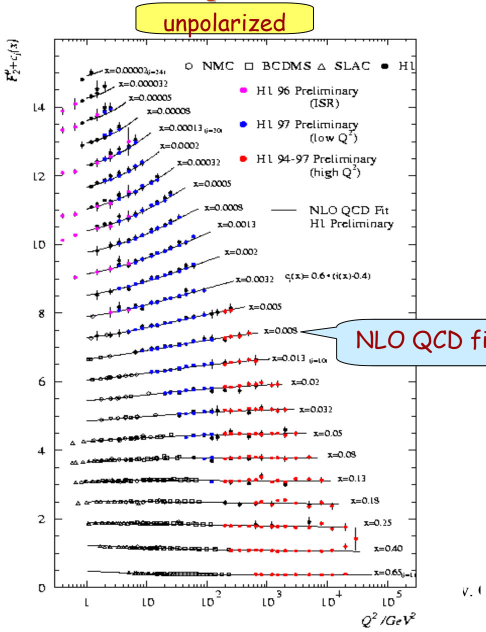
Q^2 evolution g_1

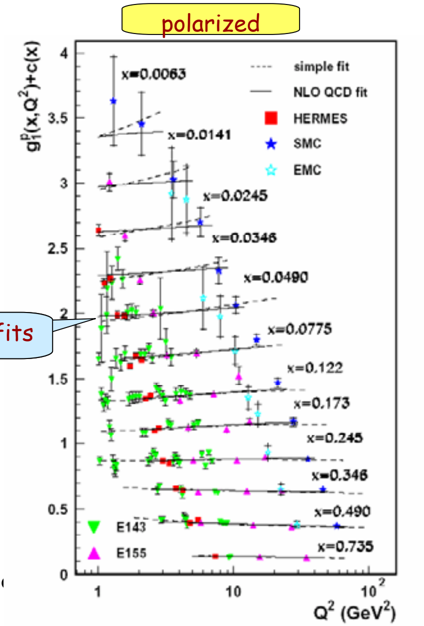
- F_1 varies with Q^2 according to DGLAP equations
- g_1 has a similar Q^2 dependence as F_1
- Q^2 evolution for g_1 can be calculated in QCD in a similar way as for F_1

NLO QCD fit

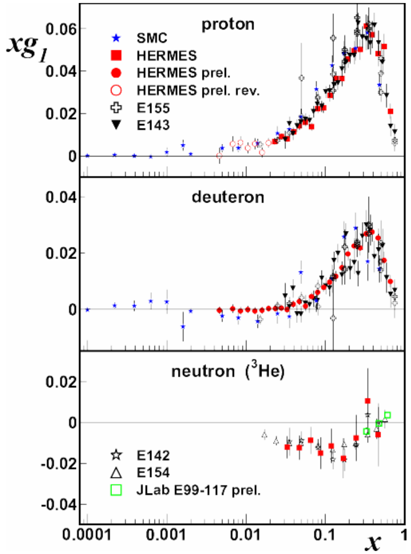


Q² evolution of F_1 and g_1





The integral of g_1



$$g_1(x) = \frac{1}{2}\sum_f e_f^2\left(q_f^+(x) - q_f^-(x)\right)$$

$$= \frac{1}{2}\sum_f e^2 \Delta q_f(x)$$

helicity distributions

(polarised quark distributions)

Sum rules for g_1

$$\Gamma_1^{p,n} = \int_0^1 dx\, g_1^{p,n}(x) \xrightarrow{\text{QPM}} \sum_q e_q^2(\Delta q + \Delta\bar{q})$$

Same symbol for function and integral!

$$\Delta q \equiv \int_0^1 dx\, \Delta q(x)$$ related to axial charges of proton:

$$a_3 = \Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d} \cong 1.26$$ $SU(2)_f$

$$a_8 = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2\Delta s - \Delta\bar{s} \cong 0.58$$ $SU(3)_f$

measured in weak baryon decays

Sum rules for g_1

$$\Gamma_1^{p,n} = \int_0^1 dx\, g_1^{p,n}(x) \xrightarrow{\text{QPM}} \sum_q e_q^2(\Delta q + \Delta\bar{q})$$

→Bjorken sum rule:
(isospin symmetry)

$$\Gamma_1^p - \Gamma_1^n = \frac{a_3}{6} \cong 0.21$$

fundamental QCD prediction

→Ellis-Jaffe sum rule:
$\Delta s = 0$
$SU(3)_f$ symmetry

$$\Gamma_1^{p(n)} = \frac{5}{36}a_8 + (-)\frac{1}{12}a_3 \cong 0.19(-0.02)$$

Sum rules for g_1

$$\Gamma_1^{p,n} = \int_0^1 dx\, g_1^{p,n}(x) \xrightarrow{QPM} \sum_q e_q^2 (\Delta q + \Delta\bar{q})$$

→Bjorken sum rule:

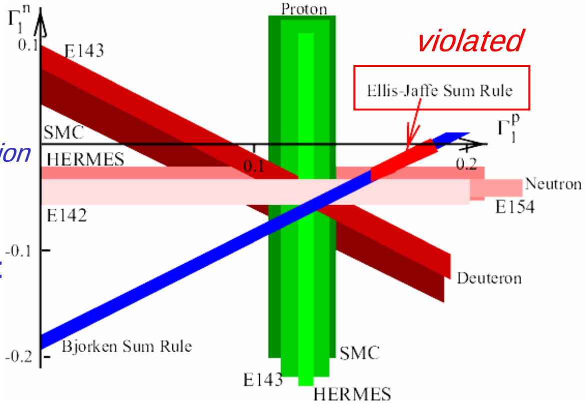
(isospin symmetry)

fundamental QCD prediction

→Ellis-Jaffe sum rule:

$\Delta s = 0$

$SU(3)_f$ symmetry



Bjorken sum rule confirmed @ 8% C.L.

Spin crisis

- $SU(3)_f$ decomposition of first moment of structure function:

$$\Gamma_1^{p(n)} = \int_0^1 g_1^{p(n)}(x)\,dx = \frac{1}{12}\left(\pm a_3 + \frac{a_8}{3}\right) + \frac{1}{9}a_0 + \text{QCD corrections}$$

with

$$a_3 = g_a/g_v = F + D = \Delta u - \Delta d$$
$$a_8 = 3F - D = \Delta u + \Delta d - 2\Delta s$$
$$a_0 = \Delta\Sigma = \Delta u + \Delta d + \Delta s$$

System of equations with three variables and two known values (F and D)

- EMC measurement allows to solve the system of equations:

$$\tfrac{1}{18}(4\Delta u + \Delta d + \Delta s) = \int g_1^p(x)dx = 0.126$$

$\Delta s \approx -10\%$

SPIN CRISIS: large negative strange quark polarization and a small total quark spin!

Compatible with zero!

- Later it was realised that the total spin carried by quarks can be interpreted in different ways
- It becomes scheme dependent in higher order QCD calculations (due to the Adler-Bell-Jackiw anomaly and the mixing with the gluon spin distribution)

Δq from $g_1(x,Q^2)$

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

one step further:

$$g_1^{NLO}(x) = g_1^{LO} + \frac{\alpha_s}{2\pi}\frac{1}{2}\sum_q e_q^2 [\Delta q(x,Q^2) \otimes C_q + \Delta G(x,Q^2) \otimes C_g]$$

parameterised

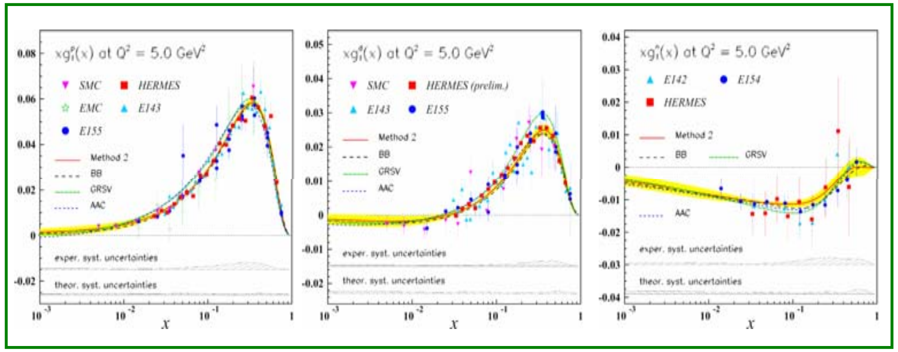
χ^2 minimisation :

$$\chi^2 = \sum_{data} \frac{(g_1^{meas} - g_1^{calc})^2}{\sigma_{stat}^2}$$

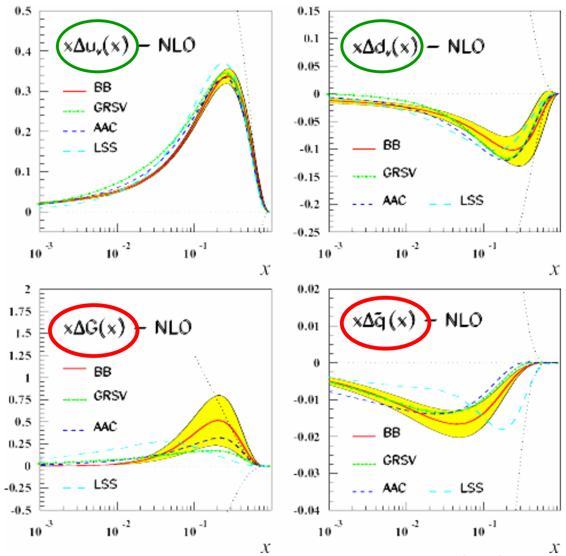
→evaluate parameter

Δq from $g_1(x,Q^2)$

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



Δq and ΔG from $g_1(x,Q^2)$



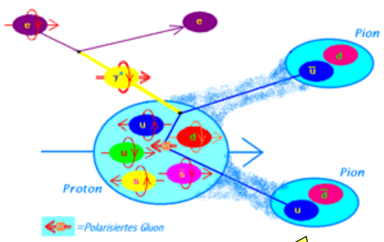
- Δu_v and Δd_v (quite) well determined
- $\Delta\bar{q}$ and ΔG weakly constraint by data

need more direct probes
→flavour separation
→ΔG

Gluon spin

- How can the gluon polarization be measured?

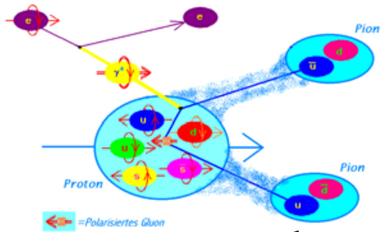
Virtual photons do **not** couple to gluons directly



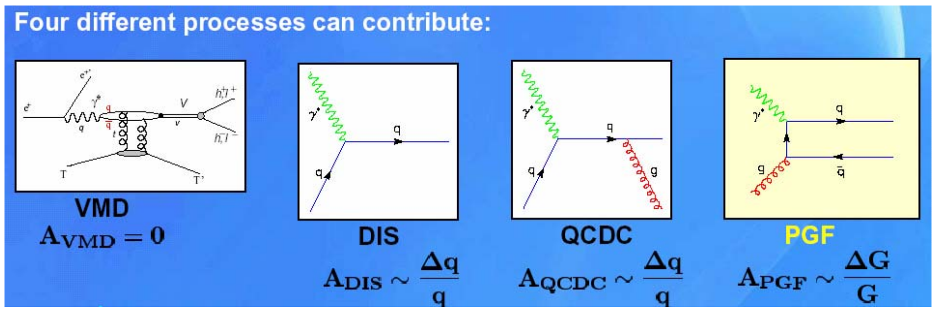
- Tricks:
  - Use QCD evolution equations, which involve ΔG(x)
  - Photon gluon fusion (PGF) graph allows direct measurement
    Select PGF e.g. by charmed hadrons, large pT jets,... (Compass, RHIC)

HERMES selects two hadrons with large opposite transverse momentum to enhance event sample

Gluon spin at HERMES



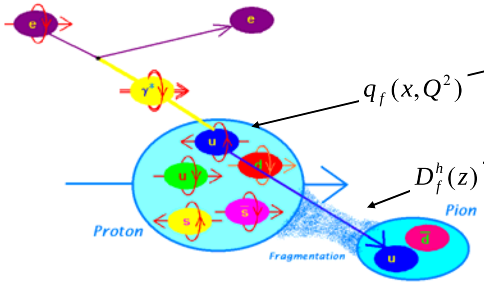
HERMES selects two hadrons with large opposite transverse momentum to enhance event sample



Semi-inclusive DIS

Semi-inclusive DIS: extract the spin-flavor distributions

Probability to find a **quark flavor f** with momentum fraction x in the proton



Factorization of

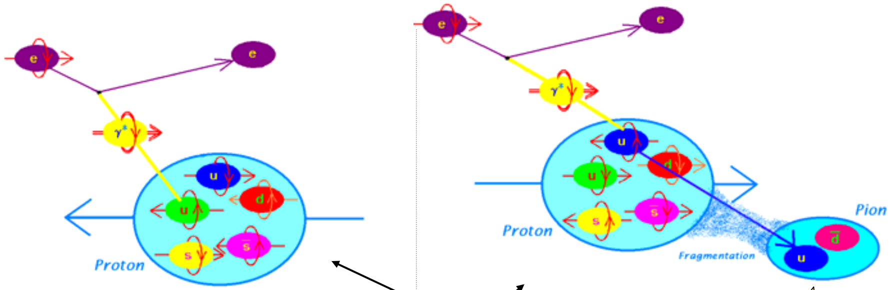
1. Quark scattering (described by quark distribution function) $q_f(x,Q^2)$
2. Hadron generation (described by fragmentation function) $D_f^h(z)$

Probability to produce a **hadron h** from a **quark f** with energy fraction $z=E_h/\nu$

Fragmentation function: $D_f^h(z)$

$$\frac{1}{\sigma_{tot}}\frac{d\sigma(eN\to e'hX)}{dz}=\frac{1}{N}\frac{dN^h}{dz}=\frac{\sum_f e_f^2 q_f(x,Q^2)D_f^h(z)}{\sum_f e_f^2 q_f(x,Q^2)}$$

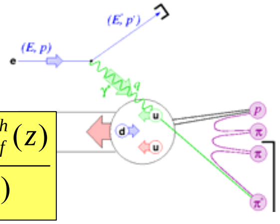
How are spin distributions of quarks measured?
Principle: Helicity conservation in polarized DIS



- Polarized beam
  - Exchanged photon (spin 1) is polarized
  - It is absorbed by quark (spin½) with opposite spin
- Target spin is flipped experimentally
  - Measured asymmetry related to quark polarization

Hadron tagging selects quark flavor

Purity formalism



Fragmentation function: $D_f^h(z)$

$$\frac{1}{\sigma_{tot}}\frac{d\sigma(eN\to e'hX)}{dz}=\frac{1}{N}\frac{dN^h}{dz}=\frac{\sum_f e_f^2 q_f(x,Q^2)D_f^h(z)}{\sum_f e_f^2 q_f(x,Q^2)}$$

$$A_1^h(x)=\frac{\sigma_{1/2}^h-\sigma_{3/2}^h}{\sigma_{1/2}^h+\sigma_{3/2}^h}\sim\frac{\sum_q e_q^2\,\Delta q(x)\int dz\,D_q^h(z)}{\sum_q e_q^2\,q(x)\int dz\,D_q^h(z)}$$

$$=\sum_q\underbrace{\frac{e_q^2\,q(x)\int dz\,D_q^h(z)}{\sum_{q'} e_{q'}^2\,q'(x)\int dz\,D_{q'}^h(z)}}_{\equiv\mathcal{P}_q^h(x,z)\ \text{“Purity”}}\cdot\frac{\Delta q(x)}{q(x)}$$

Here one assumes that the fragmentation process is independent of the spin of the fragmenting quark! That should be especially true for the fragmentation into scalar mesons (pions, kaons,...)

$D_q^h(z)$ = probability to produce a **hadron h** from a **quark f** with energy fraction z

$P_q^h(z)$ = probability that a **hadron h** with energy fraction z originates from a **quark f**

Purity formalism

$$A_1^h(x)=\frac{\sigma_{1/2}^h-\sigma_{3/2}^h}{\sigma_{1/2}^h+\sigma_{3/2}^h}\sim\frac{\sum_q e_q^2\,\Delta q(x)\int dz\,D_q^h(z)}{\sum_q e_q^2\,q(x)\int dz\,D_q^h(z)}$$

$$=\sum_q\underbrace{\frac{e_q^2\,q(x)\int dz\,D_q^h(z)}{\sum_{q'} e_{q'}^2\,q'(x)\int dz\,D_{q'}^h(z)}}_{\equiv\mathcal{P}_q^h(x,z)\ \text{“Purity”}}\cdot\frac{\Delta q(x)}{q(x)}$$

Matrix equation to invert and solve:

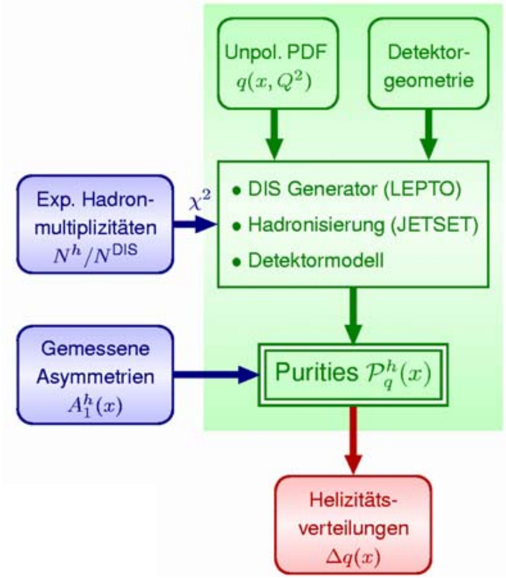
$$\vec{A}=P\vec{Q}\qquad\vec{Q}=P^{-1}\vec{A}$$

$$A^h=\sum_q P_q^h\frac{\Delta q}{q}$$

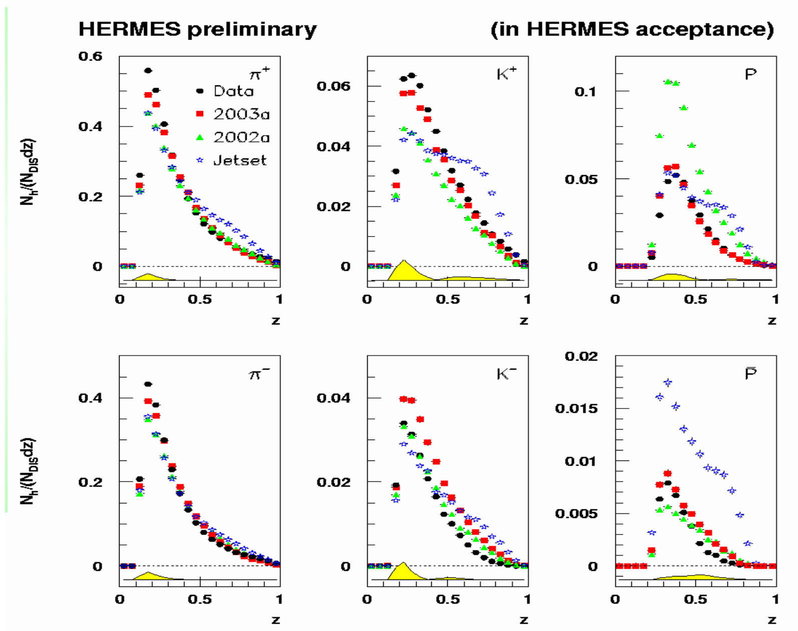
$$\vec{Q}=\left(\frac{\Delta u}{u},\frac{\Delta\bar{u}}{\bar{u}},\frac{\Delta d}{d},\frac{\Delta\bar{d}}{\bar{d}},\frac{\Delta s}{s},\frac{\Delta\bar{s}}{\bar{s}}=0\right)(x)$$

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

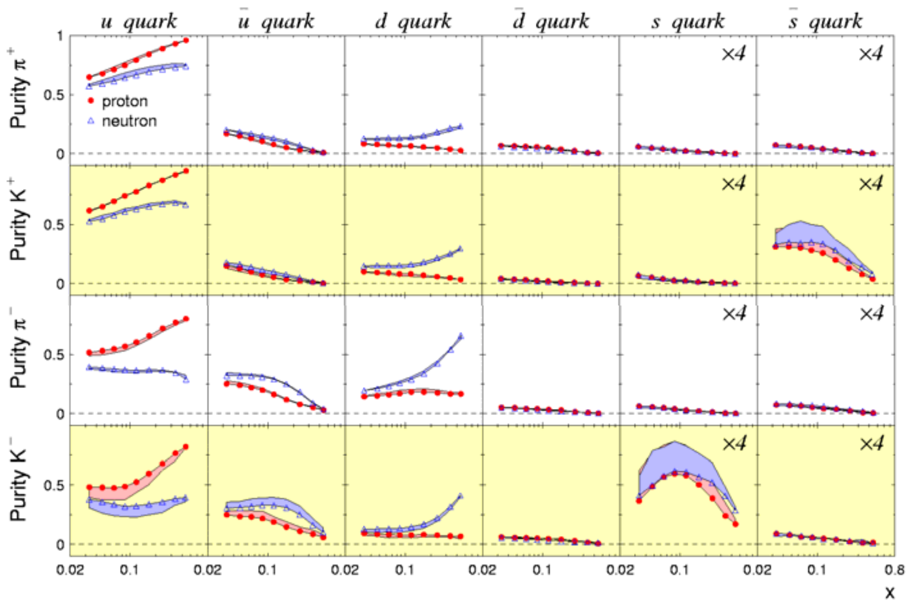
Monte Carlo extraction of purities and quark polarization



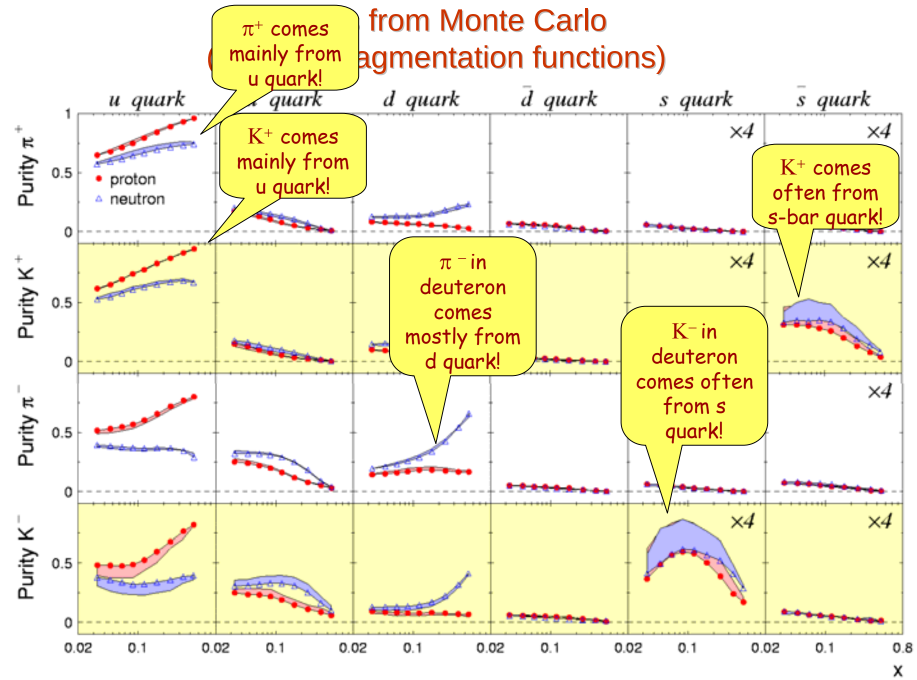
Tuning of hadron multiplicities in MC



Purities from Monte Carlo
(inverted fragmentation functions)

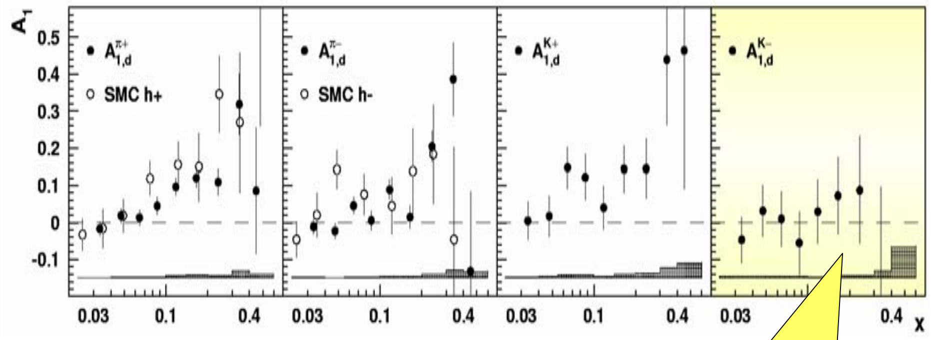


from Monte Carlo
agmentation functions)



Semi-inclusive spin asymmetries (deuterium)

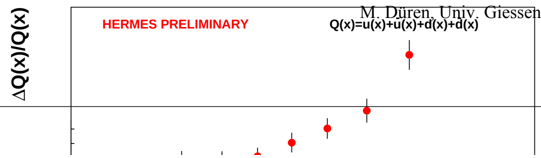
Hadron selection: $0.2 \leq z = E_h/\nu \leq 0.8, \quad x_F \geq 0.1, \quad W^2 \geq 10$ GeV²



K⁻ asymmetry is small!

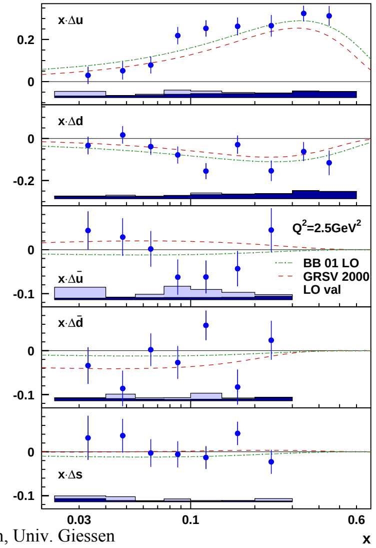
$K^- = \bar{u}s$

→ sea asymmetry is small!



Semi-inclusive spin asymmetries
Results of the 5 parameter fit

- Δu(x) is large and positive
- Δd(x) is smaller and negative
- Δs(x) is approx. zero i.e.
  - SU(3)$_f$ is broken and
  - only ~30% of the spin of the nucleon is due to the spin of the quarks



up>>0

down<0

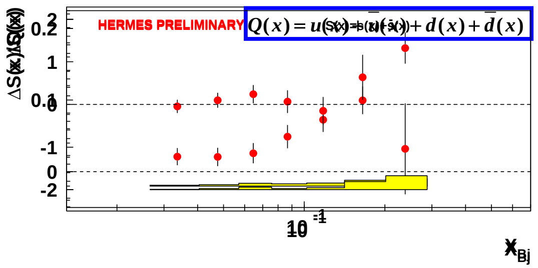
ū≈0

d̄≈0

strange ≈ 0

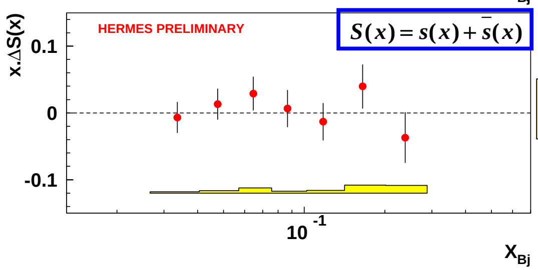
Spin of the nucleon

Latest results!



$$\int_{0.02}^{1} \Delta Q \, dx = 0.29 \pm 0.03 \pm 0.01$$

~30% up and down quark contribution in valence region



$$\int_{0.02}^{1} \Delta S \, dx = 0.006 \pm 0.029 \pm 0.007$$

<3% strange quark contribution

Transversity

Where do we stand?
Helicity sum rule:

$$\tfrac{1}{2} = \tfrac{1}{2}(\Delta u + \Delta d + \Delta s) + \Delta G + L_q + L_g$$

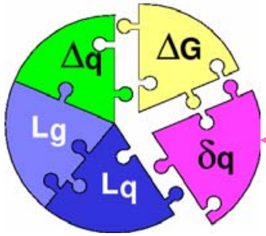
quark spin
- Semi-inclusive DIS

gluon spin
- Photon gluon fusion

HERMES, Compass, Rhic

orbital angular momentum
- Hard exclusive scattering

GPDs: generalized parton distributions: HERMES recoil project



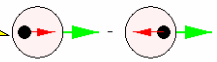
Why do we need this extra piece?

The almost forgotten twist-2 quark distribution

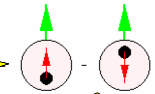
Transversity: $\delta q_f(x, Q^2)$

- Non-relativistically: The **transverse quark spin distribution** in a **transversely polarized proton** is **identical** to the longitudinal spin distribution in a longitudinally polarized target!
- In relativistic kinematics, this is NOT the case as boost and rotation do not commute! $\delta q(x) \neq \Delta q(x)$

Helicity basis



Transversity basis



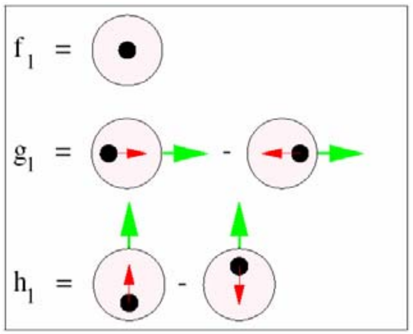
- **Interesting properties:**
- **QCD-evolution independent of gluon distribution** (to be tested by experiment)
- 1st moment of **dq** is **tensor charge** (pure valence object) predicted by lattice QCD: $\delta\Sigma = 0.562 \pm 0.088 \text{ at } Q^2 = 2\,\text{GeV}^2$

Fundamental twist-2 distribution function!

- Soffer bound: $|h_1(x)| \leq \frac{1}{2}(f_1(x) + g_1(x))$ $\quad h_1(x) = \frac{1}{2}\sum_i e_i^2 \delta q_i(x)$
- Transversity is chiral odd (i.e.does not contribute to inclusive DIS cross section!)

Transverse spin distribution of quarks

- There are three leading-twist structure functions:



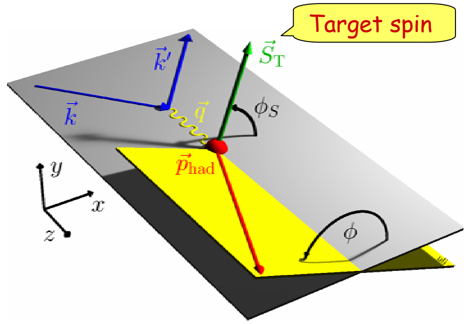
$\sim \bar{\psi}\gamma^\mu\psi$ Quark density

$\sim \bar{\psi}\gamma^\mu\gamma_5\psi$ Helicity distribution

$\sim \bar{\psi}\sigma^{\mu\nu}\gamma_5\psi$ Transversity

Transverse spin distribution of quarks

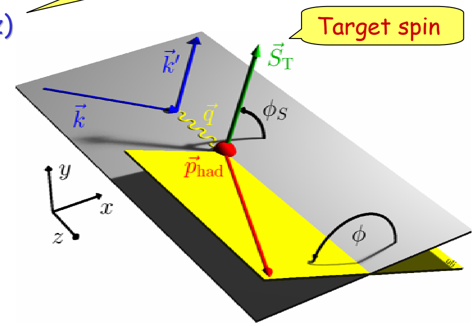
- The azimuthal angular distributions of hadrons from a transversely polarized target show two effects:
  - Collins asymmetry in $\phi+\phi_s$
  - Sivers asymmetry in $\phi-\phi_s$



Transverse spin distribution of quarks

- The azimuthal angular distributions of hadrons from a transversely polarized target show two effects:
  - Collins asymmetry in $\phi+\phi_S$
    Product of the chiral-odd transversity distribution $h_1(x)$ and the chiral-odd fragmentation function $H_1^{\perp}(z)$
    → related to the transverse spin distribution of quarks
  - Sivers asymmetry in $\phi-\phi_S$

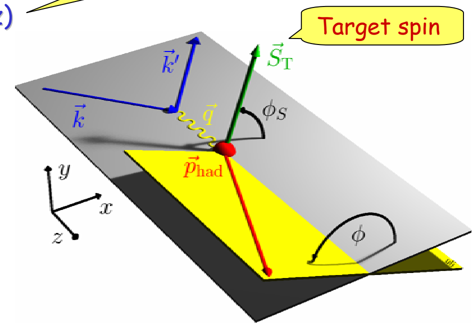
First results from Belle



Transverse spin distribution of quarks

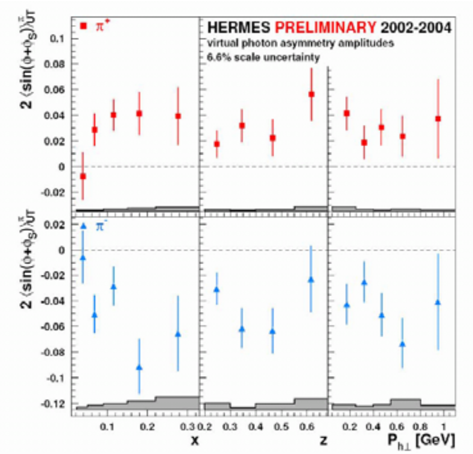
- The azimuthal angular distributions of hadrons from a transversely polarized target show two effects:
  - Collins asymmetry in $\phi+\phi_S$
    Product of the chiral-odd transversity distribution $h_1(x)$ and the chiral-odd fragmentation function $H_1^{\perp}(z)$
    → related to the transverse spin distribution of quarks
  - Sivers-Asymmetrie in $\phi-\phi_S$:
    Product of the T-odd distribution function $f_{1T}^{\perp}(x)$ and the ordinary fragmentation function $D_1(z)$
    → related to the orbital angular momentum of quarks

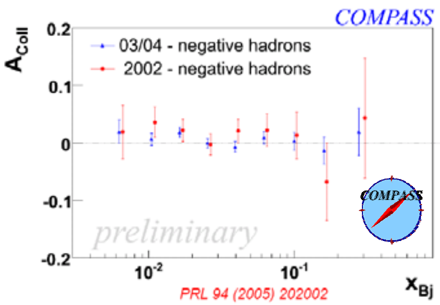
First results from Belle



Collins asymmetries

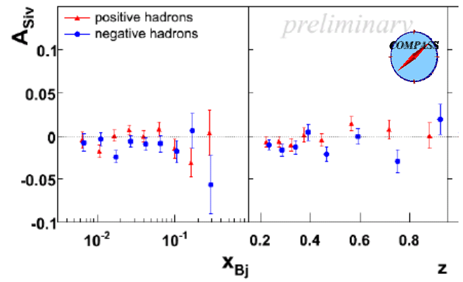
- at HERMES (H) significantly positive/negative for π^+/π^-
- at COMPASS (D) compatible with zero

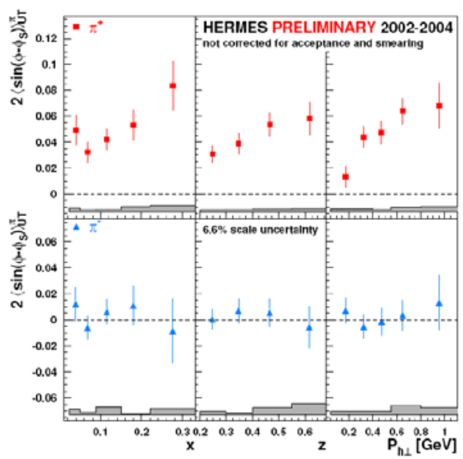




Sivers asymmetries

- at HERMES (H) positive/zero for π^+/π^-
- at COMPASS (D) compatible with zero





The results are unexpected but not inconsistent

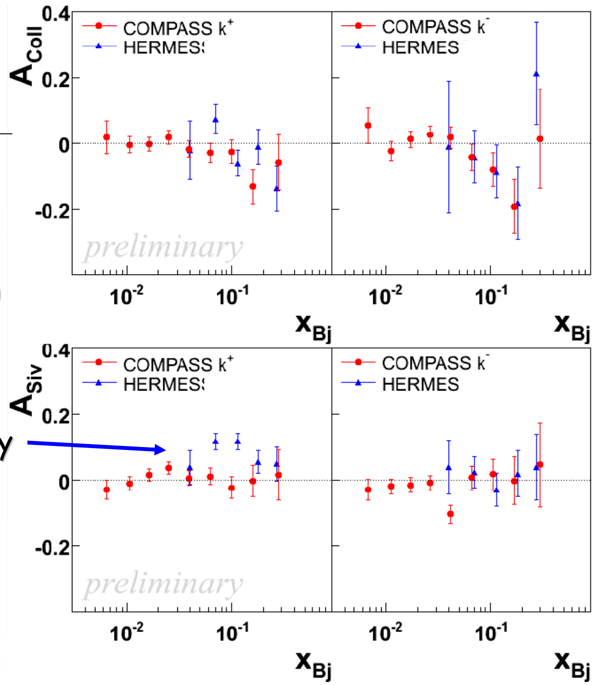
Collins and Sivers Kaon asymmetries

- at HERMES (H)

and

- at COMPASS (D)

are similar except for the Sivers K+ asymmetry



Hard exclusive reactions

Quantum phase-space „tomography" of the nucleon

Quantum phase-space Wigner distribution

- A classical particle is defined by its coordinate and momentum (x,p): **phase-space**
- A state of classical identical particle system can be described by a phase-space distribution f(x,p). The time evolution of f(x,p) obeys the Boltzmann equation.
- In quantum mechanics, because of the uncertainty principle, the phase-space distributions seem useless, but…
- **Wigner introduced the first phase-space distribution in quantum mechanics (1932)**
- Wigner function:

$$W(x,p) = \int \psi^*(x-\eta/2)\psi(x+\eta/2)e^{ip\eta}d\eta \ ,$$

Wigner function

- When integrated over x, one gets the momentum density.
- When integrated over p, one gets the probability density.
- Any dynamical variable can be calculated from it!

The Wigner function contains the *most complete (one-body) info* about a quantum system. **!**

- A Wigner operator can be defined that describes quarks in the nucleon $\hat{\mathcal{W}}_\Gamma(\vec{r},k) = \int \overline{\Psi}(\vec{r}-\eta/2)\Gamma\Psi(\vec{r}+\eta/2)e^{ik\cdot\eta}d^4\eta \ ,$
- The reduced Wigner distribution is related to *Generalized parton distributions* (GPDs)

What is a GPD?

- A proton matrix element which is a hybrid of elastic form factor and Feynman distribution
- Depends on
  x: *fraction of the longitudinal momentum carried by parton*
  $t=q^2$: *t-channel momentum transfer squared*
  ξ: *skewness parameter*

There are 4 important GPDs (among others):

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

Limiting cases:

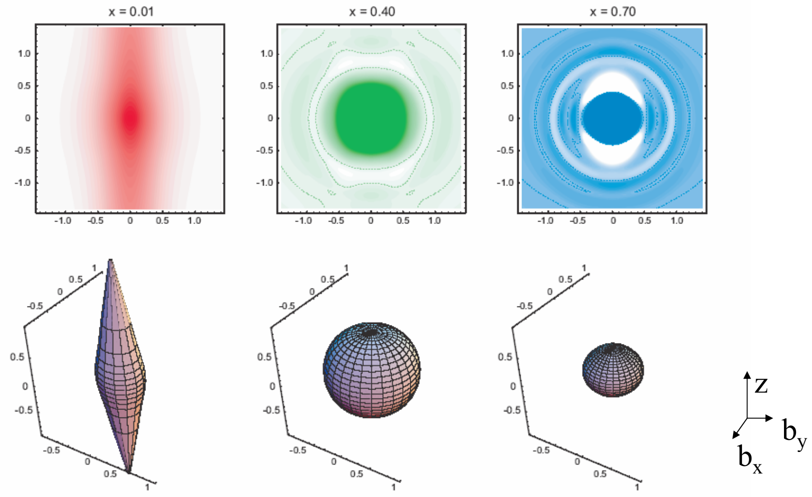
- t→0: Ignoring the impact parameters leads to ordinary parton distributions

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

- Integrating over x: Parton momentum information is lost, spatial distributions = form factors remain

$$F_1{}^q(t) = \int H^q(x,\xi,t)\,dx$$
$$F_2{}^q(t) = \int E^q(x,\xi,t)\,dx$$

3-D contours of quark distributions for various Feynman x values



Fits to the known form factors and parton distributions
with additional theoretical constraints (e.g. polynomiality) and model assumptions

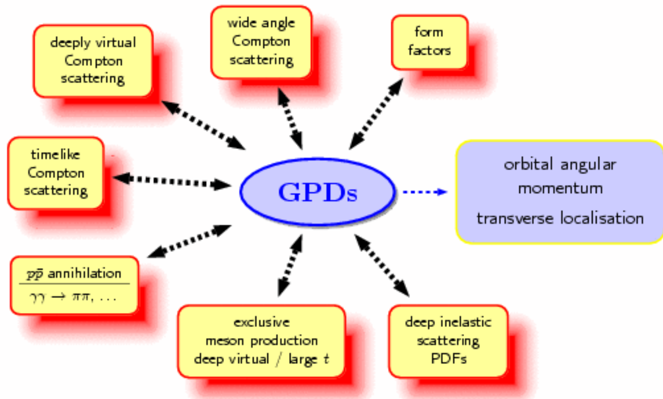
Conclusions: Quarks in the quantum mechanical phase-space

- Elastic form factors → charge distribution (space coordinates)
- Parton distributions → momentum distribution of quarks (momentum space)
- *Generalized parton distributions (GPDs) are reduced Wigner functions* → correlation in phase-space → e.g. the orbital momentum of quarks: $L = r \times p$
- *Angular momentum of quarks can be extracted from GPDs:*

Ji sum rule: $$J_q = \tfrac{1}{2}\int_{-1}^{1} x dx \left[H_q(x,\xi,0) + E_q(x,\xi,0)\right]$$

- *GPDs provide a unified theoretical framework for various experimental processes*

Generalized Parton Distributions

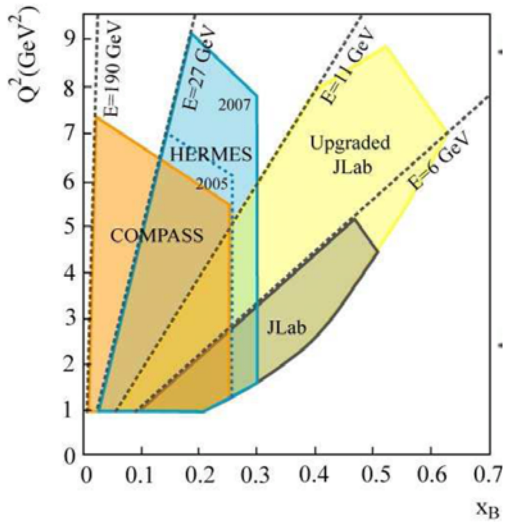


→ Quantum number of final state selects different GPDs:
Vector mesons (ρ, ω, φ): H E
Pseudoscalar mesons (π, η): $\widetilde{H}$ $\widetilde{E}$
DVCS (γ) depends on H, E, $\widetilde{H}$, $\widetilde{E}$

Hard exclusive reactions at hermes

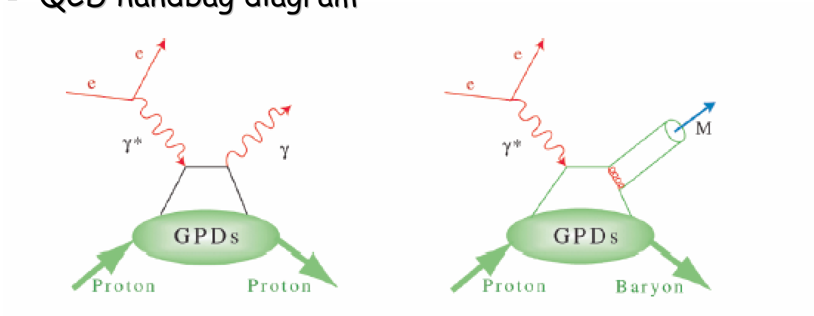
Kinematic coverage

Fixed-target experiments



Experimental Access to GPDs

- QCD handbag diagram

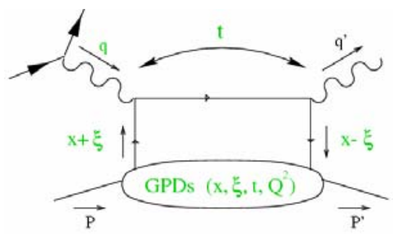


Deeply virtual Compton scattering (DVCS)

Hard exclusive meson production (HEMP)

Deeply virtual Compton scattering (DVCS)

- DVCS is the cleanest way to access GPDs: $\gamma^* N \rightarrow \gamma N$



Factorization theorem is proven!

Handbag diagram separates

- hard scattering process (QED & QCD) and
- non-pertubative structure of the nucleon (GPDs)

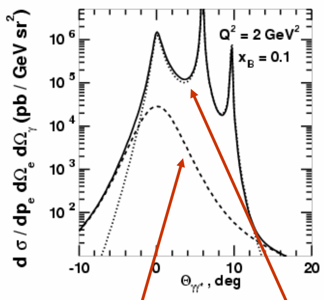
$x+\xi$: longitudinal momentum fraction of the quark

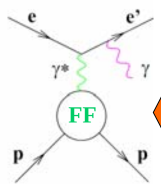
-2ξ: exchanged longitudinal momentum fraction $\xi = \frac{1}{2}\frac{x_B}{1 - x_B/2}$

t :squared momentum transfer

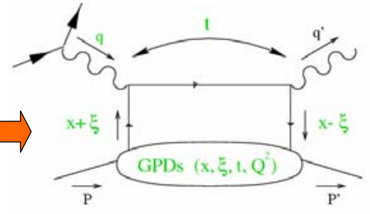
GPDs = probability amplitude for N to emit a parton ($x+\xi$) and for N' to absorb it ($x-\xi$)

DVCS and BH Interference ($ep \rightarrow e'\gamma p$)





Bethe-Heitler (BH)



DVCS

$$d\sigma \propto |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

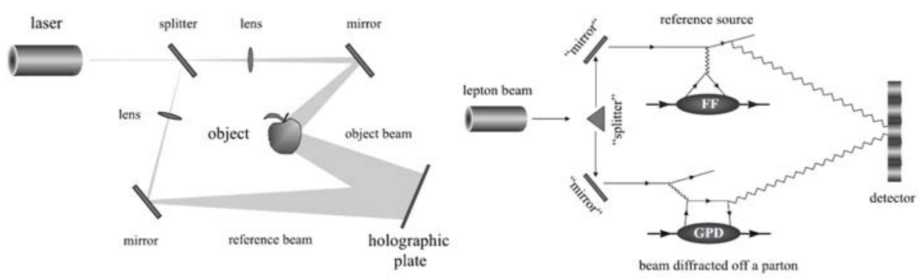
DVCS-BH interference I gives non-zero azimuthal asymmetry

Kinematics:

- $x \in [-1,1]$ $\xi \approx x_B/(2- x_B)$
- $t=(q-q')^2$ $Q^2=-q^2$

Use BH as a vehicle to study DVCS.

Laser and nucleon holography



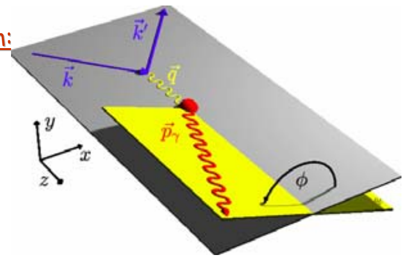
(Belitsky/Mueller)

Azimuthal asymmetries in beam spin and beam charge

Fourier decomposition of interference term:

$$I \propto \pm\left(c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi)\right)$$

charge spin



Access to real and imaginary part of helicity conserving amplitude $M^{1,1}$ (GPDs enter in linear combinations in amplitudes)

- beam spin asymmetry (BSA)

$$d\sigma(\vec{e}p) - d\sigma(\overleftarrow{e}p) \propto s_1^I \sin\phi \propto \sin\phi \cdot \mathrm{Im}\, M^{1,1}$$

- beam charge asymmetry (BCA)

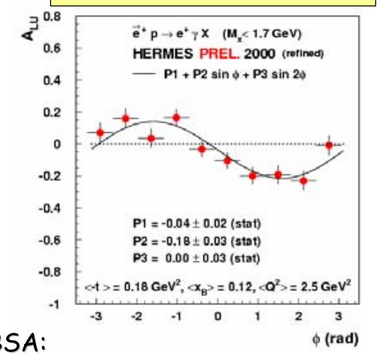
$$d\sigma(e^+p) - d\sigma(e^-p) \propto c_1^I \cos\phi \propto \cos\phi \cdot \mathrm{Re}\, M^{1,1}$$

HERMES is the only experiment which measures BCA

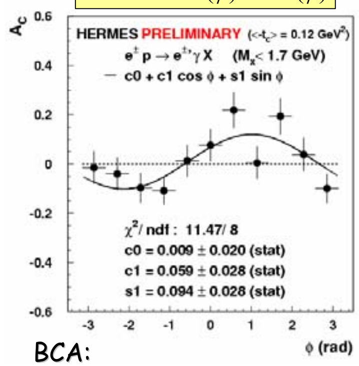
Results: BSA and BCA on proton

$$A_{LU}(\phi) = \frac{1}{\langle|P_B|\rangle} \frac{\vec{N}(\phi) - \overleftarrow{N}(\phi)}{\vec{N}(\phi) + \overleftarrow{N}(\phi)}$$

$$A_C(\phi) = \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$



BSA:
Significant sin(ϕ) dependence



BCA:
Significant cos(ϕ) dependence

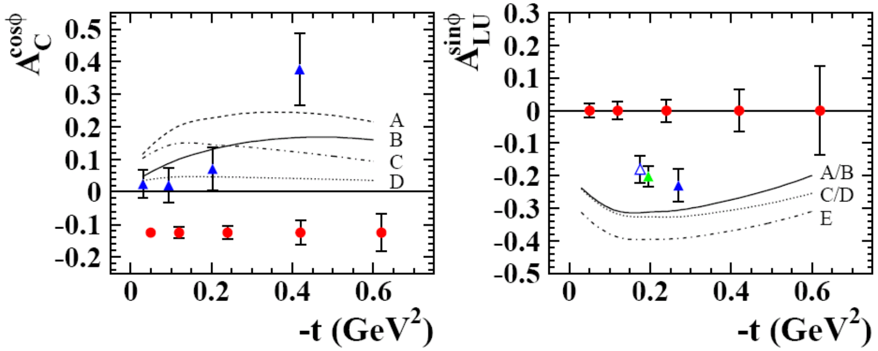
$$d\sigma(\vec{e}p) - d\sigma(\overleftarrow{e}p) \propto s_1^I \sin\phi \propto \sin\phi \cdot \mathrm{Im}\, M^{1,1}$$

$$d\sigma(e^+p) - d\sigma(e^-p) \propto c_1^I \cos\phi \propto \cos\phi \cdot \mathrm{Re}\, M^{1,1}$$

BCA and BSA on proton

HERMES results

and projected error-bars of the recoil running

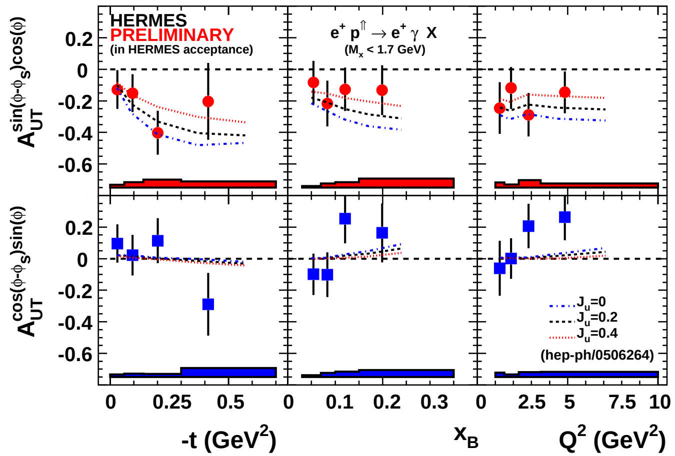


△ HERMES PRL 2001 HERMES hep-ex/0605108 ▲ HERMES hep-ex/0212019

▲ CLAS PRL 2001

• HERMES 1996-2007

DVCS: Transverse Target Spin Asymmetry

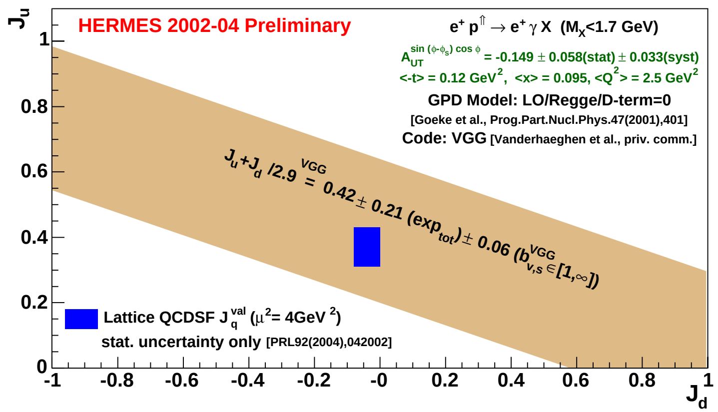


$A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)} \sim \mathrm{Im}(F_2 H - F_1 E)$

$A_{UT}^{\cos(\phi-\phi_s)\sin(\phi)} \sim \mathrm{Im}(F_2 \tilde{H} - F_1 \xi \tilde{E})$

- **first model dependent extraction of J_u possible**
  Code: VGG
  J_d assumed to be zero

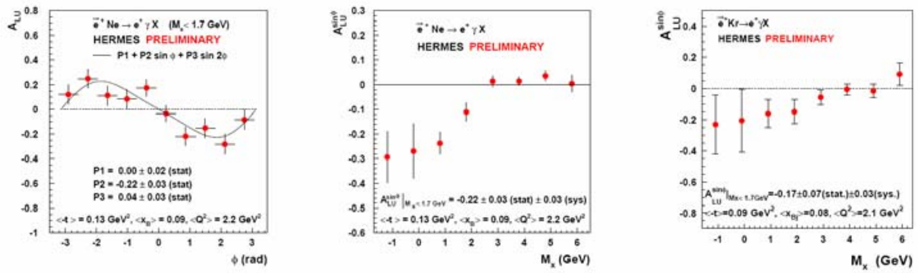
HERMES can constrain the total angular momentum of up and down quarks (J_u+J_d)!



- **same statistics with electron beam on tape**
  ⟹ **independent data set to constrain (J_u+J_d)**

Generalized EMC-Effect in nuclear DVCS

- Beam spin asymmetries in **nuclear** DVCS (Neon)



- More to come: ^{2}H,^{4}He,^{14}N,^{20}Ne,$^{82\text{-}86}$Kr,$^{129\text{-}134}$Xe:

A-dependence of coherent DVCS processes to study quarks in nuclei

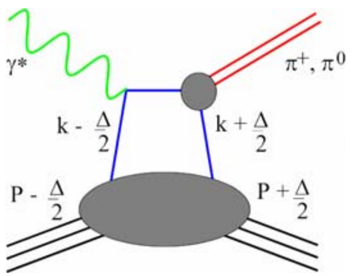
First results for Hard Exclusive Meson Production (HEMP) from HERMES: Pseudoscalar Mesons

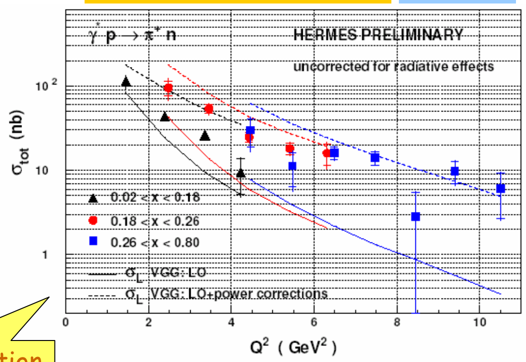
$\sigma_L \approx \left[S_\perp \sigma_L + S_\parallel \sigma_{LT}\right] \cdot A_{UL}^{\sin\varphi} \sin\varphi$

$\sigma \propto |S_T| \sin\varphi \cdot \tilde{E} \cdot \tilde{H}$

→ Pion form factor

→ Δq

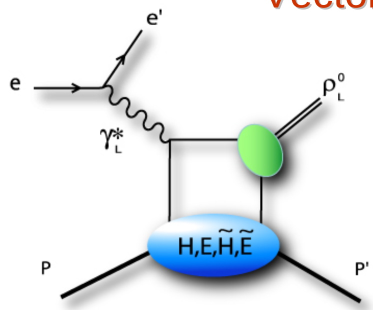


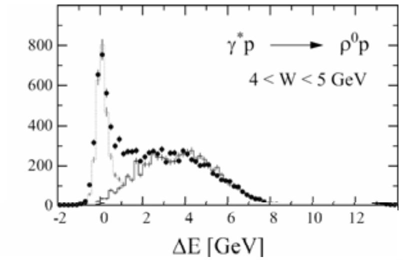


HEMP cross section
ep → e'n π⁺

GPD Model:
Vanderhaeghen, Guichon, Guidal

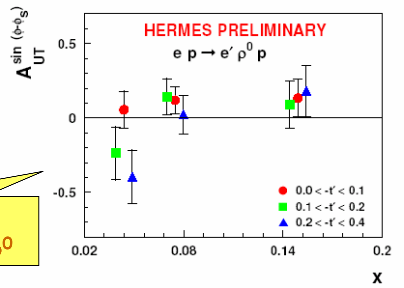
First results for HEMP from HERMES: Vector Mesons (ρ^0,ϕ,ω)





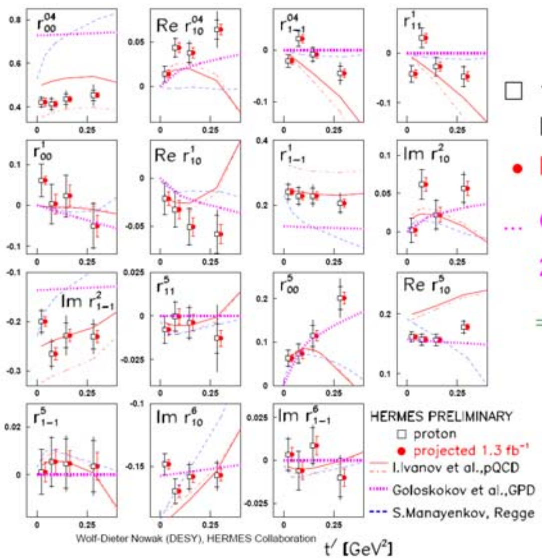
-Clean signal without background subtraction;

-DIS-background well described by MC;



HEMP target spin
asymmetry ep → e'p ρ^0

ρ^0 Spin-density-matrix Elements vs. t



- □ 15 'unpolarized' SDMEs from HERMES 1996-2000 proton data
- ● Projection 1996-2007 data
- ... GPD-based model ($Q^2 > 3$ GeV^2 2-gluon exchange only
  - ⇒ waiting for inclusion of quark-exchange into GPD-based model

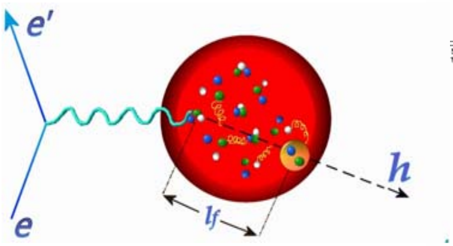
(hoping for lower Q^2-limit then

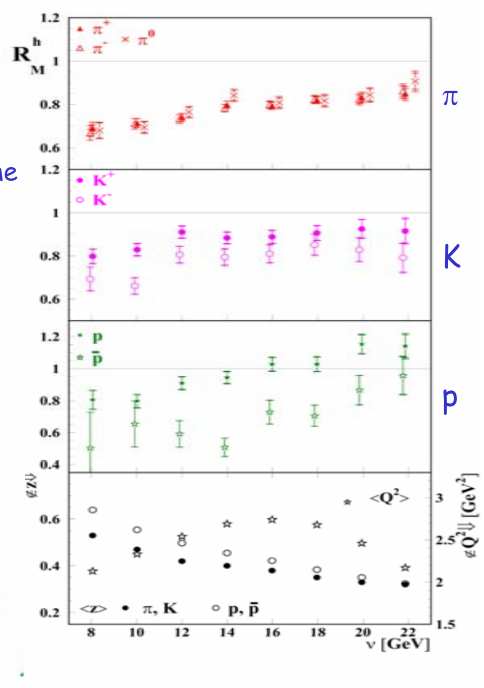
Quarks in nuclei

Study fragmentation in nuclei

→ understanding of the space-time evolution of the hadron formation process

$$R_M^h(z) = \frac{\left(\frac{N_h(z)}{N_e}\right)_A}{\left(\frac{N_h(z)}{N_e}\right)_D}$$





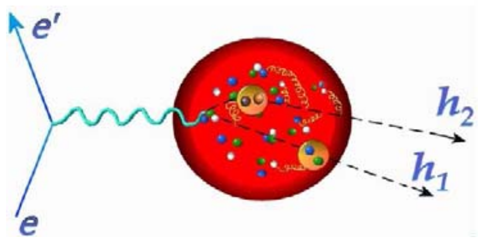
2-hadron production in nuclei

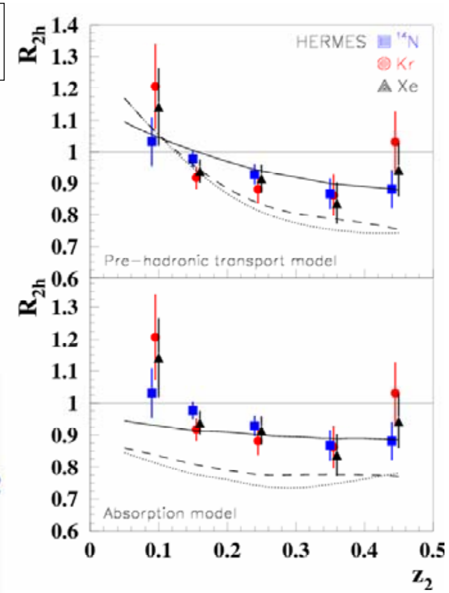
→ disentangle absorption and energy loss models

leading hadron: $z_1 > 0.5$

subleading hadron: $z_2 < z_1$

$$R_{2h}(z_2) = \frac{\left(\frac{N_2(z_2)}{N_1}\right)_A}{\left(\frac{N_2(z_2)}{N_1}\right)_D}$$





Conclusions

- HERMES has done and still does unique and pioneering measurements in the fields of
  - Spin structure of the nucleon
  - Exclusive reactions and GPDs
  - Hadronization studies in nuclei
  - …
- We have millions of interesting events on tape that might have more surprises waiting for being analyzed by YOU!