# Spin Physics at hermes

**An experiment to study the spin structure of the nucleon**

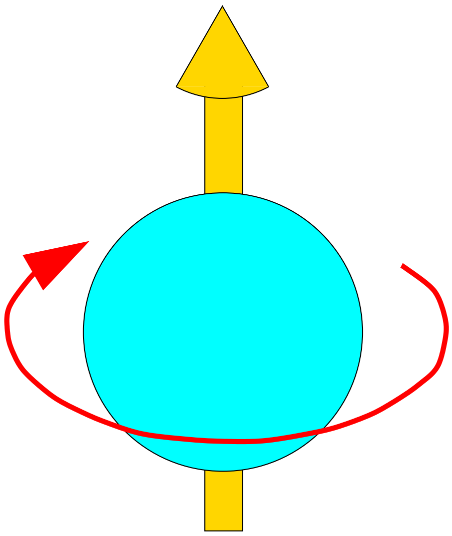
Erika Garutti (NIKHEF)

DESY Hamburg, 1 December 2000

- What is spin ?
- What do we know about the nucleon spin?
- The HERMES experiment
- Measurements at HERMES
- Unpolarized physics results

# What is spin ?

- Intrinsic spinning of a body around its axis:



Intrinsic property as: $m, q, \tau$

Quantum Mechanics:

$\boxed{\text{Quantized in units of } \hbar/2}$

- Spin is everywhere:
  - Astrophysics: spinning of galaxies as a proof of existence of Dark Matter
  - Solid-State physics: Superconductivity is a consequence of electron pairs with $S_{pair} = 0$
  - Medical physics: MRI-technique based on spin-flip of the proton

# Knowledge of the Universe

The study of the Universe requires:

**Study of Matter**

$u$ $c$ $b$

$d$ $s$ $t$

$e$ $\mu$ $\tau$

$\nu_e$ $\nu_\mu$ $\nu_\tau$

$\Rightarrow$ Spin = 1/2

**Study of Forces**

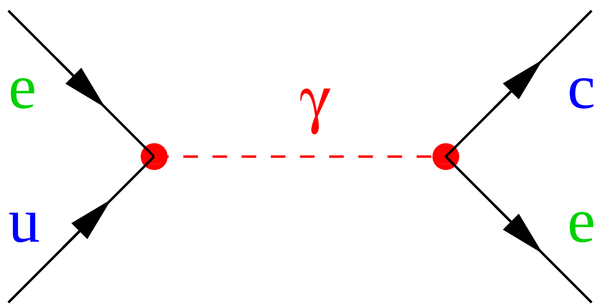
$\gamma$ $W^{\pm}$

$H$ $G$

$Z_0$ $g$

$\Rightarrow$ Spin = 0,1,2

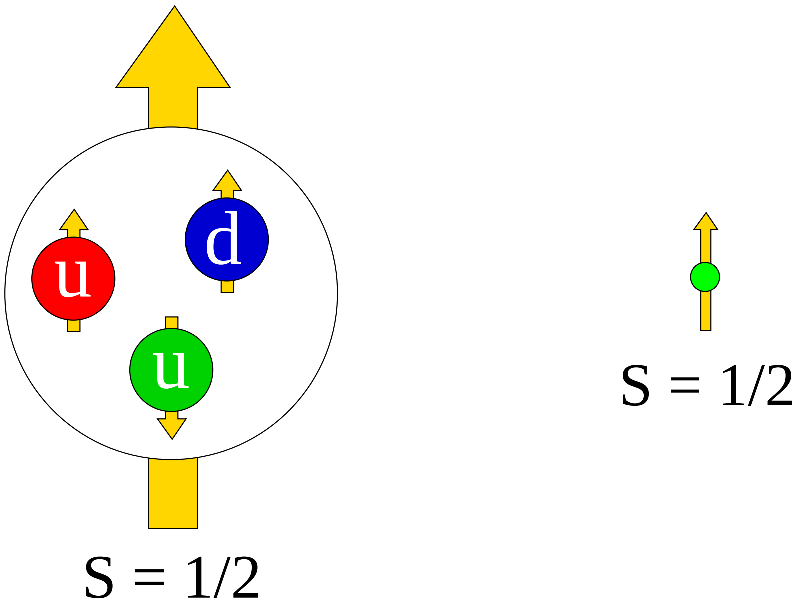
Matter interacts through Forces:




$\Rightarrow$ Spin is conserved in interactions

# Spin and Particles

- Proton and electron both have $S = \frac{1}{2}\hbar$ :




... but the proton is a composite object !

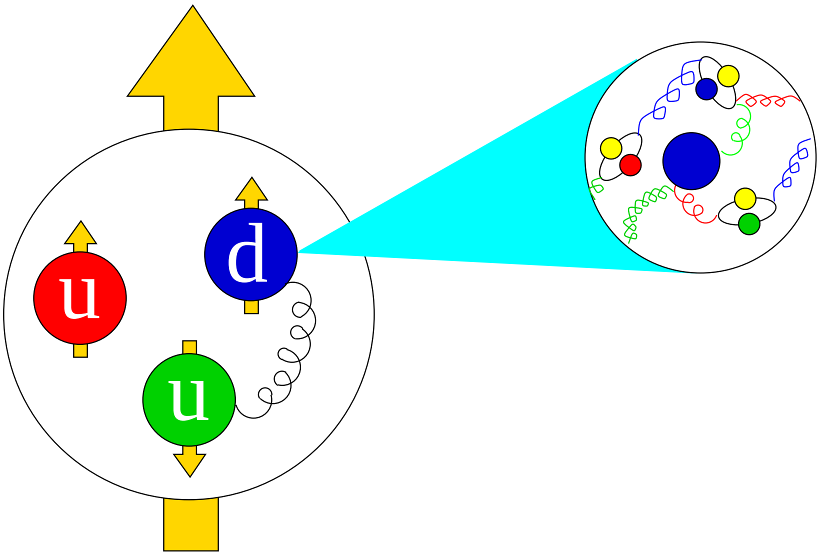
- In the naive model:
  - the proton has a $(\uparrow\downarrow\uparrow)$ structure:

$$S_{proton} = \Sigma\, S_{quarks} = \frac{1}{2} - \frac{1}{2} + \frac{1}{2} = \frac{1}{2}$$

- but we know there is more to it...

# Where is the Spin of the Nucleon?

*"... the nucleon is an object we thought we knew so well, but which reveals a new face when it spins." J.Ellis*




$$S_z^N = \frac{1}{2} = \frac{1}{2}\overbrace{\Delta\Sigma}^{}_{\Delta u + \Delta d + \Delta s} + \Delta G + < L_z >$$

**Theory:**

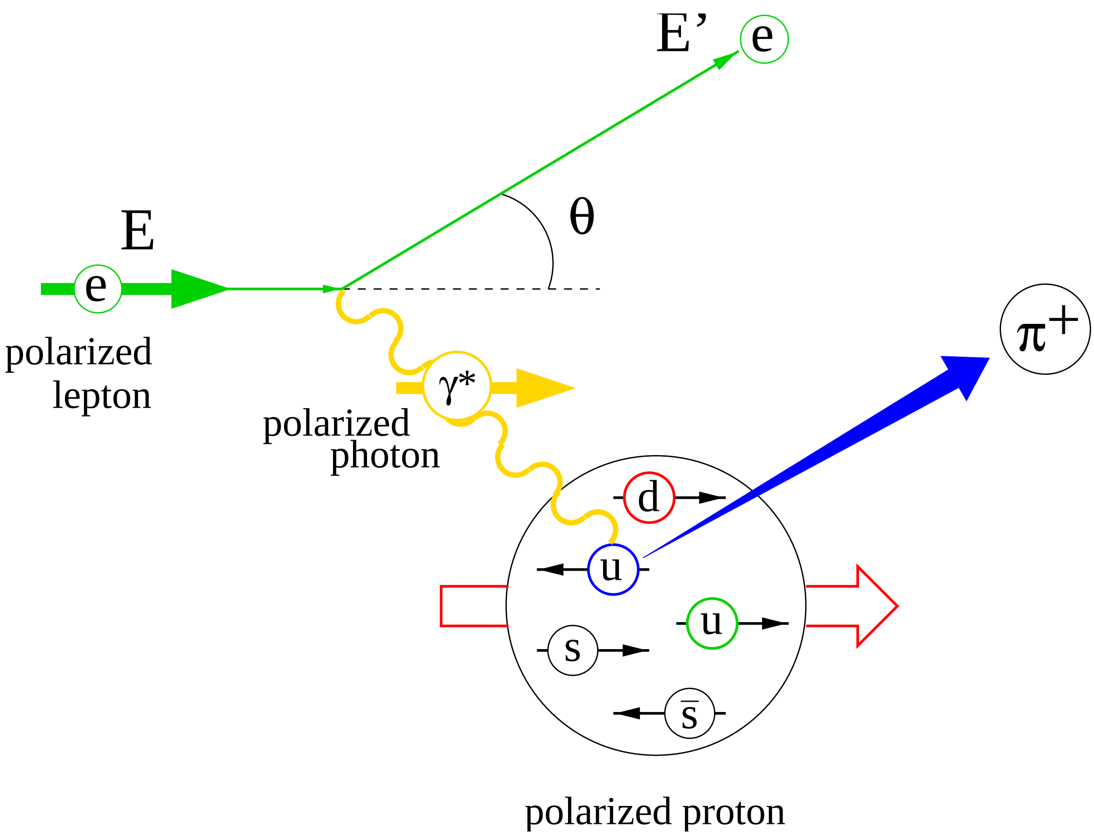
- In a simple quark model: $\Rightarrow \Delta\Sigma \sim 60\% - 75\%$

**Experiment:**

- 1987 EMC experiment at CERN
  $\Rightarrow \Delta\Sigma \sim 10\%$

# How to probe the Nucleon Spin?

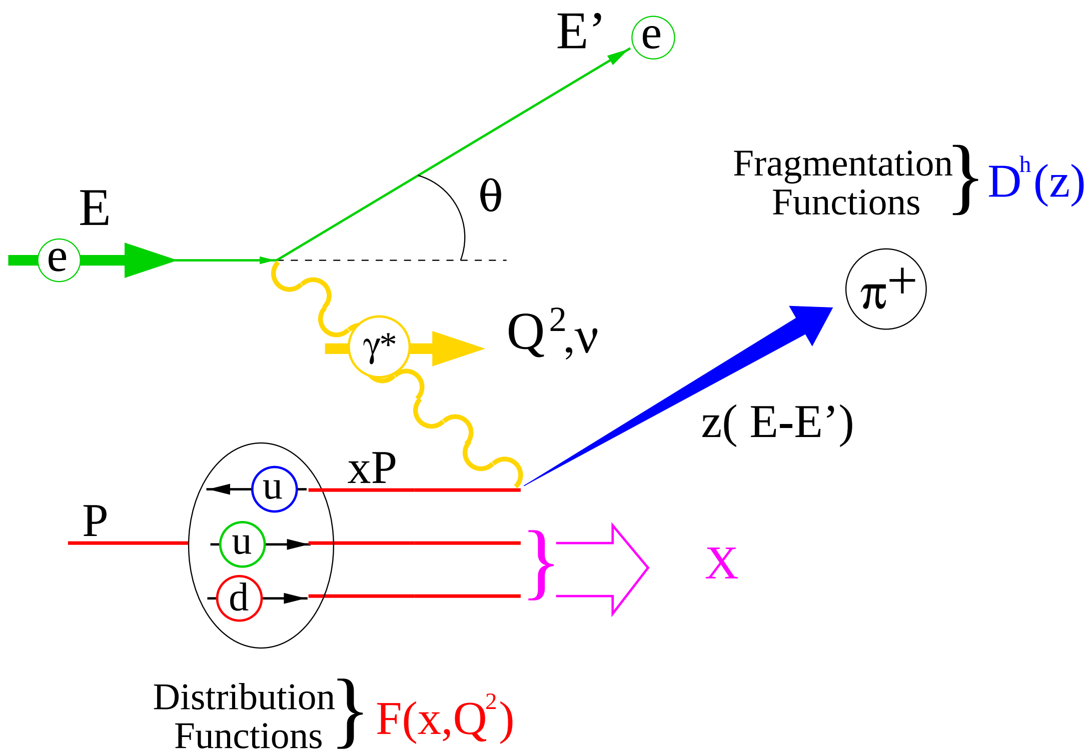
- Use *Polarized Deep Inelastic Scattering*




- Inclusive scattering:
  $\Rightarrow$ longitudinal polarization of all quarks $\rightarrow g_1(x)$

- Semi-inclusive scattering:
  $\Rightarrow$ tag struck quark with leading hadron
  $\Rightarrow$ example: $u$-quark from proton with $\pi^+$

# ... a bit of Kinematics

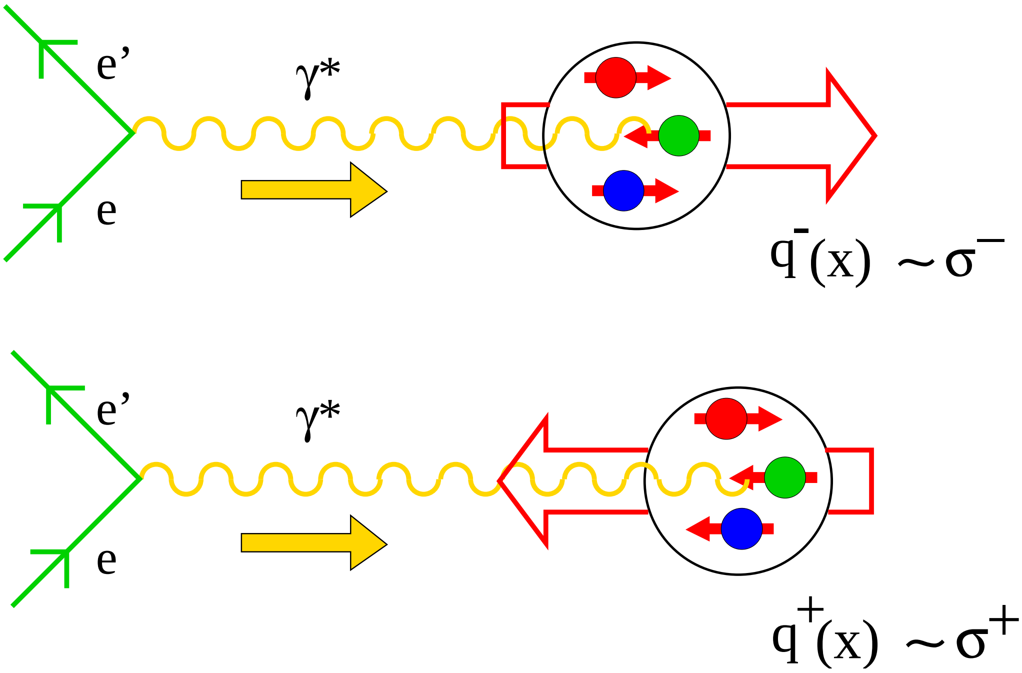



- Kinematic variables in the *lab frame*:
  - transferred four-momentum: $Q^2 = 4EE'sin^2(\theta/2)$
  - transferred energy: $\nu = E - E'$
  - Bjorken's variable: $x = Q^2/2M_p\nu$
  - hadron energy fraction: $z = E_h/\nu$

- Unpolarized semi-inclusive scattering:

$$\frac{1}{\sigma_T}\frac{d\sigma^h}{dz} = \frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}$$

# Asymmetries and Distributions




- Photon-Nucleon Asymmetry:

$$A_1^h(x) = \frac{\sigma_h^+ - \sigma_h^-}{\sigma_h^+ + \sigma_h^-}$$

- In terms of Spin distribution of quarks:

$$A_1^h(x,z) = \frac{\sum_f e_f^2 \overbrace{\left(q_f^+(x) - q_f^-(x)\right)}^{\Delta q(x)} D_f^h(z)}{\sum'_f e_{f'}^2 \underbrace{\left(q_{f'}^+(x) + q_{f'}^-(x)\right)}_{q(x)} D_{f'}^h(z)}$$

- $D_{f'}^h(z)$ are the *fragmentation function*

# ...Experimentally

- Measured asymmetry $\propto A_1^h$:

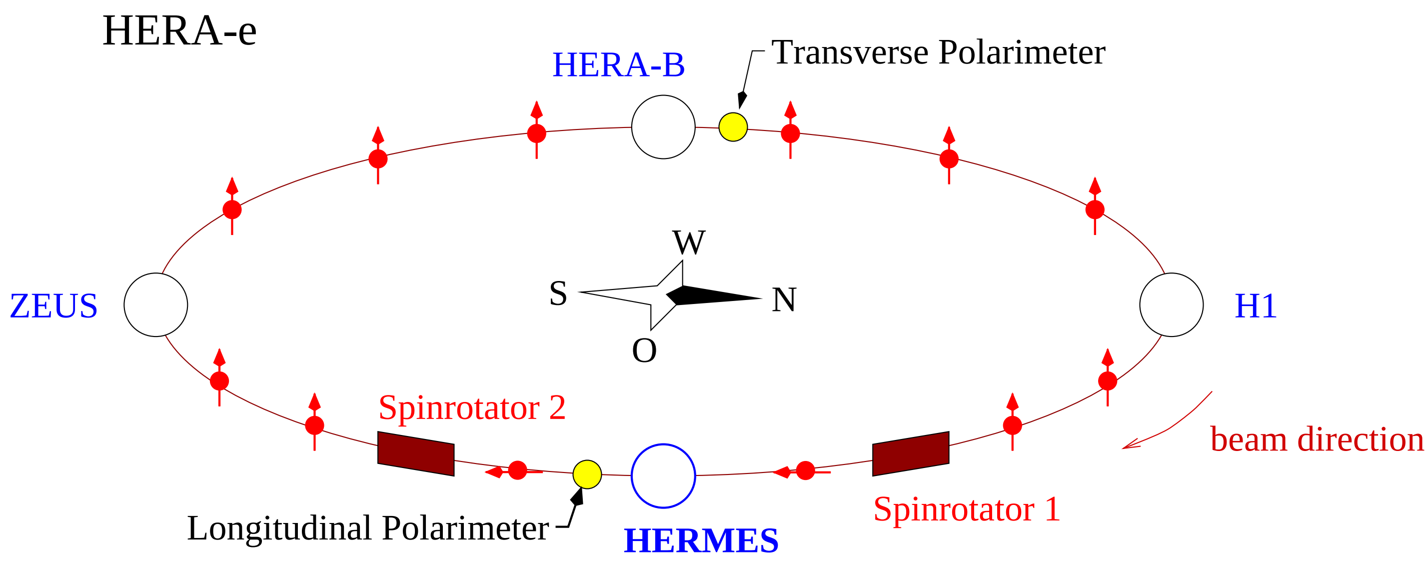
$$A_{||}^h(x,z) = \frac{\sigma_h^{\overset{\rightarrow}{\Leftarrow}} - \sigma_h^{\overset{\rightarrow}{\Rightarrow}}}{\sigma_h^{\overset{\rightarrow}{\Leftarrow}} + \sigma_h^{\overset{\rightarrow}{\Rightarrow}}}$$

- Determine spin distribution by measuring *count rate asymmetry* :

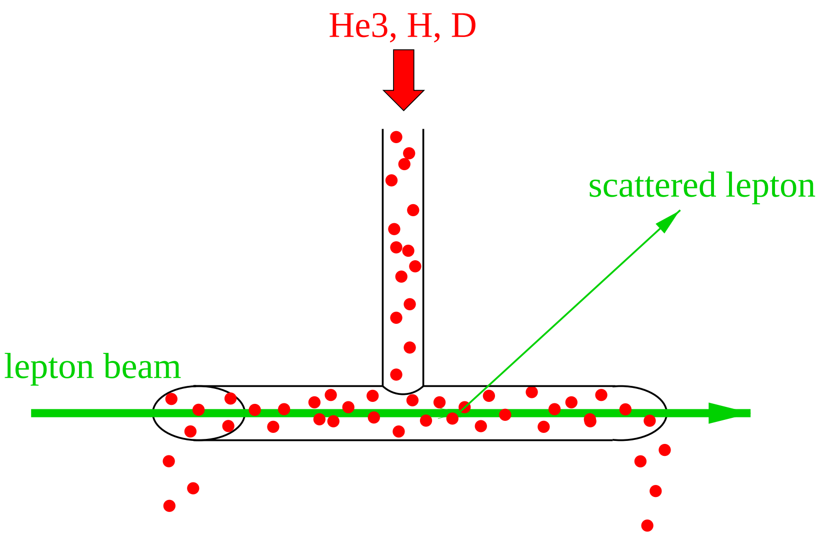
$$A_{||}^h = \frac{1}{P_B P_T} \cdot \frac{N_h^{\overset{\rightarrow}{\Leftarrow}} - N_h^{\overset{\rightarrow}{\Rightarrow}}}{N_h^{\overset{\rightarrow}{\Leftarrow}} + N_h^{\overset{\rightarrow}{\Leftarrow}}}$$

## Ingredients for the experiment

- Longitudinally polarized lepton beam
  $\sim 40 - 60\%$

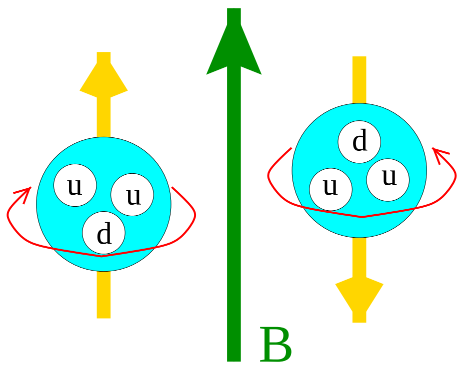


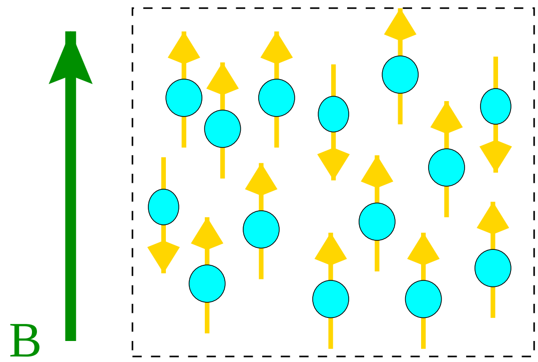

- Polarized internal gas target (H, D, 3He)
  $\sim 80 - 90\%$



# Polarization

Given an external magnetic field:



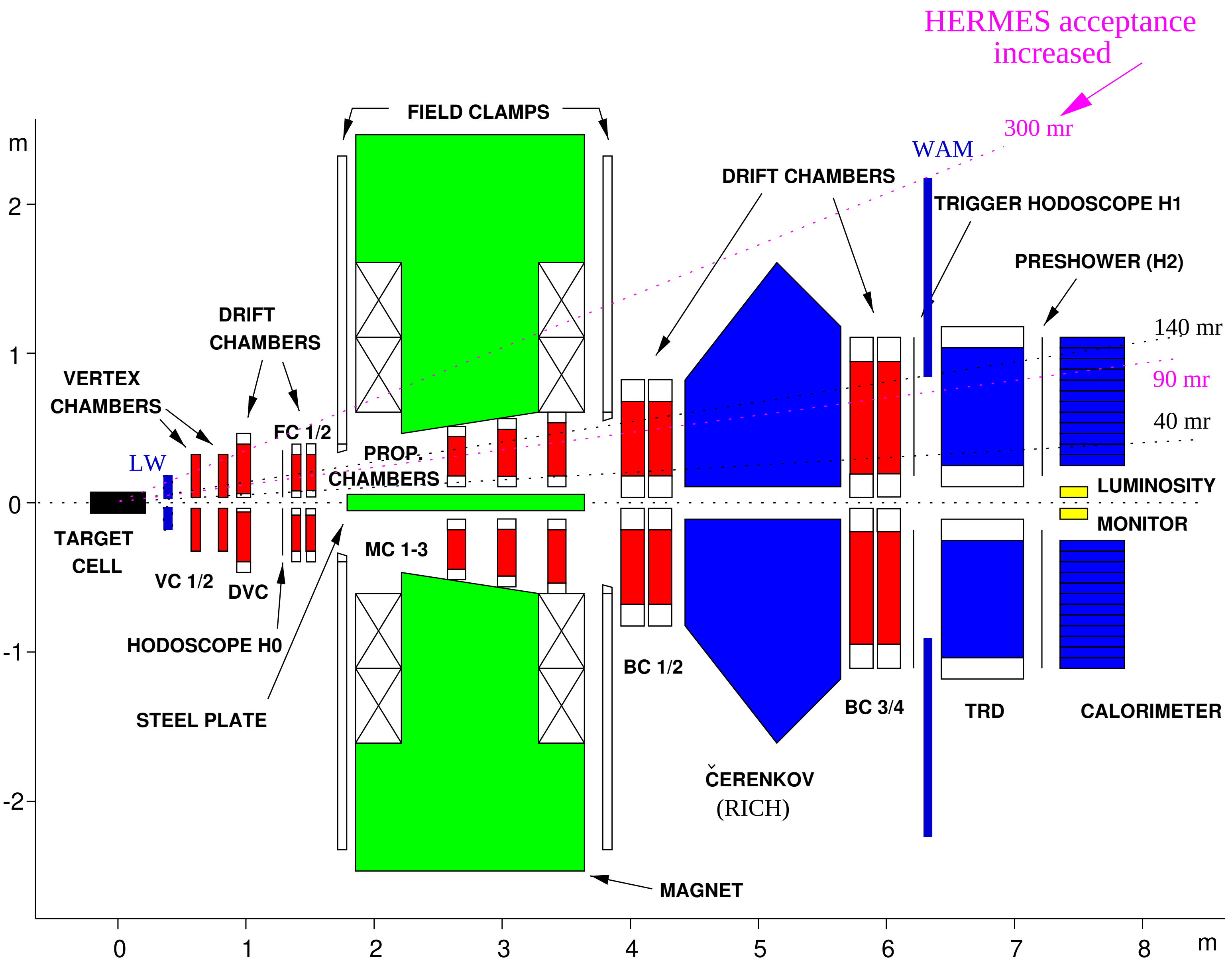




$$P = \frac{N_h^{\overset{\rightarrow}{\Leftarrow}} - N_h^{\overset{\rightarrow}{\Rightarrow}}}{N_h^{\overset{\rightarrow}{\Leftarrow}} + N_h^{\overset{\rightarrow}{\Rightarrow}}}$$

where $\rightarrow$ is the direction of B

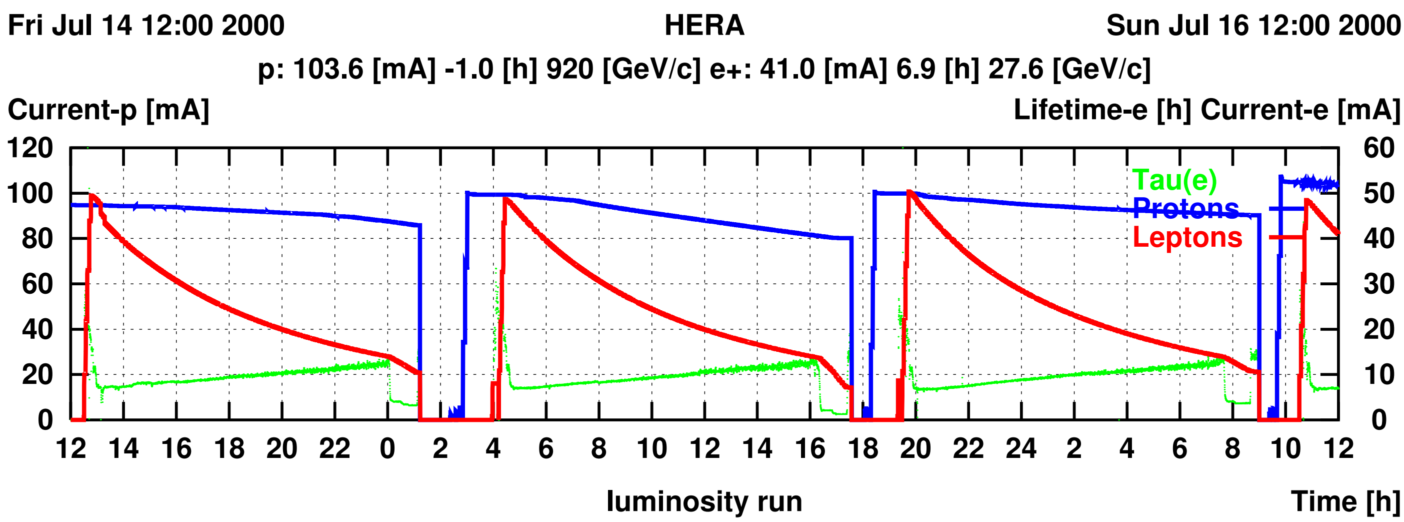
and $\Rightarrow$ is the spin direction.

# HERMES Spectrometer

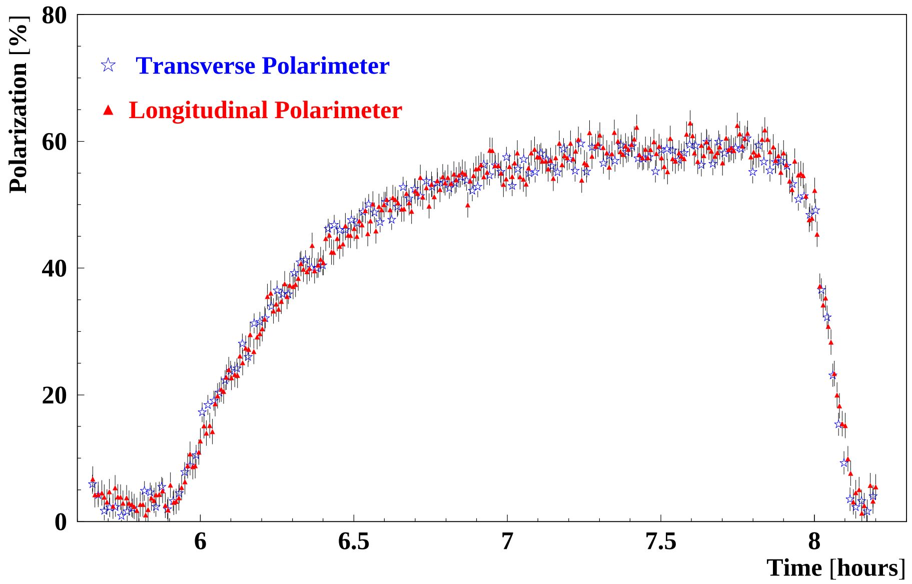


# HERA positron beam

- HERA performance in July 2000:




- Polarization measured at HERMES:



# The Extraction Method

- Rewrite Photon-Nucleon Asymmetry:

$$A_1^h(x,z) = \sum_f \underbrace{\frac{e_f^2 q_f(x) D_f^h(z)}{\sum_{f'} e_{f'}^2 q_{f'}(x) D_{f'}^h(z)}}_{\mathcal{P}_f^h(x)} \cdot \frac{\Delta q(x)}{q(x)}$$

- $P_f^h(x,z)$ is the probability that $q_f$ is struck in an event where $h$ is detected.

- Define:

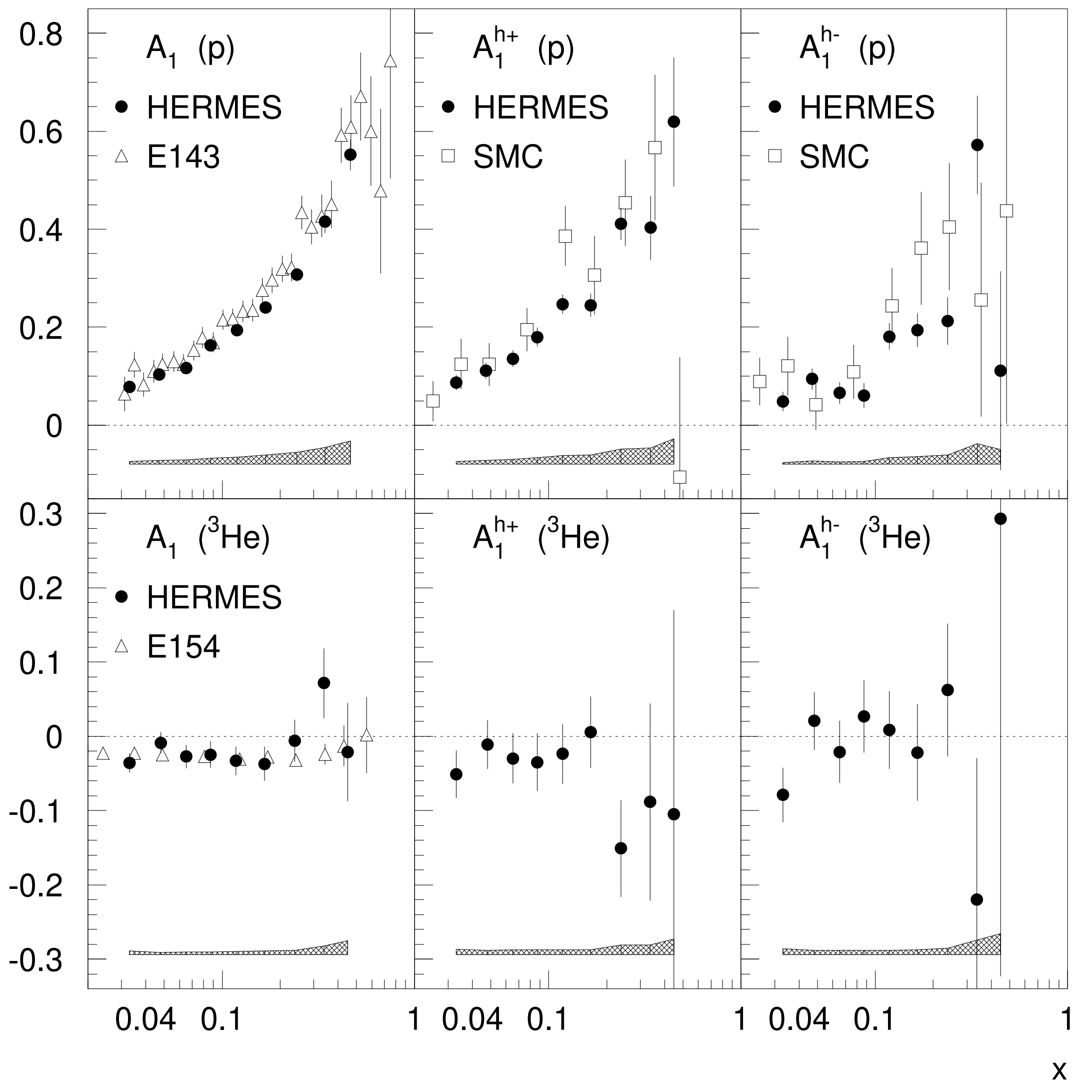
$$\vec{A} = \begin{pmatrix} A^{h_1}(x) \\ \dots \\ A^{h_m}(x) \end{pmatrix} \qquad \vec{Q} = \begin{pmatrix} \Delta q_1(x)/q_1(x) \\ \dots \\ \Delta q_n(x)/q_n(x) \end{pmatrix}$$

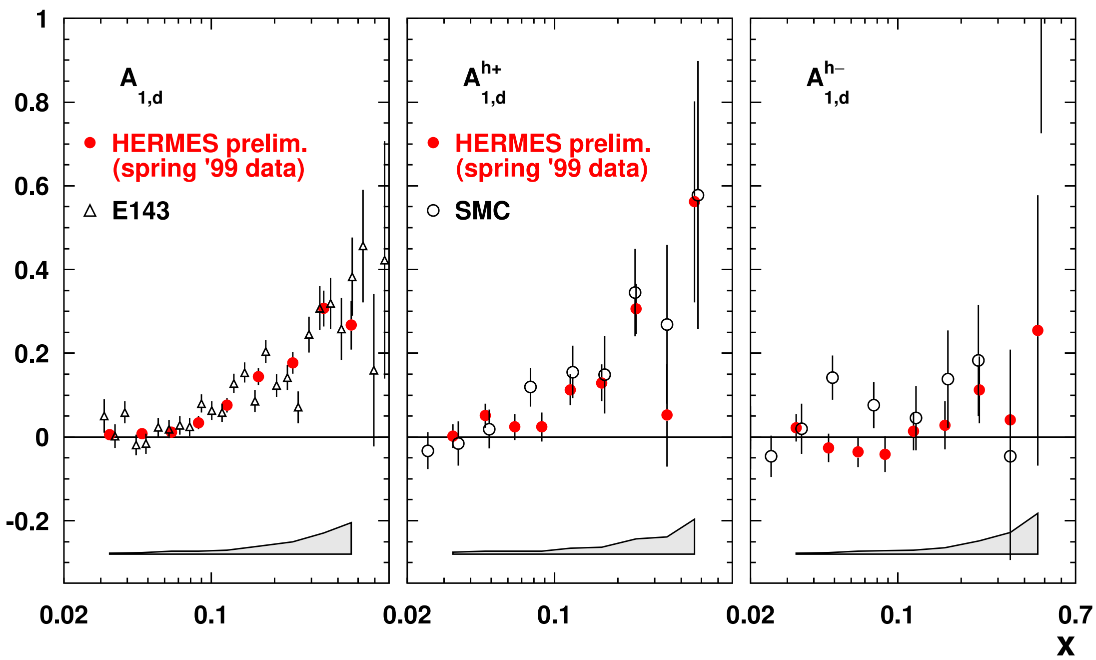
- Solve $\Longrightarrow$ $\quad \vec{A} = \mathcal{P} \cdot \vec{Q}$

- Constrain the procedure by assuming flavour symmetric sea polarization:

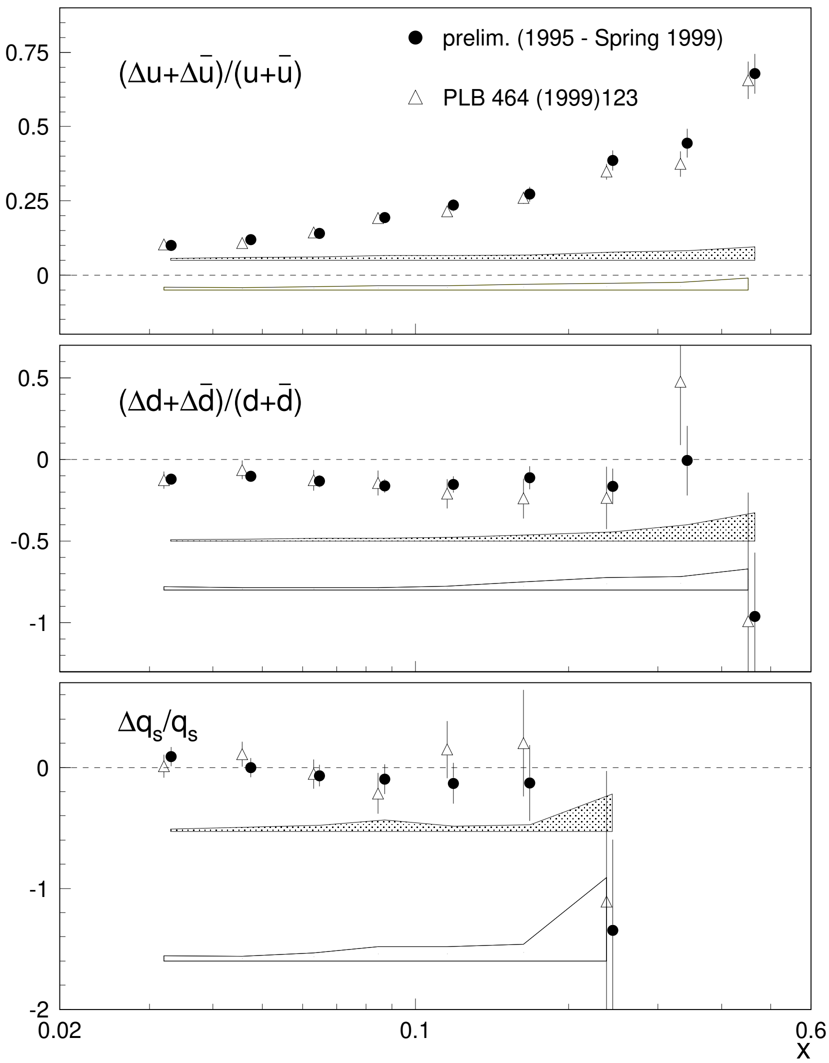
$$\frac{\Delta u_s(x)}{u_s(x)} = \frac{\Delta d_s(x)}{d_s(x)} = \frac{\Delta s(x)}{s(x)} = \frac{\Delta \bar{u}(x)}{\bar{u}(x)} = \frac{\Delta \bar{d}(x)}{\bar{d}(x)} = \frac{\Delta \bar{s}(x)}{\bar{s}(x)}$$

# Measured Hadron Asymmetries



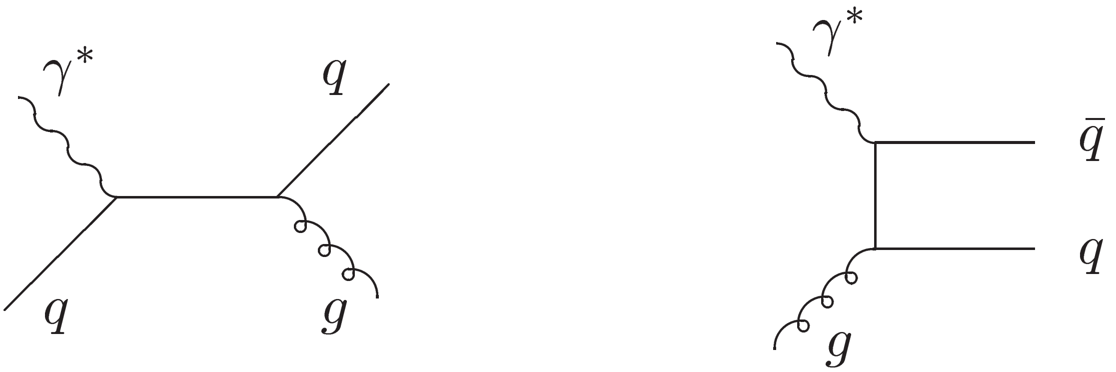
# Flavour Quark Polarization




- at HERMES: $Q^2 = 2.5GeV^2$
  $\Rightarrow \Delta\Sigma = 0.33 \pm 0.06(stat) \pm 0.06(sys)$
- consistent with EMC result when evolved at the same $Q^2$ ($\Delta\Sigma$ = 0.31)

# Gluon Contribution

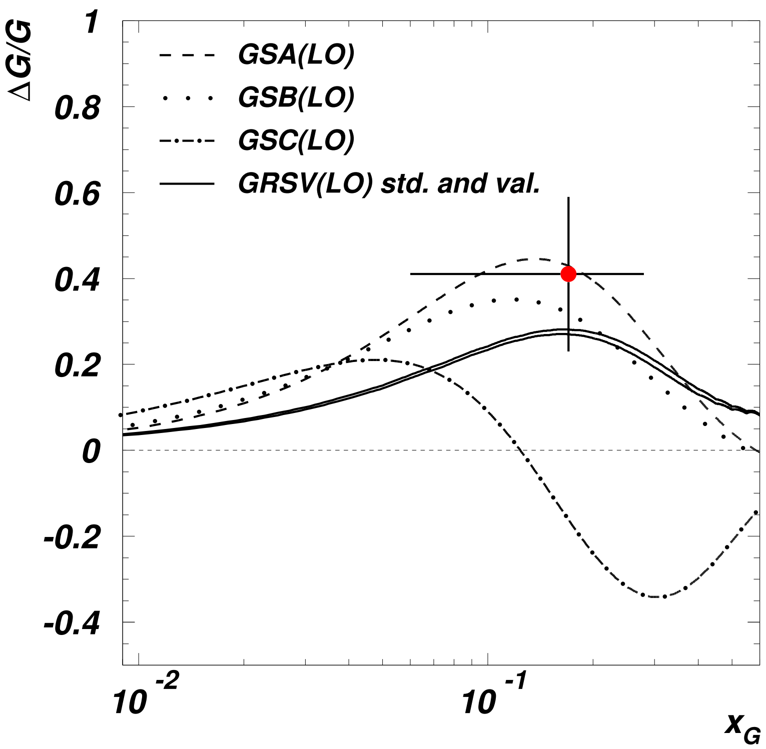
- pQCD Compton graph and Photon-Gluon Fusion:




- Asymmetry for high-$p_T$ pions:

$$A_{LL}^{eN \to h_1 h_2} \approx \hat{a}_{QCDC} \frac{\Delta q}{q} + \hat{a}_{PGF} \frac{\Delta G}{G}$$

- Extracted value of $\Delta G/G$:



# What have we learned?

- Longitudinal spin sum rule:

$$S_z^N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + < L_z >$$

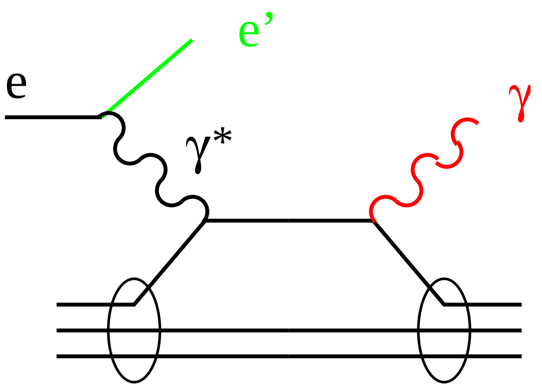
- Rough estimate of the contributions:

$$\frac{1}{2}\Delta\Sigma \approx +0.15$$

$$\Delta G \approx +1.0$$

$$L_z \approx -0.65$$

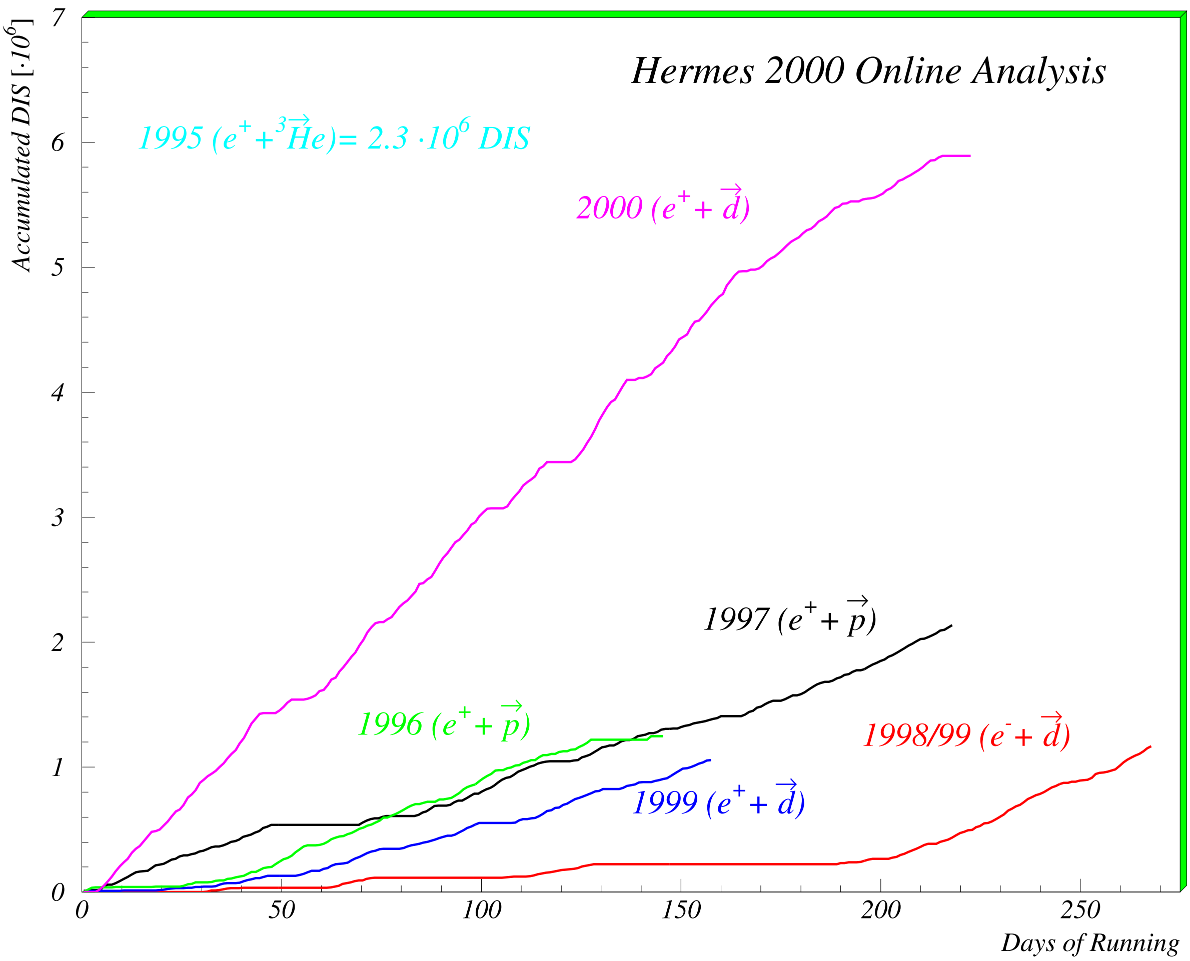
- More on $L_z$ can possibly be learned from




Deeply Virtual
Compton scattering

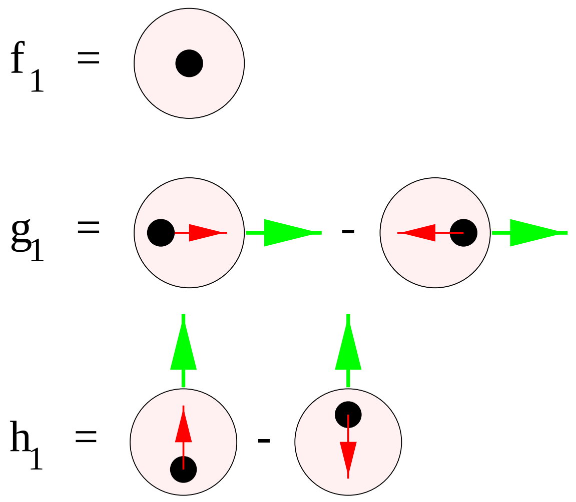
# The *Strange* future of HERMES

- So far only $A_1$, $A_1^{h^+}$ and $A_1^{h^-}$ are used
- **RICH** detector allows $\pi^\pm$, $K^\pm$ identification
- $K^- = \bar{u}s \rightarrow$ sensitivity to the *strange sea*
- ... and much more data to analyze!!! ;-)



# The Transverse Future

- Three leading order distribution functions:




momentum carried by quarks

longitudinal quark spin, $\Delta\Sigma$

transverse quark spin, $\delta\Sigma$

- Importance of $h_1(x)$ measurements:
  - HERMES data for longitudinal target and beam:

$$\boxed{\tfrac{1}{2}\Delta\Sigma \approx +0.15, \quad \Delta G \approx +1.0, \quad L_z \approx -0.65}$$

  - Using a transversely polarized target
    * Gluon splitting does not occur:

$$\boxed{\Delta\Sigma \; < \; \delta\Sigma \; < \; 1 \quad \text{(Quark Parton Model)}}$$

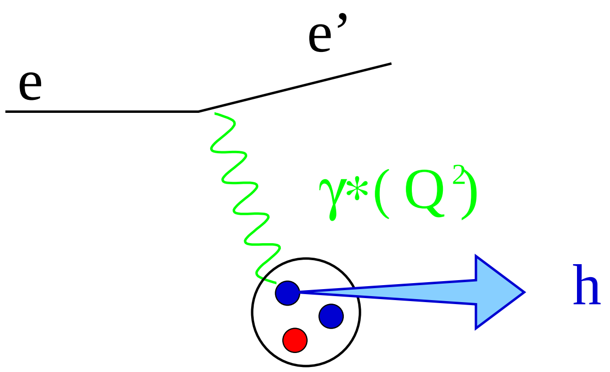
    * Lattice QCD calculation (Phys. Rev. D 56 (1997) 433):

$$\boxed{\Delta\Sigma \; = \; 0.18(10) \quad \text{and} \quad \delta\Sigma \; = \; 0.56(9)}$$

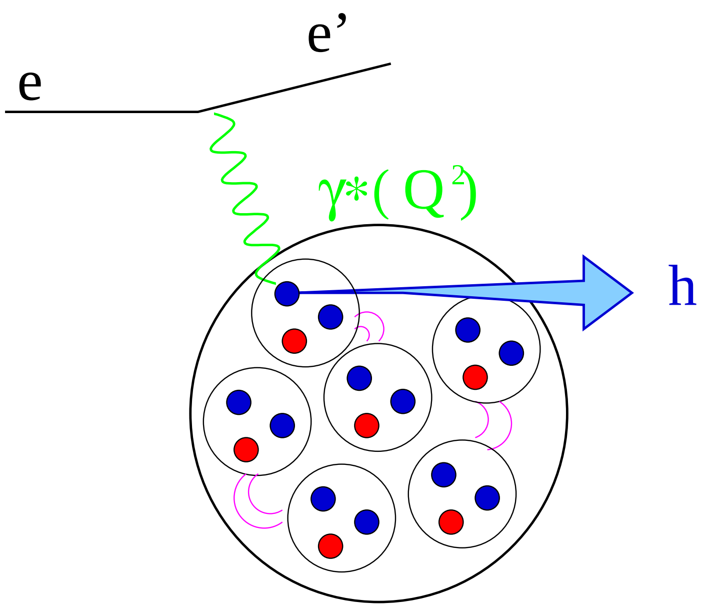
# The Unpolarized Physics

- From unpolarized gas targets ( H, D, $^3$He, N, Kr,...)
  $\Longrightarrow$ QCD description of Nucleus structure

DIS on a Nucleon




DIS on a Nucleus

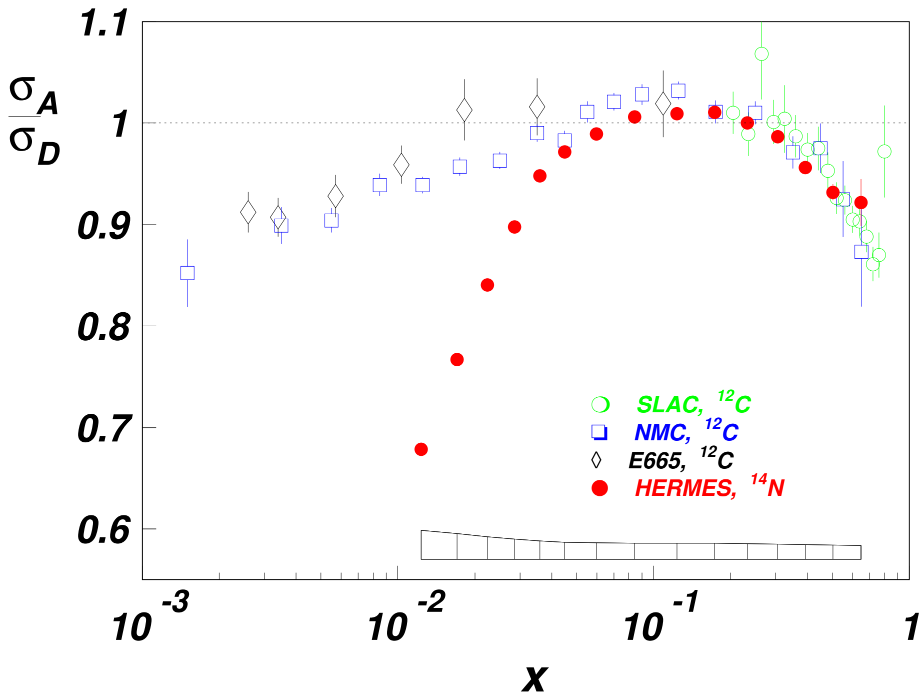



| | | | |
|---|---|---|---|
| $Q^2 < 0.01$ GeV$^2$ | $\rightarrow$ | r $>$ 10 fm | Nucleus |
| $Q^2 \simeq 0.1$ GeV$^2$ | $\rightarrow$ | r $\simeq$ 1 fm | Nucleons |
| $Q^2 > 1$ GeV$^2$ | $\rightarrow$ | r $<$ 1 fm | Quarks |

NUCLEAR EFFECTS observed at HERMES

# The discovery !!!

- Ratio of DIS cross sections on $^{14}$N and $^{2}$D:




HERMES at low x differs from NMC/E665.

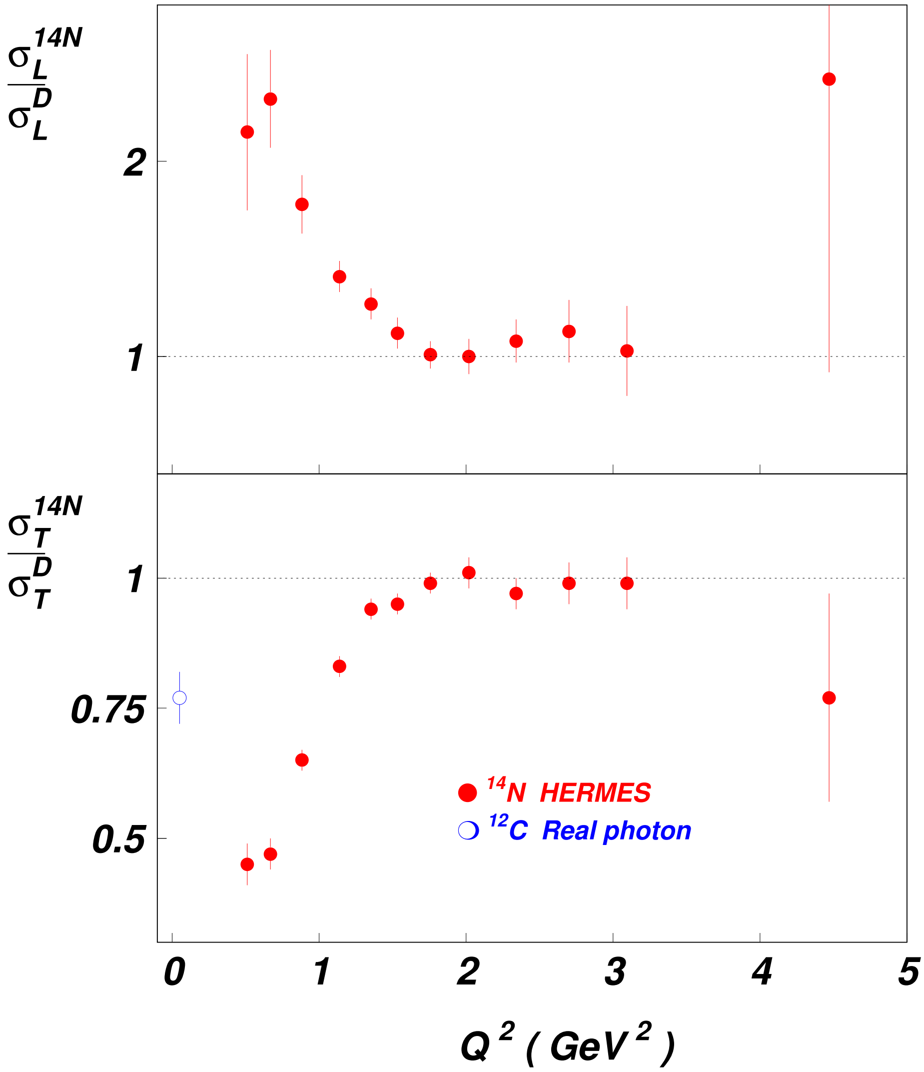
$$\frac{\sigma_A}{\sigma_D} = \frac{{\sigma_T}^A + \epsilon {\sigma_L}^A}{{\sigma_T}^D + \epsilon {\sigma_L}^D}$$

$\epsilon$ = virtual photon polarization

$$\sigma_L : h_{\gamma^*} = 0 \quad (h_{\gamma^*} \parallel q_{\gamma^*})$$
$$\sigma_T : h_{\gamma^*} = \pm 1 \quad (h_{\gamma^*} \perp q_{\gamma^*})$$

# A-dependence of $\sigma_L$ and $\sigma_T$

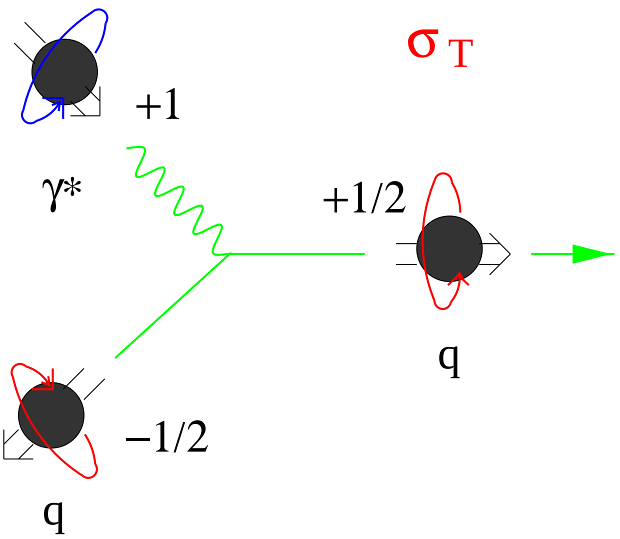
$$\frac{\sigma_A}{\sigma_D} = \frac{\sigma_T^A/\sigma_T^D + \epsilon\sigma_L^A/\sigma_L^D R_D}{1+\epsilon R_D}$$



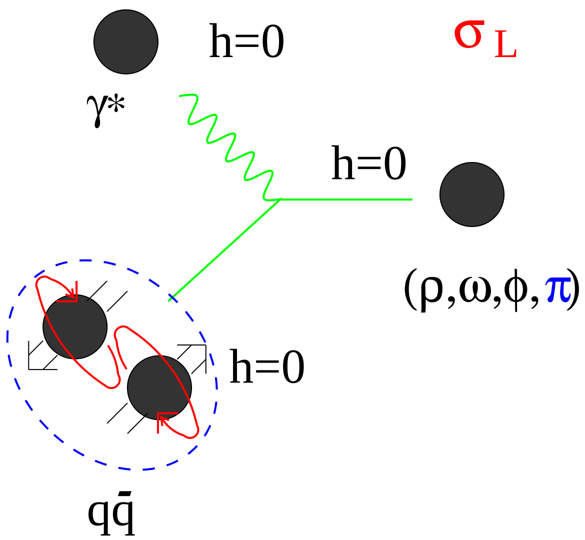

Coupling to $q\bar{q}$-pairs with $S$=0 ?

# Quark Delocalization

- High $Q^2$ $\Longrightarrow$ mainly magnetic interaction




- Low x and $Q^2$ $\Longrightarrow$ enhancement of charge-like interaction for A > D




process $1/Q^2$ suppressed

# The End of the Story

- HERMES results on nucleon spin structure
  - The quark spin contribution...
    - Precise data for $g_1^{p(n)}(x)$, $\Delta u(x)$, $\Delta d(x)$
  - ...and the contribution of the rest
    - First determination of gluon spin contribution, ($\Delta G/G(x)$
    - First hint on the angular momentum contribution from exclusive reactions
  - some surprise on nuclear effects:
    - Discovery of A-dependence of $R = \sigma_L/\sigma_T$

- The future at HERMES:
  - New data on nucleon spin structure:
    - $\Delta G/G(x)$, $\Delta s$, $h_1(x)$
    - DVCS, exclusive reactions
  - But ... THIS IS JUST THE BEGINNING !