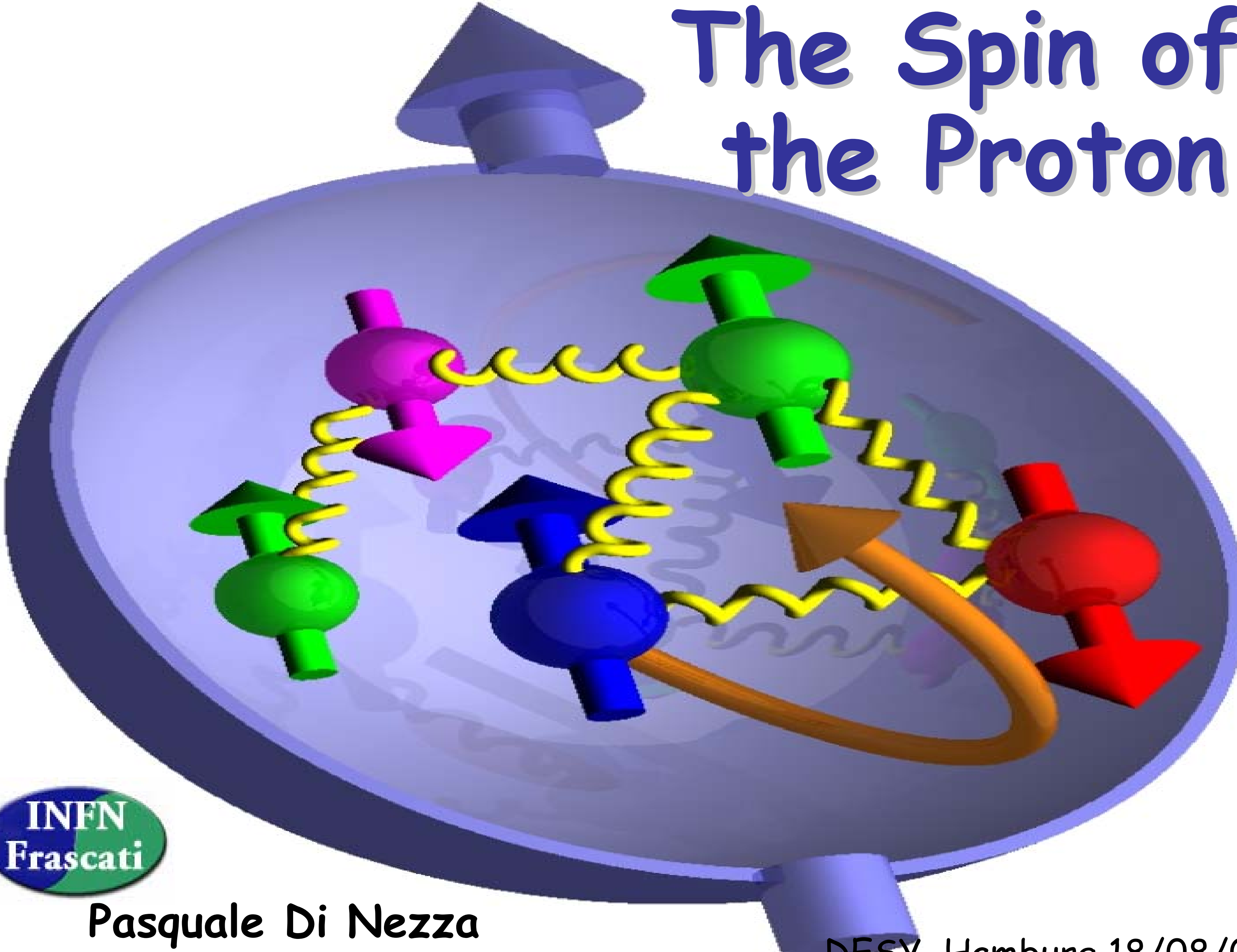
The Spin of the Proton



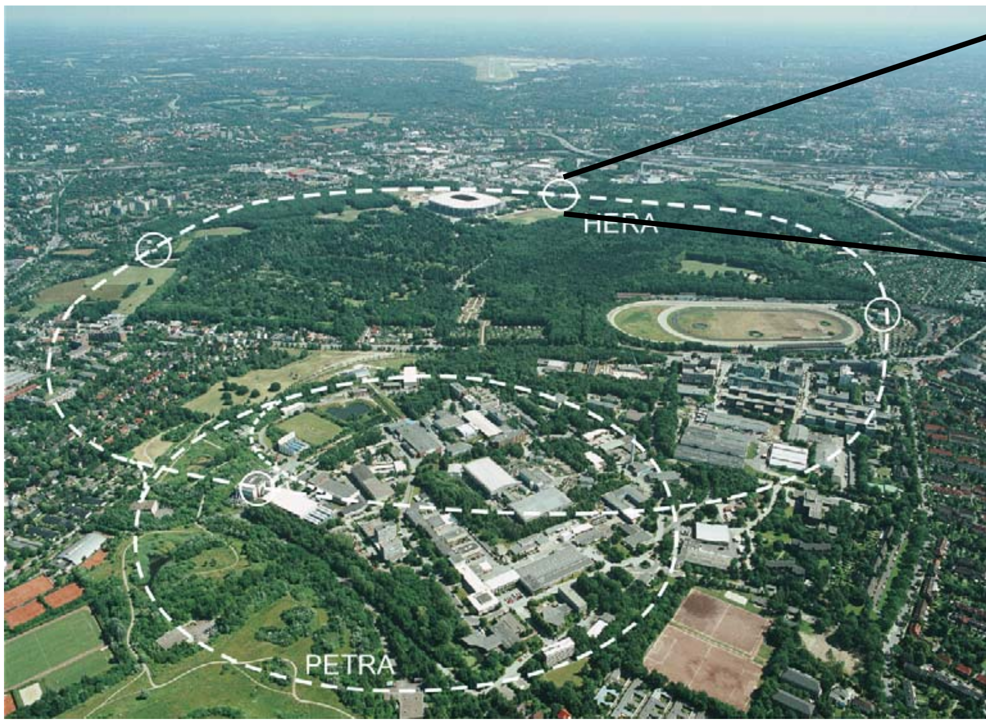
INFN Frascati

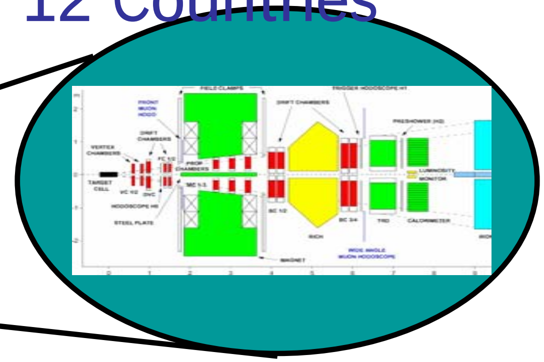
Pasquale Di Nezza

DESY, Hamburg 18/08/05

HERa MEasurement of Spin

Collaboration of 180 phys., 33 Inst., 12 Countries





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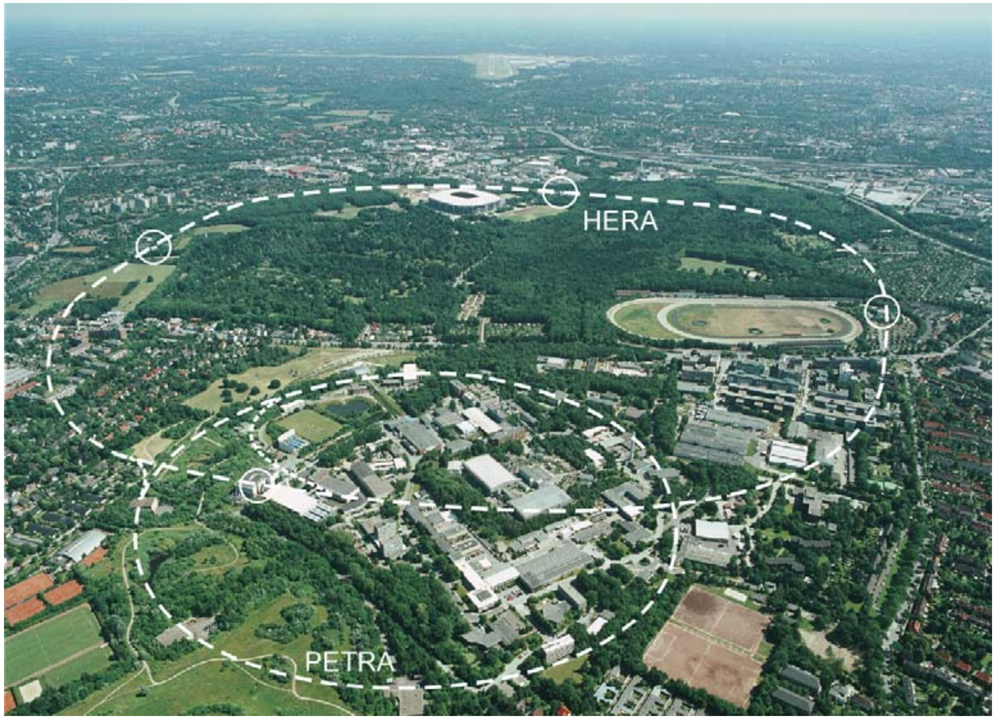
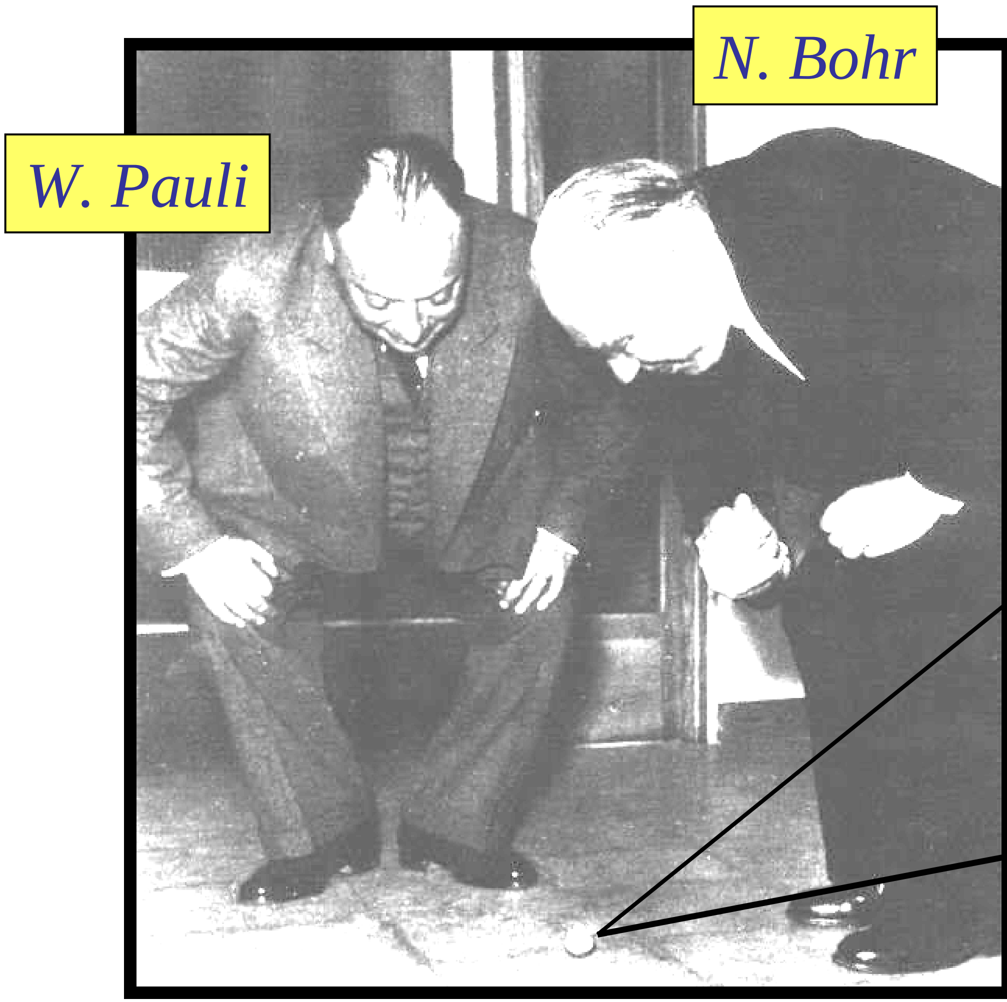
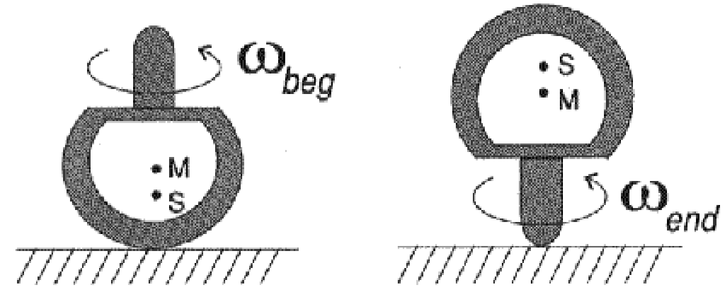


- Introduction to polarised DIS
- Prerequisites
- Polarised structure functions
- The Spin of the Nucleon

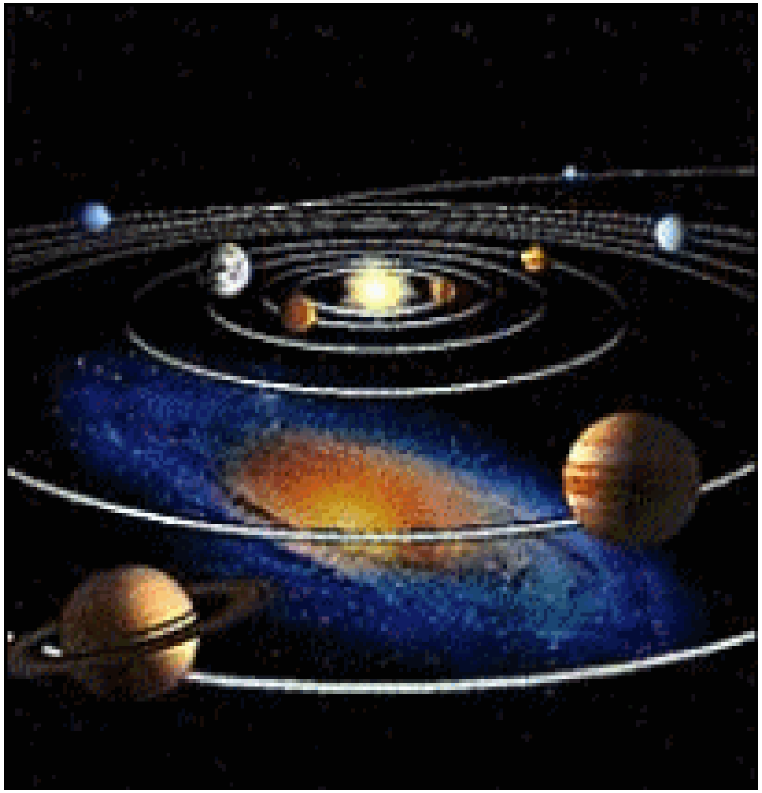
fascinated by spin …

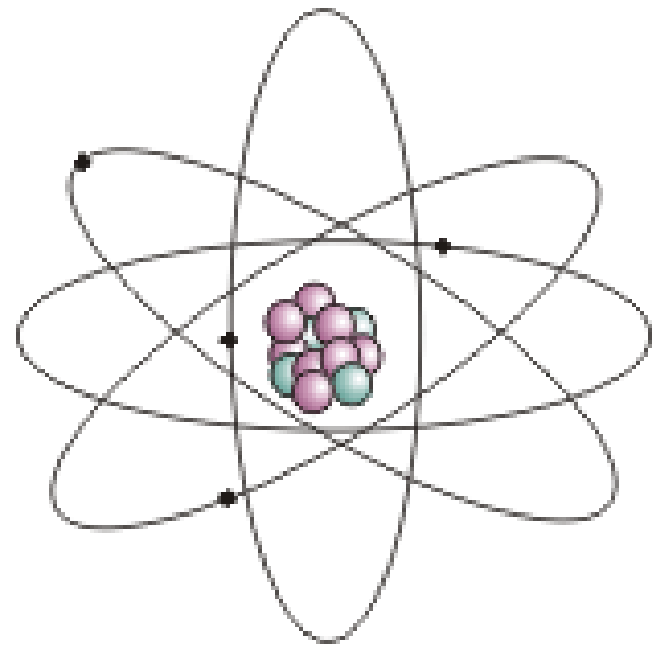
“You think you understand something? Now add spin…” -- *R. Jaffe*





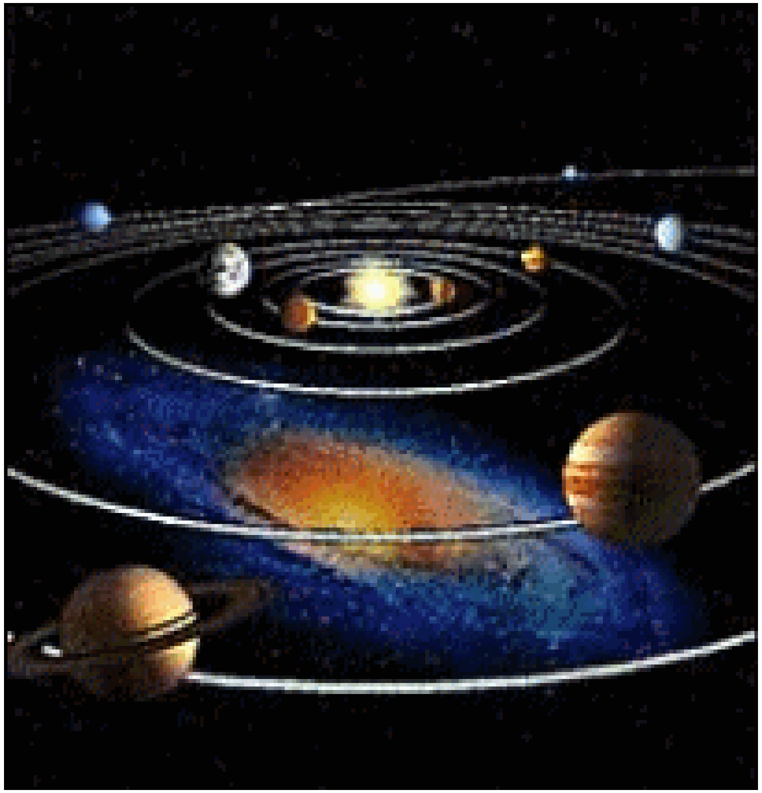
fascinated by spin … an analogy

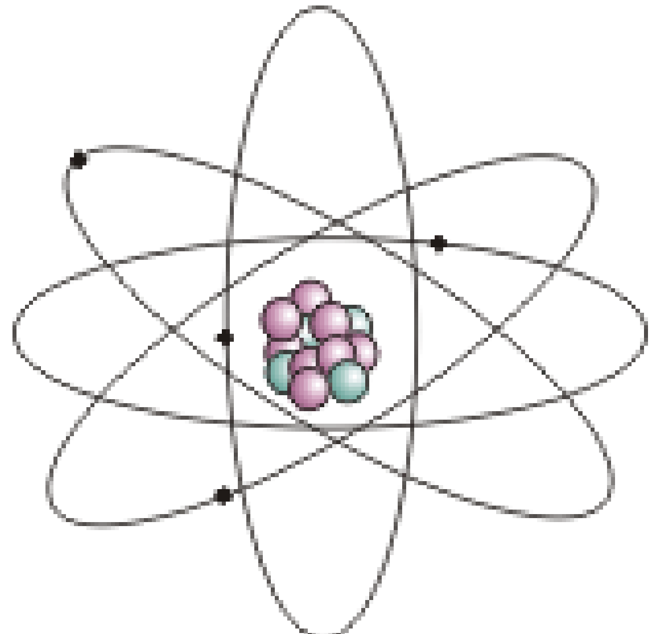




Speaking in this analogy our planet has an **orbital angular momentum** (around the sun / the nucleus) and in addition a **spin angular momentum** (around its own axis).

fascinated by spin … an analogy





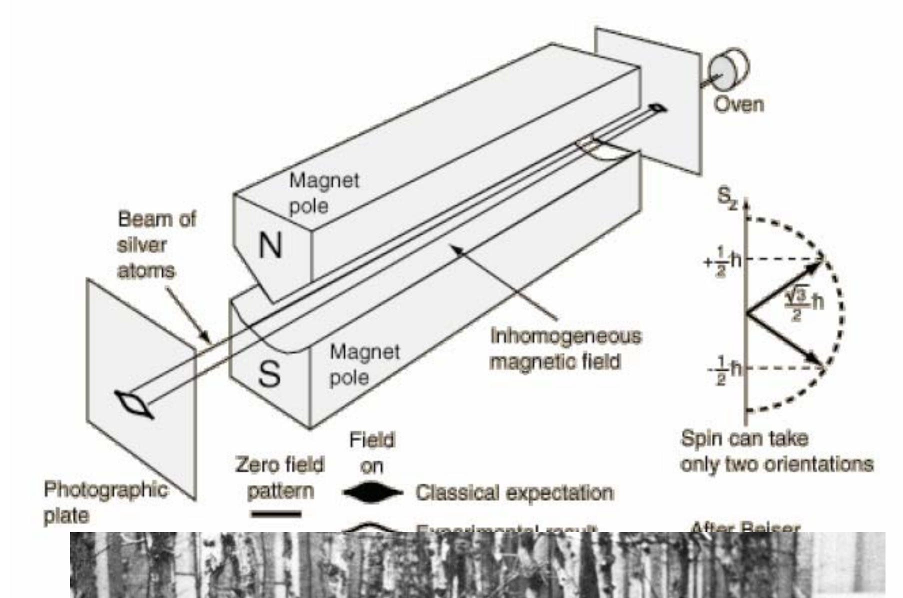
TOO naive!

Speaking in this anal… a… **rbital angular momentum** (around …/ …cleus) and in addition a **spin angular mome…** …round its own axis).

What is Spin ?

[www.markusehrenfried.de/science/physics/whatisspin.html]

- Stern-Gerlach (1921):



- Uhlenbeck, Goudsmit: (1925)

  explanation of atomic spectra

  quantum number: m_s=1/2

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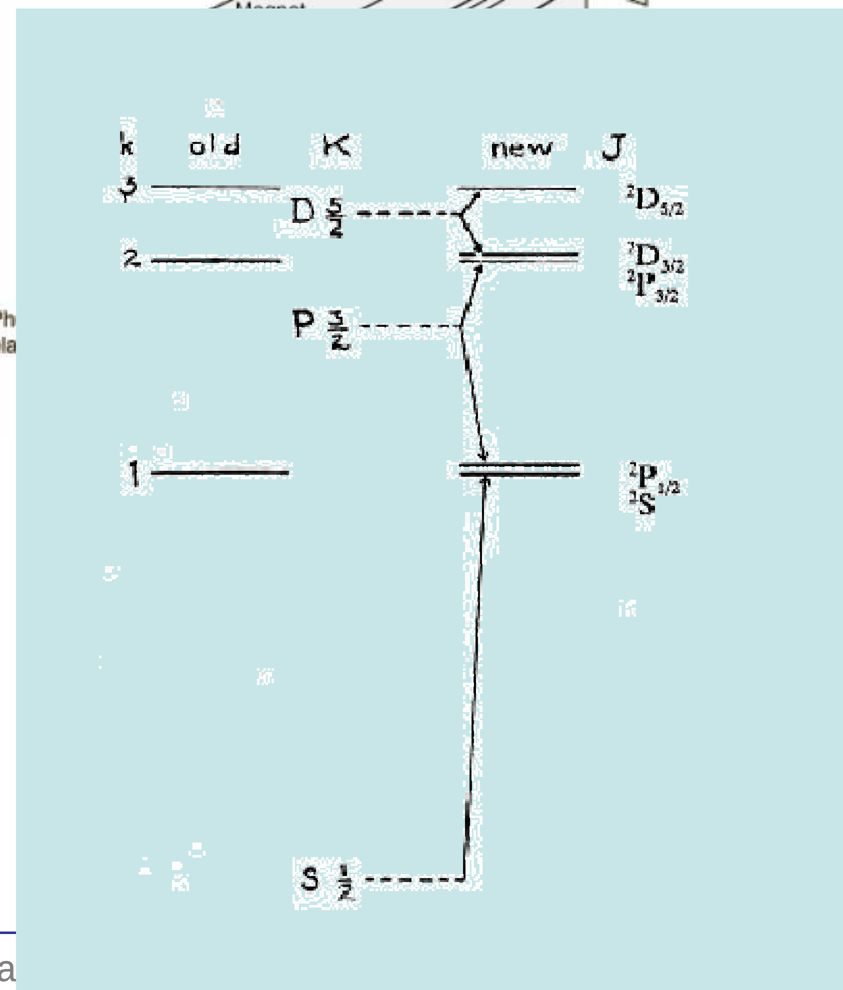
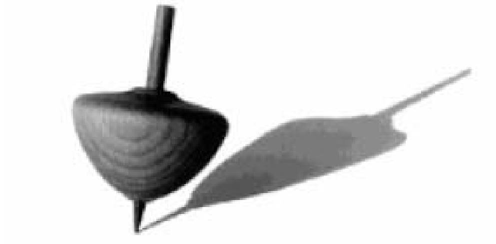




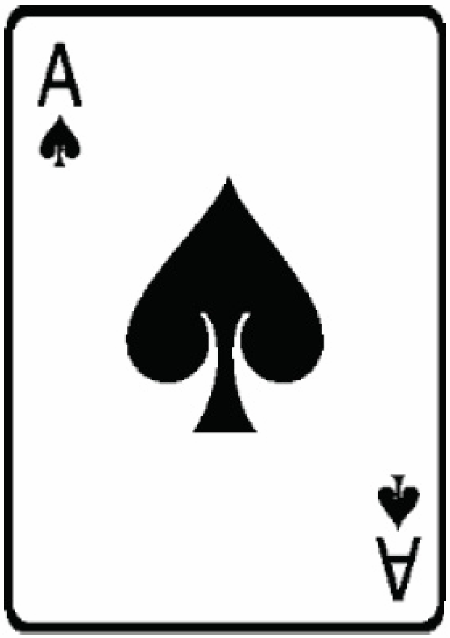
What is Spin ?

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

spin: 2

180^o

spin: 1



360^o

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

math: antisymmetric wave function

2×360^o

is spin important ?

Pauli principle ...

half integer SPIN

MATTER

→ obey Pauli principle

→ antisymmetric under exchange of identical particles

→ Fermi-Dirac statistics: *Fermions*

integer SPIN

FORCES

→ don't care for Pauli principle

→ symmetric

→ Bose-Einstein statistics: *Bosons*

is spin important ?

Pauli principle ...

nge

half integer SPIN

MATTER

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

integer SPIN

FORCES

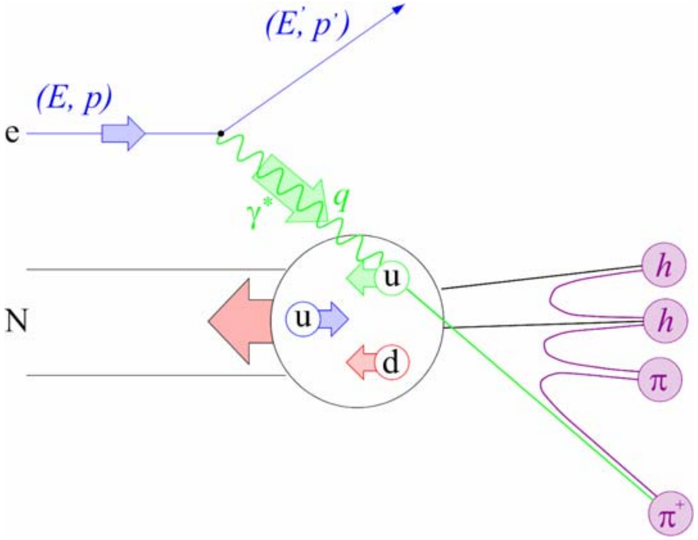
BOSONS
force carriers
spin = 0, 1, 2, ...

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

how to study the proton spin ?

... *deep-inelastic scattering (DIS)*

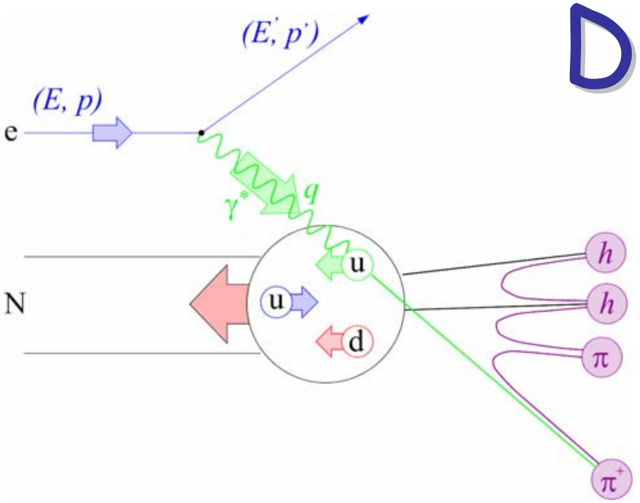


$$Q^2 = -q^2 \stackrel{\text{lab}}{=} 2EE'(1-\cos\theta)$$

$$x \stackrel{\text{lab}}{=} \frac{Q^2}{2M\nu}, \qquad \nu \stackrel{\text{lab}}{=} E - E'$$

- "deep" $\leftrightarrow$ high resolution: $Q^2 >> M^2$
- "inelastic" $\leftrightarrow$ $M_X^2 \neq M^2 \Rightarrow x < 1$

DIS cross section



$$\sigma(ep \rightarrow eX)$$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{MQ^4}\frac{E}{E'} L_{\mu\nu} W^{\mu\nu}$$

$L_{\mu\nu}$ *leptonic part* of the xsection

→ independent of proton structure

→ can be calculated explicitely

$W_{\mu\nu}$ *hadronic part* of the xsection

→ contains info on proton structure

\+ strong interaction effects

hadronic tensor $W_{\mu\nu}$

→parametrised by structure functions

(Lorentz symmetry, current conservation, parity, ecc.)

$$W_{\mu\nu} = -g^{\mu\nu} F_1(x,Q^2) + \frac{p^\mu p^\nu}{\nu} F_2(x,Q^2)$$

$$+i\varepsilon^{\mu\nu\lambda\sigma}\frac{q_\lambda}{\nu}\left(S_\sigma\, g_1(x,Q^2) + \frac{1}{\nu}\left(p\cdot q S_\sigma - S\cdot q p_\sigma\right) g_2(x,Q^2)\right)$$

hadronic tensor $W_{\mu\nu}$

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(Lorentz symmetry, current conservation, parity, ecc.)

QPM:

$$F_1(x) = \frac{1}{2}\sum_i e_i^2\left(q_i^+(x) + q_i^-(x)\right) = \frac{1}{2}\sum_i e^2 q_i(x)$$

momentum distribution of quarks

$$W_{\mu\nu} = -g^{\mu\nu}\, F_1(x,Q^2) \quad \ldots \quad \nu \quad F_2(x,Q^2)$$

$$+i\varepsilon^{\mu\nu\lambda\sigma}\frac{q_\lambda}{\nu}\left(S_\sigma\, g_1(x,Q^2) + \frac{1}{\nu}\left(p\cdot q S_\sigma - S\cdot q p_\sigma\right) g_2(x,Q^2)\right)$$

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$q_i(x)$ = Distribution Function

connected to the probability to have a struck quark with fractional momentum x

hadronic tensor $W_{\mu\nu}$

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(Lorentz symmetry, current conservation, parity, ecc.)

QPM:

$$F_1(x) = \frac{1}{2}\sum_i e_i^2\left(q_i^+(x) + q_i^-(x)\right) = \frac{1}{2}\sum_i e^2 q_i(x)$$

momentum distribution of quarks

$$W_{\mu\nu} = -g^{\mu\nu}\, F_1(x,Q^2) \ldots + \ldots F_2(x,Q^2)$$

$$+i\varepsilon^{\mu\nu\lambda\sigma}\frac{q}{\nu} \ldots$$

$q^+_i(x)$ = Polarized Distribution Function

connected to the probability to have a struck quark with fractional momentum x and **spin in the same direction of the proton**

hadronic tensor $W_{\mu\nu}$

→parametrised by structure functions

(Lorentz symmetry, current conservation, parity, ecc.)

QPM:

$$F_1(x) = \frac{1}{2}\sum_i e_i^2\left(q_i^+(x) + q_i^-(x)\right) = \frac{1}{2}\sum_i e^2 q_i(x)$$

momentum distribution of quarks

$$W_{\mu\nu} = -g^{\mu\nu}\, F_1(x,Q^2) + \ldots \frac{\ldots}{\nu} F_2(x,Q^2)$$

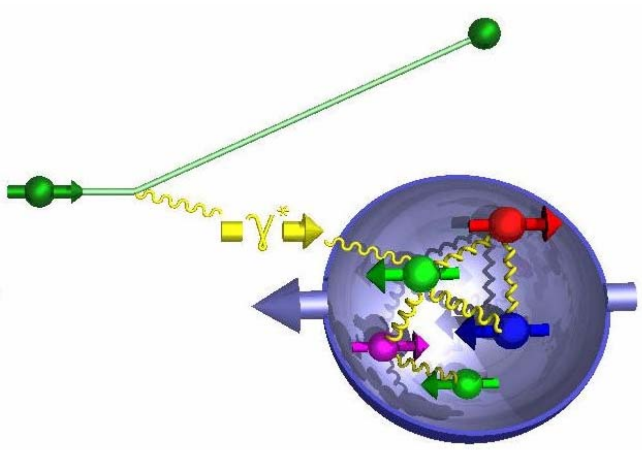
$$+ i\varepsilon^{\mu\nu\lambda\sigma}\frac{q_\lambda}{\nu}\left(S_\sigma\, g_1(x,Q^2) + \frac{1}{\nu}\left(p\cdot q S_\sigma - S\cdot q p_\sigma\right) g_2(x,Q^2) \right)$$

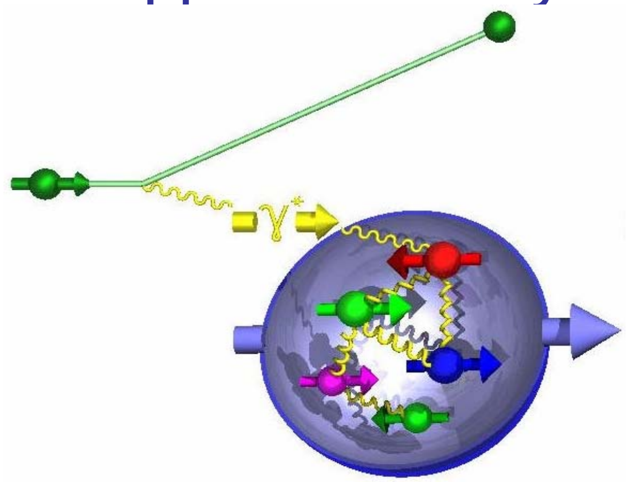
$$g_1(x) = \frac{1}{2}\sum_i e_i^2\left(q_i^+(x) - q_i^-(x)\right) = \frac{1}{2}\sum_i e^2 \Delta q_i(x)$$

helicity distribution of quarks

helicity densities Δq

because of helicity conservation, the virtual photon can couple only to a quark of opposite helicity



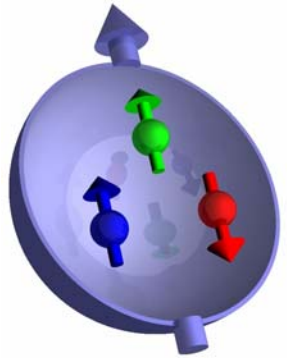


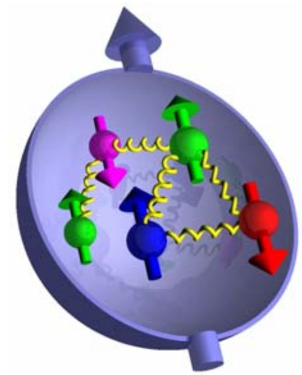
$$S_\gamma + S_N = \frac{1}{2}$$
$$\sigma_{1/2} \approx q^+(x)$$

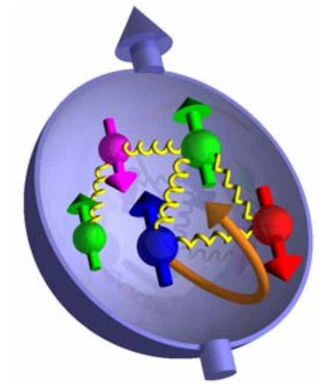
$$S_\gamma + S_N = \frac{3}{2}$$
$$\sigma_{3/2} \approx q^-(x)$$

by changing the orientation of target nucleon spin or the helicity of incident lepton beam we can select $q^+(x)$ or $q^-(x)$ → Δq

the nucleon spin structure







QPM:

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

EMC ('88) [illegible] .123 ± ...

Spin Puzzle

→SLAC, CERN, DESY: 0.2-0.4

gluons are important !

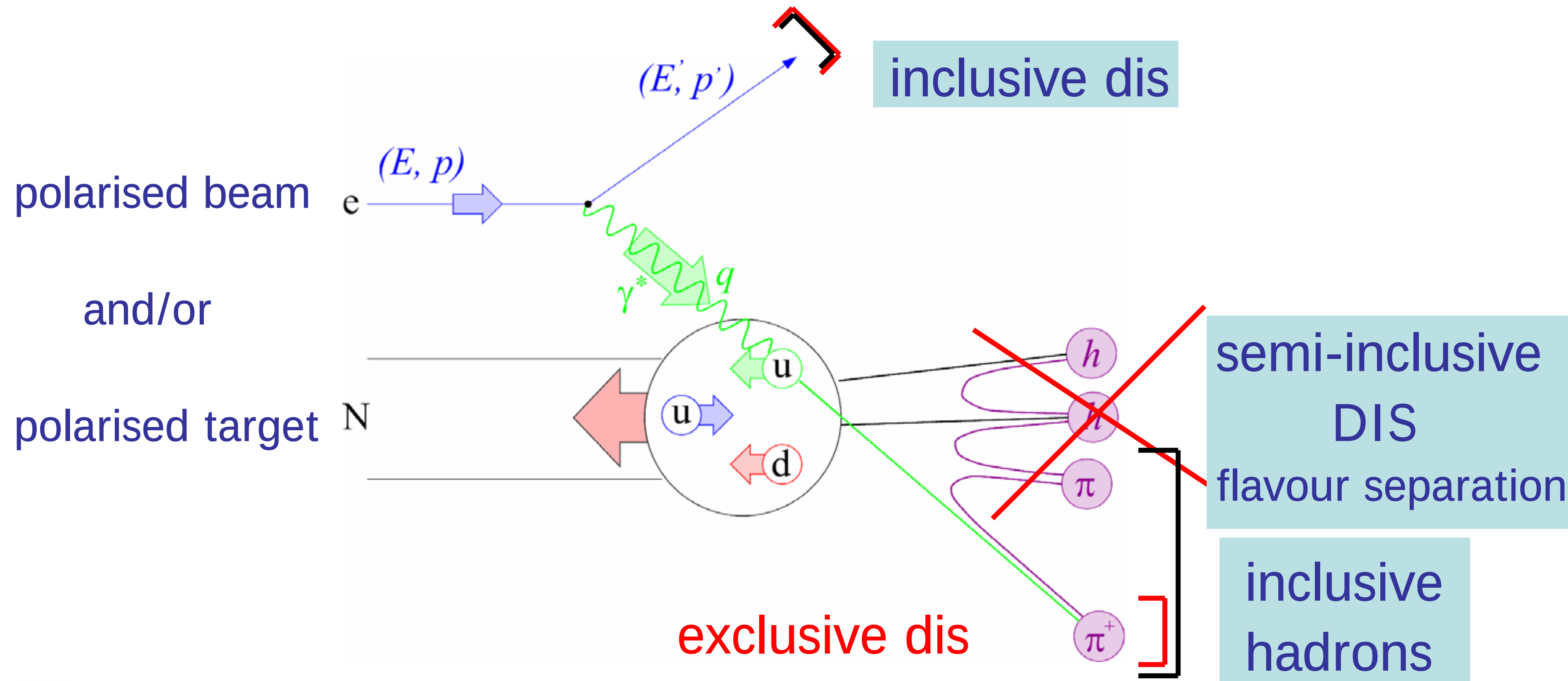
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G$$

don't forget the orbital angular momentum!

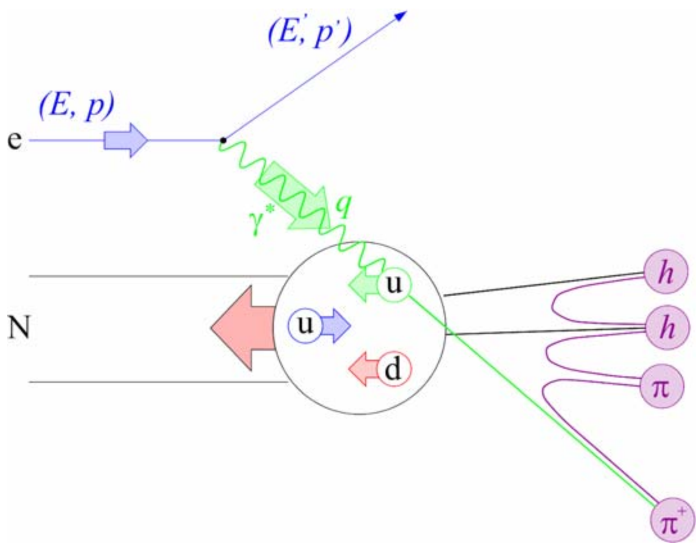
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

polarised deep inelastic scattering

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



Hermes @ DESY



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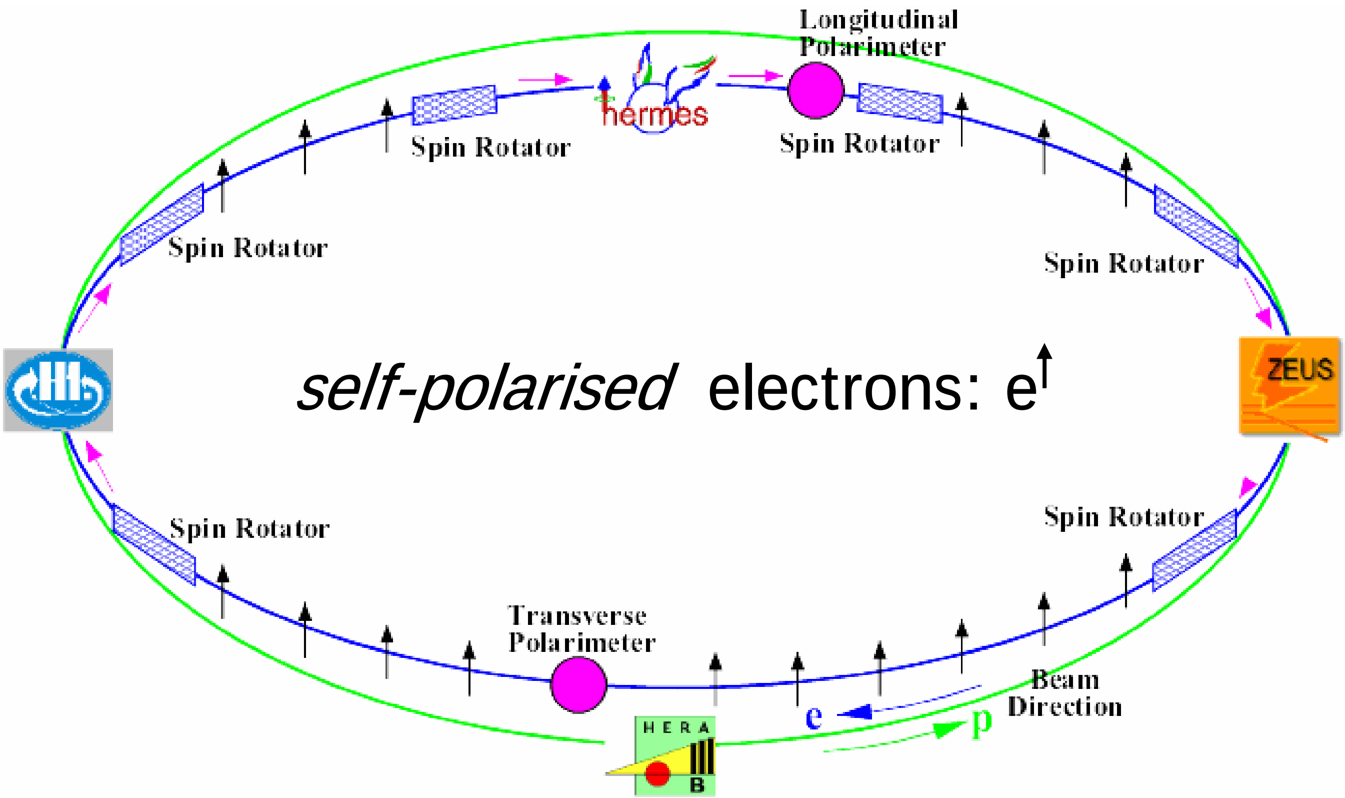
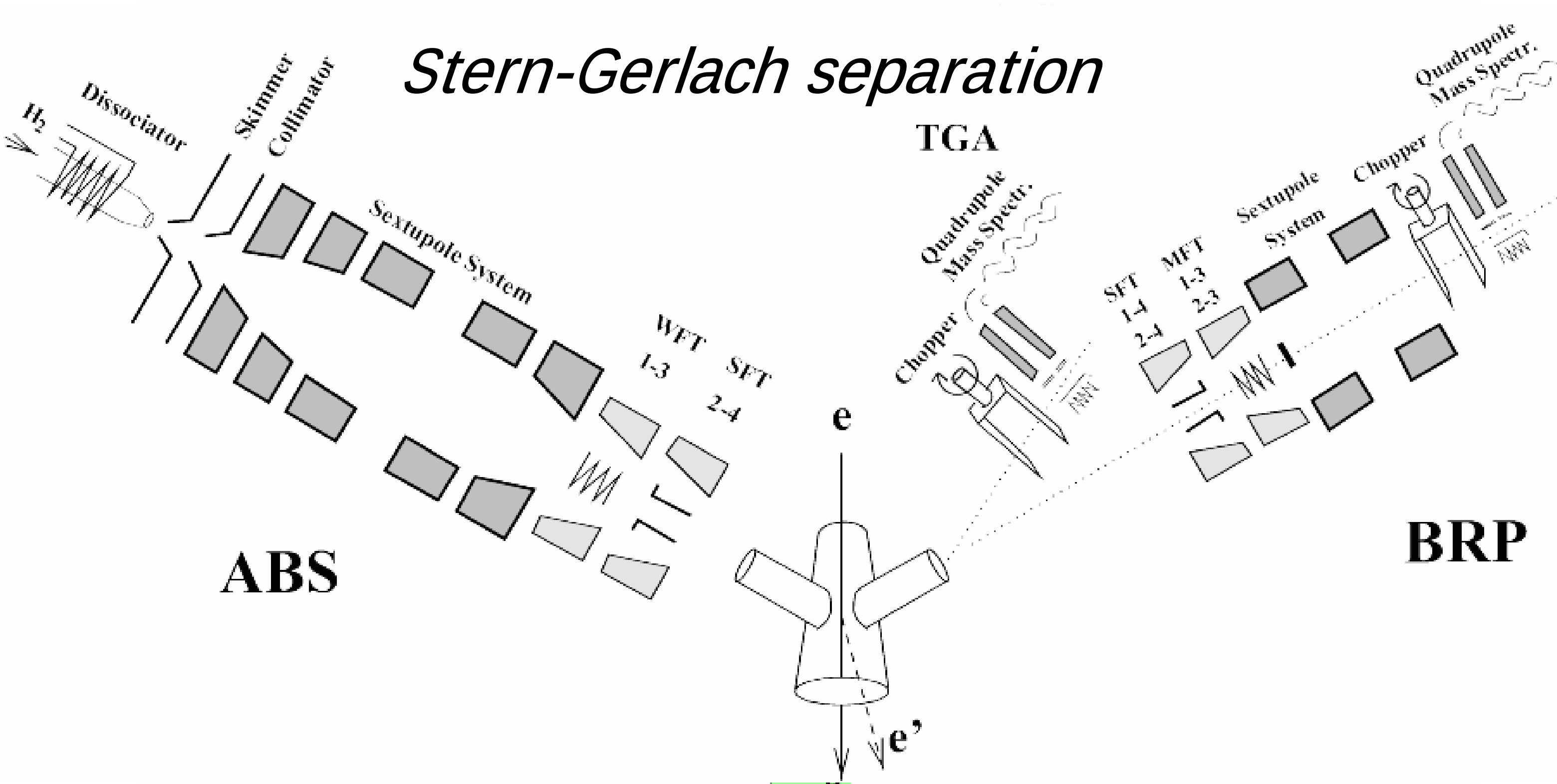
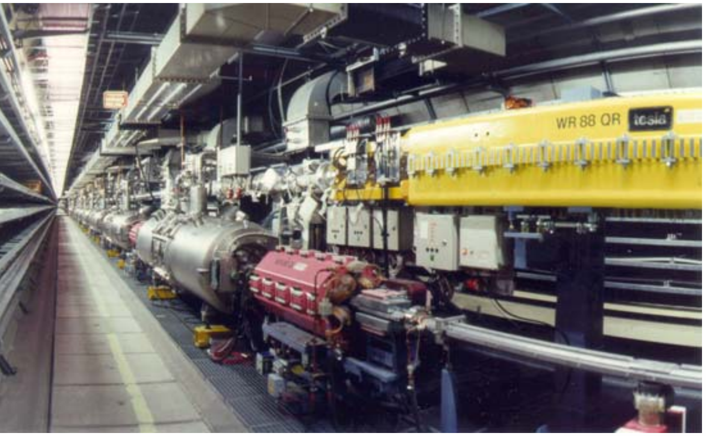

Longitudinal Polarimeter
hermes
Spin Rotator
Spin Rotator
Spin Rotator
Spin Rotator
ZEUS
self-polarised electrons: e↑
Spin Rotator
Spin Rotator
Transverse Polarimeter
Beam Direction
e
p
HERA
B

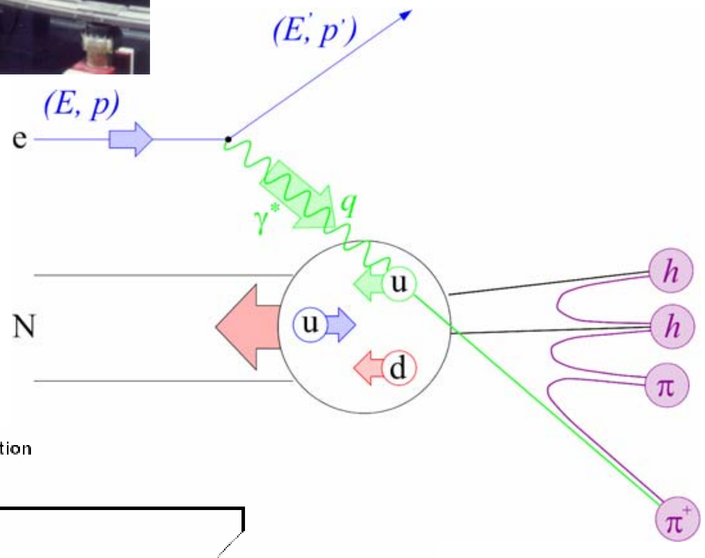
Hermes @ DESY


Stern-Gerlach separation
H_2
Dissociator
Skimmer
Collimator
Sextupole System
WFT
1-3
SFT
2-4
ABS
TGA
Quadrupole
Mass Spectr.
Chopper
e
e'
SFT
1-4
2-4
MFT
1-3
2-3
Sextupole
System
Chopper
Quadrupole
Mass Spectr.
BRP

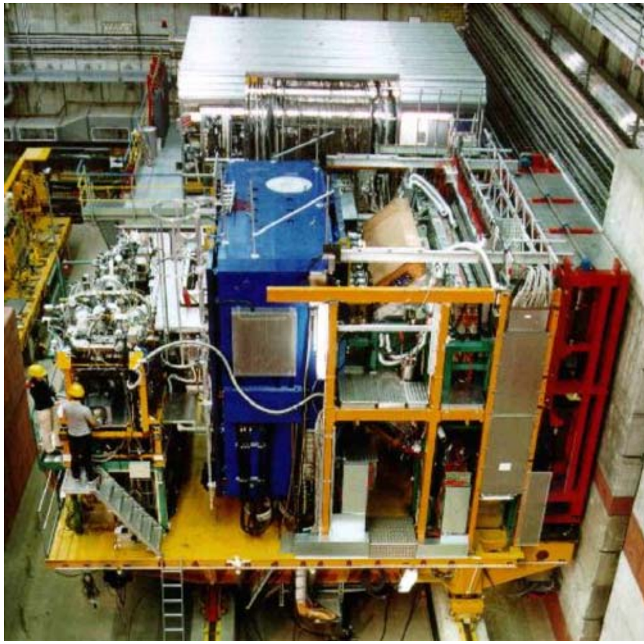
Hermes @ DESY

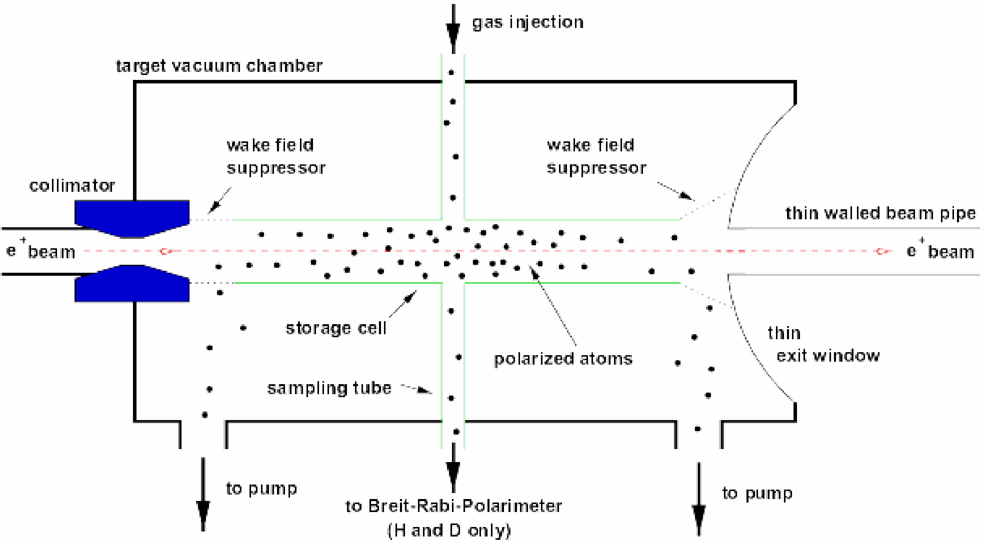


WR 88 QR
tesla



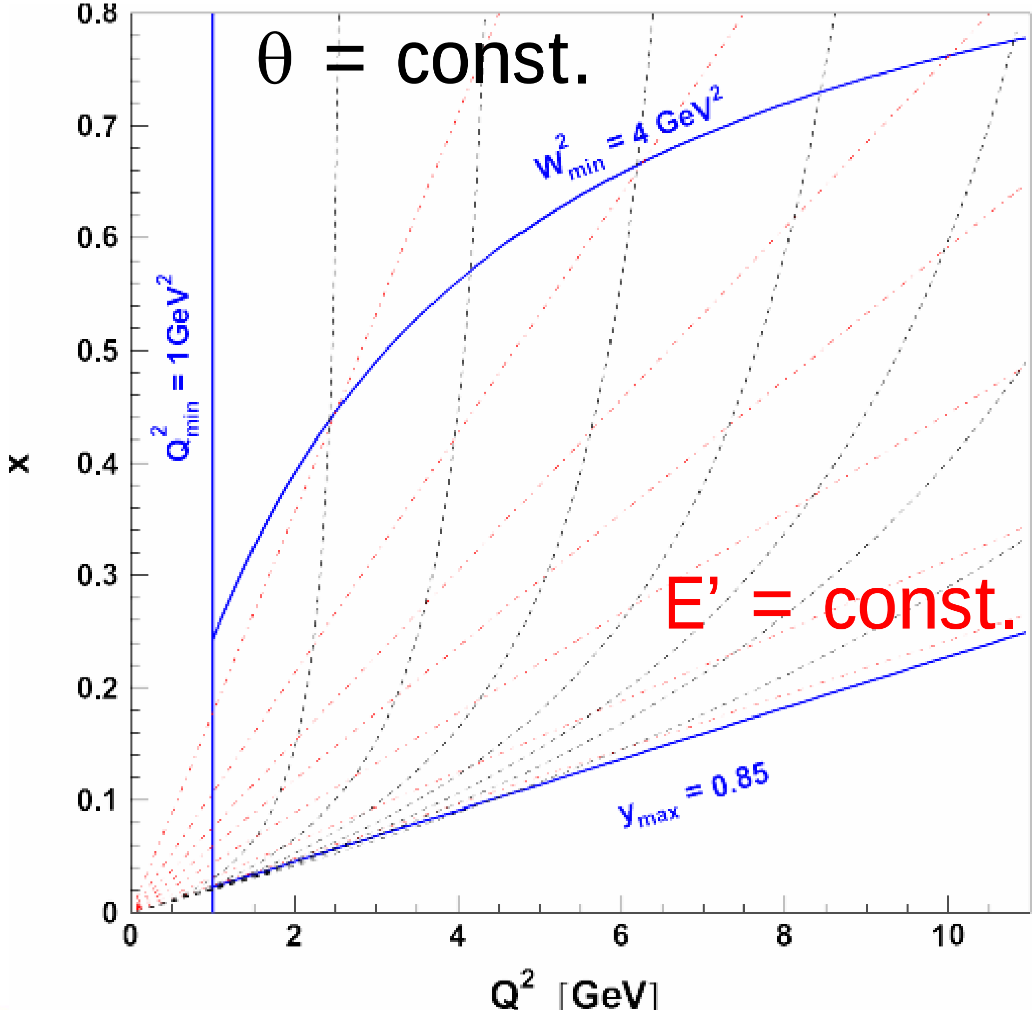
(E', p')
(E, p)
e
γ*
q
u
N
u
d
h
h
π
π+





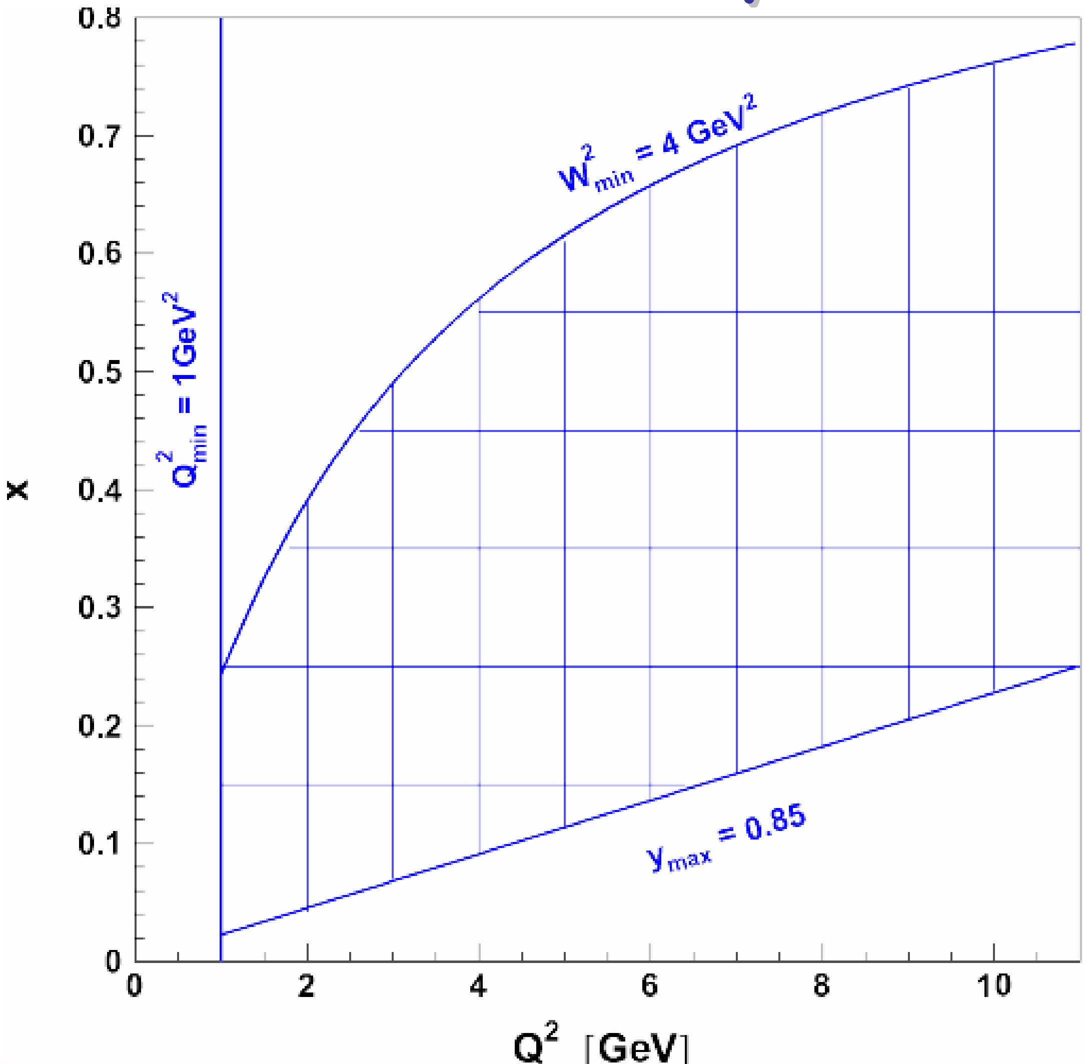
gas injection
target vacuum chamber
wake field suppressor
wake field suppressor
collimator
thin walled beam pipe
e+ beam
e+ beam
storage cell
polarized atoms
thin exit window
sampling tube
to pump
to Breit-Rabi-Polarimeter (H and D only)
to pump

how to measure xsections / asymmetries



$$\sigma(\theta, E') \leftrightarrow \sigma(x, Q^2)$$

how to measure xsections / asymmetries



$$\sigma(\theta, E') \leftrightarrow \sigma(x, Q^2)$$

$$\sigma(x, Q^2) \propto \frac{N(\Delta x, \Delta Q^2)}{L}$$

how to measure g_1

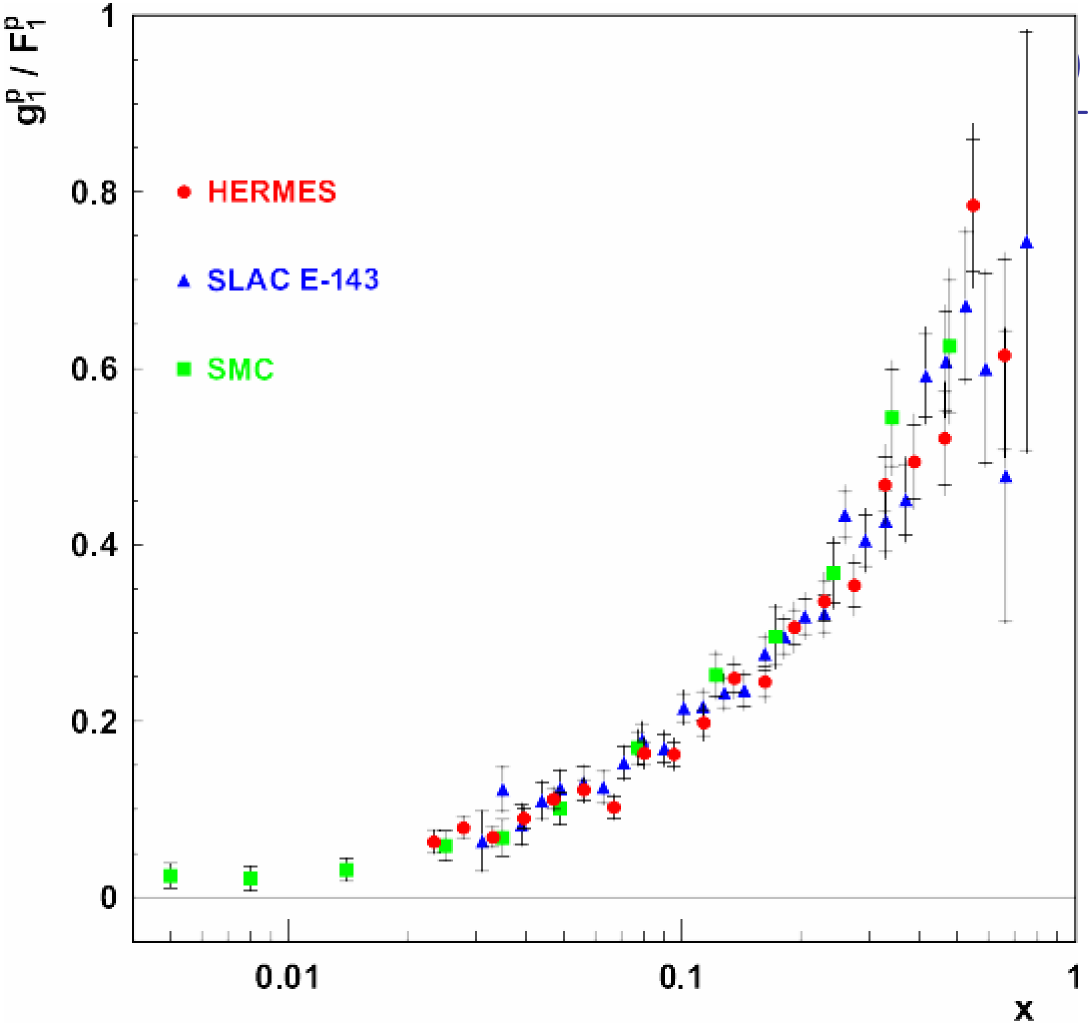
virtual photon asymmetry:

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)} \approx \frac{1}{(1+\gamma^2)D} A_{\parallel}(x,Q^2)$$

how to measure g_1

virtual photon asymmetry:

A_1 … $\approx \frac{1}{(1+\gamma^2)D} A_{\parallel}(x, Q^2)$



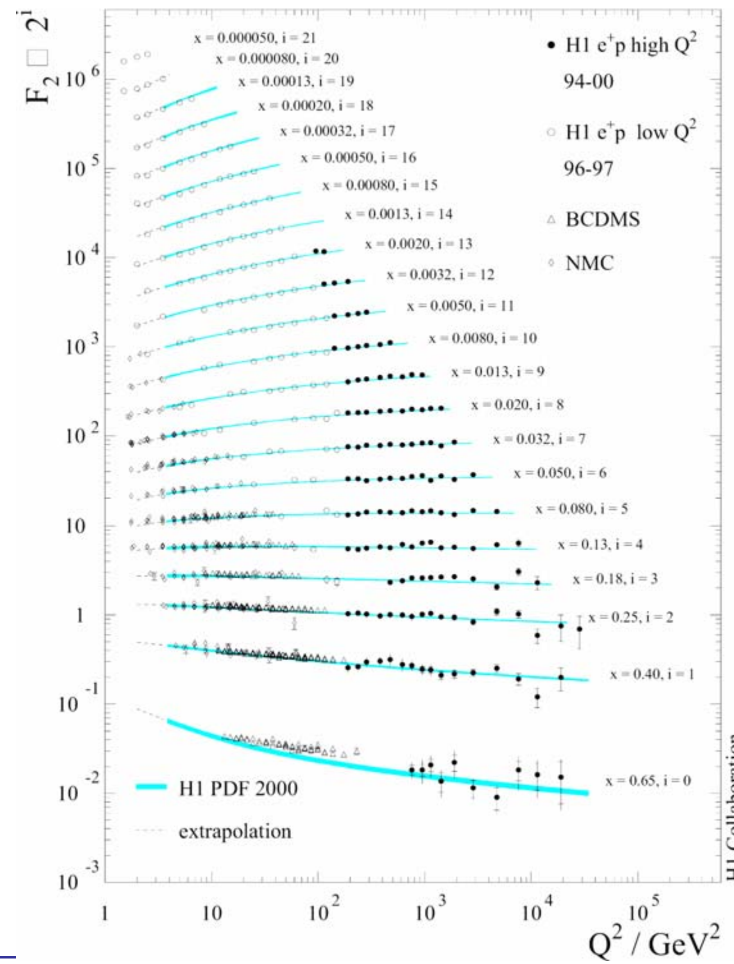
how to measure g_1

$$g_1(x,Q^2) = \left(\frac{g_1(x,Q^2)}{F_1(x,Q^2)}\right)_{meas} \cdot F_1^{param}(x,Q^2)$$

$F_1^{param}(x,Q^2):$

$$Q^2 : 1 - 10^5\ GeV^2$$

$$x : 0.000005 - 0.7$$



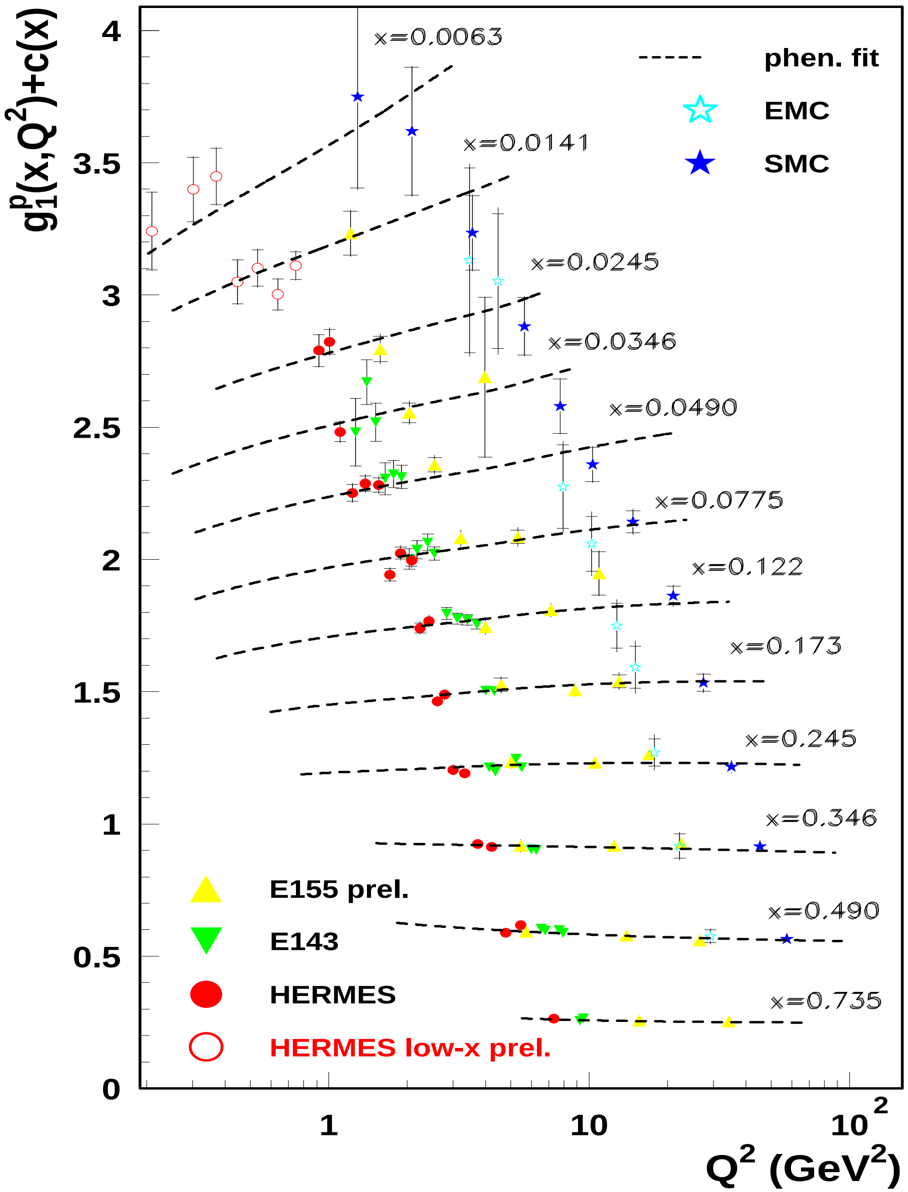
how to measure g_1

$$g_1(x,Q^2) = \left(\frac{g_1(x,Q^2)}{F_1(x,Q^2)} \right)_{meas}$$

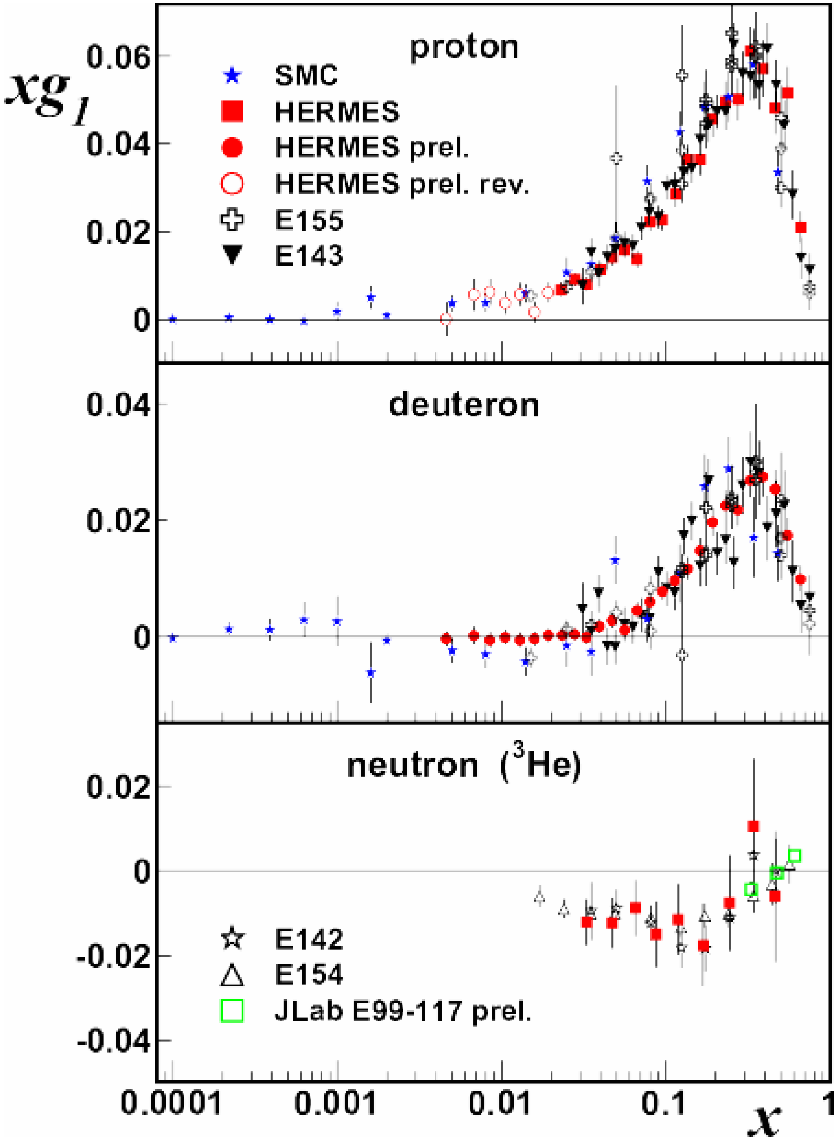
$$g_1^p(x,Q^2):$$

$$Q^2 : 1 - 10^2\ GeV^2$$

$$x : 0.006 - 0.75$$



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

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

→Bjorken sum rule:

(isospin symmetry)

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

fundamental QCD prediction

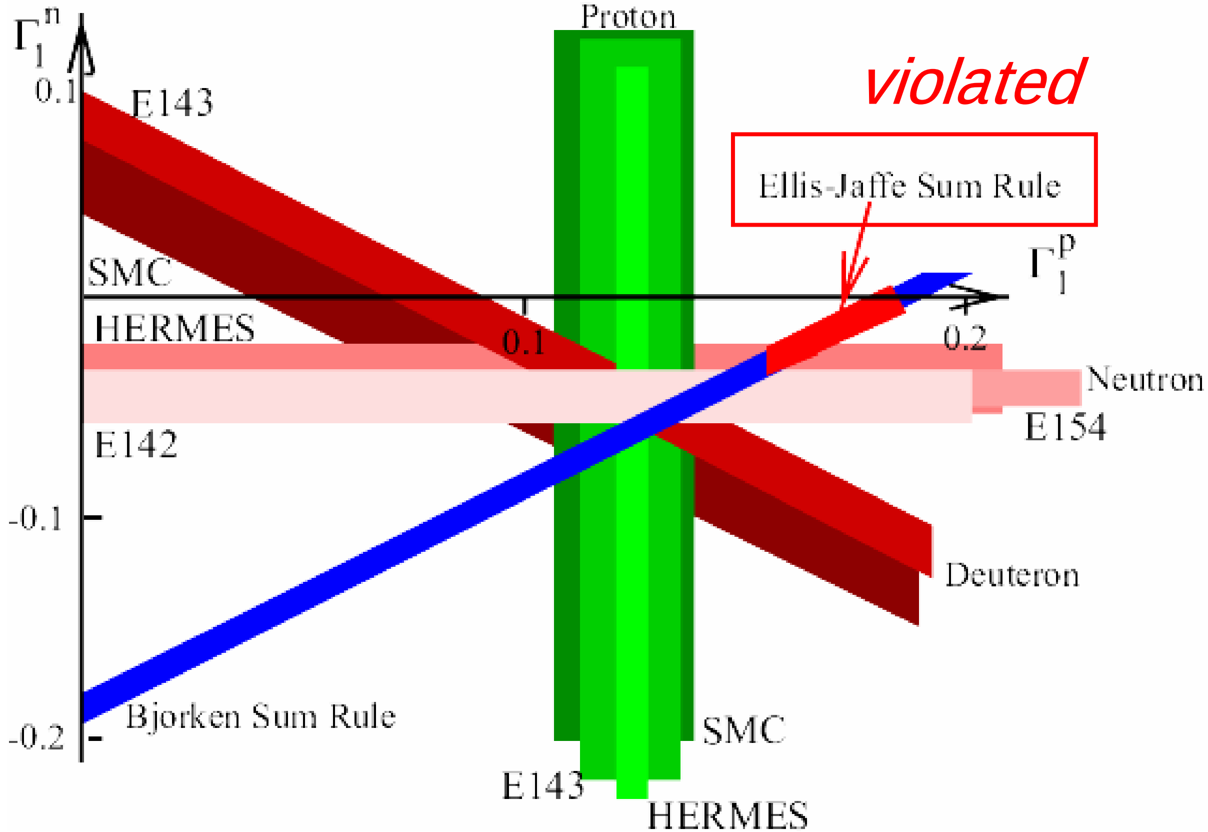
→Ellis-Jaffe sum rule:

$\Delta s = 0$

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

sum rules for g_1

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



$\Delta s=0$

Bjorken sum rule confirmed @ 8% C.L.

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:

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

parameterised

χ^2 minimisation :

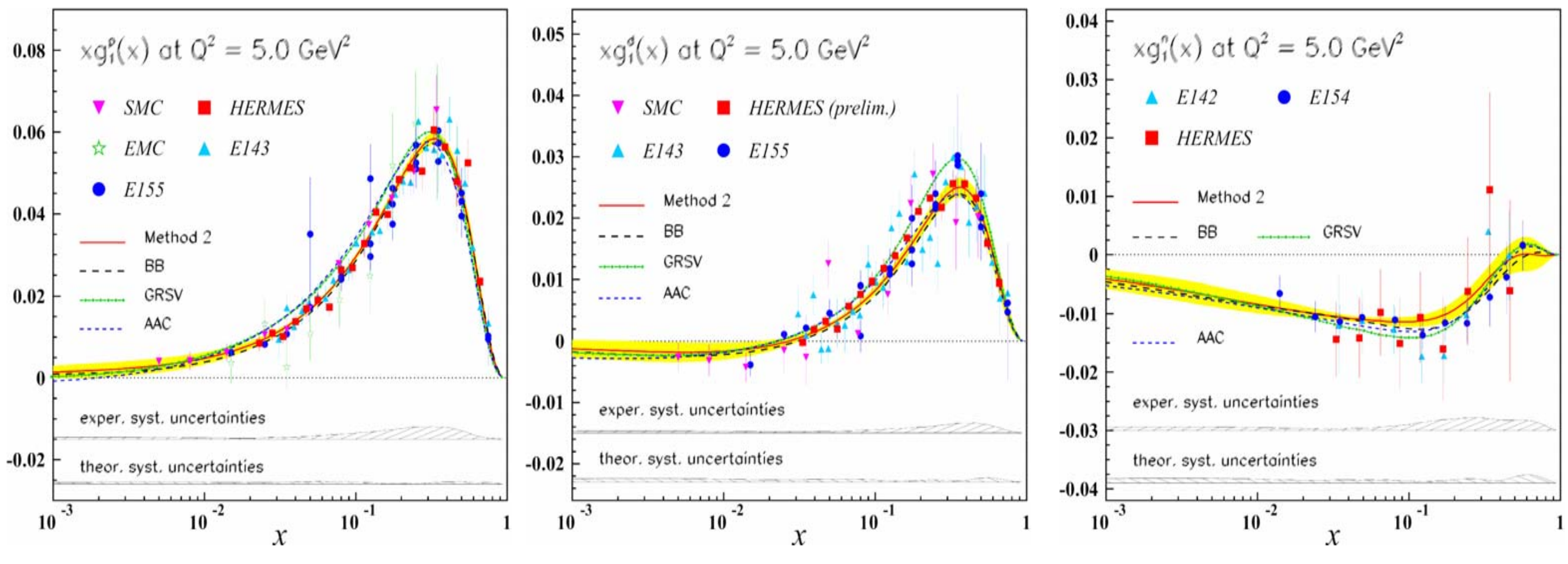
$$\chi^2 = \sum_{data} \frac{(g_1^{meas} - g_1^{calc})^2}{\sigma_{stat}^2}$$

→evaluate parameter

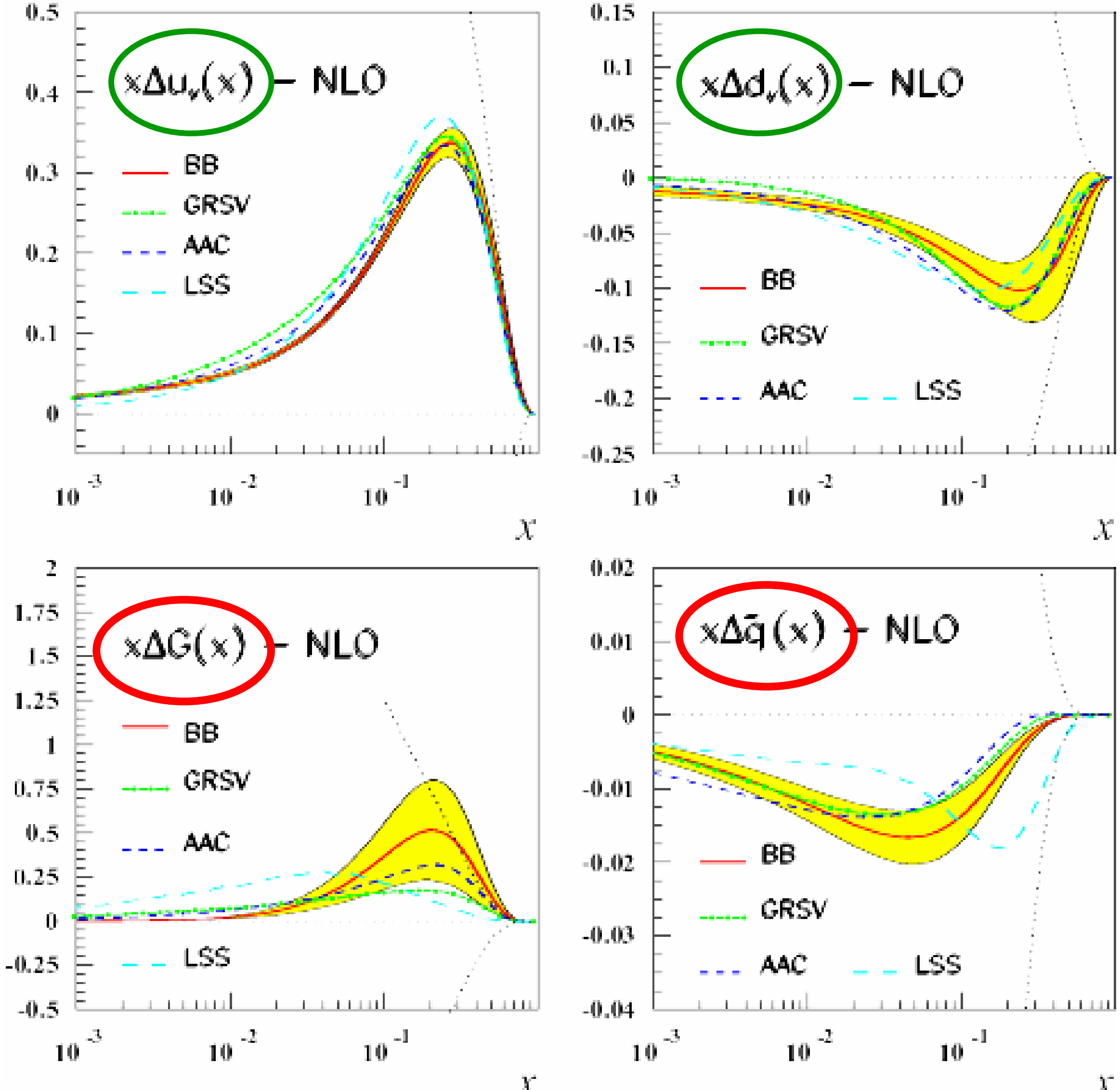
Δq from $g_1(x,Q^2)$

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

one step further:



Δq and ΔG from $g_1(x,Q^2)$

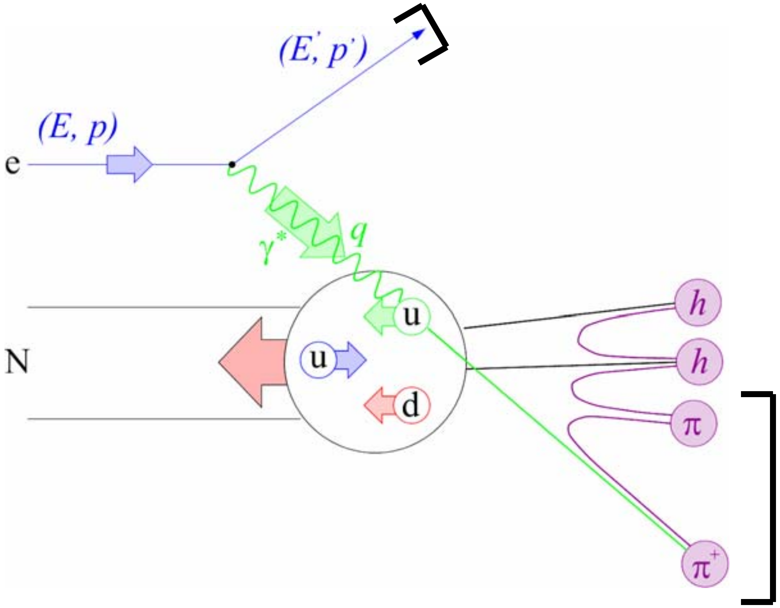


- Δu_v and Δd_v (quite) well determined

- $\Delta\bar{q}$ and ΔG weakly constraint by data

need more direct probes
→flavour separation
→ΔG

polarised semi-inclusive DIS



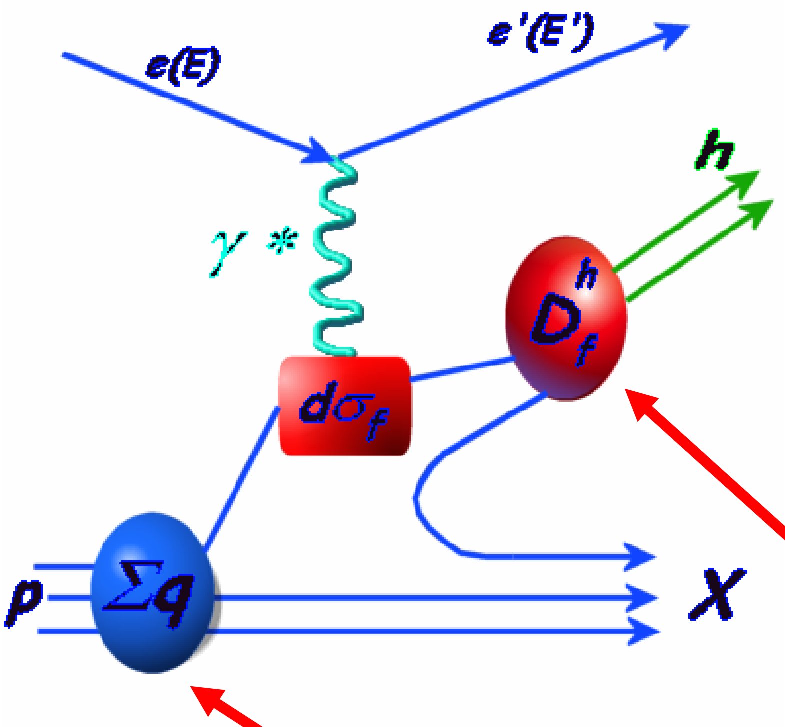
flavour tagging

π^+ $u\bar{d}$

K^- $\bar{u}s$

π^- $\bar{u}d$

polarised semi-inclusive DIS



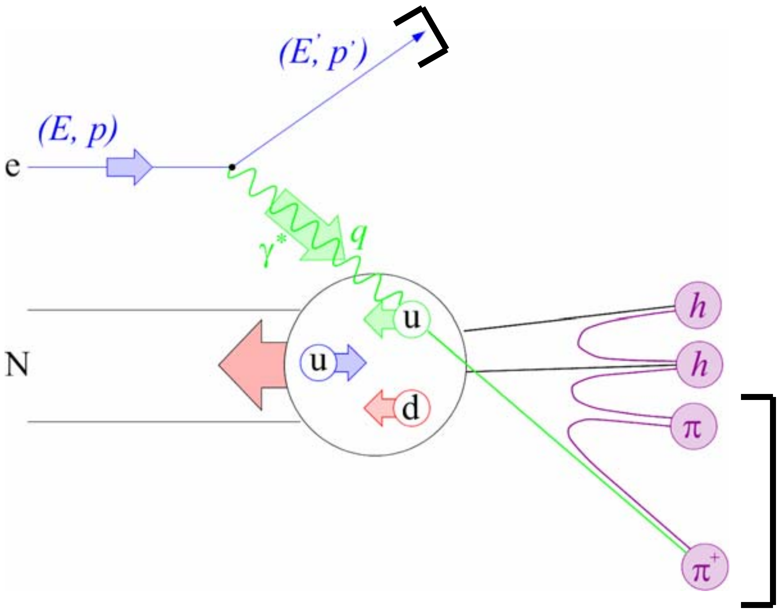
probability that struck quark of flavour f fragments into hadron of type h with energy fraction z

distribution function

fragmentation function

$$d\sigma^h(z) \propto \sum_f q_f(x) \otimes d\sigma_f \otimes D_f^{q\rightarrow h}(z) \quad , z=E_h/\nu$$

polarised semi-inclusive DIS



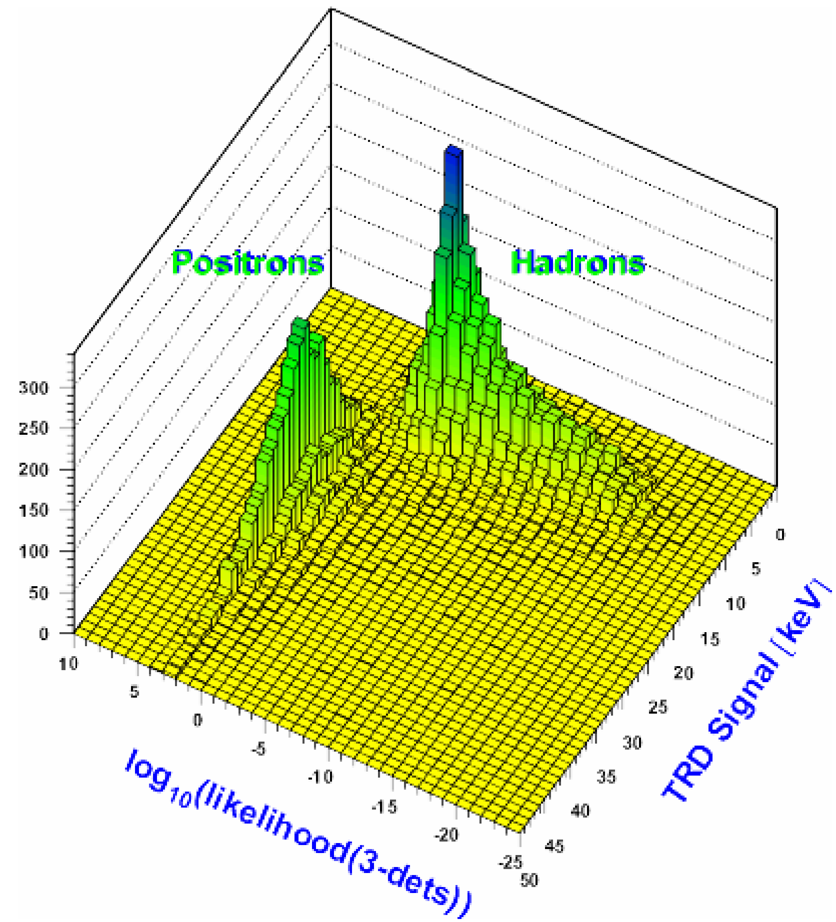
polarised parton distribution functions !

$$A_1^h(x,Q^2) = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} \approx \frac{\sum_f e_f^2 \, \Delta q_f(x,Q^2) \int dz \, D_f^h(z,Q^2)}{\sum_f e_f^2 \, q_f(x,Q^2) \int dz \, D_f^h(z,Q^2)}$$

hadron asymmetries
to be measured

known quantities

particle identification

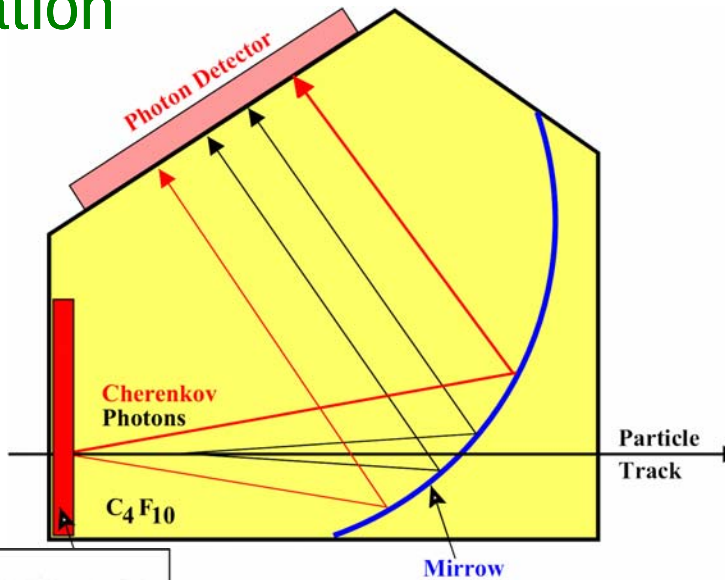


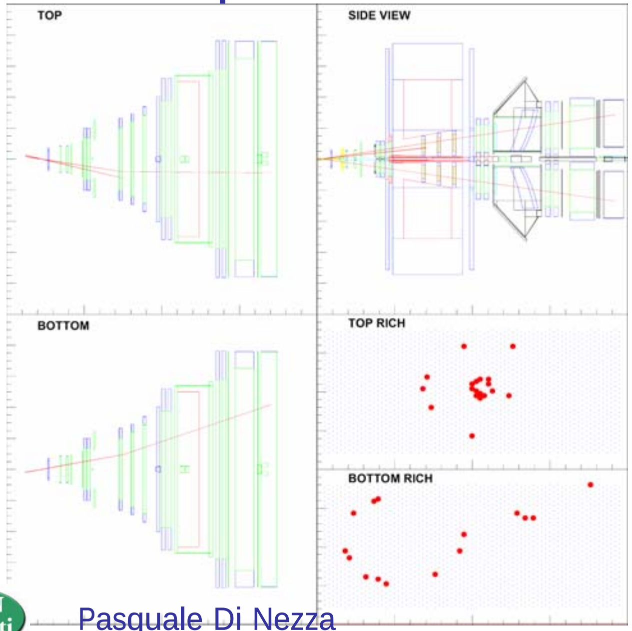
particle identification

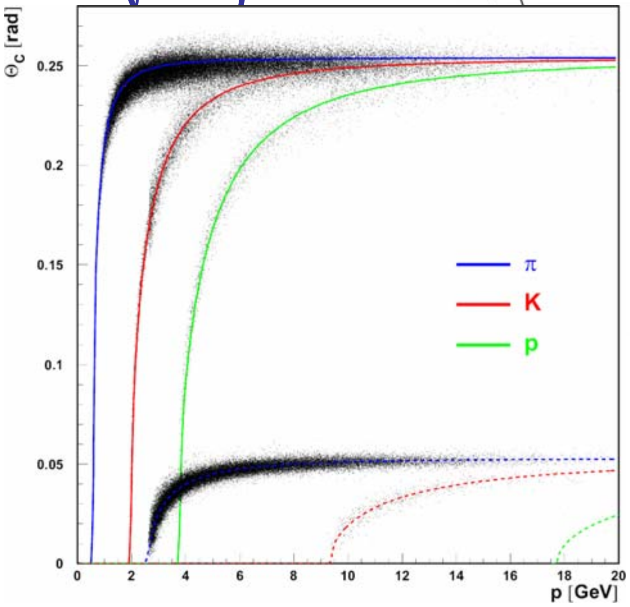
double radiator RICH for π / K / p separation
aerogel: n=1.03
C_4F_{10}: n=1.0014

Cerenkov light emission:

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







quark/anti-quark helicity distributions

$$A_1^h(x,Q^2) = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} \approx \frac{\sum_f e_f^2\ \Delta q_f(x,Q^2) \int dz\, D_f^h(z,Q^2)}{\sum_f e_f^2\ q_f(x,Q^2) \int dz\, D_f^h(z,Q^2)}$$

quark/anti-quark helicity distributions

$$A_1^h(x,Q^2) = \sum_f \underbrace{\frac{e_f^2\, q_f(x,Q^2) \int dz\, D_f^h(z)}{\sum_{f'} e_{f'}^2 q'(x,Q^2) \int dz\, D_{f'}^h(z)}}_{P_q^h(x,z)} \cdot \frac{\Delta q}{q}(x,Q^2)$$

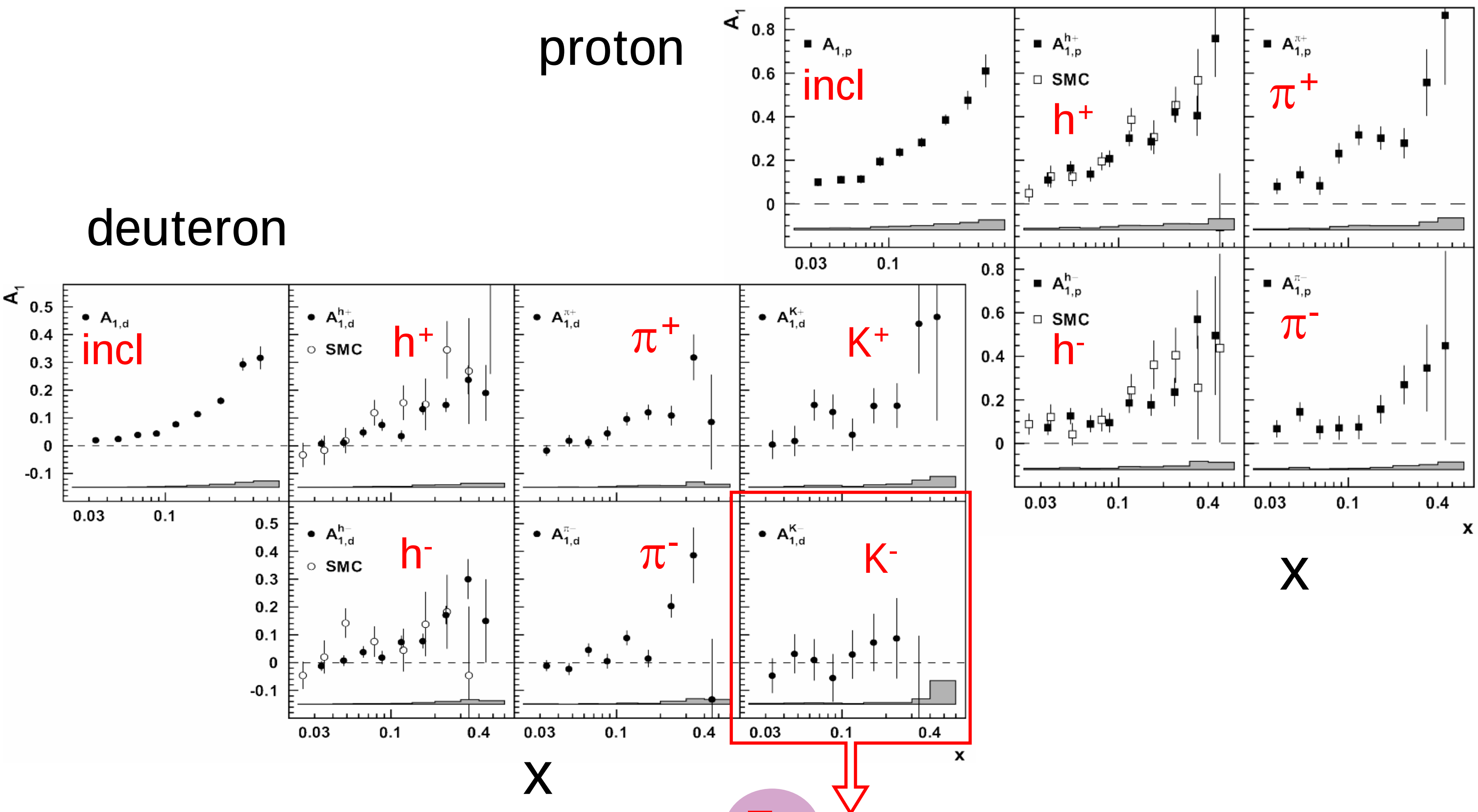
PURITY is an unpolarised quantity

needs at least six independent asymmetry sets $A_1^h(x)$ to determine six unknown helicity distributions: Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$, Δs, $\Delta\bar{s}$

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

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

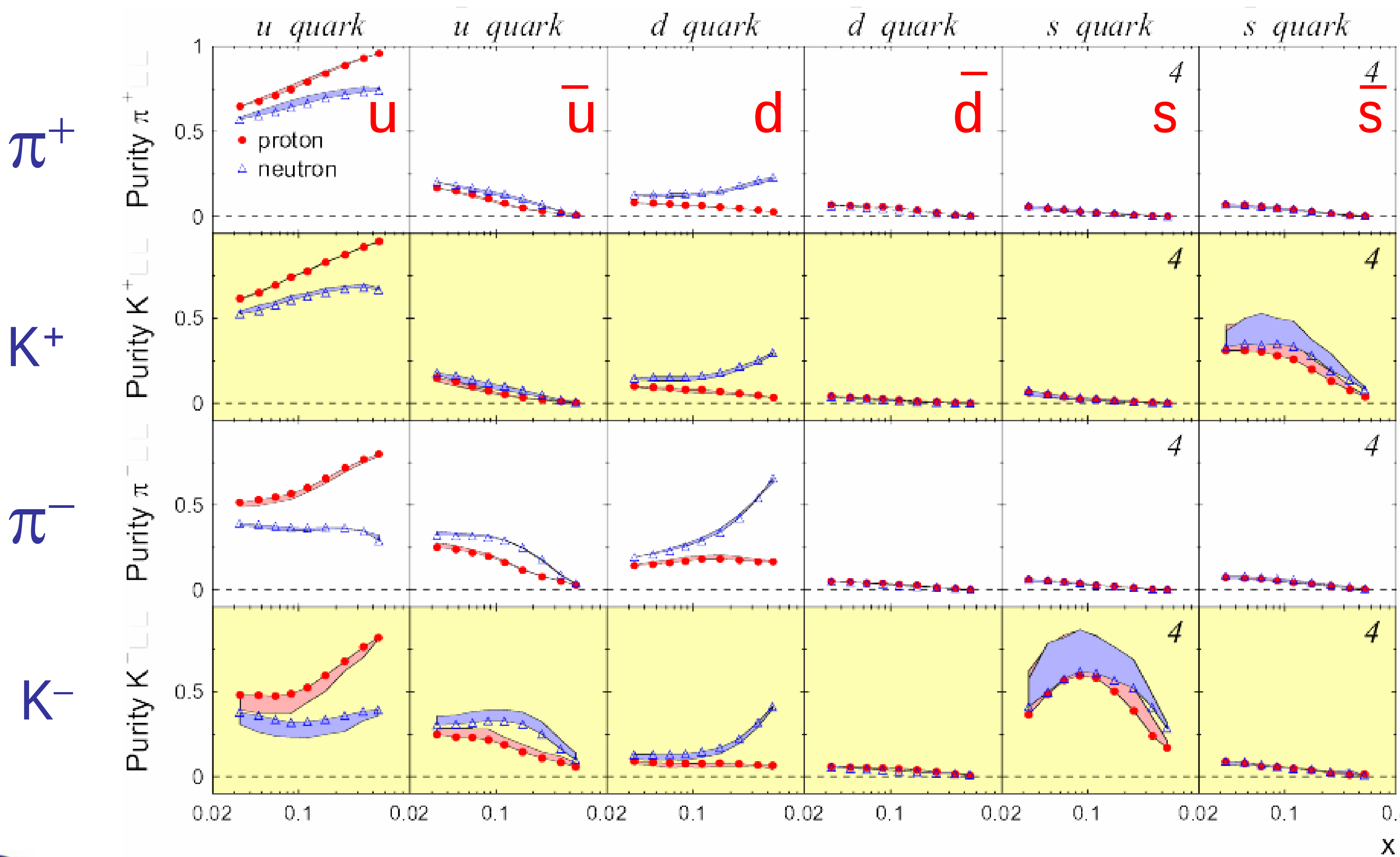
measured hadron asymmetries



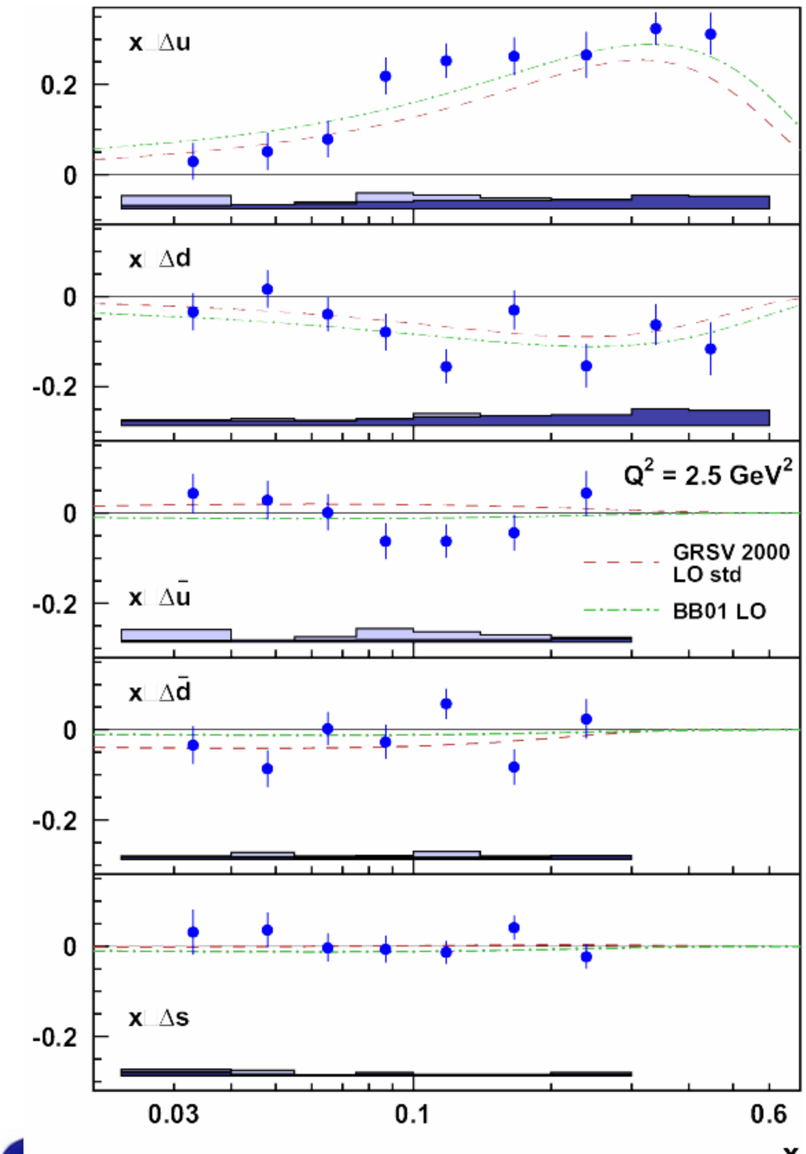
K⁻ $\bar{u}s$ all sea objects

purities

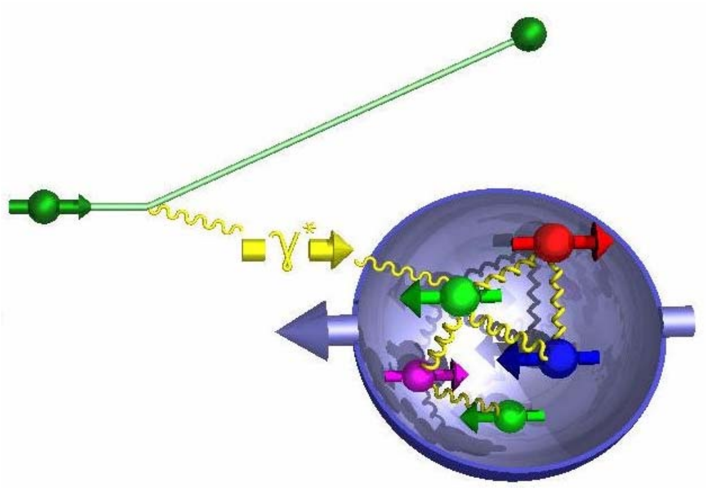
conditional probability that γ^* hits a quark of flavour q when hadron of type h was detected



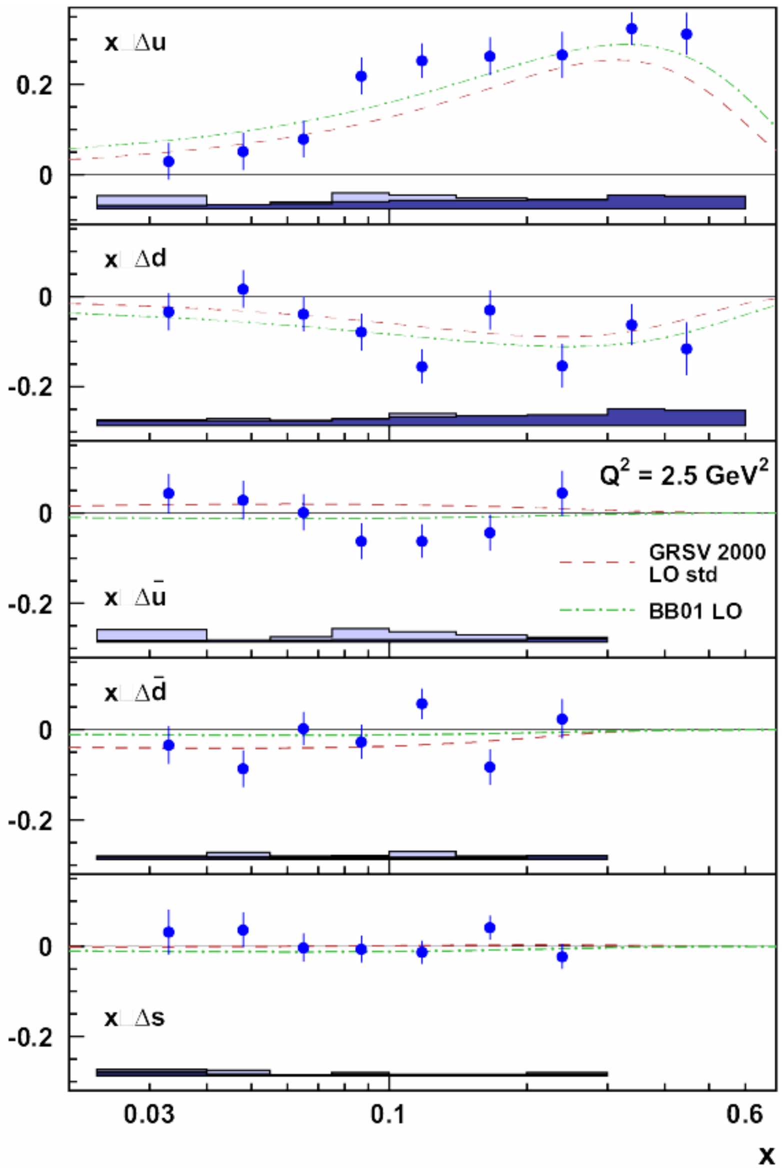
quark/anti-quark helicity distributions



u quarks large positive polarisation

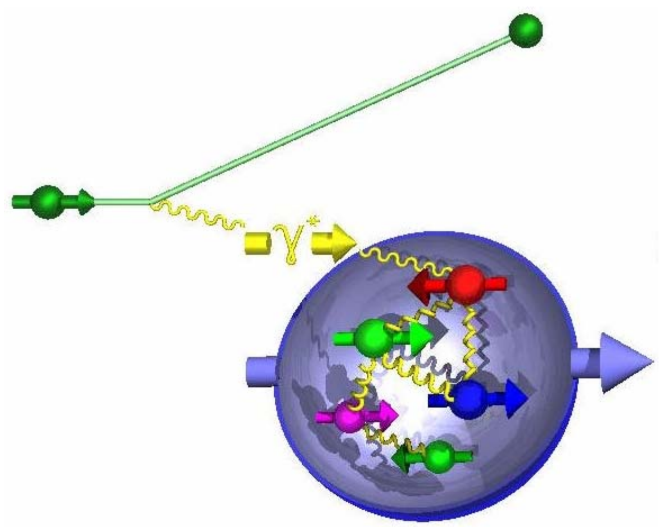


quark/anti-quark helicity distributions

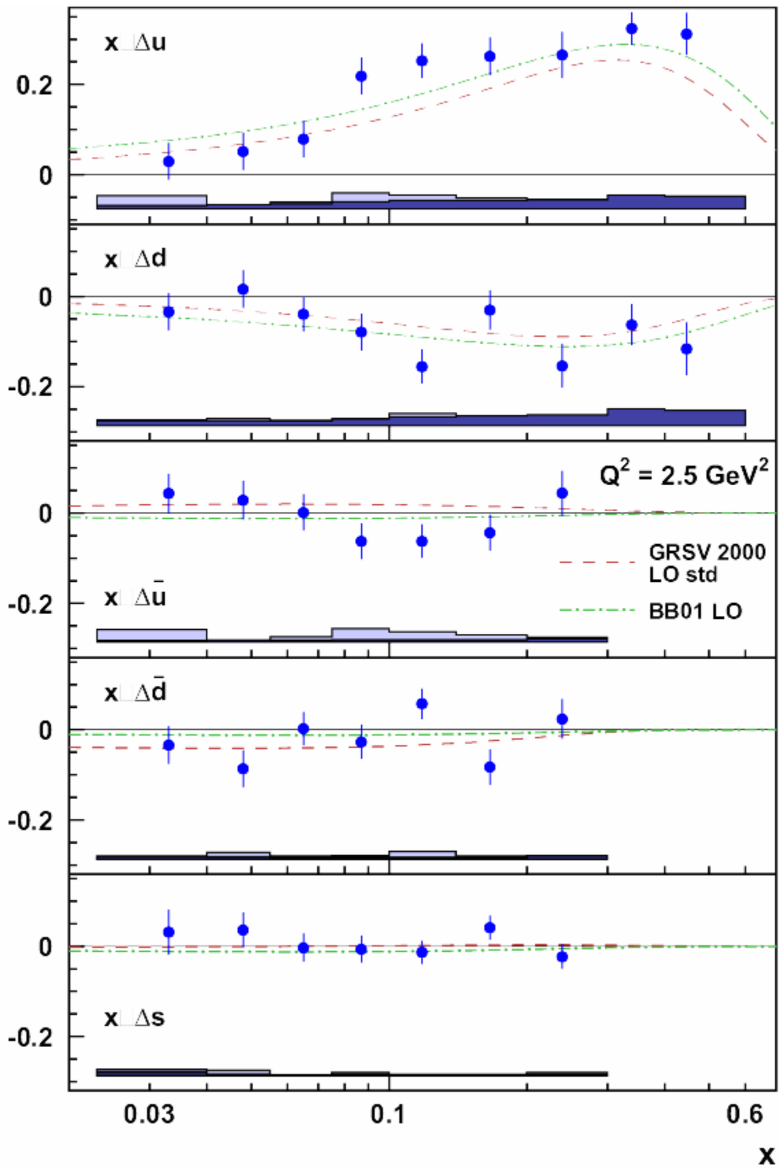


u quarks large positive polarisation

d quarks negative polarisation



quark/anti-quark helicity distributions



u quarks large positive polarisation

d quarks negative polarisation

sea quark ($\bar{u}$, $\bar{d}$, s, $\bar{s}$) compatible with 0

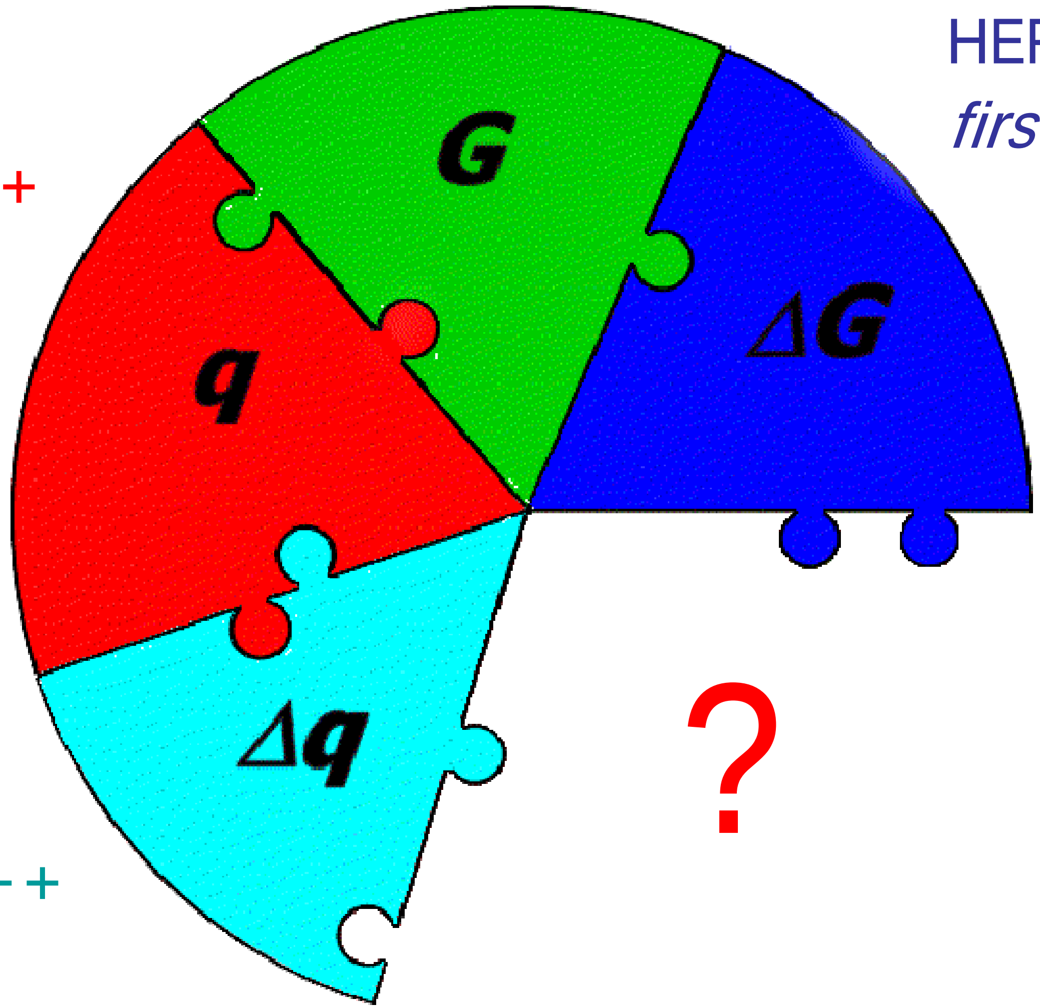
no indication for Δs < 0

where do we stand

the (spin) structure of the nucleon ...

H1, ZEUS,++

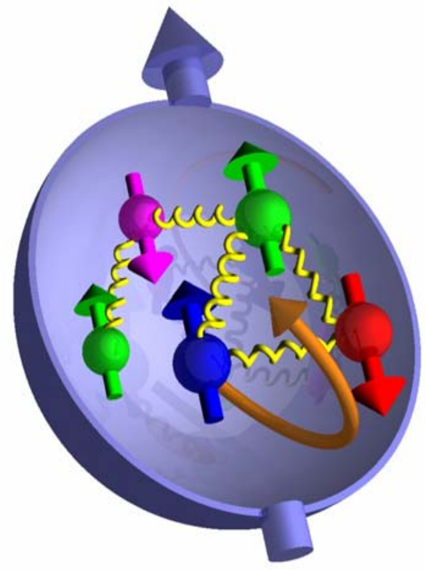
HERMES, COMPASS:
first glimpse



→HERMES
→CERN
→RHIC

HERMES, ++

don't forget the orbital angular momentum



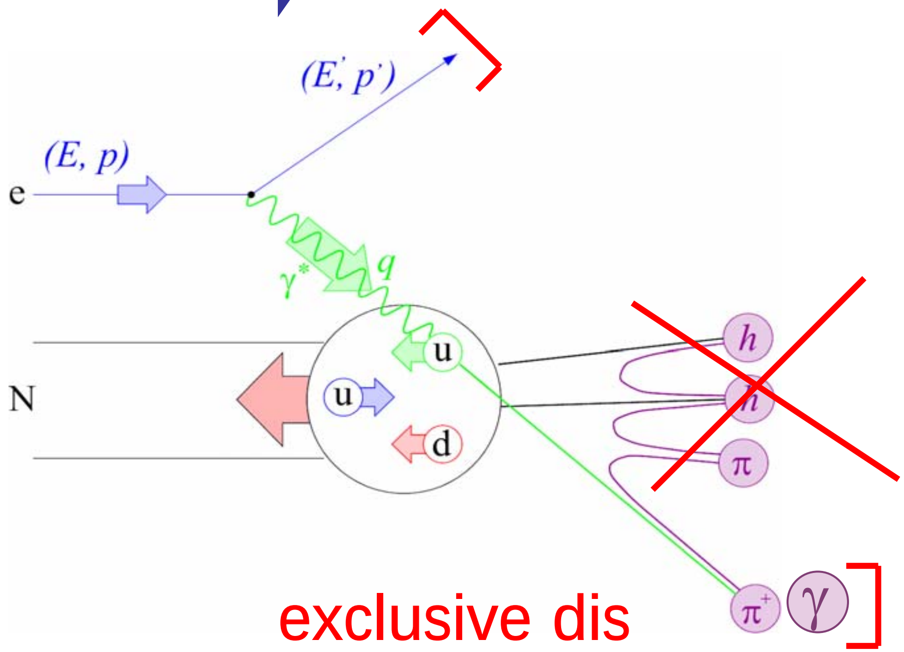
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

⇨ hard exclusive processes...

polarised beam

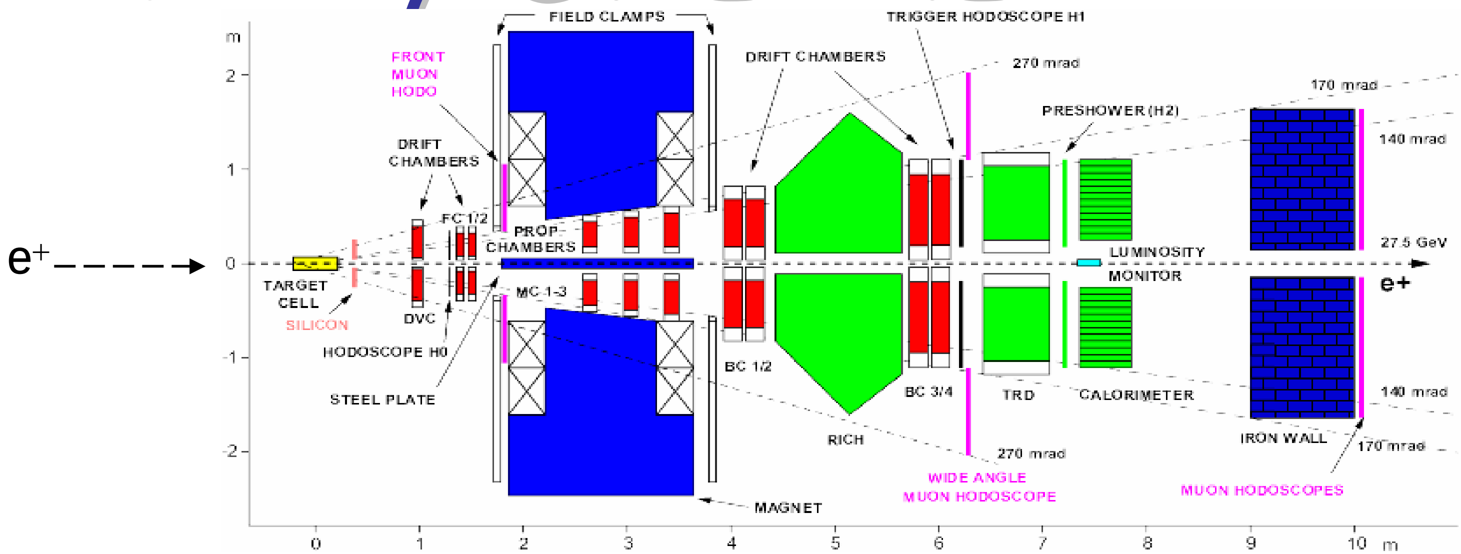
and/or

polarised target

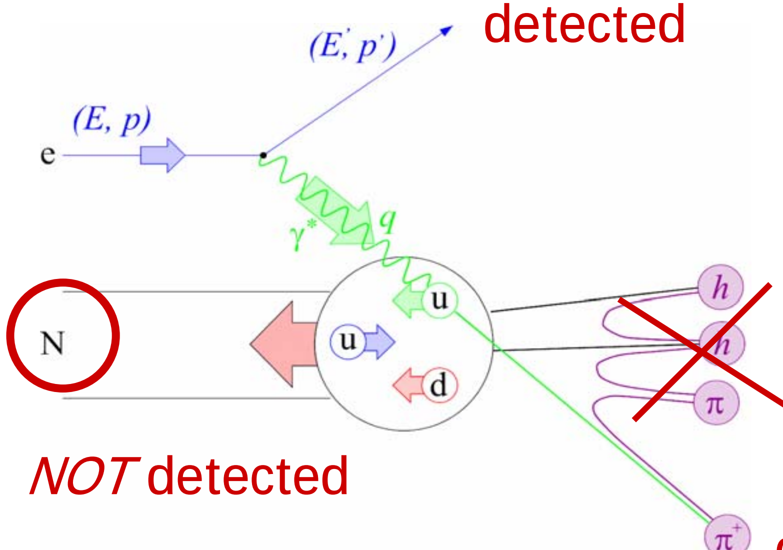


exclusive dis

exclusivity @HERMES



detected



NOT detected

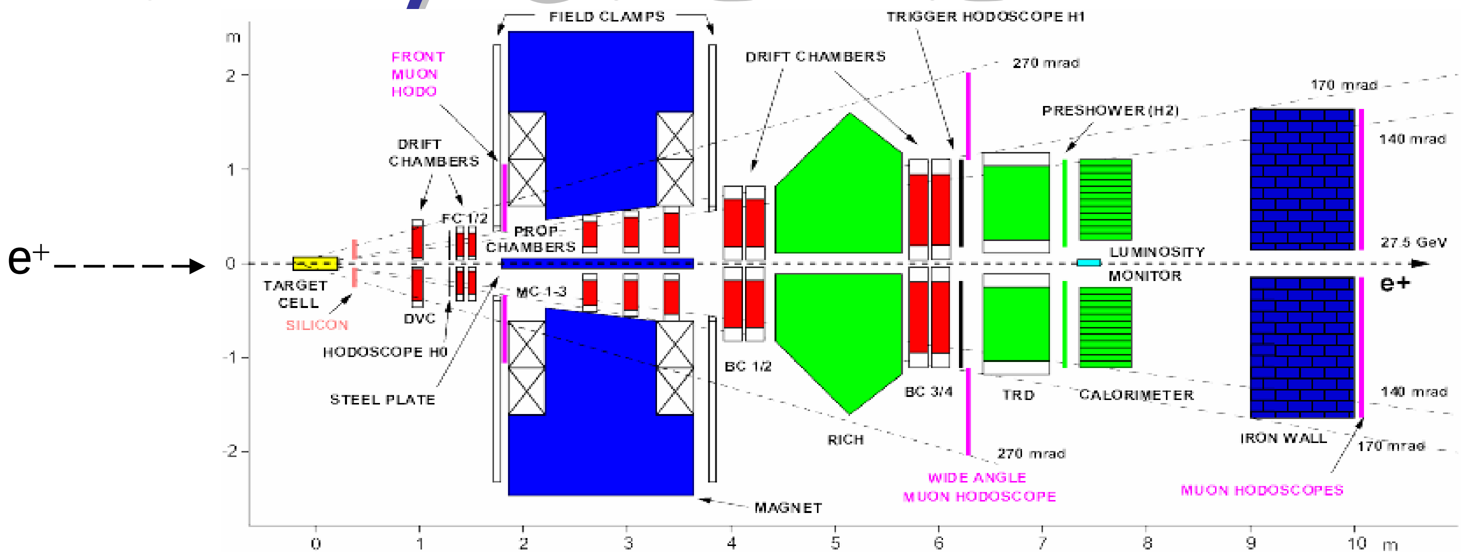
detected

missing mass technique:

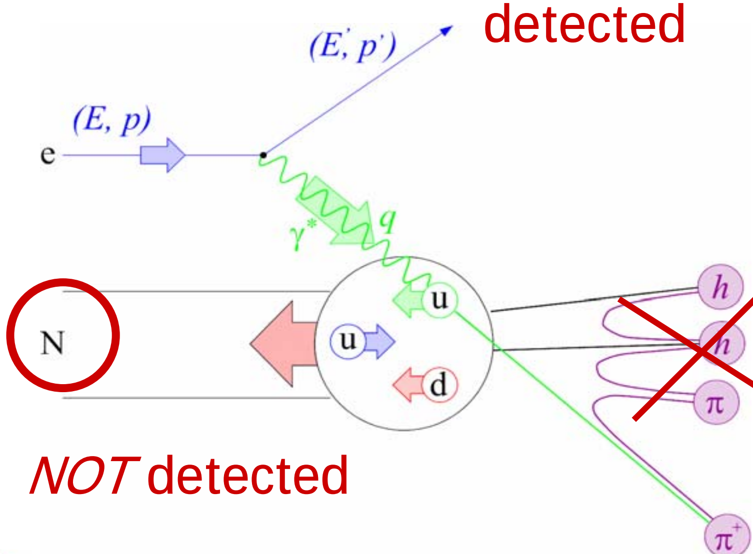
$$M_x^2=(p+q-P_{\gamma,\pi})^2$$

$$\rightarrow \sigma(M_x)\sim 0.8 \text{ GeV}$$

exclusivity @HERMES

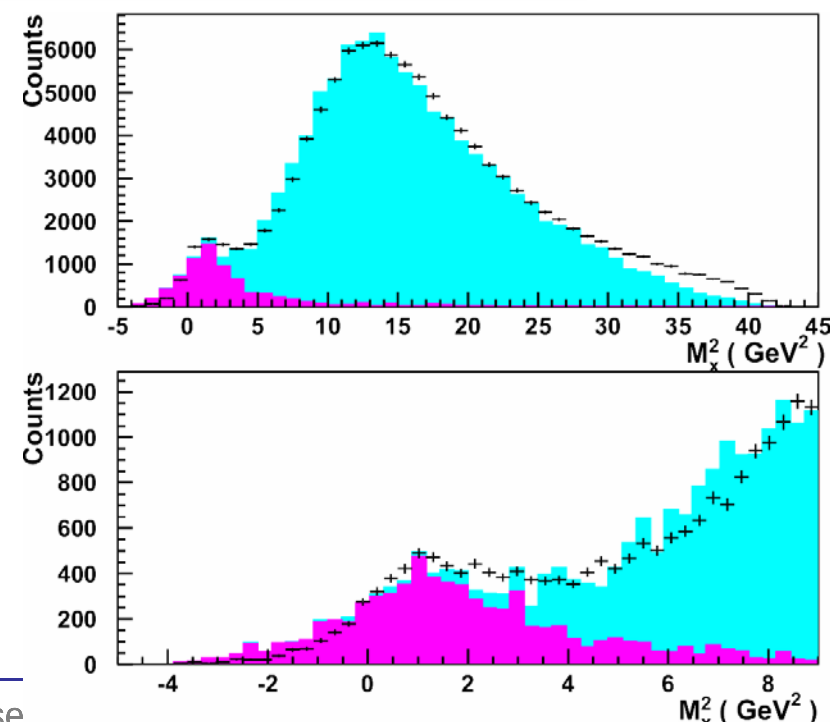


detected

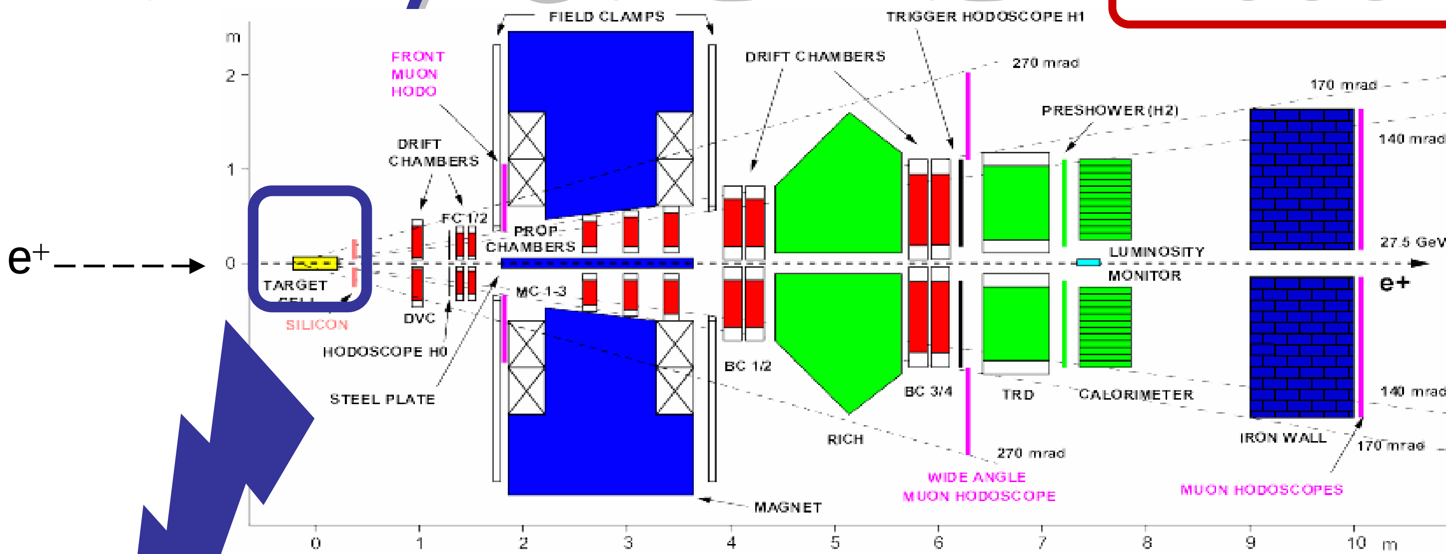


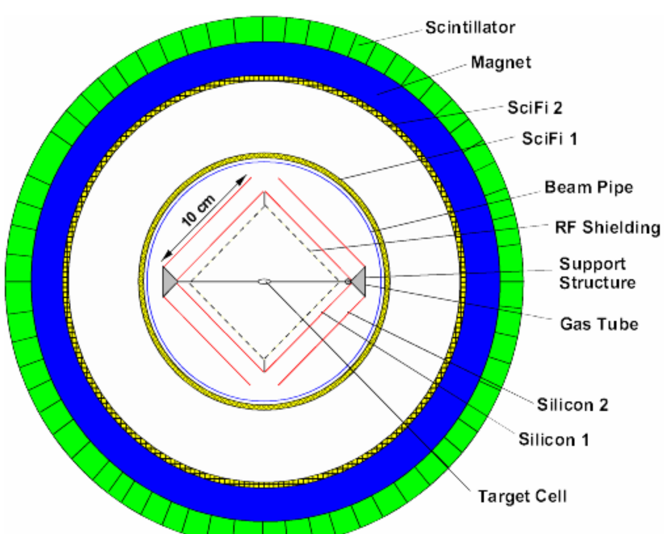
NOT detected

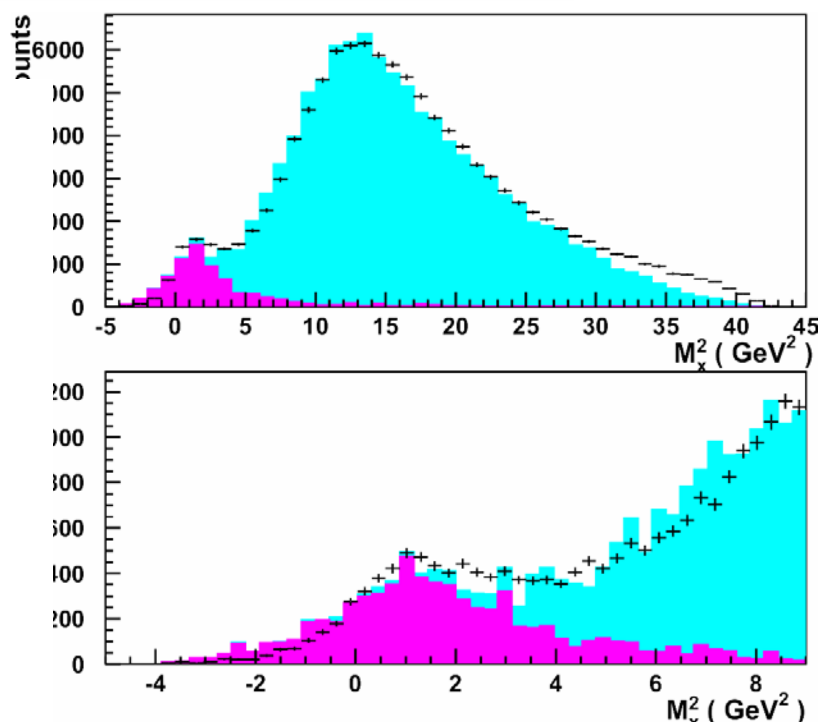
detected



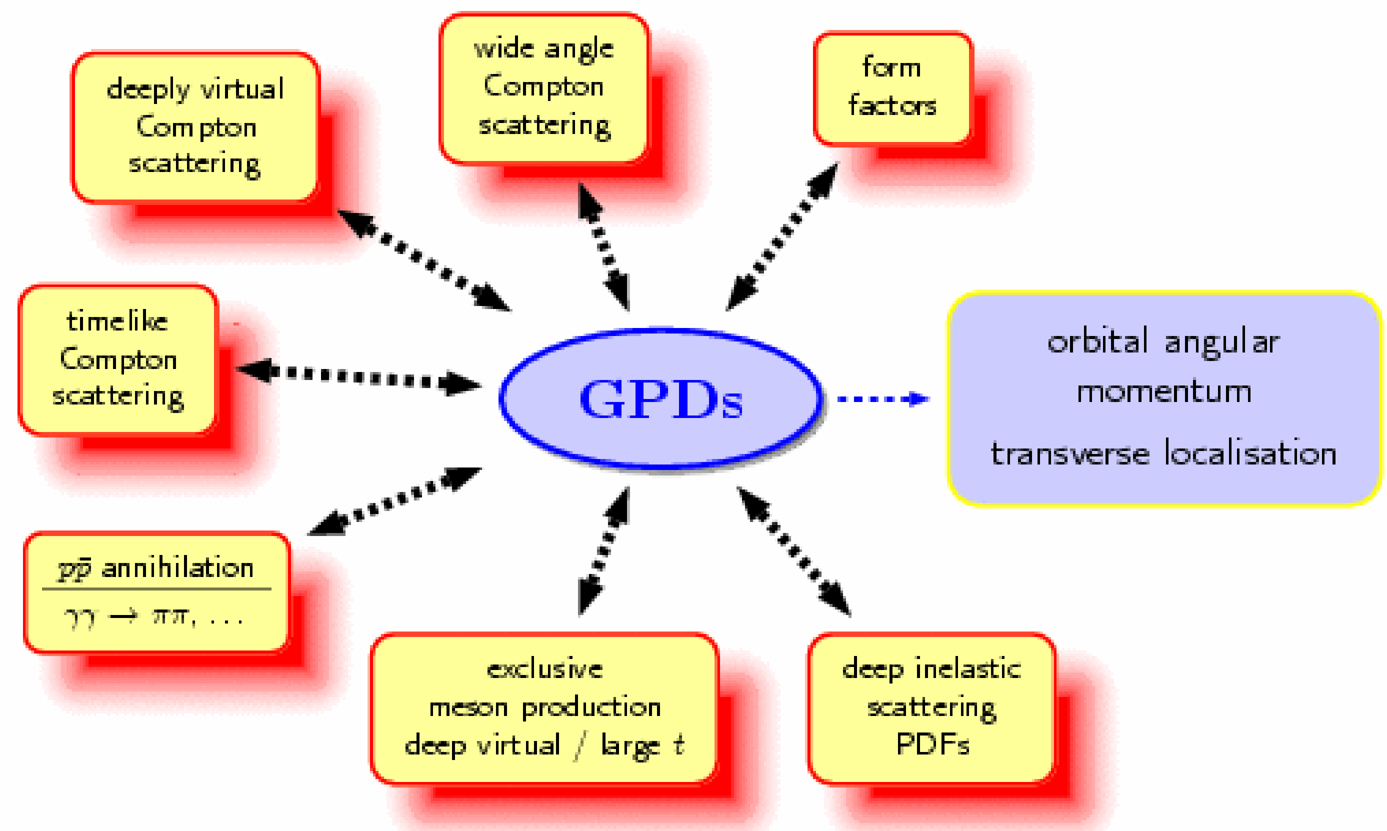
exclusivity @HERMES 2005++







Generalized Parton Distributions



→ Quantum number of final state selects different GPDs:

Vector mesons (ρ, ω, ϕ): H E

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

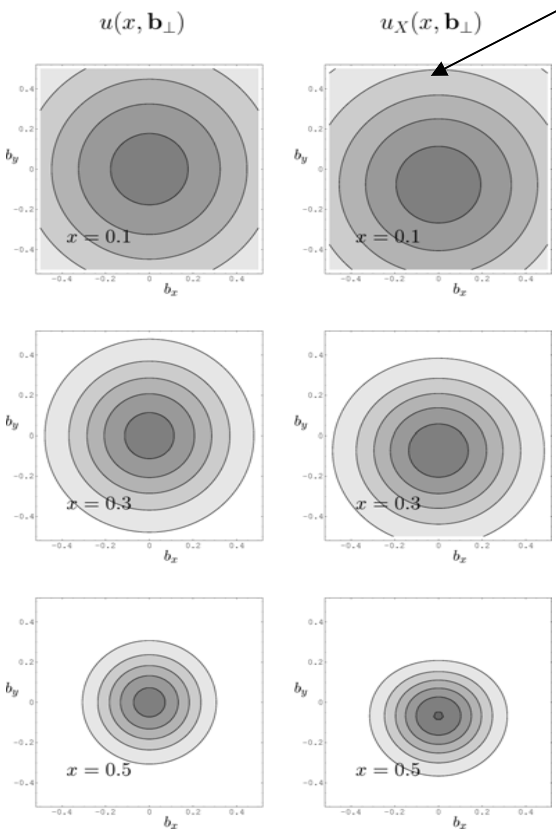
DVCS (γ) depends on H, E, $\tilde{H}$, $\tilde{E}$

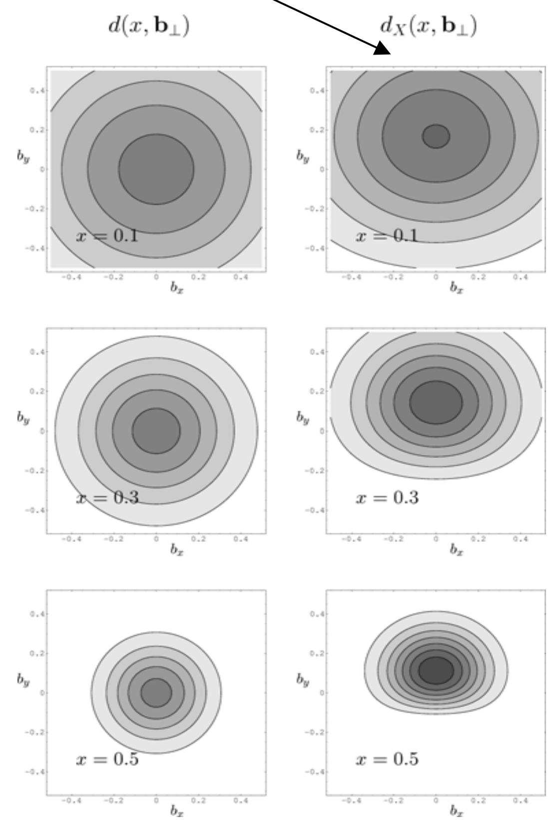
"Tomographic" Images of the Proton's Quark Content

(In the Infinite Momentum Frame)

Impact parameter: $b_\perp = \frac{1}{\sqrt{-t}}$

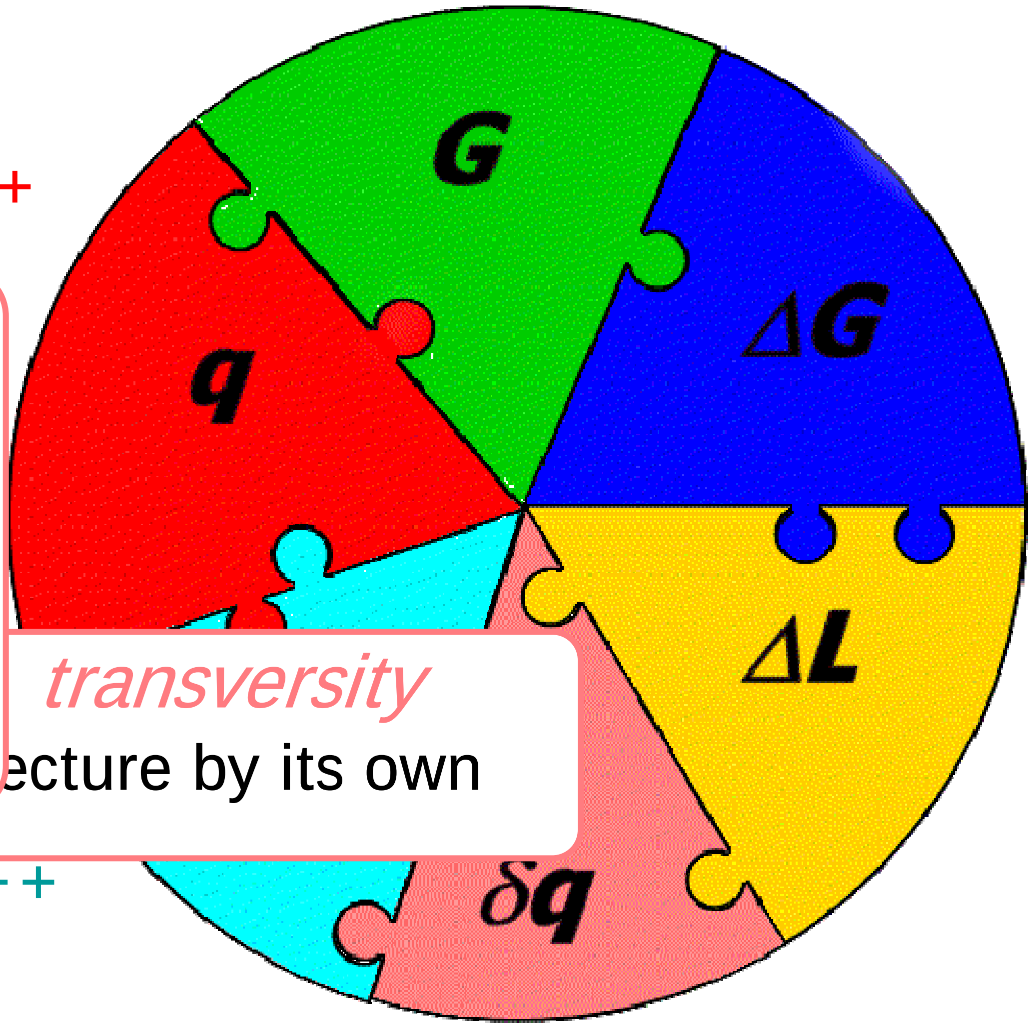
transversely polarized target





the nucleon puzzle is going to be completed

FAR



H1, ZEUS,++

→HERMES
→CERN
→RHIC
→JLab
→KEK
...ecc.

transversity
ecture by its own

HERMES, ++

HERMES:
first glimpse

→HERMES
→CERN
→RHIC
→SLAC

UPCOMING:
→HERMES
→JLab

Still fascinated by Spin ?

Thank you !