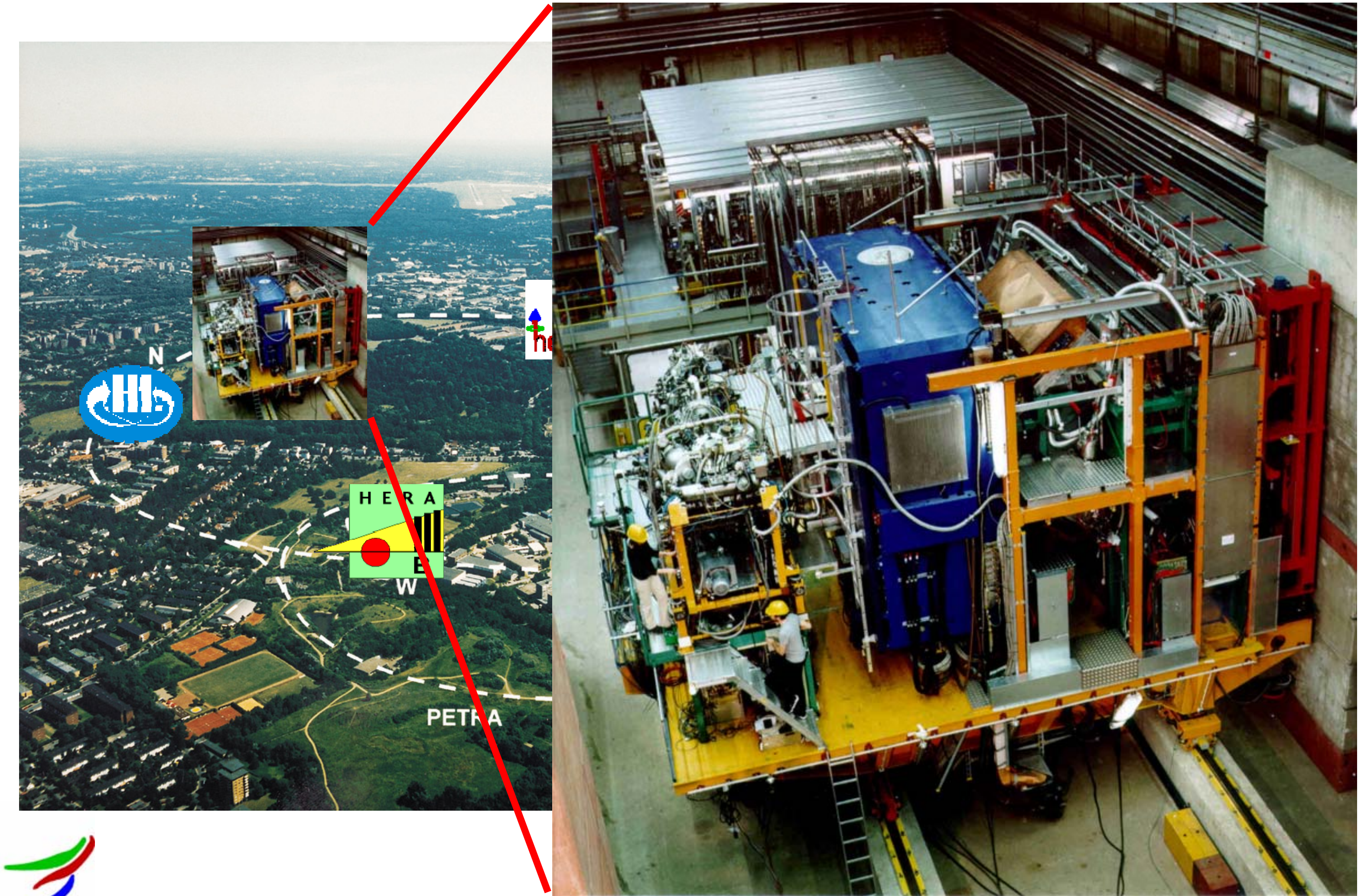
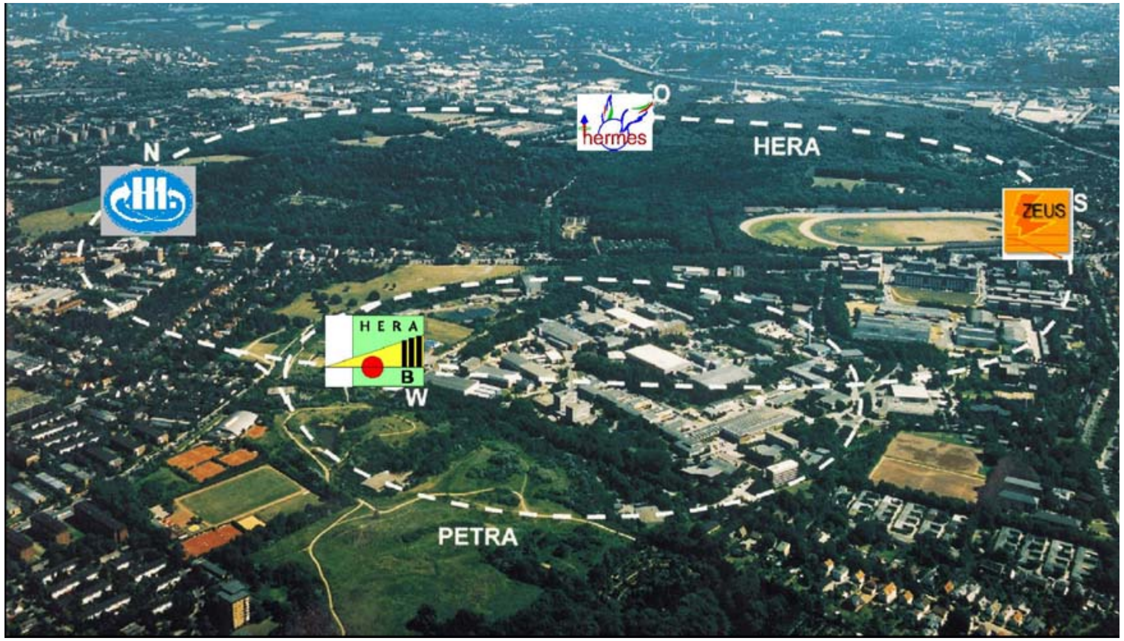
What is the HERMES Experiment?



Jim Stewart
DESY

HERa MEasurement of Spin

- Collaboration of 140 physicists
- 24 Institutions
- 12 Countries



Original goal:

Understand the spin structure of the nucleon

Present goal:

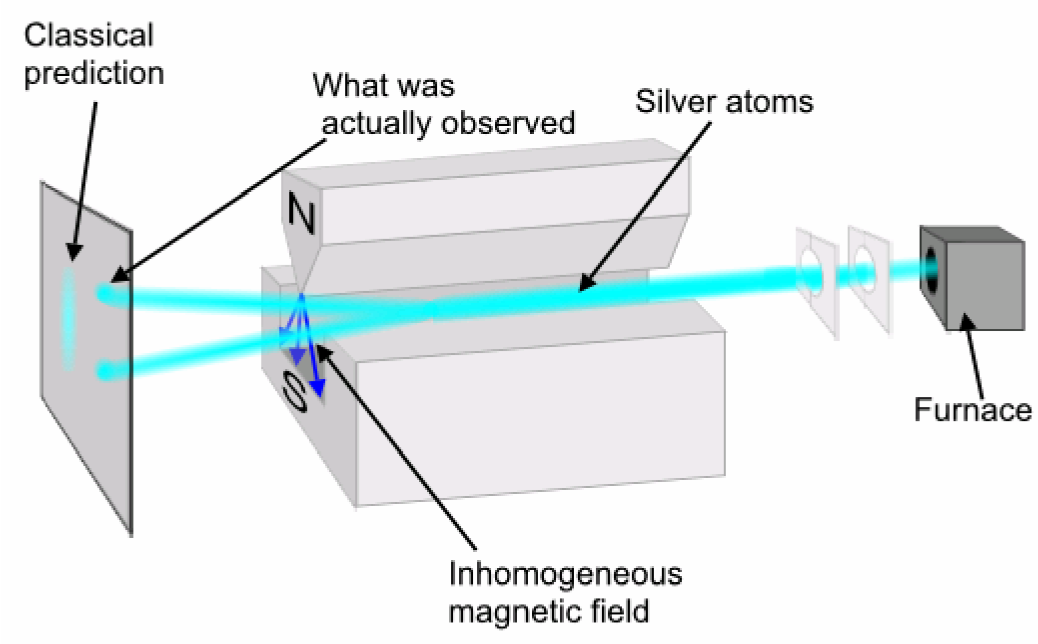
Understand the nucleon

OUTLINE

- Introduction to polarized DIS
  - → Also a bit of history
- The HERMES Detector
- The longitudinal spin Structure of the nucleon
- Going beyond the quark helicity

History of Spin

Stern-Gerlach Experiment 1922



Expectation from Classical Physics

$$F = \nabla\left(\vec{m} \bullet \vec{B}\right)$$

$$F = m_B \nabla B$$

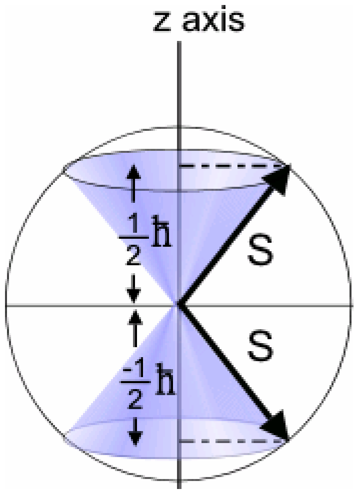
m magnetic moment vector

$\vec{B}$ the magnetic field

m_B the projection of m on B

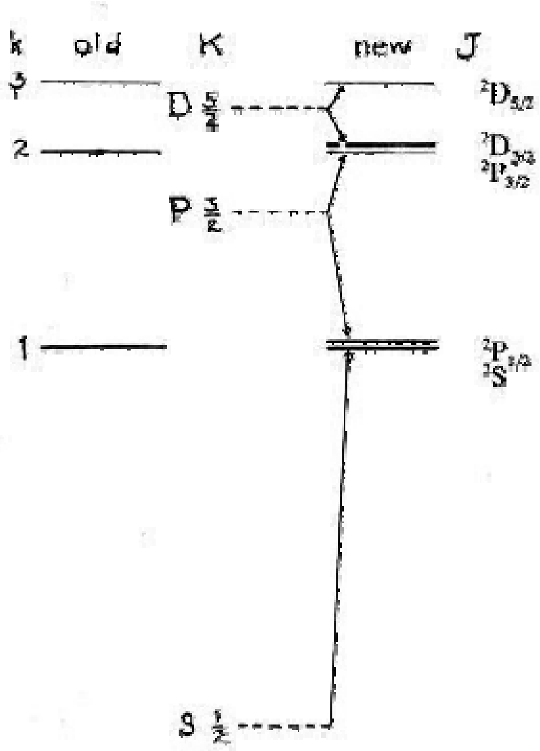
History of Spin

Uhlenbeck and Goudsmit 1926



$$M_s = \frac{g\mu_B}{\hbar} S$$

Uhlenbeck Kramers Goudsmit



The hydrogen spectrum

Is Spin Important?

Pauli principle …

Particle wavefunction is antisymmetric under interchange of identical particles.

Two particles cannot occupy the same quantum state.

- Half integer SPIN
  - → Obey Pauli principle
  - → Fermi-Dirac statistics
    - Fermions
- Integer SPIN
  - → Don’t care about Pauli principle
  - → 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/c^2	Electric charge
ν_e electron neutrino	<1×10^{-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/c^2	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/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

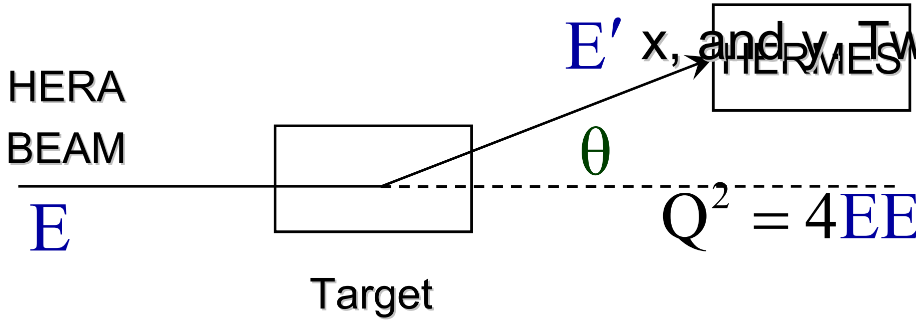
Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

E'

How to study the nucleon spin? Deep Inelastic Scattering

From E,E´,and θ three scaling variables can be computed Q^2, x, and y. Two are independent.



$$Q^2 = 4EE'\sin^2\left(\theta/2\right)$$

HERMES is a Fixed target experiment. The measured quantities in the lab system are E,E´,and θ.

$$x = \frac{Q^2}{2M\left(E - E'\right)} = \frac{Q^2}{2M\nu}$$

$$y = \left|E - E'\right| / E$$

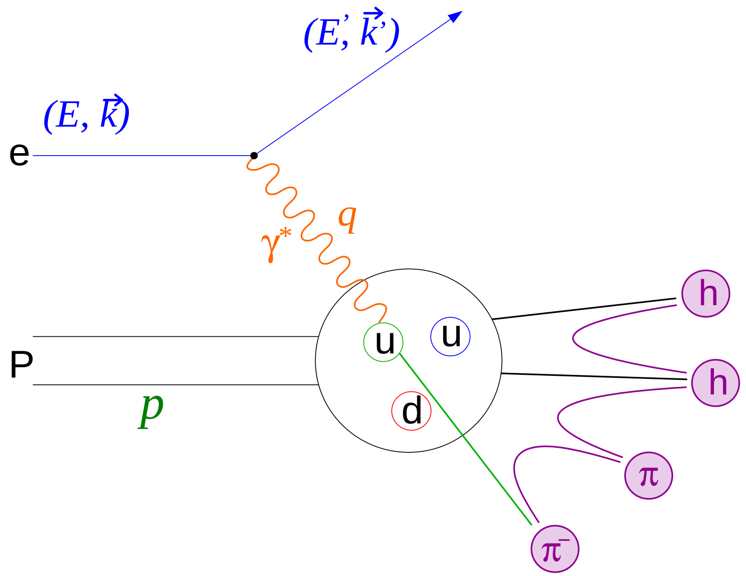
$$\text{with} \quad \nu \overset{\text{lab}}{=} E - E'$$

ν is the energy of the virtual photon in the lab frame

E'

Deep Inelastic Scattering

Quark Parton Model



$$Q^2 = -(k - k')^2 = -q^2$$

$$x = \frac{Q^2}{2\,p\bullet q} = \frac{Q^2}{2M\nu}$$

$$y = \frac{p\bullet q}{p\bullet k} = \nu/E$$

and

$$xy = Q^2/(s - M^2)$$

Q^2 is the squared 4-momentum of the virtual photon.

x The Bjorken scaling variable

- → The fraction of the total nucleon momentum carried by the struck quark.

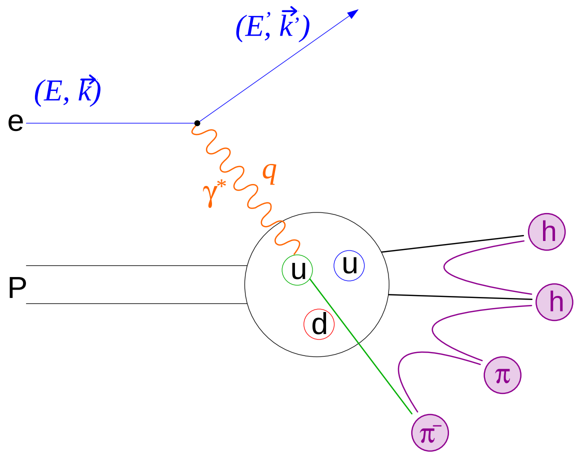
y The inelasticity

- → The fraction of the incoming momentum carried by the virtual photon.

➢ "Deep" ↔ high resolution: $Q^2 > 1 GeV^2$

➢ Inelastic ↔ $M^2_x \neq M^2$ implying $x<1$

DIS Cross Section



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

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2 E'}{2MQ^4 E} \underbrace{L_{\mu\nu}(k,q,s)}_{leptonic} \underbrace{W^{\mu\nu}(P,q,S)}_{hadronic}$$

$L_{\mu\nu}$ leptonic part of the cross section

- → Independent of the proton structure
- → Purely electromagnetic → Calculable in QED

$W^{\mu\nu}$ hadronic part of the cross section

- → Contains info on the proton structure
- → Not Calculable in QCD

Hadronic Tensor $W^{\mu\nu}$

hermes

- Parameterized by structure functions
  (Lorentz invariance, current conservation, parity, ect.)

QPM:

$$F_1 = \frac{1}{2}\sum_f e_f^2 \left(q_f^+(x) + q_f^-(x)\right) = \frac{1}{2}\sum_f e_f^2 q_f(x)$$

momentum distribution of quarks

$$W^{\mu\nu} = -g^{\mu\nu} \quad + \frac{p\ p}{\nu}$$

Symetric part → Spin independent

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

$q_f^+(x)$ = Polarized Distribution Function connected to the probability to have a struck quark with th e fraction x of the nucleon momentum a ***nd spin in the same direction as the nucle on***.

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

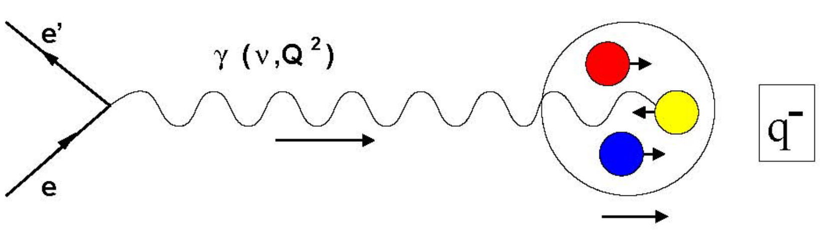
helicity distribution of quarks

$$\Delta q_f(x) = \vec{q}_f(x) - \overleftarrow{q}_f(x)$$

$$(f : u, d, s, \bar{u}, \bar{d}, \bar{s})$$

DESY

Why do polarized leptons measure quark helicity distributions?
Look at the virtual photon cross section.



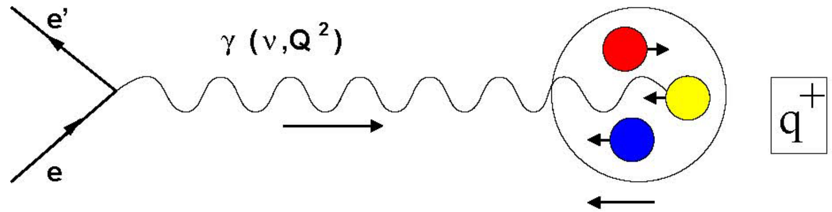
Photon and nucleon spins aligned

$$S_\gamma + S_N = 1 + 1/2 = 3/2$$

$$\sigma_{3/2}$$

$$S_N = -S_q$$

$$\sigma_{3/2} \sim q^-(x)$$



Photon and nucleon spins anti-aligned

$$S_\gamma + S_N = 1/2$$

$$\sigma_{1/2}$$

$$S_N = S_q$$

$$\sigma_{1/2} \sim q^+(x)$$

- Virtual photon can only couple to quarks of opposite helicity
- Select quark helicity by changing target polarization direction
- Different targets give sensitivity to different quark flavors

Cross section Asymmetries

$\sigma_{1/2}$ and $\sigma_{3/2}$ are roughly the same size so you cannot measure both separately and subtract the results. What you measure is the ratio of sums and differences of cross sections called asymmetries.

$$A_{\|} = \frac{\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}}}{\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}}}$$

- Both beam and target helicities are reversed as often as possible.
  - Changes to the beam, target, and detector on time scales longer than the flipping time cancel!
- Enables measuring the effect of very small cross section differences.
  - HERMES few percent
  - CP violation 10^{-6}
- As the cross section differences are small large statistics are needed.

Structure Functions and Measured Asymmetries

$$A_{\parallel} = \frac{\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}}}{\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}}} \qquad A_{\perp} = \frac{\sigma^{\uparrow\rightarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\uparrow\rightarrow} + \sigma^{\uparrow\leftarrow}}$$

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

$D, d, R, \gamma, \xi, \eta$

kinematic factors

Virtual Photon Asymmetries

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1} \qquad A_2 = \sigma_{\frac{TL}{T}} = \frac{\gamma(g_1 + g_2)}{F_1}$$

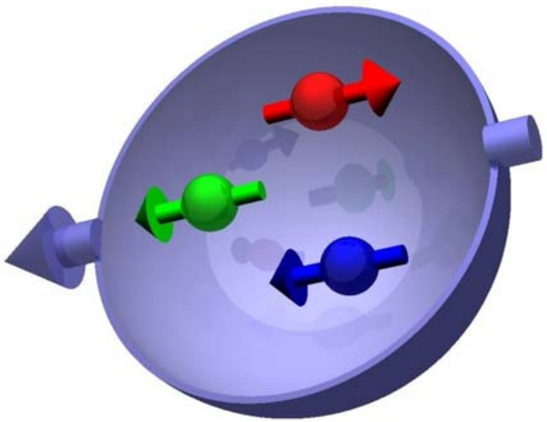
$$F_1 = \frac{1}{2}\sum_f e_f^2\left(q_f^+(x) + q_f^-(x)\right) = \frac{1}{2}\sum_f e_f^2 q_f(x)$$

Momentum distribution of the Quarks

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

Helicity distribution of the Quarks

The spin structure of the nucleon



Constituent quark model

$$\Delta u_v = \tfrac{4}{3} \qquad \Delta d_v = -\tfrac{1}{3}$$

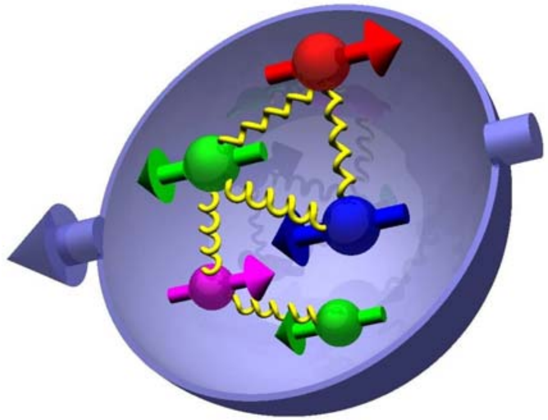
Include relativistic wavefunction

$$\Delta\Sigma \approx 0.75$$

BUT

1989 EMC measured
Σ = 0.120±0.094±0.138

⟹ Spin Puzzle



Unpolarised structure fct.

$$\Delta\Sigma = 1$$

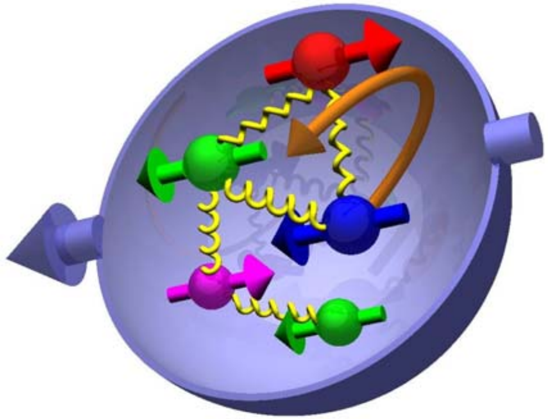
$$\frac{1}{2} = \frac{1}{2}(\underbrace{\Delta u_v + \Delta d_v}_{\Delta\Sigma})$$

Gluons are important !

⟹ ΔG

⟹ Sea quarks Δq_s

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta q_s) + \Delta G$$



Full description of J_q and J_g needs orbital angular momentum

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

$$(\Delta u_s + \Delta d_s + \Delta \bar{u} + \Delta \bar{d} + \Delta s + \Delta \bar{s})$$

The HERMES Experiment

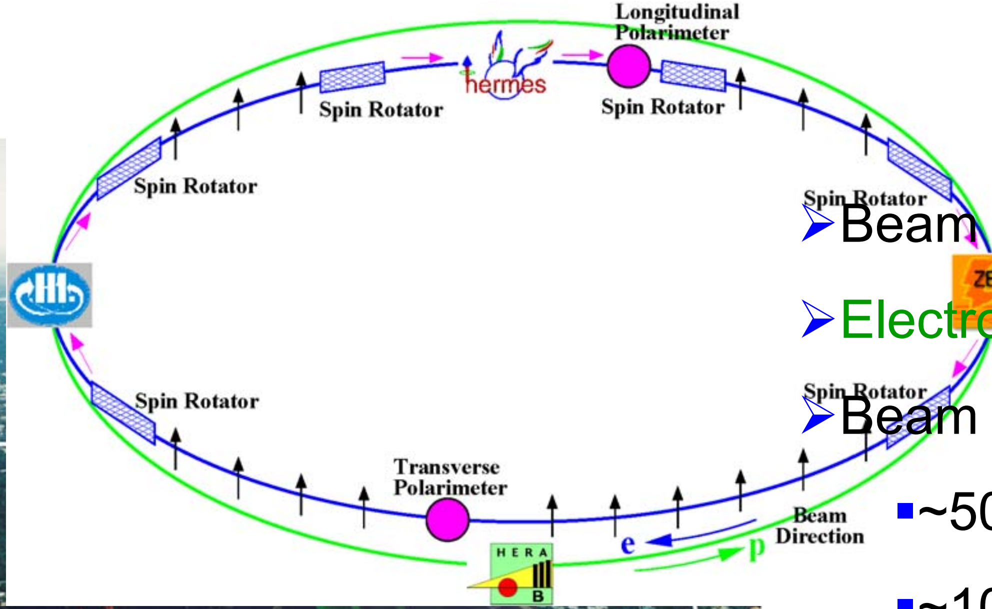
Necessary ingredients

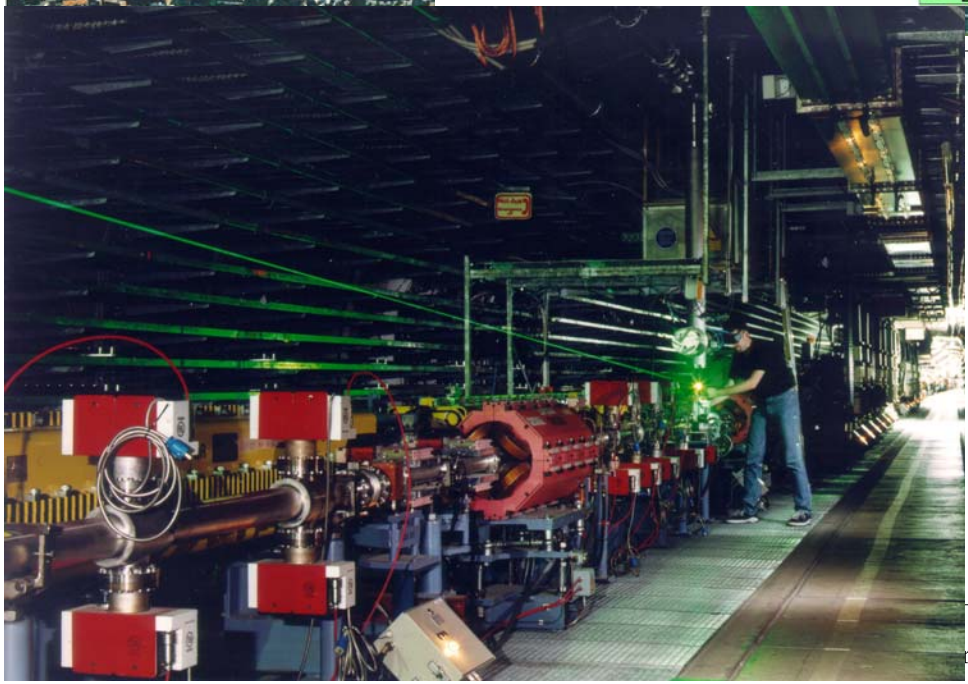
- Polarized beam
- Polarized target
- Particle identification
  - → Lepton hadron separation
- Large acceptance spectrometer

Additional capabilities

- Hadron identification
- Acceptance at large angles
- Unpolarized heavy targets

Hermes at HERA



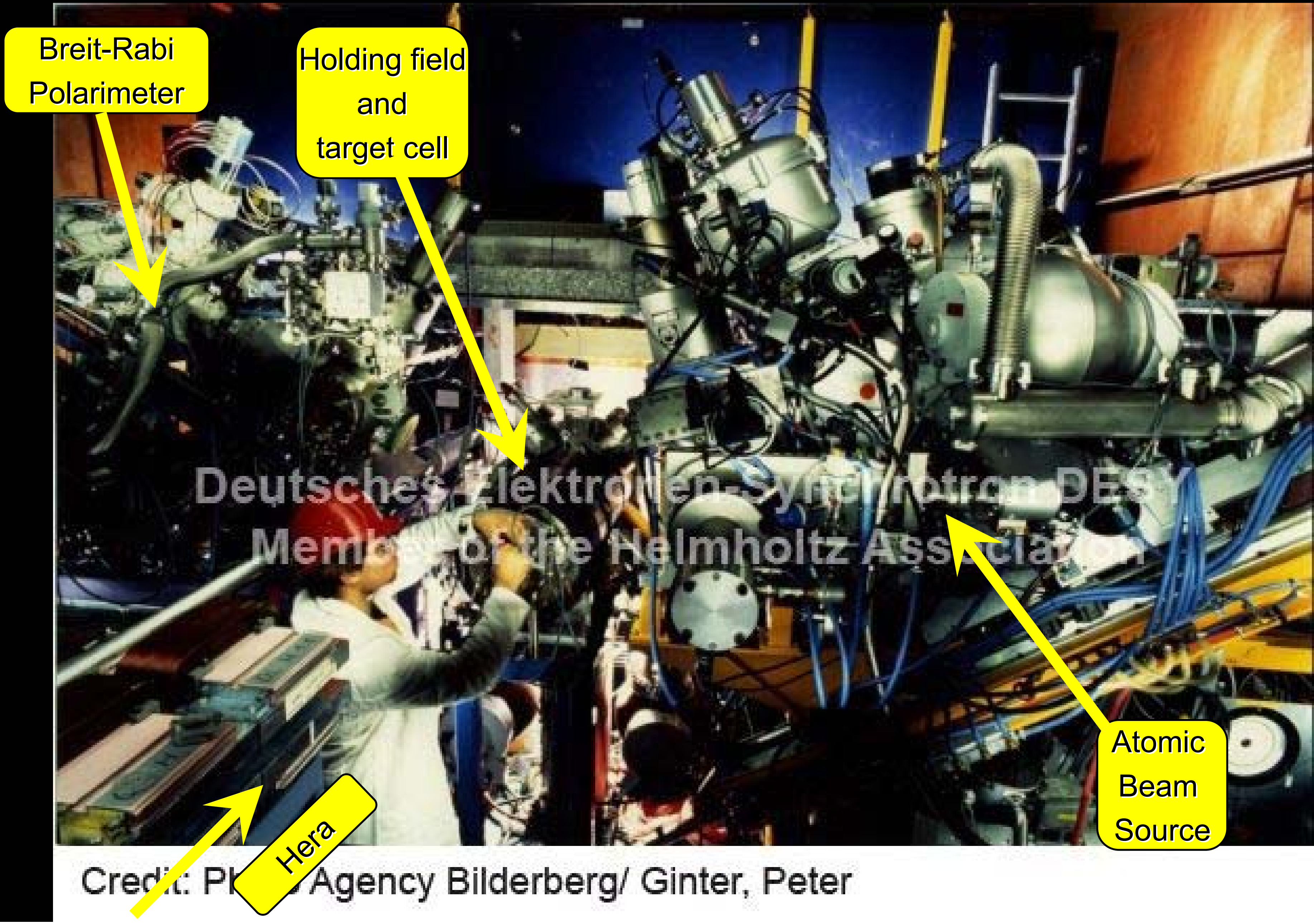


- Beam Energy: 27.5 GeV
- Electrons and positrons
- Beam current
  - ~50mA start of fill
  - ~10mA end of fill
- Polarized (<P>~53%)
  - P~45% 2007
- Beam helicity reversable
  - Can be set at each expt.

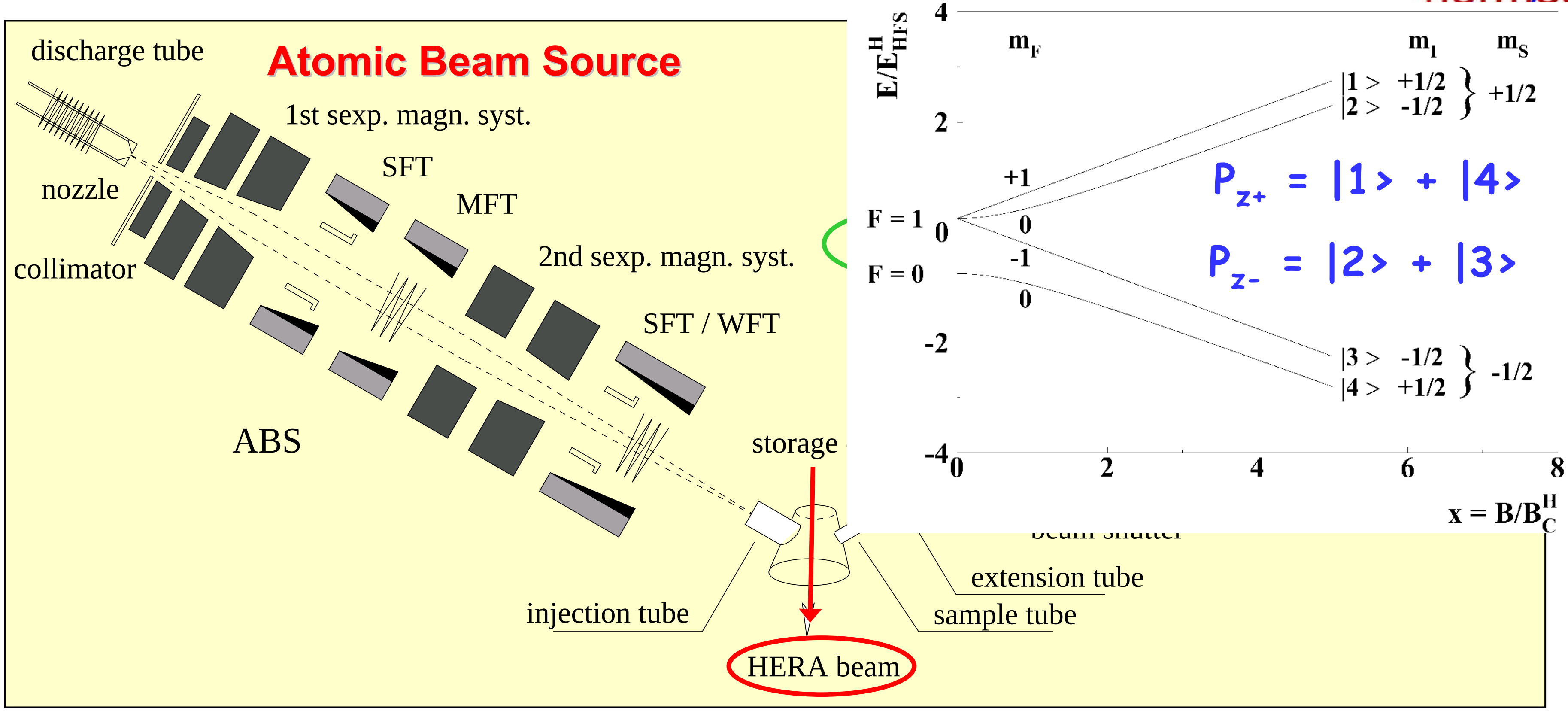
Online measurement of beam polarization with two Compton polarimeters.

$$\frac{\Delta P_B}{P_B} = 1.8 - 3.4\%$$

The Polarized Target



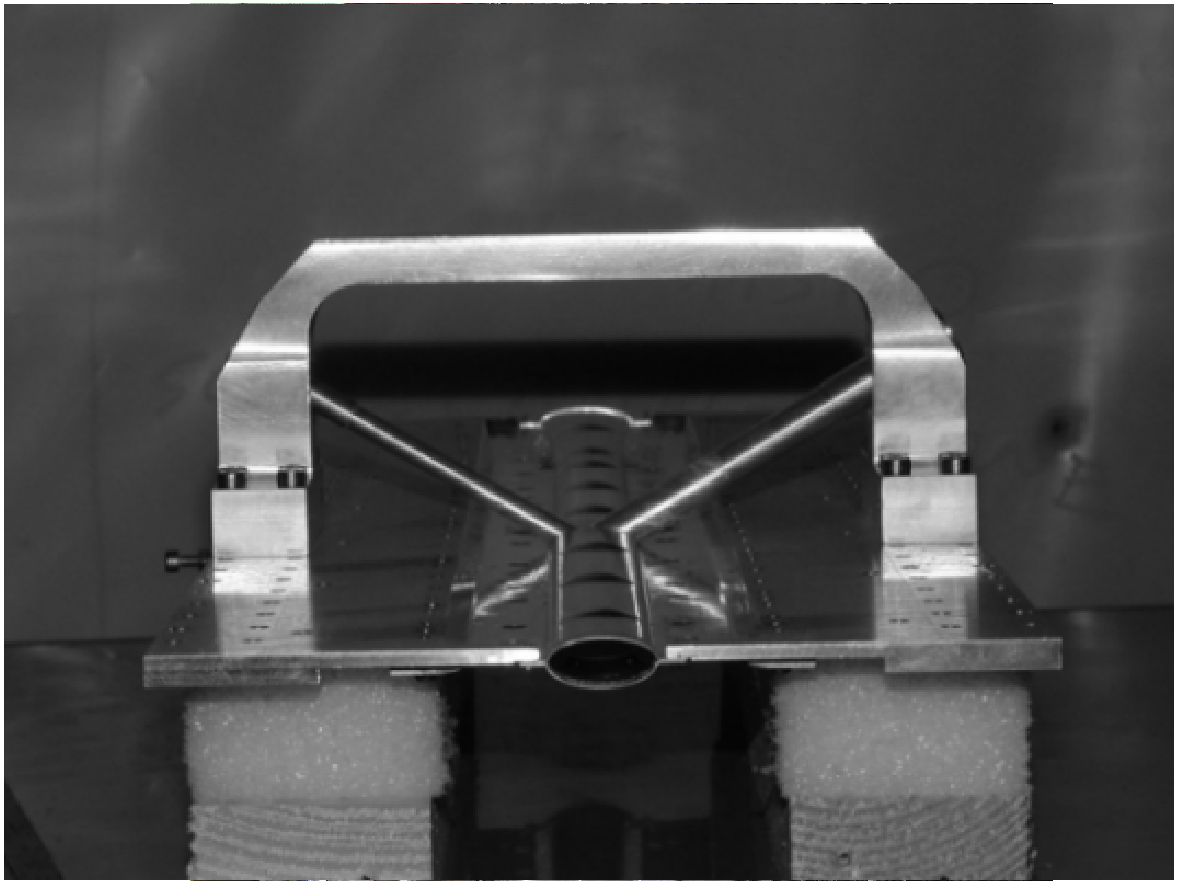
The HERMES polarised gas target



ADVANTAGES:

- no dilution; all the material is polarised
- no radiation damage
- rapid inversion of polarisation direction every 90s in less than 0.5s

The HERMES target cell



- **Material:** 75μm Al with Drifilm coating + ice
- **Size:** length 40cm, elliptical cross section (21mm x 8.9 mm)
- **Working temperature:** 100K (variable 35k – 300K)
- **Increase of density to free jet ~100 (3 – 5*10^{31} nucl/cm^2/s)**

Target Performance

Longitudinal Polarization:

1996-1997 Hydrogen $|P_T|$ = 85% ρ**=7.6 x 10^{13} nucl./cm^2**

1999-2000 Deuterium $|P_T|$ = 85 %

Transverse Polarization:

2002-2005 Hydrogen $|P_T|$ = 0.75%

$$P_T = \alpha_0 \alpha_r P_a + \alpha_0 (1 - \alpha_r) P_m$$

P_T = total target polarization

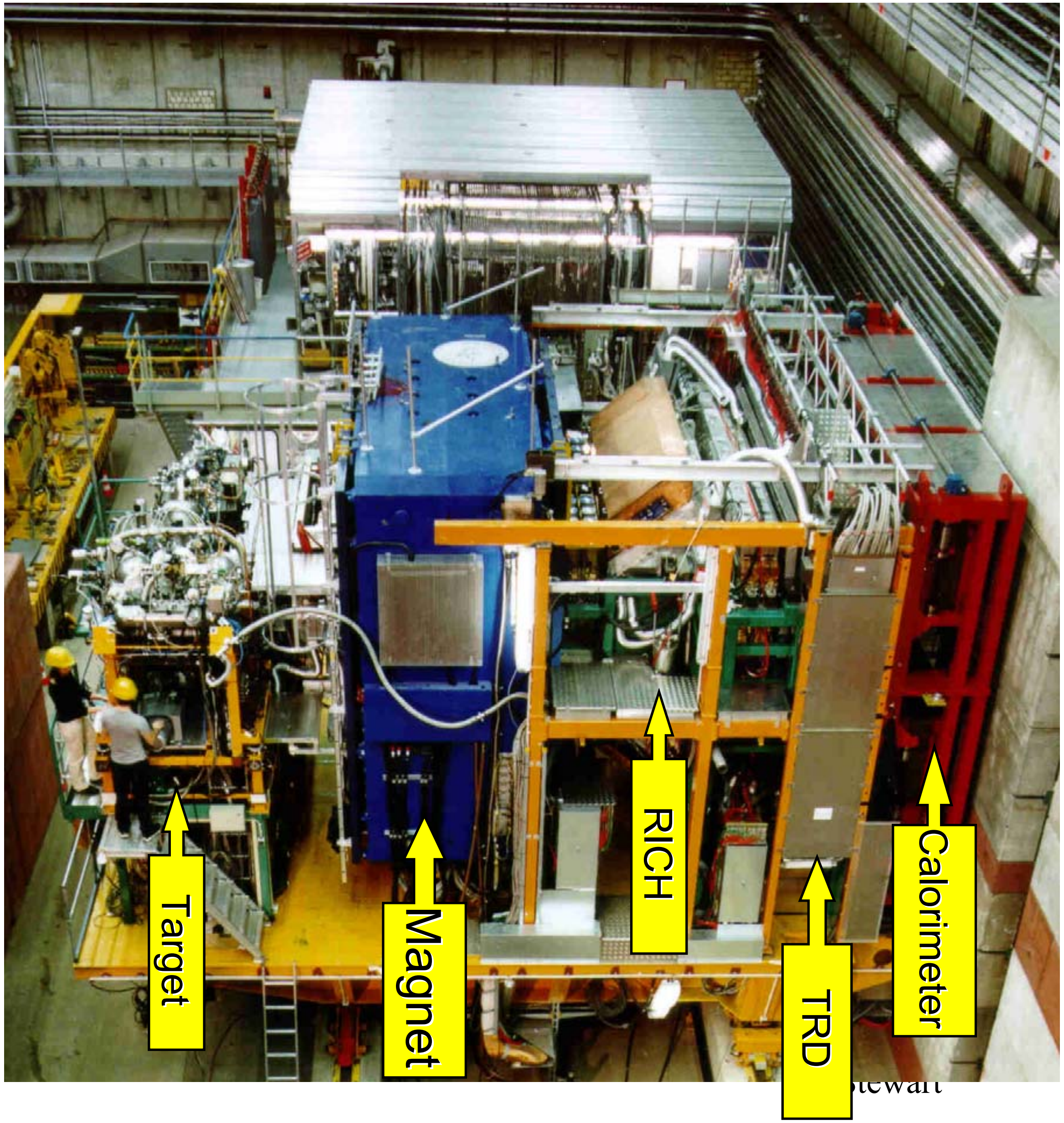
- **α_0 = atomic fraction in absence of recombination**
- **α_r = atomic fraction surviving recombination**

P_a = polarization of atoms

P_m = polarization of recombined molecules

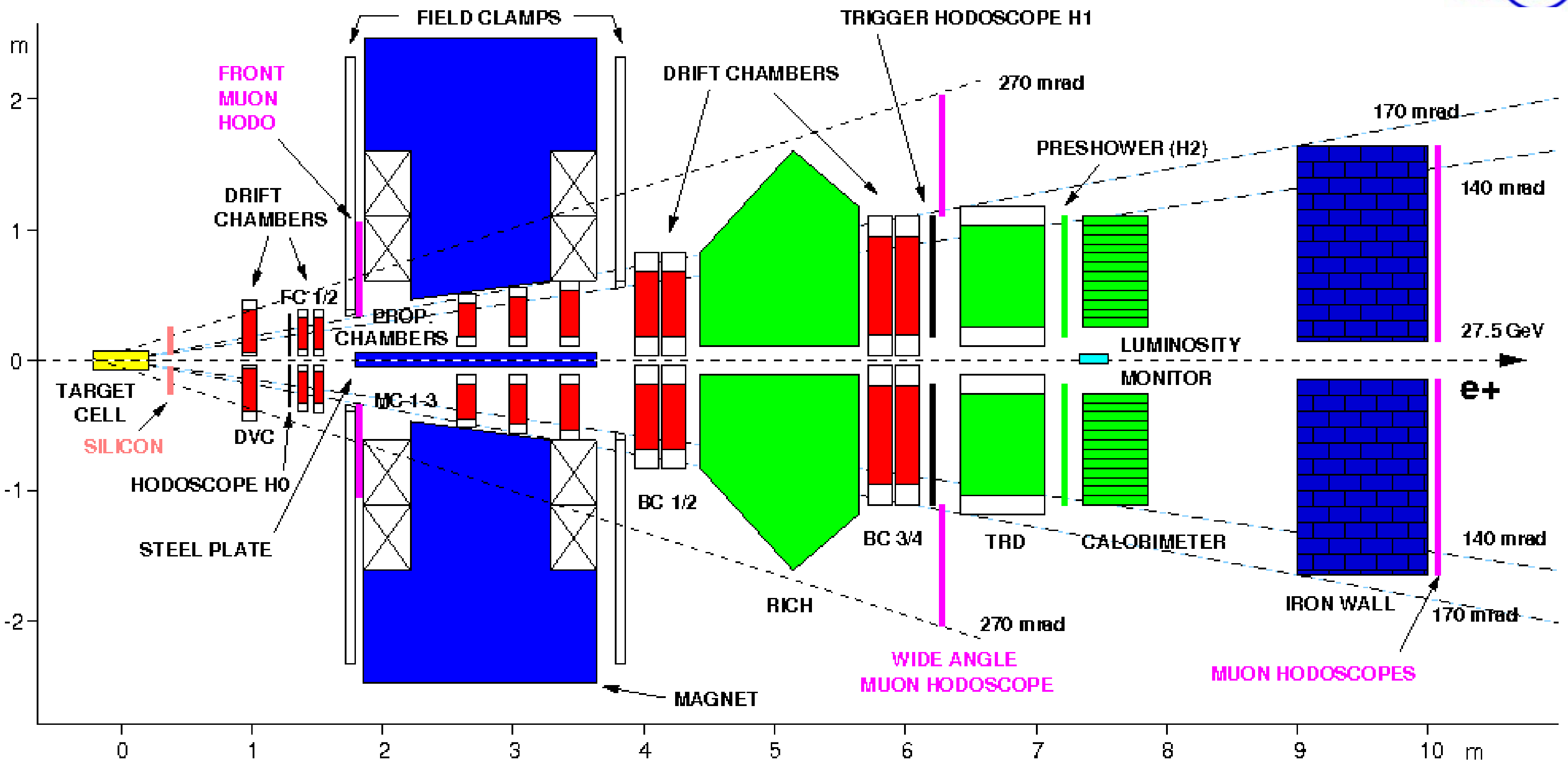
- Unpolarized Gases:
  - →H^2,D^2,He,N2,Ne,Xe

The HERMES Spectrometer



- Magnetic spectrometer for momentum measurement.
- Electromagnetic calorimeter for energy measurement and photon detection.
- Relatively large acceptance.
- Excellent particle identification.

The HERMES Spectrometer



Magnetic Spectrometer:

- ➢Top-Bottom symmetric
- ➢1.5T·m dipole field, 0.5MW
- ➢7 drift chambers, 6 planes each for tracking
- ➢Large acceptance

Kinematic Range : $0.02 \le x \le 0.8$ at $Q^2 \ge 1\text{GeV}^2$ and $W \ge 2\text{GeV}$

$\Theta_x \le 175\,\text{mrad}$, $40\,\text{mrad} \le \Theta_y \le 140\,\text{mrad}$

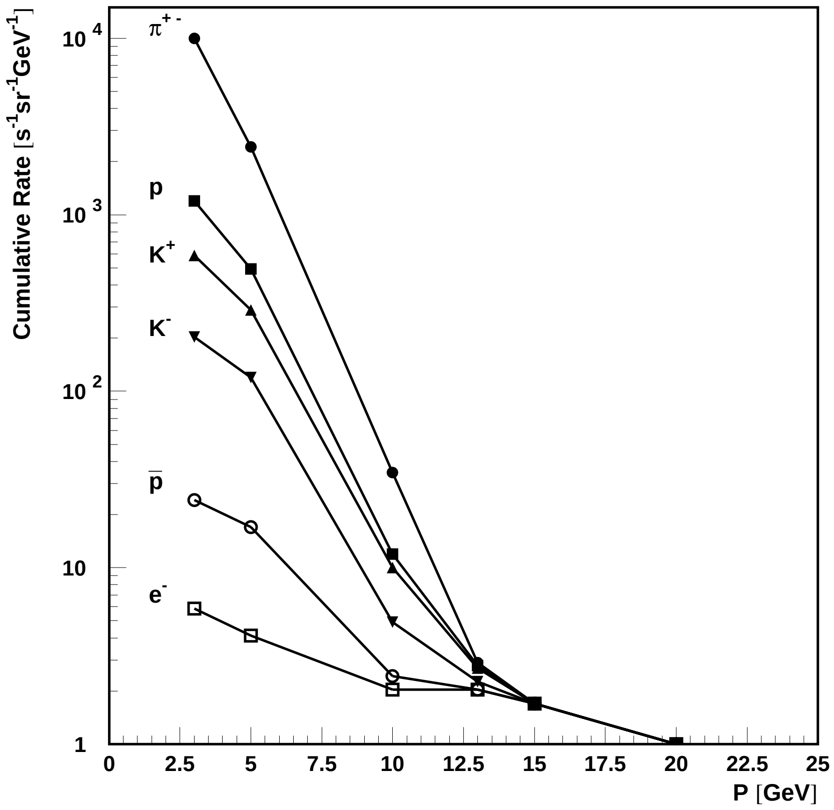
Reconstruction : $\frac{\delta p}{p} = 1.0\text{-}2.0\%$ $\delta\Theta \le 1.0\,\text{mrad}$

Particle Identification: TRD, Preshower, Calorimeter

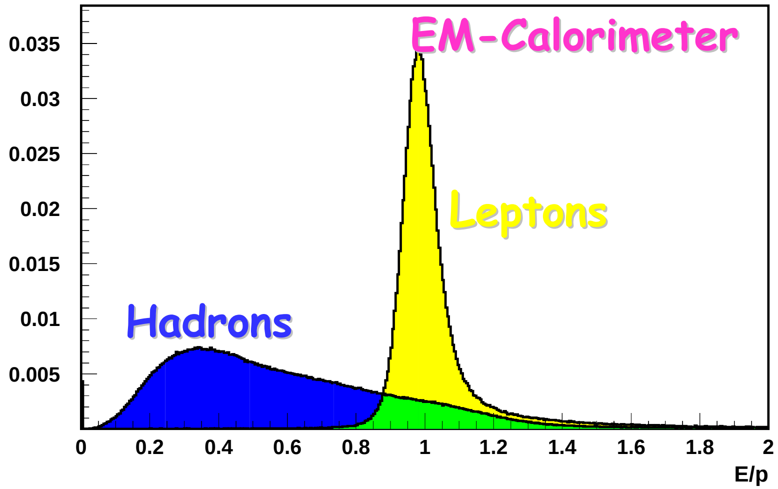
1997: Threshold Cherenkov, 1998: RICH + Muon-ID

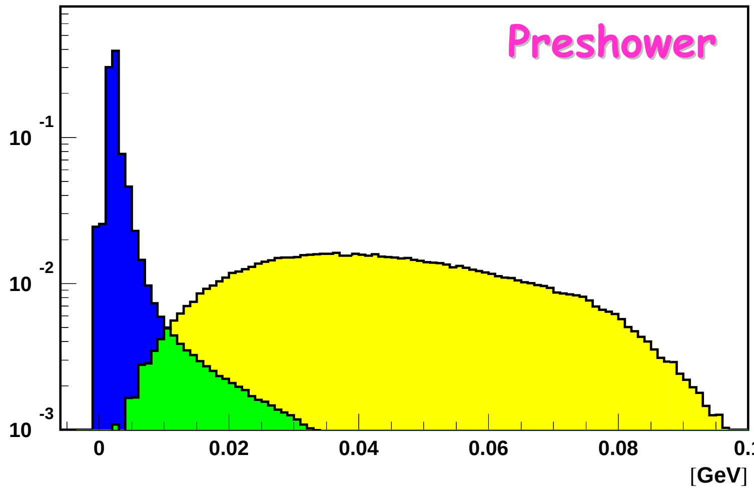
Which Particle is Which

Physics requirement: Need lepton hadron separation over wide momentum range



In worst case factor 10^5 hadron suppression is needed



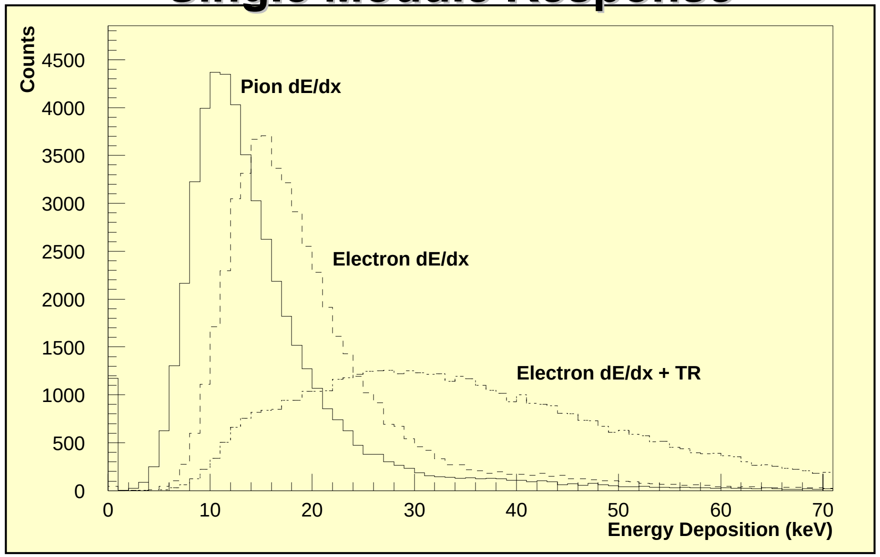


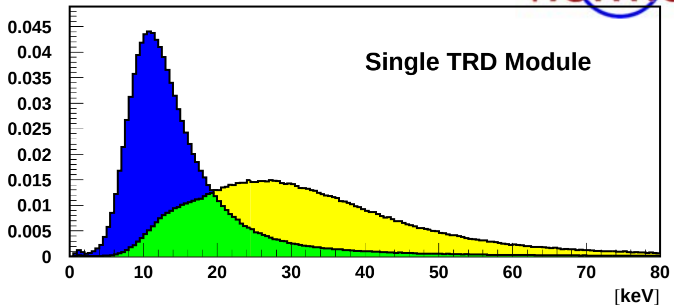
combined suppression 10^3
Factor 100 still needed

J Stewart

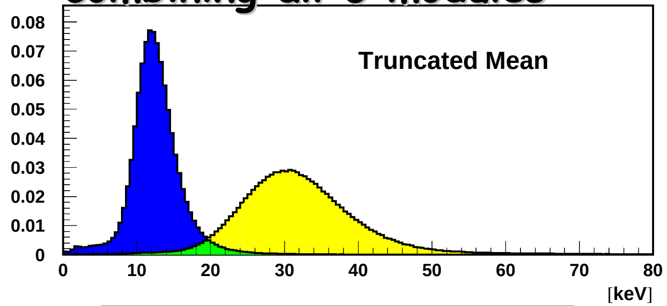
The HERMES TRD

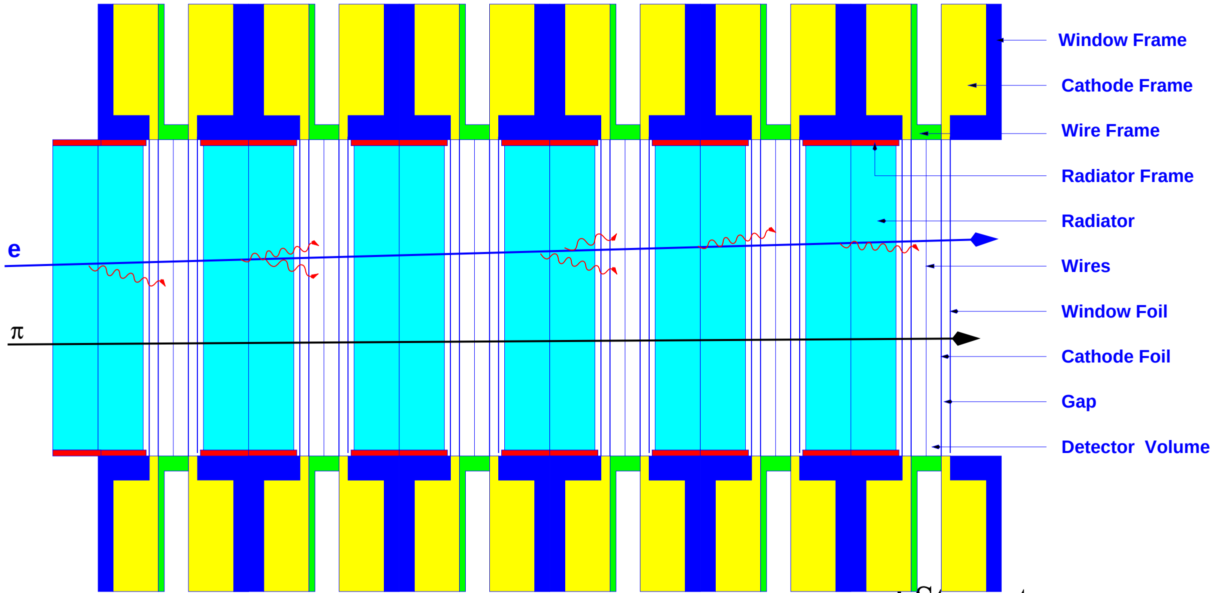
Single Module Response



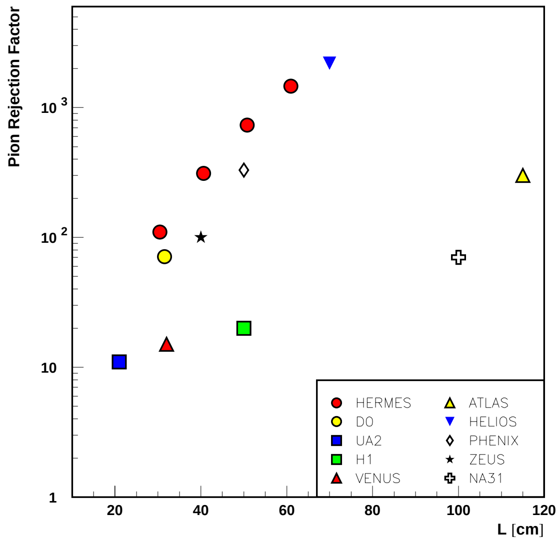


combining all 6 modules





J Stewart

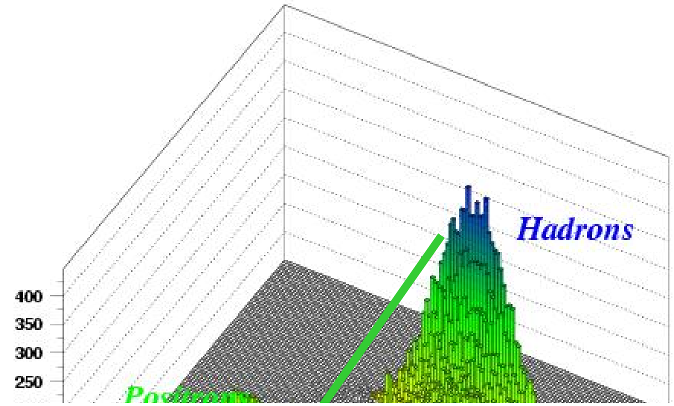


Which Hadron (π,K,p) is Which

hadron/positron separation

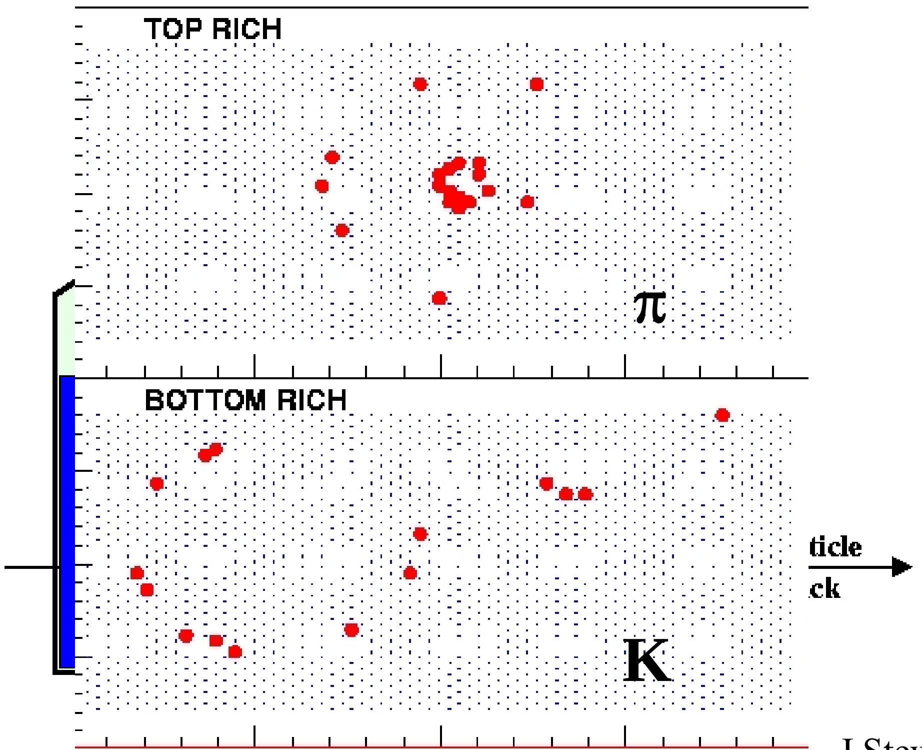
combining signals from:

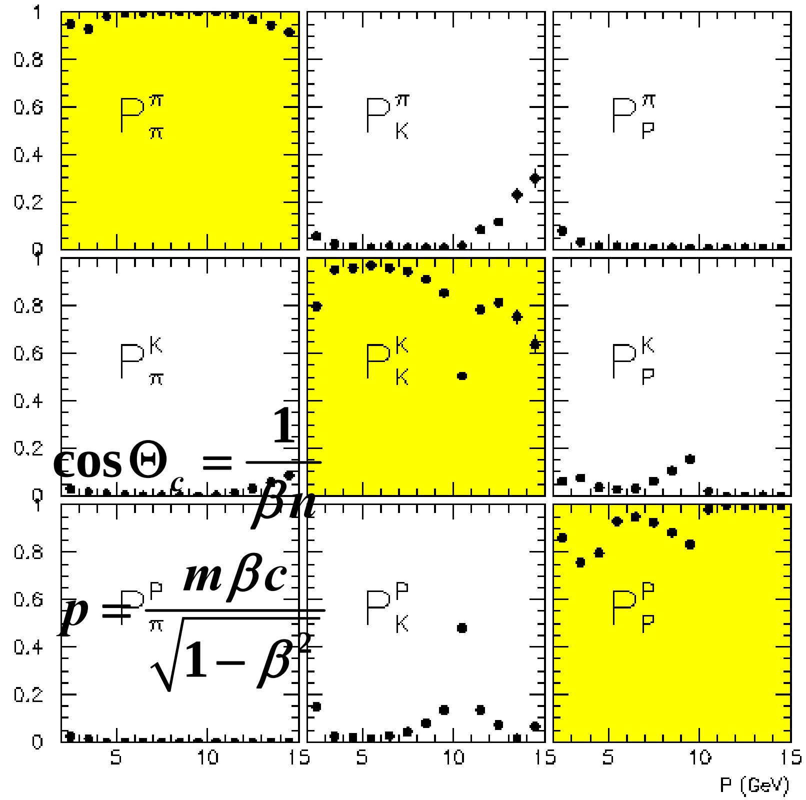
TRD, calorimeter, preshower



hadron separation

Dual radiator RICH for π, K, p



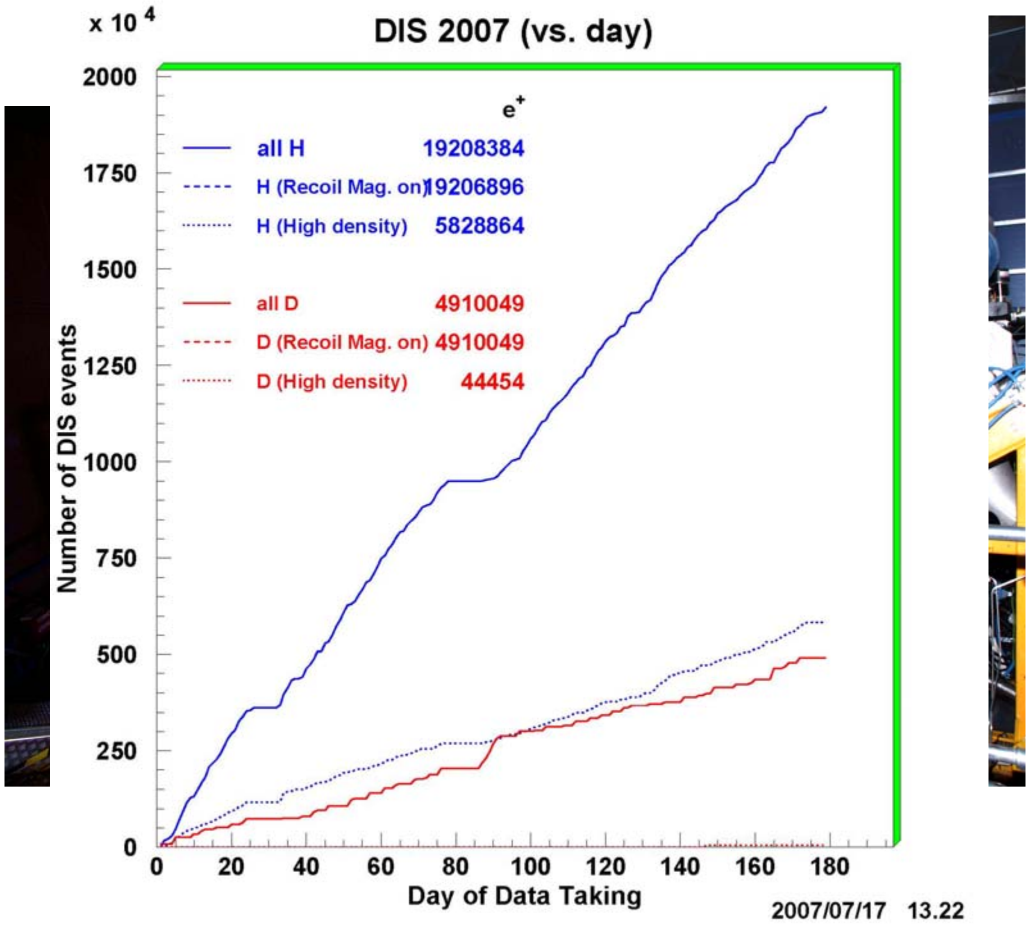


$$\cos\Theta_c = \frac{1}{\beta n}$$

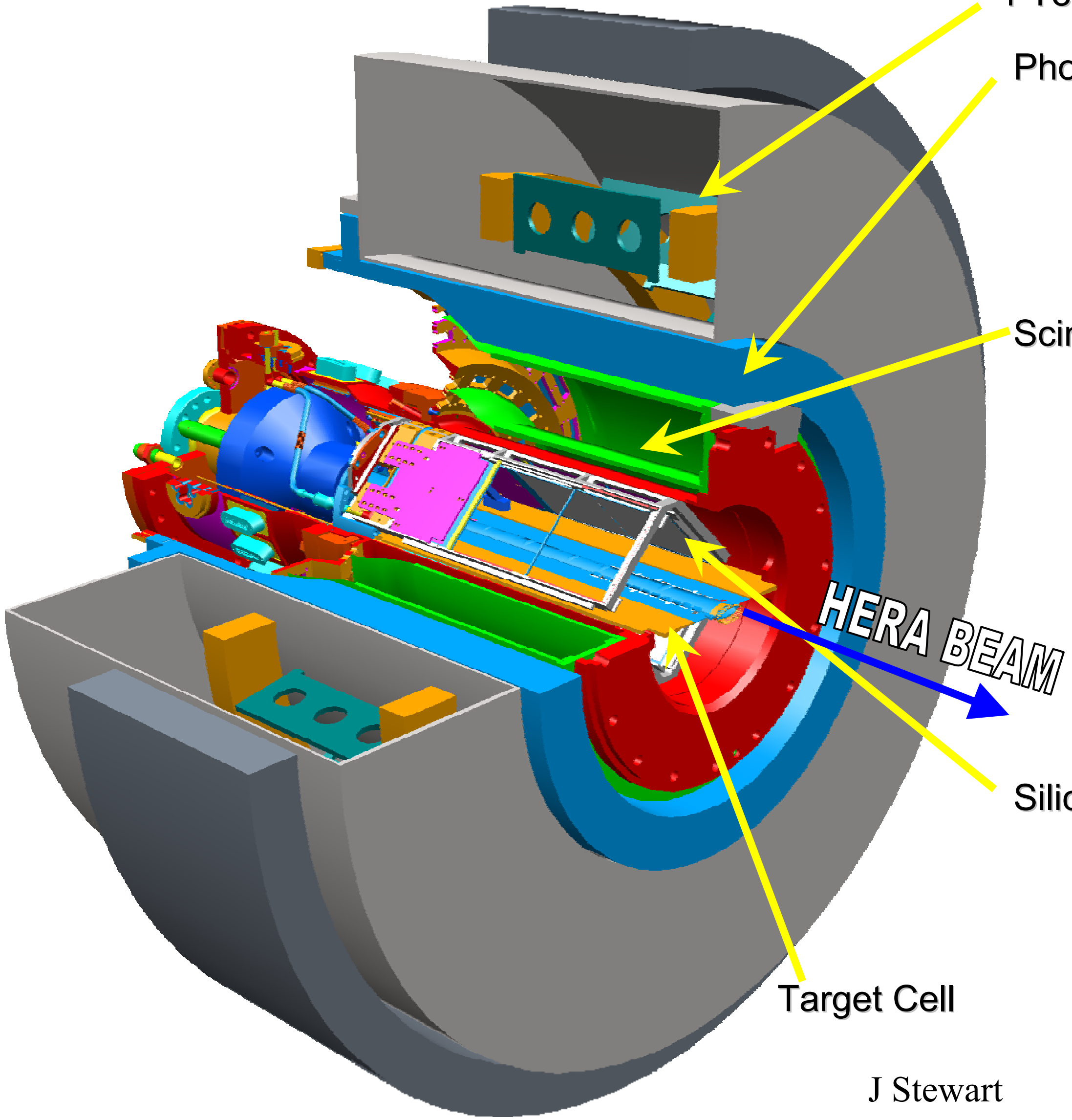
$$p = \frac{m\beta c}{\sqrt{1-\beta^2}}$$

HERMES Recoil Detector timeline

- From 1996 through 2005 HERMES ran with the polarized H/D target.
  - → November 2005 the ABS was removed.
- In January 2006 the recoil detector was installed.
- February started data taking.
  - → Scintillating fiber detector worked immediately.
- Full detector operations since September 2006.
  - → 20M DIS in 2007
  - → 20M DIS in 2006
    - Recoil only for part of data.



Recoil Detector Overview



J Stewart

1 Tesla Superconducting Solenoid

Photon Detector

- 3 layers of Tungsten/Scintillator
- PID for higher momentum
- detects $\Delta^+ \rightarrow p\pi^0$

Scintillating Fiber Detector

- 2 Barrels
- 2 Parallel- and 2 Stereo-Layers in each barrel
- 10° Stereo Angle
- Momentum reconstruction & PID

Silicon Detector

- 16 double-sides sensors
- 10×10 cm^2 active area each
- 2 layers
- Inside HERA vacuum
- momentum reconstruction & PID

Back to inclusive physics

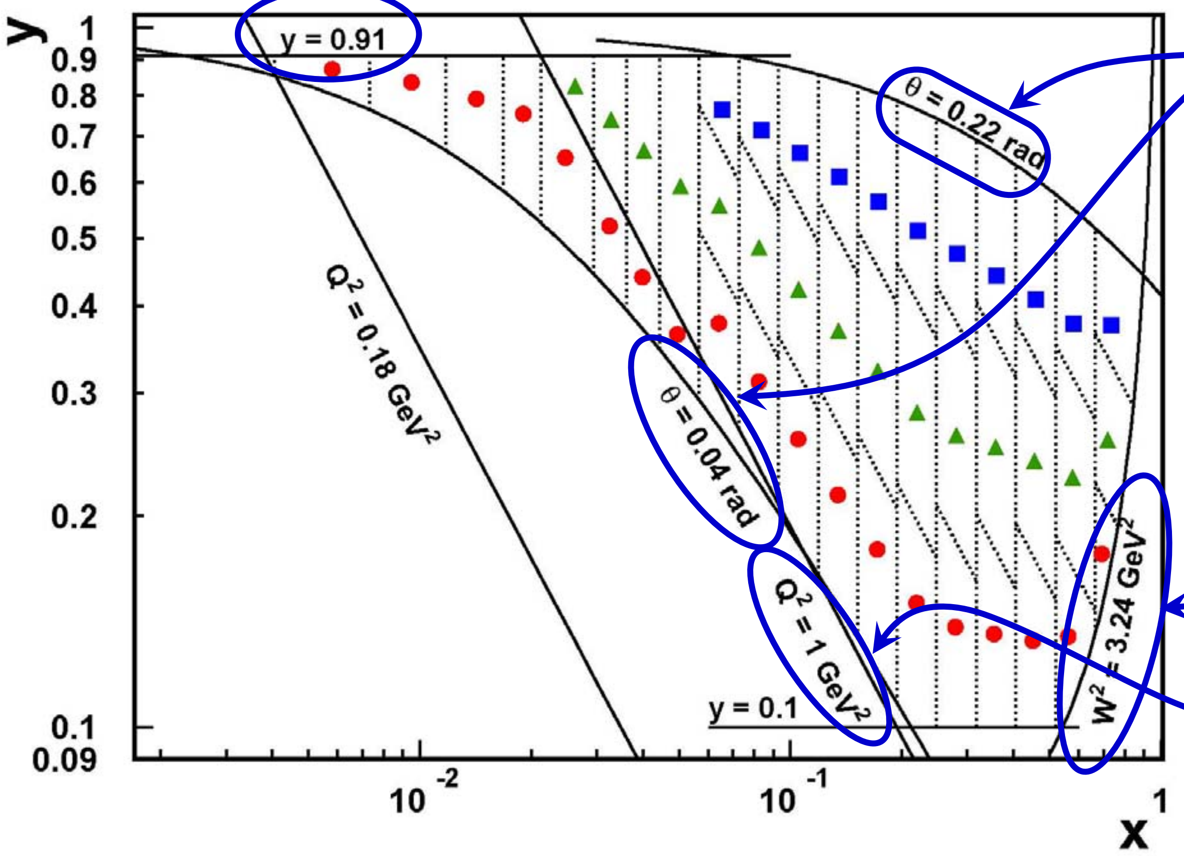
Measuring g_1

How to measure cross section asymmetries

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

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

Cut: because of radiative corrections



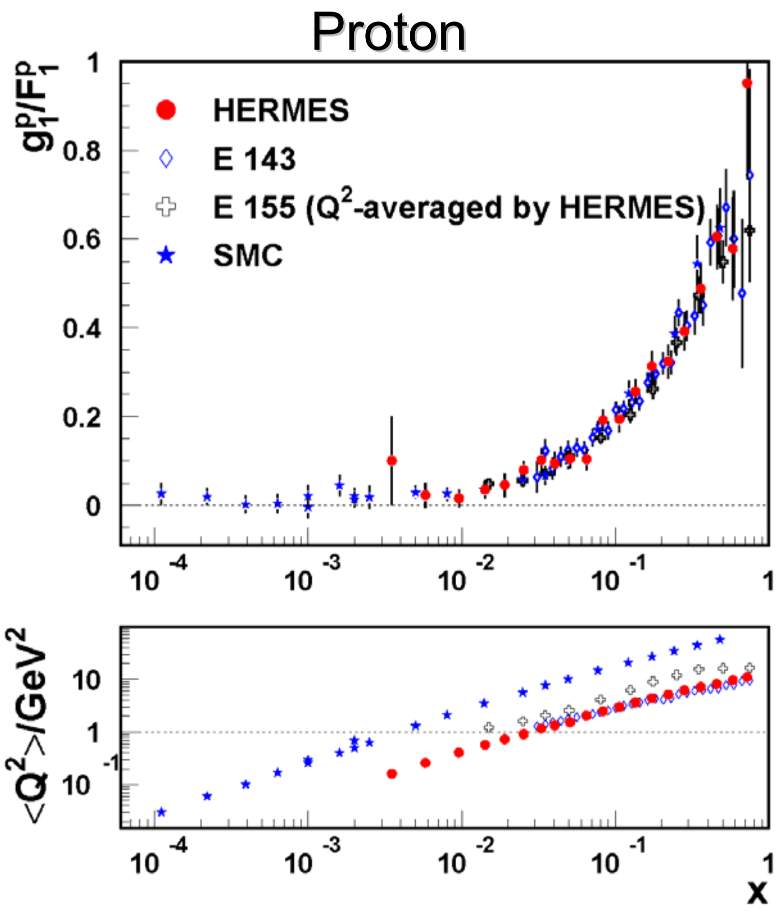
Spectrometer acceptance

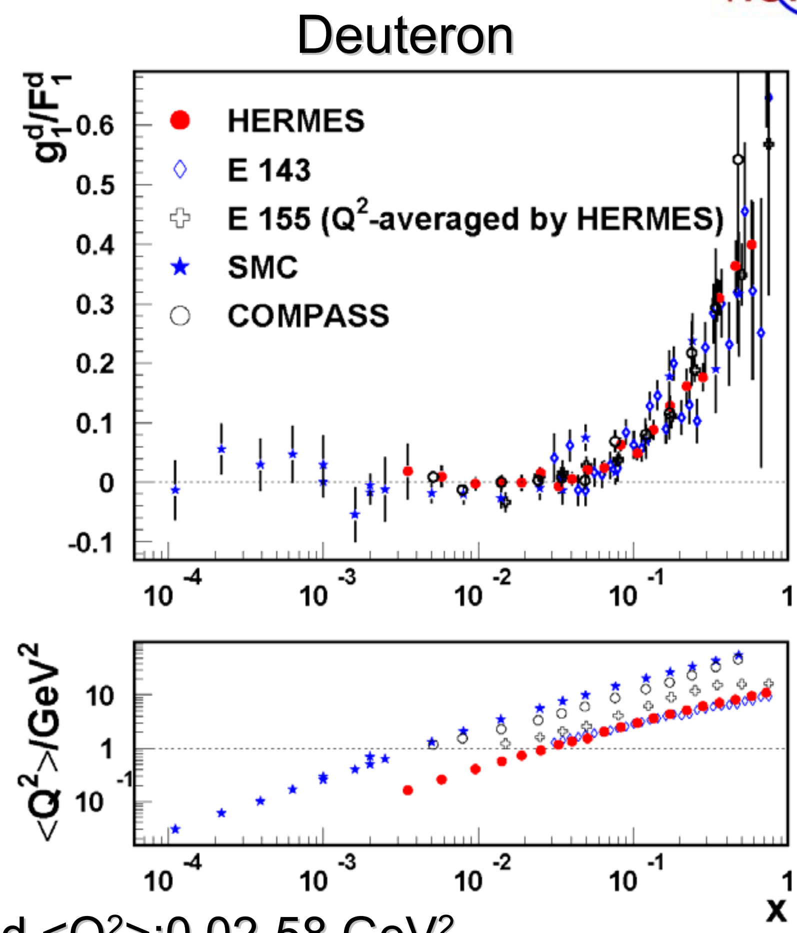
$$A_{\parallel} = \frac{1}{P_b P_t} \frac{N^{\stackrel{\rightarrow}{\Leftarrow}} L^{\stackrel{\rightarrow}{\Rightarrow}} - N^{\stackrel{\rightarrow}{\Rightarrow}} L^{\stackrel{\rightarrow}{\Leftarrow}}}{N^{\stackrel{\rightarrow}{\Leftarrow}} L^{\stackrel{\rightarrow}{\Rightarrow}} - N^{\stackrel{\rightarrow}{\Rightarrow}} L^{\stackrel{\rightarrow}{\Leftarrow}}}$$

Cut: exclude resonance region

Resolve quark structure

World Data on g_1/F_1





Data shown at measured $\langle Q^2\rangle$:0.02-58 GeV^2

$$A_{\parallel} = \frac{1}{P_b P_t}\,\frac{N^{\overset{\rightarrow}{\Leftarrow}} L^{\overset{\rightarrow}{\Rightarrow}} - N^{\overset{\rightarrow}{\Rightarrow}} L^{\overset{\rightarrow}{\Leftarrow}}}{N^{\overset{\rightarrow}{\Leftarrow}} L^{\overset{\rightarrow}{\Rightarrow}} - N^{\overset{\rightarrow}{\Rightarrow}} L^{\overset{\rightarrow}{\Leftarrow}}}$$

$$\frac{g_1}{F_1} = \frac{1}{1+\gamma^2}\left[\frac{A_{\parallel}}{D} + (\gamma+\eta)A_2\right]$$

Model-independent unfolding

- detector smearing
- QED radiative effects

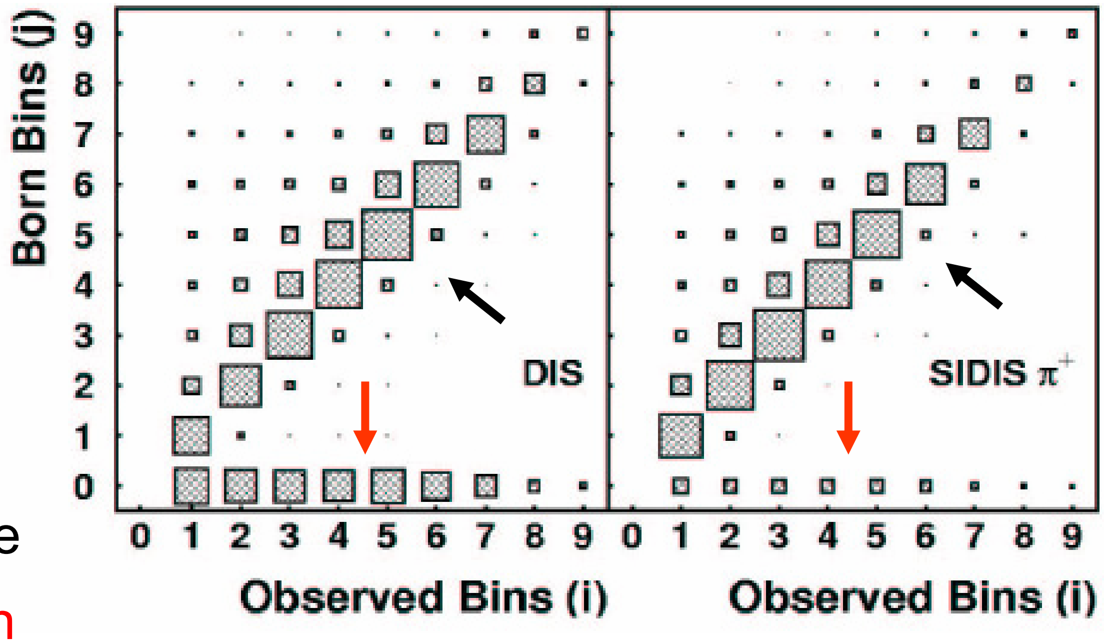
$$S_{ij} = \frac{\partial\sigma^{\text{meas}}}{\partial\sigma^{\text{born}}} = \frac{\partial N^{\text{meas}}}{\partial N^{\text{born}}}$$

$$= \frac{N(i, j)_{\overset{\rightarrow}{\Leftarrow}(\overset{\rightarrow}{\Rightarrow})}}{N^{\text{born}}(j)_{\overset{\rightarrow}{\Leftarrow}(\overset{\rightarrow}{\Rightarrow})}}$$

- kinematic migration inside acceptance for each spin state

- j=0 bin: kinematic migration *into* the acceptance

smearing within acceptance

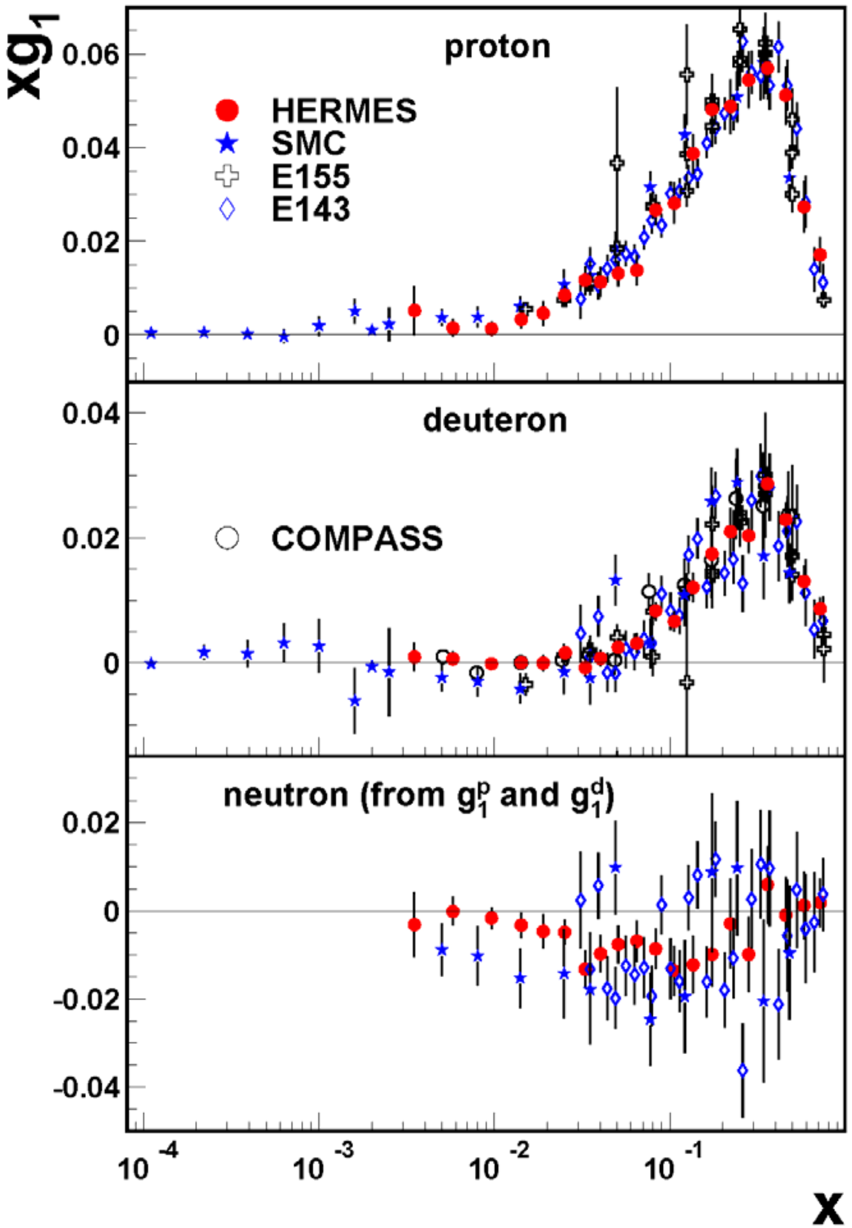


radiative effects

detector smearing

- systematic correlations between bins fully unfolded
- resulting (small) statistical correlations *known*

World Data on $xg_1(x,Q^2)$



- $g_1^p > g_1^d > g_1^{^3\text{He}}$
- Very precise proton data
- The most precise deuteron data

$$g_1^d = \tfrac{1}{2}\left(1 - \tfrac{3}{2}\mathrm{w}_d\right)\left(g_1^p + g_1^n\right)$$

- 0.021-0.9 measured range:

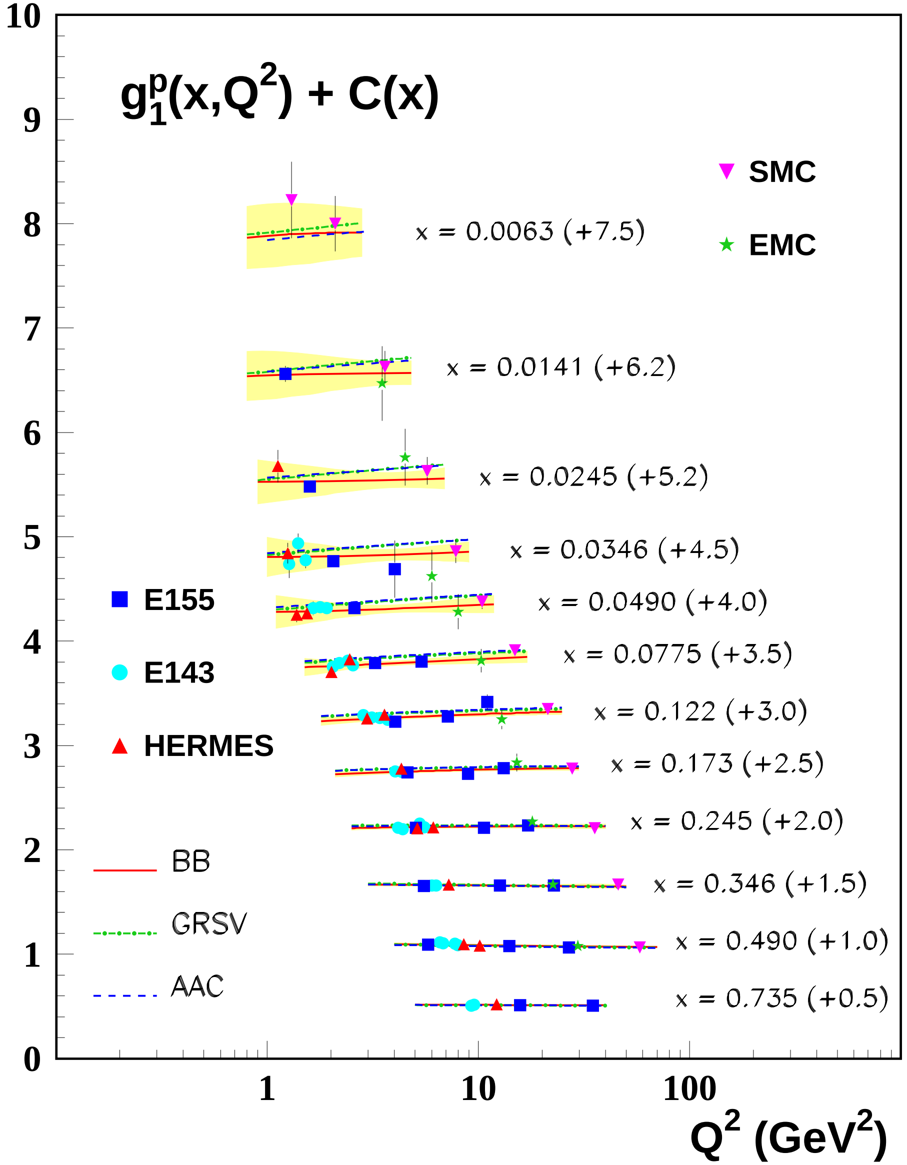
$$\int g_1^p = 0.1246 \pm 0.0032 \pm 0.0074$$

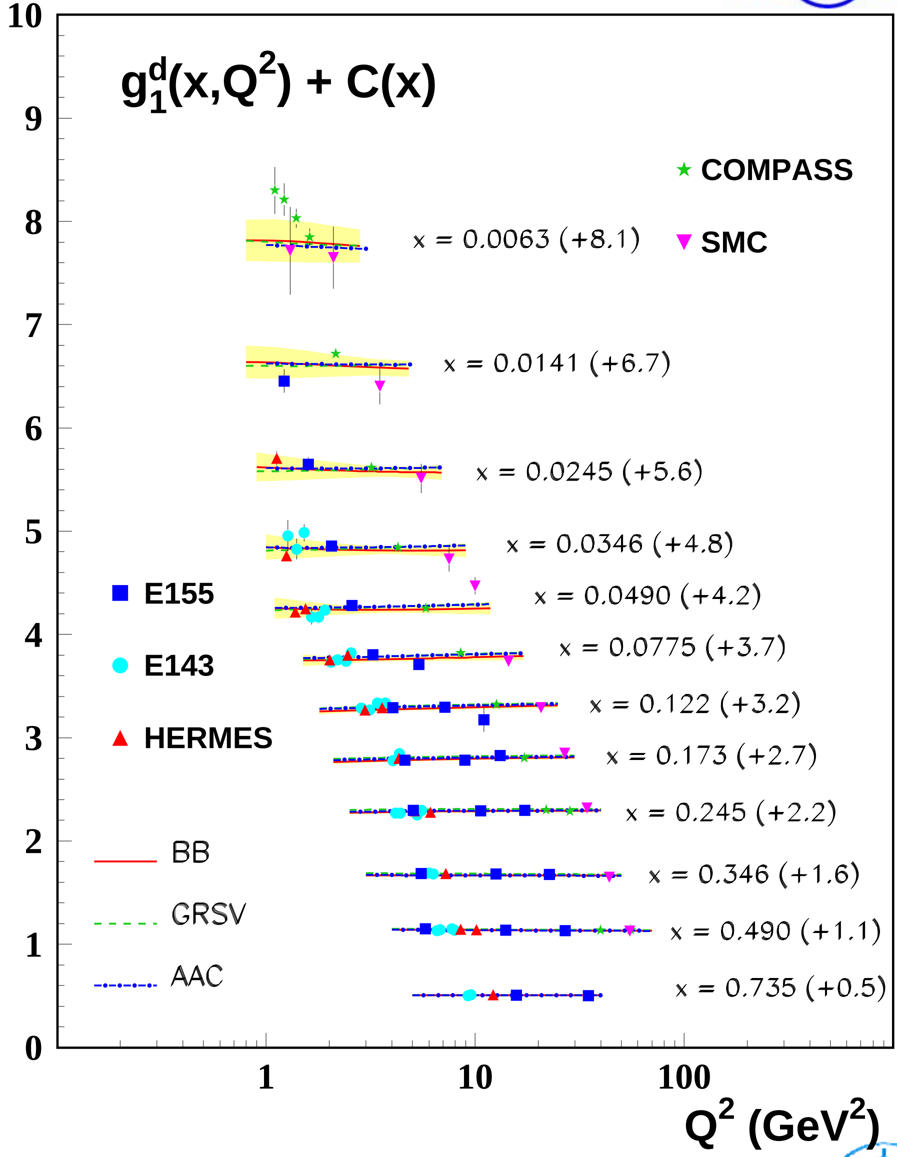
$$\int g_1^d = 0.0452 \pm 0.0015 \pm 0.0017$$

Stewart

$\Delta\Sigma = 0.33$

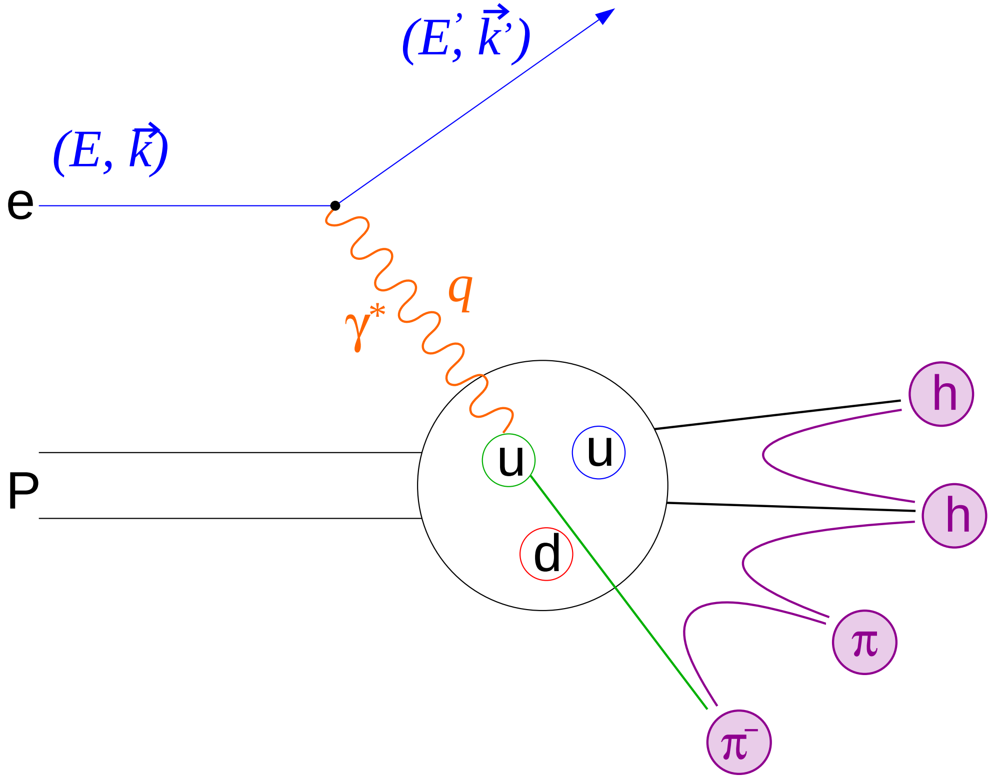
World data on g1





J Stewart

Semi-Inclusive Deep Inelastic Scattering



$$Q^2 = -q^2 = -(k - k')^2$$

$$\nu \overset{\text{lab}}{=} E - E'$$

$$x = \frac{Q^2}{2M\nu}$$

$$z \overset{\text{lab}}{=} \frac{E_{had}}{\nu}$$

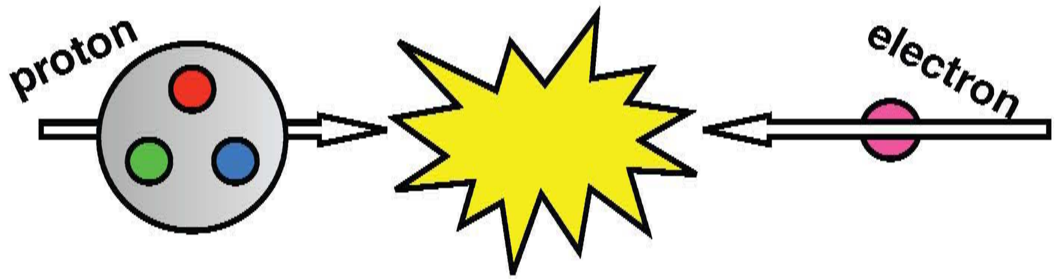
Flavor tagging

The cross section can be expressed as a convolution of a distribution function and a fragmentation function.

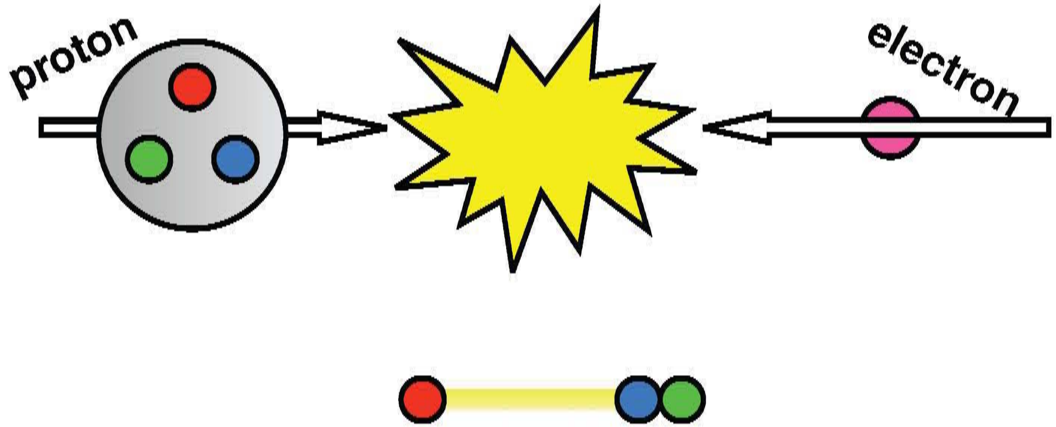
$$\sigma^{ep \to eh} \sim \sum_q DF^{p \to q} \otimes \sigma^{eq \to eq} \otimes FF^{q \to h}$$

Fragmentation

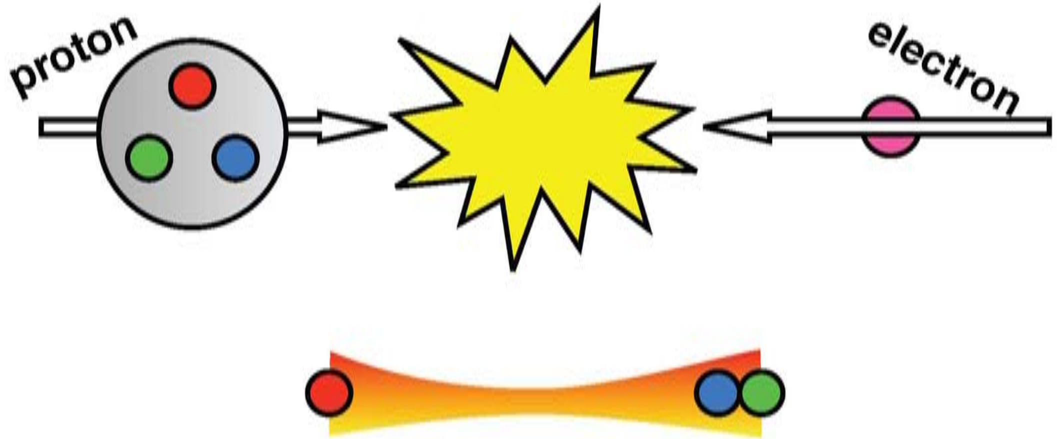
Fragmentation



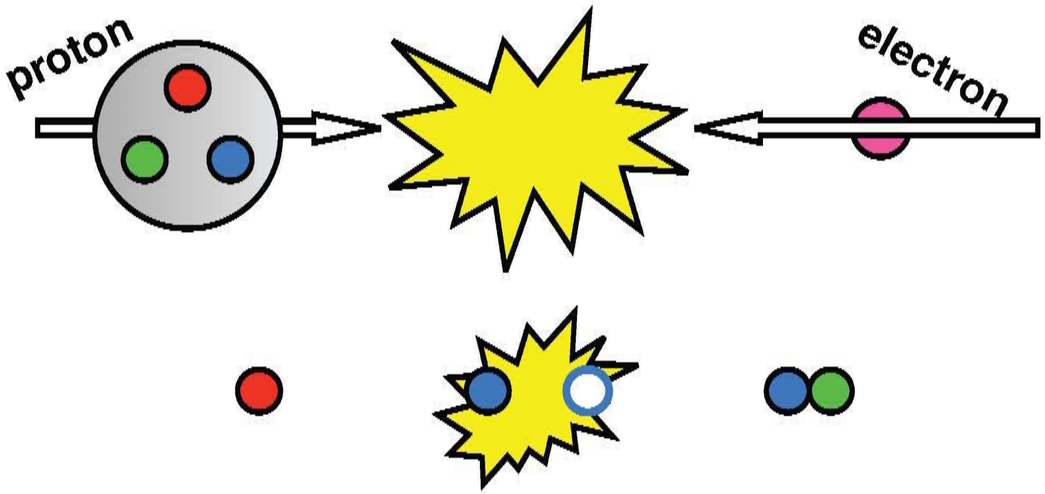
Fragmentation



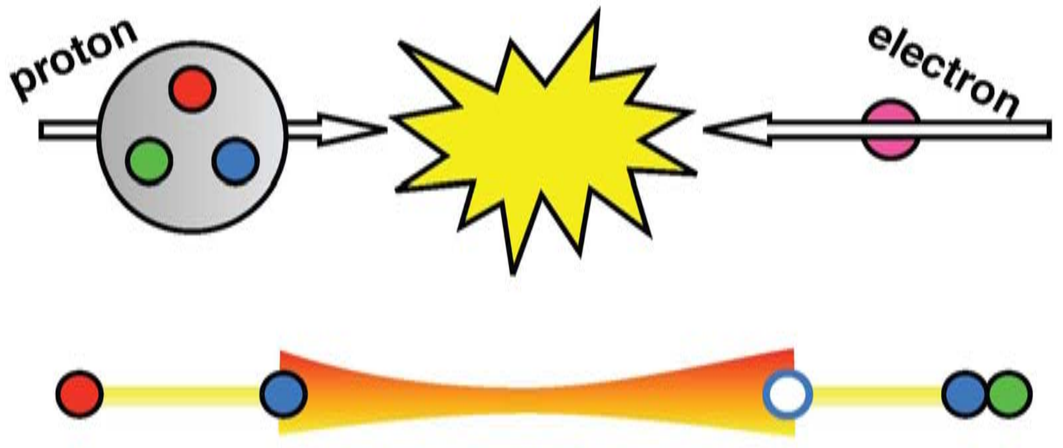
Fragmentation



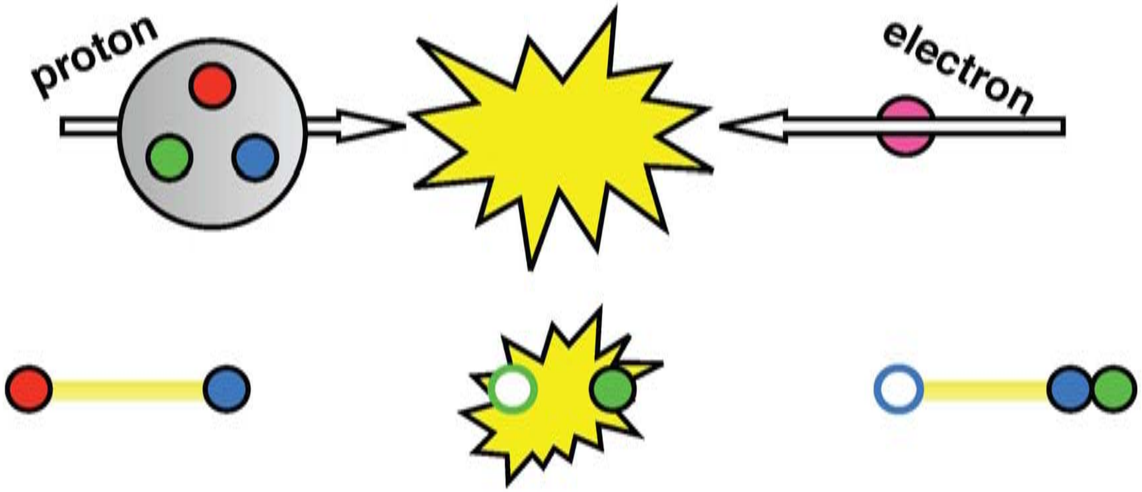
Fragmentation



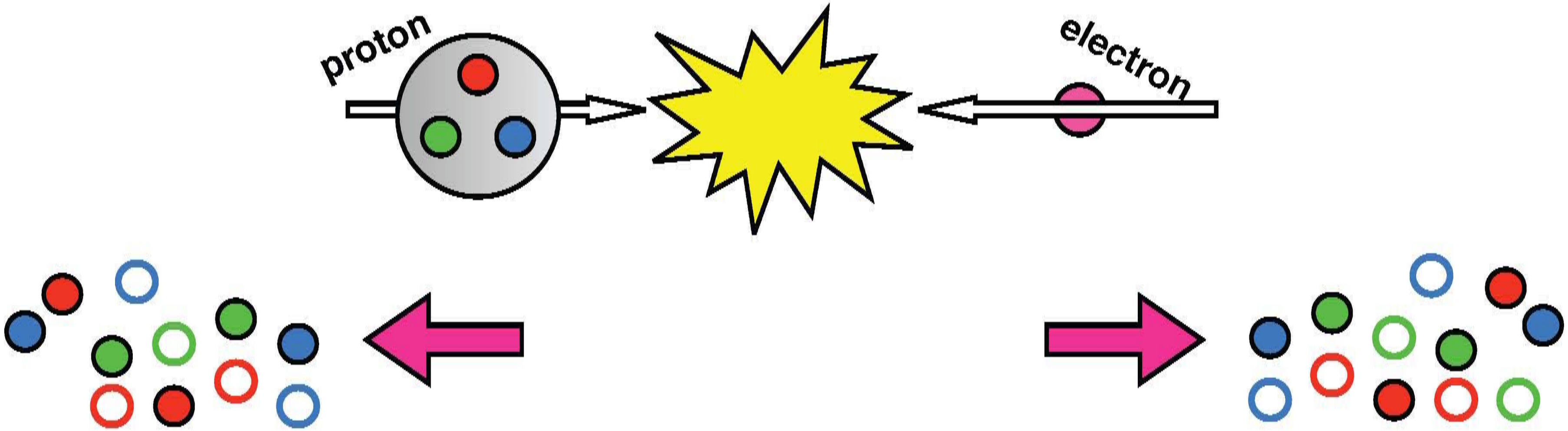
Fragmentation



Fragmentation

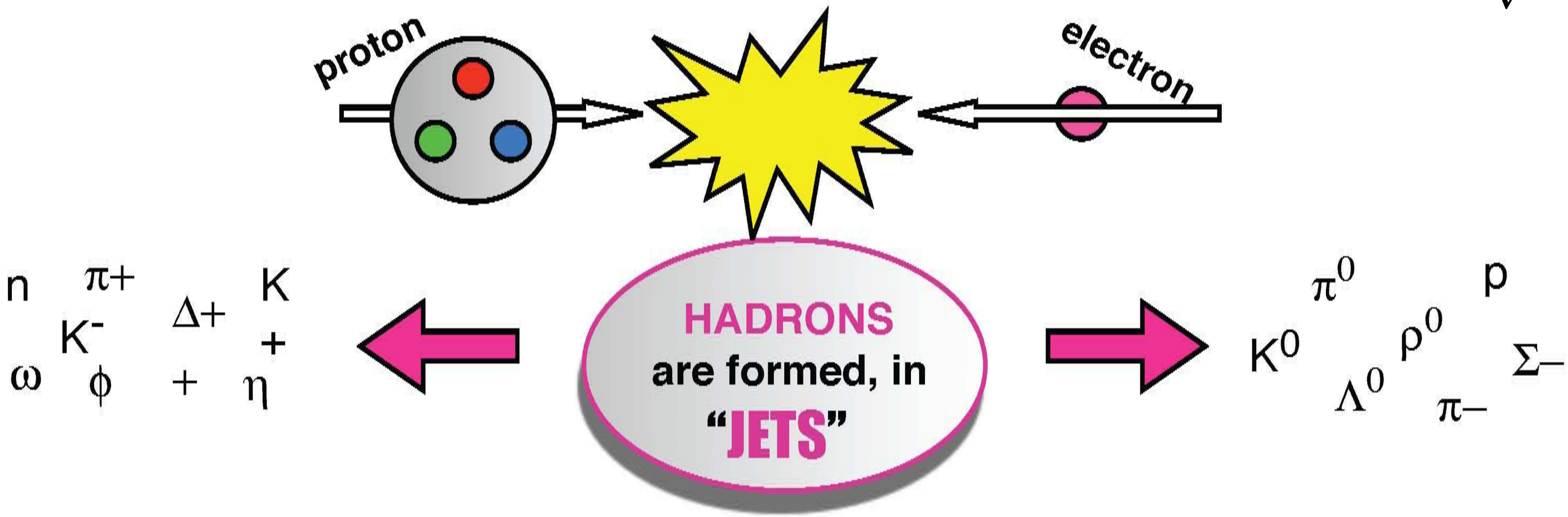


Fragmentation



Fragmentation

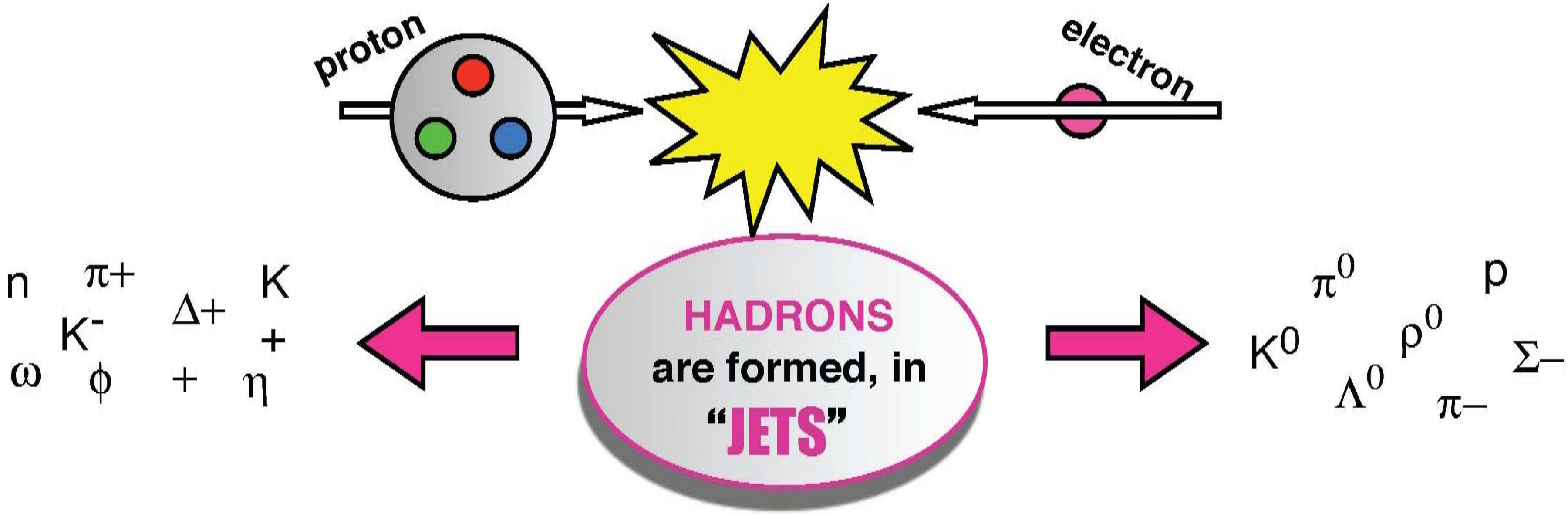
$$z = \frac{E^{lab}_{had}}{\nu}$$



Fragmentation functions:

$FF^{q \to h}(z)$ The probability that if a quark q was struck that a hadron h is formed with a fraction z of the energy of the virtual photon.

Fragmentation

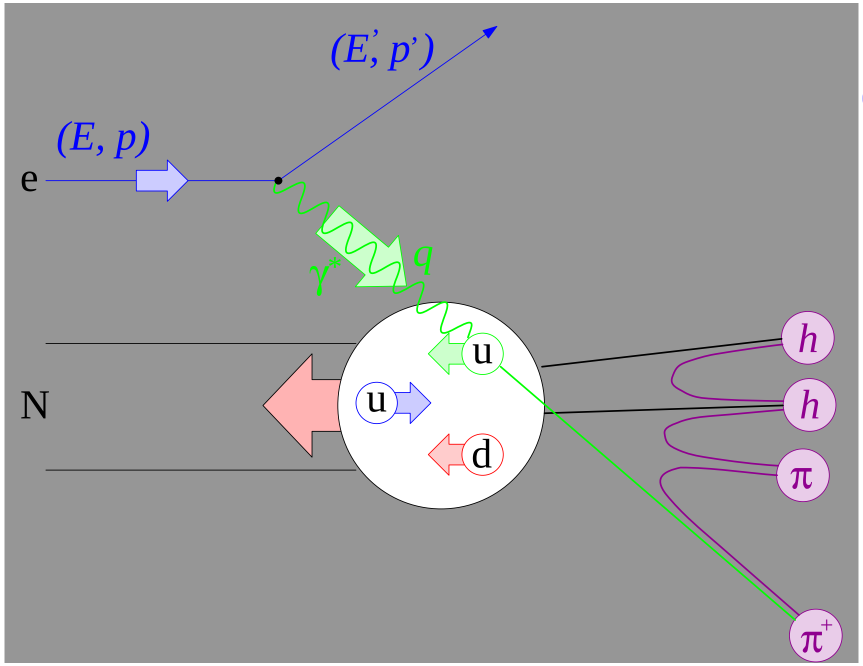


- Normally lund string model is used to simulate the fragmentation process.
  - Need to tune the model to the data.
- The fragmentation process cannot be calculated theoretically.

$$z = \frac{{}^{lab}E_{had}}{\nu}$$

Favored: struck quark is in the formed hadron $\pi^{+} = ud$

Favored $D_{u}^{\pi^{+}}(z, Q^{2})$ J Stewart Unfavored $D_{\bar{u}}^{\pi^{+}}(z, Q^{2})$



Quark Polarizations

Correlation between detected hadron and the struck quark allows flavor separation

Inclusive DIS $\rightarrow \Delta\Sigma$

Semi-inclusive $\rightarrow \Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}, \Delta s$

$$A_1^h(x,Q^2) = \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h} \sim \frac{\sum_f e_f^2 \Delta q_f(x,Q^2) \int dz D_f^h(z,Q^2)}{\sum_f e_f^2 q_f(x,Q^2) \int dz D_f^h(z,Q^2)} \sim \sum_f \underbrace{\frac{e_f^2 q(x) \int dz D_f^h(z,Q^2)}{\sum_{f'} e_{f'}^2 q_{f'}(x) \int dz D_{f'}^h(z,Q^2)}}_{P_q^h(x,z)} \frac{\Delta q(x)}{q(x)}$$

Linear System in $\vec{Q}$

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

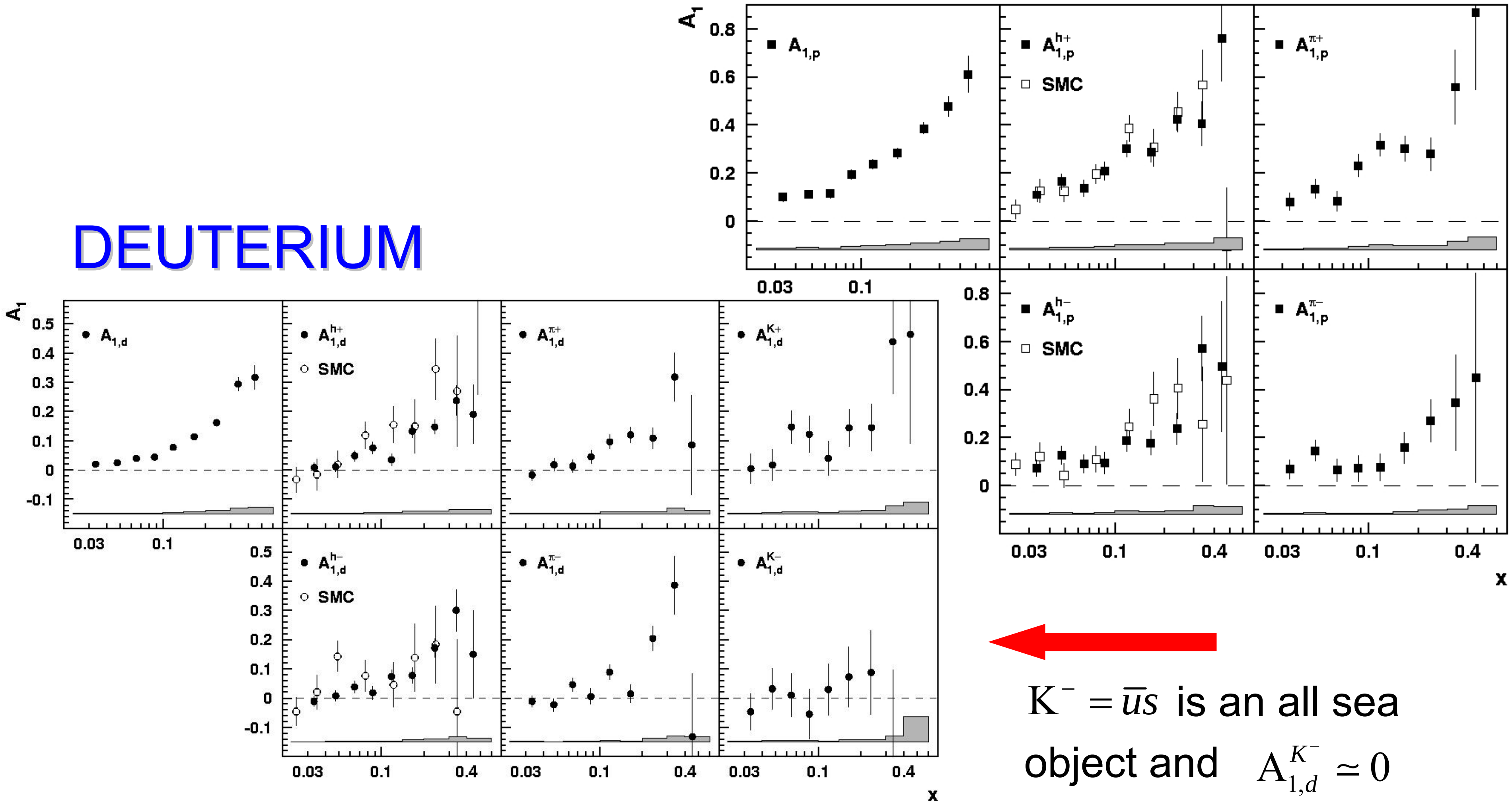
$$\vec{Q} = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta\bar{u}}{\bar{u}}, \frac{\Delta\bar{d}}{\bar{d}}, \frac{\Delta s}{s}, \frac{\Delta\bar{s}}{\bar{s}} = 0 \right)$$

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

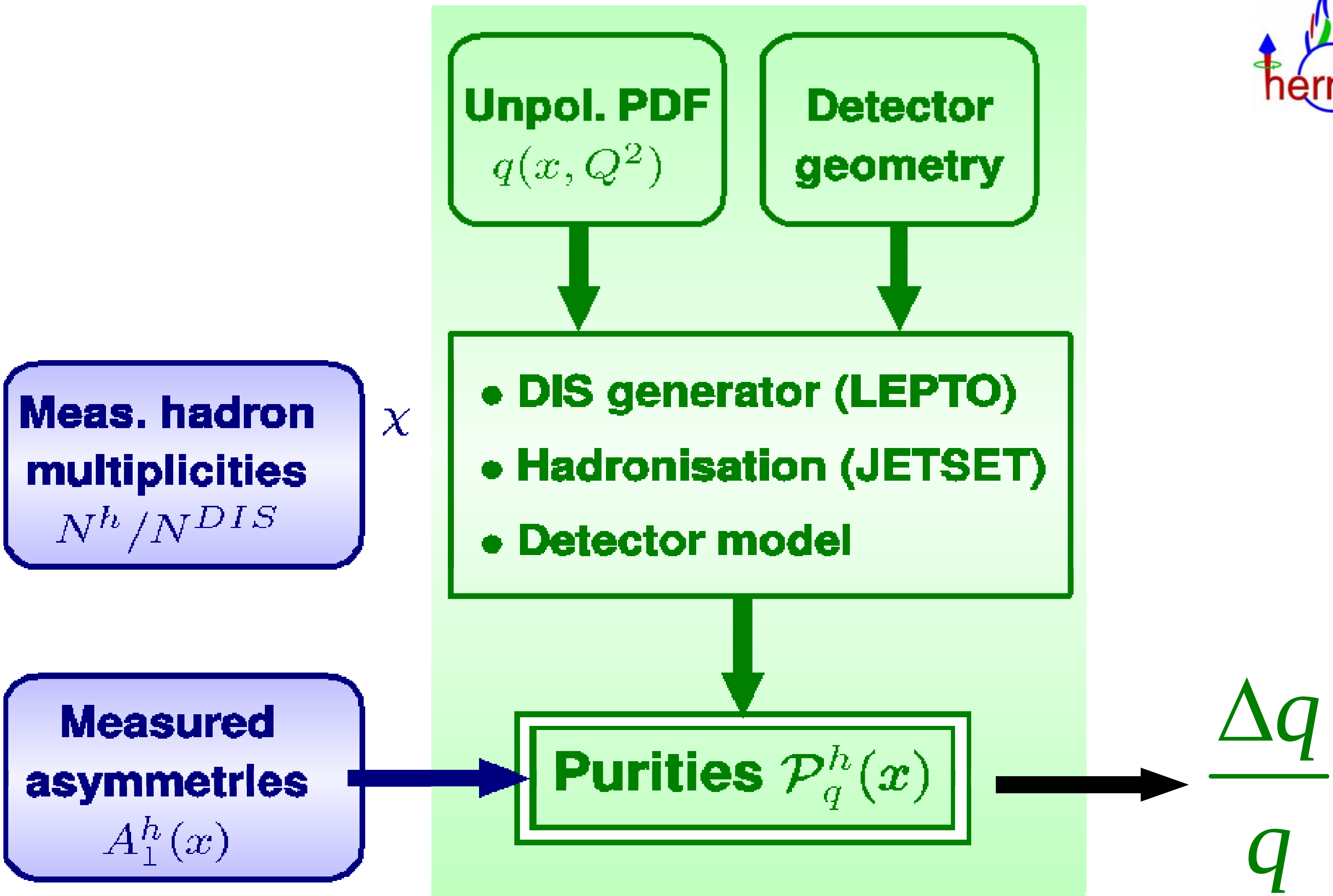
The Measured Hadron Asymmetries

PROTON

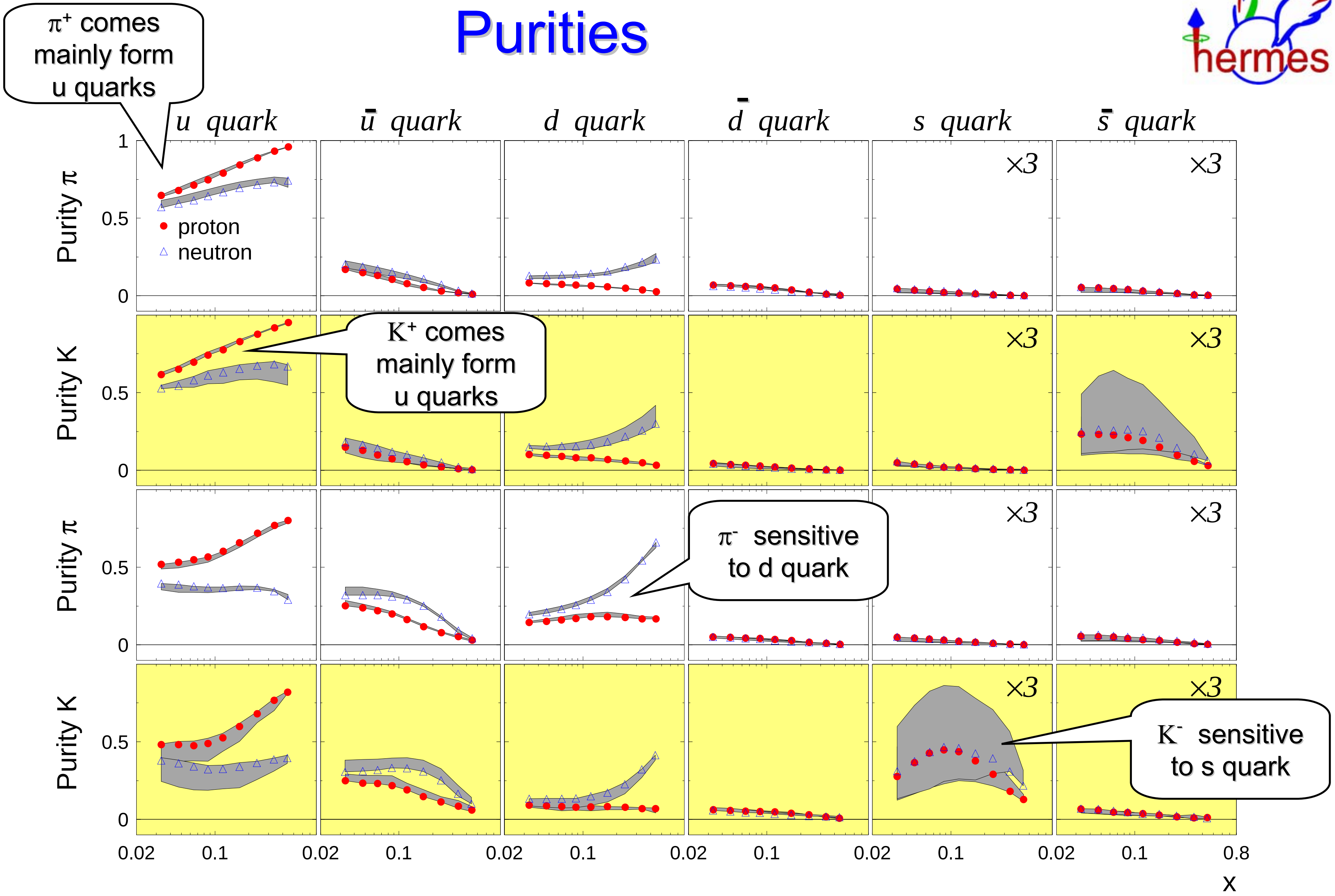
DEUTERIUM



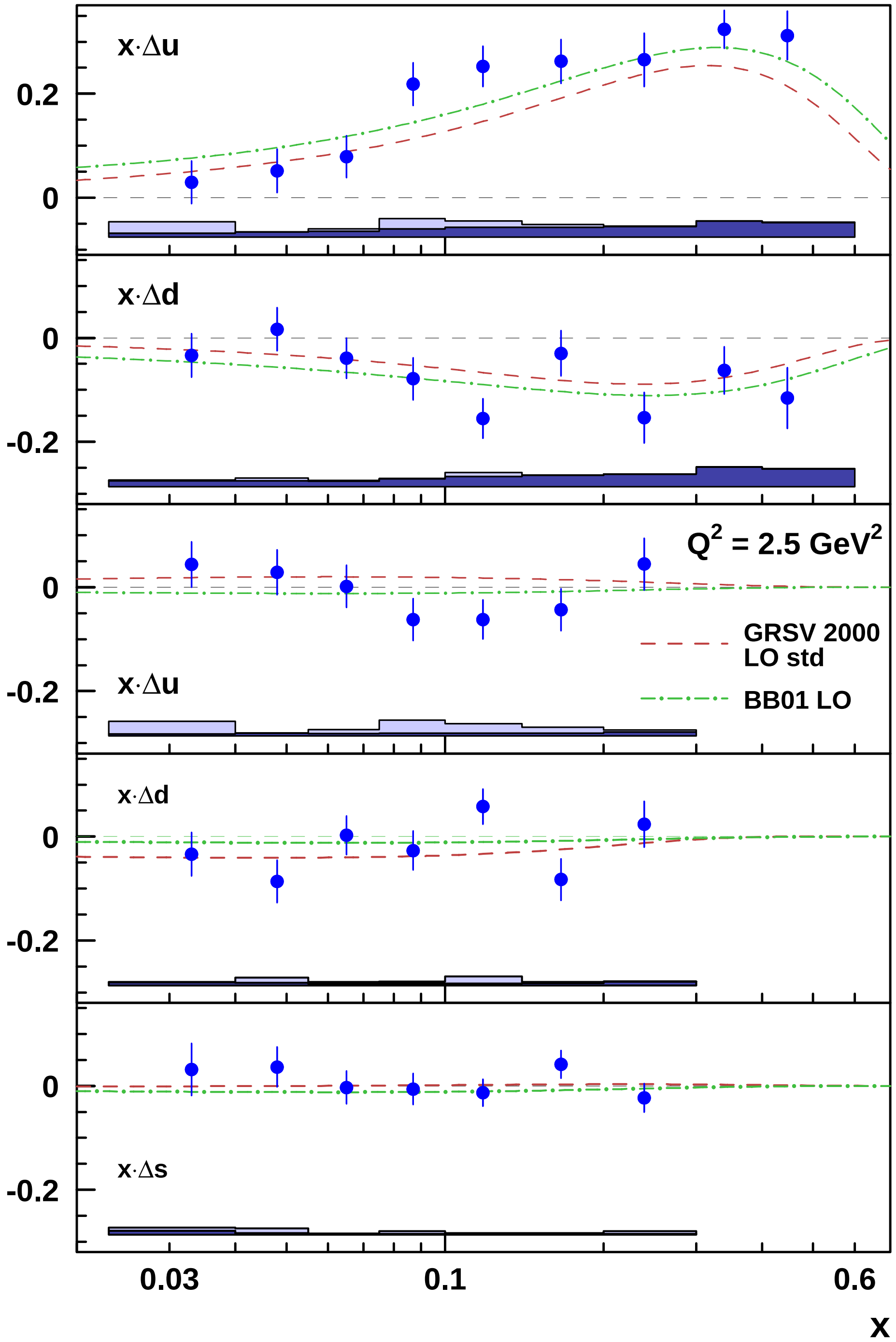
$K^{-} = \bar{u}s$ is an all sea object and $A_{1,d}^{K^{-}} \simeq 0$


Unpol. PDF
$q(x, Q^2)$
Detector geometry
Meas. hadron multiplicities
N^h/N^{DIS}
χ
• DIS generator (LEPTO)
• Hadronisation (JETSET)
• Detector model
Measured asymmetries
$A_1^h(x)$
Purities $\mathcal{P}_q^h(x)$
$\frac{\Delta q}{q}$

Purities



J Stewart



Polarized Quark Densities

$$\Delta q(x) = \vec{q}(x) - \overleftarrow{q}(x)$$

$\Delta u(x) > 0$

- Polarized parallel to the proton

$\Delta d(x) < 0$

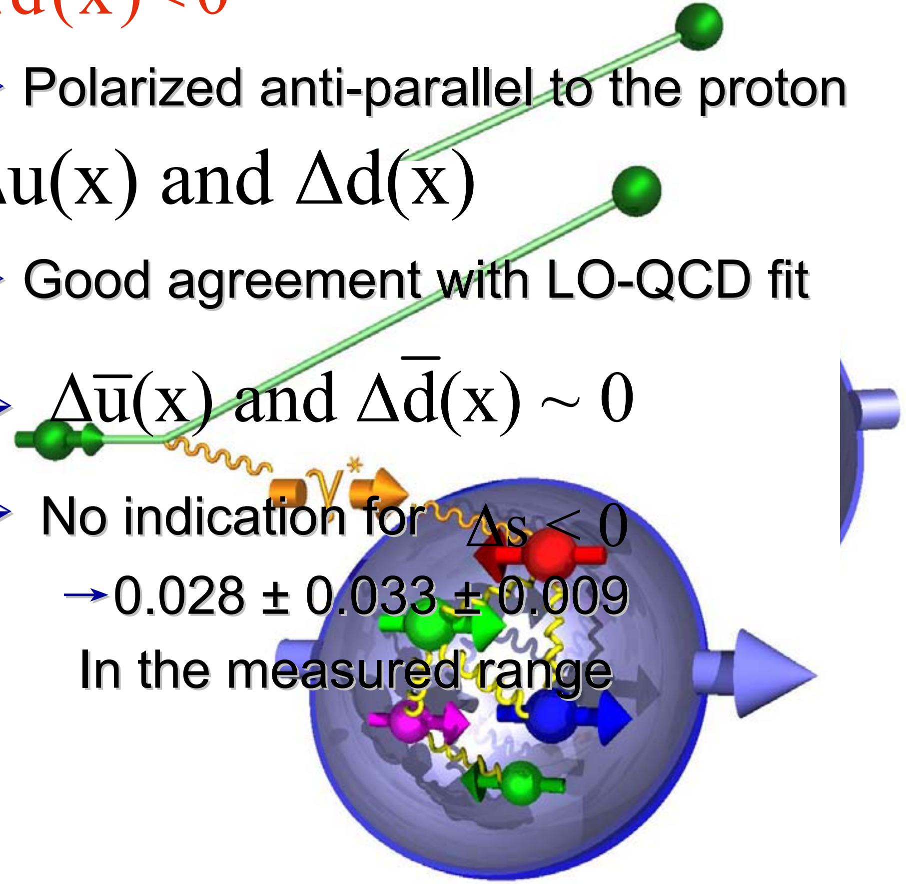
- Polarized anti-parallel to the proton

$\Delta u(x)$ and $\Delta d(x)$

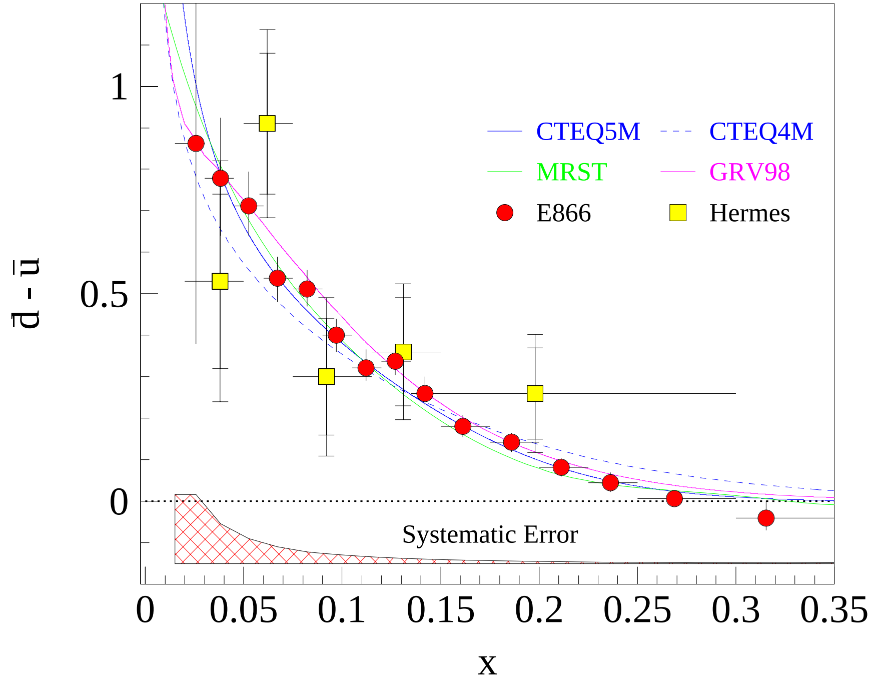
- Good agreement with LO-QCD fit
- $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x) \sim 0$
- No indication for $\Delta s < 0$

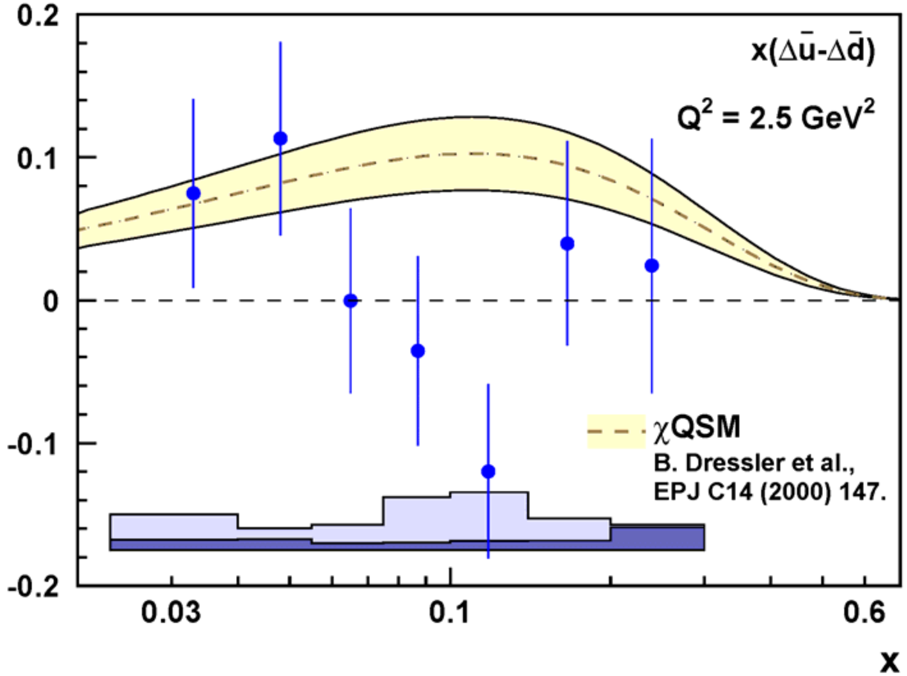
  → 0.028 ± 0.033 ± 0.009

  In the measured range



Polarized Sea





- Unpolarized data on sea shows the Gottfried sum rule is broken

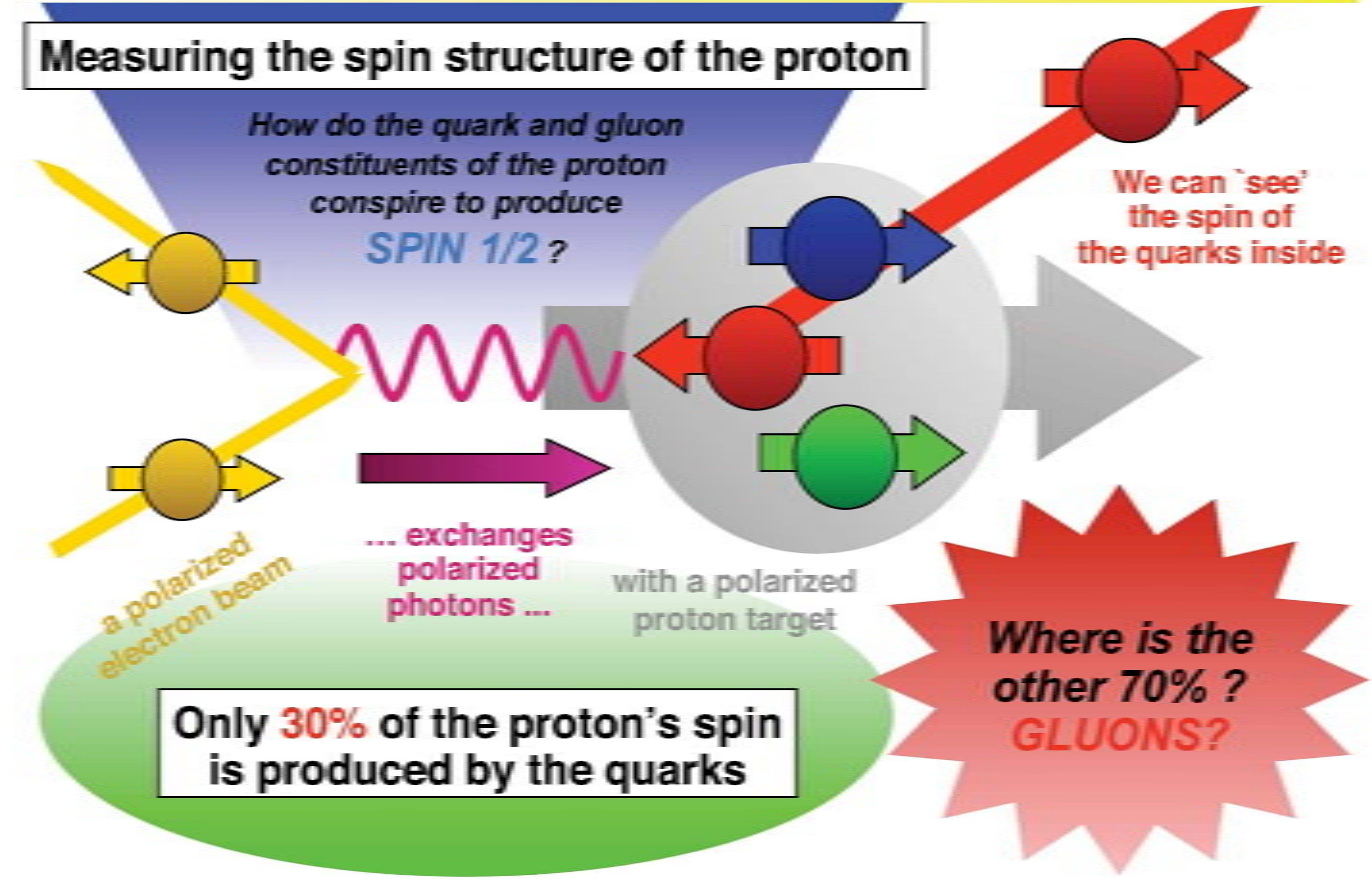
$$\bar{d} - \bar{u} > 0$$

- Reanalyze polarized data: Fit for $\vec{Q} = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta\bar{u}-\Delta\bar{d}}{\bar{u}-\bar{d}}, \frac{\Delta s}{s} \right)$

- Polarized data favor a symmetric sea $\Delta\bar{d} - \Delta\bar{u}$,but large uncertainties

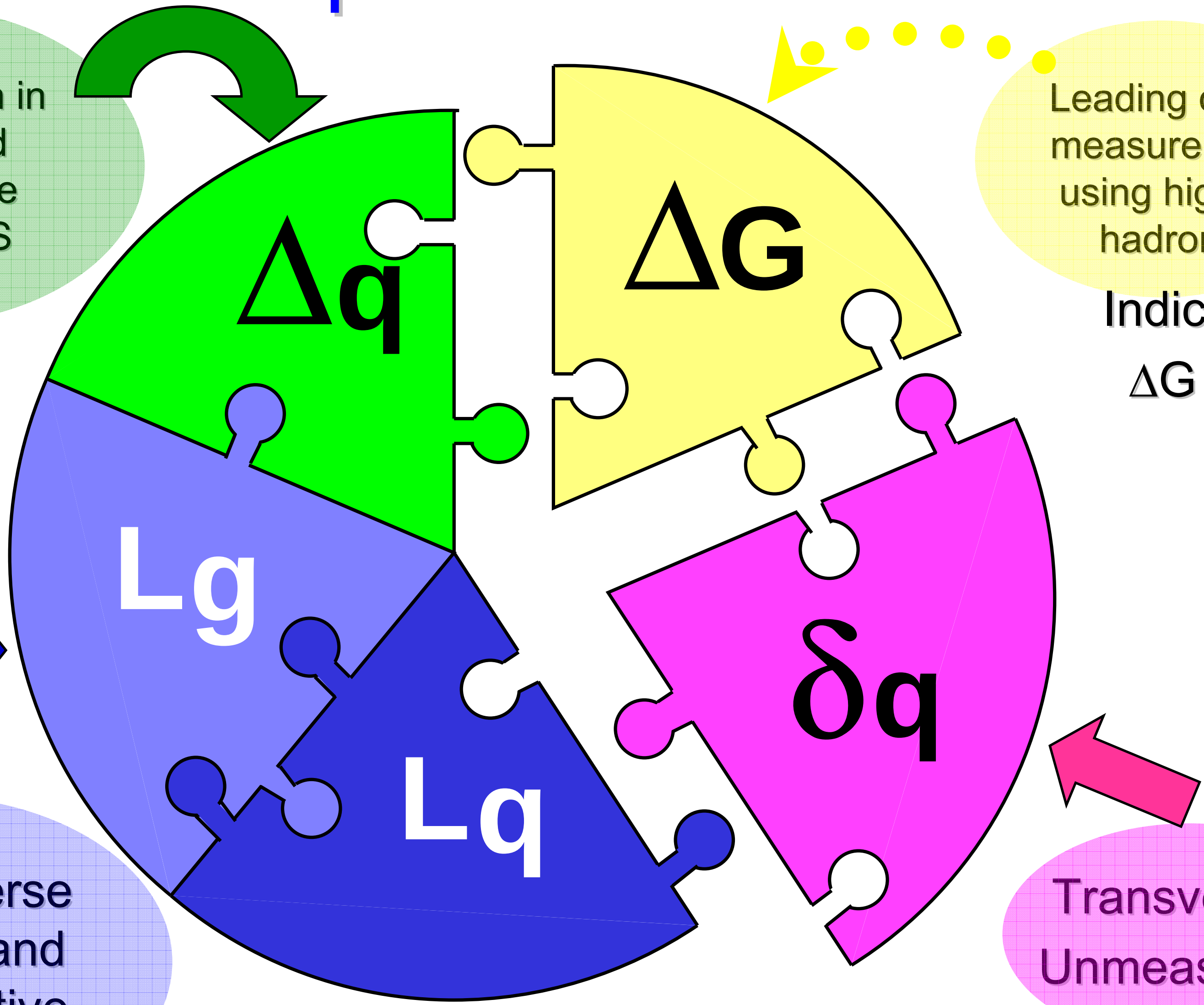
The HERMES Experiment

Hamburg, Germany



The Spin Puzzle

Measured both in inclusive and semi-inclusive polarized DIS



Leading order measurement using high pt hadrons

Indications ΔG small

Both transverse target data and GPDs sensitive to L

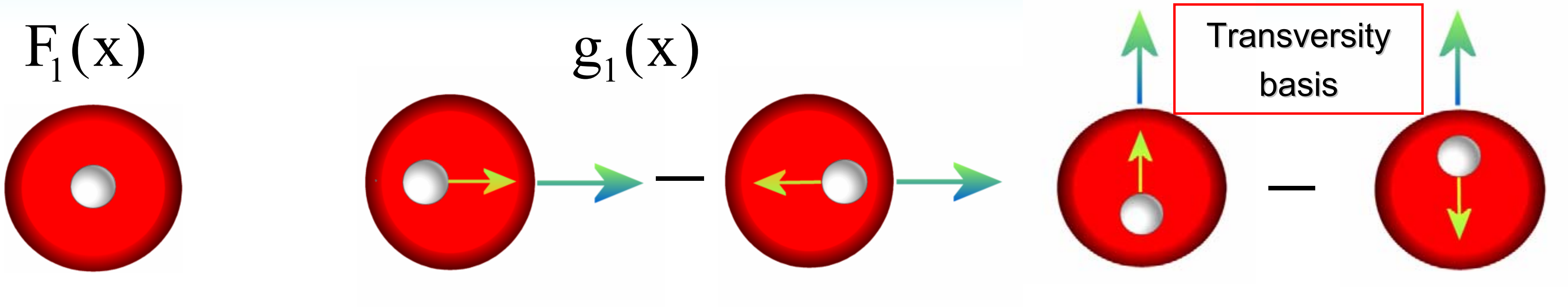
Transversity Unmeasured!

Distribution Functions

Leading Twist

- 3 distribution functions survive the integration over transverse quark momentum

unpolarized DF	Helicity DF	Transversity DF
$q(x)=\vec{q}(x)+\overleftarrow{q}(x)$	$\Delta q=\vec{q}(x)-\overleftarrow{q}(x)$	$\delta q=q^{\uparrow}(x)-q^{\downarrow}(x)$
$F_1(x)$	$g_1(x)$	



vector charge   axial charge   tensor charge

$$\Phi(x)=\frac{1}{2}q(x)\not{P}+\frac{1}{2}\lambda\Delta q(x)\gamma_5\not{P}+\frac{1}{2}\delta q(x)\not{P}\gamma_5\not{S}_\perp$$

Quark Correlation Matrix

HERMES 1996-2000   2002-2005

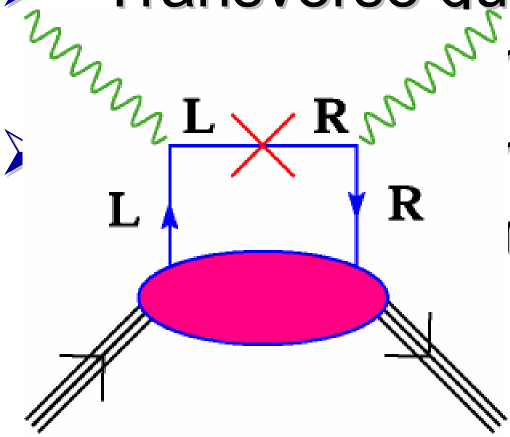
Properties of the Transversity DFs

- For non-relativistic quarks $\delta q(x)=\Delta q(x)$
  - → $\delta q(x)$ probes the relativistic nature of the quarks
- Due to Angular Momentum Conservation
  - → Different QCD evolution
  - → No gluon component
- $\delta\Sigma(x)=\sum_q\left[\delta q(x)-\delta\overline{q}(x)\right]$
  - → Predominately sensitive to valence quarks
- Bounds
  - $|\delta q(x)|\leq q(x)$
  - Soffer Bound: $|\delta q(x)|\leq\left[q(x)+\Delta q(x)\right]$
- T-even
- Chiral odd
  - → Not measurable in inclusive DIS

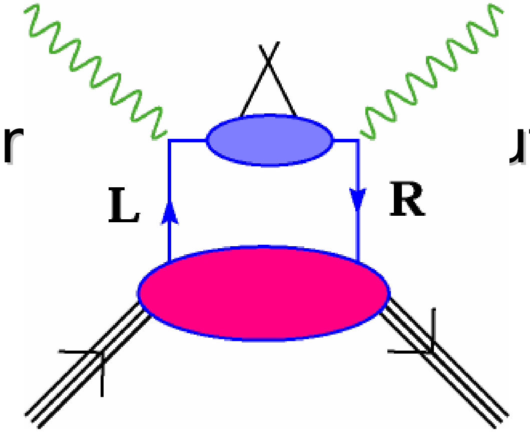
Measuring Transversity

$$\sigma^{ep \rightarrow eh} \sim \sum_q DF^{p \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes FF^{q \rightarrow h}$$

- Need a chiral odd fragmentation function: 'Collins FF'
- Transverse quark polarization affects transverse ...ntum
- ...mmetry in azir... ...ut ...ng plane



•Forbidden



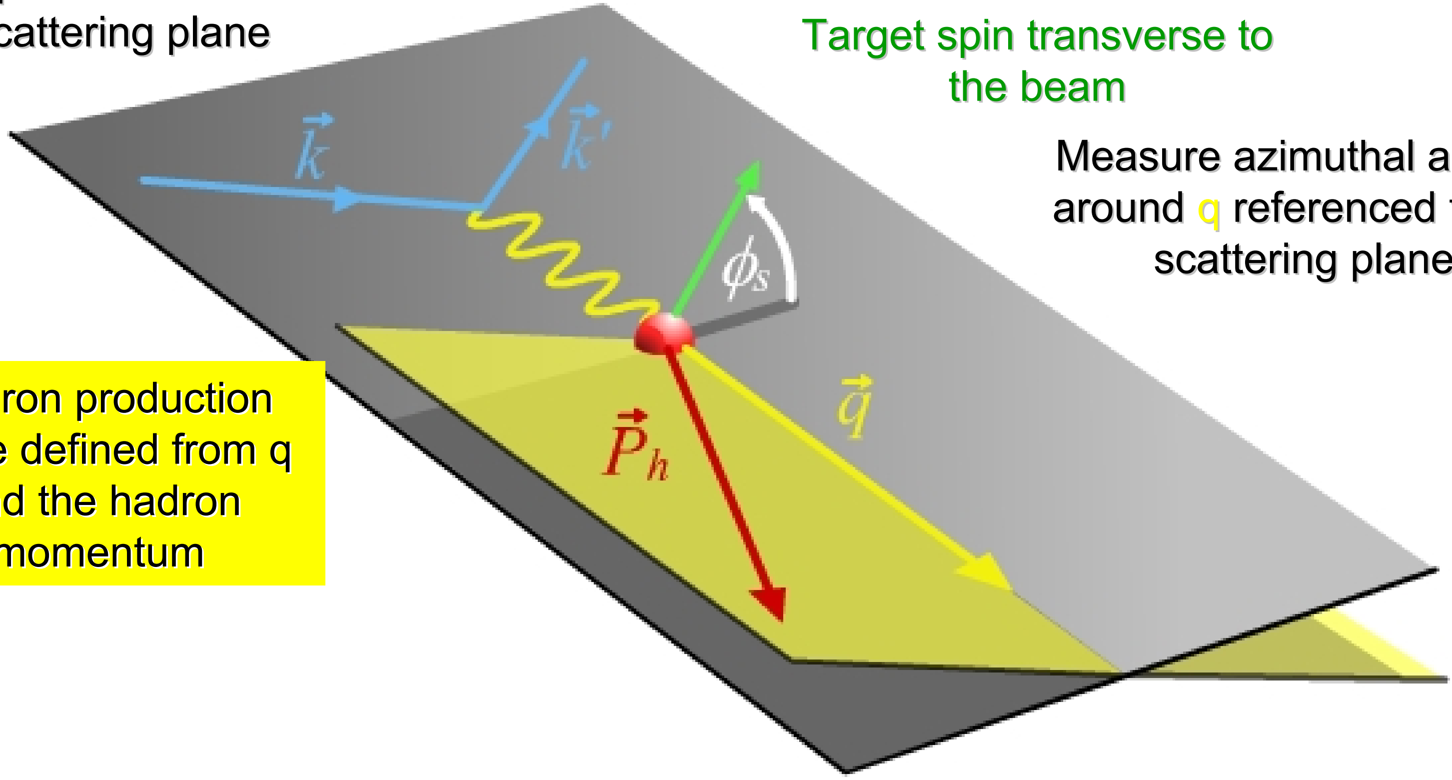
•Need chiral odd fragmentation function

Azimuthal angles and asymmetries

Beam and scattered lepton define the scattering plane

Target spin transverse to the beam

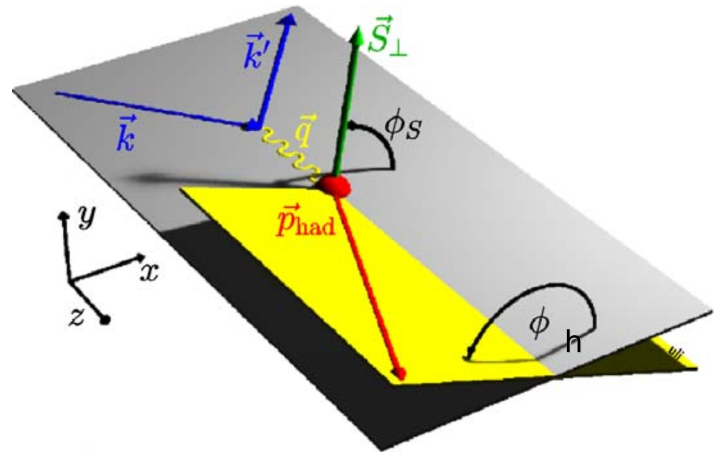
Measure azimuthal angles around q referenced to the scattering plane

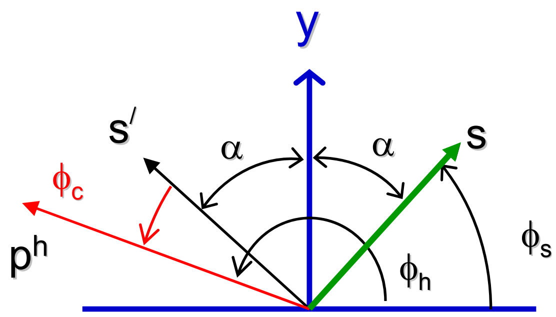


Hadron production plane defined from q and the hadron momentum

ϕ_h angle between hadron prod. plane and scattering plane

ϕ_s angle between proton spin and scattering plane





lepton plane

Quark photon interaction preserves spin component out of plane and reverses component in plane

α=α

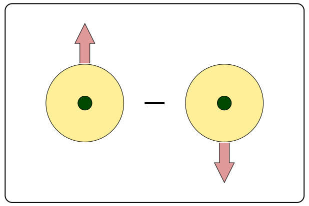
$$\pi + (\varphi_h - \varphi_S)$$

$(\varphi_h + \varphi_S)$ **angle of hadron relative to *final* quark spin (Collins)**

$$A_{coll} \propto h_1(x) H_1^{\perp}(z)$$

$(\varphi_h - \varphi_S)$ **angle of hadron relative to *initial* quark spin (Sivers)**

$$A_{Sivers} \propto f_{1T}^{\perp}(x) D_1(z)$$

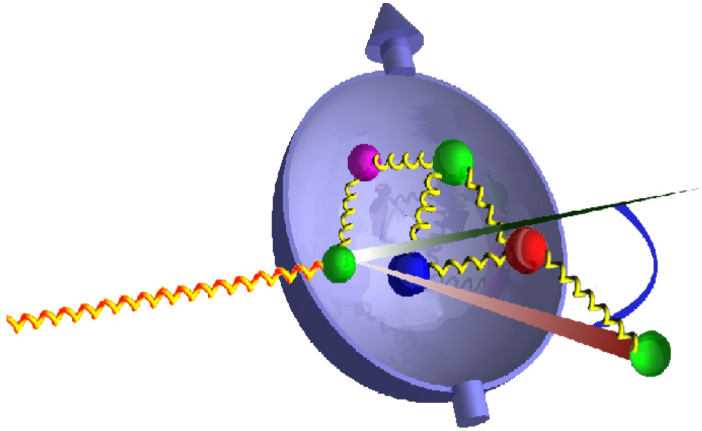


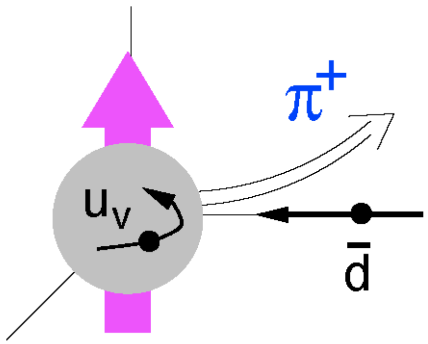
Sivers Function $f_{1T}^{\perp(1/2)}$

$$\sigma^{ep\to eh} \sim \sum_q DF^{p\to q} \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$$

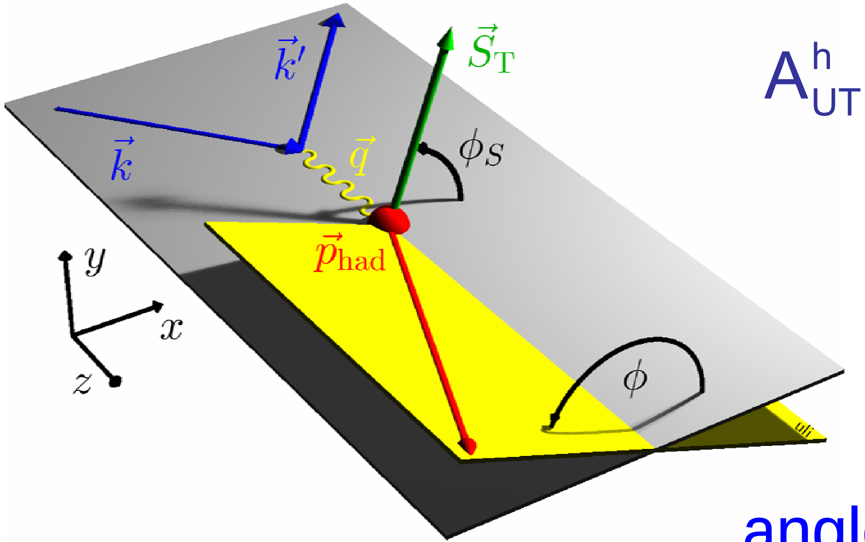
$$A_{UT} \sim \sin(\phi_h - \phi_S) \sum_q e_q^2 f_{1T}^{\perp(1/2)}(x) D_1^q(z)$$

- Distribution function
  - Naïve T-ODD
  - Chiral even
- a remnant of the quark transverse momentum can survive the photo-absorption and the fragmentation process
- Can be inherited in the transverse momentum component
  - influence azimuthal distribution
- Non-vanishing Sivers function requires quark orbital angular momentum
- Cross section depends on the angle between the target spin direction and the hadron production plane





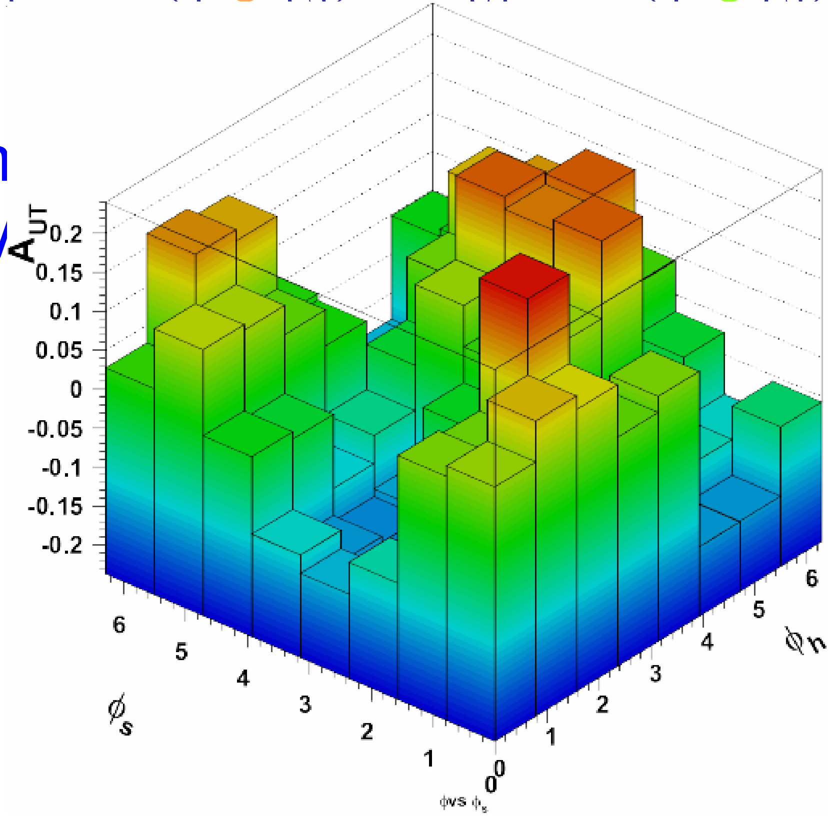
Single target-spin asymmetry



$$A^h_{UT}(\phi,\phi_S) = \frac{1}{|S_T|}\frac{N^{\uparrow}_h(\phi,\phi_S) - N^{\downarrow}_h(\phi,\phi_S)}{N^{\uparrow}_h(\phi,\phi_S) + N^{\downarrow}_h(\phi,\phi_S)} =$$

$$= A^{Collins}_{UT}\sin(\phi + \phi_S) + A^{Sivers}_{UT}\sin(\phi - \phi_S)$$

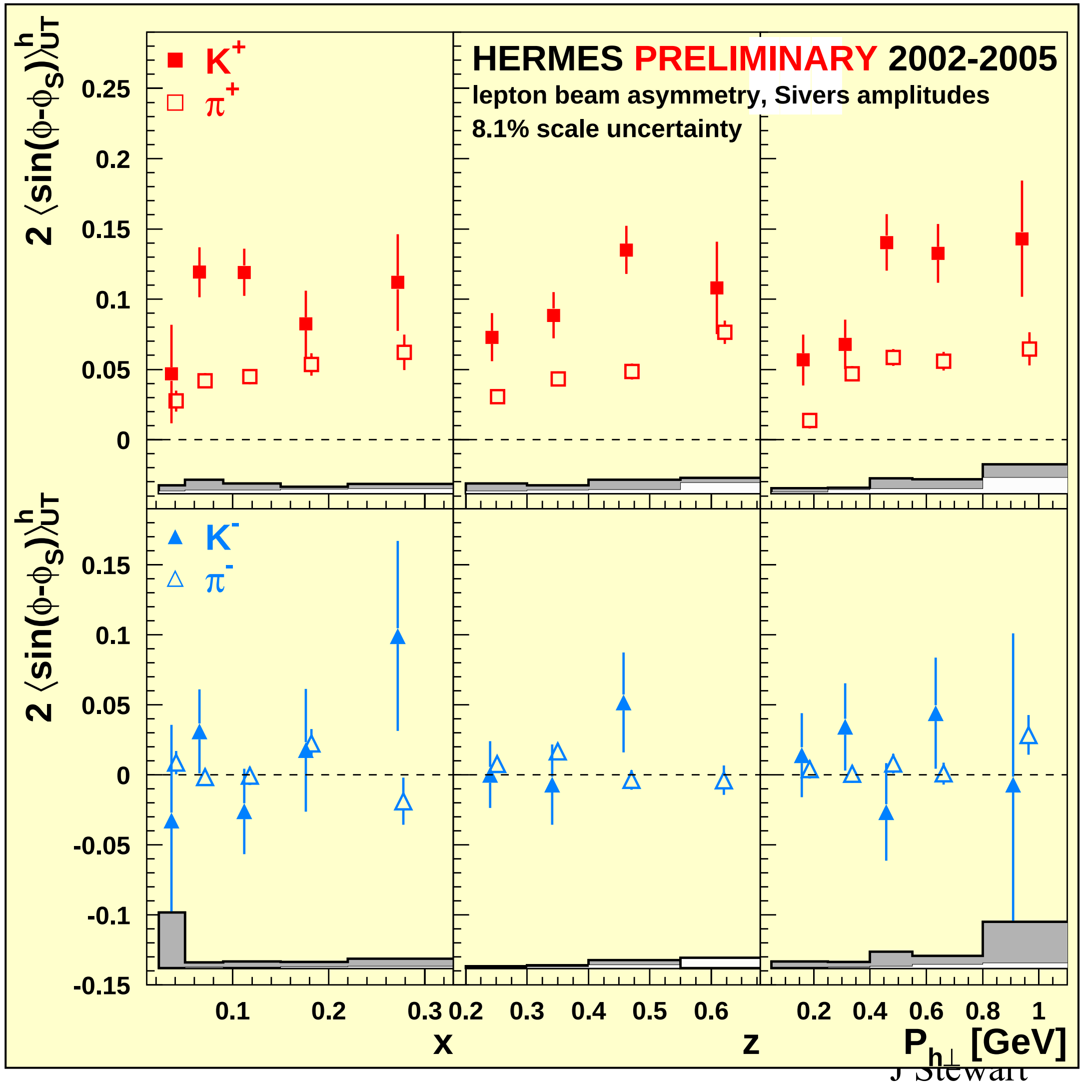
angle of h
to *final*



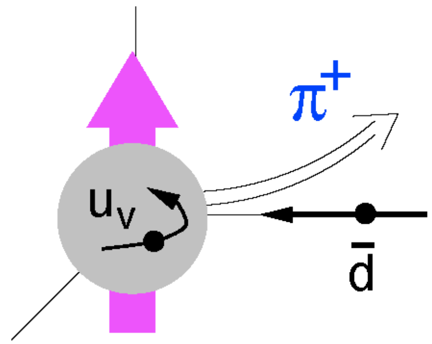
amplitudes fit *simultaneously*
(prevents mixing effects
due to acceptance)

Sivers moments

$$A_{Sivers} \propto f_{1T}^{\perp}(x) D_1(z)$$



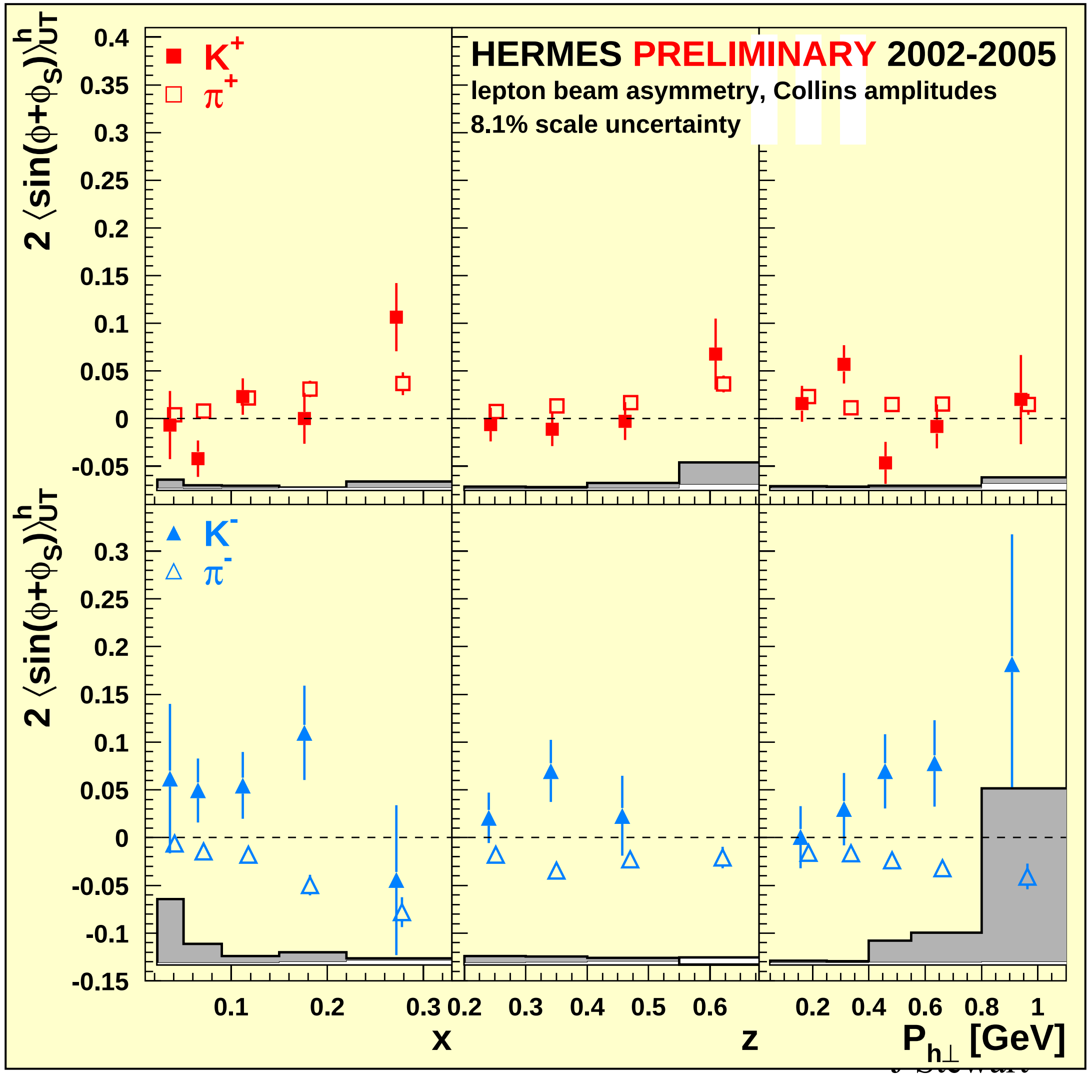
- **Sivers moment:**
  $\pi^+ > 0$ $\pi^- \sim 0$
- **$K^+ > 0$ $K^- \sim 0$**
  $K^+ > \pi^+$
  - **sea quarks important**
- **non-zero orbital angular momentum in p-wave fct.**
  - **L_q ??**



J Stewart

Collins moments

$$A_{coll} \propto h_1(x) H_1^{\perp}(z)$$



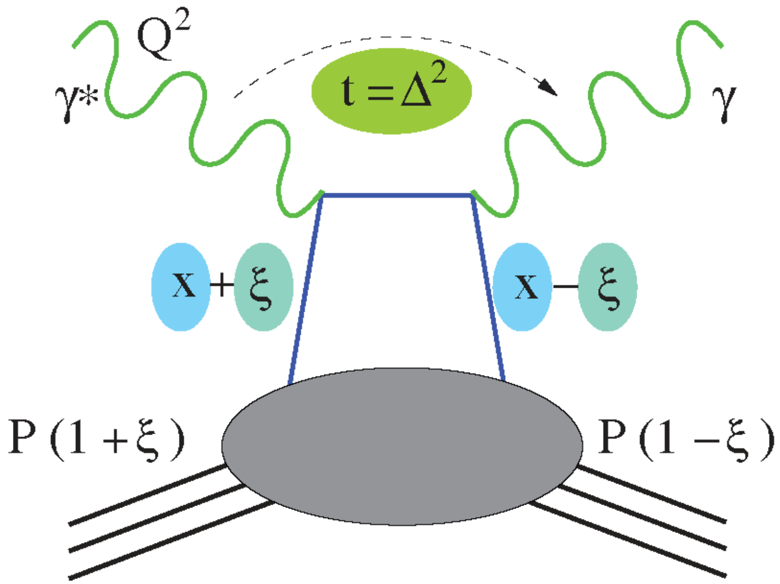
- Collins moment:
  $\pi^+ > 0$ $\pi^- < 0$
- π^- unexpected large
  - ➡ role of unfavoured FF
    $H_{fav} = - H_{unfav}$
- first data for Collins-FF available from Belle
  - ➡ extraction of h_1 from Hermes asymmetries
- $K^+ > 0$ $K^- > 0$
  K^+ and π^+ consistent with u-quark dominance
- K^- and π^-
  complicated sea quark contr.

Generalized Parton Distributions

Analysis of ***hard exclusive processes*** leads to a new class of parton distributions

Cleanest example: Deeply Virtual Compton scattering

DVCS



x: average quark momentum frac^n

ξ: "skewing parameter" = $x_1 - x_2$

t: 4 momentum transfer^2

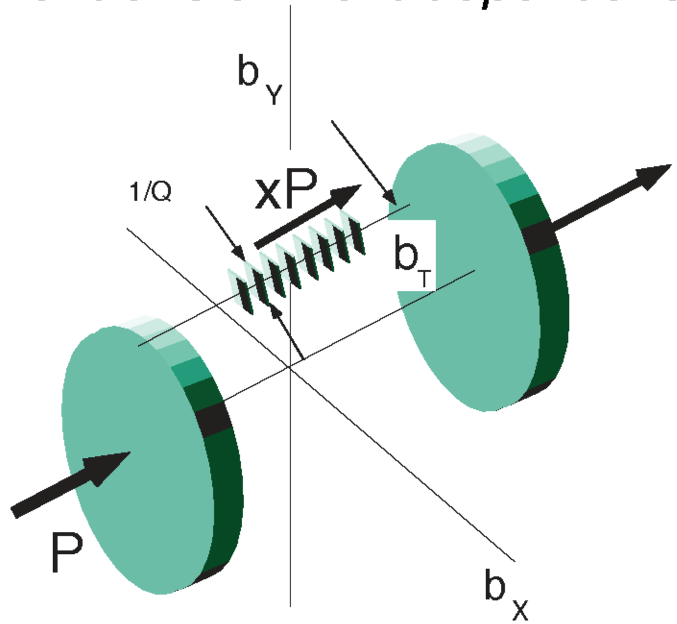
Four new distributions = "GPDs"

helicity conserving $\longrightarrow$ $H(x,\xi,t), E(x,\xi,t)$

helicity flip $\longrightarrow$ $\tilde{H}(x,\xi,t), \tilde{E}(x,\xi,t)$

"Femto-photography" of the proton

Fourier transform of t-dependence ...



→ ***spatial distribution*** of partons

Summary

- Quark helicity distributions are now well measured.
  - → Inclusive using NLO fits (sea assumption)
  - → Semi-inclusive data using flavor tagging
- Gluon polarization extracted using leading order extraction from high pt hadrons.
- Transversity data now being analyzed. Clear signal is seen.
- Large DVCS data set collected for the GPD determination.
- First steps toward understanding angular momentum.