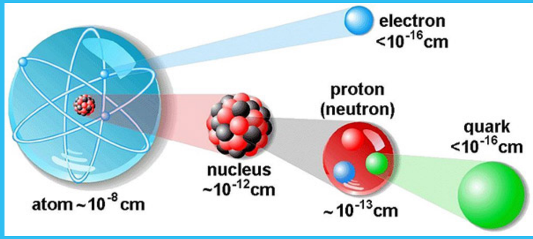
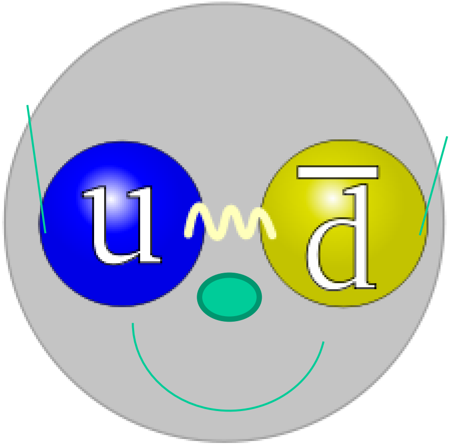
Nucleon Structure – 3D!

Tanja Horn





Paul the Pion

The Catholic University of America

HUGS Summer School

Jefferson National Laboratory

Lecture 3 of 6

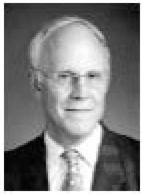
Morning trivia….

- **Nobel Prize Winning Ladies**

Marie Curie, 1903 "… for researches on the radiation phenomena…"

Maria Goeppert-Mayer, 1963
"for discoveries concerning nuclear shell structure"

- **Paper citations: who has more?**



For the discovery of asymptotic freedom in QCD (2004 Nobel Prize)

Asymptotic freedom

vs.

His most cited paper

Intro and Overview

- **Lecture 1 & 2: General Overview of QCD and imaging**
  - Introduction and importance of nucleon structure
  - From form factors to GPDs in electron scattering

- **Lecture 3 & Lecture 4: Valence quark imaging at JLab**
  - Jefferson Lab – the place to study nucleon structure
  - Comments on experimental techniques, e.g., Compton Scattering and Deeply Virtual Meson Production
  - Review of results and future prospects

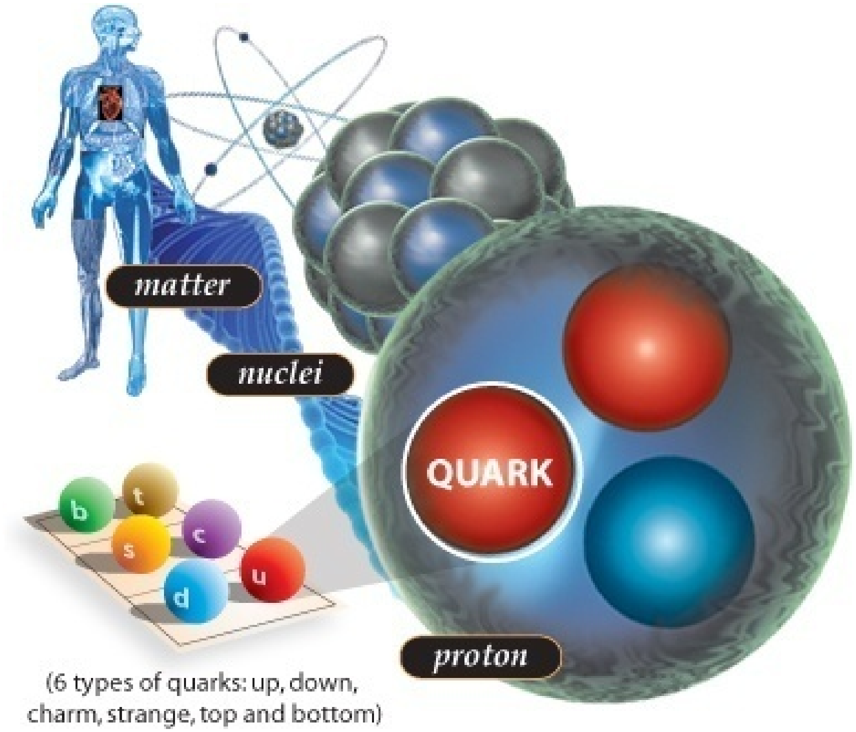
- **Lecture 5: Future of imaging studies**
  - Opportunities at future facilities

Fundamental Matter

- Ordinary matter (atoms and molecules) is made up of protons, neutrons and electrons

- Over 99.9% of the atom's mass is concentrated in the nucleus

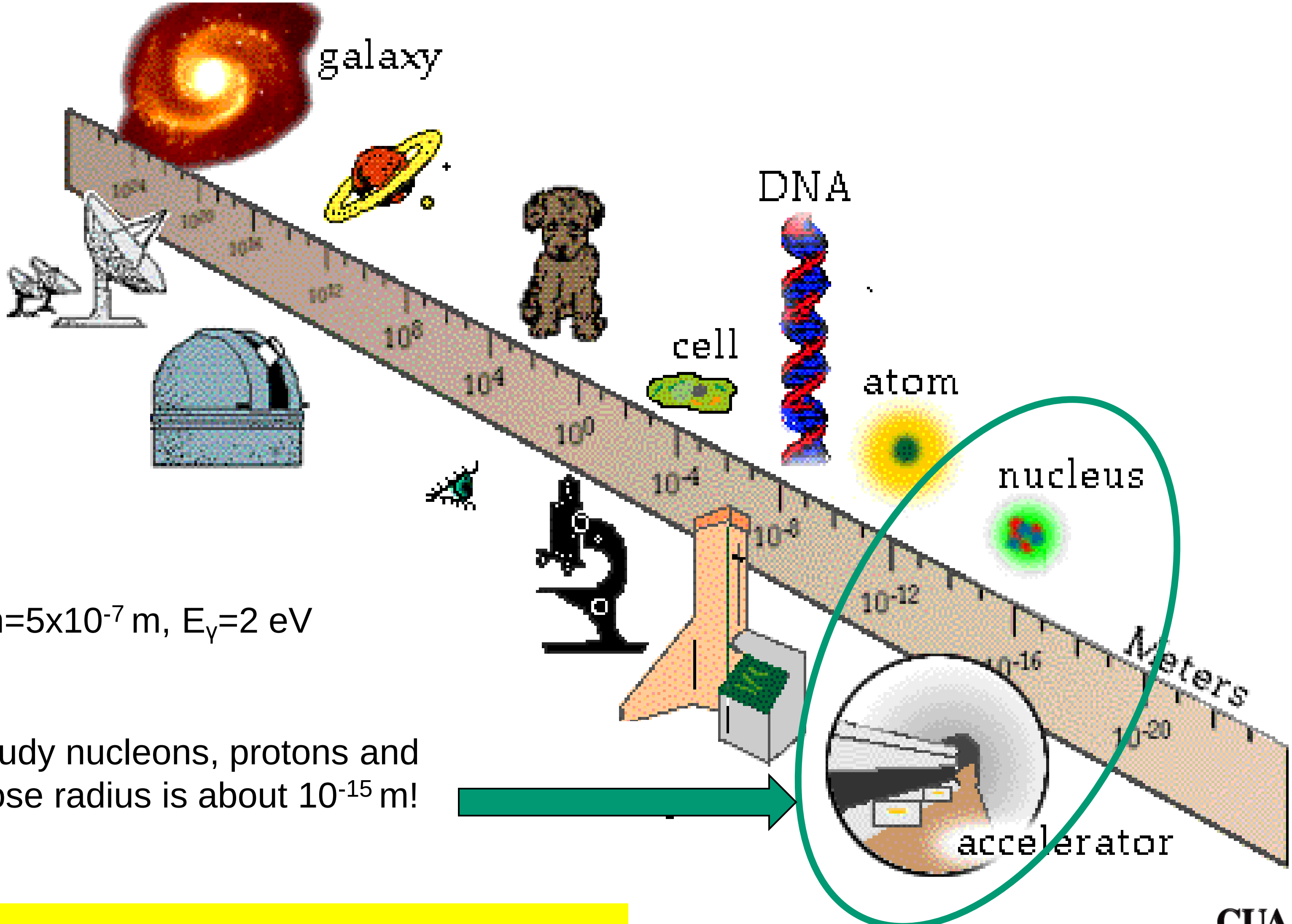
- The proton internal structure is complex
  - No exact definition for quantum mechanical reasons
  - Typically use concept of mass, energy, and particles



We want to understand the structure of matter
The proton's substructure, including the quarks inside a proton and the workings of the force that binds them.

CUA

How do we *see* different size objects:



- Visible light:
  → λ=500 nm=5x10^{-7} m, E_γ=2 eV

- We want to study nucleons, protons and neutrons, whose radius is about 10^{-15} m!

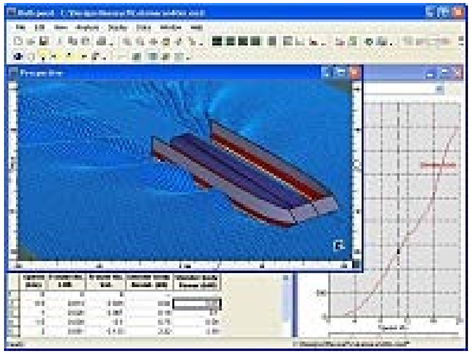
Need photons with E=1 keV·nm/λ=10^9 eV=1 GeV!

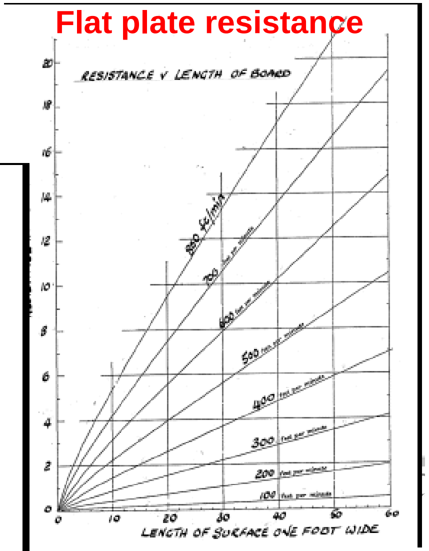
Concept: Form Factors

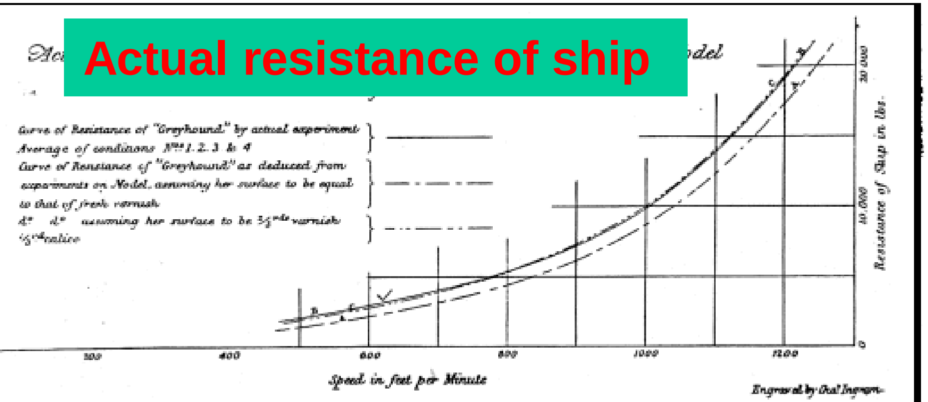
- An example from hydrodynamics: design of a ship's hull
  - Need to calculate the resistance for different geometries

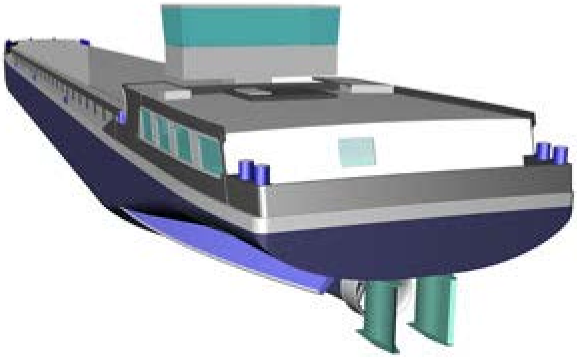
- Factorize the total resistance into parts that contain
  - calculable effects, e.g., skin friction of a flat plate
  - information about the three dimensional nature of the specific hull under consideration

- Form factor represents the effect of the deviation from the flat plate

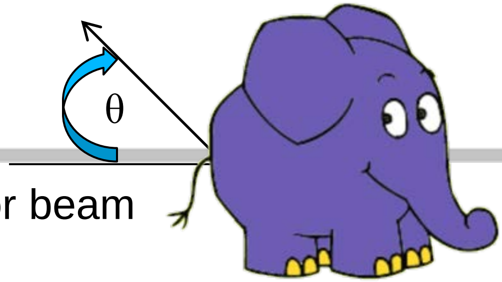








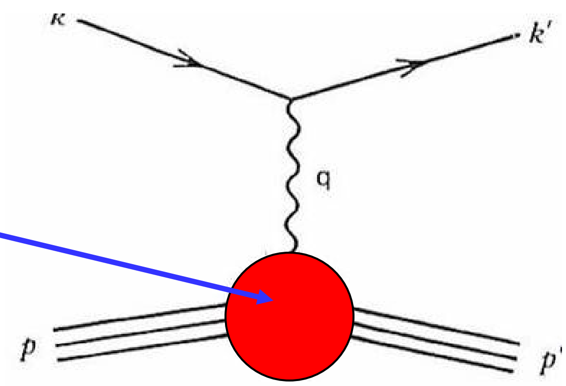
Elastic Form Factors



Scattering cross section, dσ= probability for beam particles to scatter by an angle θ

- The elastic scattering cross section can be factorized into that of a point object and a part that gives information about the spatial distribution of the constituents

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{point object}} \times |F(Q^2)|^2$$



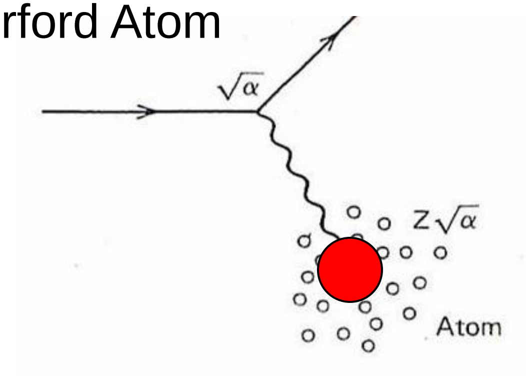
- The spatial distribution (form factor) is a Fourier transform of the charge distribution

$$F(Q^2) = \int \rho(r) e^{iq\cdot r/\hbar} d^3r$$

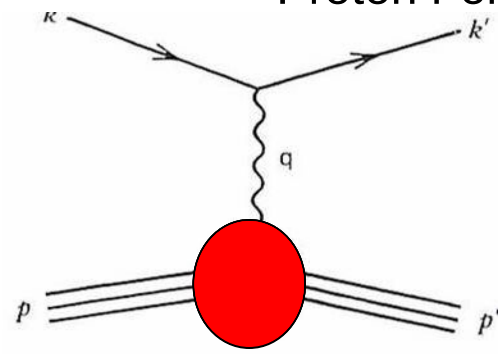
- *Spin 0 mesons (π^+, K^+)* have electric charge form factor only
  - Spin ½ nucleons have electric and magnetic form factors

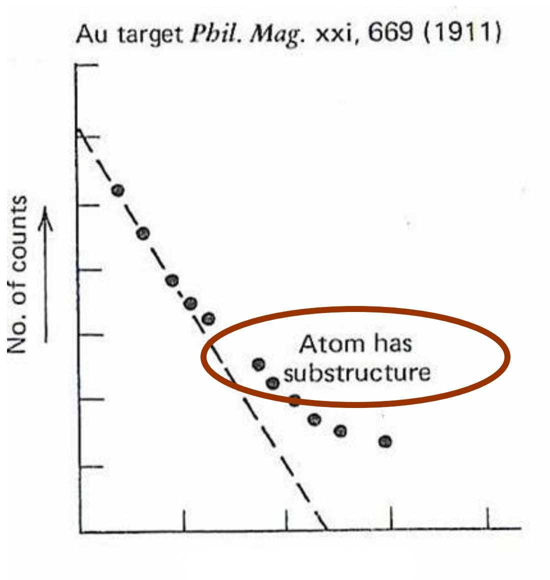
Atomic and Nuclear Substructure

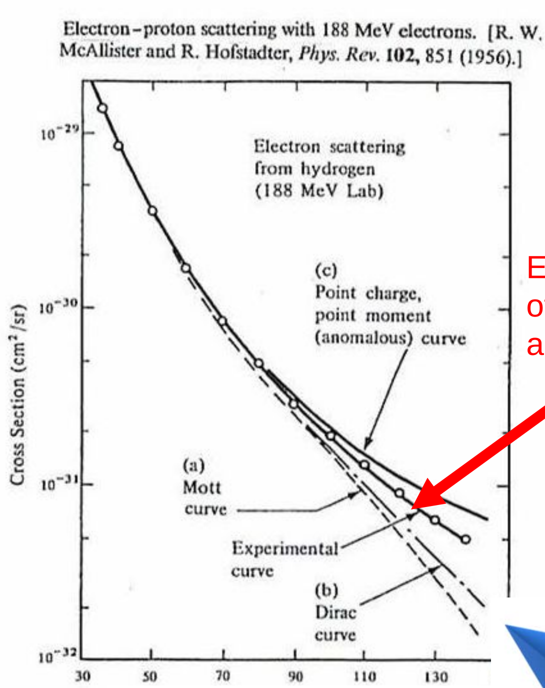
Rutherford Atom



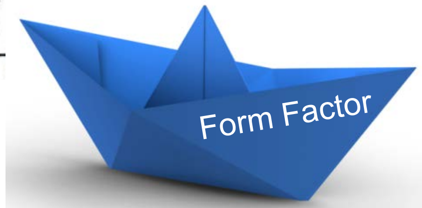
Proton Form Factor







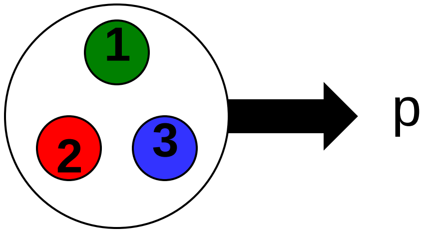
Experimental curve falls off faster than the one for a point charge

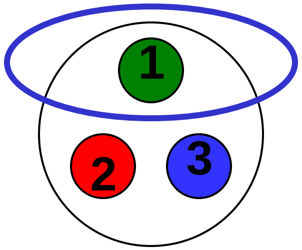


Nucleon with some momentum

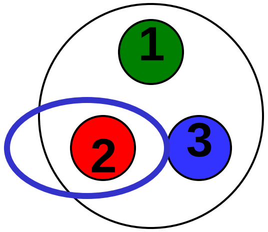
- Now that we know how to measure the spatial distribution of quarks in the nucleon, what about their momentum?

- x is the fraction of longitudinal momentum carried by a quark in a nucleon momentum moving quickly to the right





$x = P_1/p$

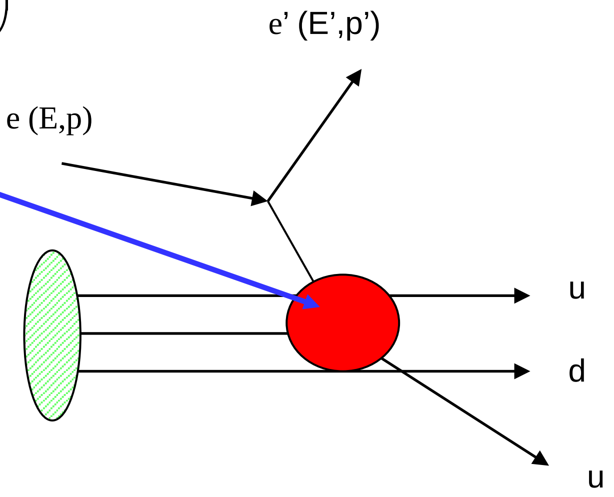


$x = P_2/p$

Deep Inelastic Scattering

- Cross section can be factorized into that of a point object and a part that gives information about the momentum distribution of the constituents in the nucleon

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



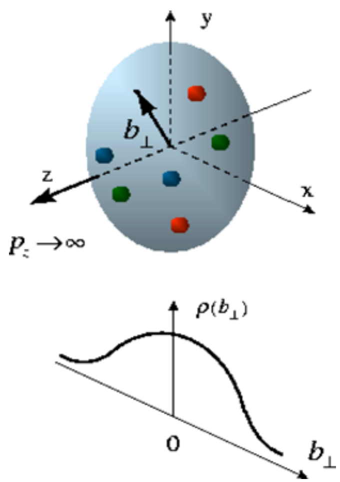
- The longitudinal momentum distribution is given by the *quark distribution functions*

$$F_2 = F_2(x) = x\sum_i e_i^2(q_i(x) + \bar{q}_i(x))$$

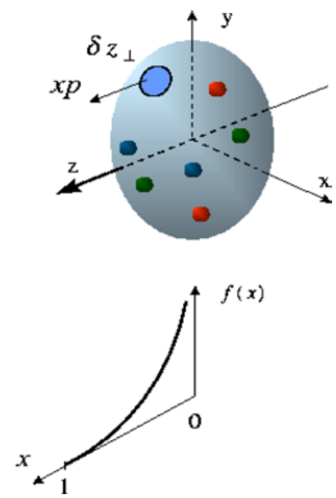
By measuring quark distribution functions, one cannot say anything about the momentum fraction perpendicular to the direction of motion

Studies of the Nucleon

Form Factors
Transverse spatial size of the nucleon



Parton Distributions (PDFs)
Longitudinal momentum distribution

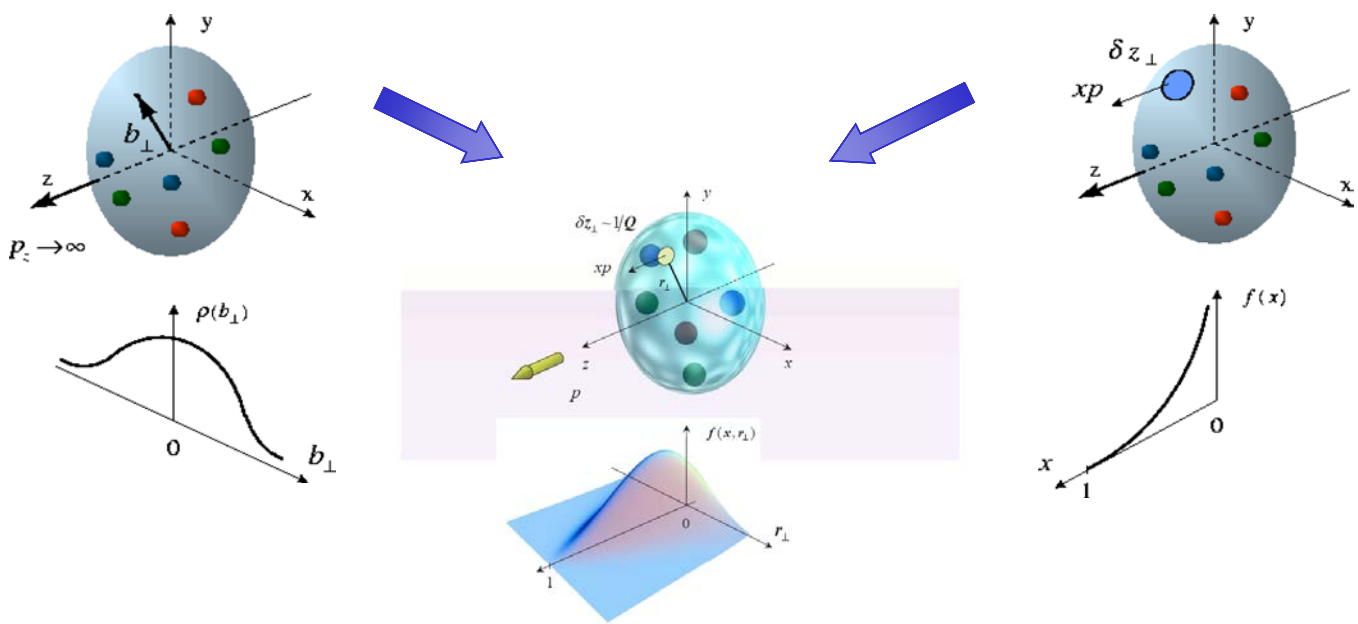


- How can we learn about the transverse spatial distribution of partons?
  - Processes for this other than elastic and inclusive scattering?

Studies of the Nucleon

Form Factors
Spatial size of the nucleon

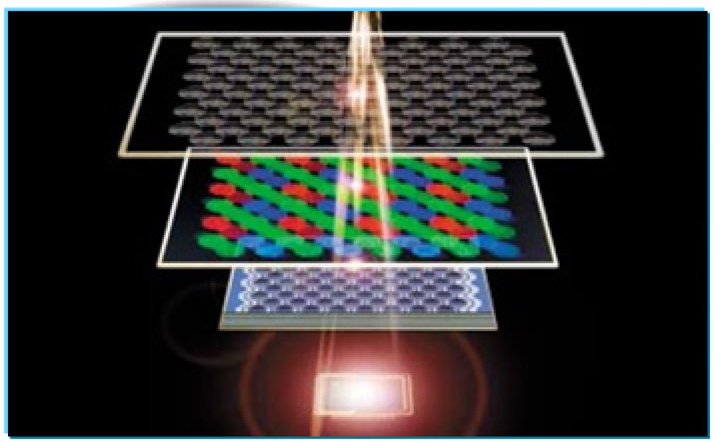
Parton Distributions (PDFs)
Longitudinal momentum distribution



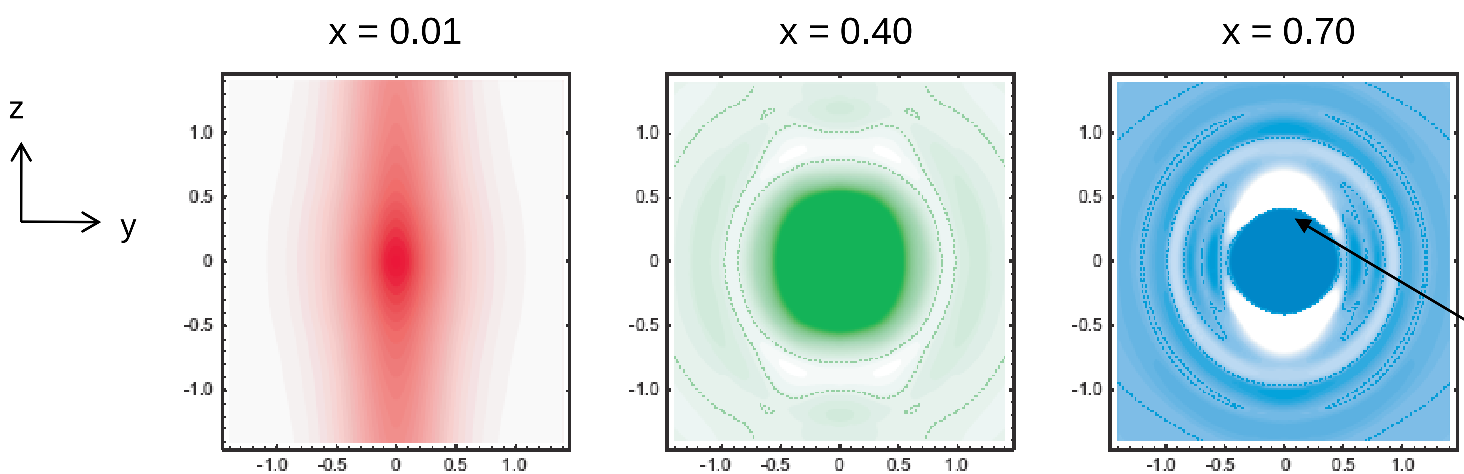
Generalized Parton Distributions (GPDs)
Transverse spatial distribution of quarks with longitudinal momentum fraction x

GPDs "unify" form factors and parton distributions

Generalized Parton Distributions (GPDs)



- Wigner quantum phase space distributions provide a simultaneous, correlated, 3-dimensional description of both the position and momentum.
- They are the closest analogue to a classical phase space density allowed by the uncertainty principle.



Pictures show transverse plane for different quark momentum fractions x

Interference pattern

Wigner distributions provide the language for the Generalized Parton Distributions (GPDs), which allow us to create a complete map of the behaviour of partons (quarks and gluons) inside of the nucleon.

Some GPD references

GPD reviews:

A. Belitsky and A. Radyushkin, hep-ph/0504030

M. Diehl, hep-ph/0307382

K. Goeke, hep-ph/0106012

GPD original papers:

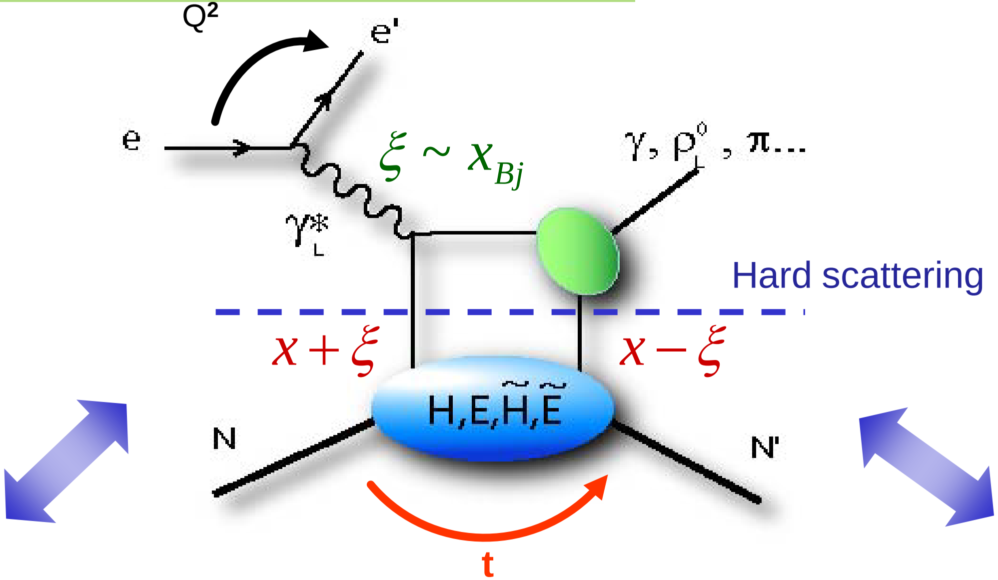
D. Mueller, hep-ph/9812448

X. Ji, hep-ph/9603249

A. Radyushkin, hep-ph/9704207

M Burkardt, hep-ph/0005108, hep-ph/0207047

Limits of GPDs



Form Factors

$$\int_{-1}^{+1} dx\, H^q(x,\xi,t) = F_1^q(t) \qquad \int_{-1}^{+1} dx\, \tilde{H}^q(x,\xi,t) = g_A^q(t)$$

$$\int_{-1}^{+1} dx\, E^q(x,\xi,t) = F_2^q(t) \qquad \int_{-1}^{+1} dx\, \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

PDFs

$$H^{q,g}(x,\xi=0,t=0) = q(x)$$

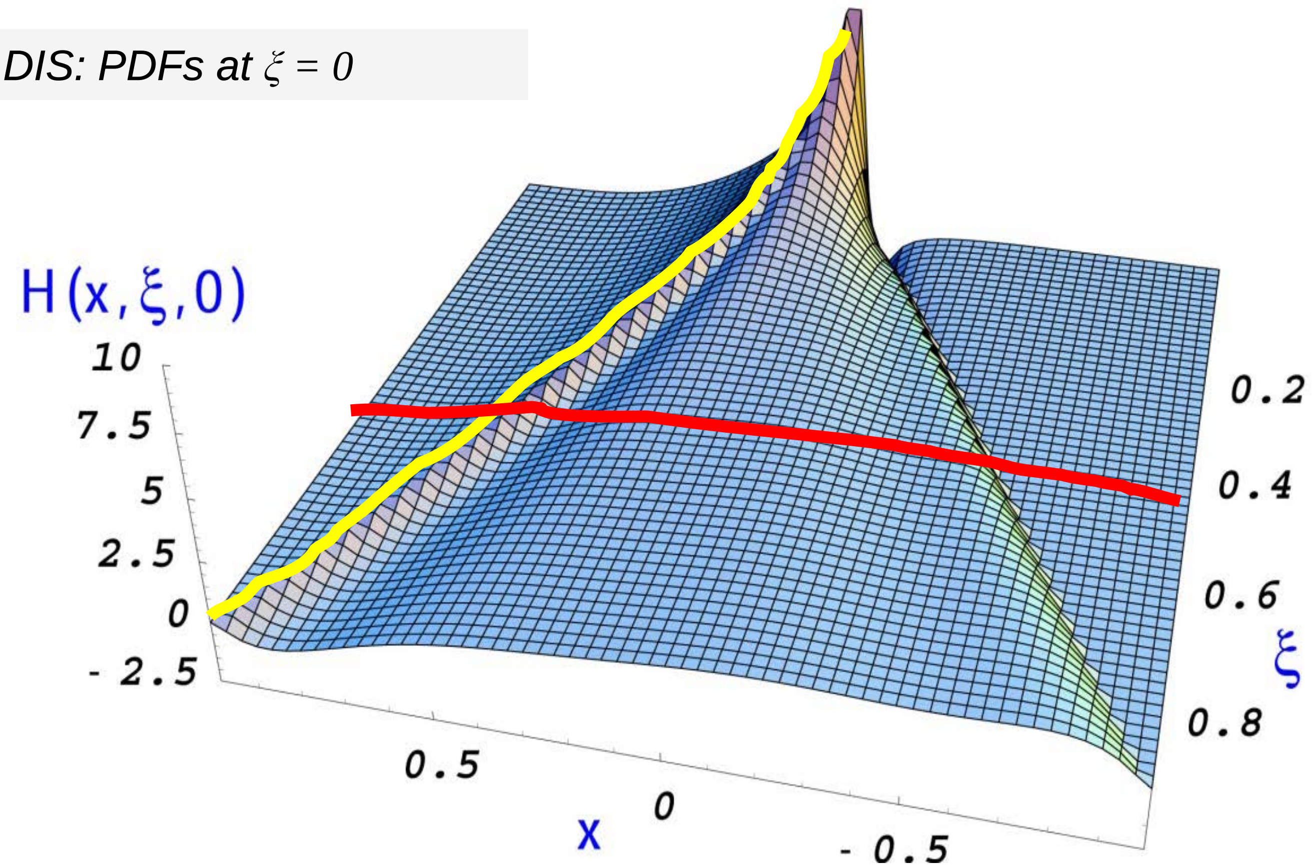
$$\tilde{H}^{q,g}(x,\xi=0,t=0) = \Delta q(x)$$

$E, \tilde{E}$: *nucleon helicity flip:* don't appear in DIS

A good determination of the form factors is essential for modeling GPDs, in particular their t-dependence

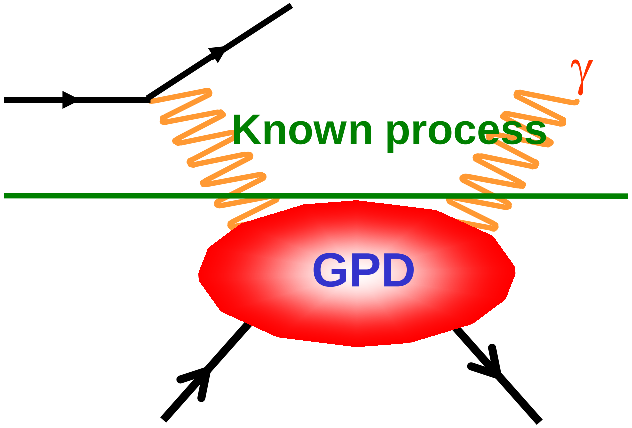
GPD model

DIS: PDFs at $\xi = 0$



Probing GPDs in the Nucleon

- Analogous to the form factor measurements, we need to find a process, which we can describe by factorizing it into:
  - a known part that we can calculate, and
  - one that contains the information we are after

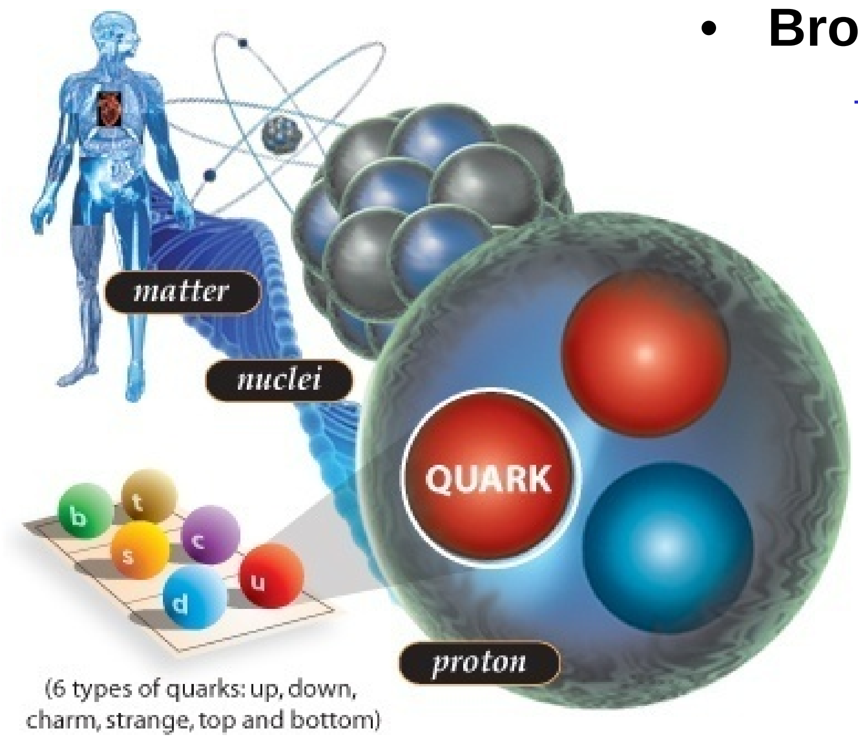


- For some reactions it has been proven that such *factorization* is possible, but only under very extreme conditions
  - In order to use them, one needs to show that they are applicable in "real life"

A decisive test is to look at the scaling of the cross section (interaction probability) as a function of Q^2, and see if it follows the QCD prediction for scattering from a cluster of point-like objects

Exploring the Strong Force

- The US has two nuclear physics labs exploring QCD



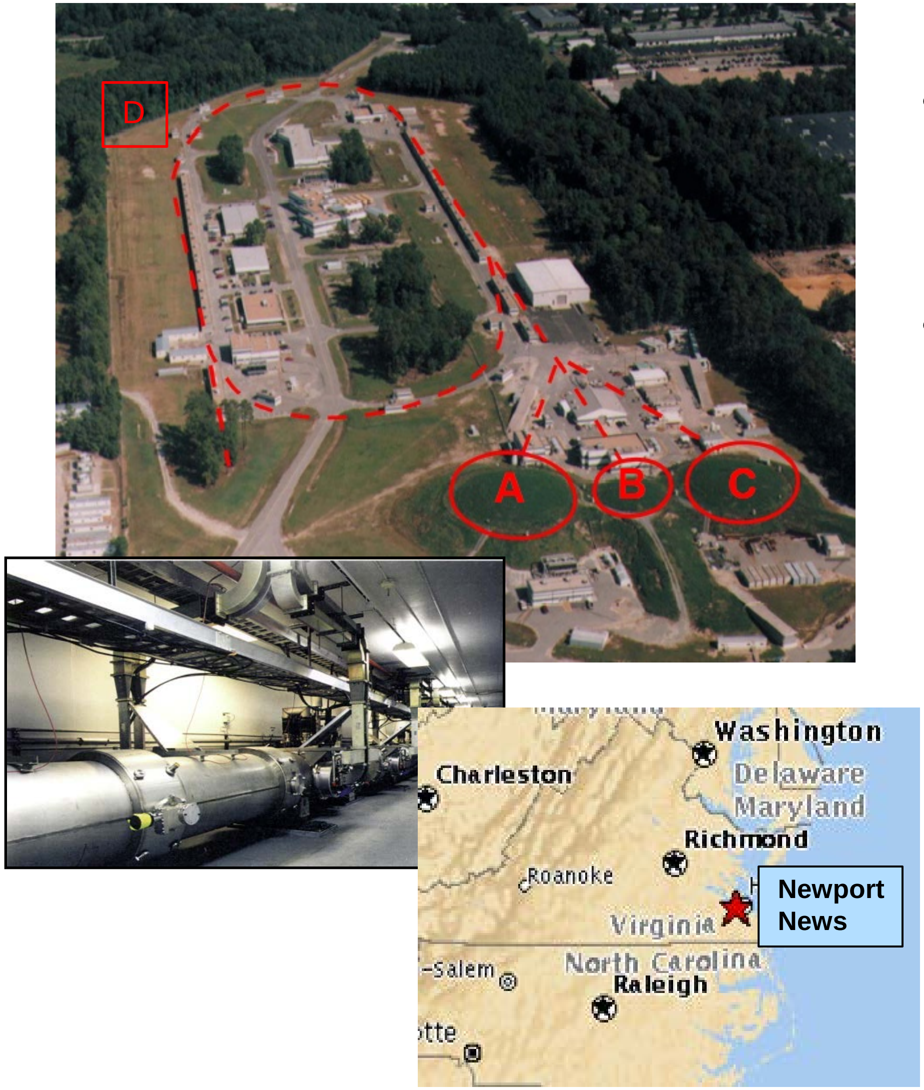
- **Brookhaven National Lab (BNL)**
  - *RHIC* takes us "back in time" to the point where there were no protons and neutrons (quark-gluon plasma) by smashing nuclei together.

- **Jefferson Lab (JLab)**
  - *CEBAF* provides precision measurements of the innermost structure of matter to reveal the secrets of confinement.

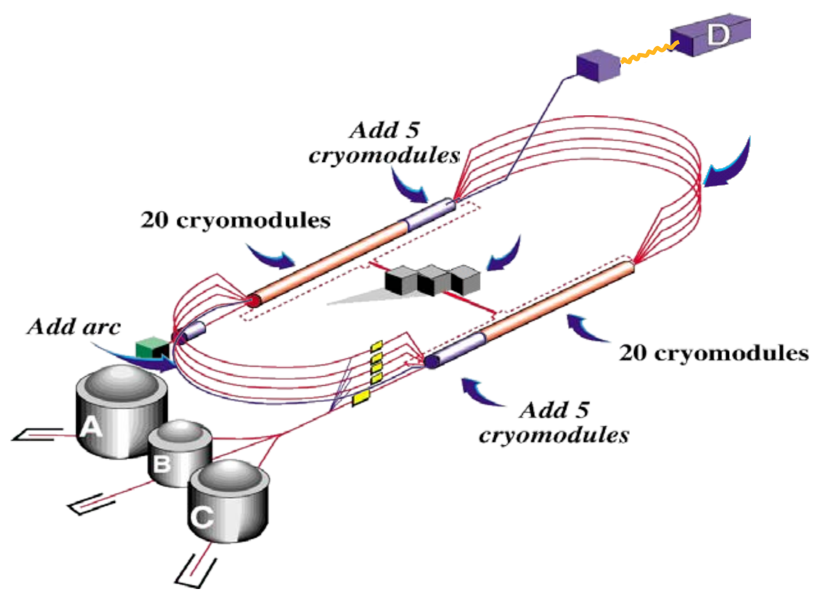
Experimental Physics

Soon I knew the craft of experimental physics was beyond me - it was the sublime quality of patience - patience in accumulating data, patience with recalcitrant equipment - which I sadly lacked. - *Abdus Salam*

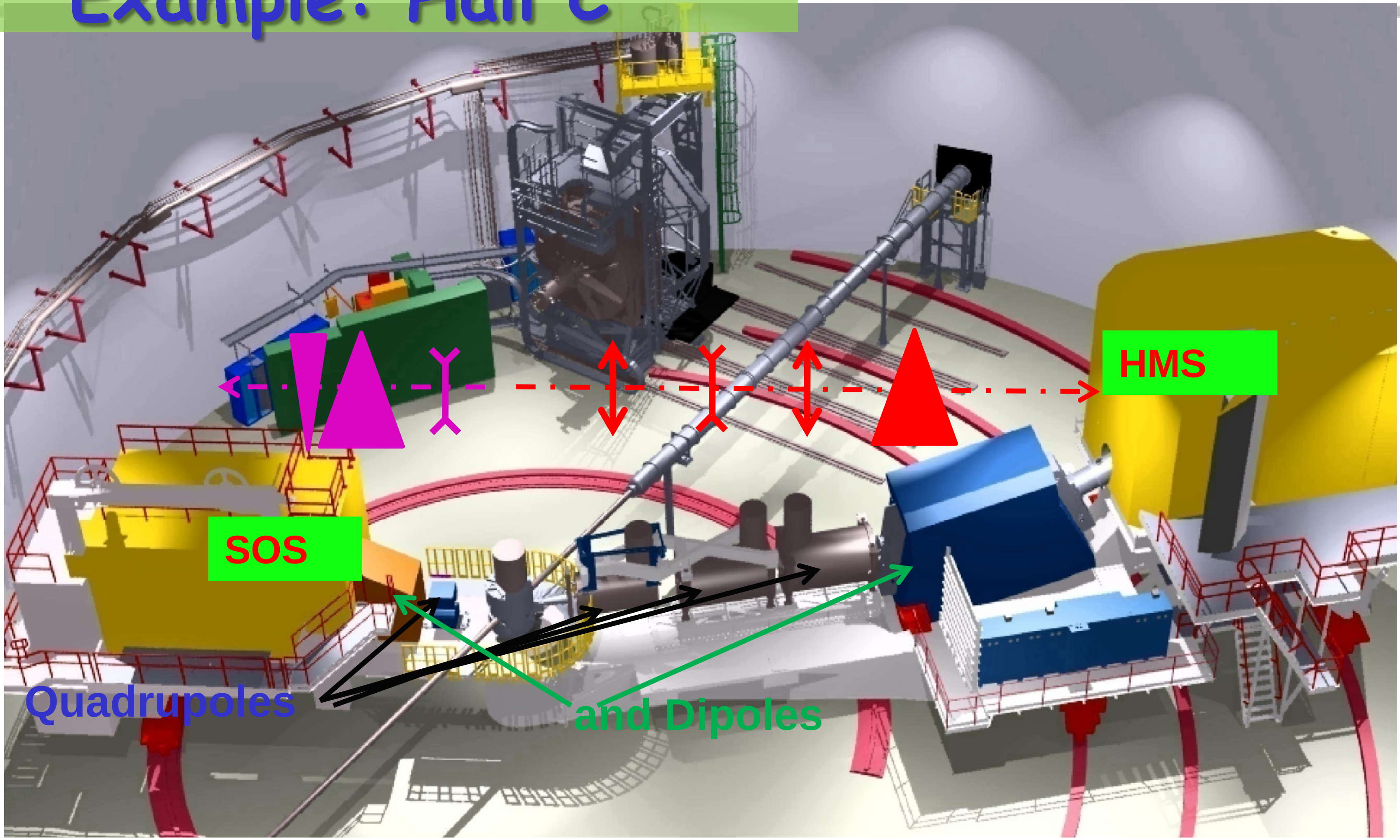
The facility: Jefferson Lab



- Superconducting accelerator provides 100% duty factor beams with energies up to 12 GeV – soon!
- Four experimental halls that can make measurements simultaneously



Experimental Setup Example: Hall C

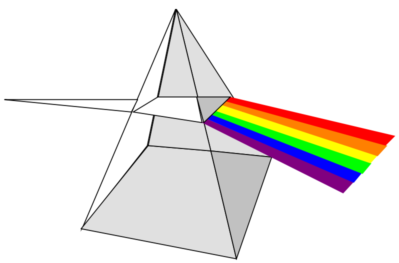


- Magnetic fields bend and focus beams of charged particles
- Hall C has two magnetic spectrometers for particle detection
- Electron beam interacts with hadrons in the cryogenic target

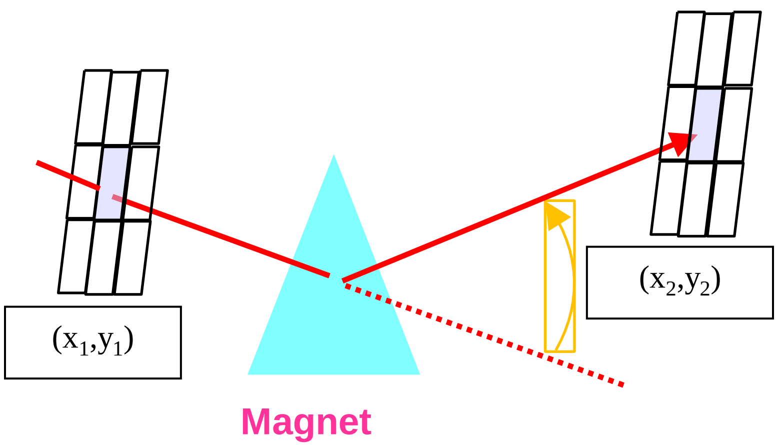
Particle Detector Example: a spectrometer

QQQD Design

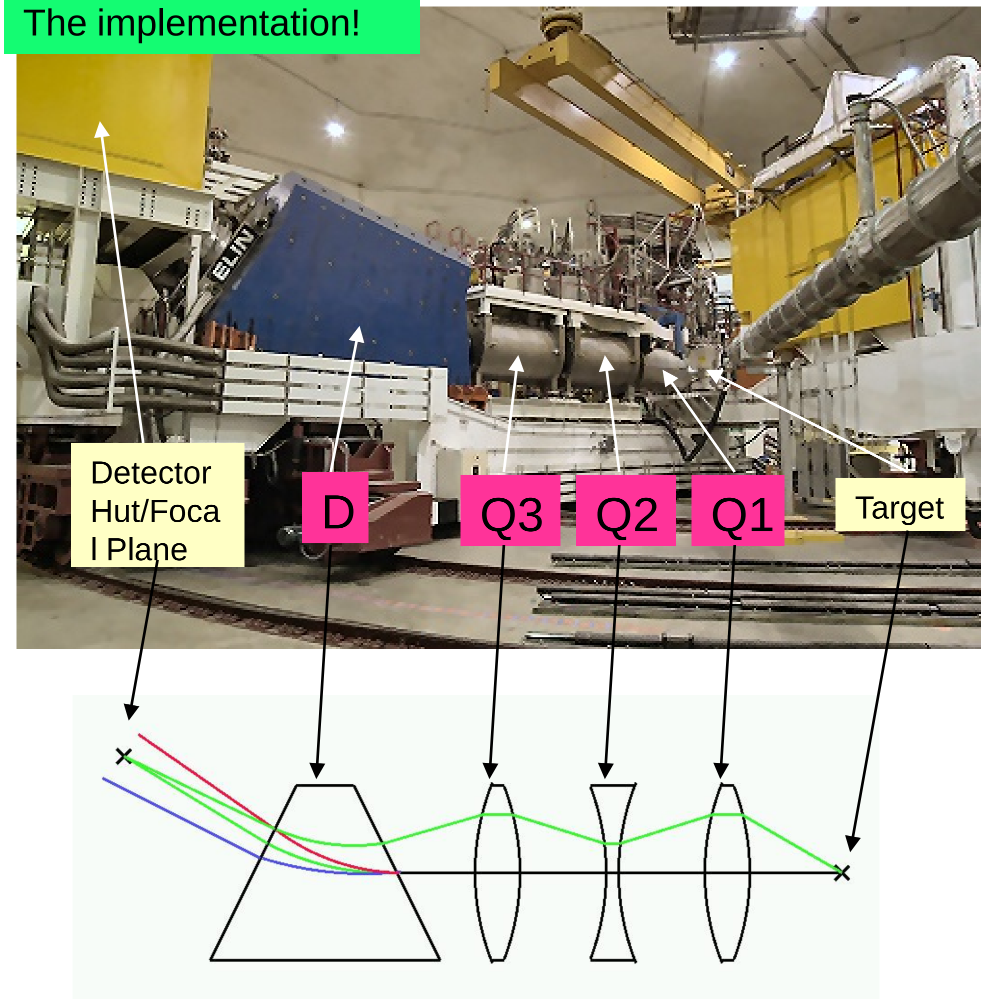
The concept



Light of different colors is bent differently by a prism

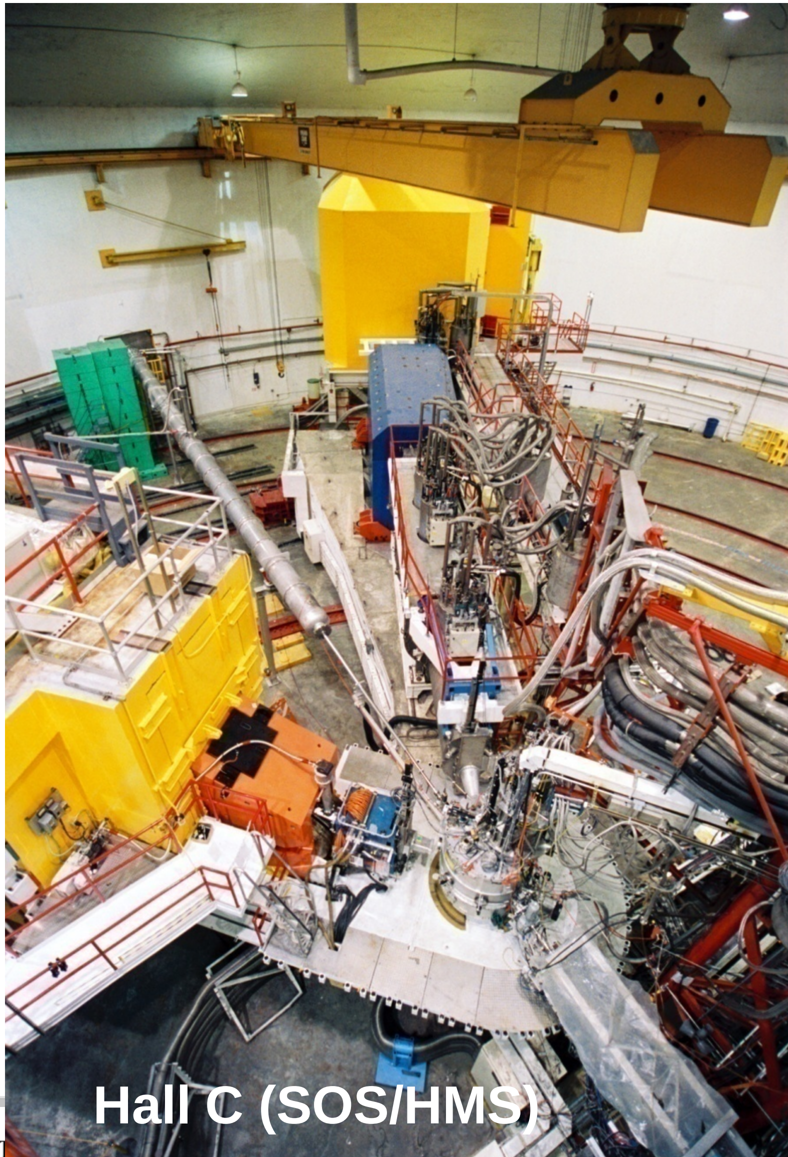


The implementation!

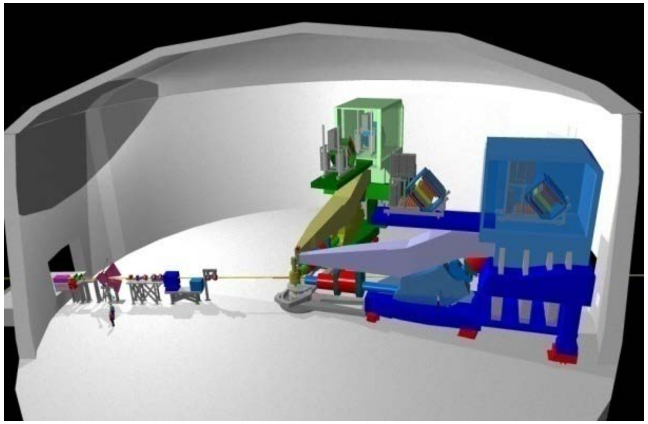


Nature lets us measure the momentum of a charged particle by seeing how much its path is deflected by a magnet

Jlab 6 GeV Experiment Equipment

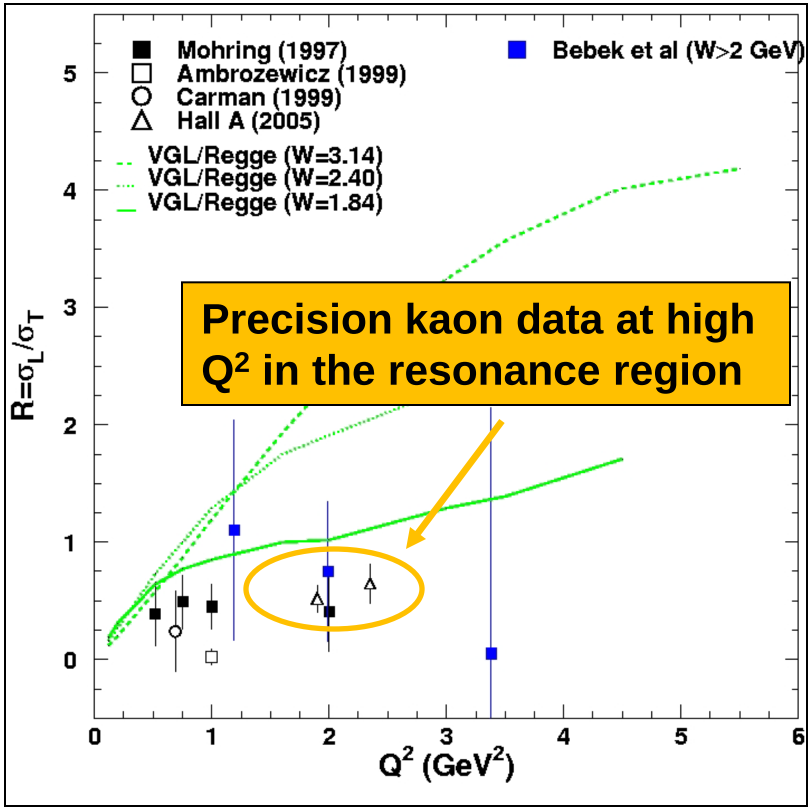


Experimental Hall A

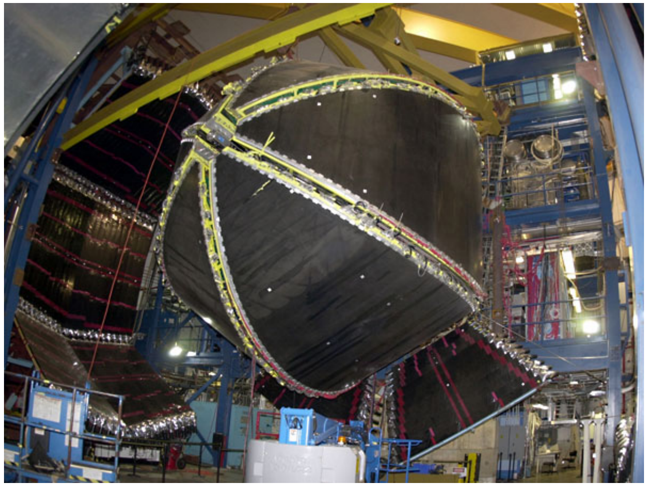


High Resolution Spectrometers (HRSs) detect particles with momenta up to about 4 GeV

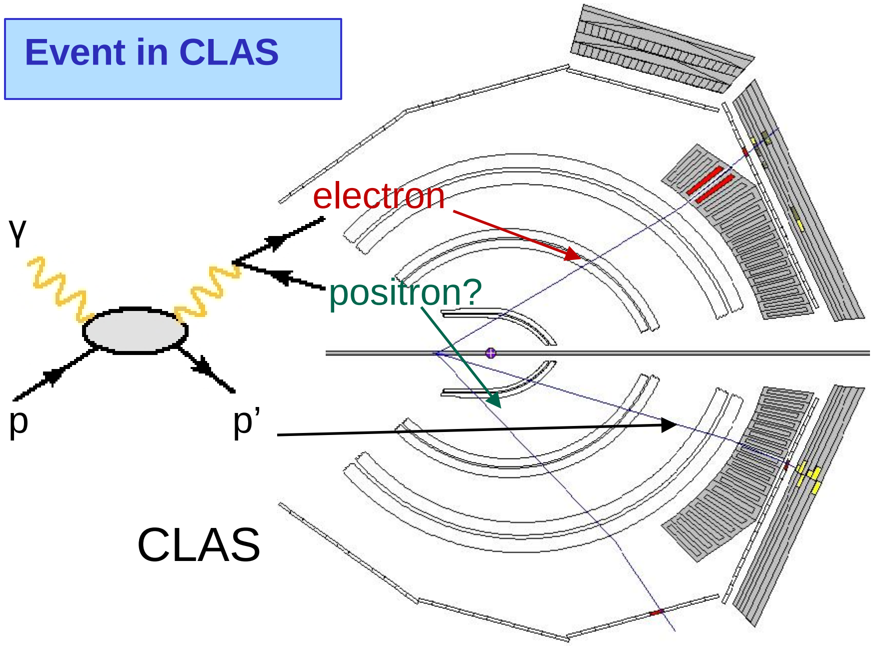
- Physics highlights:
  - Short range correlations
  - Hypernuclear spectroscopy
  - Nucleon form factors
  - Nucleon and meson structure
    - Compton scattering
    - Kaon production



Experimental Hall B

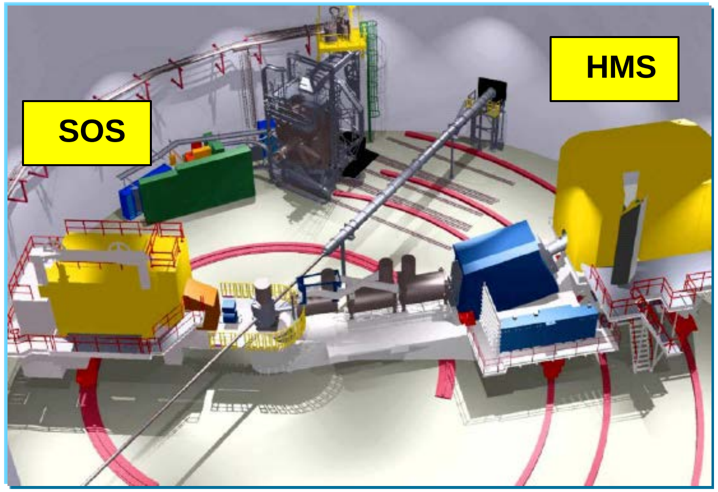


- Cebaf Large Acceptance Spectrometer (CLAS) is built around a large toroidal magnet
  - Various detectors allow for measurements of events with many different outgoing particles



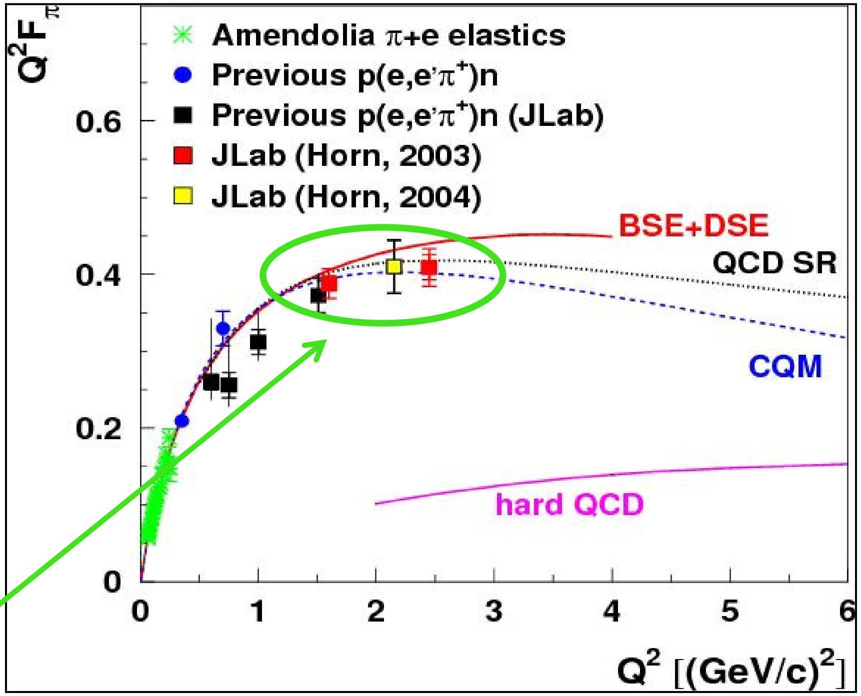
- Physics highlights:
  - First 3D images of the nucleon from Compton scattering
  - Baryon spectroscopy
  - Hadrons in the nuclear medium

Experimental Hall C



- Hall C has two magnetic spectrometers for particle detection
  - Short Orbit Spectrometer (SOS) for short lived particles
  - High Momentum Spectrometer (HMS) for high momentum particles

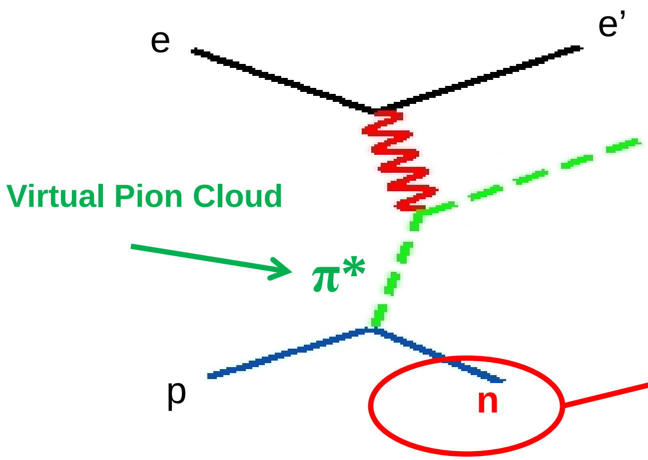
- Physics highlights:
  - The transition from hadrons to quarks
  - Strange quark content of the proton
  - Form factor of the pion and other simple quark systems

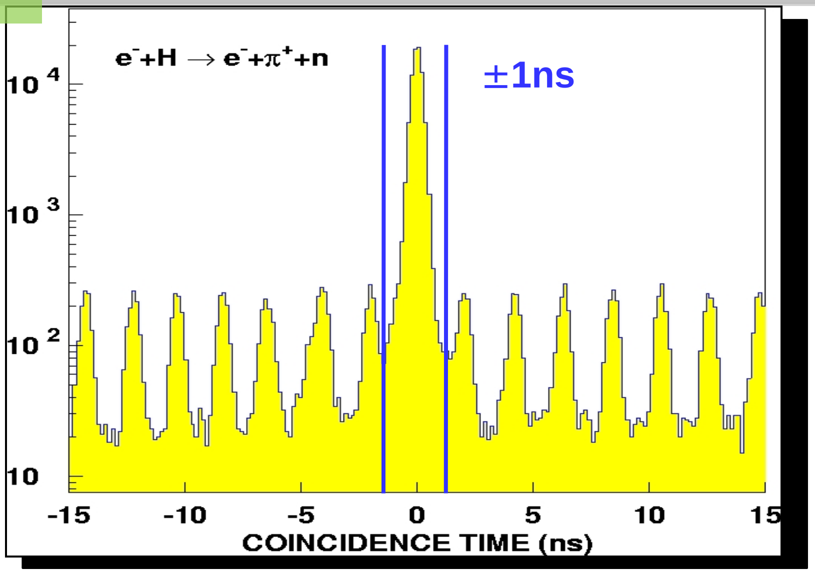


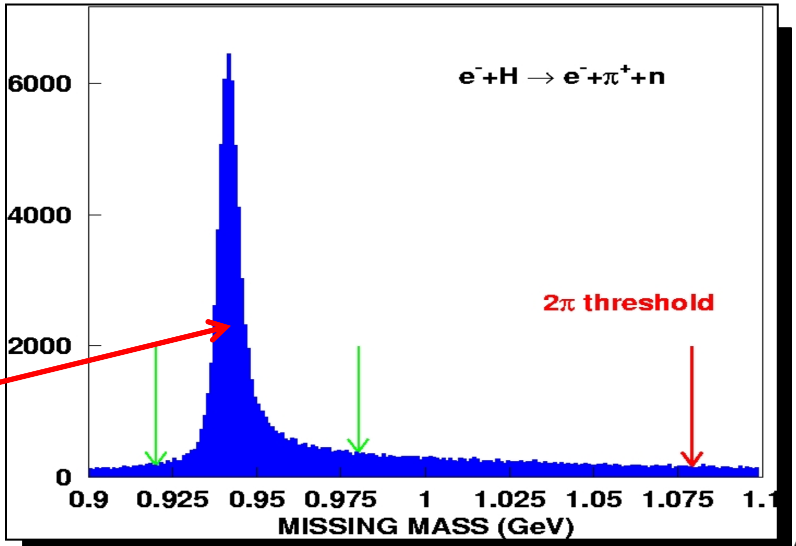
Highest Q^2 pion form factor data

e p → e'π⁺n Events

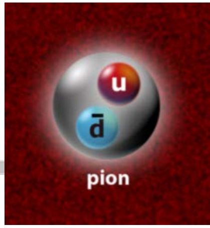
- The time difference between the HMS and SOS reveals the interaction from the reaction of interest
- Electron and π^+ are detected in the spectrometers
- The remaining neutron is identified through momentum and energy conservation





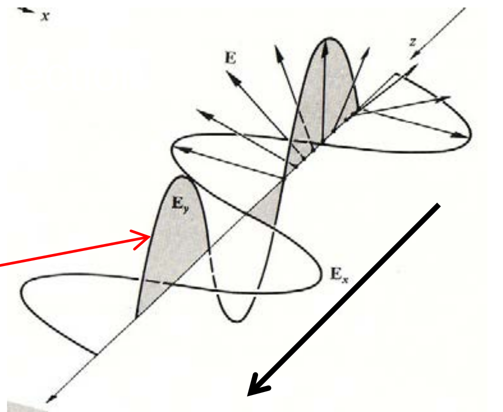


Pion and Kaon Electroproduction



- The photon in the e p → e' π^+ n reaction can be in different polarization states, e.g. along or at 90° to the propagation

- The interaction probability includes all possible photon polarization states



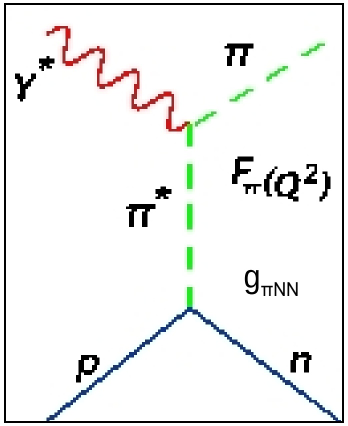
"Transverse Photons"

$$2\pi \frac{d\sigma}{dt\,d\phi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon\,(1+\varepsilon)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

"Longitudinal Photons"

- Longitudinal photons have no classical analog (must be virtual)
  - Dominate at high Q^2 (virtuality)

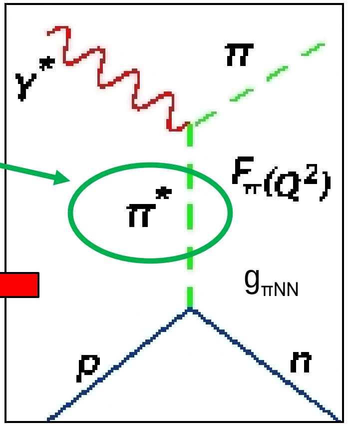
- Interference terms are also allowed in this quantum mechanical system



Pion and Kaon Form Factors

- At low $Q^2<0.3$ GeV^2, F_π and F_K can be measured exactly using the high energy π^+/K^+ scattering from atomic electrons *[S.R. Amendolia et al., NP **B277** (1986)]*

- No "free pion" target, so to extend the measurement to larger Q^2 values, must use the "virtual pion cloud" of the proton



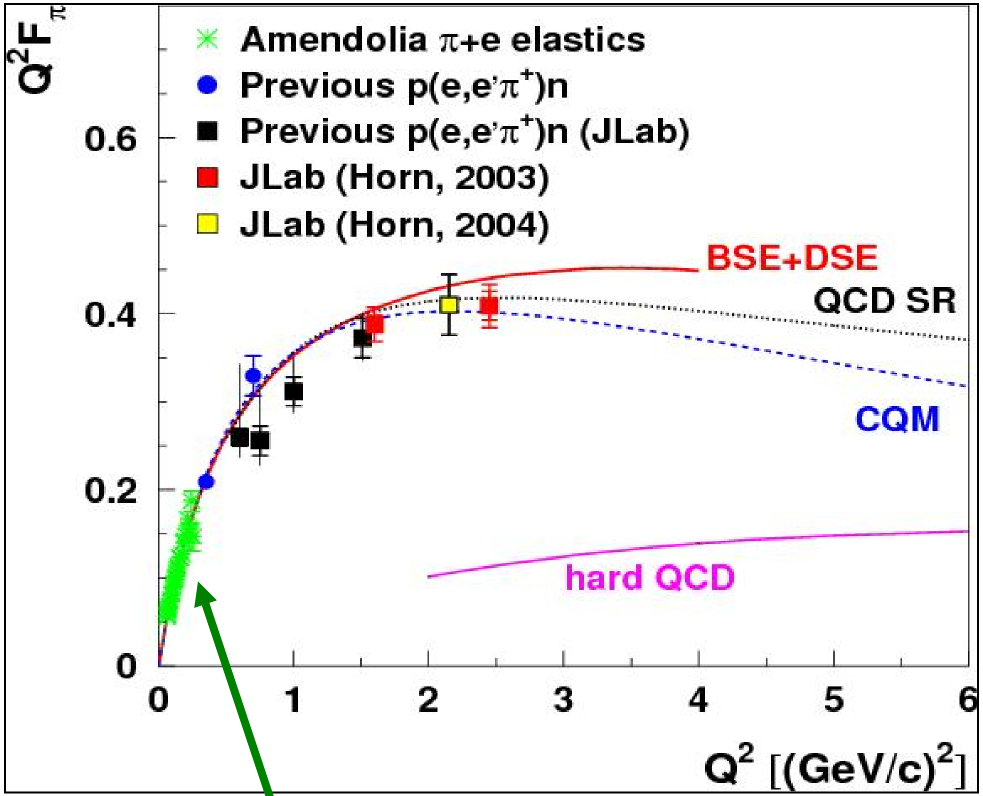
$$2\pi\frac{d\sigma}{dt\,d\varphi}=\frac{d\sigma_T}{dt}+\varepsilon\frac{d\sigma_L}{dt}+\sqrt{2\varepsilon(1+\varepsilon)}\frac{d\sigma_{LT}}{dt}\cos\varphi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\varphi$$

$$\varepsilon=\left[1+2(1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}$$

$$\boxed{\frac{d\sigma_L}{dt}\propto\frac{-t\,Q^2}{(t-m_\pi^2)}\,g_{\pi NN}^2(t)\,F_\pi^2(Q^2,t)}$$

The Pion Form Factor: spatial quark distribution

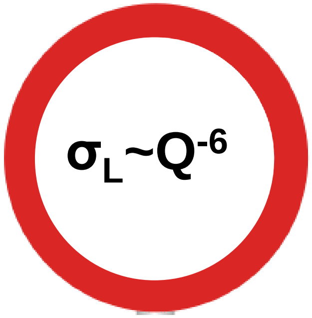
- Highest possible value of Q^2 with 6 GeV beam at JLab
- At low Q^2: good agreement with elastic data
- At higher Q^2 many models describe the data
  - How do we know which one is right?



300 GeV π+e elastic scattering data from CERN SPS

Now let's move on to the more general measurement….

Watch out for speed traps…



In order to combine the spatial and momentum distributions of quarks in the nucleon in our studies of the pion, we still need to check if the factorization conditions hold