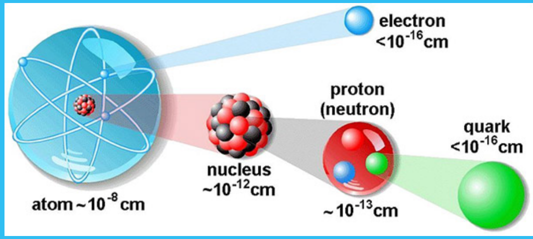
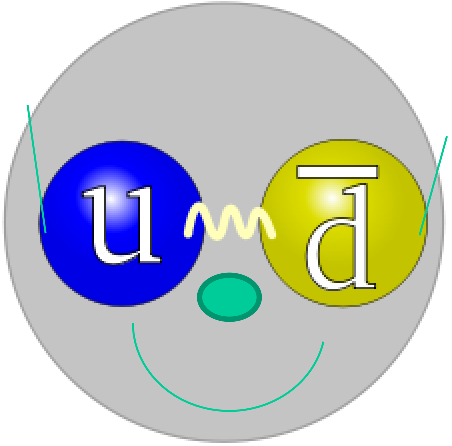
Nucleon Structure – 3D!

Tanja Horn





Paul the Pion

THE CATHOLIC UNIVERSITY of AMERICA

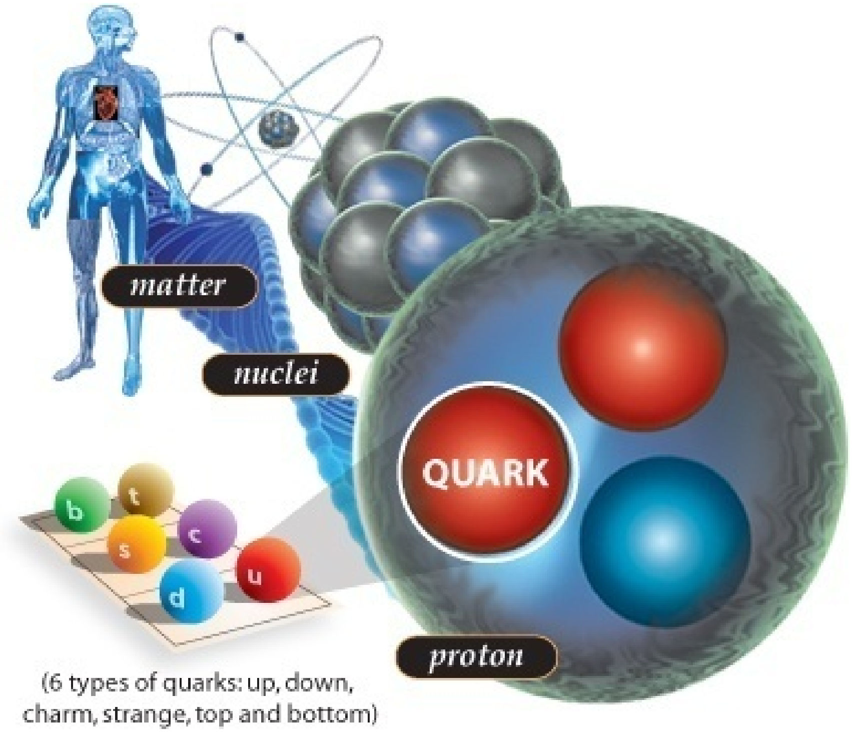
HUGS Summer School

Jefferson National Laboratory

Lecture 1 of 6

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

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

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	$<1\times10^{-8}$	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

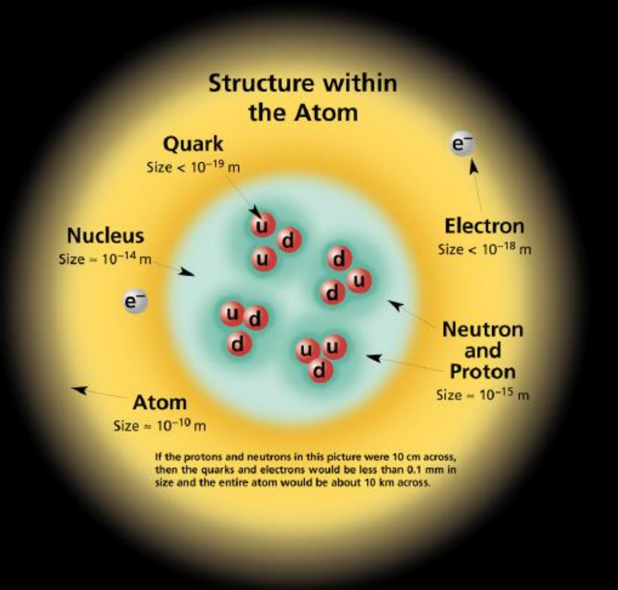
Quarks spin = 1/2

Flavor	Approx. Mass GeV/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

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

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

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

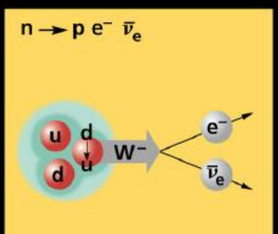
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

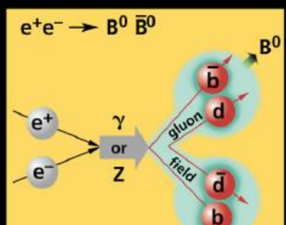
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

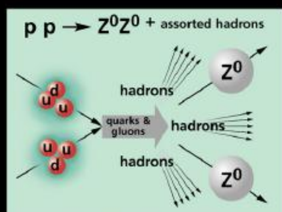
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
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Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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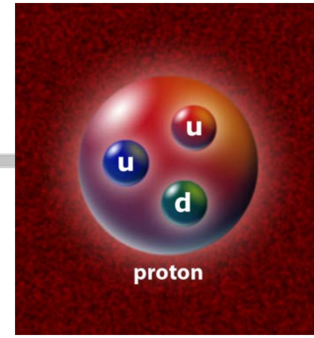
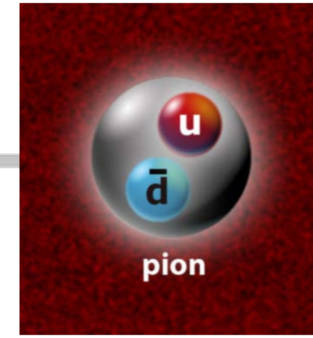
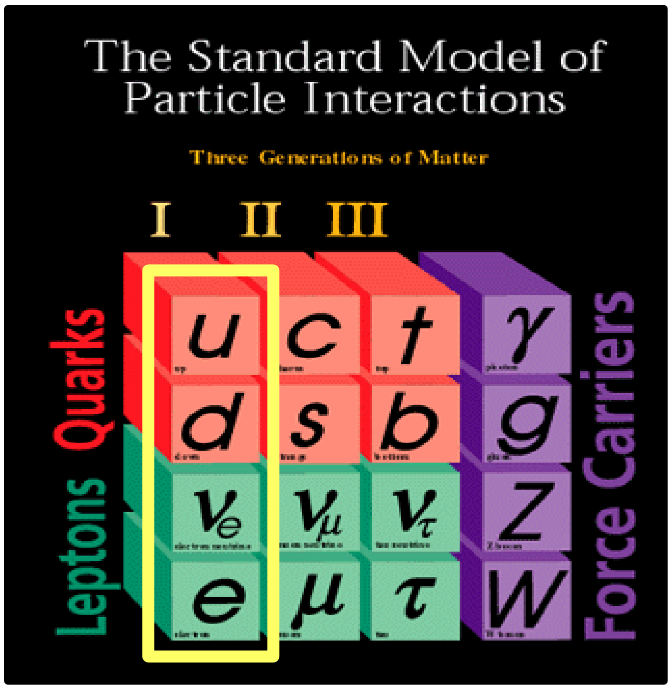
http://CPEPweb.org





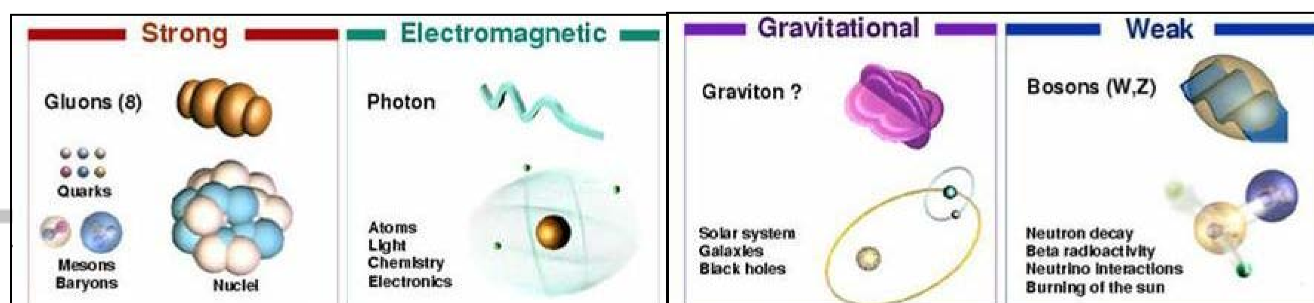


1. Fermions are the building blocks

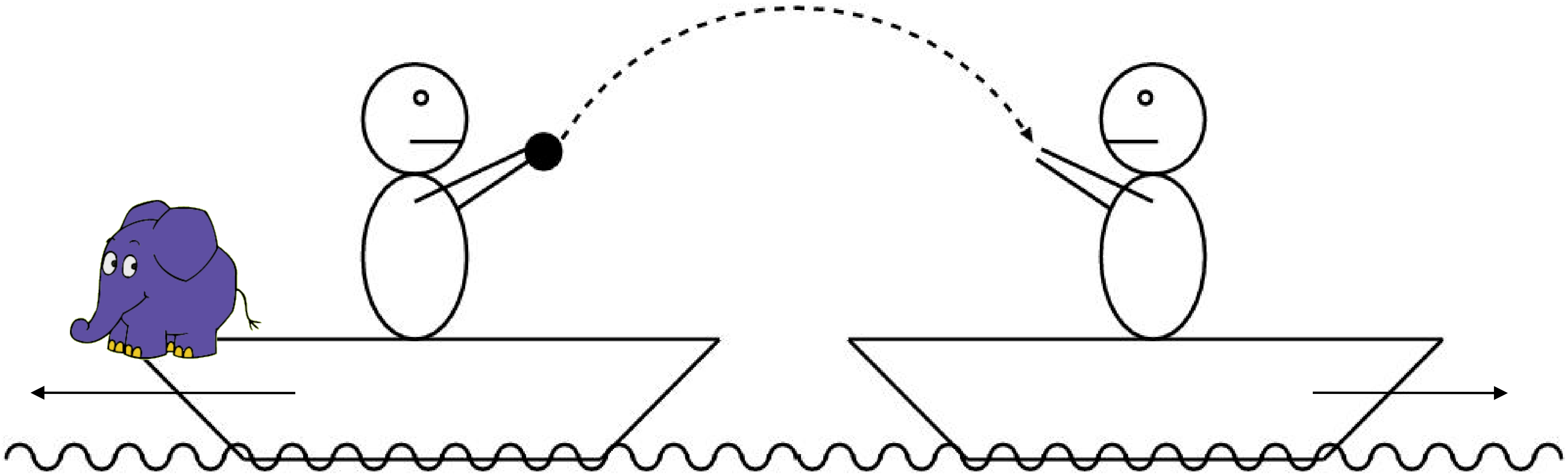
- Conserve particle number
- Try to distinguish themselves from each other by following the Pauli principle

2. Bosons form the force carriers that keep it all together

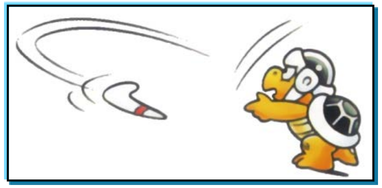
- electromagnetism, gravity, weak, strong



Concept: Virtual Particles as Force Carriers



- Exchanged (thrown) particles can create repulsive and attractive forces
  - for the latter, consider throwing a boomerang in the other direction!

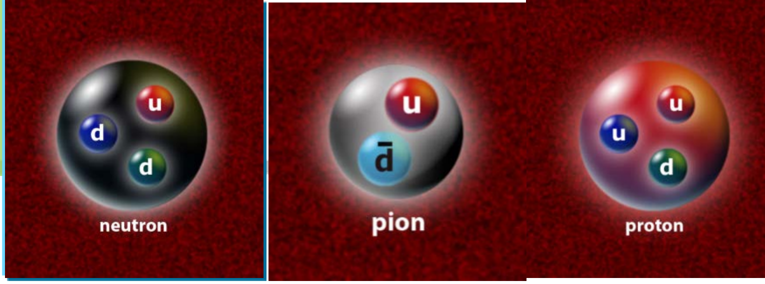


- These particles are not real, but virtual, created from the vacuum

- The brief existence of virtual particles is allowed by the Heisenberg uncertainty principle
  - Even elephants may show up, if they disappear quickly enough!

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

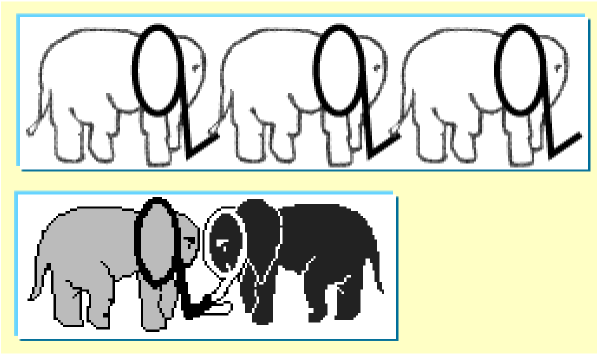
The building blocks: Hadrons



- Hadrons are composed of quarks with:
  - ✓ *Flavor*: u, c, t (charge +2/3) and d, s, b (charge -1/3)
  - ✓ *Color*: R, G, B
  - ✓ *Spin*: ½ (fermions)

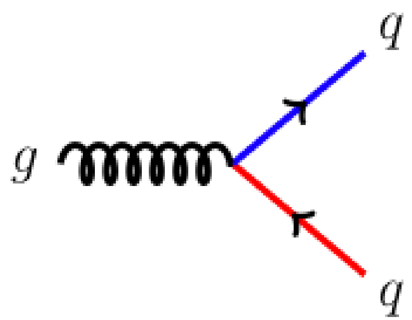
Up +2/3 +1/2	Charm +2/3 +1/2	Top +2/3 +1/2
Down -1/3 +1/2	Strange -1/3 +1/2	Bottom -1/3 +1/2

- Two families of hadrons:
  - ✓ Baryons: valence *qqq*
  - ✓ Mesons: valence $\bar{q}q$

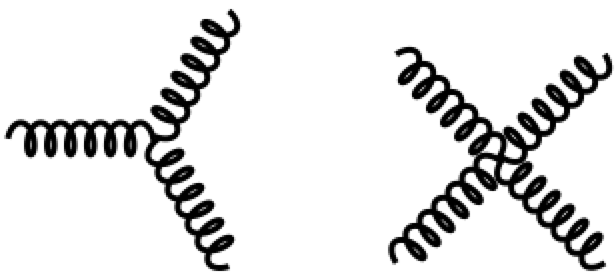


QCD vs. QED Differences

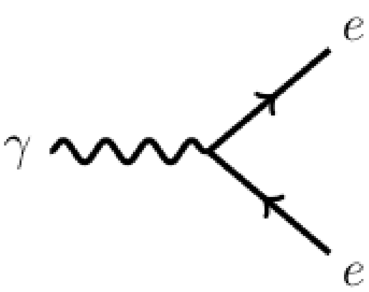
- Gluons are the messengers for the quark-quark interactions
  - Quantum Chromo Dynamics (QCD) is the theory that governs their behaviour



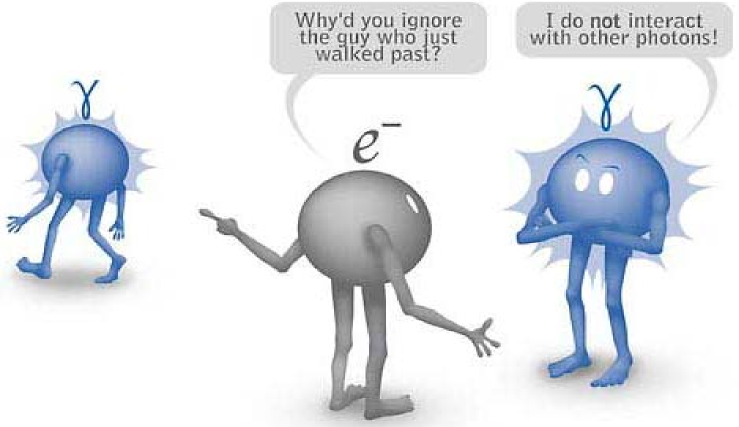
- Gluons carry color charge, and we can we draw 3- and 4-gluon diagrams (self-interaction)



- Photons are the messengers for the electromagnetic interactions
  - Quantum Electro Dynamics (QED) is the theory that governs their behaviour



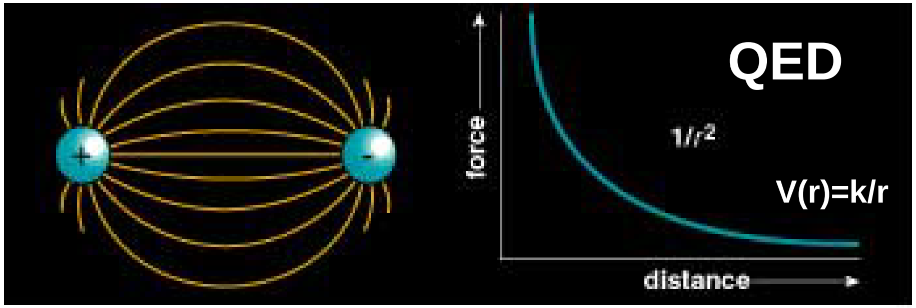
- Photon do not carry charge



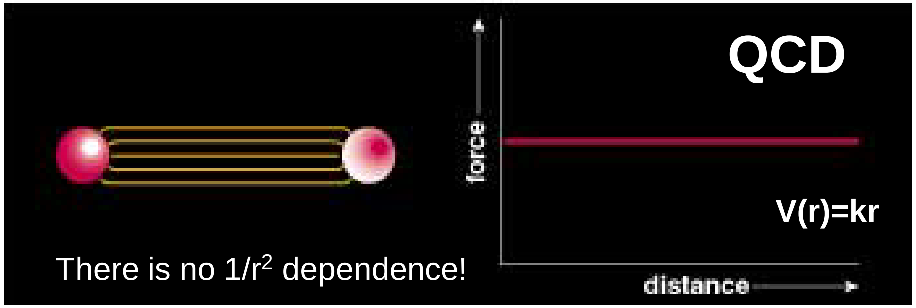
Dynamics of the Strong Force

- The strong force does not get weaker with large distances (opposite to the EM force), and blows up at distances around 10^{-15} m, the radius of the nucleon

> ➢ We never see a free quark



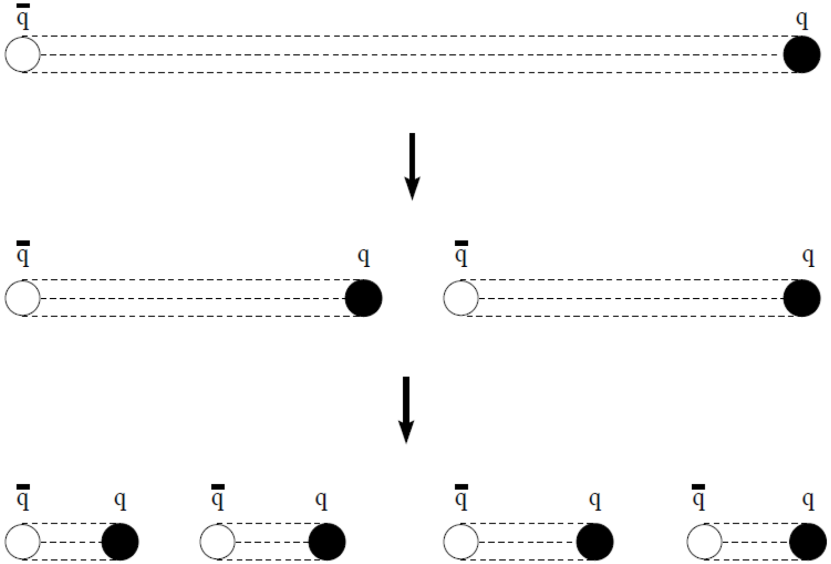
- Has a property called *confinement:*
  - at low energy, when the distance between two charges increases, a flux tube is formed.
  - *Quarks behave independently when they are close, but they cannot be pulled apart. An unprecedented hypothesis: Confinement! (Wilczek, 2004)*

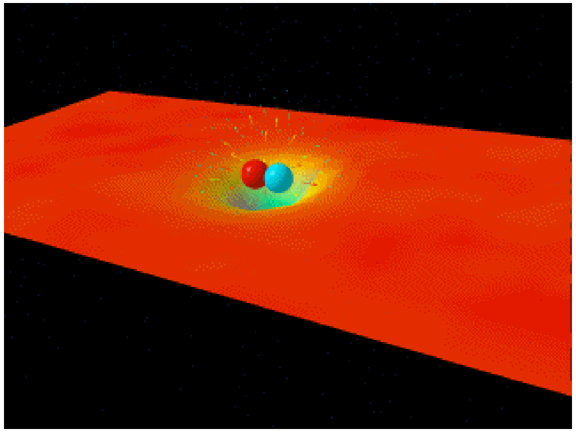


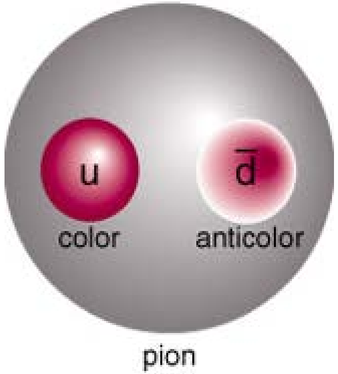
> ➢ Only colour neutral particles can thus exist!

Dynamics of the Strong Force

- Eventually the potential energy will create a new quark-antiquark pair in the middle of the tube, which breaks, forming two particles.



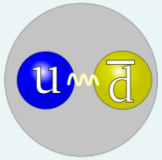




✓ This also shows the attraction of colour and anti-color carried by quarks and antiquarks which can form particles called mesons.

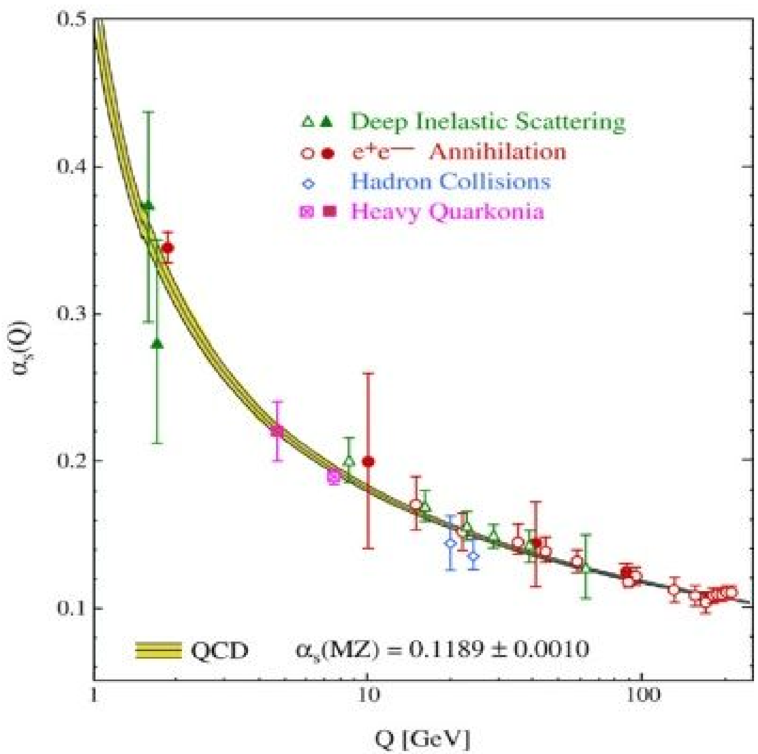
✓ Exchange of virtual mesons binds the nucleus in a “van der Waals” kind of way.

Dynamics of the Strong Force



QCD coupling α_s

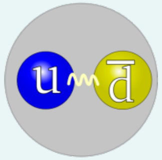
For the discovery of asymptotic freedom in QCD (2004 Nobel Prize)



W. Melnitchouk et al., Phys.Rept.406:127-301,2005

- At infinite Q^2 (short distances, high energy), quarks are asymptotically free
  - *Equivalent to "turning off" the strongest force of nature: Freedom! (Wilczek, 2004)*
- We know how to calculate these short distance quark-quark interactions
  - Perturbative QCD (pQCD)
- At low Q^2 (long distances), these calculations are complex, because quarks are confined in hadrons
  - Need to resort to QCD based models

Dynamics of the Strong Force



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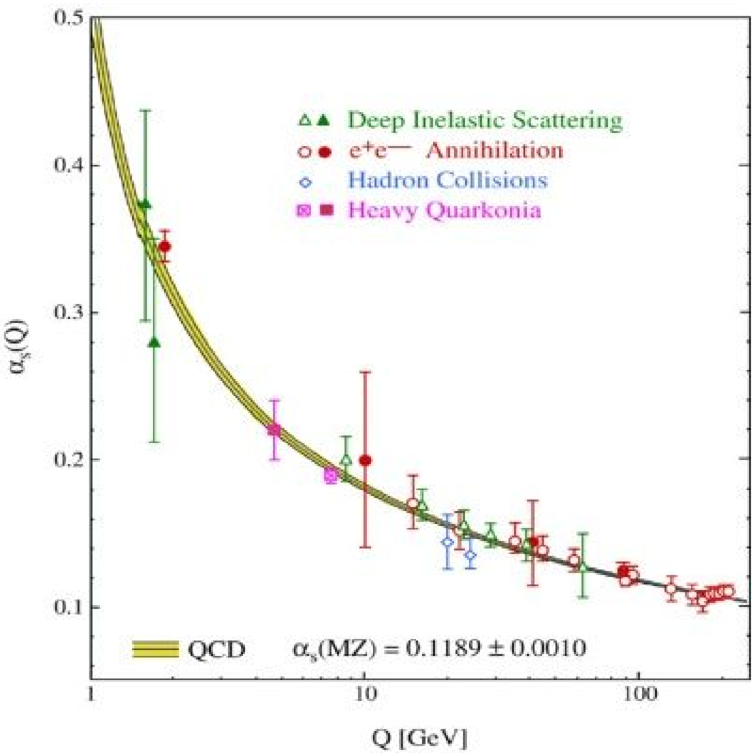


Asymptotic freedom ⟺ antiscreening

$$\frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0$$

Compare EM:

$$\frac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0$$

D. Gross, F. Wilczek, Phys. Rev. Lett. **30, 1343** (1973).

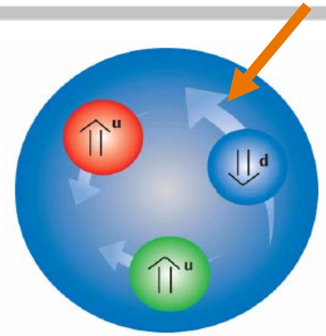
H. Politzer, Phys. Rev. Lett. **30,** 1346 (1973)

Citations: 2800+!!

Mysteries of the Strong Force

What about?

u + u + d = proton
Mass: 0.003 + 0.003 +0.006 ≠ 0.938 GeV

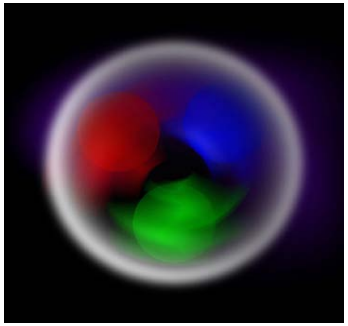


u + u – d = proton

Spin: 1/2 + 1/2 – 1/2 = 1/2 √

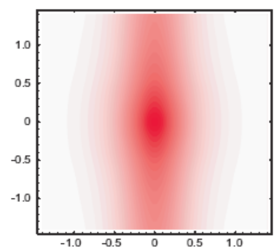
- 98% of the mass of visible matter is dynamically generated by the motion of real and *virtual* quarks and gluons.
  - The proton mass arises from the strong interaction, described by Quantum Chromo Dynamics (QCD)
- QCD dynamics also determines proton spin.
- The strong coupling at low energy (Q^2) makes QCD very complicated (non-perturbative).

Is all mass dynamically generated?

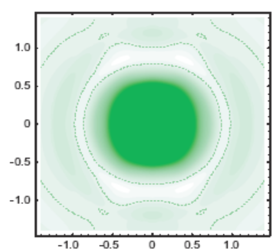


We need to understand *confinement* to know how proton properties arise from its quark and gluon constituents

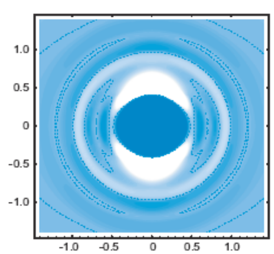
Let us focus on the Landscape of the Nucleon and Imaging



x = 0.01

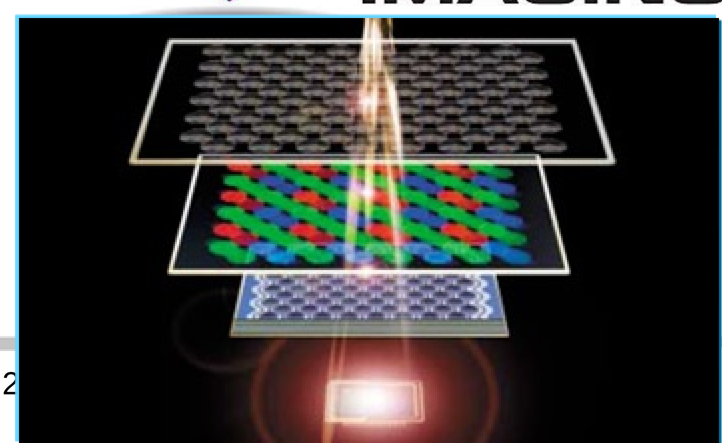


x = 0.40



x = 0.70

3D IMAGING



Brief history of nucleon structure

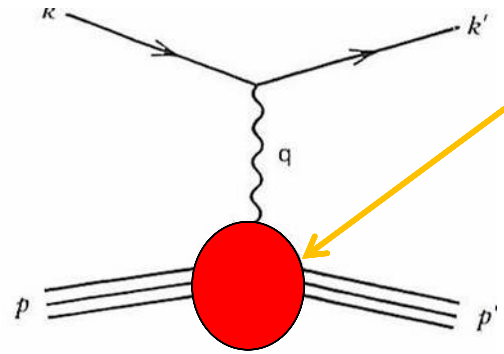
- The exploration of the internal structure of the proton began in the 1950's with Hofstadter's experiments.

For the discoveries concerning the structure of nucleons (1961 Nobel Prize)

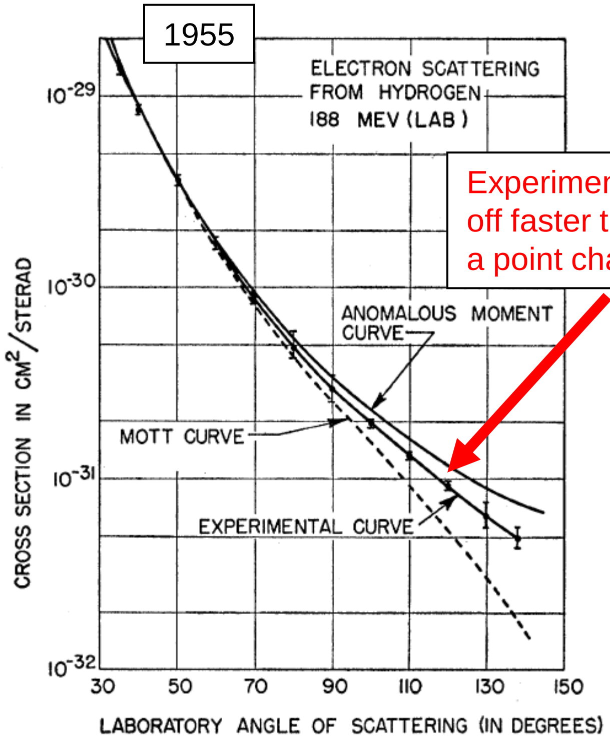
Proton is not a point particle it has finite size

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

Proton Form Factor



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



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

R. Hofstadter, R. McAllister, *Phys. Rev.* **98, 217** (1955).

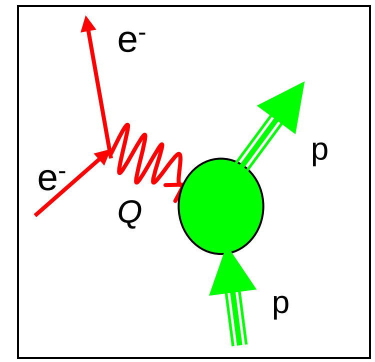
Proton Form Factor today

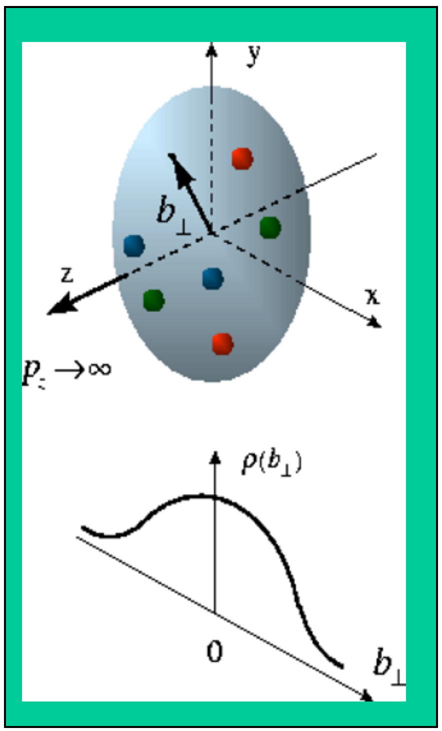
Elastic form factor experiments continue to this day, and with very high precision.

$$\left(\frac{d\sigma}{d\Omega}\right)=\left(\frac{d\sigma}{d\Omega}\right)_{Mott}\cdot\left[\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau}+2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right]$$

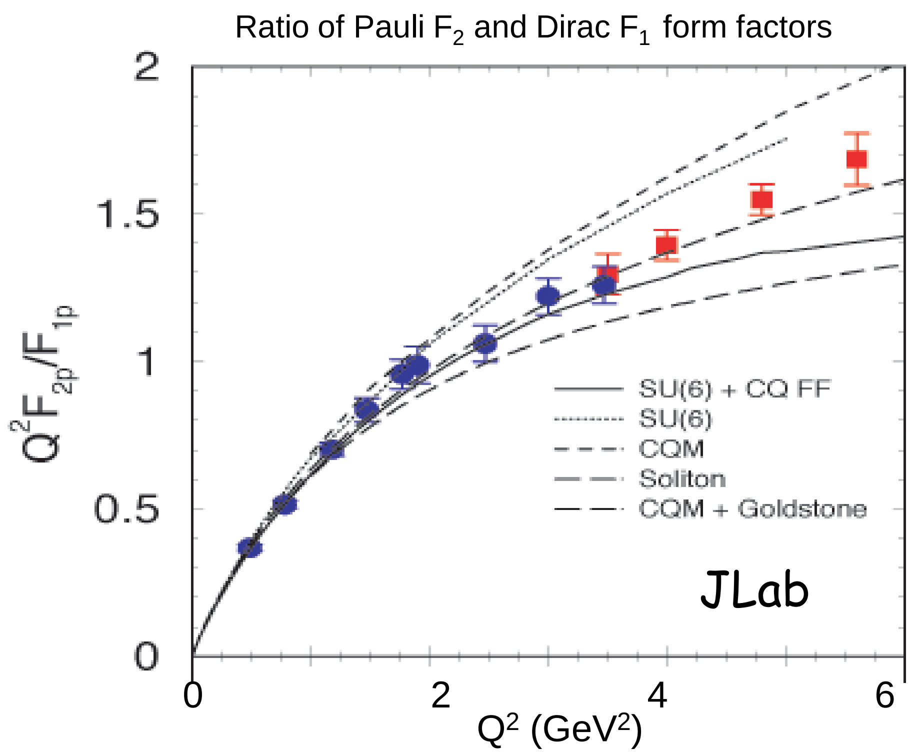
$$G_E=F_1+\frac{\kappa q^2}{4M^2}F_2$$

$$G_M=F_1+\kappa F_2$$

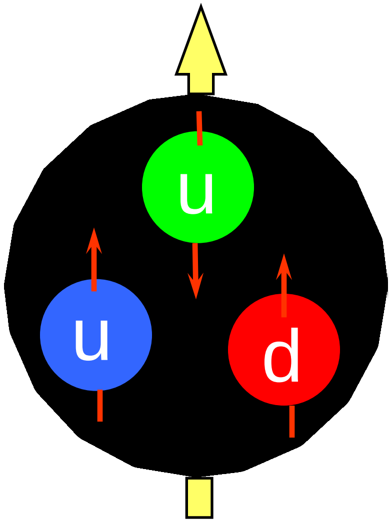




Proton form factors, transverse charge & current densities



Models of the Nucleon



Constituent Quark model

The proton is build from three quarks of spin s = 1/2 moving in the s-state (L = 0) and having masses m_q ~ 300 MeV.

M. Gell-Mann, 1964 , G. Zweig, 1964

- Proton mass: $m_p \approx 3m_q$
- Proton spin: $\vec{S} = \vec{\tfrac{1}{2}} \oplus \vec{\tfrac{1}{2}} \oplus \vec{\tfrac{1}{2}}$

Solely built from the quark spins!

Tremendously successful model in description of

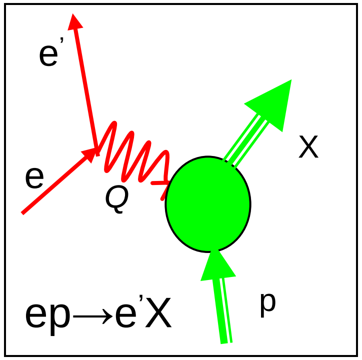
- ✓ Hadron mass spectra
- ✓ Magnetic moments

e.g., $\mu_p = 2.79 \frac{e\hbar}{2m_p c} \approx \frac{e\hbar}{2(m_p/3)c}$

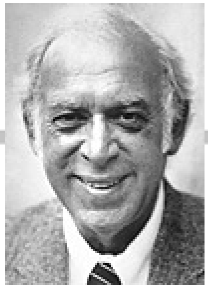
"The quark model works, but its rules are very strange"

(Wilczek Nobel prize lecture 2004)

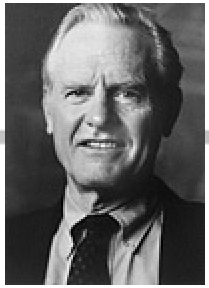
Deep Inelastic Scattering



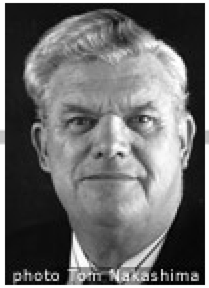
1968: SLAC experiments show that proton is not elementary



J. Friedman



H. Kendall



R. Taylor

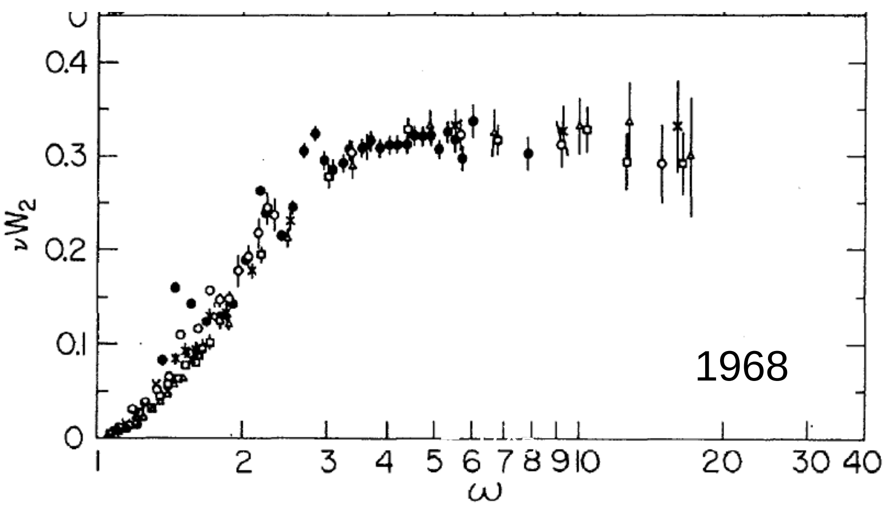
For pioneering investigations in DIS, which has been essential for the development of the quark model (1990 Nobel Prize)

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[W_2 + 2W_1 \tan^2 \tfrac{\theta}{2}\right]$$

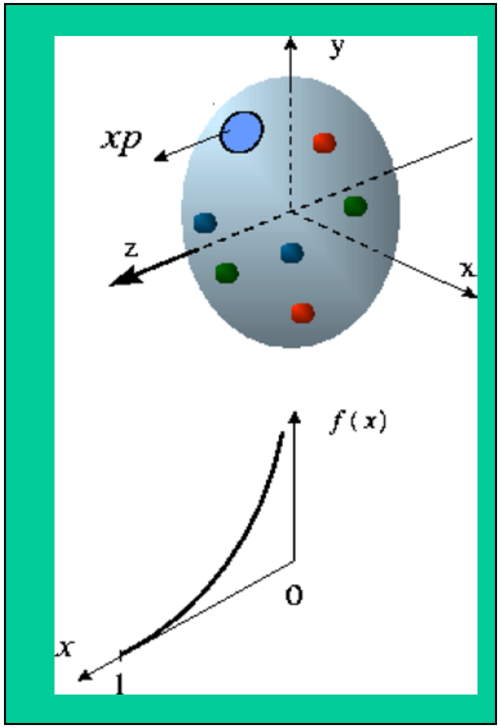
Detect only the scattered electron.

$$2MW_1(\nu, q^2) \rightarrow F_1(\omega)$$

$$\nu W_2(\nu, q^2) \rightarrow F_2(\omega)$$



Scaling => Quarks are point-like objects!

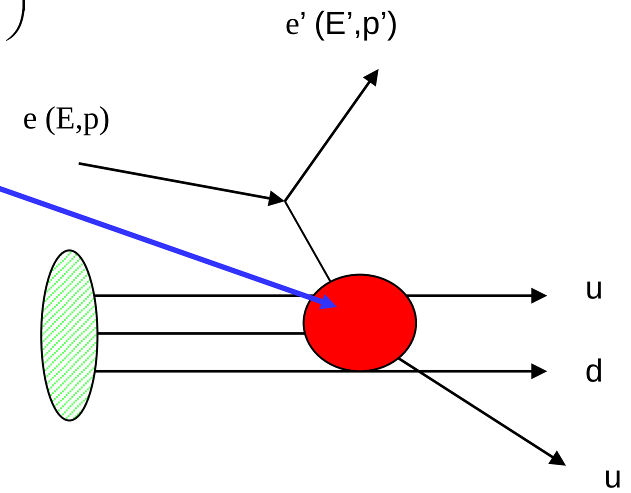


Structure functions, quark longitudinal momentum & helicity distributions

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

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



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

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

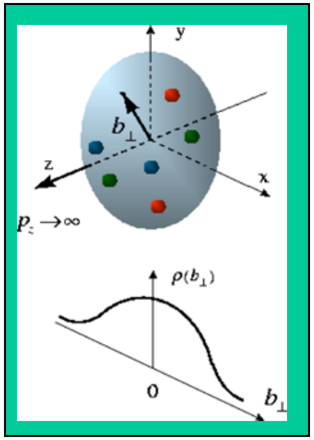
Determine quark momentum distribution F(x).

Quarks carry ~ 50% of the proton momentum.

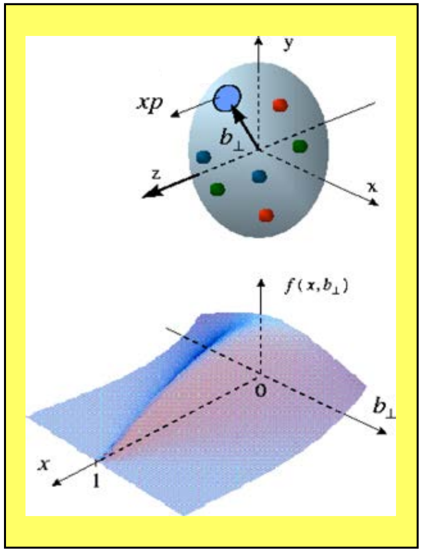
However, by measuring quark distribution functions, one cannot say anything about the momentum fraction perpendicular to the direction of motion

Combine spatial and momentum distributions

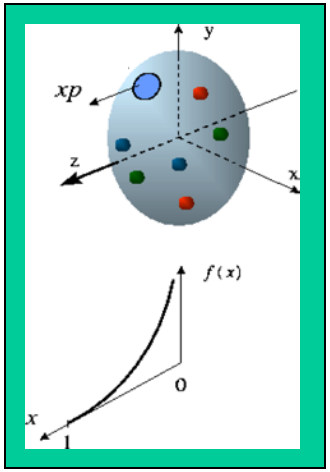
How are proton's charge and current distributions related to the quark momentum and spin distributions?



Proton form factors, transverse charge & current densities



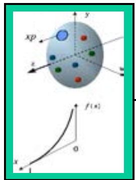
Correlated quark momentum and helicity distributions in transverse space - GPDs



Structure functions, quark longitudinal momentum & helicity distributions

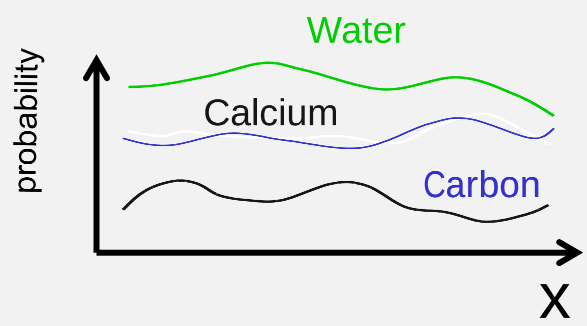
Wigner distributions provide the language for the Generalized Parton Distributions (GPDs), which allow us to create a complete map of the behaviour of partons (quarks and gluons) inside of the nucleon.

A macroscopic analogy…

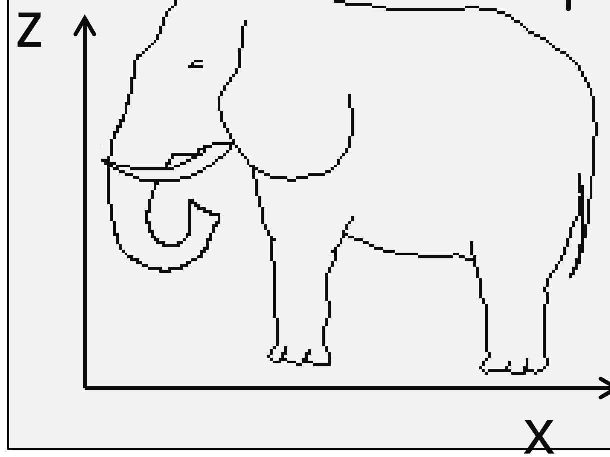


Deep Inelastic Scattering & PDFs

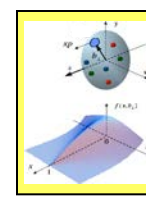
1-D Elephant



2-D Elephant



3-D Elephant!!



Deeply Virtual Exclusive Processes & GPDs

And there is more yet: spin!

In elastic scattering can also probe the spin of the quarks!

European Muon Collaboration (EMC, 1989) found that the total quark helicity

$\Delta s_q = \Delta u + \Delta d + \Delta s$ constitutes only ~20% of the proton spin.

- "Spin crisis" or puzzle

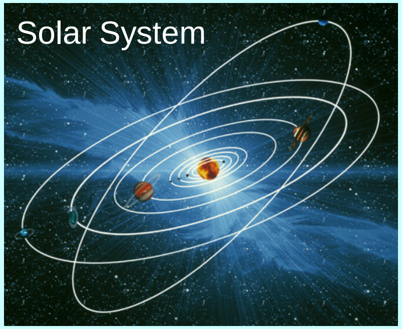
Angular momentum sum rule for proton (Ji, 1992):

$$J = ½\cdot(\Delta s_q + \Delta L_q + \Delta G)$$

↑

~20%

Over-simplification? – consider the "spin" of the sun & the planets contributes only 2% to the total angular momentum of the solar system, 98% are the result of the orbital motion of the planets.



Two complimentary ways to tackle proton spin: 1) measure quantities that can be related to the angular momentum, and 2) measure ΔG

Story of proton structure

The proton is a very complicated object

- Composite of quarks and gluons
- It's spin (s=1/2) could get contributions from quarks, gluons, and their orbital motion

Would it not be awesome if we could look deep inside the proton?!

Nucleon structure in the last century

- Rutherford (1911)

  Atoms have substructure

- Hofstadter (1955)

  Proton is not a point particle; it has a finite size

- Gell-Mann, Zweig (1964)

  Schematic model of baryons and mesons

- Friedman, Kendall, Taylor (1968)

  Quarks are point-like objects; carry ~50% of proton momentum

- Gross, Politzer, Wilczek (1973/74)

  Asymptotic freedom in QCD

- European Muon Collaboration (1989)

  Spin crisis – quarks carry only ~20% of the proton spin

- Radyushkin, Belitsky, Mueller, Schaefer(1987/88)

  Non-forward parton distributions -> first ideas on transverse spatial structure

- Hoodbhoy, Ji, Lu(1998)

  Quark orbital angular momentum distributions

Proton structure today

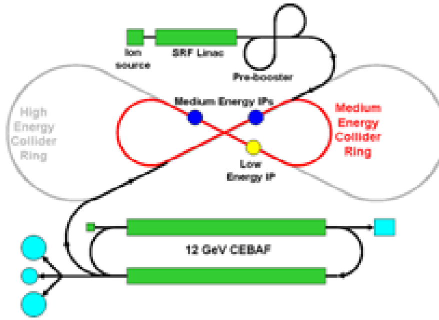
One may argue that the 20th century was a century of advancements and surprises in understanding nucleon structure … and there is more to come…

"As for the forces, electromagnetism and gravity we experience in everyday life. But the weak and strong forces are beyond our ordinary experience. So in physics, lots of the basic building blocks take 20th- or perhaps 21st-century equipment to explore."

Edward Witten

1960's — Late 1990's/early 2000-present — 2030's?

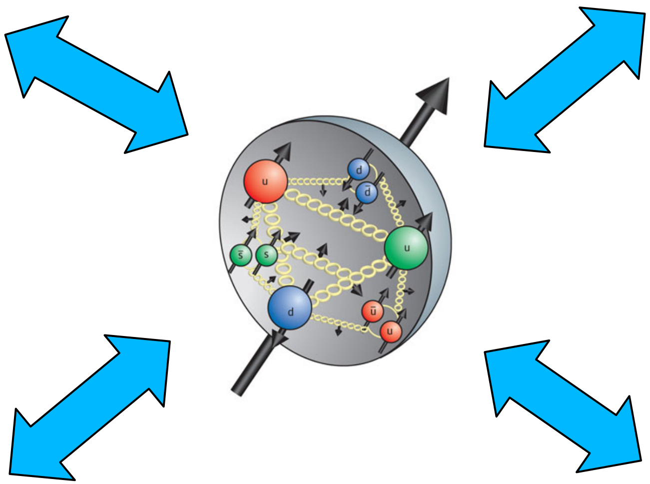


Exploring the Nucleon

Know what we are made of

Test our ability to use QCD:
asymptotic freedom, factorization



Explore and understand
QCD: lattice, models

Nucleon as a tool for discoveries

Proton structure tools in everyday life

MRI – Magnetic Resonance Imaging

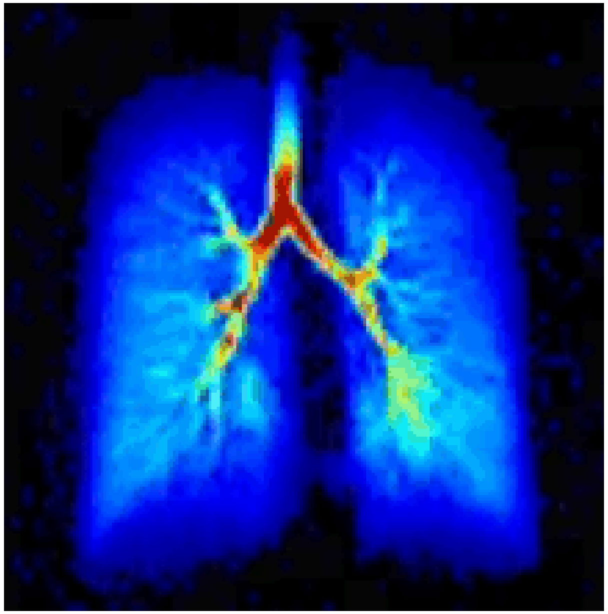
- Body tissue contains lots of water and water molecules contain hydrogen (protons).
- Place these protons in a high external magnetic field and let them align their average magnetic moment
- Alter the alignment of this magnetization systematically using pulses of EM radiation (what are those force carriers again!?) from, e.g., a radio frequency transmitter, that excite the proton.
- Turn off the external field so that the excited protons fall back to their original state by emitting EM radiation, which can be detected
- The depolarization rate, depth, field gradients are crucial for detailed 3D reconstruction

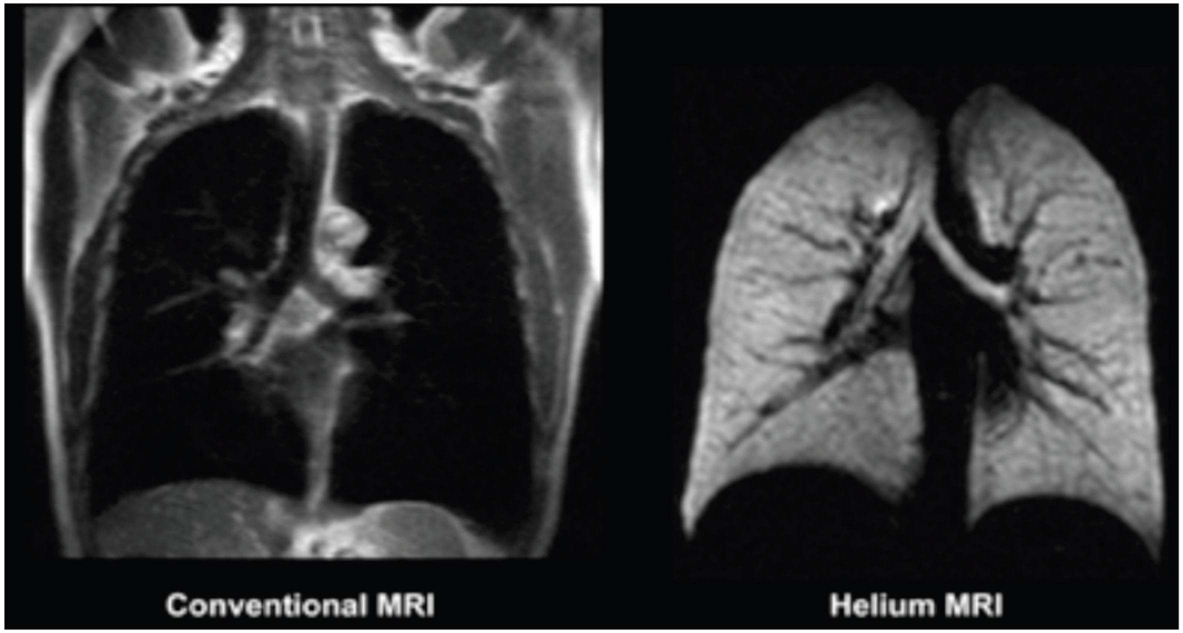
MRI Image

Proton structure tools in everyday life

MRI – Magnetic Resonance Imaging

Breathing He-3





Conventional MRI: protons (in water) in blood stream

Hyperpolarized helium (neutron) MRI, UVa, School of Medicine

Organization

In these lectures we will roughly follow the time line

- Explore the idea of looking inside the proton
- How we learnt there is more than one perspective on the internal structure of the nucleon
- What is being done to understand the nucleon landscape now
- What is currently being envisioned for the future

Organization

Emphasis will be on transverse spatial structure or understanding of the orbital angular momentum of the nucleon

- Bias towards exclusive reactions
- Bias towards non-perturbative QCD and transition region as this is where experiments are performed

This is not to say that other reactions are not interesting. They will be covered in other lectures in this school

This is not to say that perturbative QCD is not interesting. They will be covered in other lectures.

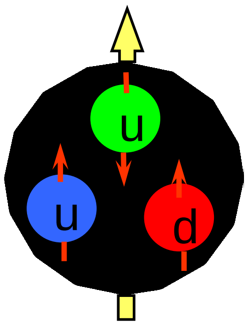
Intro and Overview

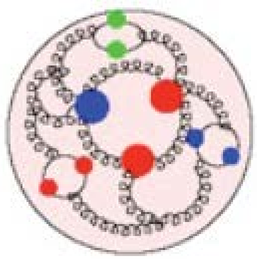
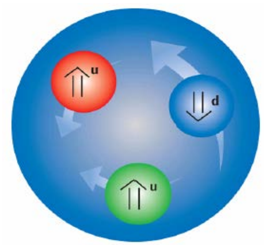
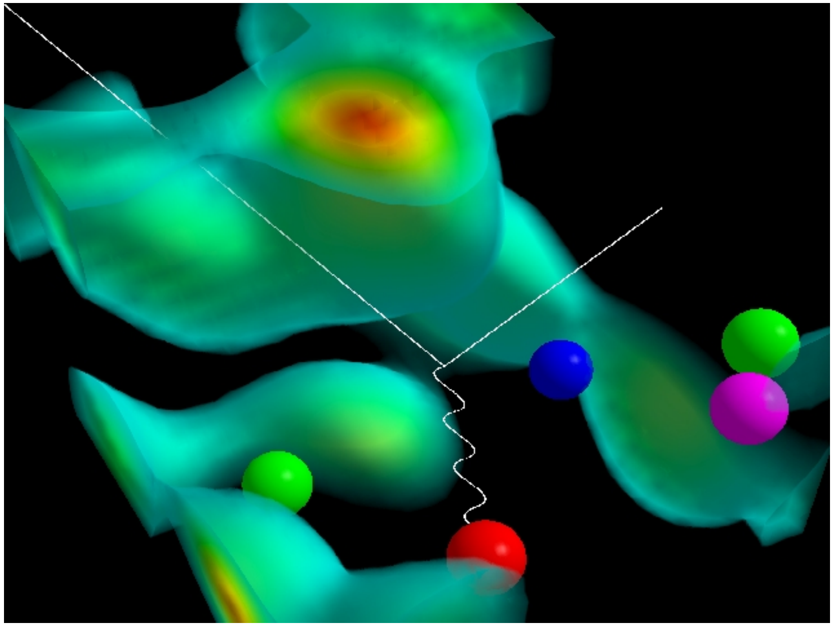
- **Lecture 1 & 2: General Overview of QCD and imaging** ⟵
  - Introduction and importance of nucleon structure
  - From form factors to GPDs in electron scattering

- **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**
  - Jefferson Lab – the place to study nucleon structure

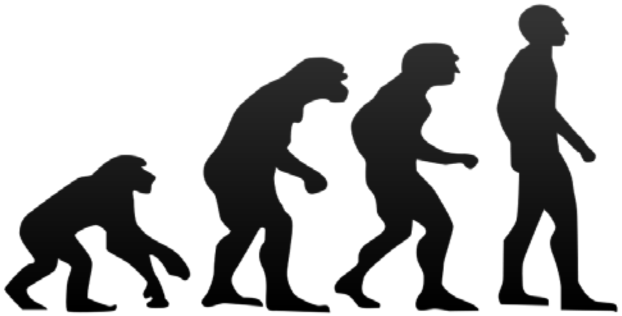
Evolution: our understanding of nucleon structure



If I can't visualize I don't understand it…
[Famous physicist]

1963 → present




We have come a long way, but do we really understand the nucleon?

A list of references

F. Halzen, A. D. Martin, *Quarks and Leptons*, Wiley (1984)

M.E. Peskin, D.V. Schroeder, *Intro to Quantum Field Theory*, Perseus (1995)

F. Mandl, G. Shaw, *Quantum Field Theory*, Wiley (1984)

A. Lahiri, P. B. Pal, *First Book of Quantum Field Theory*, CRC (2001)

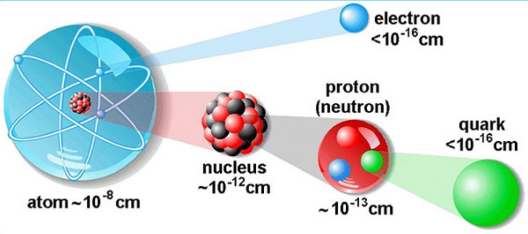
F. Wilczek, Nobel Prize Lecture (2004)

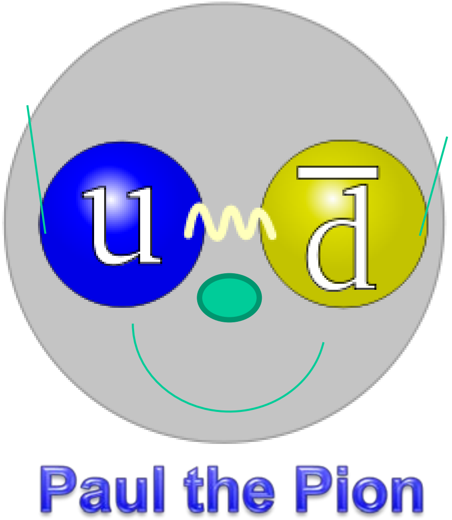
J.L. Friedman, Nobel Prize Lecture (1990)

R. Hofstadter, Nobel Prize Lecture (1961)

Nucleon Structure - 3D!

Tanja Horn





THE CATHOLIC UNIVERSITY of AMERICA

HUGS Summer School

Jefferson National Laboratory

Lecture 2 of 6

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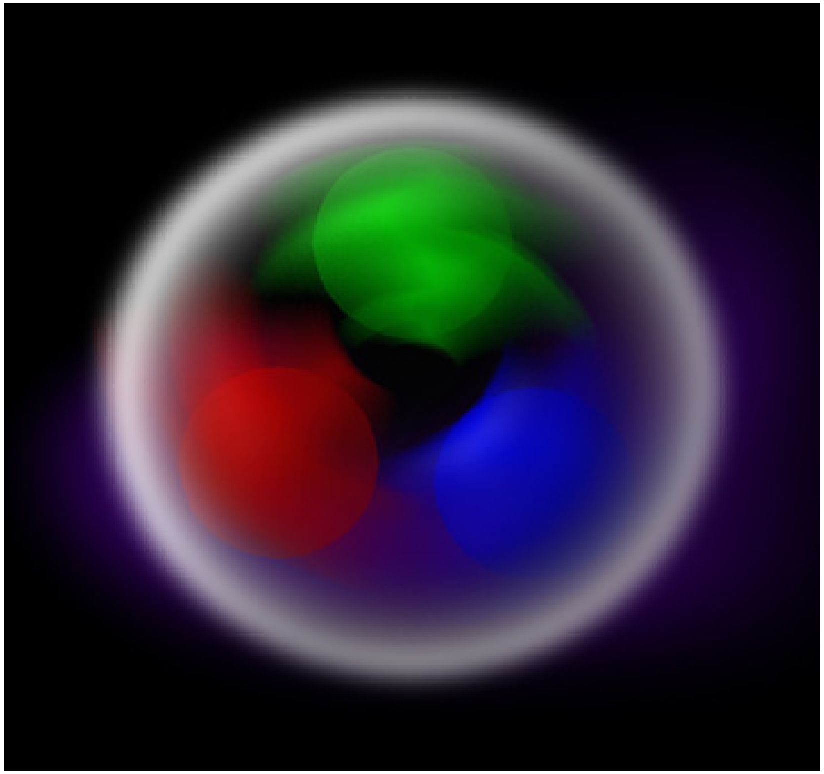
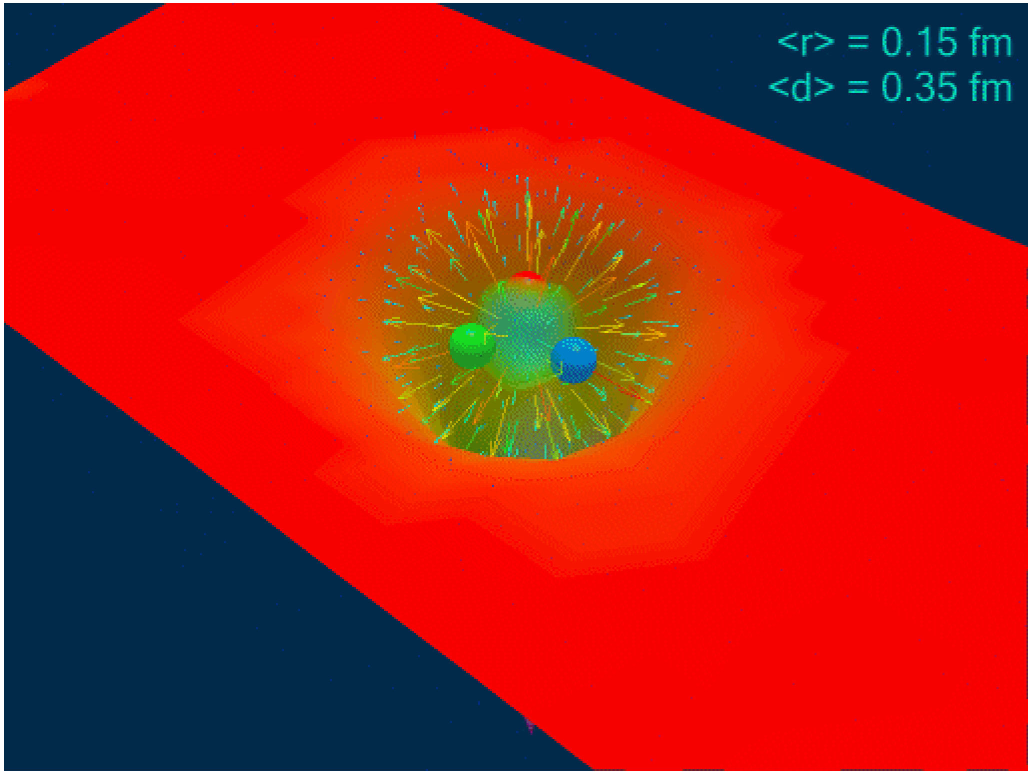
Two Pictures of the Nucleon



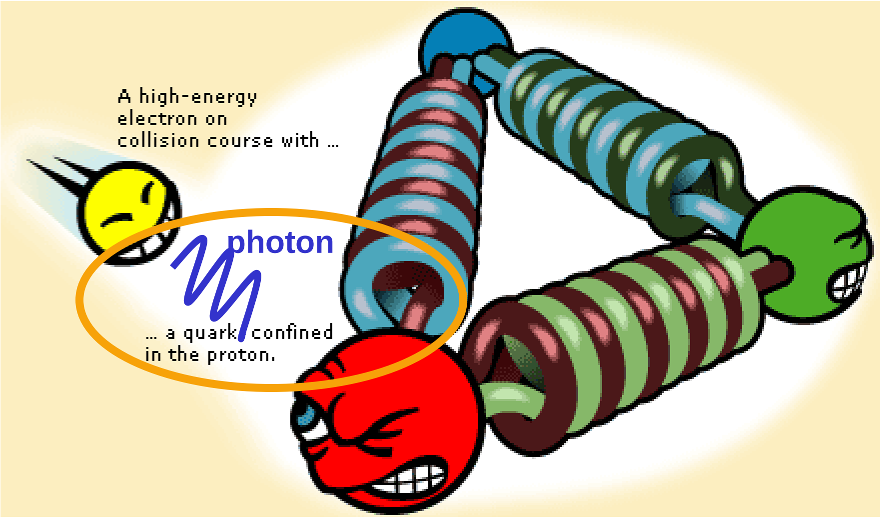


Does the nucleon consist of *heavy quarks*, each with its own cloud of virtual particles, or *light quarks* in a common sea of virtual gluons and quark-antiquark pairs?

To answer this question we need to learn about Q^2 and x, which define the landscape of the nucleon.

Q^2 and x

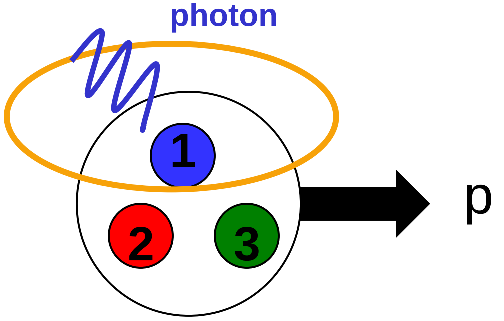
Q^2



- Real photons have no mass, but virtual ones do. The mass (with a minus sign) is called Q^2.
- Q^2 is a measure of the "size" of the probe. The larger the Q^2, the deeper the electron penetrates the cloud of virtual particles.
- Real photons ($Q^2 = 0$) cannot distinguish the quarks from the cloud around them.

x

- x is the fraction of the nucleon momentum carried by the struck quark in a frame where the nucleon is moving quickly to the right. Naively, one would expect x = 1/3.
- Photons with high energy and low Q^2 do, however, probe small values of x. This rarely means that the struck quark does not follow the other two, but rather that most of the momentum is carried by the virtual particles.



$$x = p_1 / p_{proton}$$

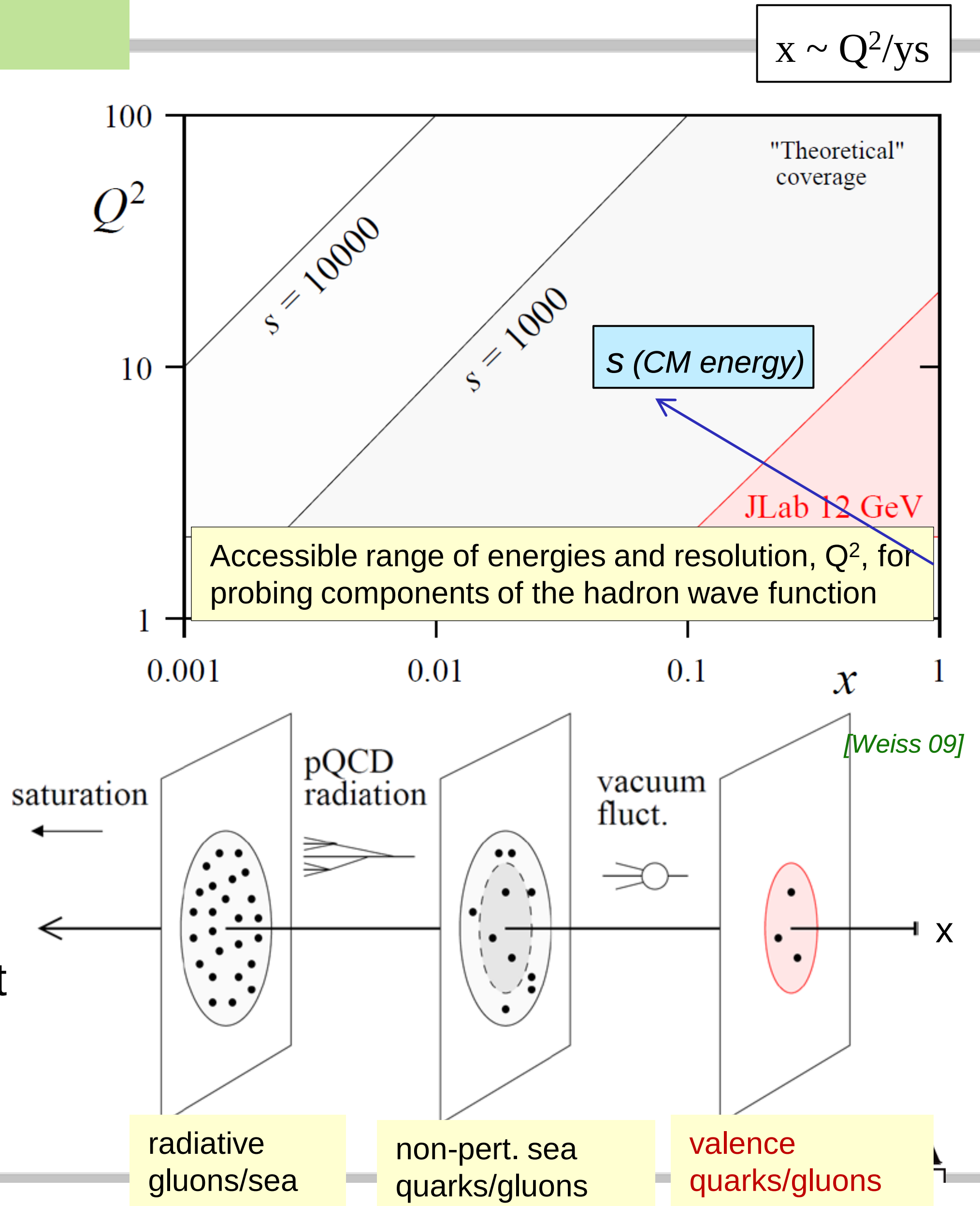
$$x = Q^2 / 2\, m_{proton}\, E_{photon}$$

Internal Landscape of the Nucleon

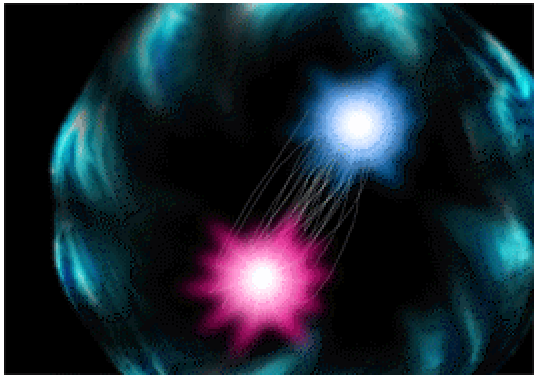
- Hadrons in QCD are relativistic many-body systems
  - Hadron properties encoded in the wave function

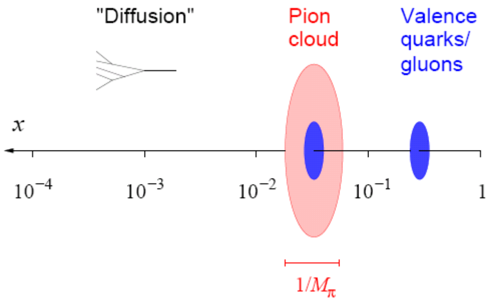
- Probe the wave function by scattering a high resolution and high energy probe off of hadrons
  - Probe in electron scattering is virtual photon
  - Resolution scale is given by Q^2
  - Energy related to x

- Depending on x one probes different regimes of the wave function

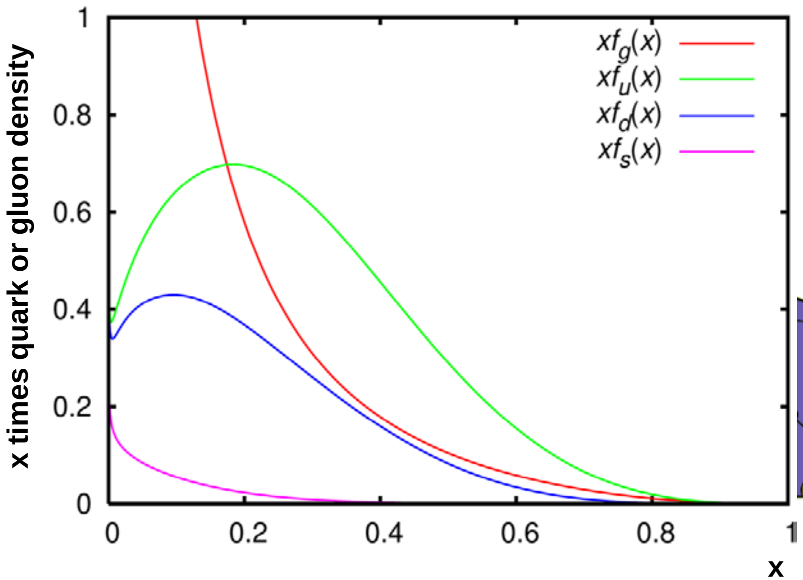


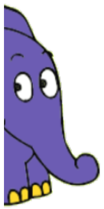
The Nucleon Ground State





- The sea of virtual *gluons* and *quark-antiquark* pairs is an important part of the nucleon, carrying a significant part of the momentum and spin.





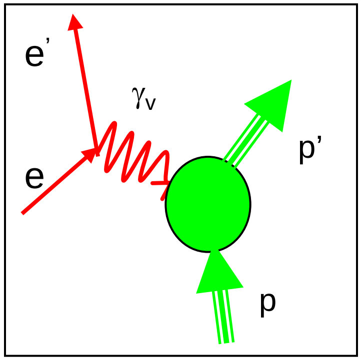
- To understand the *ground state*, we need to map the spatial and momentum distributions of the three "valence" quarks, and the sea surrounding them, over a large range in x and Q^2.

- Only recently have advances in theory and experiment have made it possible to create such a tomographic picture.

Electromagnetic Scattering

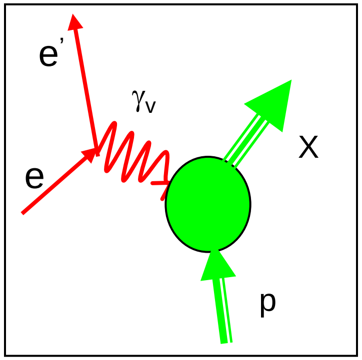
EM interaction very successful in probing the structure of the nucleon in a quest to understand the strong interactions between quarks and the gluons that bind them

elastic



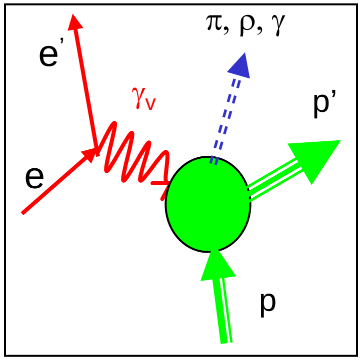
Scattering leaves proton intact

inclusive



Scattering breaks the proton and get a lot of final state particles. Detect only the scattered electron.

exclusive



Restrict the reaction so that there is only one final state particle. Detect the active parton.

Equations that describe the reaction dynamics:

$Q^2 = -(e-e')^2$ — Q^2 is spatial sensitivity of virtual γ

$\nu = E_e - E_{e'}$

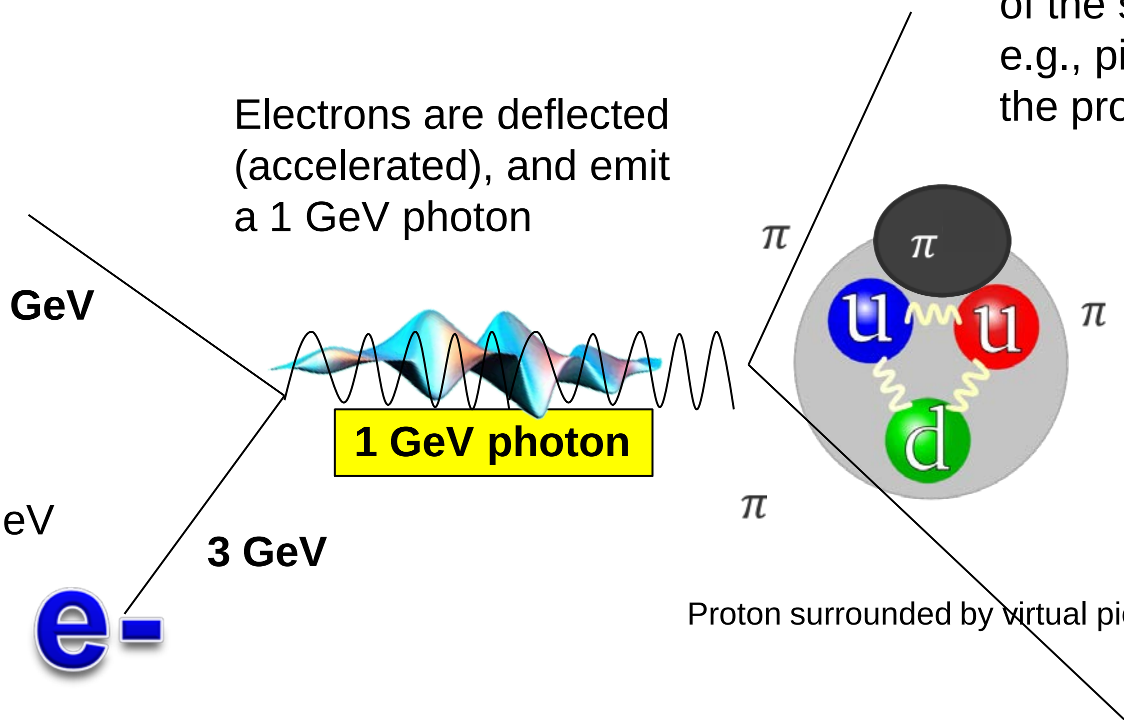
$x_B = Q^2/2M\nu$ — $x_B = 1$ (for elastic scattering)

$t = -(p-p')^2$

Example: exclusive meson production

The higher the beam energy, and the shorter the wavelength of the photon, the more detail in the target structure is revealed

By analyzing the properties of the scattered meson, e.g., pion, can learn about the proton structure



Proton also recoils

Accelerate electrons to 3 GeV

- Instead of photon energy, we typically use:

$$Q^2 = p^2 - E^2$$

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