IDPASC

Otranto School

Joint 9th IDPASC SCHOOL and
XXXI INTERNATIONAL SEMINAR of
NUCLEAR and SUBNUCLEAR
PHYSICS "Francesco Romano"

Otranto School - May 2019

Hadron physics and prospects for the Electron Ion Collider

M.Battaglieri
INFN-GE
Italy

Inspired by lectures/talks of:
Rolf Ent, Rik Yoshida, Jianwei Qiu, Abhay Deshpande, Daria Sokan

Practicalities

- 4 lectures (2x50mn on Tuesday and 2x50 on Thursday)
- Some 'exercises' distributed over the text. We can discuss them in the questions-time

A red-border rectangle covers the text with the request of deriving some results

- Ask questions and interrupt me whenever you want

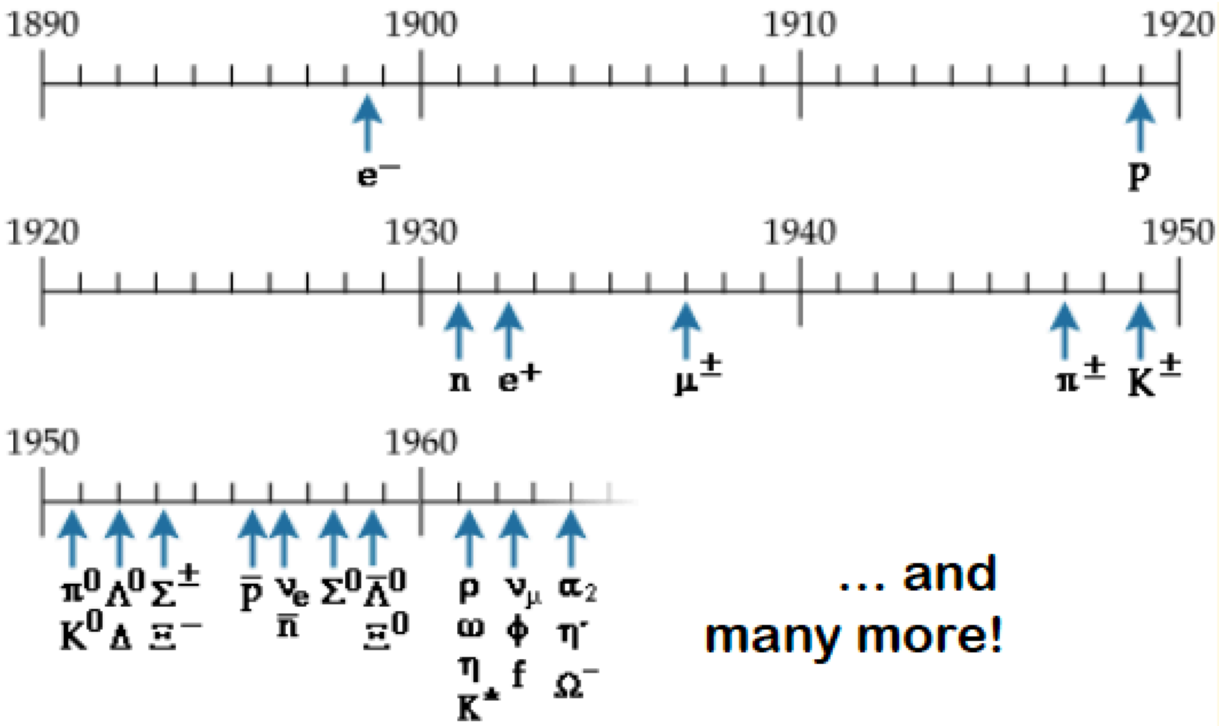
Plan for lectures

- Are hadrons elementary particles?
- Elastic electron scattering
  - Early experiments
  - Form factors and new measurements
- There quark model of hadrons
- Inclusive electron scattering
  - Early experiments
  - Parton model
- From 1D to femto-tomography
- The Electron Ion Collider
  - The physics case
  - EIC options

Not talking about

- Baryon/meson spectroscopy
- Gluons and confinement
- Mass of hadrons
- Proton radius
- Exotic hadrons
- Reaction Amplitudes
- Lattice QCD
- The spin of the nucleon
- Hadron/parton duality
- Correlations in nuclei
- … many other open questions in hadron physics

Early proliferation of new hadrons – “particle explosion”:



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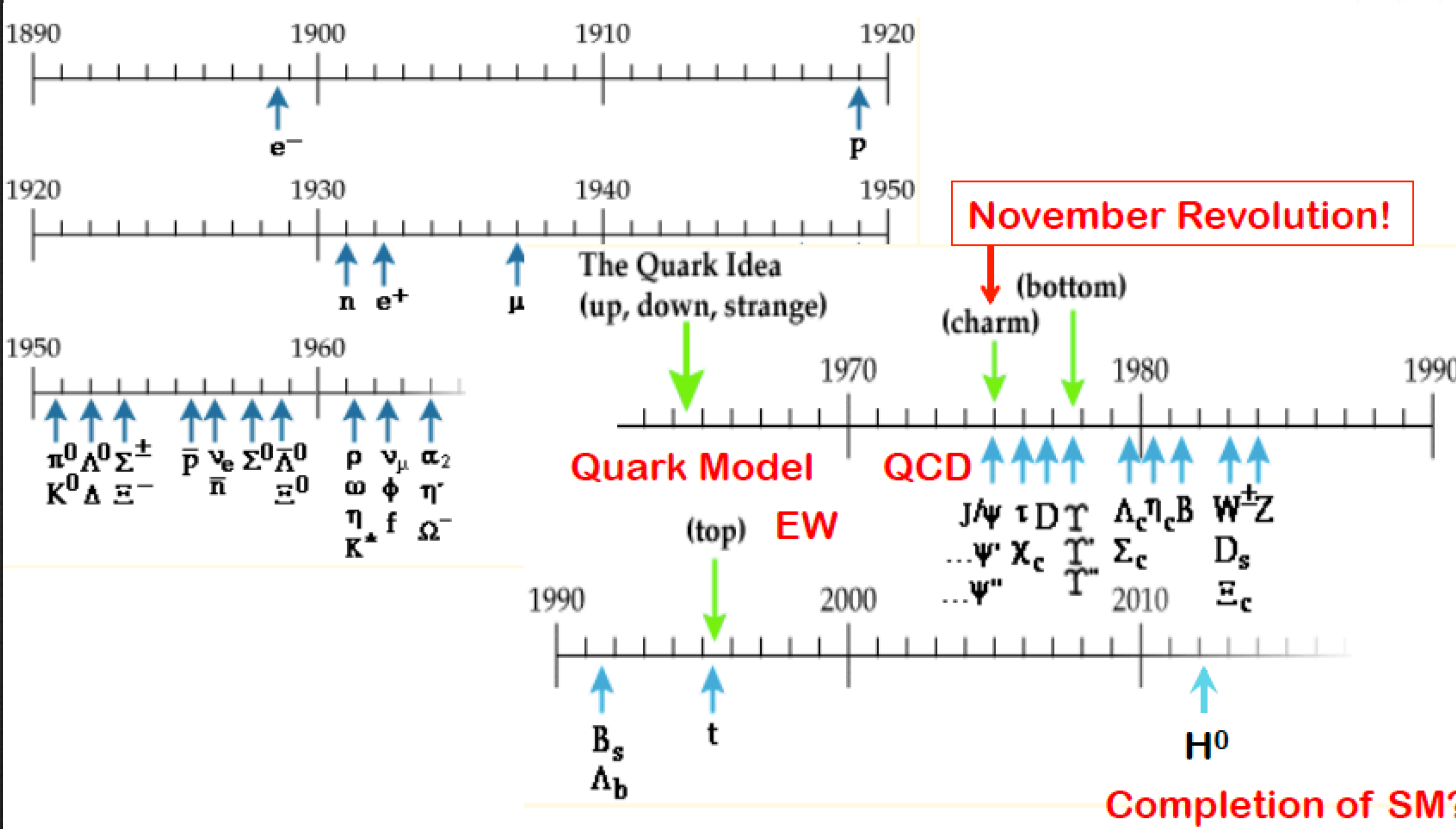

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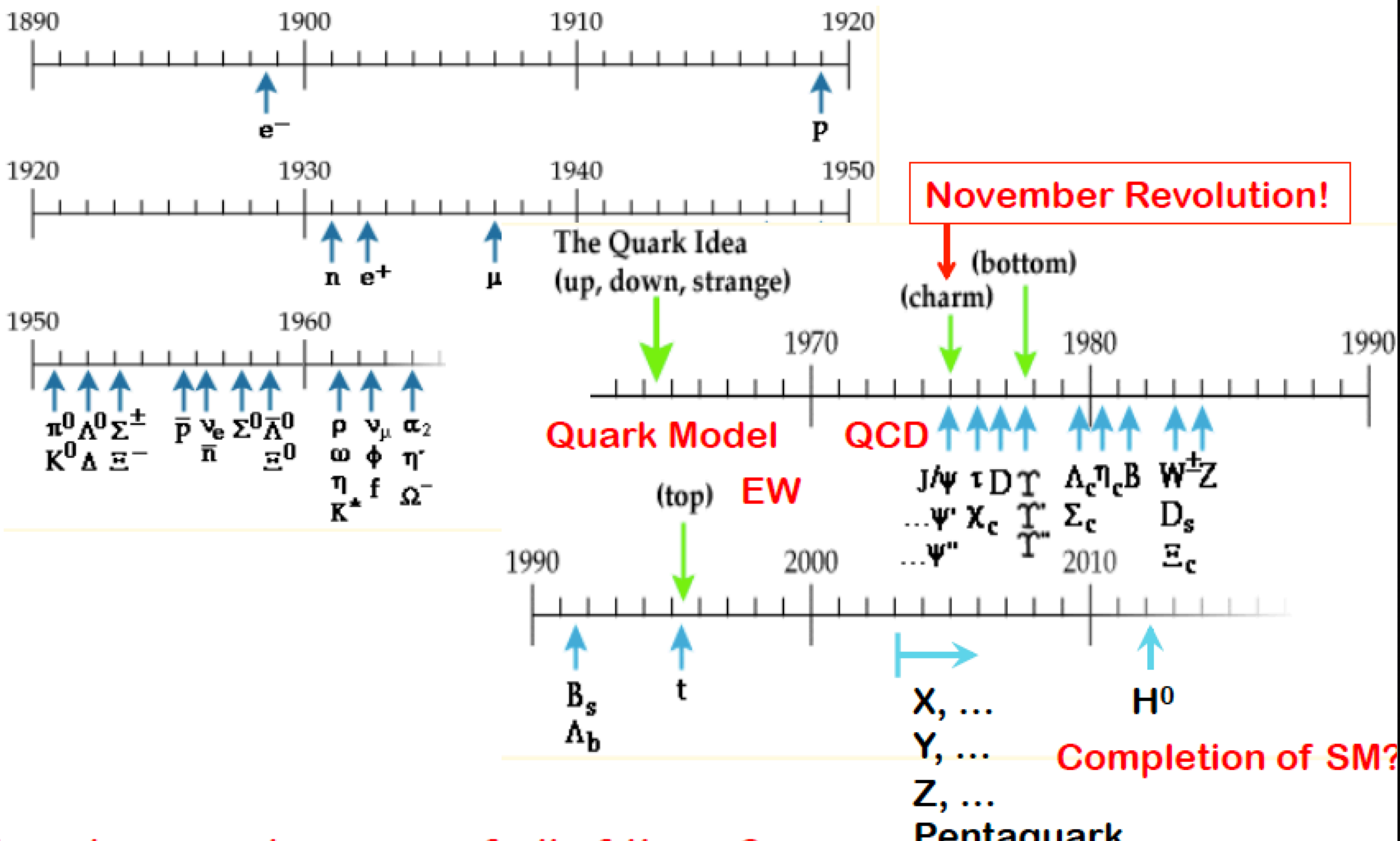
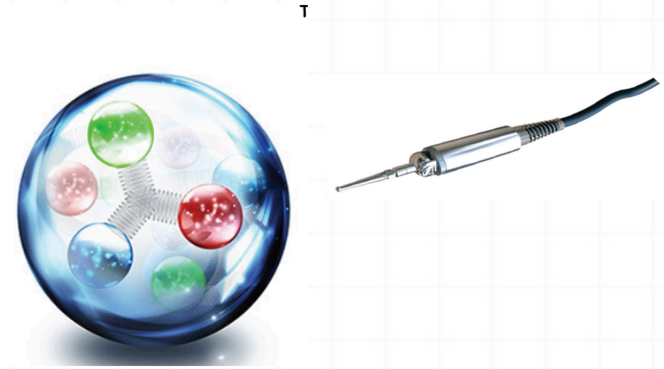


How do we make sense of all of these?

Another particle explosion?

Particles are ‘elementary’?

Elementary = not substructure
(not made by smaller pieces, no internal dynamics)
but,
how to look inside a particle?



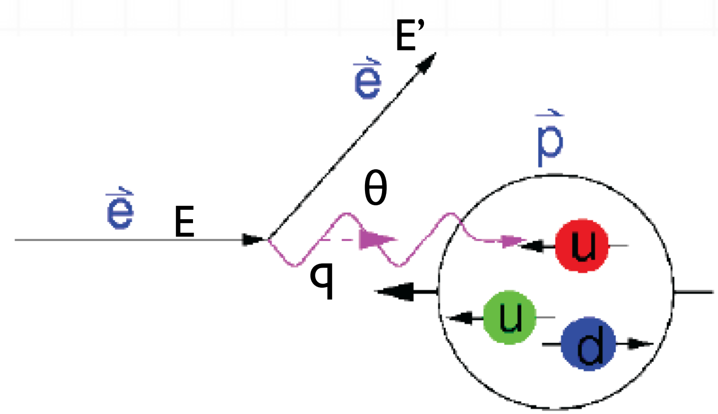
Ordinary instruments are a million billion times too big!

We can use electromagnetic interaction (light!)

- weaker than strong interaction
- therefore calculable perturbatively
- based on the well-known QED

High energy collisions of electrons with nuclei, proceed via “virtual photon”, which acts as a probe

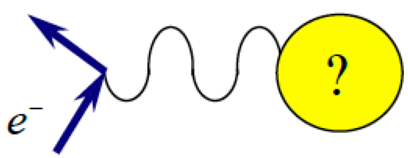
$$Q^2 = -q\,q = 4EE'\sin^2(\theta/2)$$
$$\nu = E - E'$$
$$x_B = Q2 / 2M_p\nu$$



Scales of resolution – an elephantine analogy

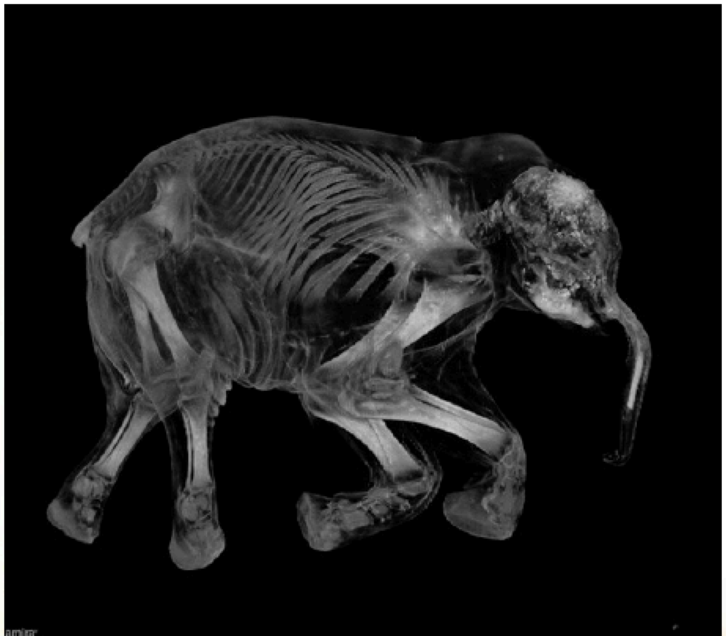
Lyuba, baby mamoth found in Siberia, imaged with visible light…

International Mammoth Committee



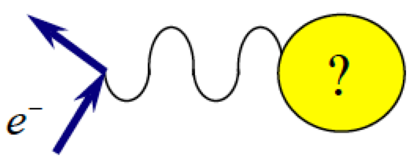
Q^2 ~ MeV^2

Scales of resolution – an elephantine analogy

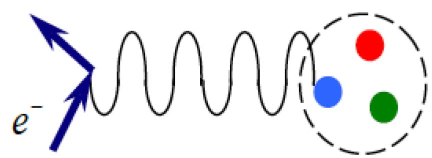


Lyuba, baby mamoth found in Siberia, imaged with visible light...
... and X-rays.

International Mammoth Committee



Q^2 ~ MeV^2



Q^2 >> GeV^2

Equivalent wavelength of the probe:

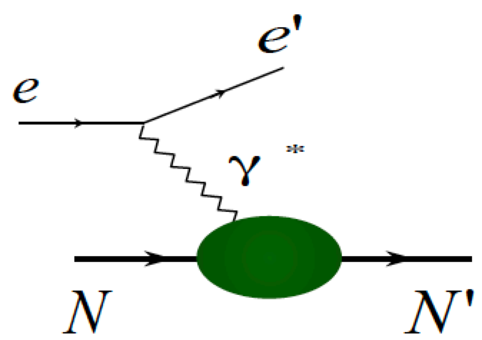
$$\lambda \approx \frac{1}{\sqrt{Q^2}}$$

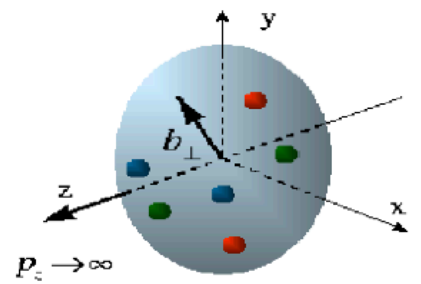
What you see depends on what you use to look...

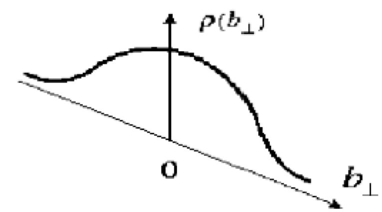
The 2D spatial image

Lepton (eg: electron, neutrino) scattering off a nucleon reveals different aspects of nucleon structure.

Elastic Scattering







Cross-section parameterised in terms of Form Factors (Pauli, Dirac, axial, pseudo-scalar)

Transverse quark distributions: charge, magnetisation.

Elastic electron-proton scattering: Rosenbluth

PHYSICAL REVIEW VOLUME 79, NUMBER 4 AUGUST 15, 1950

High Energy Elastic Scattering of Electrons on Protons

M. N. Rosenbluth
Stanford University, Stanford, California
(Received March 28, 1950)

- Quantum Mechanics develops rapidly after 1924

1933: Proton's magnetic moment

Otto Stern

Nobel Prize 1943

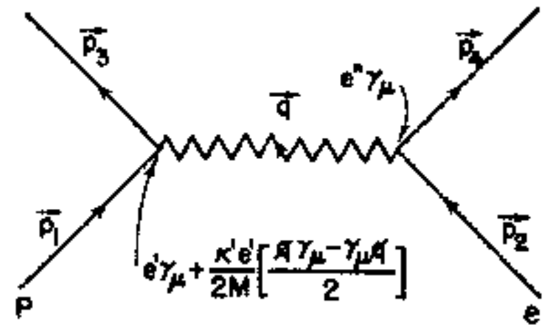
$$\mu_p = g_p \left(\frac{e\hbar}{2m_p}\right)$$

$$g_p = 2.792847356(23) \neq 2!$$

$$\mu_n = -1.913 \left(\frac{e\hbar}{2m_p}\right) \neq 0!$$

- QED becomes fully mature by late 1940's
- 1950, Rosenbluth writes down the general cross-section for elastic electron-proton scattering.

Fig. 1. Diagram for the elastic scattering of a physical proton and a physical electron. (The letter "q" with the bar through it in this figure is the same as the German letter, q, used in the text.)



$$\sigma_p(\theta) = \sigma_{NS}\left\{1 + \frac{q^2}{4M^2}\left[2(1+\mu)^2 \tan^2\tfrac{1}{2}\theta + \mu^2\right]\right\}$$

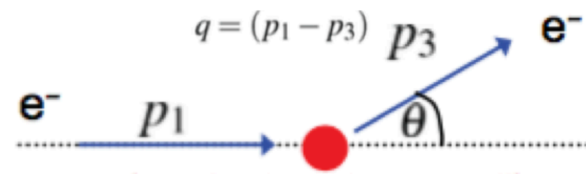
where

$$\sigma_{NS} = \frac{e^4}{4E^2}\,\frac{\cos^2\frac{1}{2}\theta}{\sin^4\frac{1}{2}\theta}\,\frac{1}{1+(2E/M)\sin^2\frac{1}{2}\theta}$$

and

$$q = \frac{2}{\lambda\!\!\!^{-}}\,\frac{\sin\frac{1}{2}\theta}{\left[1+(2E/M)\sin^2\frac{1}{2}\theta\right]^{\frac{1}{2}}}.$$

ePElastic Cross-Section



Scattering of a relativistic electron from a spin ½ point-like "proton"

$$\frac{d\sigma}{d\Omega} = \underbrace{\frac{\alpha^2}{4E_1^2\sin^4\theta/2}}_{\text{Rutherford}}\,\underbrace{\frac{E_3}{E_1}}_{\text{Proton recoil}}\left(\underbrace{\cos^2\frac{\theta}{2}}_{\text{Electric/ Magnetic scattering}} - \underbrace{\frac{q^2}{2M^2}\sin^2\frac{\theta}{2}}_{\text{Magnetic term due to spin}}\right)$$

Taking the extended size of the proton into account

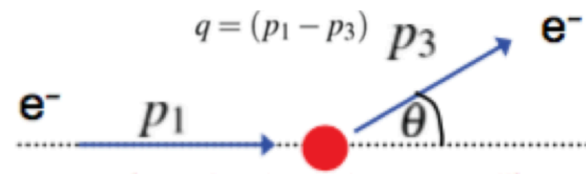
$$\boxed{\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2\sin^4\theta/2}\frac{E_3}{E_1}\left(\frac{G_E^2 + \tau G_M^2}{(1+\tau)}\cos^2\frac{\theta}{2} + 2\tau G_M^2\sin^2\frac{\theta}{2}\right)}$$

$$\boxed{\tau = -\frac{q^2}{4M^2} > 0}$$

Rosenbluth Formula

Note: for fixed θ, E_3 (scattered e energy) fixed

ePP Elastic Cross-Section



Scattering of a relativistic electron from a spin ½ point-like “proton”

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \times \left[G_E^2 + \frac{\tau}{\epsilon}\, G_M^2\right] \frac{1}{(1+\tau)},$$

$$\epsilon = [1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}]^{-1}$$

$$\tau = \frac{Q^2}{4M^2}$$

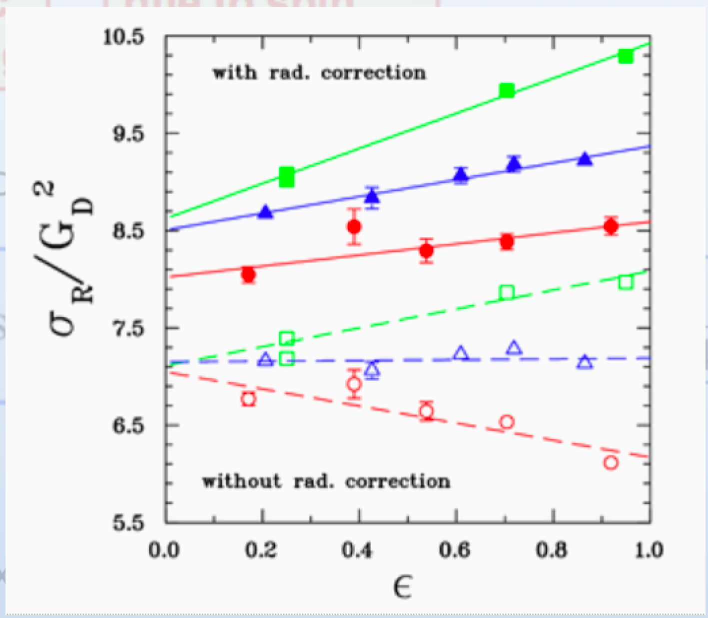
recoil

Magnetic scatterin

Taking the extended size of the proton into

Rosenbluth separation

Rosenbluth Formula



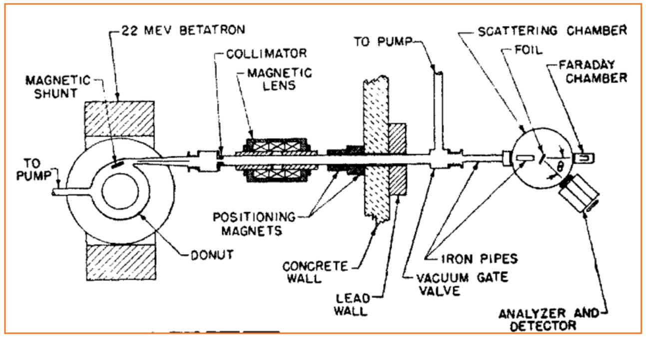
Note: for fix

First evidence of elastic electron-Nucleus scattering

Scattering of 15.7-Mev Electrons by Nuclei*

E. M. Lyman, A. O. Hanson, and M. B. Scott†
Department of Physics, University of Illinois, Urbana, Illinois

(Received July 3, 1951)



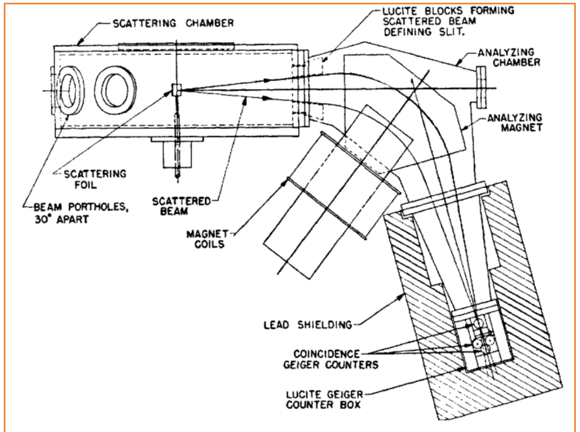
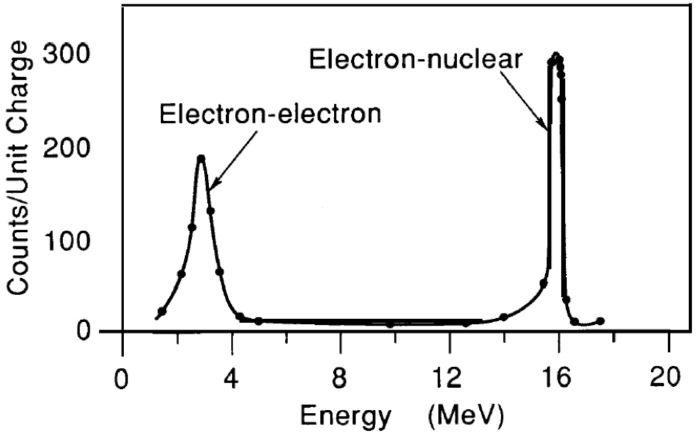


Fig. 2. Scattering chamber.

D.W. Kerst
(betatron)

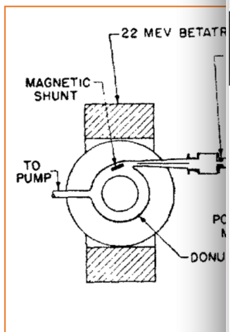
$$E' = \frac{E_0}{1 + \frac{2E_0}{M}\sin^2\frac{\theta}{2}}$$



First evidence of elastic electron-Nucleus scattering

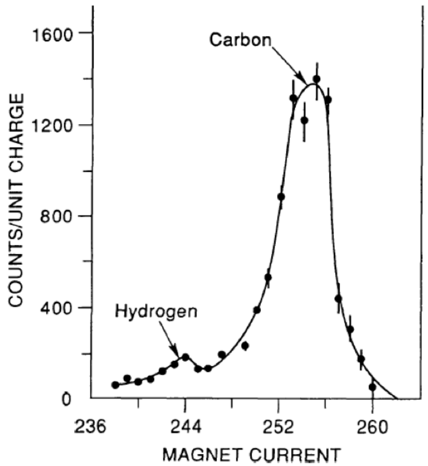
Scattering of 15

E. M. LYMAN,
Department of Physi

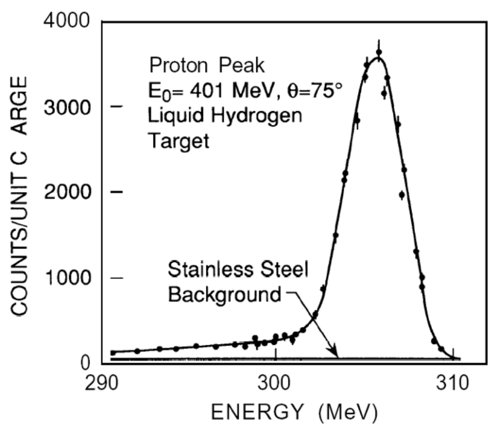


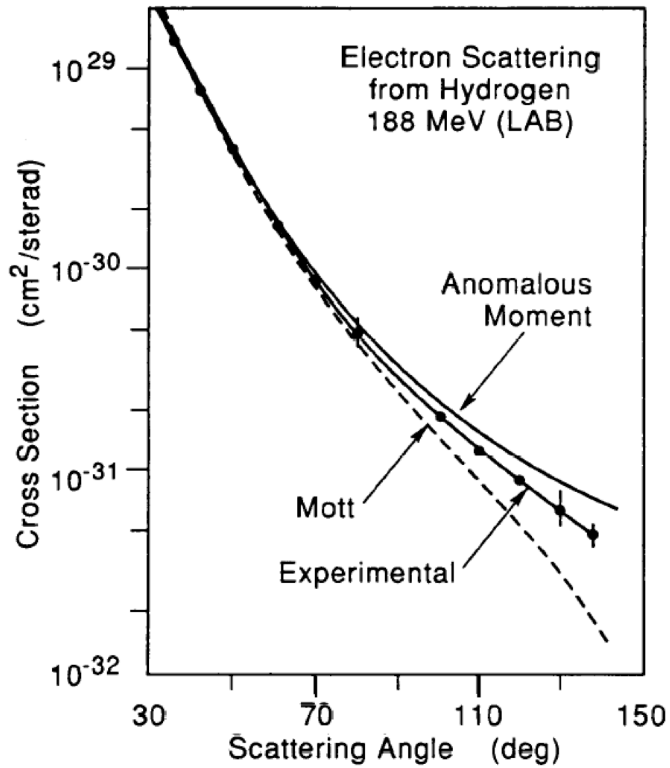
D.W. Kerst
(betatron)

R. Hofstadter: ep and eA elastic scattering (1953->)



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_0^2 \sin^4 \theta/2} \cdot \cos^2 \theta/2 \cdot \frac{E'}{E_0}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2 \theta/2\right]$$





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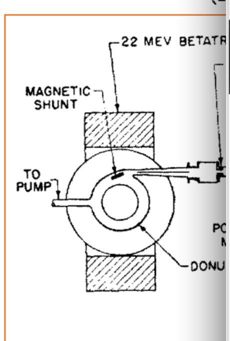

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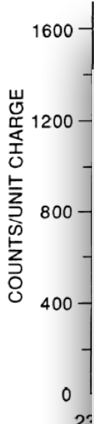
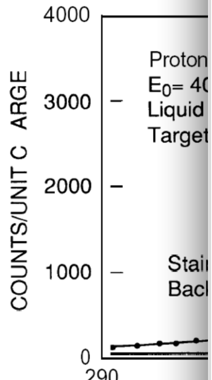
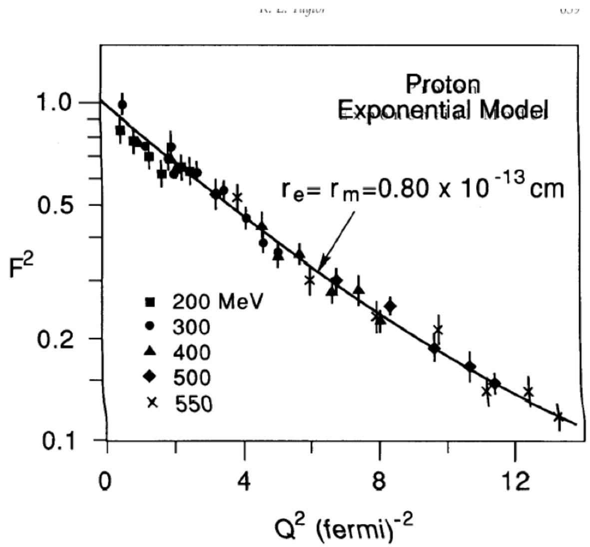
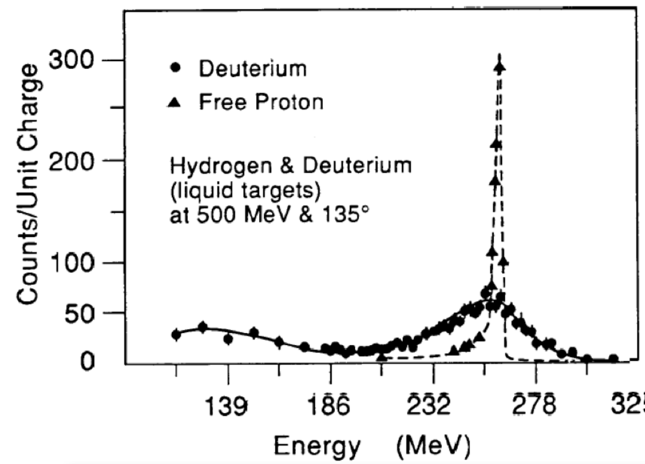




R. Hofstadter: e-d elastic scattering





Why elastic e-scattering (quasi-elastic) on nucleons in nuclei gets smeared?

First determinations of the proton's form factors

First evidence of elastic electron-Nucleus scattering

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E. M. LYMAN,
Department of Physi...

R. Hofstadter: ep and eA elastic scattering (1953->)

The proton has an internal structure!

"As we have seen, the proton and neutron, which were once thought to be elementary particles are now seen to be highly complex bodies. It is almost certain that physicists will subsequentely investigate the constituent parts of the proton and neutron - the mesons of one sort or another. What will happen from that point on? One can only guess at future problems and future progress, but my personal conviction is that the search for ever-smaller and ever-more-fundamental particles will go on as Man retain the curiosity he has always demonstrated"

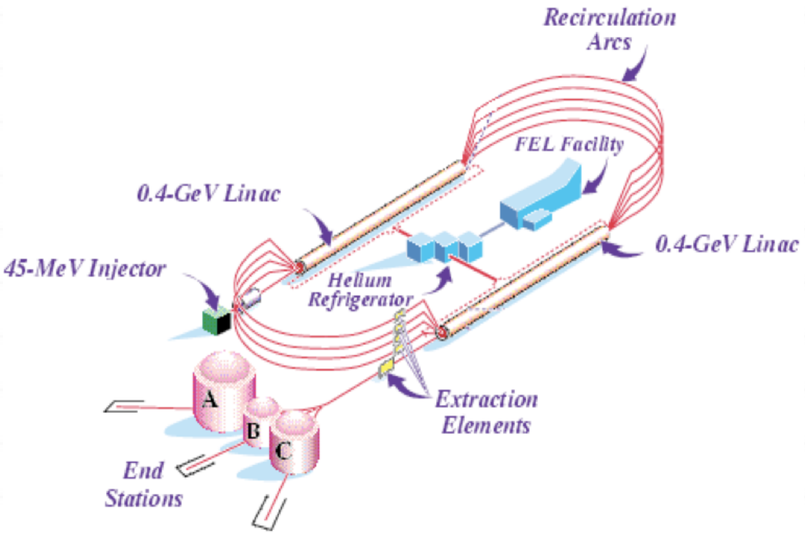
from the Nobel lecture, 1961

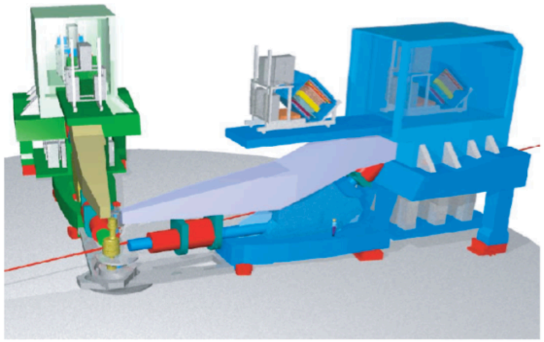
0 4 8 12

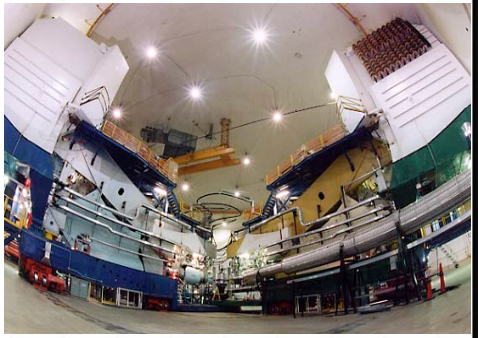
Q^2 (fermi)$^{-2}$

First determinations of the proton's form factors

Jefferson Lab







- ✳ Primary Beam: Electrons
- ✳ Beam Energy: 4 GeV (original)

  $10 > \lambda > 0.1$ fm
  nucleon → quark transition
  baryon and meson excited states

- ✳ 100% Duty Factor (cw) Beam

  coincidence experiments

  Three Simultaneous Beams with Independently Variable Energy and Intensity

  - ✳ complementary, long experiments

- ✳ Polarization (beam and reaction products)

  spin degrees of freedom

  weak neutral currents

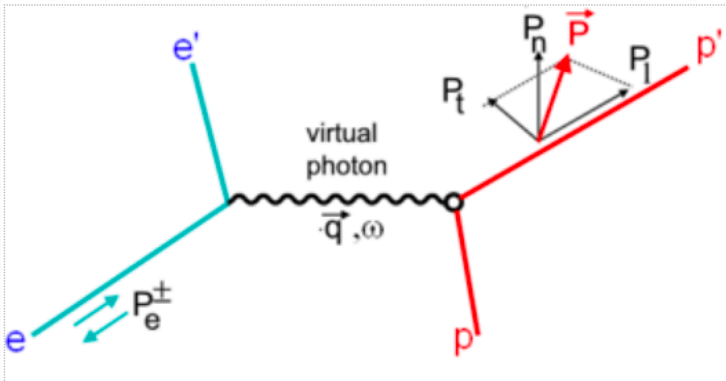
High Resolution Spectrometers (HRS)

- Resolution 1×10^{-4} FWHM
- Large momentum range (0.3-4.3 GeV, 0.3-3.3 GeV)
- Max luminosity 10^{38}cm^{-2}s^{-1}
- Proton Polarimeter

L > 10^6 x SLAC at the time of the original DIS experiments!

Elastic form factors using polarisation

- Measurement of ep elastic scattering with polarised electron and polarised protons
- Polarization observables are sensitive to G_E/G_M

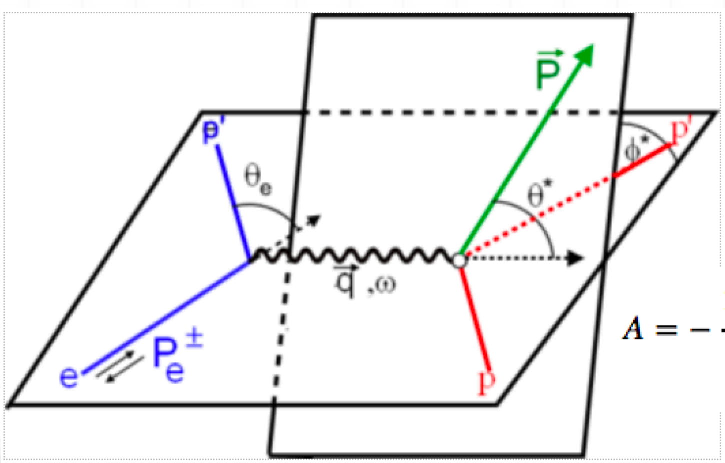


- Longitudinally polarised electrons on unpolarized proton
- Observable: ratio of polarisation components (par and perp) measured in a polarimeter

$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan\frac{\theta_e}{2},$$

$$I_0 P_\ell = \frac{1}{M}\left(E_e + E_e'\right)\sqrt{\tau(1+\tau)} G_M^2 \tan^2\frac{\theta_e}{2}$$

$$I_0 \propto G_E^2 + \frac{\tau}{\epsilon} G_M^2$$



- Longitudinally polarised electrons on polarised proton
- Observable: beam-spin asymmetry obtained flipping the e- helicity

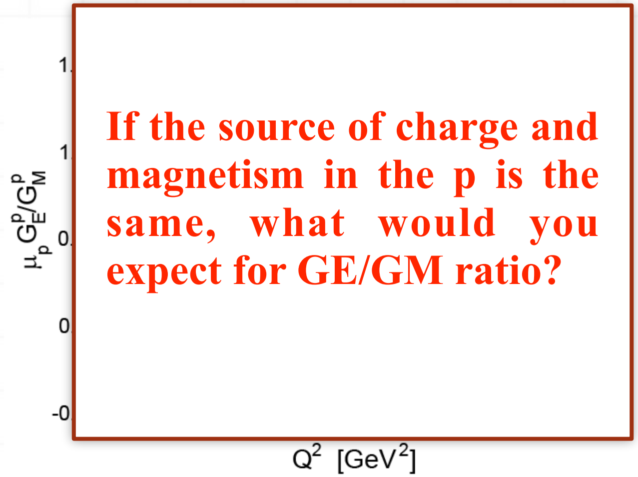
$$A = -\frac{2\sqrt{\tau(1+\tau)}\tan(\theta_e/2)}{G_E^2 + \frac{\tau}{\epsilon} G_M^2}\left[\sin\theta^*\cos\phi^* G_E G_M + \sqrt{\tau[1+(1+\tau)\tan^2(\theta_e/2)]}\cos\theta^* G_M^2\right].$$

$$\theta^* = \pi/2 \text{ and } \phi^* = 0^o \text{ or } 180^o$$

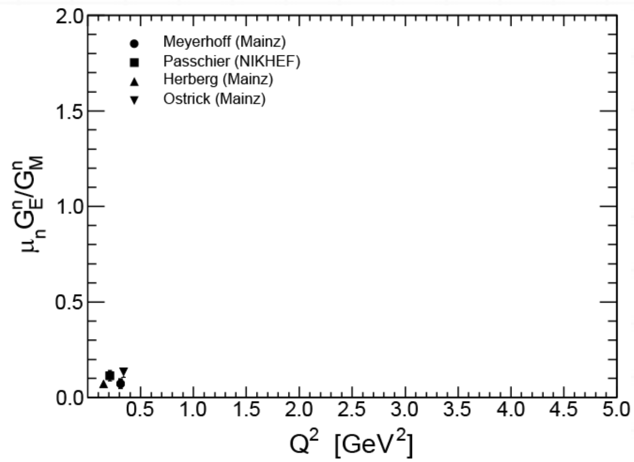
Elastic form factors

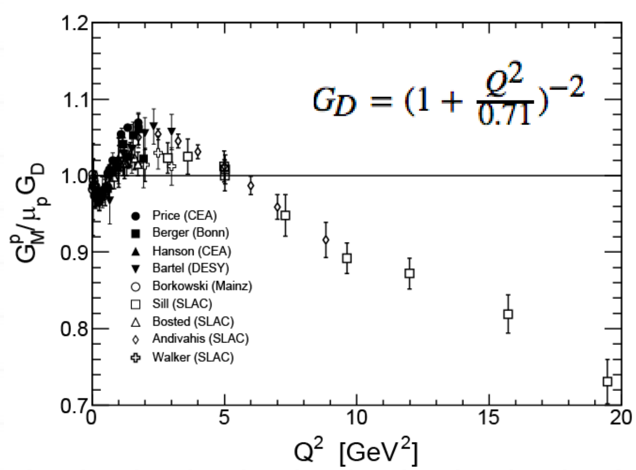
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

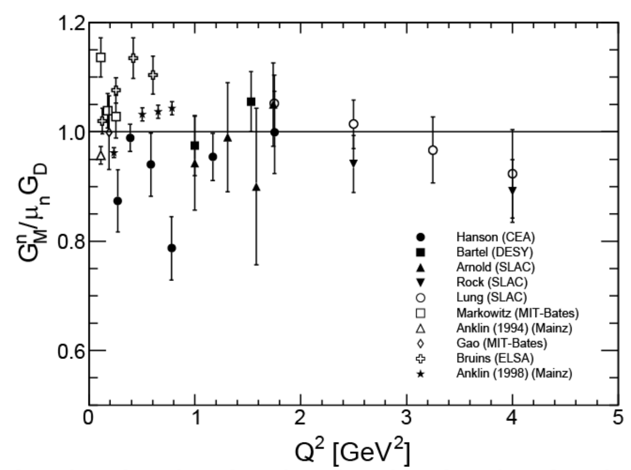
Before JLab and Recent non-JLab Data



If the source of charge and magnetism in the p is the same, what would you expect for GE/GM ratio?







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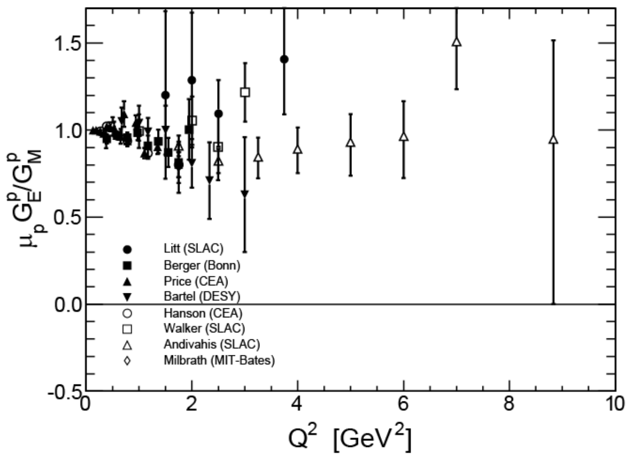
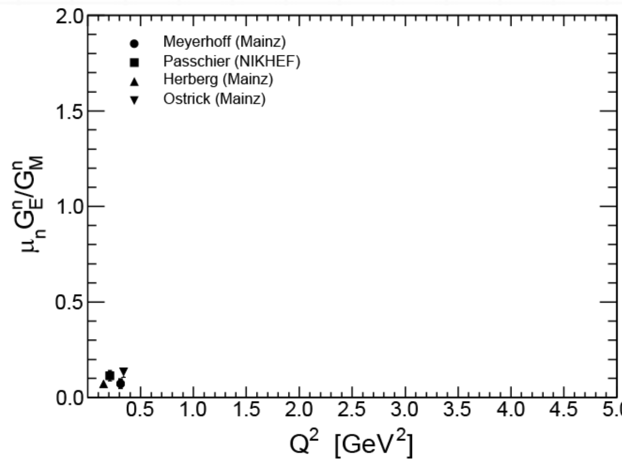
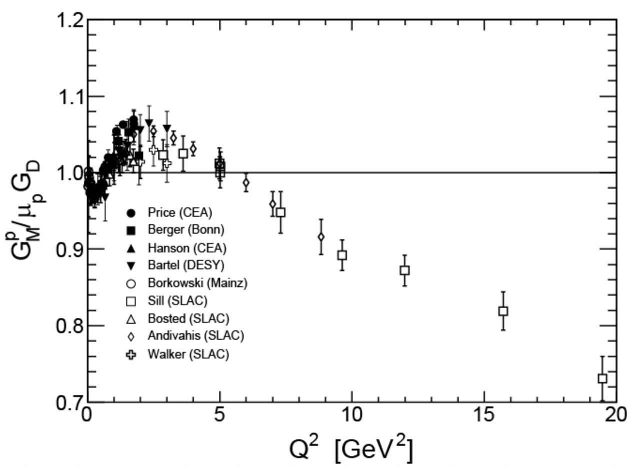
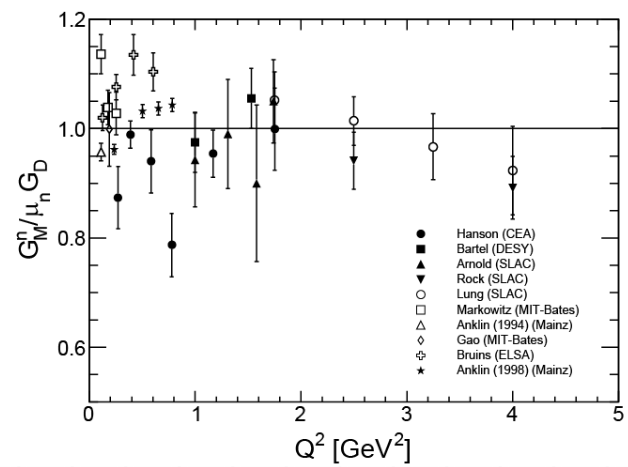




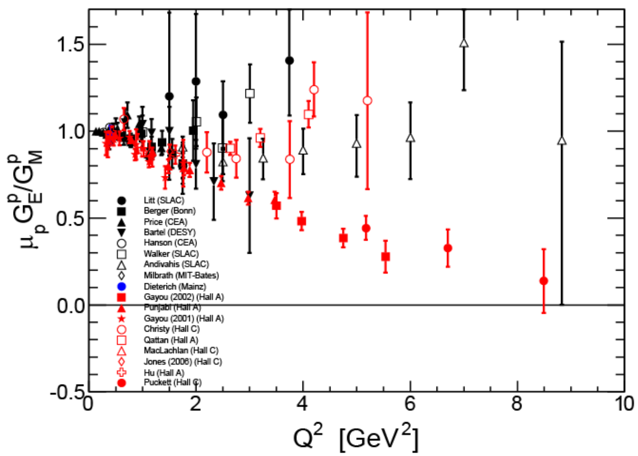


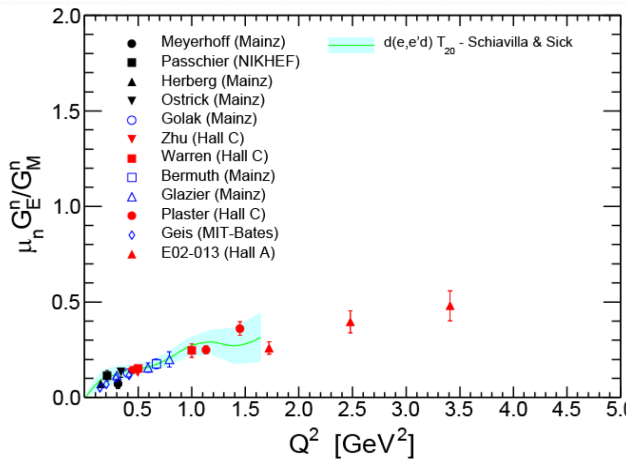


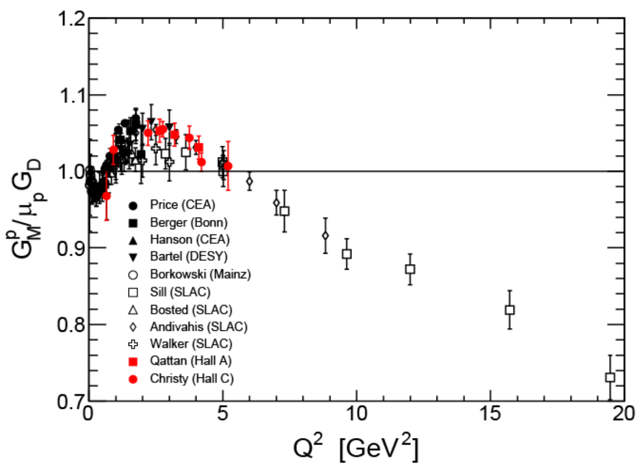
Elastic form factors

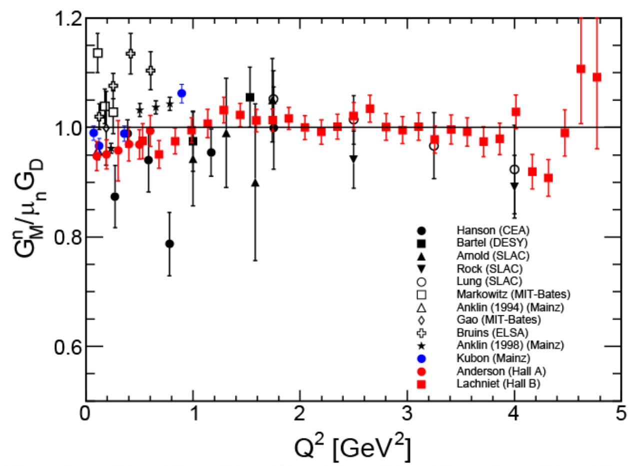
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

Today, including JLab Data









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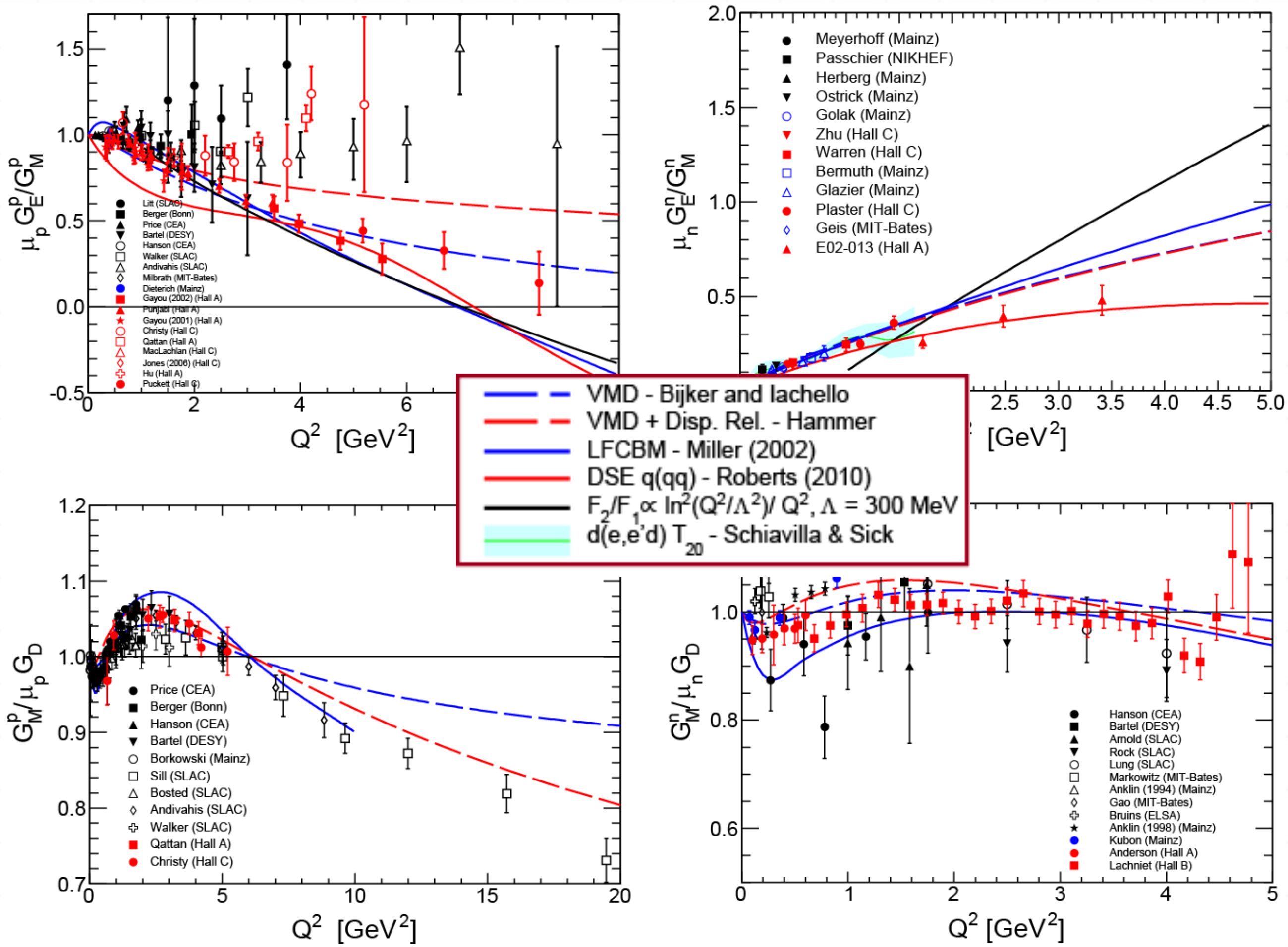
Today, including JLab Data and compared to theory



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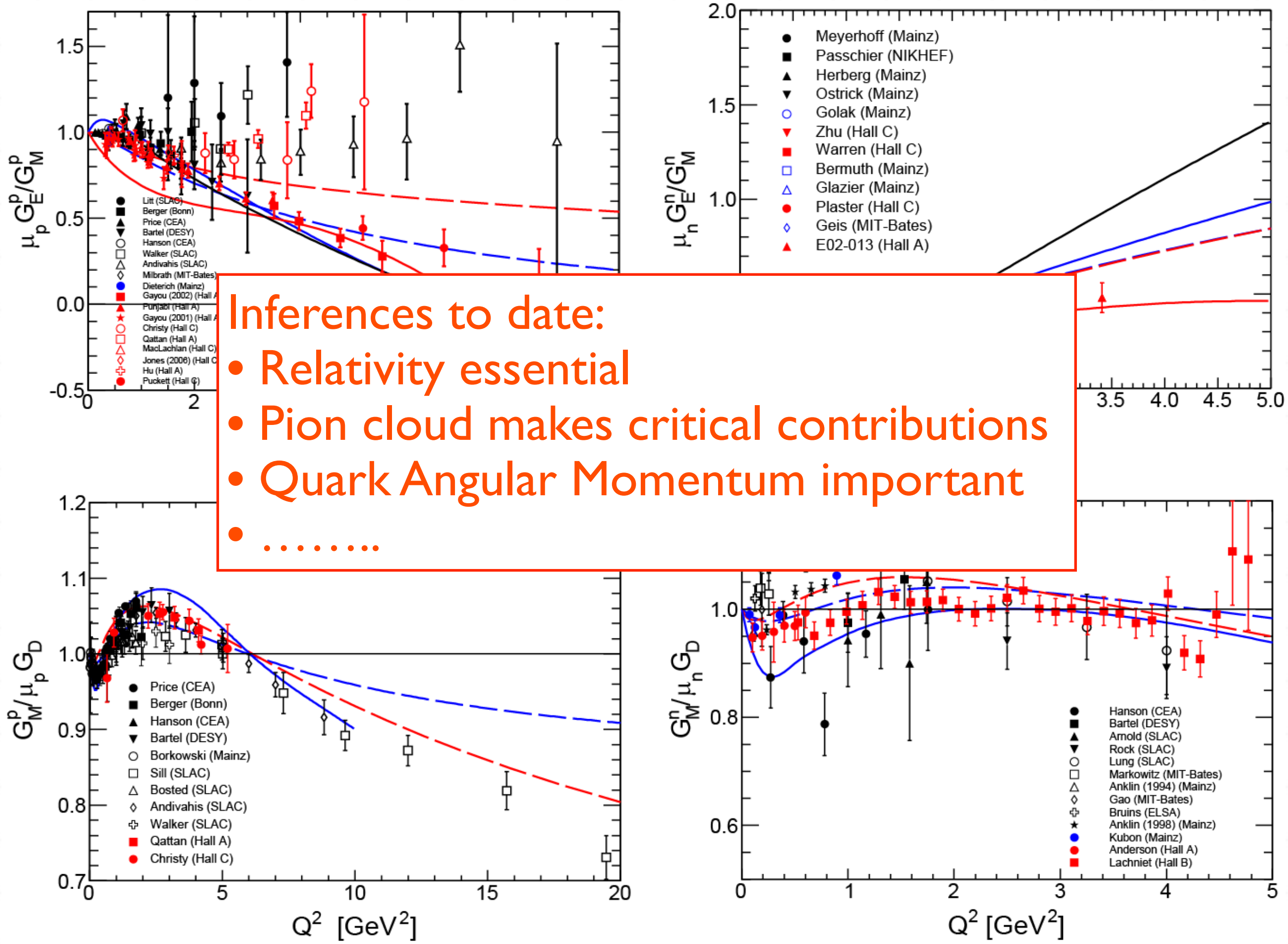
JLab data on the EM form factors provide a testing ground for theories constructing nucleons from quarks and glue

Today, including JLab Data and compared to theory



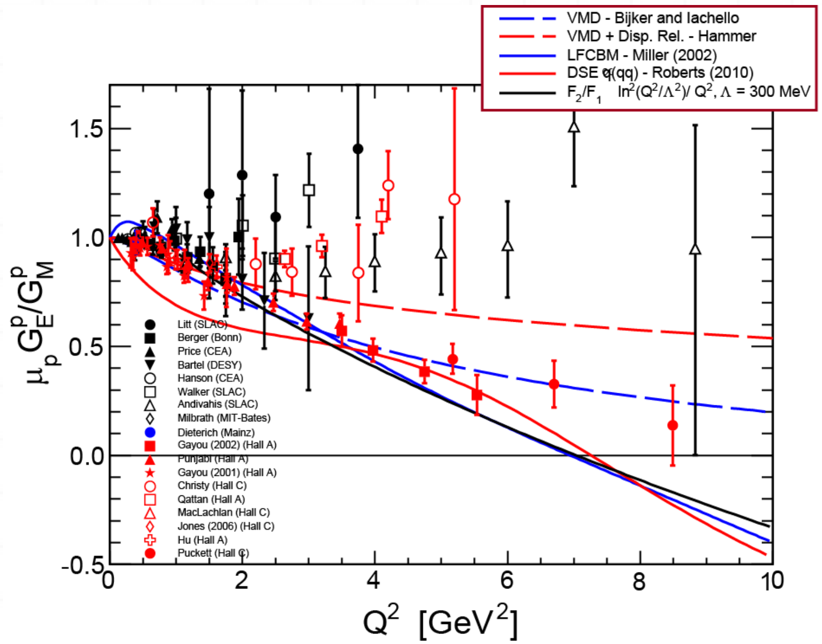
Inferences to date:

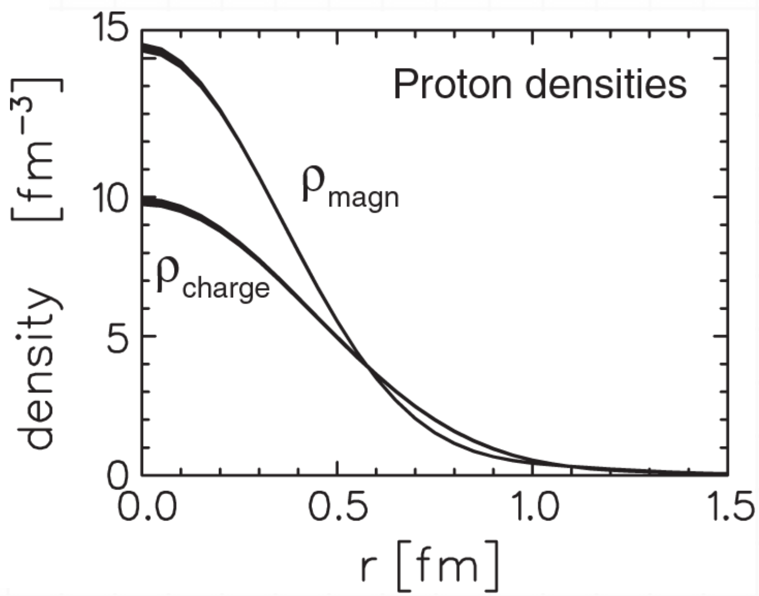
- Relativity essential
- Pion cloud makes critical contributions
- Quark Angular Momentum important
- ……..

These data are elucidating the nucleon's structure

The inequality of G_E^p and μG_M^p was a surprise.

- Rosenbluth separation - polarization transfer are incompatible
- Reconciliation: radiative corrections, TPE, ...
- Demonstrated that a proper treatment of quark orbital angular momentum and relativity + pion cloud is essential in describing nucleon structure

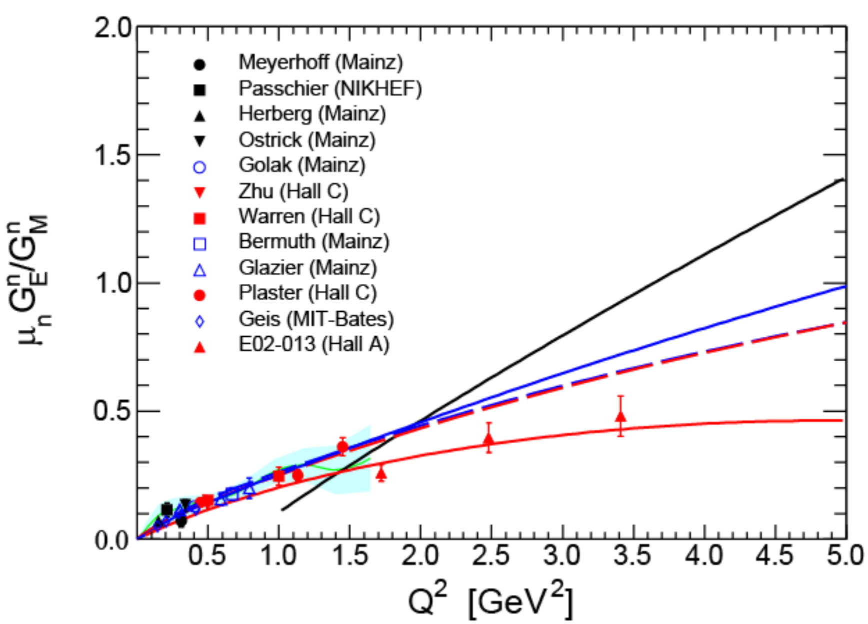


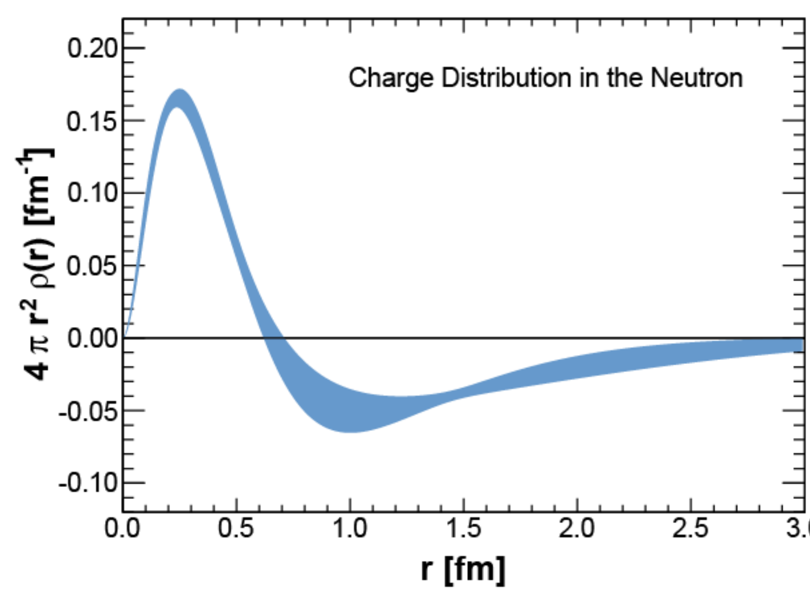


These data are elucidating the nucleon's structure

The charge form factor of the neutron is particularly interesting

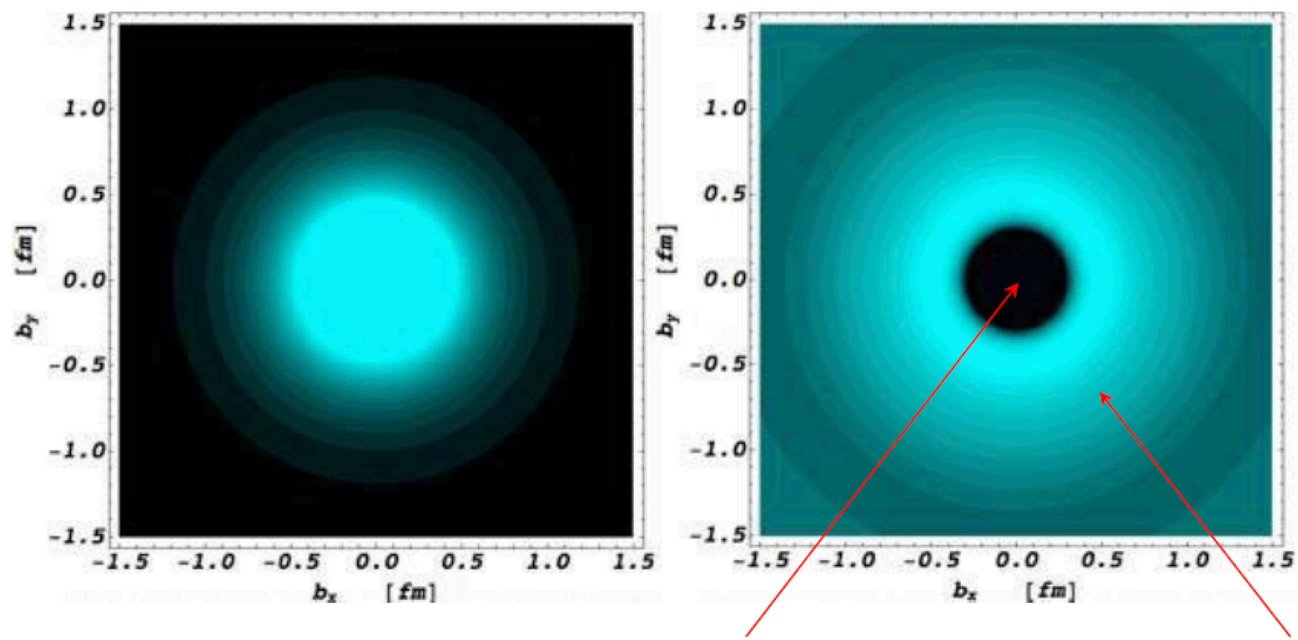
- Neutron electric form factor data reveal the shape of the charge distribution
- Confirm the importance of relativistic effects and pion cloud in nucleon structure
- Dressed quark-diquark model using the Dyson-Schwinger and Faddeev equations in good agreement





Charge density inside a nucleon

Proton **Neutron**

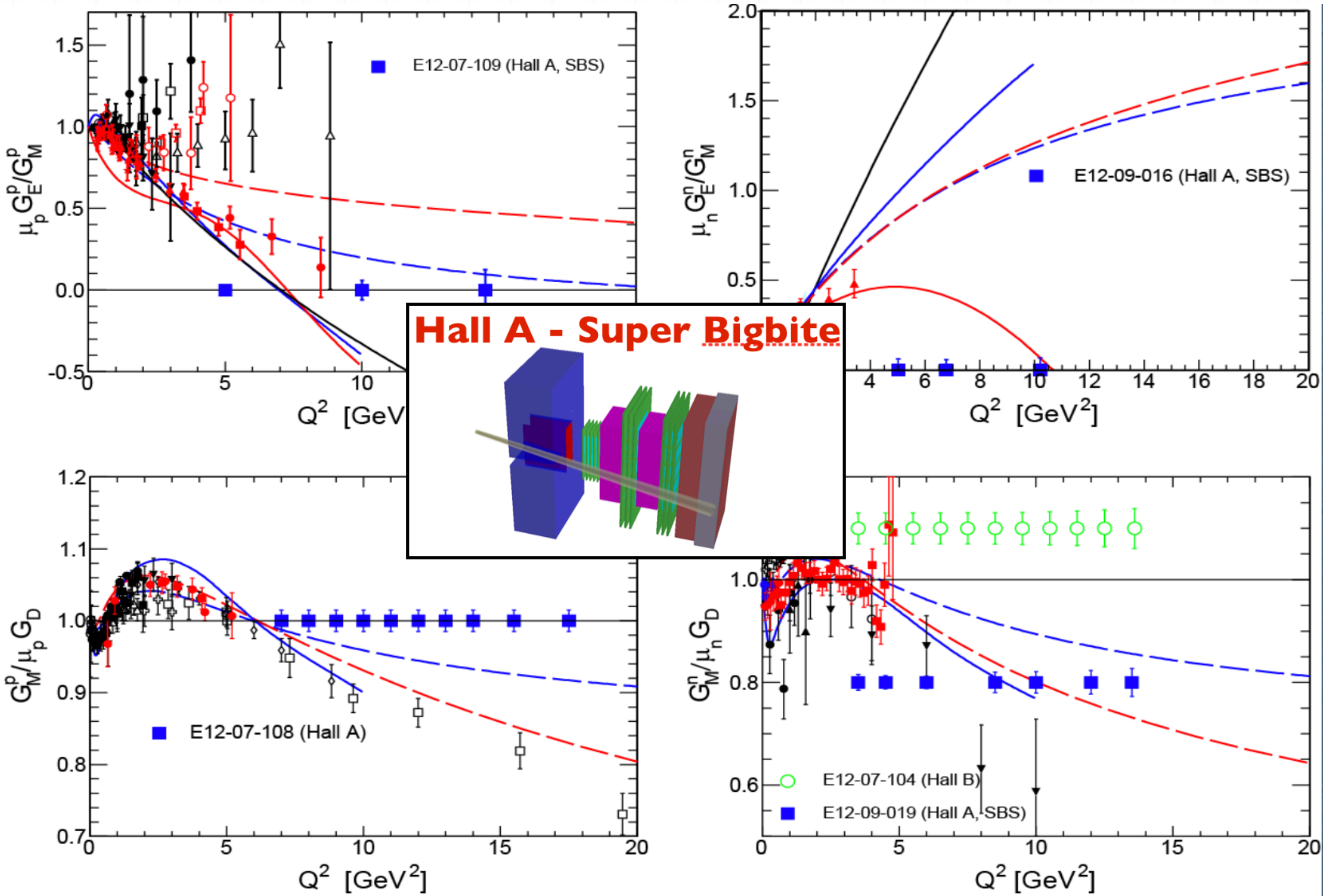


negative
inner core

positive outer
surface

C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)

Plans for JLab @ 12 GeV



The particle zoo

Discoveries of new "*elementary*" particles continued in the 50s and 60s and led to what is known as the **particle zoo.**

In the early 60s, **tens of baryons** (p, n, Λ^0, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^-, N^{*++},…) and **mesons** (π^+, π^0, π^-, η, K^+, K^0, K^0, K^-, η', ρ^+, ρ^0, ρ^-, ω, …) had been experimentally observed:

- Masses ranged from about a hundred of MeV to 1.5 GeV
- Charge ranged from -1 to +2
- Except for the proton and the neutron, the other particles were unstable, decaying in most of the cases to protons, neutrons and pions
- Life time for these decays ranged from 10^{-23} s to 10^{-10}s
- "Strange" particles seemed to be produced in pairs
- No theory capable of explaining their interaction and properties was available
- The number of particles seemed to increase with time…

This puzzling situation led physicists to look for some **underlying symmetry** that could be used to related properties of different particles and make predictions

The possibility that some of them may **not** be **elementary** particles started to be considered

Quarks and SU(3)

- The scheme proposed to organize the zoo of baryons and mesons was based on SU(3) symmetry
- Baryons and mesons were assumed to be composite states of three quarks and quark-antiquark pairs
- Gives natural explanation for Isospin $I_3 = \frac{1}{2}\left(n_u - n_d + n_{\bar{d}} - n_{\bar{u}}\right)$ n_i number of i quarks
- Masses of u and d quark are almost equal

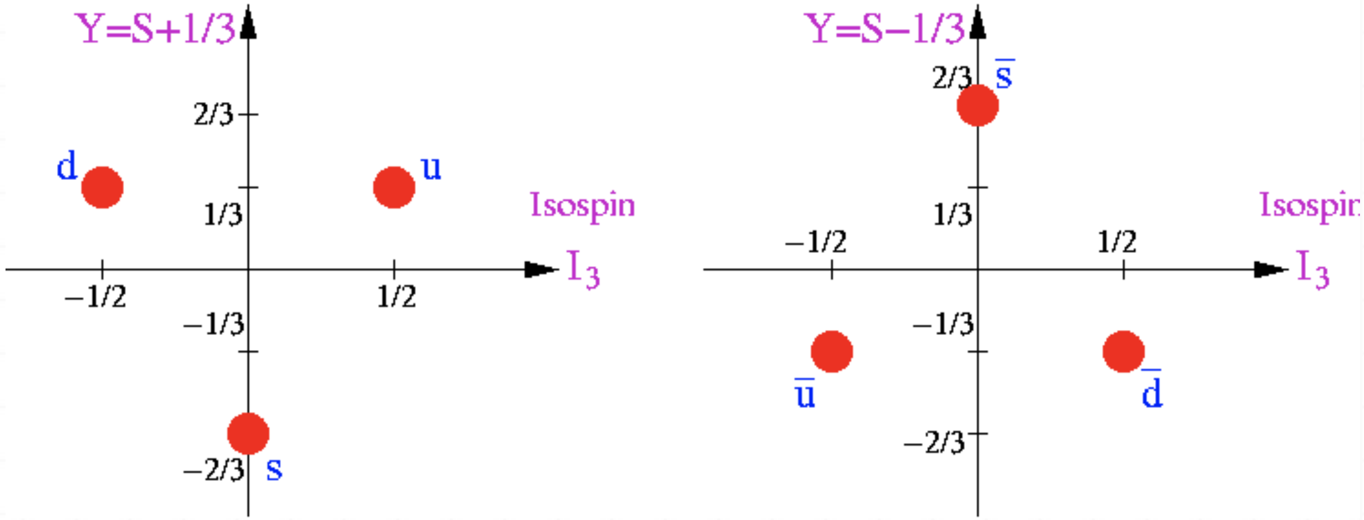
"Fractional charge bothered me because I wanted a correspondence between leptons and constituents of hadrons. To have one set of these particles integrally-charge and the other set fractionally-charge was ugly, but at this point there seemed to be no choice"(G. Zweig)

- Quarks were assumed to have:
  - spin=1/2
  - fractional charge
  - baryonic number B=1/3
  - mass ~1/3 of the nucleon mass

Quark	Charge Q [e]	Isospin $\lvert I, I_3 \rangle$	Strange-ness S
up (u)	+2/3	$\lvert \frac{1}{2}, +\frac{1}{2} \rangle$	0
down (d)	-1/3	$\lvert \frac{1}{2}, -\frac{1}{2} \rangle$	0
strange (s)	-1/3	$\lvert 0,0 \rangle$	-1

Quarks and SU(3)

- Charge, Isospin and Strangeness
- Additive quark quantum numbers are related $Q = I_3 + 1/2(S + B)$ Gell-Mann Nishijima
- Baryon number B quarks B = +1/3 anti-quarks B = -1/3
- Hypercharge Y = S + B is useful quantum number
- Quark model gives natural explanation for Isospin and Strangeness



Constituent Quark Model

Mesons are bound $q\bar{q}$ states

$$|\psi\rangle = \frac{1}{\sqrt{3}}\left|r\bar{r} + g\bar{g} + b\bar{b}\right\rangle$$ Zero net colour charge

$B = +1/3 + (-1/3) = 0$ Zero net baryon number

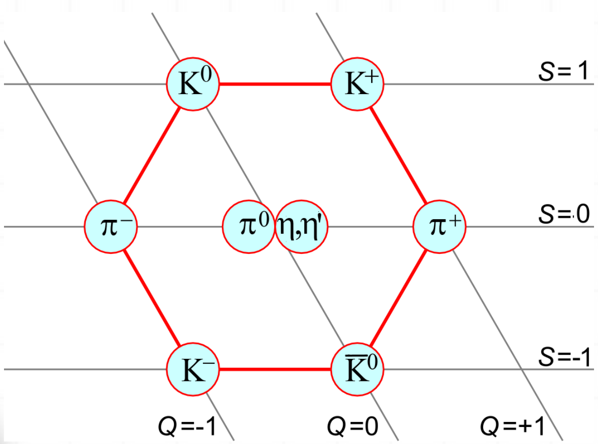
In a world with three flavors…

The symmetry of strong interaction is SU(3) and the **up** ($q=2/3, I_z=1/2, s=0$), **down** ($q=1/3, I_z=-1/2, s=0$) and **strange** ($q=-1/3, I_z=0, s=-1$) quarks form a triplet which represents the fundamental representation of the symmetry group

$$u, d, s = \mathbf{3}$$

Mesons, being made by q and q, transform as

$$\mathbf{3} \cdot \bar{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$$



non-zero flavour states $u\bar{d}, u\bar{s}, d\bar{u}, d\bar{s}, s\bar{u}, s\bar{d}$

zero net flavour states $u\bar{u}, d\bar{d}, s\bar{s}$

have identical additive quantum numbers

Physical states are mixtures

$K^+ = u\bar{s}$

$K^0 = d\bar{s}$

$\bar{K}^0 = s\bar{d}$

$K^- = s\bar{u}$

$\pi^+ = u\bar{d}$

$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$

$\pi^- = d\bar{u}$

$\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$

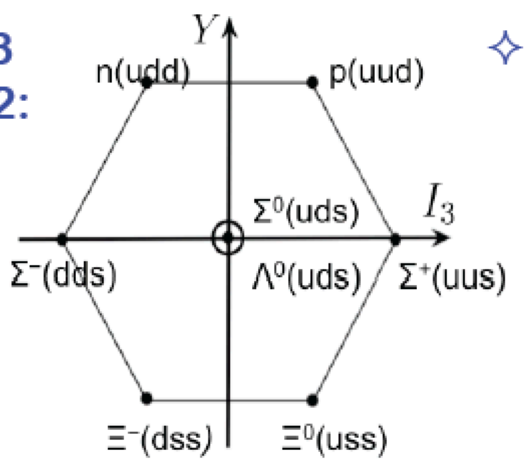
$\eta' = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$

Baryons

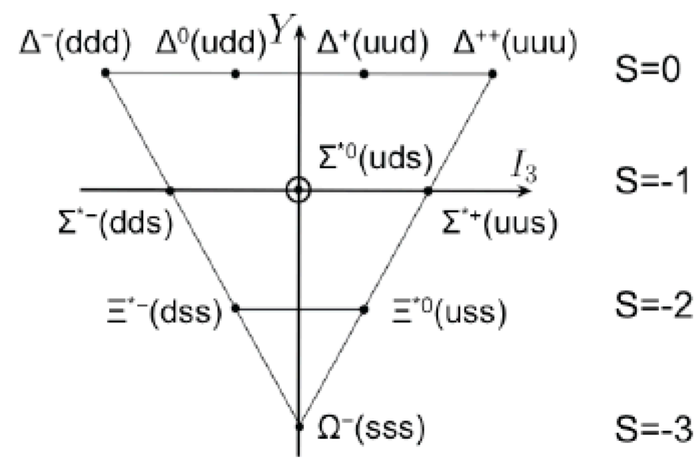
3 quark qqq states: $B = 1$

- Group theory says:
  - ✧ Flavor: $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10}_S \oplus \mathbf{8}_{M_S} \oplus \mathbf{8}_{M_A} \oplus \mathbf{1}_A$

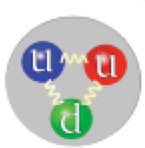
    S: symmetric in all 3 q, M_S : symmetric in 1 and 2,
    M_A : antisymmetric in 1 and 2, A : antisymmetric in all 3
  - ✧ Spin: $\mathbf{2} \otimes \mathbf{2} \otimes \mathbf{2} = \mathbf{4}_S \oplus \mathbf{2}_{M_s} \oplus \mathbf{2}_{M_A} \Longrightarrow S = \frac{3}{2}, \frac{1}{2}, \frac{1}{2}$
- Physical baryon states:
  - ✧ Flavor-8 Spin-1/2:



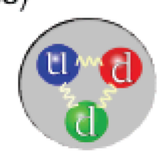
  - ✧ Flavor-10 Spin-3/2:



Proton



Neutron



Δ^{++}(uuu), …

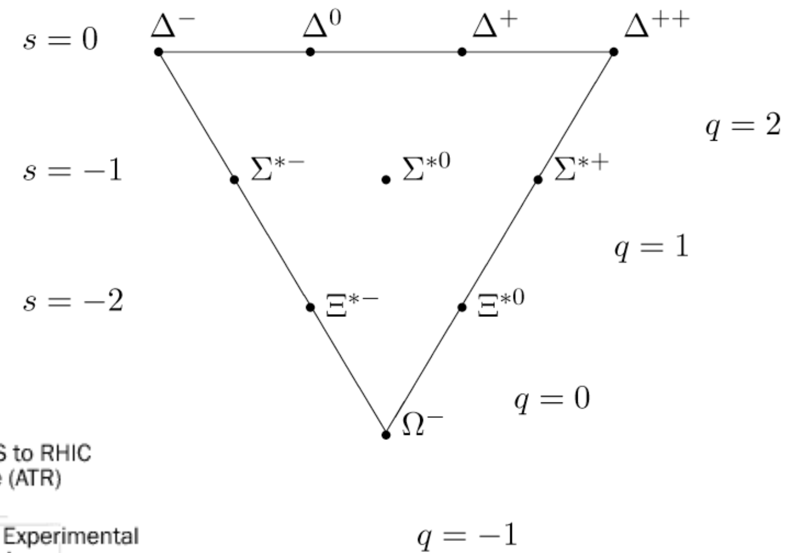
Violation of Pauli exclusive principle

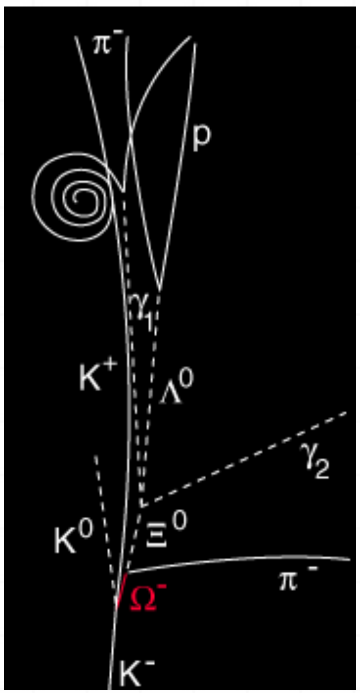
⟹ *Need another quantum number - color!*

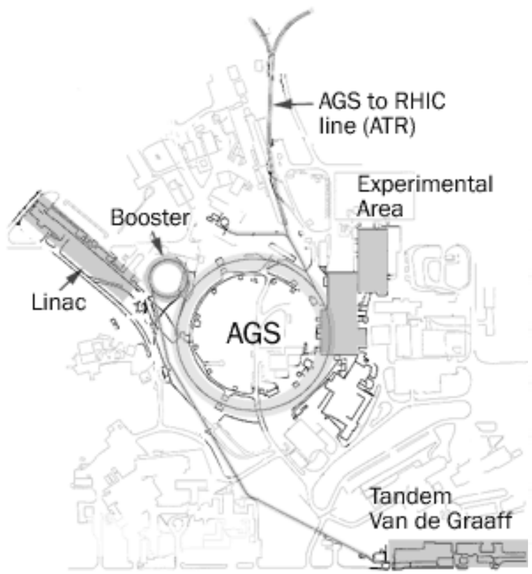
SU(3) and Discovery of the Ω-

1961: SU(3) symmetry (Gell-Man, Ne'eman)

Predicts the existence, mass and decay products of the Omega particle.



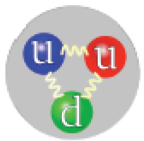


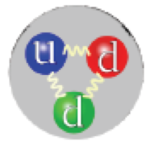


Brookhaven AGS:
33 GeV protons in 1960
(Now serves as injector for RHIC)

1964: Omega-minus Baryon discovered at Brookhaven National Laboratory

The proton revealed (*uud*)

Proton 

Neutron 

1960s: the Quark Model. Nucleons are composed of three valence quarks! Gell-Mann (Nobel Prize 1969), Zweig.

- **Wave function – the state:**

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\left[uud(\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow -2\uparrow\uparrow\downarrow) + udu(\uparrow\uparrow\downarrow + \downarrow\uparrow\uparrow -2\uparrow\downarrow\uparrow) + duu(\uparrow\downarrow\uparrow + \uparrow\uparrow\downarrow -2\downarrow\uparrow\uparrow)\right]$$

- **Normalization:**

$$\langle p\uparrow|p\uparrow\rangle = \frac{1}{18}[(1+1+(-2)^2) + (1+1+(-2)^2) + (1+1+(-2)^2)] = 1$$

- **Charge:** $\hat{Q} = \sum_{i=1}^{3} \hat{Q}_i$

$$\langle p\uparrow|\hat{Q}|p\uparrow\rangle = \frac{1}{18}[(\tfrac{2}{3}+\tfrac{2}{3}-\tfrac{1}{3})(1+1+(-2)^2) + (\tfrac{2}{3}-\tfrac{1}{3}+\tfrac{2}{3})(1+1+(-2)^2) + (-\tfrac{1}{3}+\tfrac{2}{3}+\tfrac{2}{3})(1+1+(-2)^2)] = 1$$

- **Spin:** $\hat{S} = \sum_{i=1}^{3} \hat{s}_i$

$$\langle p\uparrow|\hat{S}|p\uparrow\rangle = \frac{1}{18}\{[(\tfrac{1}{2}-\tfrac{1}{2}+\tfrac{1}{2}) + (-\tfrac{1}{2}+\tfrac{1}{2}+\tfrac{1}{2}) + 4(\tfrac{1}{2}+\tfrac{1}{2}-\tfrac{1}{2})] + [\tfrac{1}{2}+\tfrac{1}{2}+4\tfrac{1}{2}] + [\tfrac{1}{2}+\tfrac{1}{2}+4\tfrac{1}{2}]\} = \frac{1}{2}$$

- **Magnetic moment:**

$$\mu_p = \langle p\uparrow|\sum_{i=1}^{3}\hat{\mu}_i(\hat{\sigma}_3)_i|p\uparrow\rangle = \boxed{\text{to be calculated}}$$

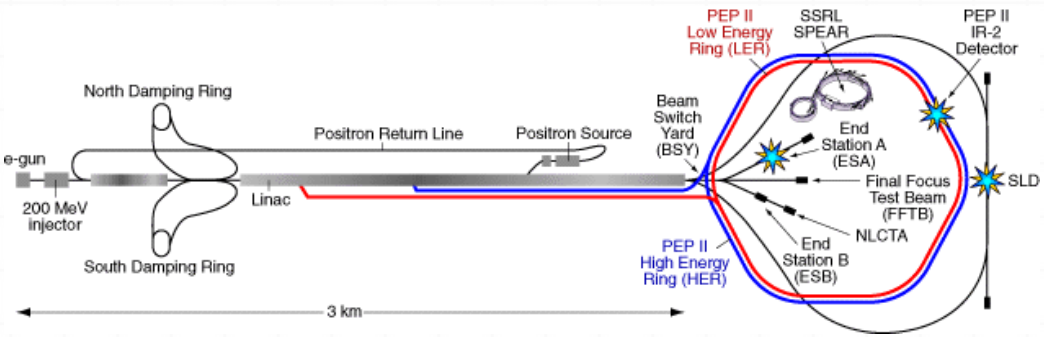
$$\mu_n = \boxed{\text{to be calculated}} \qquad \frac{\mu_u}{\mu_d} \approx \boxed{\text{to be calculated}}$$

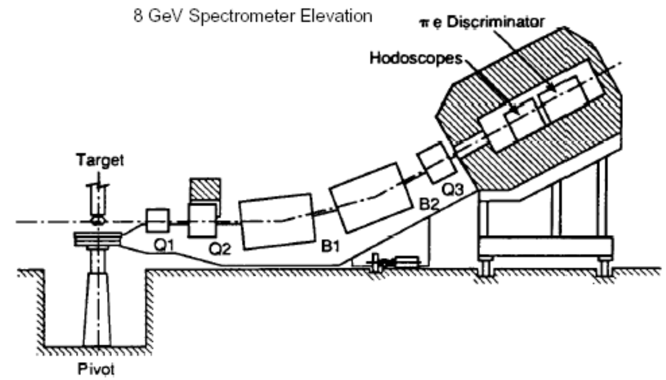
$$\left(\frac{\mu_n}{\mu_p}\right)_{\text{QM}} = \boxed{\text{to be calculated}}$$

$$\left(\frac{\mu_n}{\mu_p}\right)_{\text{Exp}} = -0.68497945(58)$$

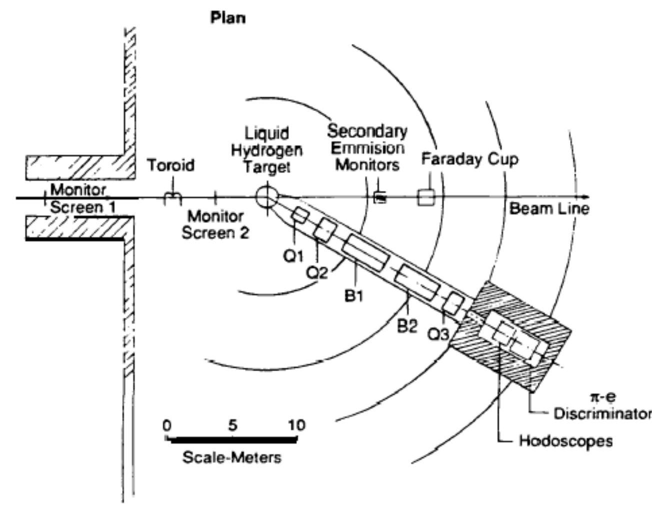
Stanford Linear Accelerator Center

On april 10, 1956, Stanford staff met in Prof. W. Panofsky's home to discuss Hofstadter's suggestion to build a linear accelerator that was at least 10 times as powerful as the Mark III. This idea was called "The M(onster)-project" because the accelerator would need to be 2 miles long!!





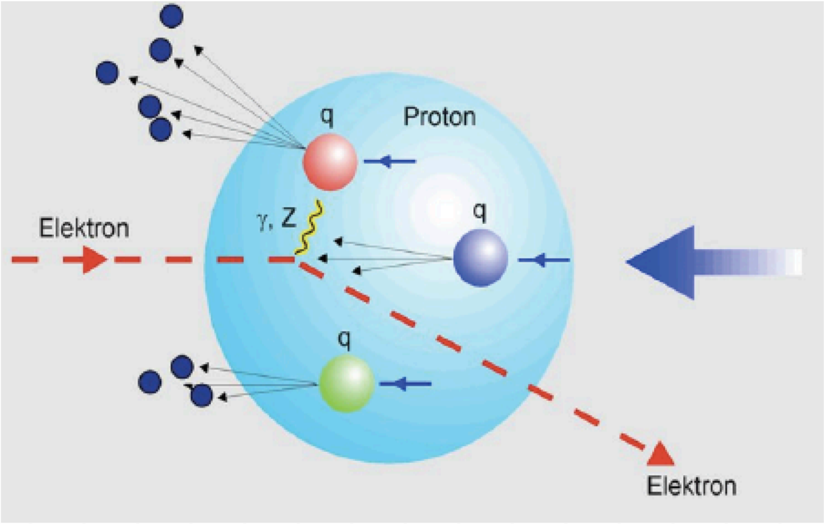
7-18 GeV electrons on Hydrogen



SLAC-MIT results: ep inelastic collisions

❑ Modern Rutherford experiment – Deep Inelastic Scattering:

SLAC 1968: $e(p) + h(P) \to e'(p') + X$



✧ **Localized probe:**

$$Q^2 = -(p - p')^2 \gg 1\ \text{fm}^{-2}$$

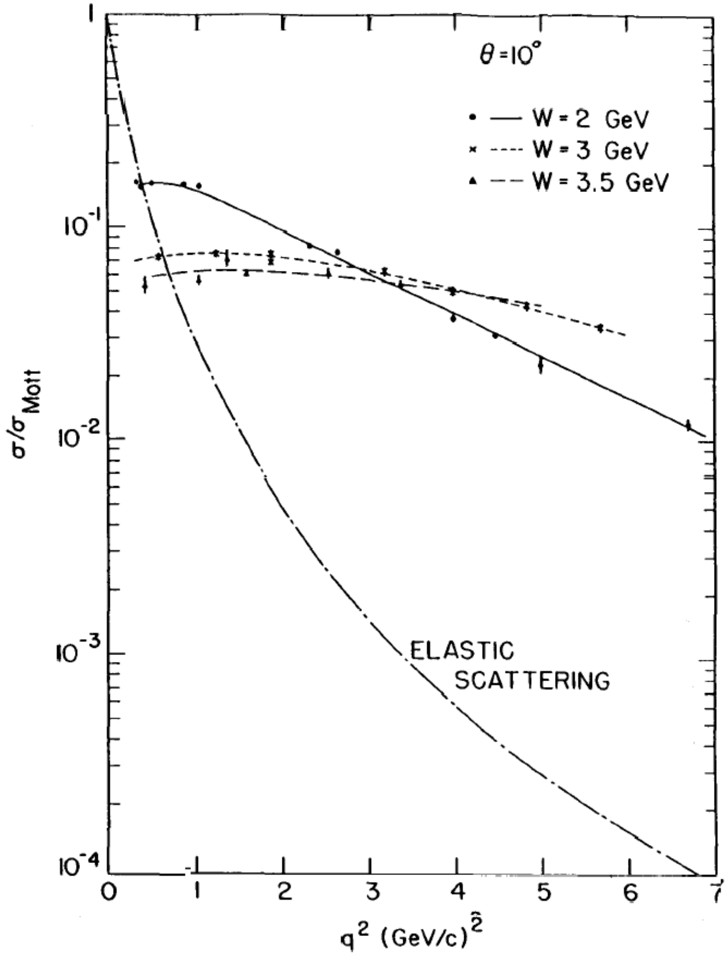
$$\Rightarrow \quad \frac{1}{Q} \ll 1\ \text{fm}$$

✧ **Two variables:**

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

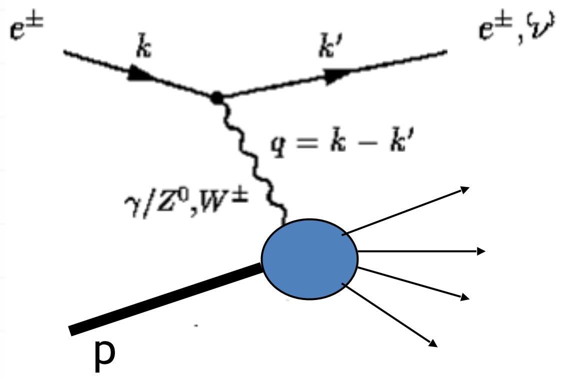
$$x_B = \frac{Q^2}{2m_N \nu}$$

$$\nu = E - E'$$



- $\sigma/\sigma_{\text{point-like}}$ = Independent of q^2
- Very weak dependence on W

Deep Inelastic Scattering



$$W^2 = m_p^2 + 2m_p\nu + q^2$$

$$Q^2 = -q^2$$

x = $Q^2/2p \bullet q$

Since W =! Mp, the four momentum transfer q2 and inelasticity ν are independent variables.

Parton rapidity $y = \frac{p_2 \cdot q}{p_2 \cdot p_1} = \frac{\nu}{E_1}$

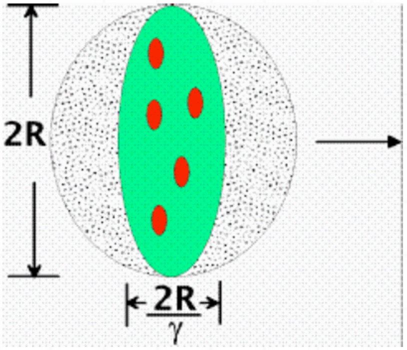
$$|\mathcal{M}|^2 = \frac{e^4}{q^2} L_e^{\mu\nu} (W_{\text{hadron}})_{\mu\nu}$$

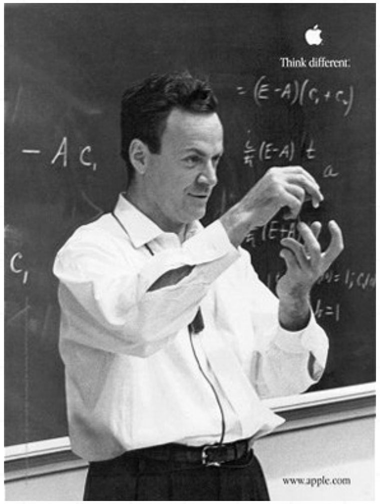
$$\frac{d\sigma}{dE_3 d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4 \frac{\theta}{2}} \left(W_2(\nu, Q^2) \cos^2 \frac{\theta}{2} + 2W_1(\nu, Q^2) \sin^2 \frac{\theta}{2} \right)$$

$$m_p W_1(\nu, Q^2) \rightarrow F_1(x) \qquad \nu W_2(\nu, Q^2) \rightarrow F_2(x)$$

Feynman's Parton Model (1969)

- What if proton (or any other hadron) was made up of point-like constituents—call them partons.
- If the proton is moving very fast, then the partons are frozen transversely because of time-dilation.
- Each parton, does carry a part of the longitudinal momentum of the proton.
- If two such protons (or hadrons) collide then, it can be thought of as a collision between two such partons which are not related to the behavior of other partons.
- The fact that partons must be interacting each other in the proton matters only "after" the collision happens.





Bjorken Scaling (1969)

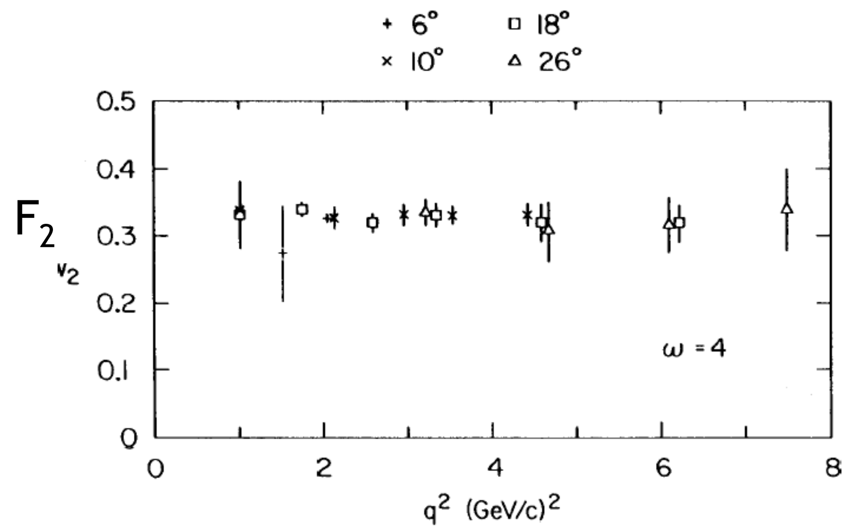
In the parton model:

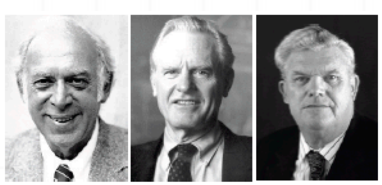
x = fraction of longitudinal momentum of the proton carried by the parton

Point-like parton p has some distribution in x:
i.e. p(x)

Then the structure function F_2 (x, Q^2) is simply
$F_2(x, Q^2) = x\, \Sigma_p\, e_p\, p(x) = F_2(x)$
i.e. No dependence on Q^2

In other words, if F_2 "scales", protons are consistent with being made up of partons.





1968: Deep Inelastic scattering at SLAC: scaling observed. The proton consists of point-like charges: partons! Friedman, Kendall, Taylor: Nobel Prize 1990

Quantum Chromo Dynamics (QCD)

= A quantum field theory of quarks and gluons =

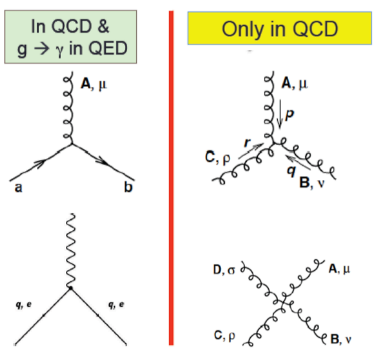
- **Fields:**

  $\psi_i^f(x)$ — Quark fields: spin-½ Dirac fermion (like electron)
  Color triplet: $i = 1, 2, 3 = N_c$
  Flavor: $f = u, d, s, c, b, t$

  $A_{\mu,a}(x)$ — Gluon fields: spin-1 vector field (like photon)
  Color octet: $a = 1, 2, ..., 8 = N_c^2 - 1$

- **QCD Lagrangian density:**

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - g A_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij} \right] \psi_j^f$$
$$- \frac{1}{4} \left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - g C_{abc} A_{\mu,b} A_{\nu,c} \right]^2$$
$$+ \text{gauge fixing} + \text{ghost terms}$$



- **QED – force to hold atoms together:**

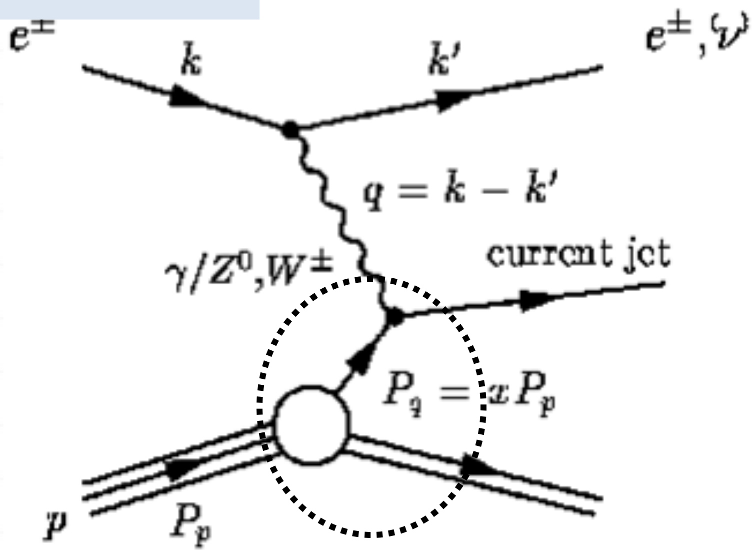
$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f \right] \psi^f - \frac{1}{4} \left[\partial_\mu A_\nu - \partial_\nu A_\mu \right]^2$$

QCD is much richer in dynamics than QED

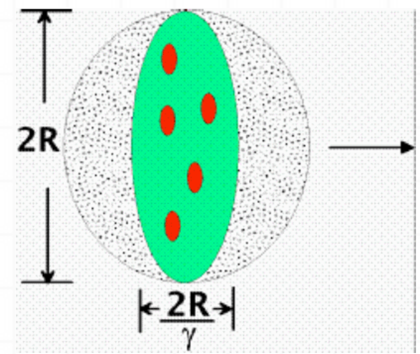
Gluons are dark, but, interact with themselves, NO free quarks and gluons

Deep Inelastic Scattering II

ep
collision



proton in "∞" momentum frame



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

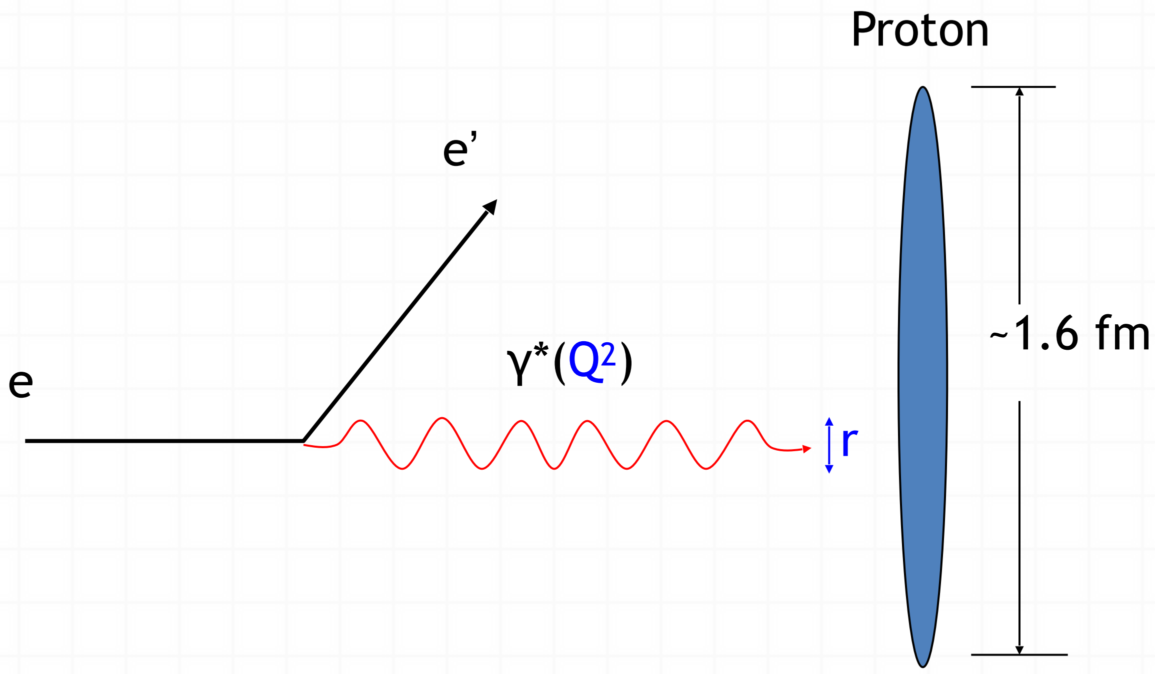
$\boxed{0 \leq x \leq 1}$

x = fractional longitudinal momentum carried by the struck parton

$\sqrt{s}$ = ep cms energy

$Q^2 = -q^2$ = 4-momentum transfer squared (or virtuality of the "photon")

Deep Inelastic Scattering II



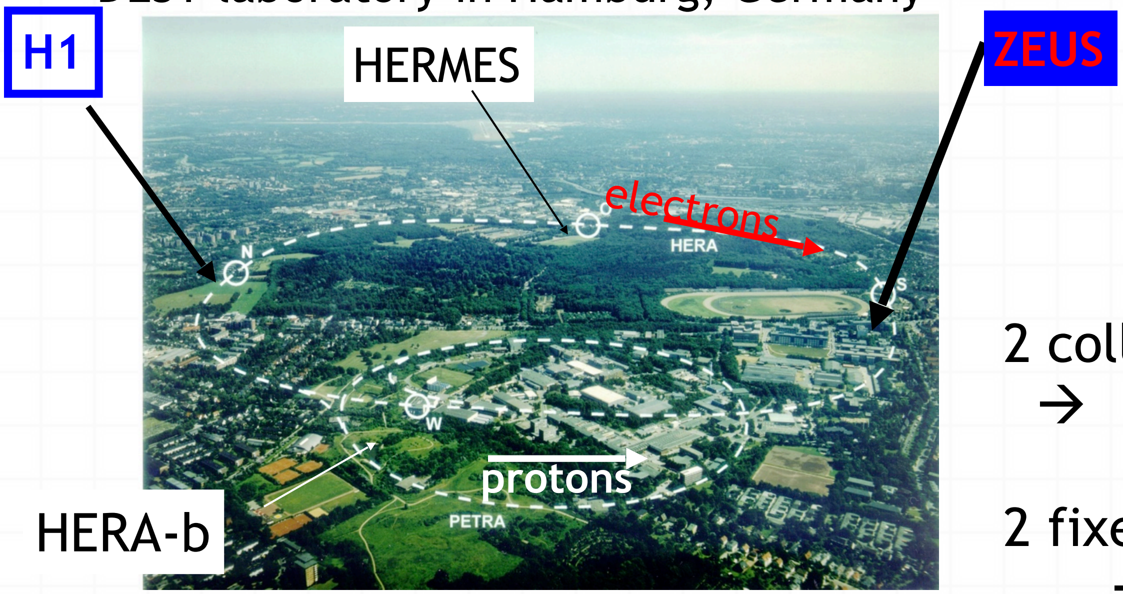
Virtuality (4-momentum transfer) Q gives the distance scale r at which the proton is probed.

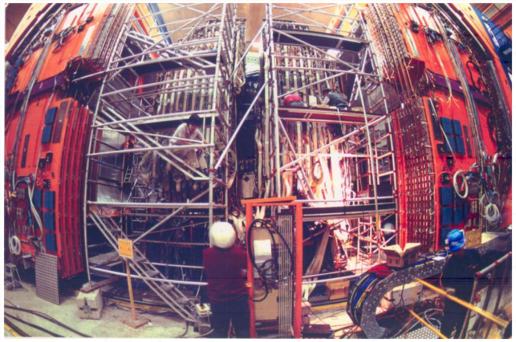
$r \approx \hbar c/Q = 0.2\text{fm}/Q[\text{GeV}]$

e.g. HERA ep collider DIS: $r_{min} \approx$ 1/1000 proton d

HERA Electron-Proton Collider (1992-2007)

DESY laboratory in Hamburg, Germany





2 collider experiments
→ ZEUS and H1

2 fixed target experiments
→ HERMES and HERA-b

- 920 GeV protons (820 before1998)
- 27.5 GeV $e^{\pm}$
- 300/318 GeV c.o.m. energy
- 220 bunches, 96ns. crossing time
- 90 mA protons,40 mA positrons
- Instantaneous luminosity: $1.8 \times 10^{31} cm^2 s^{-1}$

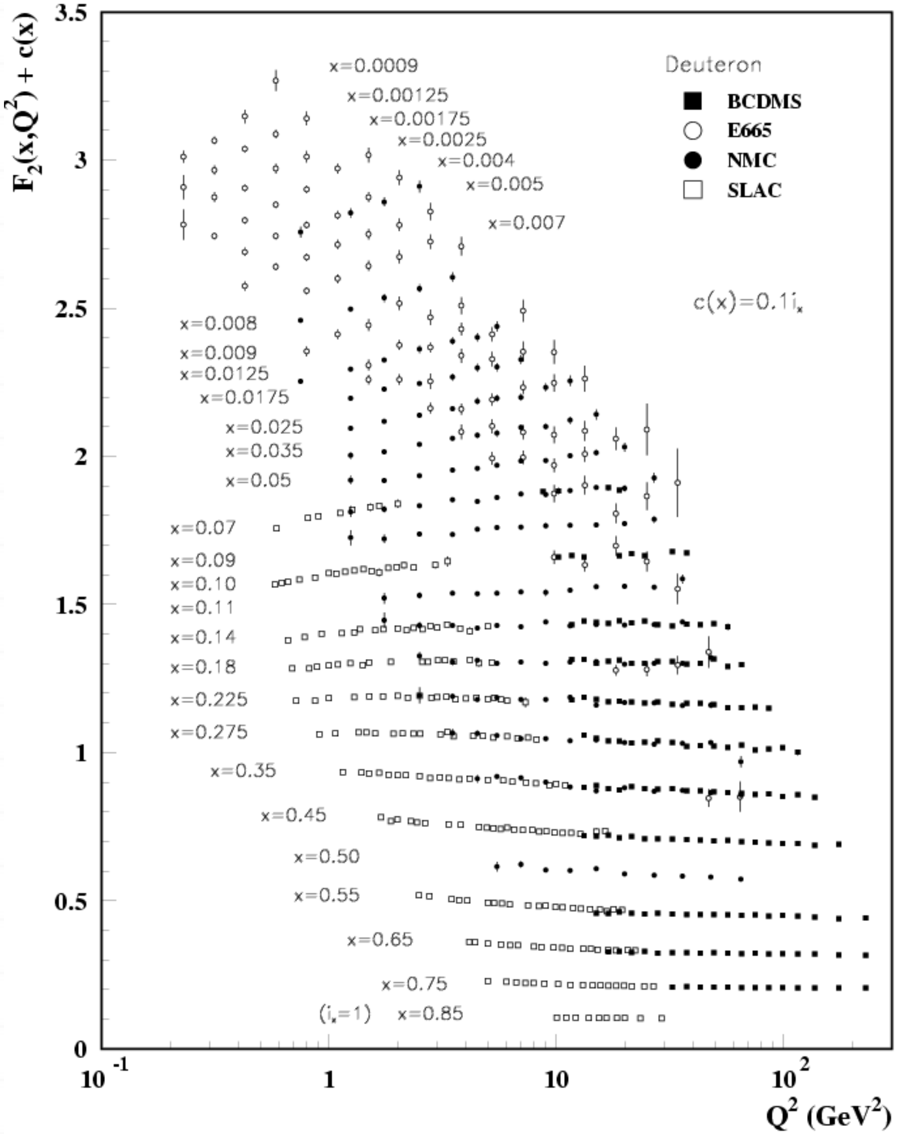
HERA Data taking 1991-2007

Mission: Explore QCD at highest scale (Q^2). Search for new phenomena.

$5.12 \times 10^{31} cm^2 s^{-1}$ after upgrade

DIS results

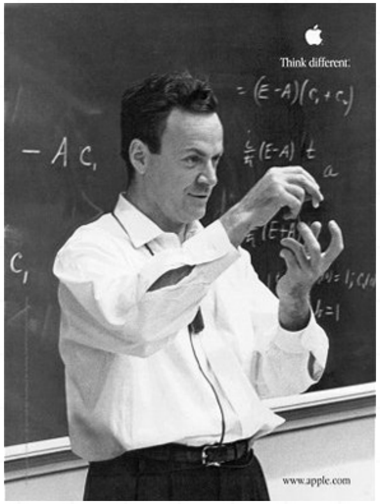
F_2: $1 < Q^2 < 200\ \mathrm{GeV}^2$



Partons in the proton

Feynman's parton model: the nucleon is made up of point-like constituents (later identified with quarks and gluons) which behave incoherently.
The probability f(x) for the parton f to carry the fraction x of the proton momentum is an intrinsic property of the nucleon and is process independent.

-Protons are just a "beam of partons" (incoherent)
-The f(x)s, the "beam parameters", could be measured in some other process. (process independent)



Quarks and Gluons as partons

$u(x)$: up quark distribution
$\bar{u}(x)$: up anti-quark distribution
etc.

Momentum has to add up to 1 ("momentum sum rule")

$$\boxed{\int x[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)+s(x)+\bar{s}(x)+ \\ \ldots.]dx = 1}$$

Quantum numbers of the nucleon has to be right

So for a proton:

$$\int[u(x)-\bar{u}(x)]dx=2 \qquad \int[d(x)-\bar{d}(x)]dx=1$$

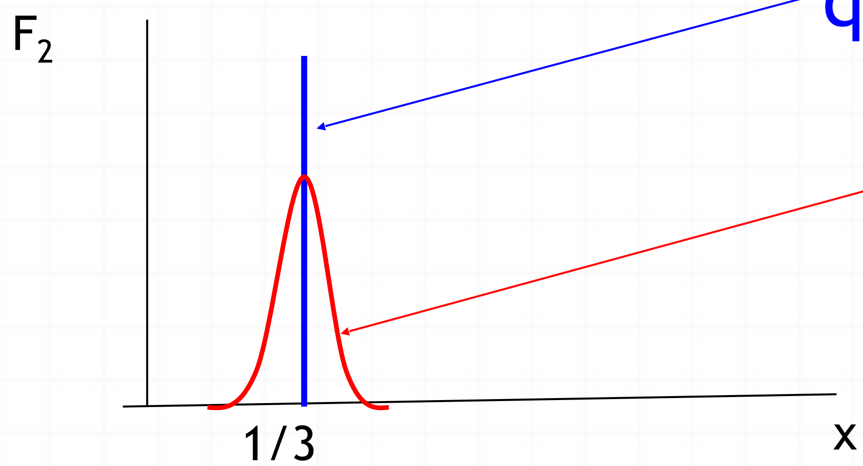
$$\int[s(x)-\bar{s}(x)+\ldots\ldots]dx=0$$

IF, proton was made of 3 quarks each with 1/3 of proton's momentum:

no anti-quark!

$$F_2 = x\Sigma(q(x) + \bar{q}(x))^2 e_q$$

$q(x)=\delta(x-1/3)$

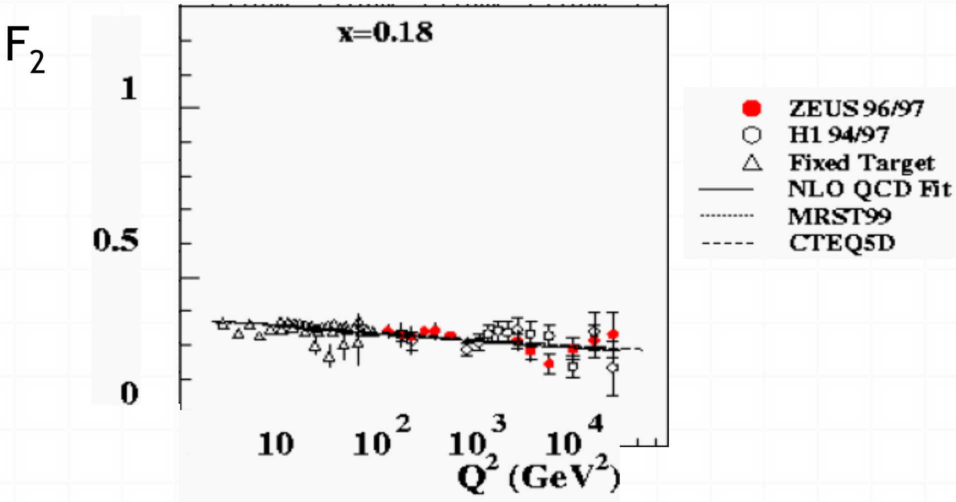


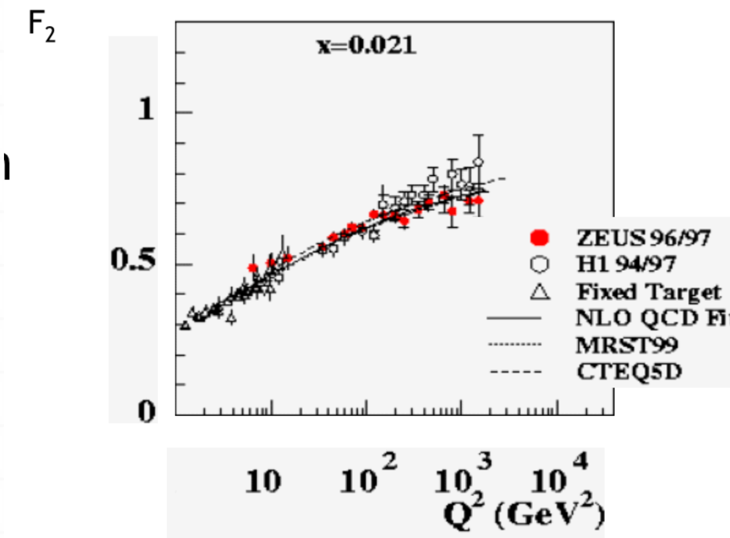
or with some smearing

The partons are point-like and incoherent then Q^2 shouldn't matter.

→ Bjorken scaling: F_2 has no Q^2 dependence.

Let's look at some data→



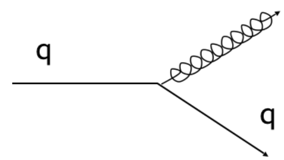


Seems to be....

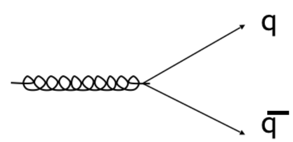
NOT (at small x)

QCD, of course:

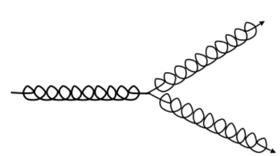
So what does this mean..?



quarks radiate gluons

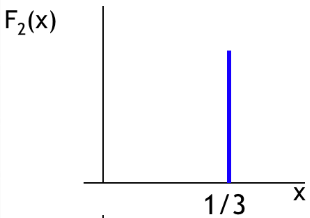


gluons can produce $\bar{q}q$ pairs

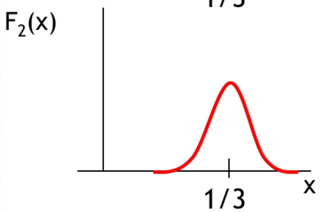


gluons can radiate gluons!

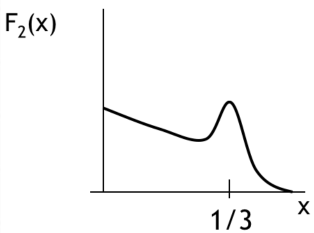
what do we expect F_2 as a function of x at a fixed Q^2 to look like?



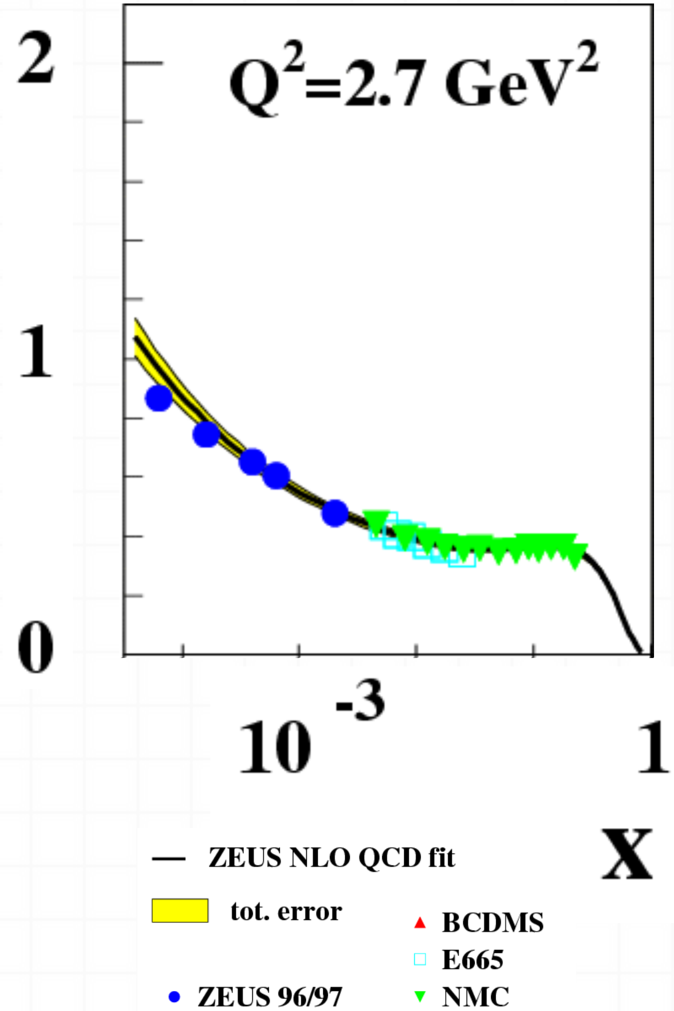
Three quarks with 1/3 of total proton momentum each.



Three quarks with some momentum smearing.



The three quarks radiate partons at low x.

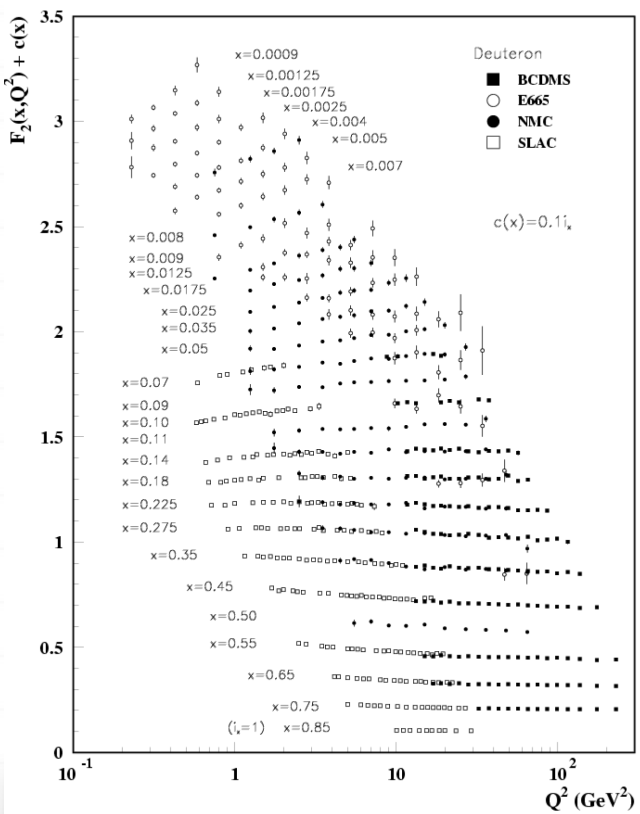


How this change with Q^2 happens quantitatively described by the:

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (**DGLAP**) equations

DIS results and F_2 interpretation (pQCD)

F_2: $1 < Q^2 < 200$ GeV^2



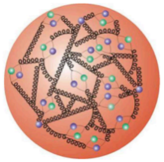
pQCD

Quarks are asymptotically free!

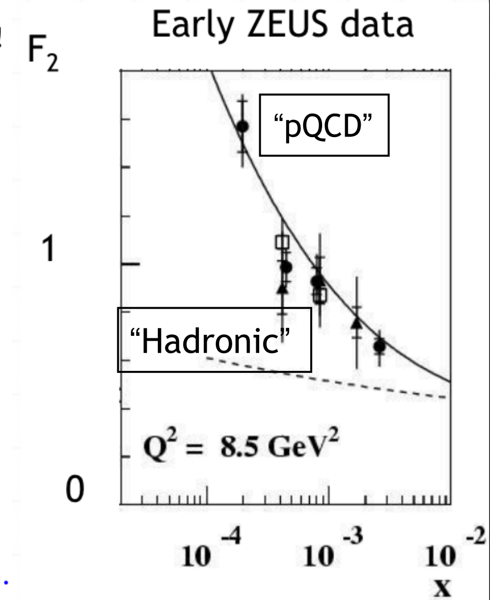
Proton is a beam of partons whose behavior can be understood using perturbative QCD!

OR

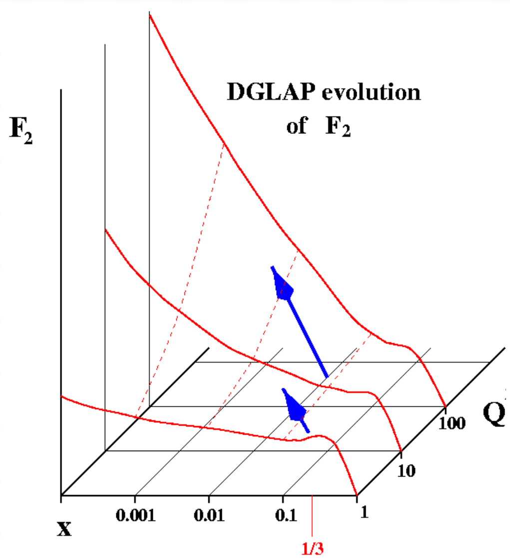
Hadronic



Protons are hadrons—whose constituents are confined. The behavior of hadrons is not understood from the first principles of QCD: however we have relatively good phenomenology to describe them.



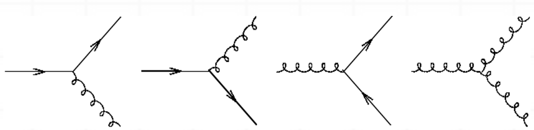
Protons at high momentum can be treated as a beam of partons - now identified as free quarks and gluons: (**Asymptotic freedom!**)

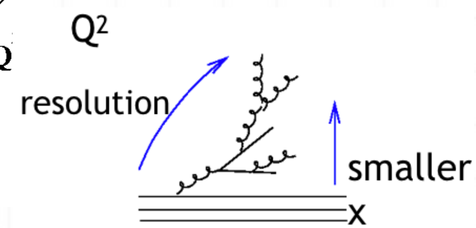


DGLAP evolution equations:

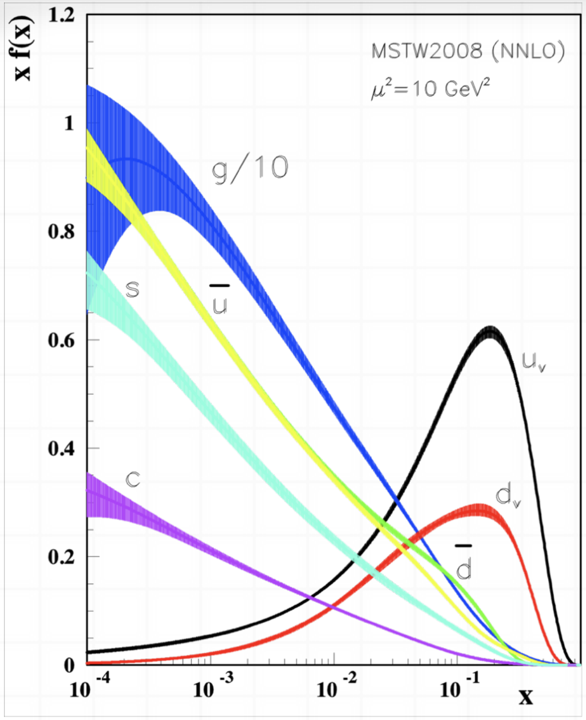
$$\frac{\partial f_p}{\partial \ln Q^2} \sim f_p \otimes P$$

P's are splitting functions:



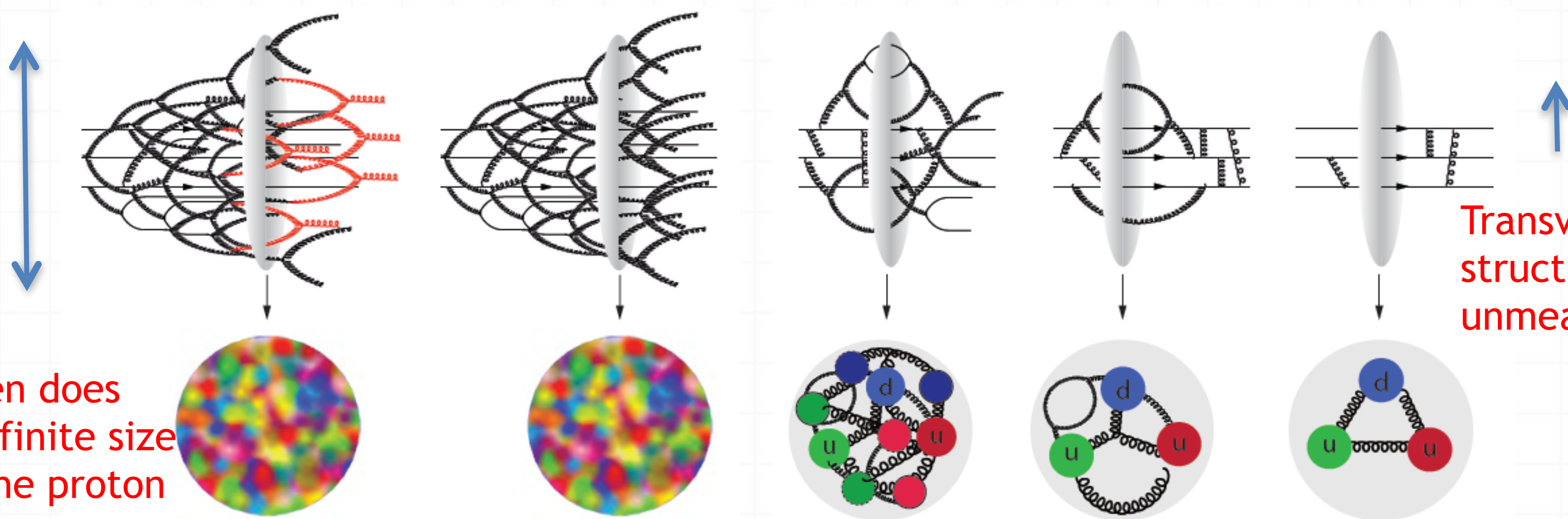


Evolution in Q^2 →many gluons at low x



pQCD picture of the proton

- Proton structure is embedded in the quark and gluon distributions.
- Gluons dominate below x of 0.1
- We imagine a proton looks something like the cartoon below.
- But we so far only have longitudinal information…



Transverse structure unmeasured

When does the finite size of the proton begin to matter (saturation! confinement!)

X (longitudinal) structure measured