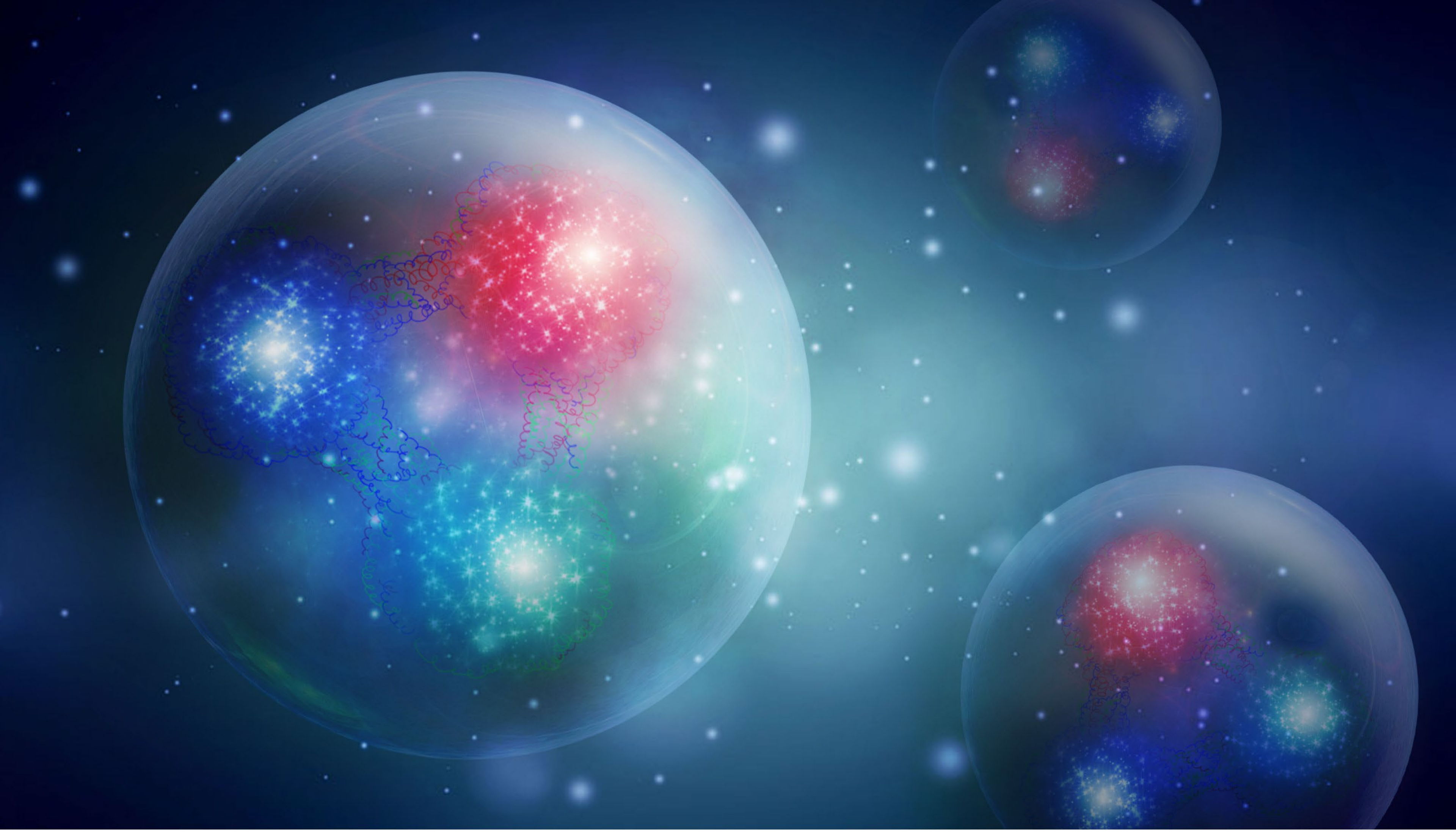


Electron-Ion Collider

NNPSS Lectures 2017 (Day1) Rik Yoshida, Jefferson Lab

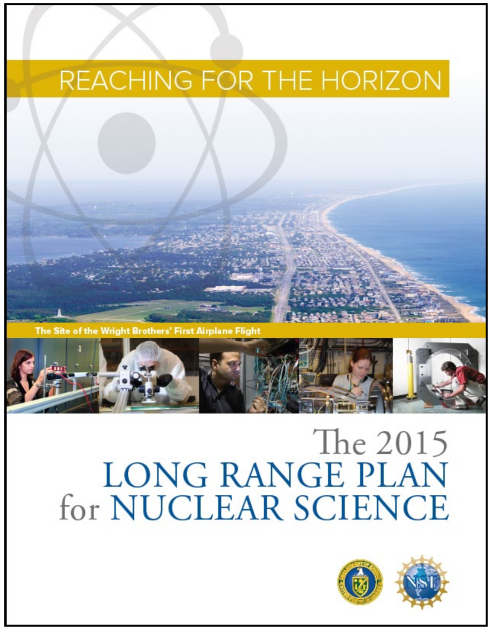
PROLOGUE:

Nuclear Science Long-Range Planning

- Every 5-7 years the US Nuclear Science community produces a Long-Range Planning (LRP) Document
- The final document includes a *small* set of recommendations for the field of Nuclear Science **for the next decade**

October 2015 ->Latest Report Finalized
(Including cost review of EIC)

USDOE (NP) is acting based on this planning
National Academy Science Review being commissioned
(Larger science case must be endorsed)



Recommendations - shorthand

1. **The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.**
   - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
   - **FRIB** – understanding of nuclei and their role in the cosmos
   - **Fundamental Symmetries Initiative** – physics beyond the SM
   - **RHIC** – properties and phases of quark and gluon matter

   The ordering of these four bullets follows the priority ordering of the 2007 plan

2. **We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.**

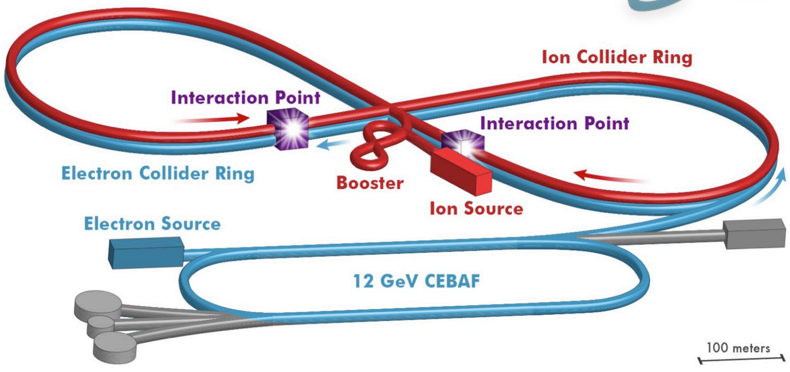
3. **We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.**

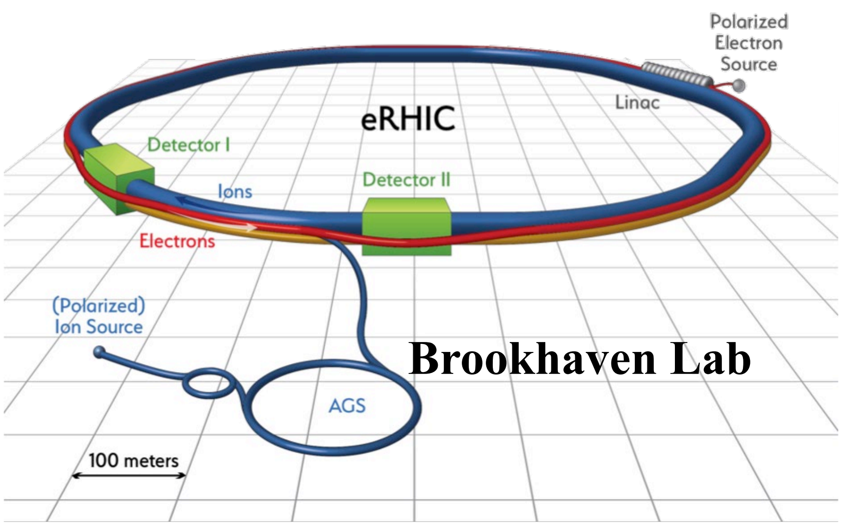
4. **We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.**

US EIC Parameters and Realization Plans

- US EIC Machine design aims from the EIC Whitepaper
  - Highly polarized (~70%) electron and nucleon beams.
  - Ion beams from deuterons to the heaviest nuclei (uranium or lead).
  - Variable center of mass energies from ~20 - ~ 100 GeV, upgradable to ~140 GeV.
  - High luminosity: ~10 $^{33-34}$ cm^{-2} s^{-1}
  - Possibility of having more than one interaction region.
- Two proposed realization plans
  - Jefferson Lab: building on the existing 12 GeV CEBAF. JLEIC Design.
  - BNL: building on the existing RHIC. eRHIC Design.
  - Recent review of acc. R&D
- Similar performances, cost according to LRP assessment.
- US EIC will likely be down-selected from one of these proposals.

Jefferson Lab





Brookhaven Lab

EIC Realization Imagined

With a formal NSAC/LRP recommendation, what can we speculate about any EIC timeline?

• A National Academy of Sciences study has been initiated and the committee is now formed. Charge: "assess the scientific justification for a U.S. domestic electron ion collider facility, " (Wider Science Community) Likely to take until end 2017.

• DOE project "CD0" (Establish Mission Need) will be after the NAS study: i.e end 2017, early 2018.

• EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20.

→ Most optimistic scenario would have EIC construction start (CD3) in FY20, perhaps more realistic FY22-23 timeframe

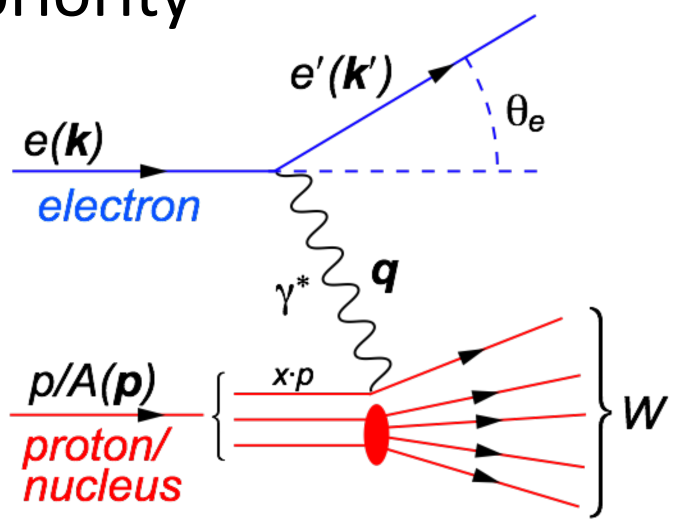
→ Best guess for EIC completion assuming formal NSAC/LRP recommendation would be 2025-2030 timeframe

Electron Ion Collider (EIC)

- Electron Ion Collider (EIC)
  - It is a Deep Inelastic Scattering Collider
  - Point-like probe interacts with p/A
  - So why is EIC the highest priority

  for new construction for

  US Nuclear Physics?



[Won't get to answers until Day 2..]

PLAN FOR THE LECTURES

Day 1:

- **Prologue**
- **Some History**
- **Deep Inelastic Scattering and Parton Distributions (I)**

Day 2:

- DIS and PDF (II)
- Beyond parton distributions.

Day 3:

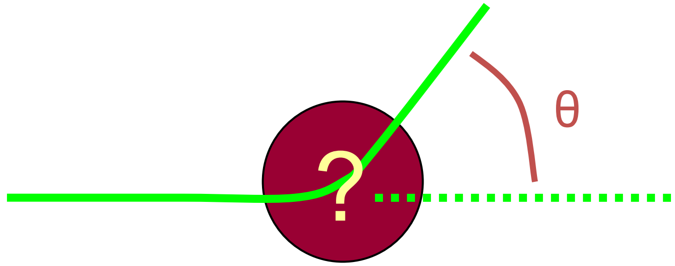
- EIC accelerator and detector realizations
- Other facilities and EIC physics topics.
- EIC and physics topic at other facilities.
- EIC and the future of Nuclear Physics.
- Epilogue

A lot of stolen material from Enrico Tassi, Allen Caldwell, Mark Thomson

SOME HISTORY

Ernest Rutherford (1911): Discovery of the Nucleus

- Beginning of learning about structure of matter through scattering.



- *Geiger and Marsden* observed that a particles were sometimes scattered through very large angles.

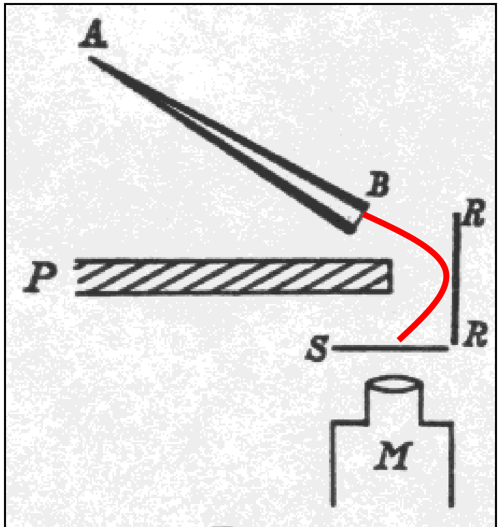
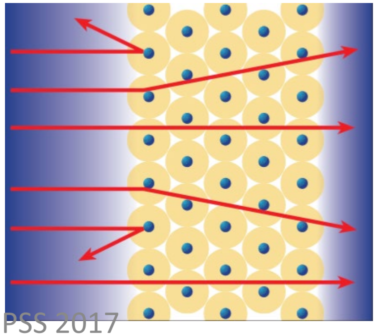


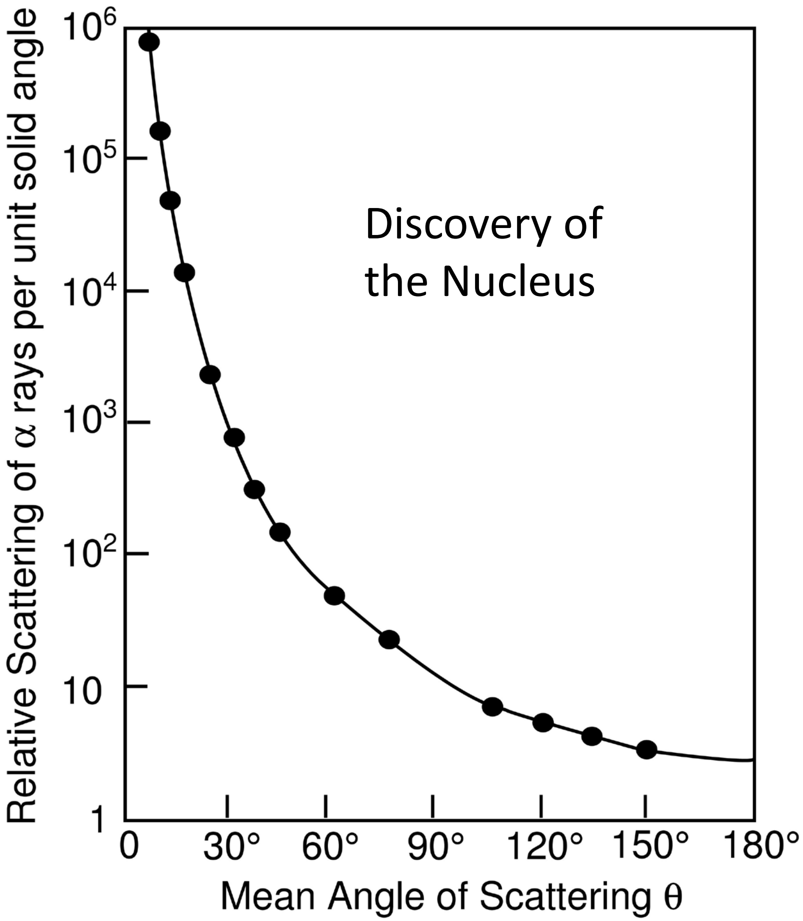
FIG. 1.

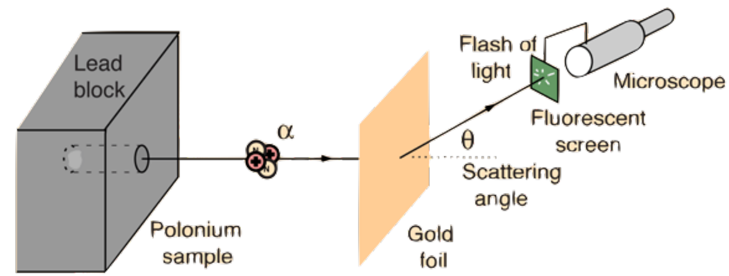
- Rutherford interpreted these results as due to the Coulomb scattering of a particles with the point like heavy "center" with charge Z..

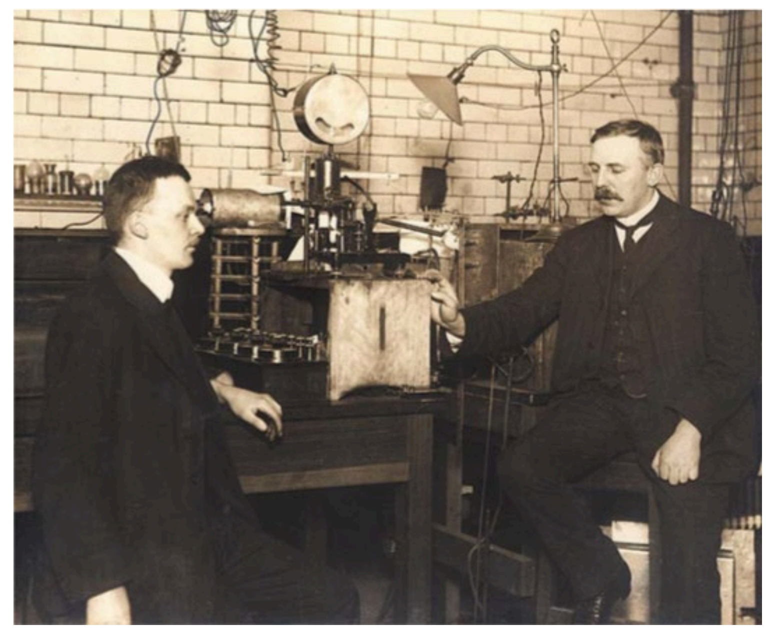


$$\sigma(\theta) = \frac{z^2 Z^2 e^4}{16E^2}\,\frac{1}{\sin^4\frac{1}{2}\theta}$$

α-Au Scattering Experiment



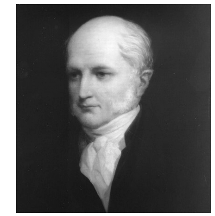




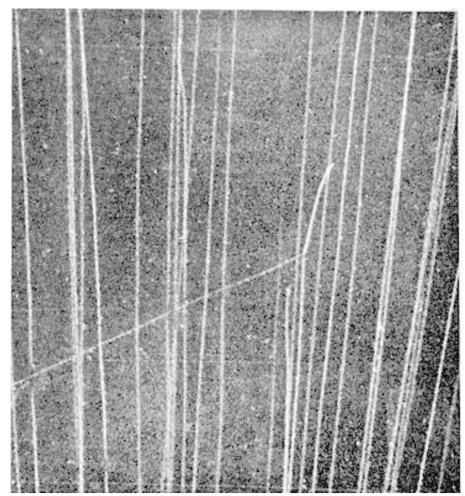
Ernest Rutherford (1917): Discovery of the Proton

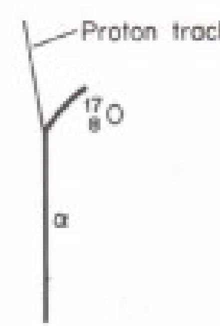
- van den Broek/Moseley (1913) the place of each element in the periodic table is equal to its nuclear charge.
- An old idea: all atoms are made up of hydrogen atoms (William Prout: 1815)
- Rutherford shows that “hydrogen atoms” can be produced from a particles (1917). Later named protons (1920).
- Reconciling masses of nuclei vs. charge remains a mystery.—Are electrons inside nuclei? (No)

Moseley



Prout



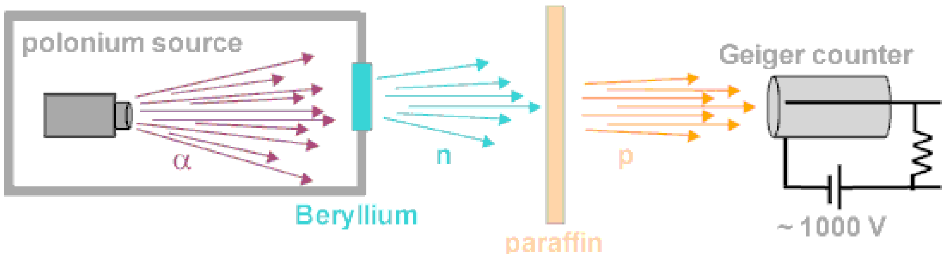


Cloud Chamber picture (much later than Rutherford)

$$^{14}N + \alpha \rightarrow {}^{17}O + p$$

James Chadwick (1930): Discovery of the Neutron

- Chadwick deduces the existence of neutrons from alpha scattering.
- From kinematics deduced the mass of the neutron.
- 1930: Three elementary particles. The electron, the proton and the neutron. The proton and the neutron make up the nucleus.



$\alpha + {}^{9}Be \rightarrow {}^{12}C + n$

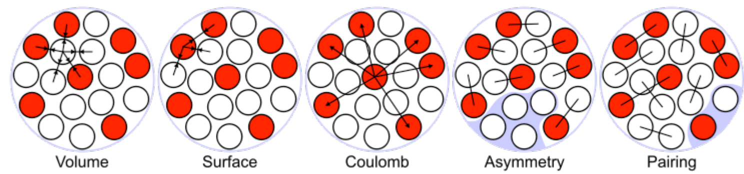
Chadwick

Determined mass

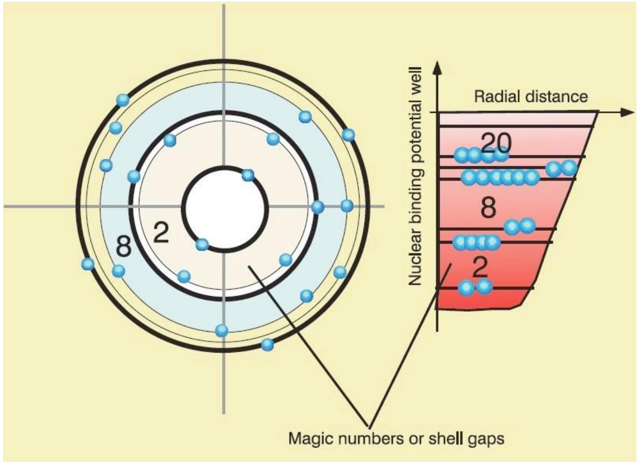
938 ± 1.8 MeV
compare to present
939.57 MeV

Beginnings of Nuclear Structure Theory

- How do the properties of the nuclei emerge from the protons and neutrons that make them up?
- Liquid Drop model (Weizsacker 1935)
- Nuclear Shell model (Wigner, Mayer, Jensen 1949)

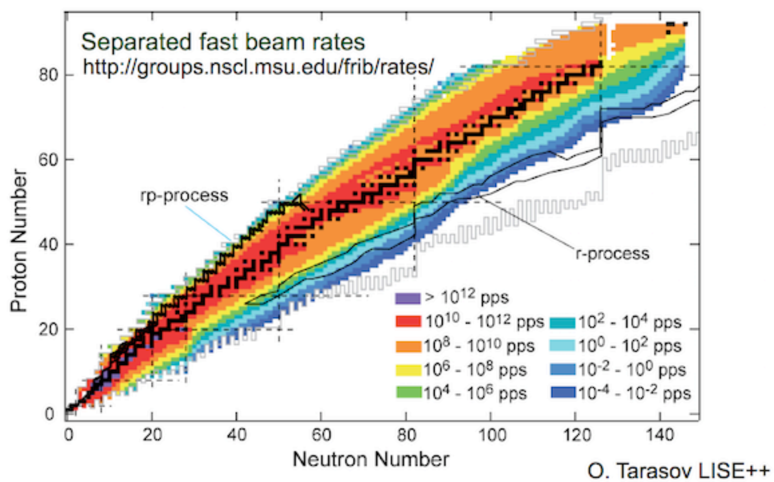


(semi-classical fluid made of p and n)



Highly successful description of nuclei

Nuclear Structure Theory



- Building up the understanding of nuclei through models of effective NN interactions.
- Modeling two and three body interactions to approximate many-body interactions.
- Advent of QCD in the 60's.
- Connection to cosmology:
  - Neutron Stars
  - Genesis of Elements
- Latest facility in US: Facility for Rare Isotope Beams (FRIB) in construction at Michigan State University. (One of the last high priority construction items before EIC)

More on this topic from other lectures: Our story goes a bit different way

Elastic ep Scattering: Rosenbluth

- Quantum Mechanics develops rapidly after 1924
- QED becomes fully mature by late 1940's
- 1950, Rosenbluth writes down the general cross-section for *elastic* electron-proton scattering.

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)

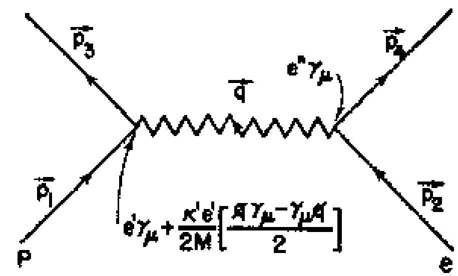


FIG. 1. Diagram for the elastic scattering of a physical proton and a physical electron. (The letter "q" with the bar through it in this figure is the same as the German letter, q, used in the text.)

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

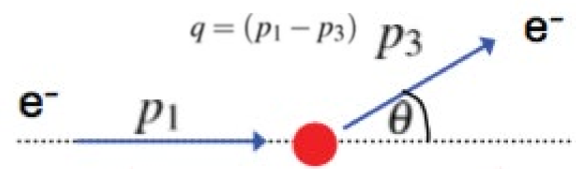
where

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

and

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

eP Elastic 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

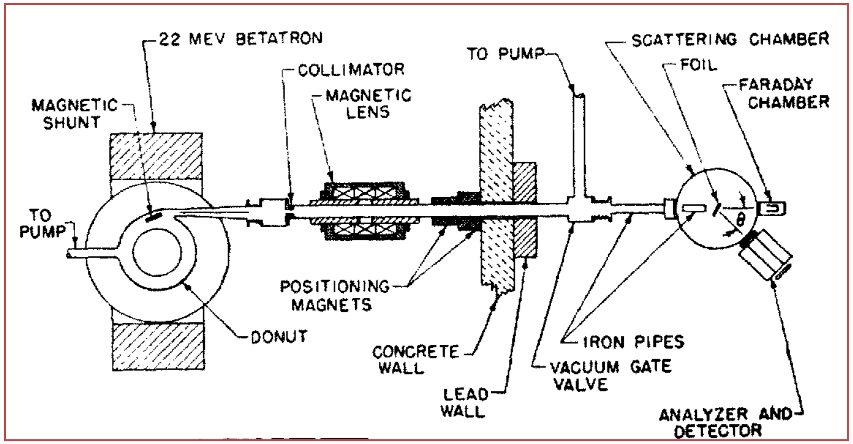
Note: for fixed θ, E_3 (scattered e energy) fixed

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)



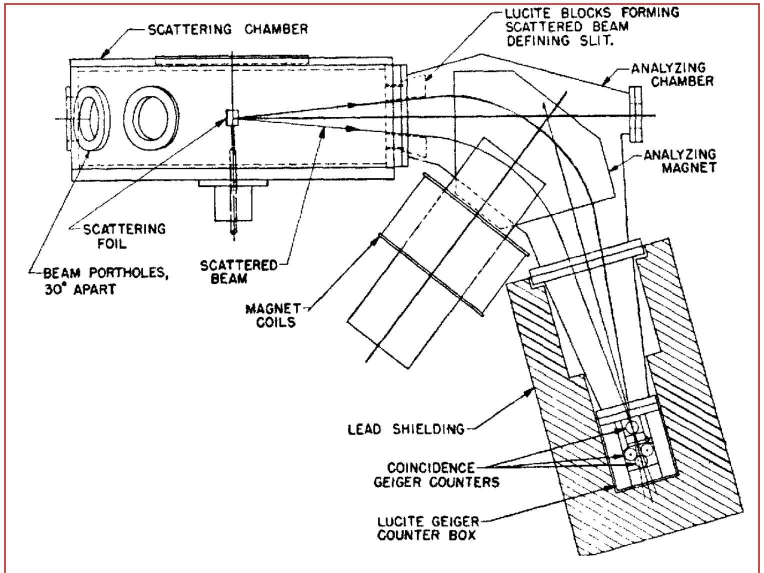
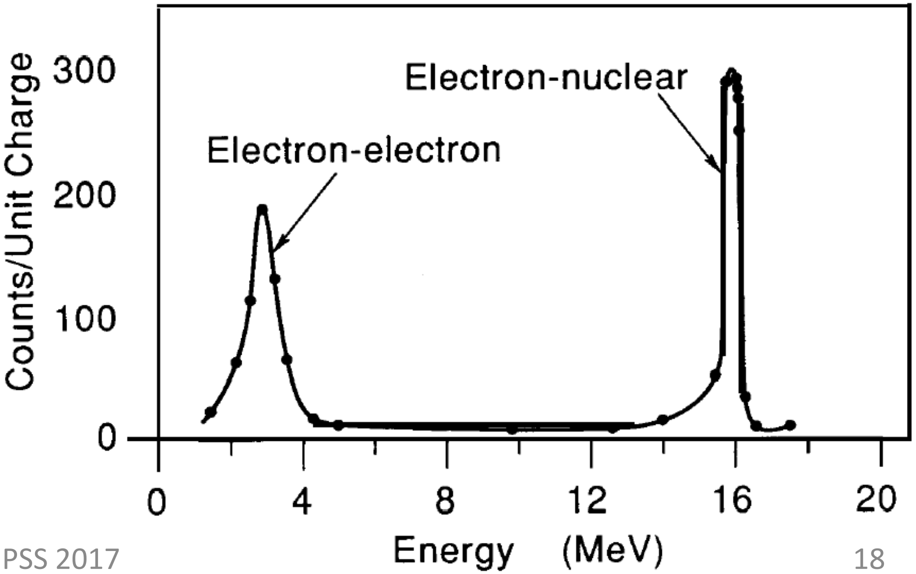


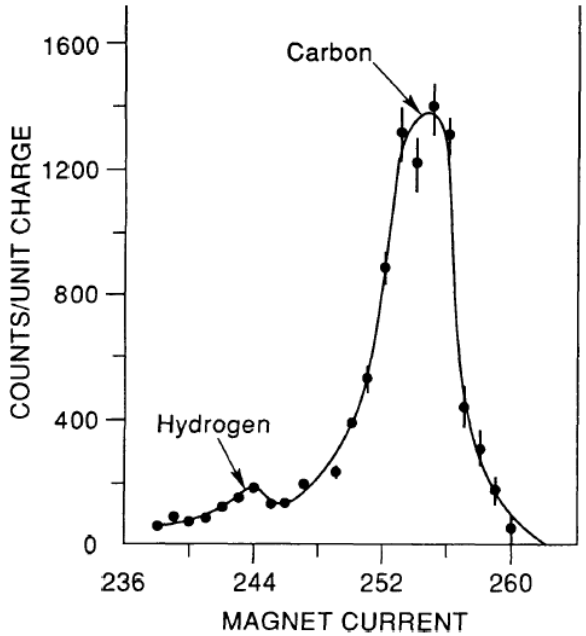
FIG. 2. Scattering chamber.

D.W. Kerst
(betatron)

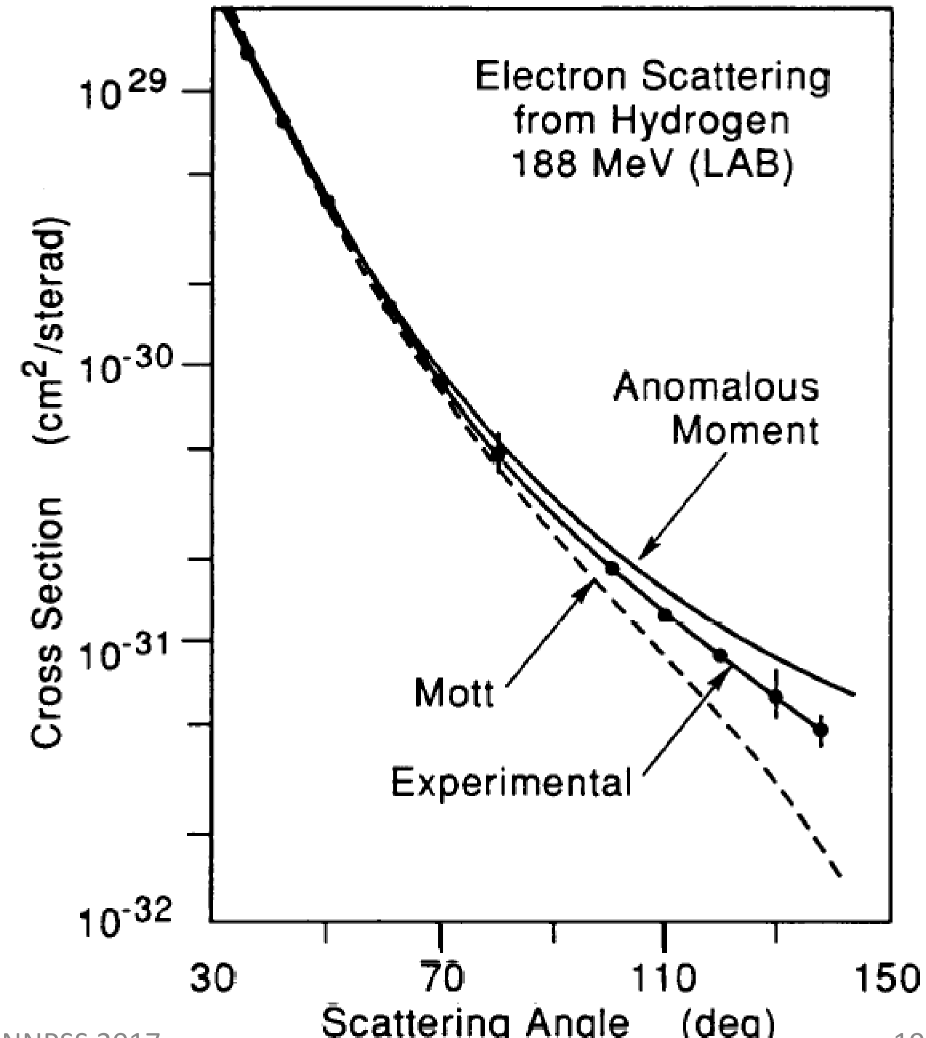
$$E' = \frac{E_0}{1 + \frac{2E_0}{M}\sin^2\frac{\theta}{2}}$$

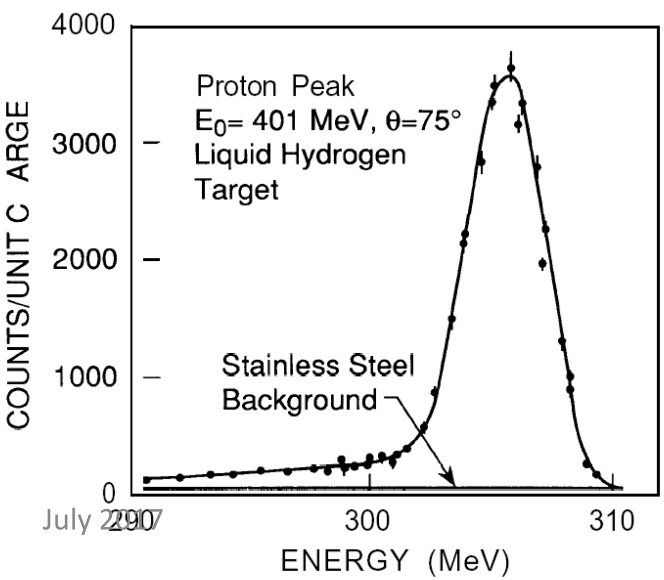


R. Hofstadter: ep and eA elastic scattering (1953->)

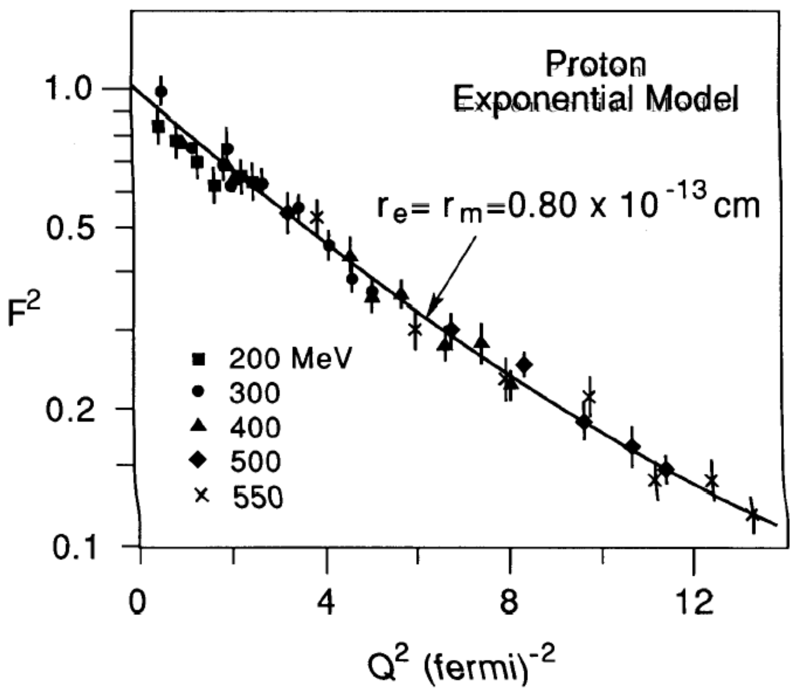


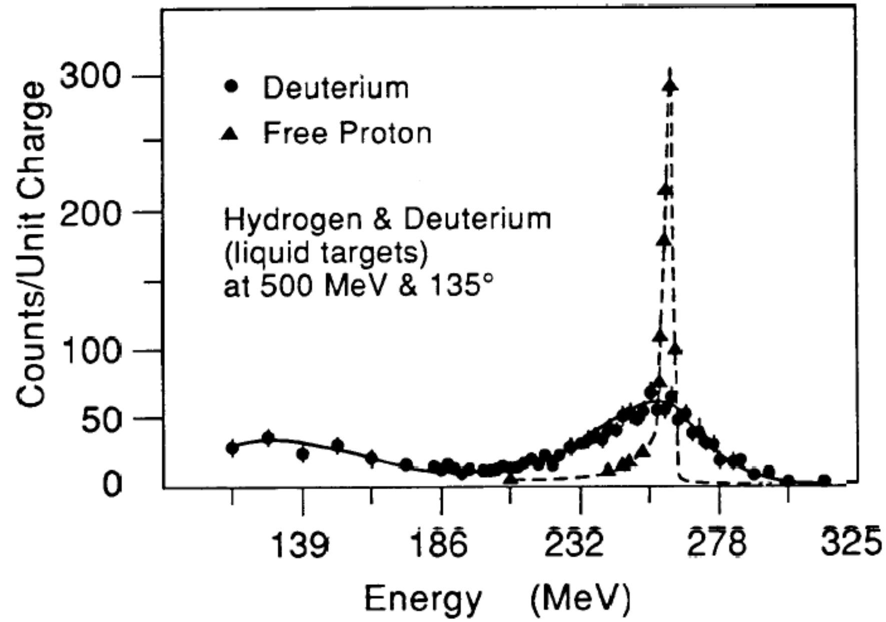
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_0^2 \sin^4 \theta/2} \cdot \cos^2 \theta/2 \cdot \frac{E'}{E_0} \left[\frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \theta/2 \right]$$





R. Hofstadter: e-d elastic scattering





Electron deuteron scattering
(Fermi motion…)

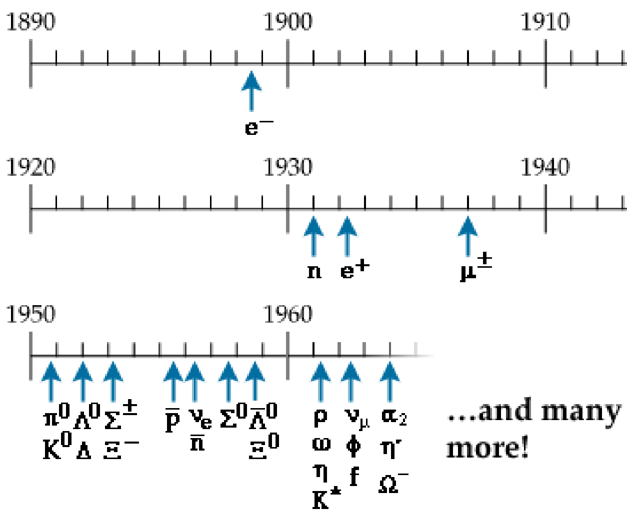
First determinations of the proton's form factors

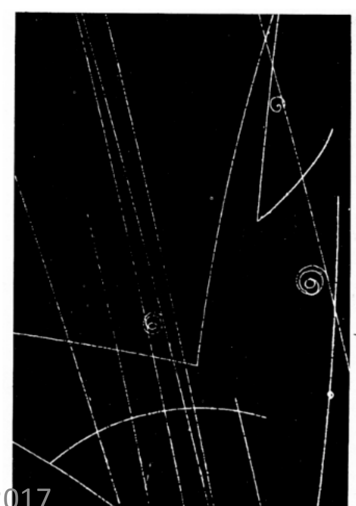
R. Hofstadter: e-N and e-p elastic scattering

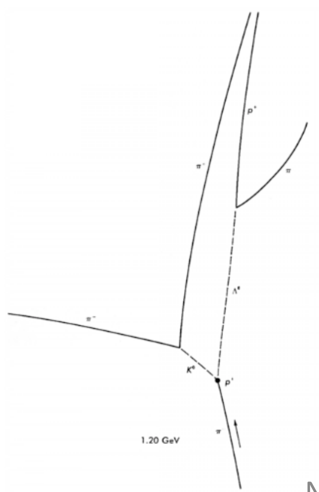
"As we have seen, the proton and neutron, which were once thought to be elementary particles are now seen to be highly complex bodies. It is almost certain that physicists will subsequentely investigate the constituent parts of the proton and neutron - the mesons of one sort or another. What will happen from that point on ? One can only guess at future problems and future progress, but my personal convinction 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

Meanwhile: Particle Zoo (1950-60's)





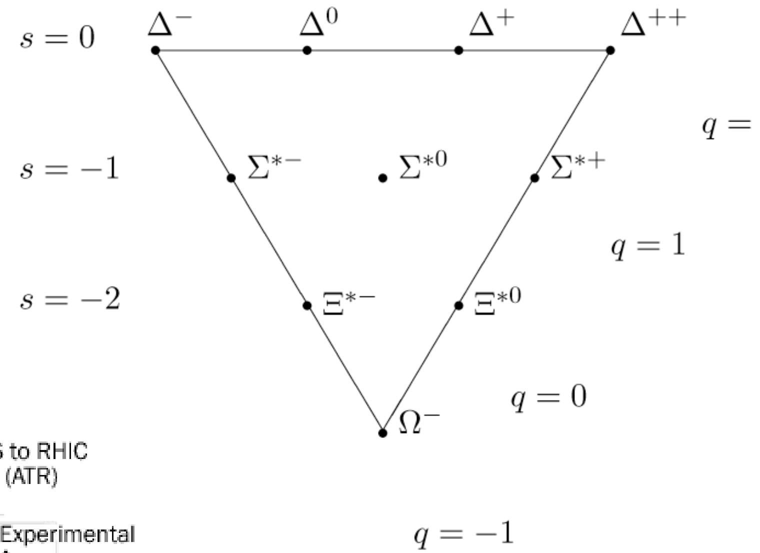


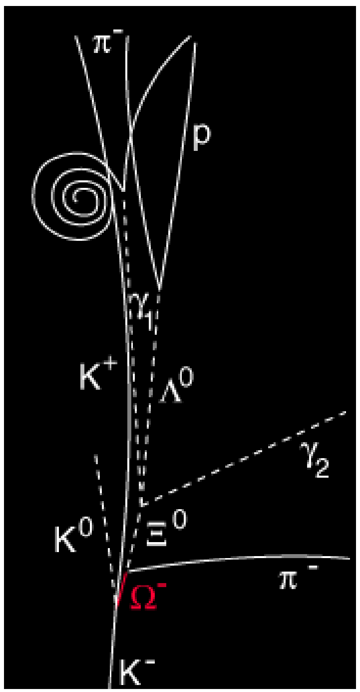
CERN Conference (1962)

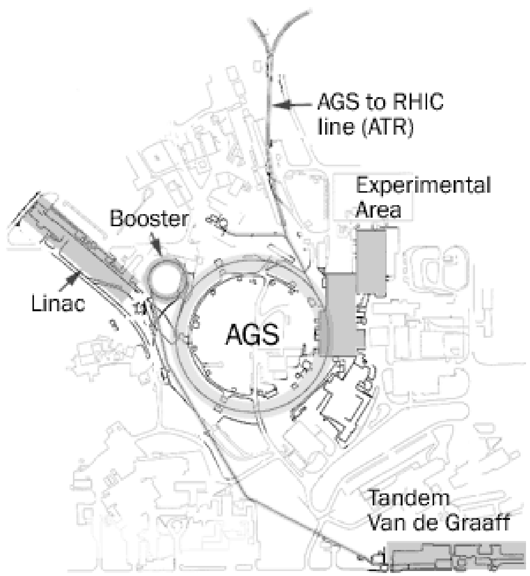
SU(3) and Discovery of the Ω^-

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)

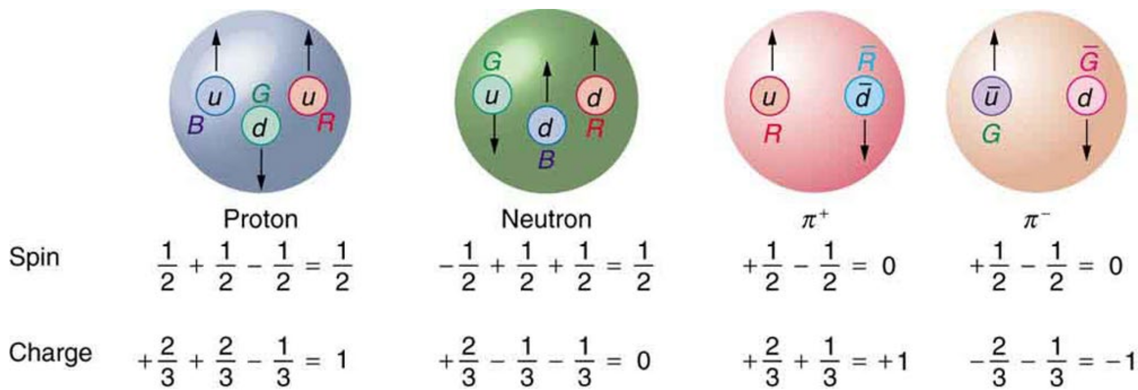
1964: Omega-minus Baryon discovered at Brookhaven National Laboratory

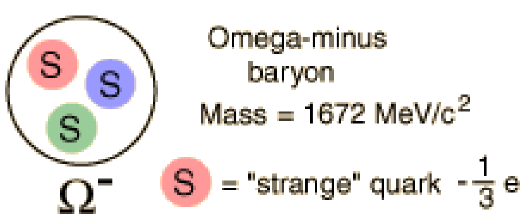
The Quark Model

Gell-Mann and Zweig (1964)

SU(3) symmetry can be expressed as hadrons being constituted out of quarks.

Flavor	B	J	I	I3	S	Q
u	1/3	½	1/2	+1/2	0	2/3
d	1/3	½	½	-1/2	0	-1/3
s	1/3	1/2	0	0	-1	-1/3





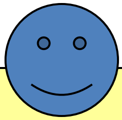
Idea of color leads to QCD (1970’s)

SLAC and “Project M”

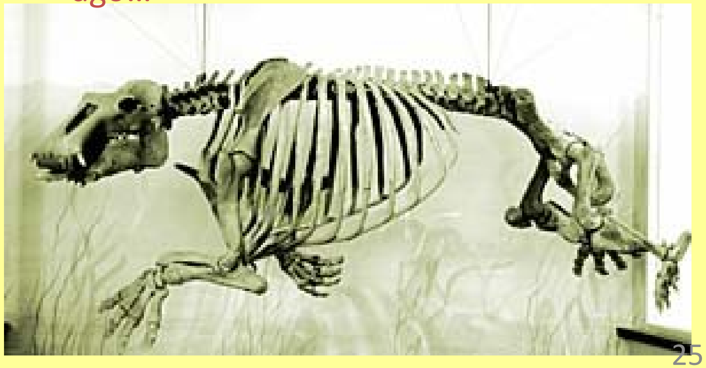
On april 10, 1956, Stanford staff met in Prof. W. Panofsky’s home to discuss Hofstadter’s suggestion to build a linear accelerator that was at least 10 times as powerful as the Mark III. This idea was called “The M(onster)-project” because the accelerator would need to be 2 miles long!!

- 1957 A detailed proposal was presented
- 1959 Eisenhower said yes
- 1961 The Congress approved the project ($114 Million dollars)

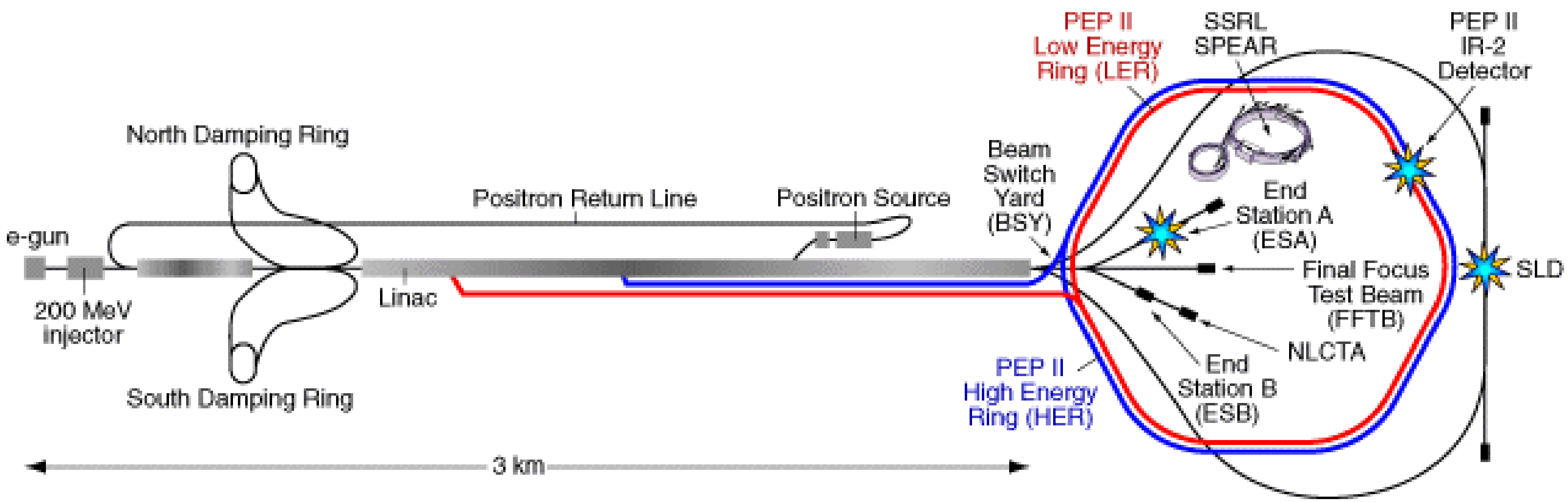
One year later construction started



While excavating for SLAC the workers discovered a nearly complete skeleton of a 10-foot mammal, *Paleoparadoxia*, which roamed earth 14 millions years ago…

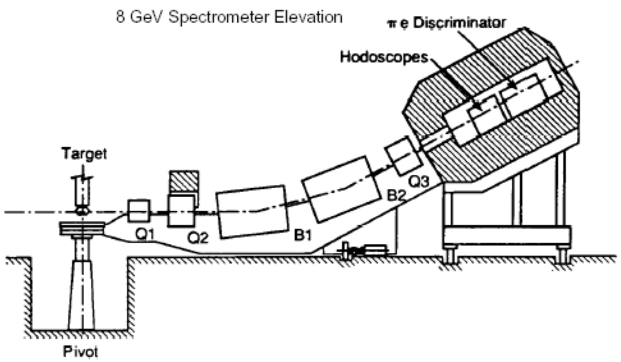


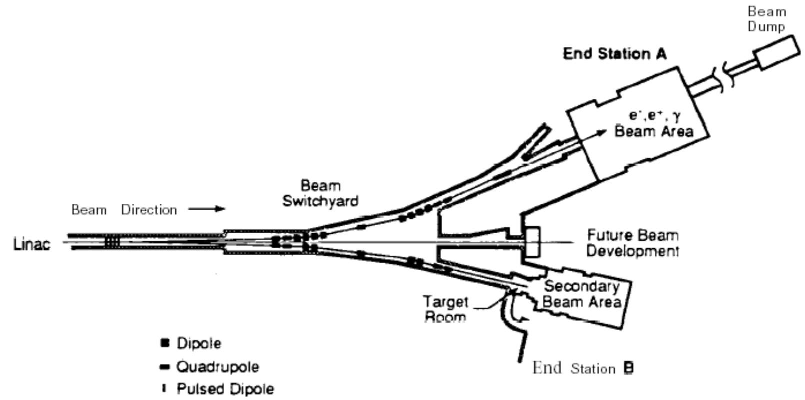
“Project M” becomes the Stanford Linear Accelerator Center

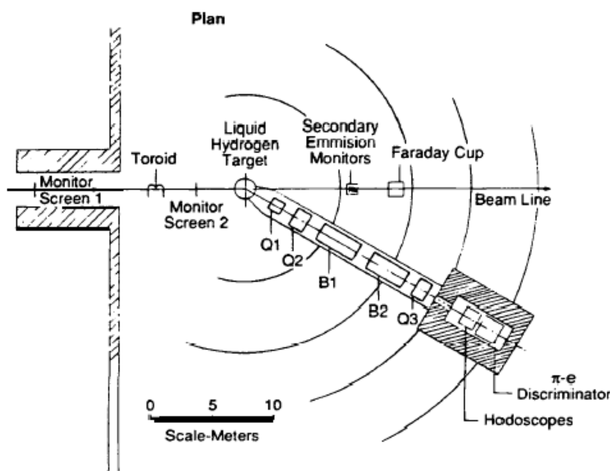


The SLAC-MIT Experiment (1969)

Under the leadership of Taylor, Friedman, Kendall

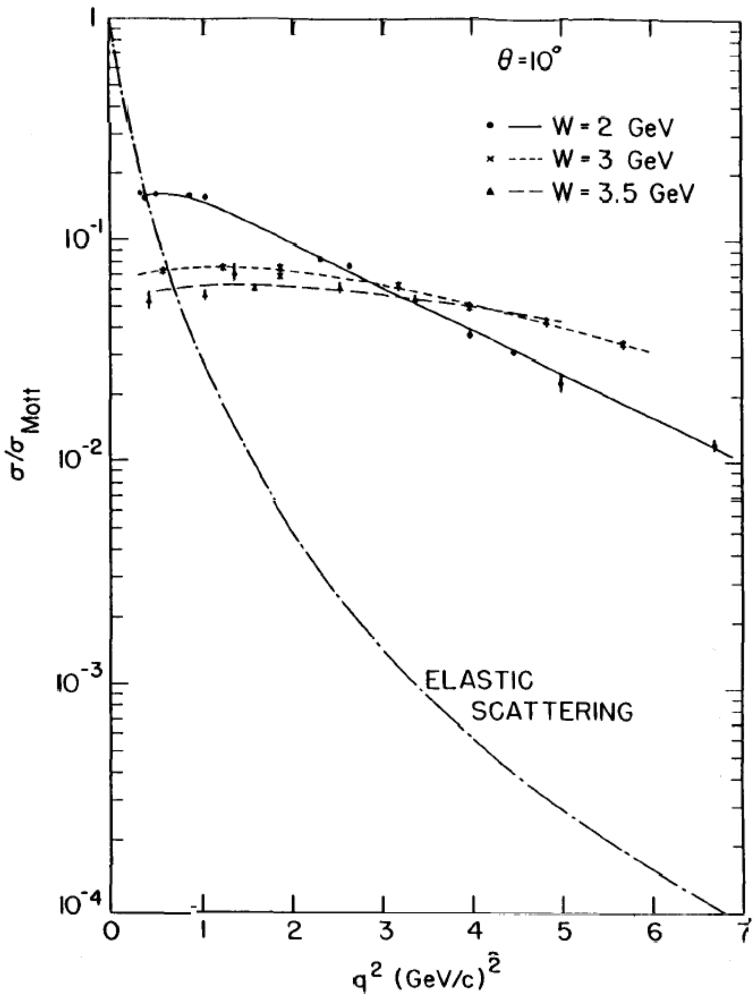


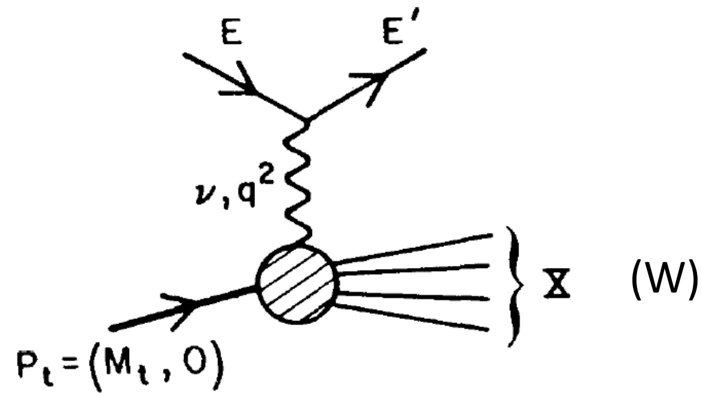




7-18 GeV electrons on Hydrogen

SLAC-MIT results: ep inelastic collisions

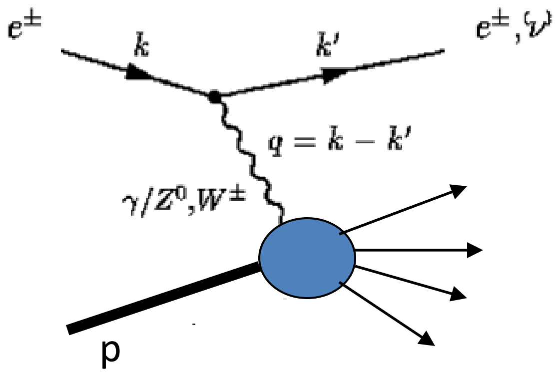




$\sigma/\sigma_{\text{point-like}}$ = Independent of q^2

Very weak dependence on W

Deep Inelastic Scattering



Described by 2 kinematic variables

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

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

$$\frac{d\sigma^2_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+ F_2 - y^2 F_L \mp Y_- xF_3)$$

Mostly about F_2

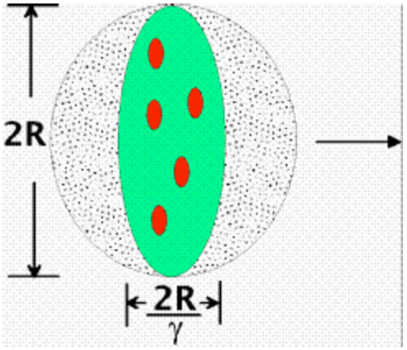
$y = Q^2/xs$, the inelasticity parameter, $Y_\pm = (1 \pm (1-y)^2)$

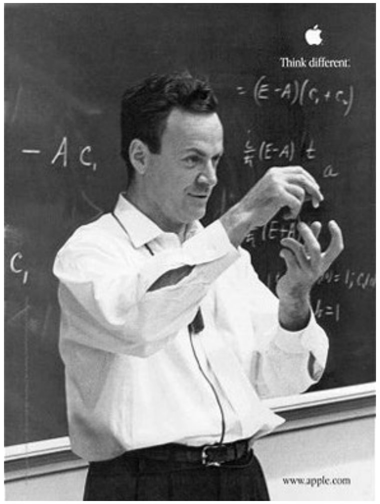
F_2, F_L, and xF_3 are structure functions of the proton.

- F_L: longitudinal component, damped by y^2.
- xF_3: Small at $Q^2 \ll M_Z^2$,

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

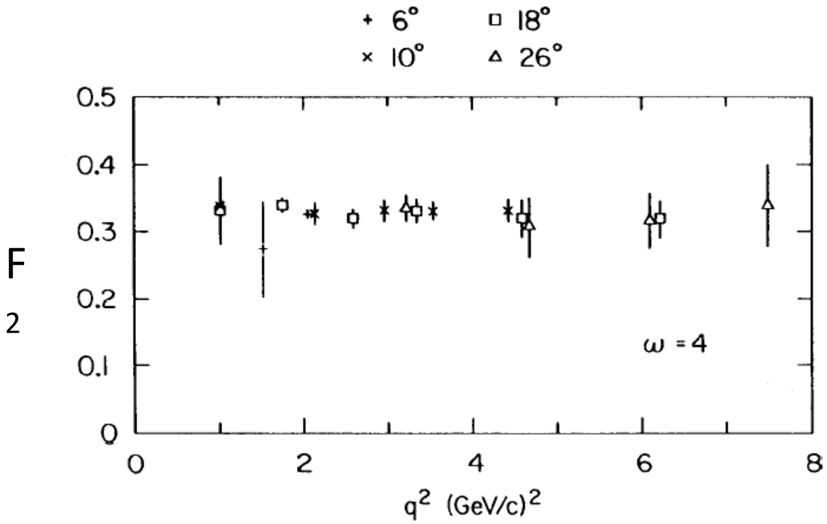
Point-like parton p has some distribution in x:
i.e. p(x)

Then the structure function F_2 (x, Q^2) is simply

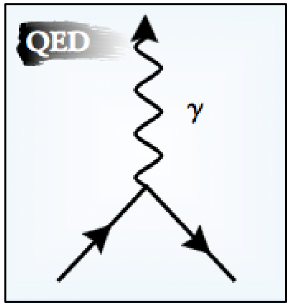
$$F_2\,(x, Q^2) = x \sum_p e_p\, p\,(x) = F_2(x)$$

i.e. No dependence on Q^2

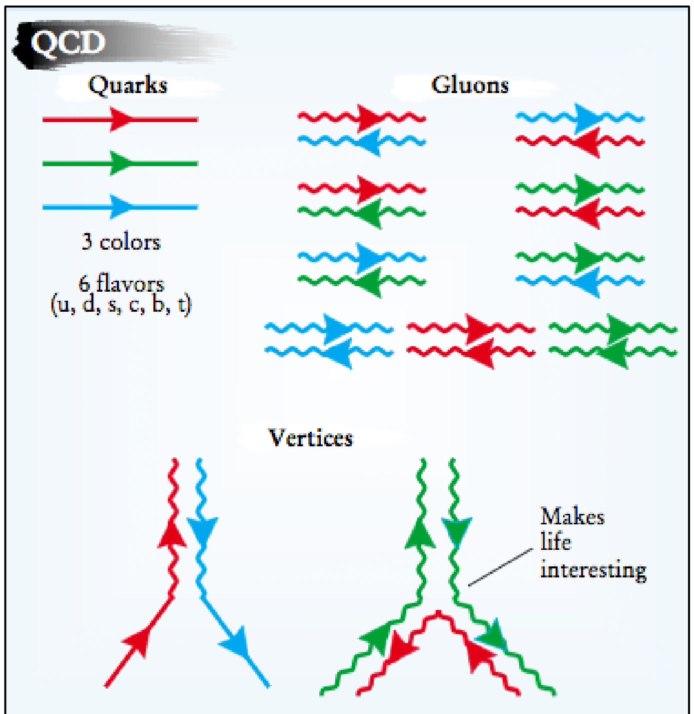
In other words, if F_2 “scales”, protons are consistent with being made
up of partons.



Quantum Chromodynamics (1970's)



Photons couple to electric charge.



Fritzsch, Leutweyler and Gell-Mann (1973)

For QCD:
electrons → quarks
photons → gluons
electric charge → color

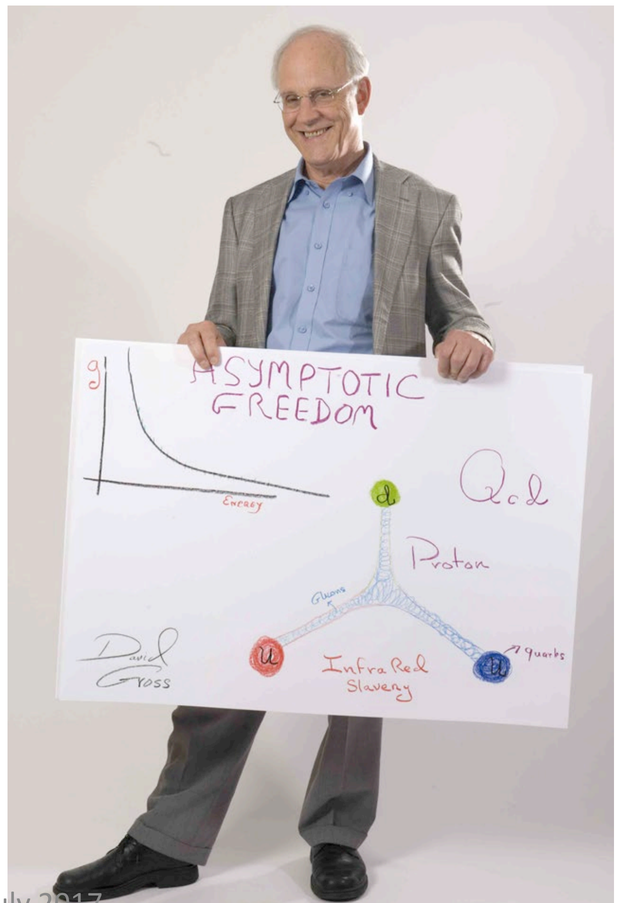
gluons (unlike photons) carry charge
and thus couple to gluons.

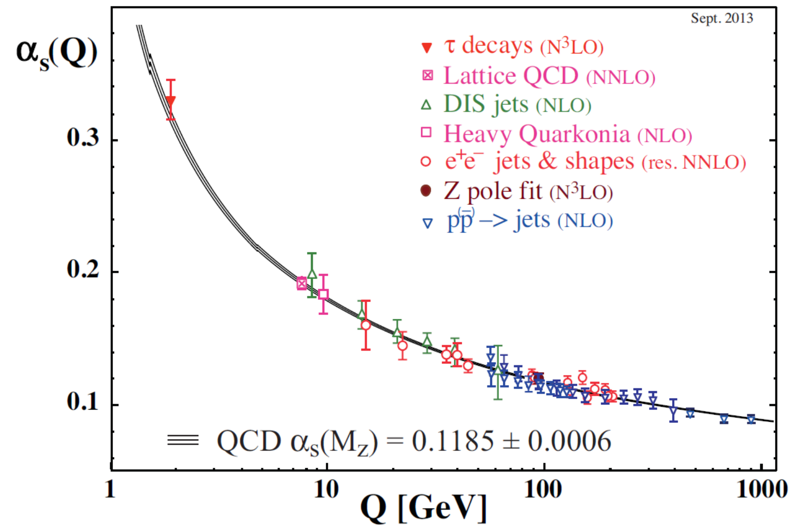
Is this a viable theory? Interactions at short distances are infinitely strong??

Asymptotic Freedom and Confinement

Gross, Politzer and Wilcek (1973)

Nobel Prize 2004

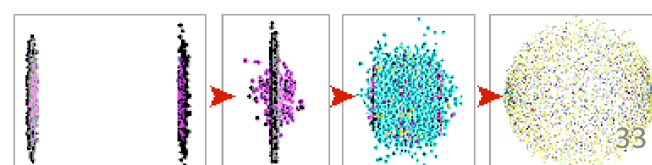




In high-energy interactions, quarks are weakly bound.

- QCD is a viable theory of quark interactions.
- partons = quarks is a viable hypothesis.

Also implies quark-gluon plasma



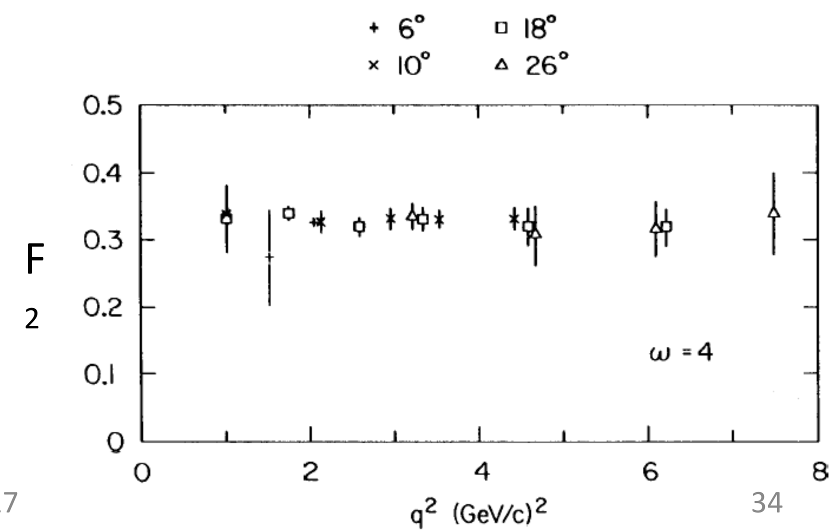
Quarks are Partons!

1990 Nobel Prize

FRIEDMAN, KENDALL AND TAYLOR WIN NOBEL PRIZE FOR FIRST QUARK EVIDENCE

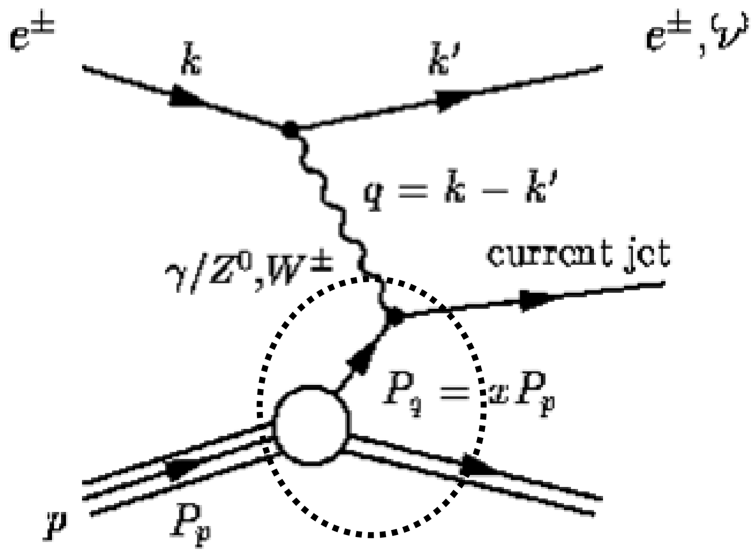
SLAC and its detectors

Quarks discovered !

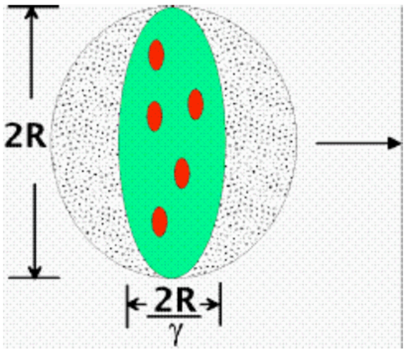


Deep Inelastic Scattering II

ep collision



proton in "∞" momentum frame



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

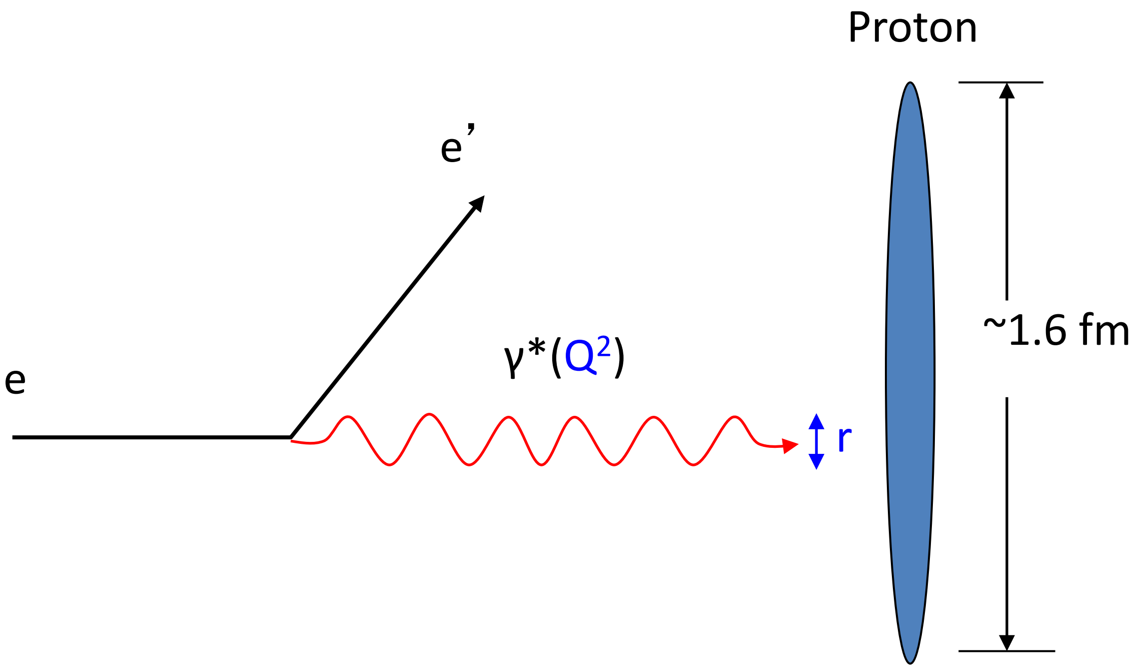
$0 \leq x \leq 1$

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

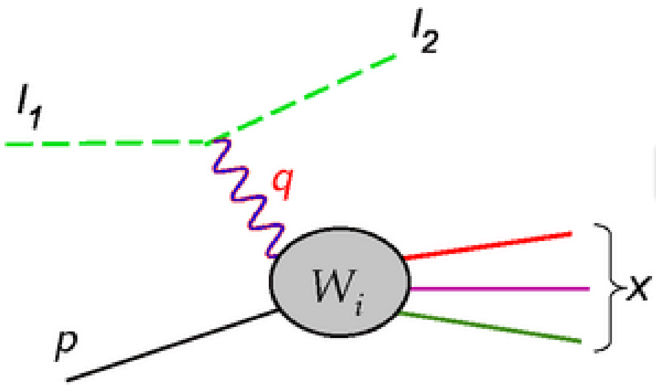


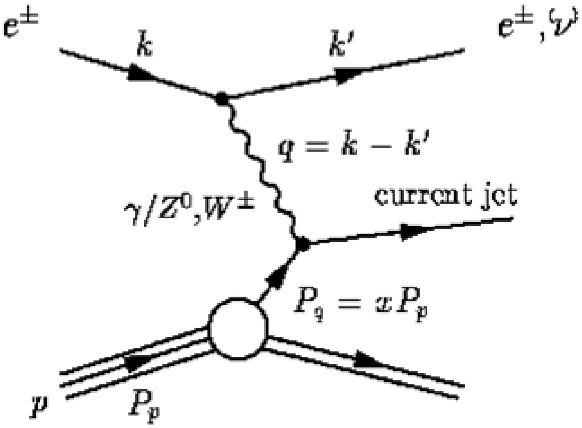
Virtuality (4-momentum transfer) Q gives the distance scale r at which the proton is probed.

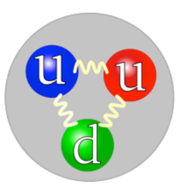
$r \approx \hbar c/Q = 0.2\text{fm}/Q[\text{GeV}]$

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

QCD and the Parton Picture







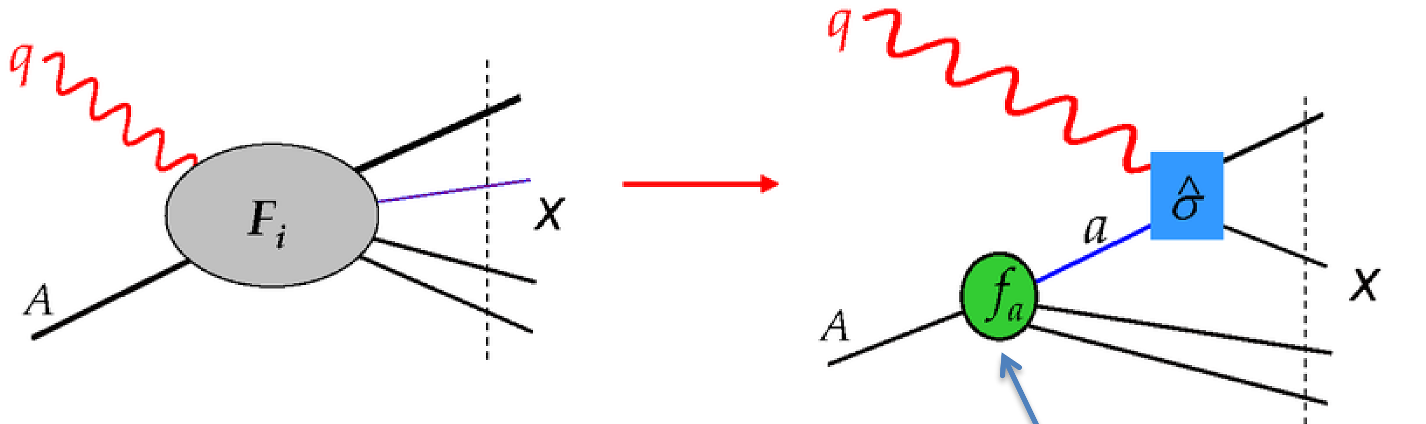
In general: $$\sigma = |A|^2 \neq f \otimes \sigma'$$

But…

Factorization

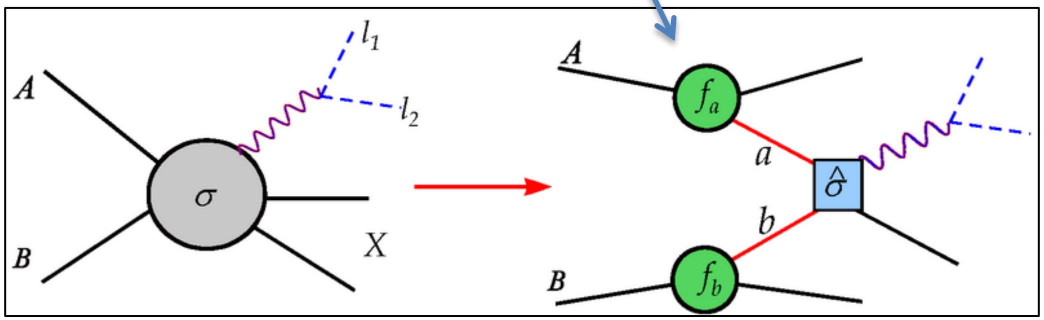
QCD-Factorization

$$\lim_{Q^2 \to \text{large},\, x\,\text{fixed}} F_i(x, Q^2) = f_a \otimes \sigma$$



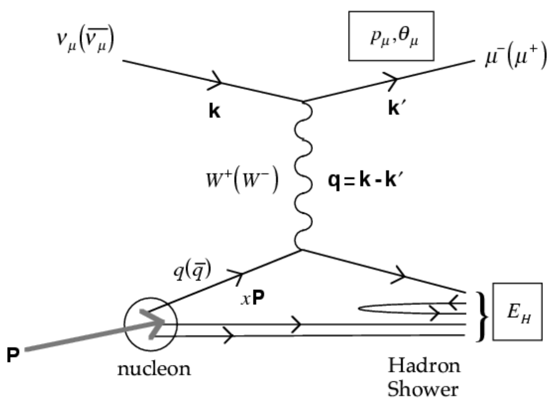
Same Parton Distributions

Different process

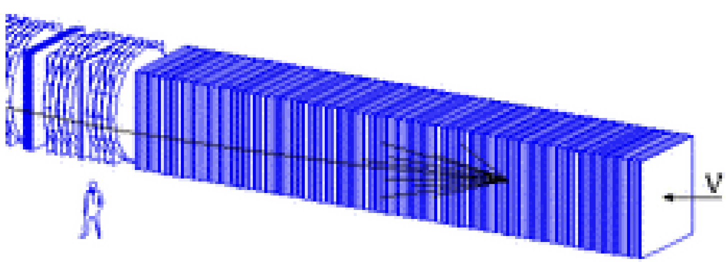


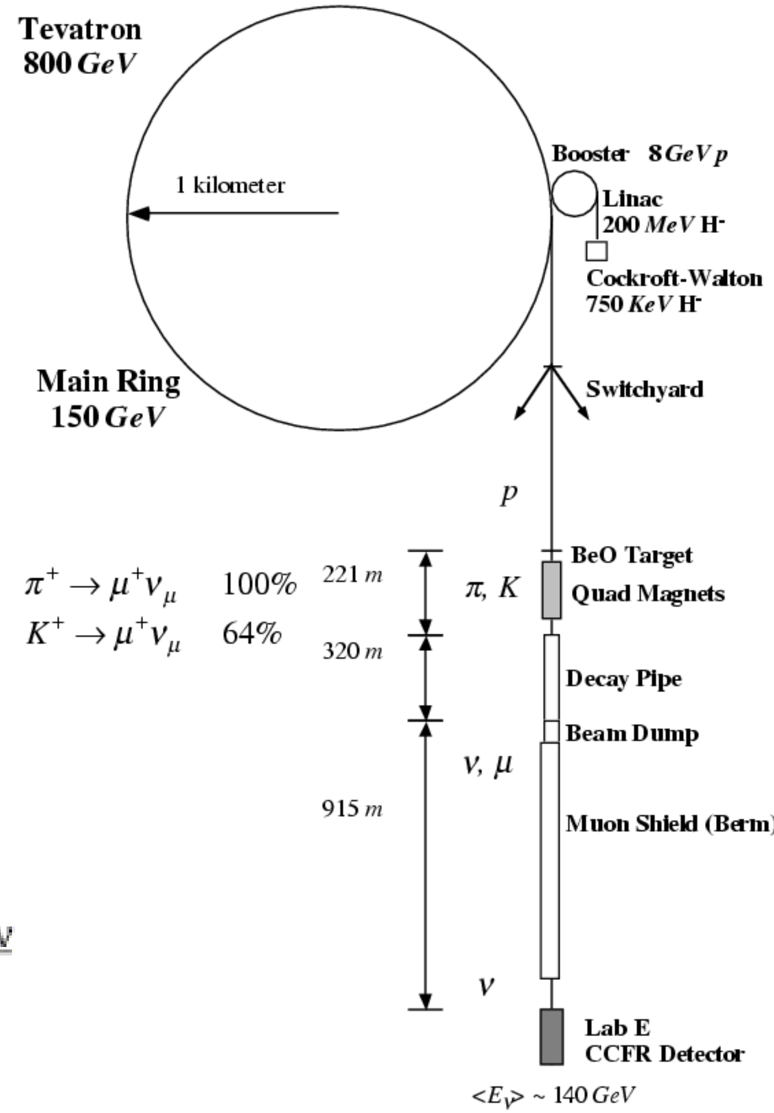
Parton distributions are process independent!

Fixed-target DIS experiments (example: CCFR)



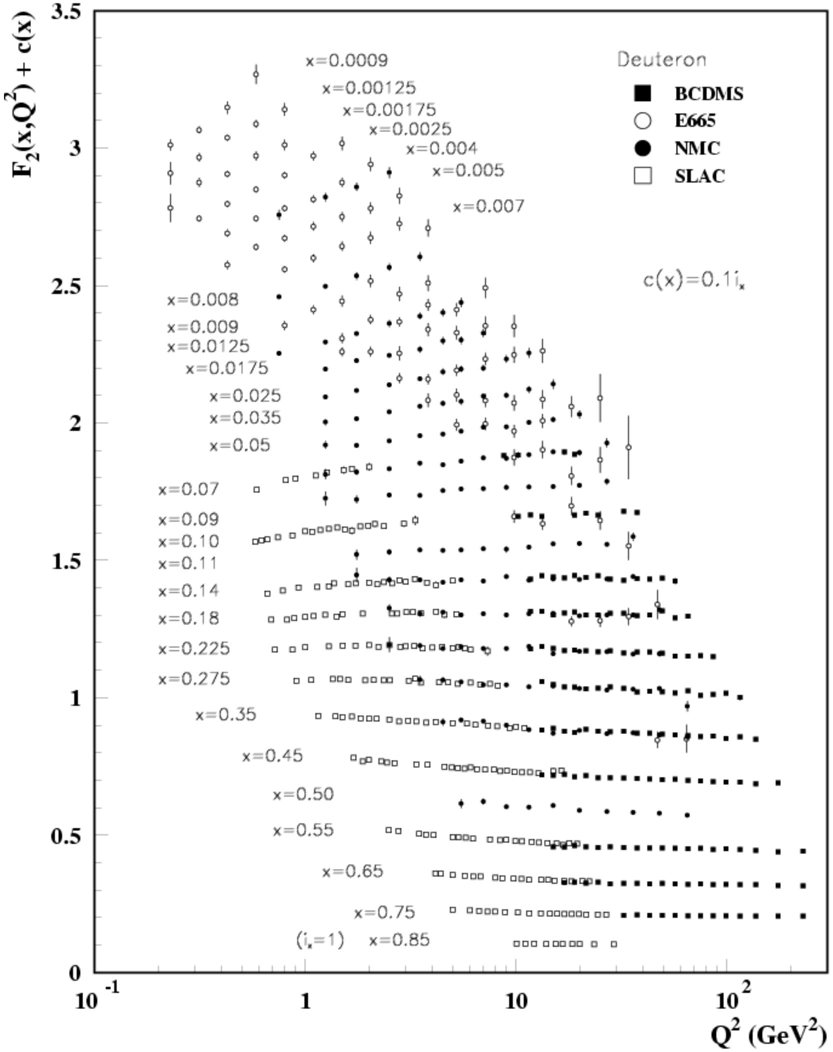
$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dx\,dy} = \frac{G_F^2 ME}{\pi}\left[\left(1 - y - \frac{Mxy}{2E}\right)F_2^{\nu(\overline{\nu})} + \frac{y^2}{2}2xF_1^{\nu(\overline{\nu})} \pm y\left(1 - \frac{y}{2}\right)xF_3^{\nu(\overline{\nu})}\right]$$



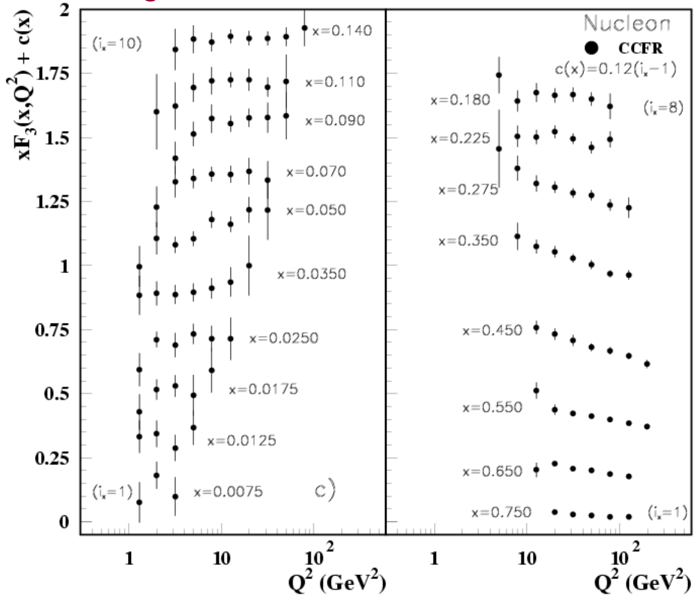


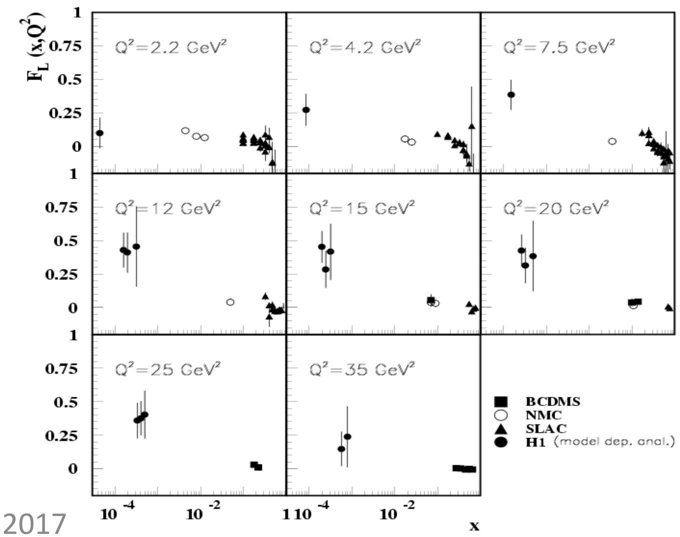
Fixed targets results: An overview (PDG)

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



F_3: $1 < Q^2 < 200$ GeV^2

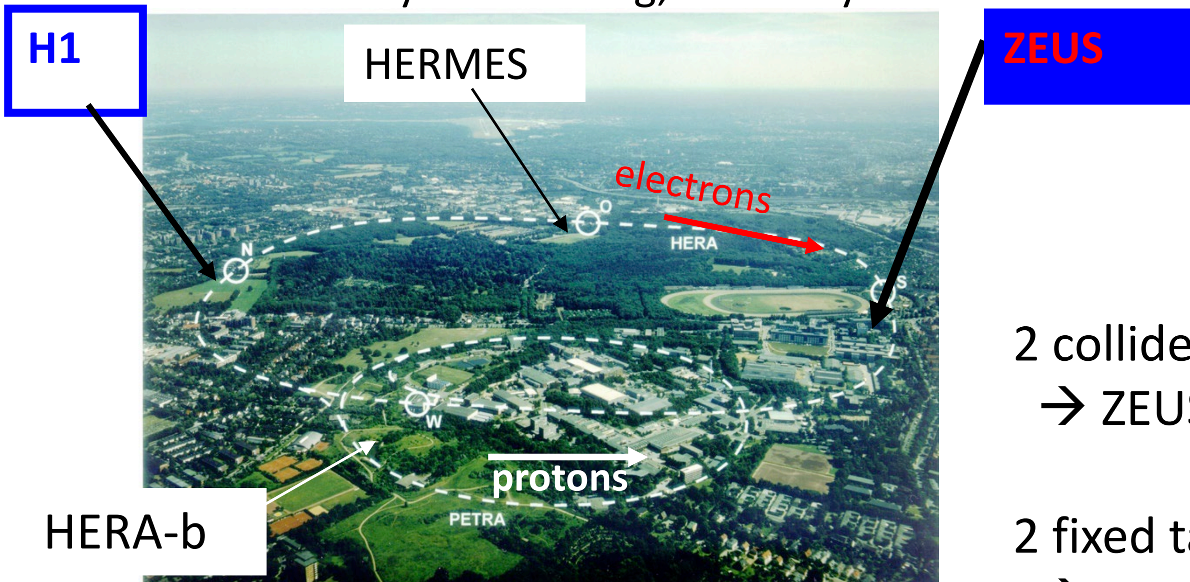


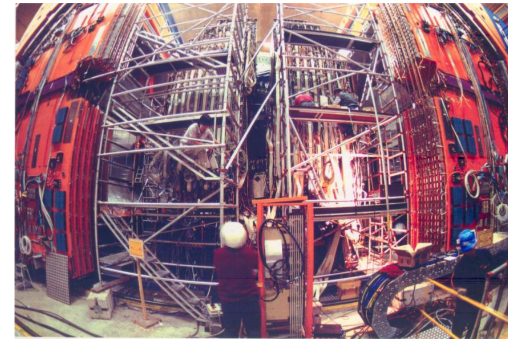


F_L

HERA Electron-Proton Collider (1992-2007)

DESY laboratory in Hamburg, Germany





2 collider experiments
→ ZEUS and H1

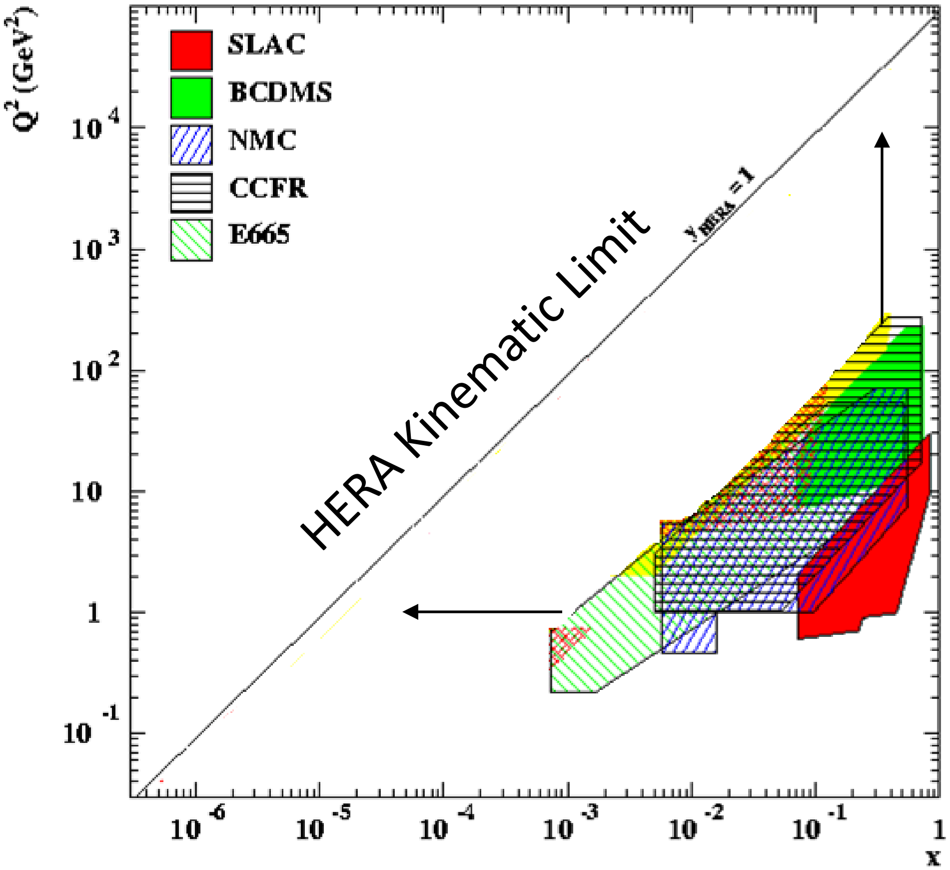
2 fixed target experiments
→ HERMES and HERA-b

- 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.

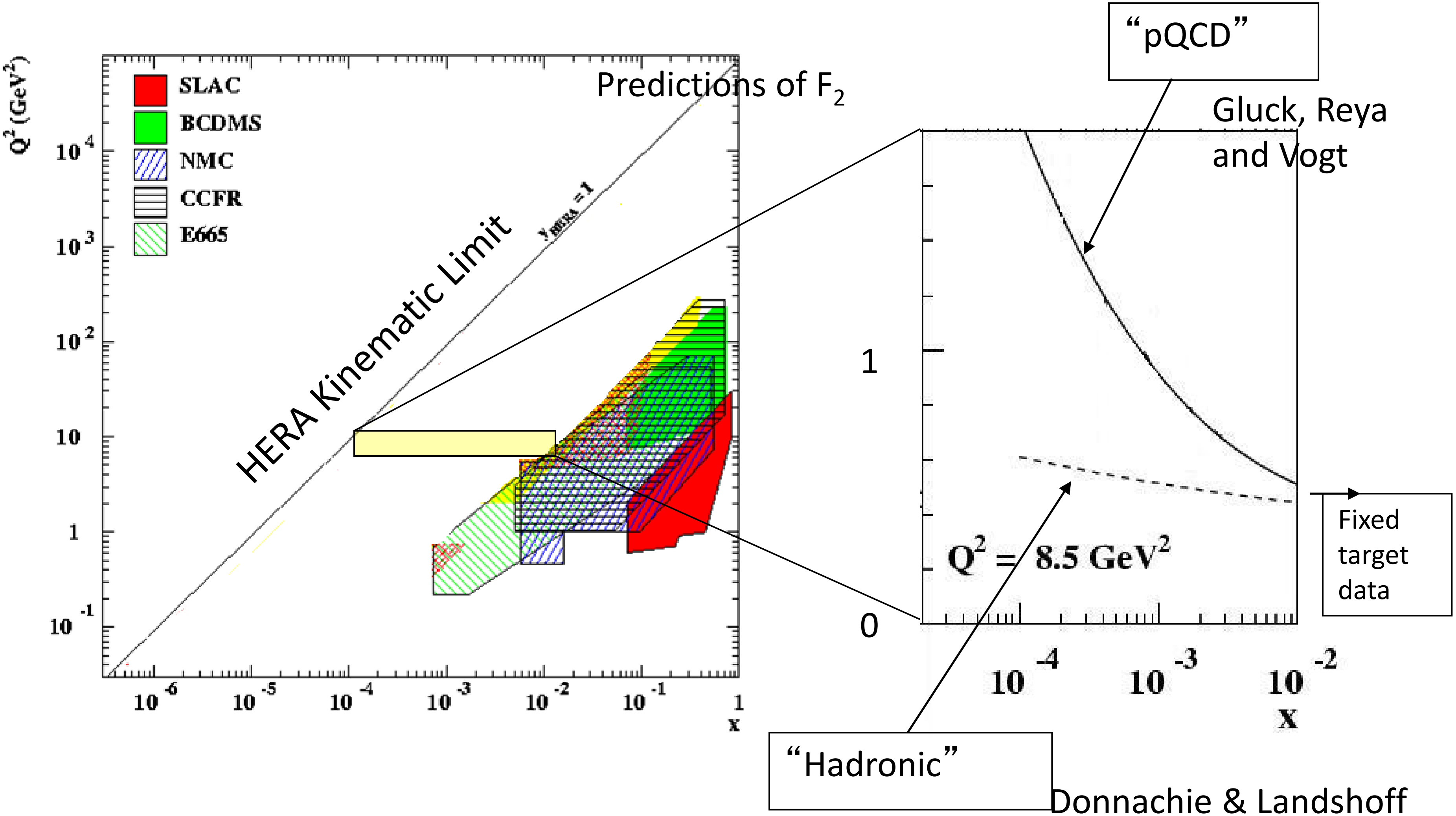
$5.12 \times 10^{31} cm^2 s^{-1}$ after upgrade



In the early 90's, HERA was about to push the proton structure function measurements by 2 orders of magnitude in x and Q^2.

Clearly, the first measurements would be in relatively low Q^2 and would extend to low x.

What were the expectations?
What would be the proton structure at low x?

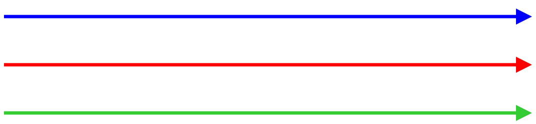


Why such different predictions?

Two ways to think about the problem

pQCD

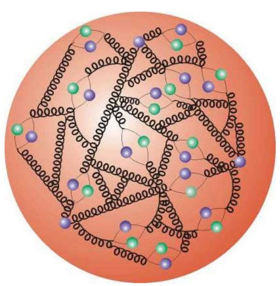
Quarks are asymptotically free!



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

OR

Hadronic



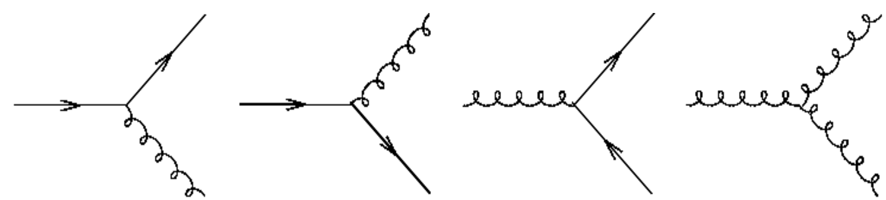
Protons are hadrons—whose constituents are confined. The behavior of hadrons is not understood from the first principles of QCD: however we have relatively good phenomenology to describe them.

pQCD view of F_2

DGLAP evolution equations:

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

***P*'s are splitting functions:**



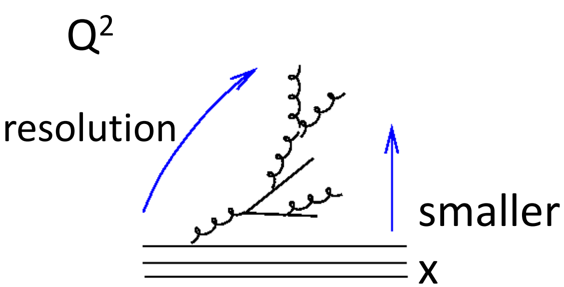
And (LO (or in DIS scheme..))

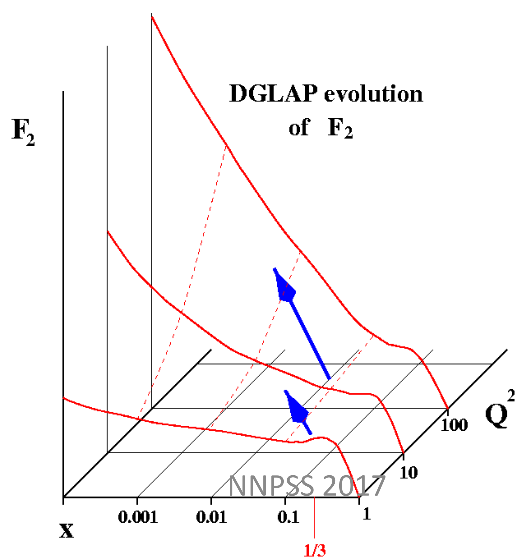
$$F_2(x,Q^2) = x \sum_q e_q^2 (q(x,Q^2) + \bar{q}(x,Q^2))$$

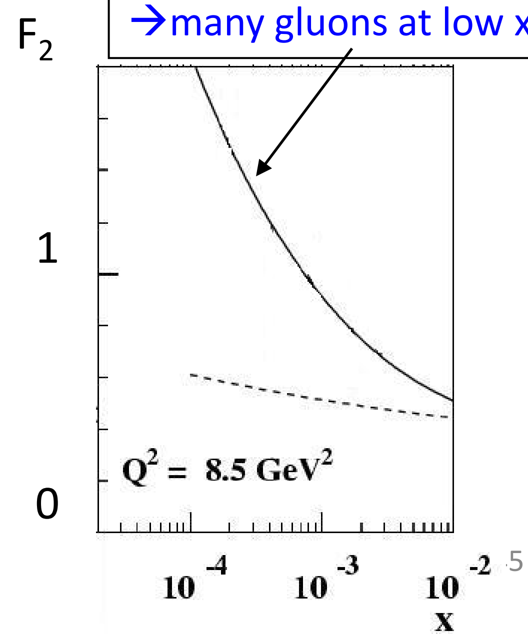
where q, $\bar{q}$ are quark, antiquark densities in the proton.

Predict:

Evolution in Q^2
→many gluons at low x



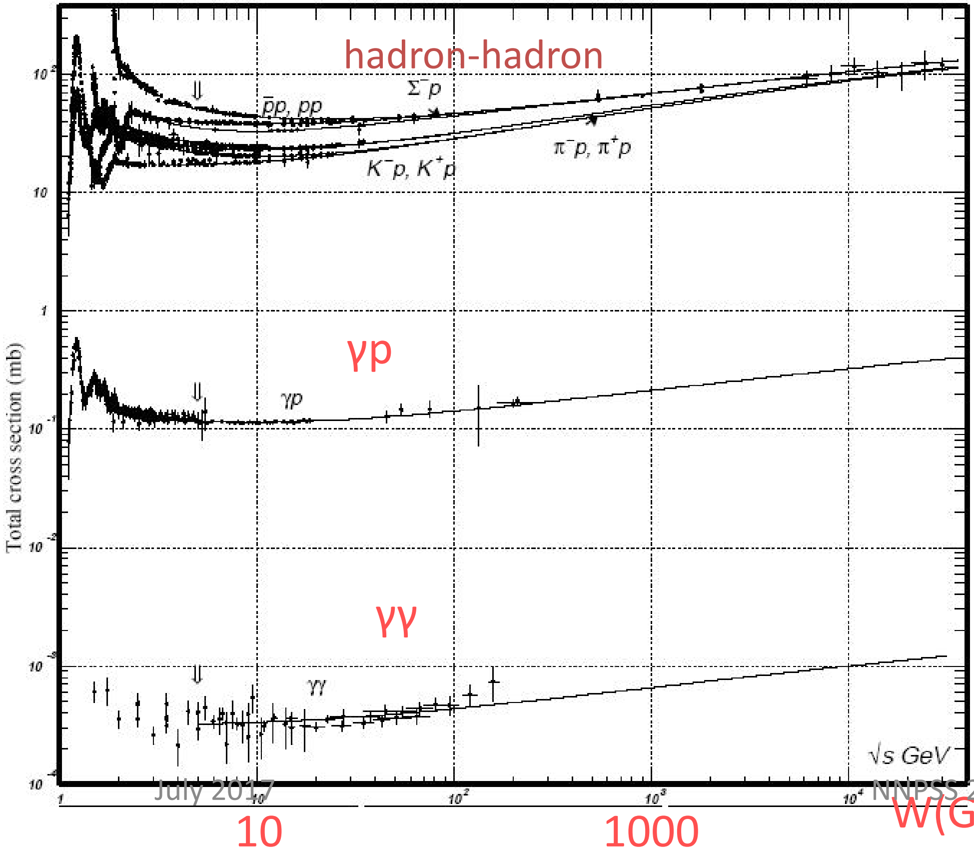




Before HERA: hadronic view of the proton and F_2

W: γ*P cms energy

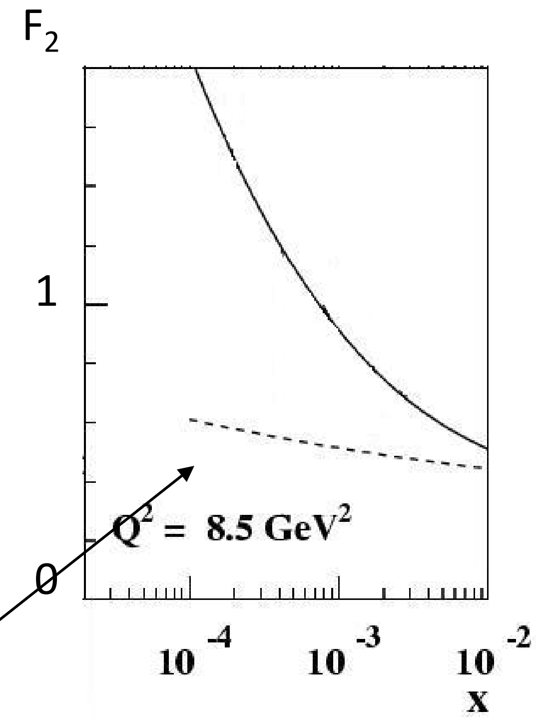
$$\sigma_{tot}(\gamma^* p) \approx \frac{4\pi^2\alpha}{Q^2} F_2(W, Q^2)$$



- F_2 at low x is simply related to the total γ*P cross-section.
- $x \approx Q^2/W^2$ so as x falls W rises
- small x limit of DIS is a large energy limit of the γ*p cross-section.
- at HERA W goes up to ~300 GeV.
- Large energy limit of total cross-sections is where the Pomeron trajectory dominates in Regge phenomenology: slow rise of the cross-section.

Hadronic view of F_2

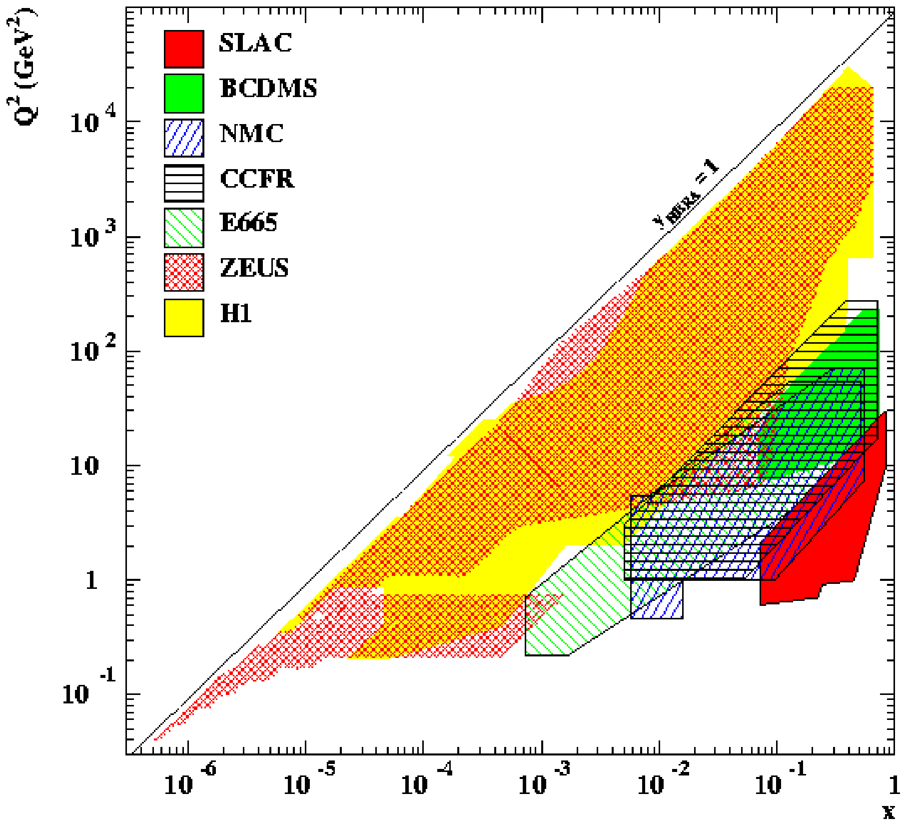
- We do not understand how hadrons are formed and behave from first principles.
- We do, however, have a phenomenology that describes most of the properties of hadron-hadron collisions. (Regge) This is somehow the result of QCD in the strong coupling limit.
- Virtual-photon proton cross section (or F_2 at low x) is yet another total cross-section which should be dominated by the properties of the proton as a hadron → governed by the same Pomeron trajectory as other hadronic cross-sections: slow power rise with W (or 1/x) .



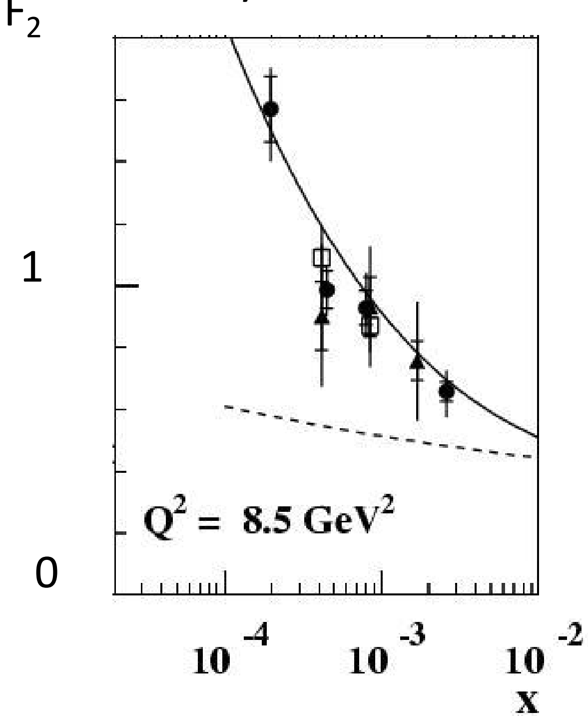
Donnachie and Landshoff (1993)

against x. If the HERA experiments find results for νW_2 significantly larger at small x than our extrapolations, we claim that this will be a clear signal that they have discovered new physics. Of course, the hope is that they will discover the Lipatov pomeron. In relation

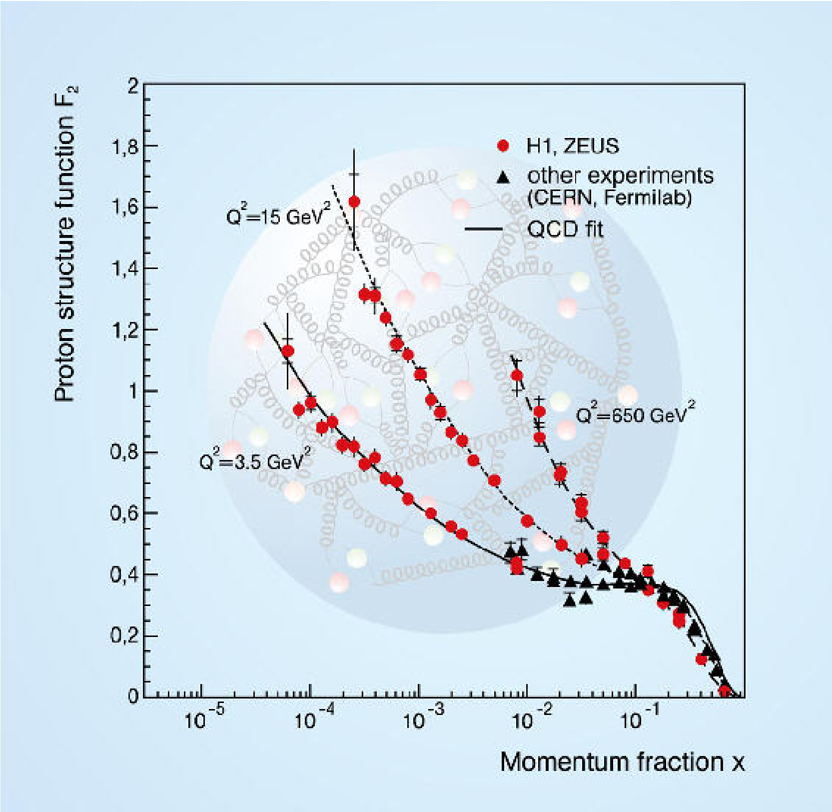
Measurements at HERA

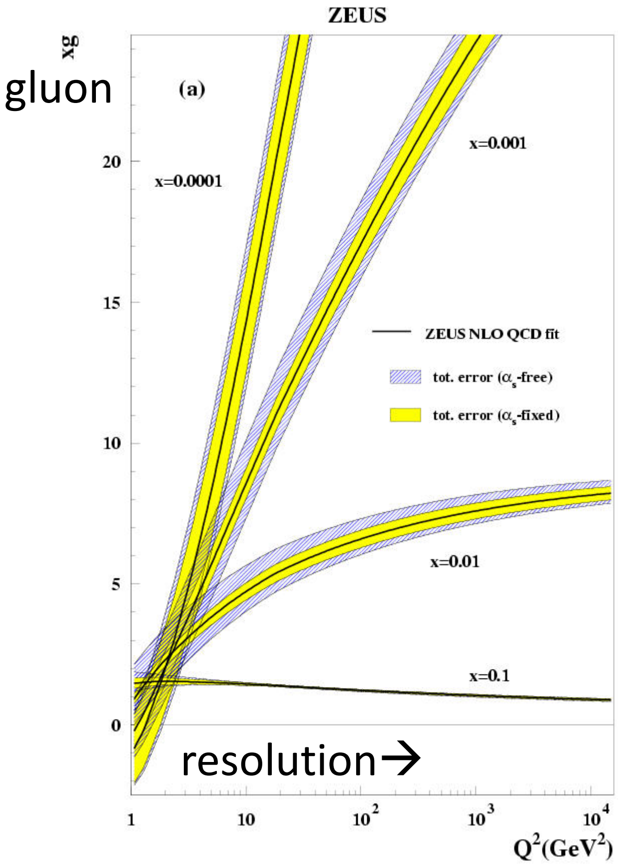


Early ZEUS data



Triumph of perturbative QCD





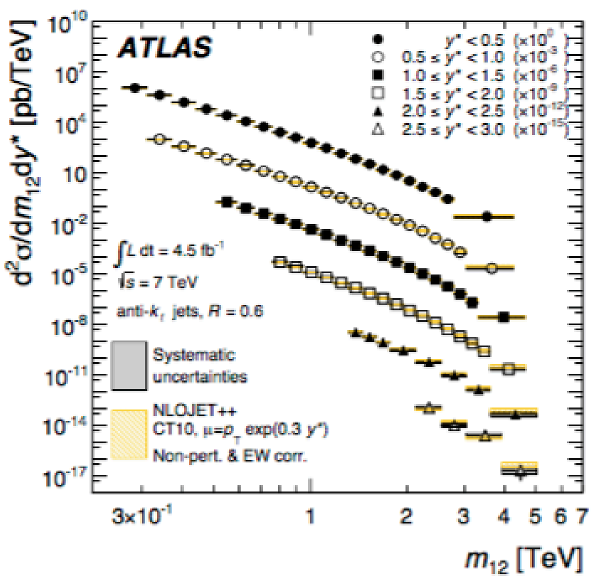
A part of Wilczek's comments upon the Nobel Prize announcement

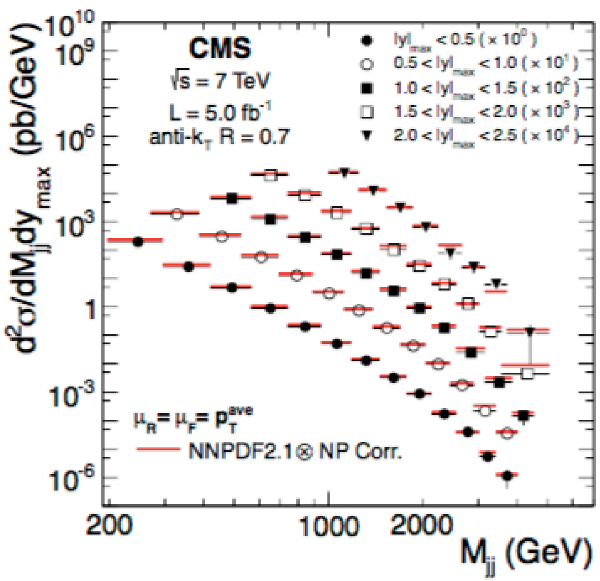
proposed specific experimental tests of our ideas. In the fourth paper some technical objections to the theory were cleared up, and in the fifth and sixth papers further experimental consequences, regarding the pointwise evolution of structure functions, were derived. The most dramatic of these, that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was clearly verified at HERA twenty years later.

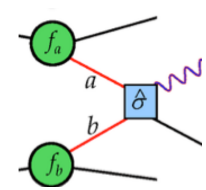
Using pQCD to understand protons: so far

- Protons at high momentum can be treated as a beam of partons— now identified as free quarks and gluons: (Asymptotic freedom!)
- You can measure DIS (and other) cross-sections -> extract pdfs -> predict cross-sections for another process. (Factorization!)

Jet cross-sections at the LHC predicted and measured

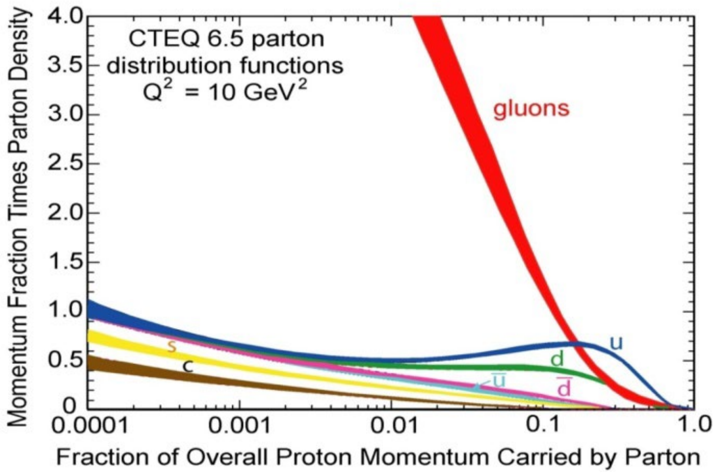




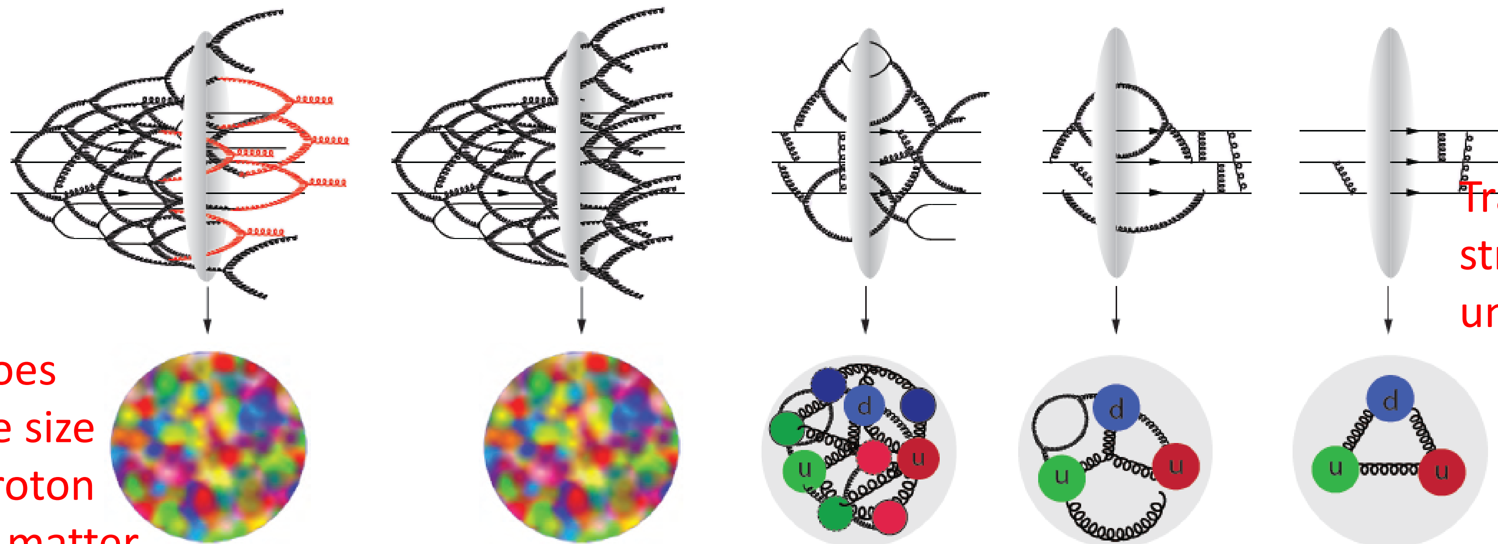


This is great if you are interested in studying the hard interaction (LHC physics)

What about 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…



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

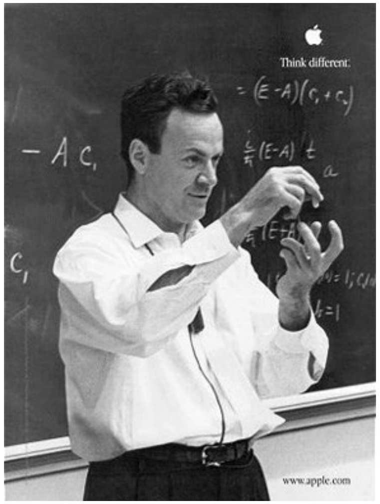
Transverse structure unmeasured

X (longitudinal) structure measured

DEEP INELASTIC SCATTERING AND PARTON DISTRIBUTIONS (I)

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

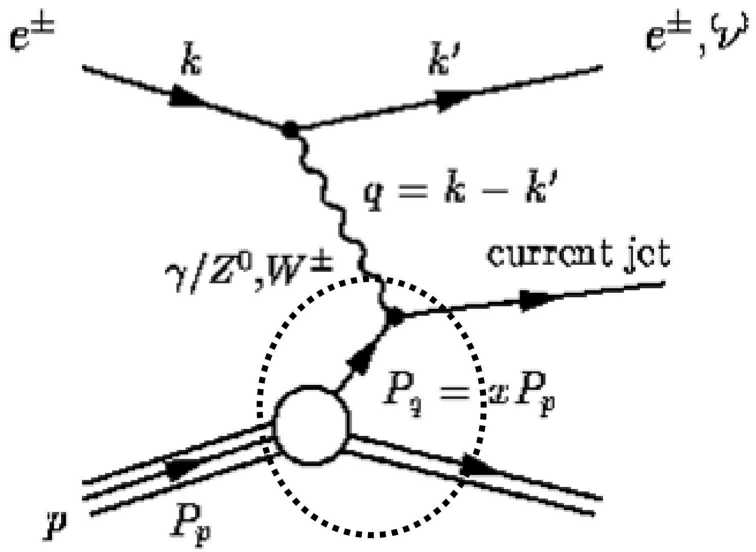
So for a proton:

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

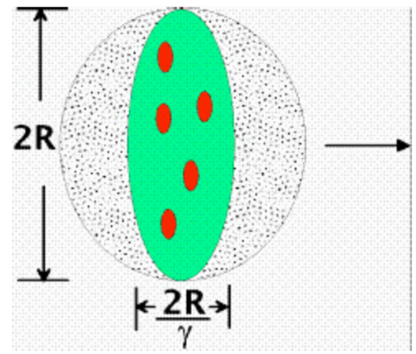
$$\int[s(x)-\bar{s}(x)+\ldots\ldots]dx=0$$

DIS kinematics

ep collision



proton in "∞" momentum frame



No transverse momentum

$0 \leq x \leq 1$

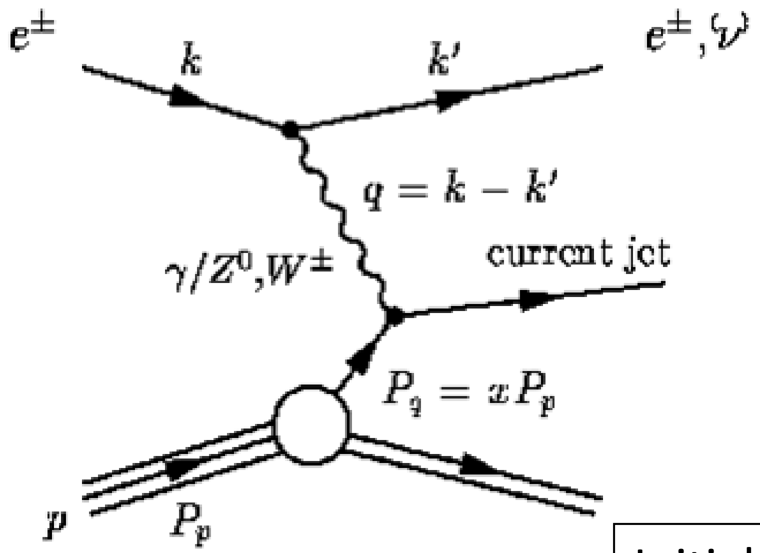
x = fractional longitudinal momentum carried by the struck parton

$\sqrt{s}$ = ep cms energy

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

DIS kinematics

ep collision



Final electron energy

Initial electron energy

$Q^2 = -q^2 = -(k-k')^2 = 2E_e E'_e(1+\cos\theta_e)$

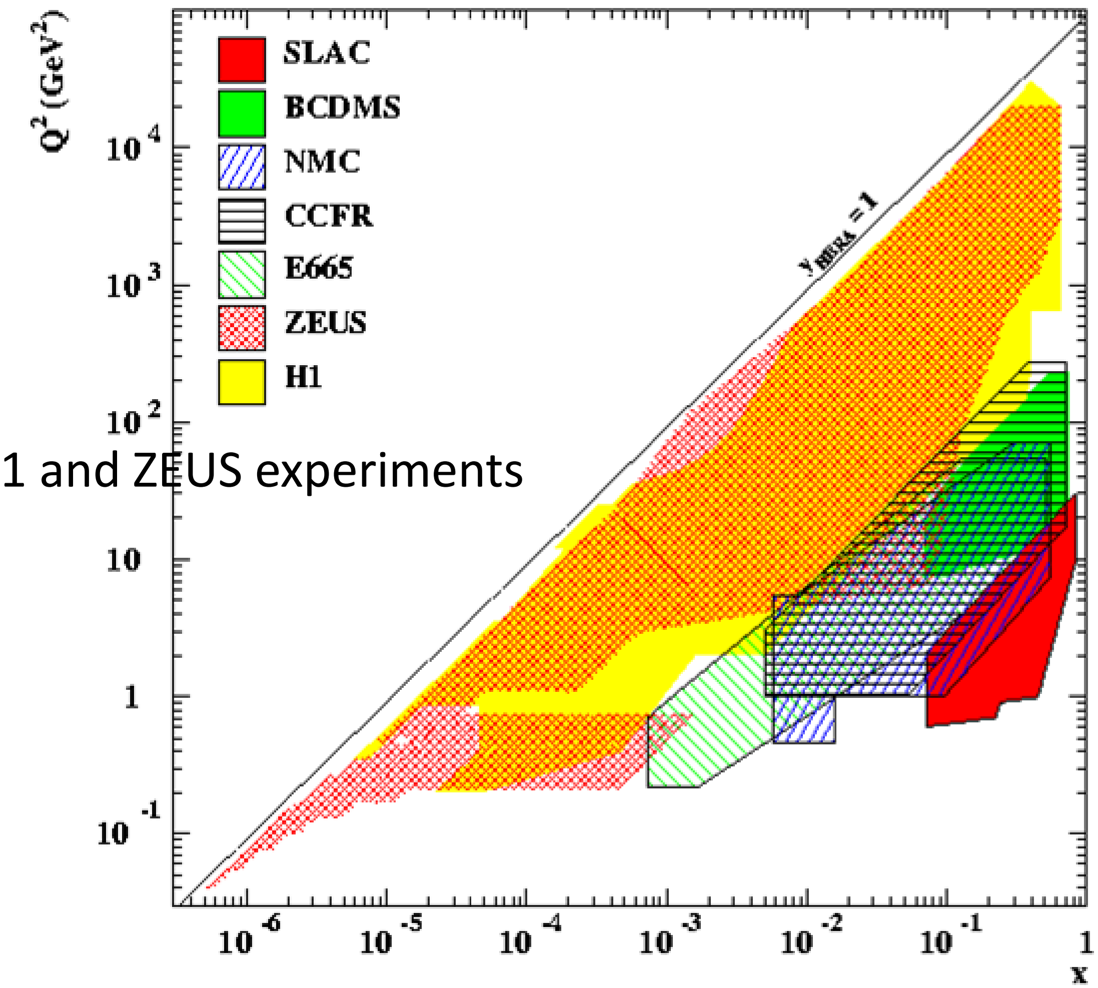
$$x = Q^2/2P \bullet q = \frac{E_e}{E_P} \frac{E'_e(1+\cos\theta_e)}{2E_e - E'_e(1-\cos\theta_e)}$$

Initial proton energy

Electron scattering angle

Everything we need can be reconstructed from the measurement of E'_e and θ_e. (in principle)

Deep Inelastic Scattering experiments



HERA collider: H1 and ZEUS experiments
1992 – 2007

Fixed target DIS at SLAC, FNAL and CERN

e^-p Neutral Current (NC) cross-section:

We'll come back to these →

Has to do with long. photon. Only large at largest y

Has to do with Z_0 exchange: small for $Q \ll M_Z$

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2) + Y_- xF_3(x,Q^2)\right]$$

$$Y_\pm = 1 \pm (1-y)$$

$y = Q^2/xs \quad 0 \le y \le 1$ "inelasticity"

So for now:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ F_2(x,Q^2)$$

quark charge

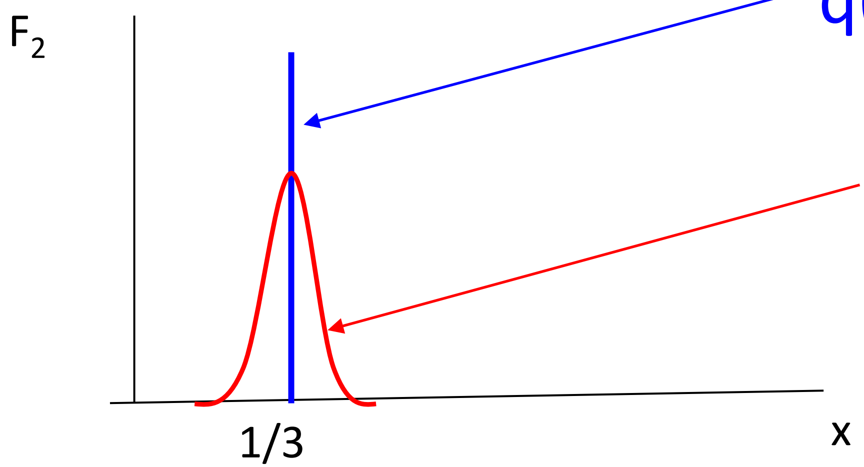
$$F_2 = x\sum \underbrace{(q + \bar{q})}_{\text{quark and anti-quark distributions}} e_q^2 + \text{Z-exchange}$$

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

no anti-quark!

$$F_2 = x\sum(q(x) + \cancel{q(\bar{x})})\, e_q^{\,2}$$

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



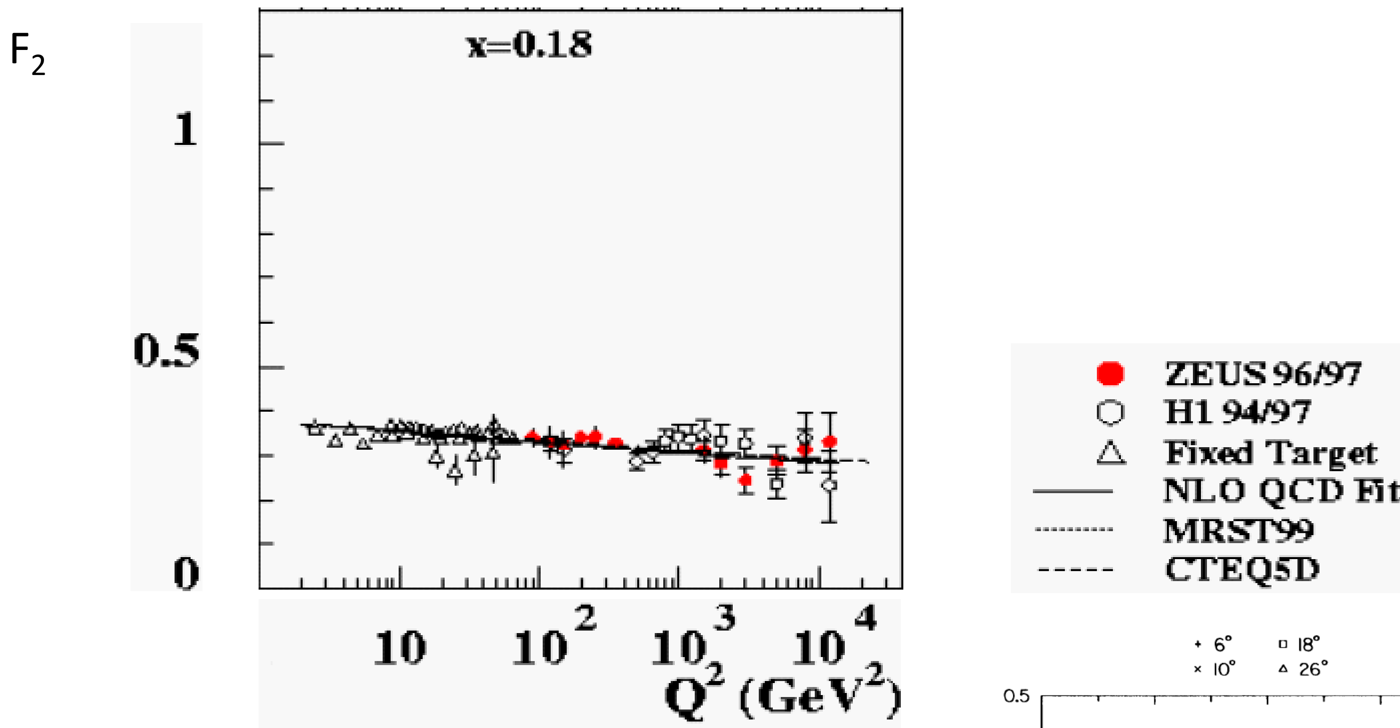
or with some smearing

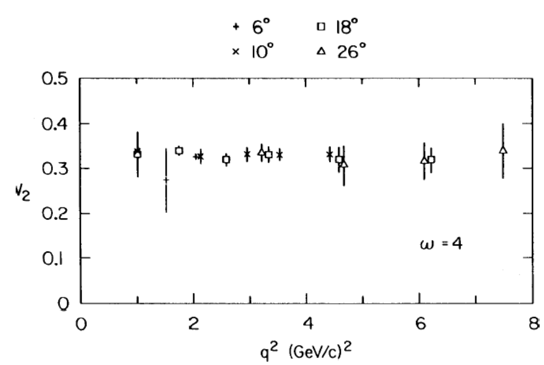
The partons are point-like and incoherent then Q^2 shouldn't matter.

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

Let's look at some data →

Proton Structure Function F_2

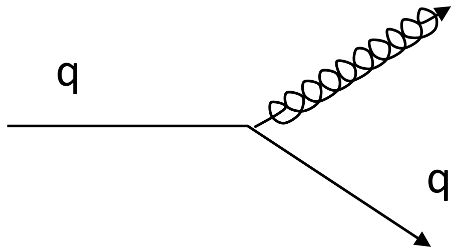




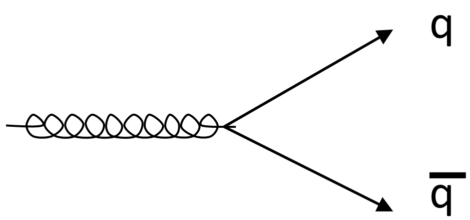
Seems to be…. NOT

So what does this mean..?

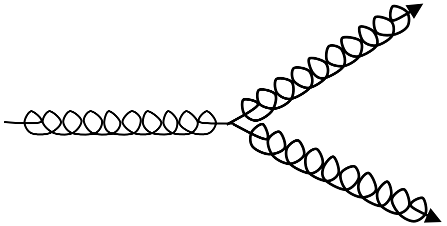
QCD, of course:



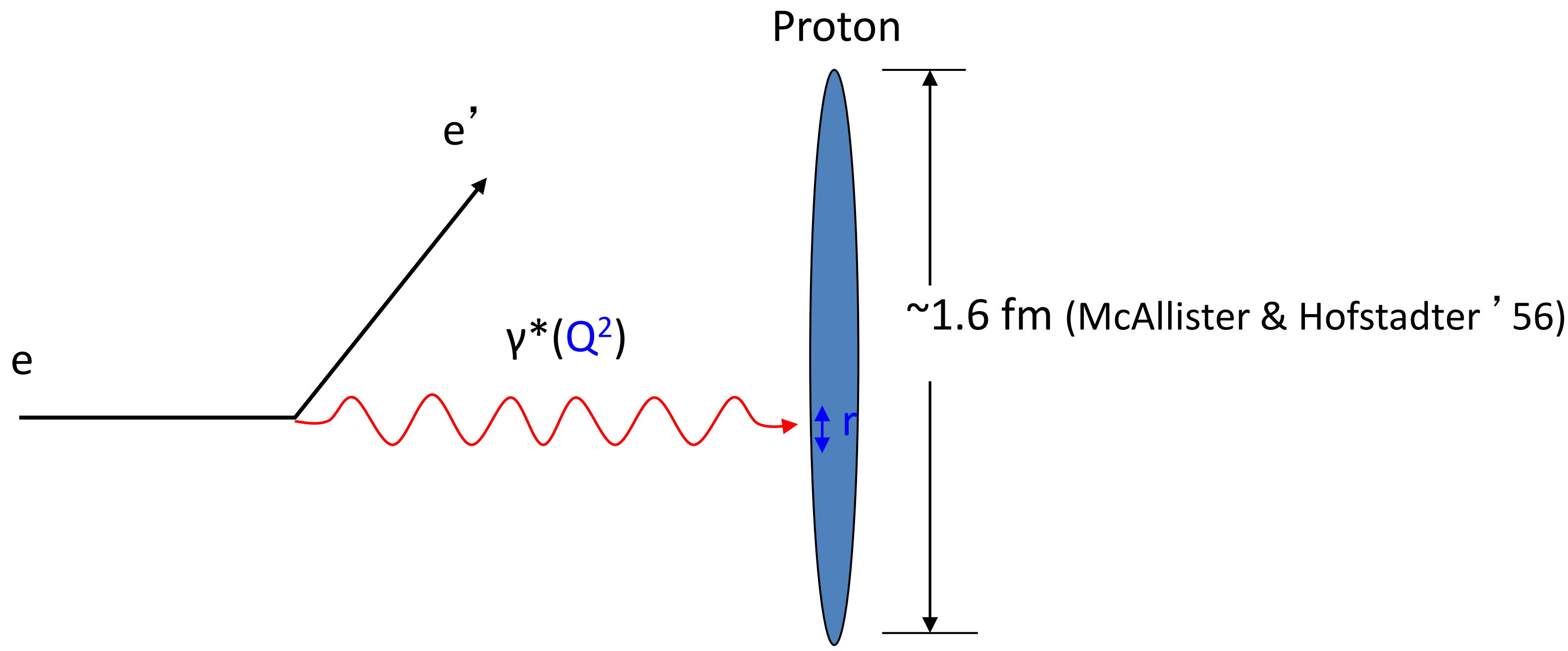
quarks radiate gluons



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



gluons can radiate gluons!



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

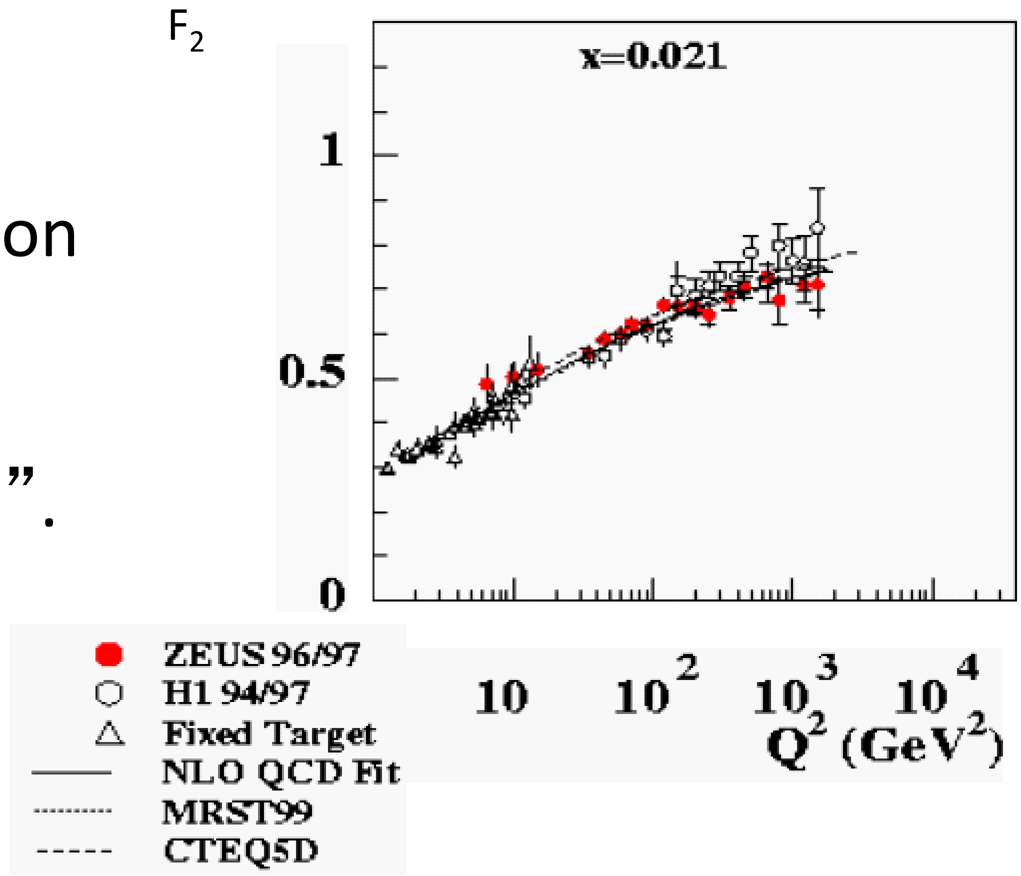
$r \approx \hbar c/Q = 0.2\text{fm}/Q[\text{GeV}]$

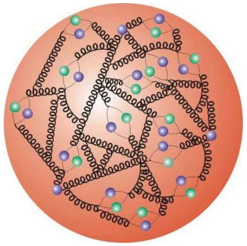
CERN, FNAL fixed target DIS: $r_{min} \approx 1/100$ proton dia.

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

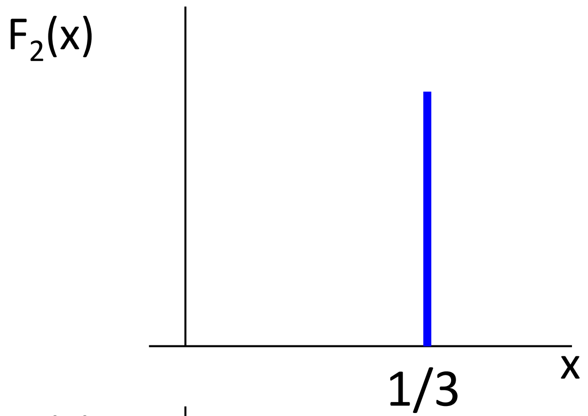
HERA: E_e=27.5 GeV, E_P=920 GeV

Higher the resolution
(i.e. higher the Q^2)
more branchings
to lower x we "see".

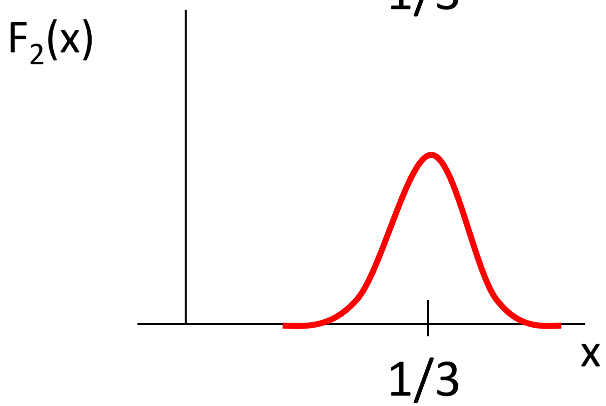




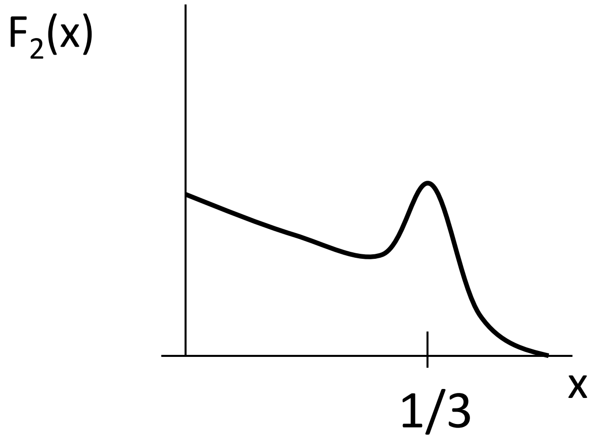
So what do we expect F_2 as a function of x at a fixed Q^2 to look like?



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



Three quarks with some momentum smearing.

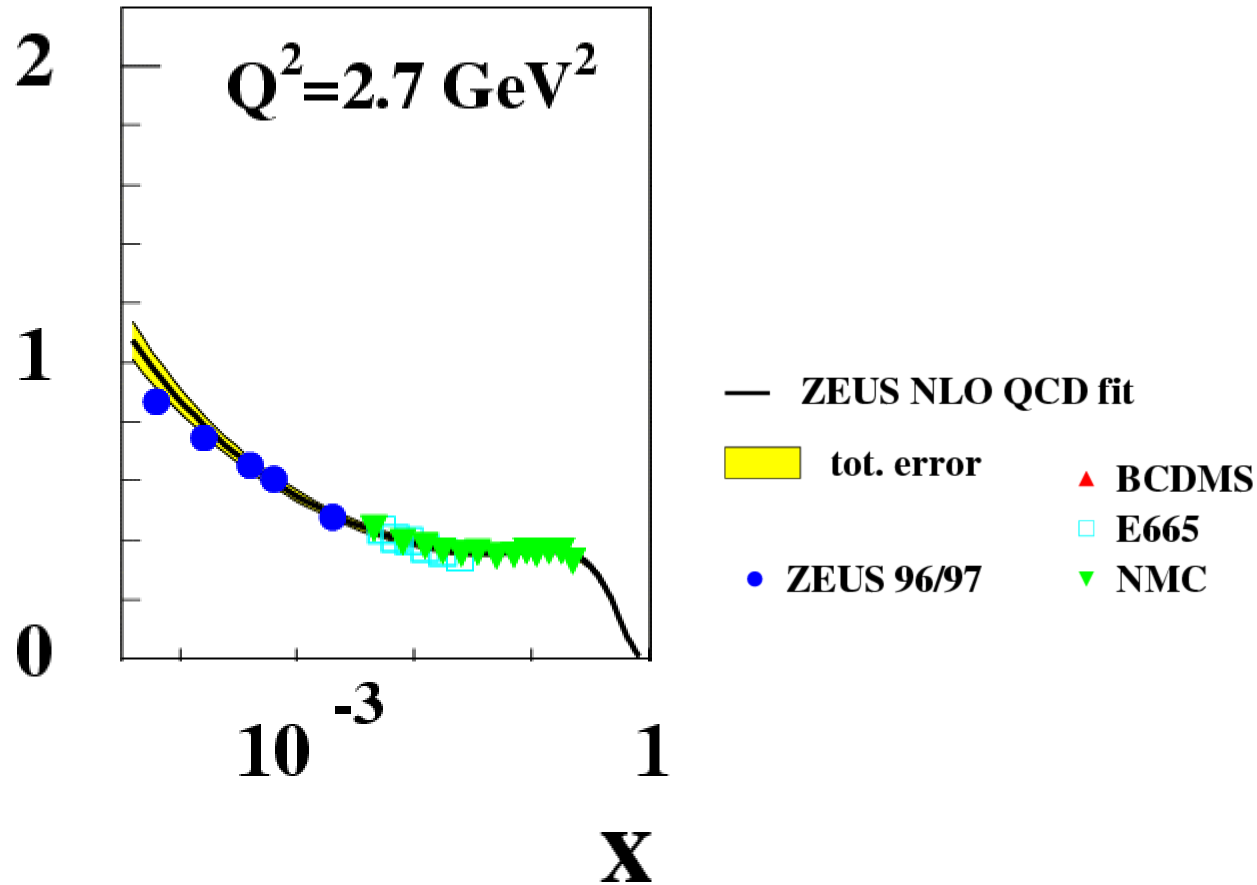


The three quarks radiate partons at low x.

Proton Structure Function F_2

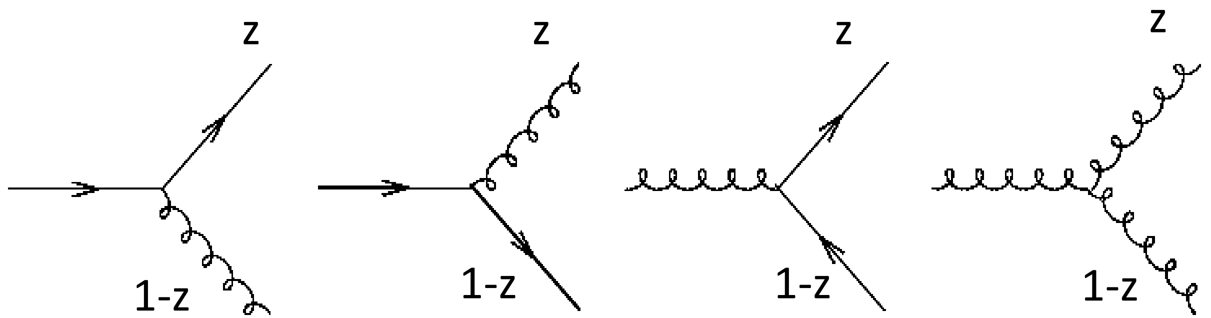
How this change with Q^2 happens quantitatively described by the:

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



DGLAP equations are easy to "understand" intuitively

First we have the four "splitting functions"



$P_{ab}(z)$: the probability that parton a will
radiate a parton b with the fraction
z of the original momentum carried by a.

Now DGLAP equations (schematically)

$$\frac{dq_f(x,Q^2)}{d \ln Q^2} = \alpha_s \, [q_f \otimes P_{qq} + g \otimes P_{gq}]$$

convolution

strong coupling constant

Change of quark distribution q with Q^2
is given by the probability that q and g radiate q.
Same for gluons:

$$\frac{dg(x,Q^2)}{d \ln Q^2} = \alpha_s \, [\sum q_f \otimes P_{qg} + g \otimes P_{gg}]$$

DGLAP fit (or QCD fit) extracts the parton distributions from measurements.

Here's a 1 min description:

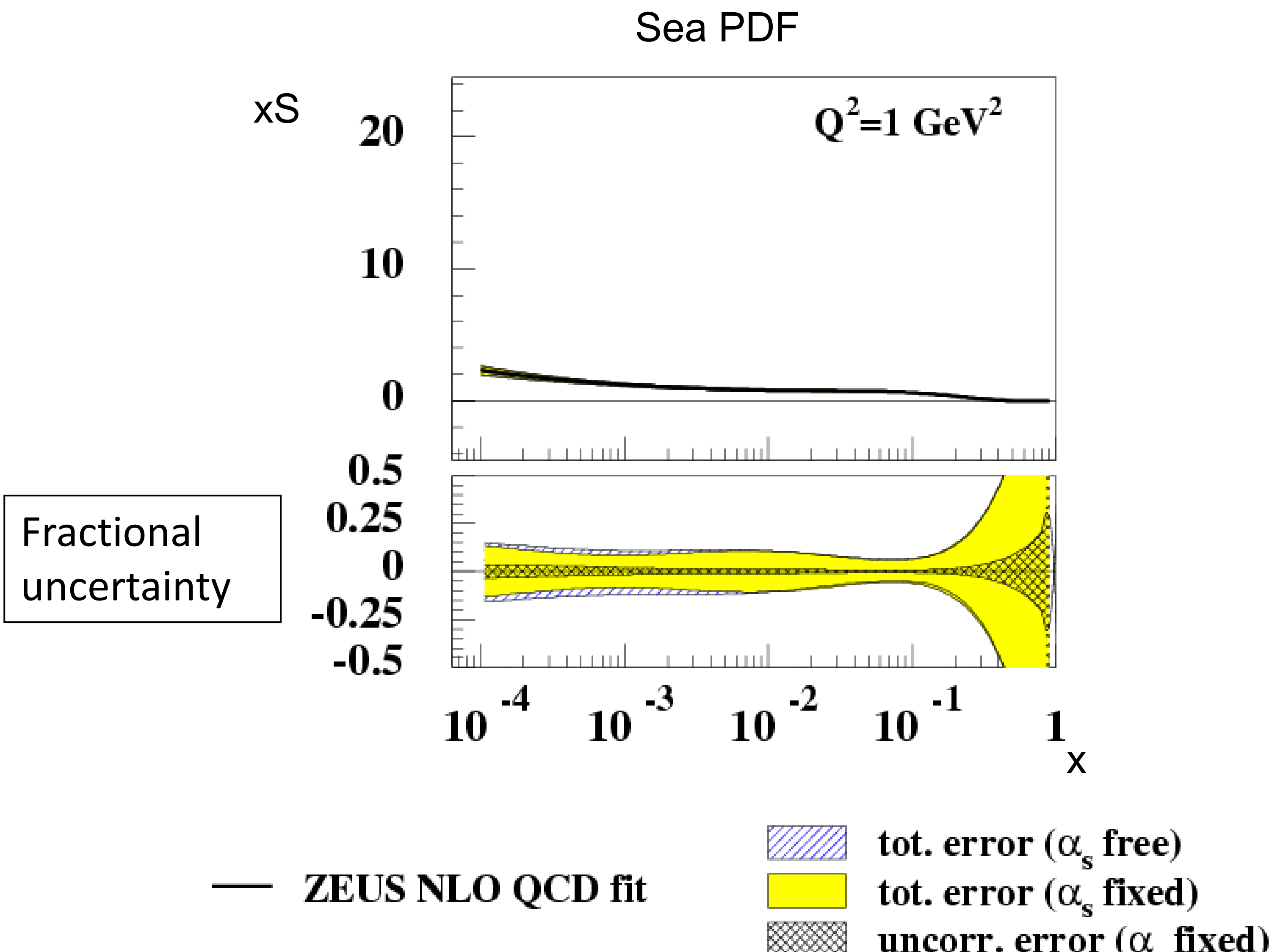
Step 1: parametrise the parton momentum desity $f(x)$ at some Q^2. e.g.

$$f(x)=p_1 x^{p2}(1-x)^{p3}(1+p_4\sqrt{x}+p_5 x)$$

$u_v(x)$ u-valence
$d_v(x)$ d-valence
"The orginal three quarks"
$g(x)$ gluon
$S(x)$ sum of all "sea" (i.e. non valence) quarks

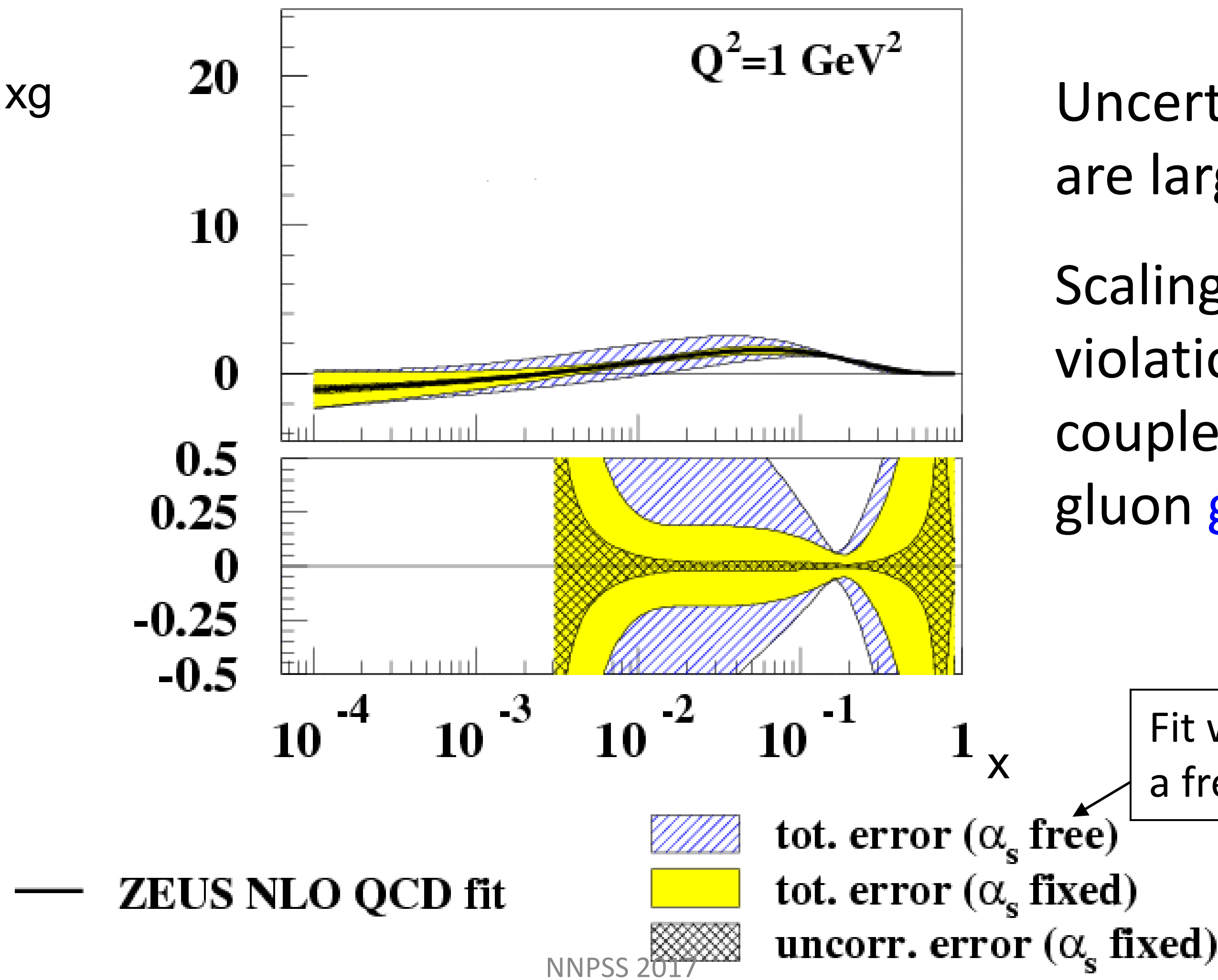
Step 2: find the parameters by fitting to DIS (and other) data using DGLAP equations to evolve $f(x)$ in Q^2.

At x<<1/3, quarks and (antiquarks) are all "sea". Since F2 = $e_q^2 \sum x(q + \bar{q})$, xS is very much like F_2



Gluons, on the other hand, are determined from the scaling violations $dF_2/d\ln Q^2$ via the DGLAP equations.

Gluon PDF



Uncertainties are larger.

Scaling violations couple α_s and gluon g

Fit with α_s also a free param.

So far:

$F_2 \sim \sum(q+\bar{q}) \approx S$ (sea quarks) measured directly in NC DIS

Scaling violations

$dF_2/d\ln Q^2 \sim \alpha_s \bullet g$ Scaling violations gives gluons (times α_s). DGLAP equations.

What about valence quarks?

$\sum(q-\bar{q}) = u_v + d_v$ can we determine them separately?

Can we decouple α_s and g ?

End of Day 1

- Tomorrow we'll carry on with DIS and PDF.
- Ask what is beyond PDF.. and begin to answer the question "why EIC".