The Electron-Ion Collider

Lecture 1

Thomas Ullrich (BNL/Yale)

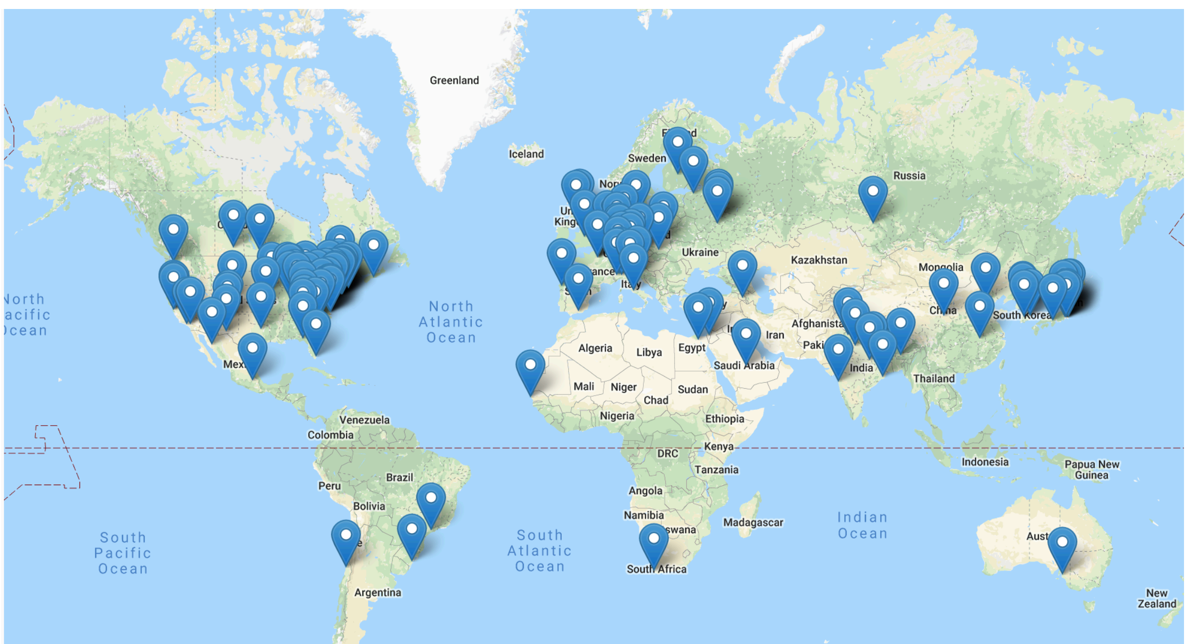
NNPSS, June 25, 2018

Yale BROOKHAVEN NATIONAL LABORATORY

The Electron-Ion Collider does not exist

The Electron-Ion Collider does not exist

Yet!!



Over 800 people from 169 institutions and 29 countries are working hard to make it happen within the next decade.

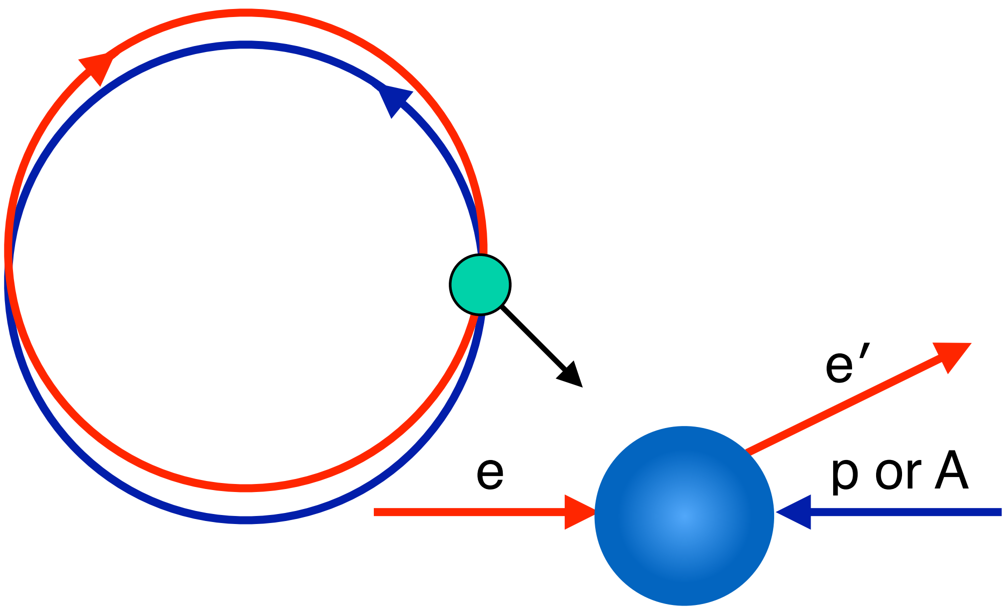
I am one of them.

The Electron-Ion Collider on One Page

The Electron-Ion Collider will be a machine for unlocking the secrets of gluons that binds the building blocks of visible matter in the universe.

Tools:

- The world's first polarized electron-polarized proton collider
- The world's first electron-heavy ion collider
- Fine resolution inside proton down to 10^{-18} meters



- Counter rotating beams of electrons and protons/ions collide at an interaction point
- The probe (electron) is structure-less and scatters off a "target". The process is called Deep Inelastic Scattering.

Outline (Lecture 1)

1. Probing Matter
   1.1. Scattering Experiments
   1.2. Electron Scattering
2. Quark Models and QCD
   2.1. Static Quark Model
   2.2. QCD
   2.3. Gluons
3. Studying Matter at the Smallest Scale
   3.1. DIS & Kinematics
   3.2. Structure Functions
   3.3. Parton Distribution Function

Related Lectures

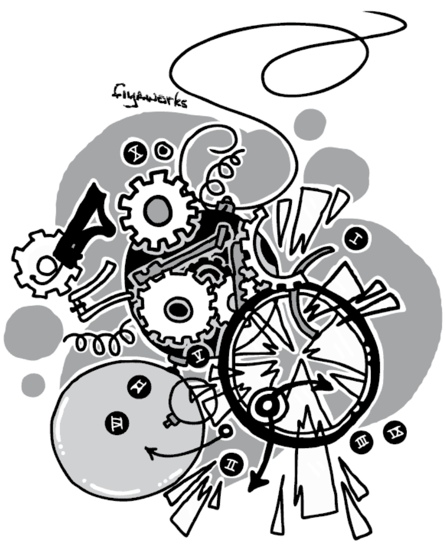
- Heavy Ion Theory, Bjoern Schenke
- Heavy Ion Experimental, Megan Connors

- Hadron Structure Theory, Alexei Prokudin
- Hadron Structure Experimental, Anselm Vossen

1. Probing Matter

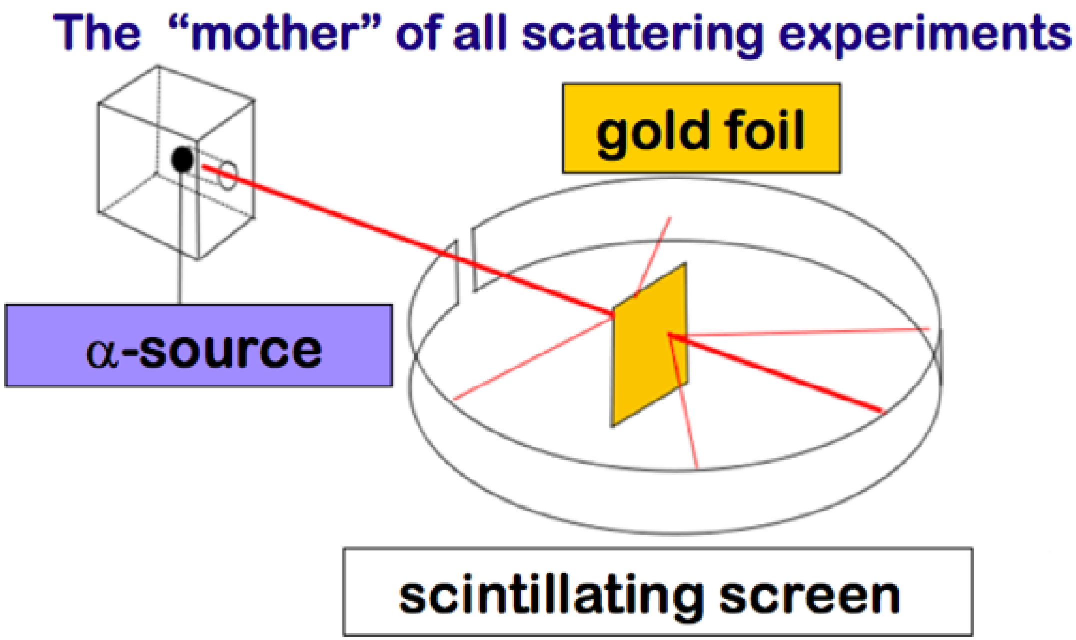
Scattering of protons on protons
is like colliding Swiss watches to find out
how they are build.

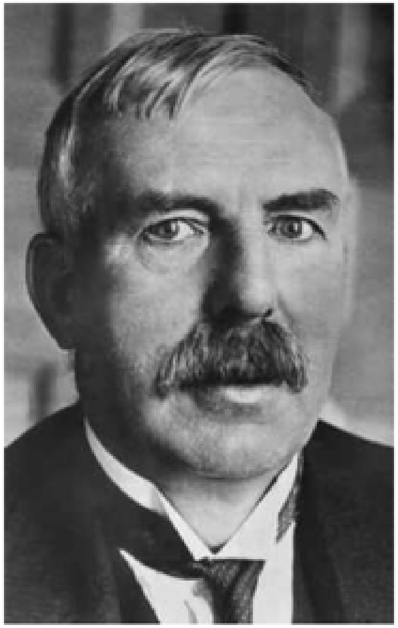
R. Feynman



Probing Matter (1909)

The first exploration of subatomic structure was undertaken by Rutherford at Manchester using Au atoms as targets and α particles as probes.





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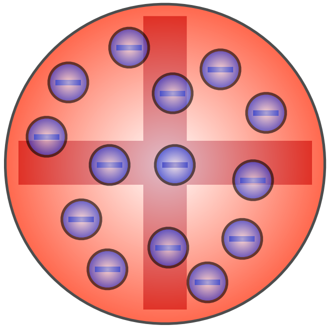
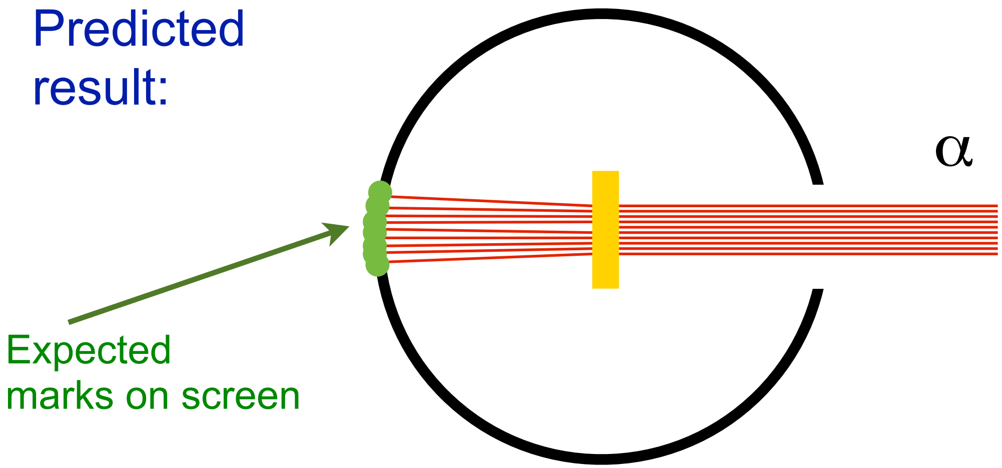
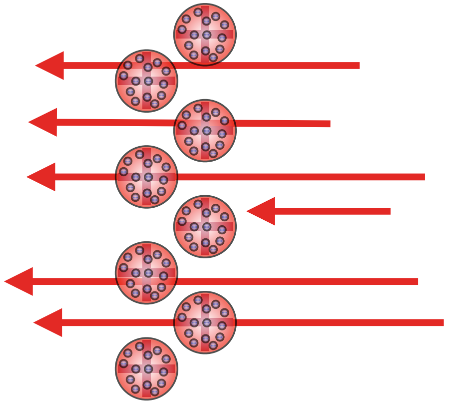


Thomson's
Plum Pudding Model

Predicted
result:



Detail of gold foil (Thomson):



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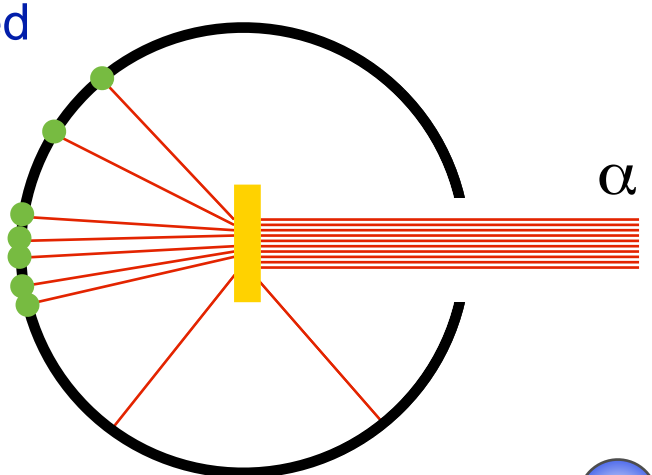
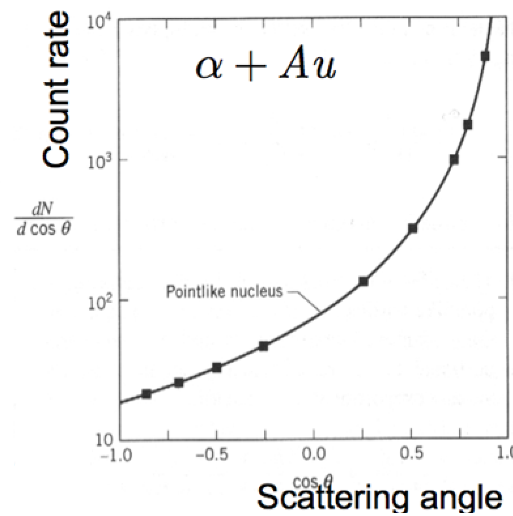
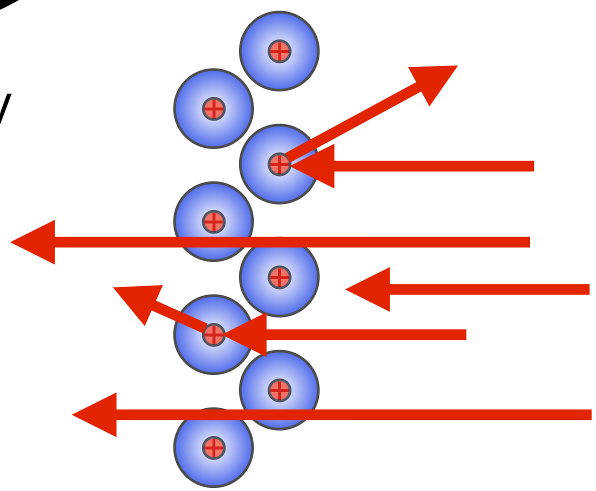
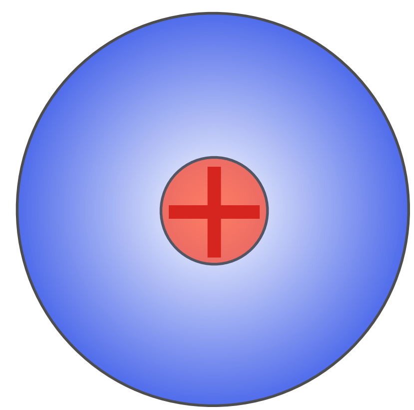
Observed result:





Positive Nucleus Theory explain α deflection:





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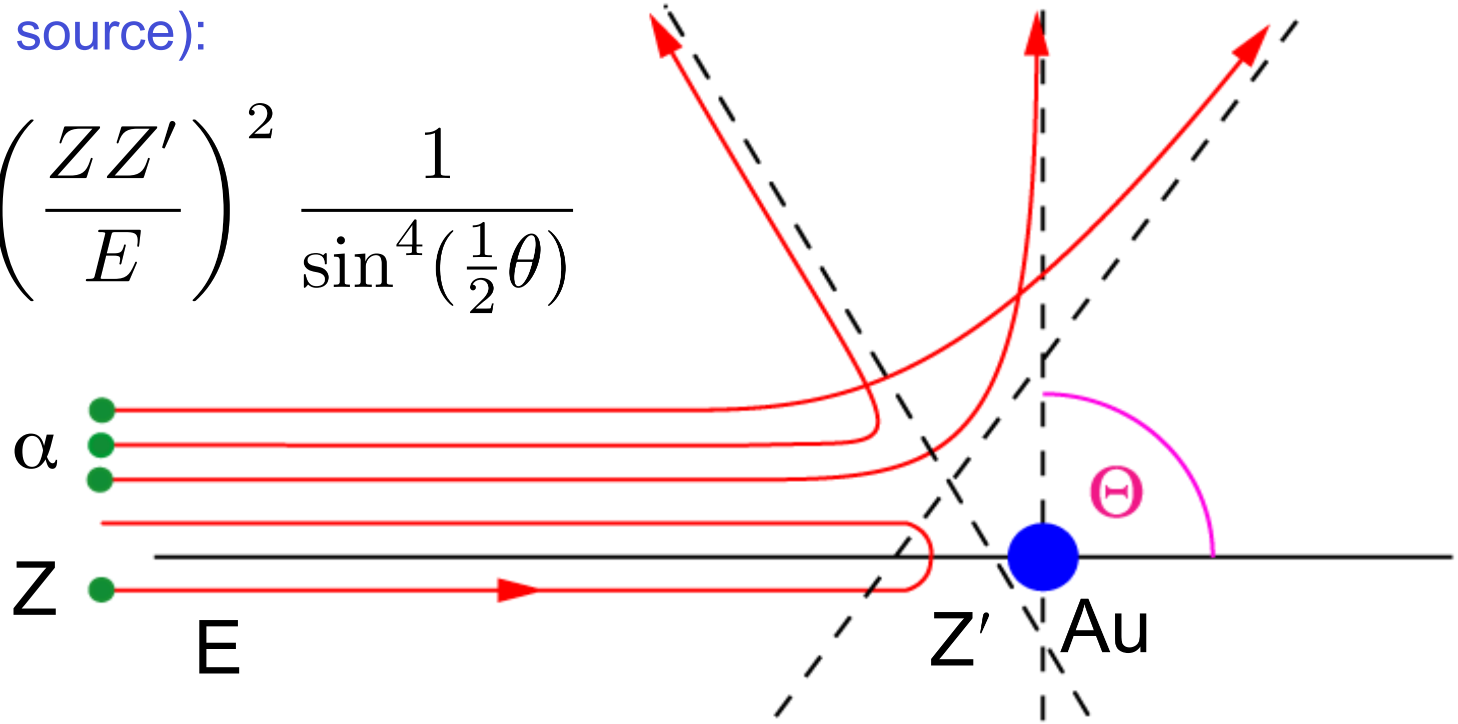
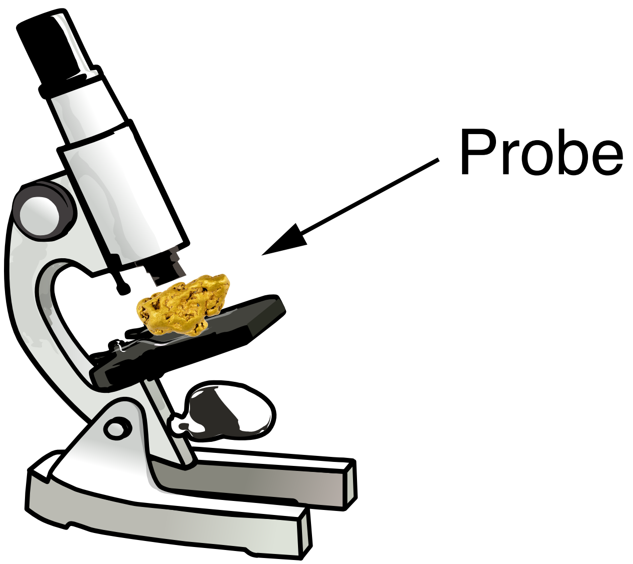
Elastic scattering of charged particles in Coulomb field (point-like source):

$$\frac{d\sigma}{d\Omega} = \left(\frac{ZZ'}{E}\right)^2 \frac{1}{\sin^4(\frac{1}{2}\theta)}$$

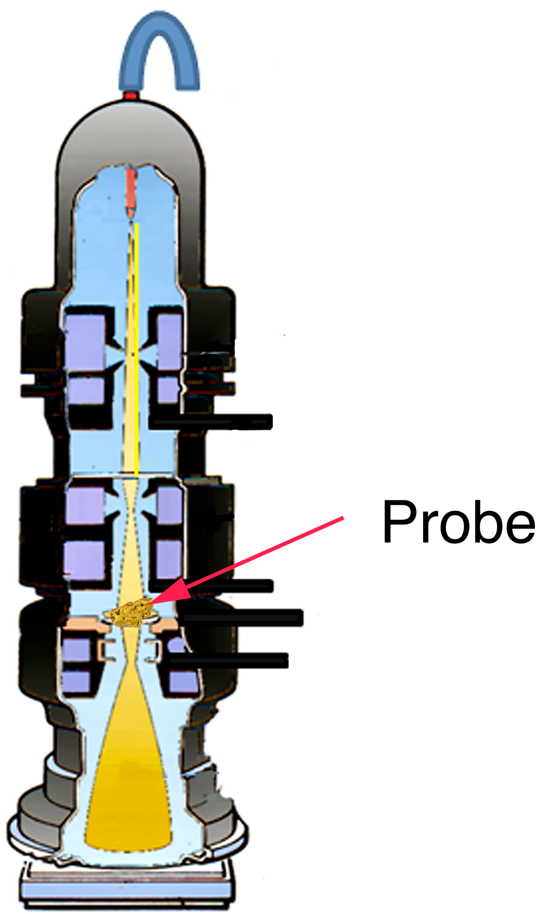


Studying Matter at Small Scales

Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm



Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm

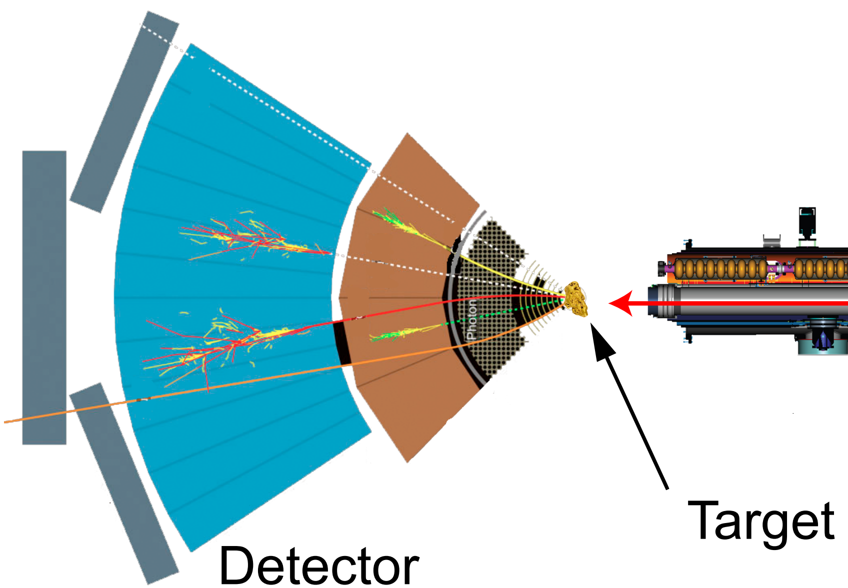


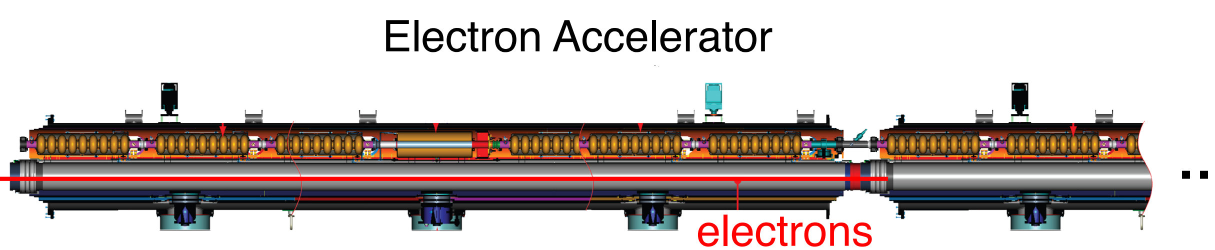
Studying Matter at Small Scales

Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm

Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm

Fixed Target Particle
Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm

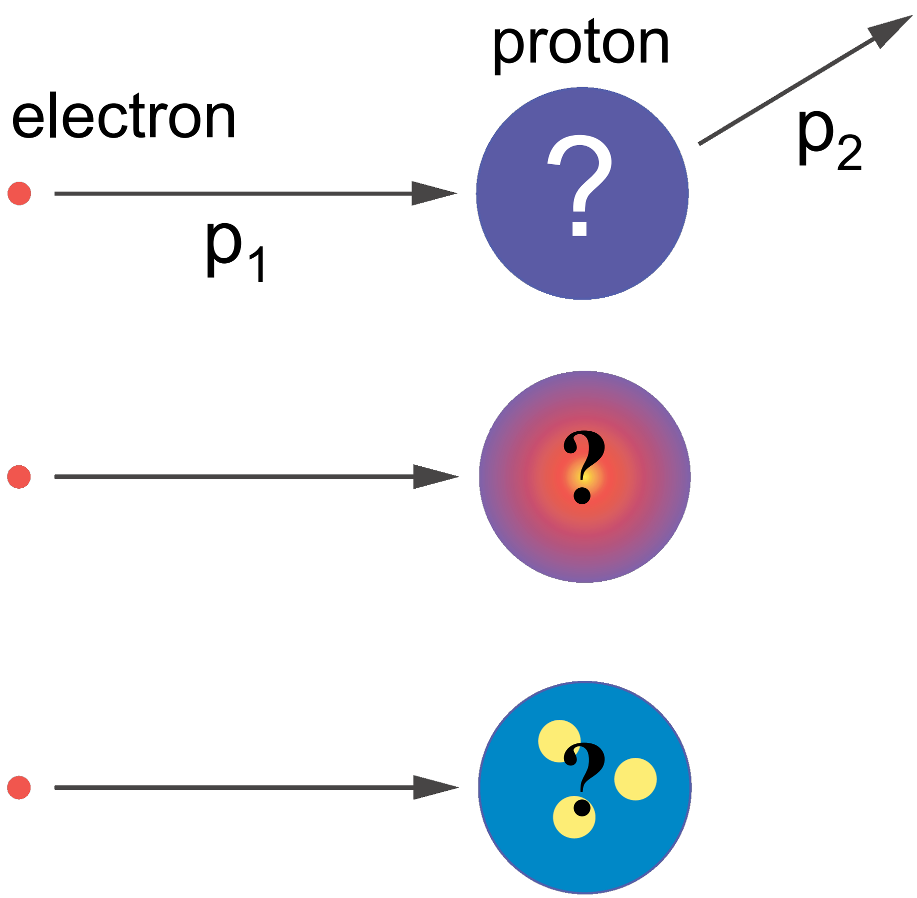




SLAC, EMC, NMC, E665, BCDMS, HERMES, JLab, COMPASS, …

Probing Matter with Electrons

The SLAC experiments in the 1960s established the quark model and our modern view of particle physics.



Mott = Rutherford + Spin

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(q^2)|^2$$

$$q^2 = (\mathbf{p}_1 - \mathbf{p}_2)^2$$

Formfactor: $F(q^2)$
Fourier transform
of charge distributions

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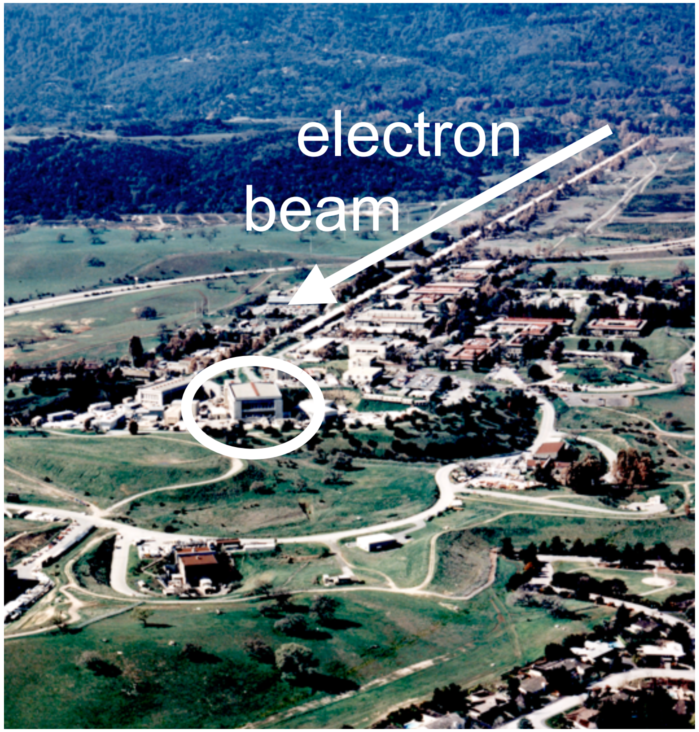

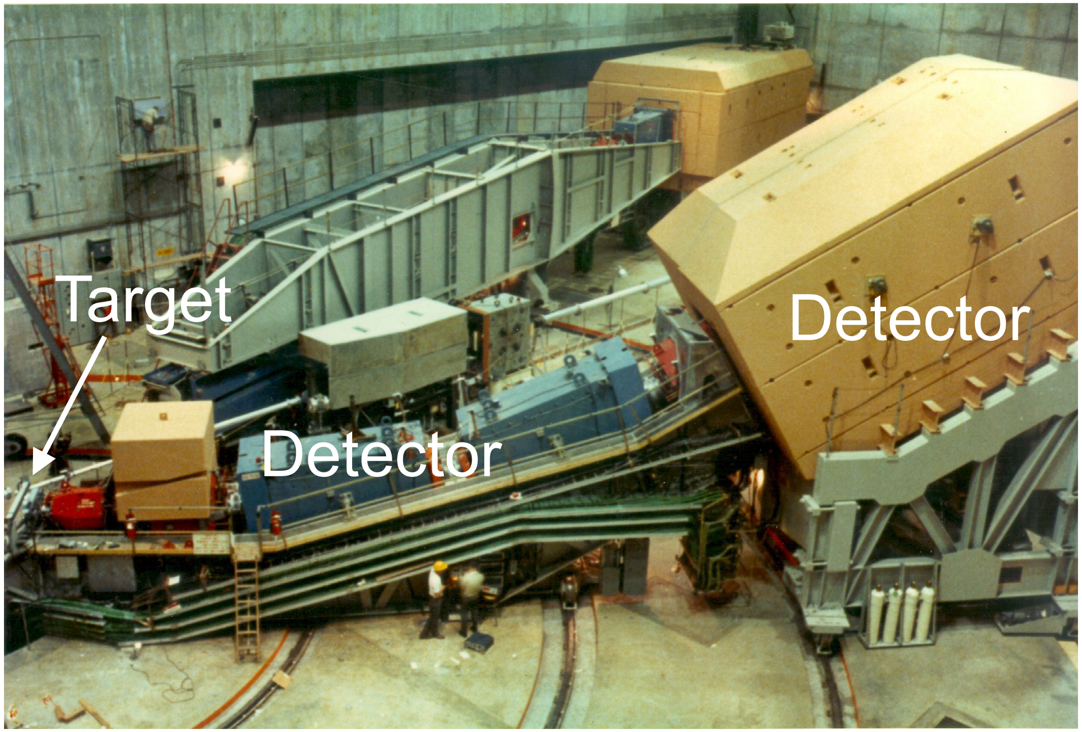

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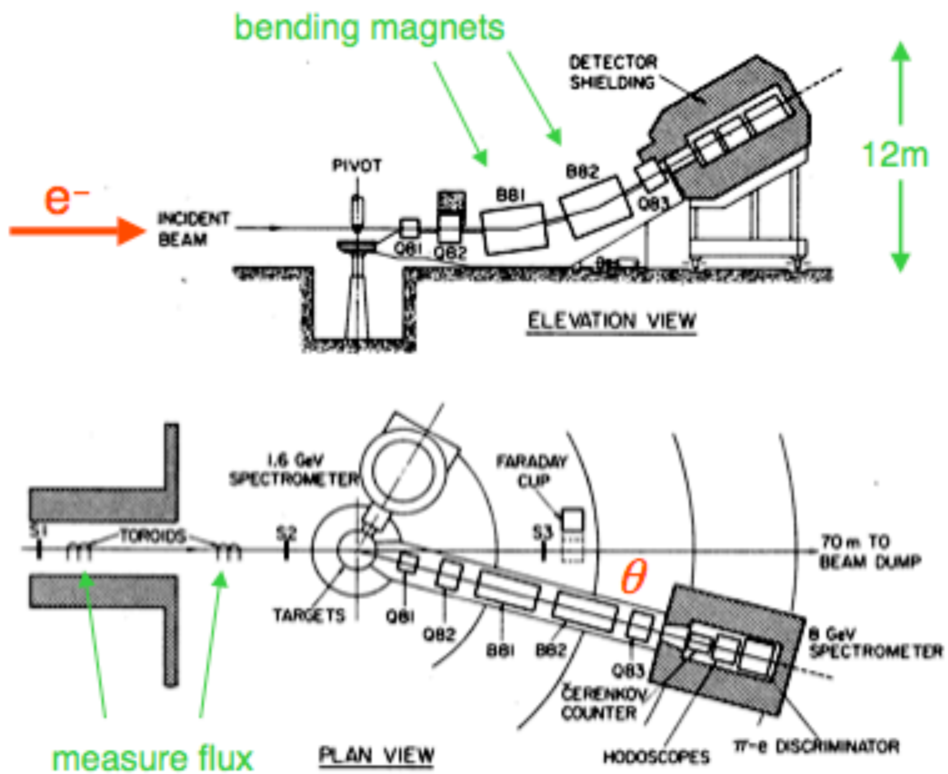

Scattered electron is deflected by a known *B*-field and a fixed vertical angle:

determine *E'*

Spectrometer can rotate in the horizontal plane,

vary θ

Probing Matter with Electrons

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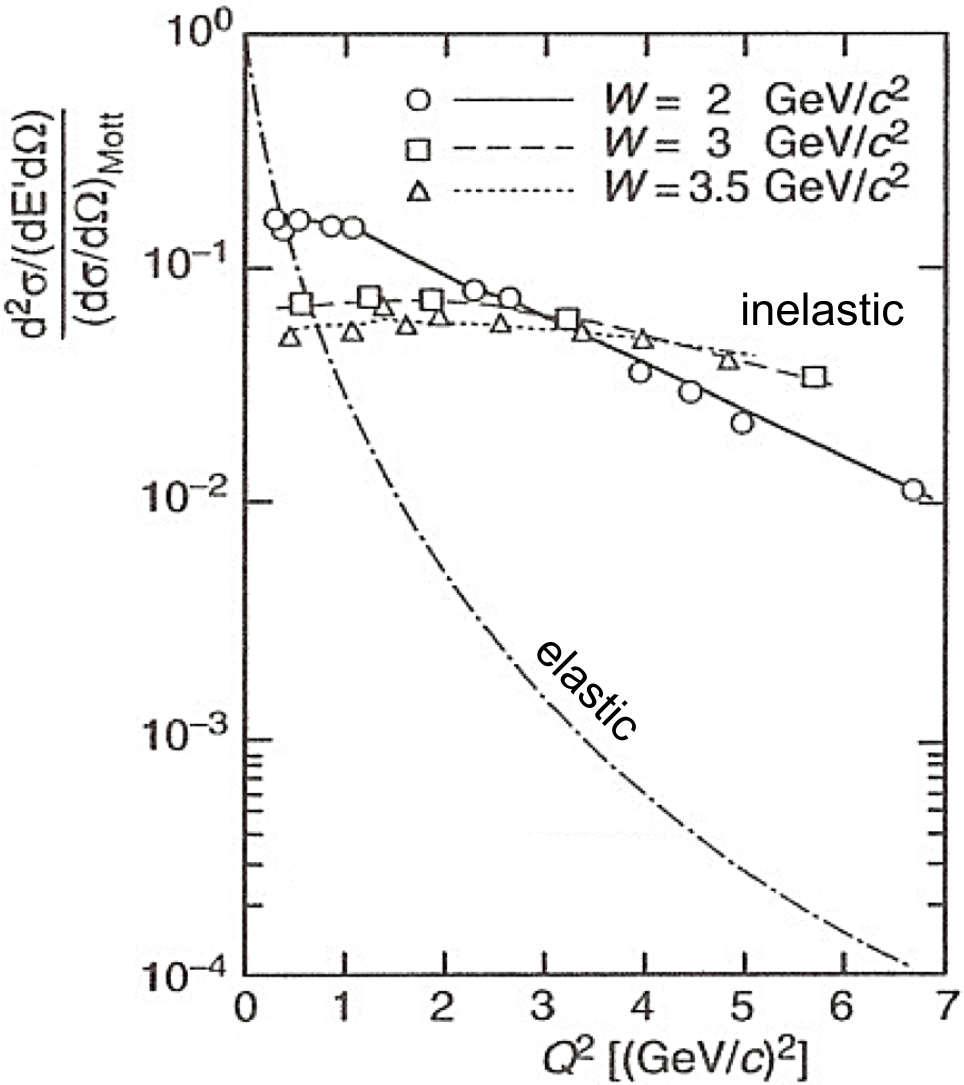
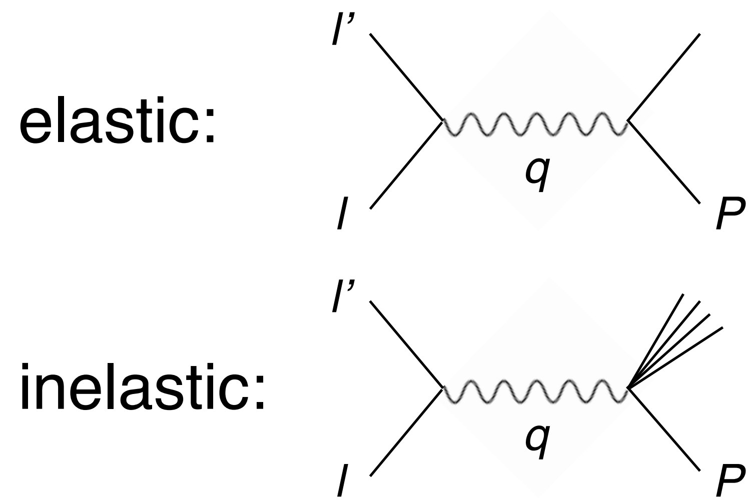
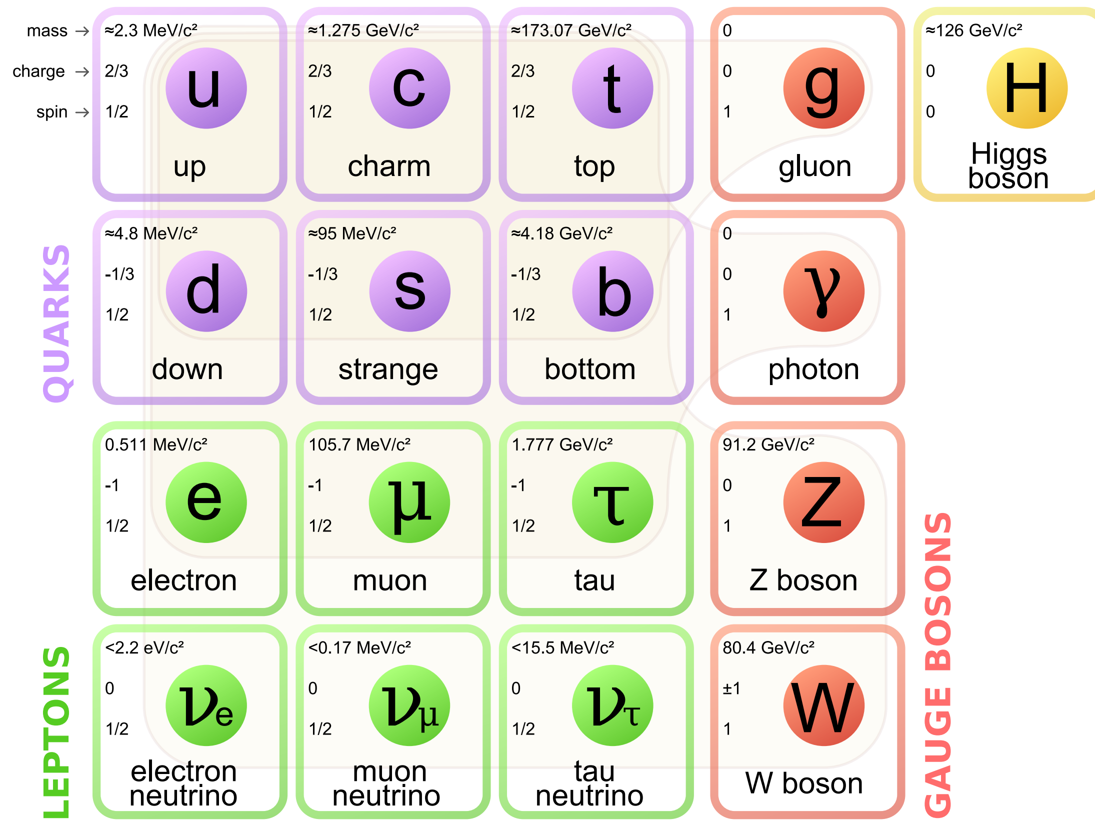




Constant $F(q^2)$:
⇒ scattering on point-like constituent of the nucleon

quarks

2. Quarks Gluons and QCD



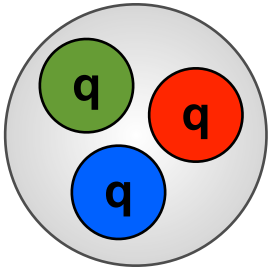
The proton is just 2 up quarks and 1 down quark, …

"Static" Quark Model

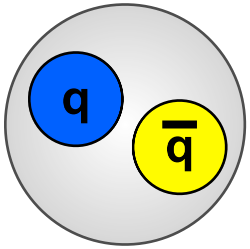
Quarks: spin 1/2 fermions, color charge

M. Gell-Mann,
K. Nishijima (> 1964)

Baryons:



Mesons:



Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	$+1$	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	$+1$

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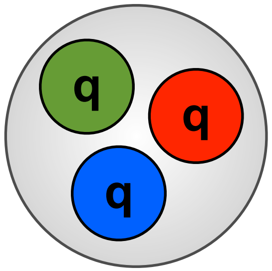

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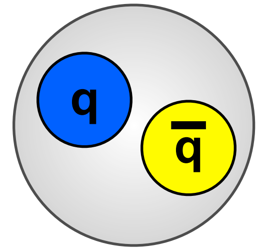
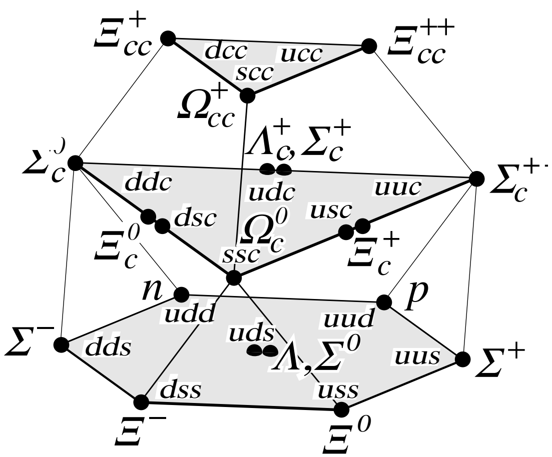
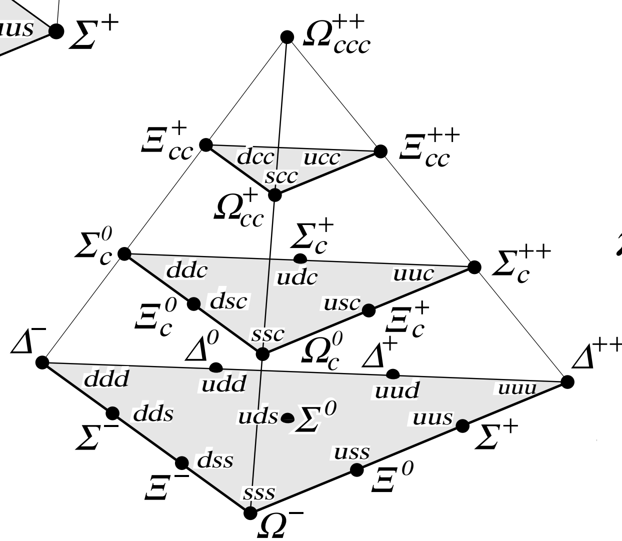
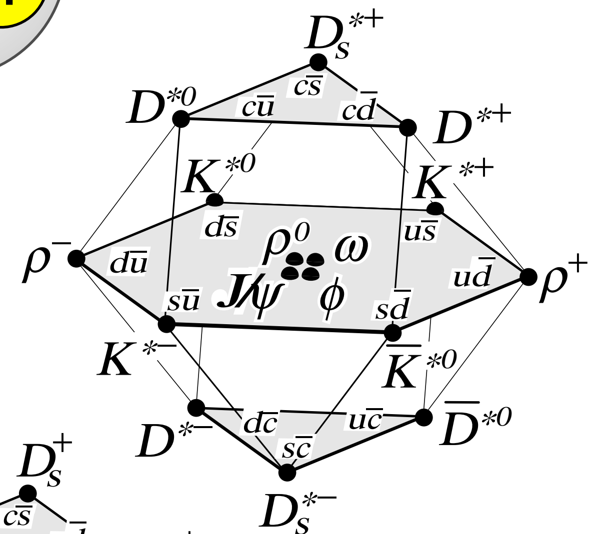
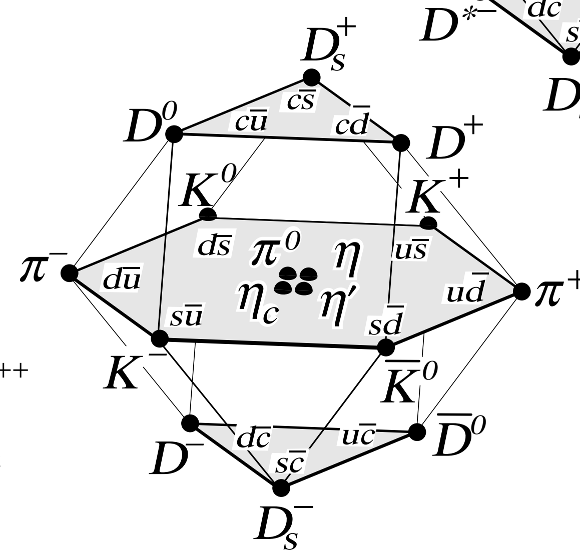




Eight-fold Way:
Account for every hadron we found so far







"Static" Quark Model

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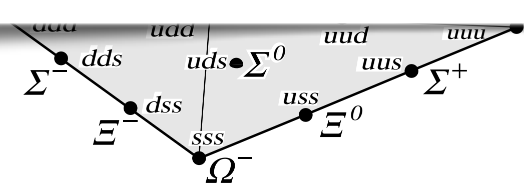
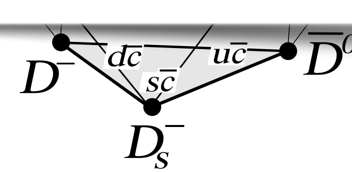
For detailed properties of multi-quark systems the static (constituent) model has failed almost completely and given no predictions which have been verified by experiment.

How can a model be so successful in the quark-antiquark and three quark systems and fail for almost everything else?

What's missing?

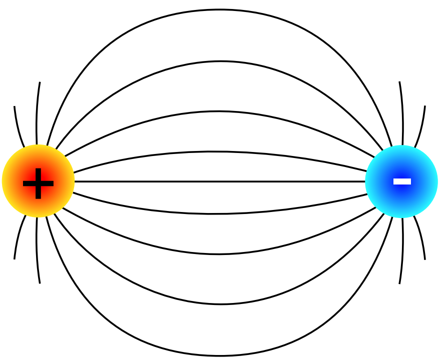


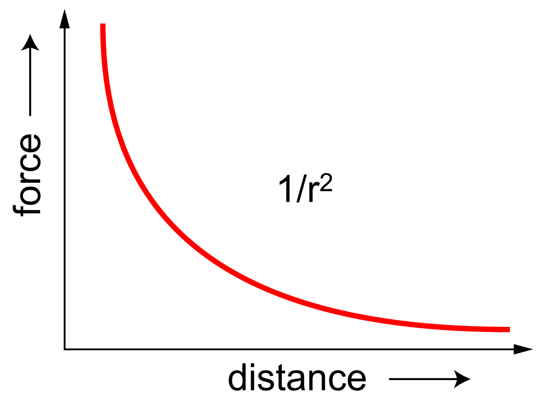


Recall: Quantum Electrodynamic

Theory of electromagnetic interactions

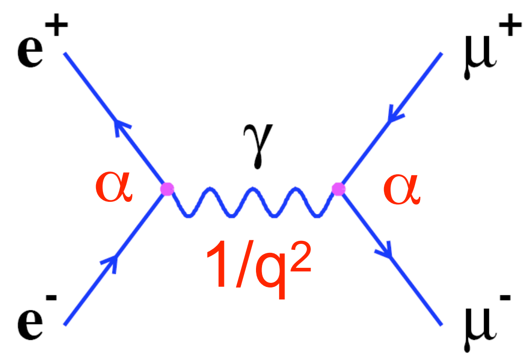
- Exchange particles (photons) do not carry electric charge
- Flux is not confined: $V(r) \sim 1/r$, $F(r) \sim 1/r^2$





$$V(r) = -\frac{q_1 \ q_2}{4\pi\varepsilon_0 \ r} = -\frac{\alpha_{em}}{r}$$

Example Feynman Diagram:
e^+e^- annihilation



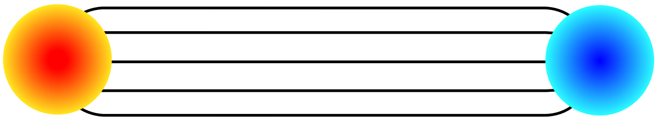
Coupling constant (α): Interaction Strength
In QED: $\alpha_{em} = 1/137$

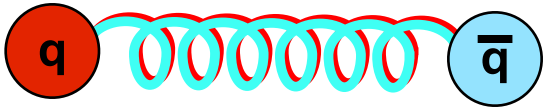
Quantum Chromodynamics (QCD)

Quantum Chromo Dynamics is the "nearly perfect" fundamental theory of the strong interactions

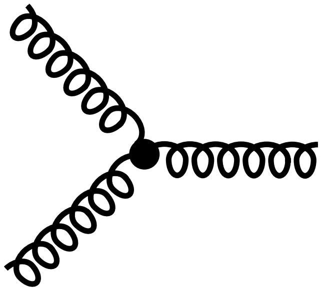
F. Wilczek, hep-ph/9907340

- Three color charges: red, green and blue





- Exchange particles (gluons) carry color charge and can self-interact



Self-interaction: QCD significantly harder to analyze than QED

- Flux is *confined*: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$

~1/r at short range

long range ~ r

Long range aspect ⇒ quark confinement and existence of nucleons

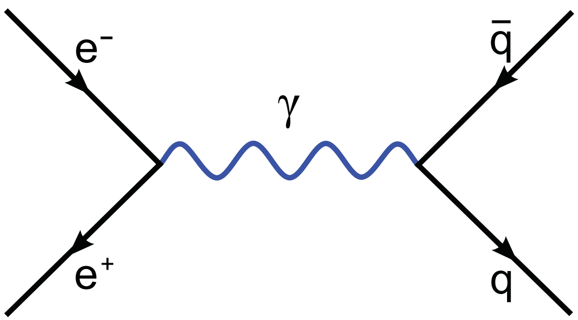
Gluons: They Exist!

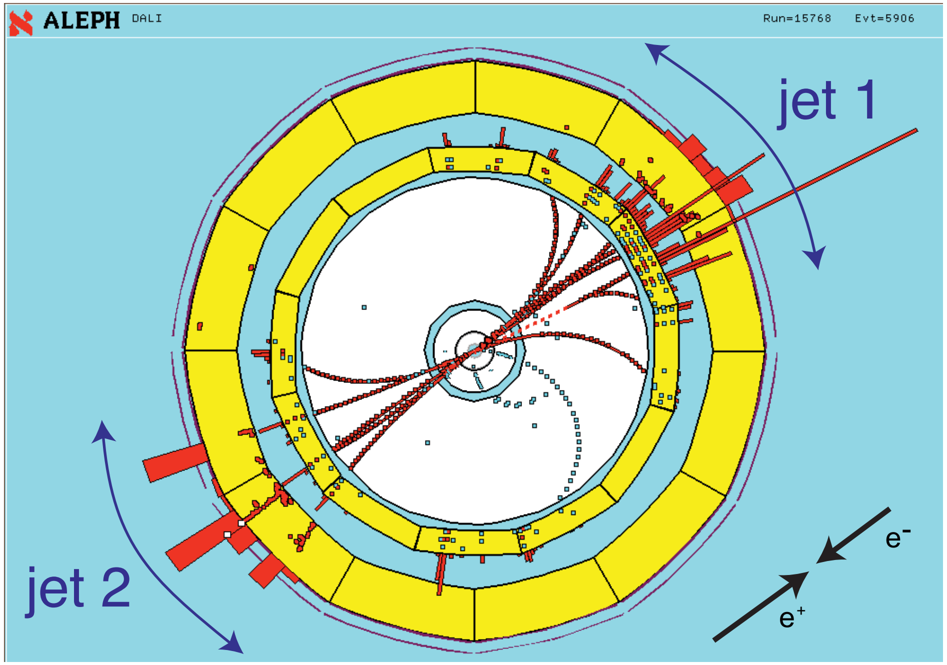
Physics Letters B, 15 December 1980

1979 Discovery of the Gluon

Mark-J, Tasso, Pluto, Jade experiment at PETRA (e^+e^- collider) at DESY ($\sqrt{s}$ = 13 - 32 GeV)

- $e^+ e^- \rightarrow q \; \bar{q} \rightarrow$ 2-jets





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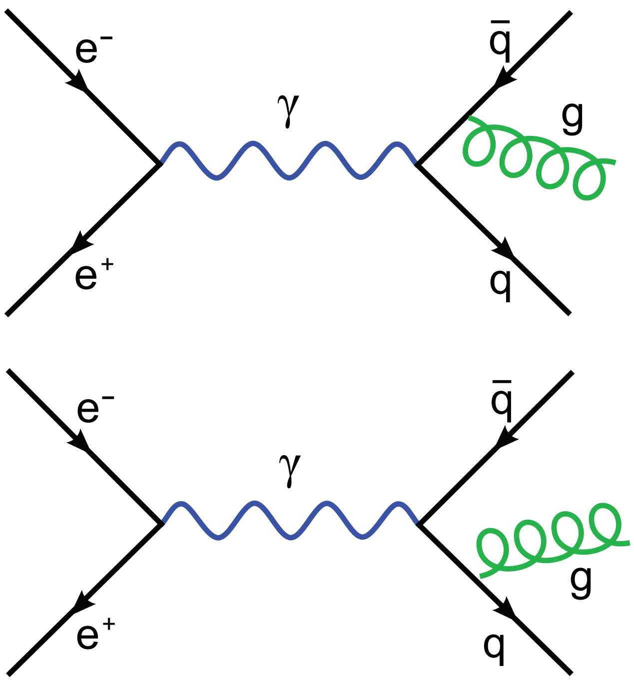

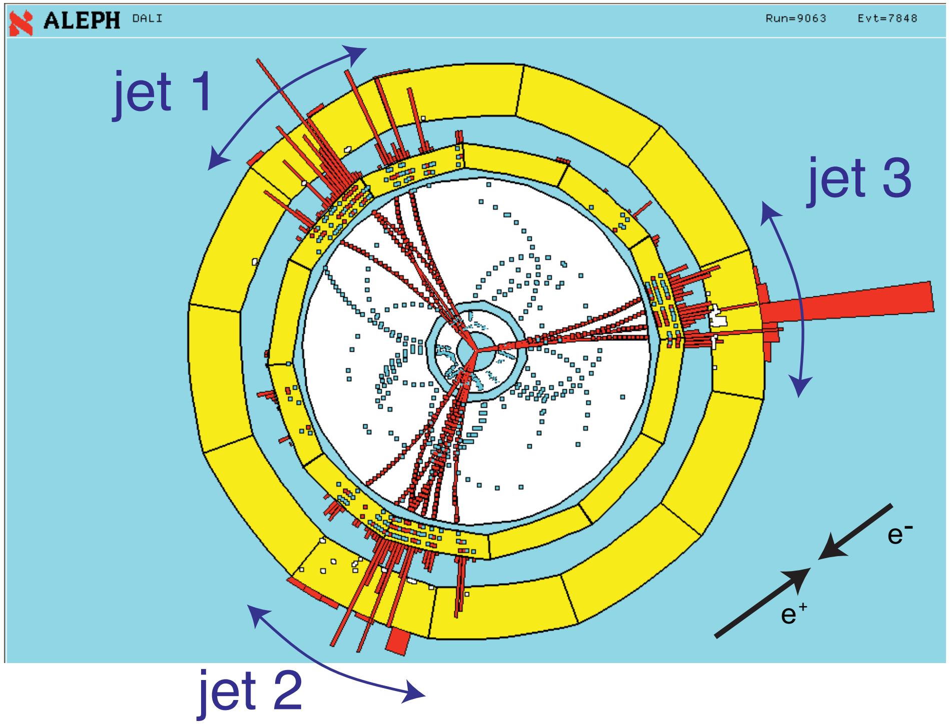

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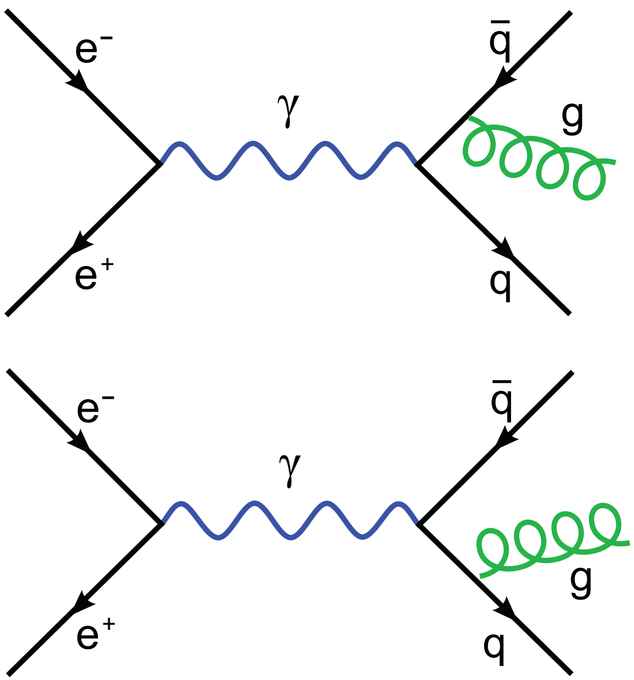
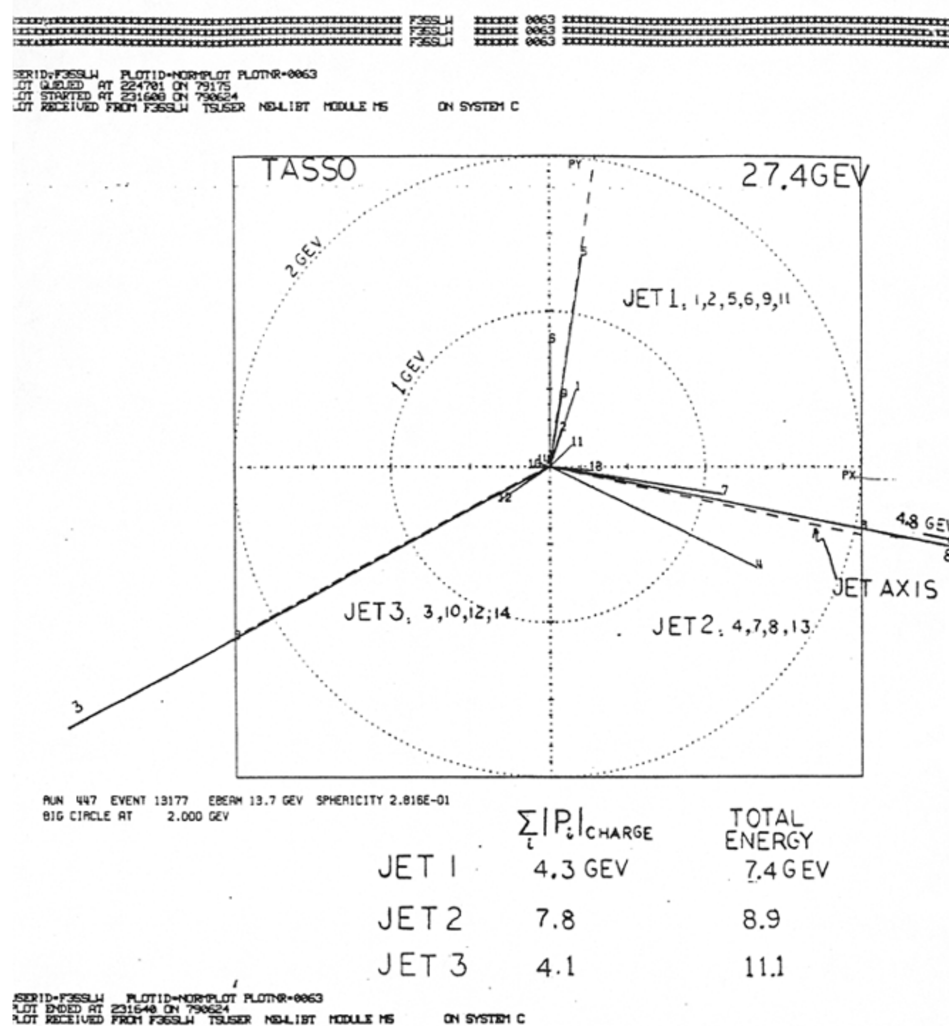
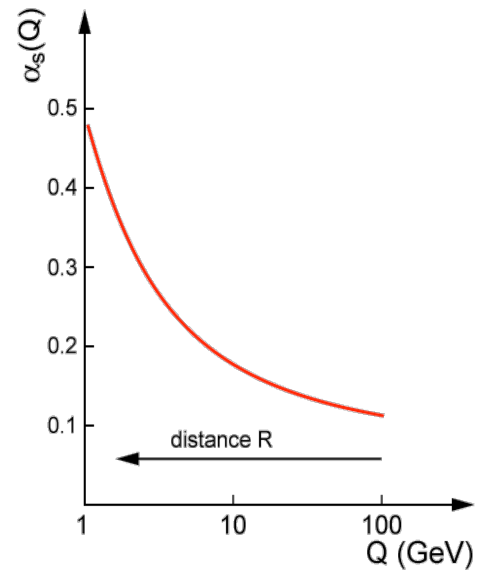




Understanding QCD ?

$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- "Emergent" Phenomena not evident from Lagrangian
- Asymptotic Freedom
  - $\alpha_s(Q^2) \sim 1 / \log(Q^2/\Lambda^2)$
  - in vacuum (Q ~ 1/R)
- Confinement
  - Free quarks not observed in nature
  - Quarks only in bound states



Understanding QCD ?

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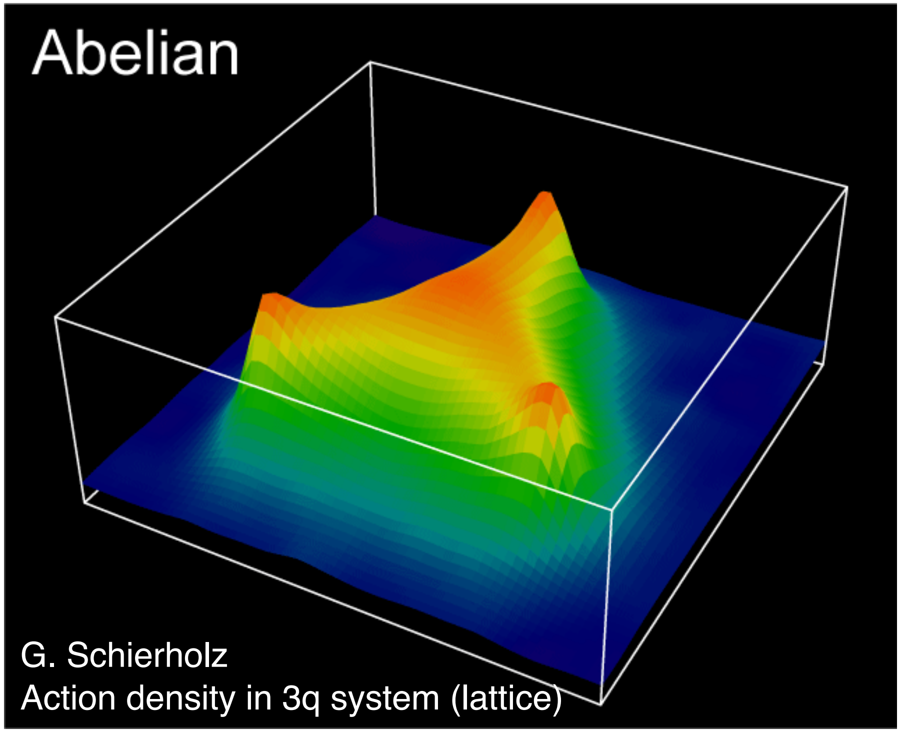

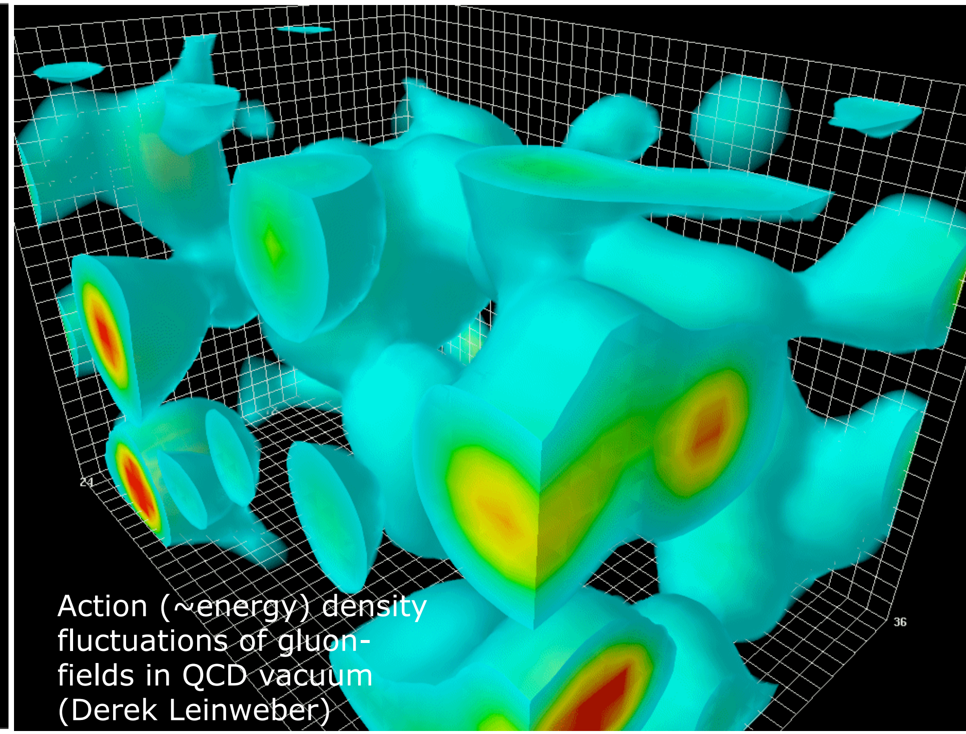

- Gluons & their self-interaction
  - Determine essential features of strong interactions
  - Dominate structure of QCD vacuum (fluctuations in gluon fields)
  - Responsible for > 98% of the visible mass in universe

Understanding QCD ?

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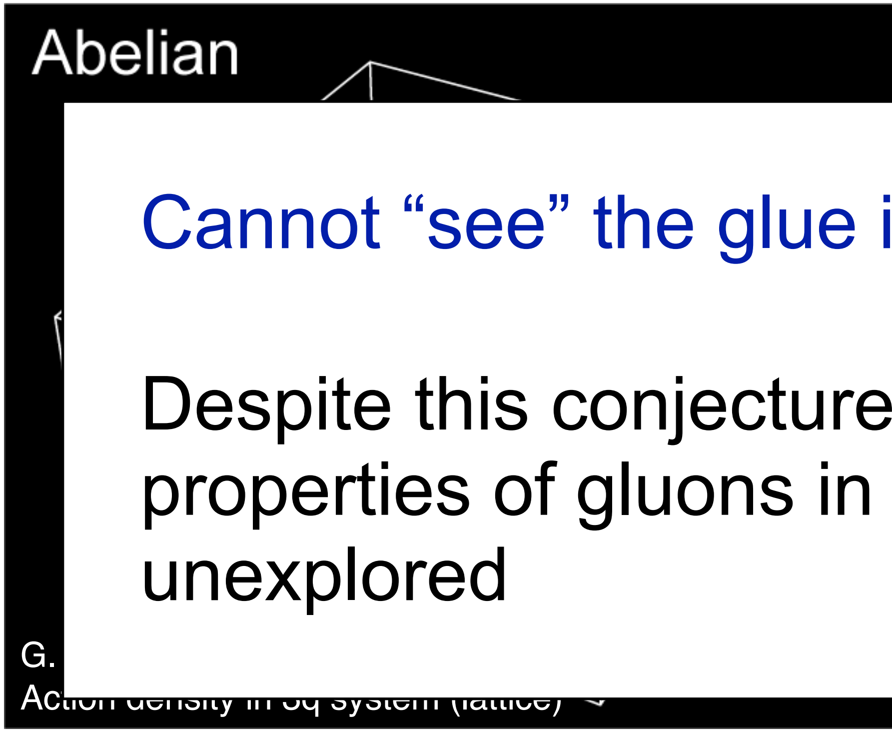
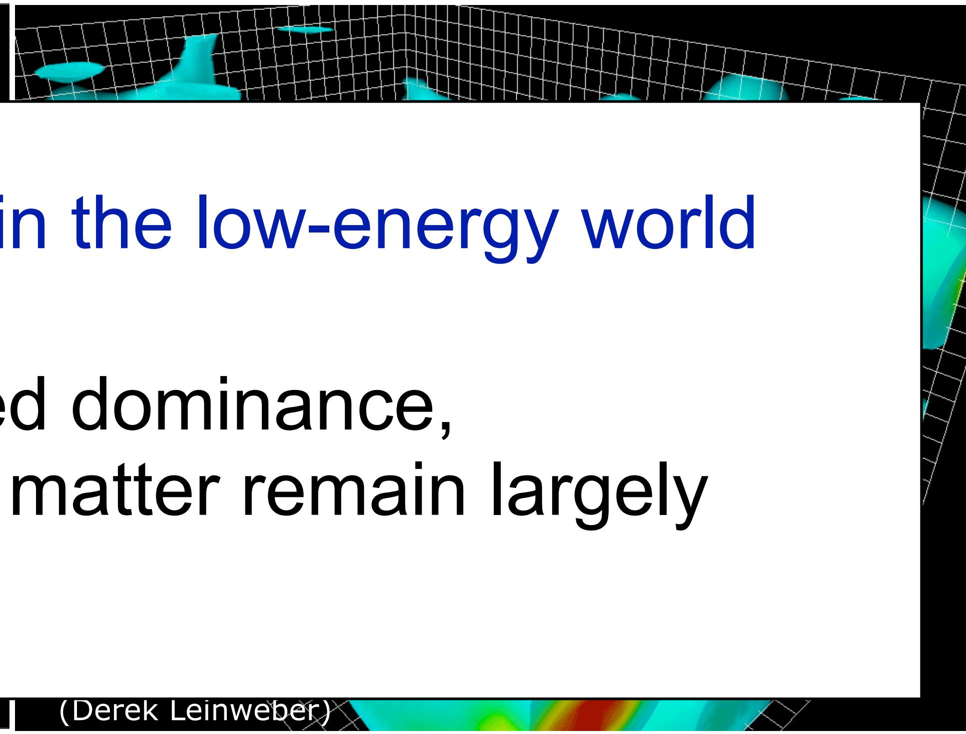


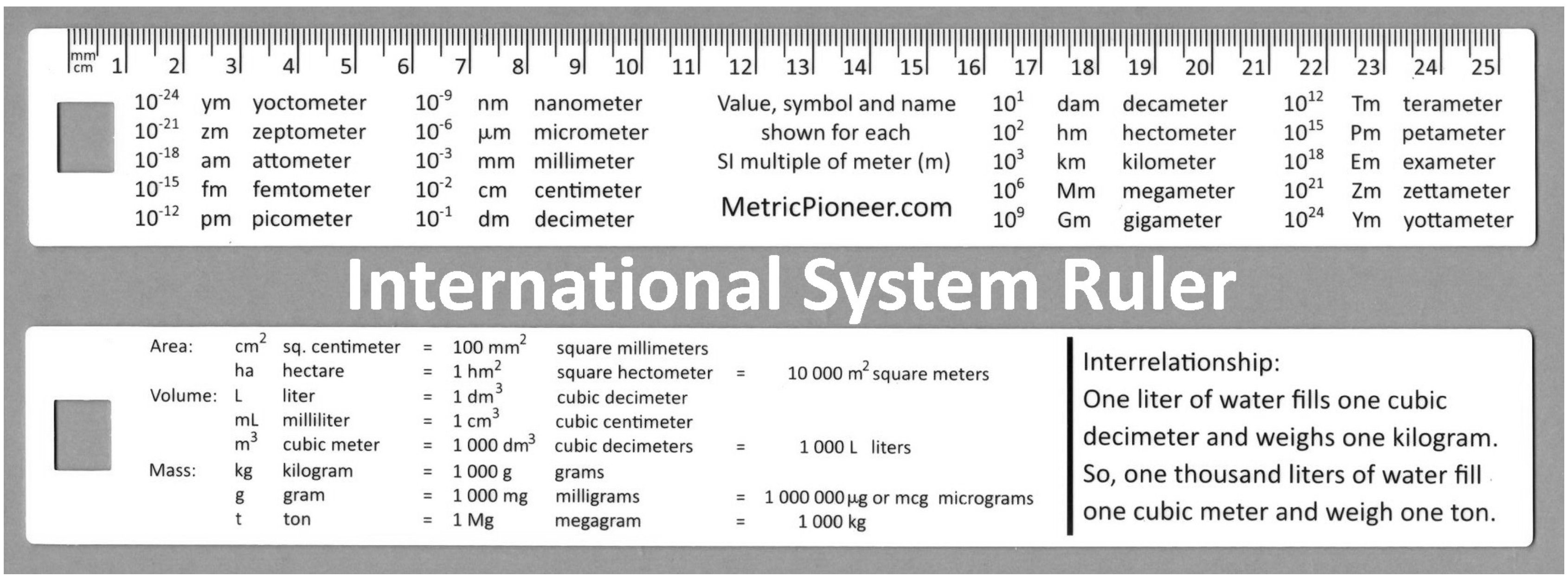


Cannot "see" the glue in the low-energy world

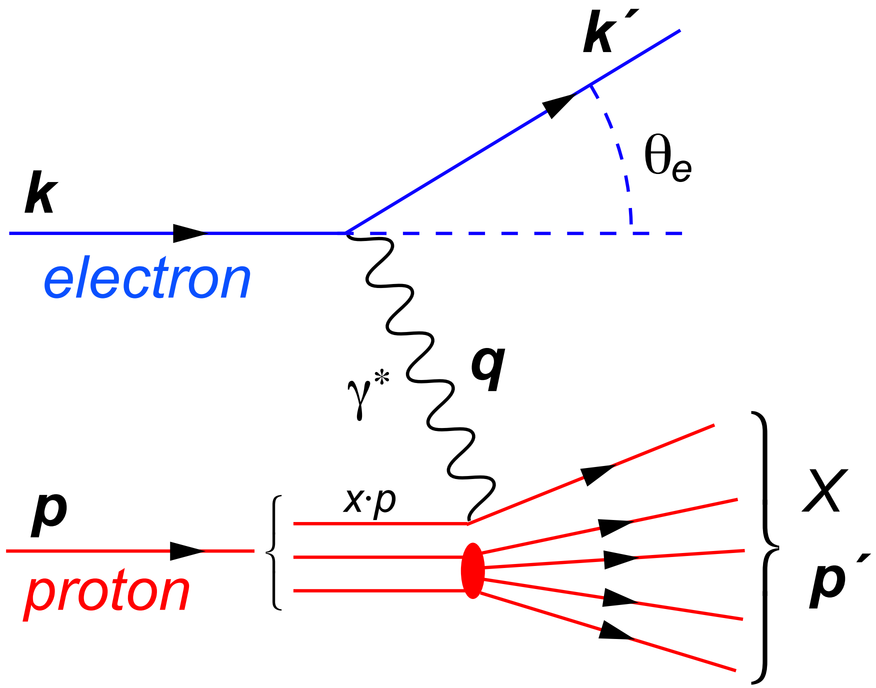
Despite this conjectured dominance, properties of gluons in matter remain largely unexplored

- Gluons & their self-interaction
  - Determine essential features of strong interactions
  - Dominate structure of QCD vacuum (fluctuations in gluon fields)
  - Responsible for > 98% of the visible mass in universe

3. Studying Matter at the Smallest Scale



Deep Inelastic Scattering (DIS)

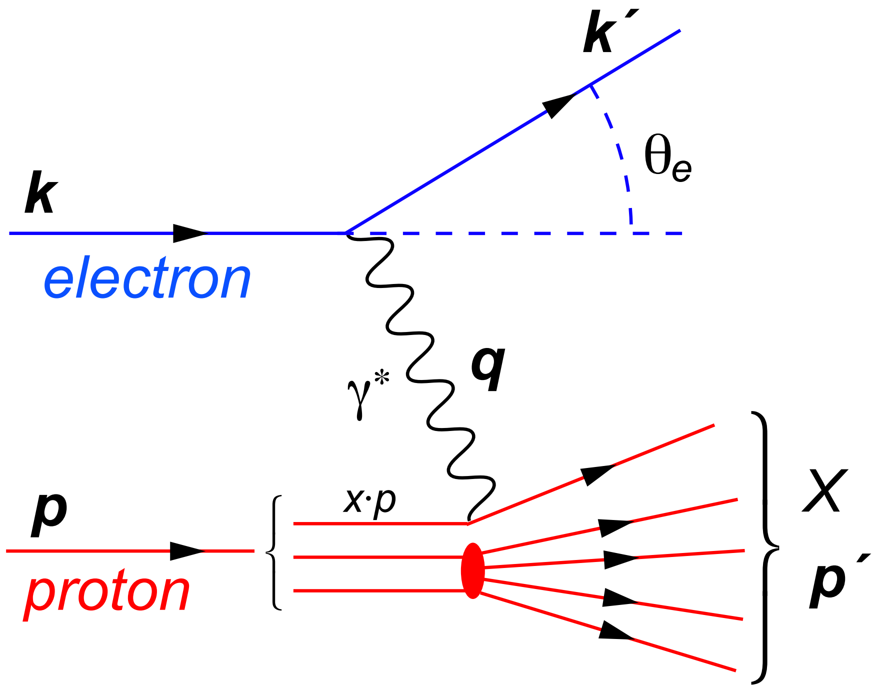


s:

$$s = (k + p)^2 \approx 4E_e E_p$$

- square of center-of-mass energy of electron-hadron system

Deep Inelastic Scattering (DIS)

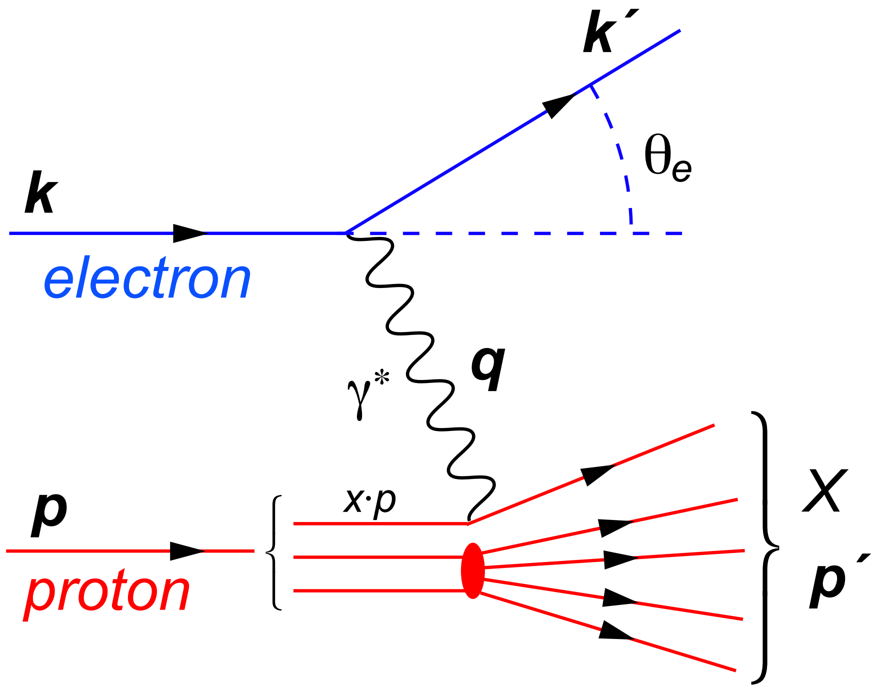


Q²:

$$Q^2 = -q^2 = -(k-k')^2$$
$$\approx 4EE'\sin^2\left(\frac{\theta}{2}\right)$$

- 4-momentum transfer from scattered electron
- invariant mass sq. of γ^*
- "Resolution" power
- Virtuality
  - real photon Q = 0

Deep Inelastic Scattering (DIS)

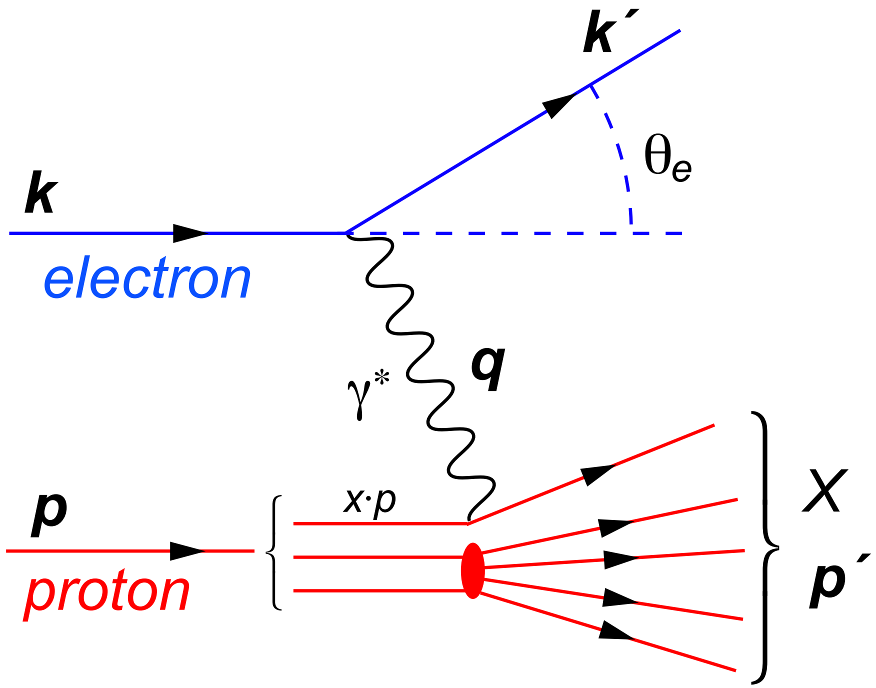


y:

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

- Inelasticity
- Fraction of electron's energy lost in nucleon restframe
- $0 < y < 1$

Deep Inelastic Scattering (DIS)

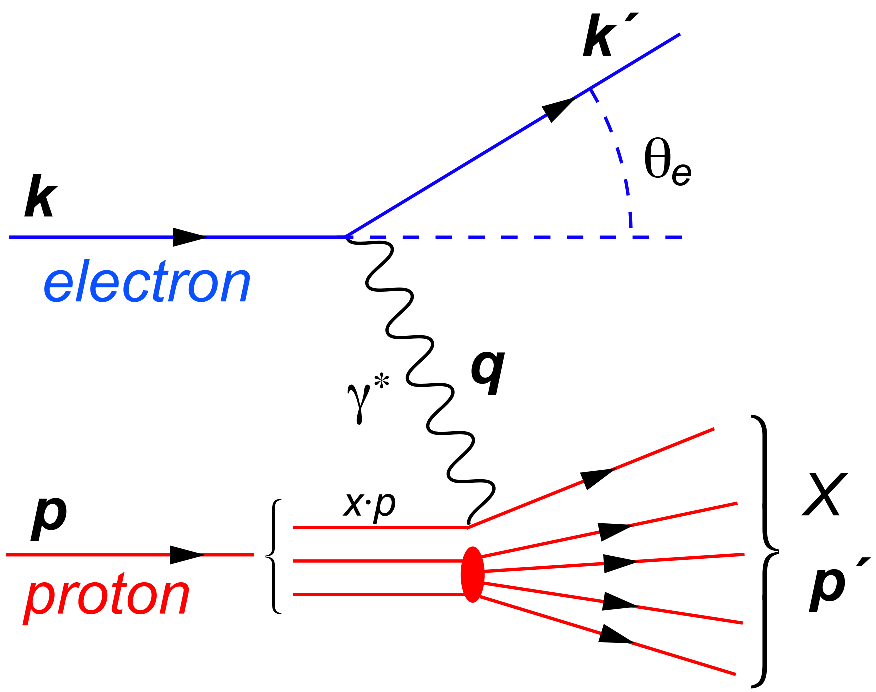


x:

$$x = \frac{Q^2}{2pq}$$

- Bjorken-x
- x is fraction of the nucleon's momentum carried by the struck quark

Deep Inelastic Scattering (DIS)



x: momentum fraction of parton

Q^2: resolution power

y: inelasticity

s: center-of-mass energy sq.

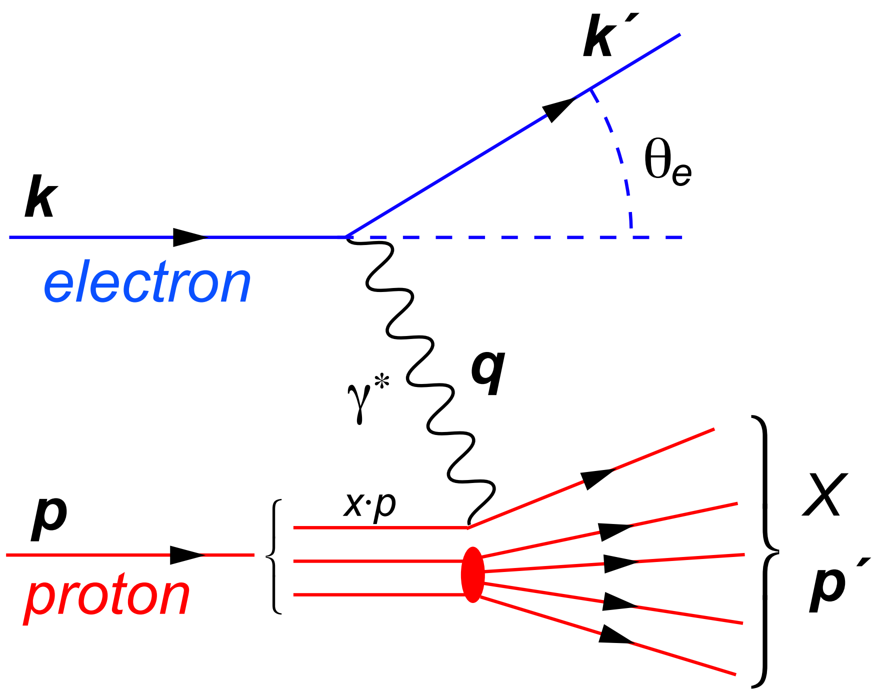
$$Q^2 \approx s \cdot x \cdot y$$

Deep ($Q^2 \gg m_p^2$)

Inelastic ($W^2 \gg m_p^2$)

Scattering = DIS

Deep Inelastic Scattering (DIS)



x: momentum fraction of parton

Q^2: resolution power

y: inelasticity

s: center-of-mass energy sq.

$$Q^2 \approx s \cdot x \cdot y$$

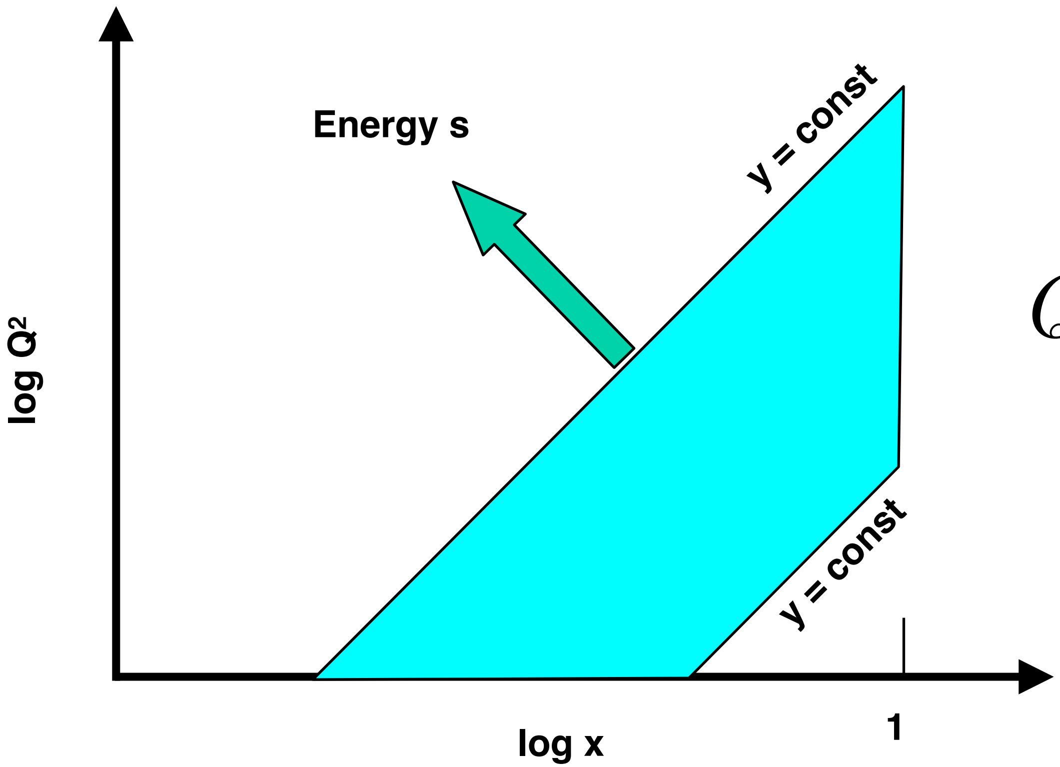
Deep ($Q^2 \gg m_p^2$)

Inelastic ($W^2 \gg m_p^2$)

Scattering = DIS

N.B.: This picture was developed in the “infinite momentum frame” (IMF). That works nicely when one assume massless quarks and gluons (partons). Despite all this it is also used for example for massive charm quarks. Some care has to be taken and x needs to be “adjusted”.

The x-Q^2 Plane



$$Q^2 \approx s \cdot x \cdot y$$

- Low-x reach requires large $\sqrt{s}$
- Large-Q^2 reach requires large $\sqrt{s}$
- *y* at colliders typically limited to 0.95 < y < 0.01

Structure Functions

Inclusive e+p collisions:
(only scattered electron is measured, rest ignored)

$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions (F_2)

gluon momentum distribution (F_L)

F_2 and F_L are key in understanding the structure of hadrons

N.B.: At very high energies a 3rd structure function comes into play: F_3
Ignored here and in the rest

More Practical: Reduced Cross-Section

Inclusive Cross-Section:

$$\frac{d^2\sigma^{eA\rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x,Q^2) - \frac{y^2}{2} F_L(x,Q^2)\right]$$

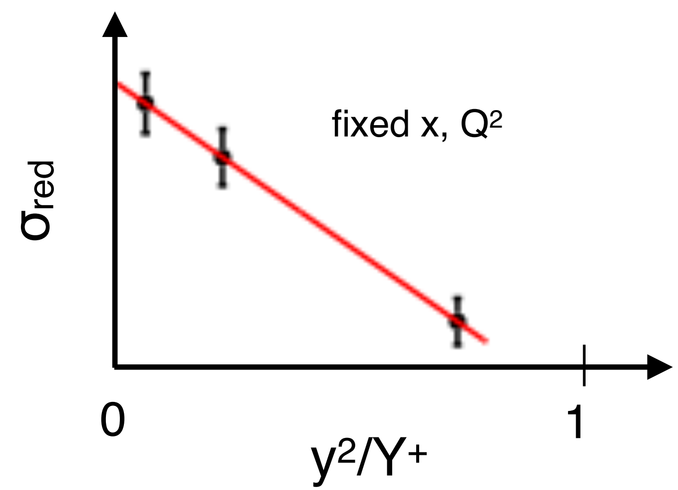
Reduced Cross-Section:

$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+} F_L^A(x,Q^2)$$

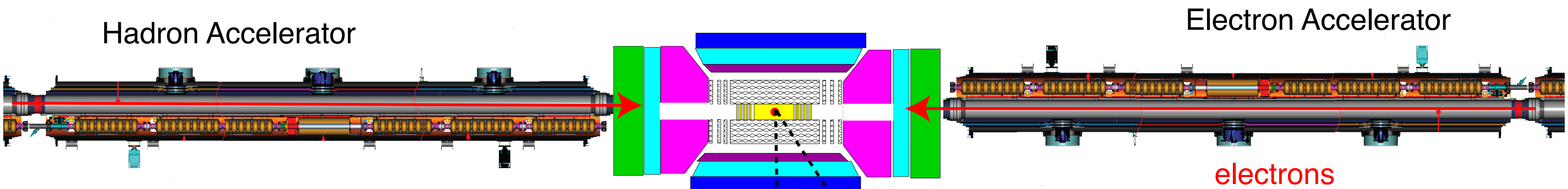
Rosenbluth Separation:

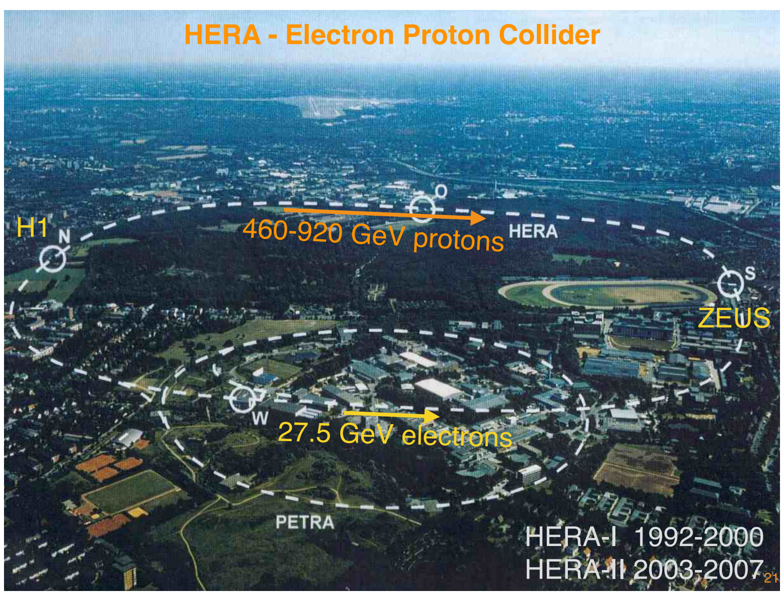
- Recall $Q^2 = x\, y\, s$
- Measure at different $\sqrt{s}$
- Plot σ_{red} versus $y2/Y^+$ for fixed x, Q^2
- F_2 is σ_{red} at $y2/Y^+ = 0$
- F_L = Slope of $y2/Y^+$

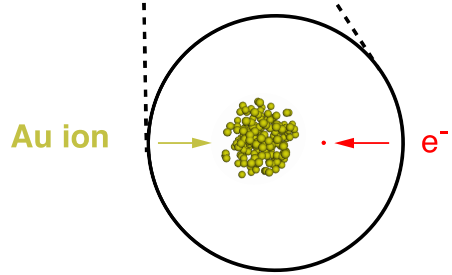


Studying Matter at the Smallest Scales

ep/eA Collider Experiments
Wave Length: 0.0001 fm (10 GeV + 100 GeV)
Resolution: ~ 0.01-0.001 fm

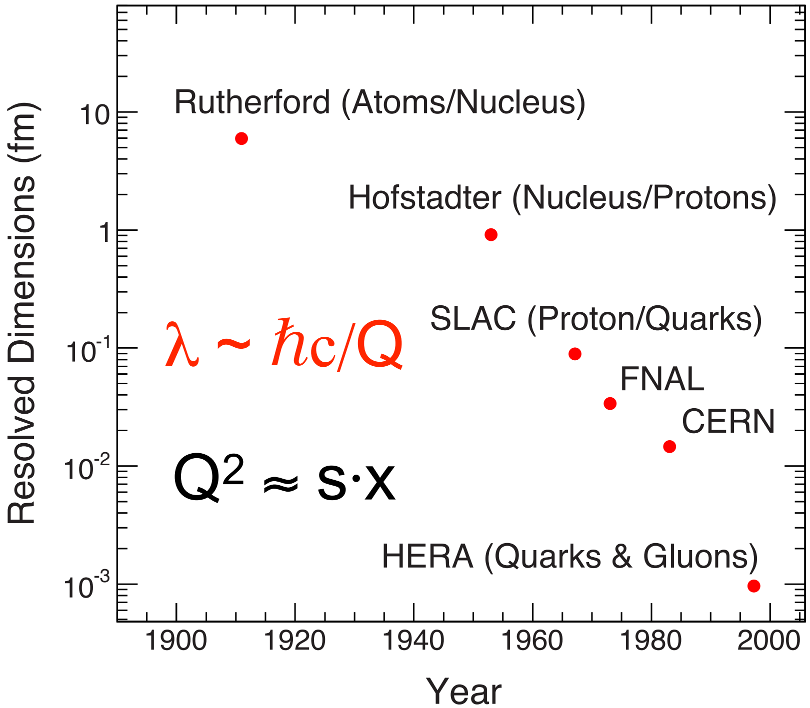


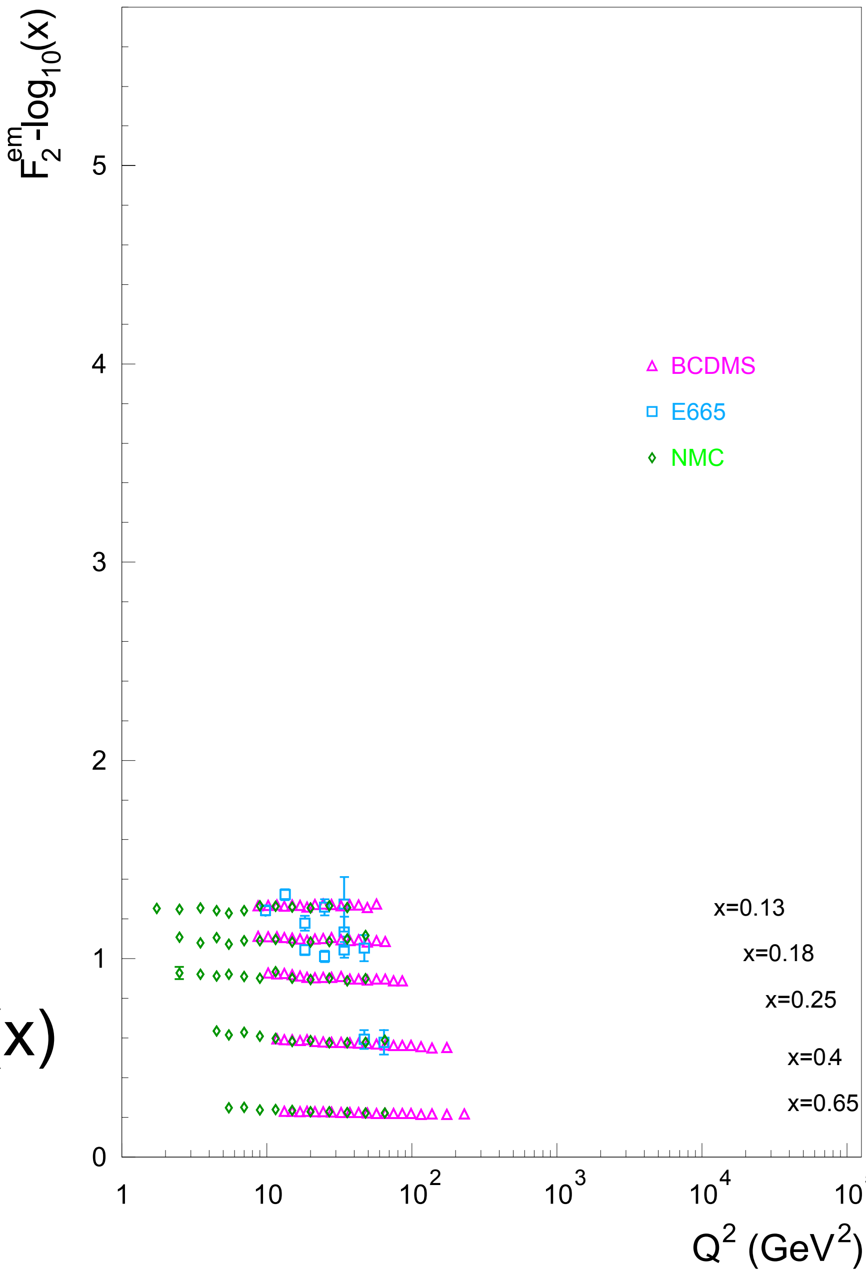




Past: HERA,
Future: EIC, LHeC, …

F_2: The Key Structure Function

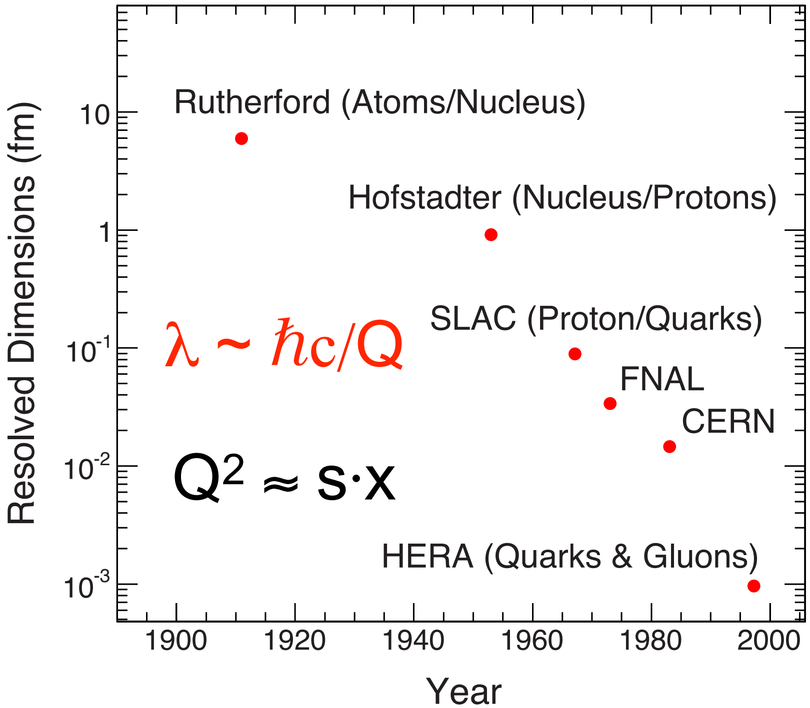




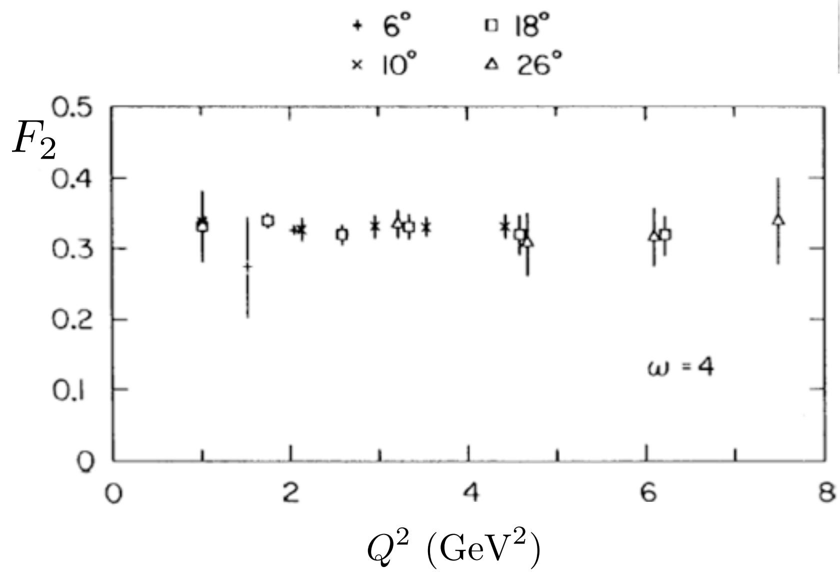
Bjorken Scaling: $F_2(x, Q^2) \rightarrow F_2(x)$

virtual photon interacts with a single essentially free quark

F_2: The Key Structure Function



Bjorken scaling:



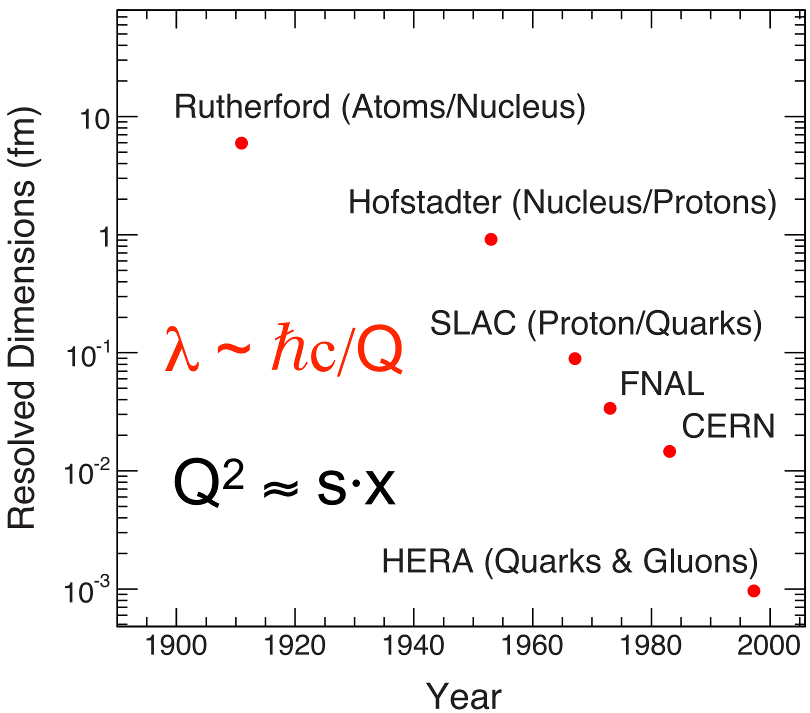
Point-like particles cannot be further resolved.

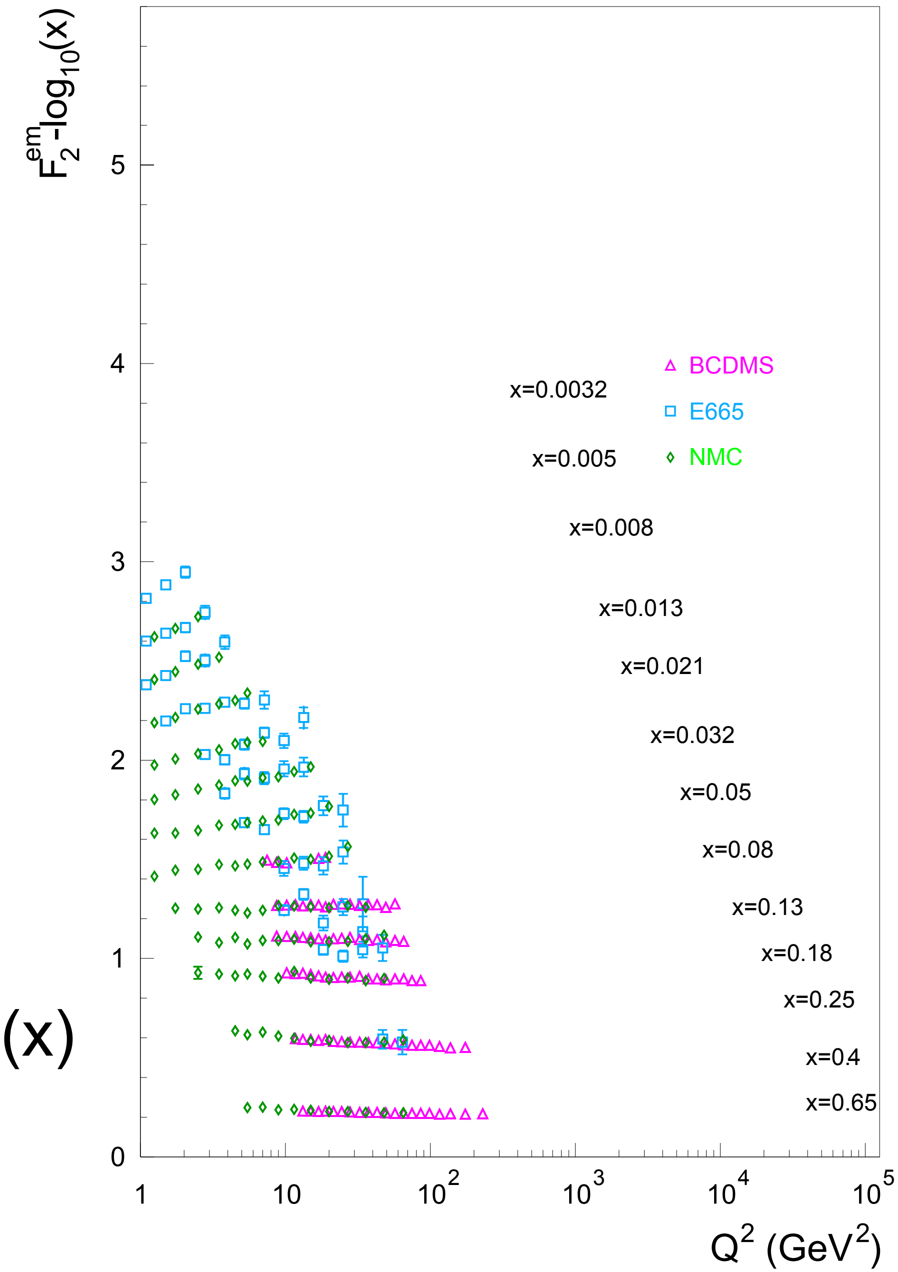
Their measurement does not depend on wavelength, hence Q^2 independence.

Bjorken Scaling: $F_2(x, Q^2) \rightarrow F_2(x)$

virtual photon interacts with a single essentially free quark

F_2: The Key Structure Function





Bjorken Scaling: $F_2(x, Q^2) \rightarrow F_2(x)$
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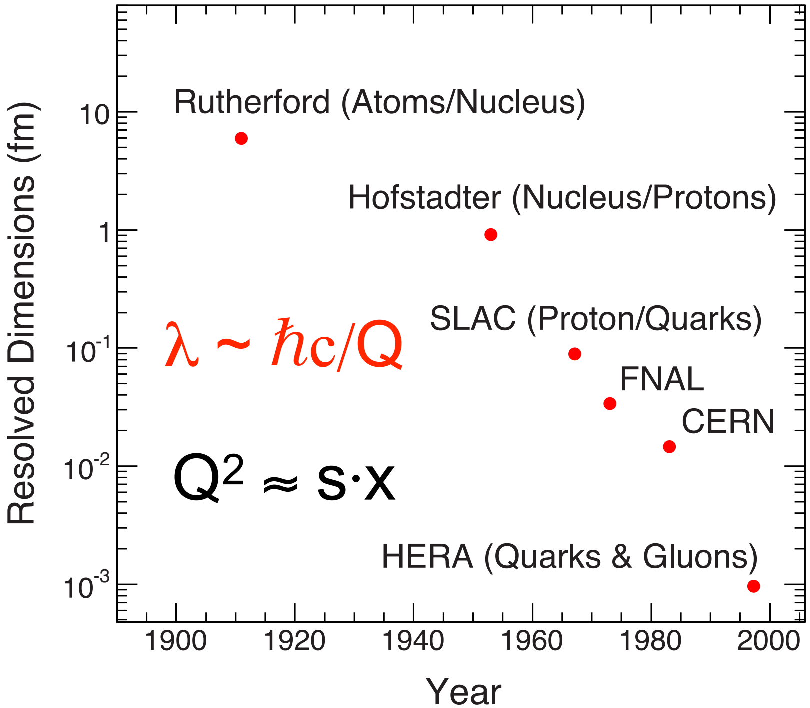
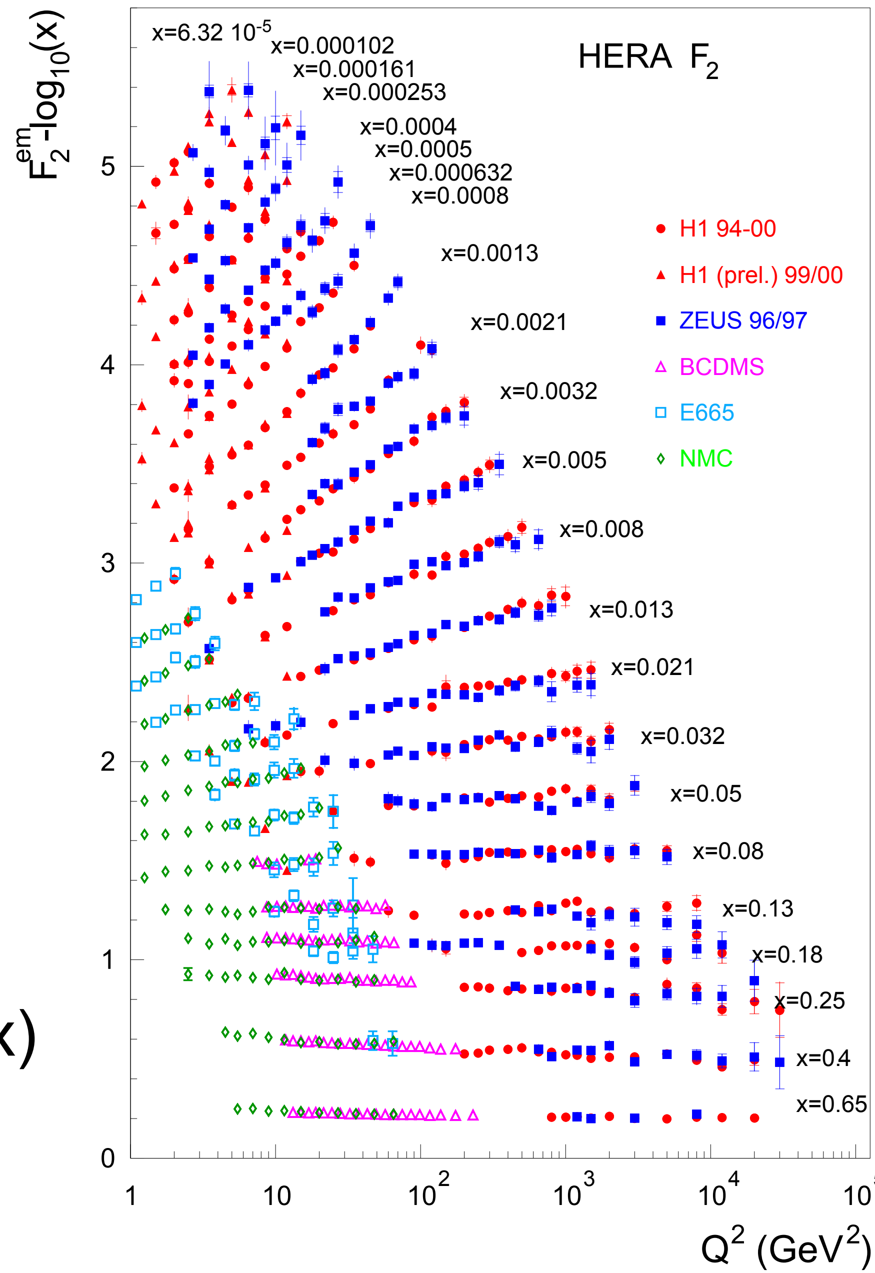
F_2: The Key Structure Function





Bjorken Scaling: $F_2(x, Q^2) \neq F_2(x)$

Broken - Big Time

It's the **Glue !!!**

Quark and Gluon Distributions

Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions (PDFs).

In LO: Probability to find parton with x, Q^2 in proton

PDF: Connecting experiment (e.g. pp) with theory

Jets, Drell-Yan, etc.: $$\sigma_o = f_{i\to a} \otimes \hat{\sigma}_{a\to o}$$

Observable

Parton Distribution Function (PDF)

Theoretical Calculations

Hadron Production: $$\sigma_o = f_{i\to a} \otimes \hat{\sigma}_{a\to b} \otimes D_{b\to o}$$

Fragmentation Functions

Quark and Gluon Distributions

Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions (PDFs).

In LO: Probability to find parton with x, Q^2 in proton

What is Needed:

- Good data
  - Best: F_2 (ep), jets, Drell-Yan (pp)
  - Bad: Hadrons
- pQCD Calculation of the processes
  - LO, NLO, NNLO
- QCD Evolution Equations
  - DGLAP: Evolution in Q^2 (small to large) at fixed x (integro-differential equations)
  - BFKL: Evolution in x at fixed Q^2

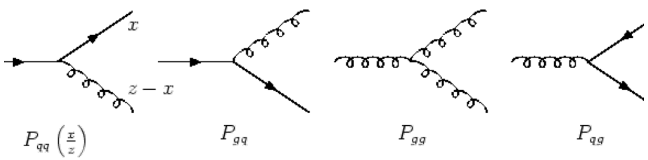
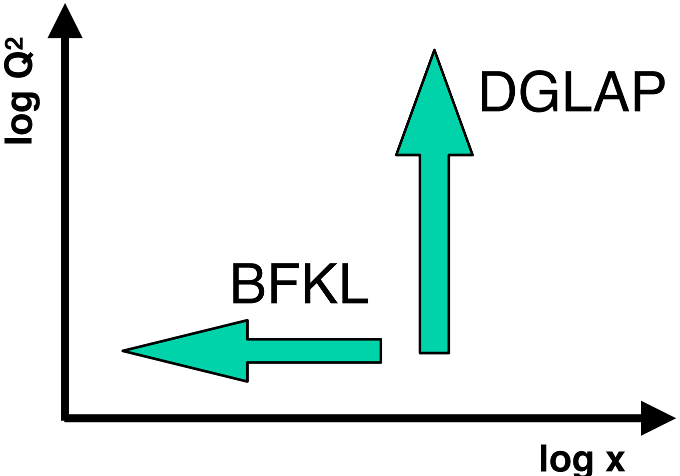
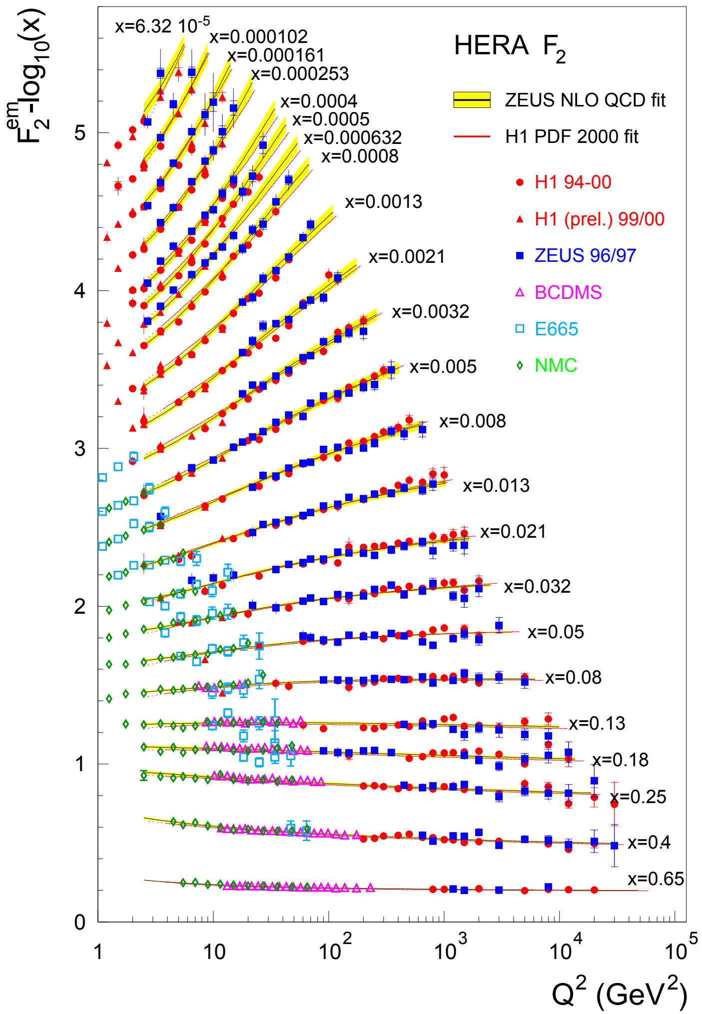


Figure 1.1: *The processes related to the lowest order QCD splitting functions. Each splitting function $P_{p'p}(x/z)$ gives the probability that a parton of type p converts into a parton of type p', carrying fraction x/z of the momentum of parton p*



Quark and Gluon Distributions

- Quarks: $q_i(x,Q^2)$ from F_2 (or reduced cross-section)
- Gluons: $g(x,Q^2)$ through scaling violation: $dF^2/dlnQ^2$



$\Longrightarrow$

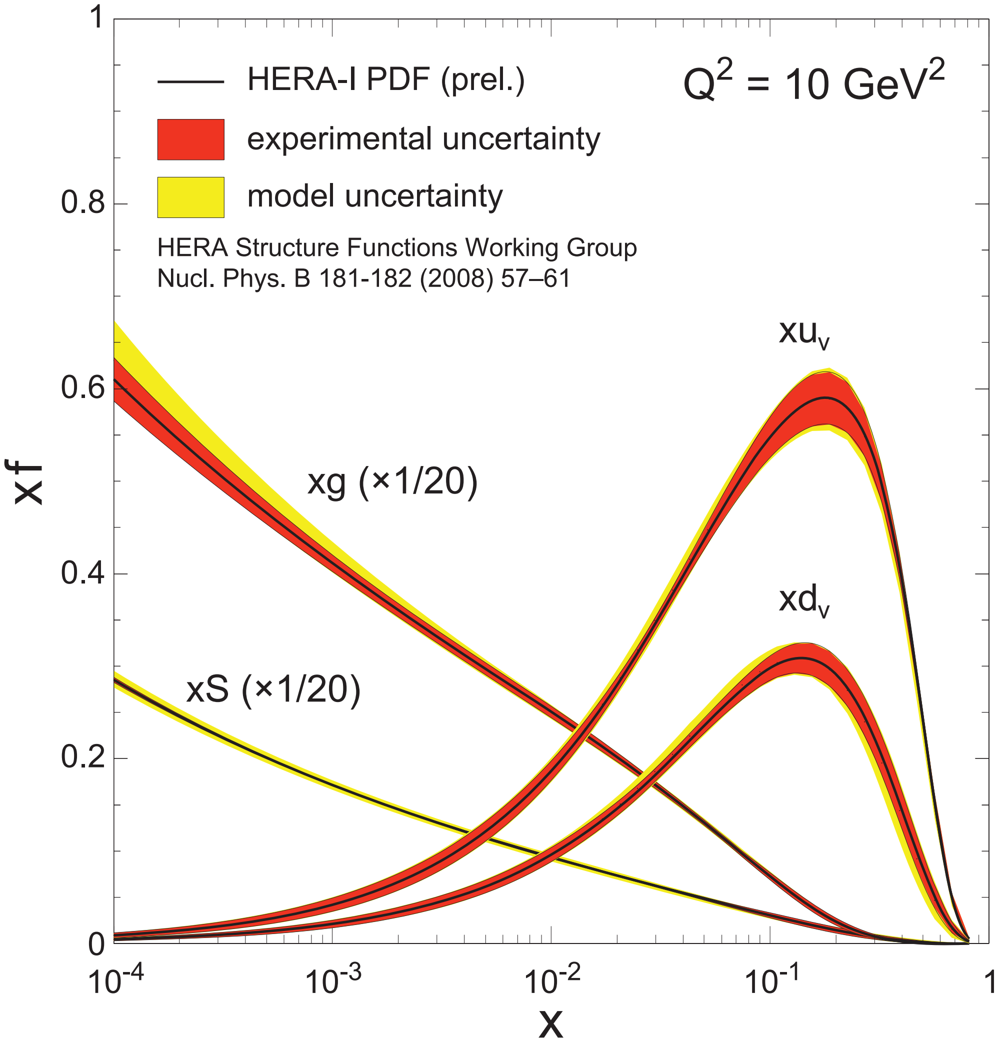
- F_2
- $dF_2/dlnQ^2$

\+ pQCD+ DGLAP Evolution

$f(x, Q_1^2) \rightarrow f(x, Q_2^2)$

Quark and Gluon Distributions

- Quarks: $q_i(x,Q^2)$ from F_2 (or reduced cross-section)
- Gluons: $g(x,Q^2)$ through scaling violation: $dF^2/dlnQ^2$



Quark and Gluon Distributions

- Quarks: $q_i(x,Q^2)$ from F_2 (or reduced cross-section)
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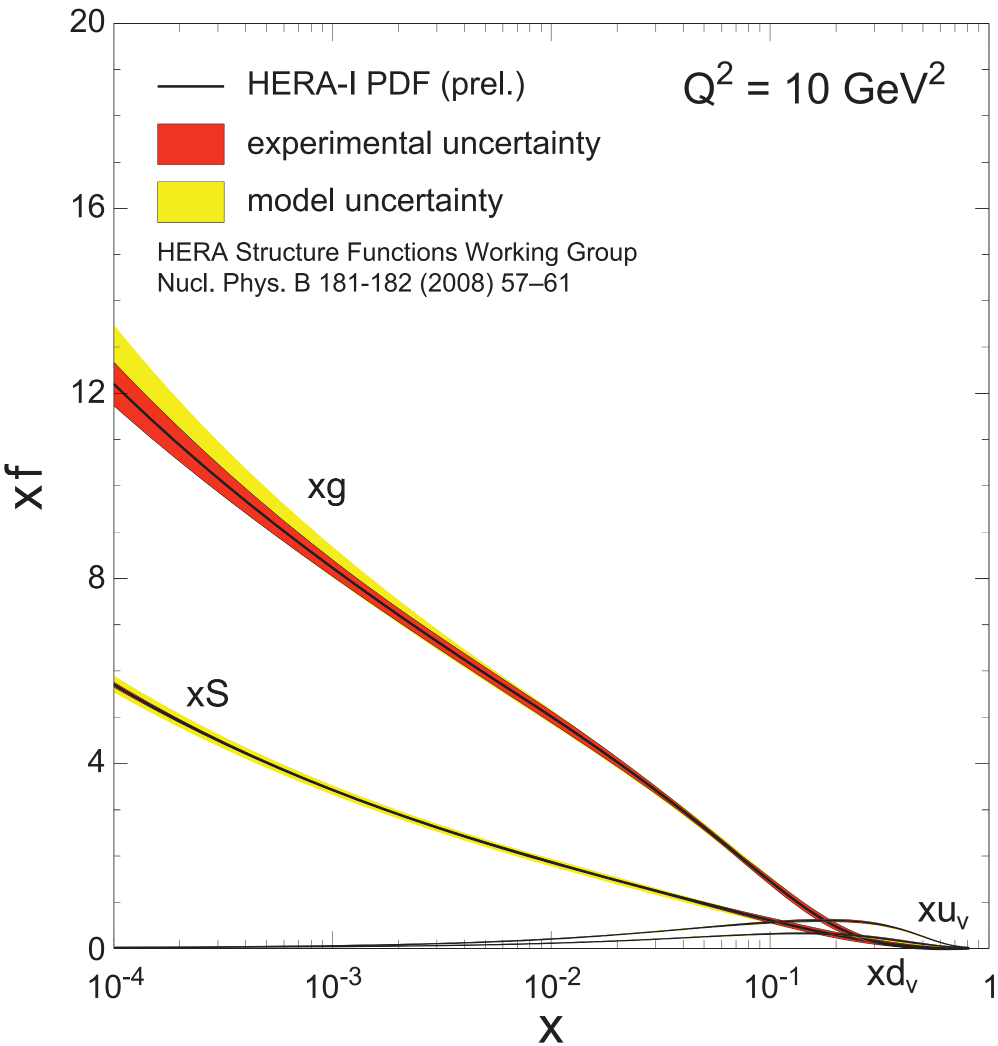


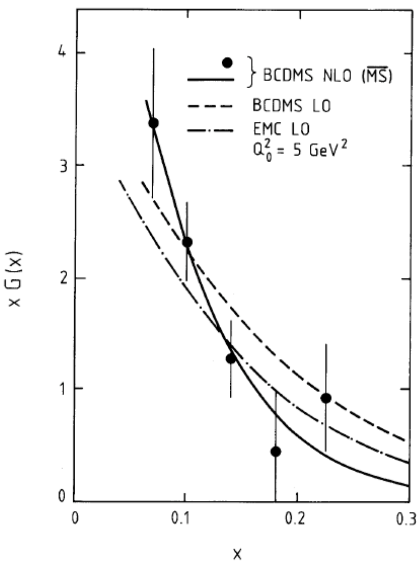
Proton is almost entirely glue for x<0.1

Here goes the naive picture that protons are made of 3 quarks (recall static quark model)

Hera’s Impact

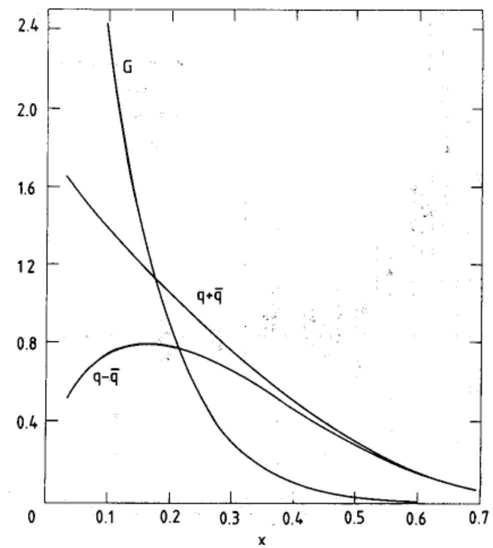
PDFs before HERA - Gluon - $xg(x,Q^2)$

BCDMS

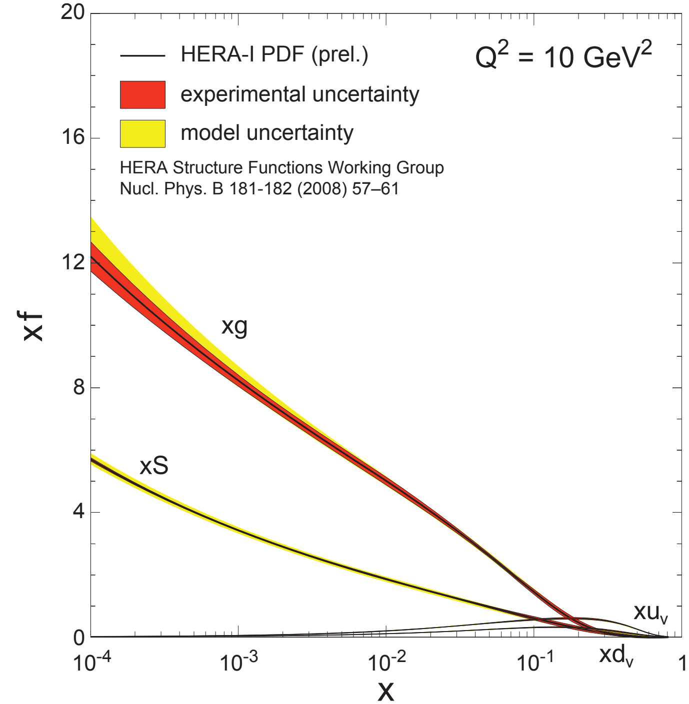


CERN-EP/89-07
January 17th, 1989

CDHS

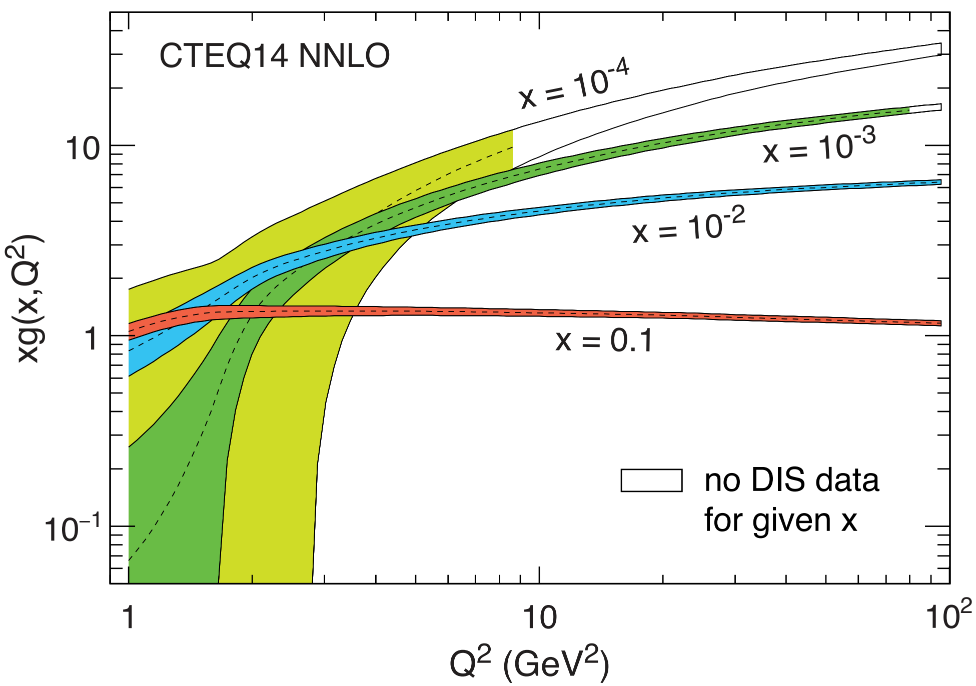


CERN-EP/89-103
15 August 1989



PDFs: Much Progress, Still Shortcomings

CTEQ14: a modern proton PDF

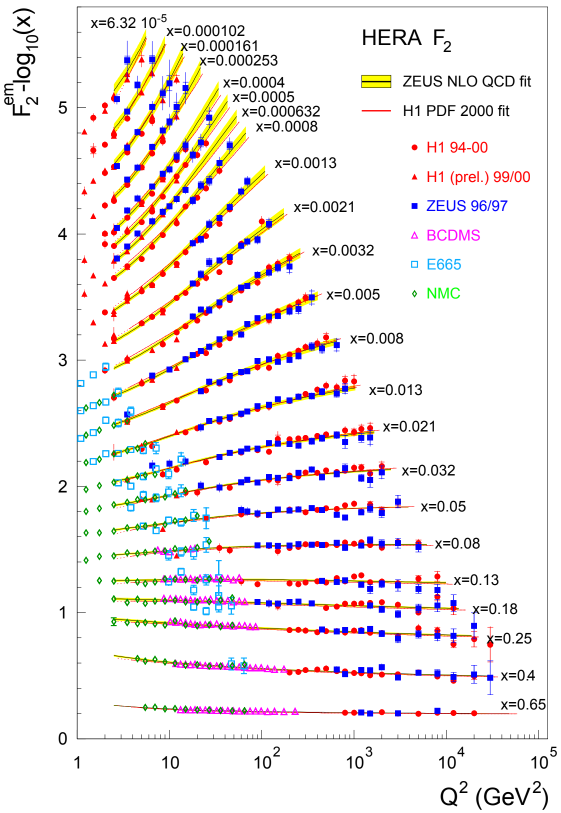


- Large uncertainties at $x=10^{-3}$ and 10^{-4} at the small Q^2 although high quality data exist.
- The precision of low Q^2 data is ineffectual due to the lack of data at the larger Q^2 (Evolution from low to high Q^2)

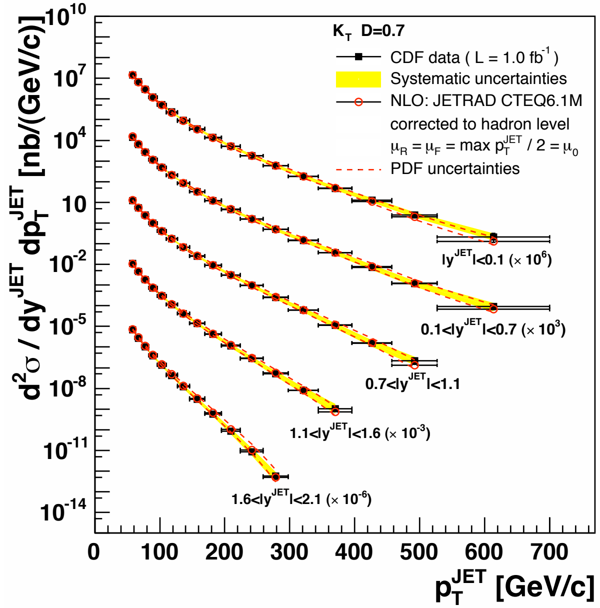
Uncertainties from PDF dominate many “BSM” searches

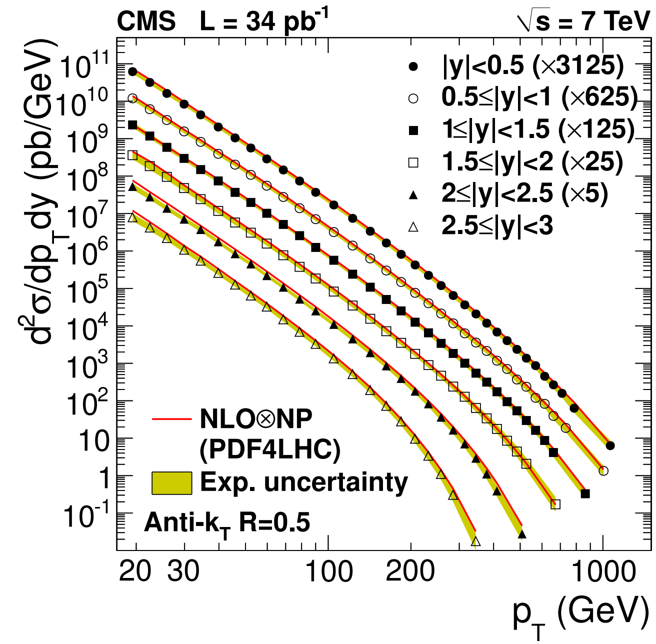
Strong Evidence that QCD is the Correct Theory

Structure functions measured at HERA ep collider

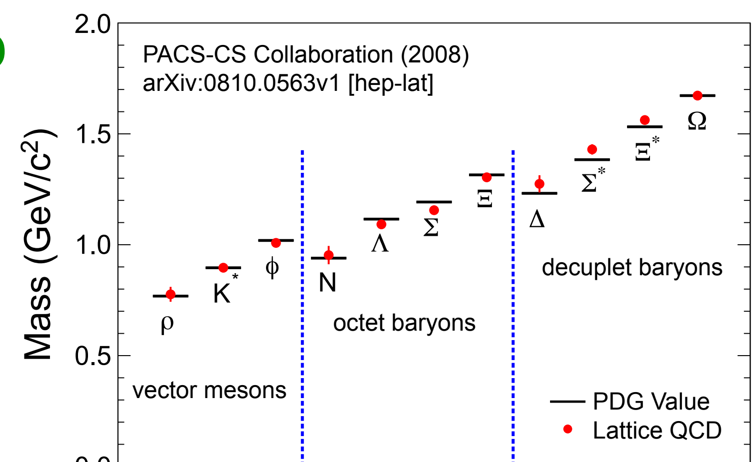


Jet cross-sections: pp collisions at LHC and $\bar{p}p$ collisions at Fermilab





Lattice QCD



Are we done?

to be continued …