Parallel Session 1: Nuclear Physics

Studying Hadrons with Electron Beams

6th edition of the biennial African School of Fundamental Physics and Applications

Mark Dalton, Jefferson Lab

Outline

Introduction: what are we trying to learn?
Introduction to electron scattering
Form factors
Deep inelastic scattering
New insights about the nucleus
Exotic spectroscopy

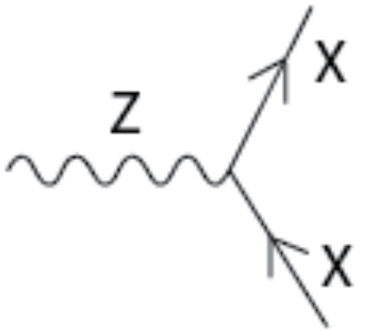
Quantum Chromodynamics

gauge field theory that describes the strong interactions of colored quarks and gluons, is the SU(3) component of the SU(3)×SU(2)×U(1) Standard Model of Particle Physics.

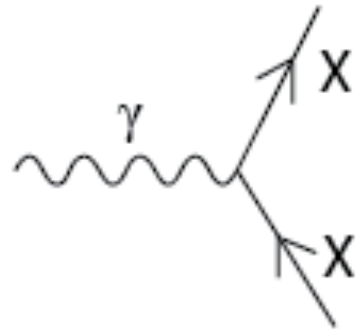
a gluon's interaction with a quark rotates the quark's color in SU(3) space.

The Feynman rules of QCD involve a quark-antiquark-gluon ($q\bar{q}g$) vertex, a 3-gluon vertex (both proportional to g_s), and a 4-gluon vertex (proportional to g_s^2).

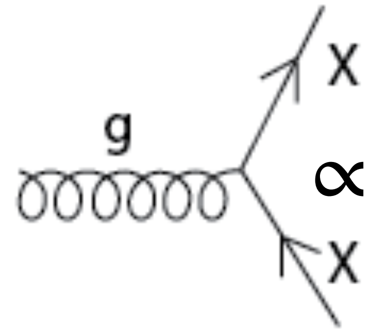
Standard Model Interactions
(Forces Mediated by Gauge Bosons)



X is any fermion in the Standard Model.

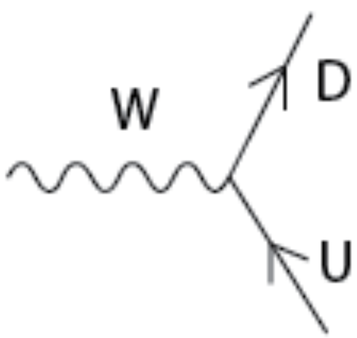


X is electrically charged.

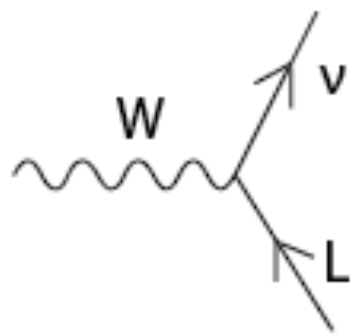


$\propto g_s$

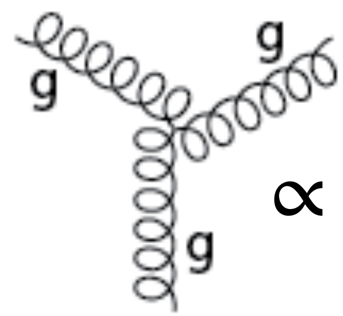
X is any quark.



U is a up-type quark; D is a down-type quark.

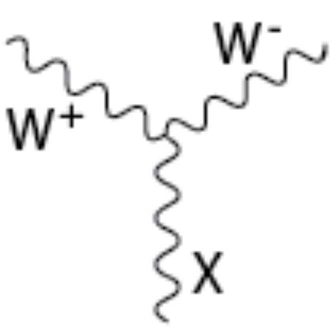


L is a lepton and ν is the corresponding neutrino.

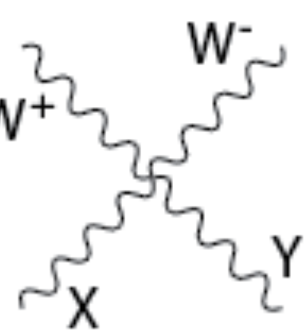


$\propto g_s$

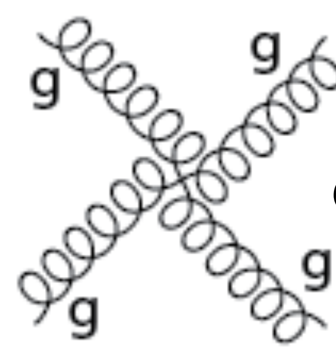
$$\alpha_s = \frac{g_s^2}{4\pi}$$



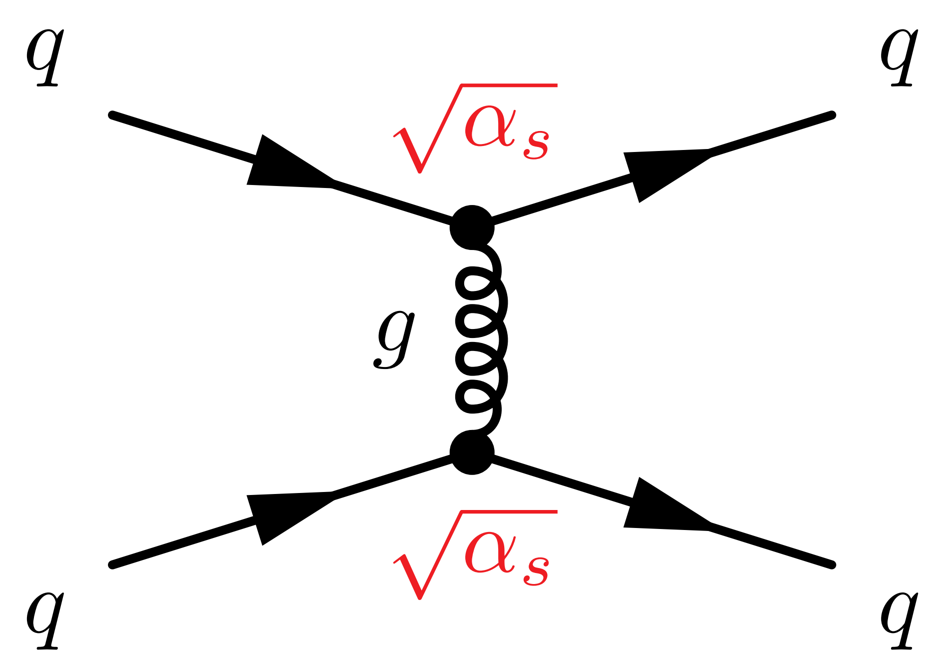
X is a photon or Z-boson.

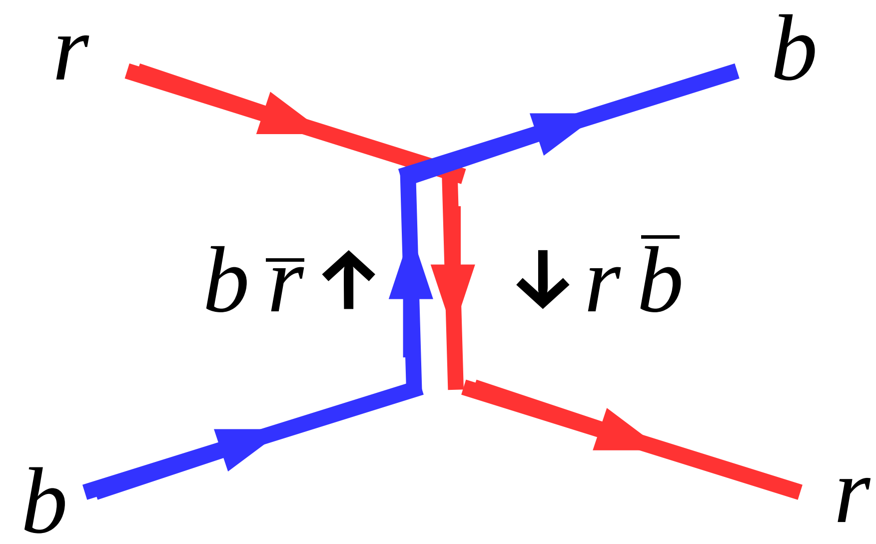


X and Y are any two electroweak bosons such that charge is conserved.

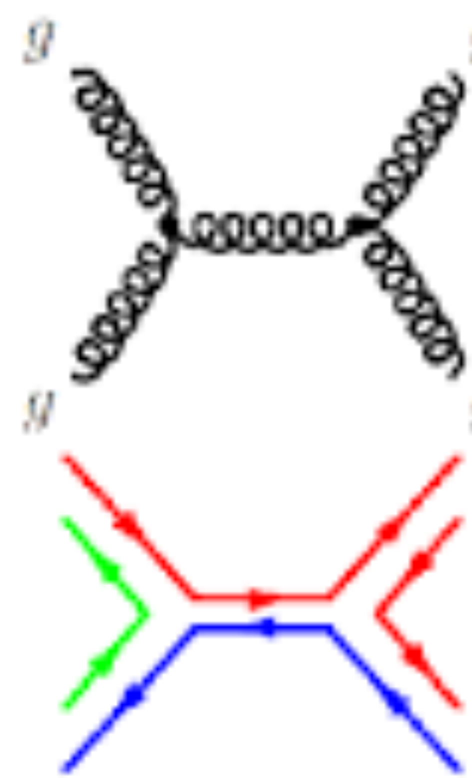


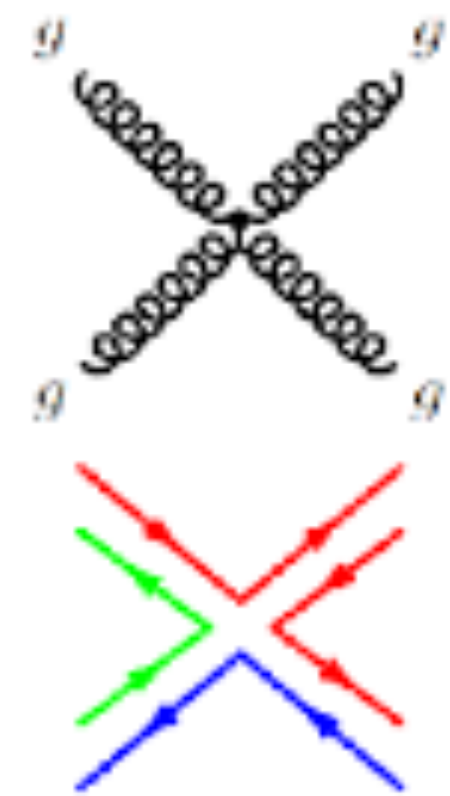
$\propto g_s^2$



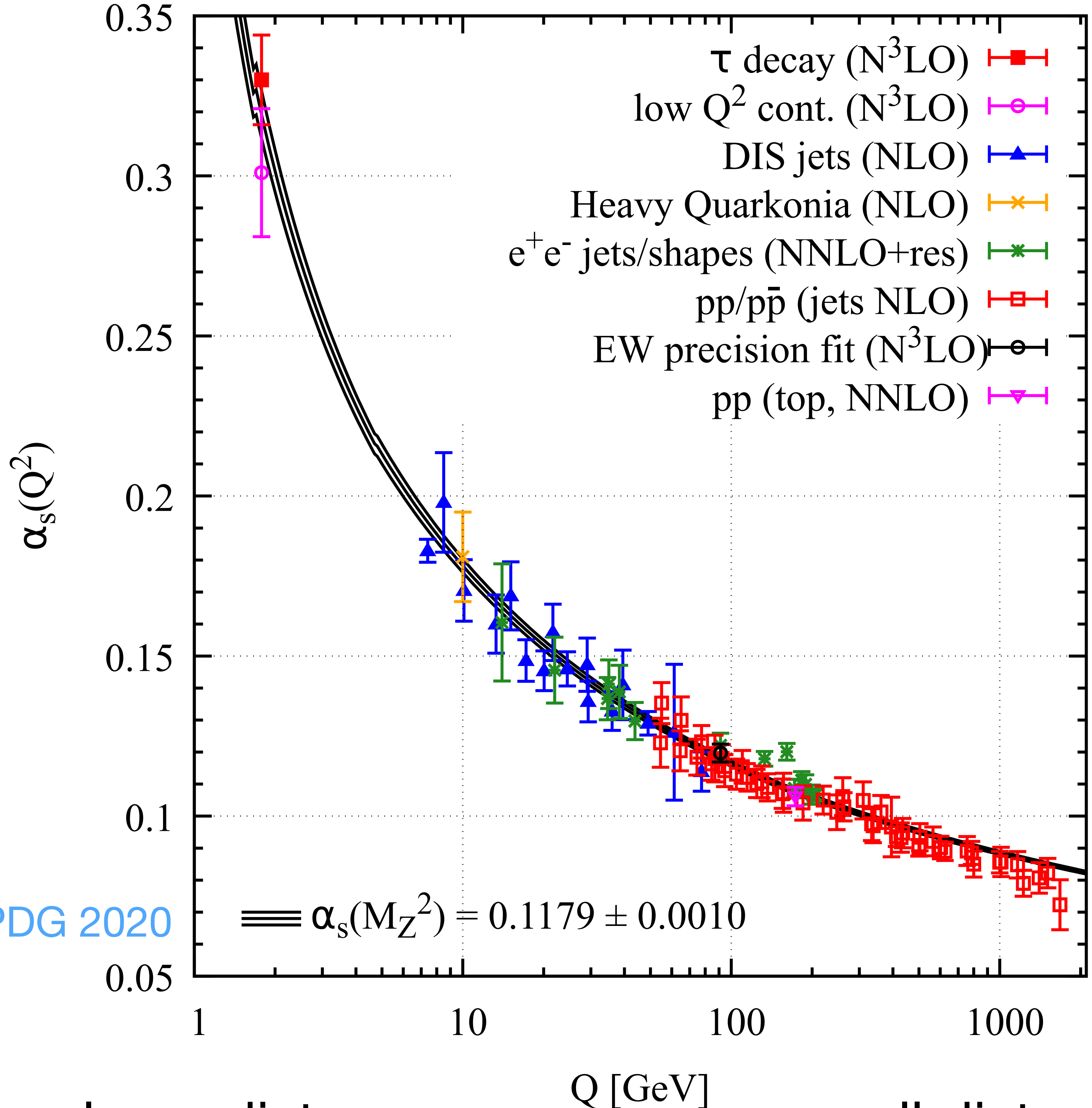


coupling is to 3 color charges
gluons carry color—anti-color
charges and self interact
color charge is conserved
QCD conserves flavor
QCD conserves parity





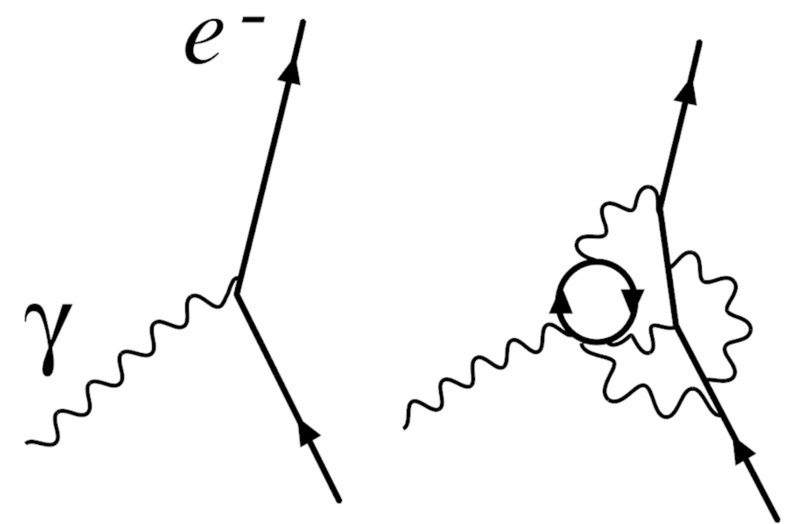
Running Coupling



PDG 2020

large distance

small distance



QED: screening of charge by fermion pairs.

QCD: screening by quarks—anitquark pairs
anti-screening by gluons (dominates)

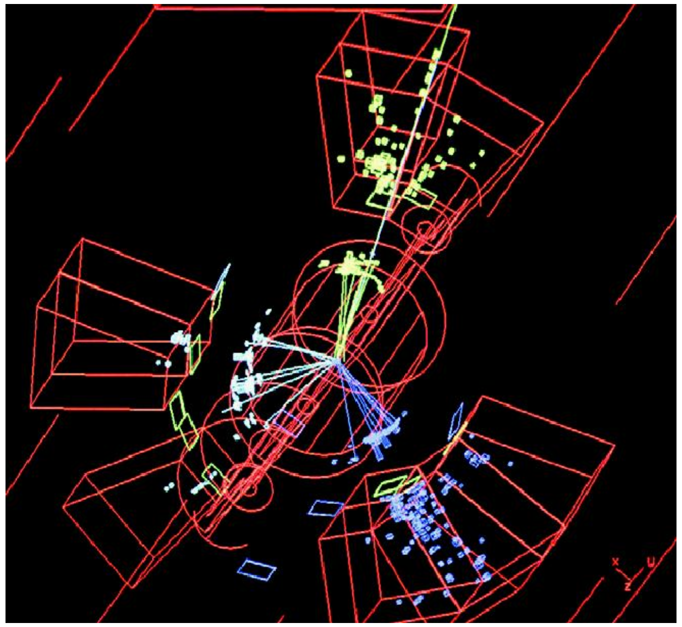
QCD

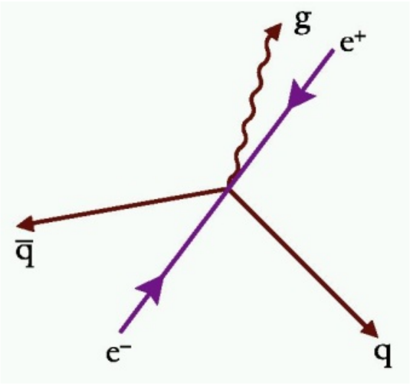
Asymptotic Freedom — Small Distance, High Energy

Confinement — Large Distance, Low Energy

Perturbative QCD

High Energy Scattering

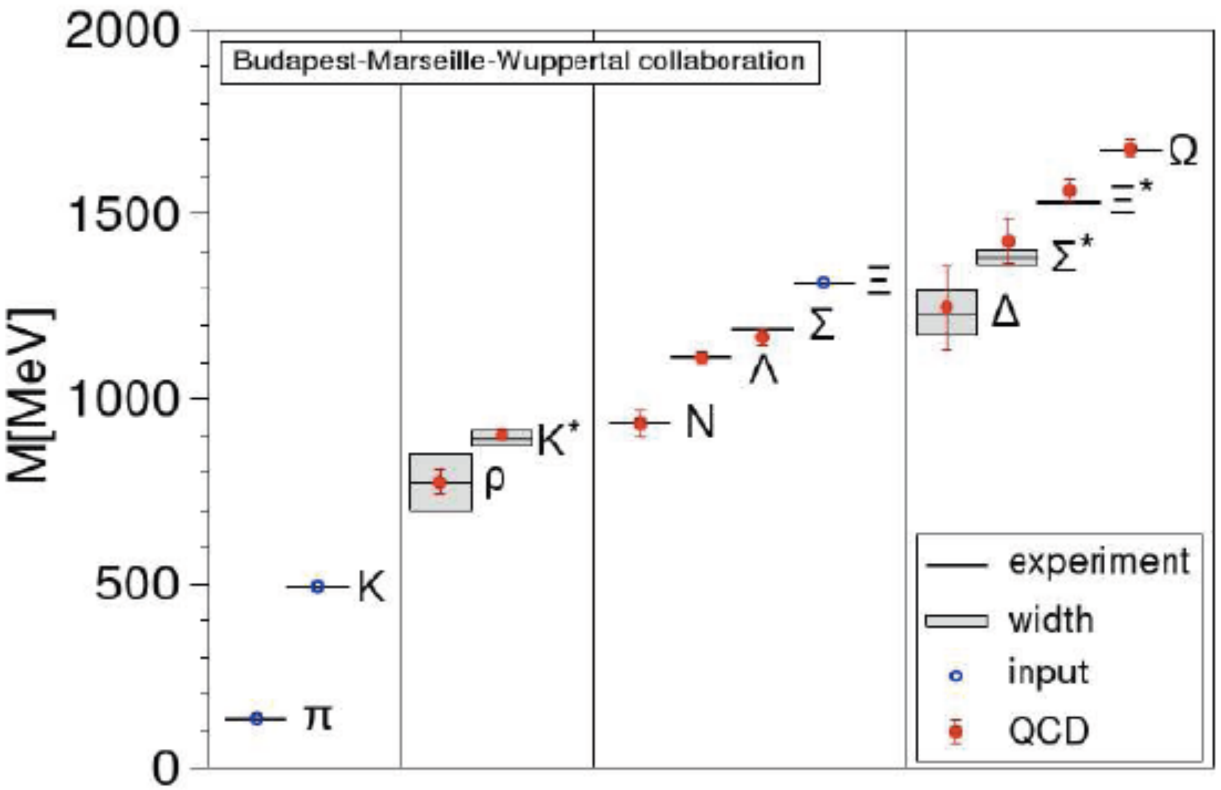


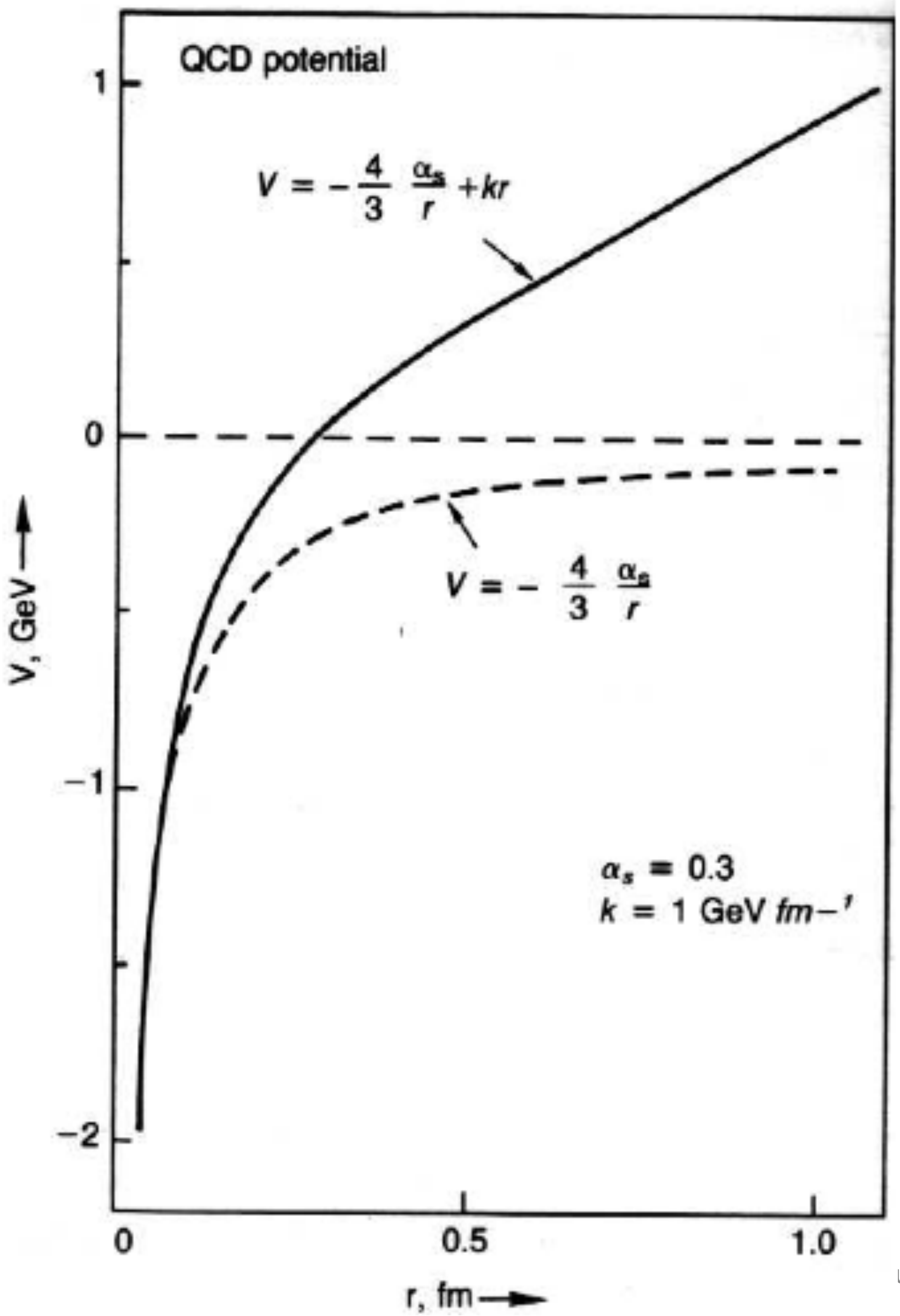


Gluon Jets Observed

Strong QCD

Hadron Spectrum - no signature of gluons?





QCD Potential

Short distance part (1/r term)
from quark-antiquark gluon exchange

$$V(q\bar{q}) = -\frac{4}{3}\frac{\alpha_s}{r} + k\,r$$

Long distance part (k r term)
is modelled on an elastic spring

k is known as the string tension

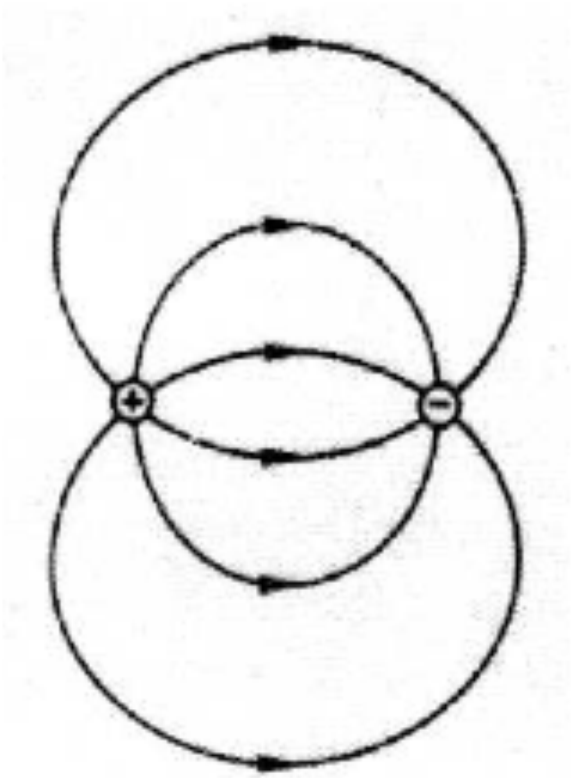
This model provides a good description of the bound states of heavy quarks:
charmonium ($c\bar{c}$)
bottomonium ($b\bar{b}$)

Colour Flux-tube Model

QED

Field lines extend out to infinity with strength $1/r^2$

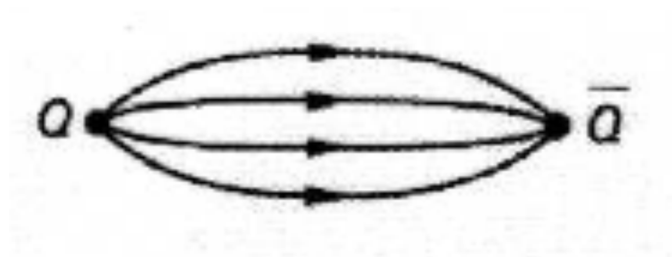
Electromagnetic flux conserved to infinity



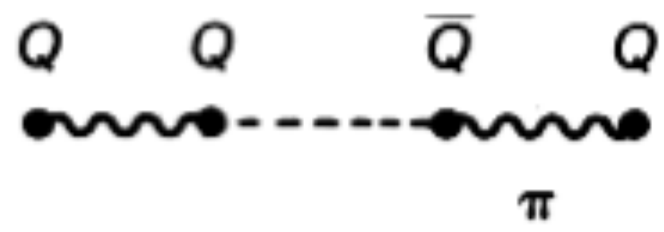
QCD

Field lines are compressed into region between quark and antiquark

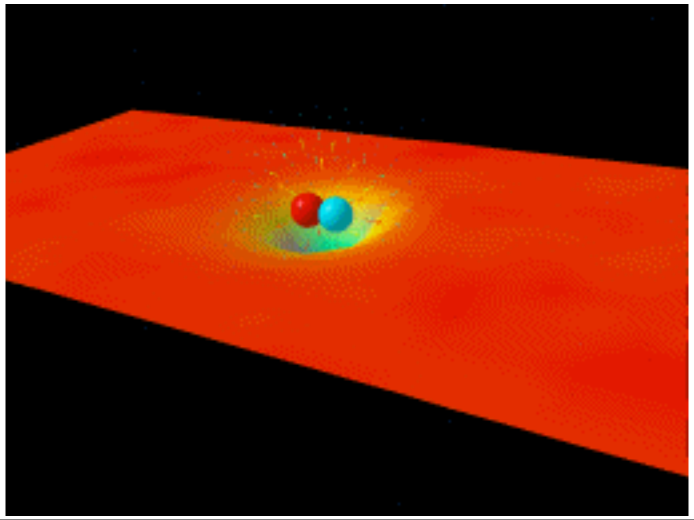
Colour flux is confined within a tube. No strong interactions outside the flux-tube .



Breaking a flux tube requires the creation of a quark-antiquark pair



Like breaking a string! Requires energy to overcome string tension



5/2/10 Particle Physics Lecture 8 Steve Playfer

Why Electron Scattering?

Well known

$$V_{int} = \rho\phi + \mathbf{JA}$$

scaler potential

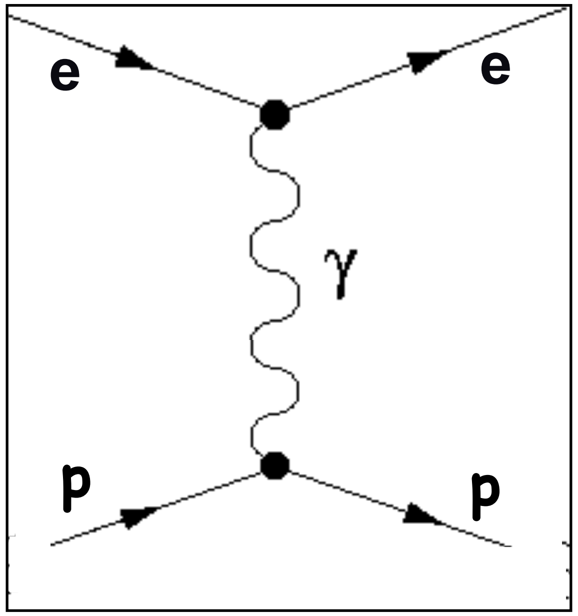
vector potential

calculable in SM using QED to high precision

Energy and momentum transfer independent

Magnetic, electric and **charge** transitions

$$M_\lambda, E_\lambda, C_\lambda$$



Charged

Difficult to access neutrons, Beam heating of the target, Bremsstrahlung, causes radiative tails and potentially large corrections

small cross section

Weak $\alpha \propto 1/137$

one photon exchange (simple)

penetrating

Light Mass

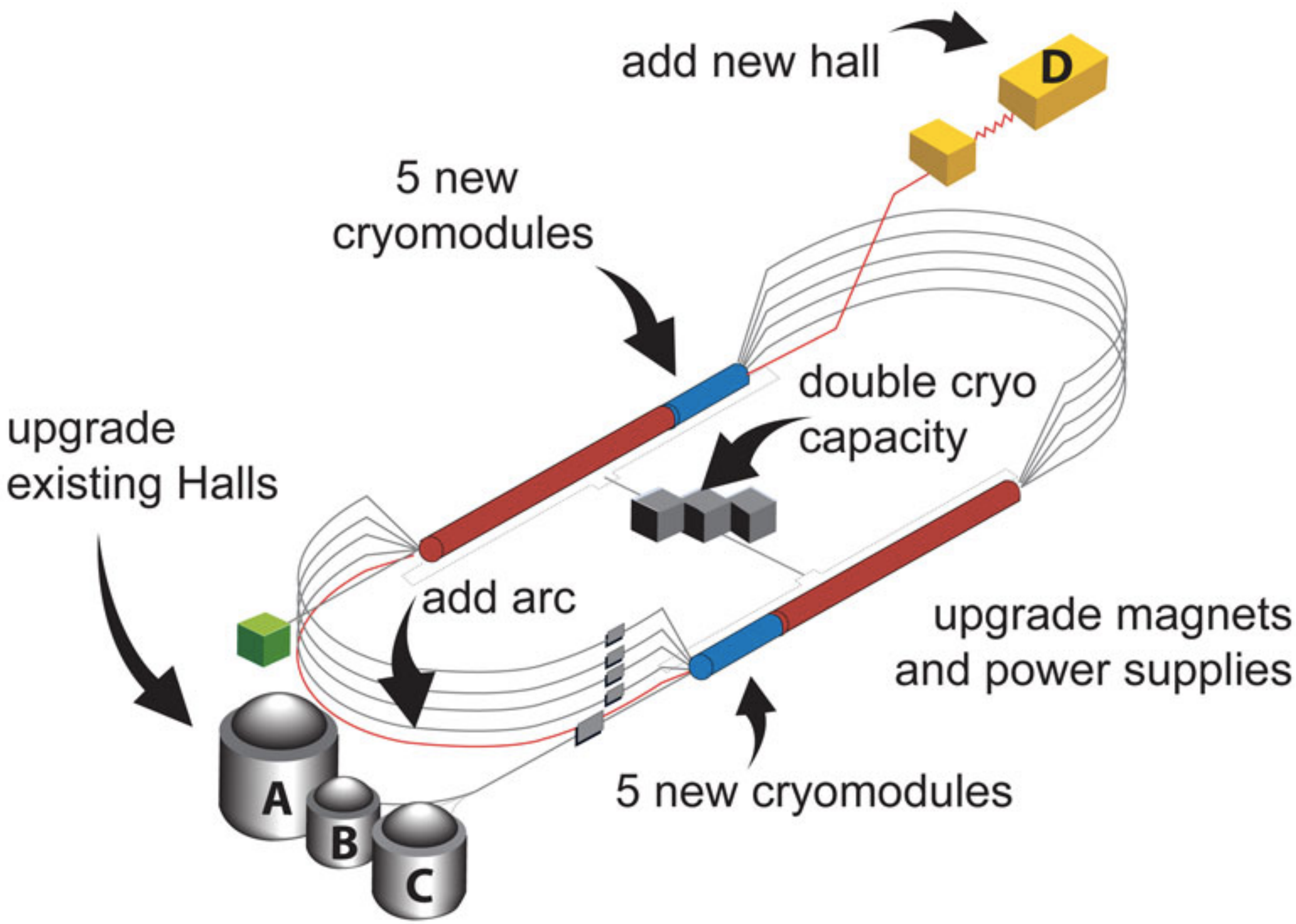
Except: charge elastic scattering of the Coulomb field of a heavy-Z nucleus

“Easy” experimentally

stable, pre-existing
high intensity, high duty cycle,
high energy, and high polarization

Jefferson Lab

CEBAF Accelerator, 12 GeV electron beam
4 experimental end stations
Newport News, Virginia, USA



Electron Scattering Kinematics

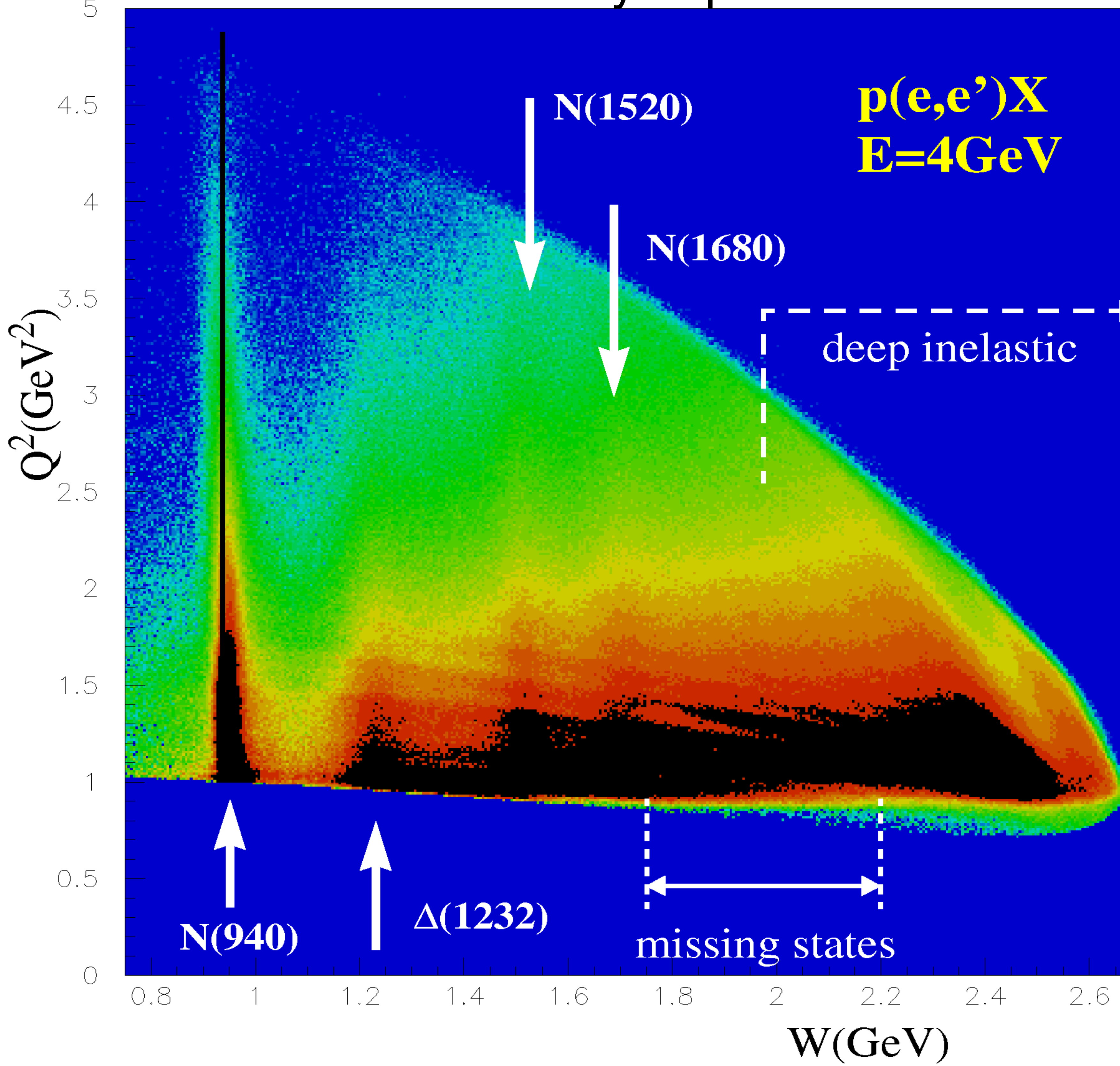
Scattering is a function of 2 variables, energy and angle

We choose to use other variables.

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

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

Early experiments at JLab

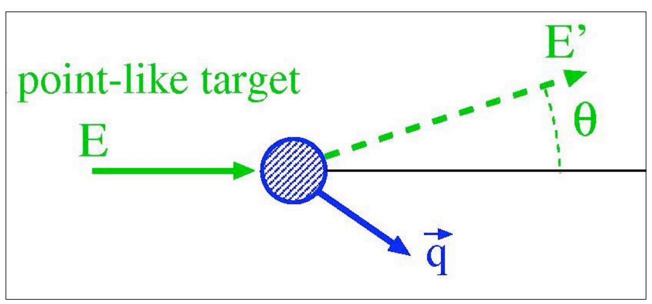


Electron Scattering

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

De Broglie wavelength $$\lambda = \frac{h}{\mathbf{p}}$$

Q^2: 4-momentum of the virtual photon

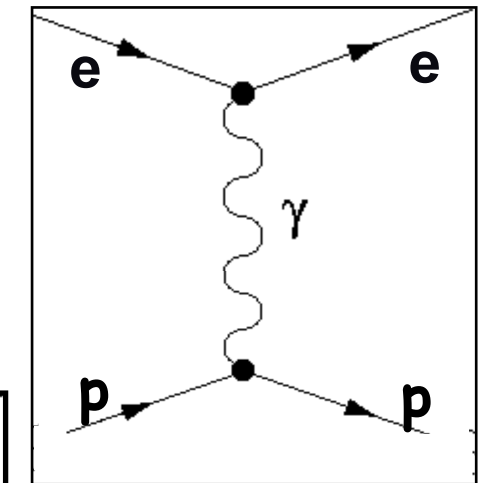


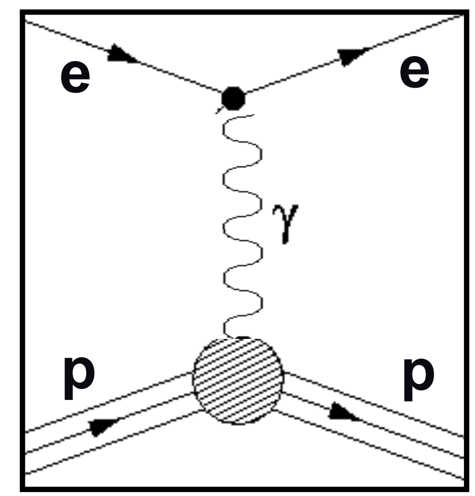
Photon is off mass shell

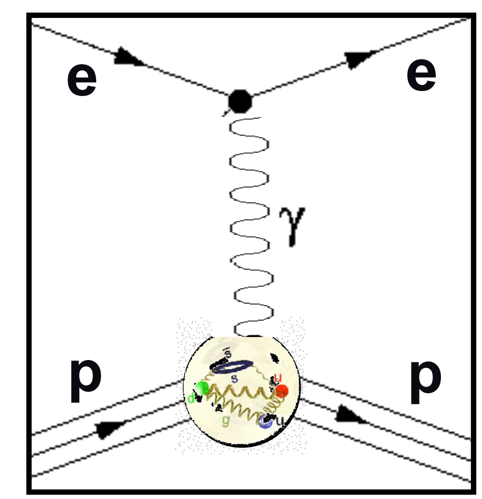
Q^2 measures

- virtuality or “mass” of the photon
- momentum transferred to the target

If photon carries low momentum
-> long wavelength
-> low resolution







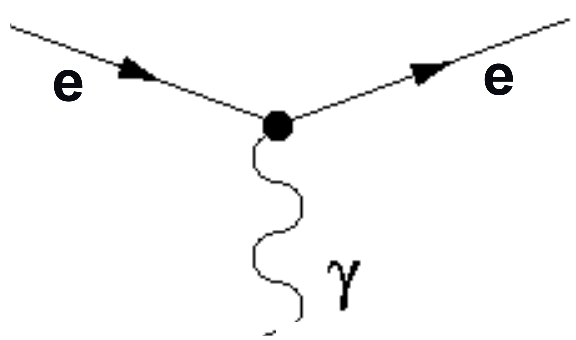
Increasing momentum transfer
-> shorter wavelength
-> higher resolution to observe smaller structures

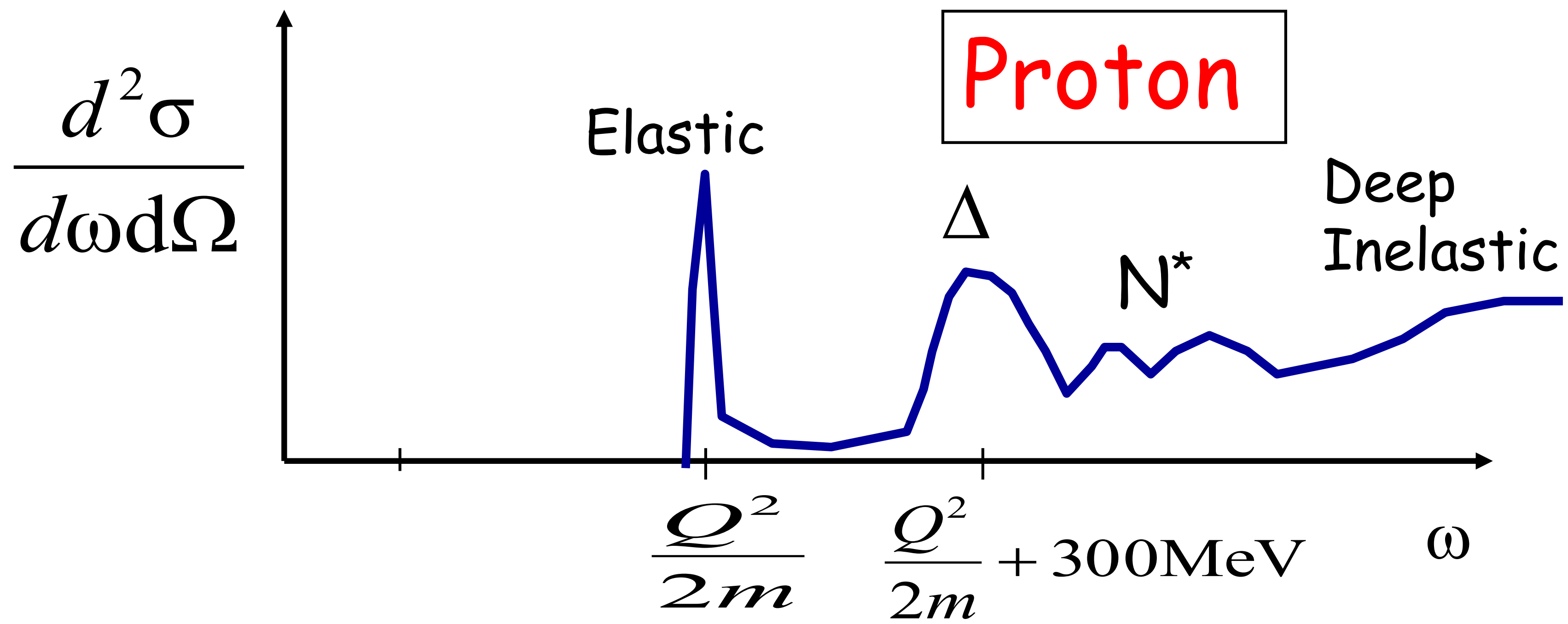
Electron Scattering

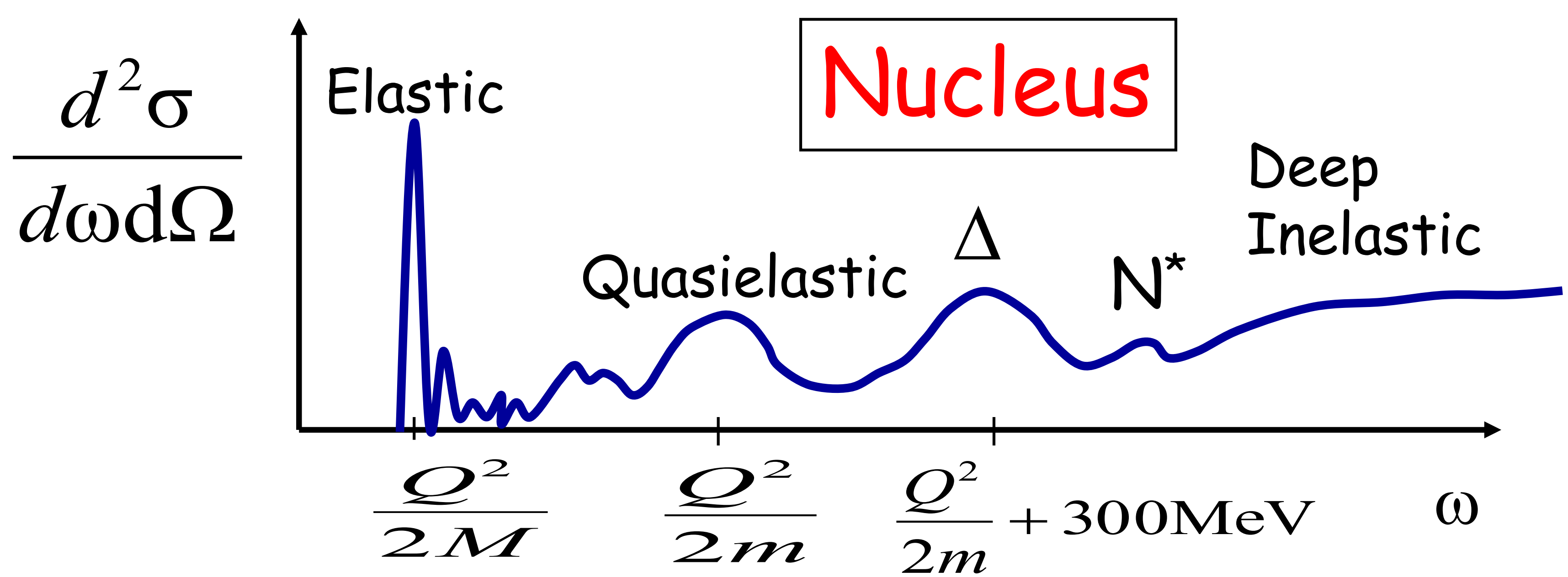
Vary energy transfer at constant momentum transfer

↓

achieved by varying the angle and energy of the scattered electron.

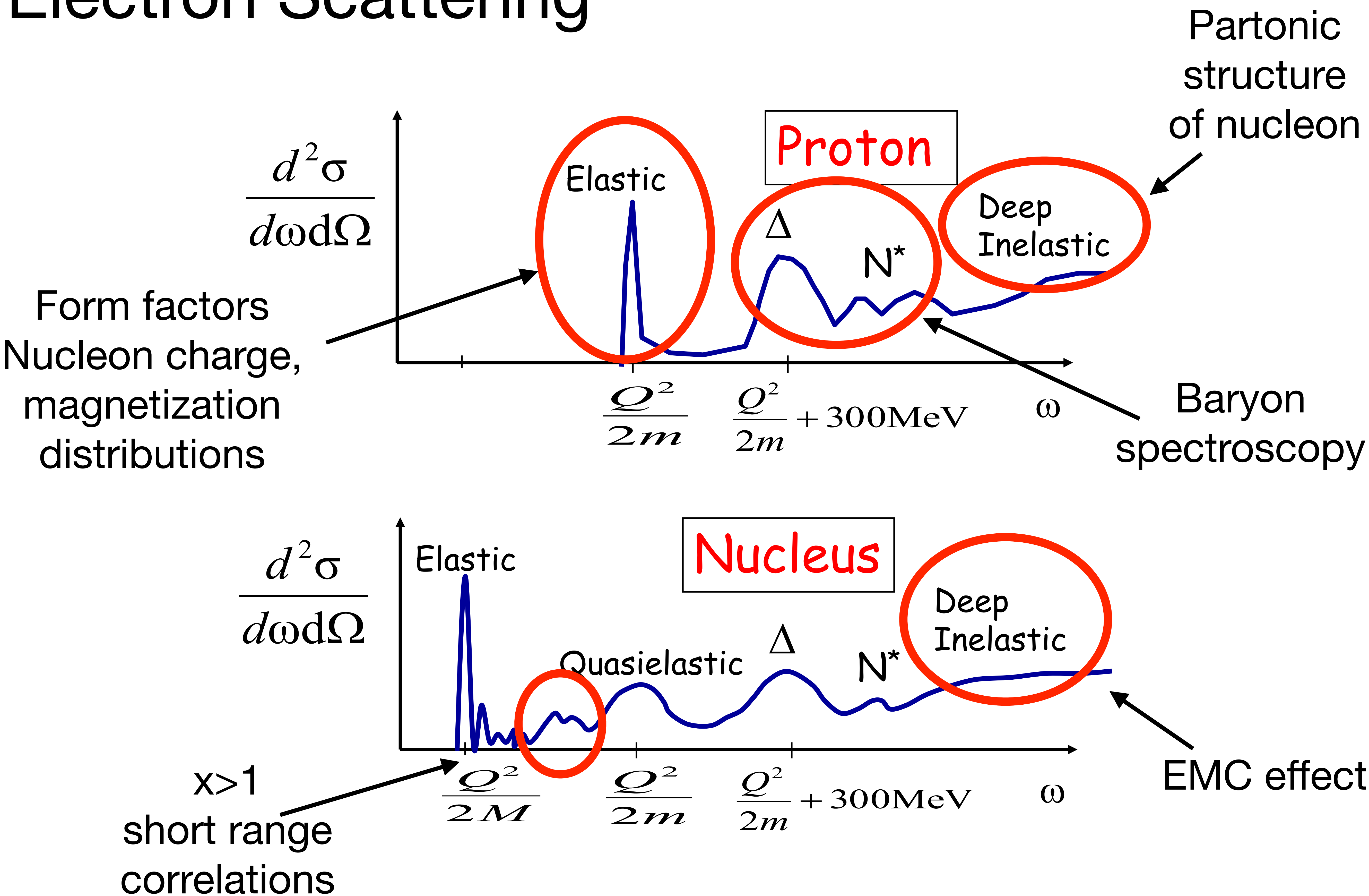






Fermi motion broadening

Electron Scattering



Elastic Scattering and Form Factors

The point-like scattering probability for elastic scattering is modified to account for finite target extent by introducing the "form factor"

Assuming spherically symmetric (spin-0) target

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

point-like target, electron spin

$$F(q) = \int e^{iqr} \rho(r) d^3 r$$

Form factor is the Fourier transform of charge distribution

This is a non-relativistic picture

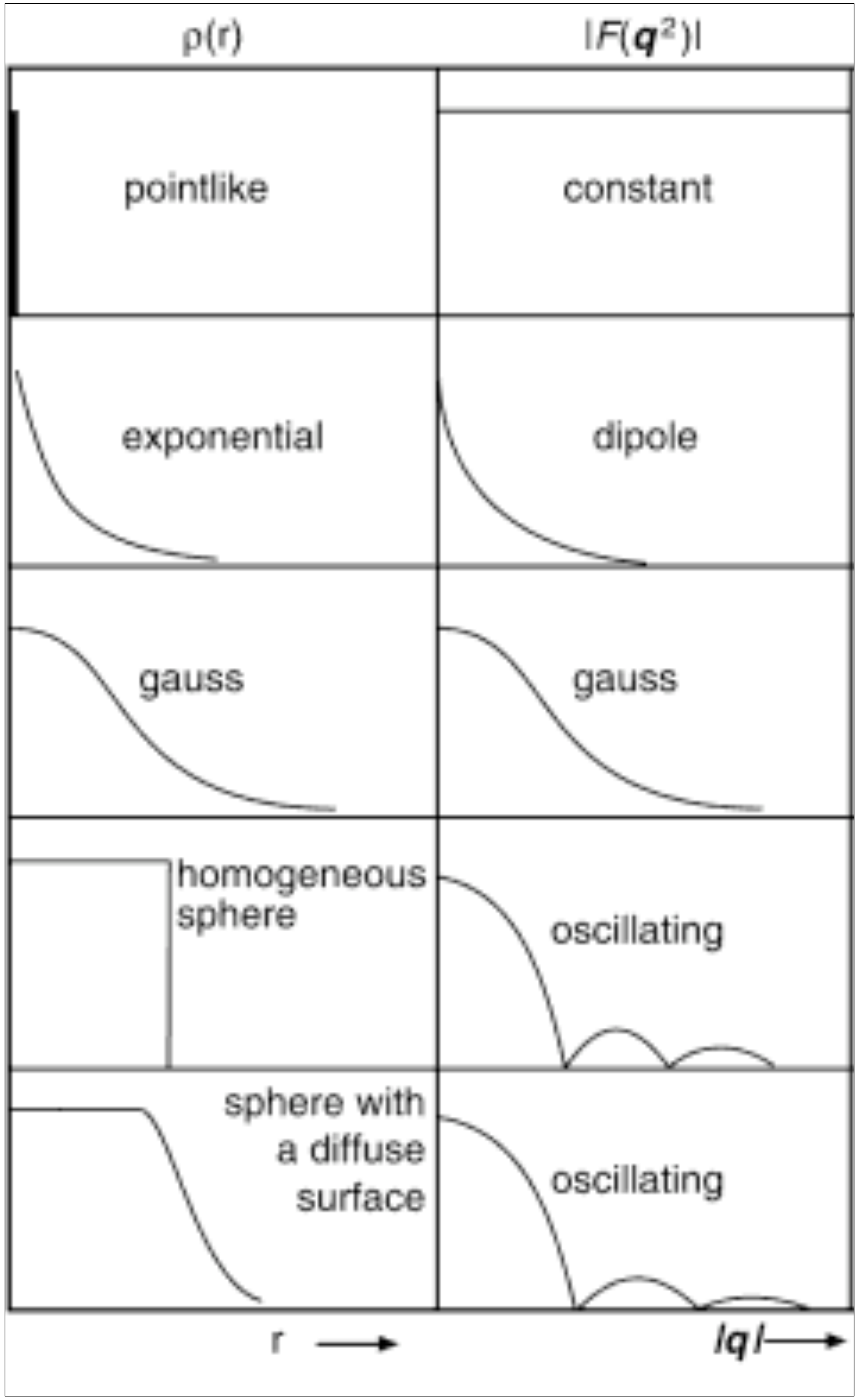
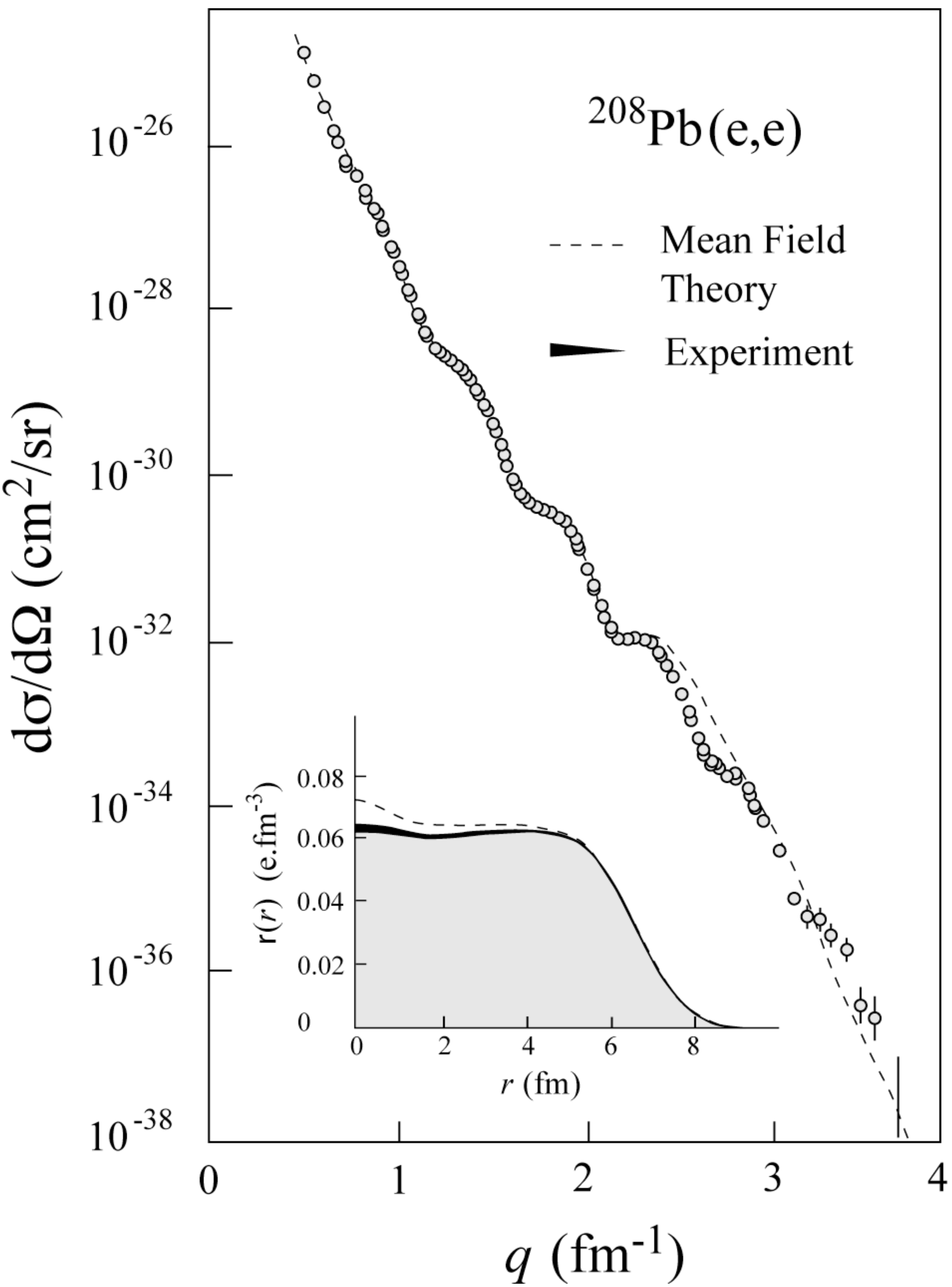
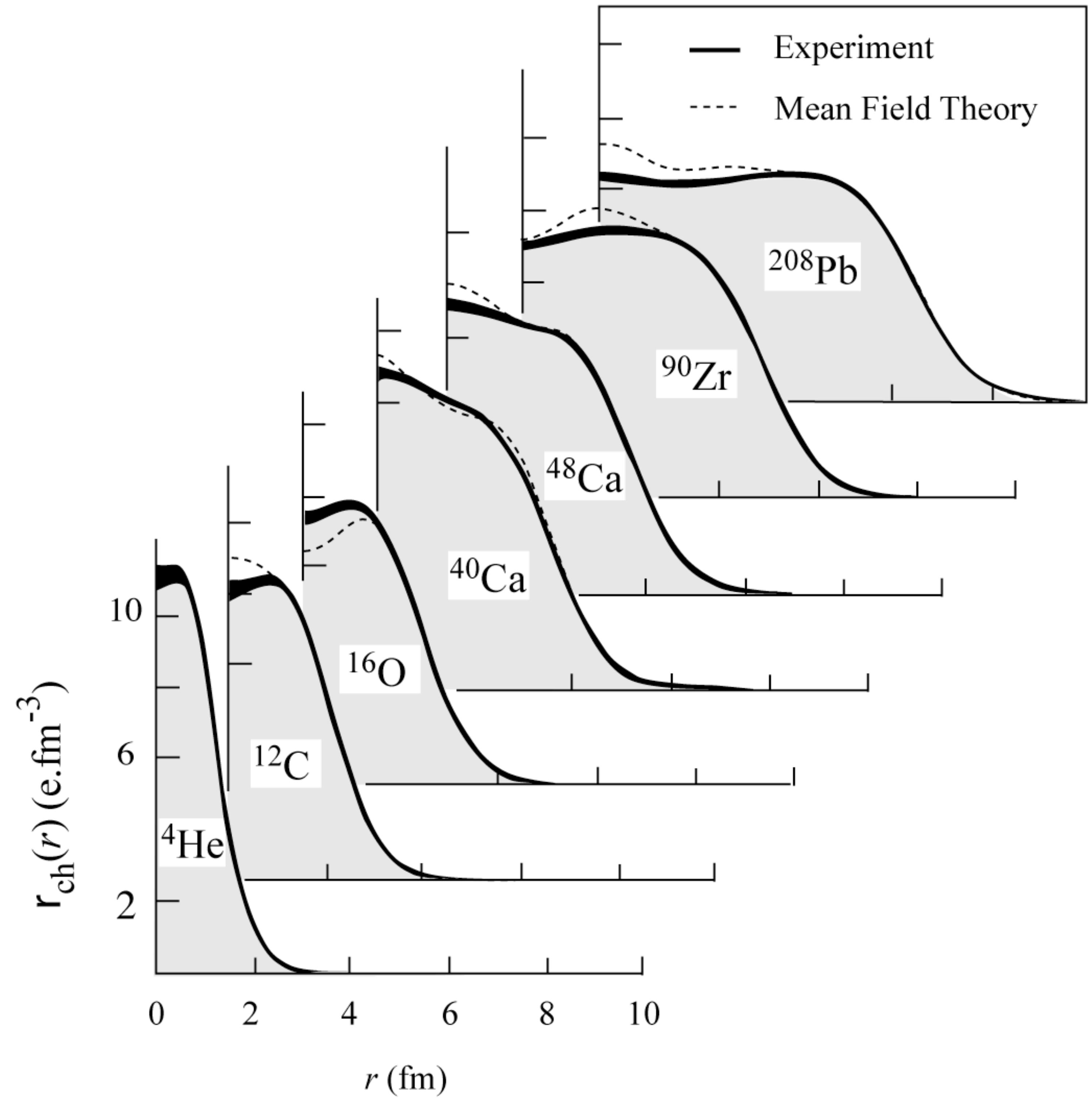


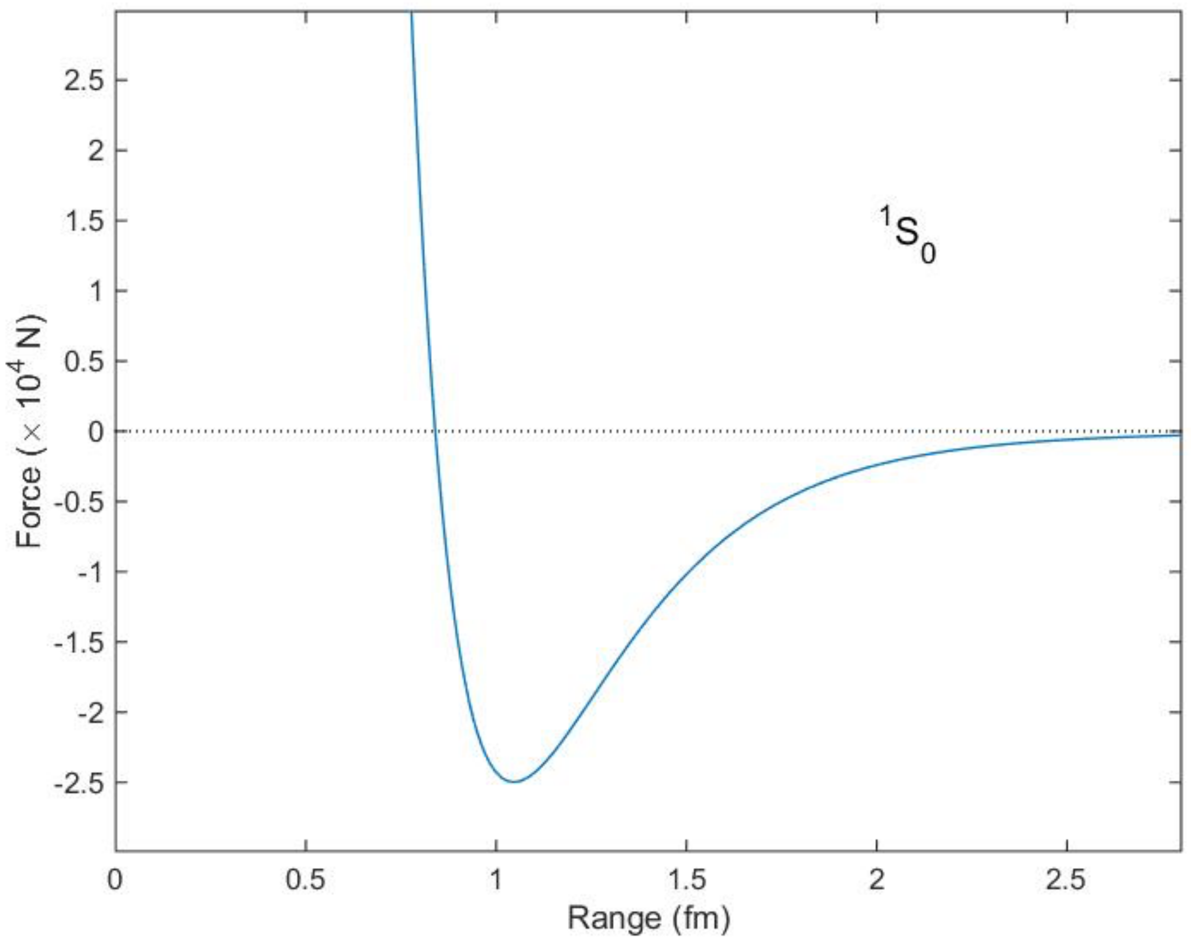
Figure from Particles and Nuclei, Povh *et al.*

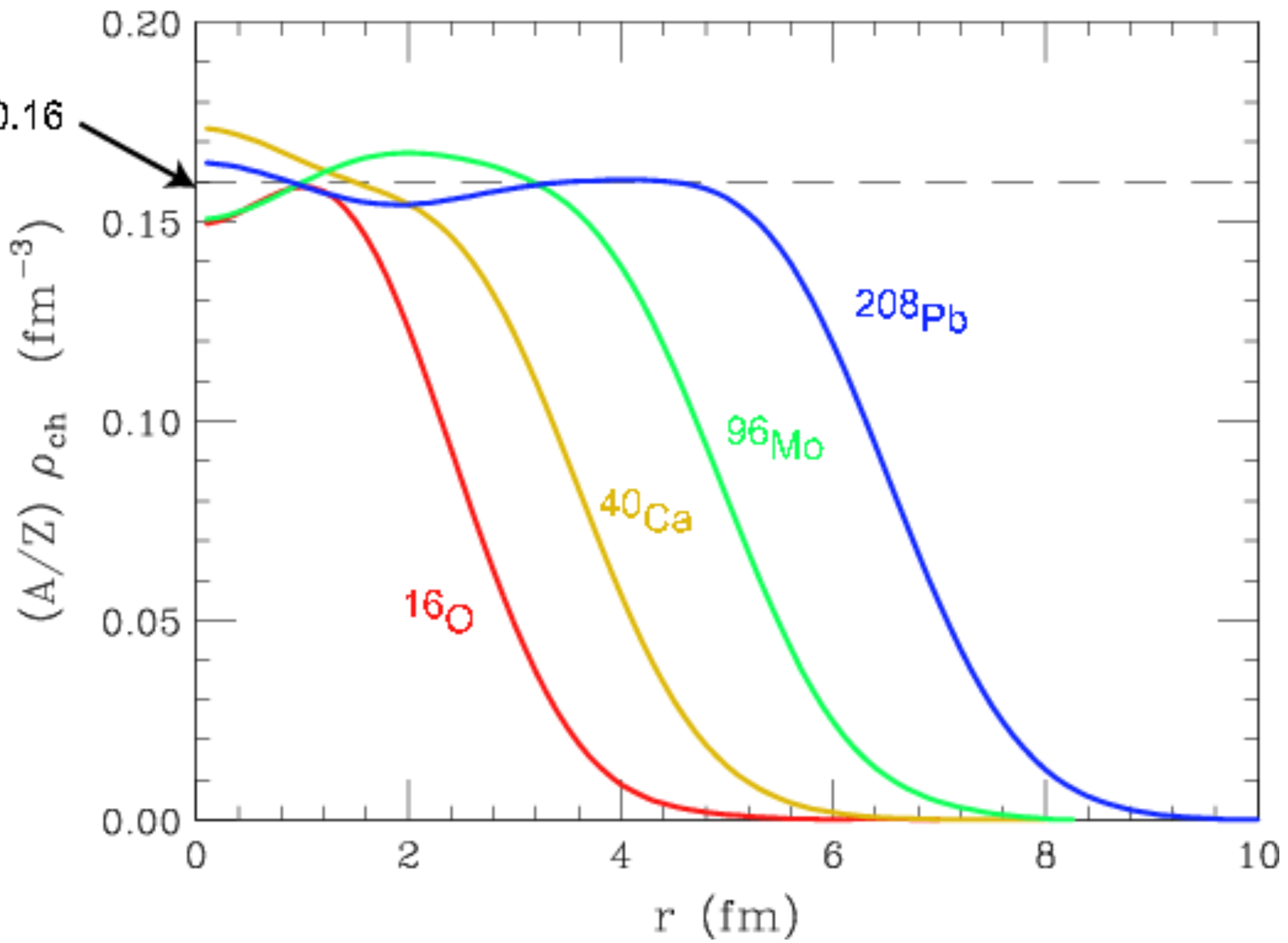
Historical Nuclear Charge Distributions





Nuclear Potential





Acta Phys.Polon.B 40 (2009) 2389-2404

depends on the nucleon spins, relative momentum of the nucleons

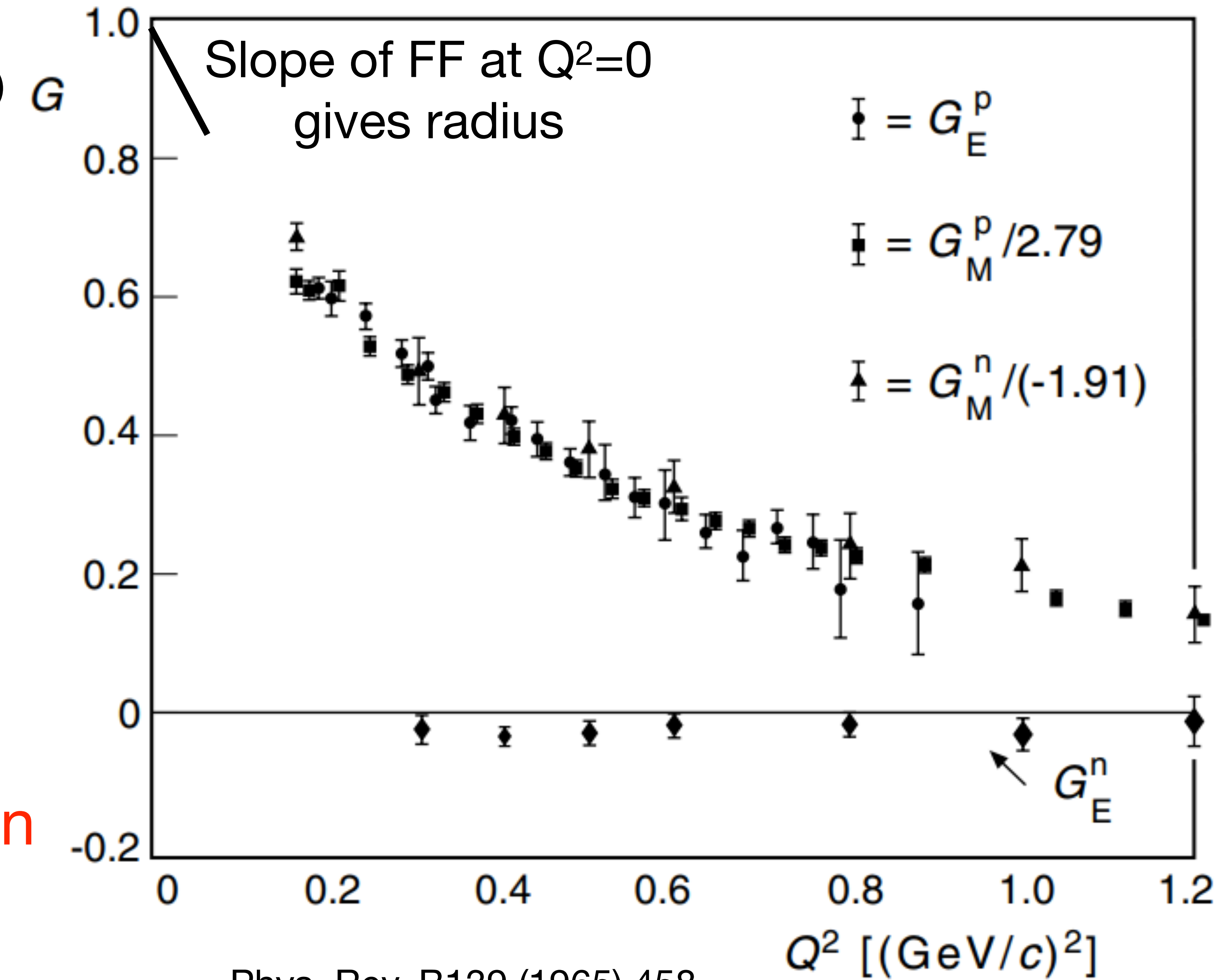
has a tensor component

Proton Form Factor

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

Kinematics make electric form factor difficult to measure at high Q^2

$$\frac{G_M^p(Q^2)}{\mu_p} \approx G_E^p(Q^2) \approx G^{\text{dipole}}(Q^2)$$



Phys. Rev. B139 (1965) 458

Measurements using polarization can measure form factor ratio directly

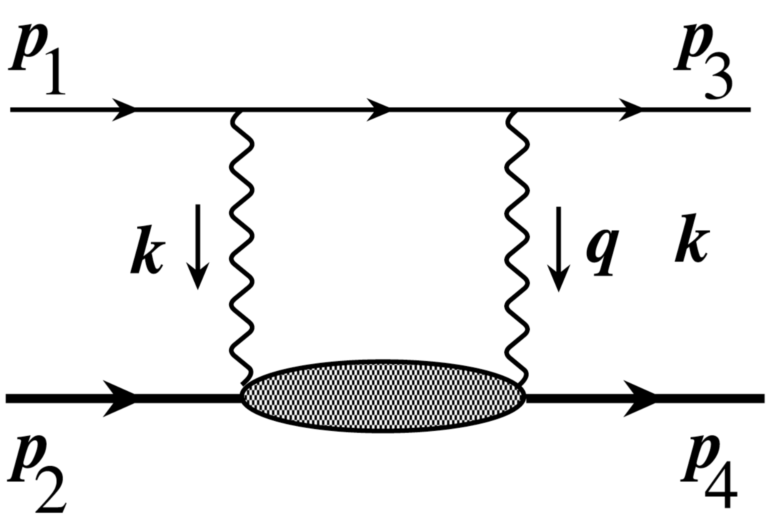
$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\sqrt{\frac{\tau(1+\epsilon}{2\epsilon}}$$

polarization of scattered proton

Many systematics cancel

Proton Form Factor

Polarization transfer measurements give different result.



2-photon exchange i.e. failure of the Born approximation

Charge & magnetization distributions in the proton are different

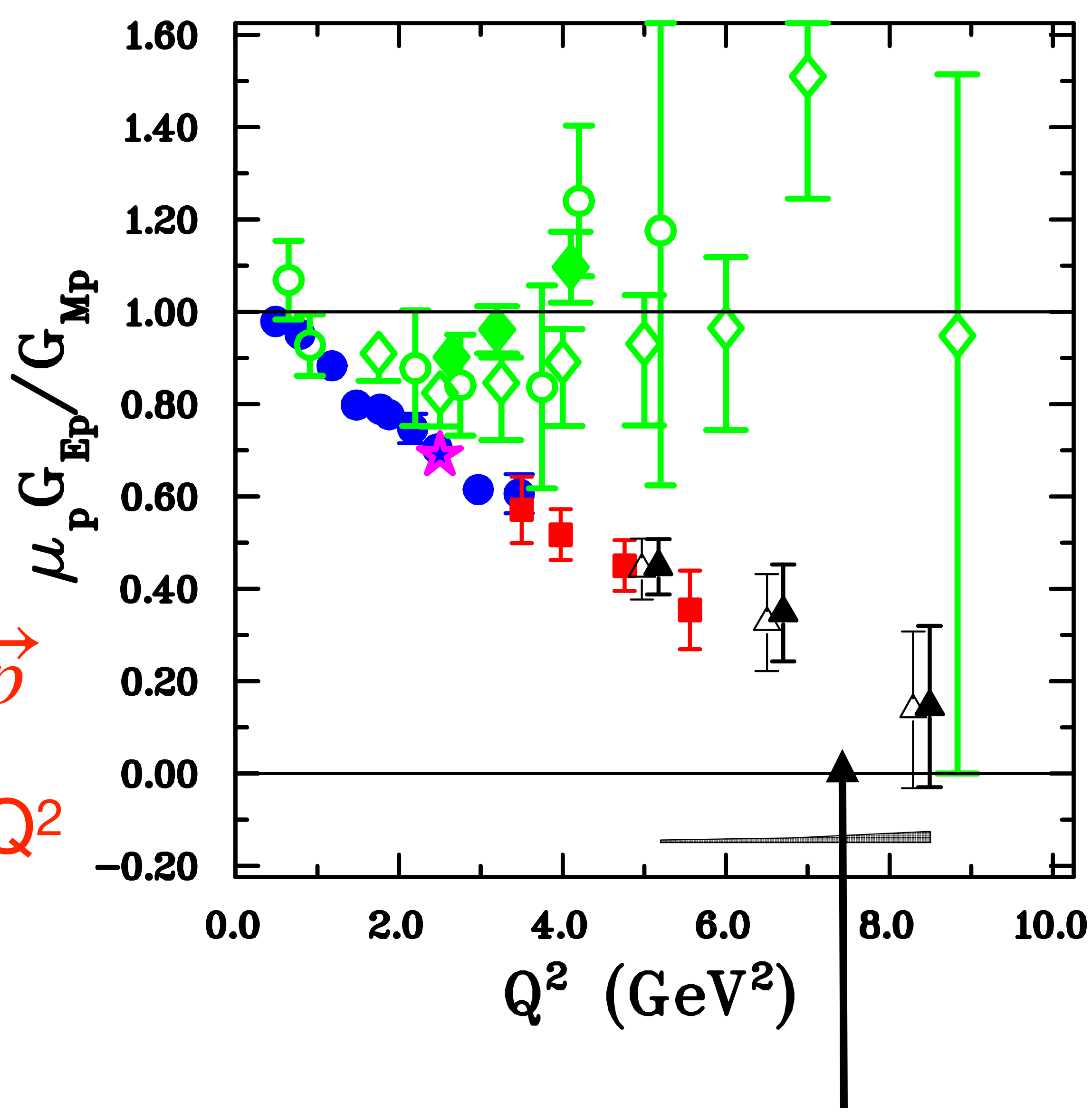
$e + p \to e' + p$

$\frac{G_E^p}{G_M^p}$ constant

$\vec{e} + p \to e' + \vec{p}$

$\frac{G_E^p}{G_M^p}$ drops with Q^2

PHYSICAL REVIEW C 96, 055203 (2017)

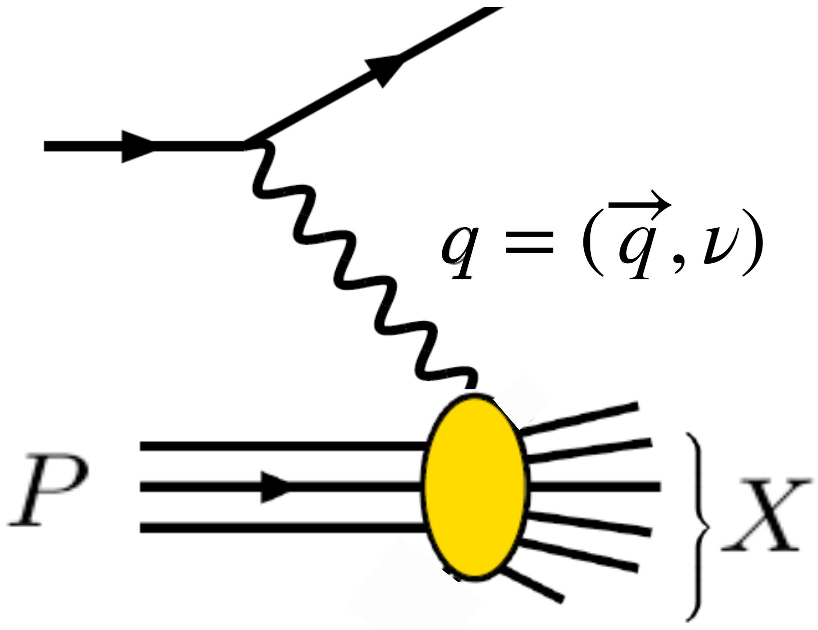


charge depletion in interior of proton

Orbital motion of quarks play a key role

(Belitsky, Ji + Yuan PRL 91 (2003) 092003)

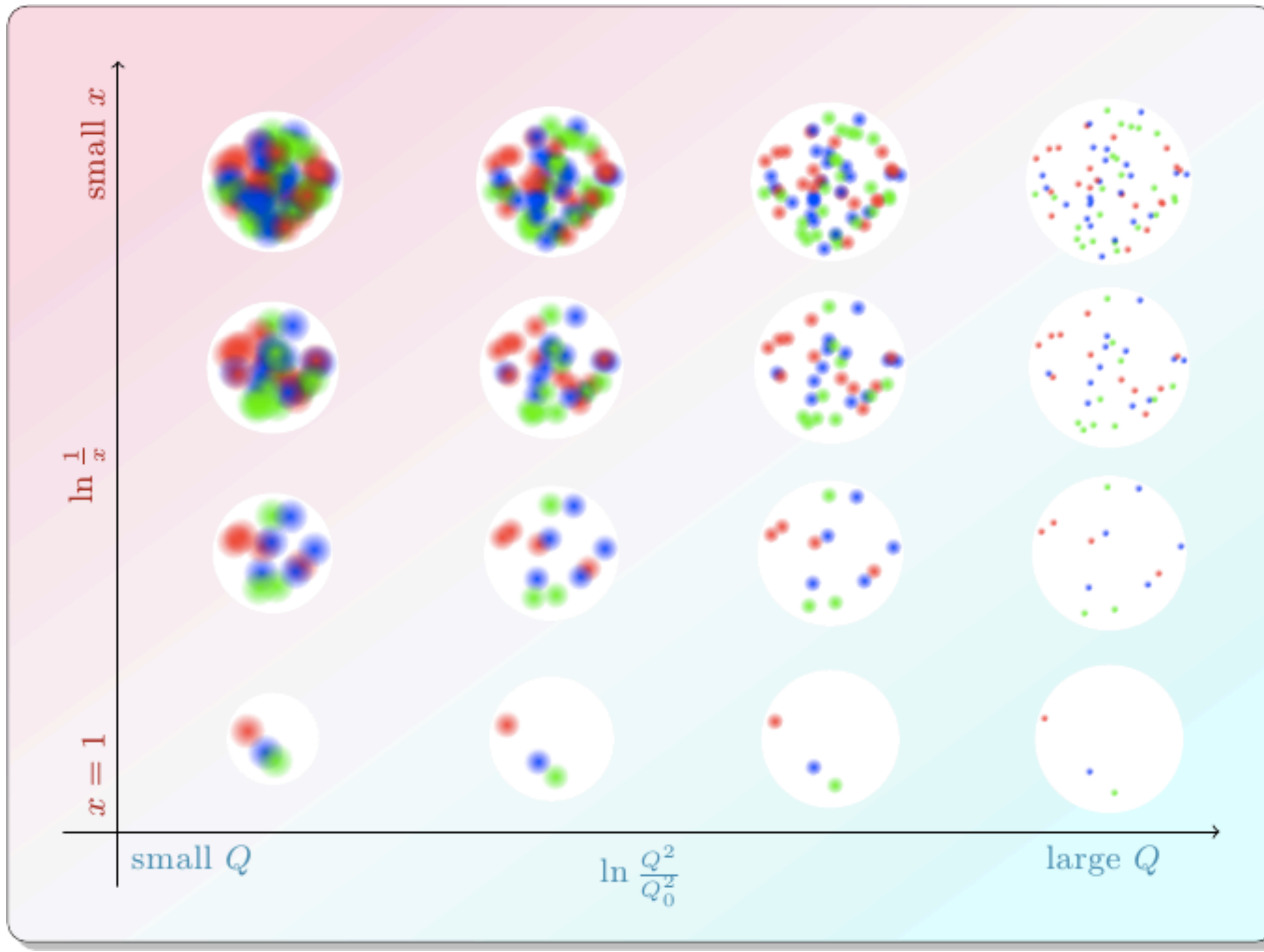
Deep **Inelastic** Scattering



Inelastic scattering requires 2 quantities to describe the kinematics

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

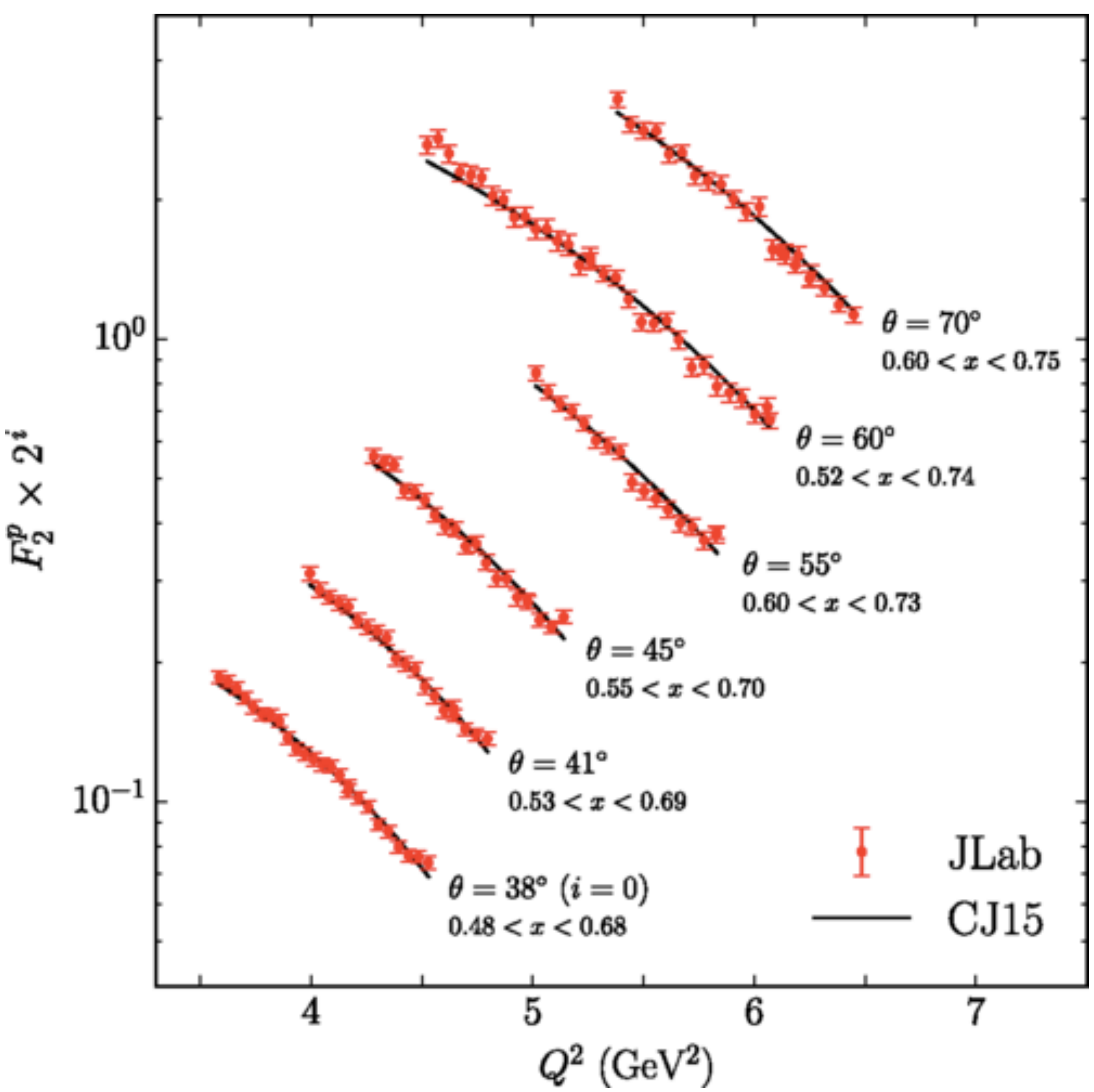
Interpreted as the fraction of nucleon momentum of the parton that was struck.

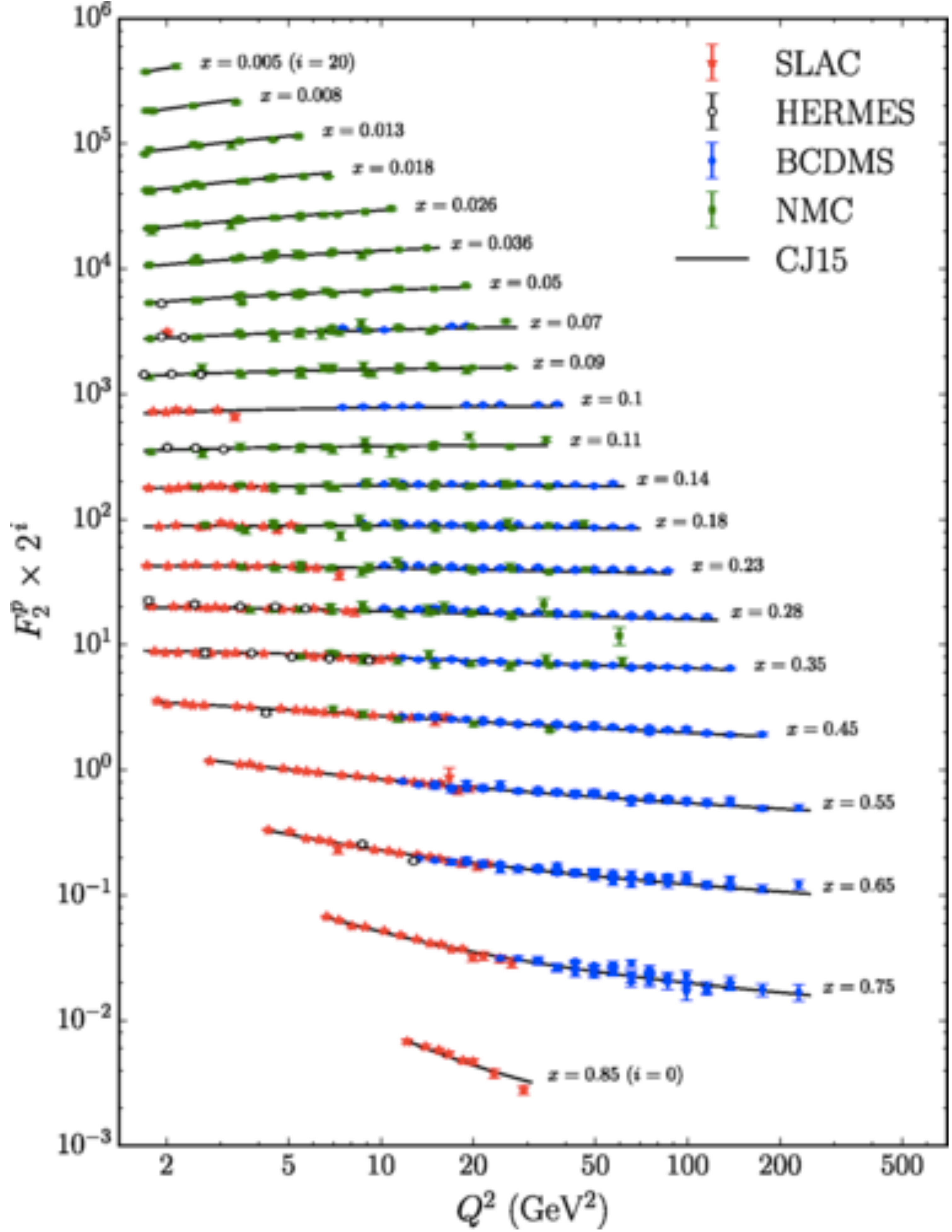


https://www.ellipsix.net/

Structure Functions

Independent of $Q^2 \Rightarrow$ quarks pointlike





Parton Distribution Function