HUGS2013, JLab, May 28 – June 14, 2013

Form Factors with Electrons and Positrons

Part 1: Overview and introduction

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Jefferson Lab

Overview

- **part 1: Overview and introduction – Wed 5/29 2:00 – 3:00**
  – History, formalism, concepts
- **part 2: Proton form factor measurements – Wed 5/29 3:15 – 4:15**
  – Unpolarized and polarized methods, two-photon exchange
- **part 3: Neutron form factor measurements – Thu 5/30 10:15 – 11:15**
  – Using H-2 and He-3, separation of quark flavors
- **part 4: Theoretical interpretation – Thu 5/30 2:15 – 3:15**
  – VMD, CQM, DSE, LQCD
- **part 5: Deuteron form factor measurements – Fri 5/31 9:00 – 10:00**
  – A, B, T_{20}, quadrupole structure
- **part 6: The proton charge radius puzzle – Fri 5/31 1:00 – 2:00**
  – … and how to possibly solve it

Nucleon Elastic Form Factors …

- Fundamental quantities
- Defined in context of single-photon exchange

- Describe internal structure of the nucleons
- Related to spatial distribution of charge and magnetism

- Rigorous tests of nucleon models
- Determined by quark structure of the nucleon
- Ultimately calculable by Lattice-QCD
- Input to nuclear structure and parity violation experiments

50 years of ever increasing activity

- Tremendous progress in experiment and theory over last decade
- New techniques / polarization experiments
- Unexpected results

Recommended review articles

- **Nucleon form factors**
  - **J. Arrington, C.D. Roberts, and J.M. Zanotti,**
    J. Phys. G: Nucl. Part. Phys 34, S23 (2007)
  - **C.F. Perdrisat, V. Punjabi, and M. Vanderhaeghen,**
    Progr. Nucl. Part. Phys. 59, 694 (2007)
  - **C.E. Hyde-Wright and C.W. de Jager, Ann. Rev. Nucl. Part. Sci. 54, 217 (2004)**
  - **H. Gao, Int. J. of Mod. Phys. E12, 1 (2003); Erratum-ibid. E12, 567 (2003)**

- **Two-photon exchange:**
  - **J. Arrington, P. G. Blunden, and W. Melnitchouk,**
    Prog. Part. Nucl. Phys. 66, 782 (2011)

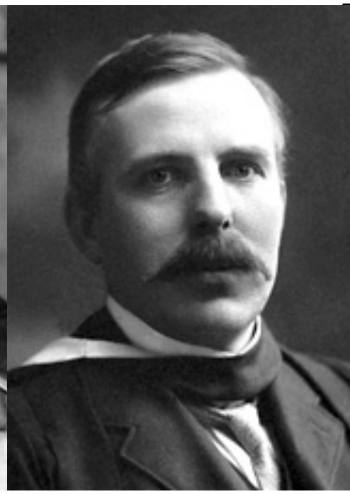
- **Deuteron form factors:**
  - **R. Gilman and F. Gross, J. Phys. G: Nucl. Part. Phys. 28, 37 (2002)**
  - **M. Garcon and J.W. Van Orden, Adv. Nucl. Phys. 26, 293 (2001)**

- **Proton radius puzzle**
  - **R. Pohl, R. Gilman, G.A. Miller, and K. Pachucki,**
    arXiv:1301.0905v1 [physics.atom-ph];
    Annu. Rev. Nucl. Part. Sci. 63 (2013), in press

Introduction

> 100 years of nuclear physics, > 50 years of form factors

Joseph Thomson
Physics 1906
“Electron”



Ernest Rutherford
Chemistry 1908
“Radioactivity”
“Nucleus”
“Proton”

Harold Urey
Chemistry 1934
“Deuteron”

James Chadwick
Physics 1935
“Neutron”

Carl Anderson
Physics 1936
“Positron”

Robert Hofstadter
NP Physics 1961
“Finite size”

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  Problem of nuclear mass and requirement of "nuclear electrons"

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- **1932:** Discovery of the "positron" (C.D. Anderson, Nobel Prize 1936) cosmic rays in cloud chamber

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- **1933:** **Proton magnetic moment μ_p = 2-3 μ_N**
  R.O. Frisch and O. Stern, Z. Phys. 95 (1933) 4

- **1940:** **Neutron magnetic moment $|\mu_n|$ = 1.93 μ_N**
  L. Alvarez and F. Bloch, Phys. Rev. 57 (1940) 111

Proton and neutron are not elementary (Dirac) particles
but must have a substructure

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Proton and neutron are not elementary (Dirac) particles but must have a substructure

- **1956:** Elastic electron scattering from hydrogen at 188 MeV
  R.W. McAllister and R. Hofstadter, PR102 (1956) 851

It took until the 1950's until R. Hofstadter established the finite proton size by electron scattering at Stanford

The beginnings

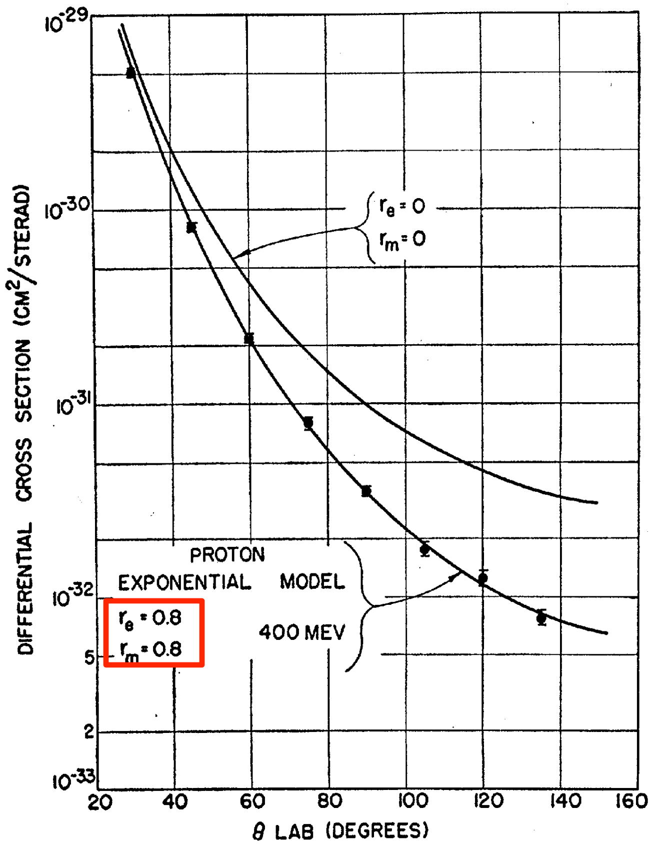


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii = 0.80×10^{-13} cm.

R. Hofstadter, Rev. Mod. Phys. 56 (1956) 214

Robert Hofstadter
Nobel prize 1961

ep-elastic
finite size of the proton
$R_p \sim 0.8$ fm

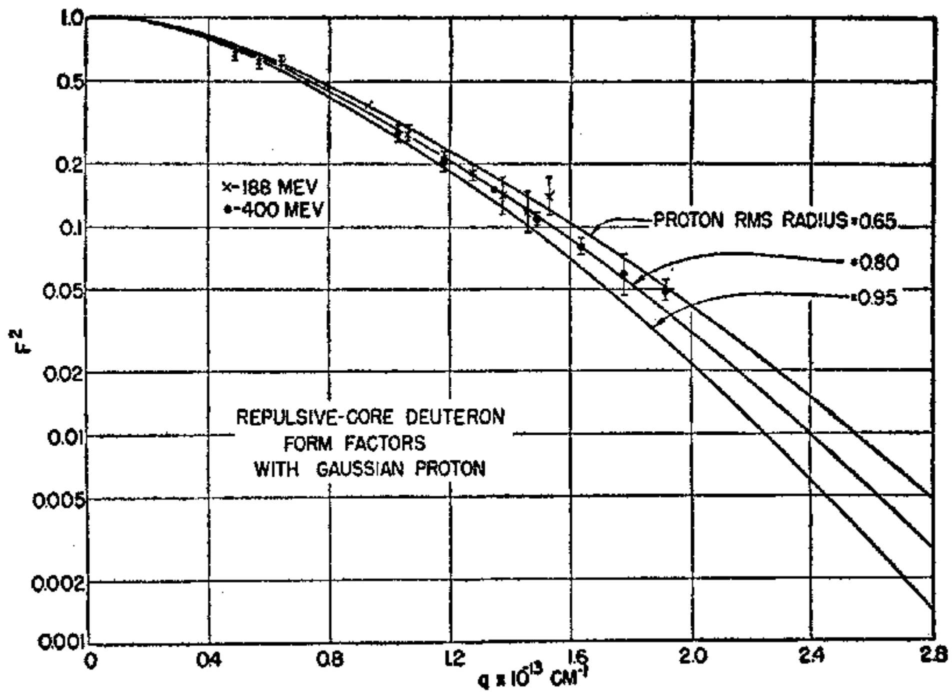
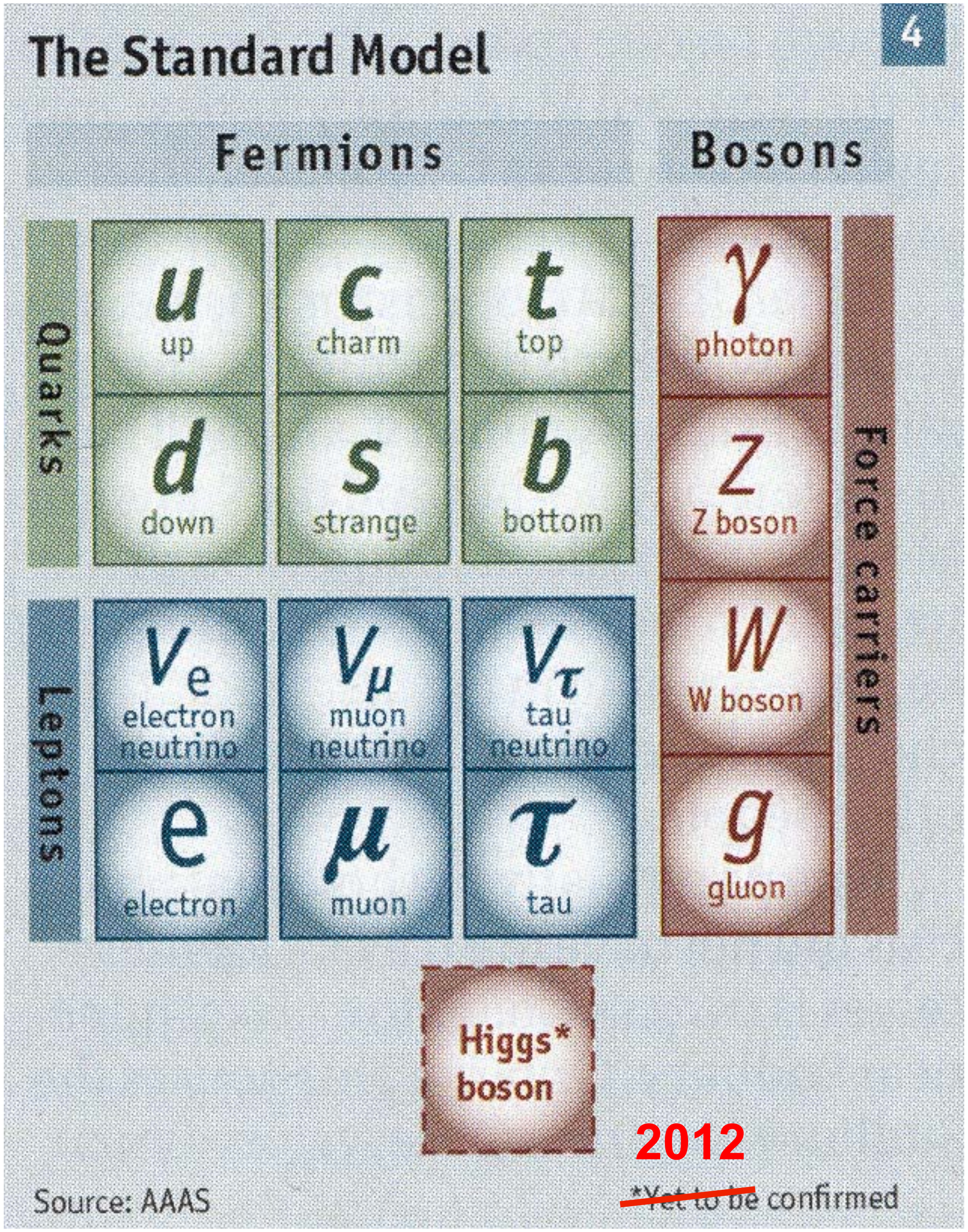


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

ed-elastic
Finite size + nuclear structure

The Standard Model

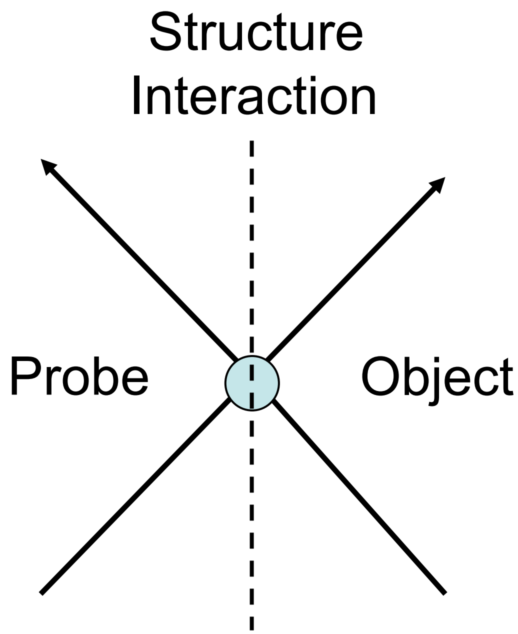


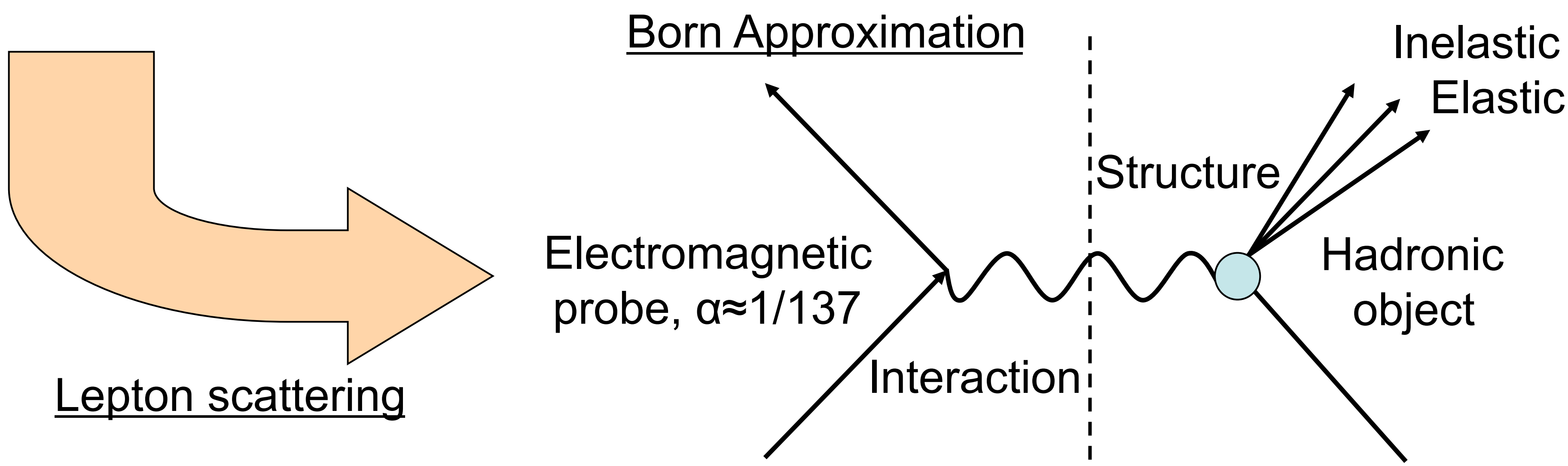
Symmetry!
3 interactions
3 generations
3 colors (QCD)
Exchange forces

Structure ↔ Symmetry

Electromagnetic	**Best**
Weak	**Well**
Strong	**???**

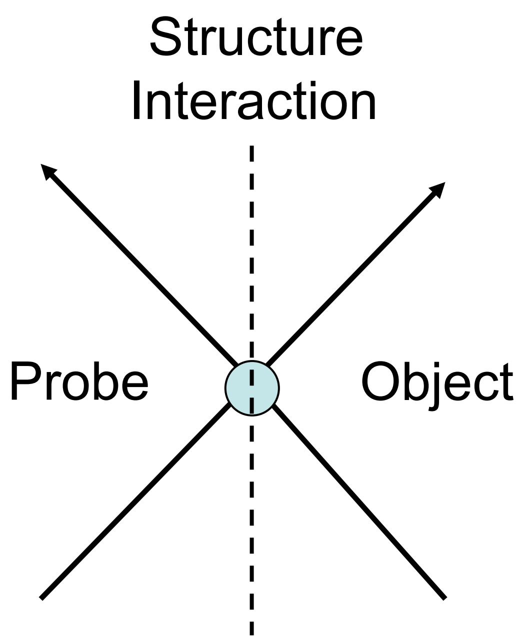
Hadronic structure and EM interaction





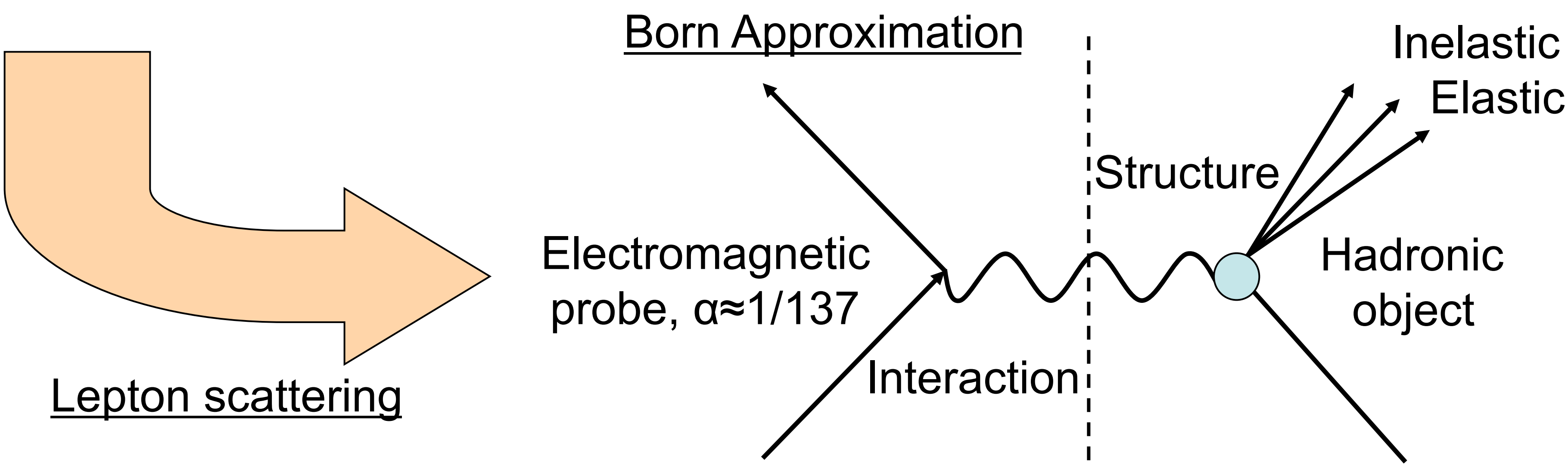
One-Photon Exchange Approximation

Hadronic structure and EM interaction



Factorization!

$$|\text{Form factor}|^2 = \frac{\sigma(\text{structured object})}{\sigma(\text{pointlike object})}$$



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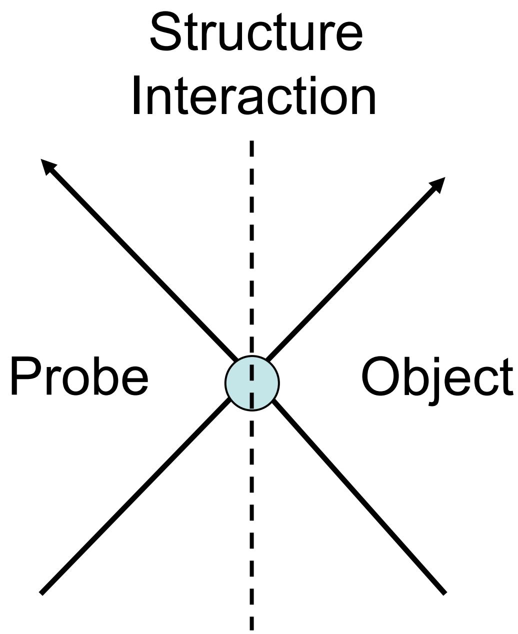

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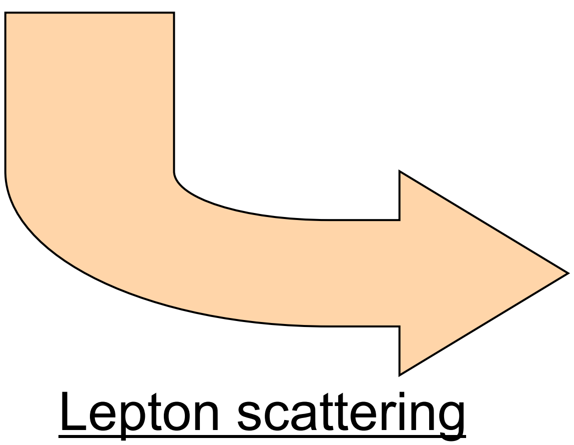
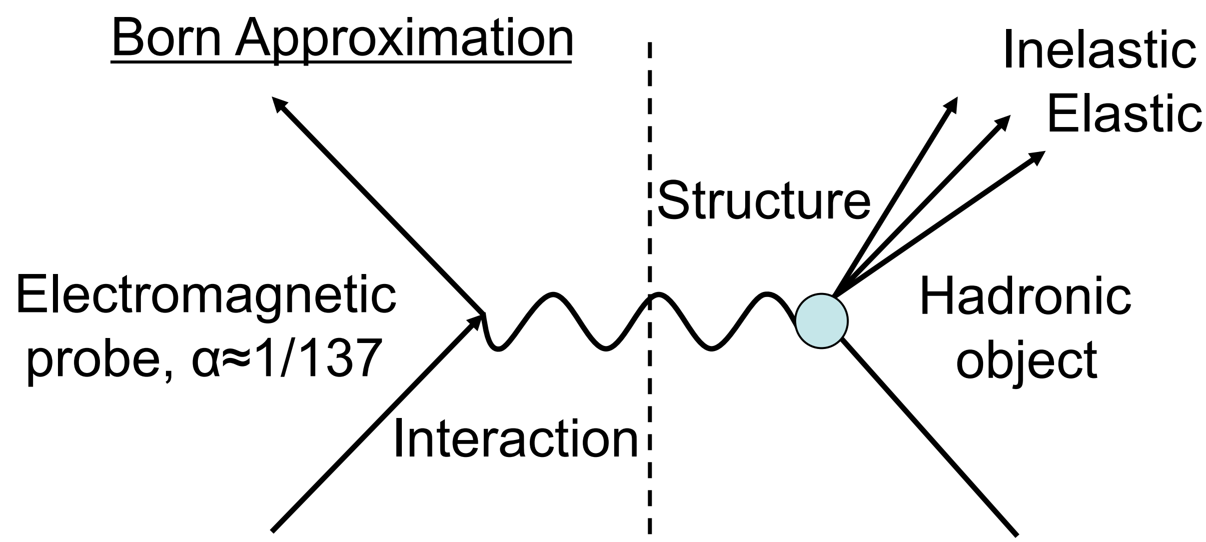
$$|\text{Form factor}|^2 = \frac{\sigma(\text{structured object})}{\sigma(\text{pointlike object})}$$

→ Interference!

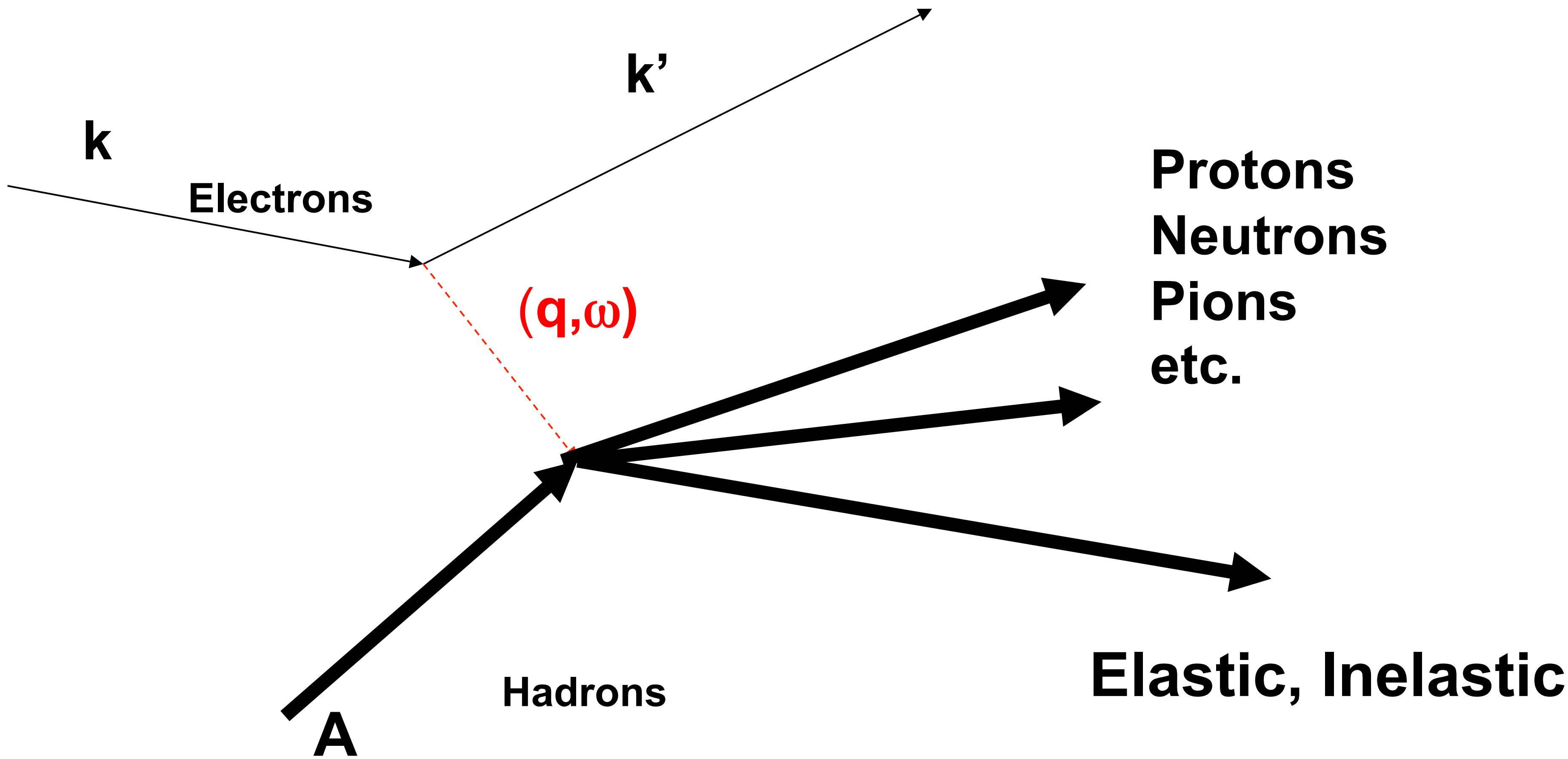
→ Utilize spin dependence of electromagnetic interaction to achieve high precision





One-Photon Exchange Approximation

The electromagnetic process



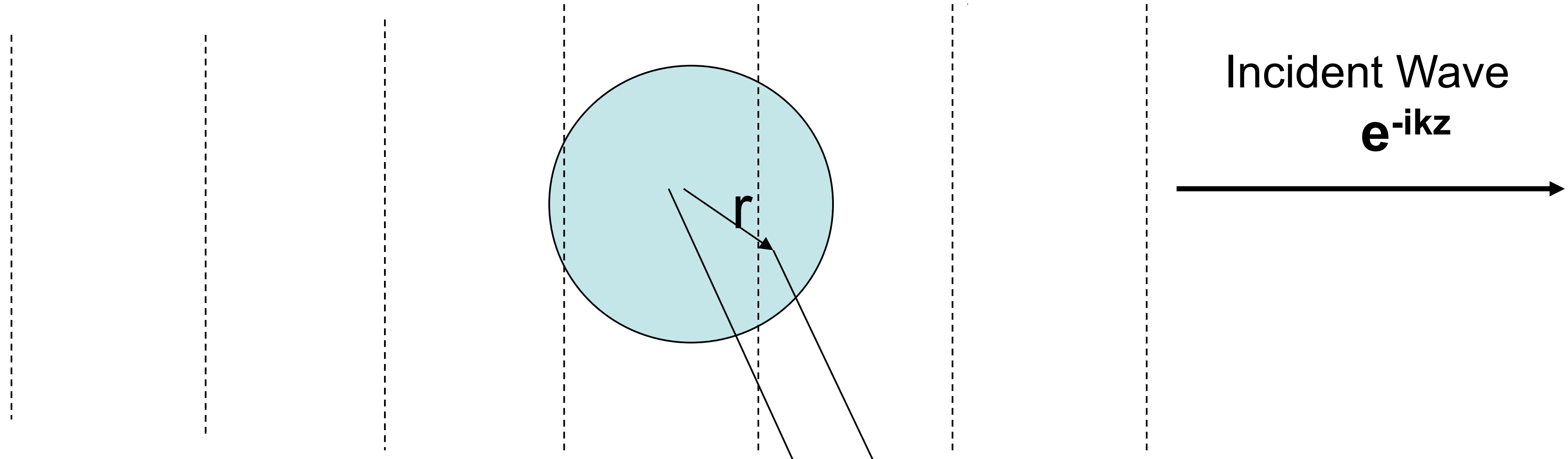
"The interaction is well understood"

It is weak and does not greatly disturb the hadronic system

Reliable matrix elements of the interaction, $\langle A|O|B \rangle$

First-order perturbation calculations are effective

‘Good old Huygens to the rescue’



Diffraction Phase Integral

Form Factor: $F(q,\omega)$

$dA \sim \rho(r)_{tr}\, e^{-(k-k')\mathbf{r}}\, dV$

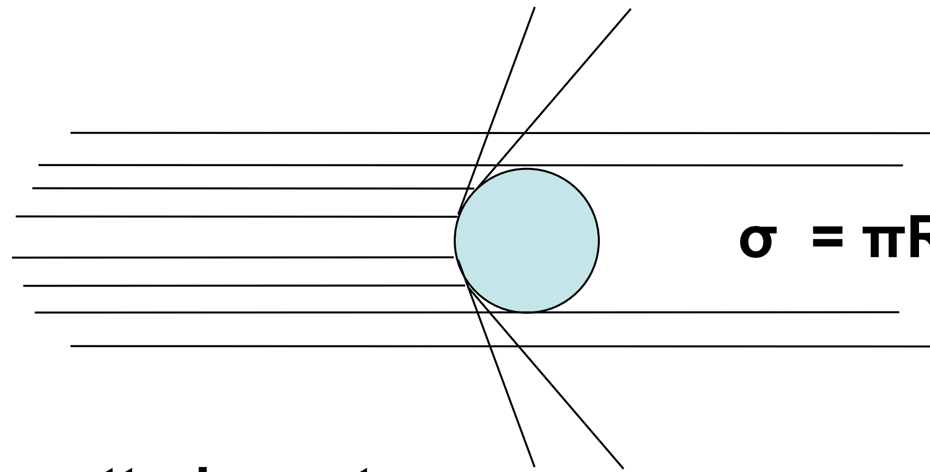
$$d\sigma/d\omega = \sigma_M\{\int\rho(r)_{tr}\, e^{-(\mathbf{k}-\mathbf{k}')\mathbf{r}}\, dV\}^2$$

$\mathbf{k} - \mathbf{k}' = \mathbf{q}$

Momentum Transfer

Concept of cross section

- Geometric "cross section"
  = area of hard scatterer



$\sigma = \pi R^2$

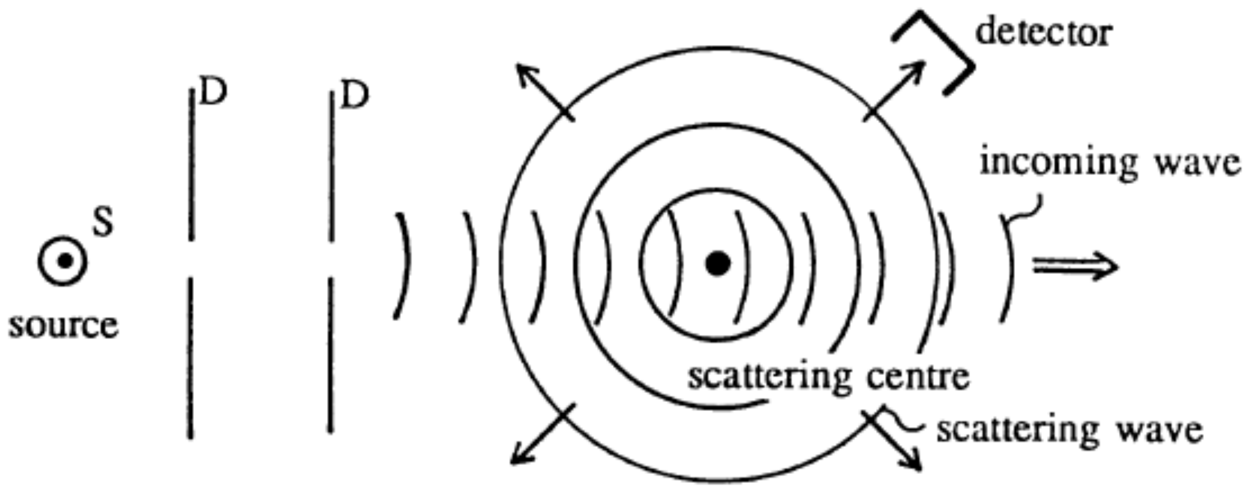
- Use cross section to describe scattering rate
  … can be differential in angles, energies, momenta
  … proportional to number of beam particles N_A per second & unit area
  … proportional to number of target particles N_B present in that area
  … proportional to probability to interact = cross section

- Rate [Hz] = Cross section [cm^2] • "Luminosity" [1/(cm^{2}s)]
  $R = \sigma \cdot L$

- Luminosity = beam particles per second per unit area [1/(cm^{2}s)]
  • target particles
  = beam current • target density • target thickness (length)
  $L = I \cdot (\rho x)$

Scattering process

- Early scattering theory: S-Matrix
- Nonrelativistic: Schrödinger Equation, potential scattering
  scattering amplitude → cross section



- Cross section = square of scattering amplitude
  (Born approximation)

HOWEVER:

- Recoil effects significant for electron-nucleon scattering
- Relativistic treatment → Dirac Equation
- Feynman rules must be applied

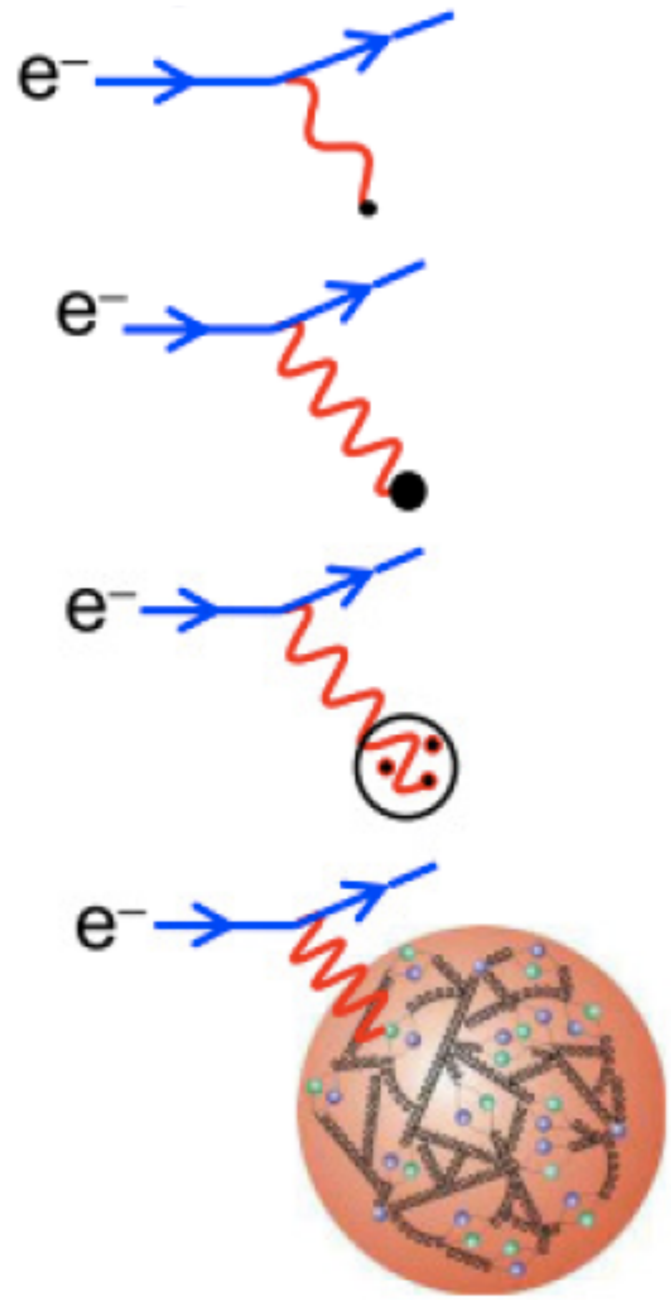
High energy required: resolution power

- **Momentum transfer: $|q| \sim= 2\,E \sin(\theta/2)$**
- **Uncertainty relation: $|q|\,\Delta x \geq 1$**
  → in order to resolve $\Delta x < 1$ fm, need momentum transfer of

  $$|q| > 1\ \mathrm{fm}^{-1} \sim= 0.2\ \mathrm{GeV}/c$$

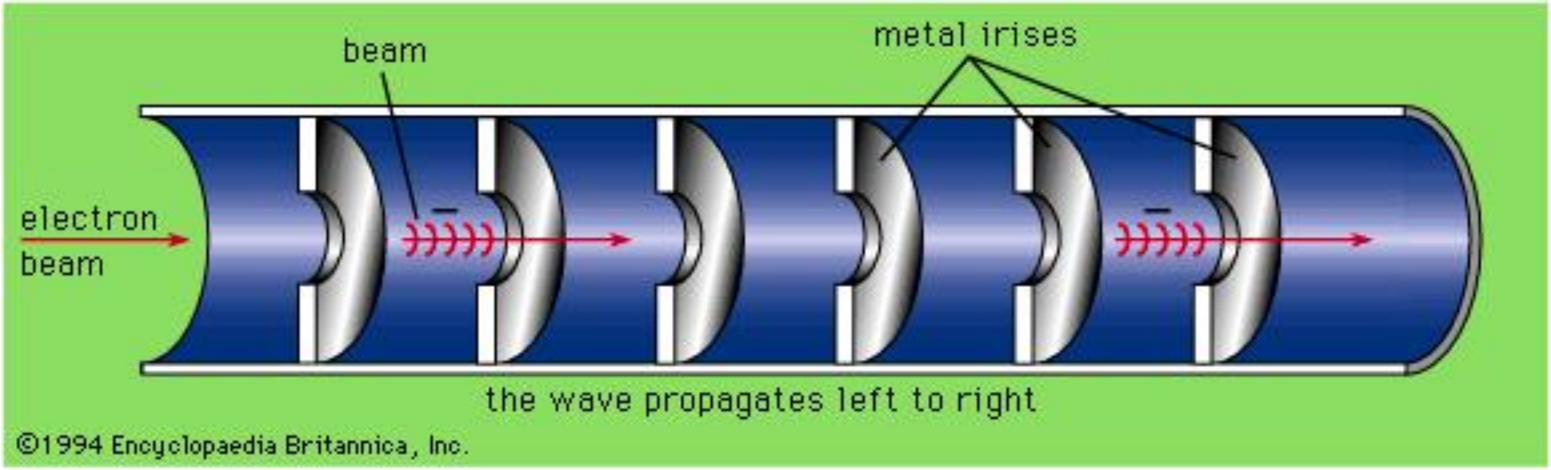
  $$Q^2 > 0.04\ (\mathrm{GeV}/c)^2$$

- **Electron energies E of a few hundred MeV to several GeV required to resolve nucleus (nucleon) and substructures of size < (<<) 1 fm**



Requirements for electron scattering

- Electron energies E of few hundred MeV to several GeV required to resolve nucleus (nucleon) and substructures of size < (<<) 1 fm
- Tremendous technical challenge! Can not create DC voltage of this size
- RF fields can be very strong for very short times; charged particles to ride on electric field wave with longitudinal component
- Solution: Use standing waves in a resonator and discrete bunches to synchronize net acceleration effect



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→ Electron accelerators have been developed since 1950's
Pioneered at Stanford in 1950's
Many laboratories
[SLAC, Cambridge, DESY, Bonn, Saclay, Bates, Novosibirsk …]

→ Problem 1: Limited intensity due to pulsed beams and low duty factor
Problem 2: High peak current leads to randoms in coinc. experiments

→ Require high energy AND high intensity and duty factor:
continous-wave mode:
stretcher rings, microtrons, superconducting recirculator

→ Presently operated state-of-the-art accelerators for electron scattering at Jefferson Lab (CEBAF, superconducting recirculator) and
Mainz (MAMI, microtron)

Intensities required

A little estimation:

- **Typical differential cross section for elastic e-p scattering**
  $d\sigma/d\Omega$ = 10^{-32} cm^2/sr = 10 nb/sr (1 barn = 10^{-24} cm^2)
- **Typical solid angle of a high-resolution spectrometer**
  $\Delta\Omega \sim 12$ msr $\sim 10^{-3} \bullet 4\pi$
- **Required luminosity for 100 Hz spectrometer event rate**
  L = 100 Hz / (10 nb/sr • 4π 10^{-3}) ~ 8 • 10^{35} / (cm^2s)
- **Typical tgt. thickness (ρx) for lq. hydrogen: ρ ~ 0.07 g/cm^3, x ~ 5 cm**
  (ρx) = [0.07 g/cm^3 / 1 g/mol] • 6•10^{23}/mol • 5 cm = 2 • 10^{23} protons/cm^2
- **Need beam current of I > [8 • 10^{35} / (cm^2s)] / [2 • 10^{23} / cm^2]**
  = 4 • 10^{12} electron/s • 1.6 10^{-19} C/e, or I > 0.25 μA
- **Required beam power for I = 100 μA and E = 10 GeV is 1 MW,**
  to be provided by RF