Hadron Structure Theory I

Alexei Prokudin

PennState
Berks

The plan:

- Lecture I:

  Structure of the nucleon

- Lecture II

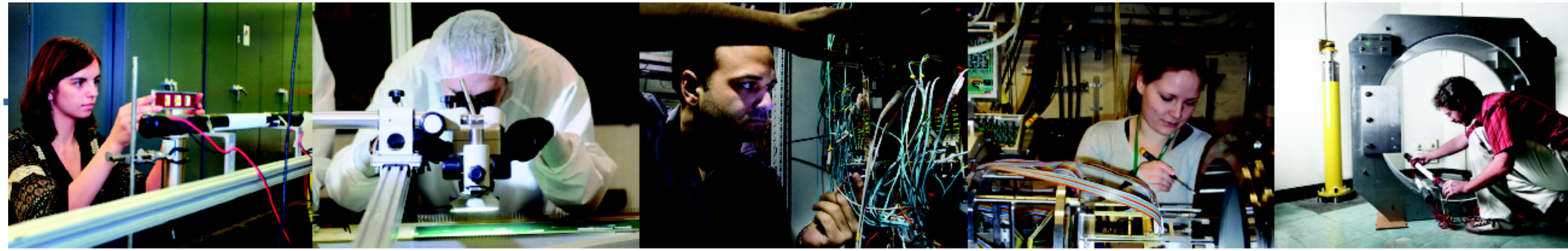
  Transverse Momentum Dependent distributions (TMDs)
  Semi Inclusive Deep Inelastic Scattering (SIDIS)

- Tutorial

  Calculations of SIDIS structure functions using Mathematica

- Lecture III

  Advanced topics. Evolution of TMDs



The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

RECOMMENDATION I

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.

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*

…

- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*

RECOMMENDATION III

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier …

DOE funded Topical Collaboration for theory

TMD Collaboration

5 years of funding of **$2,160,000**
18 institutions
Theory, phenomenology, lattice QCD
Several postdoc positions.
2 tenure track positions: Temple, NMSU
Support of undergraduates.

The TMD Collaboration
Spokespersons: William Detmold (MIT) and Jianwei Qiu (BNL)

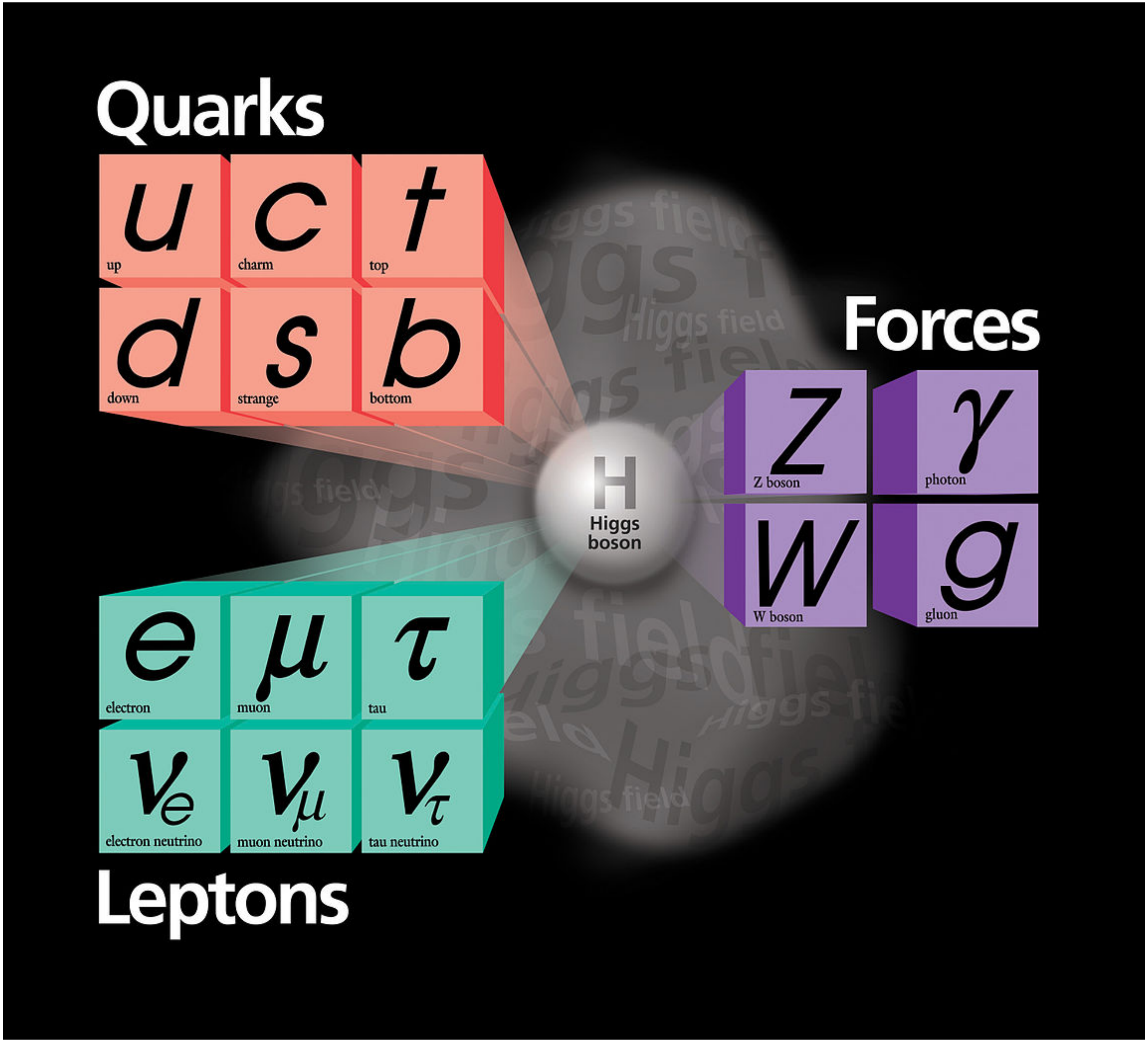
Co-Investigators - (in alphabetical order of institutions):
Jianwei Qiu and Raju Venugopalan (Brookhaven National Laboratory)
Thomas Mehen (Duke University)
Ted Rogers (Jefferson Laboratory and Old Dominion University)
Alexei Prokudin (Jefferson Laboratory and Penn State University at Berks)
Feng Yuan (Lawrence Berkeley National Laboratory)
Christopher Lee and Ivan Vitev (Los Alamos National Laboratory)
William Detmold, John Negele and Iain Stewart (MIT)
Matthias Burkardt and Michael Engelhardt (New Mexico State University)
Leonard Gamberg (Penn State University at Berks)
Andreas Metz (Temple University)
Sean Fleming (University of Arizona)
Keh-Fei Liu (University of Kentucky)
Xiangdong Ji (University of Maryland)
Simonetta Liuti (University of Virginia)

- 5 years of funding
- 18 institutions
- Theory, phenomenology, lattice QCD
- Several postdoc and tenure track positions to be created
- "To address the challenges of extracting novel quantitative information about the nucleon's internal landscape"
- "To provide compelling research, training, and career opportunities for young nuclear theorists"

Why is it so important for theory? We are a data-driven science!

PennState Berks

Standard model



Electromagnetism (photon)

Atomic and Molecular Binding

Gravitation (graviton)

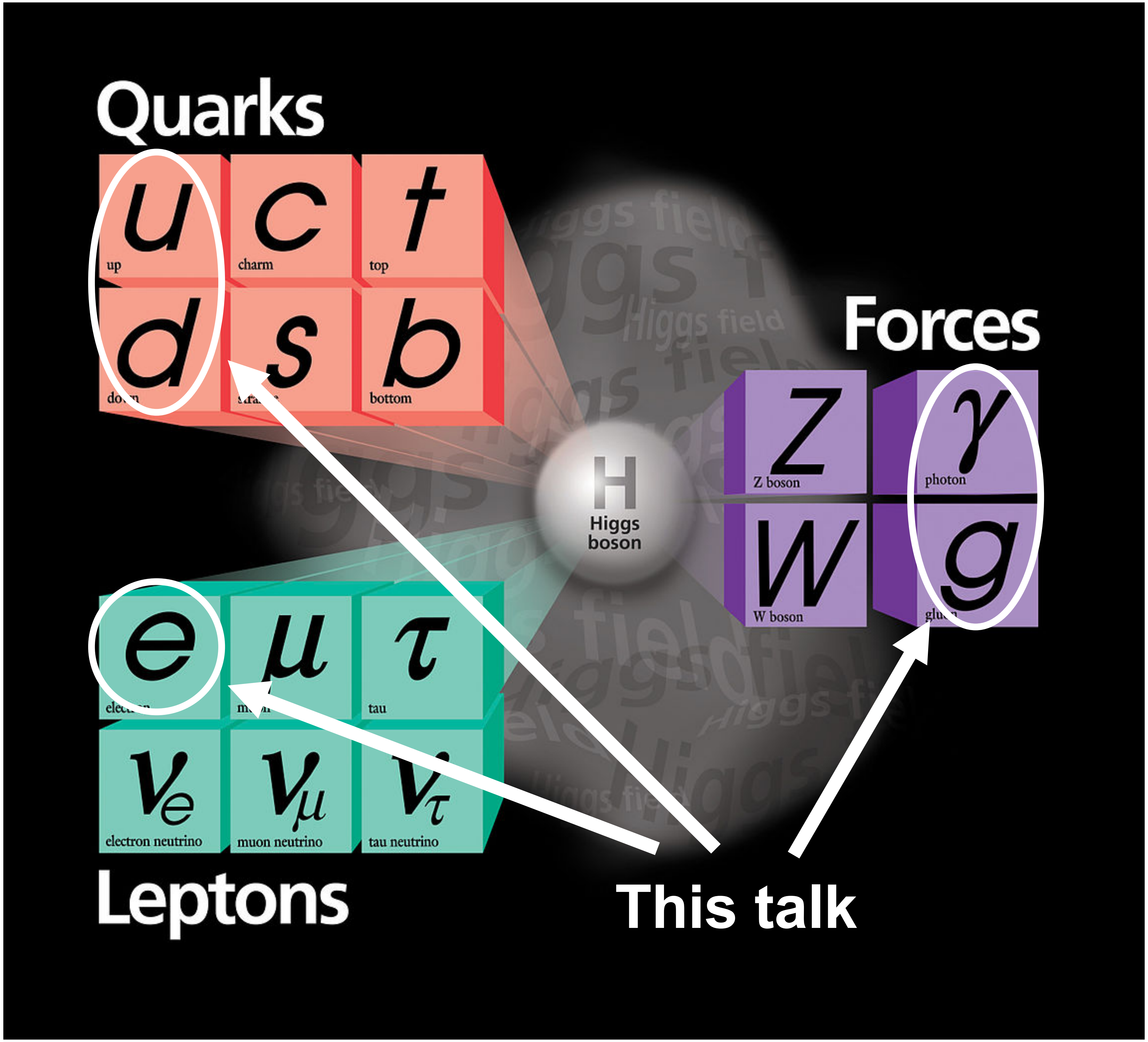
Stars and Galaxies

Weak Nuclear Interaction (W,Z bosons)

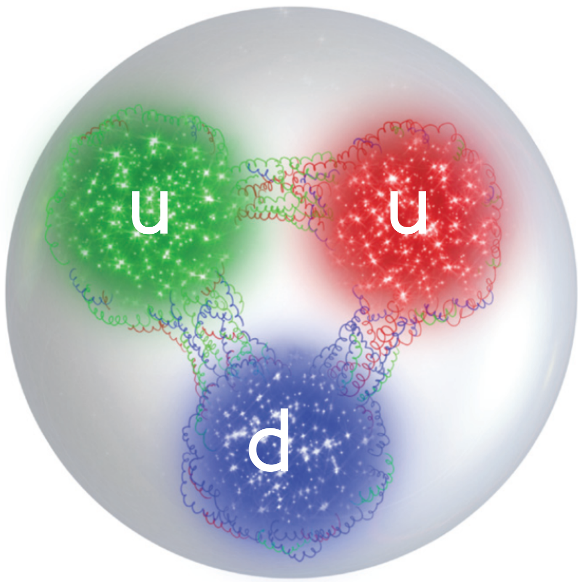
Nuclear Beta Decay

Strong Nuclear Interaction (gluon)

Nuclear Binding

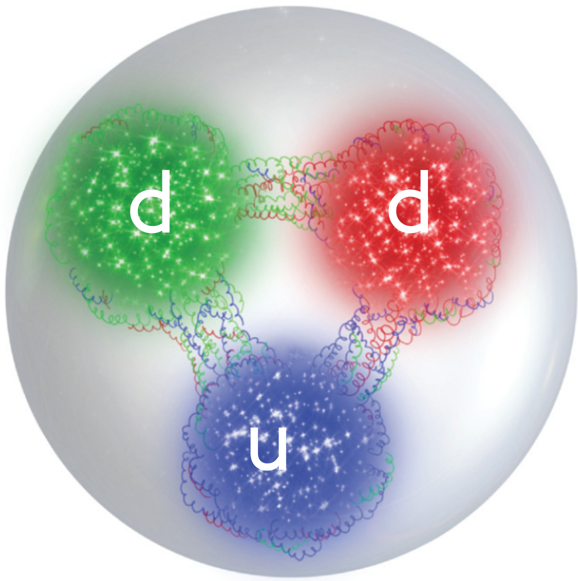

Quarks
u
up
c
charm
t
top
d
s
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
H
Higgs boson
e
μ
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
This talk

Proton



Two "up"
one "down"

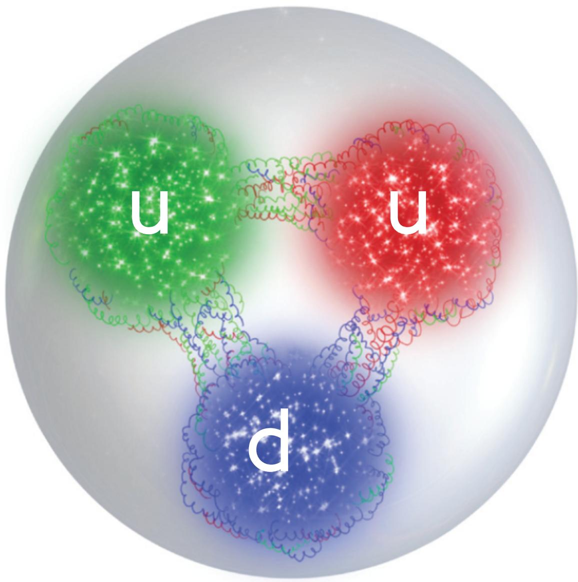
Neutron



Two "down"
one "up"

Proton

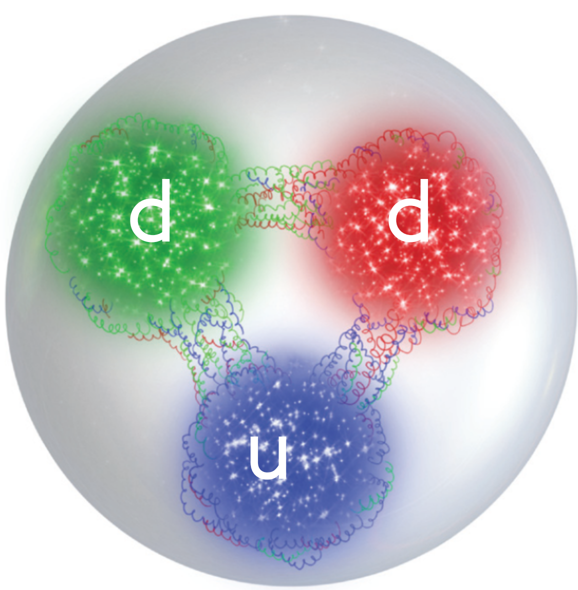
Charge



2/3 + 2/3 -1/3 = +1

Quark charges
are fractional
of positron's charge

Neutron

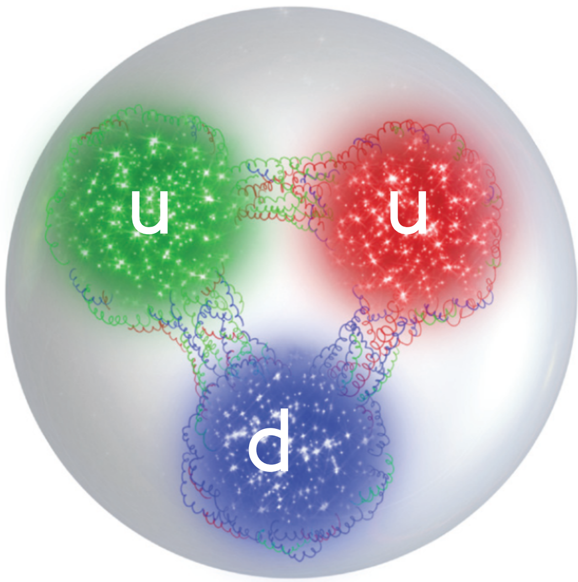


2/3 - 1/3 -1/3 = 0

Quarks are
bound (confined)
by strong interaction
(gluons)

Quark model

Proton

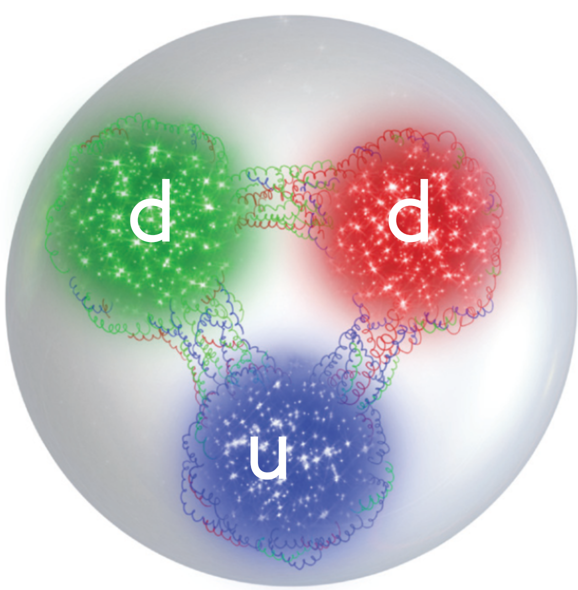


Charge

$2/3 + 2/3 - 1/3 = +1$

Quark charges
are fractional
of positron's charge

Neutron



$2/3 - 1/3 - 1/3 = 0$

Quarks are
bound (confined)
by strong interaction
(gluons)

No evidence of free quarks
observed directly in experiment

Long distance - quarks
are **confined** in hadrons

Short distance - quarks
behave as if they were free

Asymptotic freedom -
later in this talk!

PennState Berks

Quantum Electro Dynamics and Quantum Chromo Dynamics

QED

Gauge theory U(1)

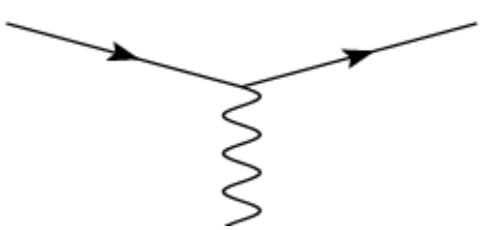
Force carrier:

photon (electrically neutral)

electron

positron

Interaction $\alpha_{em} \simeq \frac{1}{137}$



Quantum Electro Dynamics and Quantum Chromo Dynamics

QED

Gauge theory U(1)

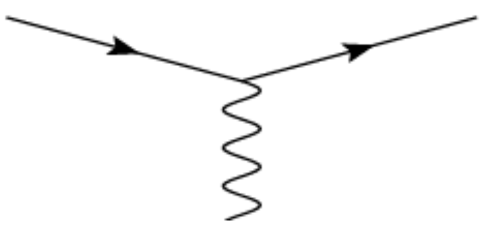
Force carrier:

 photon (electrically neutral)

 electron

 positron

Interaction $\alpha_{em} \simeq \frac{1}{137}$



Richard Feynman, Nobel Prize 1965

"for ... fundamental work in quantum electrodynamics"

Quantum Electro Dynamics and Quantum Chromo Dynamics

QED

Gauge theory U(1)

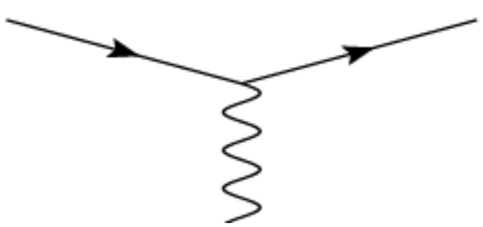
Force carrier:

 photon (electrically neutral)

 electron

 positron

Interaction $\alpha_{em} \simeq \frac{1}{137}$



Richard Feynman, Nobel Prize 1965

"for ... fundamental work in quantum electrodynamics"

QCD

Gauge theory SU(3)

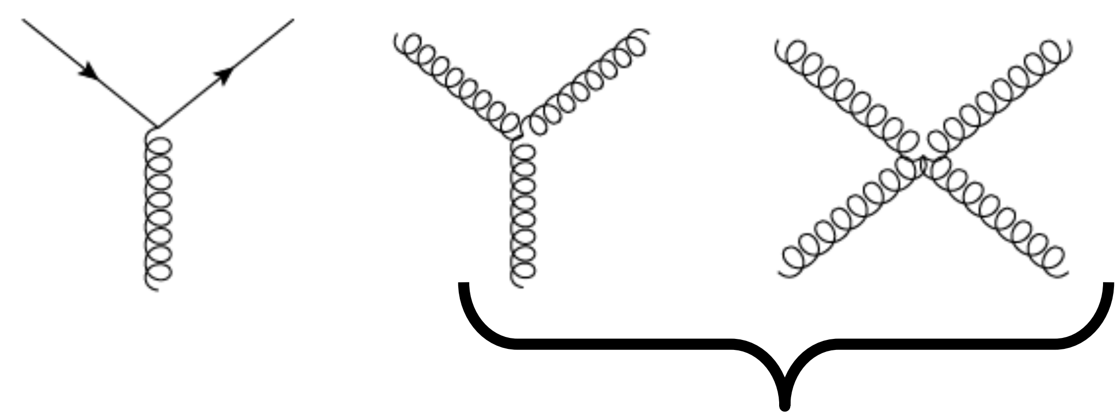
Force carriers:

 gluons (carry color)

 quark

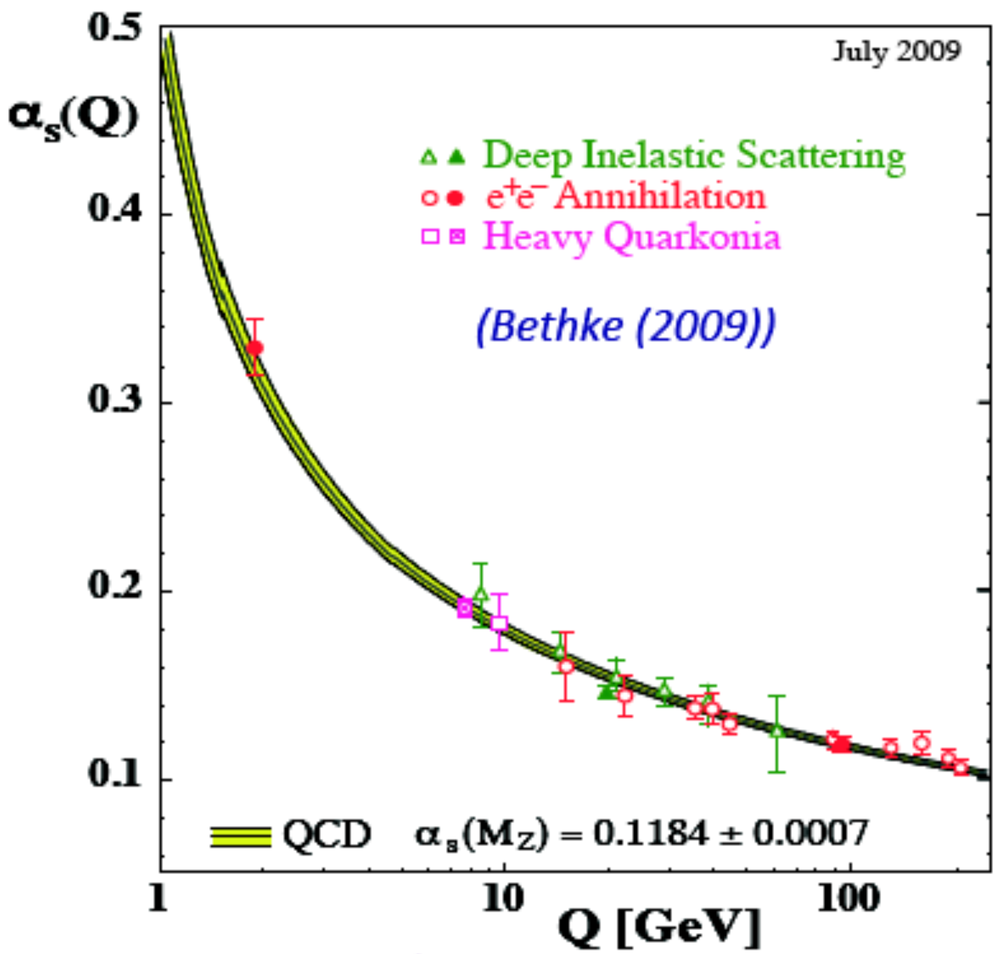
 anti-quark

Interaction $\alpha_s \sim 0.1$ strong



Gluons interact with each other - non abelian theory

Asymptotic freedom



"long" DISTANCE "short"

The coupling depends on the scale – consequence of renormalizability of the theory

At short distances quarks behave as if they were almost free particles!

"for the discovery of asymptotic freedom in the theory of the strong interaction"

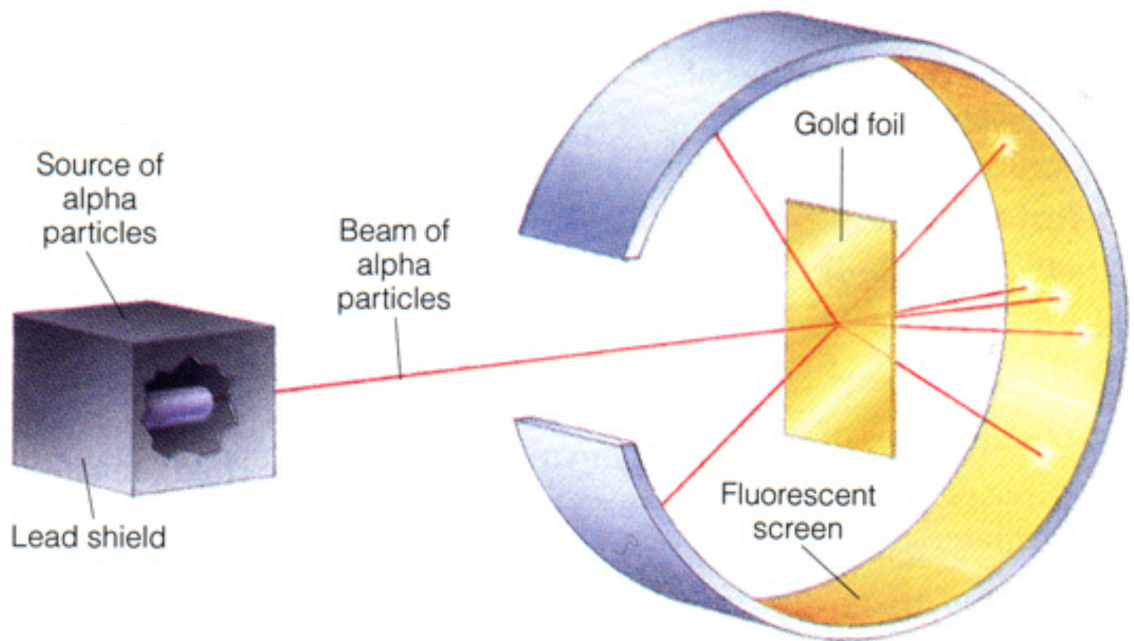


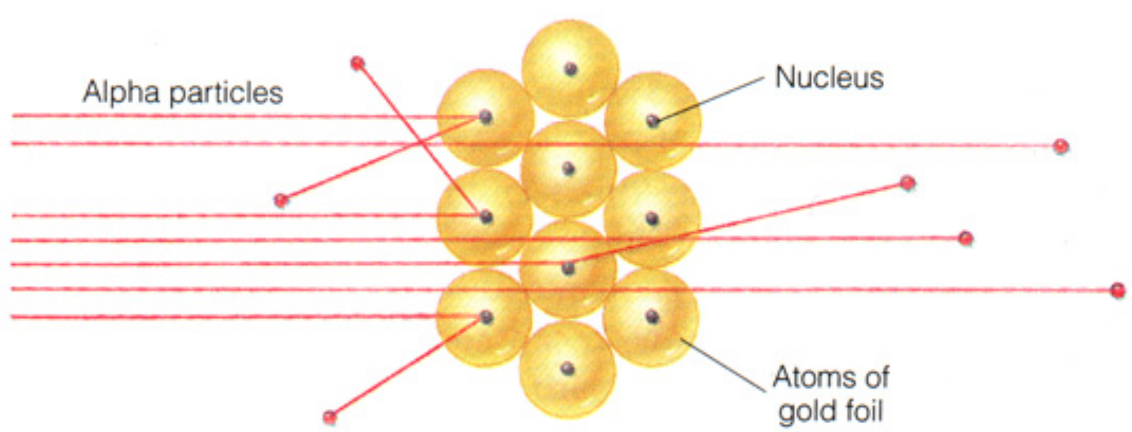

Gross, Politzer, Wilczek, Nobel Prize 2004

Scattering as the method of study

"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"

Ernest Rutherthord, Nobel Prize 1908





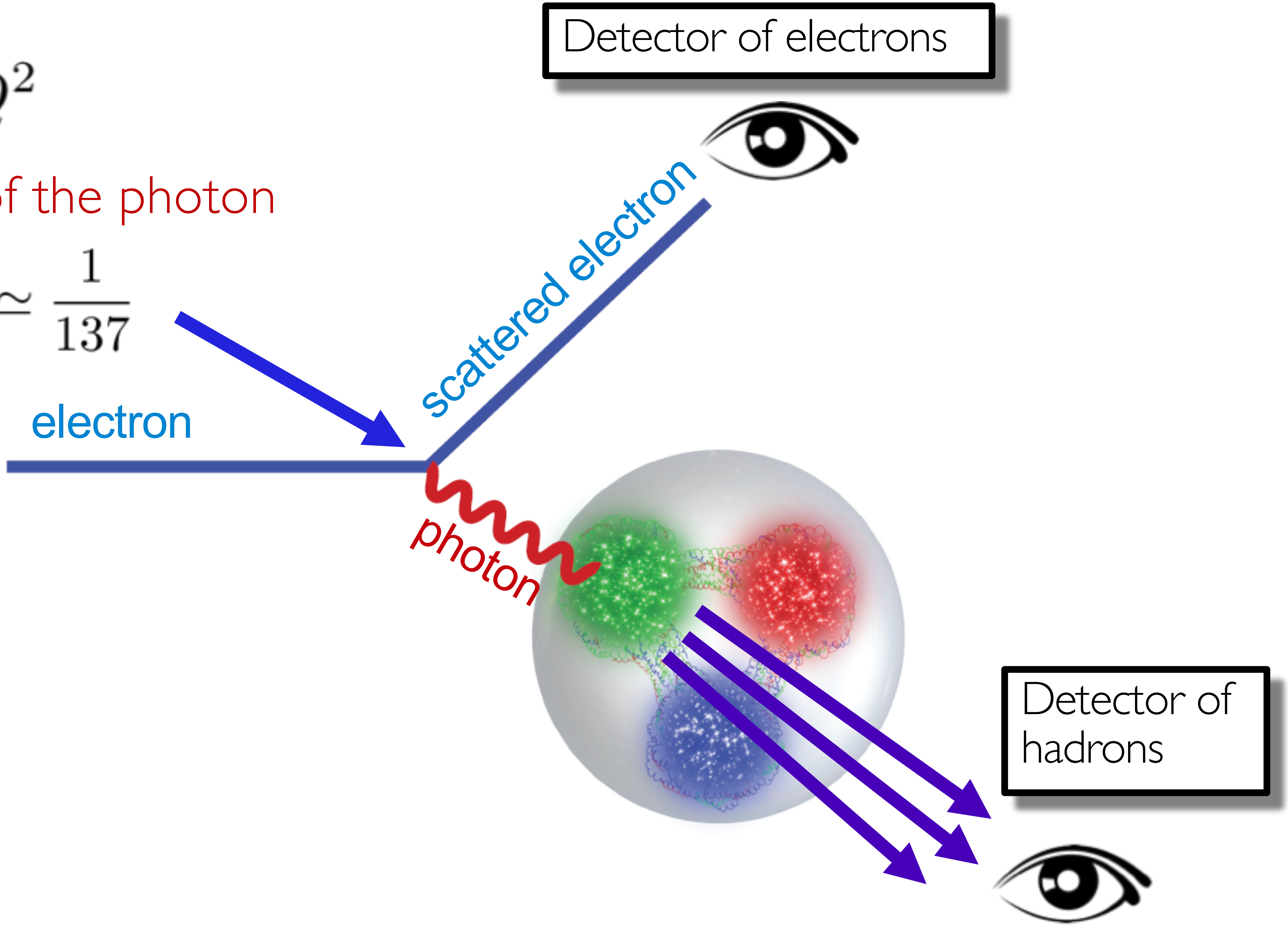
1911

Electron Scattering

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

Virtuality of the photon

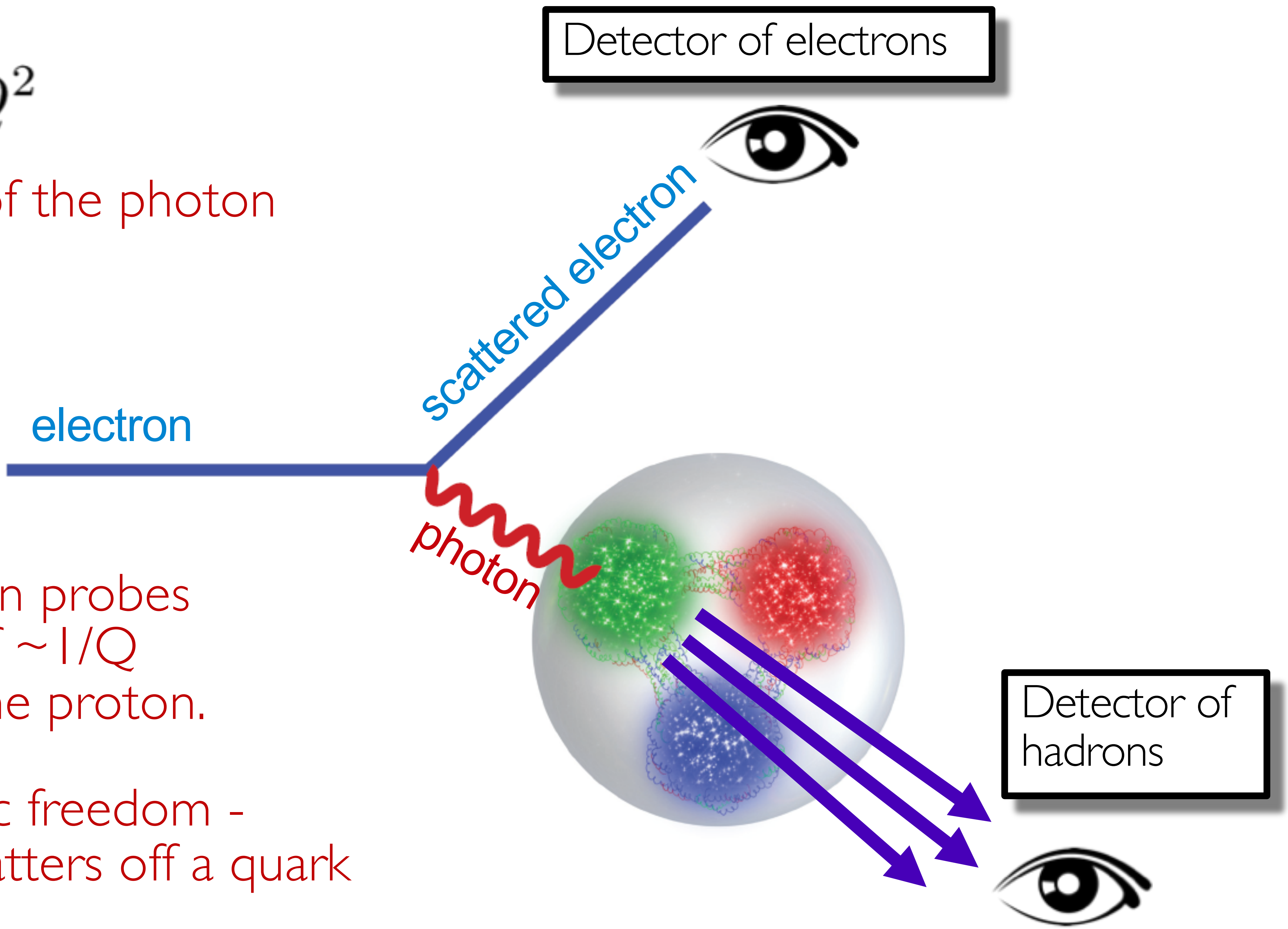
$$\alpha_{em} \simeq \frac{1}{137}$$



Electron Scattering

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

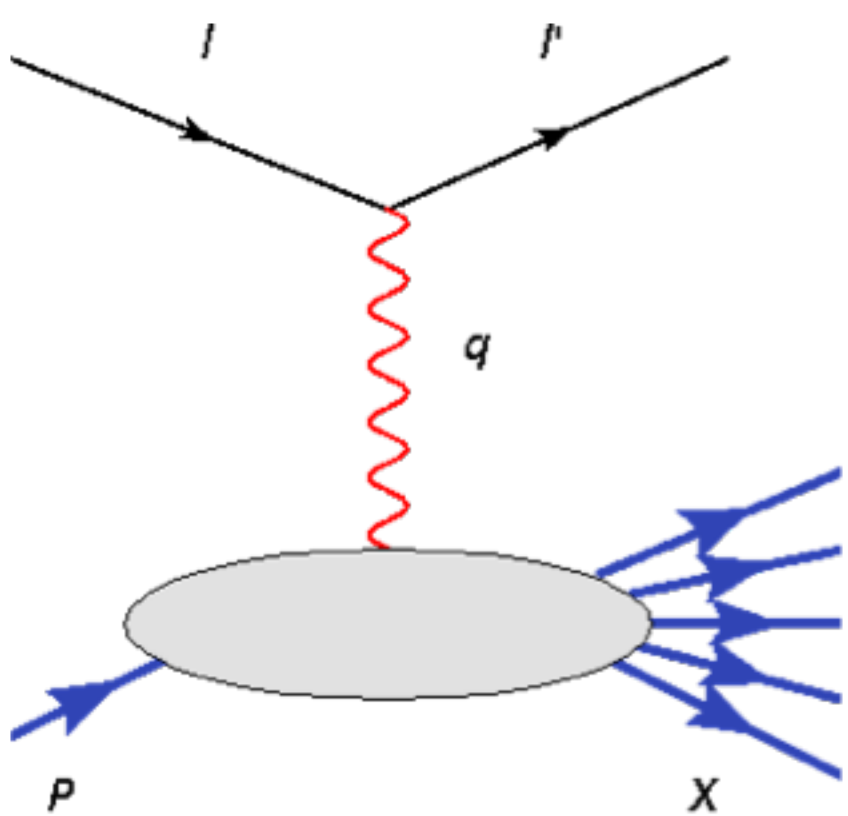
Virtuality of the photon



The photon probes distance of ~1/Q inside of the proton.

Asymptotic freedom - photon scatters off a quark

Electron Scattering: interpretation

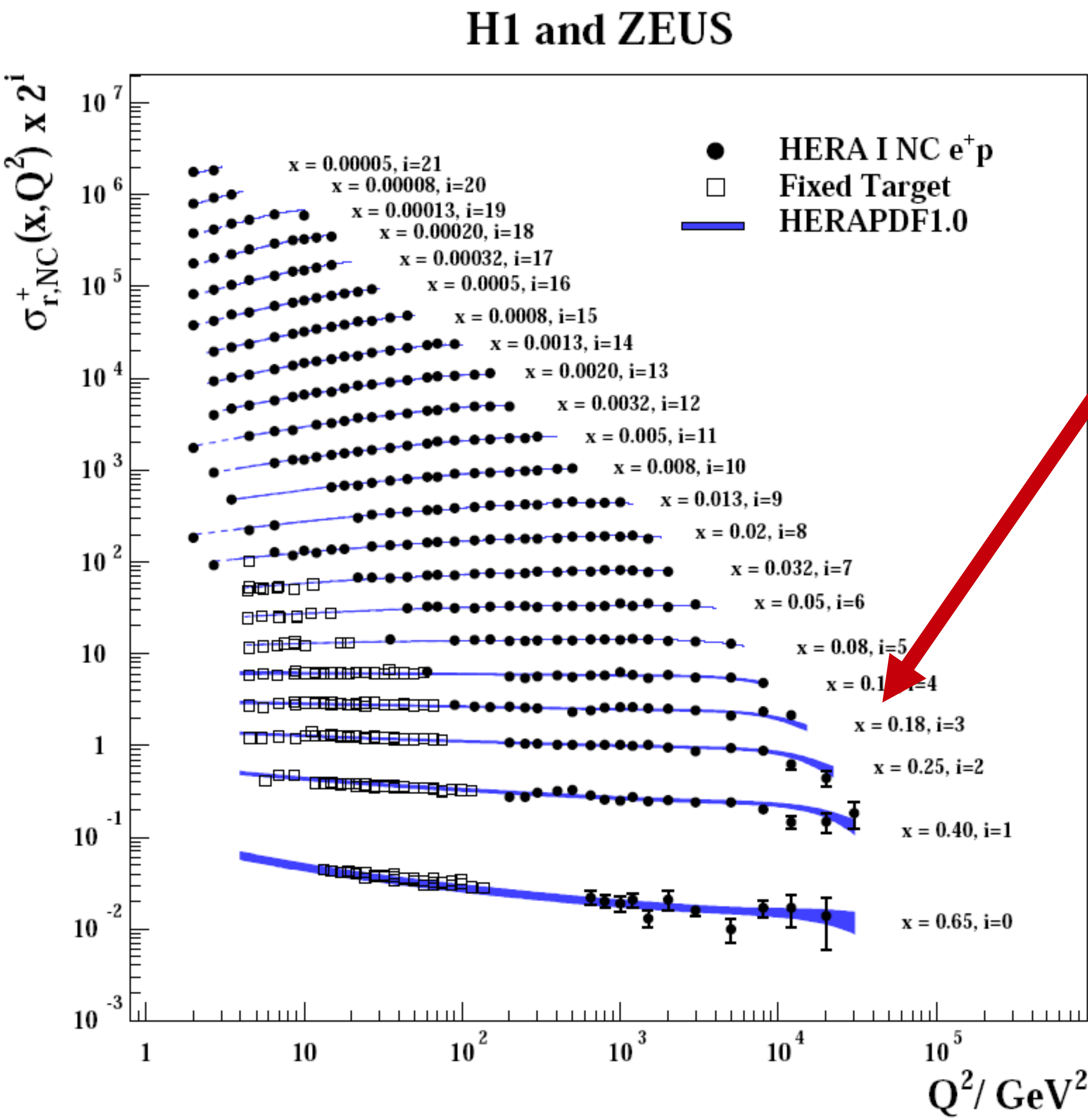


Electromagnetic probe resolves a quark or anti-quark with momentum p=xP inside of the proton of momentum P.

$$x_{Bj} = \frac{Q^2}{2P \cdot q}$$ Bjorken variable

Gives the fraction of longitudinal momentum of the proton carried by the parton

Electron Scattering: interpretation

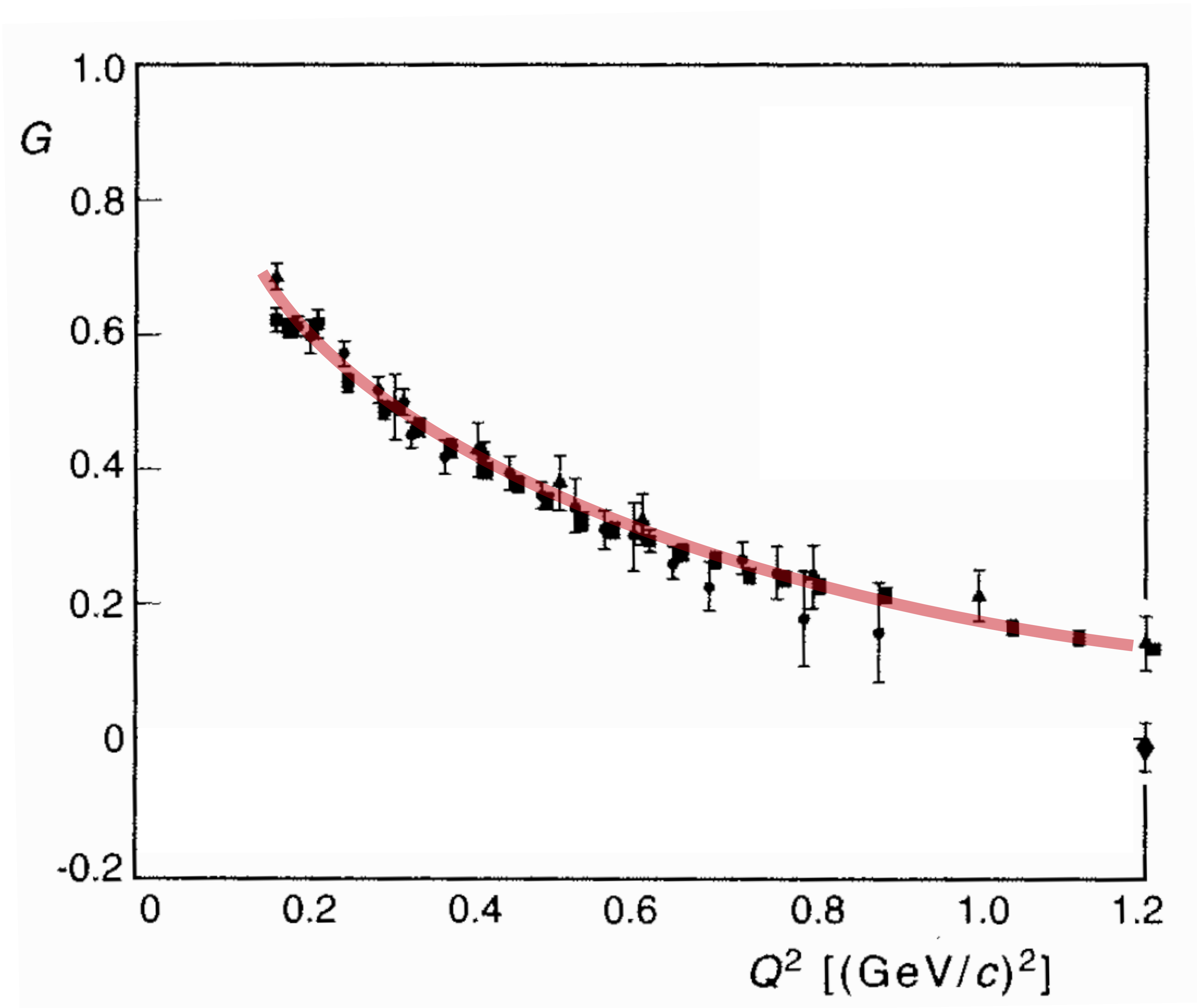


Experimental data

$$x_{Bj} = 0.18$$

Behavior is almost flat – quarks are pointlike

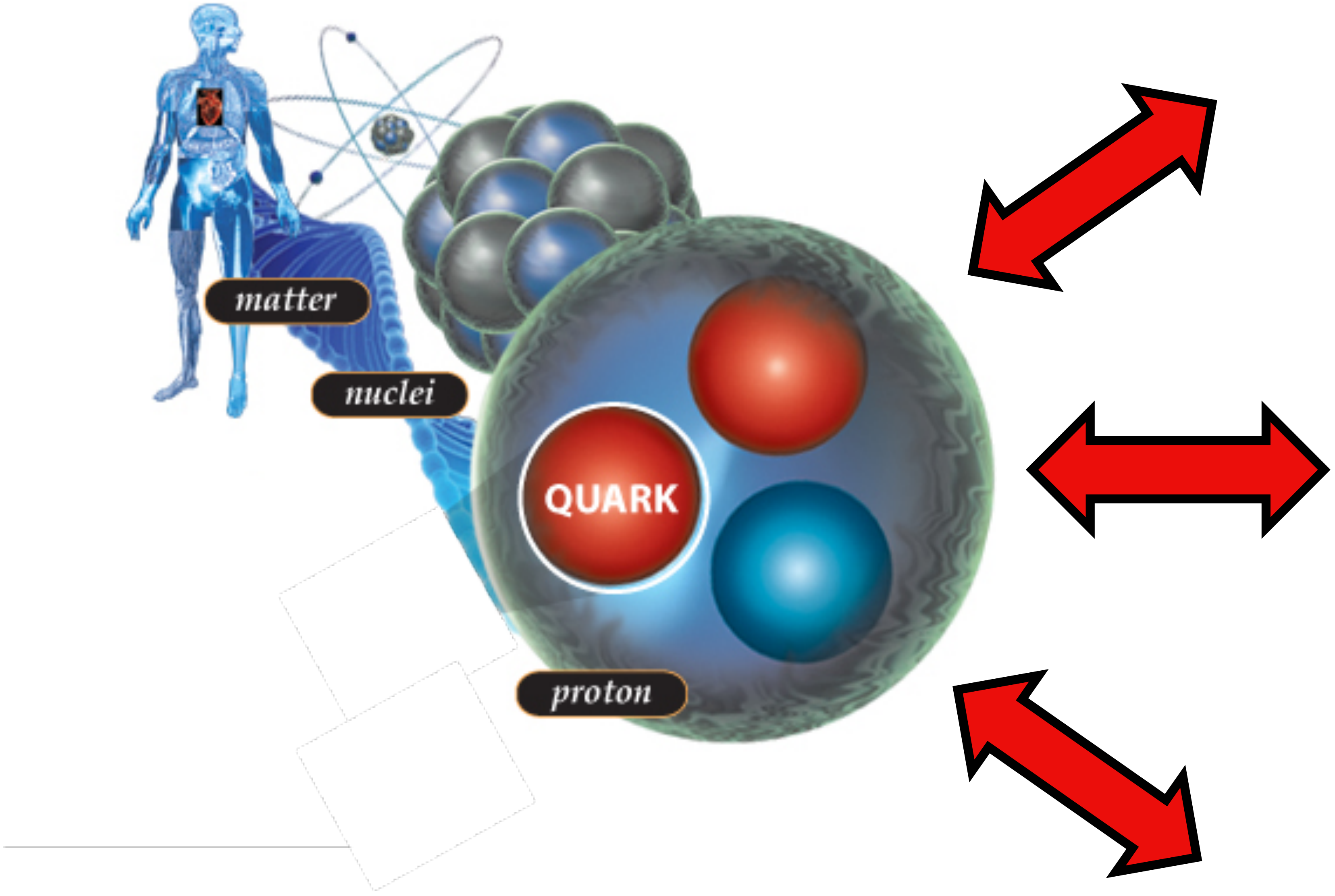
Electron Scattering: interpretation



Unlike the proton itself:

Proton size ~ 1 fm

Exploring the nucleon: a fundamental quest

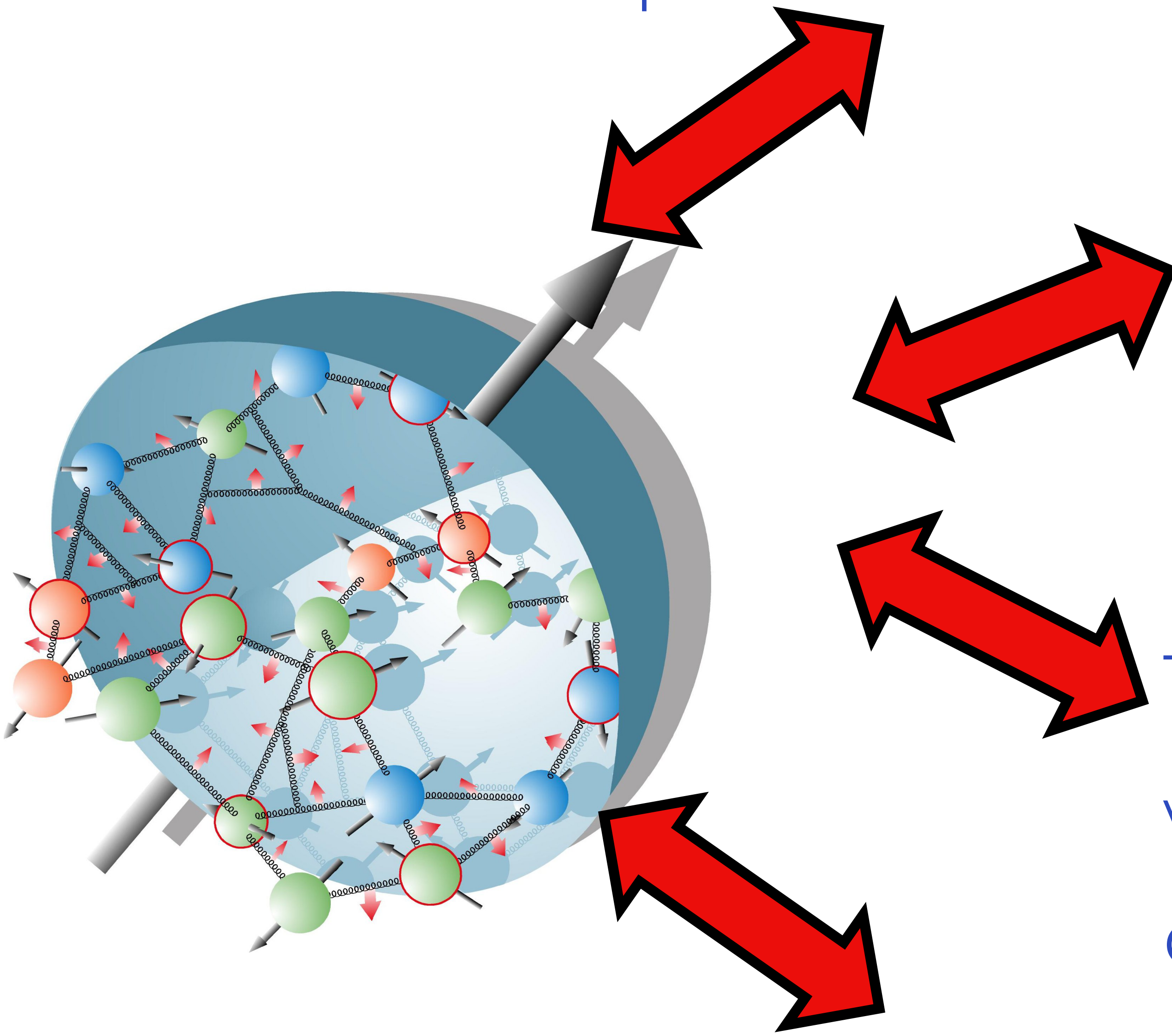


Know what we are made of !

Understand the strong force: "QCD"

Use protons as tool for discovery (e.g. LHC)

Xiangdong Ji at DIS08



Spin is a fundamental quantum degree of freedom

Spin plays a critical role in determining the basic structure of fundamental interactions

Test of a theory is not complete without a full test of spin-dependent decays and scattering

Spin provides a unique opportunity to probe the inner structure of a composite system (such as the proton)

Spin and QCD

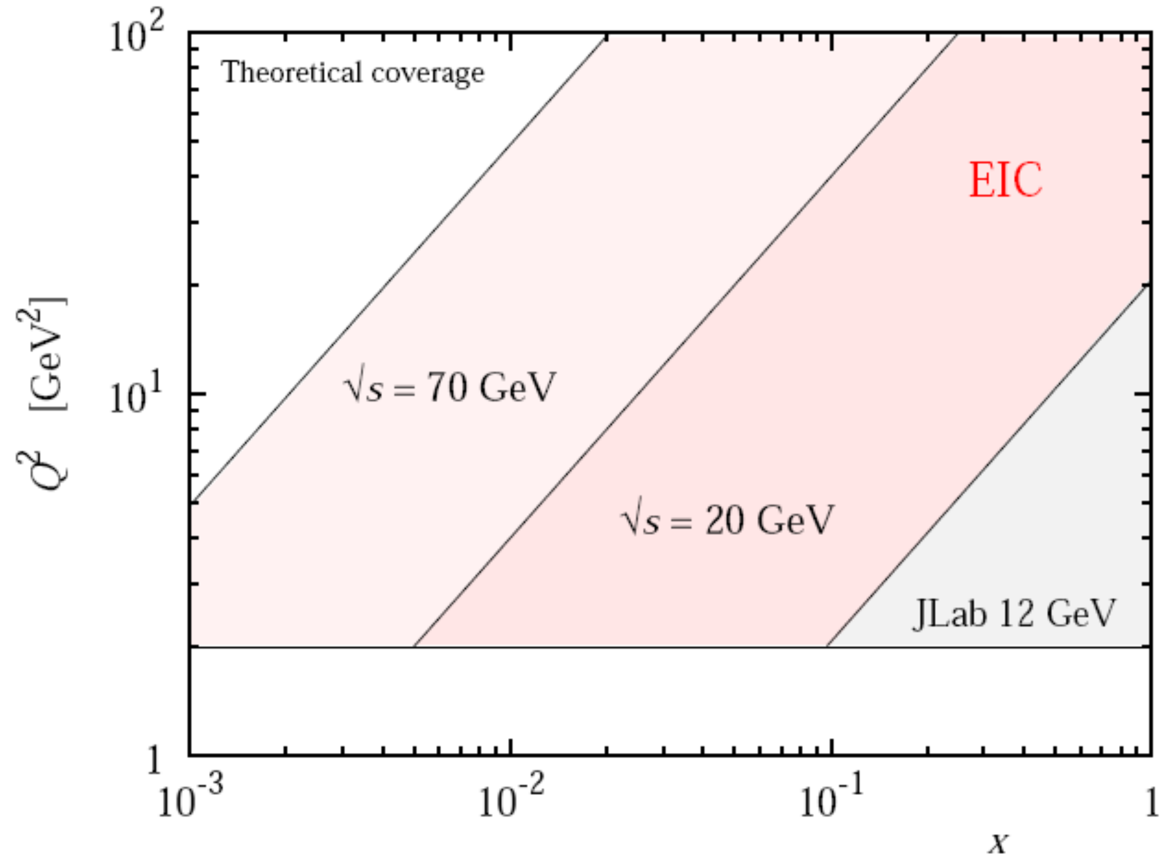
"Experiments with spin have killed more theories than any other single physical parameter"

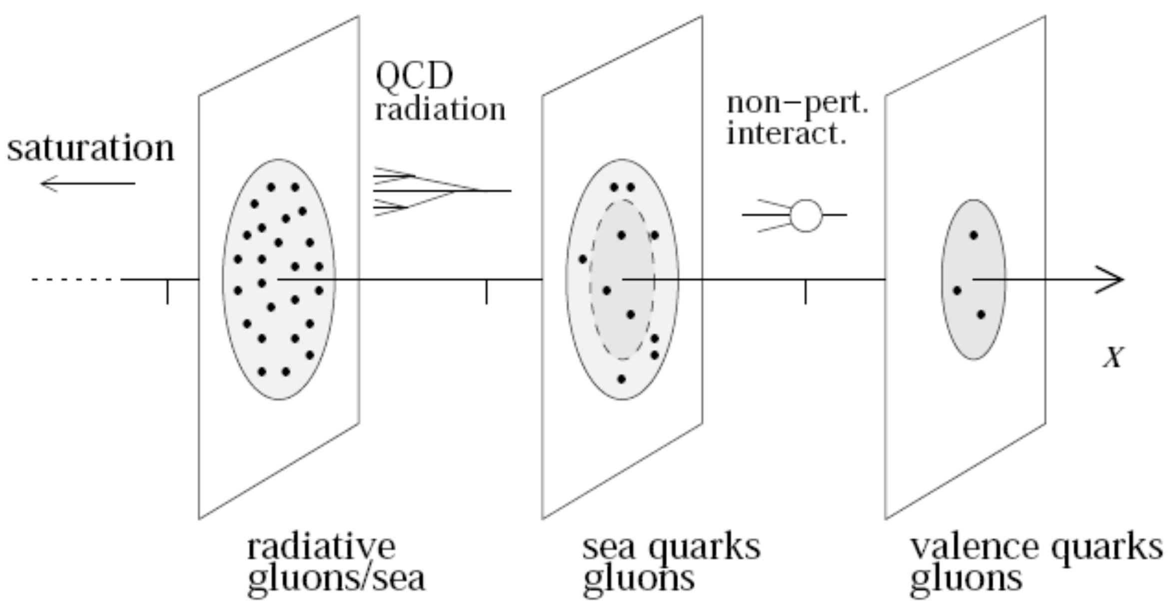
Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

"Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection."

J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).

See lectures by Thomas Ullrich and Anselm Vossen





Nucleon is a many body dynamical system of quarks and gluons

Changing x we probe different aspects of nucleon wave function

How partons move and how they are distributed in space is one of the directions of development of nuclear physics

Technically such information is encoded into Generalised Parton Distributions (GPDs) and Transverse Momentum Dependent distributions (TMDs)

These distributions are also referred to as 3D (three-dimensional) distributions

Unified View of Nucleon Structure