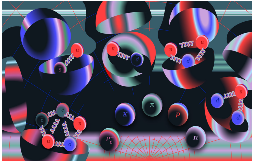
Hadron Spectroscopy: Introduction and a little bit of history

Volker Credé

Florida State University Tallahassee, Florida

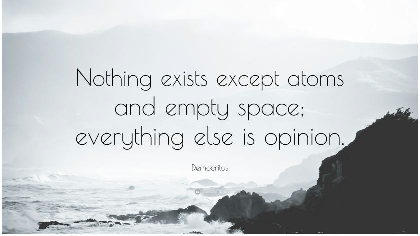
HUGS 2024



Jefferson Lab, Newport News

06/10/2024

Once upon a time ...



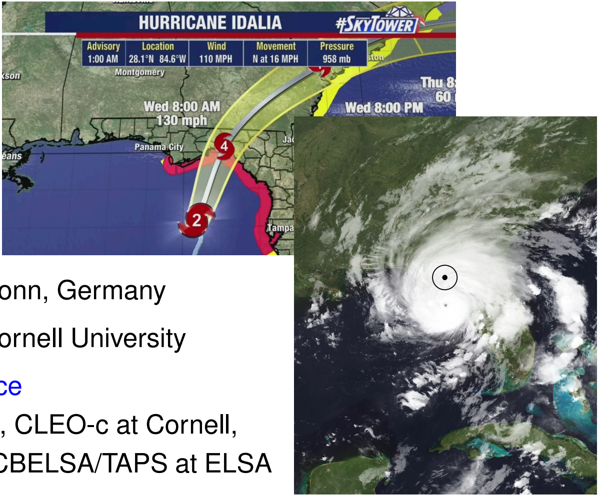
Nothing exists except atoms and empty space; everything else is opinion.

Democritus

Democritus
(c. 460 - c. 370 BC)

... the big scientific questions were solved in the bathtub.

Introduction



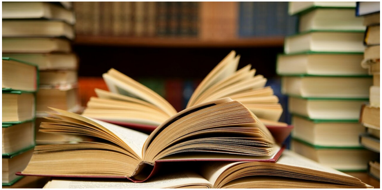
Volker Crede, crede@fsu.edu
Prof. at Florida State U.
Tallahassee, Florida

- Ph.D. at University of Bonn, Germany
- Postdoc at Bonn and Cornell University
- Collaboration Experience
  Crystal Barrel at CERN, CLEO-c at Cornell, CLAS, GlueX at JLab, CBELSA/TAPS at ELSA
- Member of Particle Data Group (PDG)

Literature and References

Talks are not considered a review of the field but personal lectures, partly based on:

- The Review of Particle Physics (2024)
  Particle Data Group, to be published in Phys. Rev. D **110**, 030001 (2024)
- 50 Years of Quantum Chromodynamics
  Eur. Phys. J. C **83**, 1125 (2023)
- Progress towards understanding baryon resonances
  Rept. Prog. Phys. **76**, 076301 (2013)
- A review of the open charm and open bottom systems
  Rept. Prog. Phys. **80**, no. 7, 076201 (2017)
  Rept. Prog. Phys. **86**, no. 2, 026201 (2023)
- The Experimental Status of Glueballs
  Prog. Part. Nucl. Phys. **63**, 74-116 (2009)
- Baryon Spectroscopy
  Rev. Mod. Phys. **82**, 1095-1153 (2010)



Outline of the Lectures

Quantum Chromodynamics (QCD) is (likely) the correct theory of strong interactions:

- However, it is still fairly untested at low energies.
- Spectroscopy is a powerful tool to scrutinize ideas.
    - What are the effective degree of freedom?
    - What are the effective forces?
    - Why are quarks confined?

Lecture 1: Introduction to hadrons, quarks and gluons, spectroscopy

Lecture 2: Light baryons

Lecture 3: Hyperons and heavy (charmed and bottom) baryons

Lecture 4: (Exotic) mesons and glueballs

Lecture 5: Outlook

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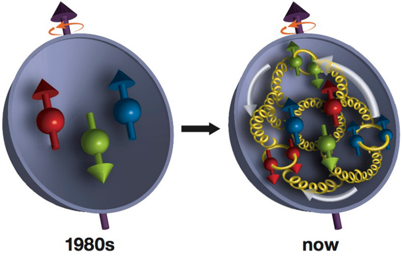
Lecture 5: Outlook

Outline

1. Introduction
   - Some History ...
   - Deep Inelastic Scattering
   - Discovery of Baryons: Infant Quark Model
2. Quantum Chromodynamics
   - Color States
   - Strong-Coupling QCD
3. Open Questions



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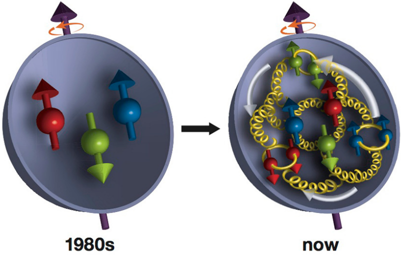
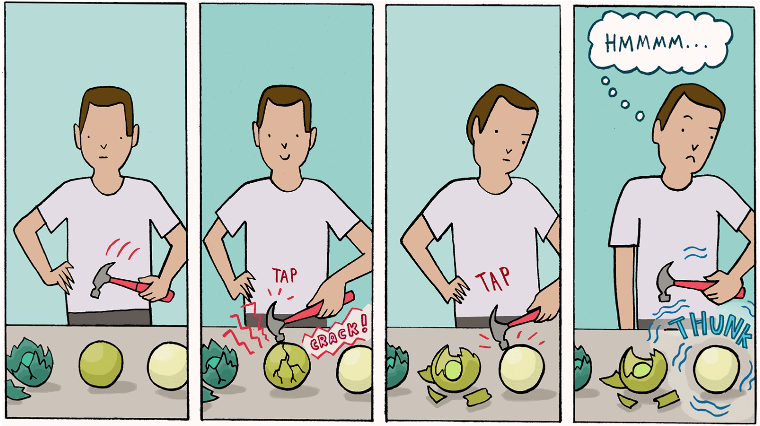
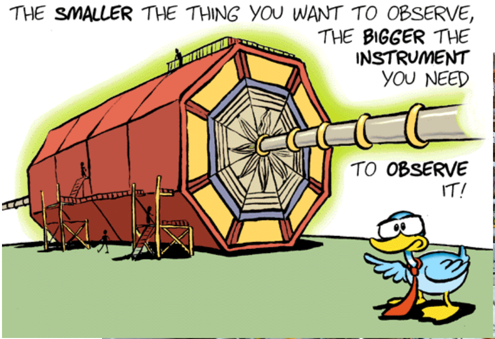


The Particle Physicist

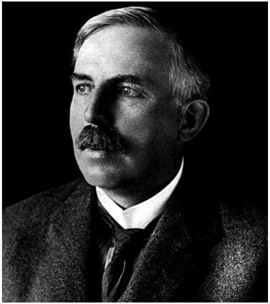
How do we find out what something is made of?



The Microscope



Early Scattering Experiments



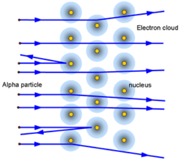
Ernest Rutherford
(30 August 1871 - 19 October 1937)

Landmark series of scattering experiments (1908 –)

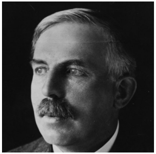
Structure of the Atom paper (1911)

Rutherford expected the relatively massive α particles would pass freely through the plum-pudding atom.

A small number of α particles were actually deflected through very large angles.



Particle Zoo

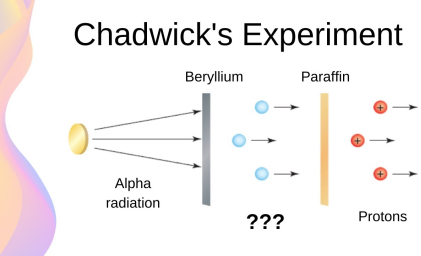


Name “proton” given to H nucleus by Rutherford in 1920

He had discovered earlier that proton was a candidate to be a fundamental particle & building block of nitrogen, and all other heavier atomic nuclei.

1932 Neutron

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



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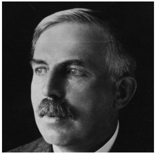

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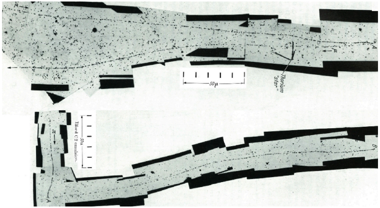
First cosmic pions



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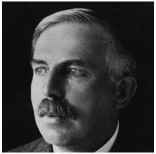

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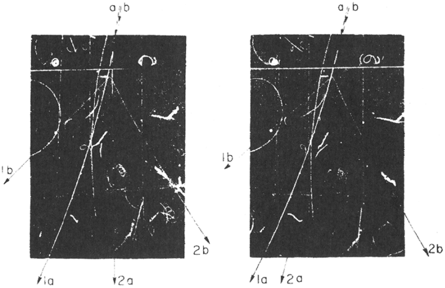
1951 Strange baryons: Λ with $|uds\rangle$

Confirmed at BNL in 1953:

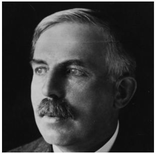
$$\pi^- \ (1.5 \text{ GeV}) \ p \ \rightarrow \ K^0 \ \Lambda^0$$

1953 “Double V” events at BNL ➜



Era of cosmic-ray physics

Particle Zoo



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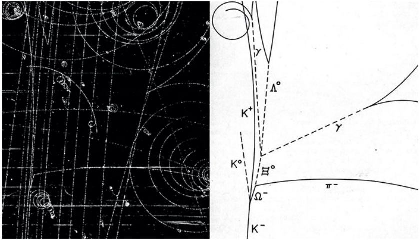
1964 Predicted: Ω^- with $|sss\rangle$

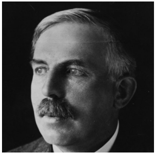
➜ Eightfold Way



Gell-Mann-Okubo mass formula:

$$M_{\Sigma^*} - M_{\Delta} = M_{\Xi^*} - M_{\Sigma^*} = M_{\Omega} - M_{\Xi^*}$$

Particle Zoo



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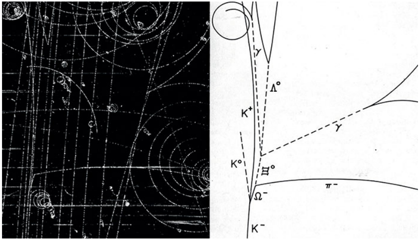
after 1970:
Quantum Chromodynamics



Development of Electroweak Theory in the 1960s

The new theory makes some remarkable predictions:

- Heavy neutral vector boson Z^0

  (+ weak reactions arising from the exchange)
- Existence of charmed quark (discovered in 1974)

Samuel Ting

Burton Richter

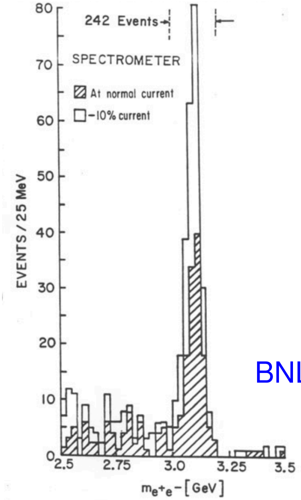
$p\,Be \rightarrow J\,(\rightarrow e^+ e^-)\,X$

at Brookhaven AGS proton synchrotron

$e^+ e^- \rightarrow \psi(1S) \rightarrow e^+ e^-$

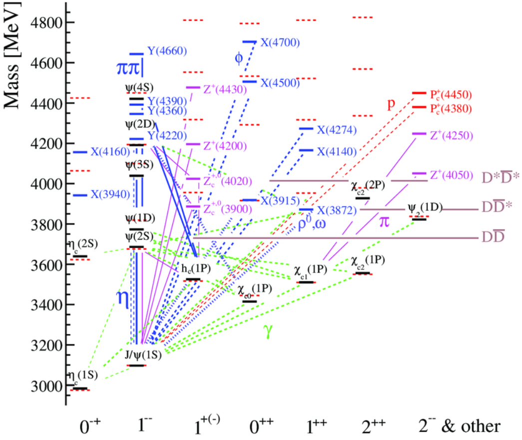
at SLAC SPEAR collider

Charmonium Spectroscopy



BNL

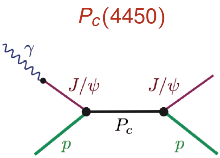
➜

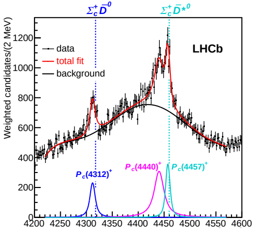


J/ψ Photoproduction Near Threshold

Photoproduction of J/ψ (near threshold) provides clean laboratory to study $c\bar{c}$:

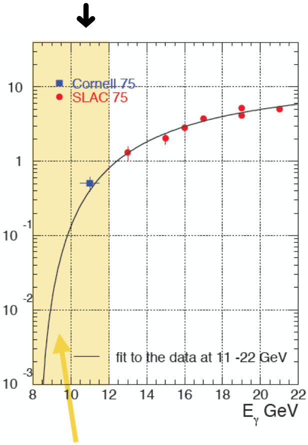
- Probes gluon distribution in proton
- Sensitive to multi-quark correlations
- Intriguing possibility of five-quark interaction





$m_{J/\psi\,p}$ [GeV]

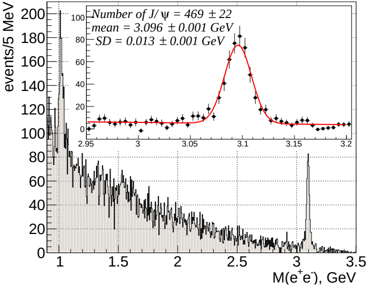
R. Aaij *et al.*, PRL **122**, 222001 (2019)



GlueX energy range

Observation of J/ψ at GlueX

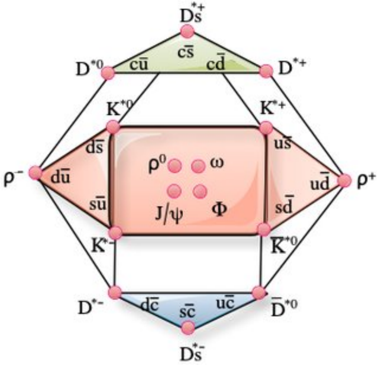
A. Ali *et al.* [GlueX Collaboration], Phys. Rev. Lett. **123**, no.7, 072001 (2019)

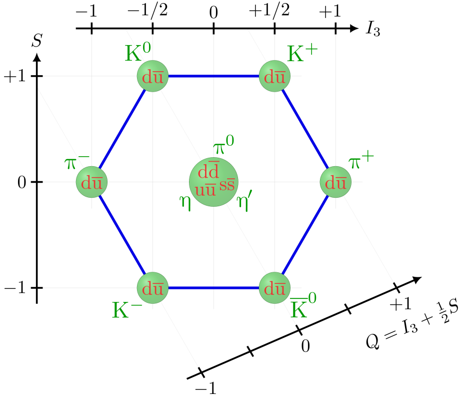


First observation of J/ψ at Jefferson Lab in $\gamma p \to p\, J/\psi \to p\, e^+ e^-$

- First detailed look at cross section near threshold.

SU(4) Multiplet Structure of Mesons

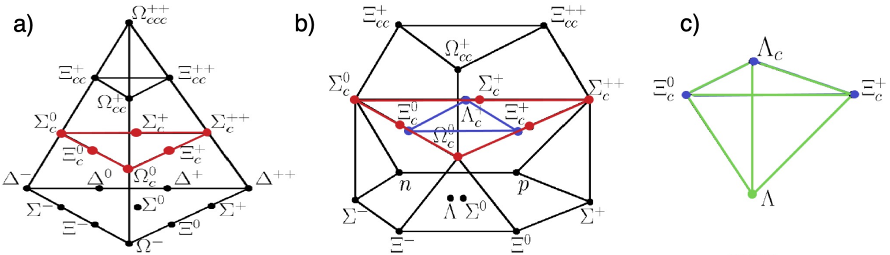


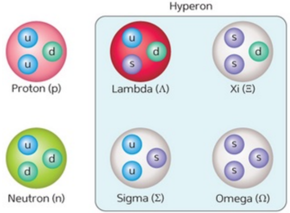


Multiplet structure for flavor SU(3):

$$3 \otimes 3 = 8 \oplus 1$$

SU(4) Multiplet Structure of Baryons





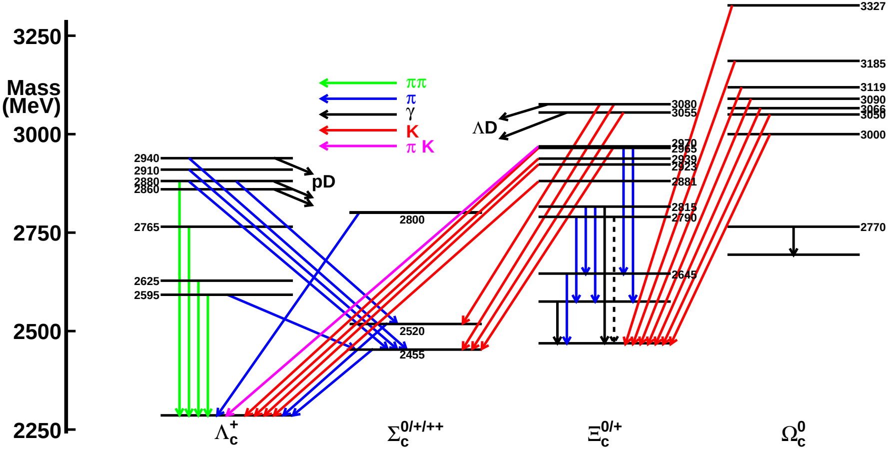
Multiplet structure for flavor SU(3):

$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$$

Multiplet structure for flavor SU(4):

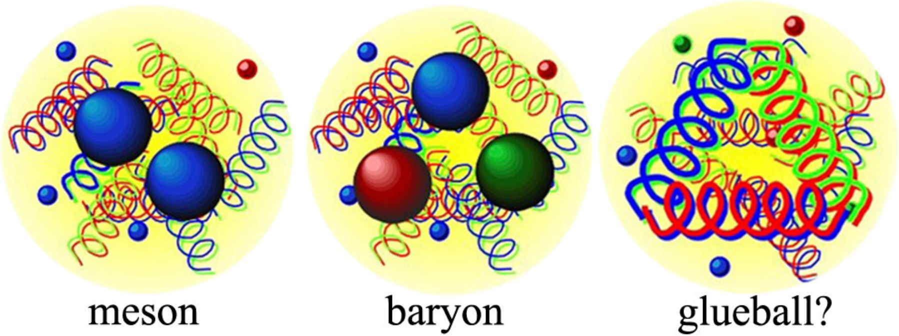
$$4 \otimes 4 \otimes 4 = 20_S \oplus 20_M \oplus 20_M \oplus 4_A$$

Charmed Baryons



Exotic Hadrons: Glueballs, Hybrids, Tetraquarks, etc.

Despite decades of intensive searches, there is no compelling evidence for the existence of glueballs.



BESIII announcement: $X(2370)$ with $J^{PC} = 0^{-+}$ from $J/\psi \to \gamma K_S K_S \eta'$

Phys. Rev. Lett. **132**, 181901 - Published 2 May 2024

Why Hadron Spectroscopy?

Spectroscopy: Powerful tool to study internal dynamics of a composite system.

- Balmer formula ➜ Hydrogen atom
- Magic numbers ➜ Tensor forces in nuclear physics
- Observation of $\Omega\,|sss\rangle$ baryon ➜ Triumph of $SU(3)$
- No 'ionized' proton ➜ Confinement
- Study of $c\bar{c}$ and $b\bar{b}$ families ➜ One-gluon exchange plus linear confinement

Baryons have $N_\mathrm{f} = N_\mathrm{c}$:

- True non-abelian system ➜ Test of QCD-inspired ideas
- Rich dynamics of three-body system ➜ Insights beyond mesons
- Truely complicated ➜ Intellectually and experimentally challenging

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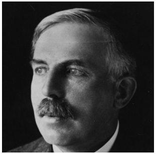
Particle Zoo and Quark Model



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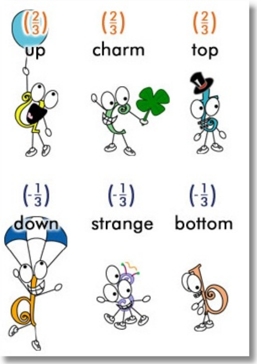


The Quark Families

How do we know about quarks?

UK

How do we know about quarks?

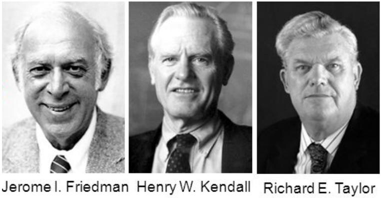
Option 1: Travel to England and visit the Lake District ...

DIS

How do we know about quarks?

Option 2: Deep Inelastic Scattering (DIS)

1960s First evidence that nucleons have a substructure of point-like charged constituents.
(Friedman, Kendall, Taylor)



“[ ] for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which were of essential importance for the development of the quark model in particle physics.”

Nobel Prize 1990

Quark Model

1. New particles (aka “hadrons”) are bound states of three families of fundamental particles (aka “quarks”).
2. Evidence for quarks in e^- and ν + proton scattering experiments
    - Point-like constituents in nucleon.
    - Spin-1/2
    - Fractional charges: $-\frac{1}{3}e$ and $\frac{2}{3}e$ (comparison between e^- and ν scattering)

    Simplest picture: Three quarks in a nucleon.

➜ Standard Model of Particle Physics

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   Simplest picture: Three quarks in a nucleon.

➜ Standard Model of Particle Physics

1. Two spin-$\frac{1}{2}$ families of fermions (leptons, quarks)
2. One spin-1 family of bosons + spin-0 Higgs

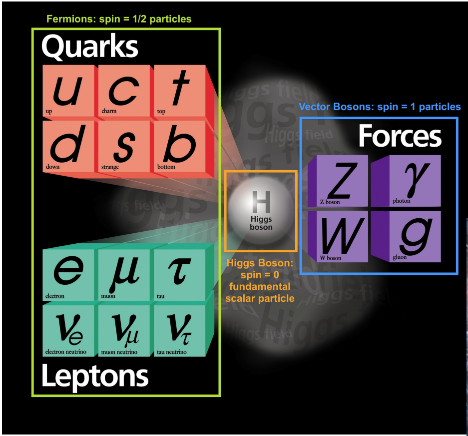
Charge

$+\frac{2}{3}$

$-\frac{1}{3}$

-1

0



Forces: electromagnetic (γ), strong (g), weak ($W^{\pm}$, Z^0), gravitational (graviton) interaction - not part of SM

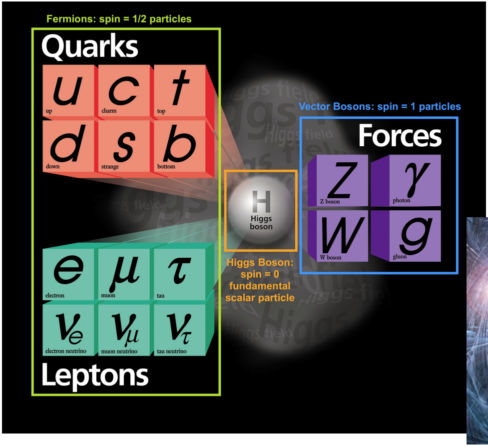
Charge

$+\frac{2}{3}$

$-\frac{1}{3}$

-1

0



Quarks and their Quantum Numbers

	Light Flavors			Heavy Flavors		
Classification	d	u	s	c	b	t
Charge	$-1/3$	$2/3$	$-1/3$	$2/3$	$-1/3$	$2/3$
Isospin I	$1/2$	$1/2$	0	0	0	0
Strangeness s	0	0	-1	0	0	0
Charm c	0	0	0	$+1$	0	0
Beauty (bottom) b	0	0	0	0	-1	0
Truth (top) t	0	0	0	0	0	$+1$
Current mass	4.7	2.2	96 MeV	1.3	≈ 4	≈ 175 GeV

Discovery of Baryons

Early 1950s – Discovery of Δ baryon with isospin $I = 3/2$:

$$\Delta^{++}|\,uuu\,\rangle, \quad \Delta^{+}|\,uud\,\rangle, \quad \Delta^{0}|\,udd\,\rangle, \quad \Delta^{-}|\,ddd\,\rangle$$

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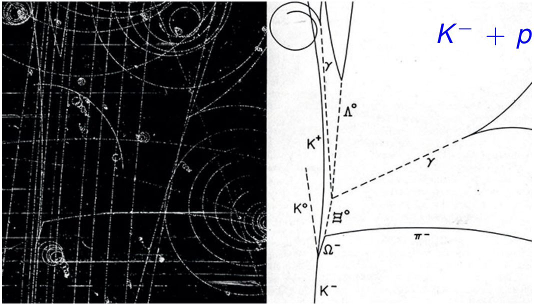
$$\Delta^{++} |\, uuu \,\rangle, \quad \Delta^{+} |\, uud \,\rangle, \quad \Delta^{0} |\, udd \,\rangle, \quad \Delta^{-} |\, ddd \,\rangle$$

1964 – Discovery of Ω^- baryon $|\, sss \,\rangle$ with $S = -3$ & $I = 0$.



$$K^- + p \to \Omega^- + K^+ + K^0$$

Discovery of Baryons

$$\text{Baryons with spin } \frac{3}{2} \begin{cases} \Omega^- & I = 0 \\ \Delta & I = \frac{3}{2} \end{cases}$$

What is the problem?

Discovery of Baryons

$$\text{Baryons with spin } \frac{3}{2} \begin{cases} \Omega^- & I = 0 \\ \Delta & I = \frac{3}{2} \end{cases}$$

What is the problem?

In the simple quark model: Spins all aligned, $|\,\Delta^{++}\,\rangle = |\,u^{\uparrow}\,u^{\uparrow}\,u^{\uparrow}\,\rangle$.

- All quark flavors the same.
- Symmetric wave function

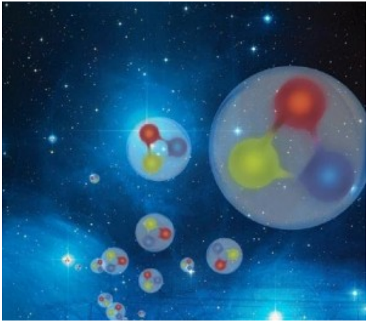
  ➜ Violates the Pauli exclusion principle.

System of identical fermions must have an antisymmetric wave function, i. e. must be antisymmetric under the exchange of any two particles.

Solution: Color Charge

A new degree of freedom (strong charge):

- Any quark (and antiquark) can exist in three different color (anticolor) states.
- Dogma: Only “color singlets” exist in nature.



➜ Color Confinement!!

(No free quarks)

QCD is invariant under rotations in color space:

$\mathrm{SU}(3)_c$ symmetry

Color Charges

Two “color charges:” Color Isospin and Color Hypercharge

(strong interaction analogues to the electric charge)

Quarks	I_3^c	Y^c	Antiquarks	I_3^c	Y^c
r	1/2	1/3	$\bar{r}$	$-1/2$	$-1/3$
g	$-1/2$	1/3	$\bar{g}$	$1/2$	$-1/3$
b	0	$-2/3$	$\bar{b}$	0	$2/3$

By assuming that hadrons are color singlets, we are requiring:

$$Y^c = I_3^c = 0$$

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1. Mesons: $\frac{1}{\sqrt{3}}\,(r\,\bar{r} + g\,\bar{g} + b\,\bar{b})$
2. Baryons (antisymmetric under color exchange):

$$\frac{1}{\sqrt{6}}\,(r_1\,g_2\,b_3 + g_1\,b_2\,r_3 + b_1\,r_2\,g_3 - r_1\,b_2\,g_3 - b_1\,g_2\,r_3 - g_1\,r_2\,b_3)$$

Remember: $\Omega^-|\,sss\,\rangle$

➜ Pauli principle applied to:

$$\Psi|\,qqq\,\rangle = |\,\mathrm{color}\,\rangle_A \cdot |\,\mathrm{space,\ spin,\ flavor}\,\rangle_S$$

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Color Charges

Photons couple to electric charges and gluons couple to color charges.

Flavor independence of strong interactions

➜ All quark flavors – u, d, s, c, b, t – have identical strong interactions (consequence of quarks existing in the same three color states).

Isospin symmetry:

Almost equal masses of proton and neutron.

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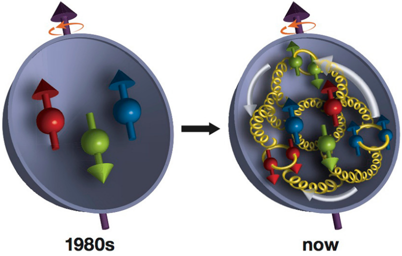


Quantum Chromodynamics

Consider spin states obtained from two spin-$\frac{1}{2}$ particles.

The four spin combinations, $\uparrow\uparrow \quad \uparrow\downarrow \quad \downarrow\uparrow \quad \downarrow\downarrow$, give four eigenstates of $\hat{S}^2$ & $\hat{S}_z$: $2 \otimes 2 = 1 \oplus 3$

$$S = 1 \left\{ \begin{array}{ll} \uparrow_1 \uparrow_2 & S_z = 1 \\ \frac{1}{\sqrt{2}}(\uparrow_1 \downarrow_2 + \uparrow_2 \downarrow_1) & S_z = 0 \\ \downarrow_1 \downarrow_2 & S_z = -1 \end{array} \right.$$

$$S = 0 \left\{ \begin{array}{ll} \frac{1}{\sqrt{2}}(\uparrow_1 \downarrow_2 - \uparrow_2 \downarrow_1) & S_z = 0 \end{array} \right.$$

The singlet state is “spinless.”

➜ Invariant under SU(3) spin transformations.

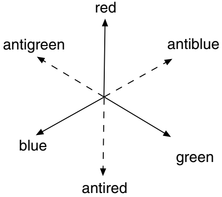
Quantum Chromodynamics

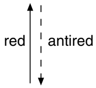
In the same way, “Color Singlets” are “colorless”!!

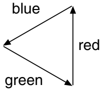
- $3 \otimes \bar{3} = 8 \oplus 1$
- They have zero color quantum numbers: $Y^c = I_3^c = 0$.
- Invariant under SU(3) color transformations.

Consider color wave function for $q\bar{q}$ (mesons):

Combination of color with anticolor (similar to combining flavor with antiflavor).







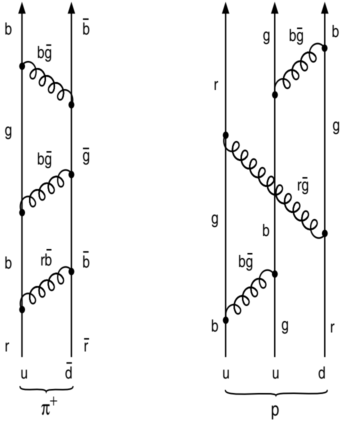
Examples: Proton and Pion

The π^+ meson has three possible color combinations:

$$|\,\pi^+\,\rangle \;=\; \begin{cases} |\,u_r\,\bar{d}_{\bar{r}}\,\rangle \\ |\,u_b\,\bar{d}_{\bar{b}}\,\rangle \\ |\,u_g\,\bar{d}_{\bar{g}}\,\rangle \end{cases}$$

To obtain a color neutral baryon, each quark must have a different color:

$$|\,p\,\rangle \;=\; \begin{cases} |\,u_b\;u_r\;d_g\,\rangle \\ |\,u_r\;u_g\;d_b\,\rangle \\ \ldots \end{cases}$$



Color

Question:

How do we know that quarks exist in just three color states?

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Define *R* ratio:

$$R \equiv \frac{e^+ e^- \rightarrow \text{hadrons}}{e^+ e^- \rightarrow \mu^+ \mu^-} \qquad \text{(almost energy independent)}$$

Color

Cross section for electron-positron to quark-antiquark pairs:

$$\sigma(e^+e^- \to q_f\bar{q}_f) = N_c\, e_f^2\, \sigma(e^+e^- \to \mu^+\mu^-)$$

1. Rate for producing quark pairs ($f = u, d, ...$) proportional to N_c.
2. Proportional also to e_f^2 (first-order electromagnetic process)
   ➜ Identical mechanism for μ pairs.
3. More precisely:

$$R = R_0 \equiv N_c(e_u^2 + e_d^2 + e_s^2 + e_c^2 + e_b^2)$$

$$= \frac{11}{9} N_c \approx 3.7 \qquad (\text{for } N_c = 3)$$

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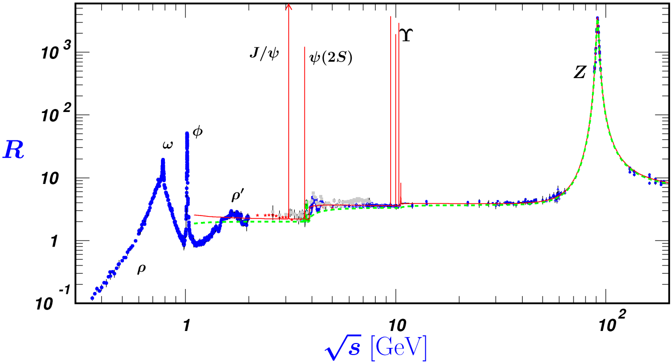
$$R = R_0 \left(1 + \frac{\alpha_s}{\pi}\right) \qquad \text{(some corrections)}$$

Color

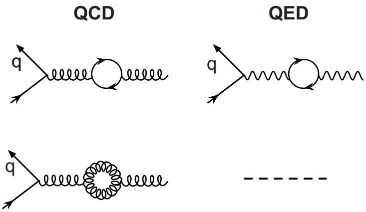
Data are in excellent agreement with theoretical predictions for number of colors $N_c = 3$.

➜ Quarks exist in just three colors!!

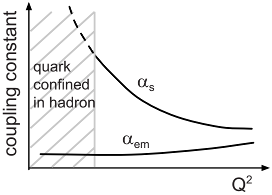


Gluons

Note: Gluon-gluon interactions have no analogue in QED:



Gluon self-coupling leads to exotic states called *glueballs*.



Properties of QCD:

- Color confinement
- Asymptotic freedom: strong interaction becomes weaker at short distances; 1973 ➜ 2004 Nobel Prize

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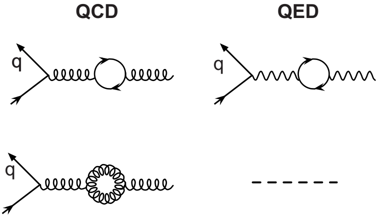

“vacuum polarization effects”

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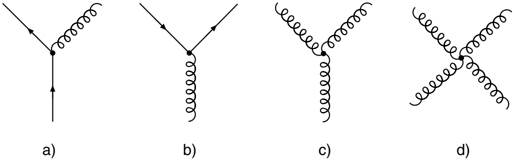

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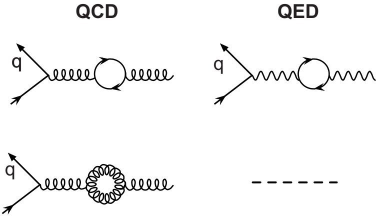

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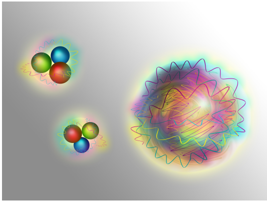
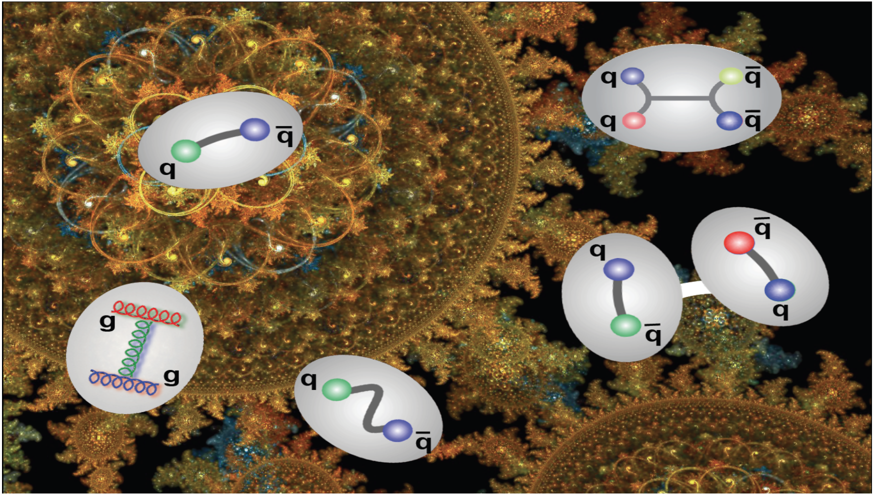
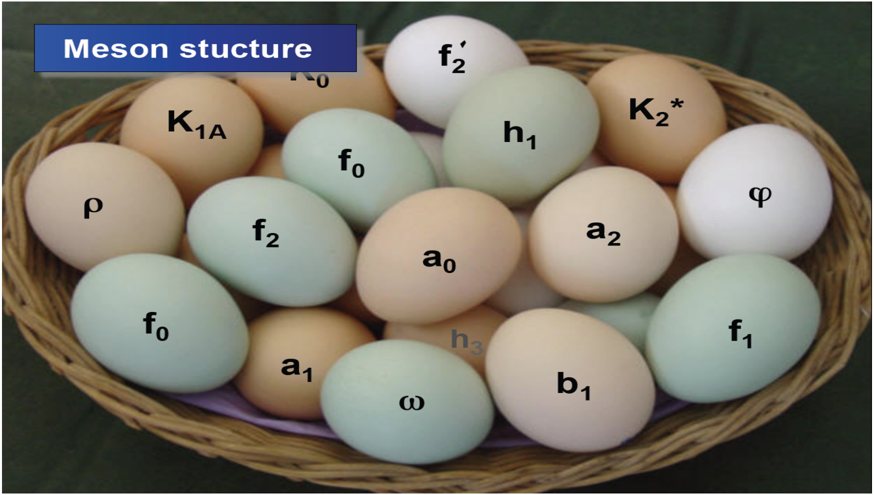


White States - Color Singlets



Other Surprises?



Other Surprises?

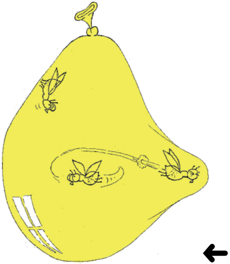
GlueX Collaboration

Strong-Coupling QCD

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{q}\,(i\gamma_\mu D^\mu \; - \; m_q)\,q \; - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

QCD = Theory of strong force

Strong processes at larger distances and at small (soft) momentum transfers belong to realm of non-perturbative QCD.



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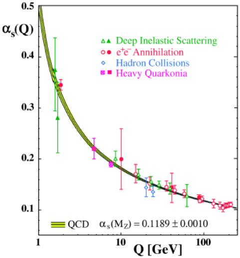

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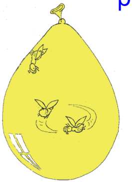
“pQCD”



Confinement & Strong QCD

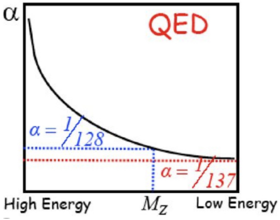
“Hadrons”

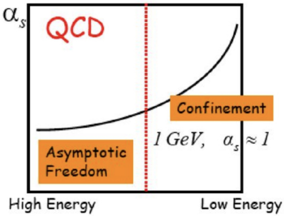
Asymptotic Freedom

Non-Perturbative QCD

In the Standard Model of particle physics, strong interactions are described by QCD, a local gauge theory with quarks and gluons as elementary degrees of freedom:

- Interaction governed by strong fine-structure constant α_s (dependent on four-momentum transfer *Q* of a given strong process).
- As α_s decreases with increasing *Q*, perturbation theory can be applied in high-energy reactions.





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- As α_s decreases with increasing Q, perturbation theory can be applied in high-energy reactions.
- At momentum scales given by typical hadron masses, perturbative QCD breaks down due to rapid increase of α_s.
  - ➜ This is the realm of 'strong QCD'. Not only α_s changes but also the relevant degrees of freedom change from *current* to *constituent quarks,* instantons, and vacuum condensates.

To understand the transition to strong QCD is one of the most challenging intellectual problems.

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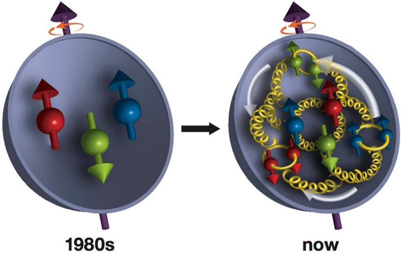

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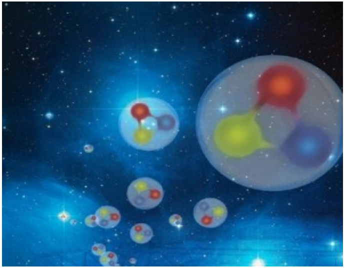


How does QCD give rise to excited hadrons?

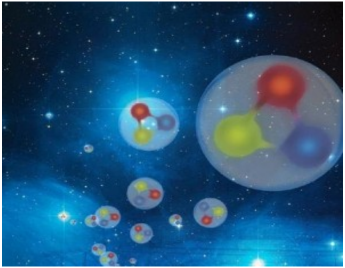
1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

Baryons: What are the fundamental degrees of freedom inside a nucleon? Constituent quarks? How do the degrees change with varying quark masses?

Mesons: What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, tetraquarks, ...)?

➜ Gluonic Excitations provide a measurement of the excited QCD potential.
Hybrid baryons are also possible ...

Non-Perturbative QCD



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Answers to these questions will not be the direct result of some experiments.

- Models need to link observables to these fundamental questions.
- Significant observables:
  - Excitation spectra and electromagnetic couplings
  - Response of hadronic properties to a dense nuclear environment