Hadron Spectroscopy

Lecture I - Overview

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U.S. DEPARTMENT OF ENERGY

About Us

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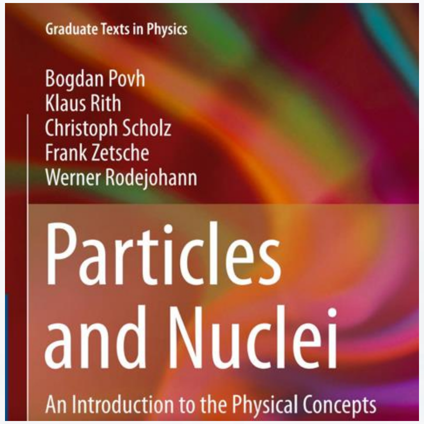
Plan

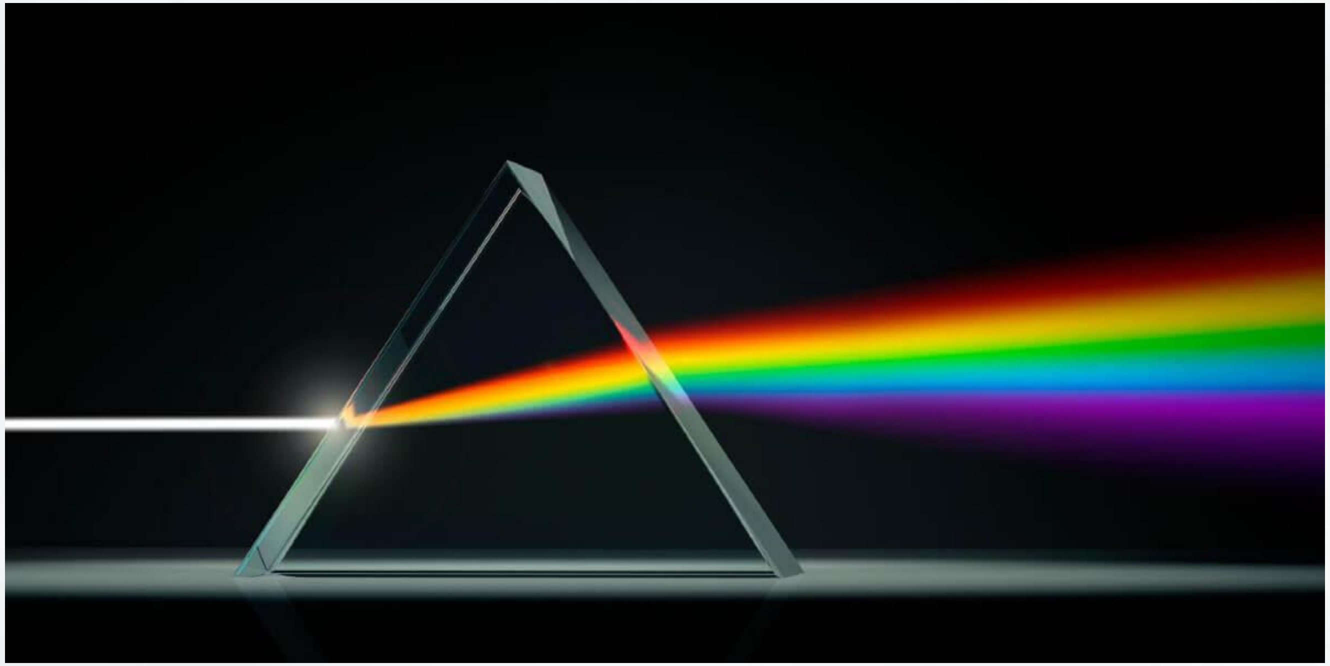
1. Lecture: General Introduction
2. Lecture: Scattering Theory – Part 1
3. Lecture: Experimental Light Quark Spectroscopy
4. Lecture: Scattering Theory – Part 2
5. Lecture: XYZ, P and T

Useful References:



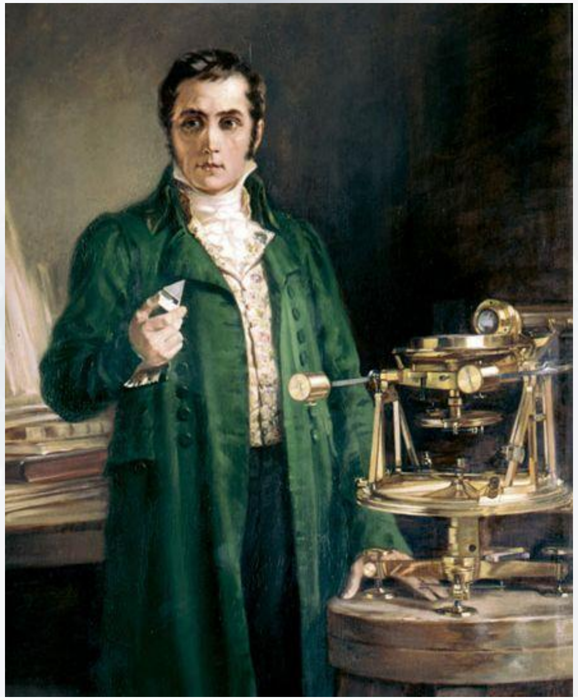
https://pdglive.lbl.gov/

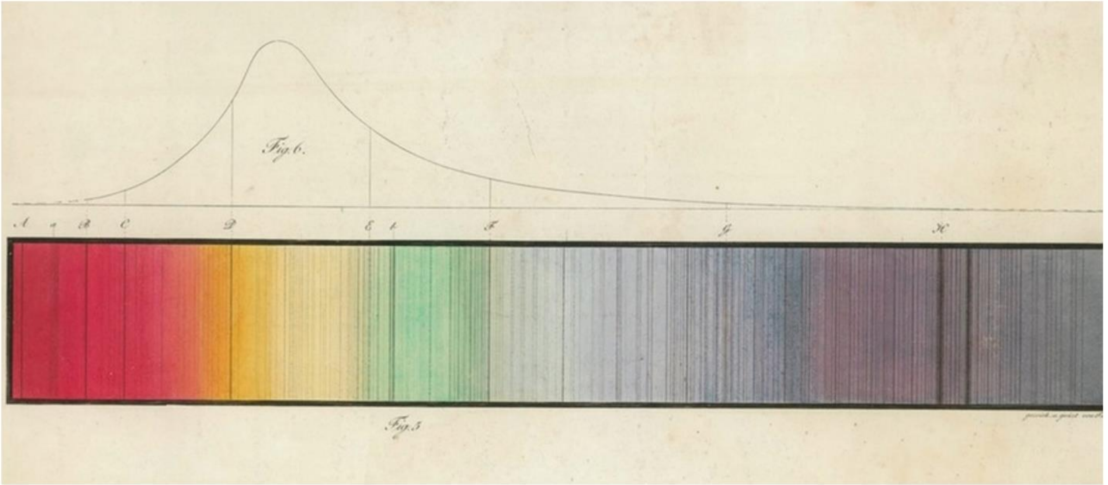
Prologue: Spectroscopy



Joseph v. Fraunhofer (1787-1826)

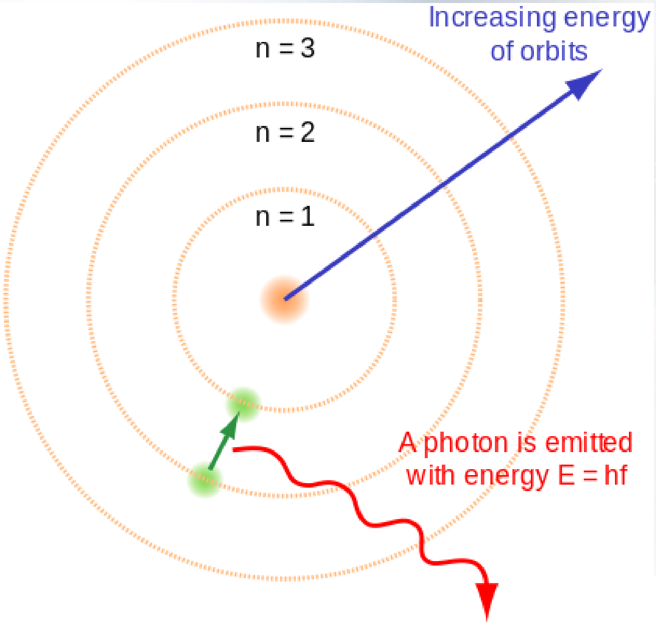
- German Physicist and Glass Manufacturer
- Inventor of the Optical Spectroscope
- Independently discovered absorption lines in the spectrum of the sun in 1814
- Precisely mapped over 570 fixed dark lines in the spectrum
- 45 years later, some of the lines were identified as emission lines for heated chemical elements
- Atoms in the solar atmosphere absorb light emitted by the solar photosphere
- Fraunhofer also studied light from different stars: Founder of Stellar Spectroscopy
- Namesake of German “Fraunhofer Society” Europe’s biggest society for applied research

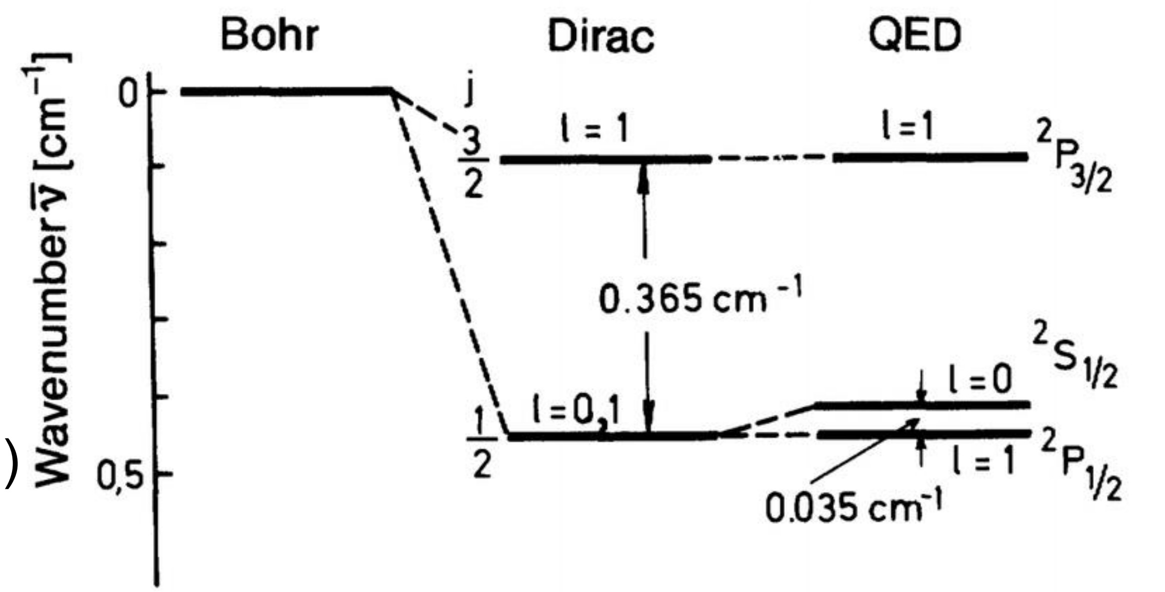




Spectroscopy of the Hydrogen Atom

- Emission spectrum of atomic hydrogen:
  Electron transitions between two energy levels
- Discrete levels explained by Bohr Model
  Nobel Price 1922 (Bohr)
- Fine Splitting: electron spin and relativistic corrections
  Measured in 1887 (Michelson, Morley)
  Explained by Dirac Equation (1928)
  Nobel Price 1933 (Dirac, Schrödinger)
- Lamb Shift: Vacuum Energy Fluctuations
  Measured in 1947 (Lamb, Retherford)
  Revolutionized Quantum Field Theory (QED)
  Nobel Price 1955 (Lamb)
  1965 (Tomonaga, Schwinger, Feynman)

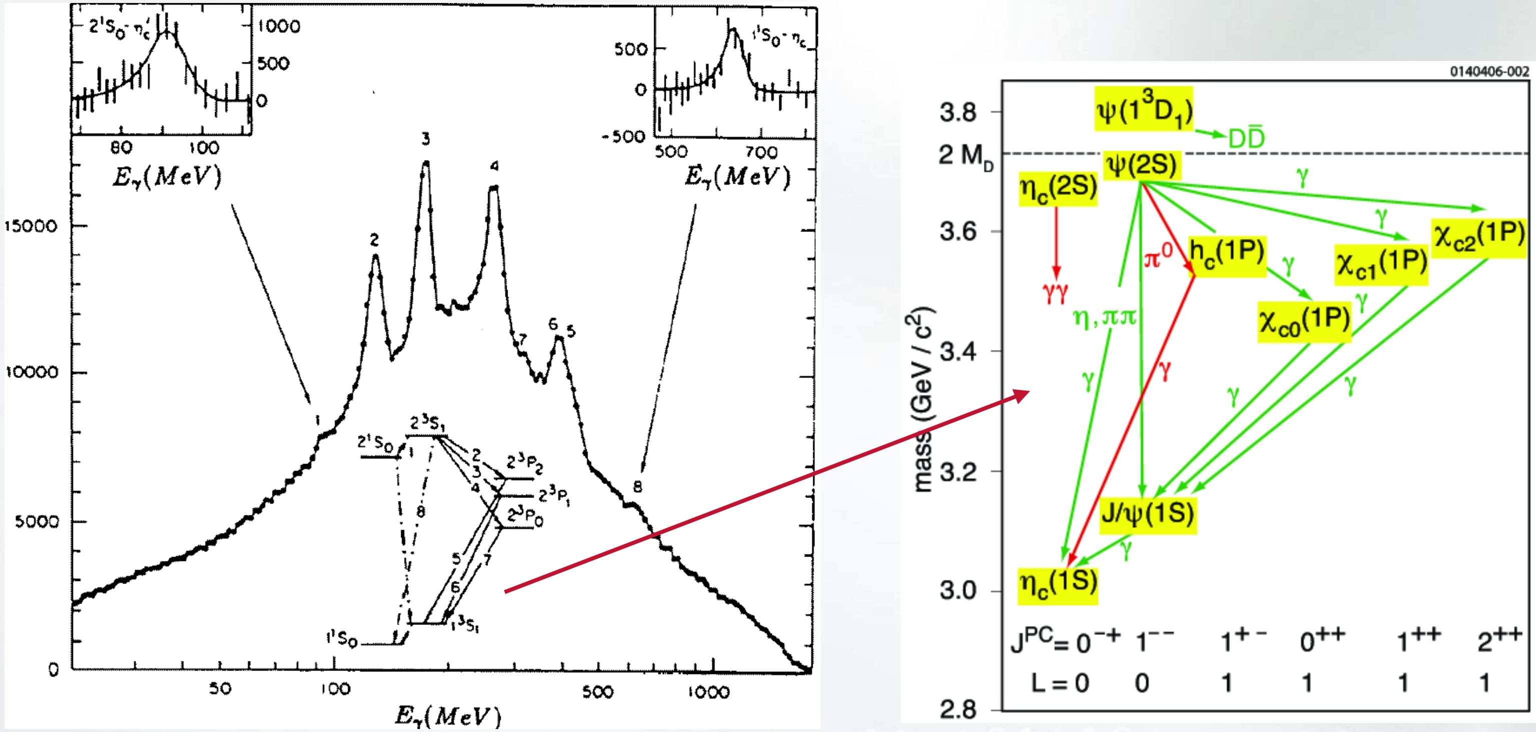




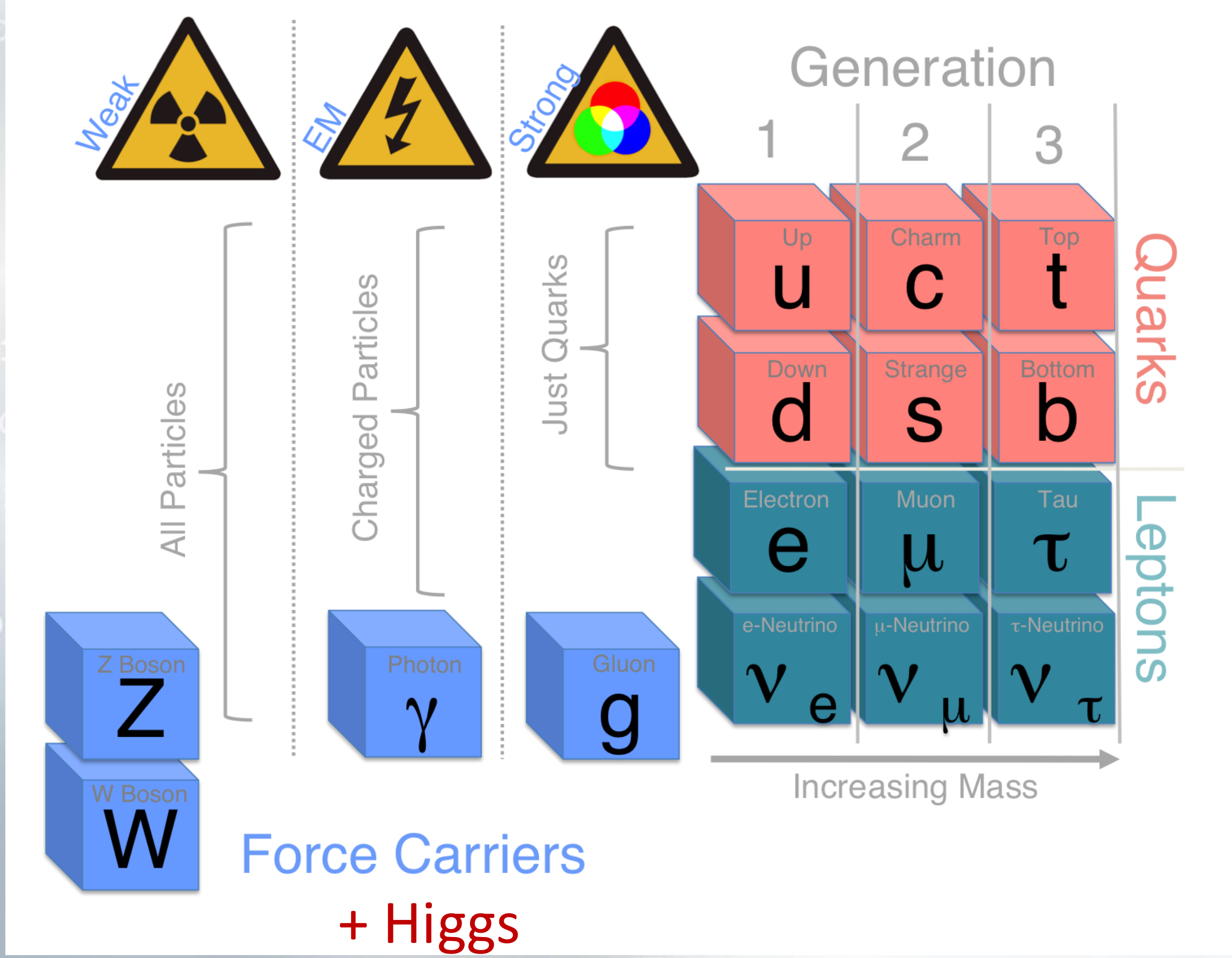
Take-away:

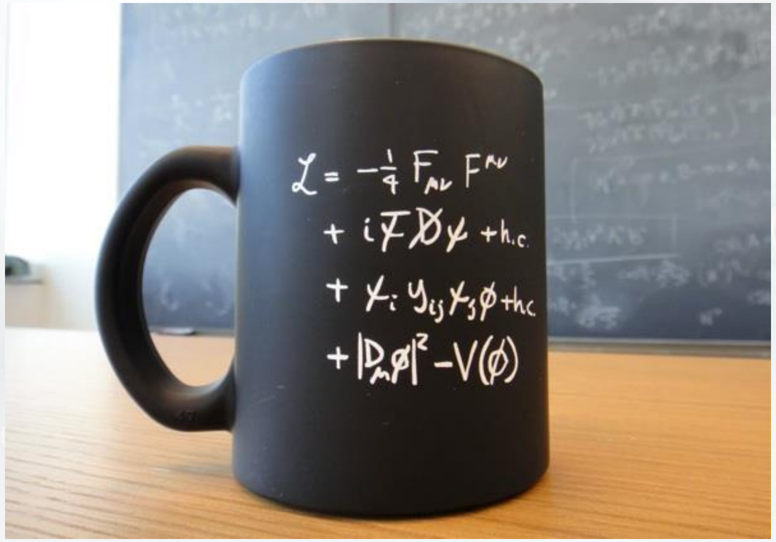
- Precise experimental studies lead to scientific advances
- Small deviations can have tremendous consequences
- May take years for results to be fully understood

Introduction: Hadron Spectroscopy



Standard Model of Particle Physics





EM and Weak Interactions:

- Precise calculations with QFT
- Experimentally confirmed predictions

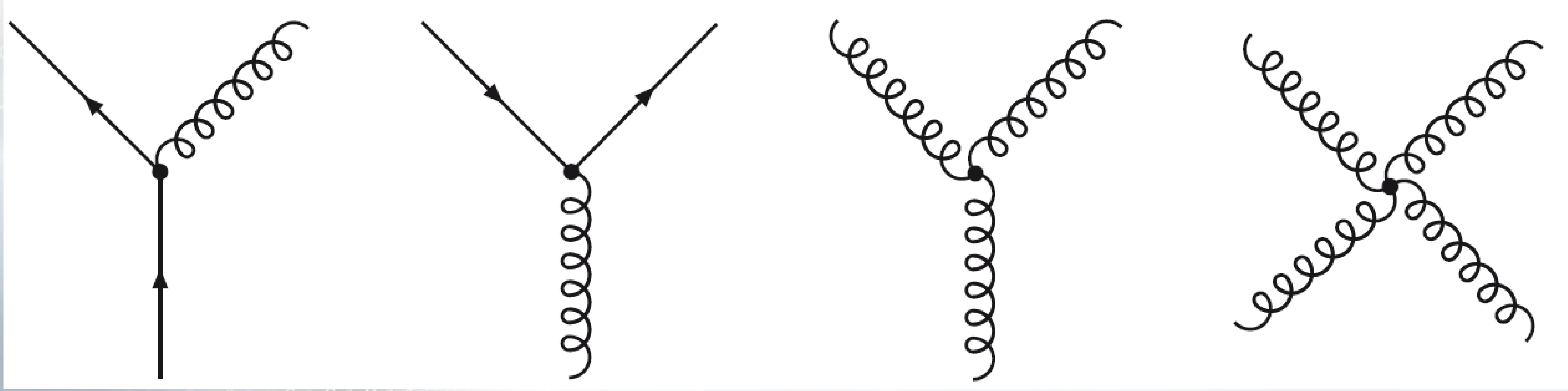
Strong Interaction:

→ See Lectures by A. Simonelli, C. Weiss

Strong Interaction

Quantum Chromodynamics (QCD):

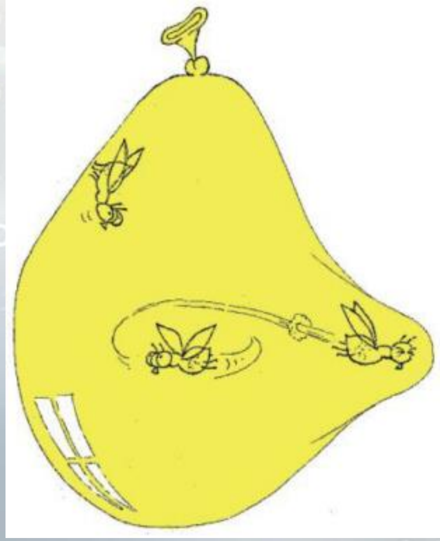
- Color-charged Quarks interact via exchange of color-charged Gluons



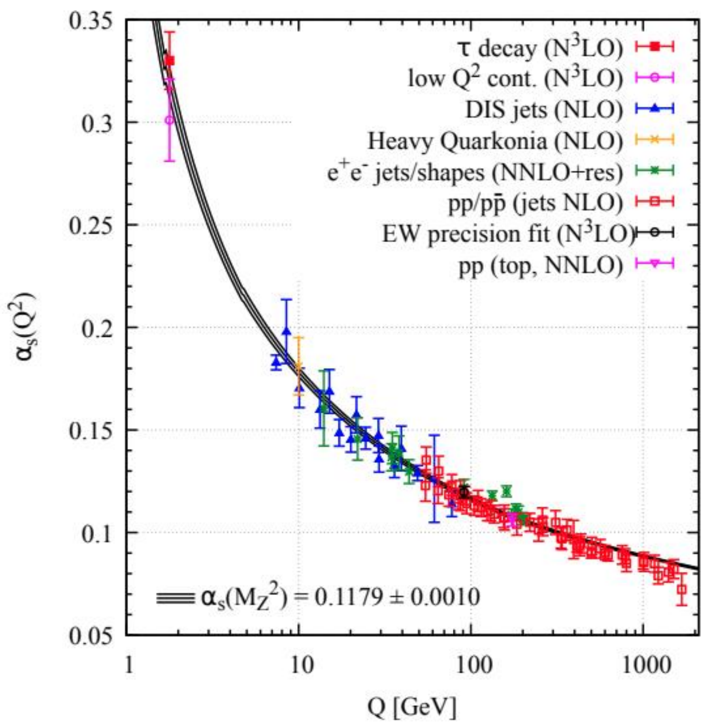
Strong Interaction

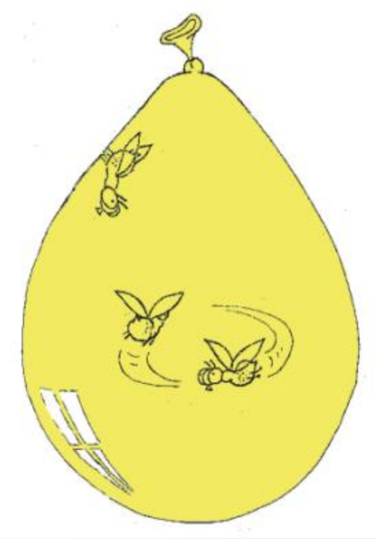
Quantum Chromodynamics (QCD):

- Color-charged Quarks interact via exchange of color-charged Gluons
- Confinement: only color-neutral objects can be observed in nature



Non-perturbative Regime:
Small energies, large distances



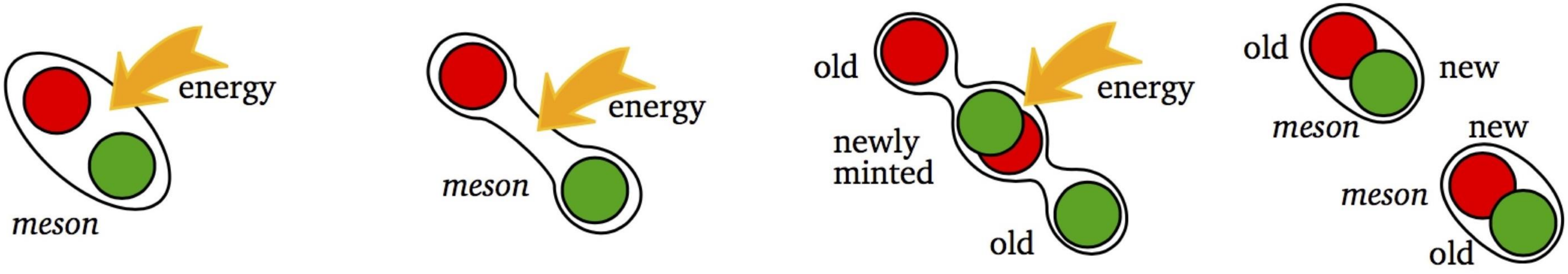


Asymptotic Freedom:
Large energies, small distances

Strong Interaction

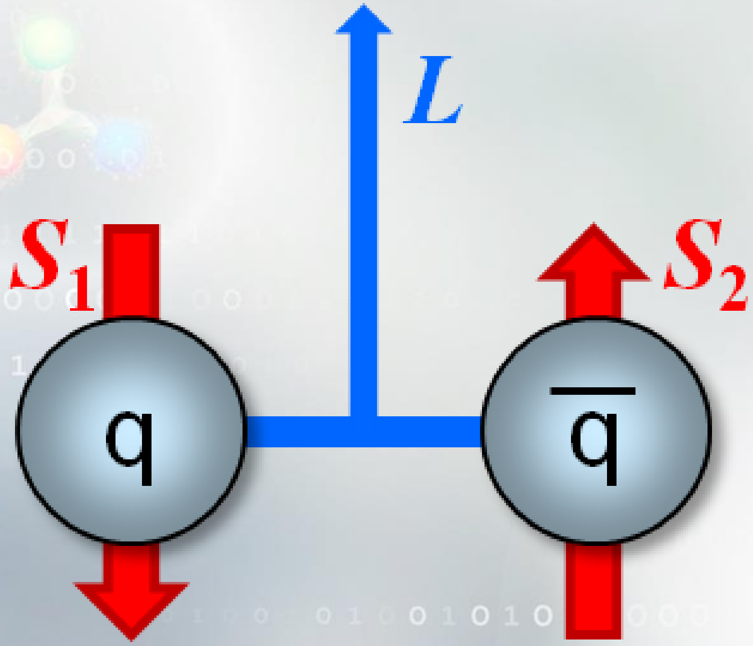
Quantum Chromodynamics (QCD):

- Color-charged Quarks interact via exchange of color-charged Gluons
- Confinement: only color-neutral objects can be observed in nature
- Baryons and Mesons as relevant degrees of freedom



Meson Spectrum

- Study of the ‘simplest’ system $q\bar{q}$, equivalent to the hydrogen atom
- Characterize by quantum numbers, mass, lifetime, quark content, decay modes, …



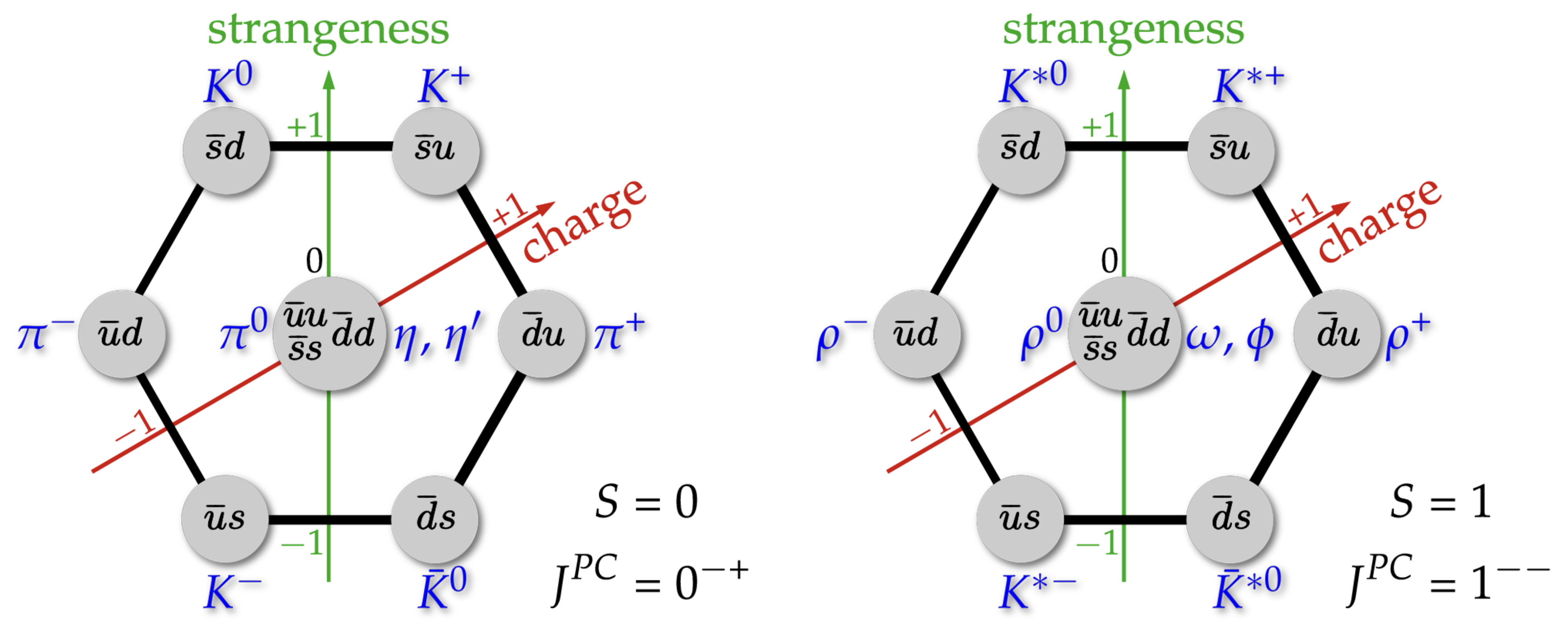
- Total intrinsic Spin: $S = S_1 + S_2 = 0$ or 1
- Angular Momentum L and Spin S couple to J
- Symmetry under space inversion:
  Parity $P = (-1)^{L+1}$
- Symmetry under particle exchange:
  Charge Conjugation $\mathrm{C} = (-1)^{L+S}$

Exercise: allowed quantum numbers $\mathrm{J}^{\mathrm{PC}} = 0^{++}, 0^{-+}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

forbidden combinations $\mathrm{J}^{\mathrm{PC}} = ?$

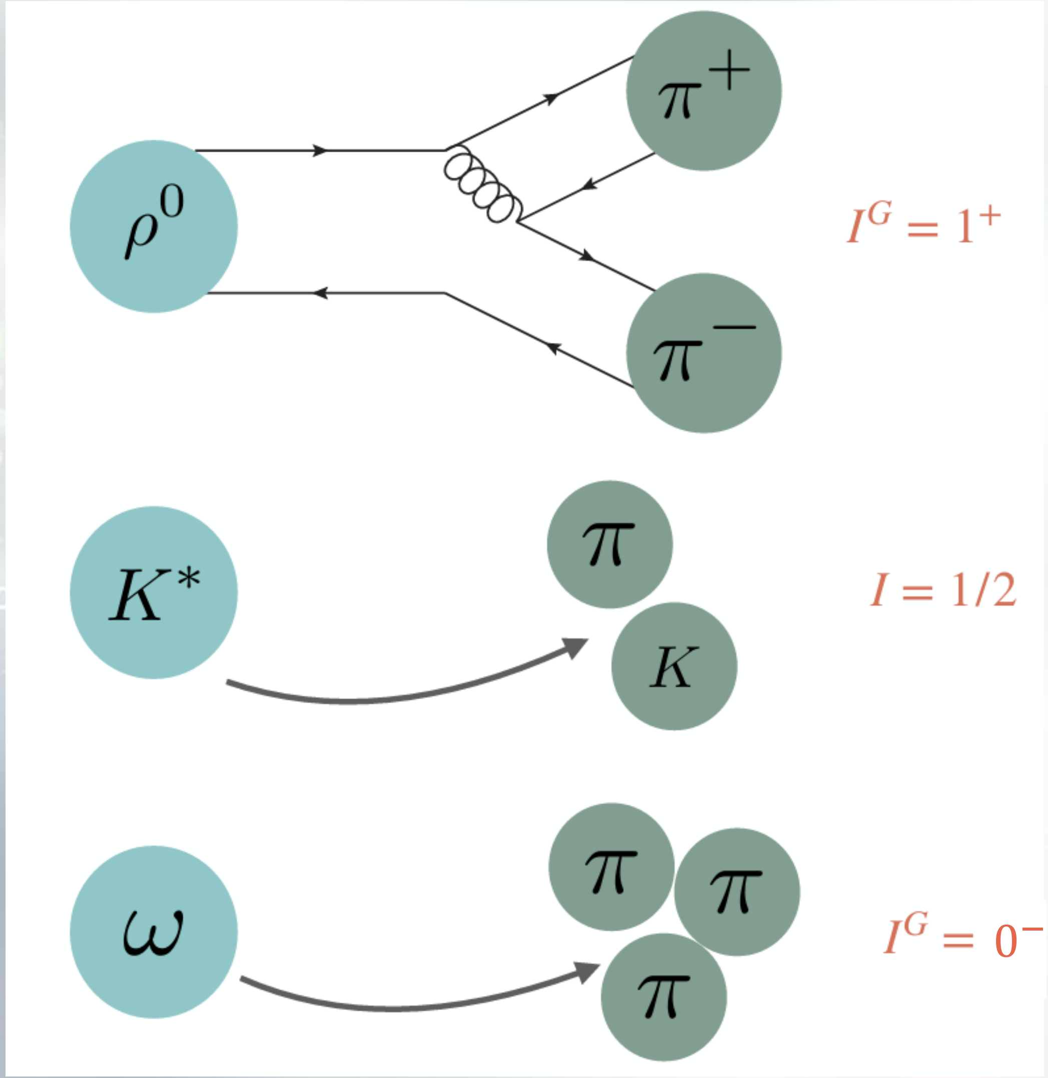
Light Quark Mesons

- Composed of u, d and s (anti)quarks
- Can be grouped into SU(3) flavor nonets



- Orbital and radial excitations → many more nonets

Isospin



Decays of Vector Mesons $J^{PC} = 1^{--}$

$m_u \approx m_d$: Isopin conservation

Classify Mesons with $I^G(J^{PC})$

Combine isospin rotation and charge conjugation:

G Parity: $G = C(-1)^I$

π^0 $\quad I^G(J^{PC}) = 1^-(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** 1 (1988).

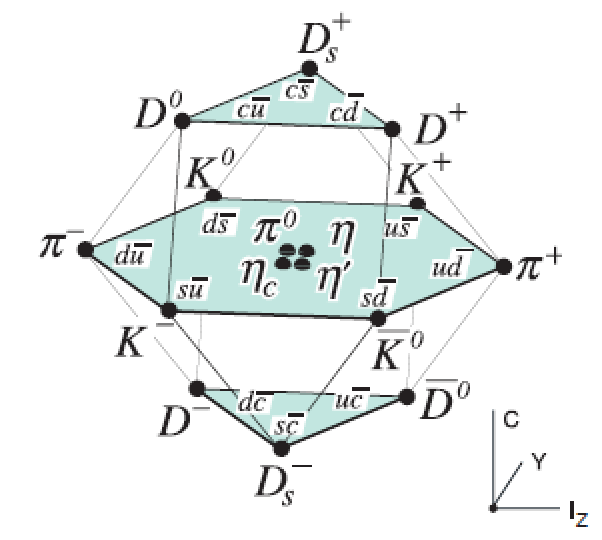
Notation

- Classify Mesons with $I^G(J^{PC})$
- Many names are historical: $\pi, \rho, \omega, J/\psi$
- Group by spin:
  Scalar (0^{++}), Pseudoscalar (0^{-+}), Vector (1^{--}), Axial/Pseudovector ($1^{+\pm}$), Tensor (2^{++}), …
- Names defined by Spin and Isospin:

$1^-(J^{++})$	$0^+(J^{++})$	$1^+(J^{+-})$	$0^-(J^{+-})$	$1^-(J^{-+})$	$0^+(J^{-+})$
a_J	f_J	b_J	h_J	π_J	η_J

N.B.: Not all combinations allowed by quark model!

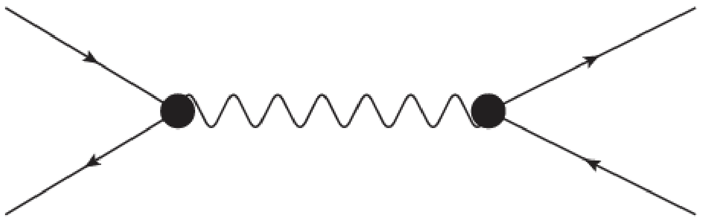
- Strange quarks: K ($d\bar{s}$, $u\bar{s}$), ϕ ($s\bar{s}$)
- Charm quarks: D ($c\bar{u}$, $c\bar{d}$), $D_s(c\bar{s})$, $\psi, \eta_c, h_c, \chi_c$ ($c\bar{c}$)
- Bottom quarks: B ($d\bar{b}$, $u\bar{b}$), $B_s(s\bar{b})$, $\Upsilon, \eta_b, h_b, \chi_b$ ($b\bar{b}$)
- Exotic combinations: X, Y, Z, T, P



Quark Model

Coupling of vector mesons $J^{PC} = 1^{--}$ to photons

ρ^0	$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}$	$\Gamma(\rho) \propto \frac{1}{2}(Q_u - Q_d)^2 = \frac{1}{18}9$
ϕ	$s\bar{s}$	$\Gamma(\phi) \propto \frac{1}{2}Q_s^2 = \frac{1}{18}2$
ω^0	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	$\Gamma(\omega) \propto \frac{1}{2}(Q_u + Q_d)^2 = \frac{1}{18}$



Theoretical expectation

$$\Gamma_{\rho^0} : \Gamma_{\omega^0} : \Gamma_\phi = 9 : 1 : 2$$

Experiment

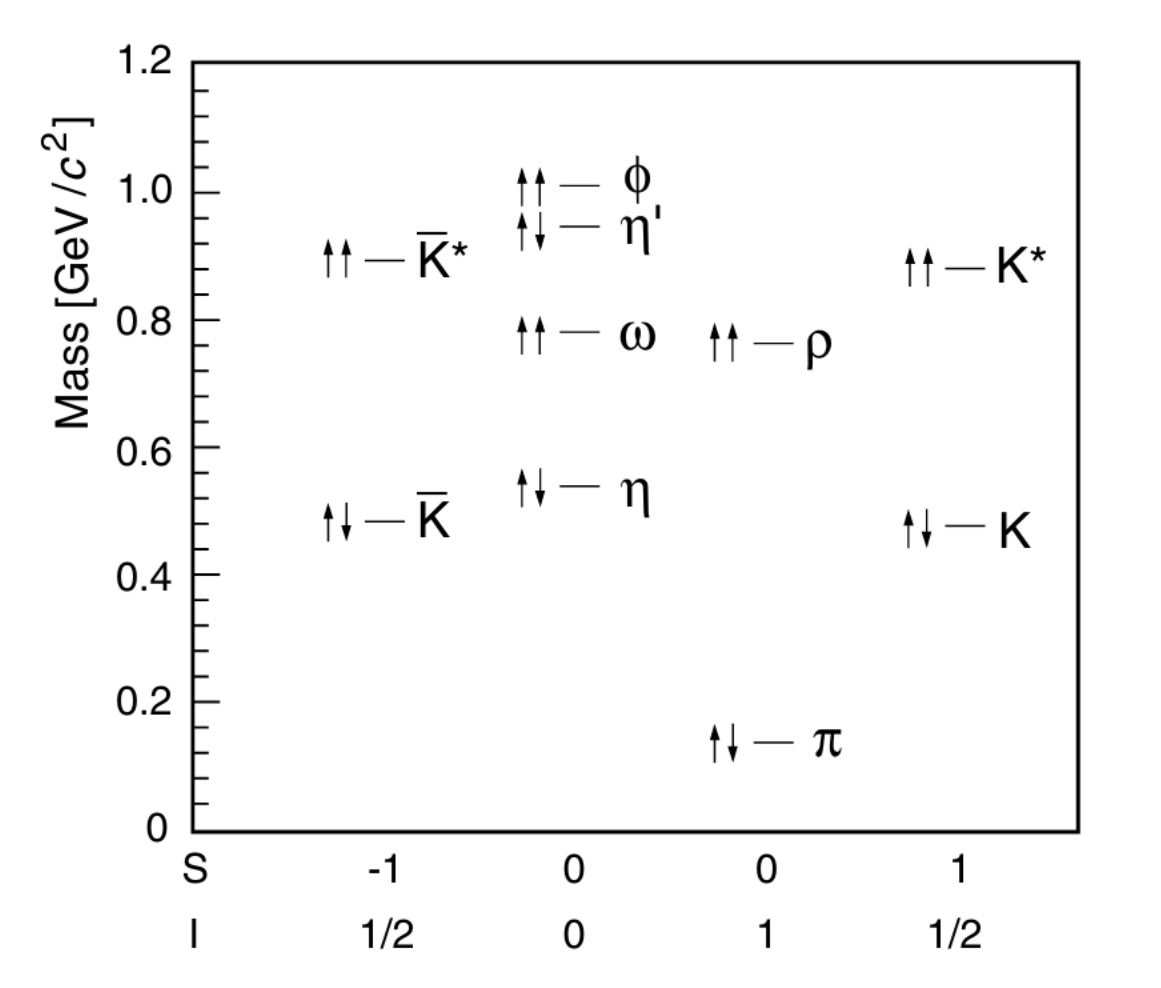
$$(8.8 \pm 2.6) \; : \; 1 \; : \; (1.7 \pm 0.4)$$

Very successful description!

Quark Model

- Vector mesons about 400-600 MeV/c^2 heavier than $J = 0$ counterparts
- Chromomagnetic spin-spin interaction (compare to hyperfine structure)
- Phenomenological formular with constituent quark masses

Meson	J^P	I	Mass [MeV/c^2] Calculated	Mass [MeV/c^2] Experiment
π	0^-	1	140	135.0 π^0; 139.6 $\pi^\pm$
K	0^-	1/2	485	497.7 K^0; 493.7 K^-
η	0^-	0	559	547.3
η'	0^-	0	—	957.8
ϱ	1^-	1	780	770.0
K^*	1^-	1/2	896	896.1 K^{*0}; 891.7 K^{*-}
ω	1^-	0	780	781.9
ϕ	1^-	0	1032	1019.4



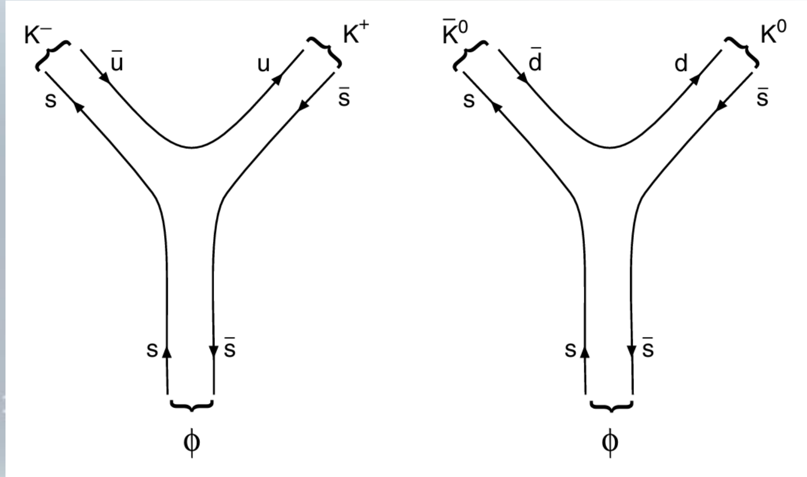
Hadron Decays

- Flavor is conserved by strong and EM force, not by weak force
- Strong decays dominate when allowed, electromagnetic decays are more likely than weak decays

Exercise: When are strong or EM decays forbidden?

Strong decay		Electromagnetic decay		Weak decays
$\rho(770) \rightarrow \pi^+\pi^-$	>>	$\pi_0 \rightarrow \gamma\gamma$	>>	$\pi^+ \rightarrow \mu^+\nu_\mu$
$\Gamma = 150\ \mathrm{MeV}$				
$\tau = 4.4 \times 10^{-24}\mathrm{s}$		$\tau = 8.5 \times 10^{-17}\mathrm{s}$		$\tau = 2.6 \times 10^{-8}\mathrm{s}$
$c\tau = 1.3\ \mathrm{fm}$		$c\tau = 26\ \mathrm{nm}$		$c\tau = 7.8\ \mathrm{m}$

- Strong decays without $q\bar{q}$ annihilation are preferred (OZI suppression)



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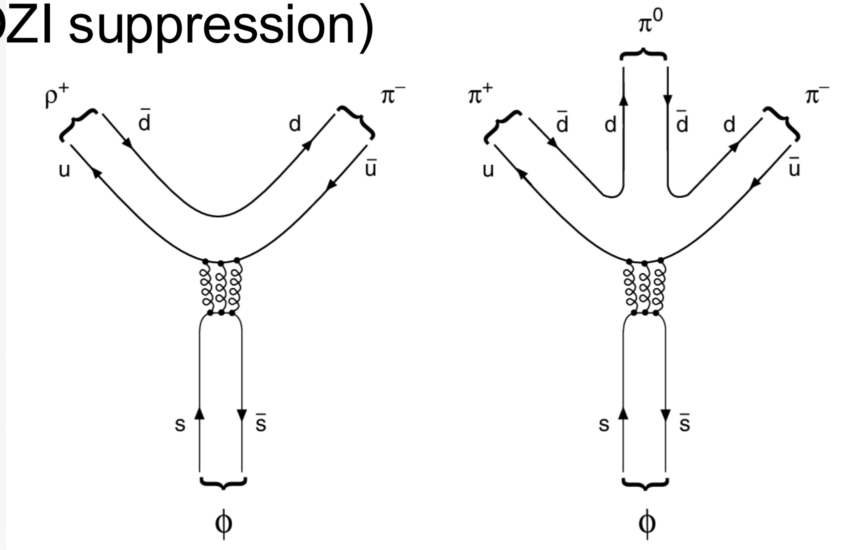
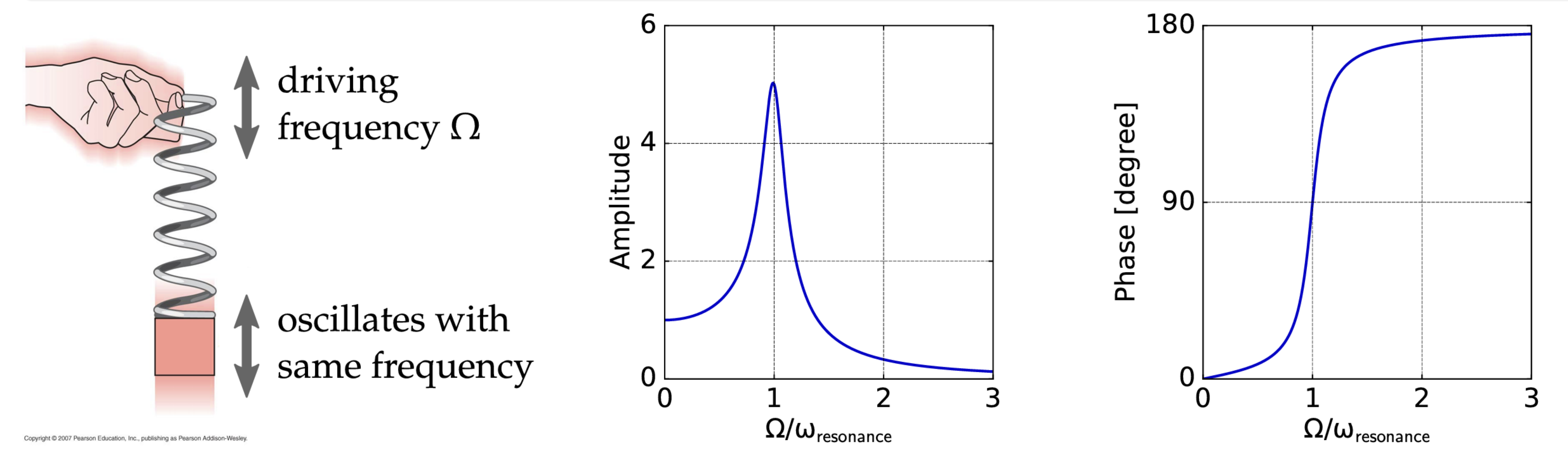


Resonances

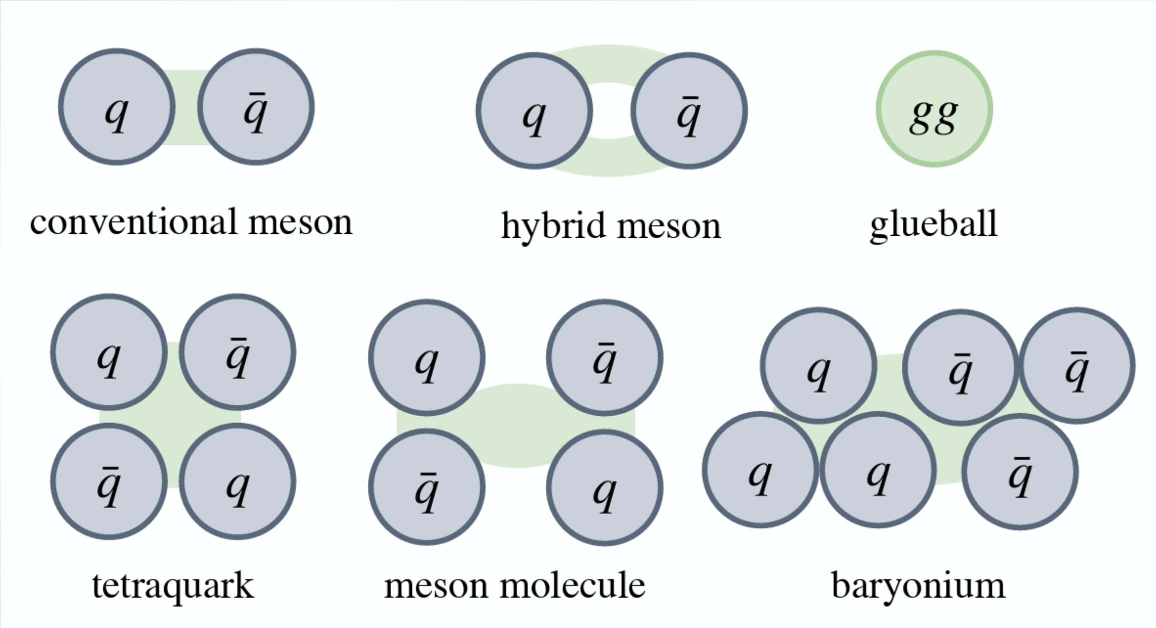
- Most mesons decay via strong interaction -> lifetimes of O(10^{-24} s)
- Uncertainty principle -> inaccuracy in energy (=mass)



- Amplitude peaks at resonance mass
- Phase rises by 180 degrees, 90 at resonance

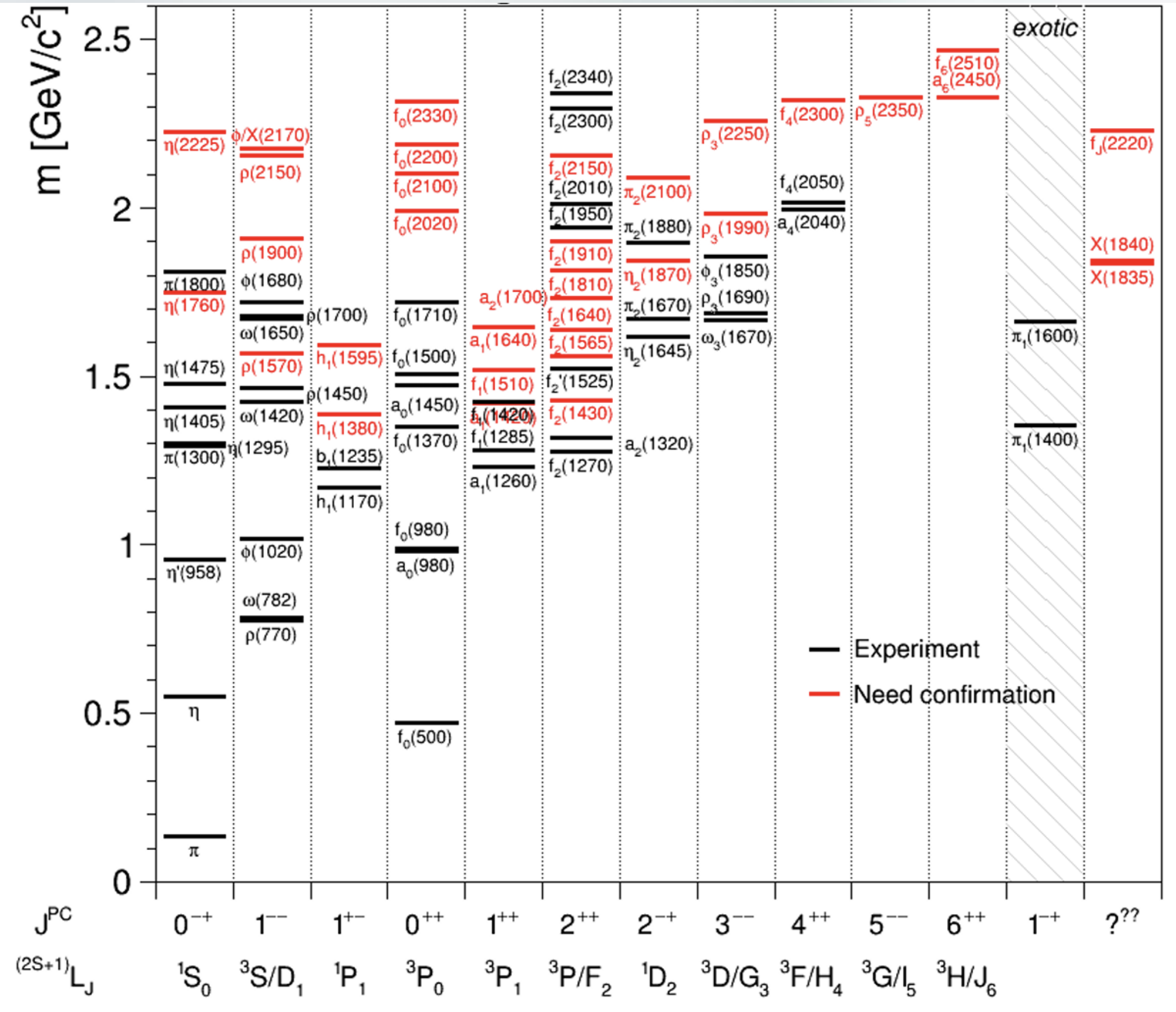
Exotic Mesons

- QCD allows other color-neutral combinations of quarks and gluons



- Spin-exotic quantum numbers cannot be $q\bar{q}$: $\mathrm{J}^{\mathrm{PC}} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$
- Establishing such states is proof for states beyond the constituent quark model
- Nature of exotic states can only be determined by models

Light Meson Spectrum



Beyond the ground states:

- Assignment to nonets not clear
- Missing states

Goal: Precision Measurement of Spectrum

- Confirm excited states
- Complete SU(3) nonets
- Search for exotic states

Take-away:

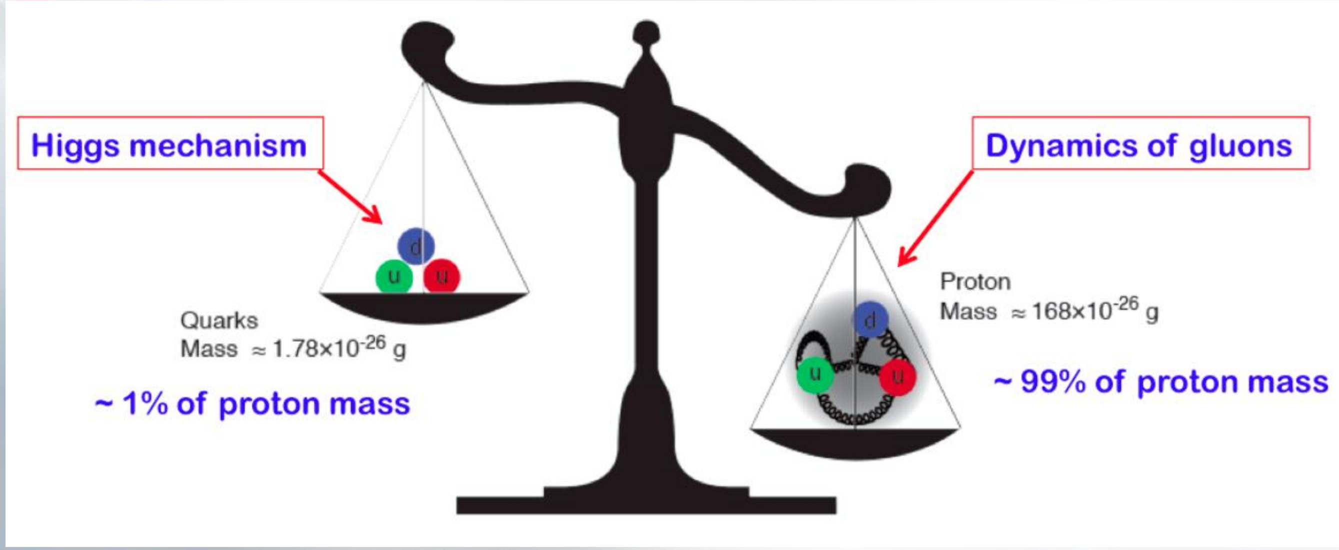
- Mesons identified by quantum numbers $I^G(J^{PC})$ and flavor
- Unambiguous naming scheme (PDG)
- Name only roughly mapped to quark content
- Experimental knowledge lacks precision

Baryon Spectrum: Proton

Quark content: uud

Mass: 938 MeV/c^2

- Current mass about 1%
- How is 99% of the mass of the visible universe generated?



Baryon Spectrum: Proton

Quark content: uud

Mass: 938 MeV/c^2

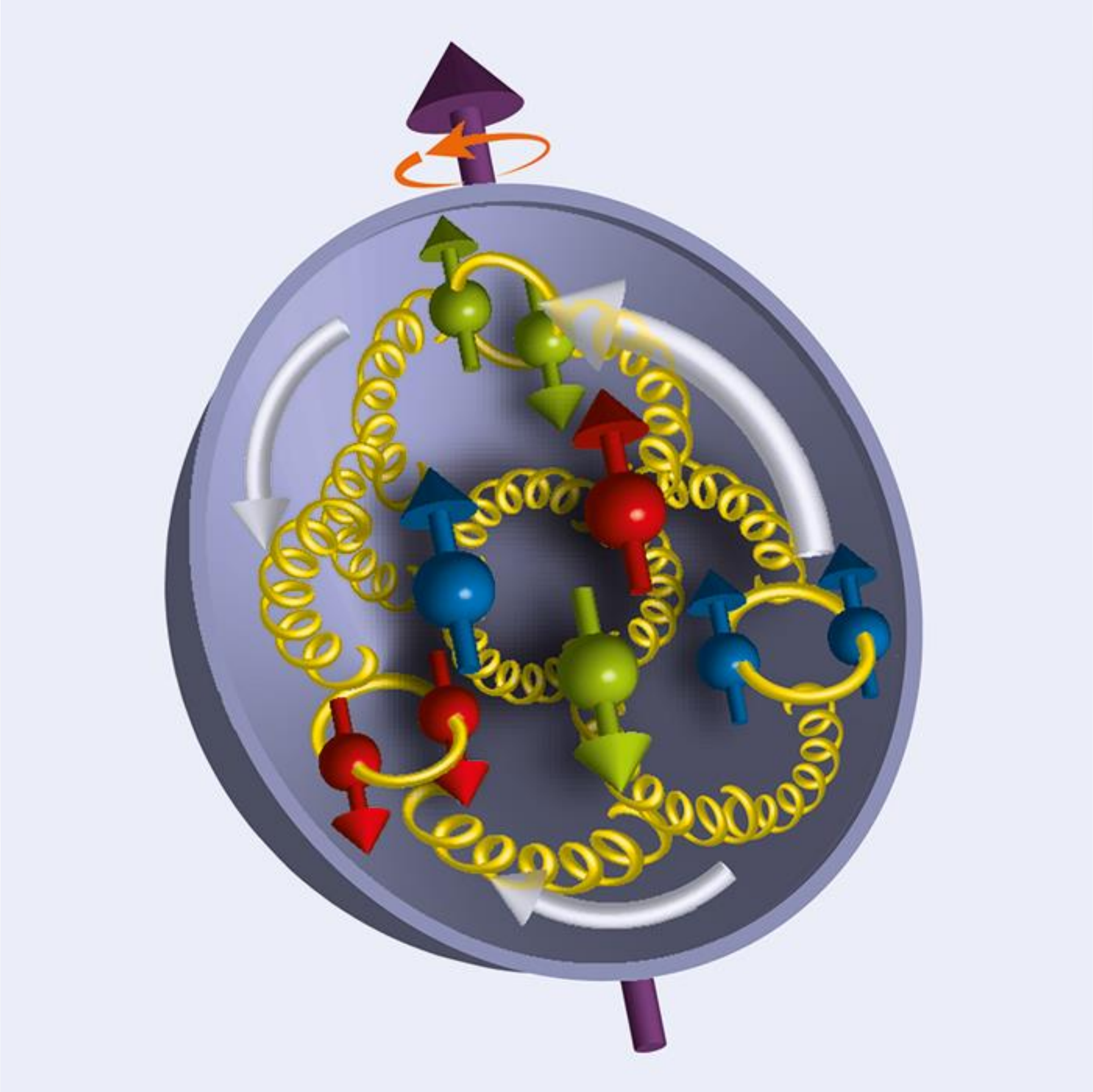
- Current mass about 1%
- How is 99% of the mass of the visible universe generated?

Spin ½

- Spin of quarks only ~30%
  Gluons? Angular momentum?
  Sea quark pairs?
  → See Lectures by Arun Tadepalli

Radius?

Excitation Spectrum?

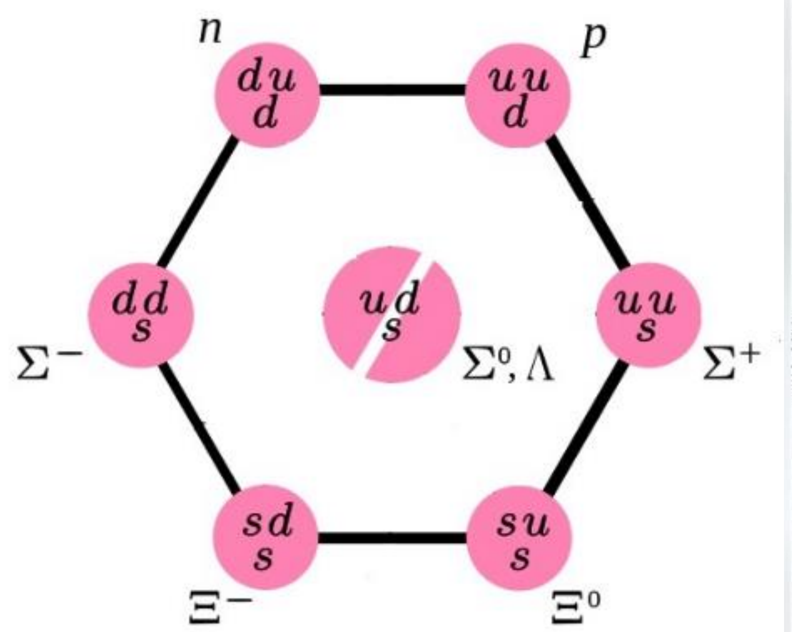


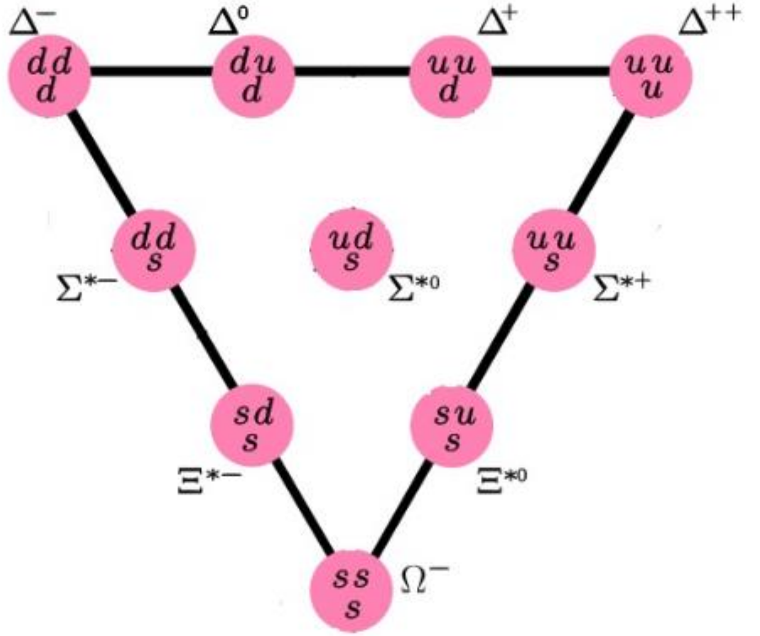
Baryon Notation:

- Conserved Baryon Number B = 1
- Consistent with qqq configuration
- Naming Convention:

Non-Strange		Strange Baryons (Hyperons)			
$I = 1/2$	$I = 3/2$	$I = 0$	$I = 1$	$\mathrm{I} = 1/2$	$I = 0$
N	Δ	Λ	Σ	Ξ "Cascade"	Ω

- Excited states with mass (Mev): $\Delta(1232)$
- Characterize by $I(J^P)$
- Historic spectroscopic notation from πN scattering: $L_{2I,2J}$ (e.g. $P_{33}(1232)$)
- Subscript c/b for charmed/bottom Baryons
- Pentaquark $P_{c\bar{c}}$: $uudc\bar{c}$



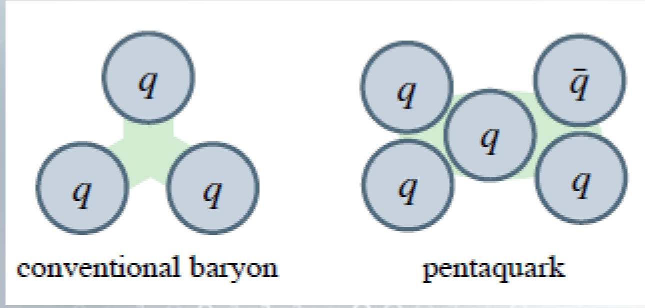


Baryon Spectroscopy:

- Large number of know states, use star rating:

****	Existence is certain, and properties are at least fairly explored
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

- No exotic quantum numbers, but many missing states or states without QN assignment (Y^*)
- Exotic multi-quark configurations:



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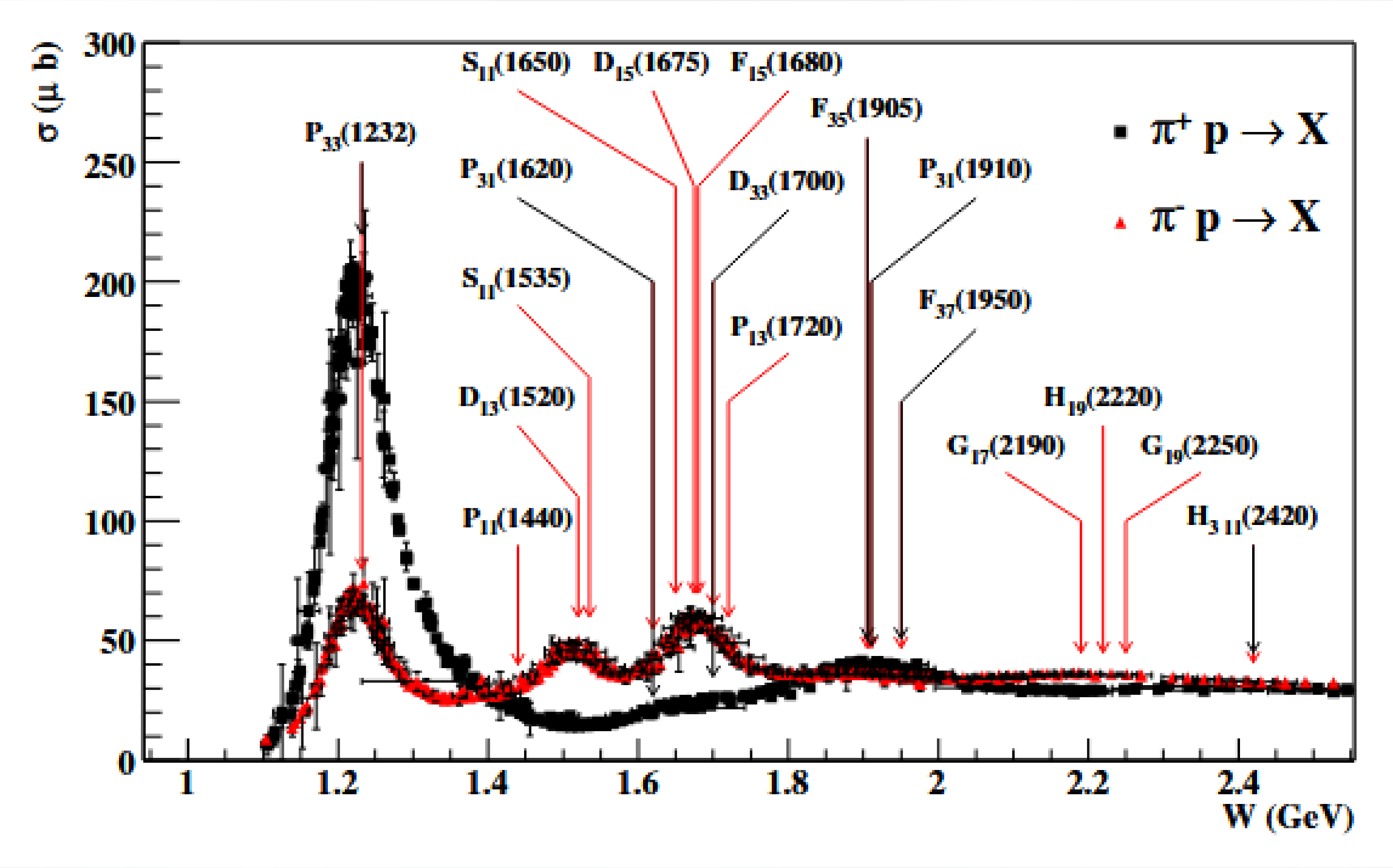
Baryon Spectroscopy:

- Large number of broad and overlapping states
- Impossible to disentangle via mass alone
  → Use as much additional information as possible
- Double polarization observables:
  Polarized targets + polarized beams
- Example: CLAS in Hall B



Exercise: QED Analogy?

Exercise: Connections

Create four groups of four!

J	Σ	d	ω
G	η	Ξ	c
π	P	s	Λ
u	ρ	Ω	C

Mistakes Remaining: ● ● ● ●

Shuffle | Deselect All | Submit

QUESTIONS?

Thank you

For inspiration for this lecture series:

- Ryan Mitchell
- Arkaitz Rodas
- Justin Stevens
- Boris Grube

Exercise: QED Analogy?

- No free gluon radiation, no strong “ions”
- Short lifetime of states → not lines, but broad and overlapping in Energy/Mass
- Decay often not to ground state, but multi-particle final state
- Measured spectrum cannot be compared to first principles

Exercise: Connections

Create four groups of four!

LIGHT QUARKS
u, d, s, c

LIGHT MESONS
π, η, ρ, ω

HYPERONS
$\Lambda, \Sigma, \Xi, \Omega$

QUANTUM NUMBERS
J, P, C, G

View Results