Hadron Spectroscopy
Lecture 1
Introduction and Motivation

National Nuclear Physics Summer School
at MIT

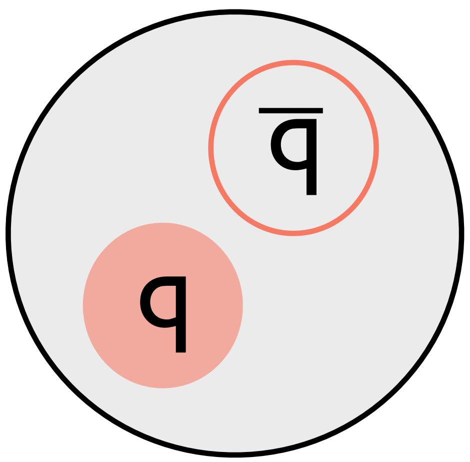
Matthew Shepherd
Indiana University

Outline

1. Overview and Motivation
    1.1. Unique features of QCD
    1.2. Why use spectroscopy as a tool to study QCD?
    1.3. How do we classify mesons?
    1.4. Introduction to experiment
2. Spectroscopy of Heavy Quark Systems
3. Spectroscopy of Light Quark Systems
4. Summary and Outlook: Present and Future Facilities

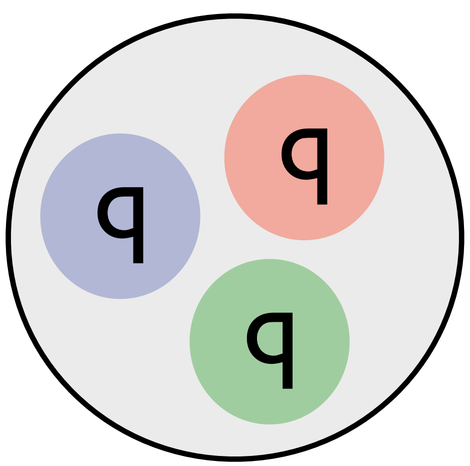
QCD in the Standard Model

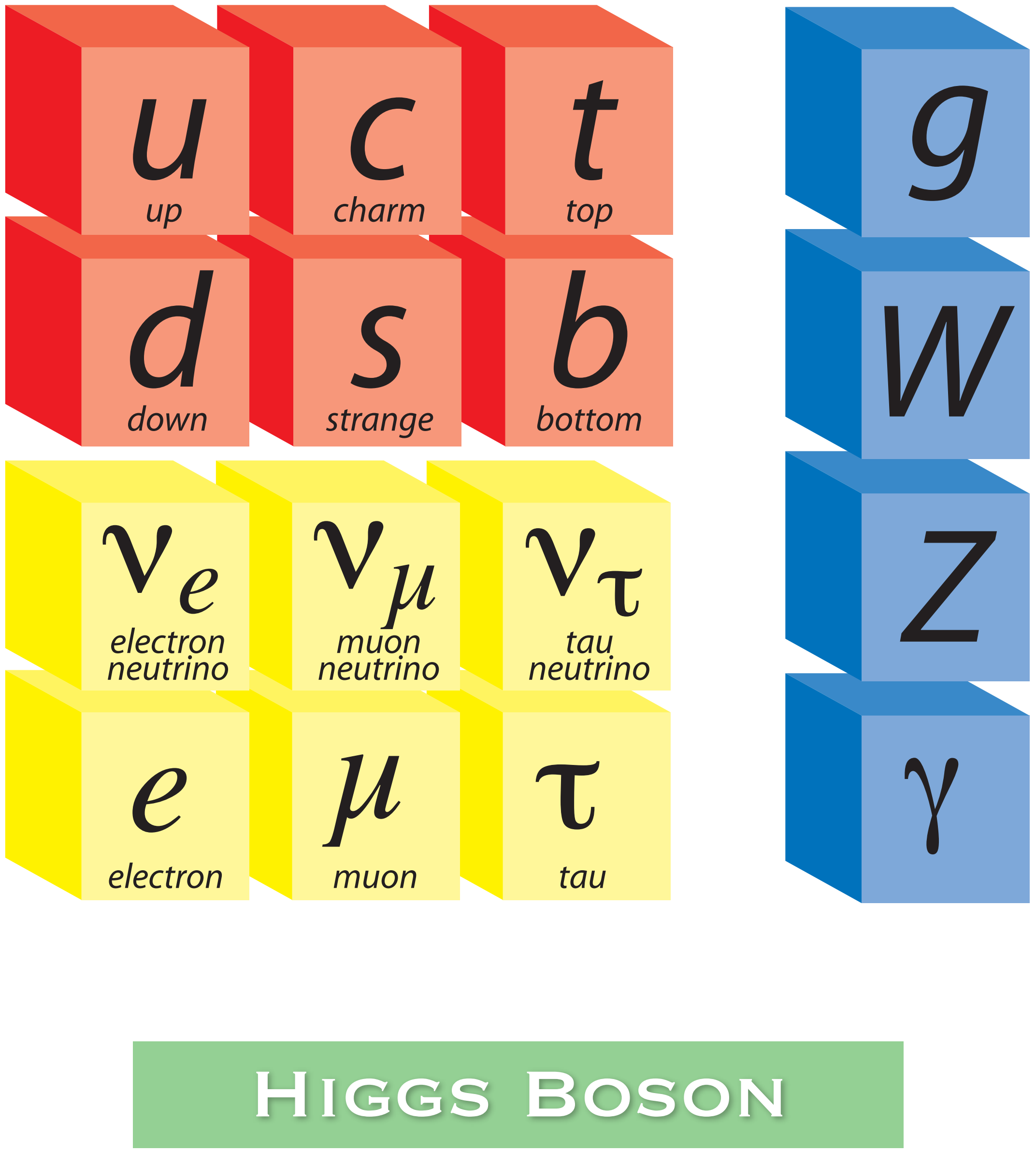
- Three quark colors
- Color singlets apparently required
- Two typical arrangements: mesons and baryons



Mesons
(e.g., π, K, D)

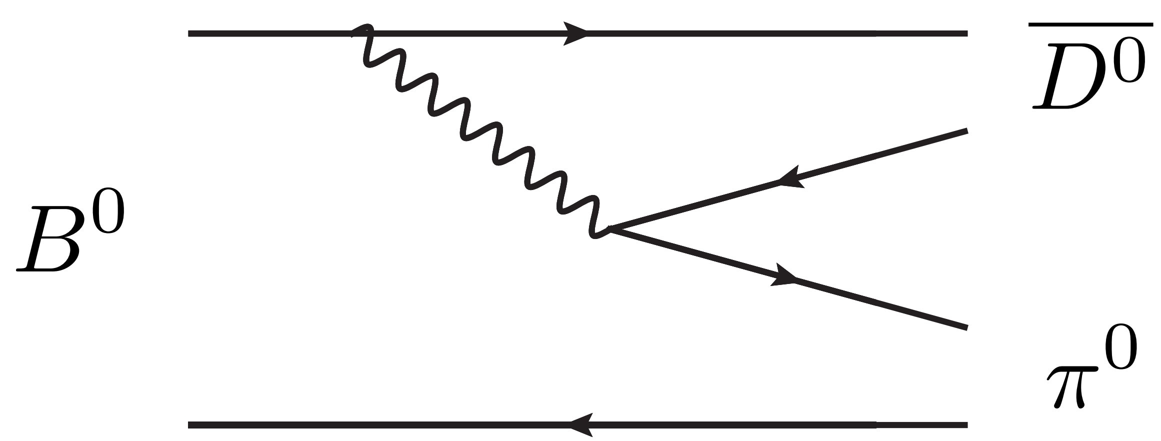
Baryons
(e.g., proton and neutron)



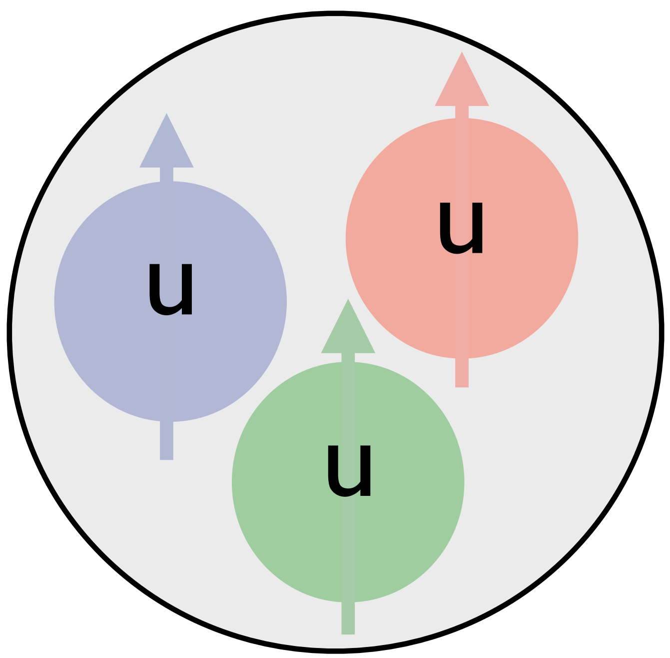


Evidence of Color

$$\mathcal{B}(B^0 \to \overline{D^0}\pi^0) = 0.26 \times 10^{-3}$$

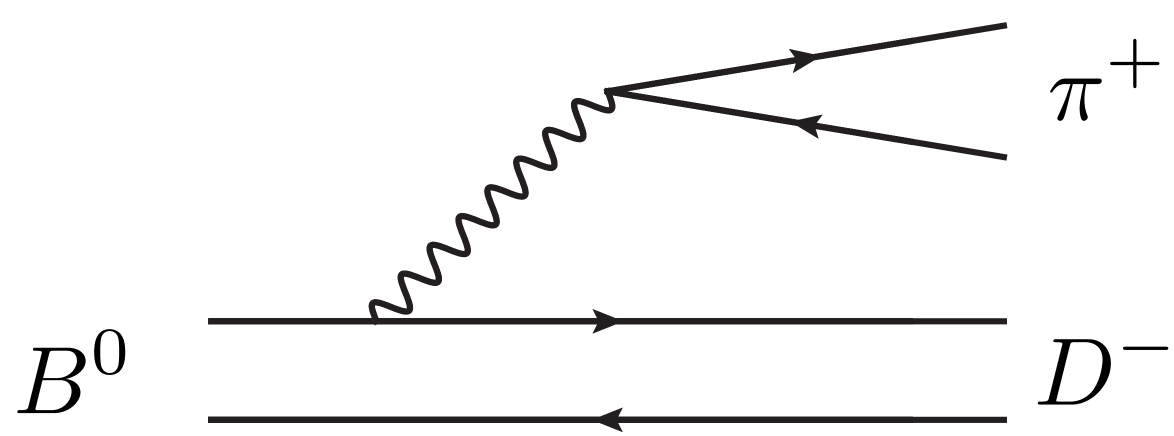


Δ^{++}

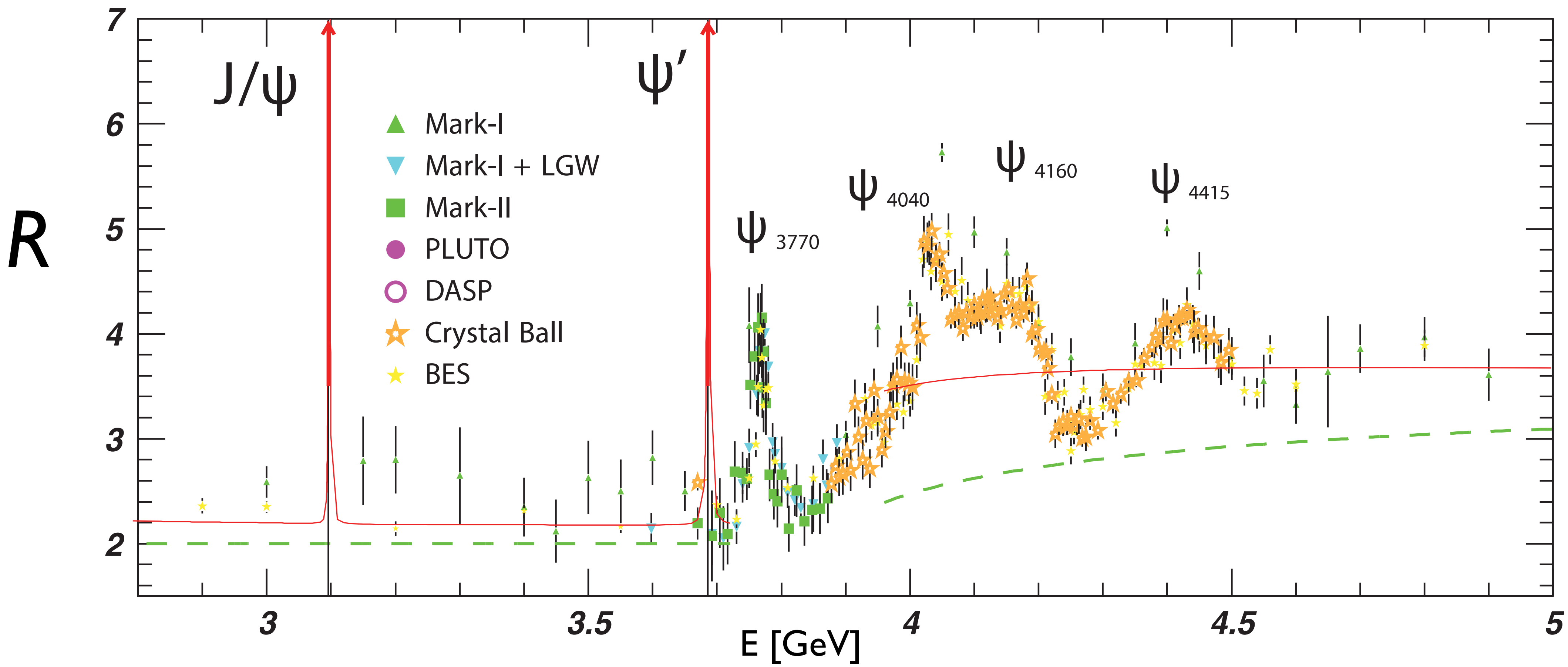


$$J = \frac{3}{2}$$

$$\mathcal{B}(B^0 \to D^-\pi^+) = 2.7 \times 10^{-3}$$

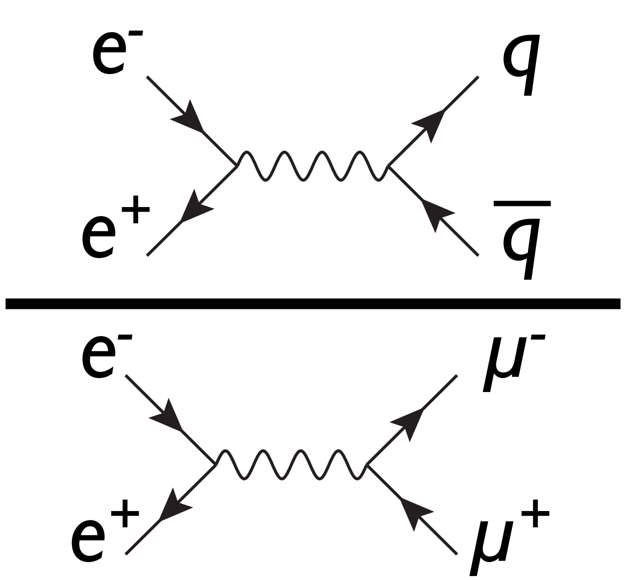


More Evidence of 3 Colors



- Probes the ratio of quark to lepton couplings in QED: $Q_q^2 \,/\, Q_\mu^2$

R =



Homework: Compute the expected value of *R* below and above charm (and bottom) thresholds under the assumptions that there are 1 and 3 colors of quarks. Compare with experimental data from the PDG.

Interactions in QED

Have: freely propagating spin-1/2 particle

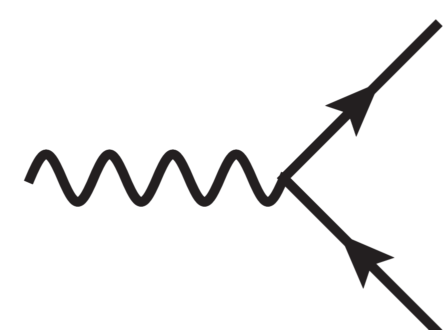
$$\mathcal{L} = i(\hbar c)\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - (mc^2)\bar{\psi}\psi$$

Want: "physics" to remain invariant under local phase transformations

$$\psi \rightarrow e^{i\theta(x)}\psi$$

Doing so requires introduction of a freely propagating massless gauge field (the photon) and the interaction of this field with spin-1/2 particles

$$-\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu}$$



$$-Q(\bar{\psi}\gamma^{\mu}\psi)A_{\mu}$$

Interactions in QCD

Have: freely propagating
spin-1/2 quark in *rgb* space

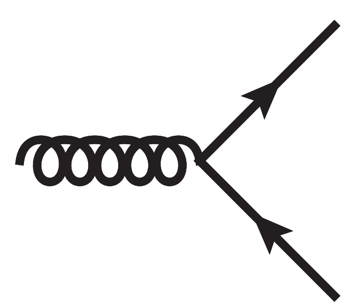
$$\mathcal{L} = i(\hbar c)\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - (mc^2)\bar{\psi}\psi$$

Want: "physics" to remain invariant
under unitary color transformations

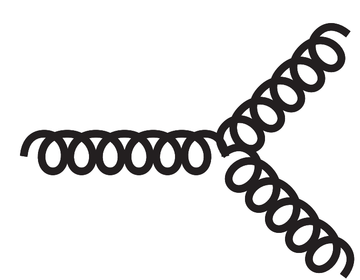
$$\begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix} \rightarrow U \begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix}$$

This requires the introduction of eight massless gauge fields (the gluons)
and several interaction terms -- *note that gluons interact with each other!*

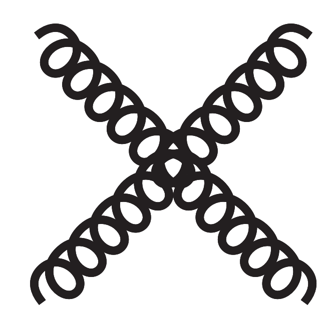
gluons



quark-gluon vertex



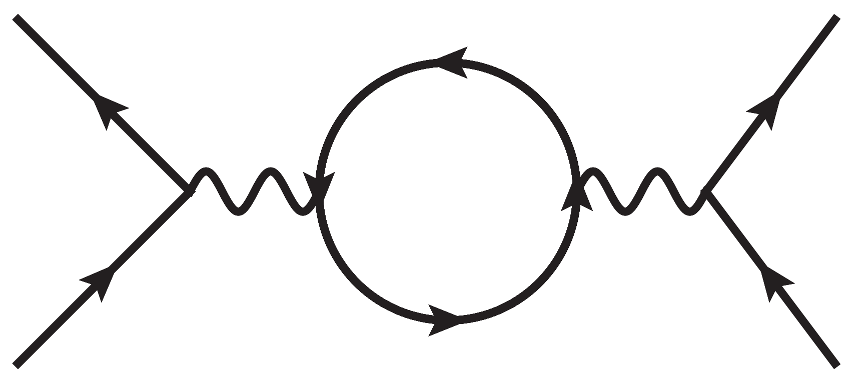
three-gluon vertex



four-gluon vertex

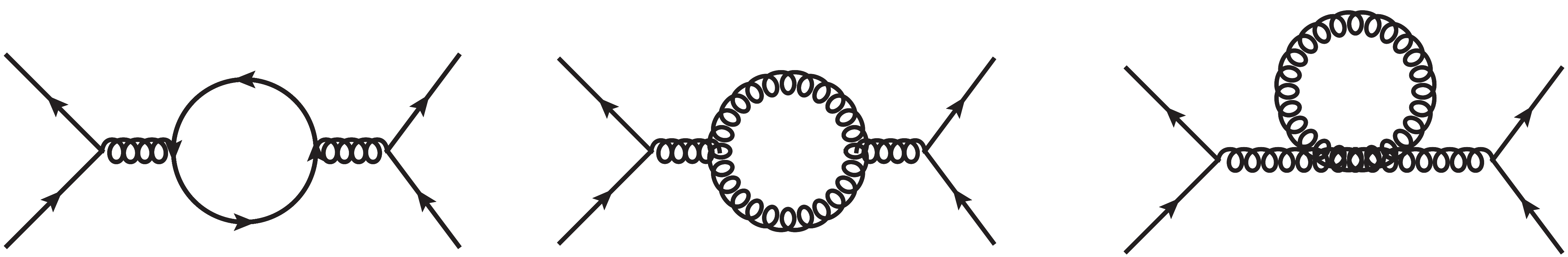
Higher Order Corrections

- In QED, vacuum polarization acts to "screen" the charges of interacting particles resulting in weaker force at large distance.



scale of corrections set by
$\alpha = 1/137$

- In QCD quark loops continue to screen the QCD force, but gluon loops provide an "anti-screening" effect that dominates, resulting in a stronger force at large distances.

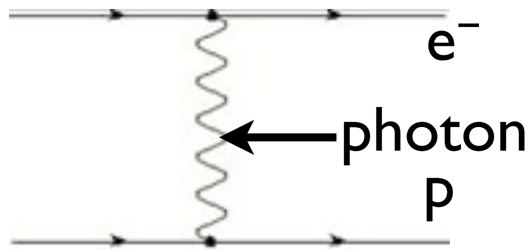


scale of QCD corrections set by $\alpha_s > 0.1$

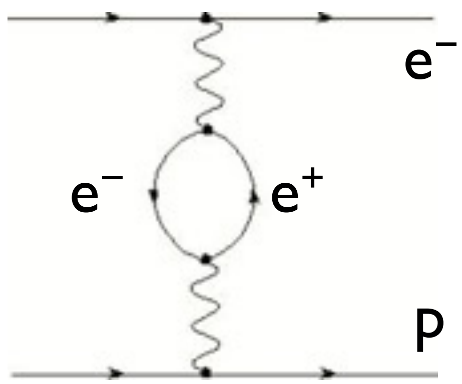
The Forces that Bind Hydrogen and Mesons

The Electromagnetic Force and Quantum Electrodynamics (QED)
(Hydrogen Atom)

Simple Term

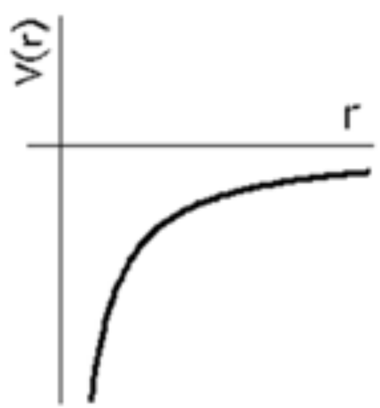


Correction



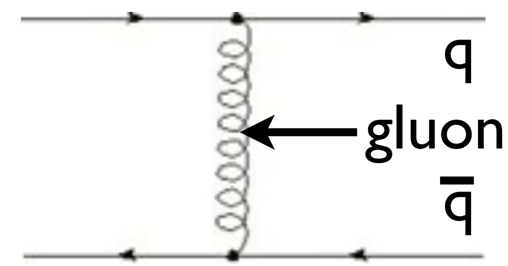
Potential

$$V(r) = -\frac{\alpha}{r}$$

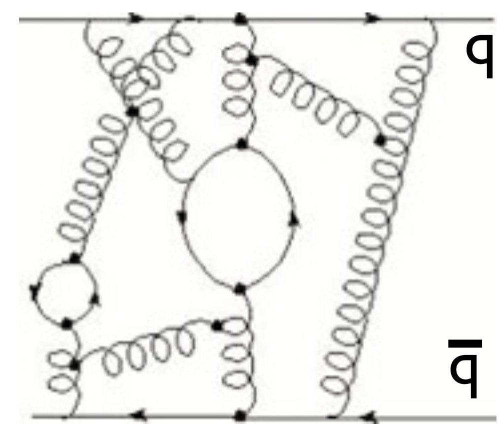


IONIZATION IS POSSIBLE

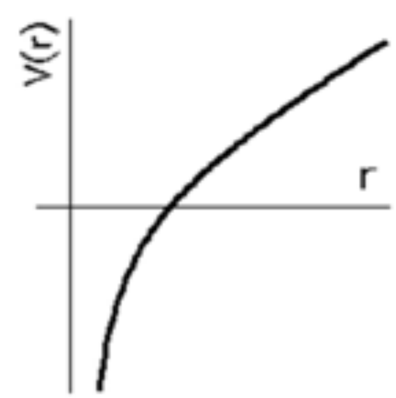
The Strong Force and Quantum Chromodynamics (QCD)
(Meson)



Simple Term
(small distances)



“Correction”
(large distances)



Potential (model)

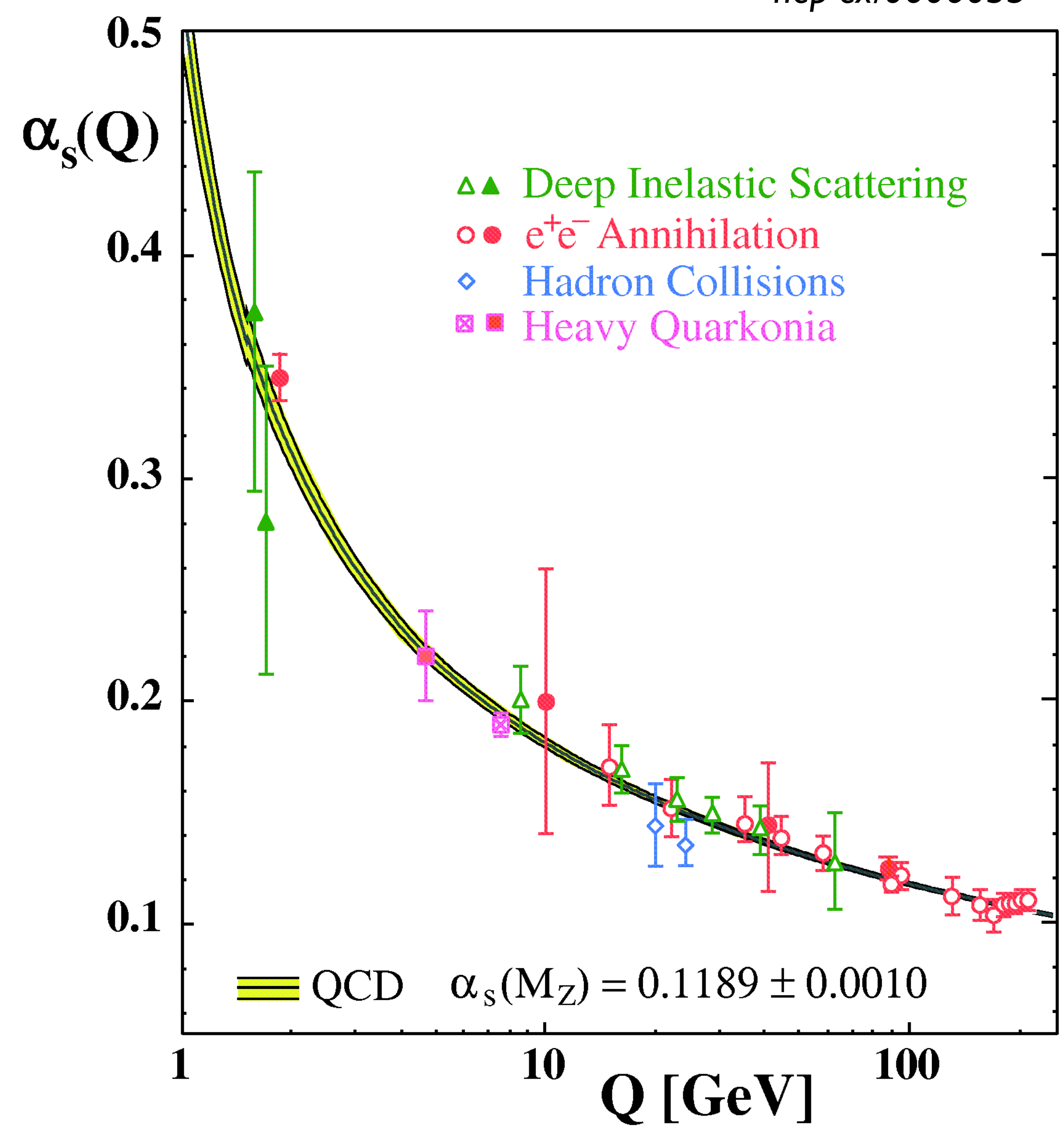
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + F_0 r$$

QUARKS ARE CONFINED

Gluon Interactions in QCD

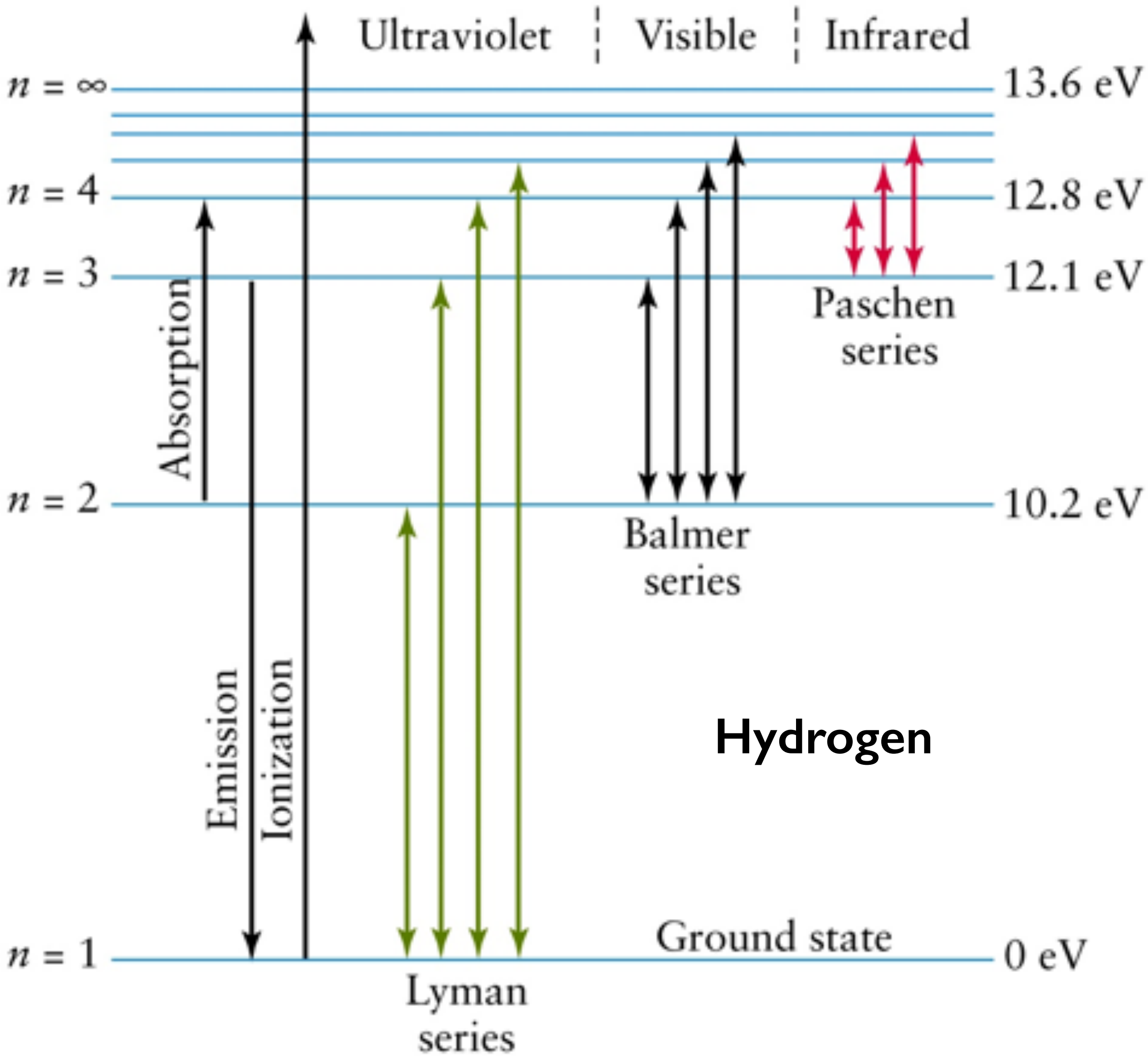
- QCD has interesting properties
  - gluon-gluon interactions
  - confinement
- Nonpurturbative in the interesting domain
- *Study QCD using hadrons*

S. Bethke
hep-ex/0606035



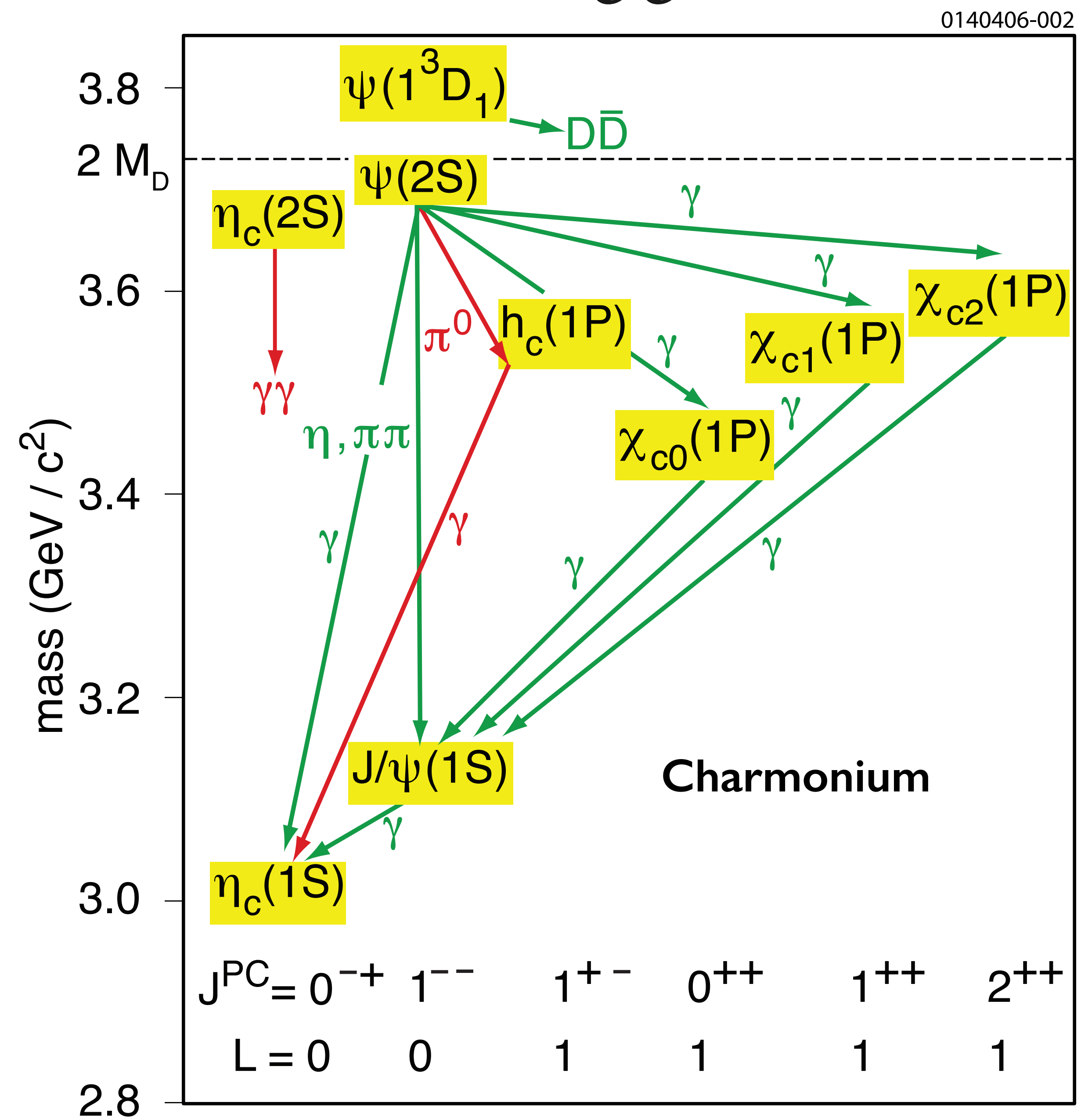
Studying Forces with Spectroscopy

Electromagnetic Force



Strong Force

$c\bar{c}$



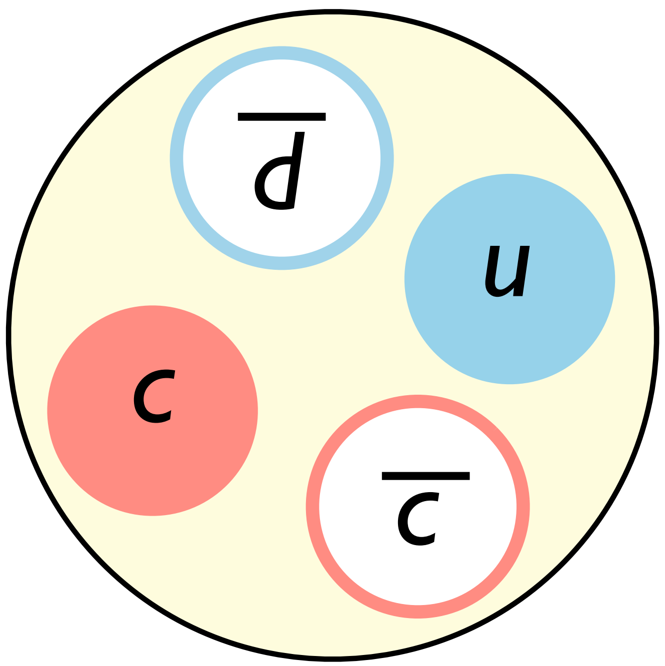
Spectroscopy and QCD

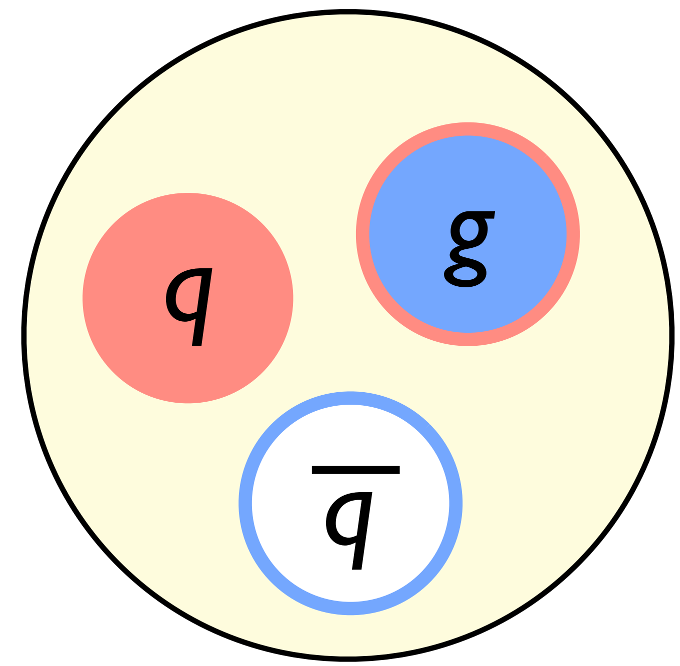
- Studying the spectrum of hadrons motivated the quark model and led to development of QCD
- QCD has interesting properties
  - confinement: force is strong at large distances
    - color neutral hadrons, which can be made with any number of quarks
  - gluon-gluon interactions

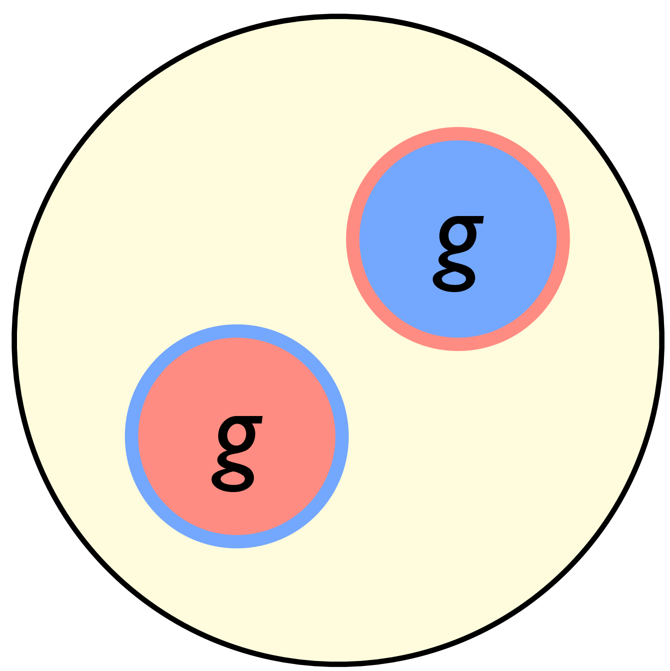
- *How do these properties exhibit themselves in experimental data?*
- *Why is the spectrum of hadrons observed in nature so simple?*

Same fundamental questions exist for mesons and baryons.
Our discussion will focus on mesons.

Other Unique States of Matter







Not forbidden by QCD -
do they exist?

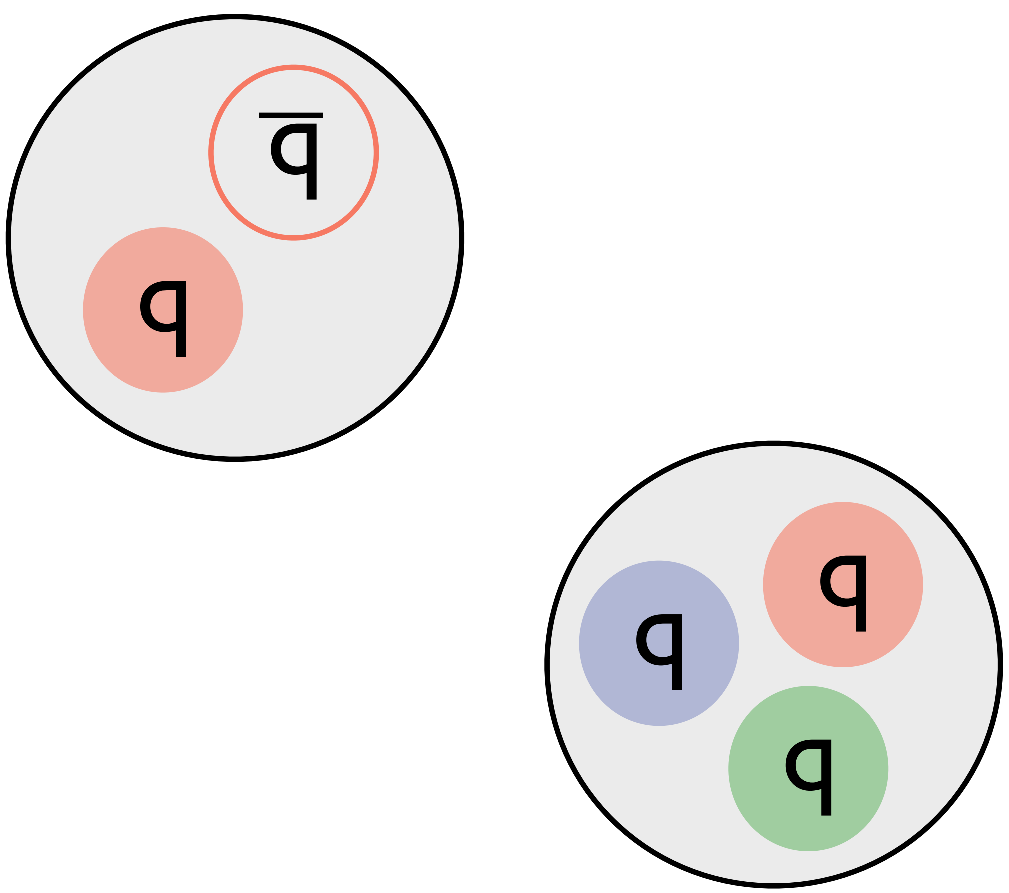
Classifying Mesons

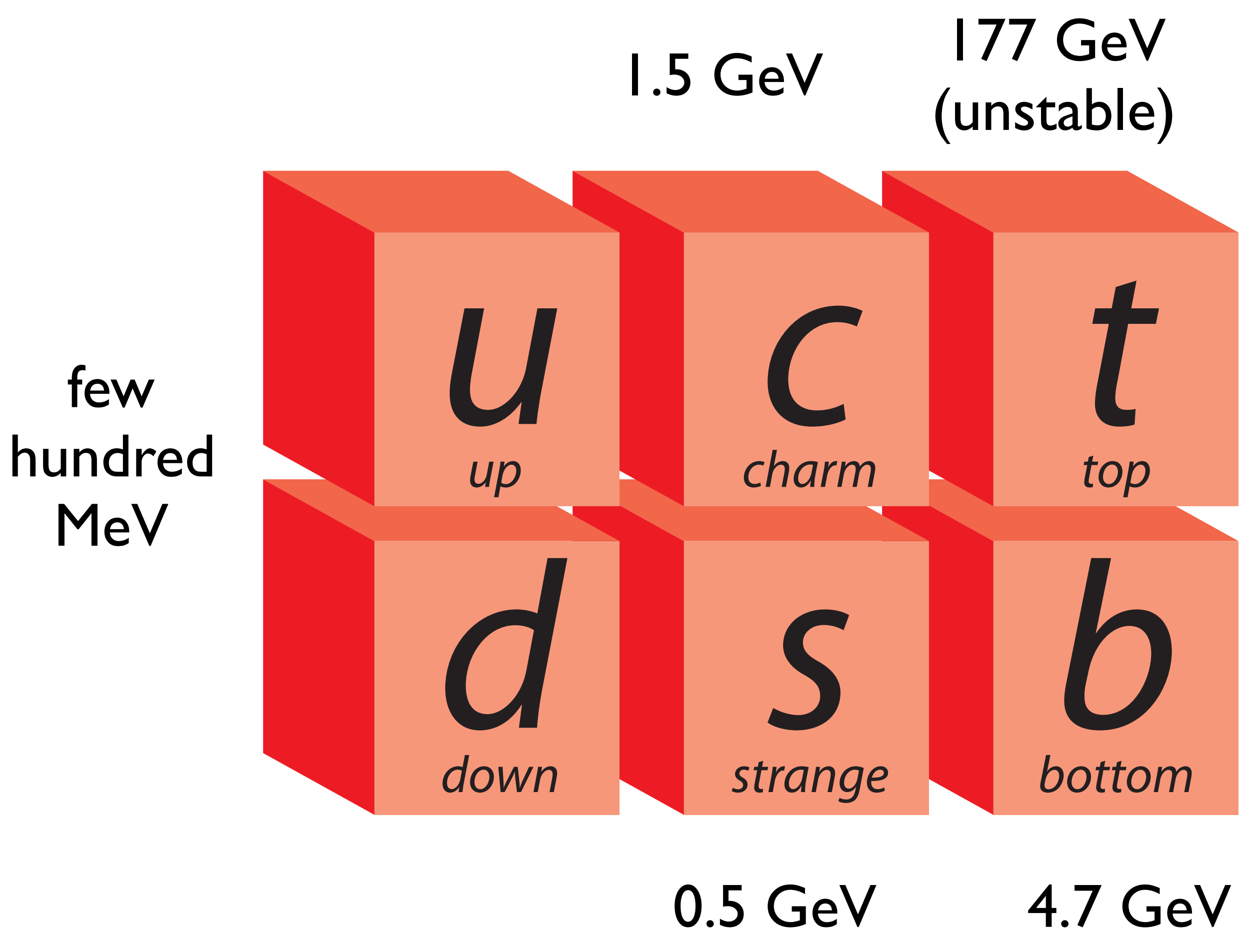
Properties of Mesons

- mass
- width or lifetime
- total angular momentum
- parity
- charge conjugation
- charge and isospin

Constituent Quark Model

- Assemble mesons from spin 1/2 constituent quarks with effective masses
    - a model: not the quark fields in the QCD Lagrangian





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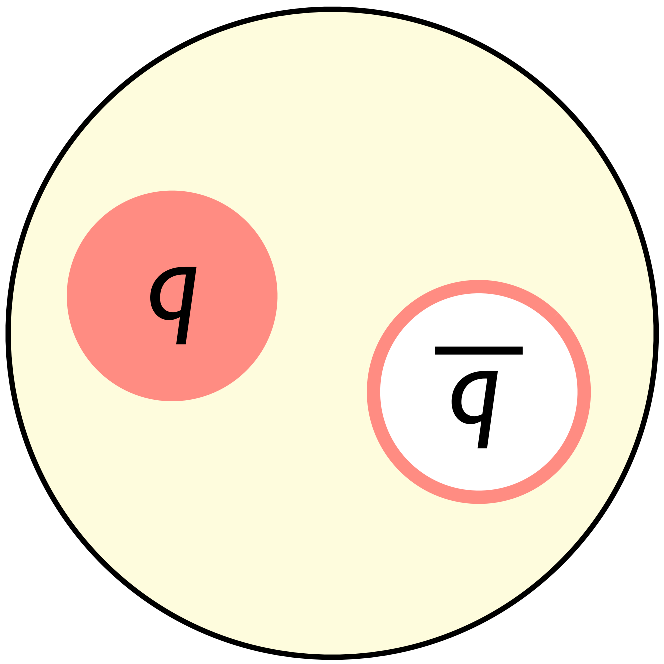
J^{PC}

color singlet
quark anti-quark



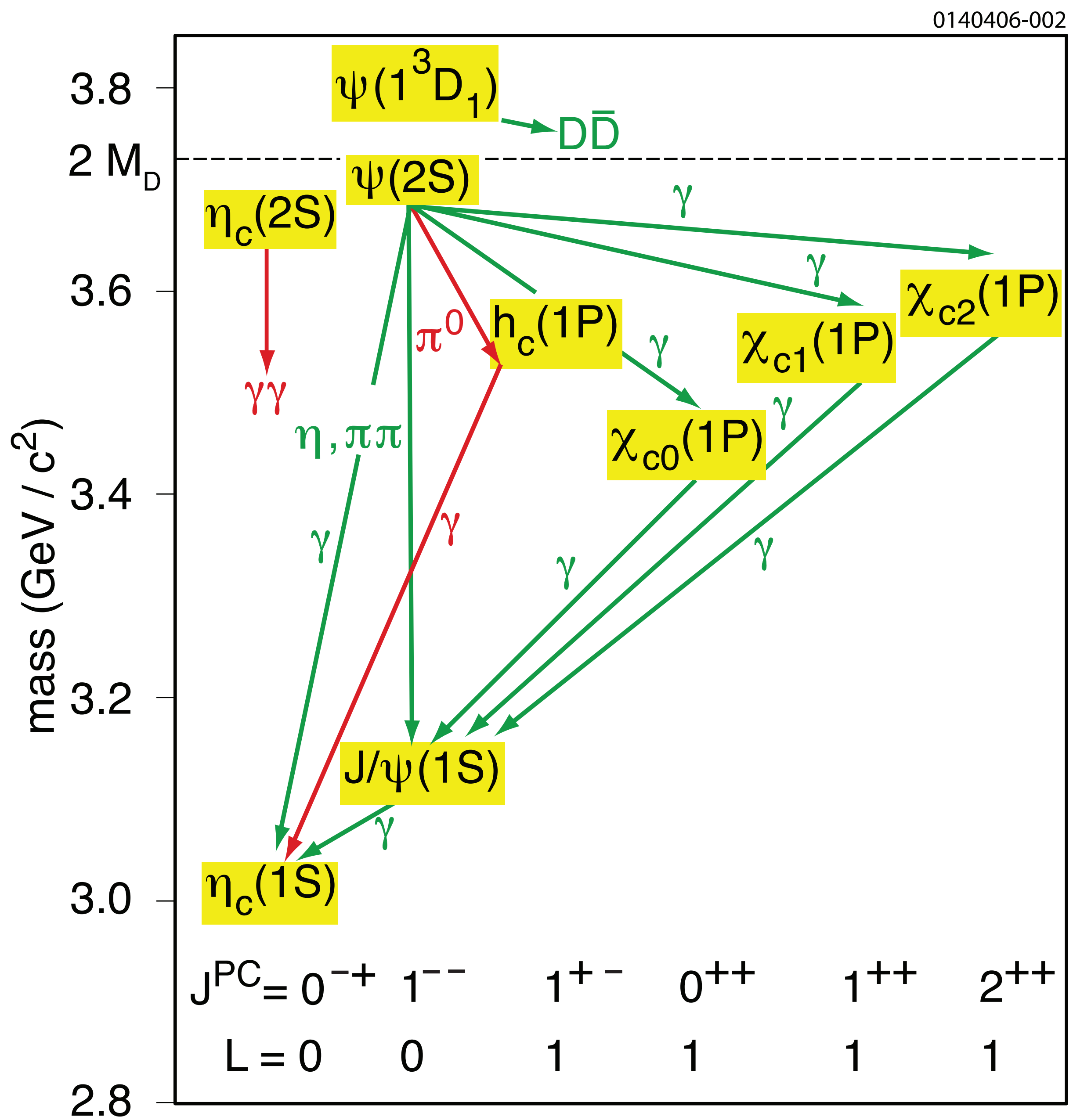
$J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

S = 0 or 1, and L = 0, 1, 2, …

- P: inverts coordinates
  - quark wave function is odd under spatial inversion for L odd: $(-1)^L$
  - Intrinsic party of quark anti-quark: 1 x -1 = -1
- C: particle → anti-particle
  - neutral eigenstates
  - spatial inversion: $(-1)^L$
  - fermion → anti-fermion: -1
  - opposite spins: -1^{S+1}

Charmonium Spectrum

- All states below 2 M_D observed
- No extra states below 2 M_D
- Good agreement with potential model calculation
- No missing states - no extra states



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M. R. Shepherd
NNPSS at MIT
July 2016

Isospin

- symmetry from $m_u \approx m_d$
- in isospin space:
  u has I = 1/2, I_z = 1/2
  d has I = 1/2, I_z = -1/2
- Combining quark antiquark elements from this vector space gives four combinations (examples for 0^{-+} given)

$$|u\bar{d}\rangle \to \pi^+$$

$$\frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right) \to \pi^0$$

$$|d\bar{u}\rangle \to \pi^-$$

triplet: isovector (I = 1)

Homework: why are these almost exactly a factor of 2 different?

$$\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi) = 0.34$$

$$\mathcal{B}(\psi(2S) \to \pi^0\pi^0 J/\psi) = 0.18$$

Homework: why is the first so much bigger than the second even though there is less phase space available?

$$\mathcal{B}(\psi(2S) \to \eta J/\psi) = 0.034$$

$$\mathcal{B}(\psi(2S) \to \pi^0 J/\psi) = 0.0013$$

$$\frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right) \to \eta$$

singlet: isoscalar (I = 0)

G Parity

- Extension of C to isovectors (charged particles):
  - apply C
  - rotate by π in isospin space: u ↔ d
- Multiplicative
- Mostly conserved in strong interactions
- **general: G = C(-1)*^{I}***

$$|u\bar{d}\rangle \rightarrow |\bar{u}d\rangle \rightarrow |\bar{d}u\rangle$$

isospin: 0 : G = C

$$|u\bar{u}\rangle + |d\bar{d}\rangle \rightarrow |d\bar{d}\rangle + |u\bar{u}\rangle$$

isospin: 1 : G = -C

$$|u\bar{u}\rangle - |d\bar{d}\rangle \rightarrow |d\bar{d}\rangle - |u\bar{u}\rangle$$

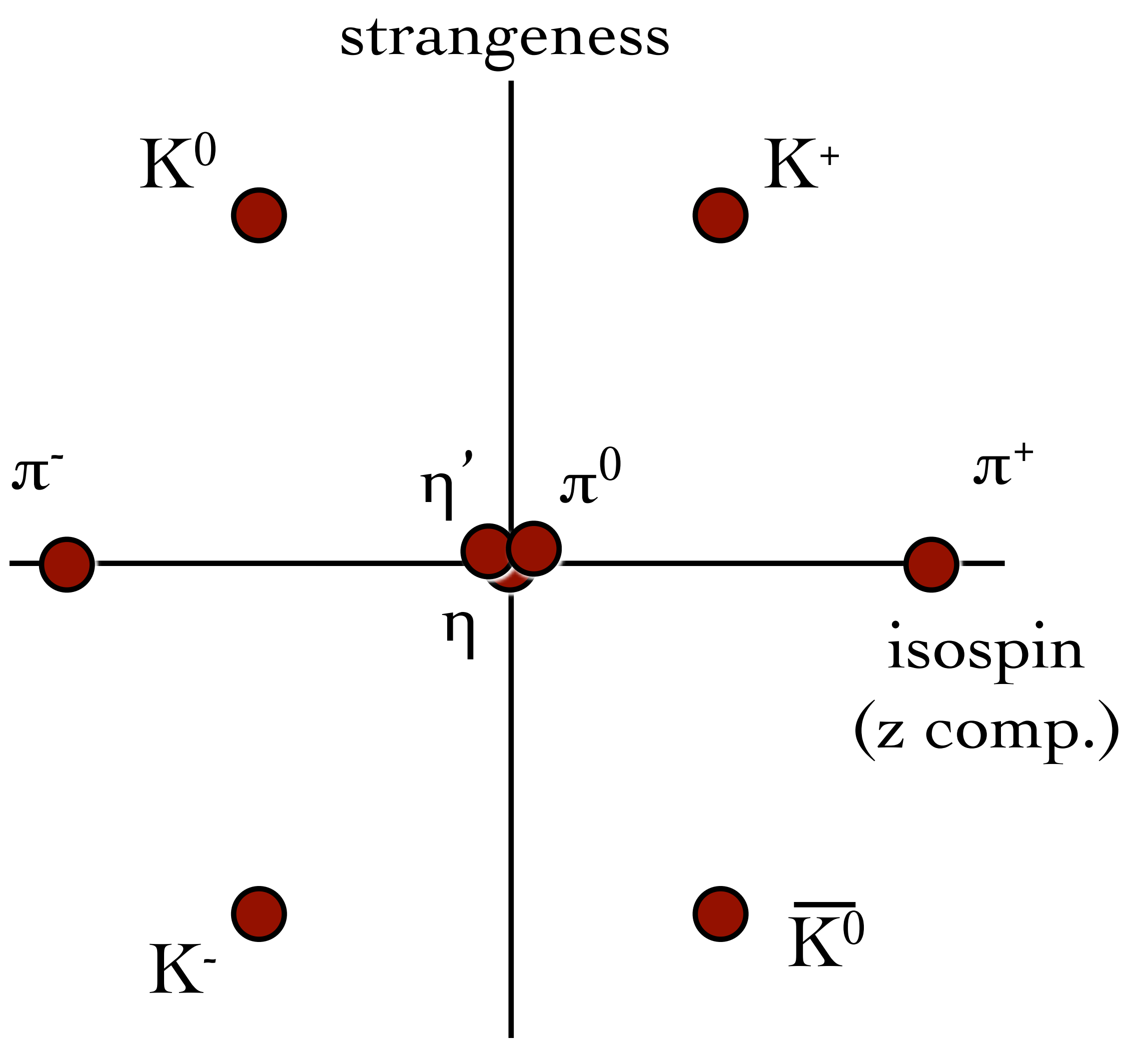
$$B(\rho^0 \rightarrow \pi^+\pi^-) \approx 1$$

$$B(\rho^0 \rightarrow \pi^+\pi^-\pi^0) = 1 \times 10^{-4}$$

$$B(\omega \rightarrow \pi^+\pi^-) = 0.015$$

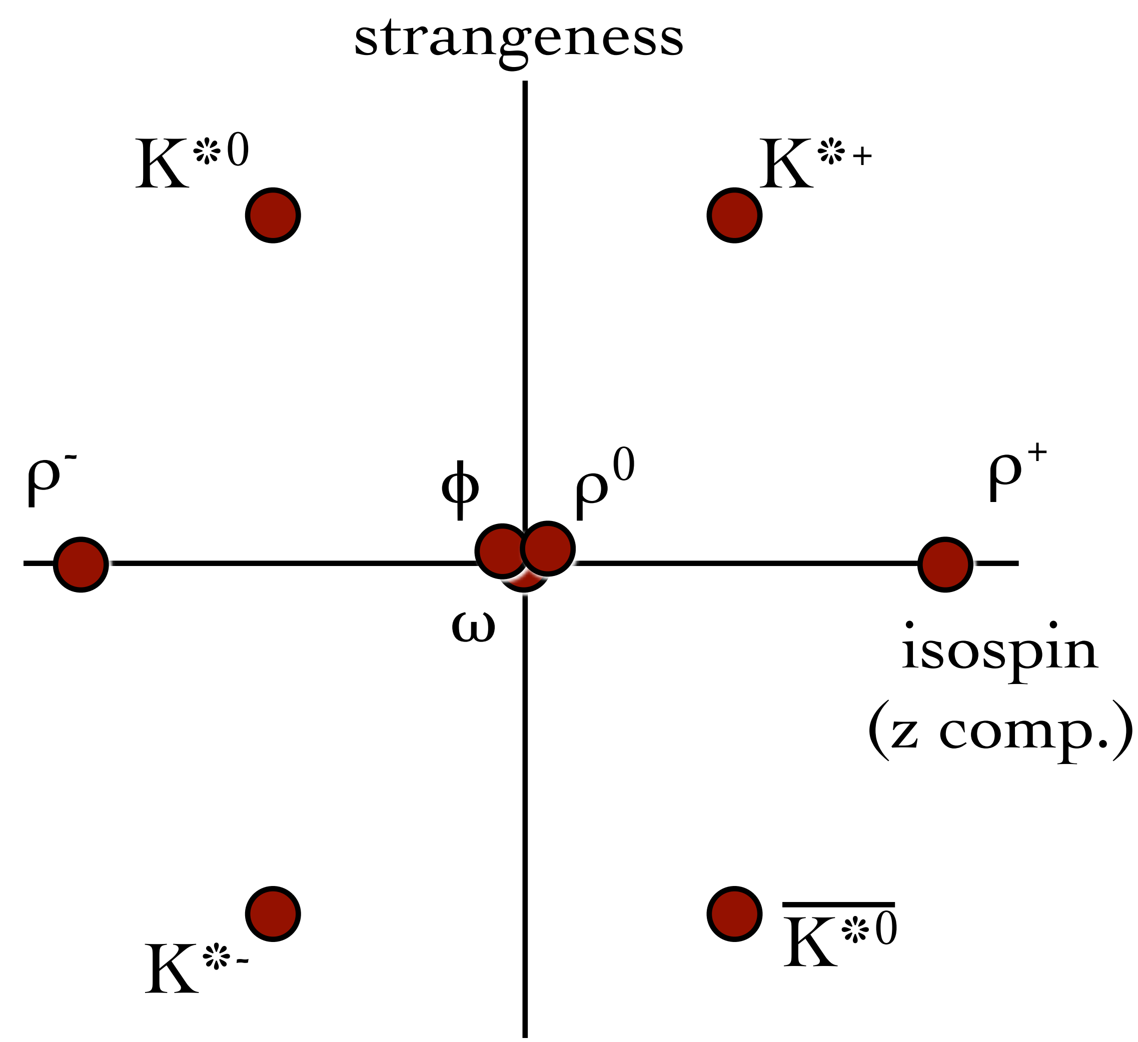
$$B(\omega \rightarrow \pi^+\pi^-\pi^0) = 0.89$$

Light Quark Nonets



0^- nonet

neutrals: C=+

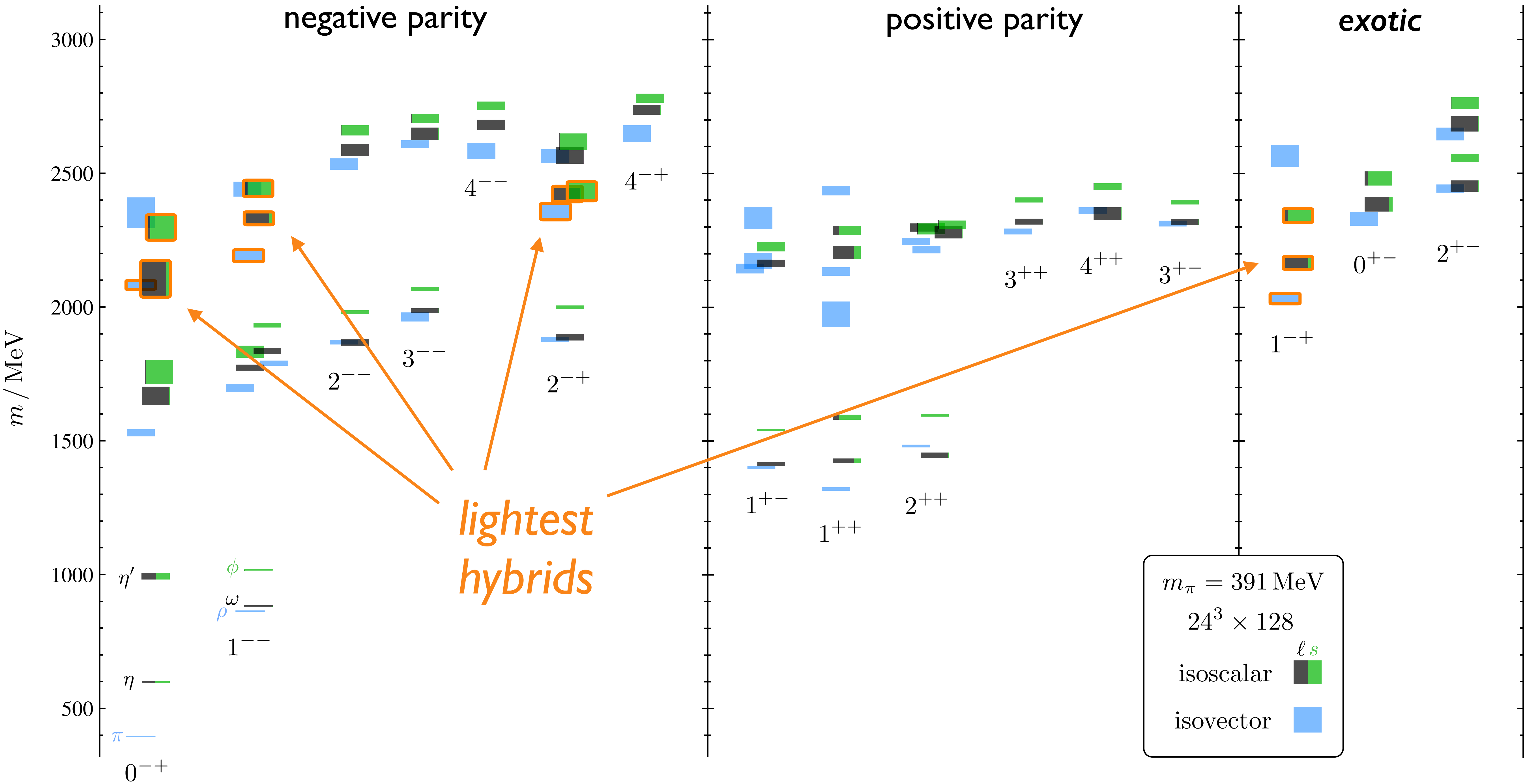


1^- nonet

neutrals: C=-

Meson Spectrum from Lattice QCD

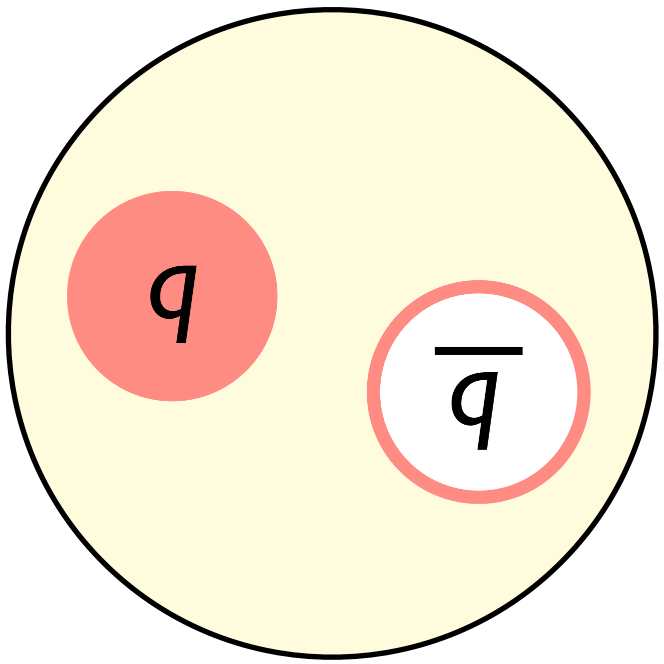
Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



All states have strangeness = 0

Hybrid Mesons

color singlet
quark anti-quark

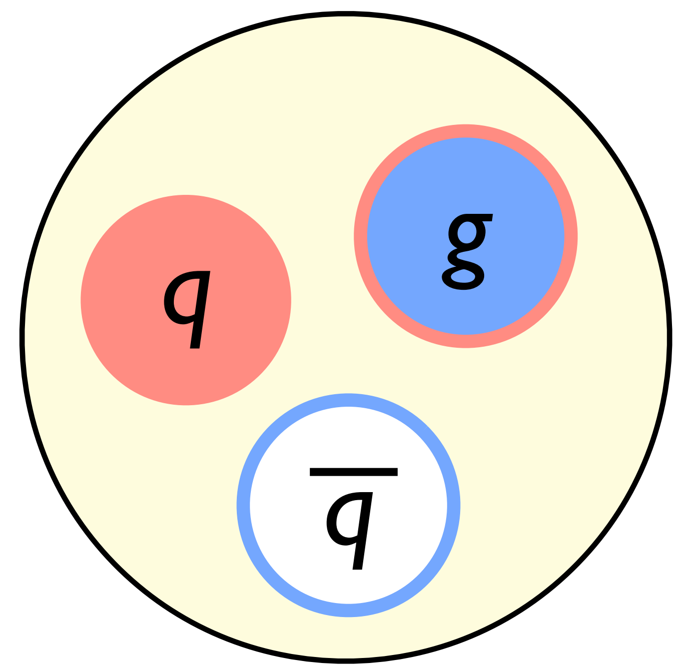


$J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$
Forbidden J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

"gluonic contribution"
$(J^{PC})_g = 1^{+-}$
mass ≈ 1.0-1.5 GeV

color-octet
$q\bar{q}$ pair



Lightest Hybrids

	$S_{q\bar{q}} = 1$	$S_{q\bar{q}} = 0$
J^{PC}:	$0^{-+}, 1^{-+}, 2^{-+}$	1^{--}

"exotic hybrid" (1^{-+})

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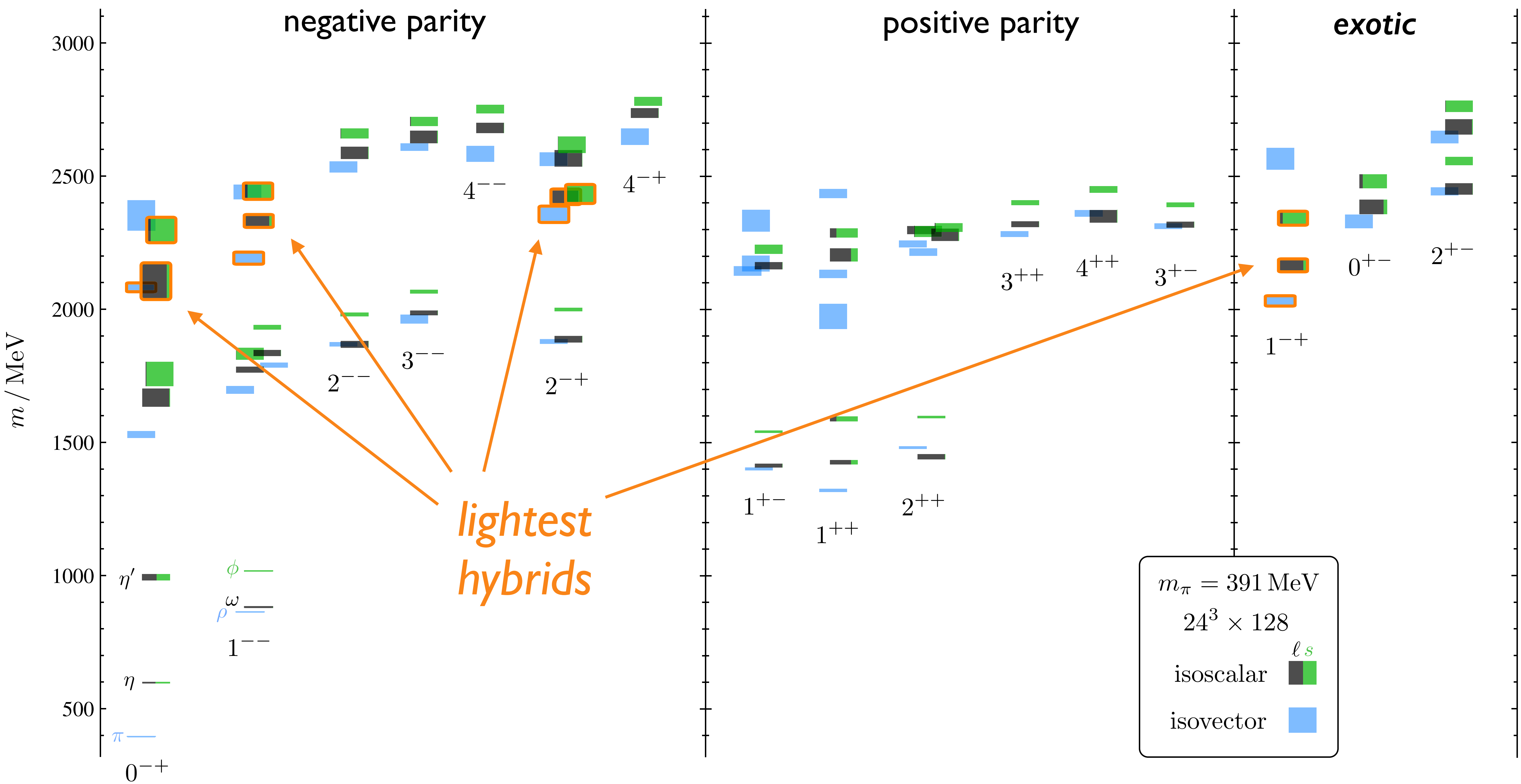
Recap

- Know how to classify and sort mesons
  - Enables identification of states that don't fit a pattern
  - New patterns suggest new degrees of freedom
- QCD predicts new states that should not fit the standard pattern
  - How do we produce them?
  - How do we detect them?
    - How do we measure the properties of mesons that we want to use to sort the spectrum?

Some Experimental Preliminaries

Meson Spectrum from Lattice QCD

Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



All states have strangeness = 0

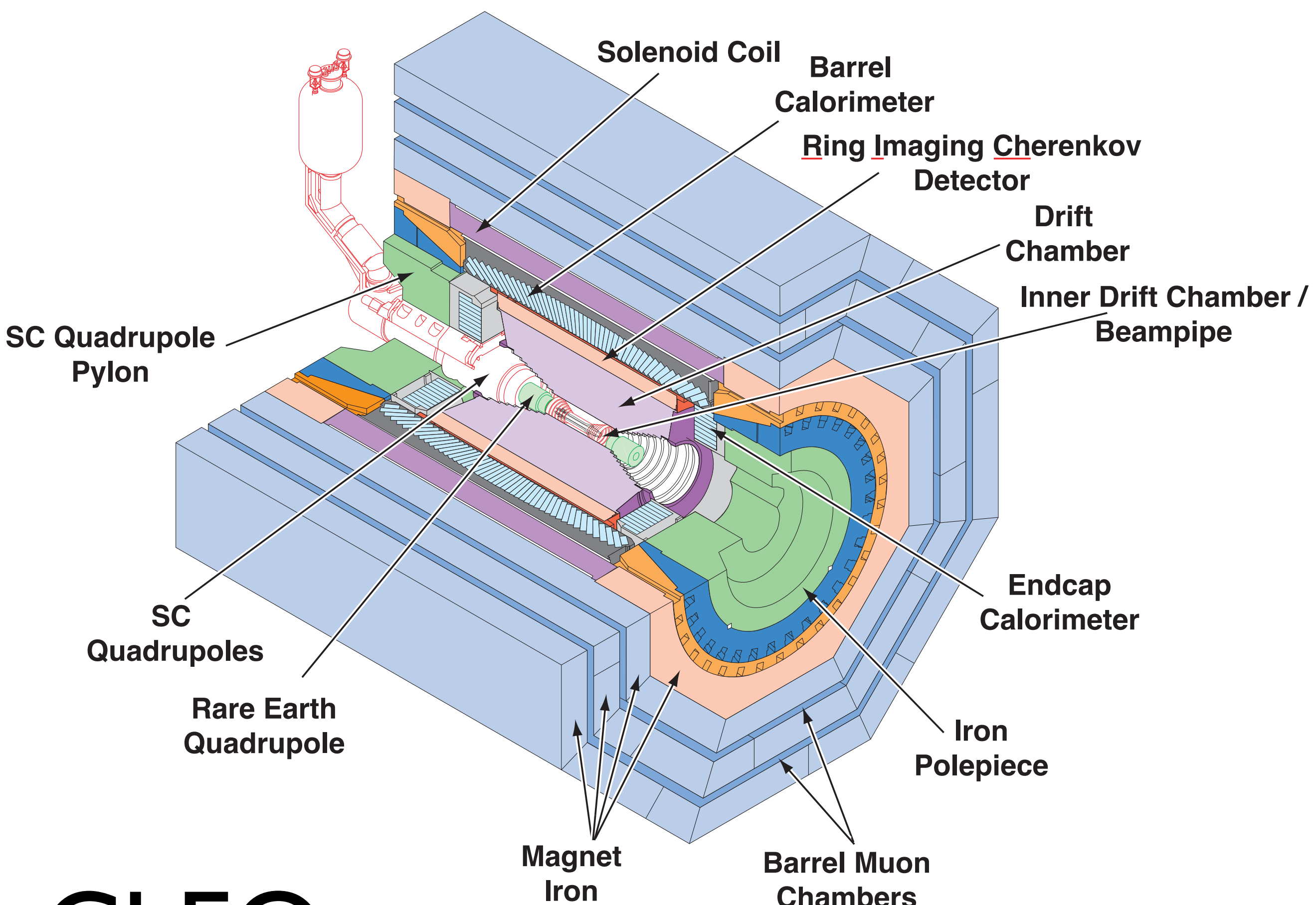
Decays and Conservation Laws

- Conservation laws that apply to all decays
  - angular momentum
  - four-momentum
  - charge
- Symmetries/conservations laws of strong interactions
  - C
  - P
  - isospin (mostly)
  - quark flavor: strangeness or charmness
- Measuring these properties for decay products directly informs us of the properties of the parent particle

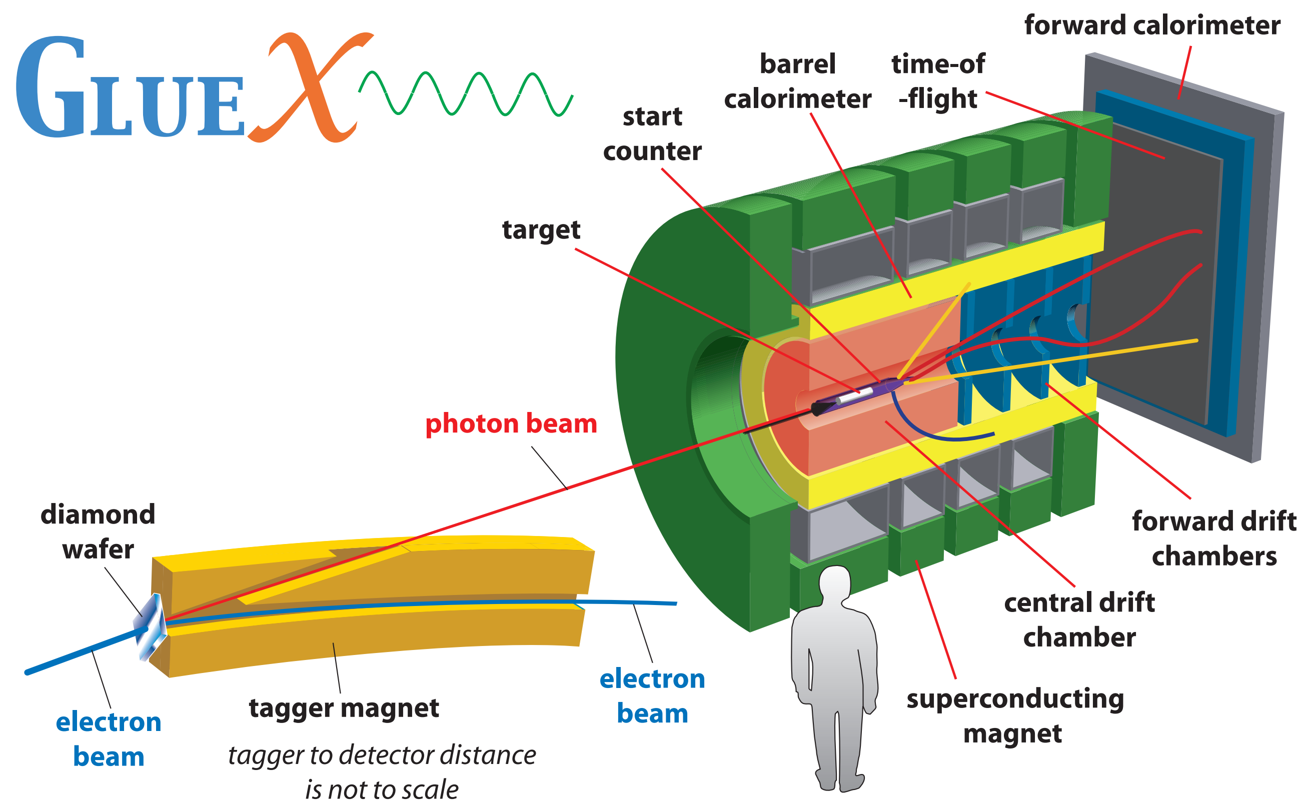
Production and Detection

Colliding Beam
e^+e^-
proton-proton
proton-antiproton

Fixed Target
electromagnetic or
hadron beams



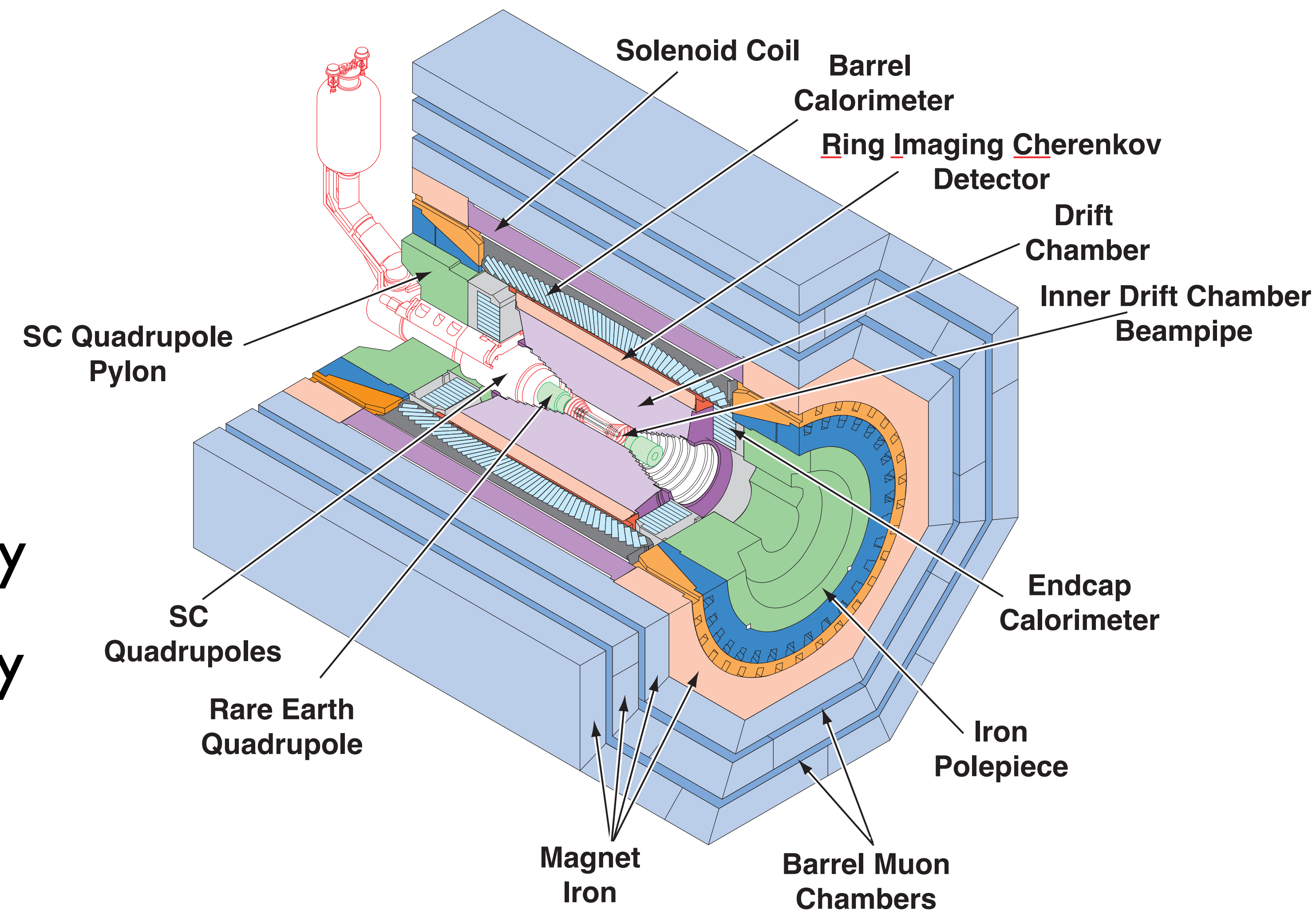
CLEO-c



Detection: Observables

- Long lived particles
  - charged: p, π, K
  - neutral: n, γ, K_L
- Types of detectors:
  - tracking: measure momentum
  - calorimetry: measure energy
  - particle ID: measure velocity
- Assemble pieces to get four-momentum

CLEO-c

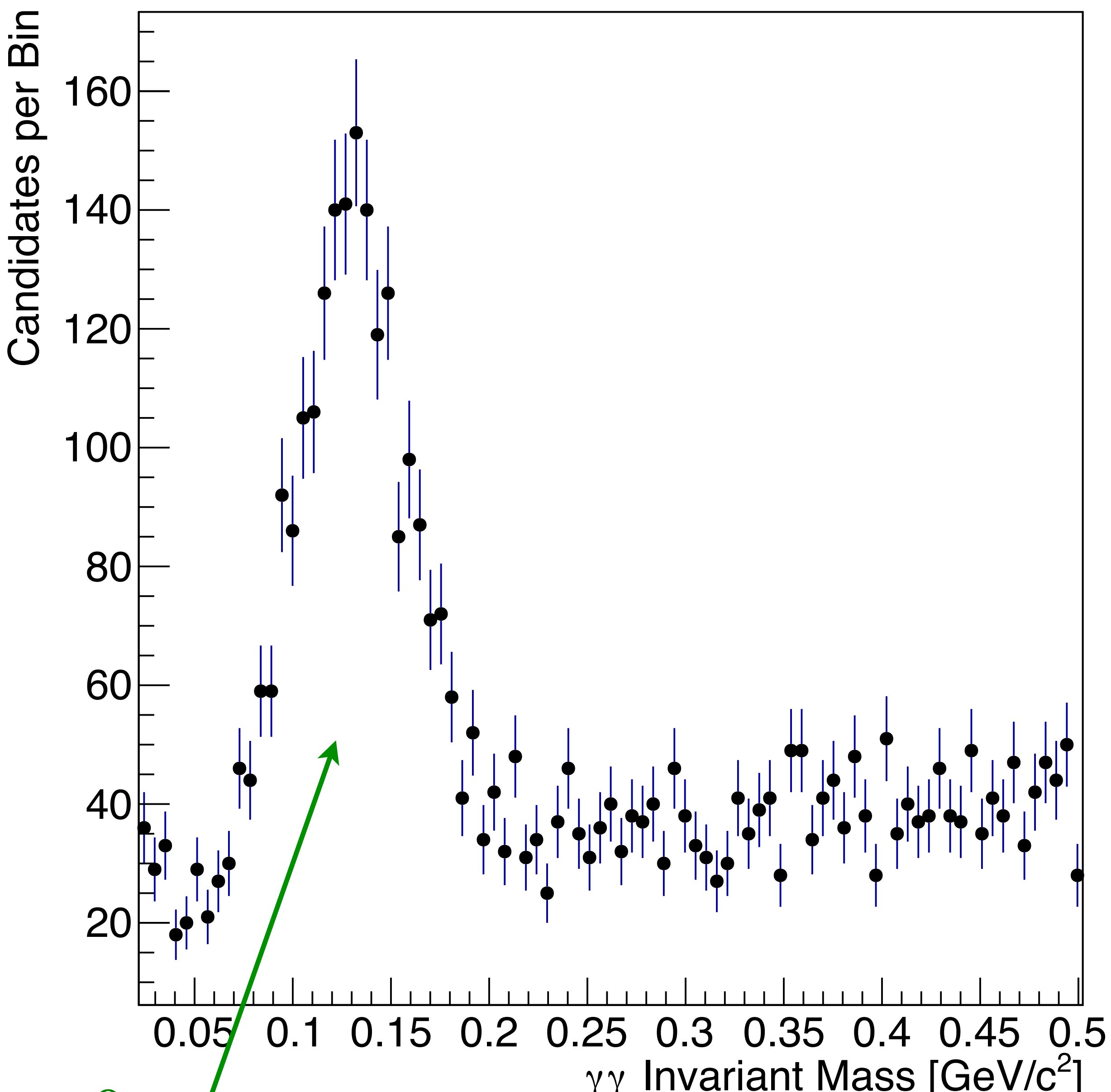


Histograms: Invariant Mass

$$\gamma p \to X$$

reconstruct all particles

consider all combinations of two photons



$\pi^0 \to \gamma\gamma$

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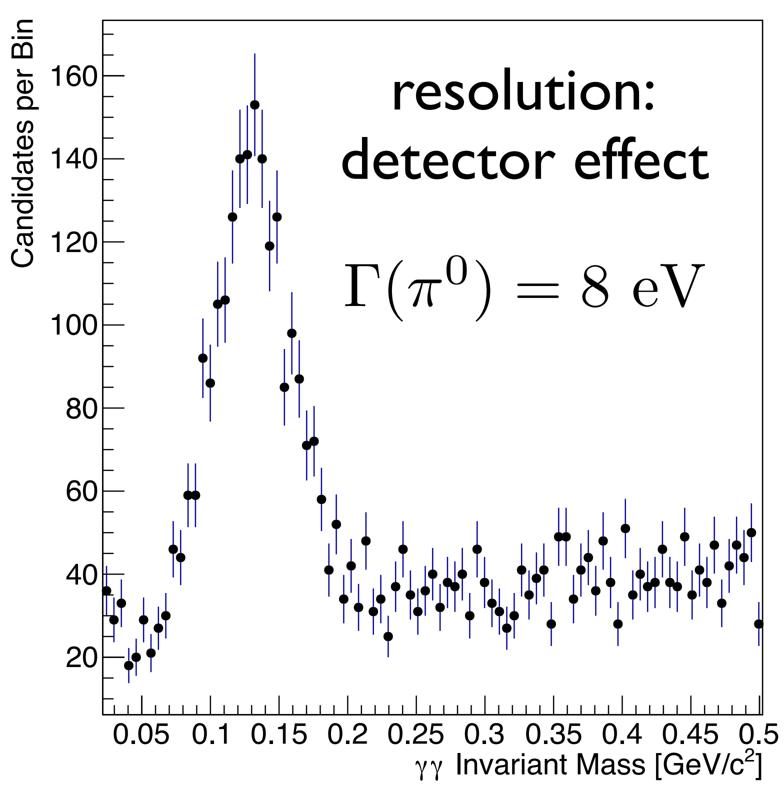
Branching Fractions and Widths

- Experimentally accessible:

$$B_i = \frac{\Gamma_i}{\Gamma_{\text{tot}}}$$

- Theoretically interesting:

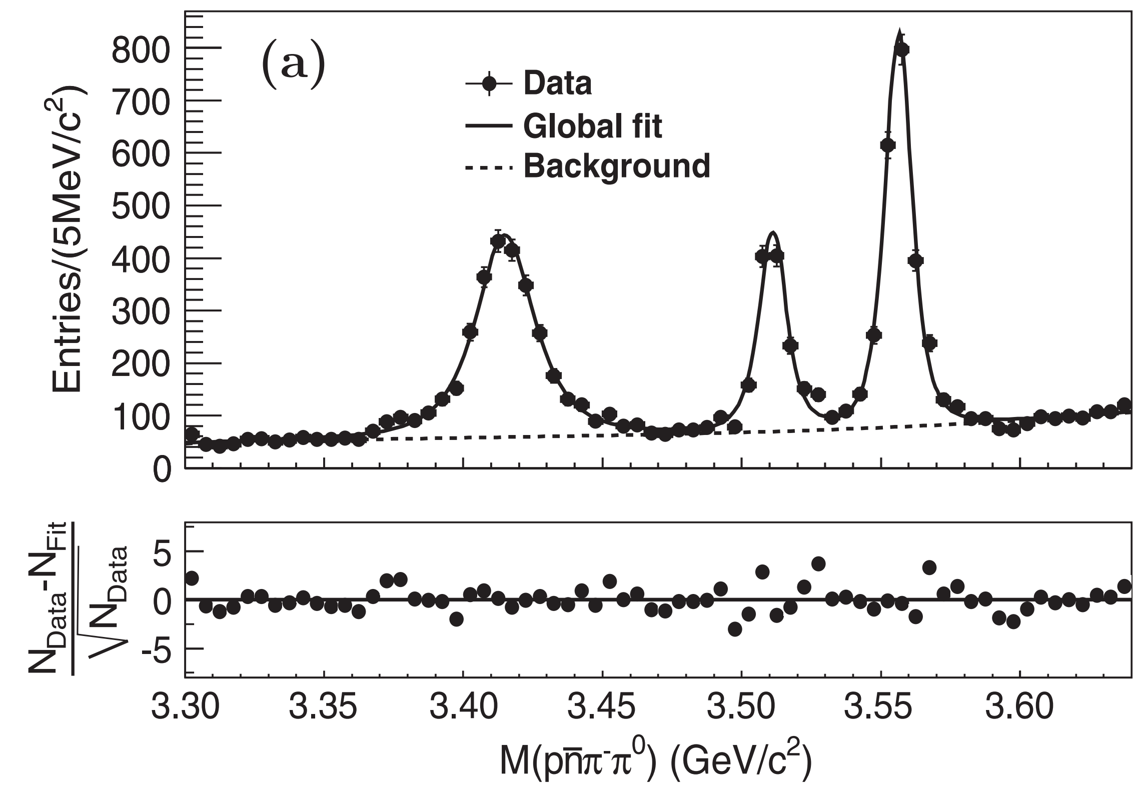
$$\Gamma_i \propto |\mathcal{M}_i|^2 \times (\text{phase space})$$



resolution:
detector effect

$$\Gamma(\pi^0) = 8 \text{ eV}$$

physics induced:
χ_{c0} is more likely to decay



PRD 86, 052011

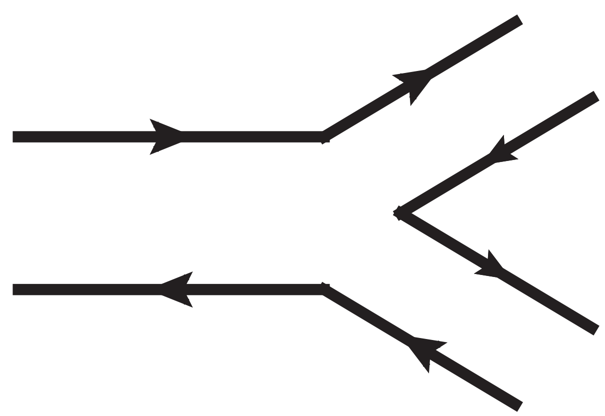
$$\Gamma(\chi_{c0}) = 10 \text{ MeV}$$

$$\Gamma(\chi_{c1}) = 0.8 \text{ MeV}$$

$$\Gamma(\chi_{c2}) = 1.9 \text{ MeV}$$

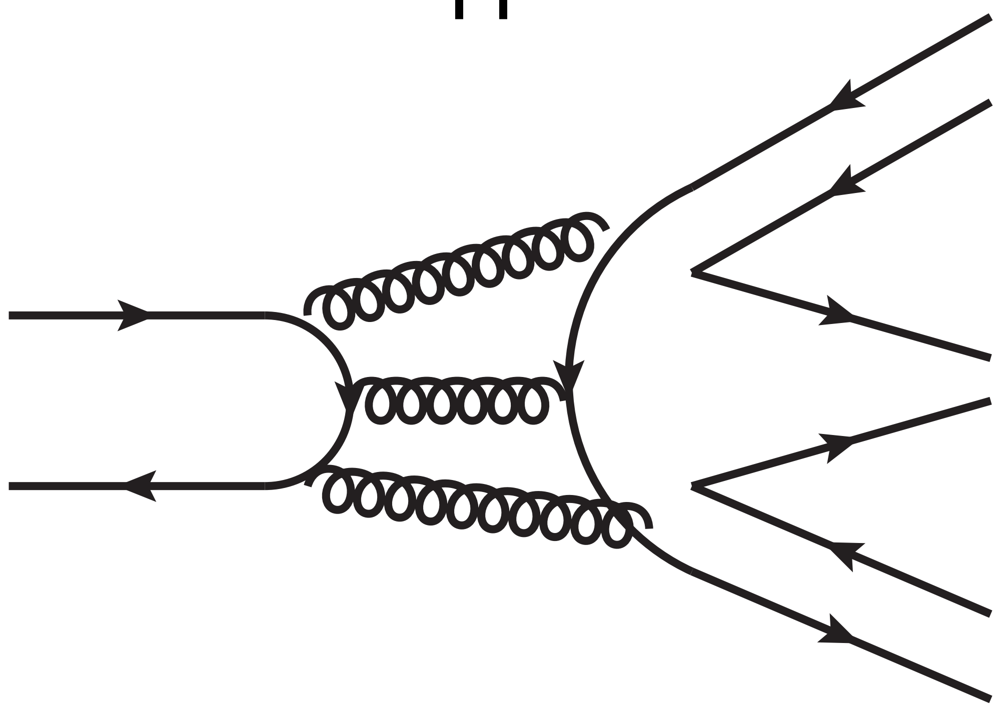
Decays: The OZI Rule
(S. Okubo, G. Zweig, and J. Iizuka)

OZI Favored



$B(\phi \to KK) = 0.83$

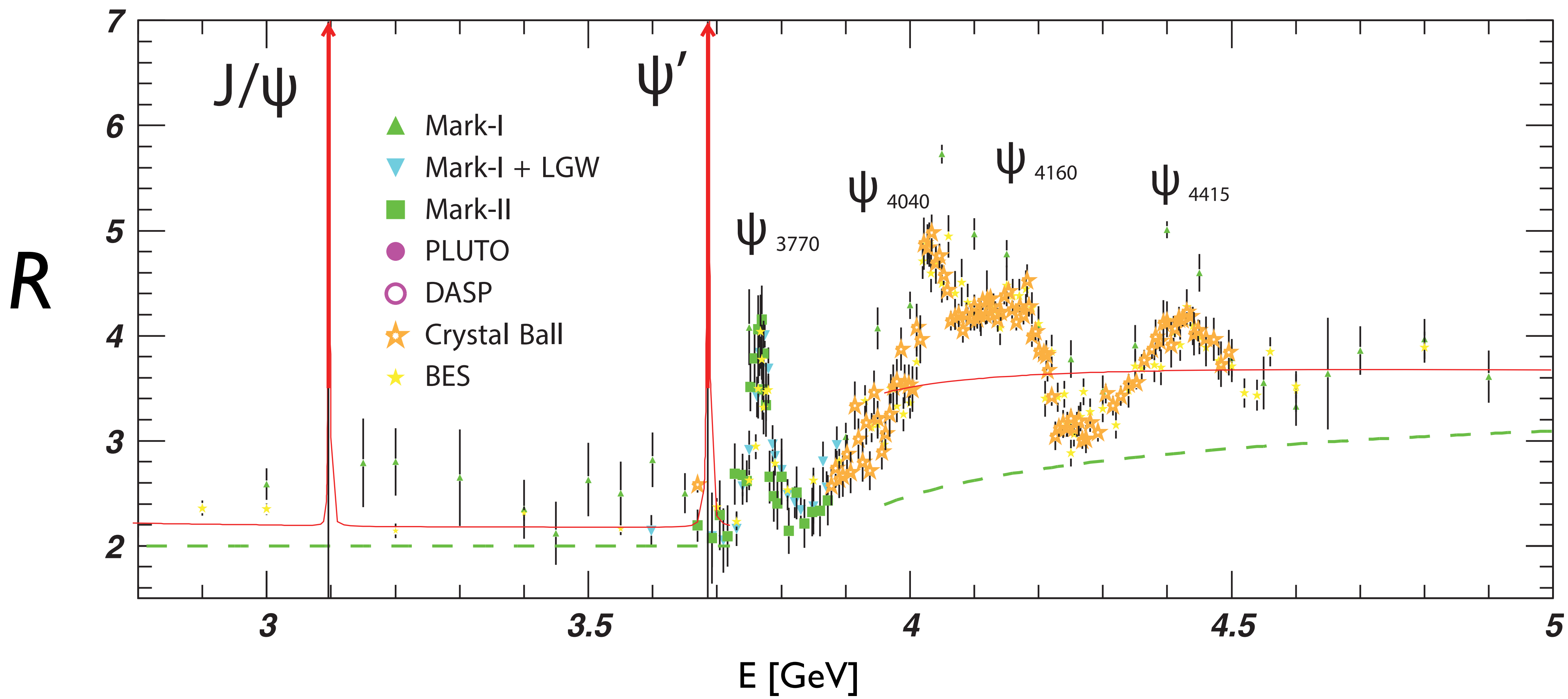
OZI Suppressed

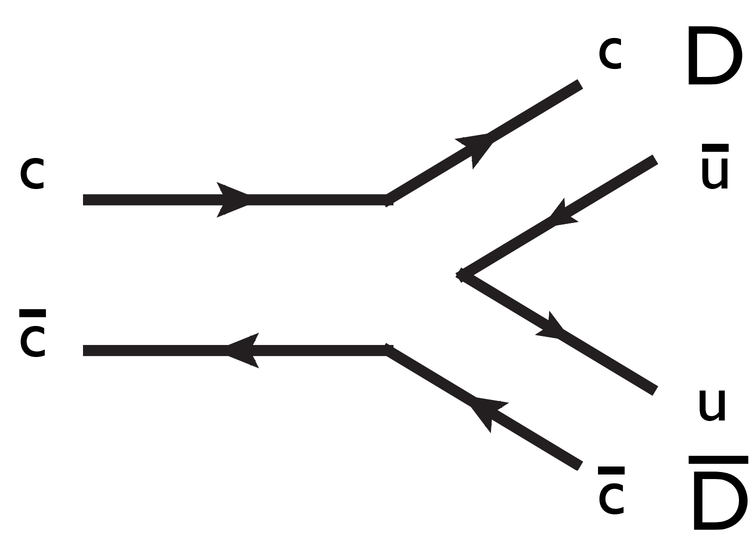


$B(\phi \to \pi^+\pi^-\pi^0) = 0.15$

Helps one infer "hidden" quark flavor of mesons.

OZI Rule and Widths



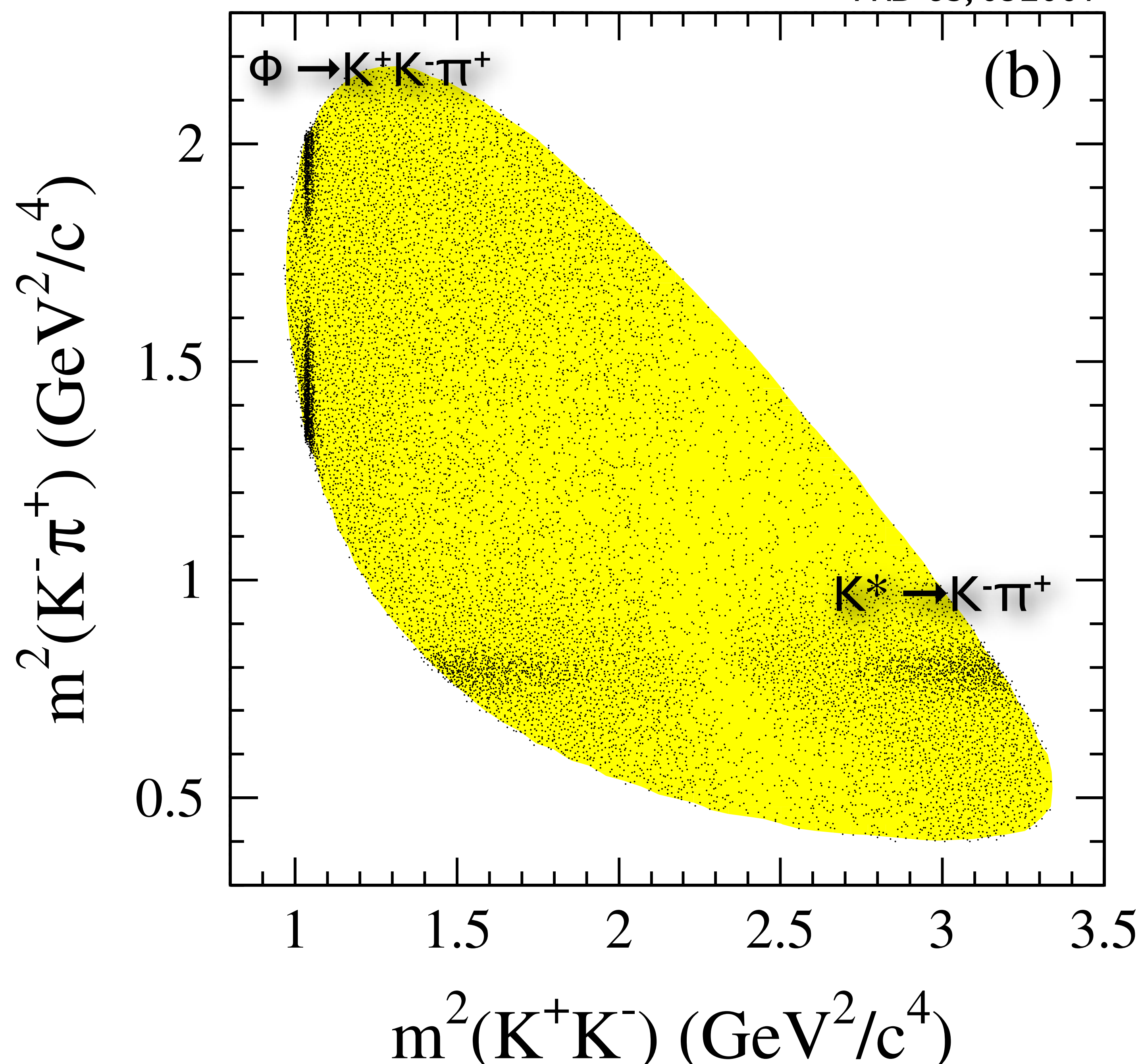


Dalitz Plots

- spinless particle → 3 spinless particles: X → 1 2 3
- $M_X^2 = M_{12}^2 + M_{23}^2 + M_{13}^2$
  - for an X, dynamics is a function of two variables: M_{12} and M_{23}
- All information about decay can be learned by studying a Dalitz plot of M_{12}^2 vs. M_{23}^2
  - phase space is uniform on this plot

$D_s^+ \to K^+K^-\pi^+$

PRD 83, 052001



Dalitz Plots

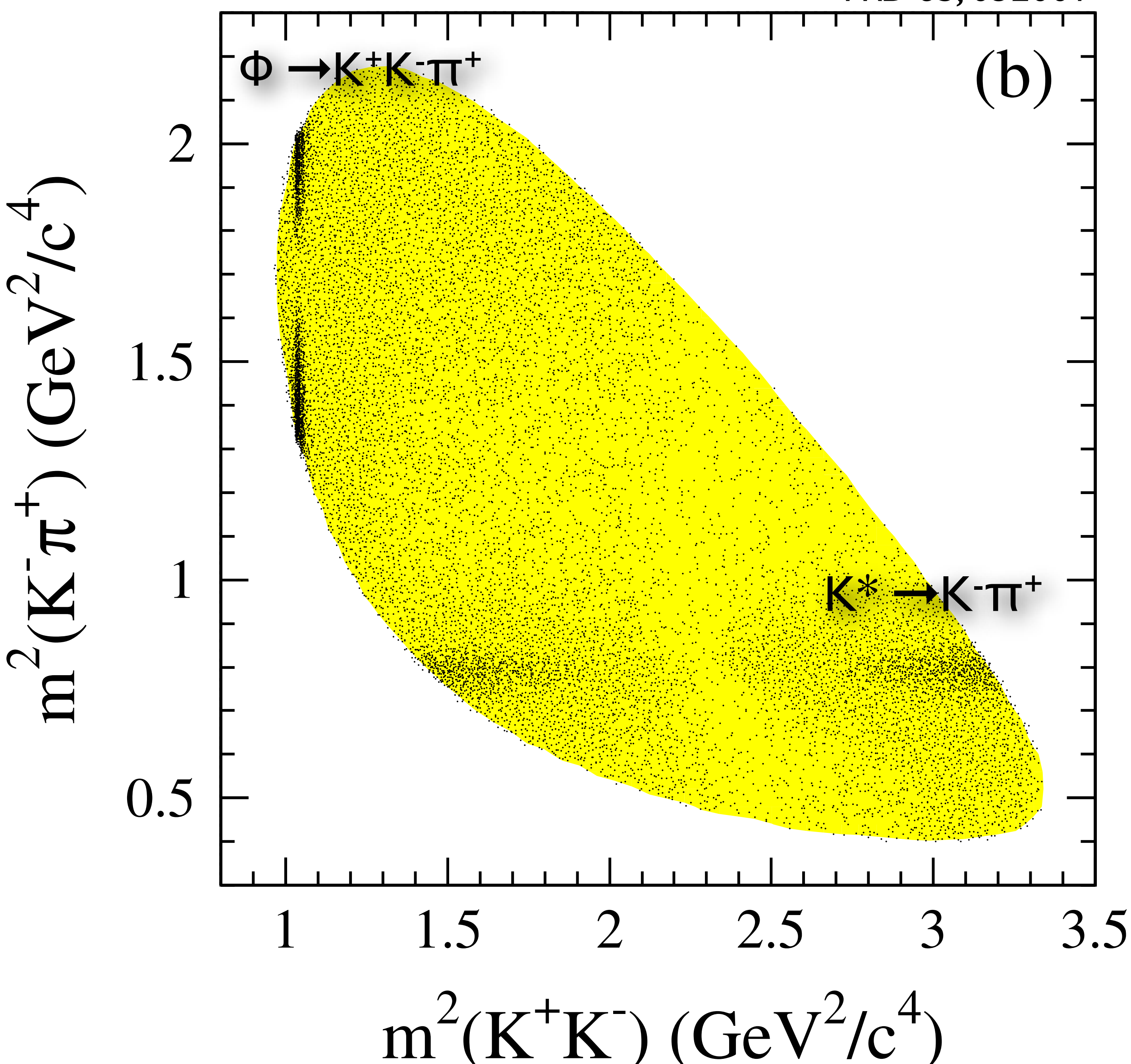
Homework: the decay of a spinless particle to 3 spinless particles can be described by 3 x 4-vectors = 12 numbers.

Use symmetry arguments and conservation laws to show that 10 of the 12 unknowns can be eliminated leaving only two remaining variables to describe the physics of the decay.

Any two variables will work, the Dalitz plot is a common choice.

$D_s^+ \rightarrow K^+K^-\pi^+$

PRD 83, 052001



Experimental Strategy

- Search for new particles
  - bumps in invariant mass spectra
  - unique decay patterns in phase space (more later)
- Measure
  - mass and width
  - decay modes
  - quantum numbers: J^{PC}
- Use to test predictions of the hadron spectrum from models or direct calculations of QCD