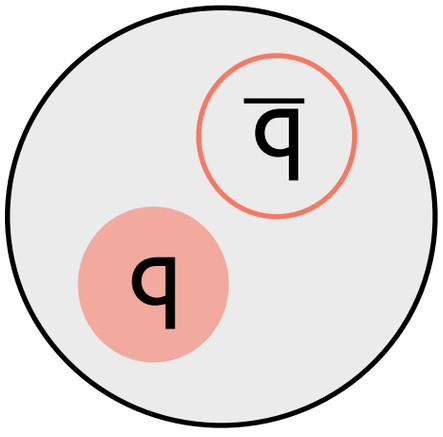
Meson Spectroscopy

Matthew Shepherd
Indiana University

GlueX Analysis Workshop
Jefferson Lab
May 11 - 13, 2016

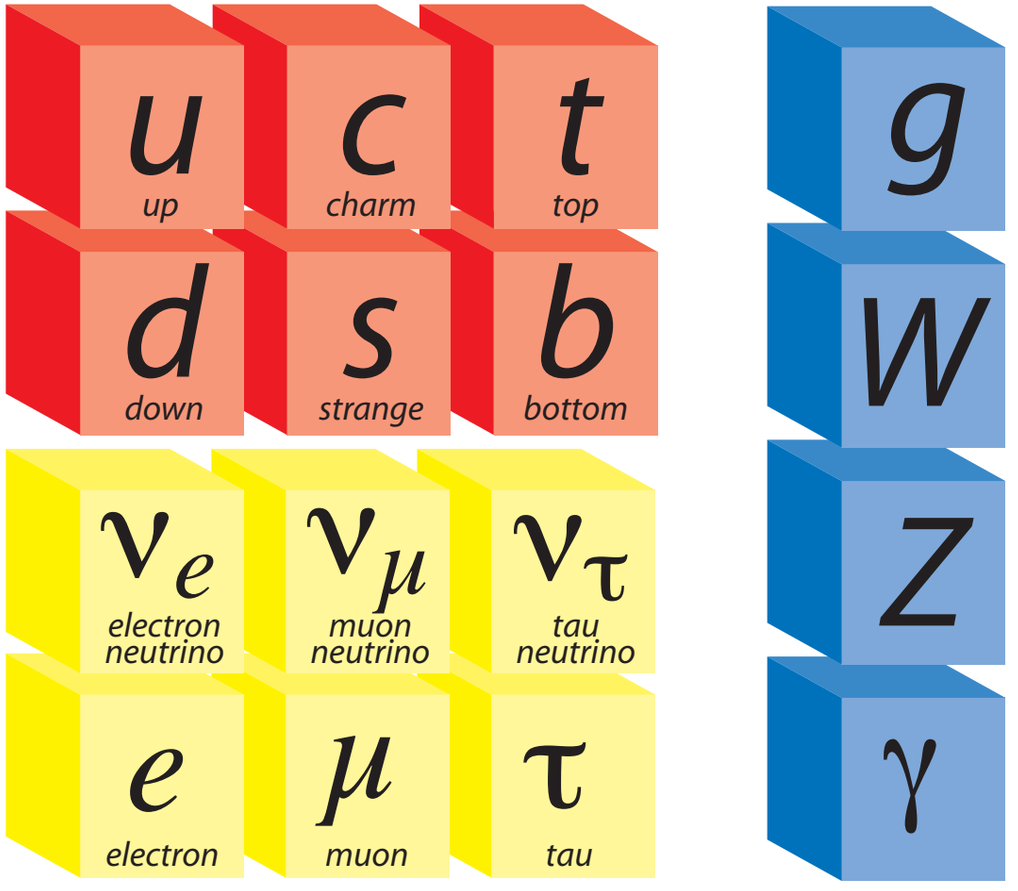
QCD in the Standard Model

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



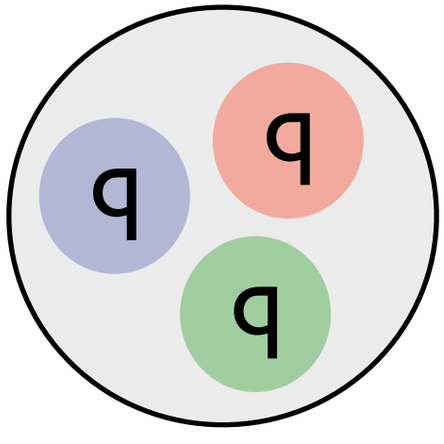
Mesons

(e.g., π, K, D)



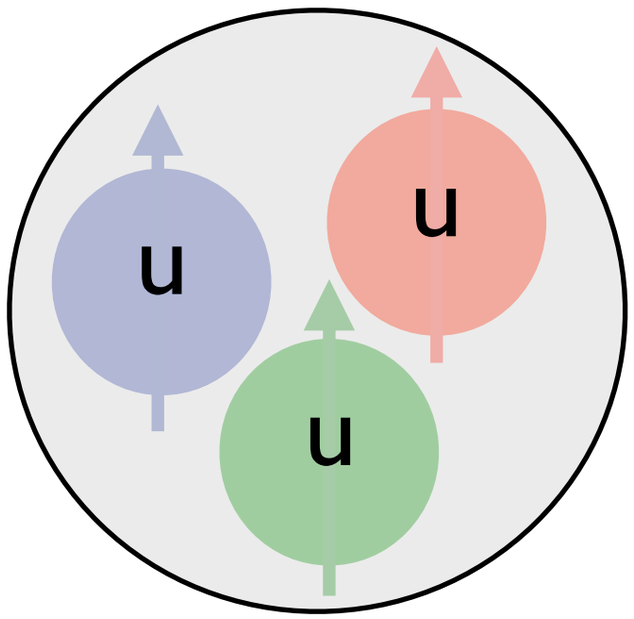
Baryons

(e.g., proton and neutron)



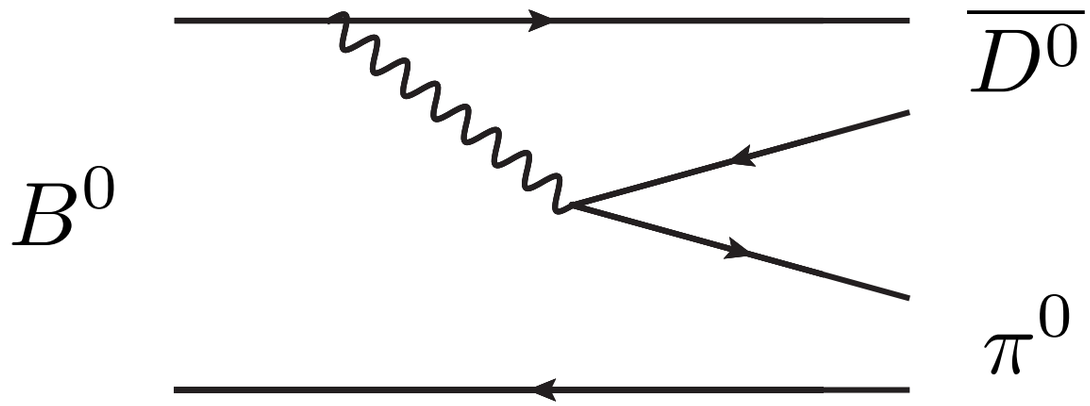
Evidence of Color

Δ^{++}

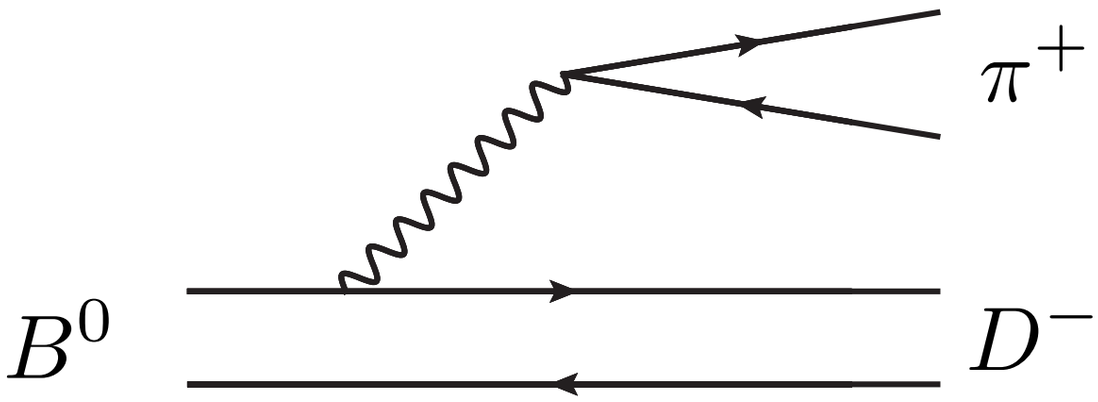


$$J = \frac{3}{2}$$

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



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



Interactions in QCD

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

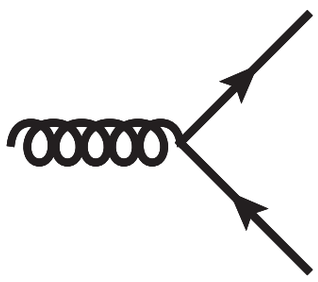
$$\mathcal{L} = i(\hbar c)\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - (mc^2)\bar{\psi}\psi$$

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

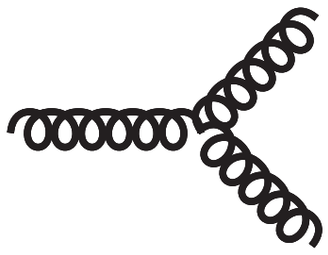
$$\begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix} \rightarrow U \begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix}$$

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

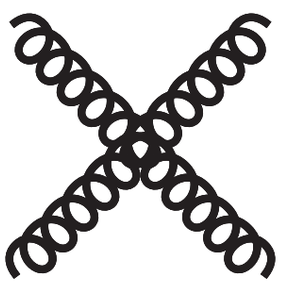
gluons



quark-gluon vertex



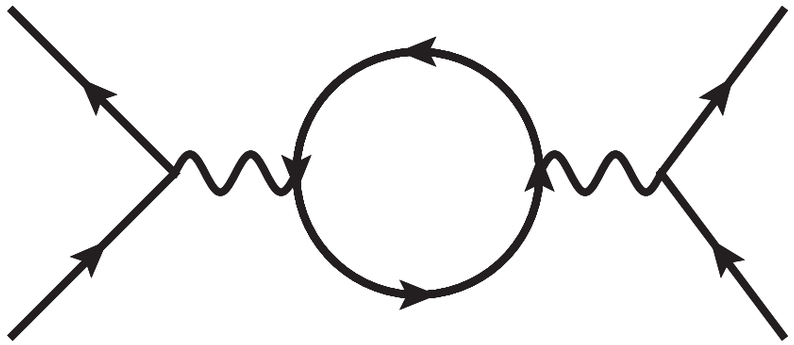
three-gluon vertex



four-gluon vertex

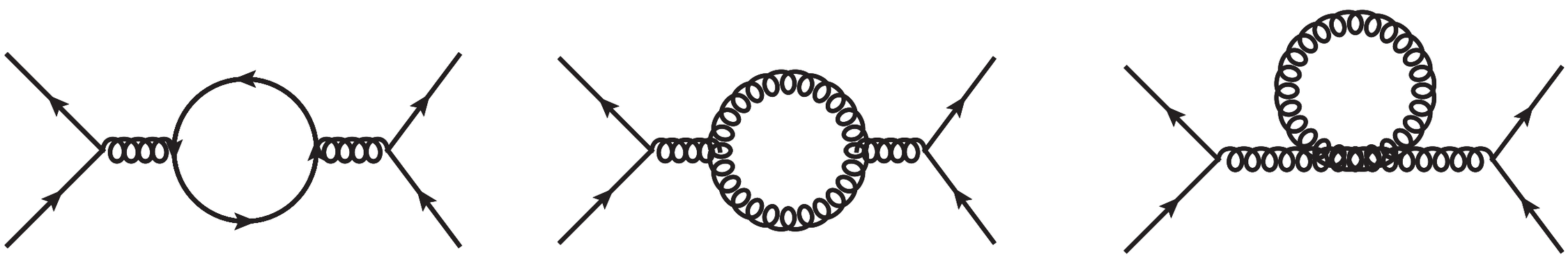
Higher Order Corrections

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

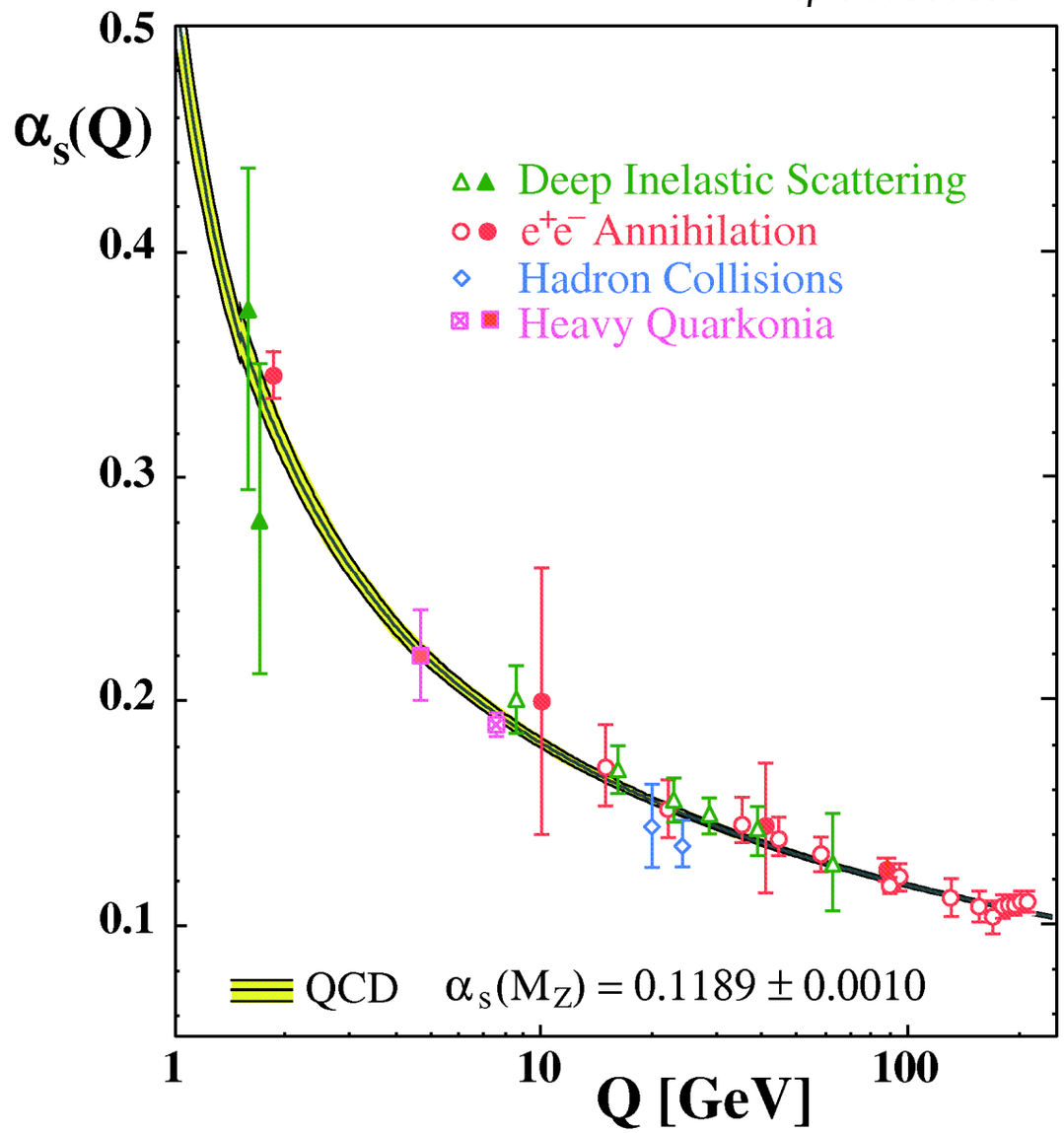


scale of QCD corrections set by $\alpha_s > 0.1$

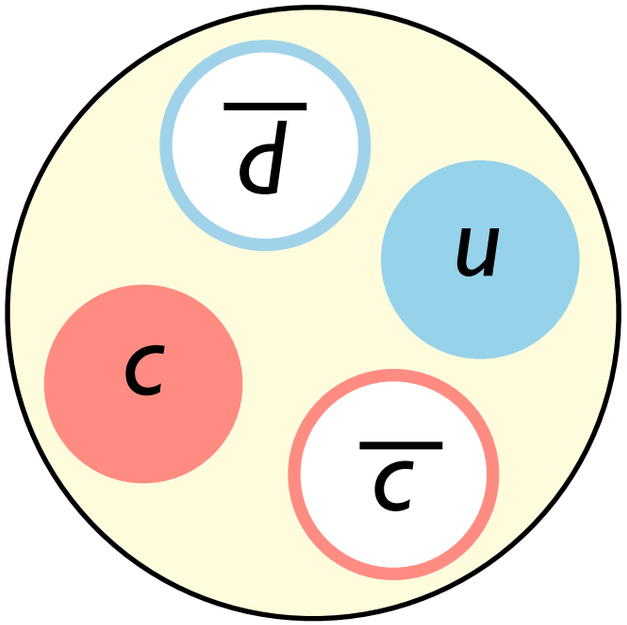
QCD Features

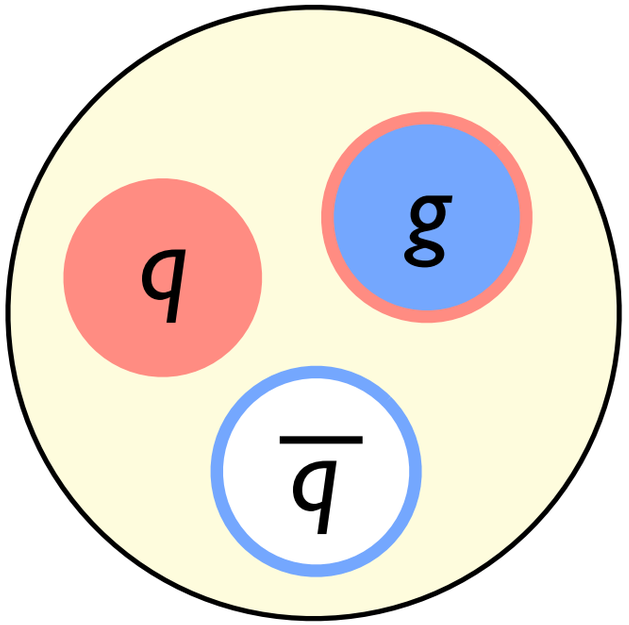
- Gluon-gluon interactions in QCD give rise to fascinating features of QCD
  - running of the effective coupling: confinement (?) and asymptotic freedom
  - generation of a significant amount of the nucleon mass
  - nonperturbative theory
- At low energy, we must study QCD through hadrons
- QCD Lagrangian suggests hadrons could be built with any colorless combination of quarks and gluons
  - > 3 quarks, glueballs, quark-gluon hybrids all seem to be allowed

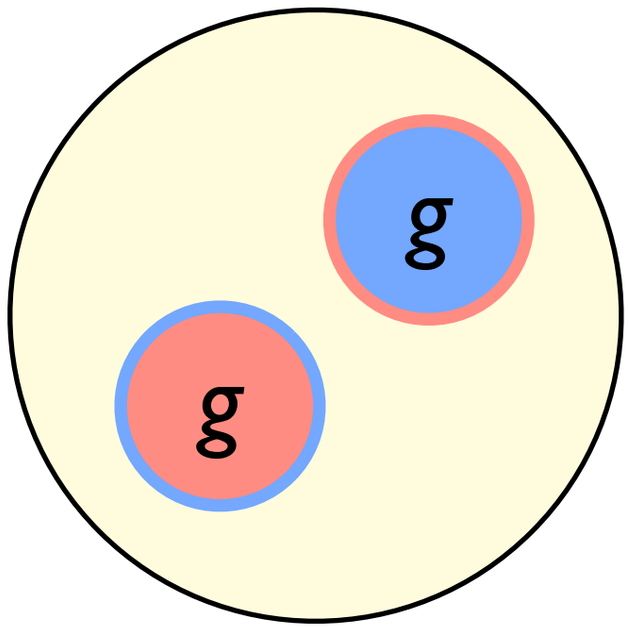
S. Bethke
hep-ex/0606035



Other Types of Hadrons







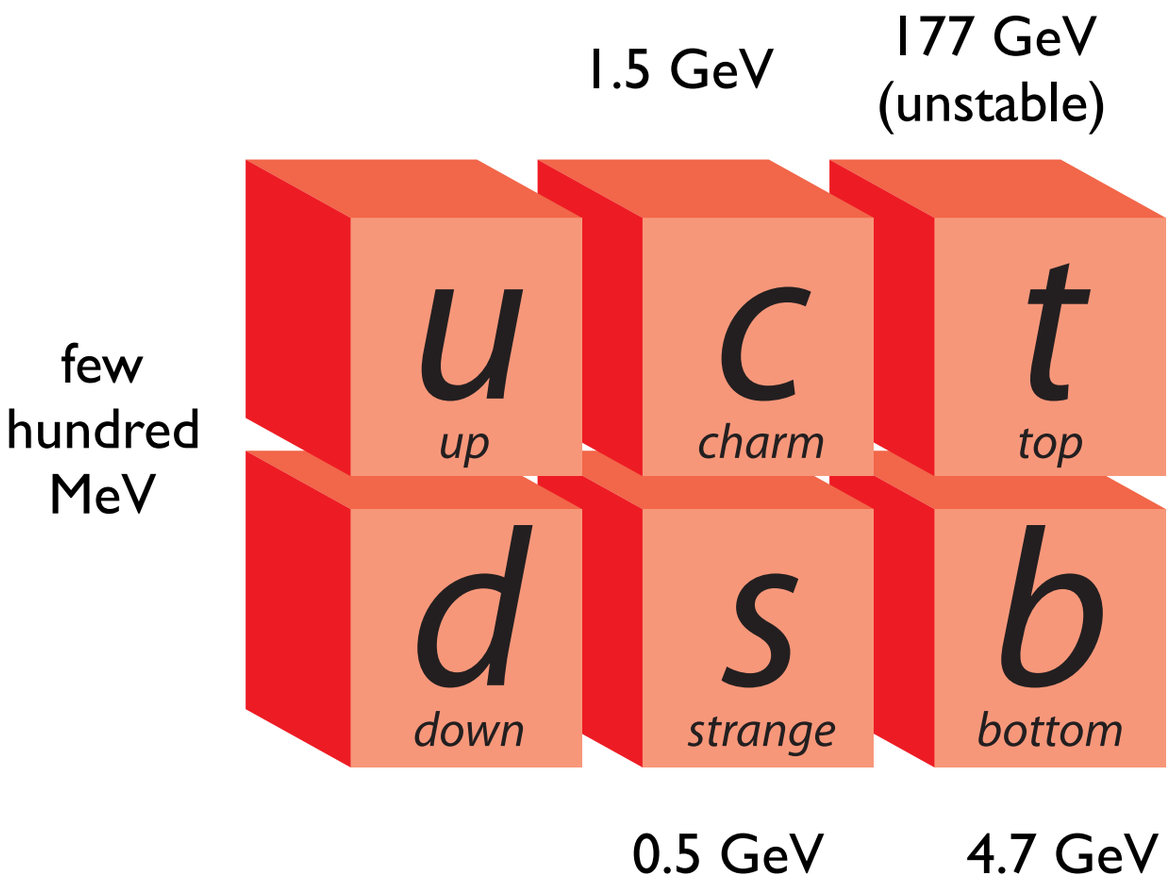
Apparently not forbidden by QCD - do they exist?

- Goal: understand what the QCD Lagrangian is telling us about the rules for building hadrons

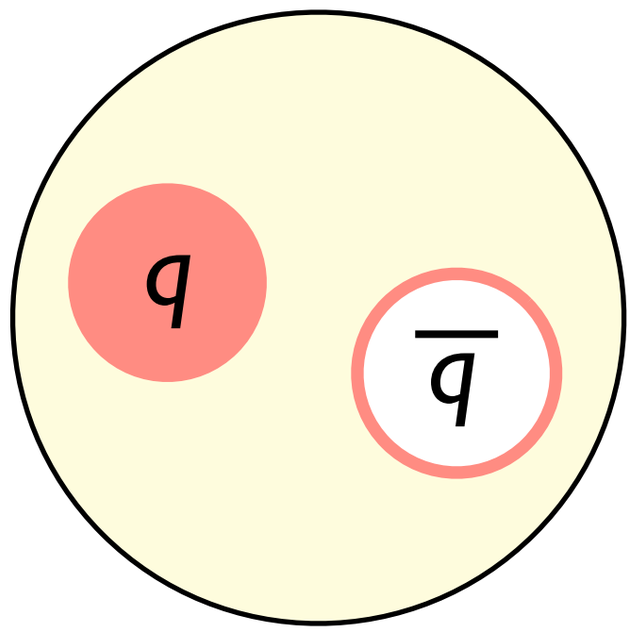
- Do this by studying the spectrum of mesons

Constituent Quark Model

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



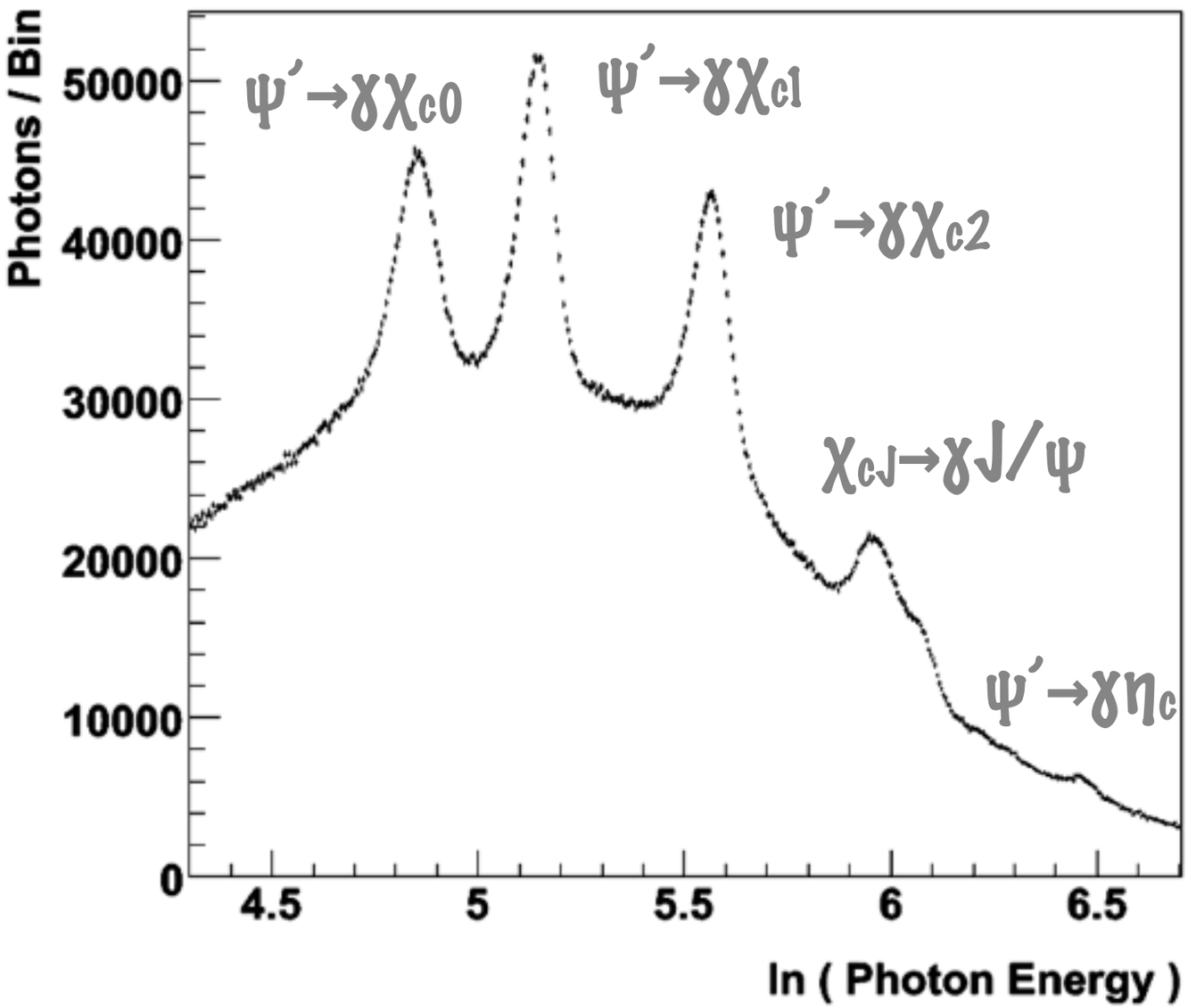
color singlet
quark anti-quark

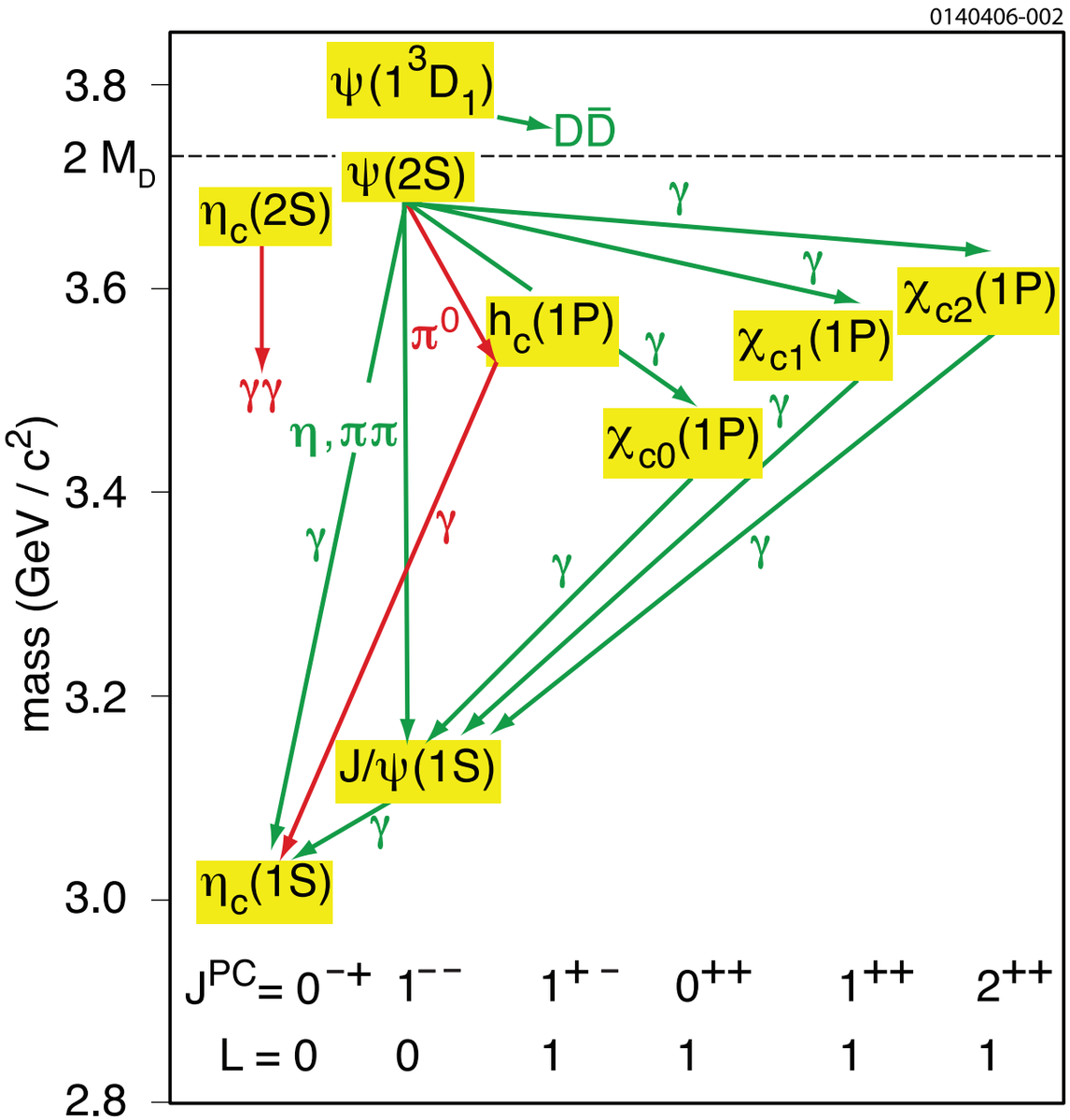


$J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

S = 0 or 1, and L = 0, 1, 2, …

Evidence for Constituent Quarks

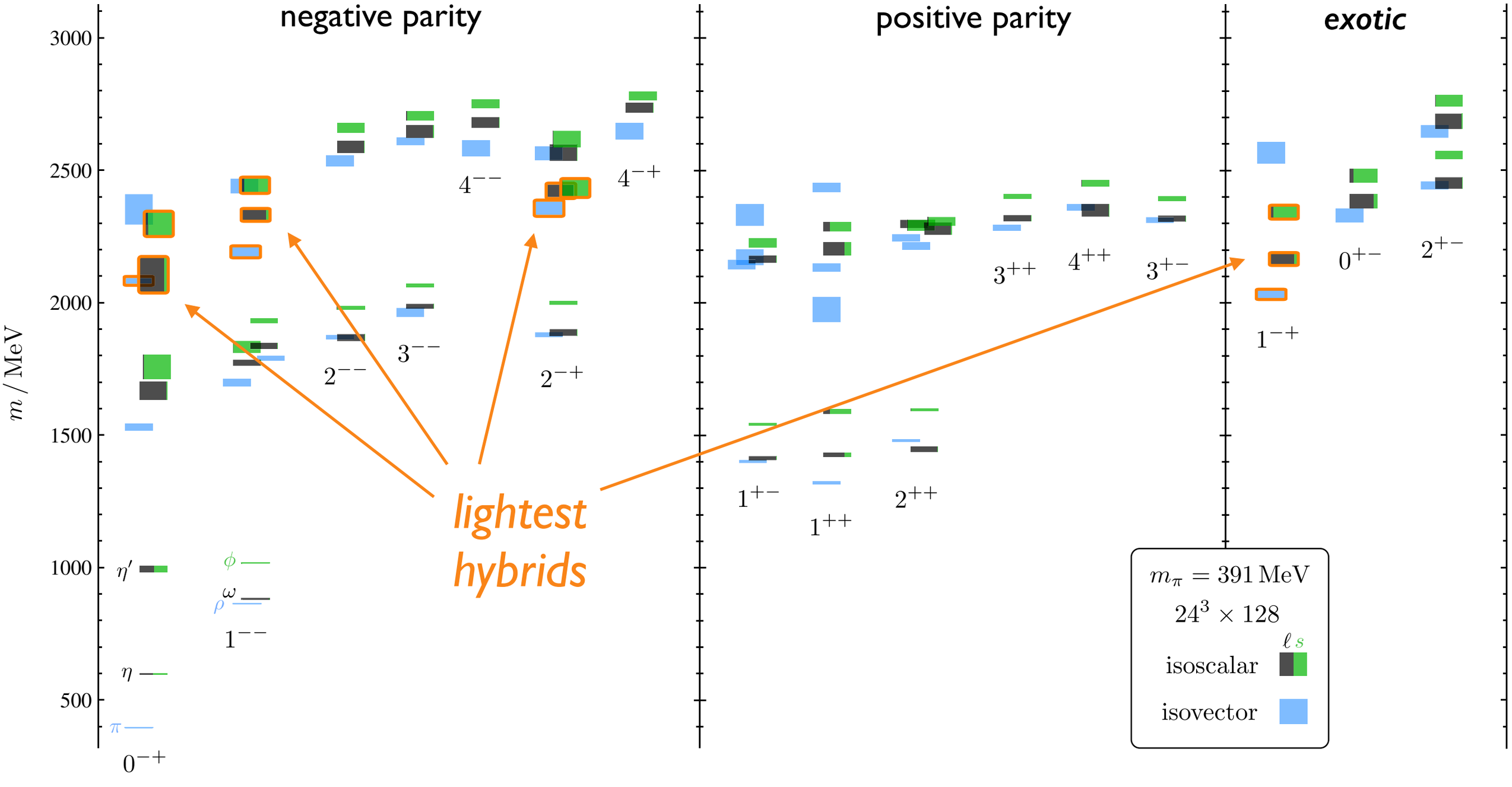




Patterns are Essential!

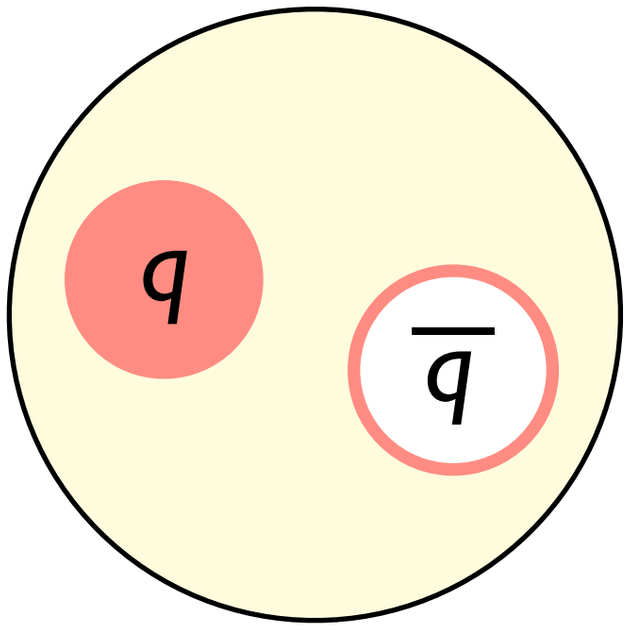
Light Quark Mesons from Lattice QCD

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



Meson Quantum Numbers

color singlet
quark anti-quark

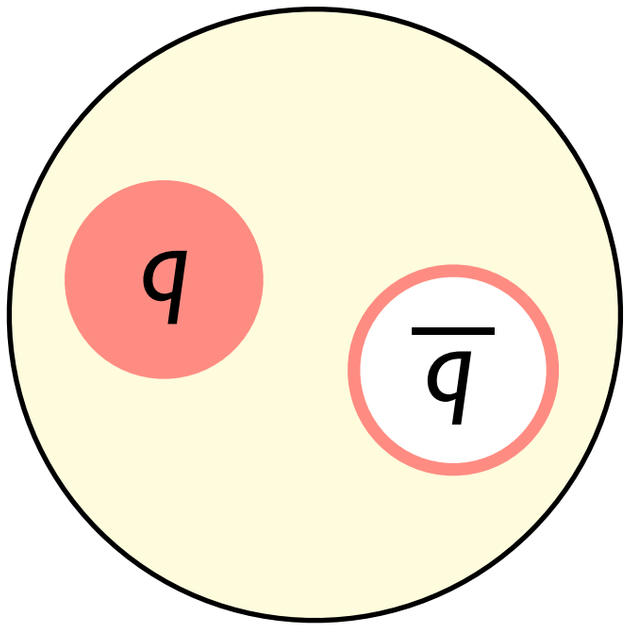


$J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

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

Meson Quantum Numbers

color singlet
quark anti-quark



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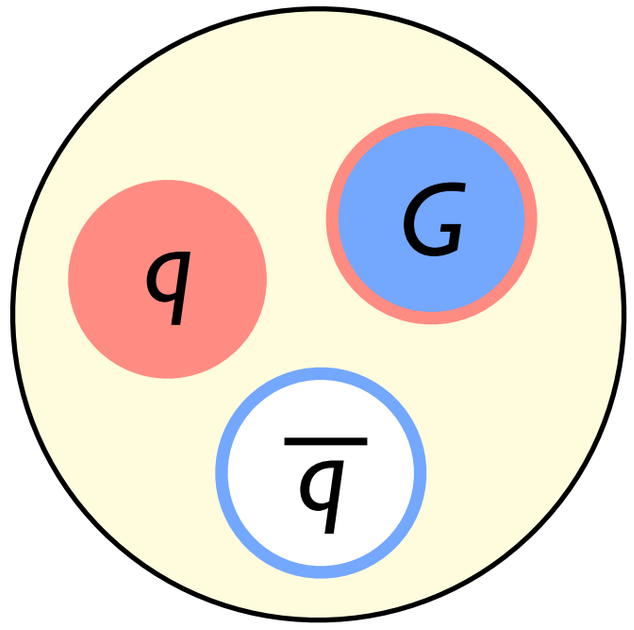
Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$
Forbidden J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

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

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



Lightest Hybrids

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

"exotic hybrid"

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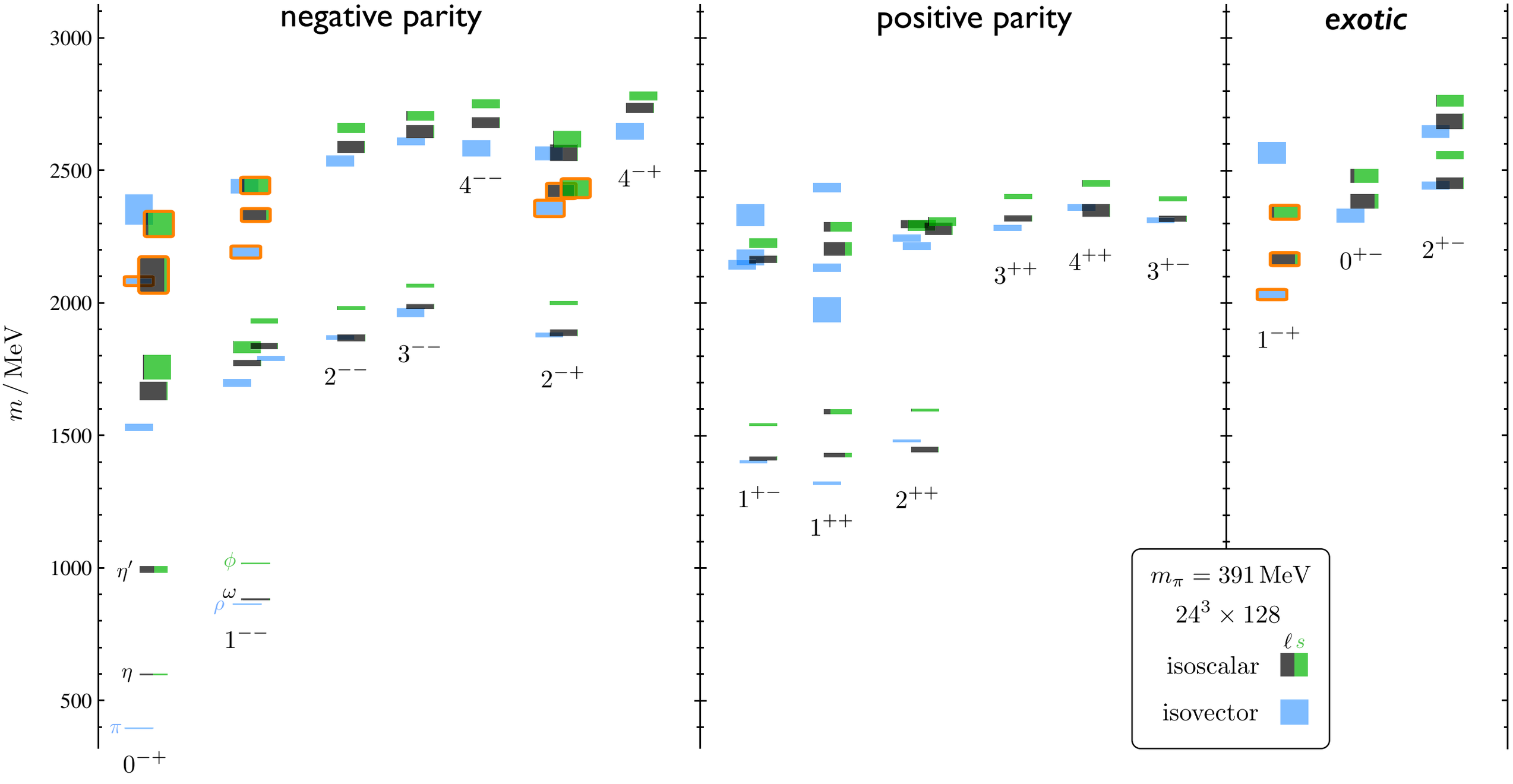
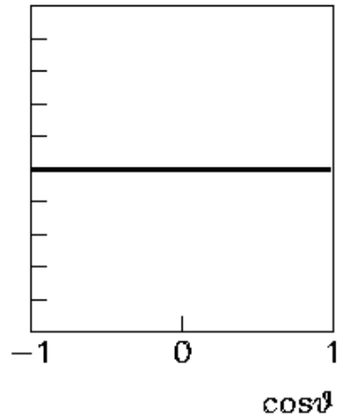


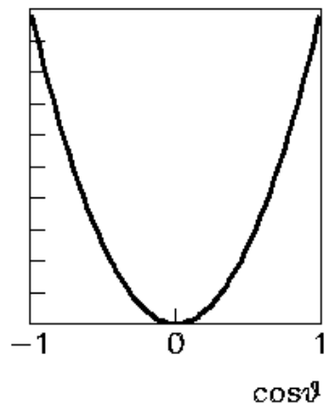
- What can we measure about a meson that informs us about its place in the spectrum?
  - mass
  - J^{PC}
  - charge
  - production and decay tendencies

An Example: Measuring J

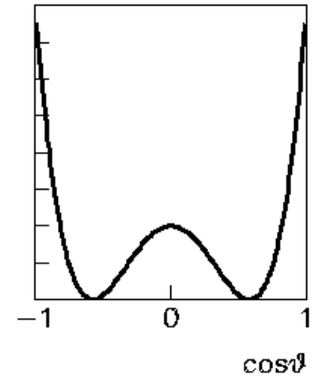
$|Y_0^0|^2$

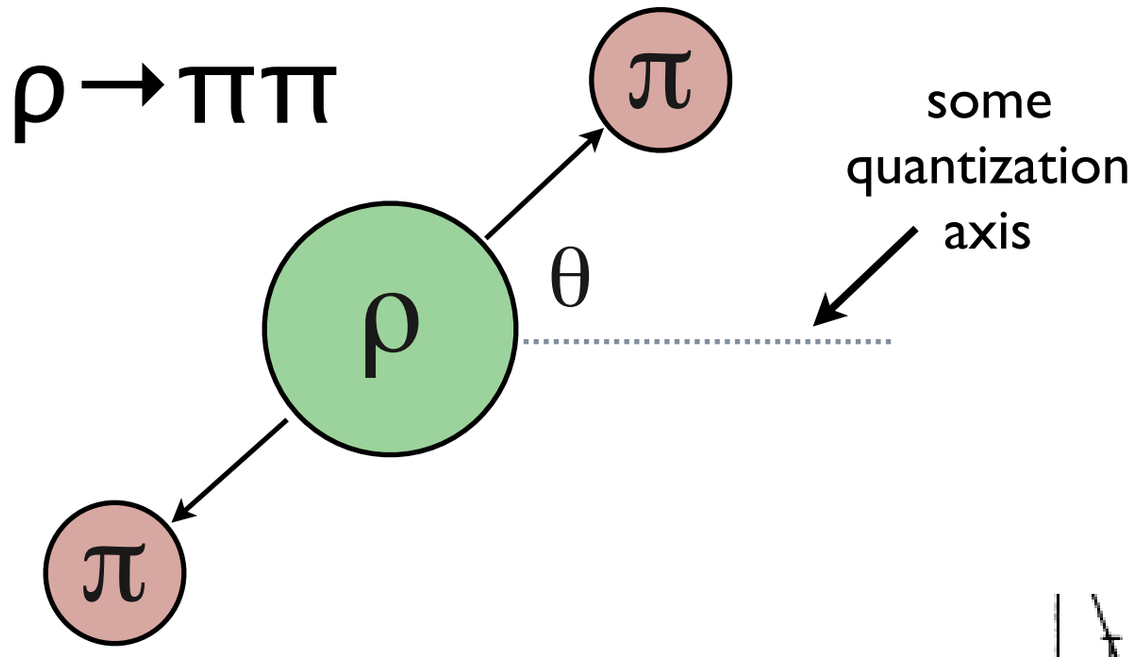


$|Y_1^0|^2$



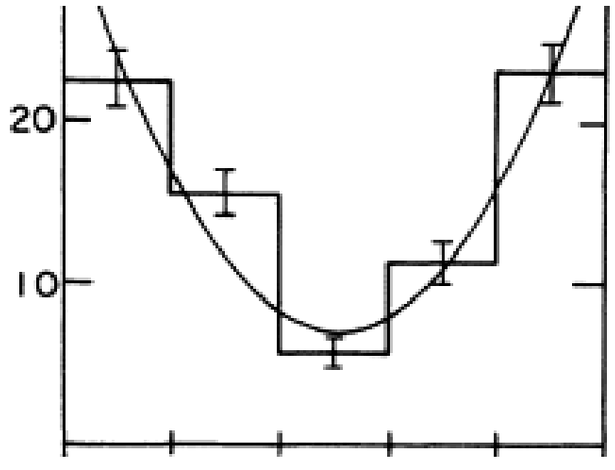
$|Y_2^0|^2$





Pions are spinless so spin of ρ is carried in the orbital angular momentum of the two pions.

From data conclude J = 1



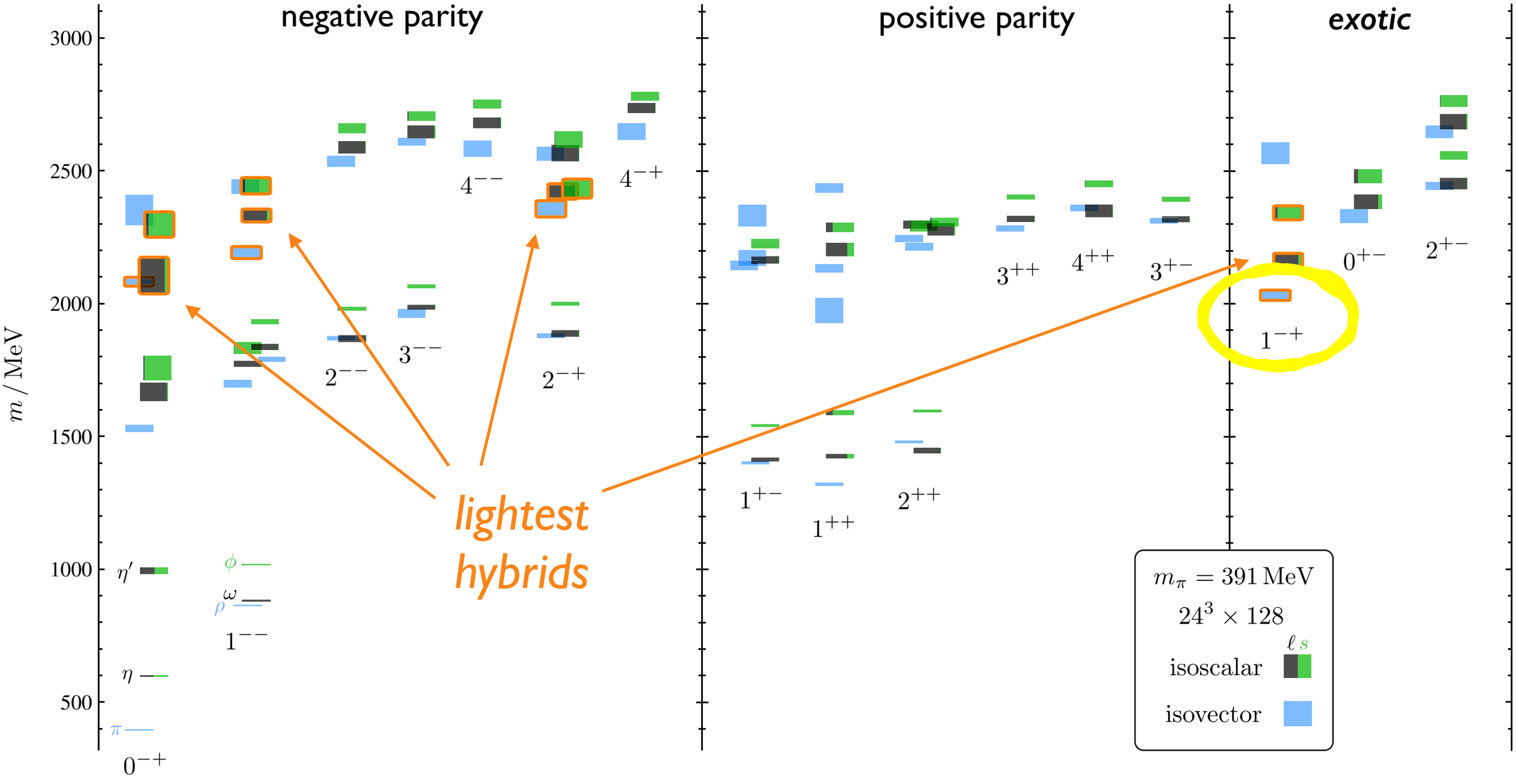
VOLUME 8, NUMBER 2 PHYSICAL REVIEW LETTERS JANUARY 15, 1962

DIFFERENTIAL π-π CROSS SECTIONS: EVIDENCE FOR THE SPIN OF THE ρ MESON*

D. Duane Carmony† and Remy T. Van de Walle‡
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received November 6, 1961; revised manuscript received December 27, 1961)

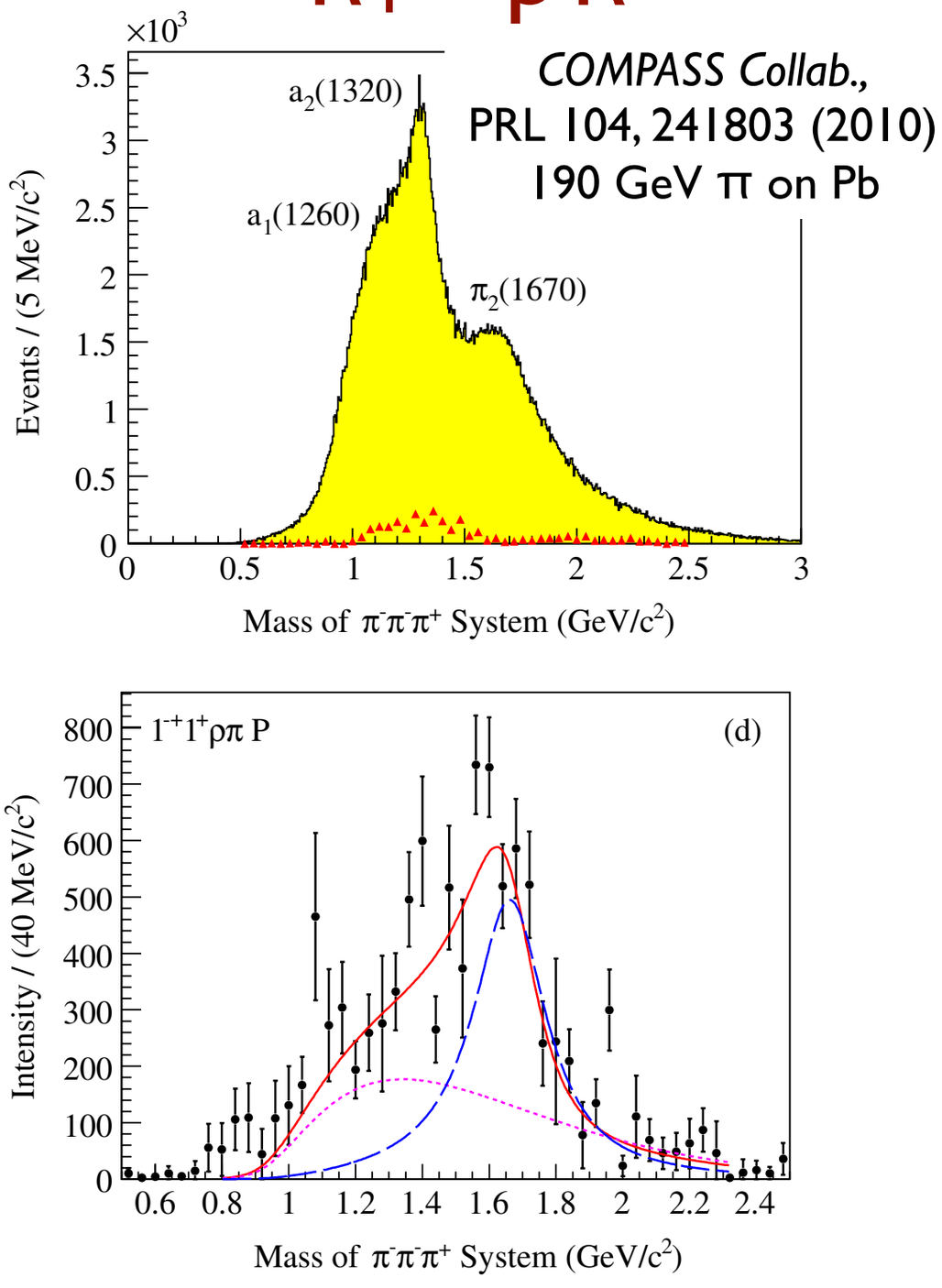
Light Quark Mesons from Lattice QCD

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



Searches for the exotic hybrid π_1

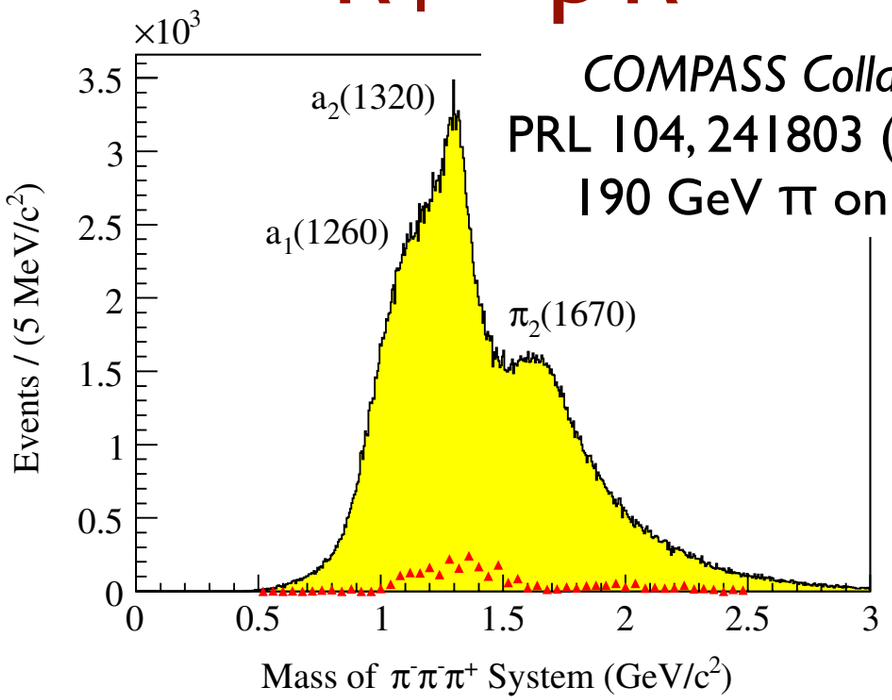
$\pi_1 \rightarrow \rho\pi$



COMPASS Collab.,
PRL 104, 241803 (2010)
190 GeV π on Pb

Searches for the exotic hybrid π_1

$\pi_1 \to \rho\pi$



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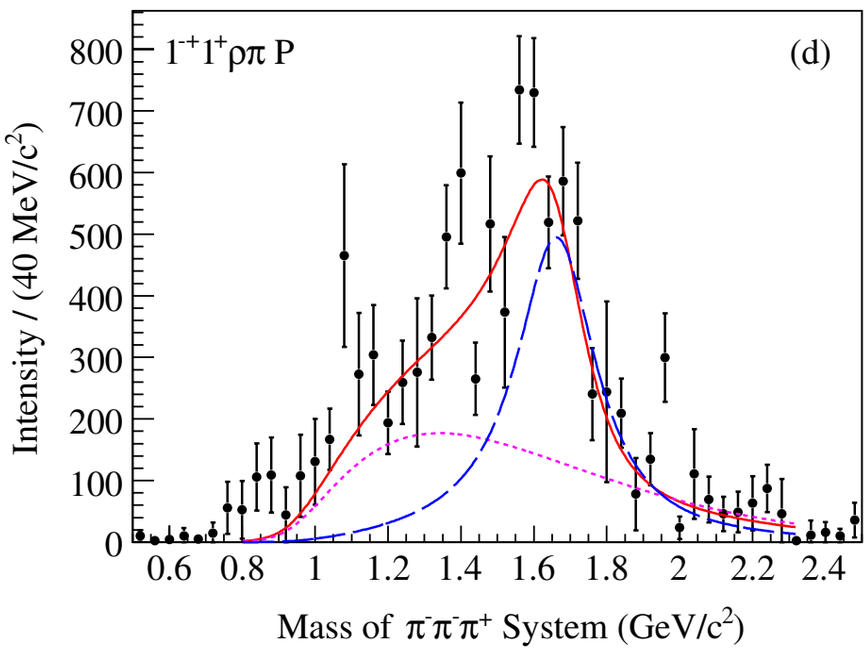
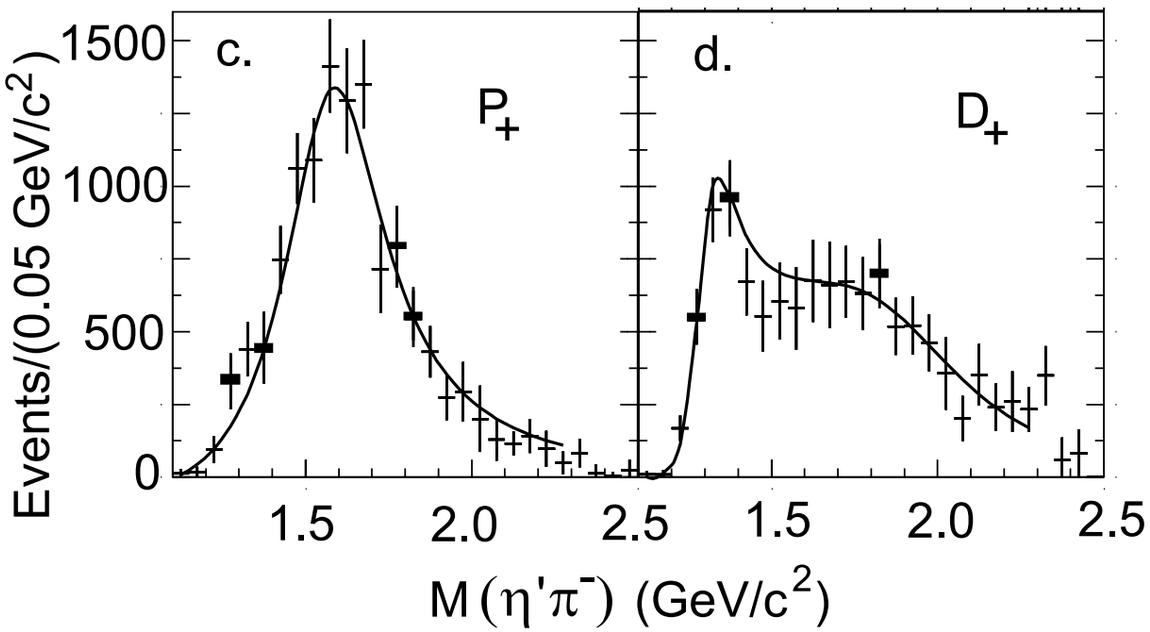


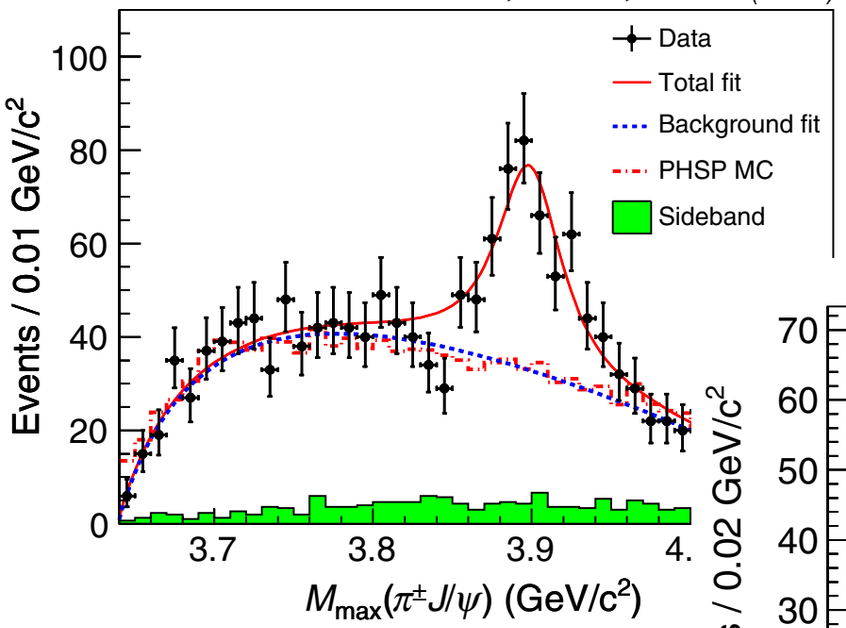
$\pi_1 \to \eta'\pi$

E852 $\pi^- p \to \eta'\pi^- p$ [PRL 86, 3977 (2001)]
18 GeV π on p

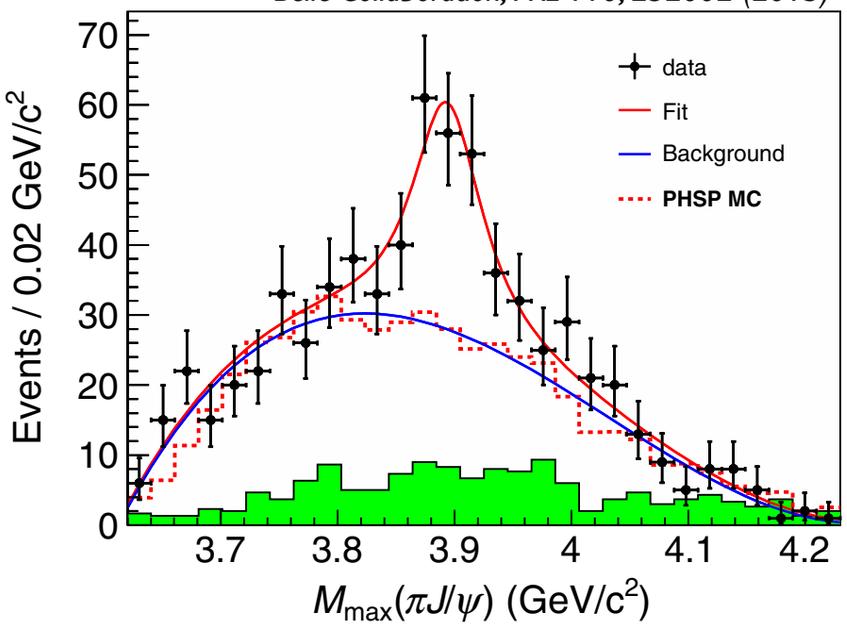


$Z(3900)^{\pm} \rightarrow \pi^{\pm} J/\psi$

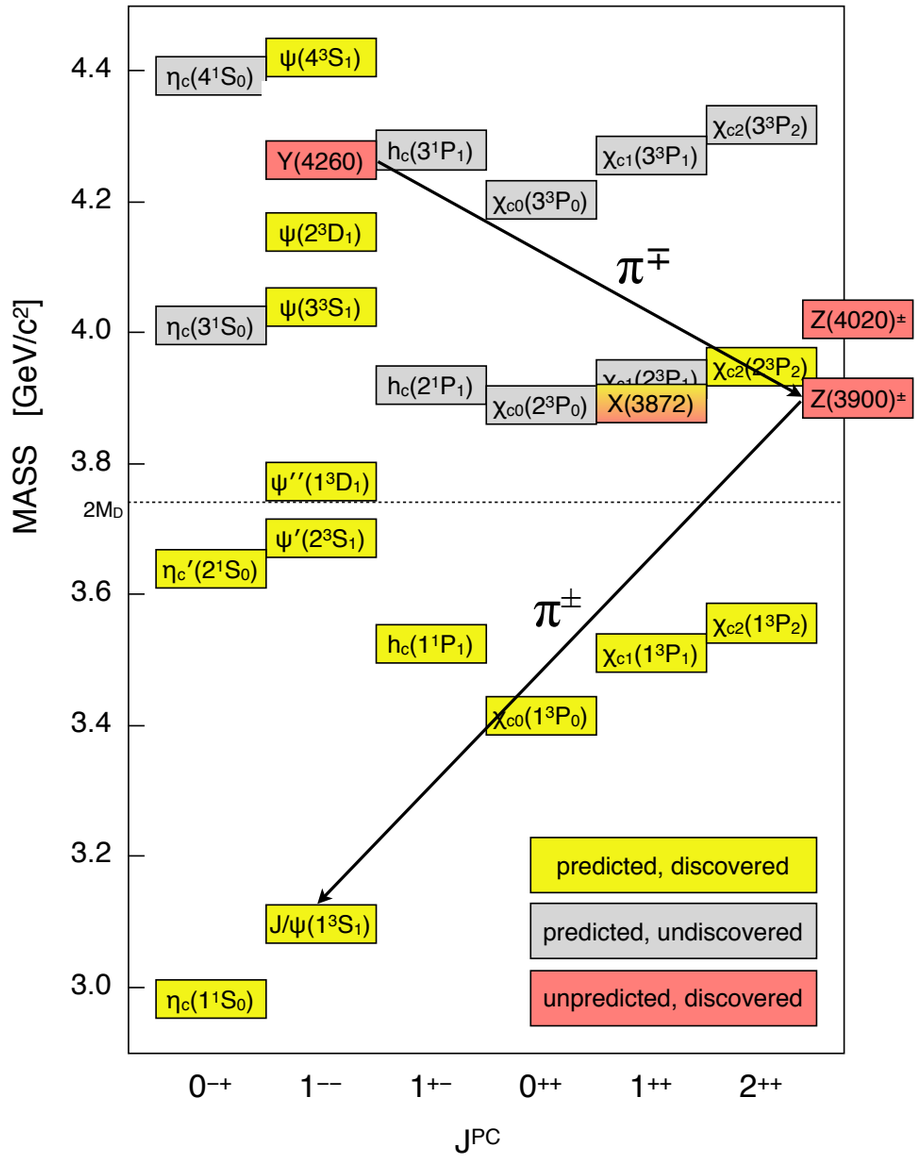
BESIII Collaboration, PRL 110, 252001 (2013)



Belle Collaboration, PRL 110, 252002 (2013)



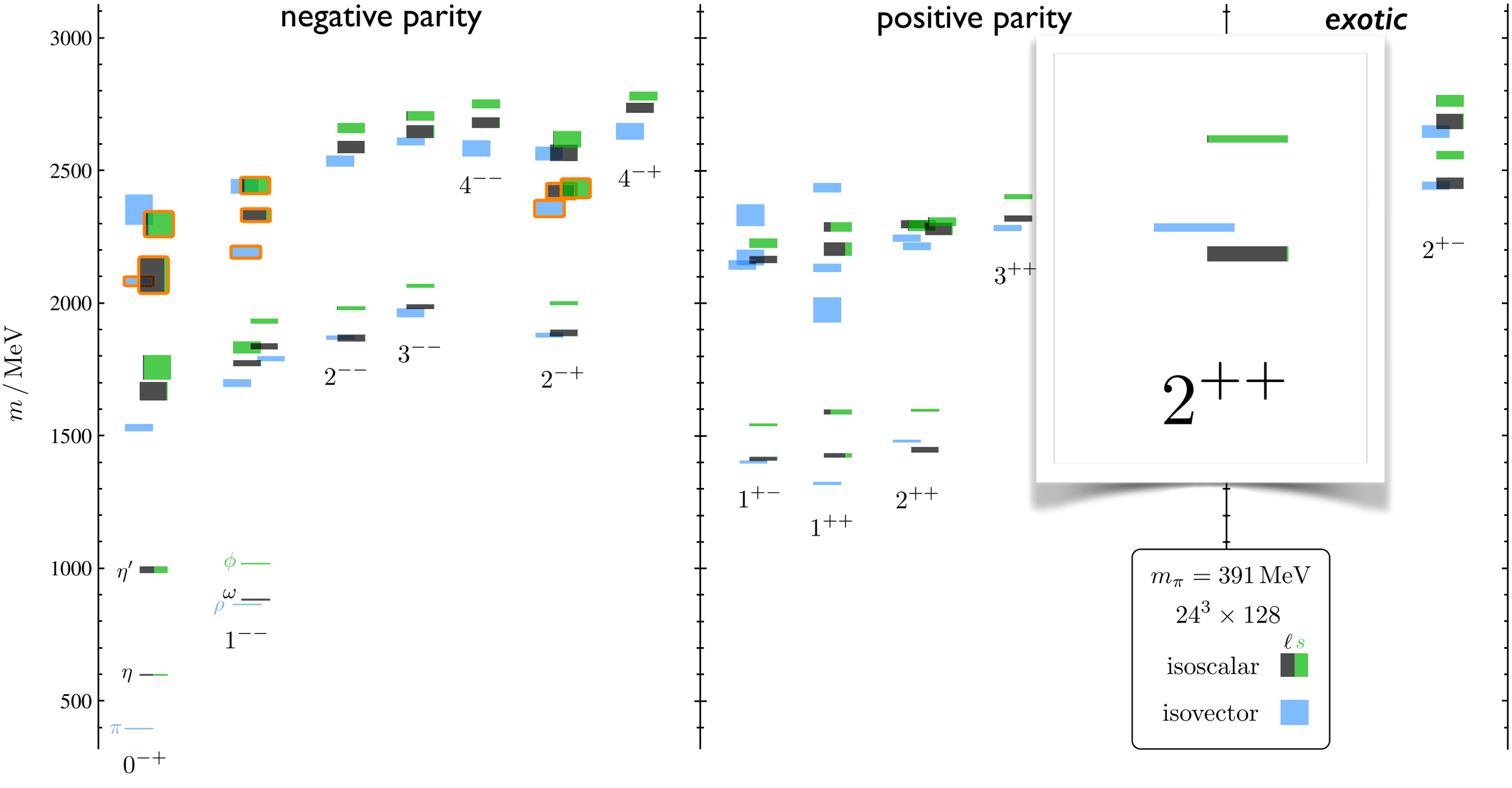
Study:
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$



- Narrow (≈50 MeV) and *charged*
- Not conventional charmonium: tetraquark?
- Evidence of neutral partner
  [*T. Xiao et al., PLB 727, 366 (2013)*]

Light Quark Mesons from Lattice QCD

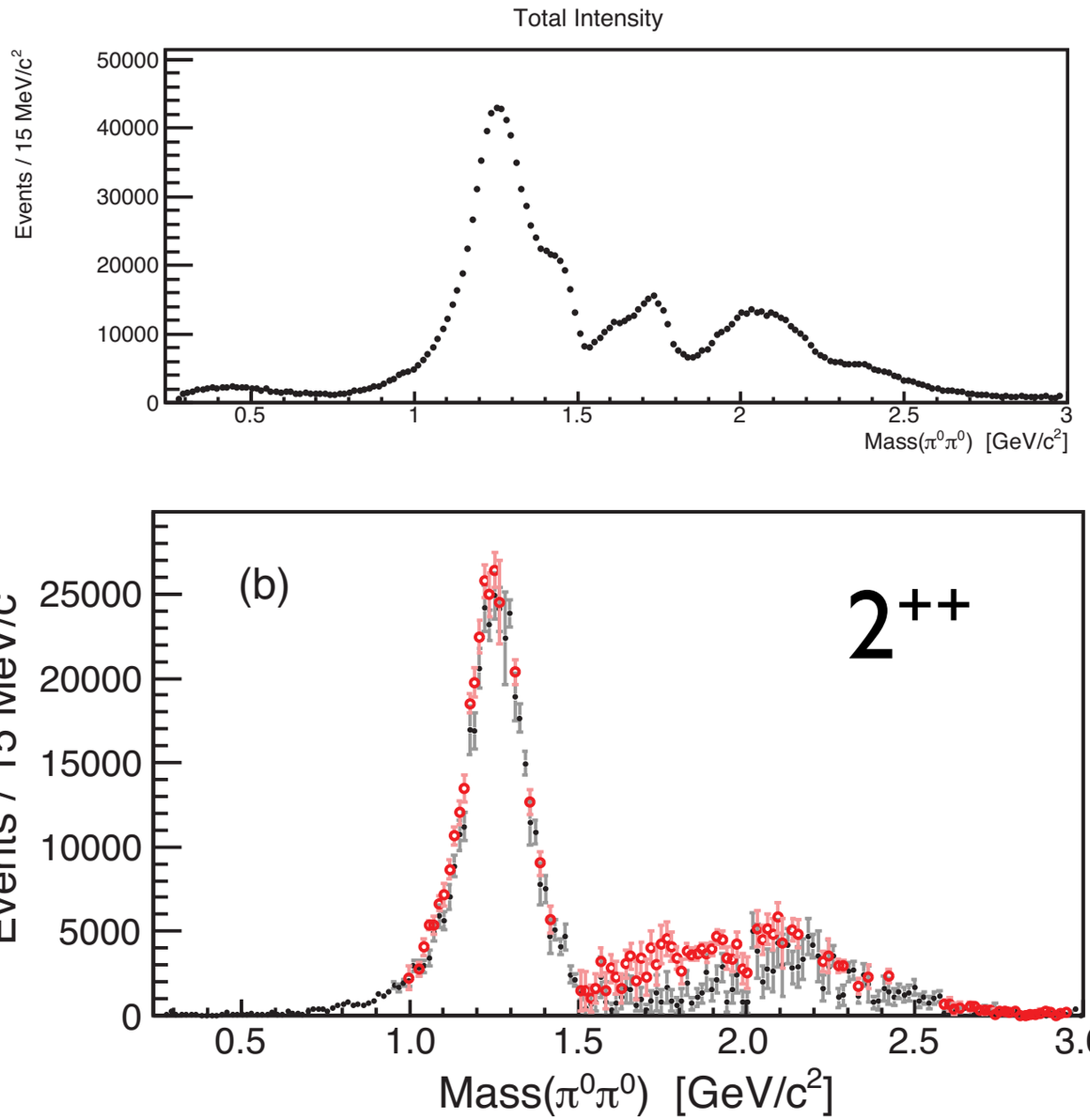
Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



$f_2(1270)$ and $f_2'(1525)$

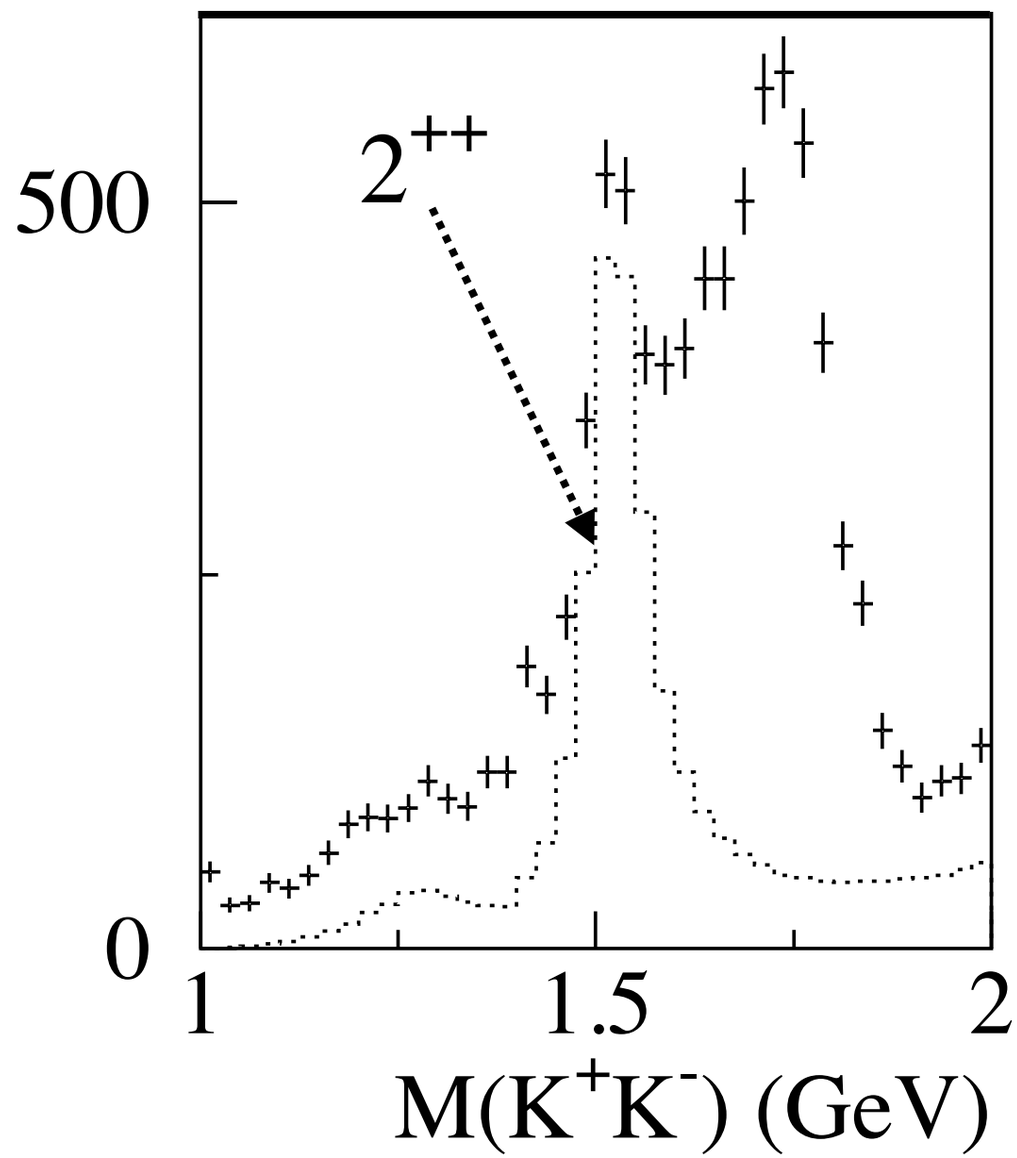
PRD 92, 052003 (2015)

$J/\psi \to \gamma\pi^0\pi^0$



PRD 68, 052003 (2003)

$J/\psi \to \gamma K^+K^-$

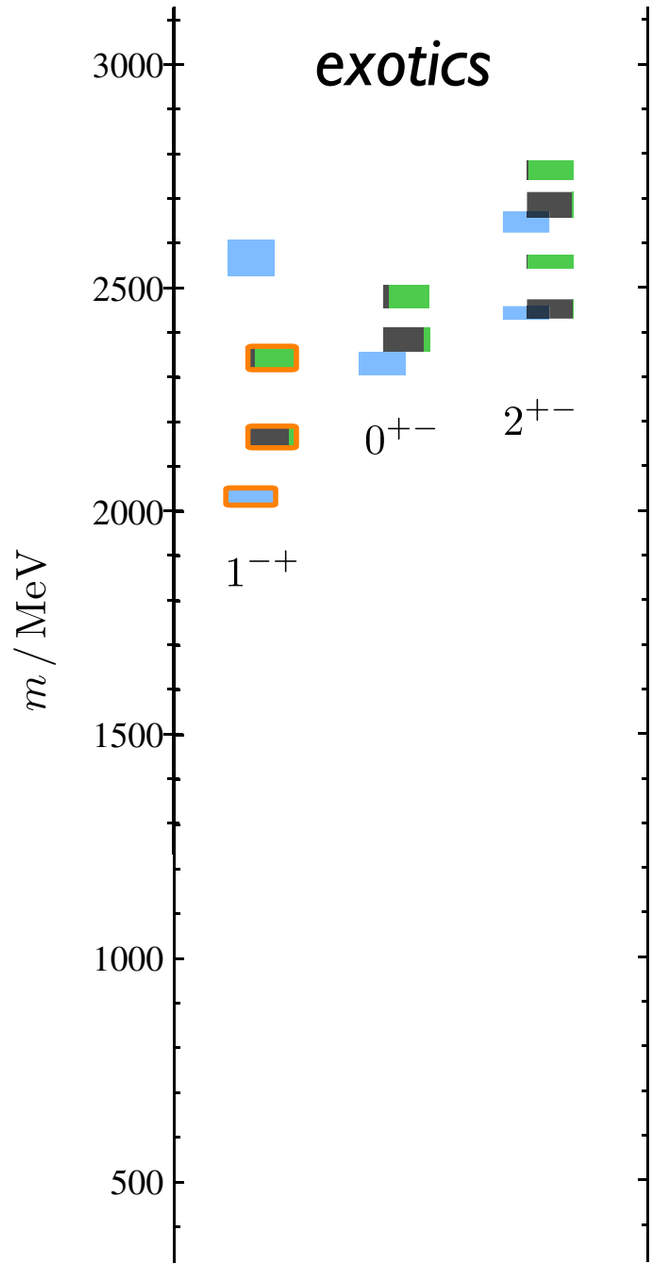


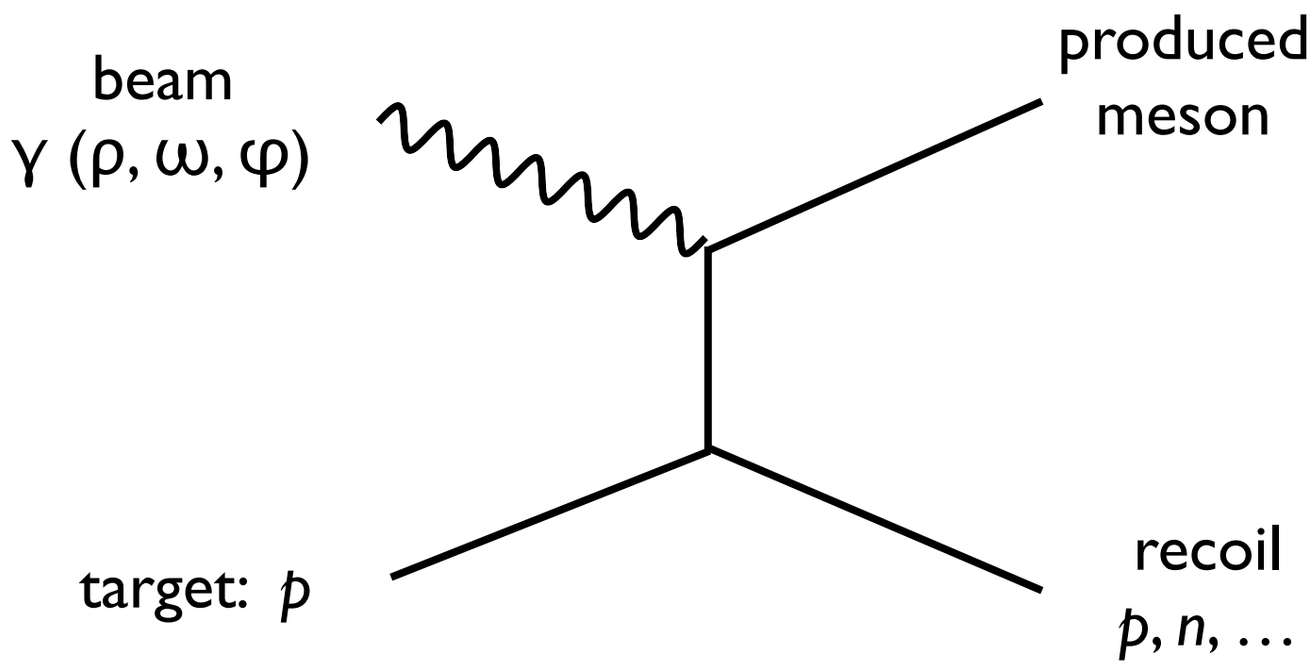
GlueX: A Unique Piece of Global Program

	hadron probes	electromagnetic probes
colliding beam	CDF, DØ (completed/analysis)	ATLAS, CMS, LHCb (ongoing/future)	BESIII (ongoing/future)	BaBar, Belle (completed/analysis)
fixed target	COMPASS (completed/analysis)	PANDA (ongoing/future)	GlueX, CLAS12 (ongoing/future)	CLAS (completed/analysis)

Photoproduction

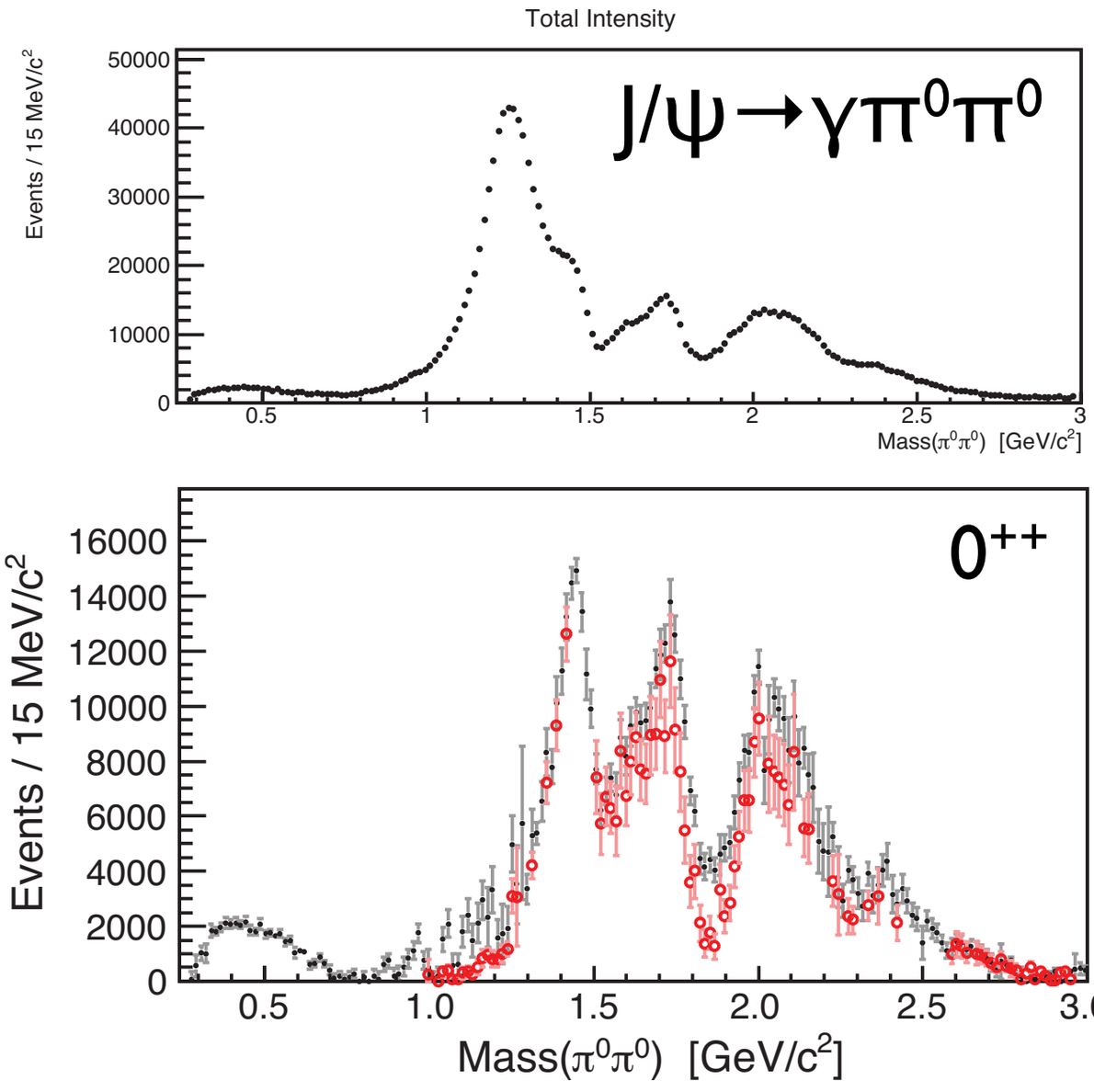
- Different beam J^{PC} than pion or kaon beams: a virtual vector meson beam
- Desire:
  - access to 1.5 - 3.0 GeV region
  - linear polarization



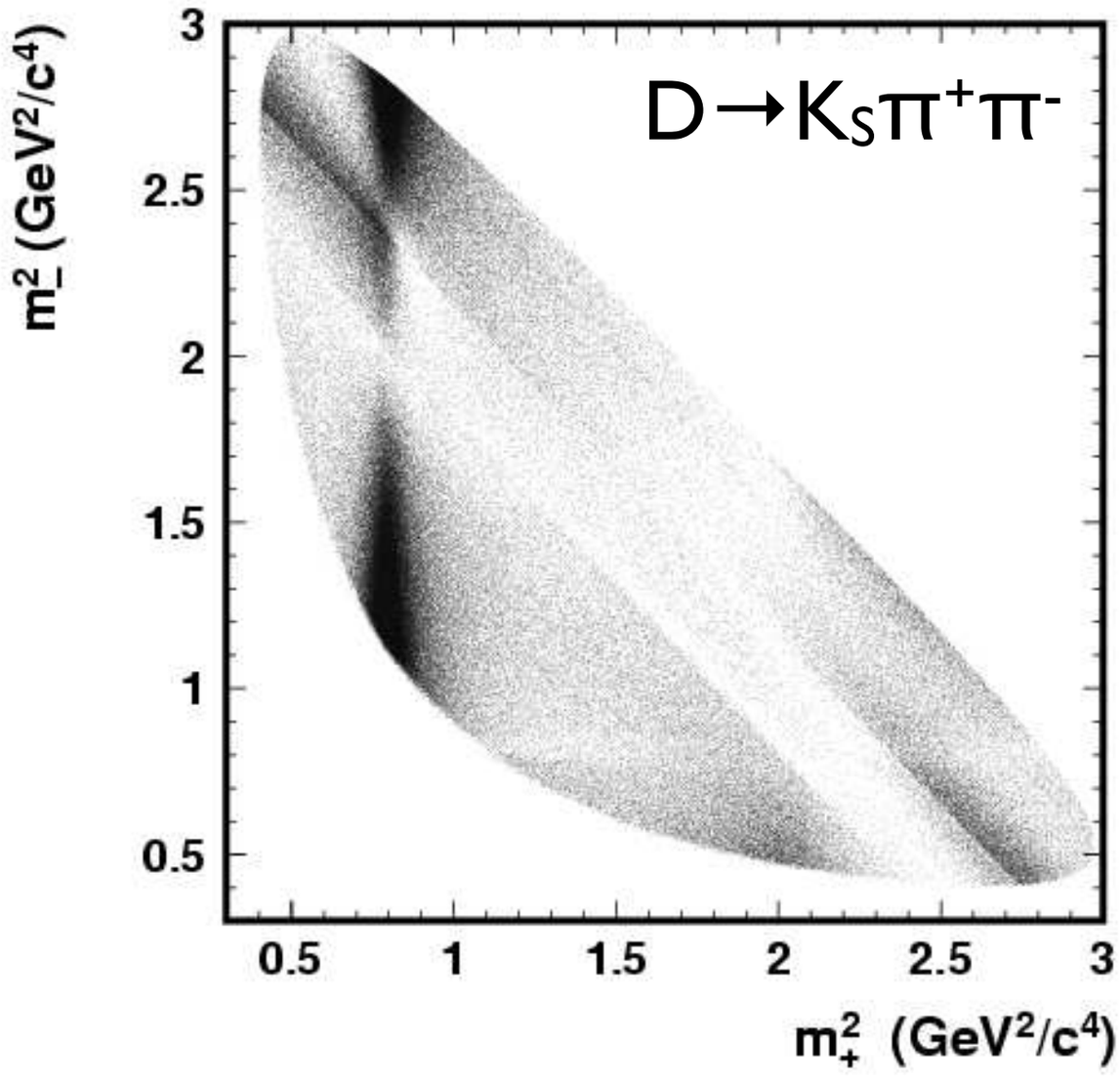


Precision Experiment

(How many resonances do you see?)



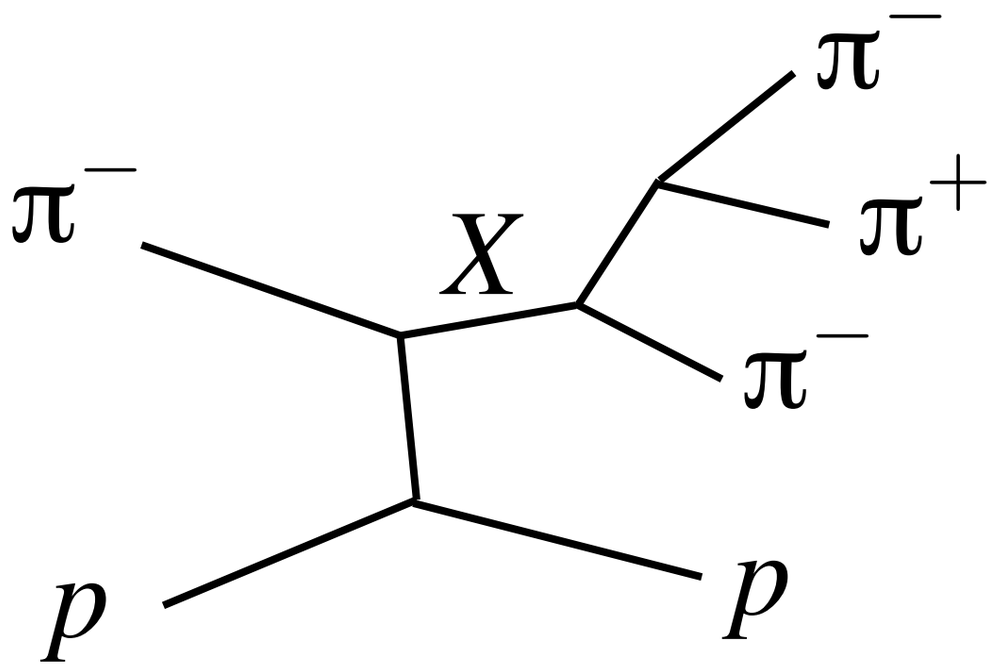
BESIII Collaboration, PRD 92, 052003 (2015)



Belle Collaboration, PRD 73, 112009 (2006)

Challenges of Precision Analysis

(that don't go away with a better understanding of the detector or more compute nodes)



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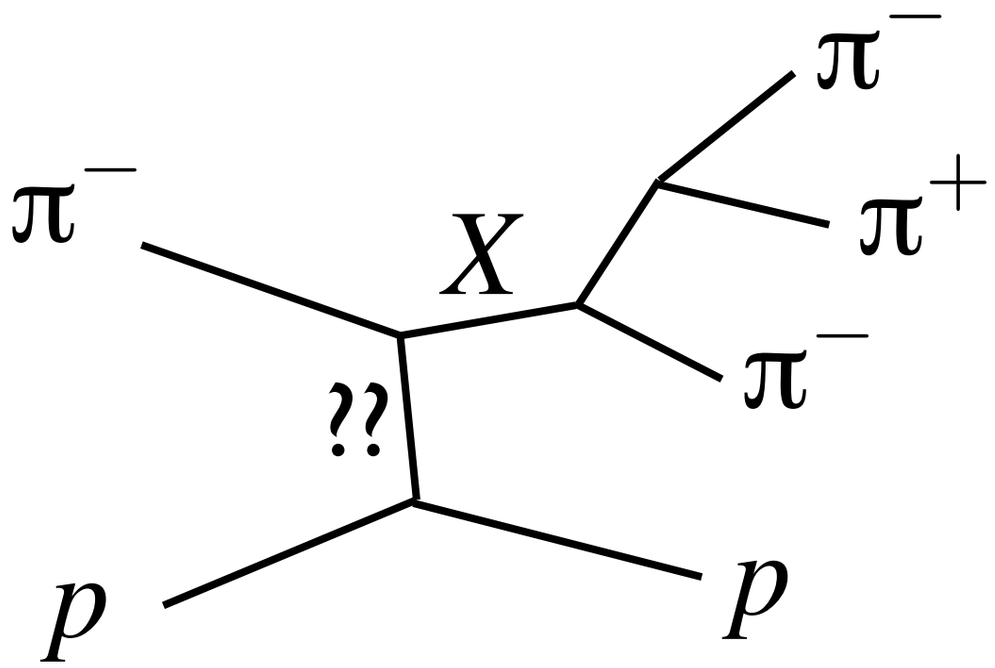
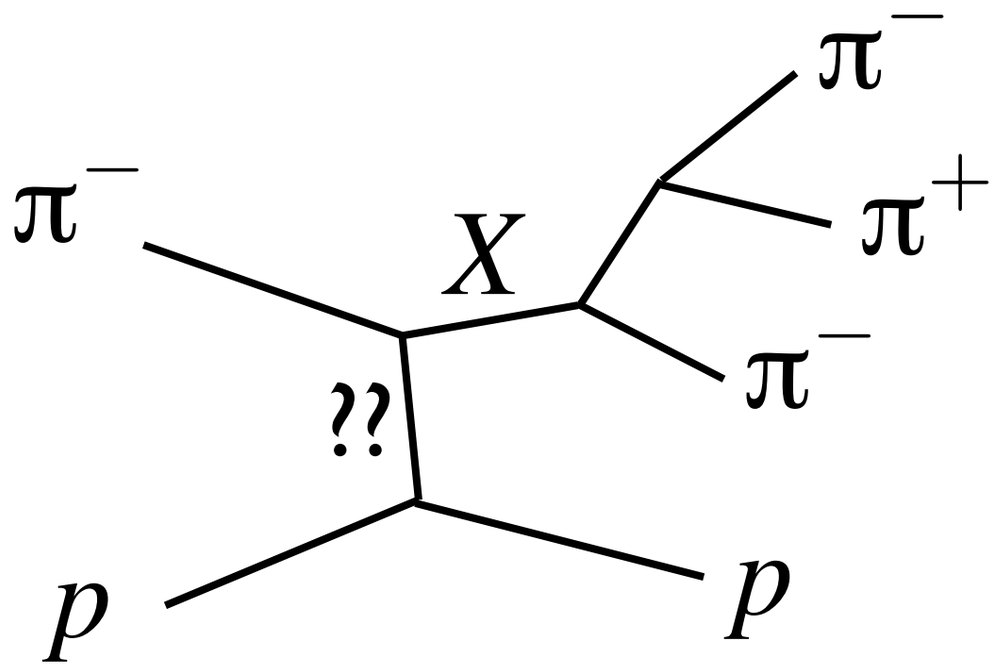
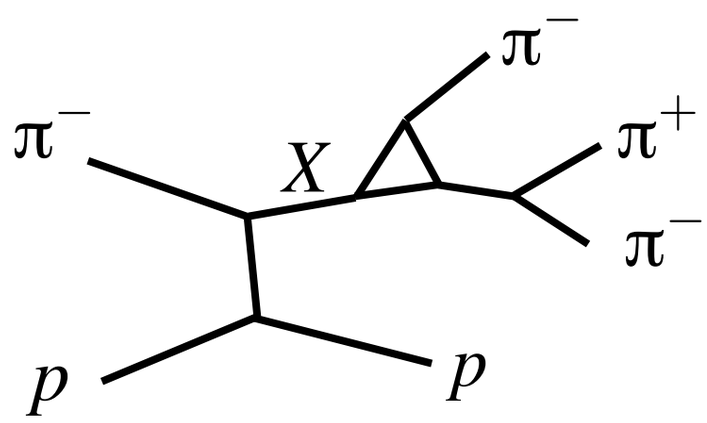


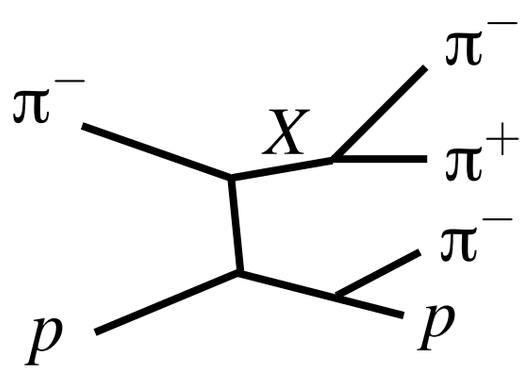
Challenges of Precision Analysis

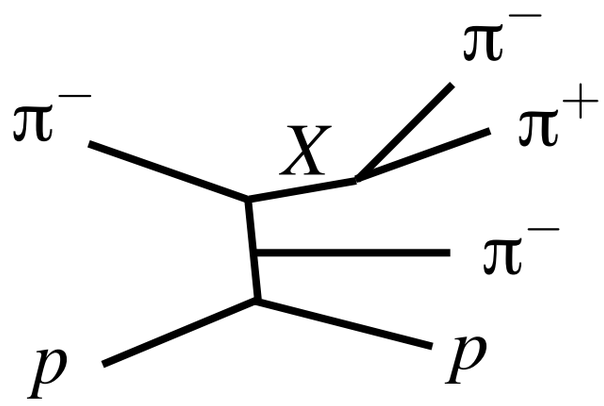
(that don't go away with a better understanding of the detector or more compute nodes)



or







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- Repeat the last two steps with increasing complexity
  - *a versatile and robust software framework for data analysis is required*