XYZ States in Theory and Experiment

Physics 290E Fall 2022

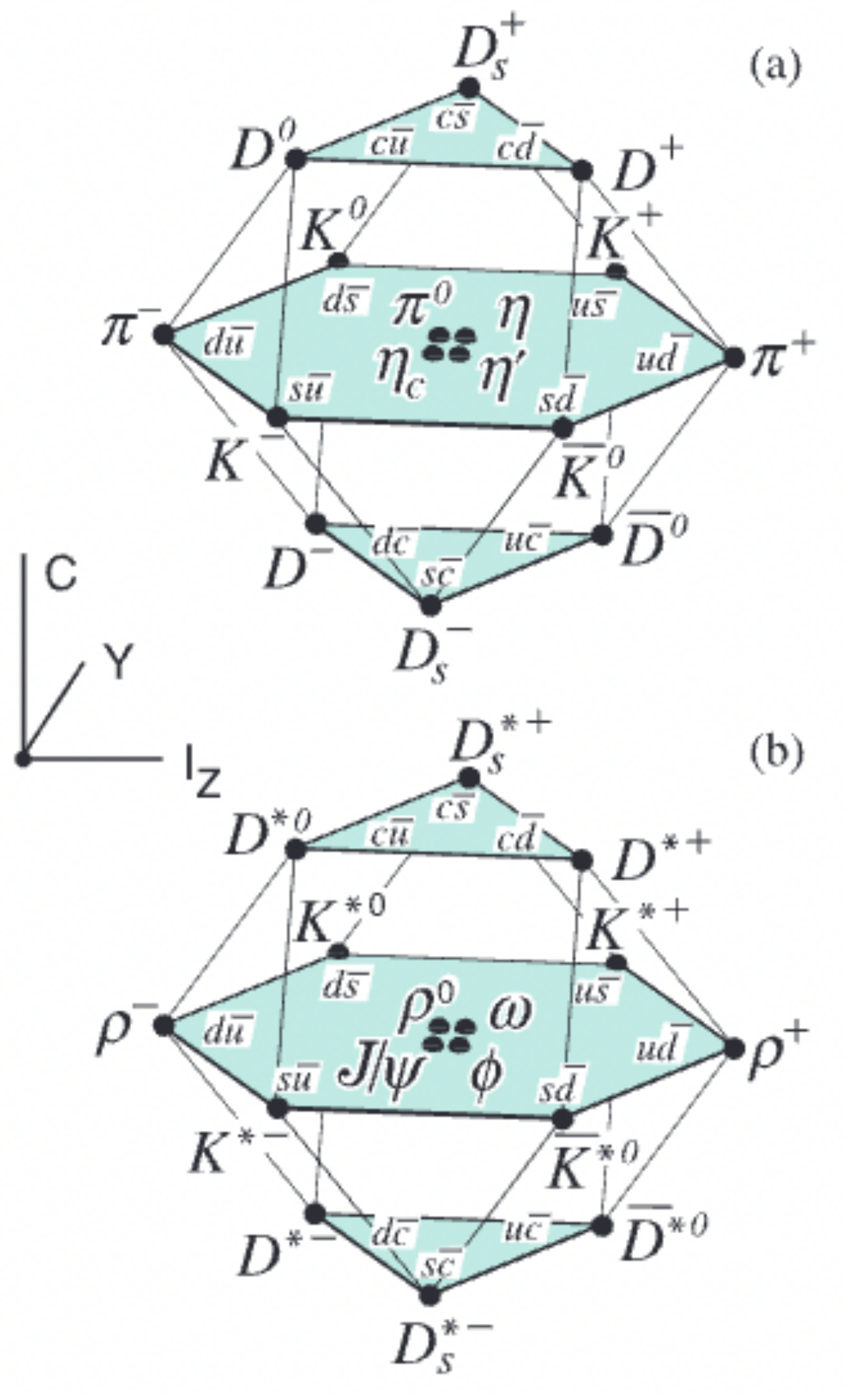
Ryan Roberts, 26 October 2022

Standard $q\bar{q}$ Mesons

Heavy Mesons in the Quark Model

Categorization and Quantum Numbers

- Valence quark content is one quark and one anti-quark.
    - Restrict ourselves to to heavy mesons - at least one c or b quark.
- Can be categorized by their quantum numbers.
    - Flavor: strangeness S, charm-ness C, bottom-ness B
    - Angular Momentum and real: spin J, orbital quantum number ℓ, spin quantum number $s = 0{,}1$.
    - Isospin: I, I_3. $0 \leq I \leq \frac{1}{2}\left(\#u + \#d\right)$.
    - Discrete symmetries: parity $P = (-1)^{\ell+1}$, charge-parity $C = (-1)^{\ell+s}$, G-parity $G = (-1)^{I+\ell+s}$.
    - Additional radial excitations possible - use quantum number n.

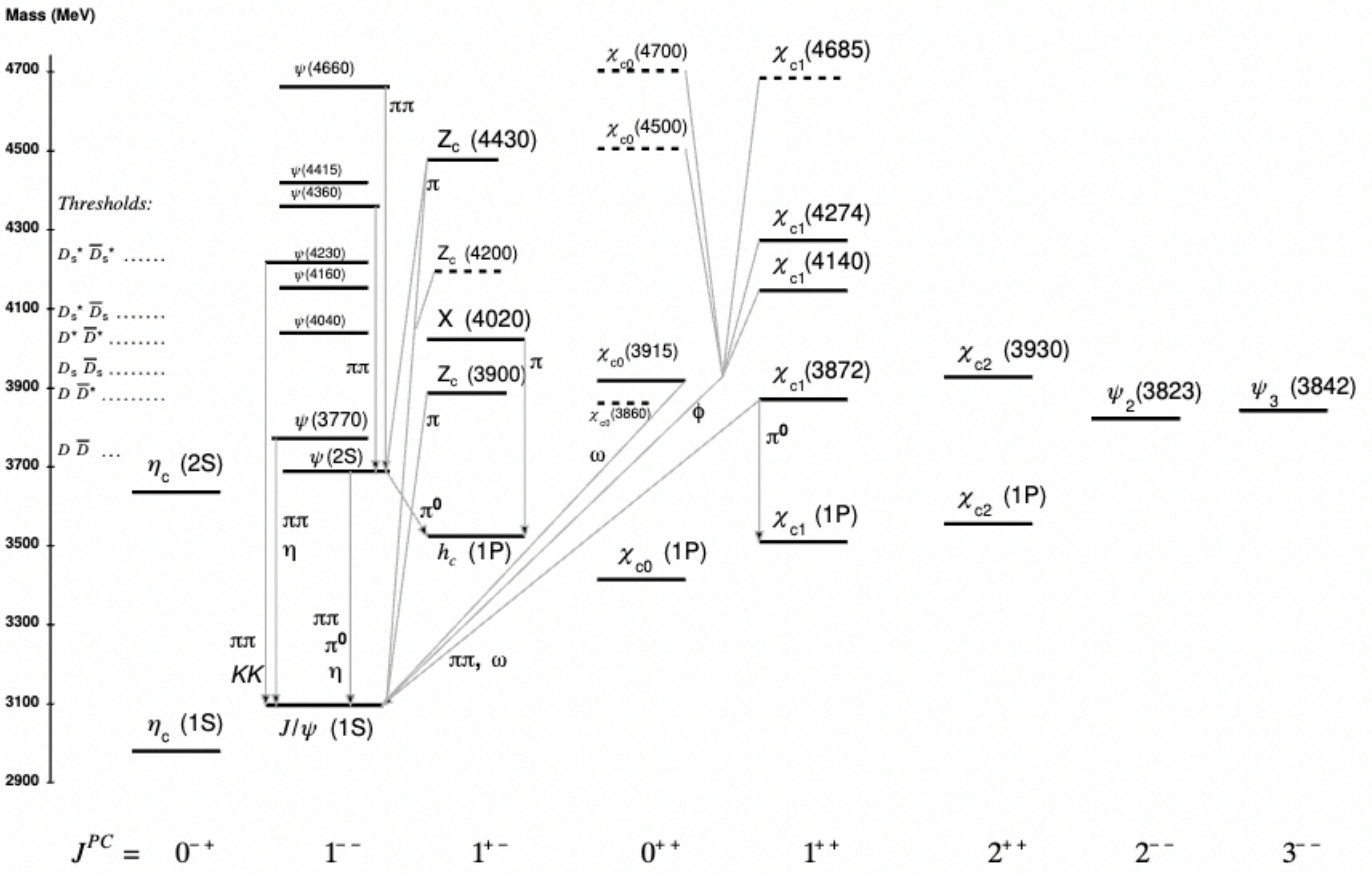


Heavy Mesons in the Quark Model

Categorization and Quantum Numbers

- $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}\ldots$ forbidden in the quark model.
- Open charm (D) and open bottom (B) mesons differ in light flavor content and excitation of orbital and spin degrees of freedom.
- $c\bar{c}$ and $b\bar{b}$, heavy quarkonia states, are named according to J^{PC} with some variations by flavor.
  - Necessarily have $I = 0$.

$J^{PC} = \{$	0^{-+}	1^{+-}	1^{--}	0^{++}
	2^{-+}	3^{+-}	2^{--}	1^{++}
	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Minimal quark content				
$u\bar{d}, u\bar{u} - d\bar{d}, d\bar{u}$ $(I = 1)$	π	b	ρ	a
$d\bar{d} + u\bar{u}$ and/or $s\bar{s}$ $(I = 0)$	η,η'	h,h'	ω,ϕ	f,f'
$c\bar{c}$	η_c	h_c	ψ^*	χ_c
$b\bar{b}$	η_b	h_b	Υ	χ_b



Introduction to XYZ States

XYZ States

Definition and History

- Apparently non-qq̄ Mesons (B=0) with multiple heavy quark content.
  - Light non-qq̄ Mesons have also been observed.
- Several theoretical explanations.
  - Most predict more states with a pattern of quantum numbers.
- First candidate found in 2003 at Belle.
  - Rapid progress, with 24 possible examples now listed in PDG.
  - Experimental observations from Belle, BaBar, BESIII, CLEO-c, LHCb, CDF, D0, CMS, ATLAS - most contributions from e^+e^- experiments focused on hadron and flavor physics.
  - Large body of theoretical work.

A Word on Notation

PDG and LHCb Naming Conventions

- Experimentally observed exotic states originally named X(mass), Y(mass), or Z(mass).
  - Y usually used for vector states, Z for $I \neq 0$.
- The PDG has adopted a convention to name these states according to their quantum numbers when known and name them X otherwise.
  - Extends previous system to add $I \neq 1$ hidden flavor states.
  - Numerical subscript to indicate J.
  - Agnostic to microscopic nature of the state.
- The LHCb Collaboration has developed a competing convention, which gives the letter T for states with minimum 4 quark content.
  - Superscript denotes parity and isospin, while subscripts denote hidden and open flavor as well as J.

LHCb Convention

Minimal quark content	Potential decay channel(s)	$I^{(G)}$, $J^{P(C)}$	Proposed name
$bc\bar{u}\bar{d}$	$B^- D^{*+}$	$I=0,\ J^P=1^+$	$T^f_{bc1}(\text{mass})^0$
$b\bar{c}\bar{u}d$	$B^- D^{*-}$	$I=1,\ J^P=1^+$	$T^a_{b\bar{c}1}(\text{mass})^{--}$
$bb\bar{u}\bar{d}$	$B^-\pi^- D^+$, $\overline{B}^0 J/\psi K^-$	$I=0,\ J^P=1^+$	$T^f_{bb1}(\text{mass})^-$
$c\bar{c}b\bar{d}$	$J/\psi \overline{B}^0$	$I=\frac{1}{2},\ J^P=1^+$	$T^\theta_{\psi b1}(\text{mass})^0$
$c\bar{s}u\bar{d}/c\bar{s}\bar{u}d$	$D_s^+\pi^+/D_s^+\pi^-$	$I=1,\ J^P=0^+$	$T^a_{c\bar{s}0}(\text{mass})^{++}/T^a_{c\bar{s}0}(\text{mass})^0$
$b\bar{b}uud$	Υp	$I=\frac{1}{2}$	$P^N_\Upsilon(\text{mass})^+$
$b\bar{c}uud$	$B_c^- p$	$I=\frac{1}{2}$	$P^N_{b\bar{c}}(\text{mass})^0$
$b\bar{u}cds$	$B^-\Xi_c^0$	$I=1$	$P^\Sigma_{bcs}(\text{mass})^-$
$c\bar{d}cus$	$D^+\Xi_c^+$	$I=1$	$P^\Sigma_{ccs}(\text{mass})^{++}$
$c\bar{c}cud$	$J/\psi\Lambda_c^+$	$I=0$	$P^\Lambda_{\psi c}(\text{mass})^+$
$c\bar{c}cus$	$J/\psi\Xi_c^+$	$I=\frac{1}{2}$	$P^N_{\psi cs}(\text{mass})^+$

PDG Convention

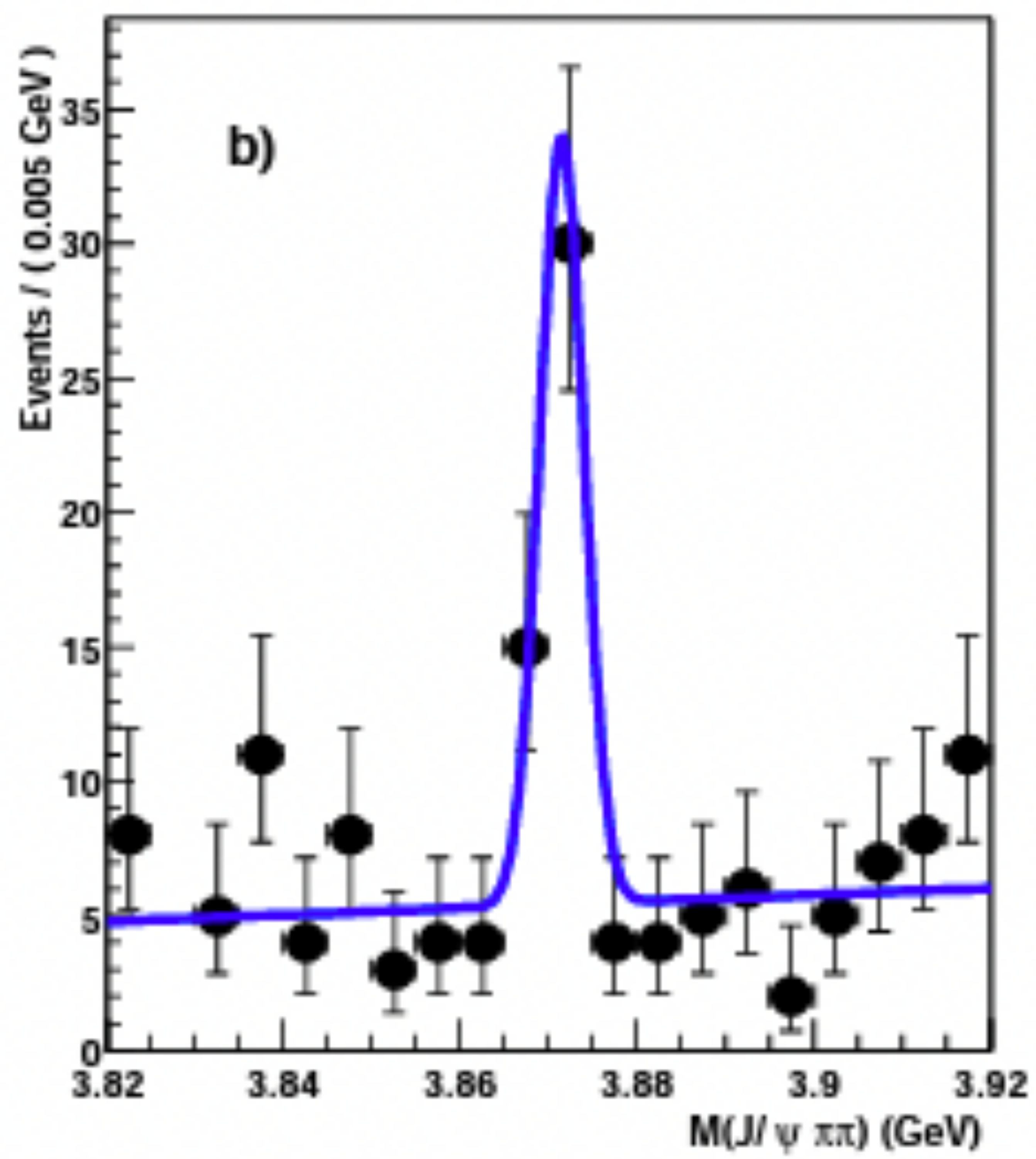
$J^{PC} =$	0^{-+}, 2^{-+}, $\vdots$	1^{+-}, 3^{+-}, $\vdots$	1^{--}, 2^{--}, $\vdots$	0^{++}, 1^{++}, $\vdots$
Minimal quark content				
$u\bar{d}, u\bar{u}-d\bar{d}, d\bar{u}$ $(I=1)$	π	b	ρ	a
$d\bar{d}+u\bar{u}$ and/or $s\bar{s}$ $(I=0)$	η,η'	h,h'	ω,ϕ	f,f'
$c\bar{c}$	η_c	h_c	ψ^*	χ_c
$b\bar{b}$	η_b	h_b	Υ	χ_b
$I=1$ with $c\bar{c}$	(Π_c)	Z_c	R_c	(W_c)
$I=1/2$ with $sc\bar{c}$	(Π_{cs})	Z_{cs}	(R_{cs})	(W_{cs})
$I=1$ with $b\bar{b}$	(Π_b)	Z_b	(R_b)	(W_b)
$I=1/2$ with $sb\bar{b}$	(Π_{bs})	(Z_{bs})	(R_{bs})	(W_{bs})

Example: The first XYZ State

$n^{2S+1}L_J$

$\chi_{c1}(3872)$ **a.k.a.** $X(3872)$

- Discovered by Belle in 2003 as resonance in $B^{\pm} \to K^{\pm}X, X \to \pi^+\pi^- J/\psi$.
- Now seen by Belle, BaBar, CDF, D0, CMS, LHCb, and BESIII.
- Mass of 3871.65 ± 0.06 MeV, very close to $M_{D_0} + M_{D_0^*} = 3871.69 \pm 0.07$ MeV.
- $J^{PC} = 1^{++}$ determined by LHCb. Pseudovector state allowed by quark model with $\ell = s = 1$.
- Leading decays are $D^0\bar{D}^0\pi^0$, $\bar{D}^{*0}D^0$, total width is 1.19 ± 0.21 MeV.
- Other observed decays include $\omega J/\psi$, $\pi^0\chi_{c1}$, $\gamma J/\psi$, $\gamma\psi(2S)$.
- Isospin is strongly violated in several of these decays, e.g. decays to $\rho J/\psi$ dominate decays to $\omega J/\psi$.



Mass peak in the original Belle observation.

Example: The first XYZ State

$\chi_{c1}(3872)$ a.k.a. $X(3872)$

- Quantum numbers consistent with charmonium state.
- Initially labeled as potentially exotic due to lack of radiative decay to $\gamma\chi_{c1}$.
    - Expected from then undiscovered $\psi(2S)$, which was a candidate.
- 100 MeV too light to be n=2 radial excitation of χ_{c1} (better candidate $X(3940)$ reported by Belle), n=1 already known with mass 3511 MeV.
- Isospin violation points to relationship with the nearby $D^0\bar{D}^{*0}$ threshold, which is separated from isospin conjugate $D^+\bar{D}^{*-}$.
    - Decays and mass consistent with some predictions for a molecular $D^0\bar{D}^{*0}$ state, but conflict with others.
    - Other explanations put forward include tetraquarks and cusp effects.

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	e^+e^-	$< 2.8\times10^{-6}$	CL=90%	1936
Γ_2	$\pi^+\pi^-J/\psi(1S)$	$(3.8\pm1.2)\%$		650
Γ_3	$\pi^+\pi^-\pi^0J/\psi(1S)$	not seen		588
Γ_4	$\omega\eta_c(1S)$	$< 33\%$	CL=90%	368
Γ_5	$\omega J/\psi(1S)$	$(4.3\pm2.1)\%$		-1
Γ_6	$\phi\phi$	not seen		1646
Γ_7	$D^0\bar{D}^0\pi^0$	$(49^{+18}_{-20})\%$		116
Γ_8	$\bar{D}^{*0}D^0$	$(37\pm9)\%$		-1
Γ_9	$\gamma\gamma$	$< 11\%$	CL=90%	1936
Γ_{10}	$D^0\bar{D}^0$	$< 29\%$	CL=90%	519
Γ_{11}	D^+D^-	$< 19\%$	CL=90%	502
Γ_{12}	$\pi^0\chi_{c2}$	$< 4\%$	CL=90%	273
Γ_{13}	$\pi^0\chi_{c1}$	$(3.4\pm1.6)\%$		319
Γ_{14}	$\pi^0\chi_{c0}$	$< 70\%$	CL=90%	
Γ_{15}	$\pi^+\pi^-\eta_c(1S)$	$< 14\%$	CL=90%	745
Γ_{16}	$\pi^+\pi^-\chi_{c1}$	$< 7\times10^{-3}$	CL=90%	218
Γ_{17}	$p\bar{p}$	$< 2.4\times10^{-5}$	CL=95%	1693
Radiative decays				
Γ_{18}	γD^+D^-	$< 4\%$	CL=90%	502
Γ_{19}	$\gamma\bar{D}^0D^0$	$< 6\%$	CL=90%	519
Γ_{20}	$\gamma J/\psi$	$(8\pm4)\times10^{-3}$		697
Γ_{21}	$\gamma\chi_{c1}$	$< 9\times10^{-3}$	CL=90%	344
Γ_{22}	$\gamma\chi_{c2}$	$< 3.2\%$	CL=90%	303
Γ_{23}	$\gamma\psi(2S)$	$(4.5\pm2.0)\%$		181

XYZ States in Experiment

XYZ States in Experiment

Production Mechanisms

- Production mechanisms affect experimental accessibility and can shed light on both the macroscopic quantum numbers and microscopic nature of a state.
    - Important to measure all possible production mechanisms of newly discovered states.
- Decays of B hadrons and bottomonium, as in the case of $\chi_{c1}(3872)$.
- Radiative decays of quarkonium(-like) states, as in $\psi(4230) \rightarrow \gamma\chi_{c1}(3872)$.
- Prompt production from parton interaction in $p\bar{p}$ and pp colliders.
- Several mechanisms of prompt production at e^+e^- colliders, including ISR, two-photon processes, double charmonium production.

XYZ States in Experiment

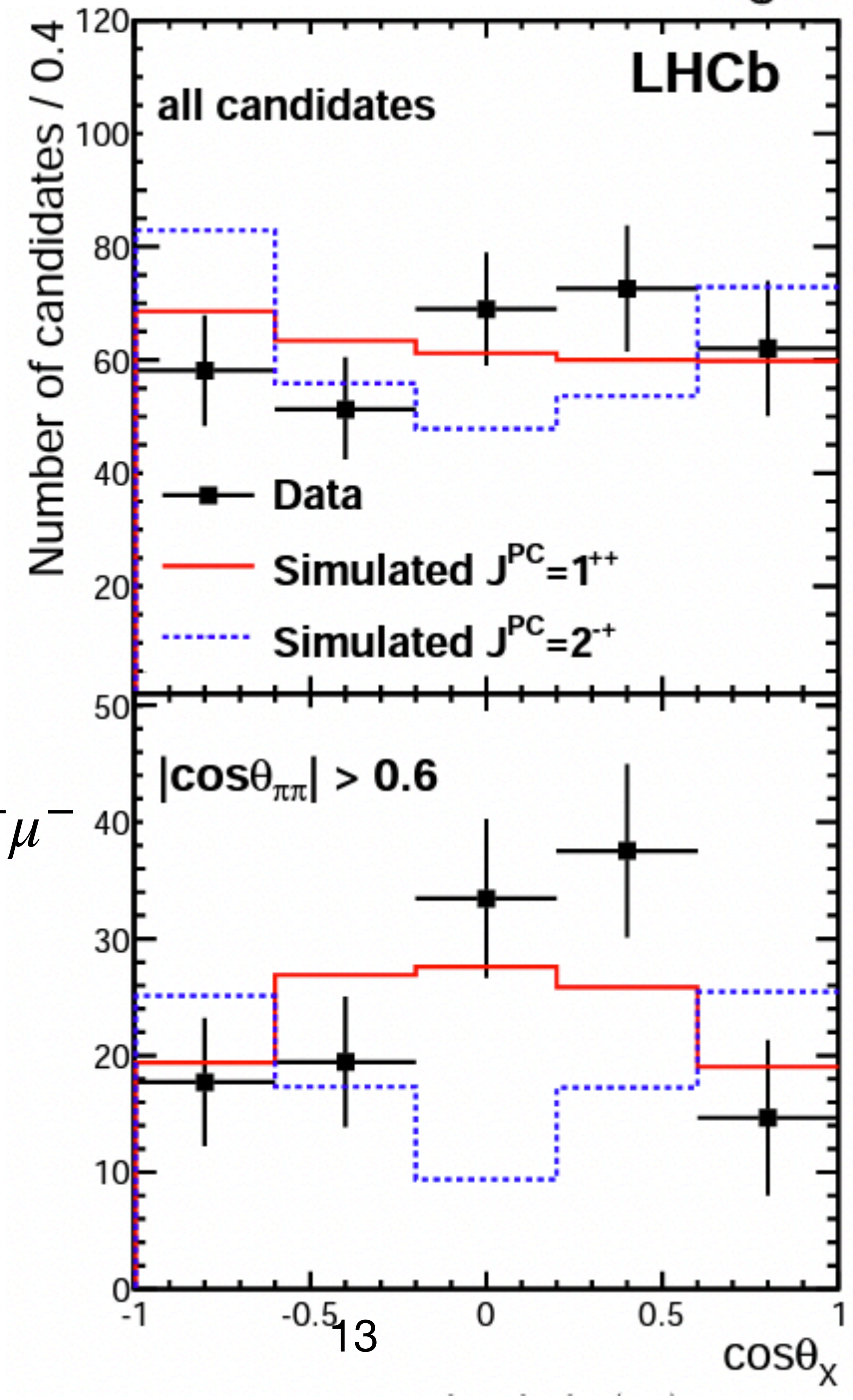
Decays

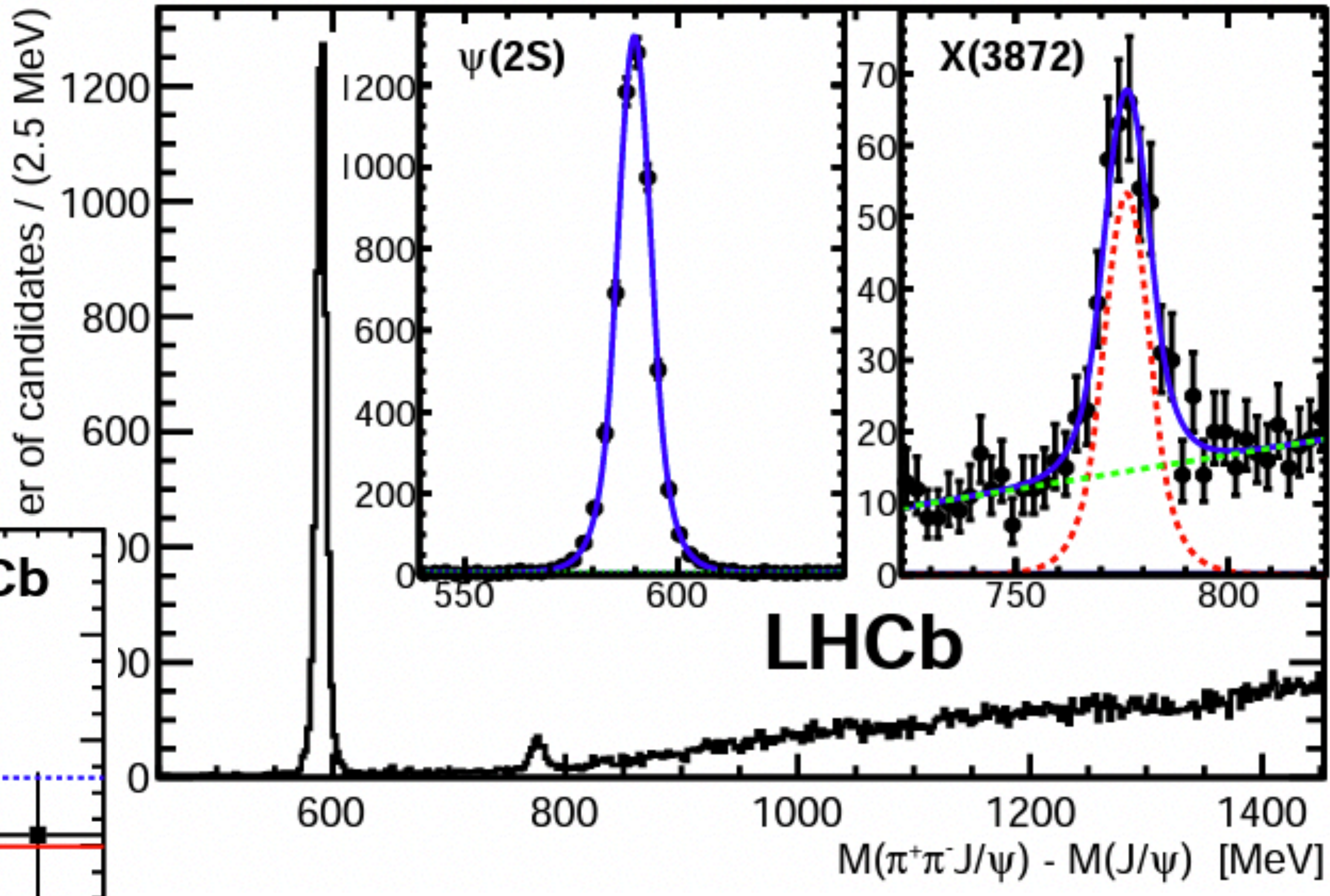
- Measuring over a wide range of decay modes and branching ratios requires large samples, accurate PID, and sufficient resolution to reconstruct the mass peak.
    - RICH detectors, drift chambers, and granular calorimeters are common detector technologies.
- Allowed decays can immediately rule out possible configurations of quantum numbers.
    - Also indicate hidden and open flavor content.
- Width can indicate decay mechanism and binding strength.
- Branching ratios reflect coupling strength to lower states as well as degree of isospin breaking.

XYZ States in Experiment

Quantum Numbers

- Flavor quantum numbers usually determined from production and decay mechanisms.
- Spin and parity information from these often incomplete.
- Angular analysis of decay chains can be used to fill in the gaps.
- e.g. 5 dimensional angular analysis in the $B^+ \to \chi_{c2}(3872)K^+, \chi_{c2}(3872) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$ decay chain used by LHCb to determine J^{PC}.
- Difficult analysis requiring more statistics and cleaner sample than observation.





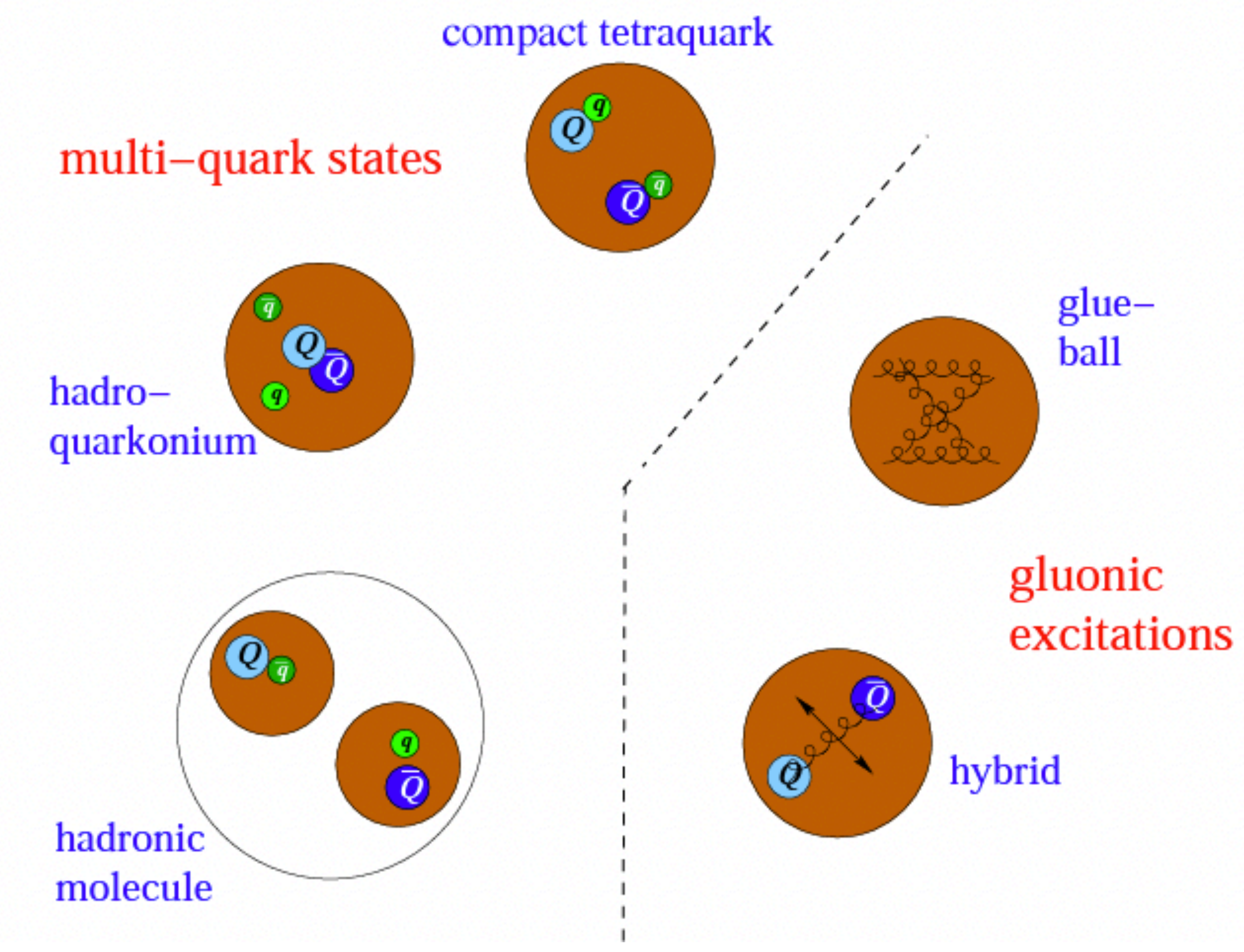
$$\Omega = (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$$

XYZ States in Theory

XYZ States in Theory

Overarching Themes

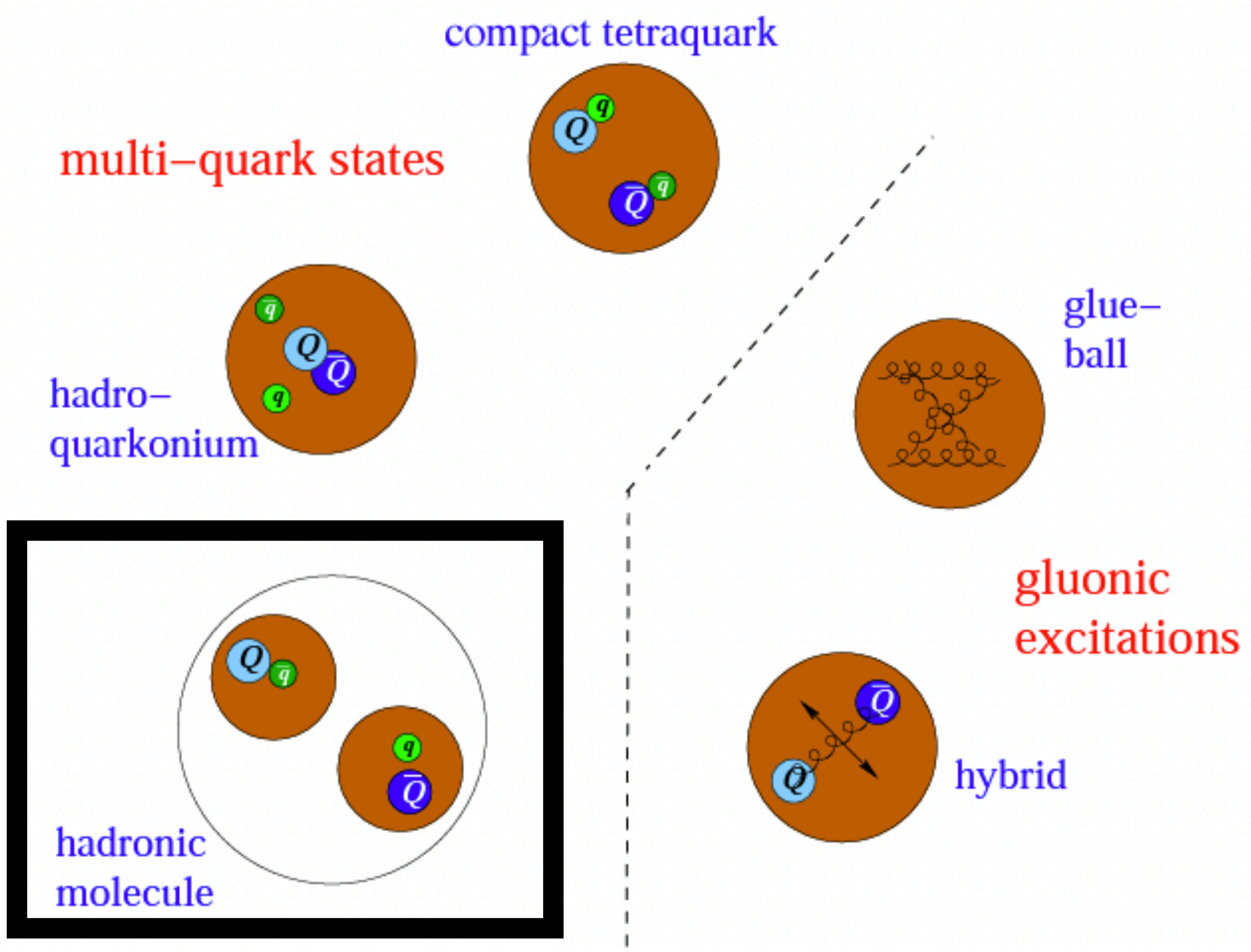
- Many varieties of exotic meson have been proposed.
- Mass calculations generally proceed from simplified Hamiltonian motivated by the relevant picture, as in the case of quark model mesons.
- Different explanations predict different structures with respect to spatial and flavor symmetries.
- Possible for multiple explanations for different states or even different components of a single wavefunction.



XYZ States in Theory

Hadronic Molecules

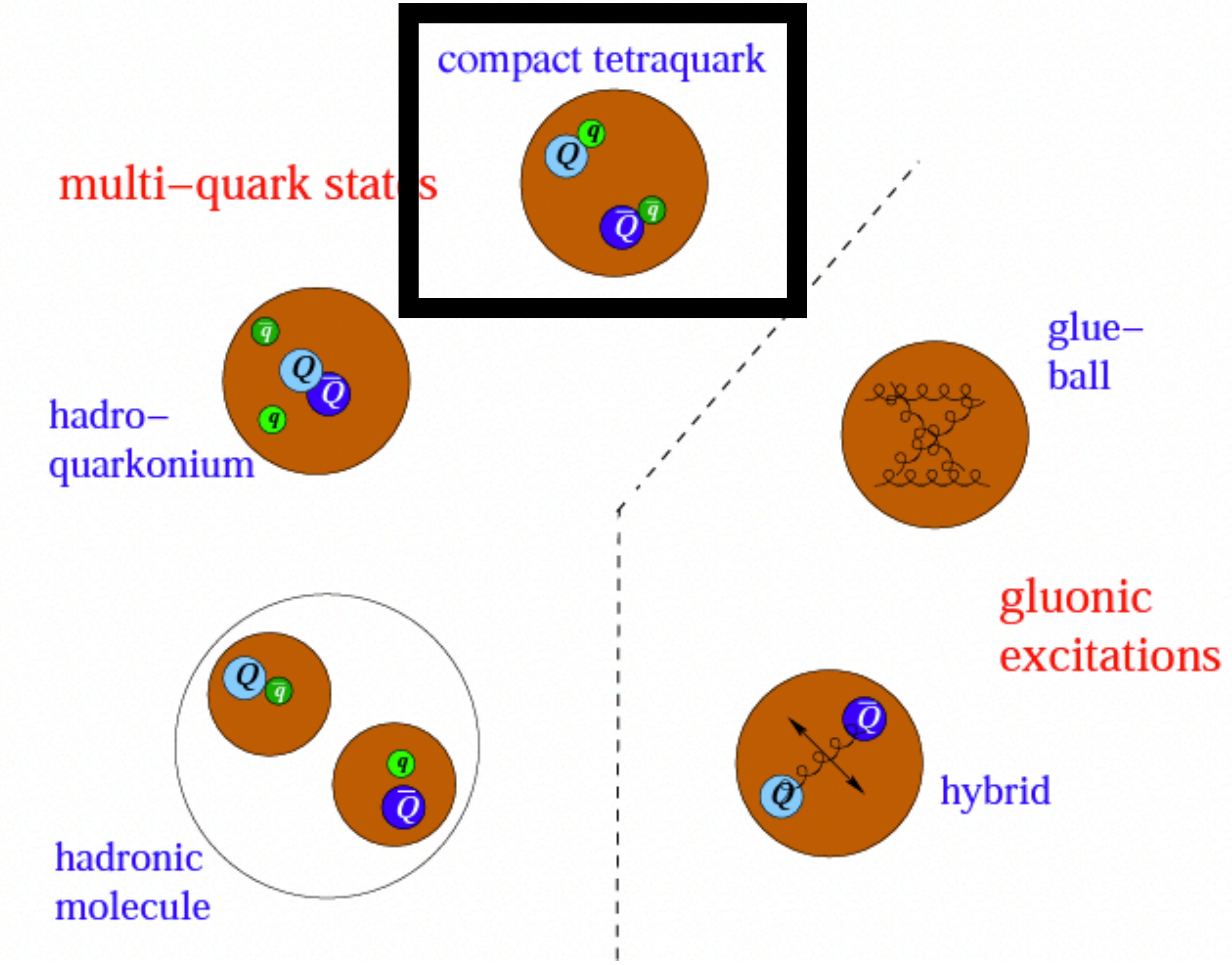
- Hadronic molecules are bound states or resonances of hadrons analogous to nuclei or molecules.
- Hadronic molecules tend to have extended physical size up to 10 fm.
- Predictions possible with EFT and on the Lattice - show that, e.g. $D\bar{D}*$ system should bind with potentials calculated from meson exchange.
- General predictions include strong coupling to component mesons, patterns for which mesons form bound states, and asymmetric line shapes.
- Many good candidates, but some have unexplained production mechanisms or do not lie close to a threshold.



XYZ States in Theory

Compact Tetraquarks

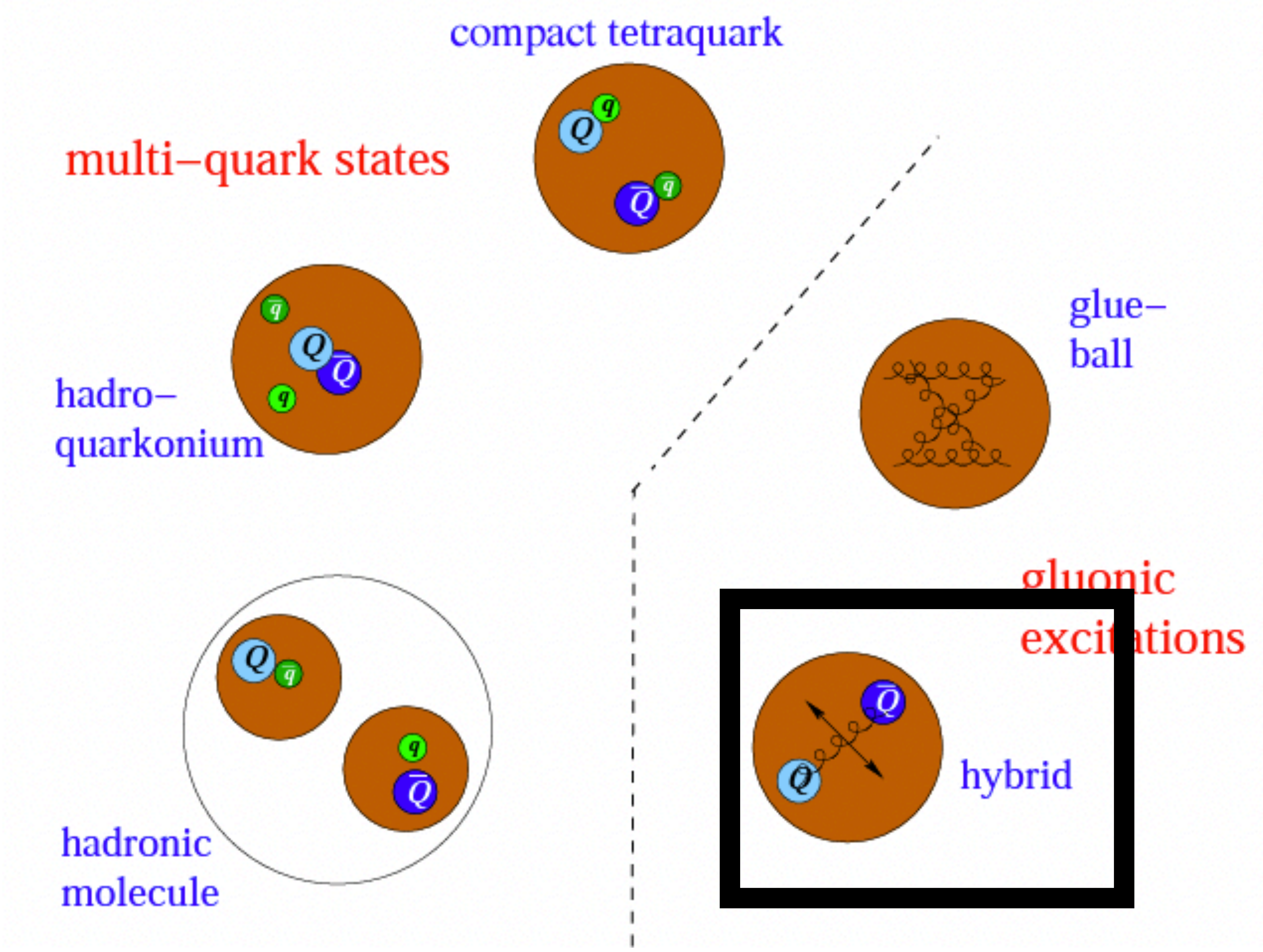
- Compact tetraquarks are compact 4 quarks structures composed of (anti-)diquarks, clusters of two (anti-)quarks.
- Mechanism for formation of diquarks not clear.
- Theories generally predict many new states - mostly unobserved - but also contain compelling matches to observed states.
- Generalization to mesons with more of fewer than 2 heavy quarks not certain.



XYZ States in Theory

Hybrids

- Hybrids are hadrons with excited gluonic degrees of freedom.
- Lowest charmonium hybrid predicted between 4.1 and 4.4 GeV.
- Bottomonium hybrid predicted around 11 GeV.
- Predict negligible decay width to leptons.

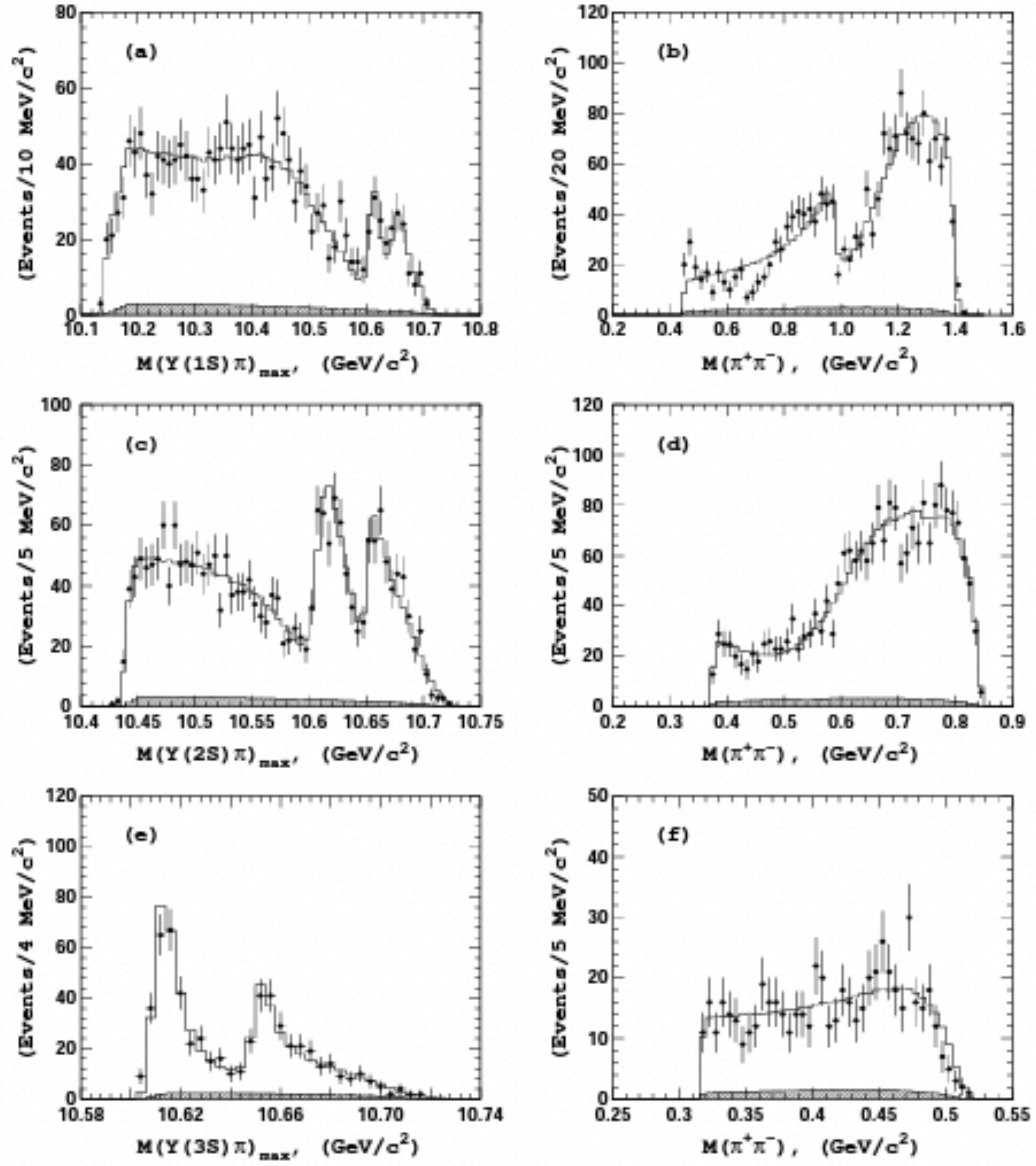


Selected Candidates for Exotic Heavy Mesons

Hidden B Isovector State

$Z_b(10610)$ and $Z_b(10650)$, $I^G(J^{PC}) = 1^+(1^{+-})$, G, C not yet confirmed.

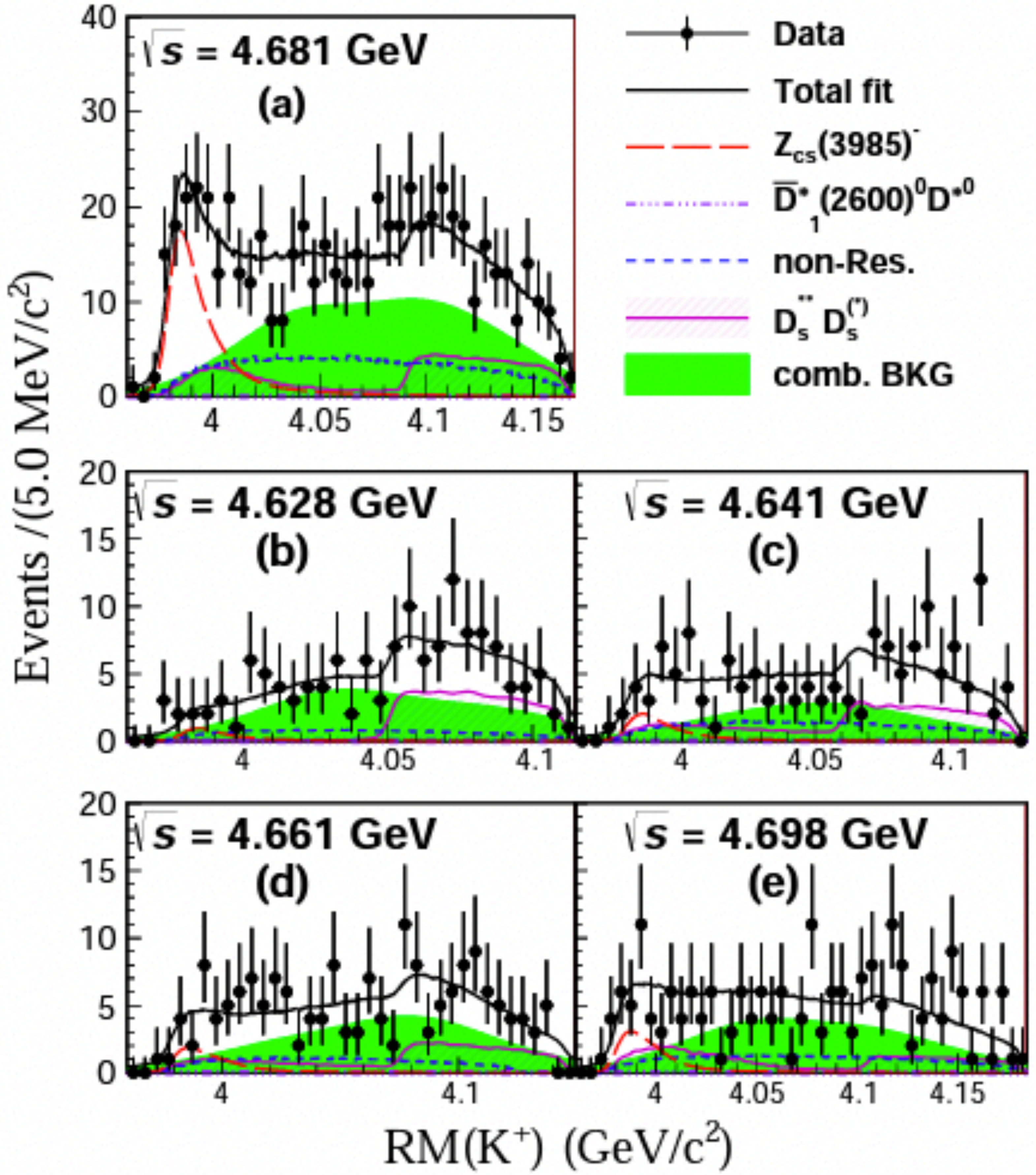
- First observed by Belle in 2012 with $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-, h_b(mP)\pi^+\pi^-$.
- Includes charged states.
- Nonzero isospin clearly implies the presence of light quarks addition to $b\bar{b}$ quark content.
- Dominant decays to $B\bar{B}^*$ and $B^*\bar{B}^*$.
- Similar set of states observed in charm.
- Molecular explanations successfully predict decay patterns, but also predict yet to be observed spin partner states. Tetraquarks structures also advanced in the case of Z_c states.



Hidden C Strange State

$Z_{cs}(3985), I^G(J^{PC}) = 1/2^?(?^{??})$

- Reported by BESIII in 2020 in $e^+e^- \to K^+D_s^-D^{*0}, K^+D_s^{*-}D^0$ at 5.3σ significance. Not yet observed elsewhere.
    - Using K^+ recoil mass and reconstructing only D_s^-.
- Apparent quark composition $c\bar{c}s\bar{u}$.
- Near D_sD^* threshold - another candidate for a molecular state.



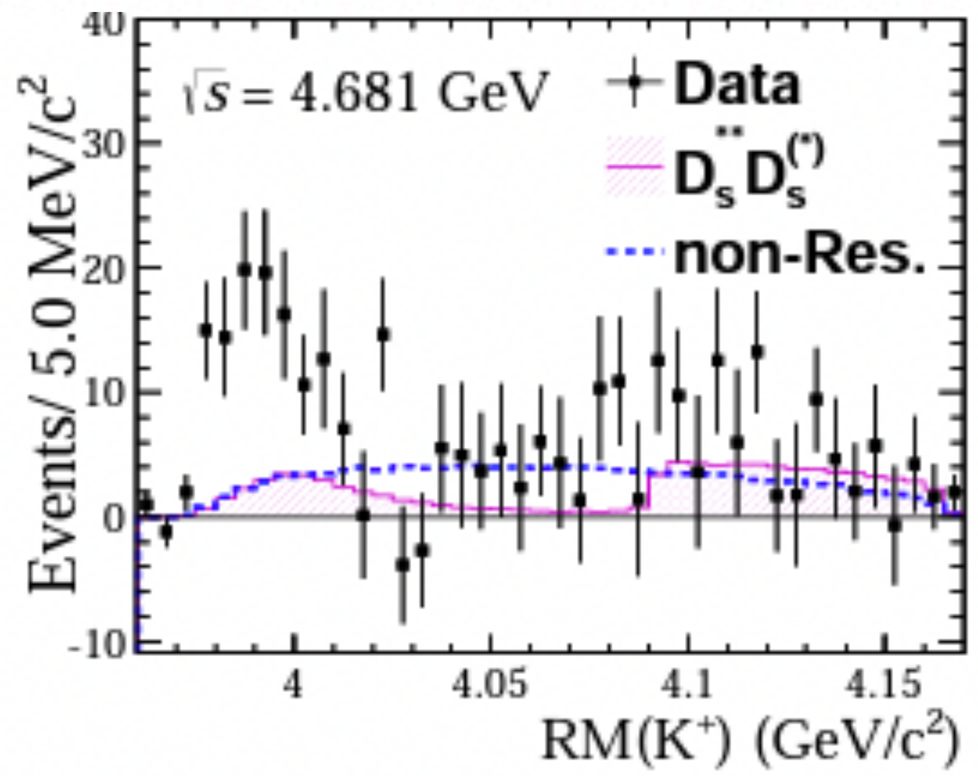


FIG. 4. The K^+ recoil-mass spectrum in data at $\sqrt{s}$ = 4.681 GeV after subtraction of the combinatorial backgrounds.

4x Heavy State

X(6900)

- Report by LHCb in 2020 as peak in $J/\psi\ J/\psi$ spectrum in the 4μ channel.
- Candidate for $c\bar{c}c\bar{c}$ tetraquark state.
- Apparently produced at high pT and significantly above non-resonant single and double Parton scattering.

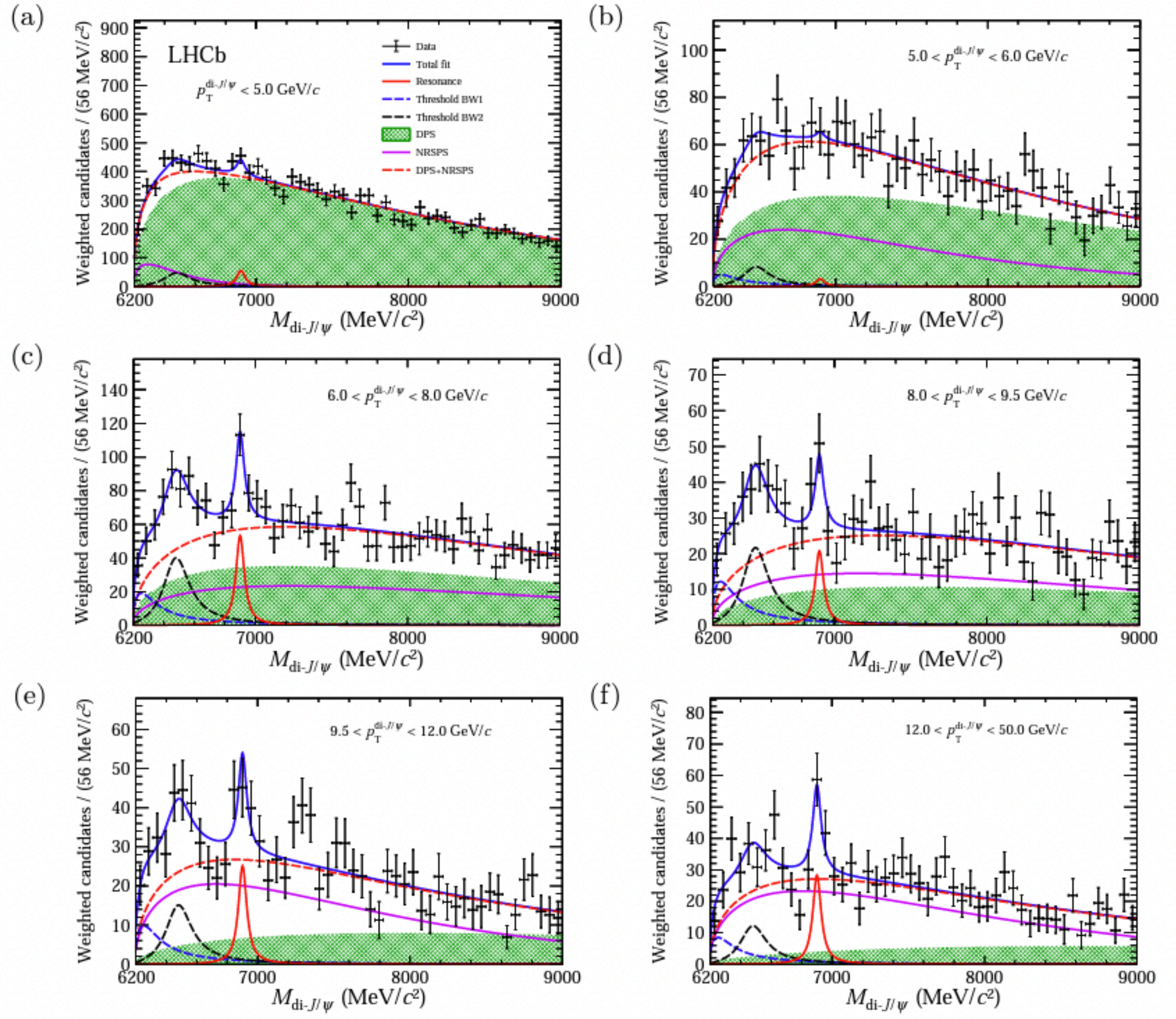
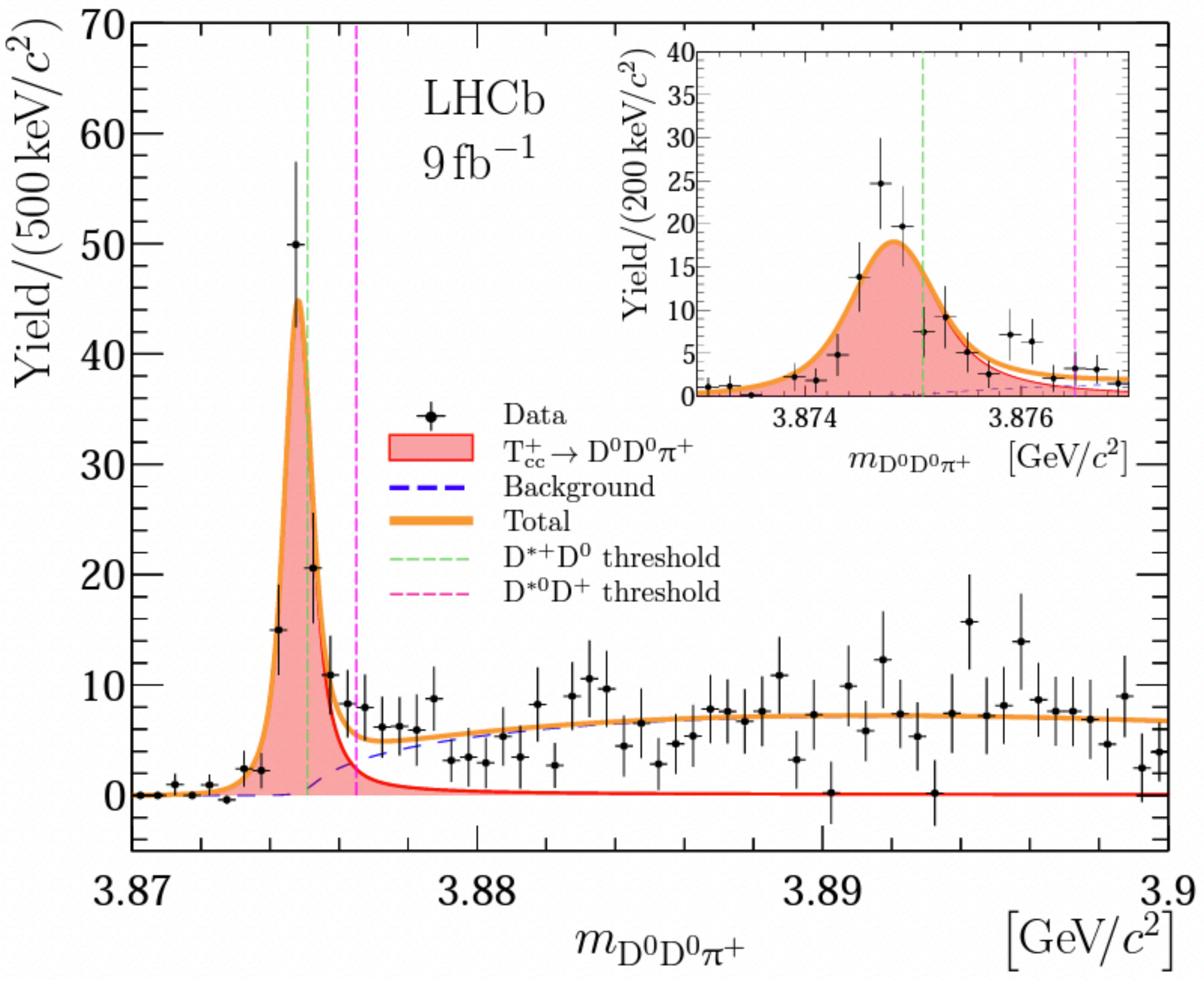


Figure 4: Invariant mass spectra of weighted di-J/ψ candidates in bins of $p_T^{\text{di-}J/\psi}$ and overlaid projections of the $p_T^{\text{di-}J/\psi}$-binned fit with model I.

Doubly Charmed Meson

X(3875)

- First observed by LHCb in 2021 in the $D^0 D^0 \pi^+$ spectrum near the $D^{*+} D^0$ threshold.
- C=2 implies two light anti-quarks (apparently $cc\bar{u}\bar{d}$).
- Corresponding bottom meson may decay weakly, if it exists.
- Described as tetraquark candidate.
- No corresponding peak in $D^0 \bar{D}^0$ channel - rules out oscillations or Cabibbo suppressed $\bar{D}^0 \rightarrow K^- \pi^+$ decays.



...And Others

LHCb 2021

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$	[36]
$\bar{c}cuud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$\bar{c}cuds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$	[20]

PDG 2022

Mesons with complete $I^G J^{PC}$ assignment	
PDG Name	Former Common Name(s)
$\psi_2(3823)^*$	$X(3823)$
$\chi_{c1}(3872)$	$X(3872)$
$Z_c(3900)$	$Z_c(3900)$
$\chi_{c2}(3930)^\dagger$	$\chi_{c2}(2P)$, $Z(3930)$
$\chi_{c1}(4140)$	$Y(4140)$
$Z_c(4200)$	$Z_c(4200)$
$\psi(4230)$	$Y(4230)$, $Y(4260)$
$R_{c0}(4240)$	$Z_c(4240)$
$\chi_{c1}(4274)$	$Y(4274)$
$\psi(4360)$	$Y(4360)$
$Z_c(4430)$	$Z_c(4430)$
$\chi_{c0}(4500)$	$X(4500)$
$\psi(4660)$	$X(4630)$, $Y(4660)$
$\chi_{c0}(4700)$	$X(4700)$
$Z_b(10610)$	$Z_b(10610)$
$Z_b(10650)$	$Z_b^{(\prime)}(10650)$

Mesons with incomplete $I^G J^{PC}$ assignment	
PDG Name	Former Common Name(s)
$X(3915)^\ddagger$	$\chi_{c0}(3915)$, $X(3915)$, $Y(3940)$
$X(3940)$	$X(3940)$
$X(4020)$	$Z_c^{(\prime)}(4020)$
$X(4050)^\pm$	$Z_1(4050)$
$X(4055)^\pm$	$Z_c(4055)$
$X(4160)$	$X(4160)$
$X(4250)^\pm$	$Z_2(4250)$
$X(4350)$	$X(4350)$

Outstanding Questions

What is the Microscopic Nature of XYZ States?
What XYZ States Remain to be Discovered?
How can we Understand XYZ States in Theory?
What can Experiments do to Answer these Questions?

Experimental Goals

- Continued measurement of discovered states understand their nature
  - Search for more decay mode and measurements of branch fractions
  - Search for states in new production channels
  - Determination of spin and parity quantum numbers
  - Measure line shapes and widths
- Search for new states to understand the underlying structure of the exotic meson spectrum
  - Confirm potential observations
  - Search for spin and other partners or in new mass regions
  - Search for flavor analogs of discovered states (i.e. $c \leftrightarrow b$)

Overall Outlook

- The exact microscopic nature of these states is still not known.
- Work needed on the theoretical side, but ultimately more data is needed to distinguish between the scenarios.
  - Combination of phenomenological, EFT, and Lattice models complicates the landscape.
- LHC experiments, BESIII, Belle II, GlueX, currently taking data.
- PANDA - A fixed target anti-proton machine at FAIR is in civil construction.

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Particle listings as well as the following reviews:

Naming Scheme for Hadrons

Quark model

Spectroscopy of mesons containing two heavy quarks

Charmonium system

Bottomonium system

Heavy Non-qqbar Mesons

Thanks!