XYZ STATES

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OUTLINE

- Introduction
  - Quark model
  - Exotics
- X(3872)
  - Discovery
  - Characteristics
  - Hypotheses
- Other XYZ states

QUARK MODEL, CONVENTIONAL BOUND STATES

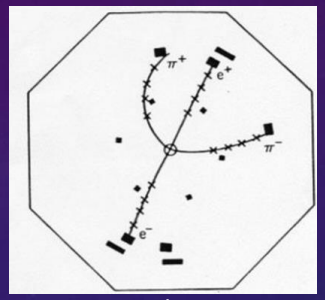
- **Introduction**
  - **Quark model**
  - **Exotics**
- **X(3872)**
  - **Discovery**
  - **Characteristics**
  - **Hypotheses**
- **Other XYZ states**

- Baryons: qqq
  - Eg. proton, neutron
- Mesons: $q\bar{q}$
  - Eg. "Charmonium": $c\bar{c} = J/\psi, \psi'$(2S state of J/ψ), etc.
  - Potential/mass spectrum fairly well understood
    - Cornell potential:

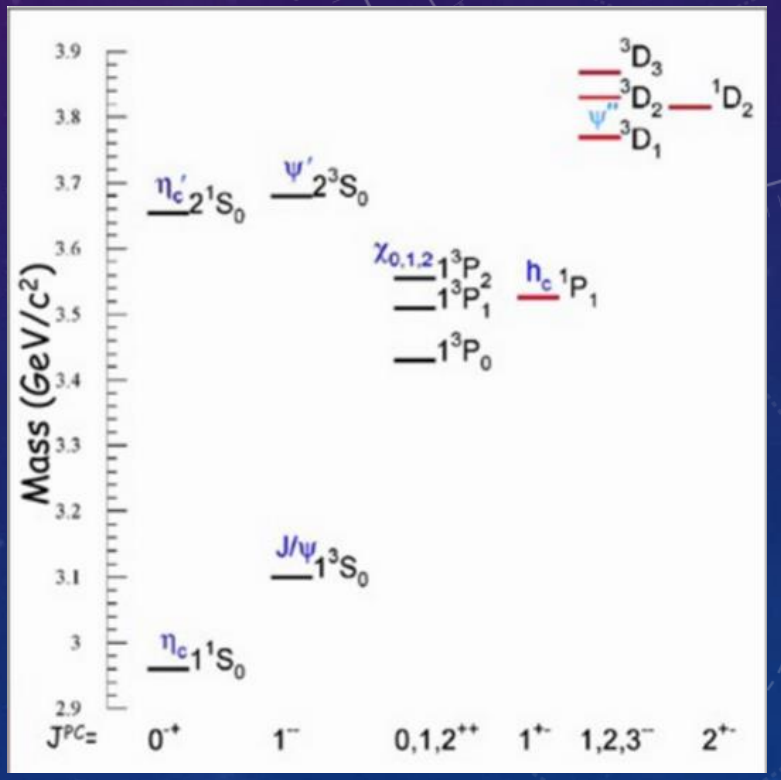
$$V(r) = -\frac{a}{r} + br$$

(Coulomb-like (gluon exchange) + confinement)

    - Other models exist
- XYZ states are (likely) neither of the above



$\psi' \to \pi^+\pi^- J/\psi$



D. Bettoni, http://slideplayer.com/slide/5234741/

EXOTIC QCD STATES

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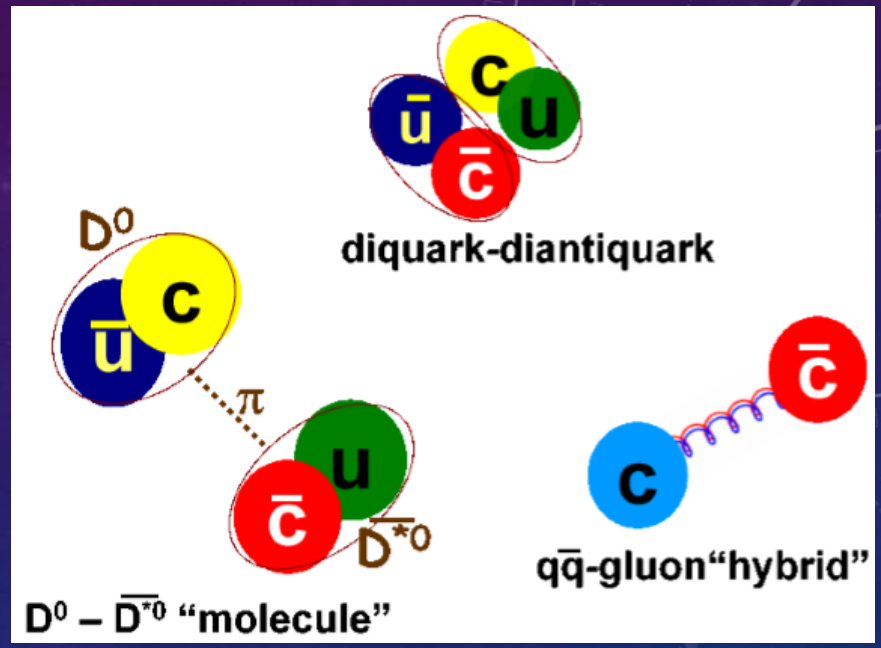
- Glueballs
  - Bound states of 2 or 3 or more gluons
- Hybrid mesons: $q\bar{q}g$
- Tetraquarks: $qqqq$
- Deusons: meson-meson “molecules”
  - Loosely bound
  - Analogous to baryon-baryon “molecules” like D_2
  - Eg. $D\overline{D}^*$ (where $D = c\bar{q}$ is a D meson)



2003 DISCOVERY OF X(3872)

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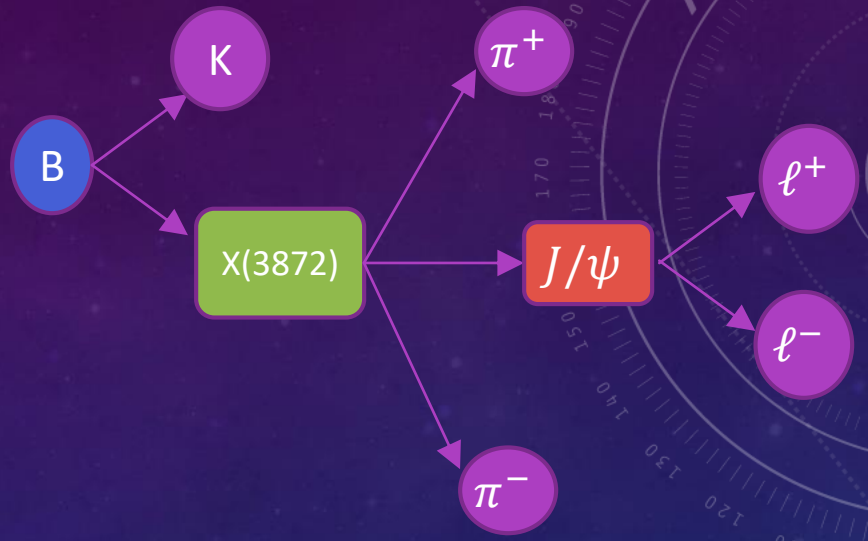
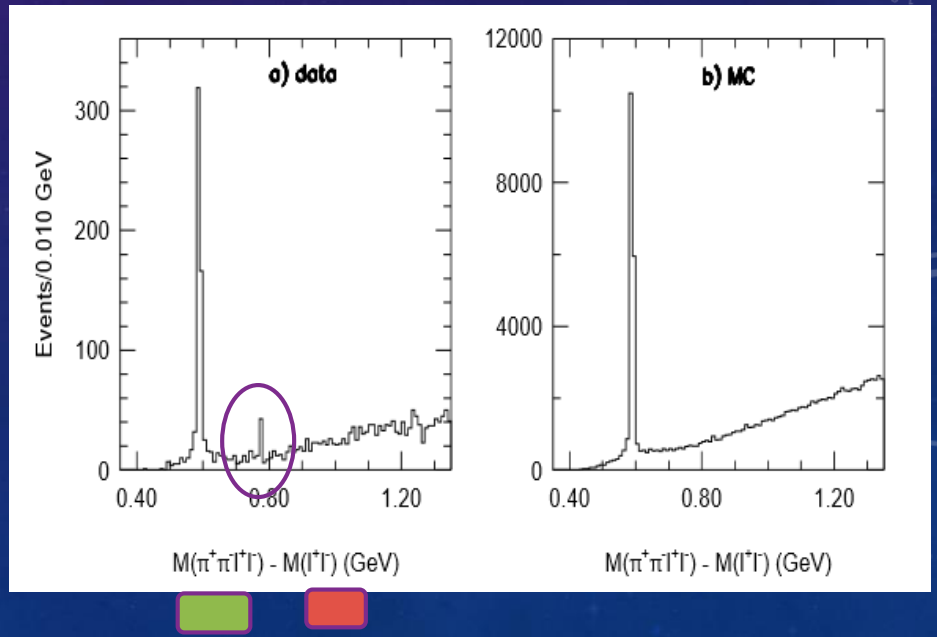
- Belle detector at KEKB e^+e^- collider ("B factory")
- $B \to \mathrm{KX(3872)}, \mathrm{X(3872)} \to \pi^+\pi^- J/\psi$, $J/\psi \to \ell^+\ell^-$
  - Background: $B \to K\psi', \psi' \to \pi^+\pi^- J/\psi$
- Invariant mass:
  - If a system of particles decayed from one parent particle, what was the parent's mass?
  - Relativistic kinematics:

$$M_{parent} = \sqrt{E_{tot}^2 - p_{tot}^2}$$





arXiv:hep-ex/0309032

CONFIRMATION OF X(3872) DISCOVERY

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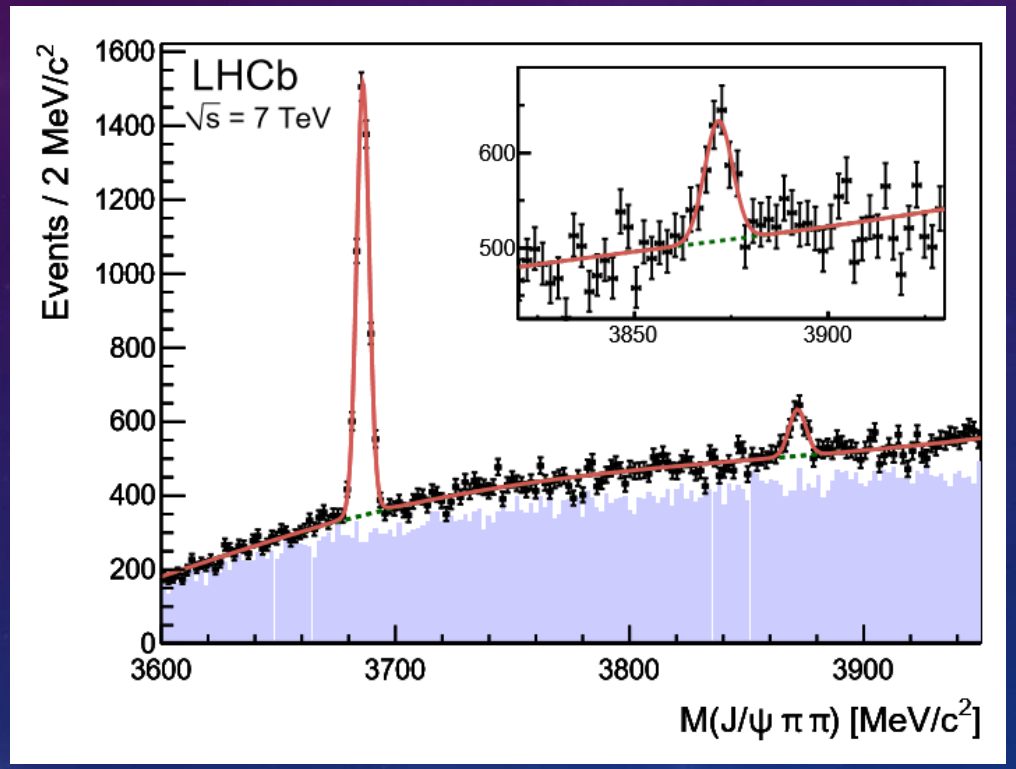
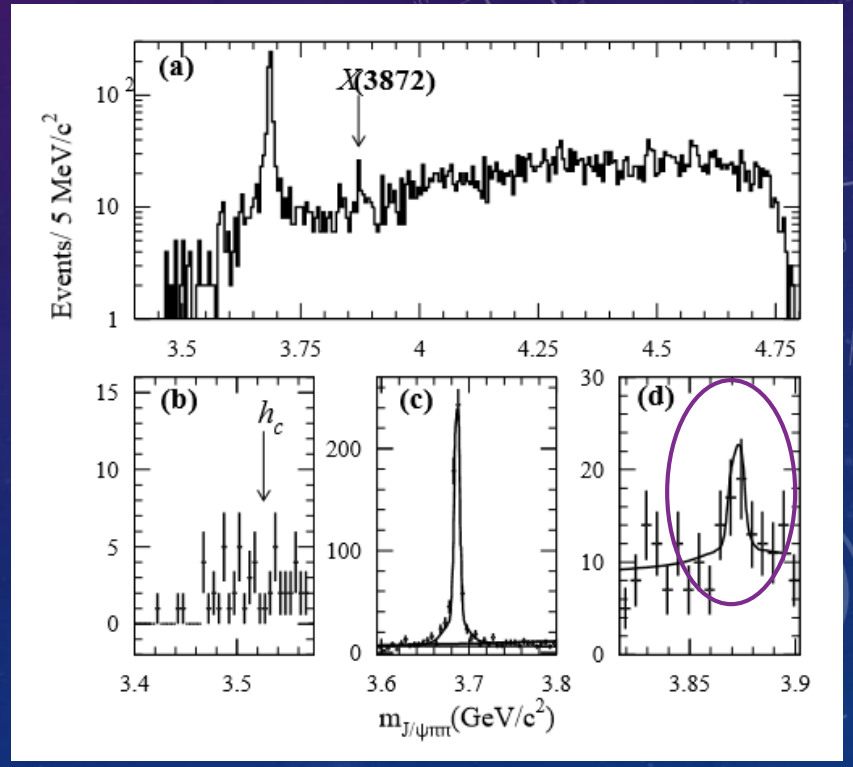


arXiv:1112.5310

LHCb, 2004 ($p\bar{p}$)



arXiv:hep-ex/0406022

BaBar, 2004 (e^+e^-)

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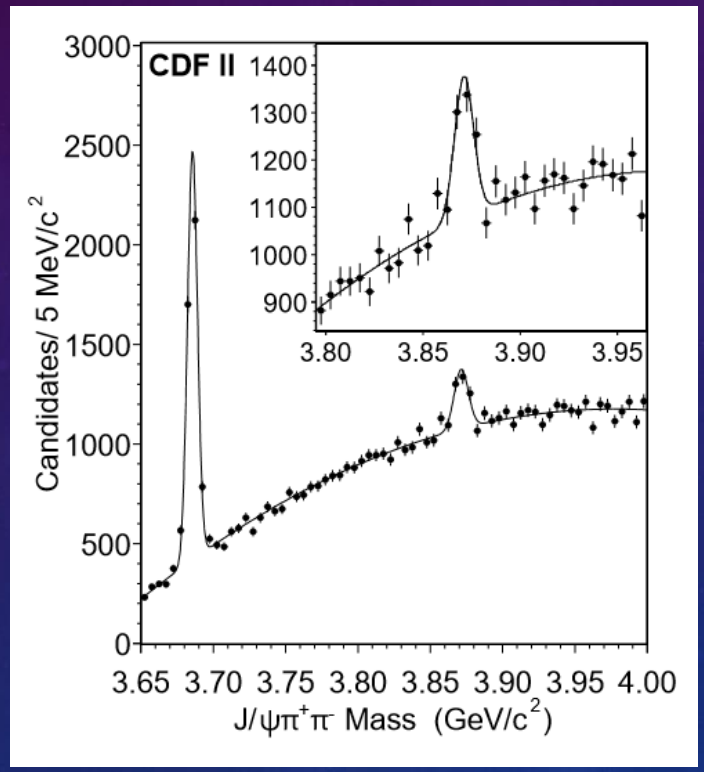
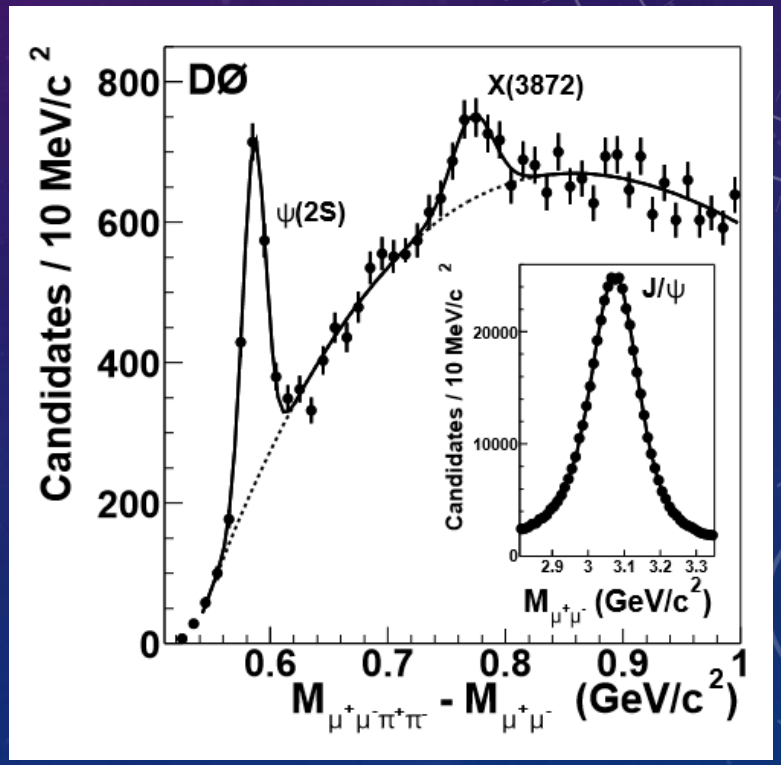


arXiv:hep-ex/0312021

CDF, 2006 ($p\bar{p}$)



arXiv:hep-ex/0405004

D0, 2004 ($p\bar{p}$)

QUANTUM NUMBERS OF X(3872)

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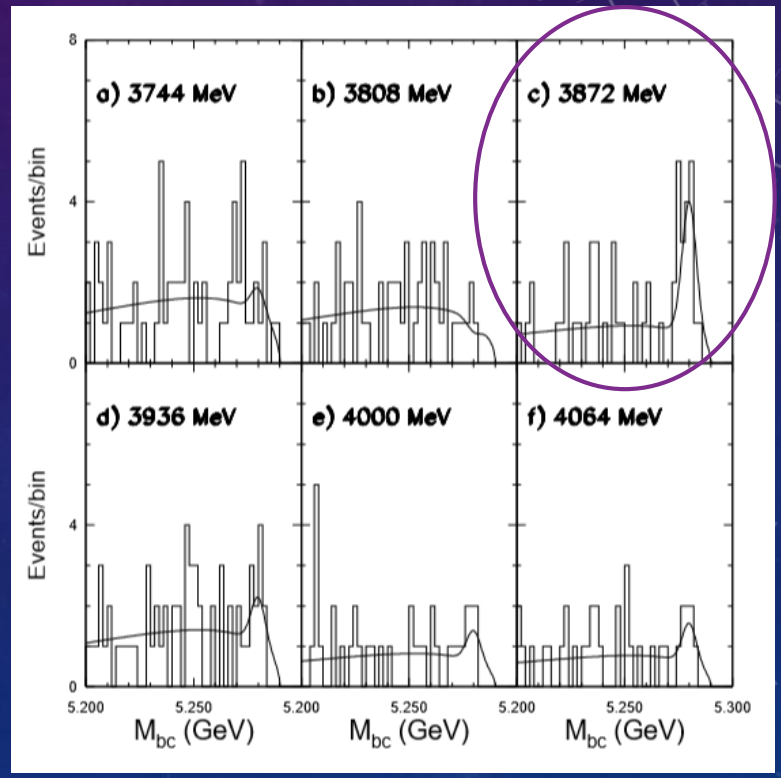
- Previous confirmations also in the $\pi^+\pi^- J/\psi$ channel
- 2005: Belle identifies the 3872 MeV peak in the $\pi^+\pi^-\pi^0 J/\psi$ and $\gamma J/\psi$ decay channels
  - Decay to neutral particles ➔ X(3872) is even under charge conjugation (C = 1)



arXiv:hep-ex/0505037

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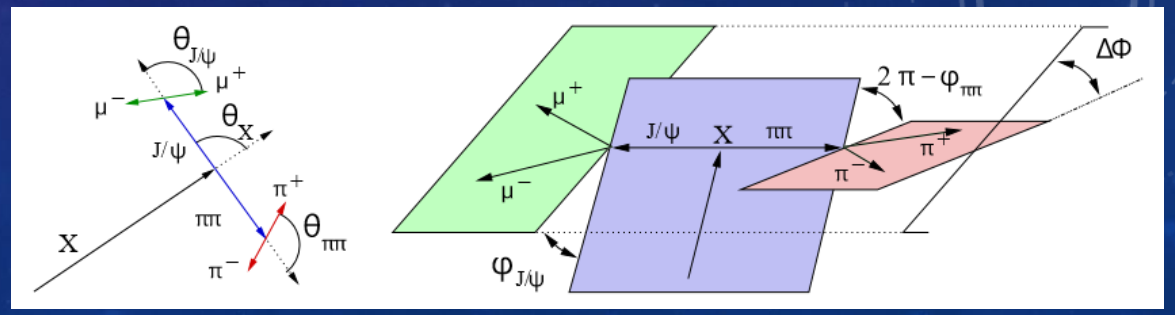
- 2006: CDF studies angular distribution of $\pi^+\pi^- J/\psi$ decay products with limited stats
- Interaction Lagrangian for 1^{++} decays: $\mathcal{L} \propto \overrightarrow{\epsilon_\chi} \cdot (\overrightarrow{\epsilon_{J/\psi}} \times \overrightarrow{\epsilon_\rho})$
  - ρ is the parent of the pions
  - Angular dependence on polarization/angular momentum direction
- Only $J^{PC} = 1^{++}$ and 2^{-+} consistent with data

J^{PC}	decay	LS	χ^2 (11 d.o.f.)	χ^2 prob.
1^{++}	$J/\psi\rho^0$	01	13.2	0.28
2^{-+}	$J/\psi\rho^0$	11,12	13.6	0.26
1^{--}	$J/\psi(\pi\pi)_S$	01	35.1	2.4×10^{-4}
2^{+-}	$J/\psi(\pi\pi)_S$	11	38.9	5.5×10^{-5}
1^{+-}	$J/\psi(\pi\pi)_S$	11	39.8	3.8×10^{-5}
2^{--}	$J/\psi(\pi\pi)_S$	21	39.8	3.8×10^{-5}
3^{+-}	$J/\psi(\pi\pi)_S$	31	39.8	3.8×10^{-5}
3^{--}	$J/\psi(\pi\pi)_S$	21	41.0	2.4×10^{-5}
2^{++}	$J/\psi\rho^0$	02	43.0	1.1×10^{-5}
1^{-+}	$J/\psi\rho^0$	10,11,12	45.4	4.1×10^{-6}
0^{-+}	$J/\psi\rho^0$	11	104	3.5×10^{-17}
0^{+-}	$J/\psi(\pi\pi)_S$	11	129	$\leq1\times10^{-20}$
0^{++}	$J/\psi\rho^0$	00	163	$\leq1\times10^{-20}$



arXiv:hep-ex/0612053

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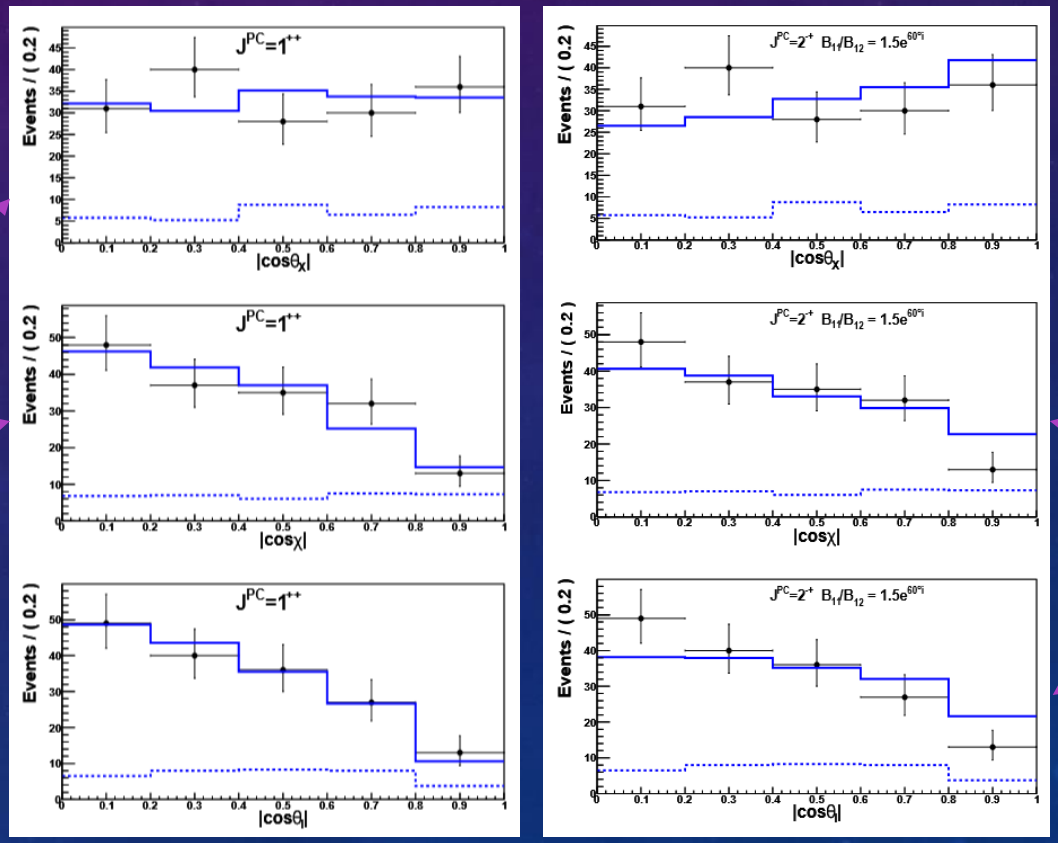
- 2011: Belle finds strong but inconclusive support for $J^{PC} = 1^{++}$

χ^2 (CL) for $J^{PC} = 1^{++}$

3.82 (0.43)
1.76 (0.78)
0.56 (0.97)



χ^2 (CL) for $J^{PC} = 2^{-+}$

4.72 (0.32)
4.60 (0.33)
5.24 (0.26)

Blue = MC, dashed blue = bkg, black = data

arXiv:hep-ex/1107.0163

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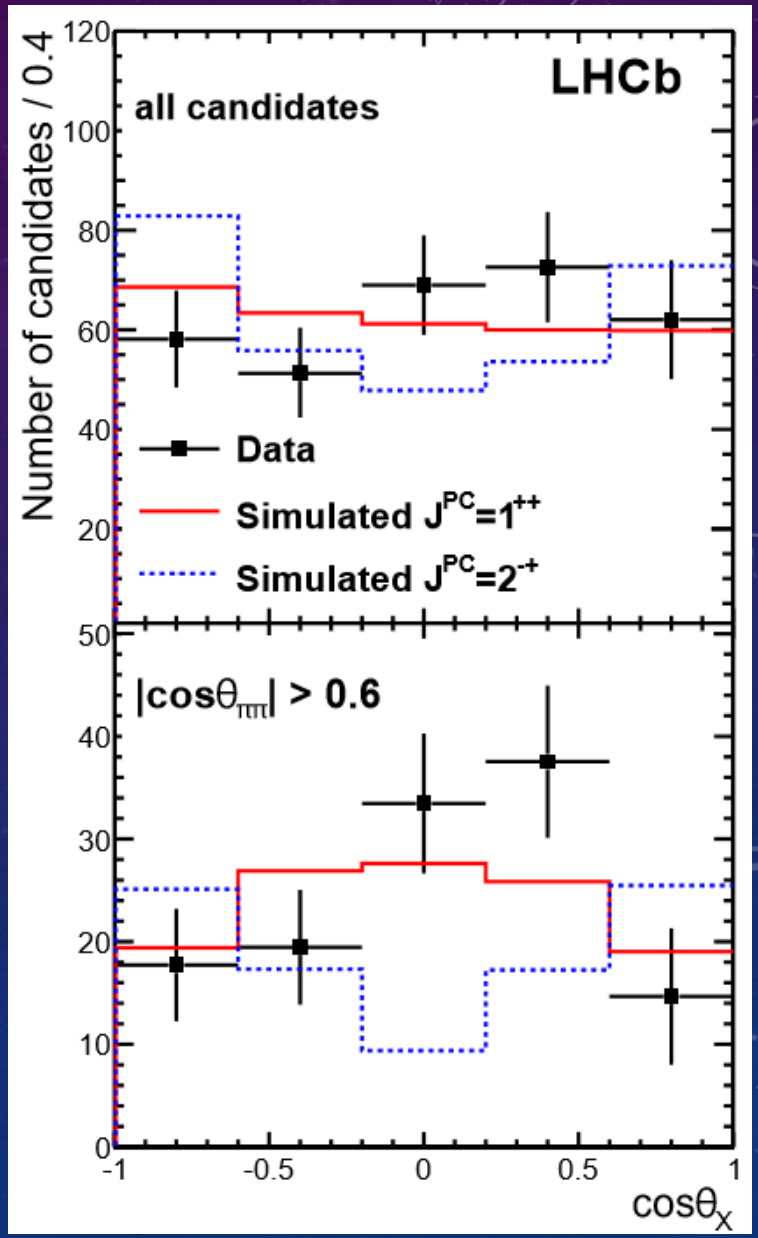
- 2013: LHCb publishes analysis of angular distribution in full angular phase space
- Conclusive support for $J^{PC} = 1^{++}$



arXiv:1302.6269

IS X(3872) AN EXCITED CHARMONIUM STATE?

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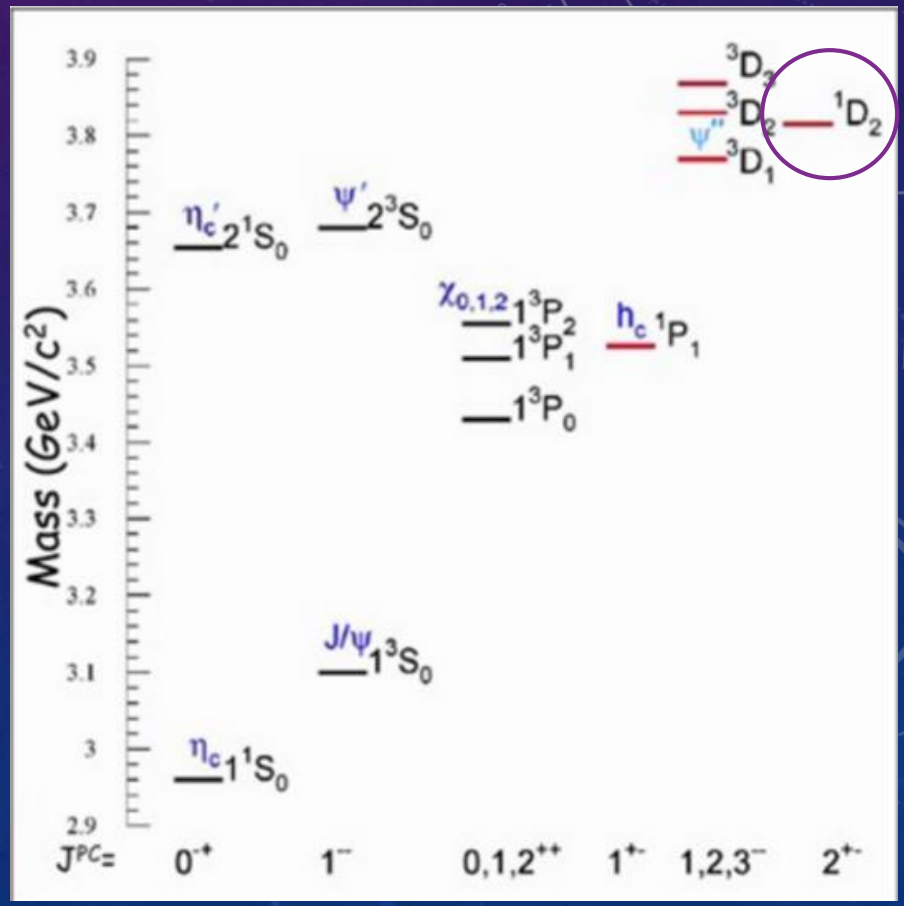
- LHCb measurement of $J^{PC} = 1^{++}$ excludes most of the candidates (by mass) excited states of traditional $c\bar{c}$, including 1^1D_2



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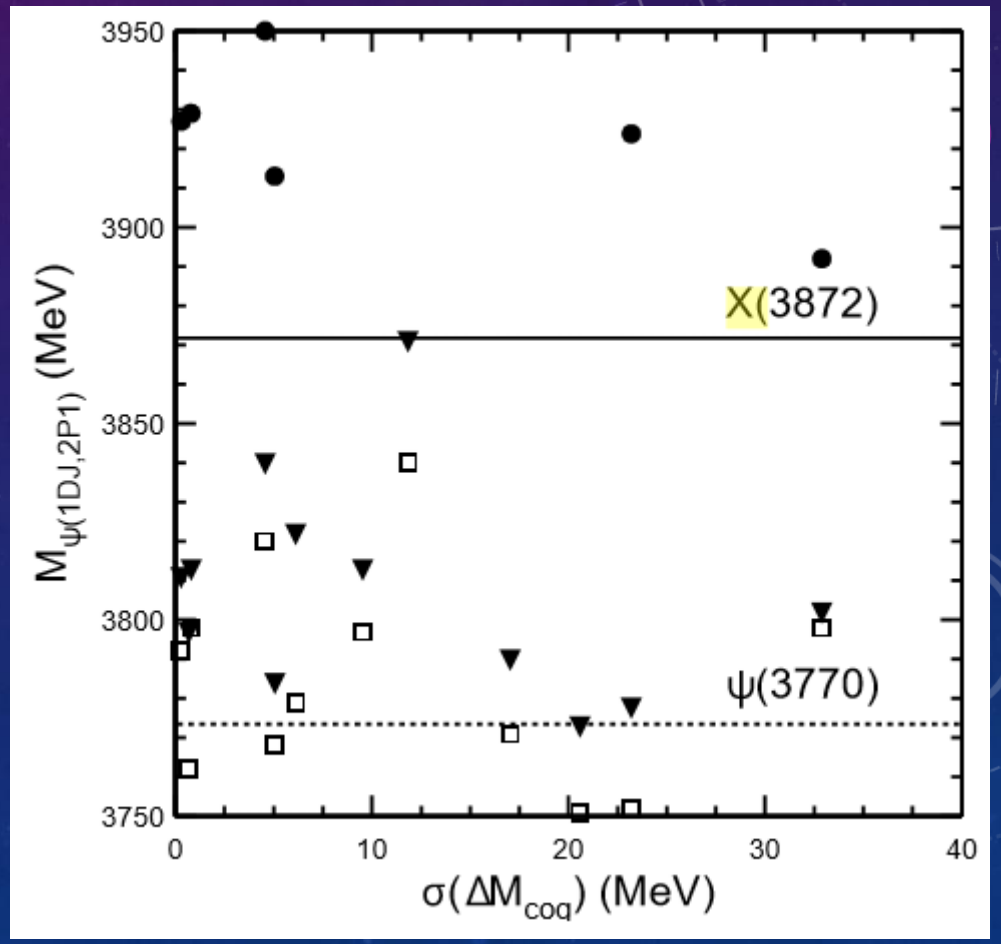
- Still feasible is the 2^3P_1 charmonium state
- Not likely due to mass considerations



Predicted masses vs quality of potential model. Circles = 2^3P_1, triangles = 1^1D_2, squares = 1^3D_1

arXiv:hep-ph/0311243

IS X(3872) A DEUSON?

- Introduction
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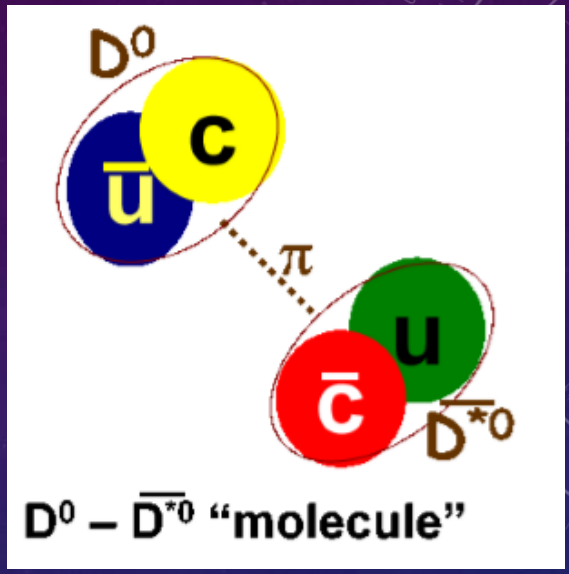
- Recall: deuson = loosely bound meson-meson molecule, similar to deuteron
- Small binding energy $M_X - M_D - M_{\overline{D^*}}$ corresponds to a large radius on the order of fm in the Cornell potential → stability/mass width implications



Composite	J^{PC}	Mass [MeV]
$D\bar{D}^*$	0^{-+}	≈ 3870
$D\bar{D}^*$	1^{++}	≈ 3870
$D^*\bar{D}^*$	0^{++}	≈ 4015
$D^*\bar{D}^*$	0^{-+}	≈ 4015
$D^*\bar{D}^*$	1^{+-}	≈ 4015
$D^*\bar{D}^*$	2^{++}	≈ 4015

arXiv:hep-ph/0402237

IS X(3872) A TETRAQUARK?

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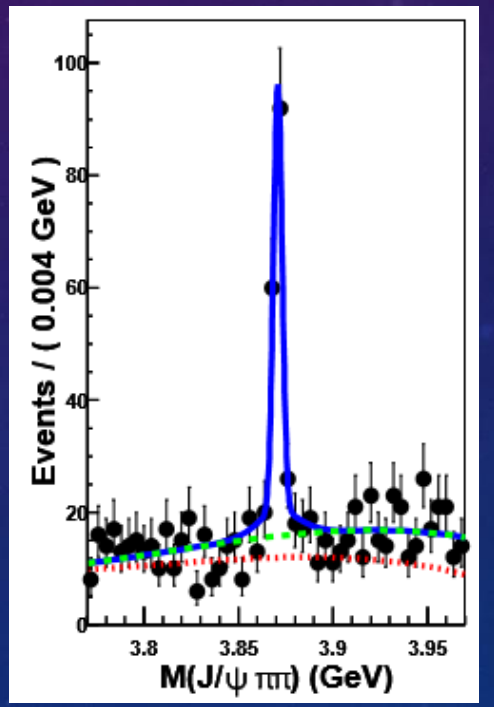
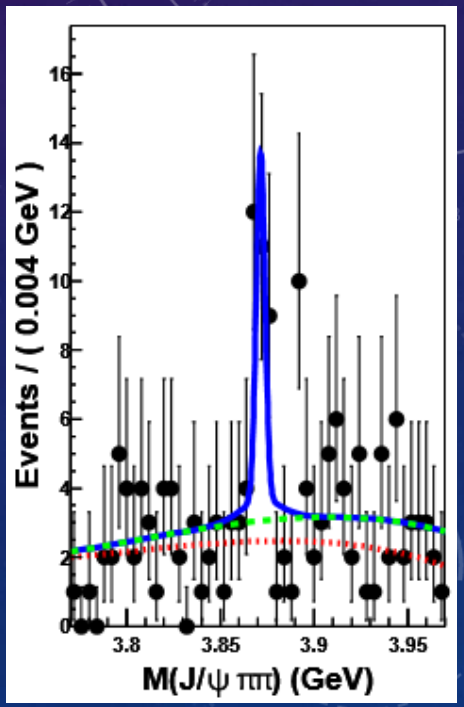
- One model proposes to identify the X(3872) with a pair of states $(|cu\bar{c}\bar{u}\rangle + |cd\bar{c}\bar{d}\rangle)/\sqrt{2}$ and $(|cu\bar{c}\bar{u}\rangle - |cd\bar{c}\bar{d}\rangle)/\sqrt{2}$
- Mass splitting predicted between the $B^+ \to K^+X(3872)$ and $B^0 \to K^0X(3872)$ decay channels
- 2011: Belle found no evidence of this mass splitting
  - $\Delta\mathrm{M} = -0.69 \pm .97$ MeV



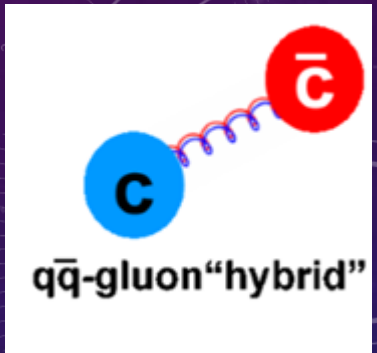
$B^+ \to K^+X(3872)$



$B^0 \to K^0X(3872)$

Phys. Rev. D 84, 052004

IS X(3872) A HYBRID?



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Most theoretical models predict higher masses for Charmonium hybrids

TABLE I. Predicted 1^{-+} Hybrid Masses.

state	mass (GeV)	model	Ref.
$H_{u,d}$	1.3-1.8	bag model	[19]
	1.8-2.0	flux tube model	[11–14]
	2.1-2.5	QCD sum rules (most after 1984)	[26–28]
H_c	≈ 3.9	adiabatic bag model	[20]
	4.2-4.5	flux tube model	[12–14]
	4.1-5.3	QCD sum rules (most after 1984)	[26–28]
	4.19(3) $\pm$ sys.	HQLGT	[23]

arXiv:hep-ph/9501405

Y(4260) FAMILY

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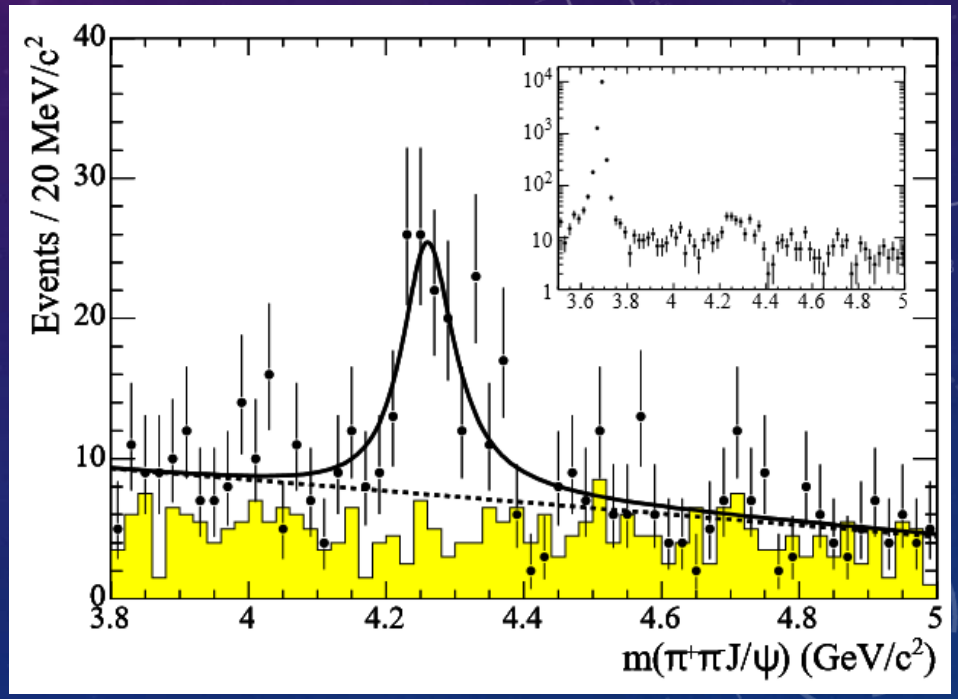
- 2005: 4260 MeV resonance detected in the $\pi^+\pi^- J/\psi$ channel at BaBar
- Production is by *initial state radiation* (ISR)
  $e^+e^- \rightarrow \gamma Y(4260)$
  - $\Rightarrow J^{PC} = 1^{--}$
- Other states observed in ISR processes at M = 4008, 4250, 4660 MeV
  decay: $\pi^+\pi^-\psi'$
  - Symmetry?
- Other, well-studied $J^{PC} = 1^{--}$ states with 4 GeV < M < 5 GeV



arXiv:hep-ex/0506081

Dashed curve = background component of fit, yellow histogram = sideband estimated background

Y(4260) FAMILY

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- 1995: Barnes et al predict Charmonium hybrids in the 4.2-4.5 GeV range
  - Some $J^{PC} = 1^{--}$ states predicted

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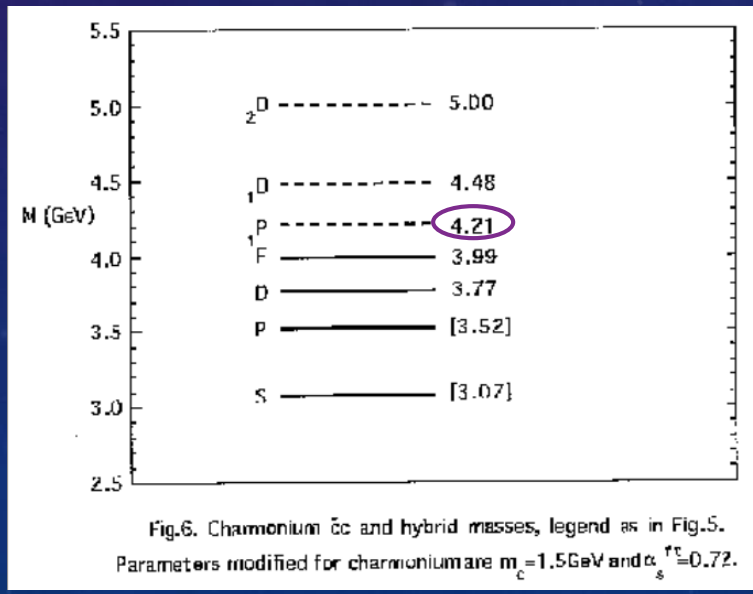

Fig.6. Charmonium $\bar{c}c$ and hybrid masses, legend as in Fig.5. Parameters modified for charmonium are m_c=1.5GeV and $\alpha_s^{\overline{MS}}$=0.72.

arXiv:hep-ph/9501405

$Z_c(3900)$

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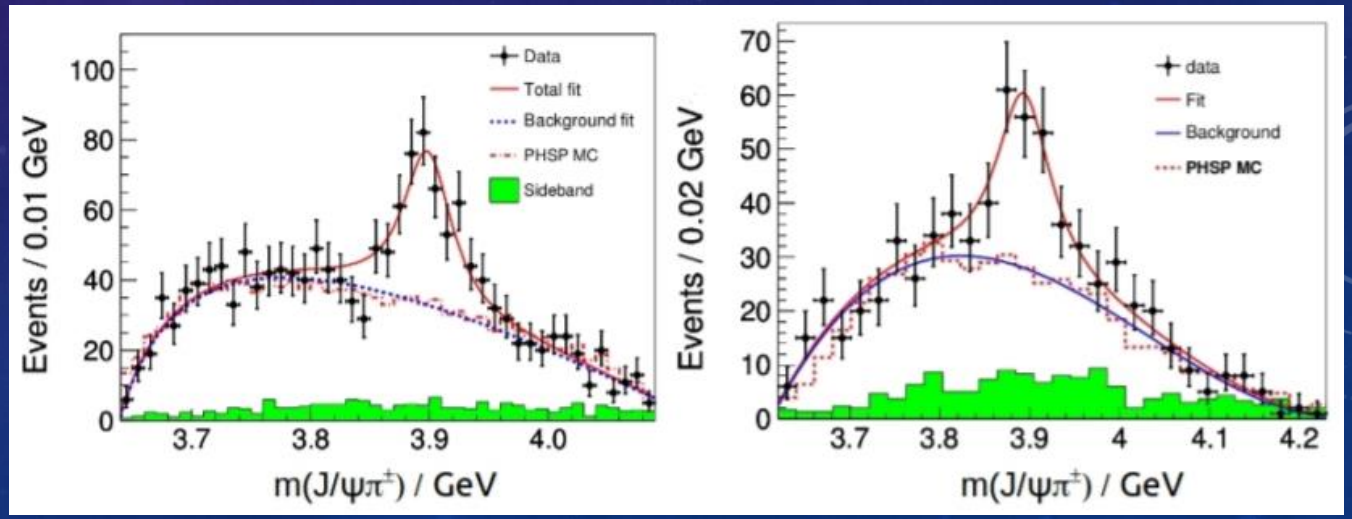
- Observed at BESIII (left) and Belle (right)
  $Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\pm}$
  - Links to Y states
- Charged = not charmonium
- Tetraquark? Deuson?



arXiv:1311.7594

SUMMARY

- Many charmonium-like states outside of the current understanding of the charmonium/bottomonium spectra have been observed
- X(3872) not likely to be a traditional charmonium state due to lack of predicted charmonium states near its mass with the same J^{PC} quantum numbers
- X(3872) not likely to be the $(|cu\bar{c}\bar{u}\rangle + |cd\bar{c}\bar{d}\rangle)/\sqrt{2}$ and $(|cu\bar{c}\bar{u}\rangle - |cd\bar{c}\bar{d}\rangle)/\sqrt{2}$ tetraquark due to lack of mass splitting between charged/neutral decay channels
  - Other tetraquark models possible?
- X(3872) could be a deuson, more investigation into lifetime/mass width and other properties needed
- X(3872) could be a hybrid meson ($q\bar{q}g$) too, but theory usually predicts larger masses than 3872 MeV
- Y(4620) family is close in mass to other $c\bar{c}$ states with the same J^{PC} quantum numbers
- Y(4620) is close in mass to a predicted hybrid $c\bar{c}g$ state
- $Z_c(3900)$ decays from Y(4620), may be tetraquark or deuson, but not charmonium due to charge