Mesons, Baryons, and Beyond?

1964: Gell-Mann & Zweig postulate Constituent Quark Model (CQM) –

- Explained all known mesonic and baryonic states
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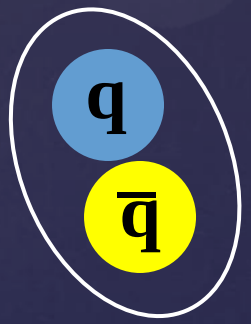
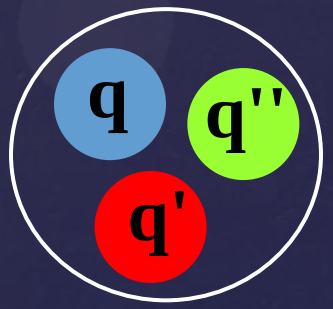
CQM ⇒ Quarks form two types of bound states:

Mesons



Baryons



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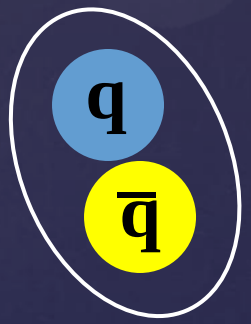

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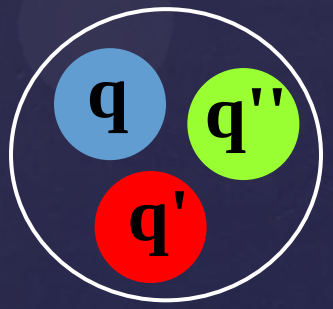

Only colorless combinations allowed

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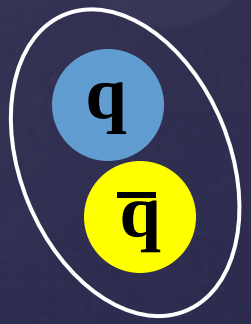

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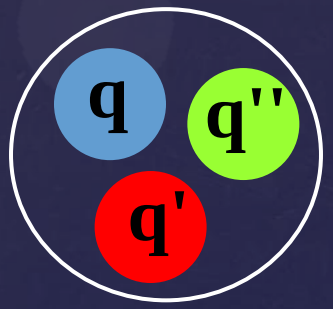


Only colorless combinations allowed

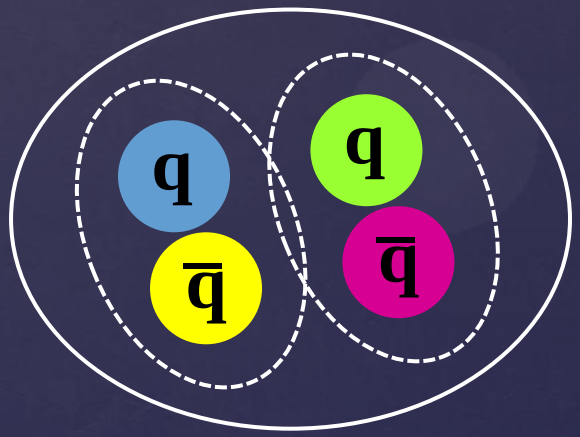
What about other combinations in bound states?

Mesons, Baryons, and Beyond?

No theoretical reason to exclude other types of (colorless) bound quark state

e.g.

Meson molecule



- Loosely bound
- Pion exchange @ large distances
- Some color exchange @ short distances
- Predicted to decay like pair of free mesons

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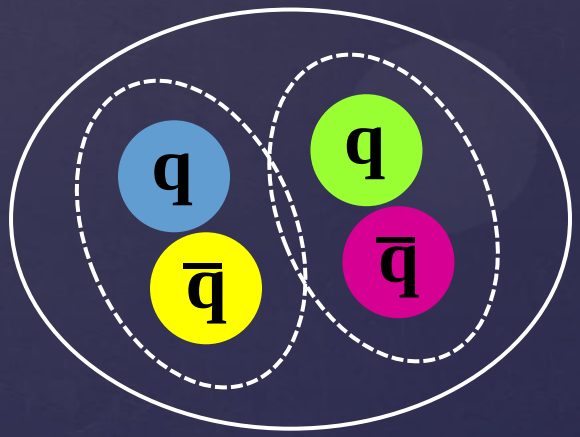
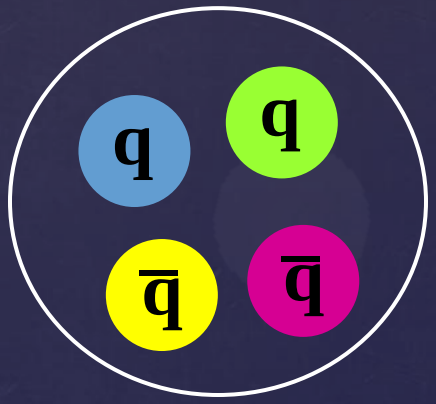


Tetraquark



- Tightly bound
- Some models group into diquark-antidiquark pairs

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e.g.

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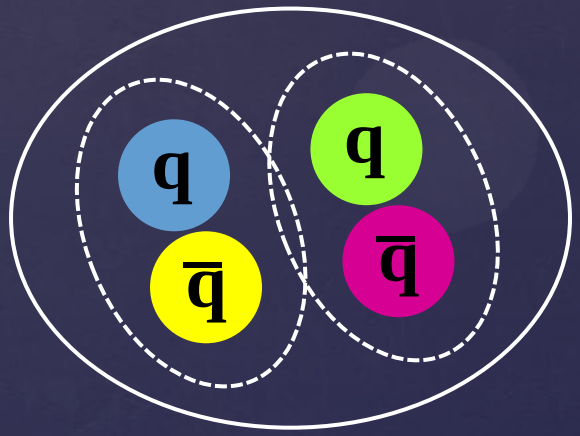

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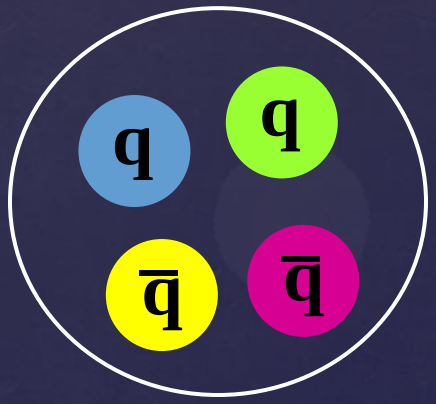
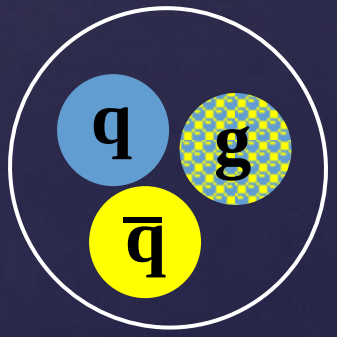


Quark-gluon hybrid



- Extra gluonic degree-of-freedom

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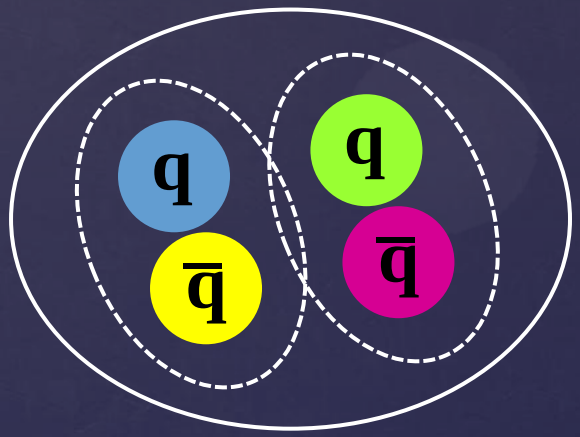

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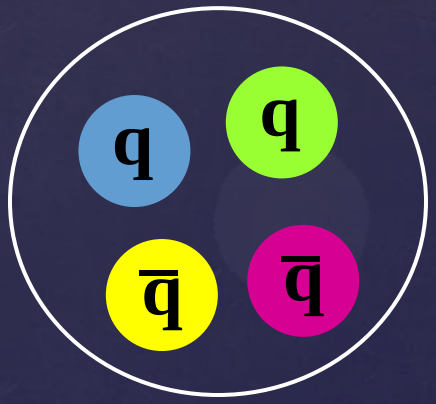

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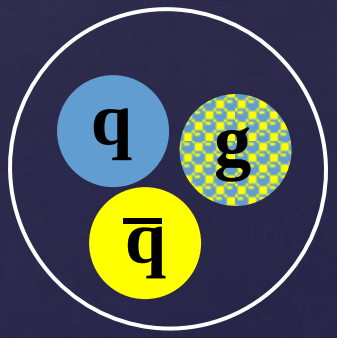

But… until recently, no experimental evidence for any such states

Charmonium

Exotic multi-quark states have been long predicted in the light quark sector

e.g. **$f_0(980)$** and **$a_0(980)$** candidates for $K\bar{K}$ molecules

But… Difficult to differentiate from conventional states – 3 light quarks, isospin symmetry, dense spectrum of predicted mesons.

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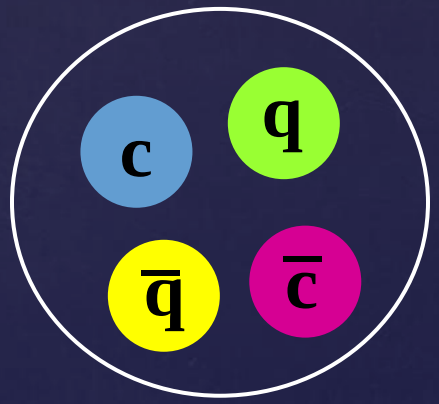
Charmonium ($c\bar{c}$) states have well-predicted conventional spectrum, and distinct properties:

- Zero charge, zero strangeness
- Constrained decay channels
- Easier to differentiate from exotic states



Exotic charmonium states can be charged ($c\bar{c}u\bar{d}$), strange ($c\bar{c}d\bar{s}$) or both ($c\bar{c}u\bar{s}$)

Charmonium

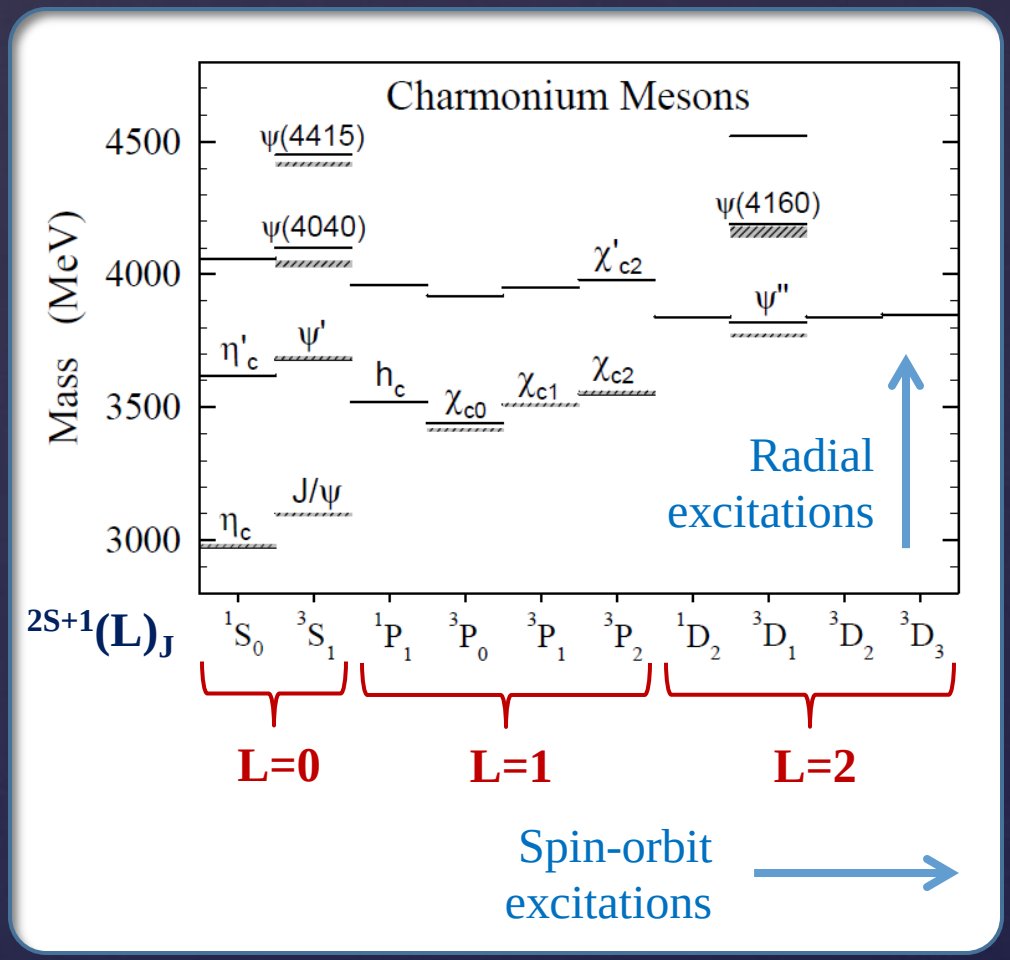
States defined by radial, spin, orbital, and total angular momentum quantum numbers

Spectrum well described by QCD quark-potential models

Later discoveries (η'_c, h_c, χ'_{c2}) agree with predictions

'Open charm' thresholds important for $c\bar{c}$ decays (i.e. DD,DD*,D*D*)

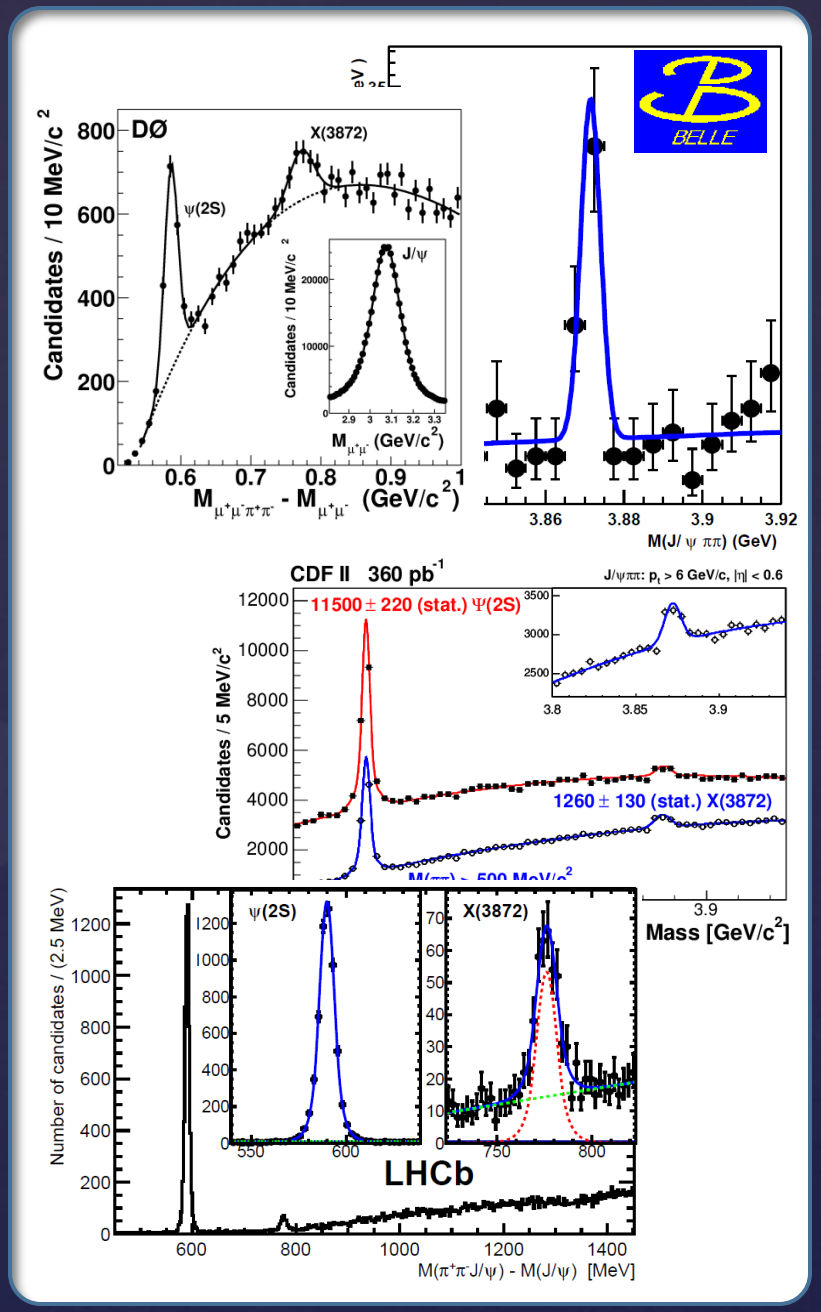
$\Rightarrow$ M(DD) $\approx$ **3770** MeV: charmonium states above this mass decay mainly to DD pairs.



First Hint: X(3872)

X(3872)→J/ψπ⁺π⁻ observed by Belle in 2003 in decays $B^- \to X(3872)K^-$

Confirmed soon after by CDF, D0, BaBar



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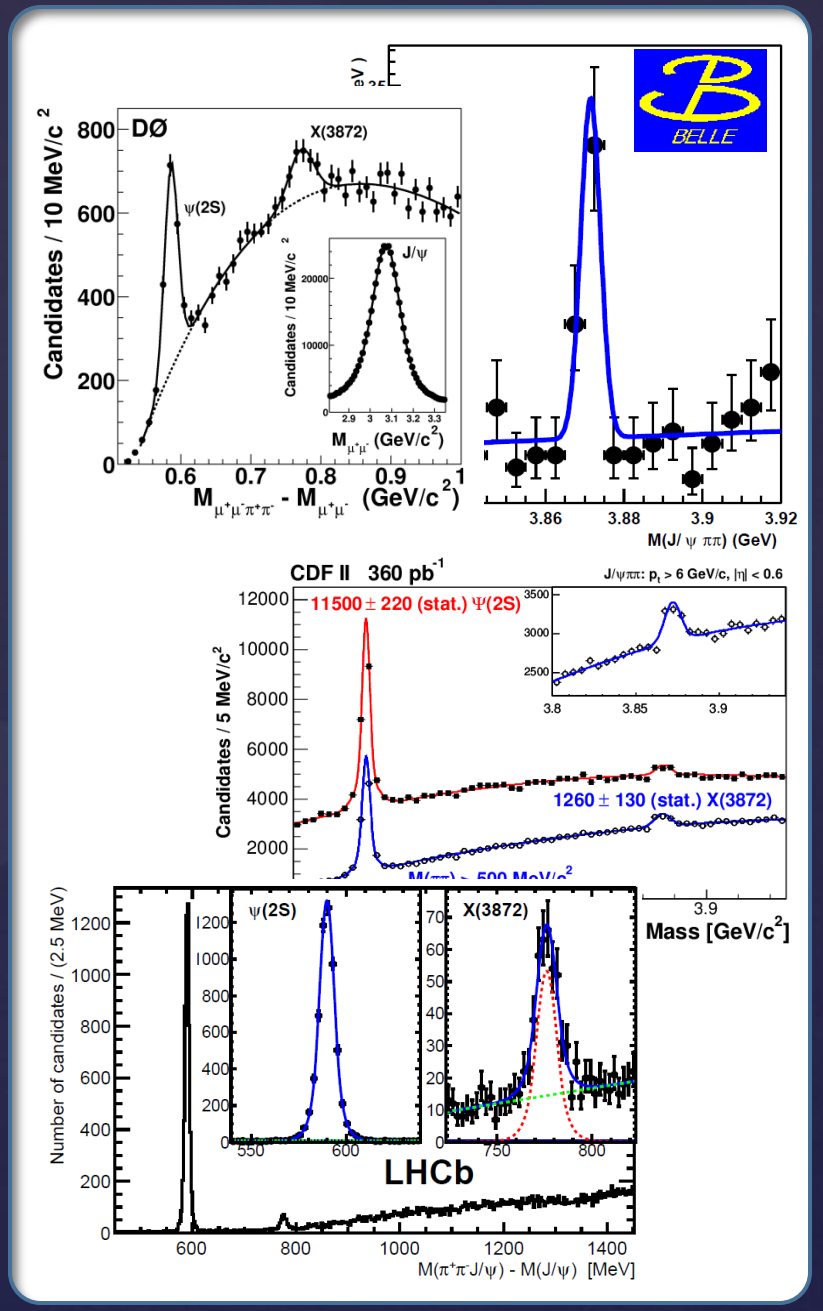
Why can't this be conventional charmonium?

1) Detailed analysis implies dipion is from decay ρ→ππ, but ***$c\bar{c}$→ρJ/ψ violates isospin***

2) Quantum numbers (determined by LHCb, 2013) are $J^{PC} = 1^{++}$, but neither of the corresponding charmonium states should decay to J/ψππ

The X(3872) very close to D^0D^{*0} threshold ⇒ likely explanation is a meson molecule.

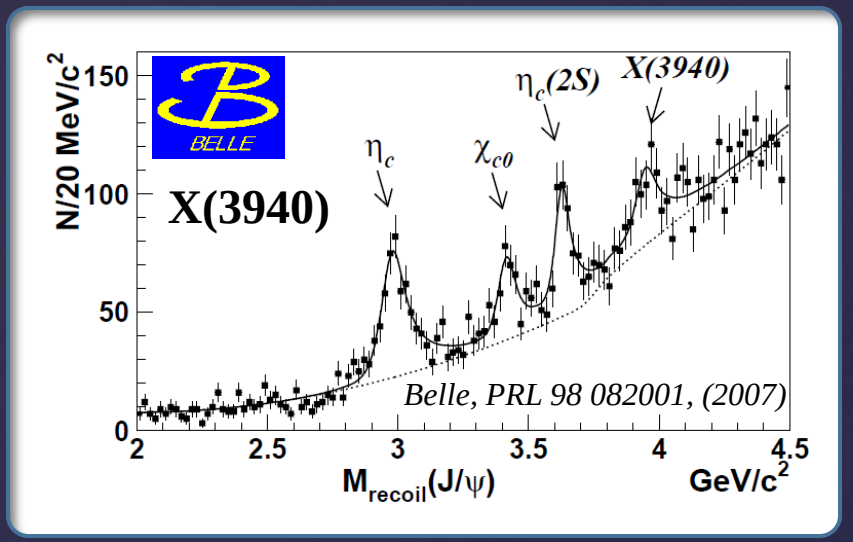
No charged equivalent (D^+D^{*0}) has been observed



More Surprises

After the X(3872) discovery, many unexpected resonances observed, inconsistent with expected charmonium spectrum

Some states subsequently adopted into existing $c\bar{c}$ scheme, others remain a mystery



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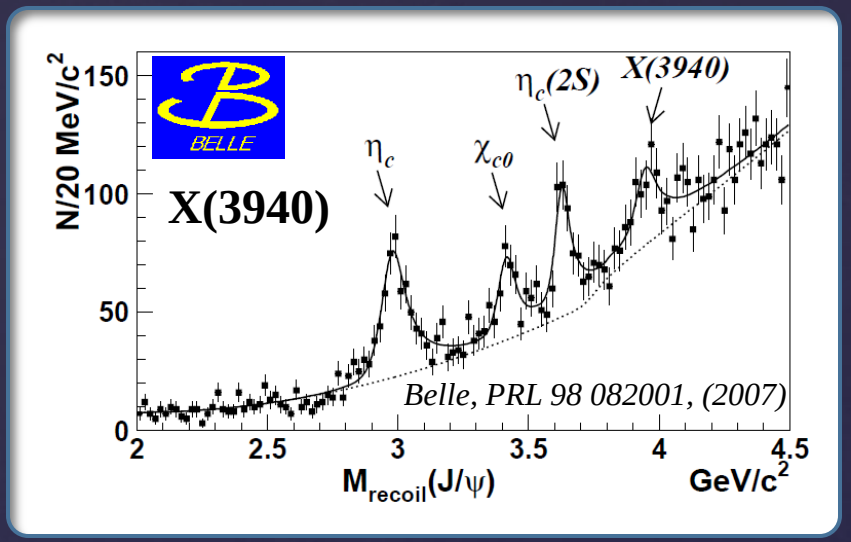

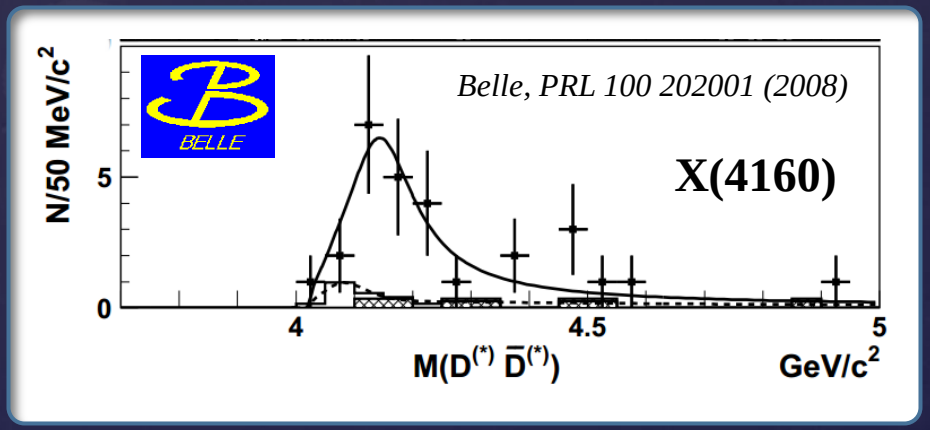

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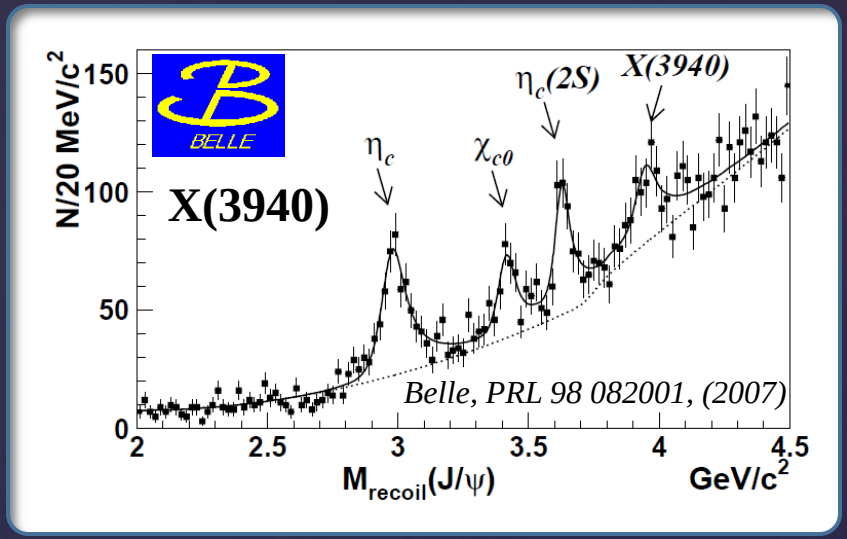

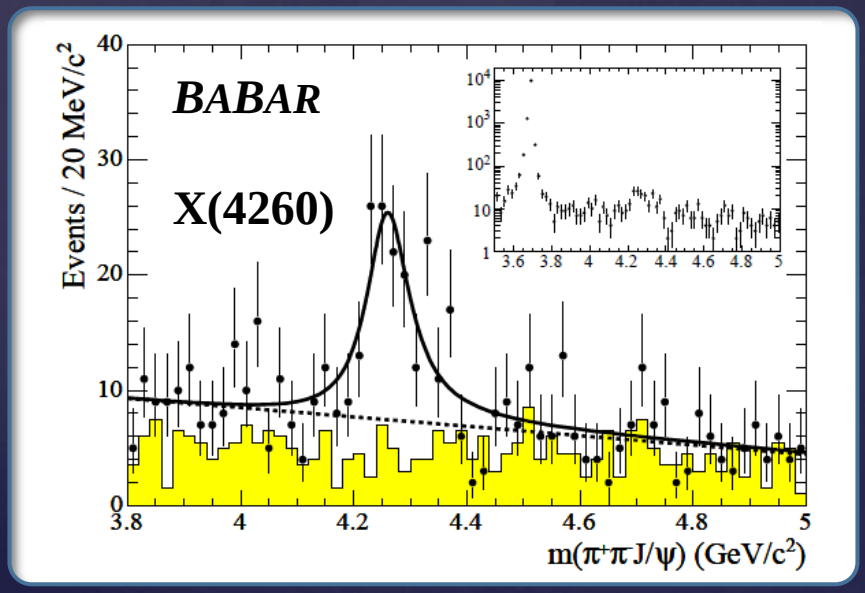

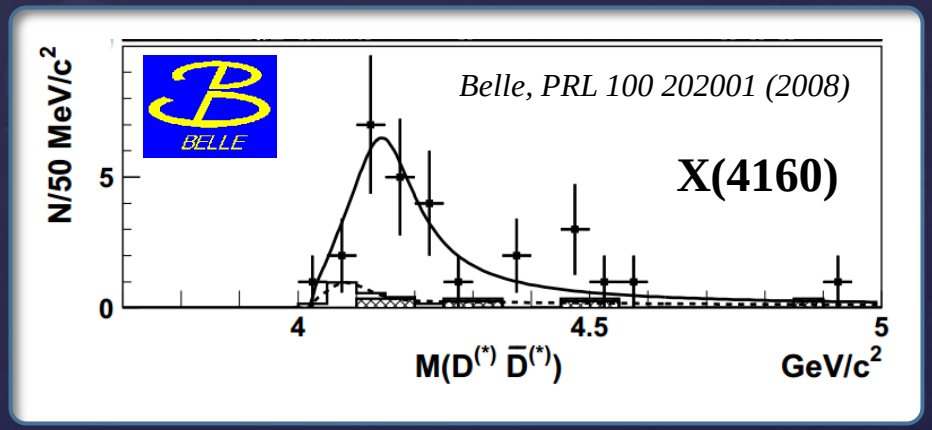

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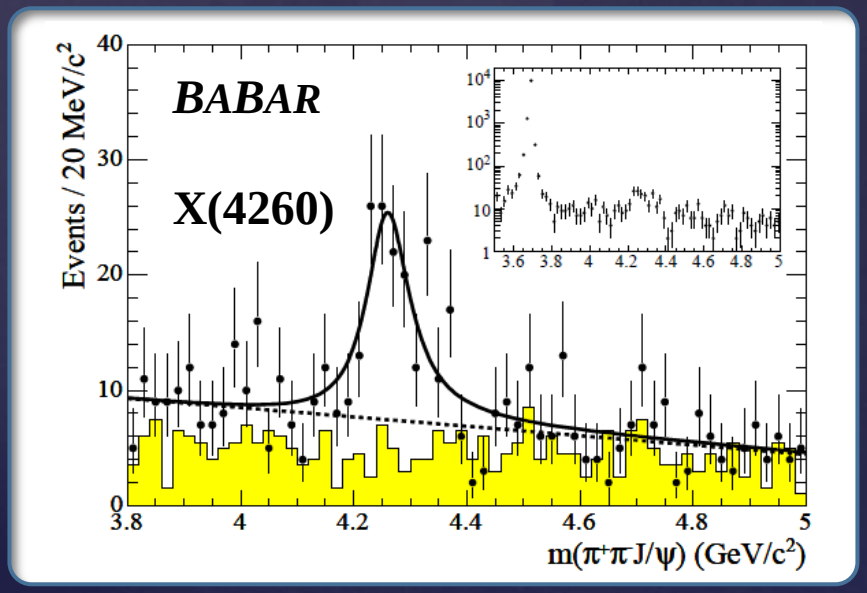

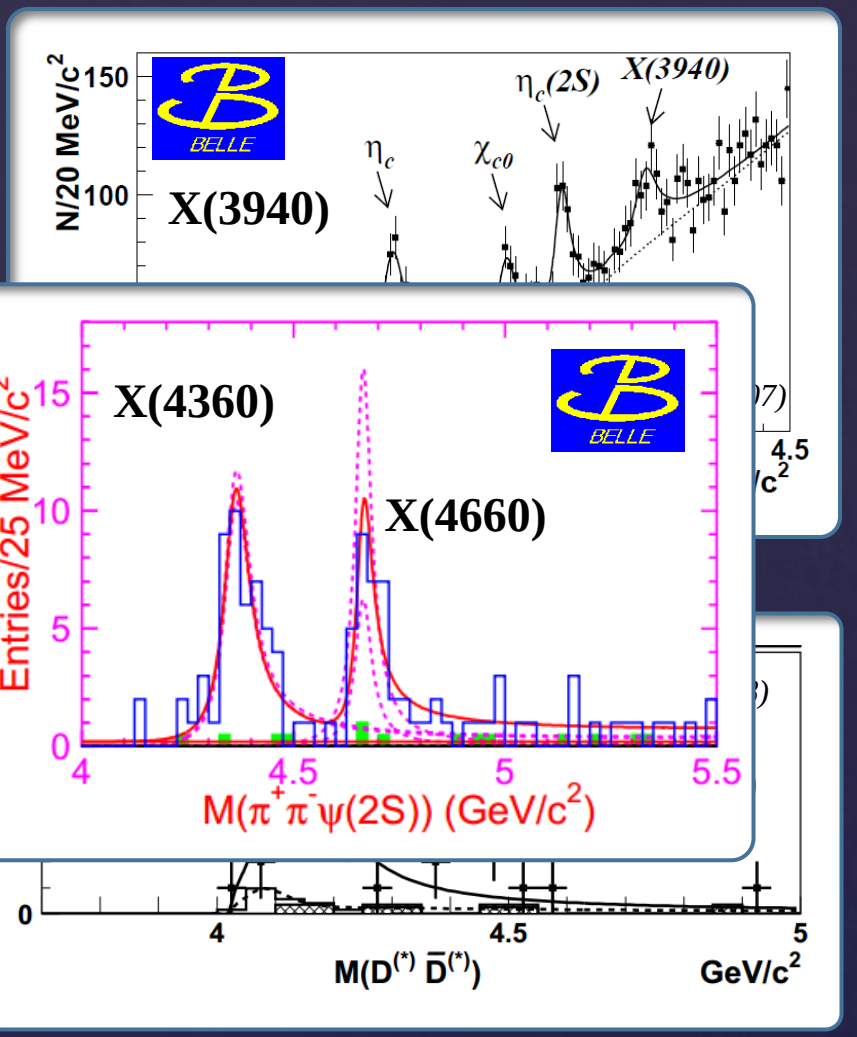

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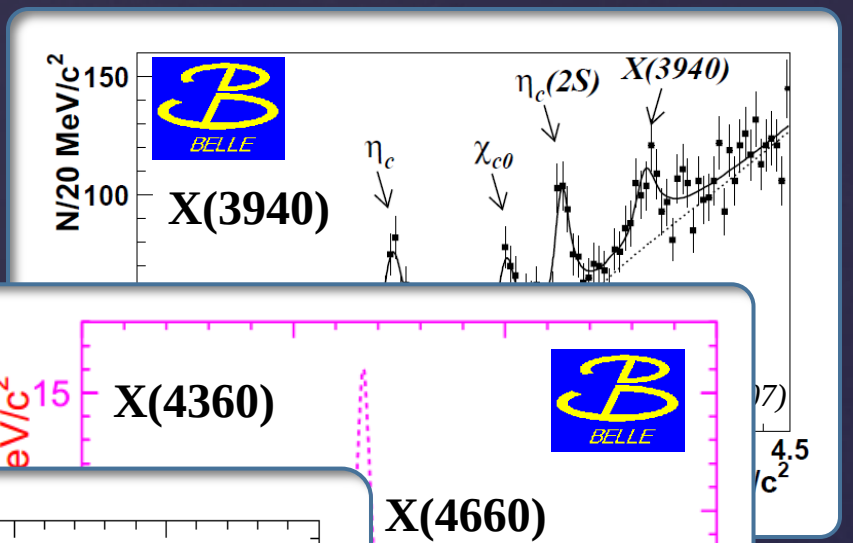

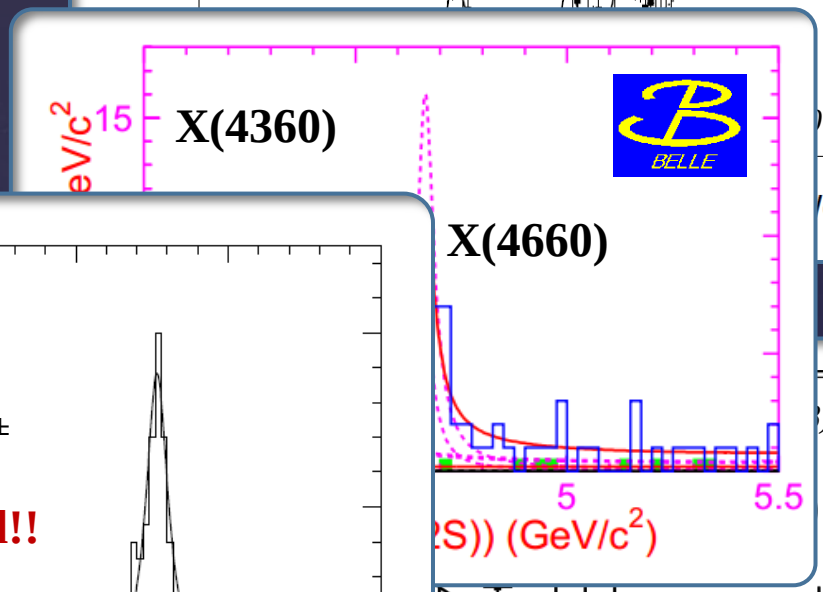

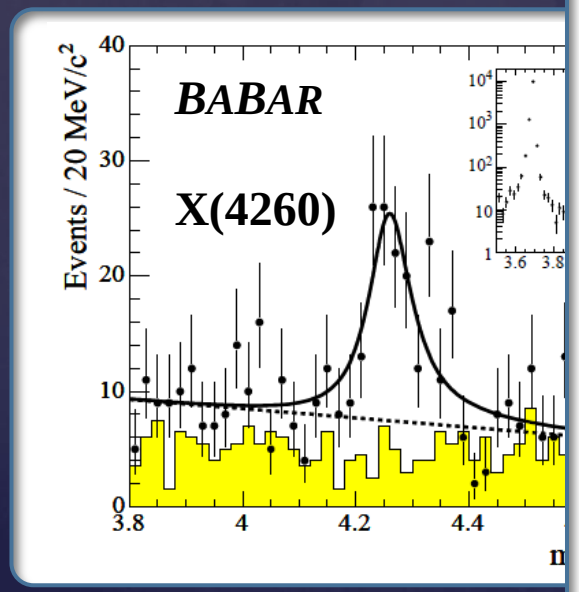

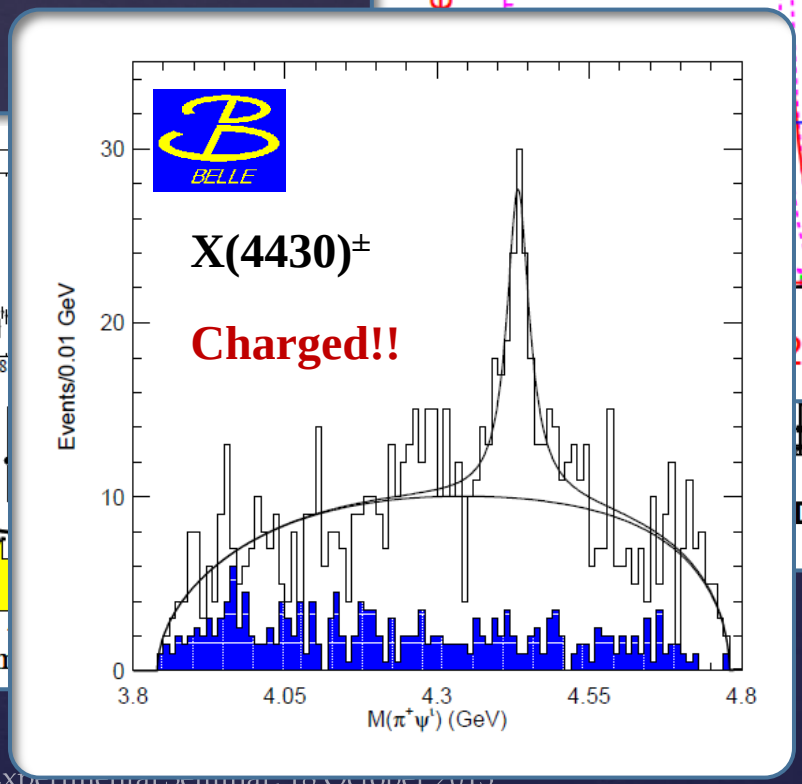

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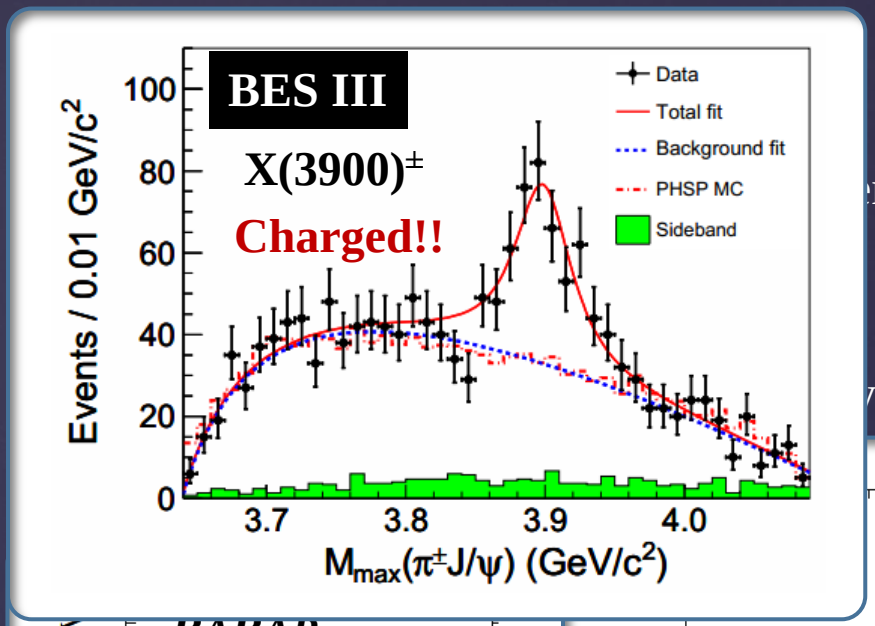

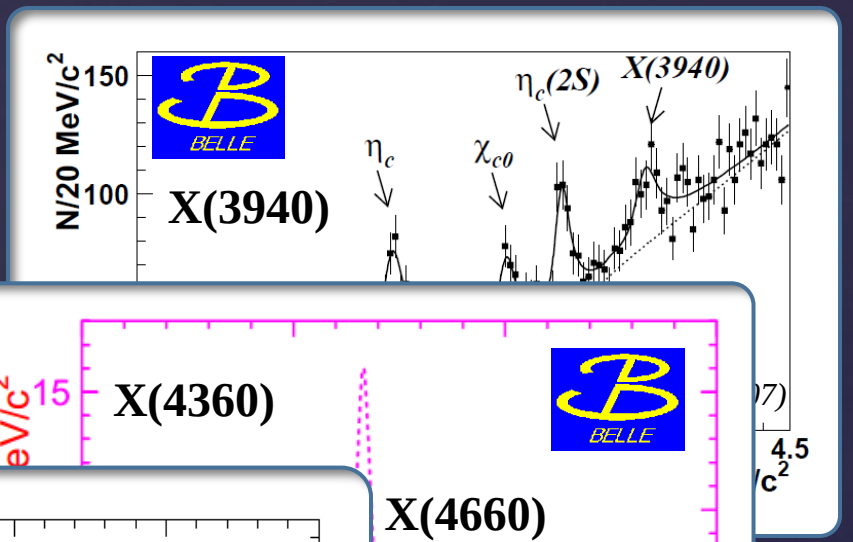

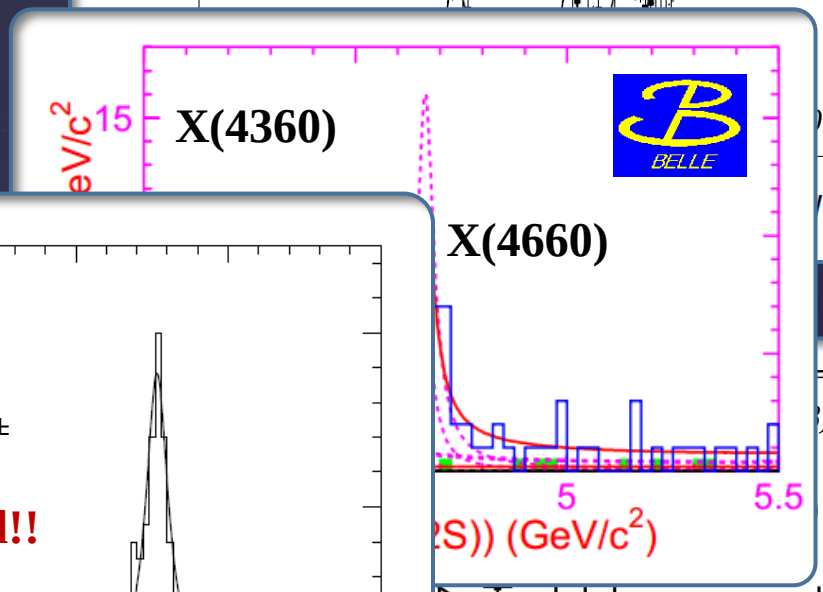

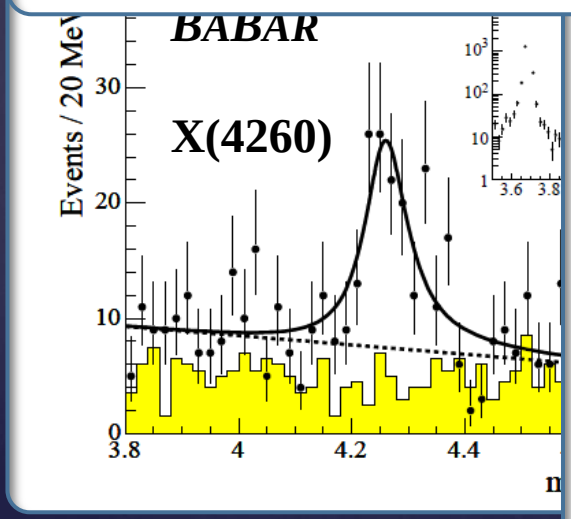

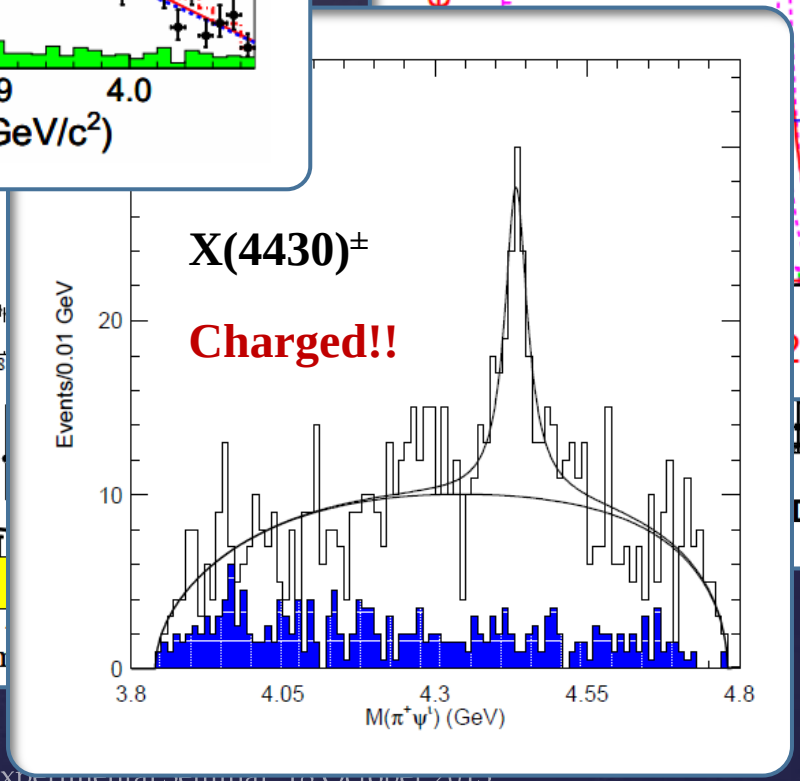

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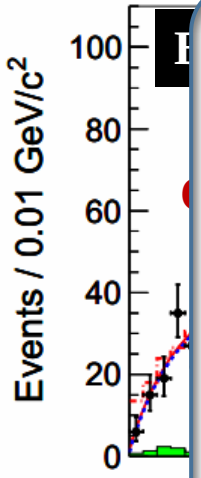

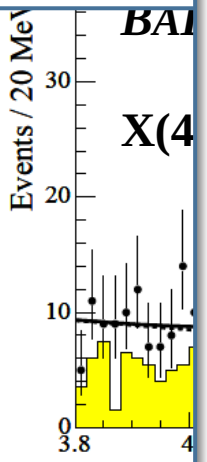

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	$1^{++}/2^{-+}$	$B \to K\,(\pi^+\pi^- J/\psi)$	Belle [36, 37] (12.8), *BABAR* [38] (8.6)	2003	OK
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$	CDF [39–41] (np), DØ [42] (5.2)		
				$B \to K\,(\omega J/\psi)$	Belle [43] (4.3), *BABAR* [23] (4.0)		
				$B \to K\,(D^{*0}\bar{D}^0)$	Belle [44, 45] (6.4), *BABAR* [46] (4.9)		
				$B \to K\,(\gamma J/\psi)$	Belle [47] (4.0), *BABAR* [48, 49] (3.6)		
				$B \to K\,(\gamma\psi(2S))$	*BABAR* [49] (3.5), Belle [47] (0.4)		
				$pp \to (\pi^+\pi^- J/\psi) + \ldots$	LHCb [50] (np)		
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	$0/2^{?+}$	$B \to K\,(\omega J/\psi)$	Belle [51] (8.1), *BABAR* [52] (19)	2004	OK
				$e^+e^- \to e^+e^-\,(\omega J/\psi)$	Belle [53] (7.7), *BABAR* [23] (np)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [54] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\,(\ldots)$	Belle [20] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma\,(D\bar{D})$	*BABAR* [55] (np), Belle [56] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [57] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K\,(\pi^+\chi_{c1}(1P))$	Belle [58] (5.0), *BABAR* [59] (1.1)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K\,(\phi J/\psi)$	CDF [60, 61] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [54] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K\,(\pi^+\chi_{c1}(1P))$	Belle [58] (5.0), *BABAR* [59] (2.0)	2008	NC!
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^- J/\psi)$	*BABAR* [62, 63] (8.0)	2005	OK
					CLEO [64] (5.4), Belle [57] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [65] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [65] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K\,(\phi J/\psi)$	CDF [61] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(\phi J/\psi)$	Belle [66] (3.2)	2009	NC!
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-\psi(2S))$	*BABAR* [67] (np), Belle [68] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K\,(\pi^+\psi(2S))$	Belle [69, 70] (6.4), *BABAR* [71] (2.4)	2007	NC!
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [72] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-\psi(2S))$	Belle [68] (5.8)	2007	NC!

arXiv:1205.4189 (June 2012)

Current Status

Proliferation of ‘charmonium-like’ resonances presents challenges

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- *Too many states for charmonium spectrum, & disagreement with predicted masses, widths, decay rates*
- *Can be threshold effects, interference (of known and as-yet-unknown states), experimental effects (reflections, acceptance effects…)*
- *Some states in experimental limbo – seen by some, not by others*

Current Status

Proliferation of 'charmonium-like' resonances presents challenges

- *Too many states for charmonium spectrum, & disagreement with predicted masses, widths, decay rates*
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Even the X(3872) is not understood, ten years after discovery, with quantum numbers confirmed, and with many thousand events seen by multiple experiments

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$\Rightarrow$ **We need more data!**

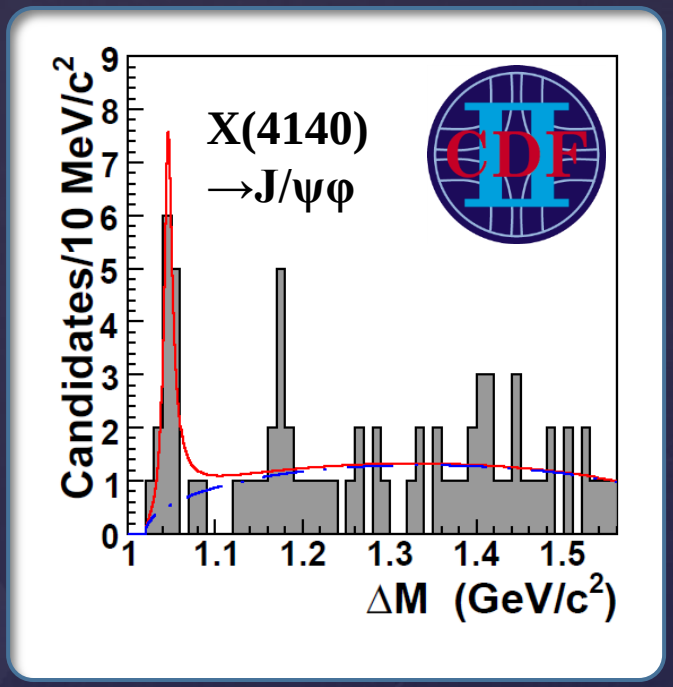
Observe zoo of mesons/baryons $\rightarrow$ Gell-Mann/Zweig develop CQM

Observe, confirm, and study as many exotic states as possible $\rightarrow$ develop more complete model of bound quark states.

X(4140)

June 2009: CDF report evidence for narrow peak in **J/ψφ** spectrum, close to threshold, in decays **$B^+ \to J/\psi\phi K^+$**

PRL 102 242002 (2009)



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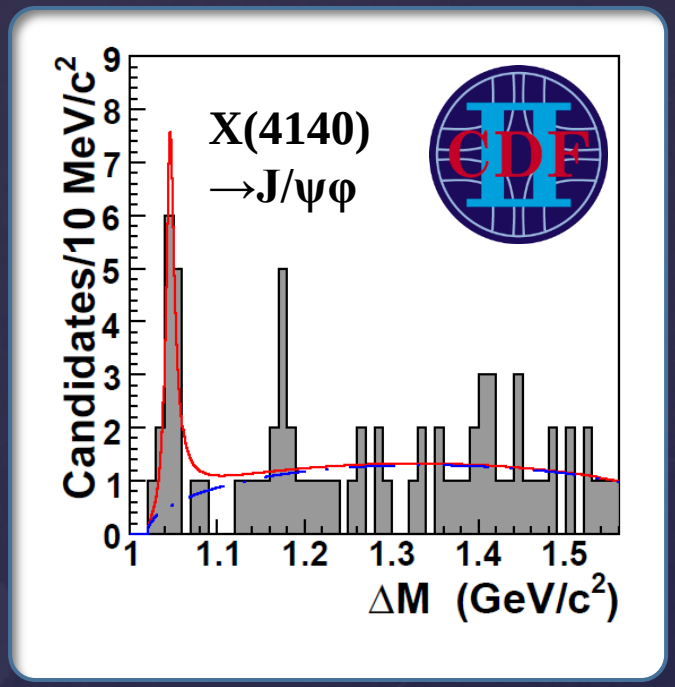
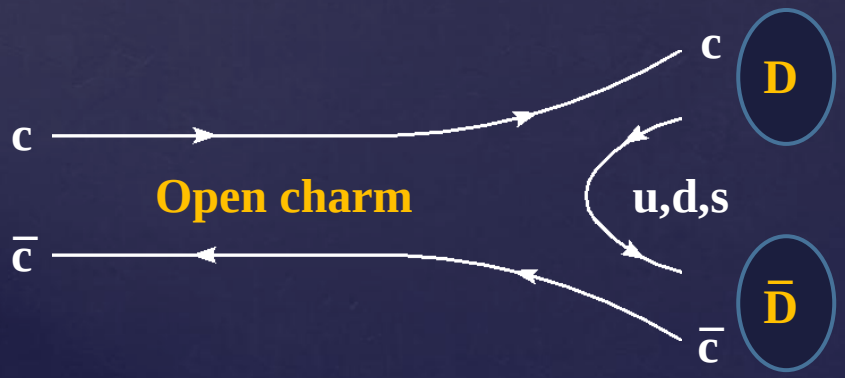
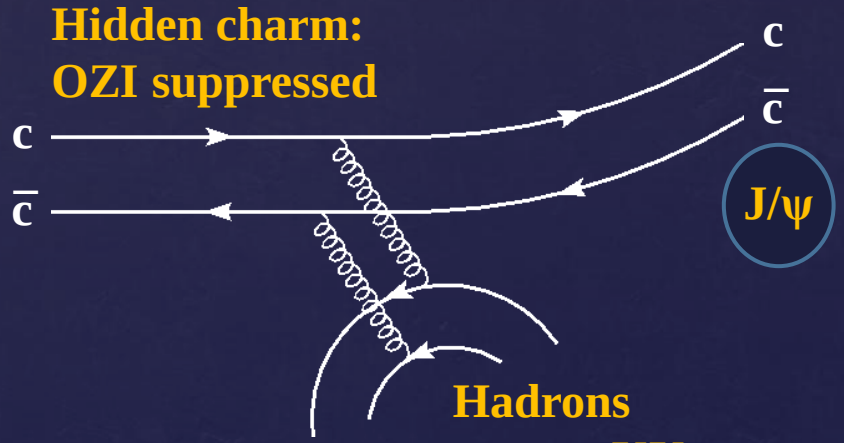


Interpretation:

Mass well above 3770 MeV open charm threshold – conventional charmonium should decay into (DD), with tiny BR to J/ψφ





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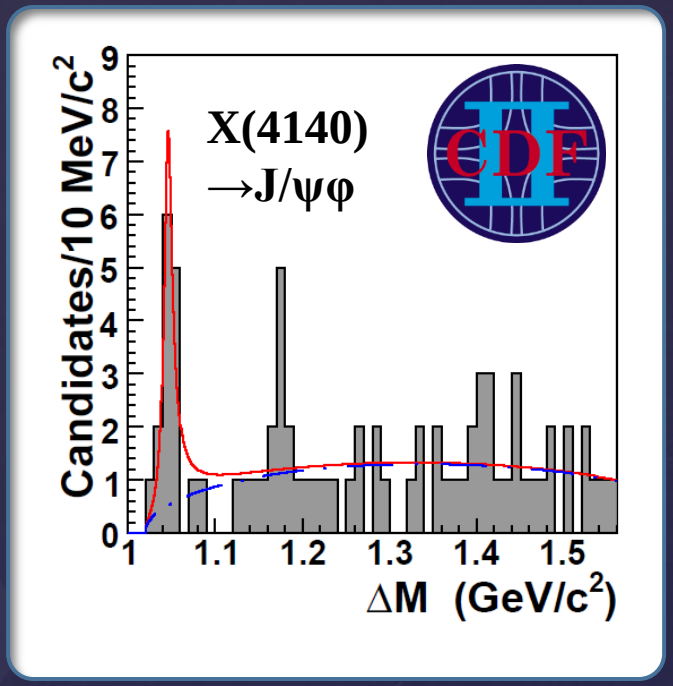

Interpretation:

X(4140) → J/ψφ ⇒ C-parity = +1

⇒ Possible states: 0^{++} 1^{++} 2^{++} 0^{-+} 1^{-+} 2^{-+} 3^{-+}

S-wave coupling P-wave coupling

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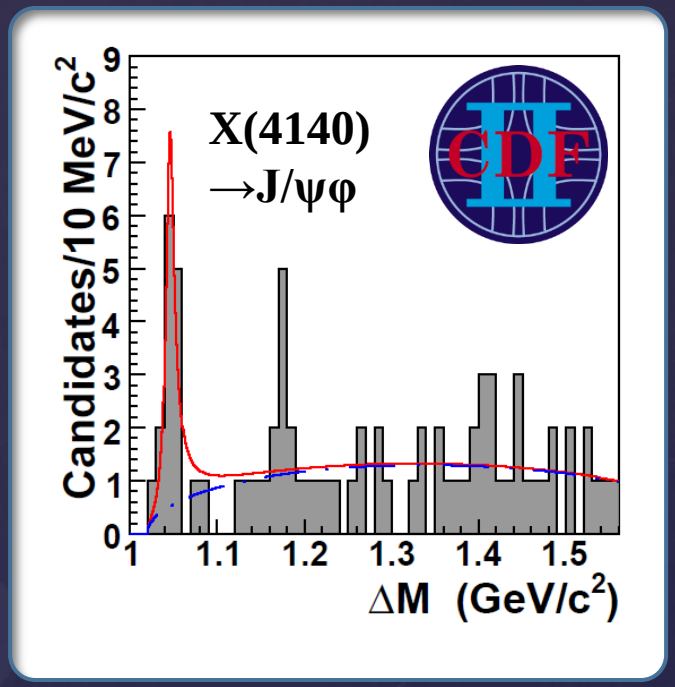
Set limit on production rate, but cannot exclude CDF peak

Lepton-photon 2009 (e.g. arXiv:0910.3138)



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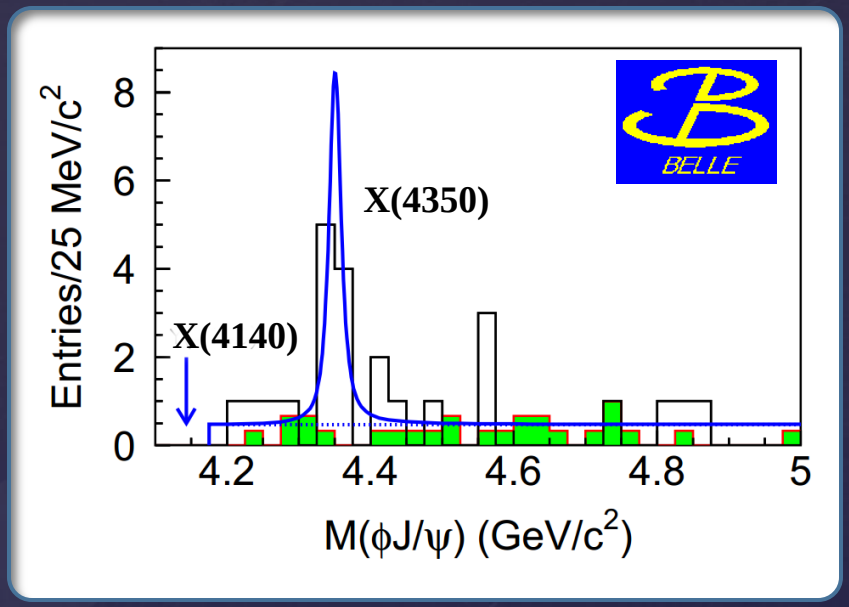
No X(4140) signal – disfavors $D_s^* D_s^*$ meson molecule interpretation

But… see 3.2σ excess at 4350 MeV

PRL 104 112004 (2010)



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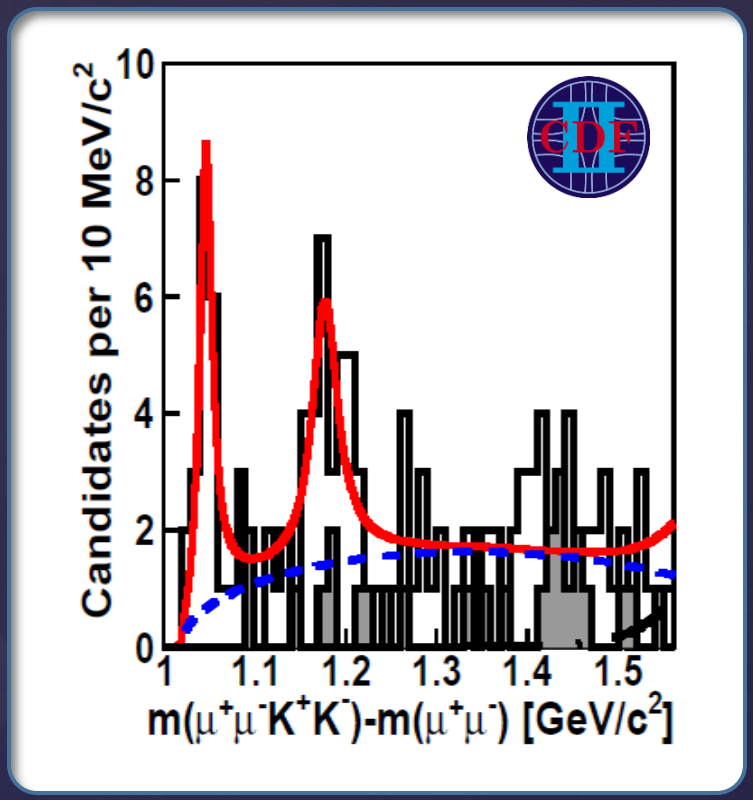
January 2011: CDF update analysis with larger dataset: **observe X(4140) with 5σ significance**

arXiv:1101.6058



CDF also see 3σ evidence for higher mass peak, but inconsistent with Belle mass

X(4140)

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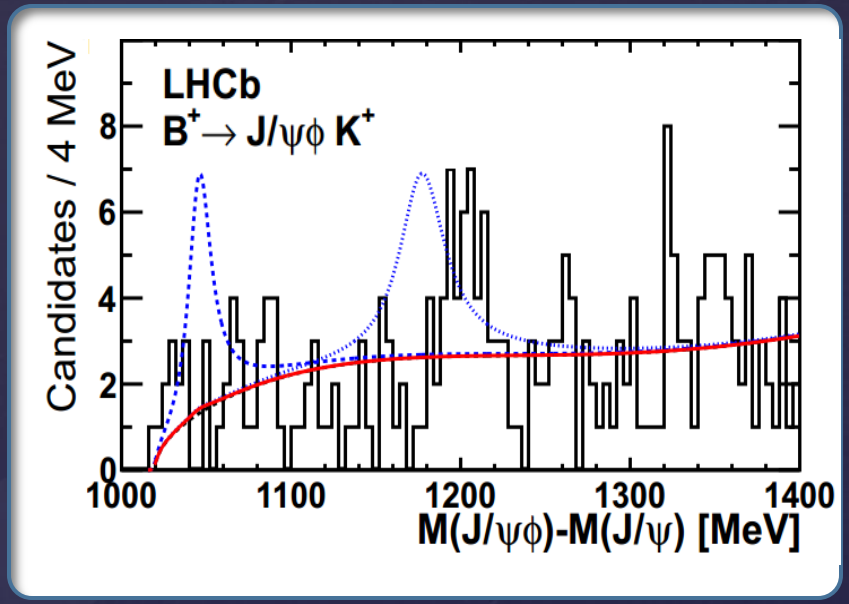

February 2012: LHCb search in $\mathbf{B^+ \to J/\psi\phi K^+}$ channel, see no X(4140) peak, **set limit at 2.4σ tension with CDF**.

PRD 85 091103(R) (2012)

X(4140)

Is X(4140) real?

If so, what is it?

Multiple interpretations (conventional $c\bar{c}$, DD molecule, $c\bar{c}q\bar{q}$ tetraquark, hybrid state, threshold effect…), none convincing yet.

Need additional data to resolve the X(4140) puzzle

Today: Search results from D0 and CMS