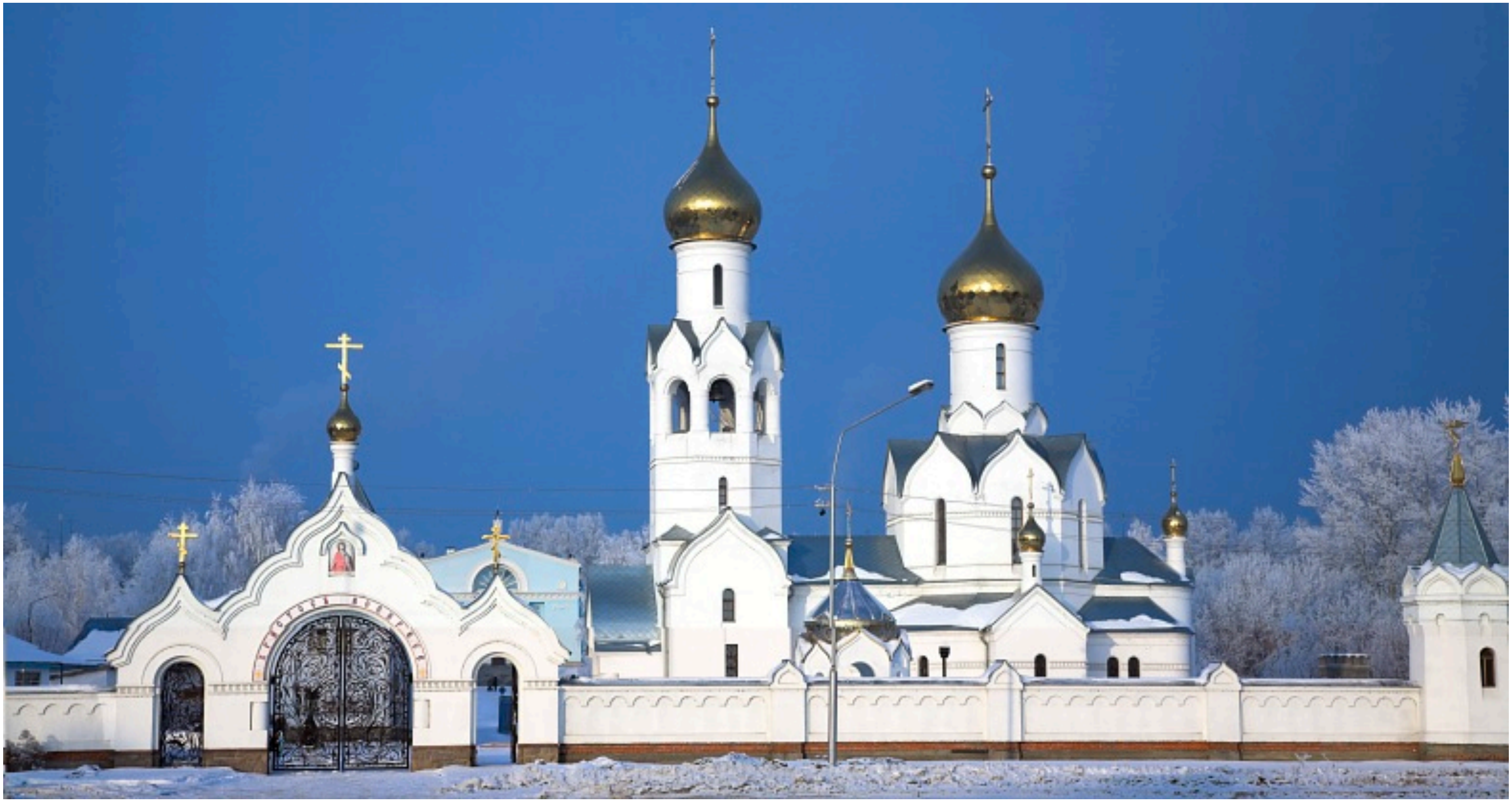
Charm & exotic hadrons from B factories



Stephen Lars Olsen UCAS

中国科学院大学
University of Chinese Academy of Sciences

Charm2018 BINP, Novosibirsk, RUSSIA, May 21-25,2018

~~Charm~~ & exotic hadrons from B factories

Xiaolong WANG's talk
(tomorrow)

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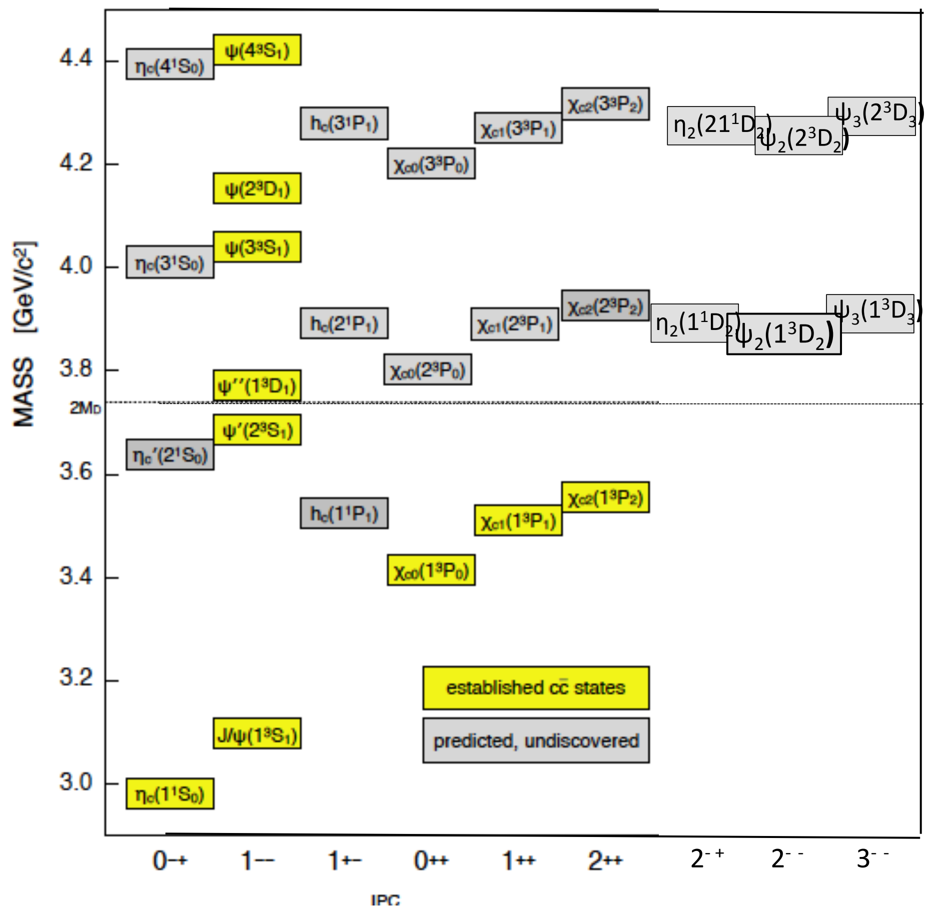
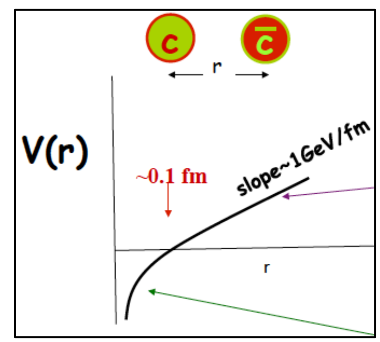
charmonium: pre B-factory



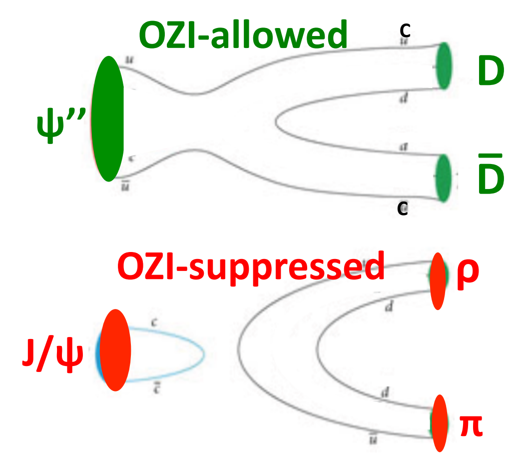
forty-plus years of work

potential model works well

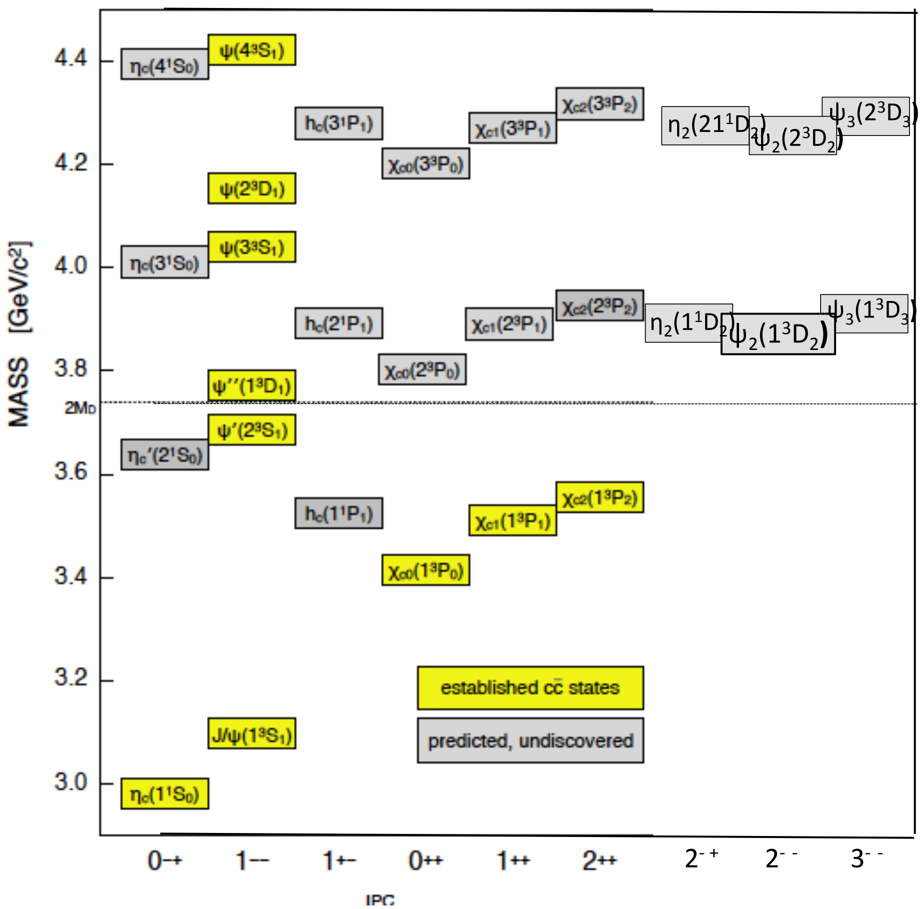


measured &
predicted masses agree

OZI-rule applies
no exceptions

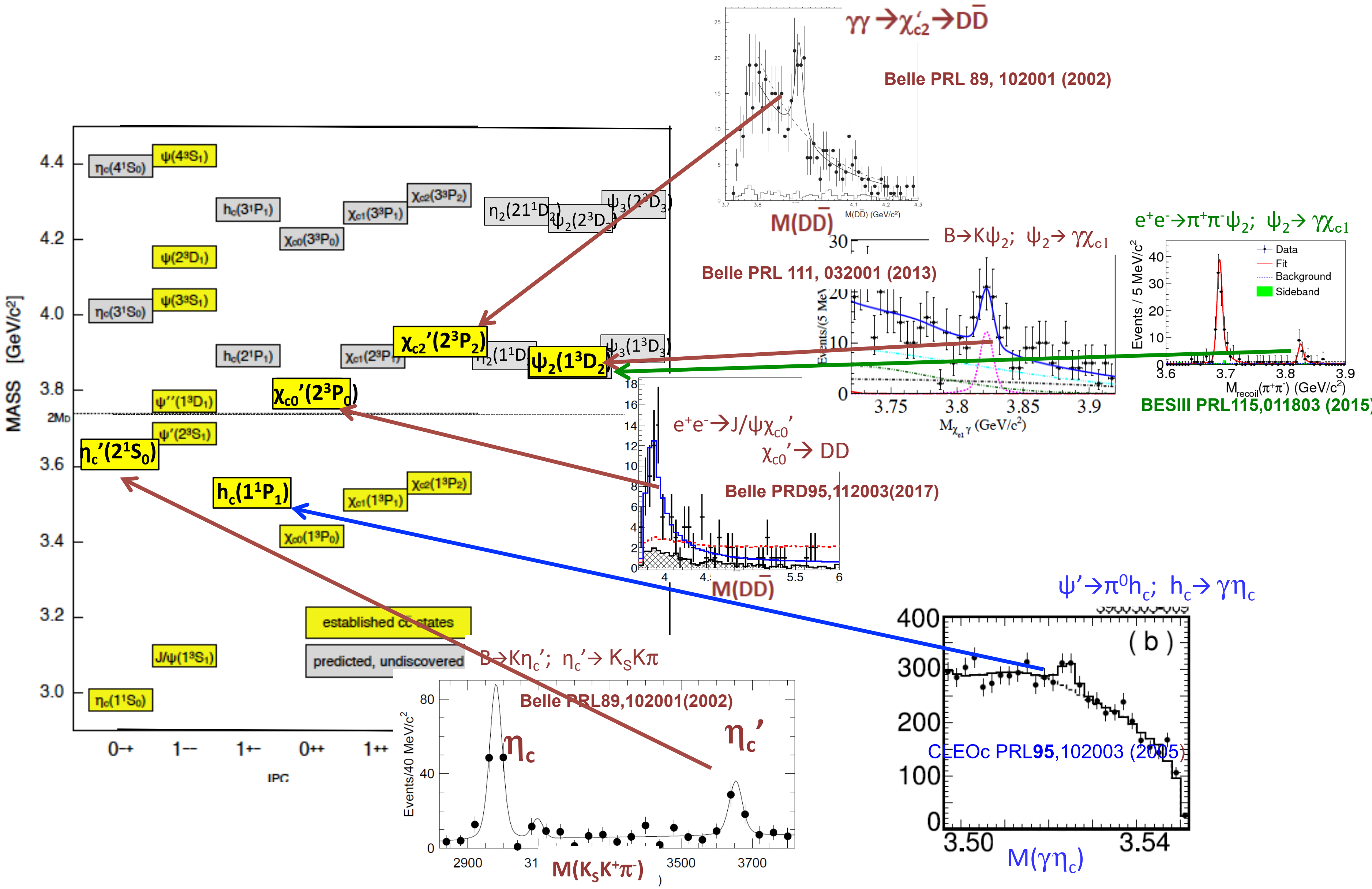


charmonium: pre B-factory plans for the B-factory era

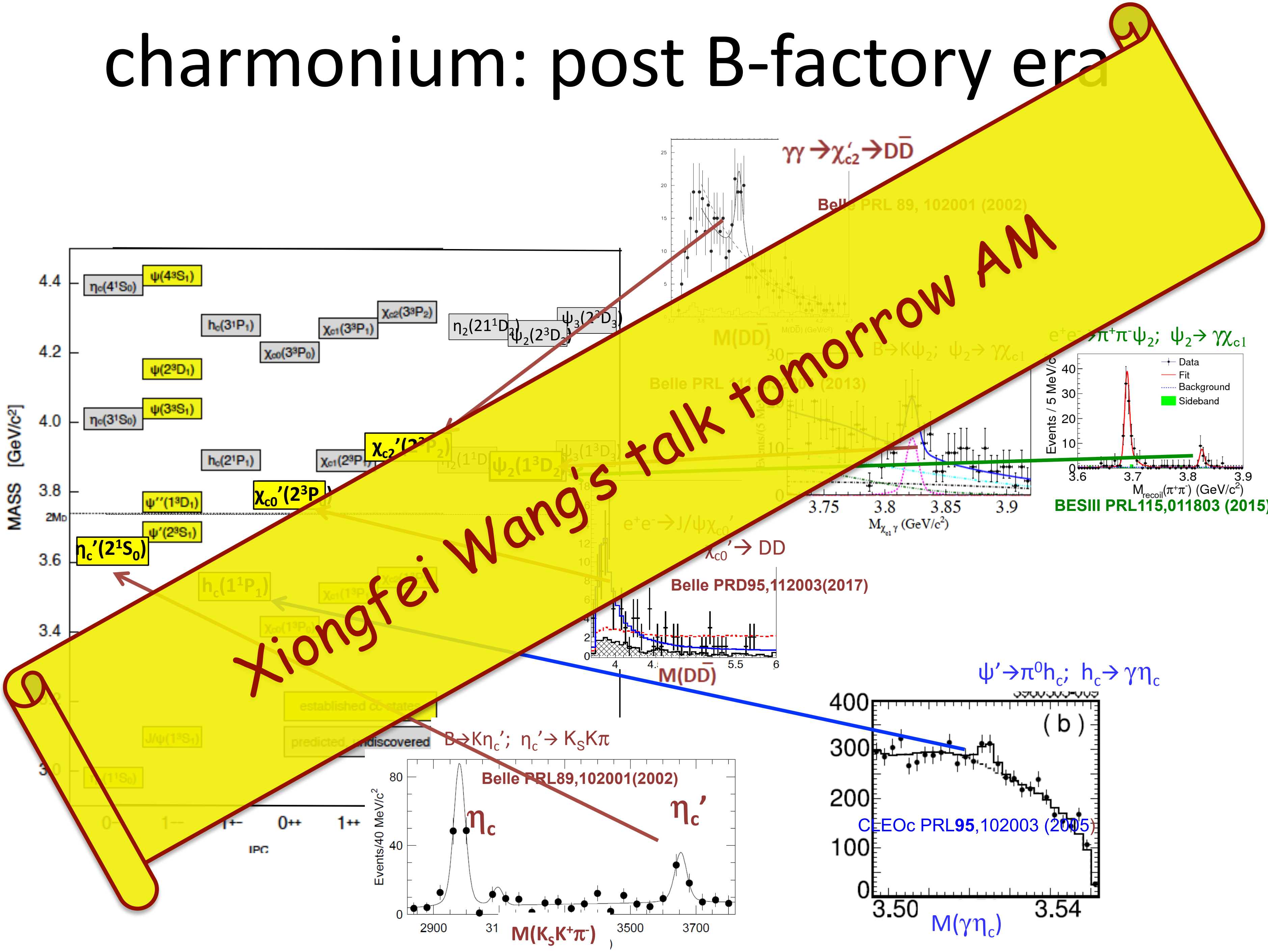


Turn the grey boxes into yellow ones

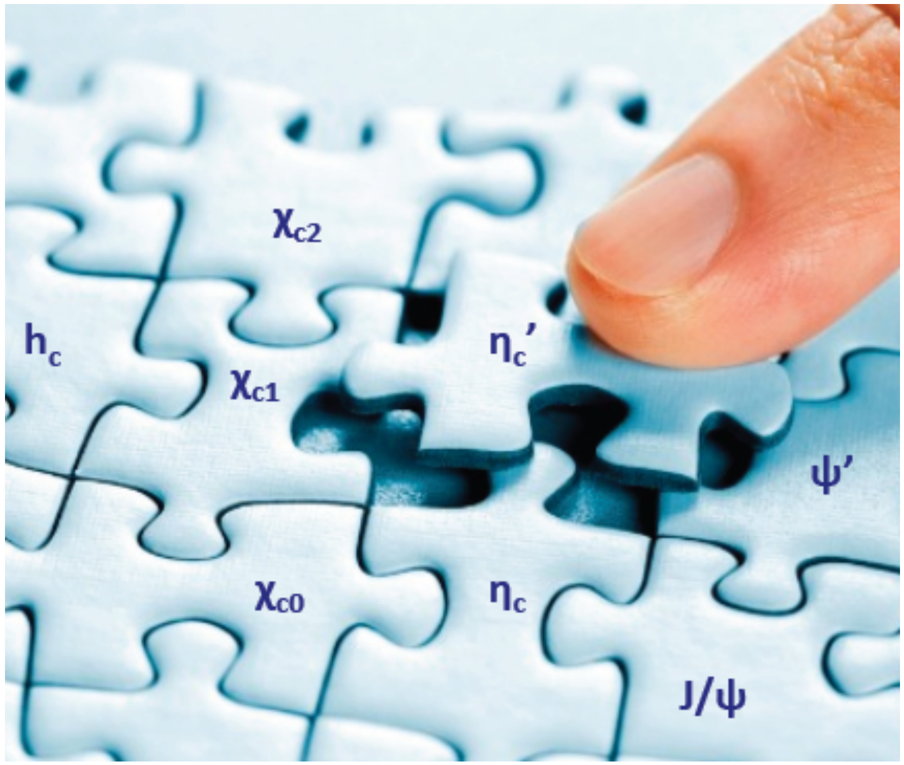
charmonium: post B-factory era



charmonium: post B-factory era

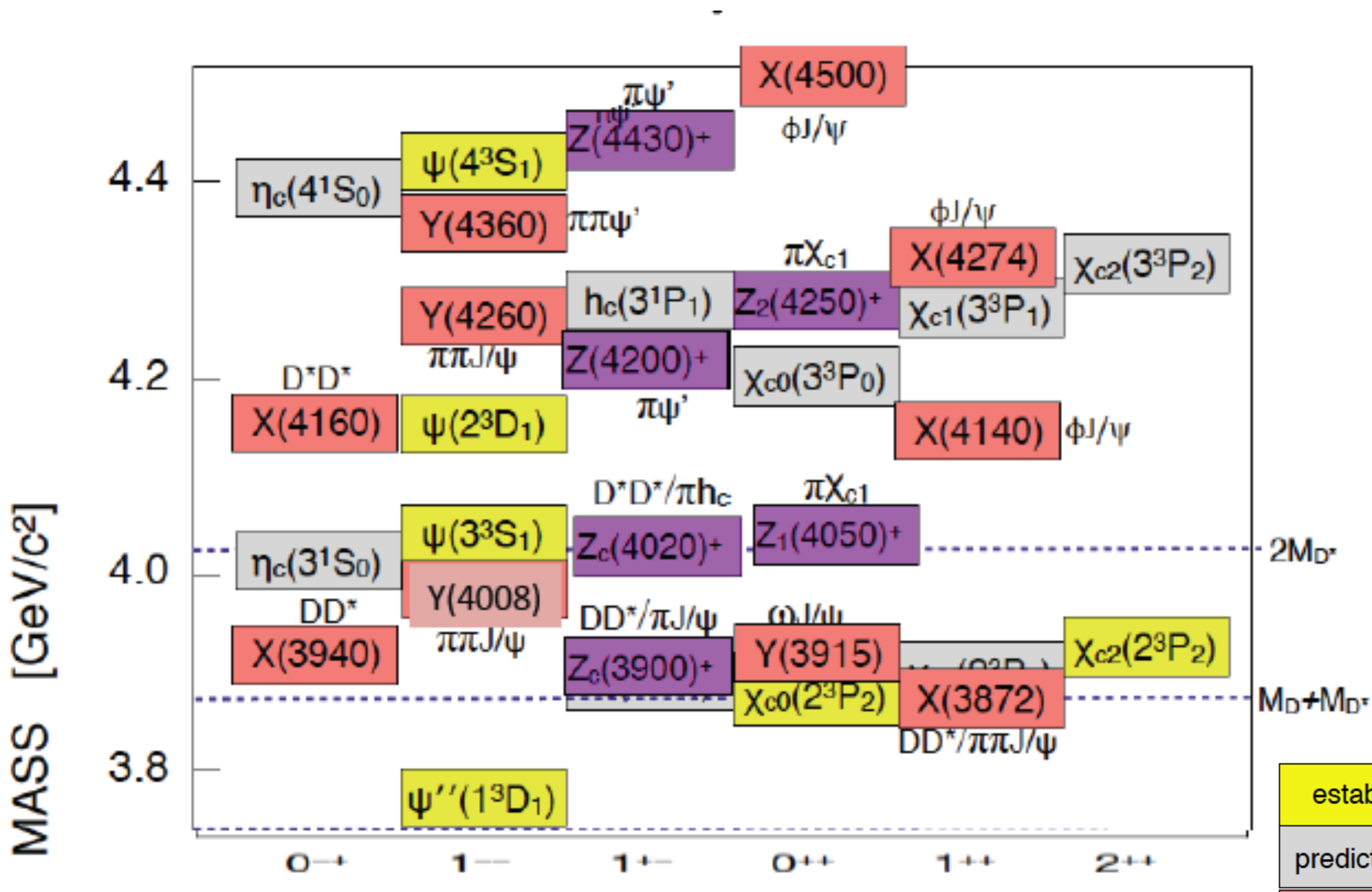


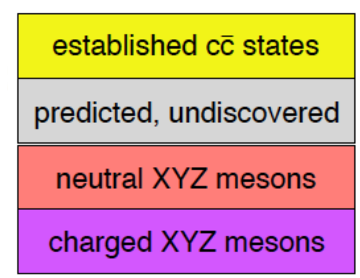
correct assignments "snap" into place



if you have to push hard, be careful …

not so simple …





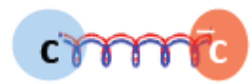
>15 charmonium-like states found that ***do not*** fit into any of the unassigned charmonium levels

what are they?

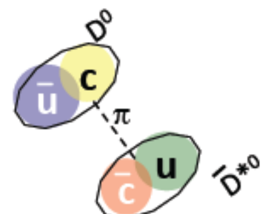
17:00	[75] XYZ states as compact tetraquarks	Prof. POLOSA, Antonio Davide
15:55	[6] Lattice Predictions for Bound Heavy Tetraquarks	Dr. FRANCIS, Anthony
09:00	[61] Charmonium and exotics from lattice QCD	Prof. KNECHTLI, Francesco
09:30	[80] Heavy hybrids and tetraquarks in EFT	Dr. TARRUS CASTELLA, Jaume

18:20	[25] XYZ states as hadronic molecules	Dr. NEFEDIEV, Alexey

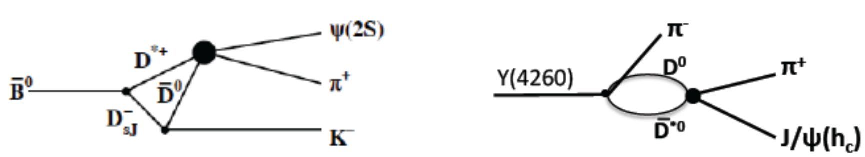
QCD tetraquarks?



QCD hybrids?



molecules?



threshold dynamics?

what are they?

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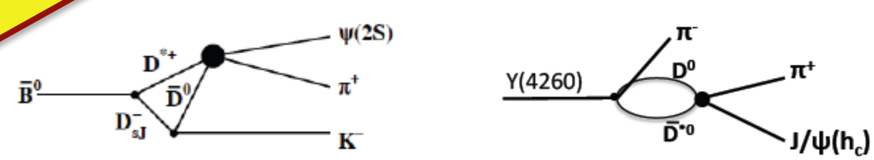
These puzzles has been around for 16 years and we still don't know what they are



threshold dynamics?

History

70 years ago

K-mesons discovered -- *associated production – strangeness – SU(3)* -- **quark model**

Dec. 1947 ← **16 years** → Jan 1964

History

70 years ago

K-mesons discovered *-- associated production – strangeness – SU(3) --* **quark model**

Dec. 1947 ← **16 years** → Jan 1964

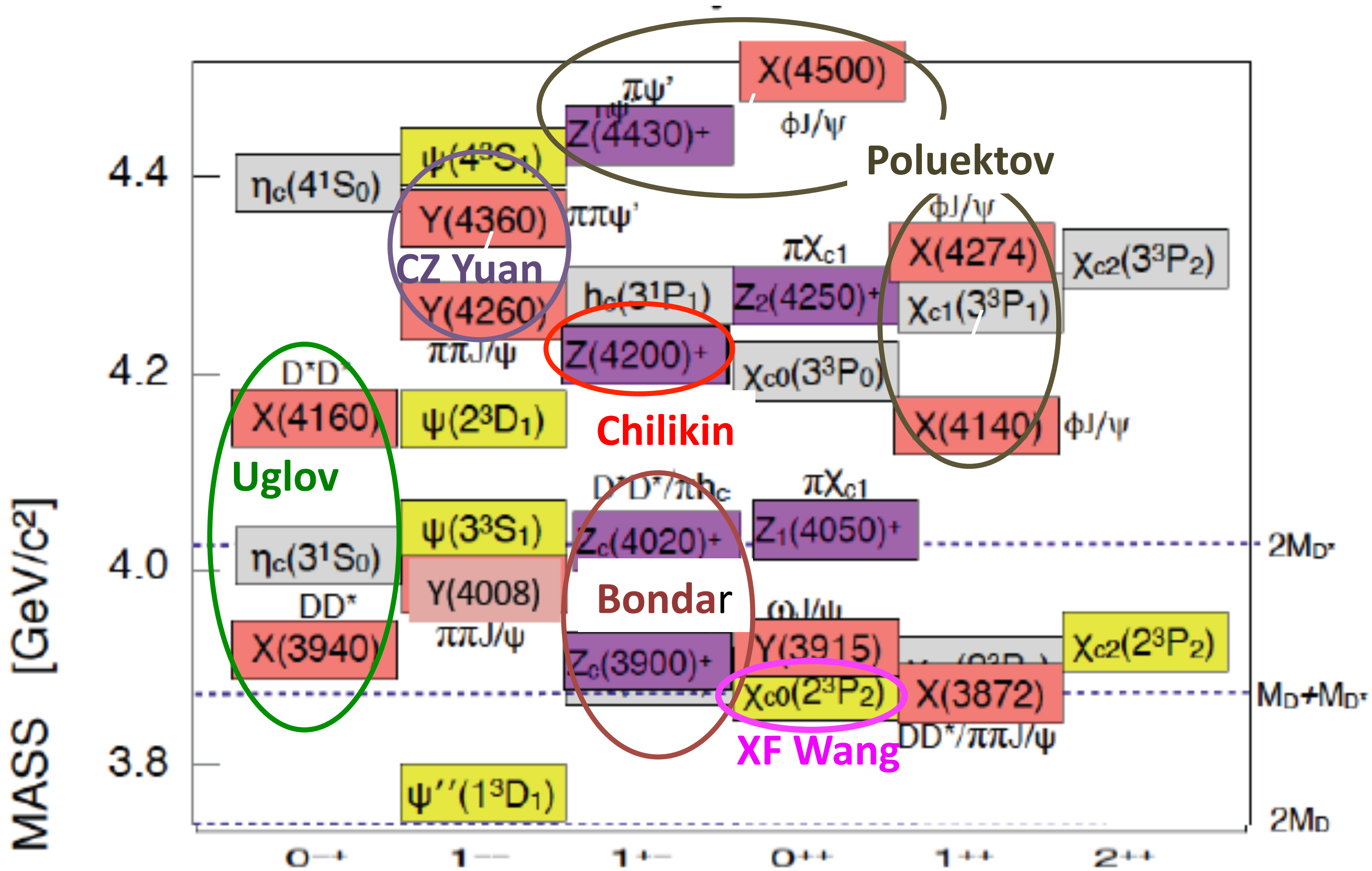
16 years ago

X(3872) discovered *-- molecule? – diquark? – molecule? – diquark? --*
– diquark? – molecule? – diquark? -- molecule? -- **????**

Aug. 2003 ← **16 years** → today

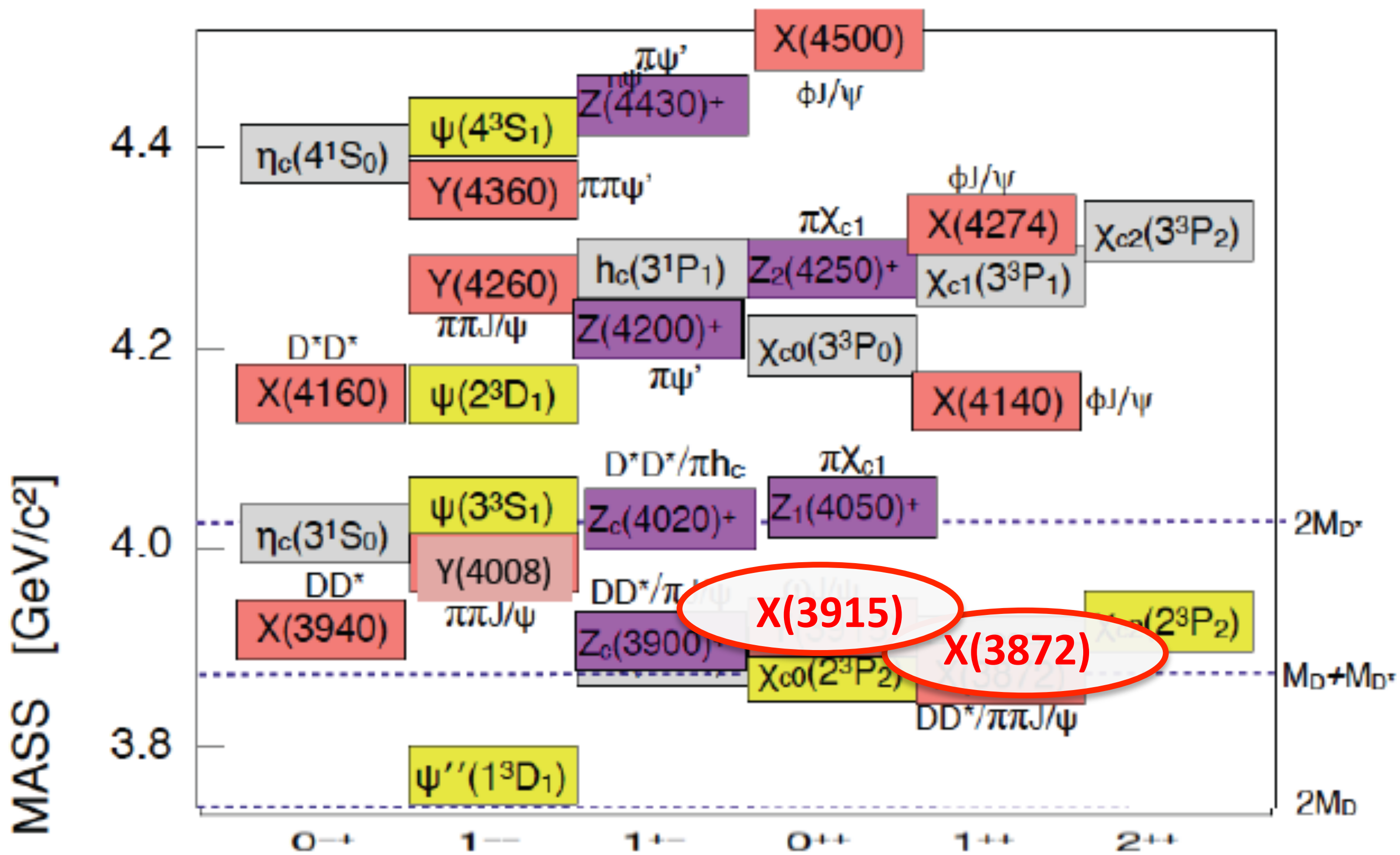
Charm 2018 talks

-- my guesses of the content --

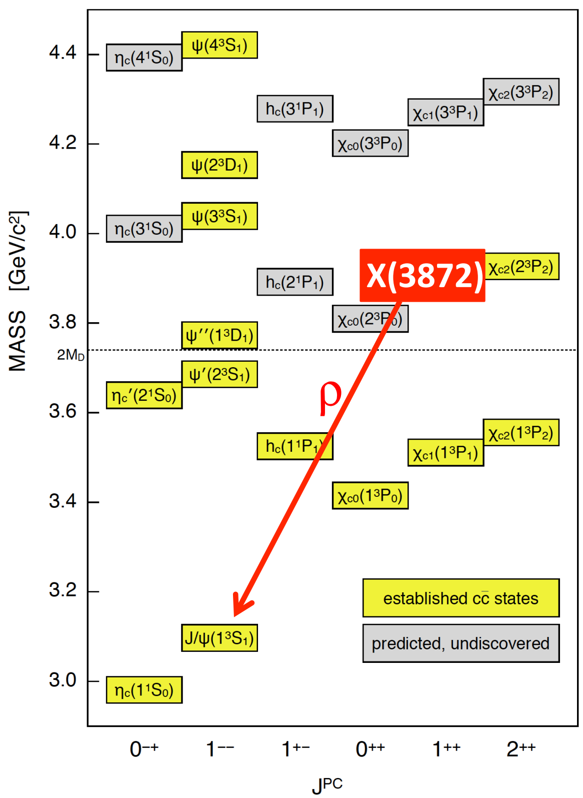


my talk

-- what's left --

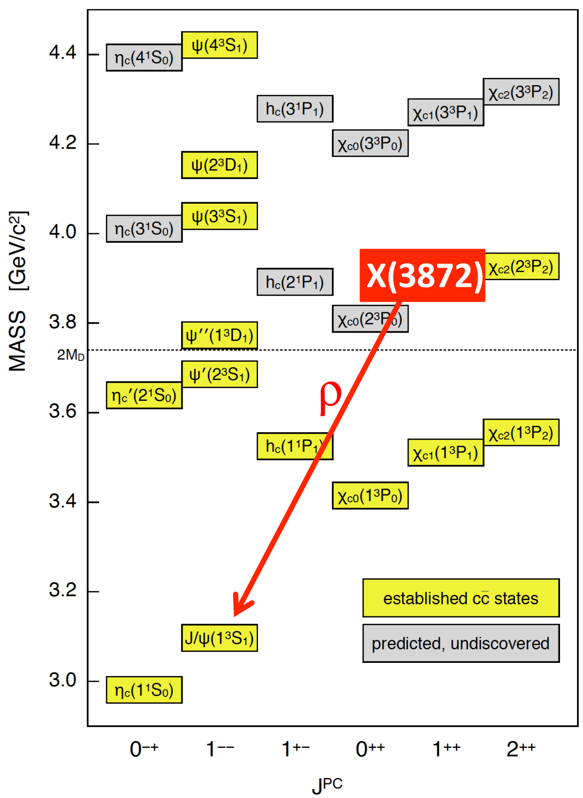


The X(3872)



MASS [GeV/c²]
4.4
4.2
4.0
3.8
2MD
3.6
3.4
3.2
3.0
ηc(4¹S0)
ψ(4³S1)
hc(3¹P1)
χc2(3³P2)
χc1(3³P1)
χc0(3³P0)
ψ(2³D1)
ψ(3³S1)
ηc(3¹S0)
X(3872)
χc2(2³P2)
hc(2¹P1)
ψ''(1³D1)
ψ'(2³S1)
ηc'(2¹S0)
ρ
χc2(1³P2)
χc1(1³P1)
hc(1¹P1)
χc0(1³P0)
established cc̄ states
predicted, undiscovered
J/ψ(1³S1)
ηc(1¹S0)
0−+
1−−
1+−
0++
1++
2++
JPC

The X(3872)



MASS [GeV/c²]
4.4
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χc2(2³P₂)
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ρ
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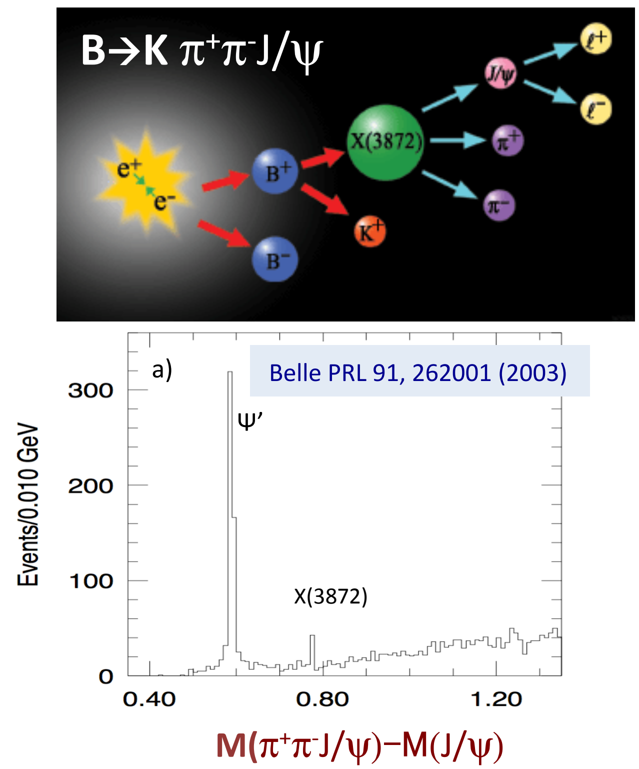
established cc̄ states
predicted, undiscovered
J/ψ(1³S₁)
ηc(1¹S₀)
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
J^PC

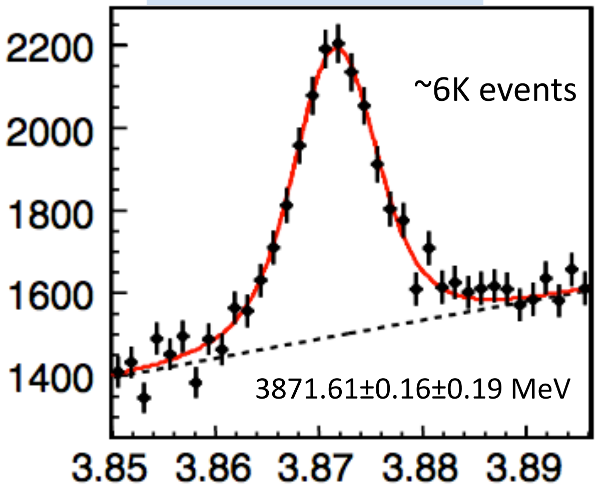


B→K π⁺π⁻J/ψ
e⁺
e⁻
B⁺
B⁻
X(3872)
K⁺
J/ψ
ℓ⁺
ℓ⁻
π⁺
π⁻
a)
Belle PRL 91, 262001 (2003)
ψ'
X(3872)
Events/0.010 GeV
300
200
100
0
0.40
0.80
1.20
M(π⁺π⁻J/ψ)−M(J/ψ)

mass and width

X(3872) & $m_{D0}+m_{D*0}$
are indistinguishable

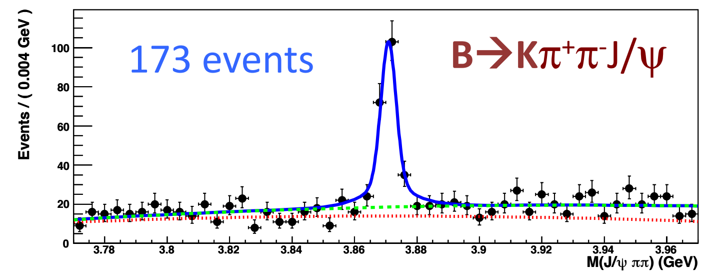
CDF PRL 103 152001 (2009)



PDG17: M_{X3872} = 3871.69±0.17
$m_{D0}+m_{D*0}$ =3871.85±0.11

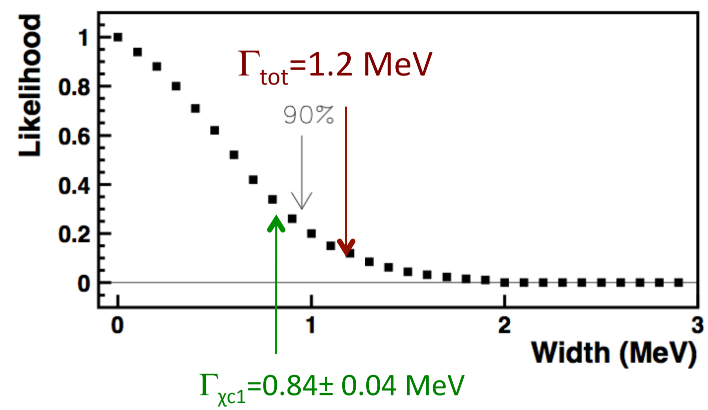
$$"BE" = (m_{D^0} + m_{D^{*0}}) - M_{X3872} = 0.16 \pm 0.20$$

$\Gamma_{X(3872)}$ can't be much
wider than $\Gamma_{\chi c1}$



$M(\pi^+\pi^- J/\psi)$

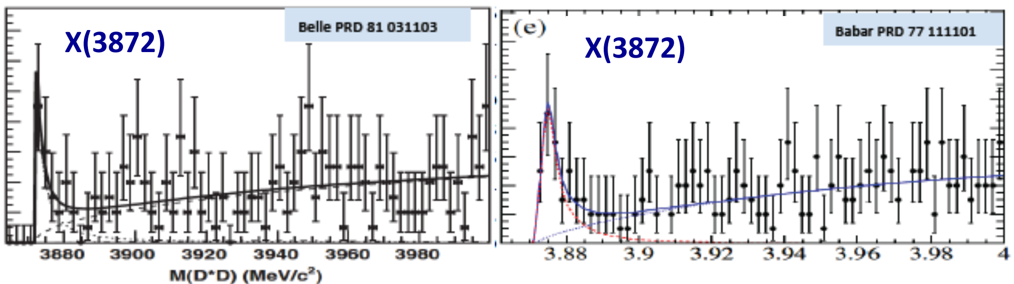
Belle PRD 84 052004 (2011)

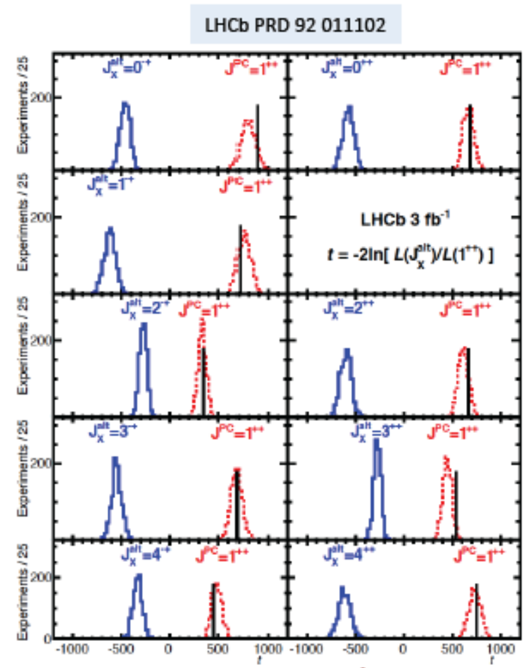


Strongly coupled to $D^0\bar{D}^{*0}$

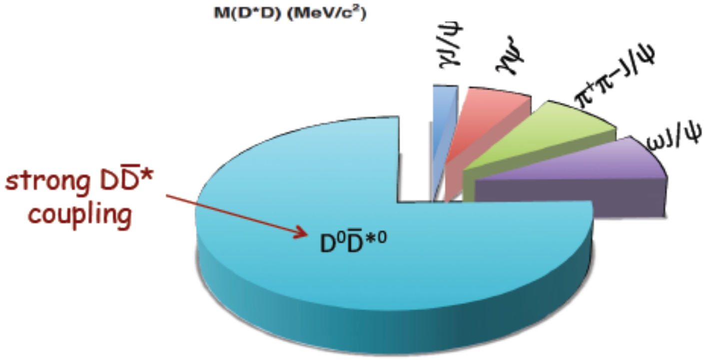
$J^{PC} = 1^{++}$

$B \to K\, D^0\bar{D}^{*0}$





D-wave<4%



$\gamma J/\psi$	>0.8%
$\gamma\psi'$	>3.6%
$\pi^+\pi^- J/\psi$	>3.1%
$\omega J/\psi$	>2.3%
$D^0\bar{D}^{*0}$	>38%
total seen	>48%

$X(3872) \to D^0\bar{D}^{*0}$

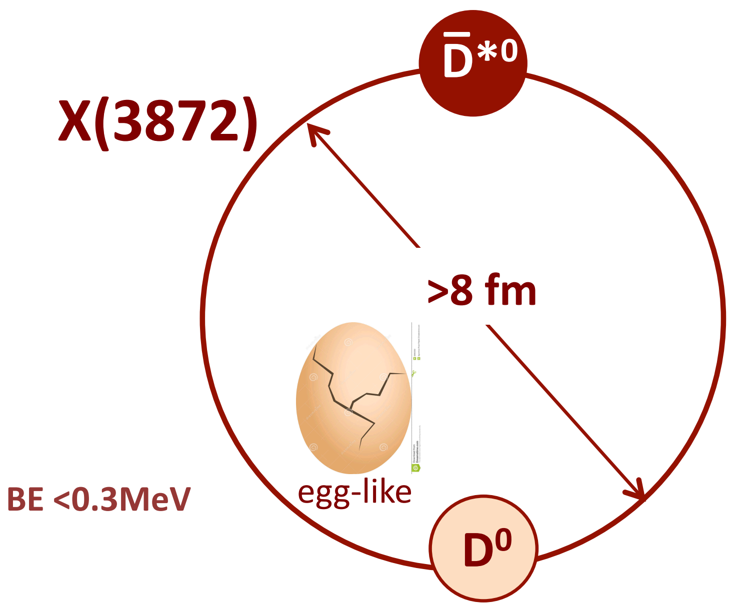
S-wave

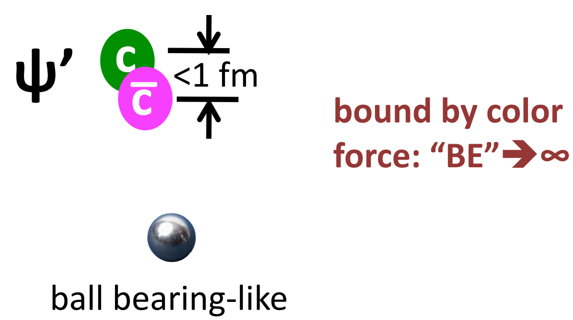
X(3872) ***has*** to be a “molecule”

Independently of the original mechanism for the resonance, the strong coupling to $D\bar{D}^*$ in an S-wave & small “BE” imply unambiguously that the X(3872) must be either a molecule (BE<0) or a virtual (BE>0) $D\bar{D}^*$ state of size $\approx 1 \big/ \sqrt{2\mu_{DD^*}|BE|} \geq 8$ fm

PRD 76 094028

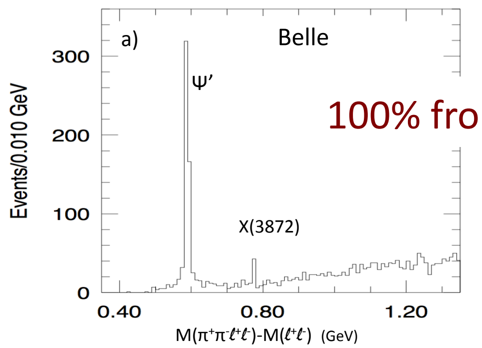
“scattering length”





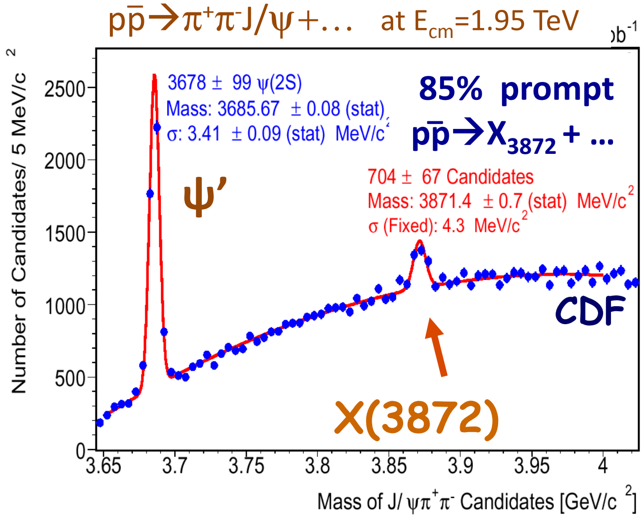
$X_{3872}\rightarrow\pi^+\pi^- J/\psi$ always ≈10% of $\psi'\rightarrow\pi^+\pi^- J/\psi$

$B\rightarrow K\,\pi^+\pi^- J/\psi$

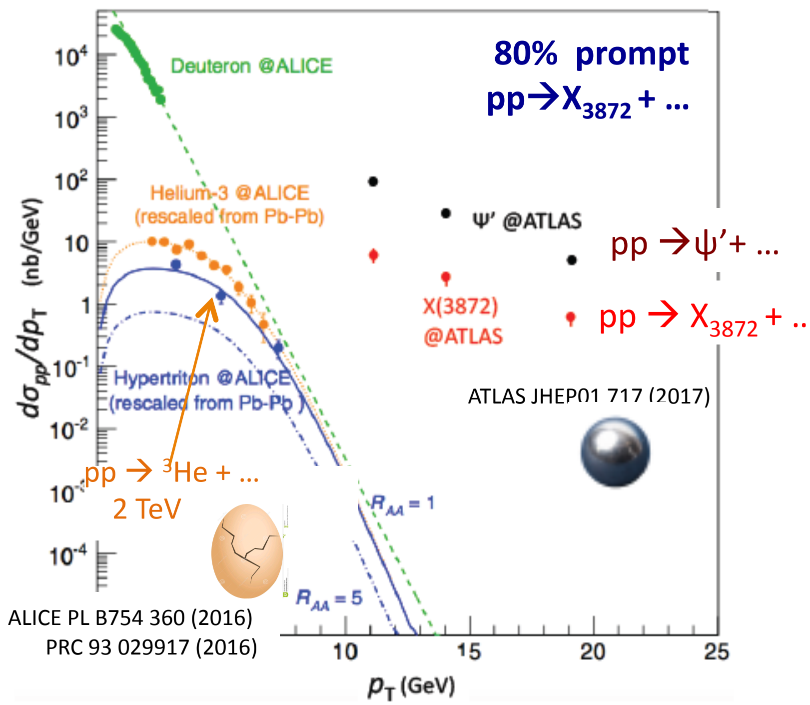


100% from B decay

$p\bar{p}\rightarrow\pi^+\pi^- J/\psi+\ldots$ at E_{cm}=1.95 TeV

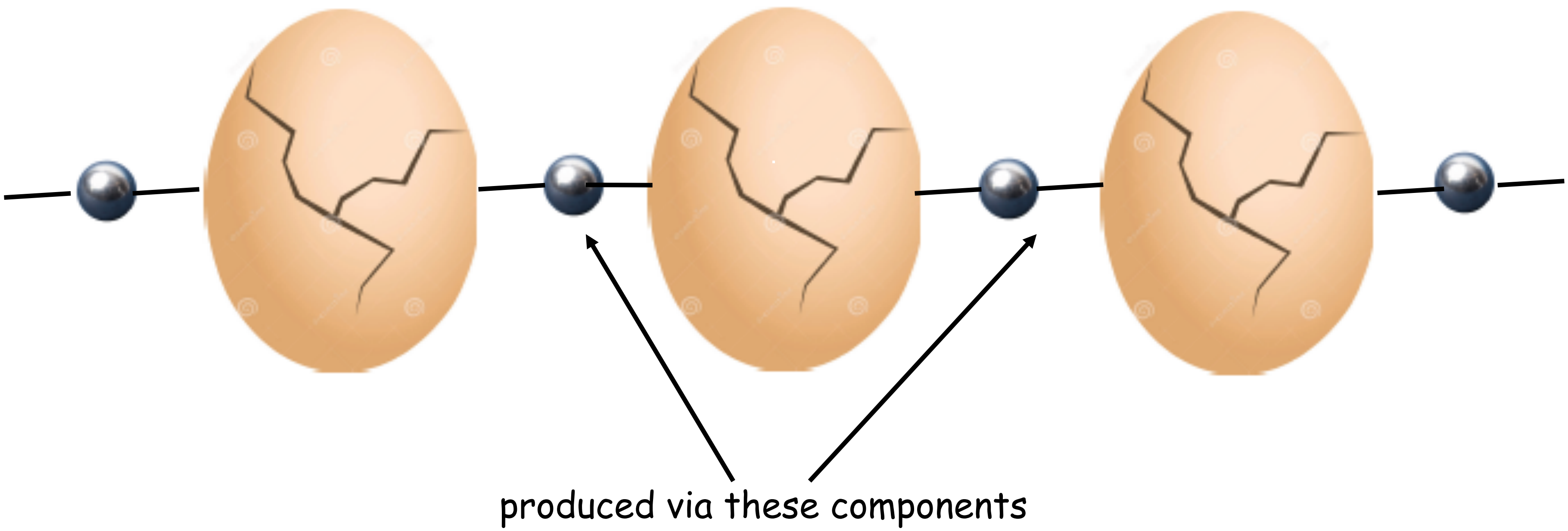


7 TeV pp collisions



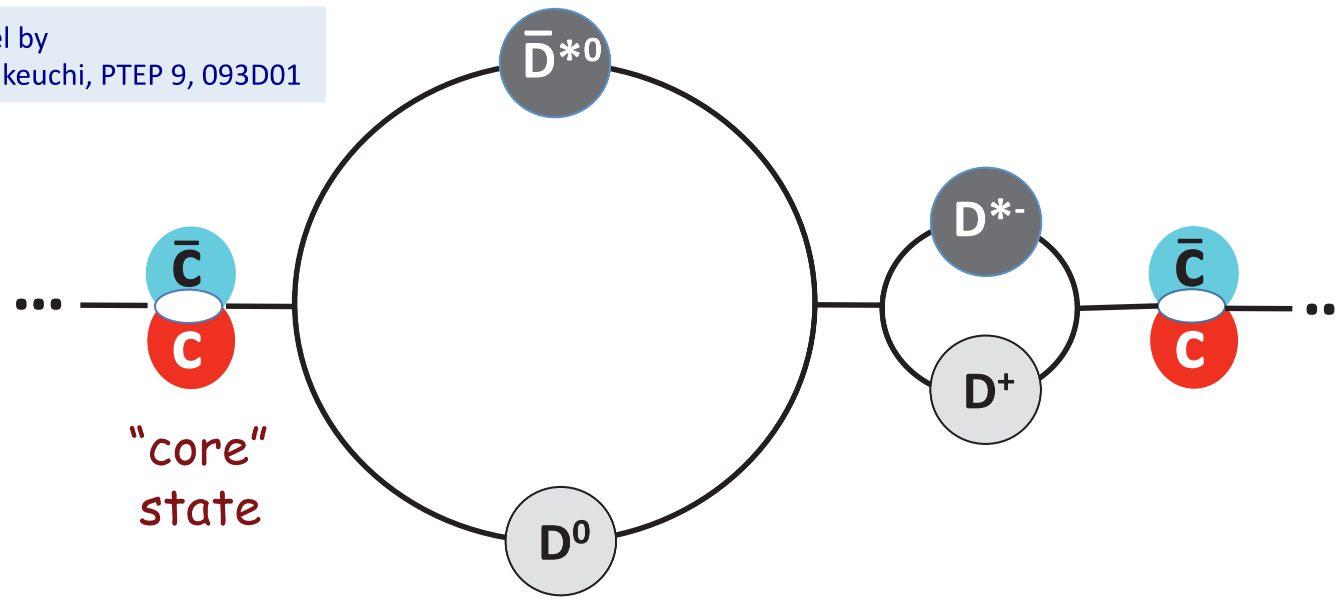
See Esposito et al., PRD 92 034028 (2015)

inescapable conclusion: QM mixture



QM mixture of $D\bar{D}^*$ & a $c\bar{c}$-like core

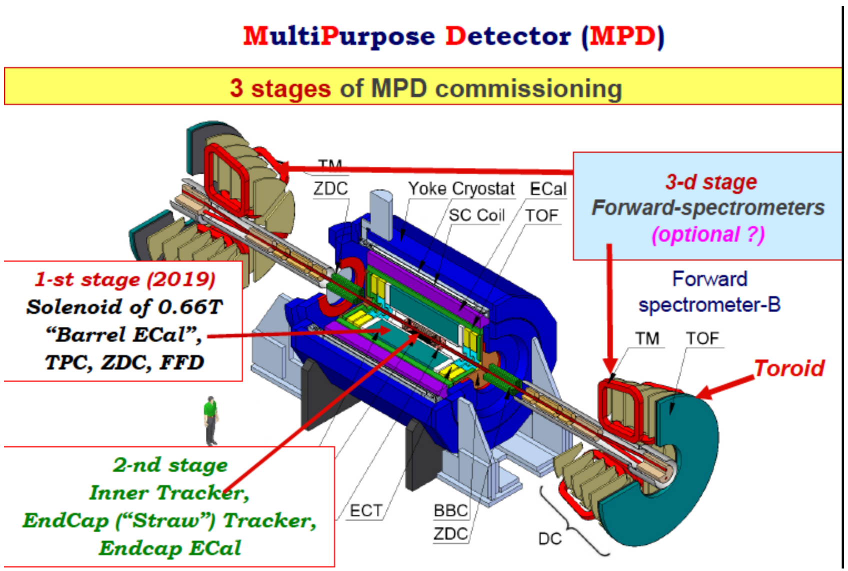
Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01

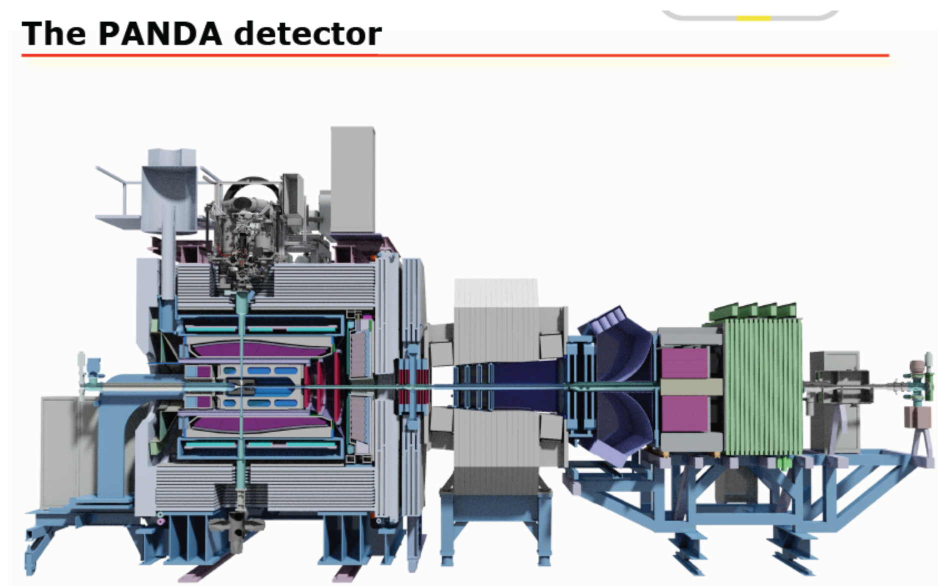


$$|X(3872)\rangle = 0.94|D^0\overline{D}^{*0}\rangle + 0.23|D^+D^{*-}\rangle - 0.24|c\overline{c}\rangle$$

Probing the X(3872) in pp & pA

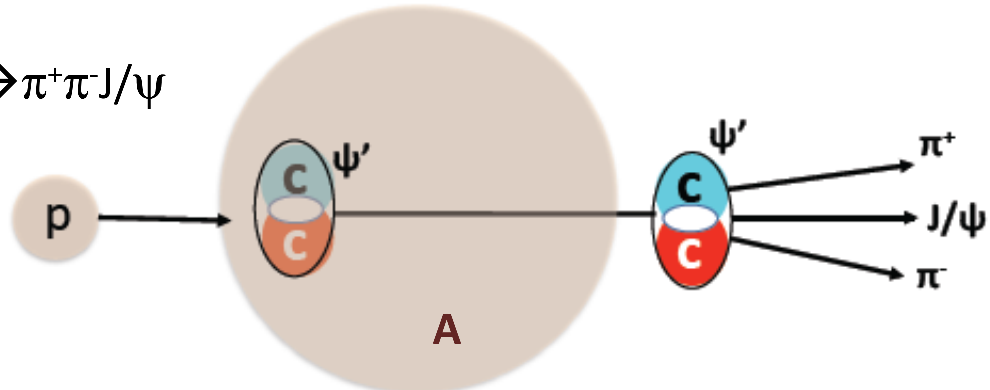
- at NICA and/or PANDA -



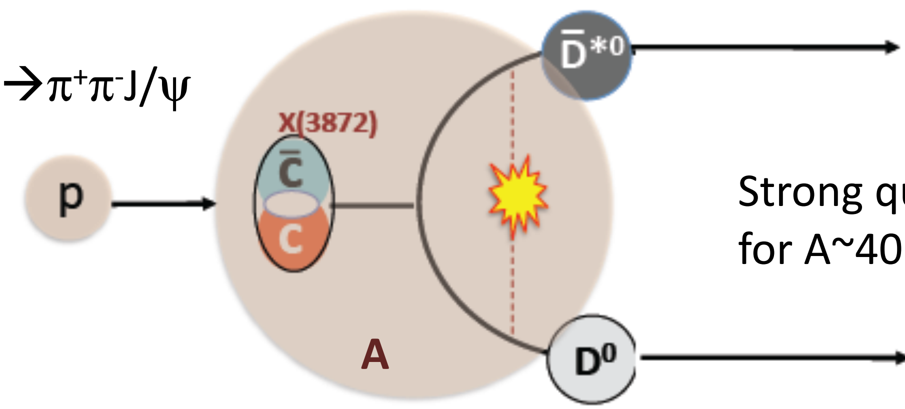


Near-threshold: $pA \rightarrow \pi^+\pi^- J/\psi$ + …

$pA \rightarrow \psi' + \ldots \rightarrow \pi^+\pi^- J/\psi$



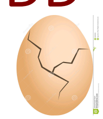
$pA \rightarrow X(3872) + \ldots \rightarrow \pi^+\pi^- J/\psi$



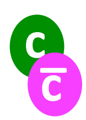
Strong quenching
for A~40 nuclei??

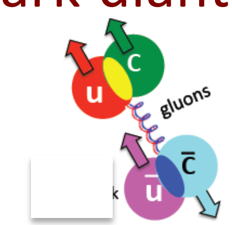
But this won’t reveal *“the original mechanism for the resonance”*

“original mechanism” = $c\bar{c}$-core? … $D\bar{D}^*$ molecule?

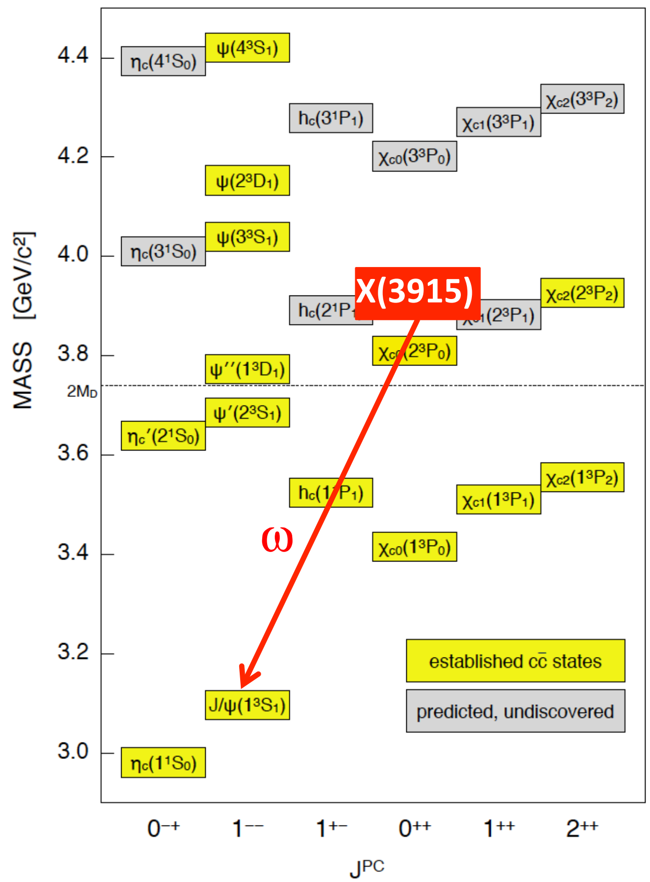


$c\bar{c}$-core = χ'_{c1}? … diquark-diantiquark?



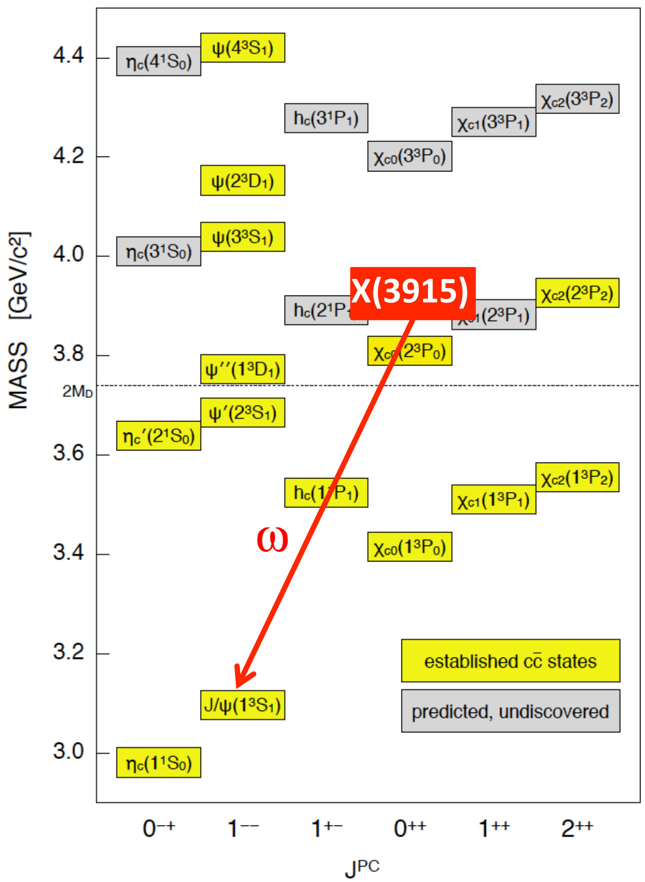


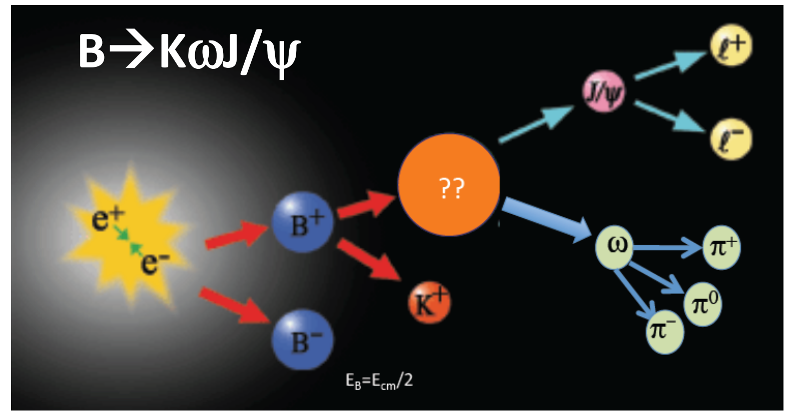
The X(3915)

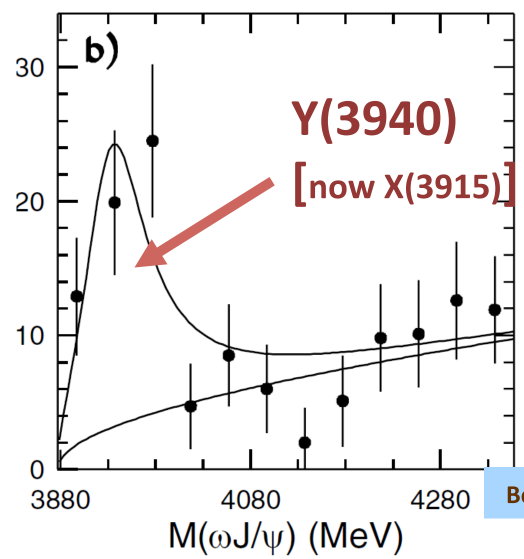


X(3915)
ω
established cc̄ states
predicted, undiscovered
MASS [GeV/c²]
2M_D
J^PC
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
ηc(4¹S₀)
ψ(4³S₁)
hc(3¹P₁)
χc0(3³P₀)
χc1(3³P₁)
χc2(3³P₂)
ψ(2³D₁)
ηc(3¹S₀)
ψ(3³S₁)
χc2(2³P₂)
ψ''(1³D₁)
ψ'(2³S₁)
ηc'(2¹S₀)
hc(1¹P₁)
χc1(1³P₁)
χc2(1³P₂)
χc0(1³P₀)
J/ψ(1³S₁)
ηc(1¹S₀)

The X(3915)

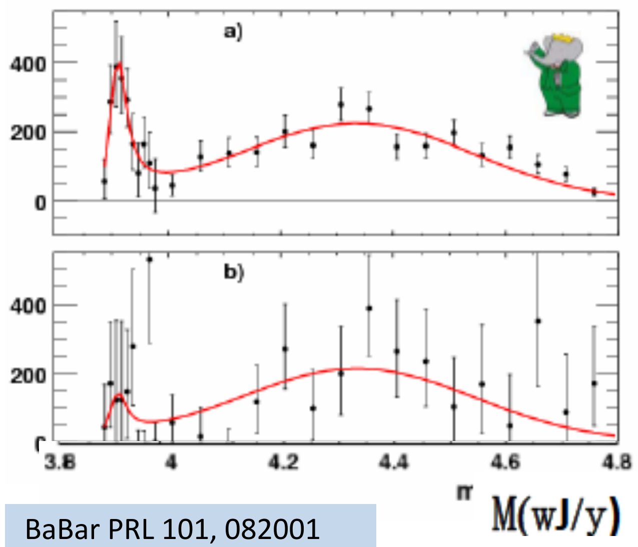






Belle PRL94, 182002 (2005)

confimed by BaBar



$B^{\pm} \rightarrow K^{\pm}\omega J/\psi$

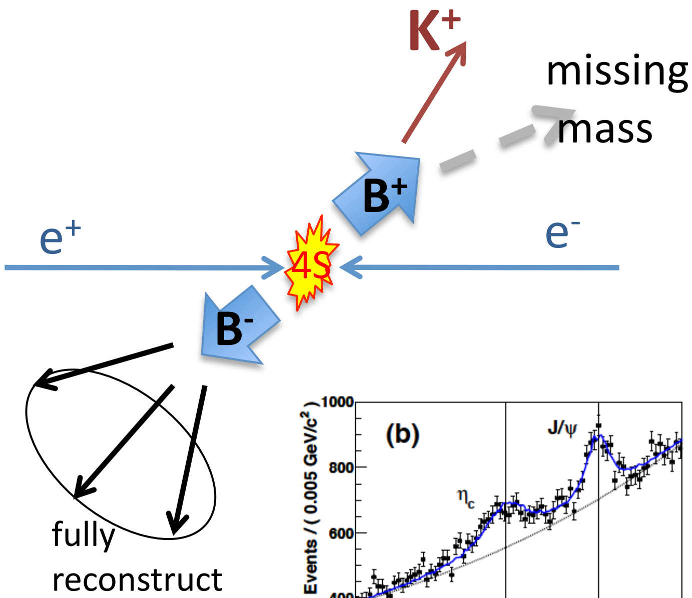
$B^{0} \rightarrow K_S\omega J/\psi$

BaBar PRL 101, 082001

	Mass (MeV)	Γ (MeV)
Belle 253 fb^{-1}	$3943 \pm 11(stat) \pm 13(syst)$	$87 \pm 22(stat) \pm 26(syst)$
BaBar 350 fb^{-1}	$3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst)$	$33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst)$

PDG2017: $Bf(B^{+} \rightarrow K^{+} X_{3915}) \times Bf(X_{3915} \rightarrow \omega J/\psi) = 3.0^{+0.9}_{-0.7} \times 10^{-5}$

2018: lower limit on $\Gamma(X_{3915}\rightarrow\omega J/\psi)$



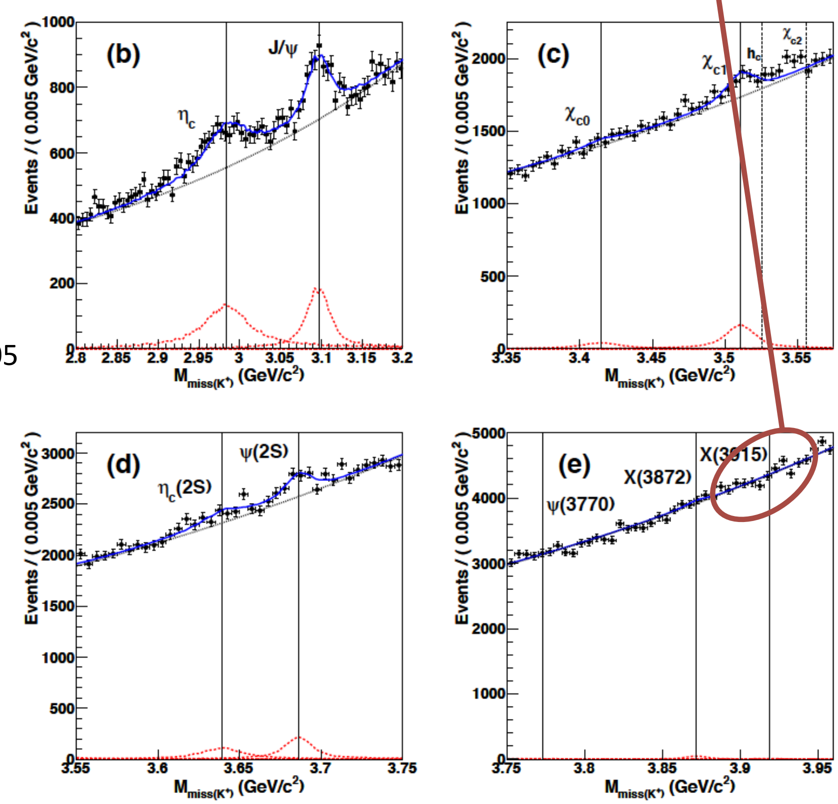
$$Bf(B^+\to K^+X_{3915})\times Bf(X_{3915}\to\omega J/\psi)=3.0^{+0.9}_{-0.7}\times10^{-5}$$

$Bf(B^+\rightarrow K^+X_{3915})<2.7\times10^{-4}$ ➔ $Bf(X_{3915}\rightarrow\omega J/\psi)>7\%$

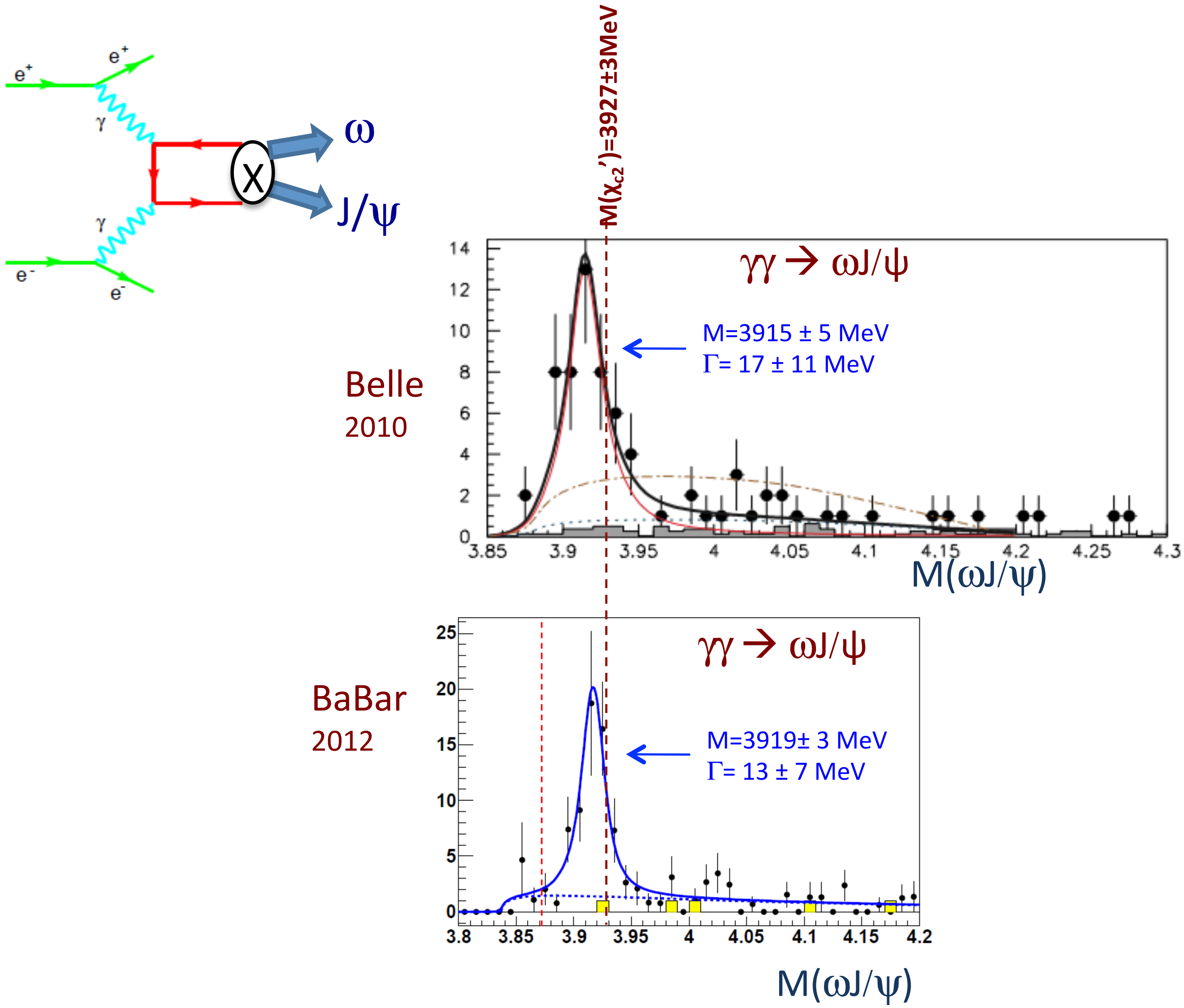
Γ_{tot}=20 ±5 MeV

$\Gamma(X_{3915}\rightarrow\omega J/\psi)>1$ MeV

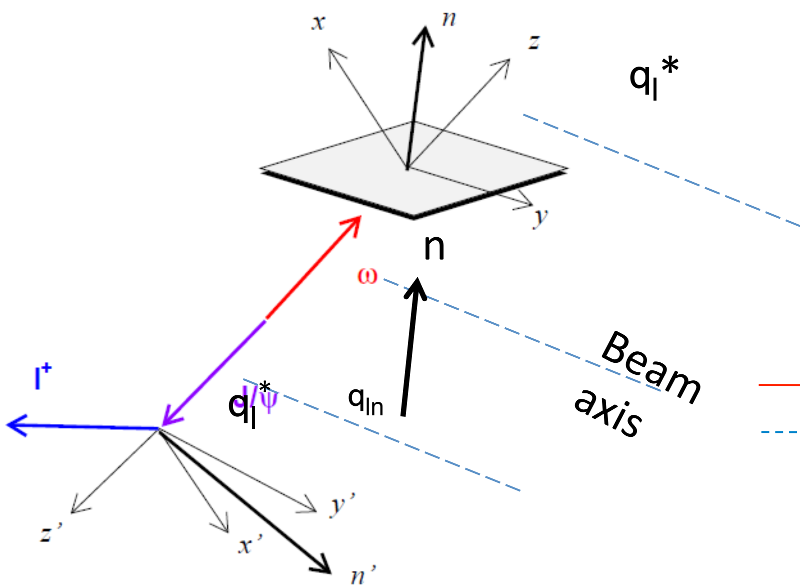
Belle PRD 97, 012005

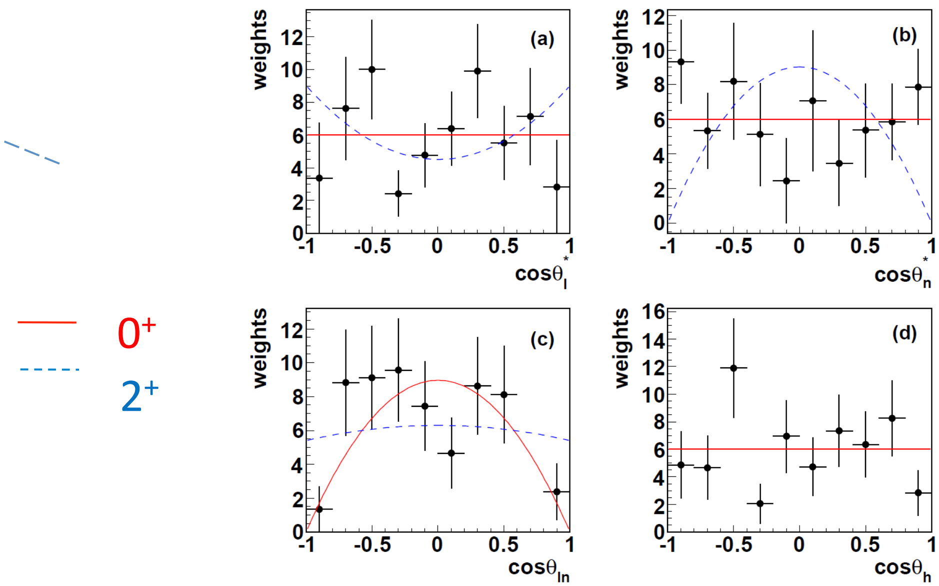


seen in $\gamma\gamma \rightarrow \omega J/\psi$



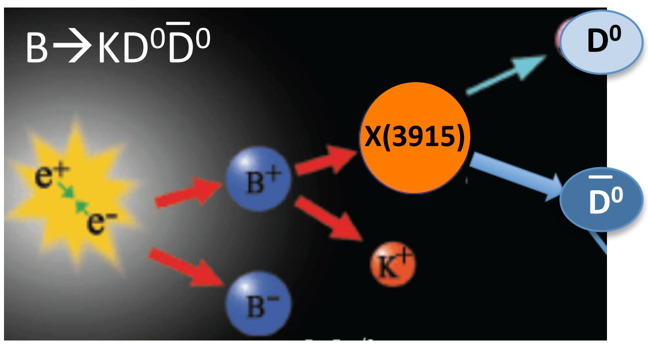
BaBar measurements determine $J^{PC}=0^{++}$

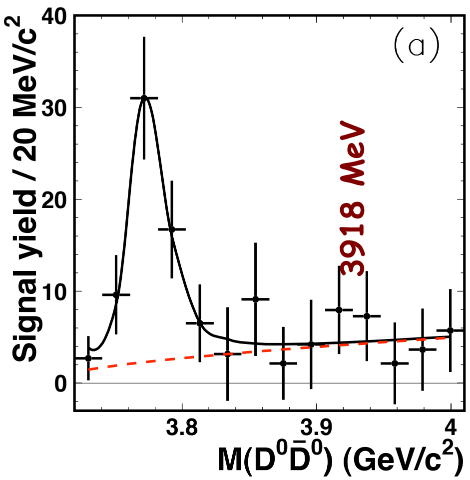




BaBar PRD 86, 072002 (2012)

no sign of X(3915) → $D\bar{D}$?

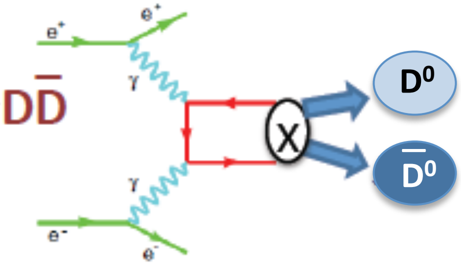


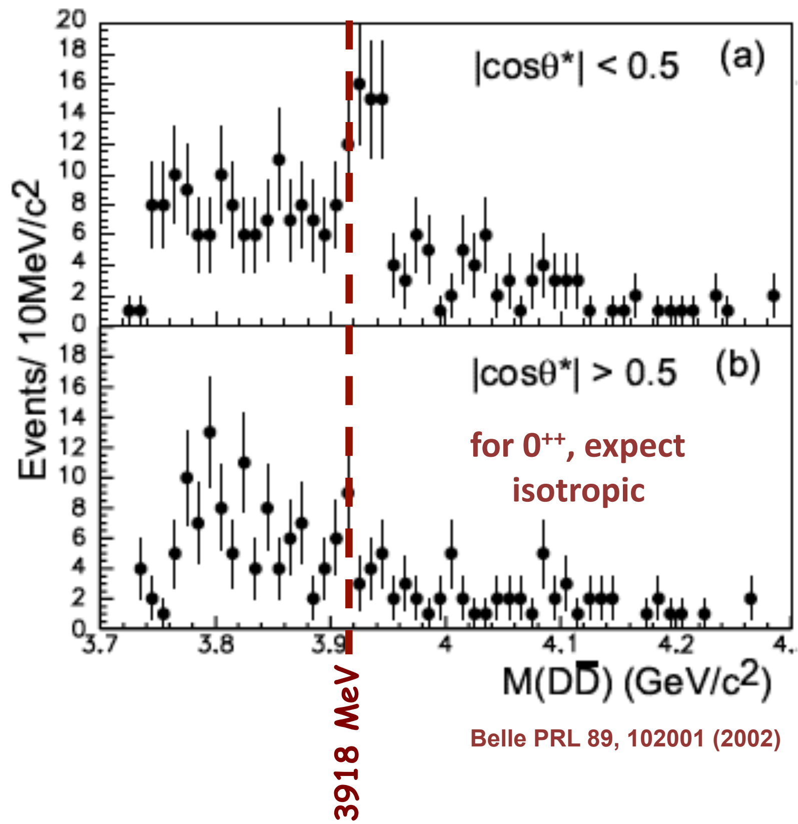


⇨ $\Gamma(X_{3915}) \rightarrow D\bar{D}) < 1$ MeV

J. Brodzicka et al. (Belle) PRD 100, 092001

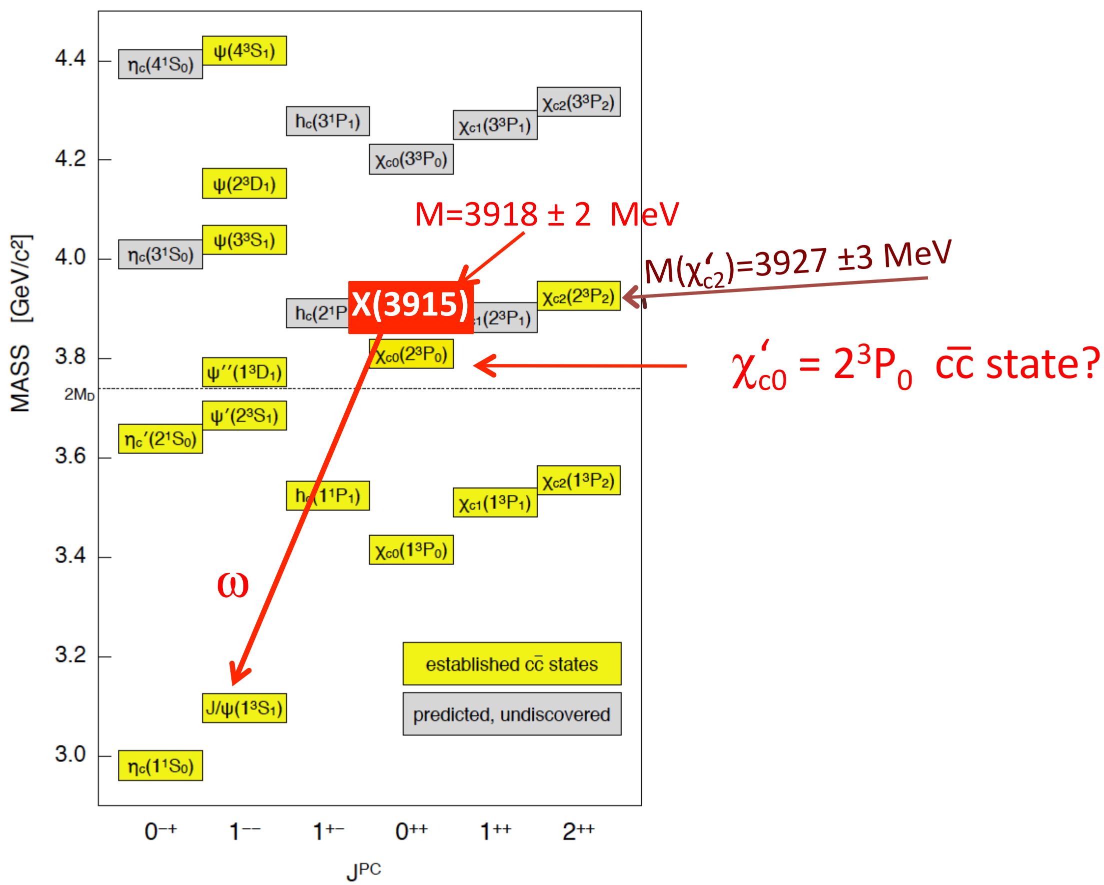
$\gamma\gamma \rightarrow \chi'_{c2} \rightarrow D\bar{D}$





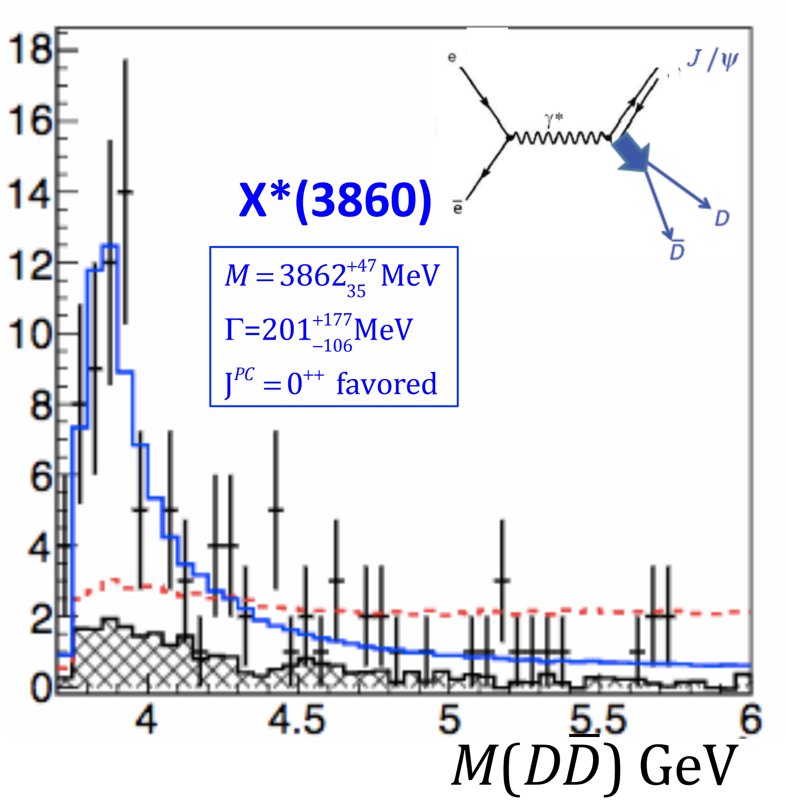
Belle PRL 89, 102001 (2002)

χ'_{c0} charmonium assignment for X(3915)?



2017: better χ_{c0}' candidate found

K. Chilikin et al. (Belle) PRD 95, 092003 (2017)



X(3915) *vs* X*(3860) as a χ_{c0}' candidate scorecard

	prediction	X(3915)	X*(3860)
Mass (MeV)	<3890	3918	3862
Width (MeV)	>40	20	2001
$\Gamma(X\rightarrow D\bar{D})$ (MeV)	>30	<1	≈200(?)
$\Gamma(X\rightarrow \omega J/\psi)$ (MeV)	≈0.1	>1	not seen

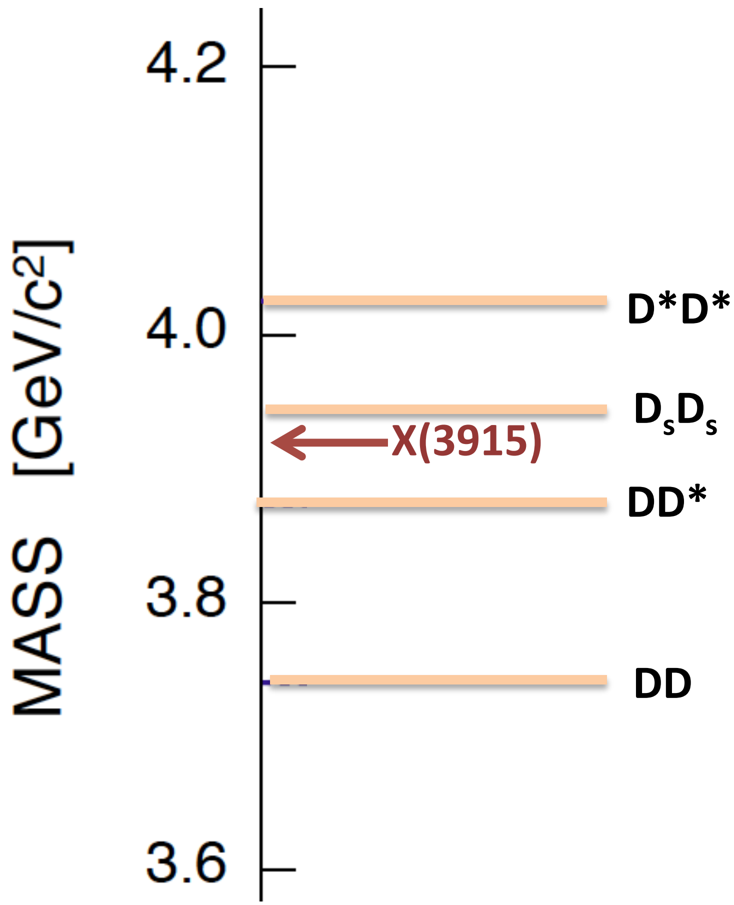
If X(3915) ≠ χ'_{c0}, what is it?

X(3915)→$\omega J/\psi$ violates OZI-rule unless it's a 4-quark state

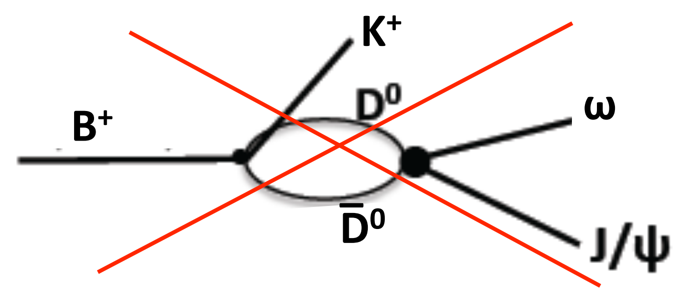
Mass is near $2m_{Ds}$ threshold: $M(X(3915)) = 2m_{Ds}$ -18 MeV

X(3915)→$D\bar{D}$ decays are suppressed: $\Gamma(X(3915) \to D\bar{D}) < 1$ MeV

no nearby thresholds



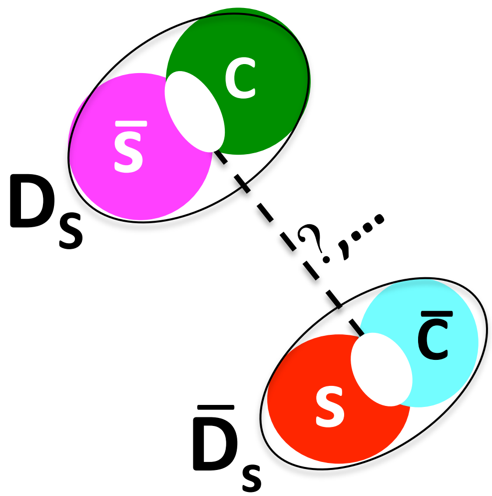
not a cusp, a triangle singularity, or the like



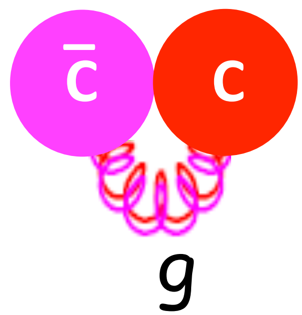
Possibilities

D_s-$\bar{D}_s$ molecule?

Li & Voloshin, PRD 91, 114014

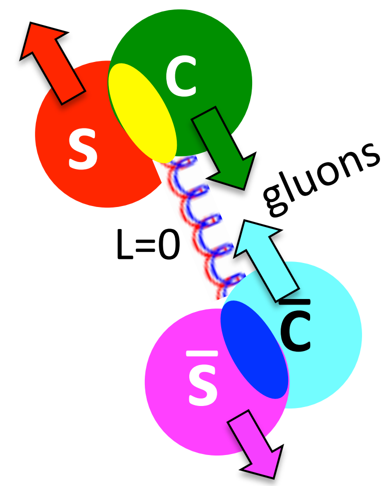


$c\bar{c}$-gluon hybrid?



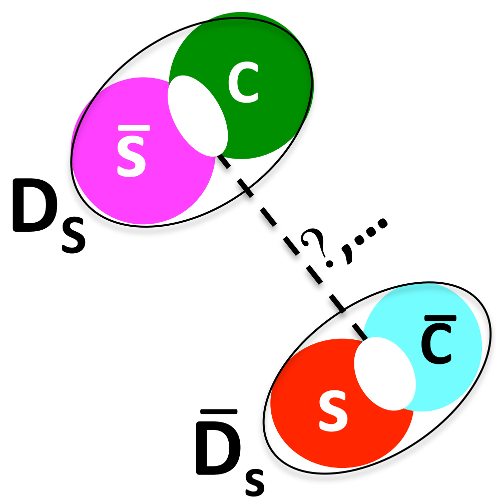
[cs][$\bar{c}\bar{s}$] tetraquark?

Lebed & Polosa, PRD 93, 094024



X(3915) as a D_s-$\bar{D}_s$ molecule?

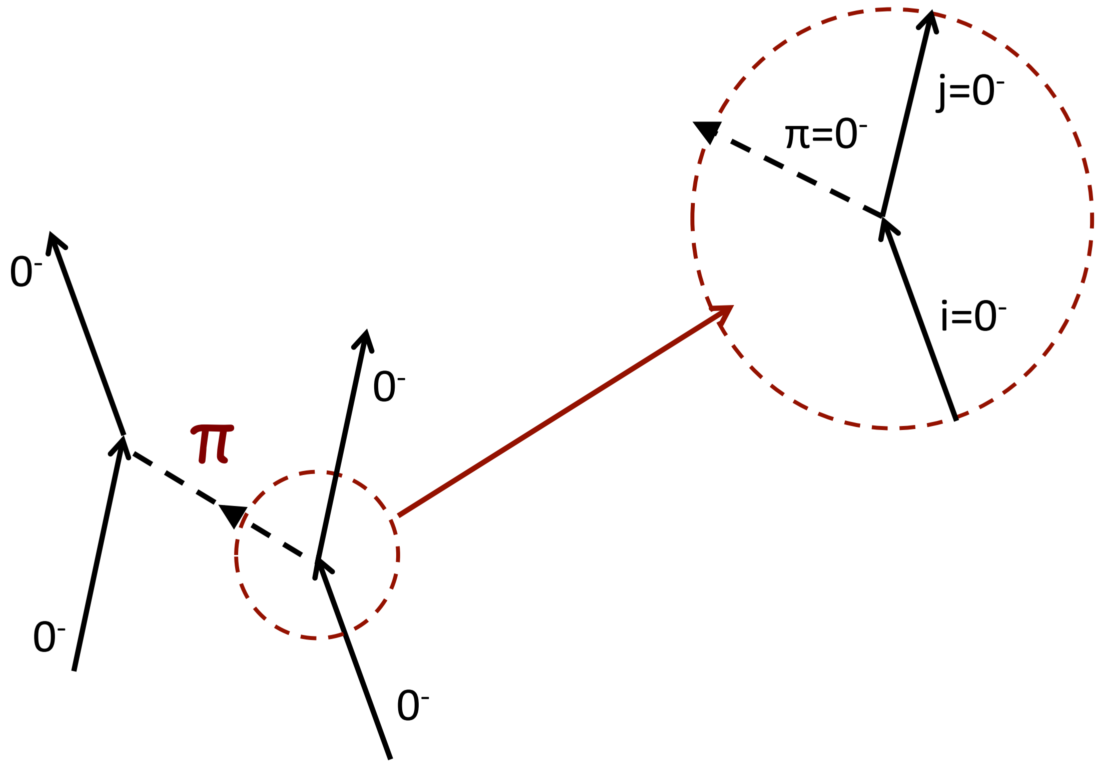
Li & Voloshin, PRD 91, 114014



what binds it?

"BE"$=2m_{Ds} - M_{X3915}=18$ MeV

$0^- \leftrightarrow 0^-$ π-exchange violates Parity



i → *j* + π

initial state

P=-1; *J*=0

to conserve *P, j* & π should be in a P-wave & not conserve *J*

0^- 0^- 0^- vertices must be 0

X(3915) as a D_s-$\bar{D}_s$ molecule?

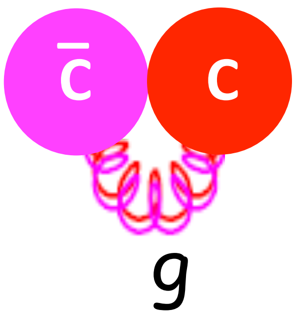
Li & Voloshin, PRD 91, 114014

what binds it?

“BE”$=2m_{Ds} - M_{X3915} = 18$ MeV

X(3915) is a very unlikely molecule

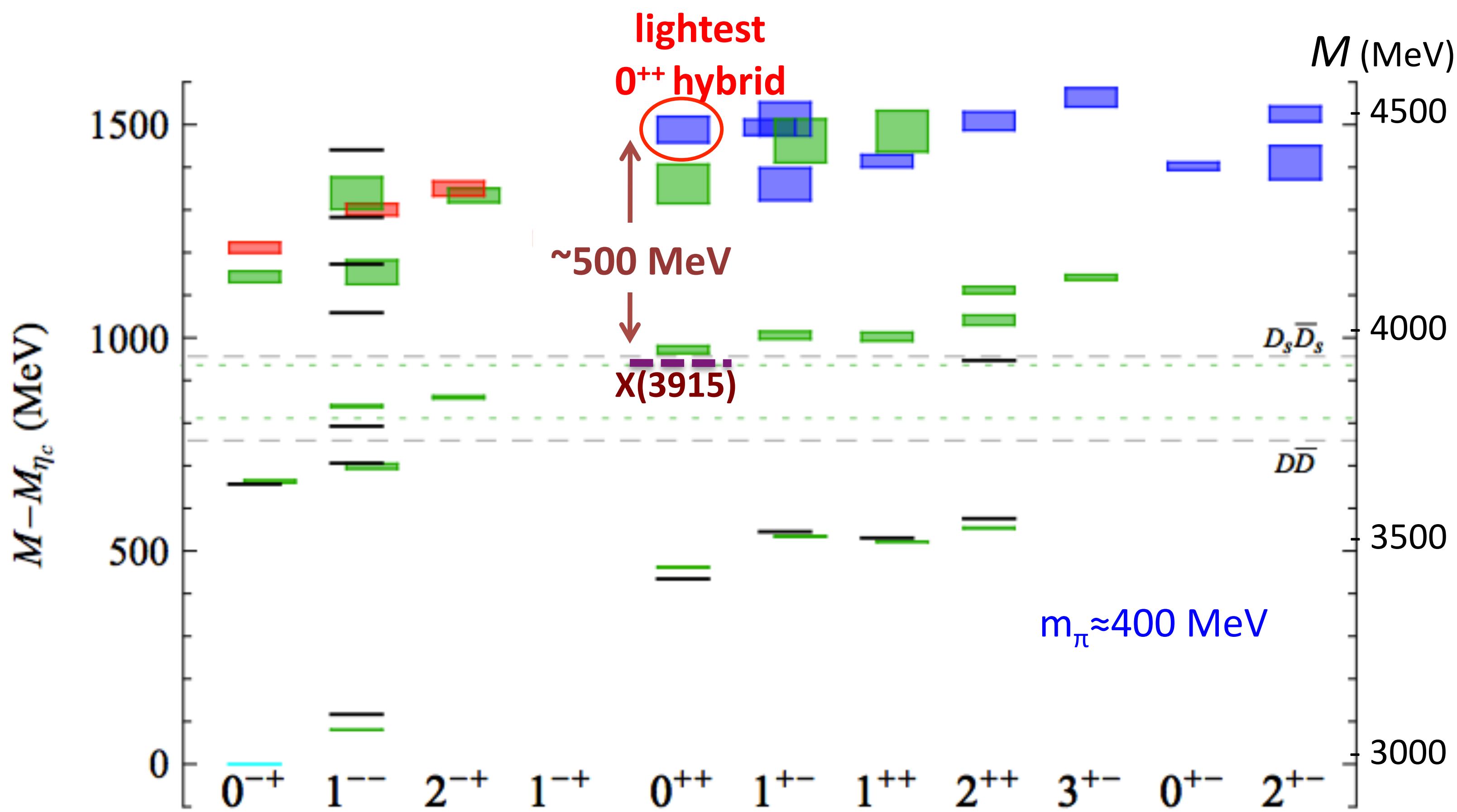
X(3915) as a $c\bar{c}$-*gluon* hybrid?



too light for 0^{++} $c\bar{c}$-hybrid?

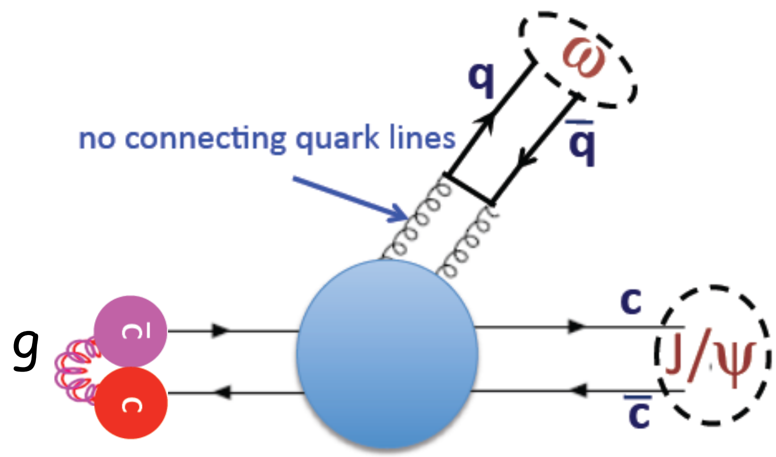
3915 MeV is too light for a 0^{++} hybrid

-- Lattice QCD calculation --



Liu, *et al* (Had Spec Collab) JHEP07,126

$c\bar{c}$-*gluon* → ω J/ψ is OZI suppressed



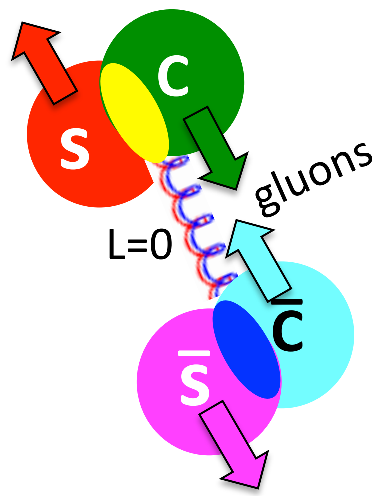
$\Gamma(X_{3915} \rightarrow \omega\, J/\psi) > 1$ MeV

X(3915) as a $c\bar{c}$-*gluon* hybrid?

X(3915) is a very unlikely $c\bar{c}$-hybrid

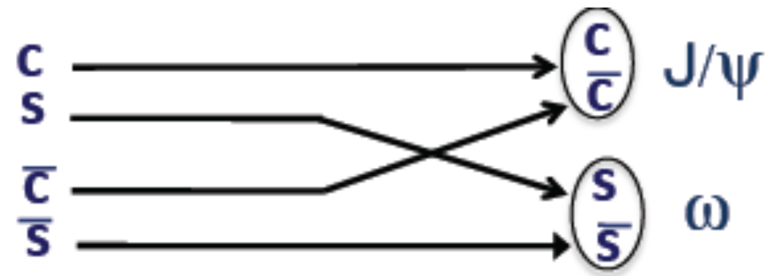
X(3915) as a [cs][$\bar{c}\bar{s}$] tetraquark?

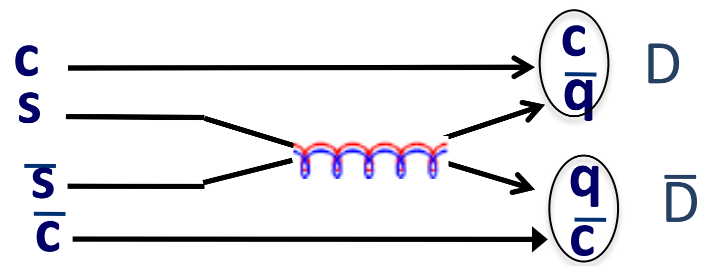
Lebed & Polosa, PRD 93, 094024



how would it decay?

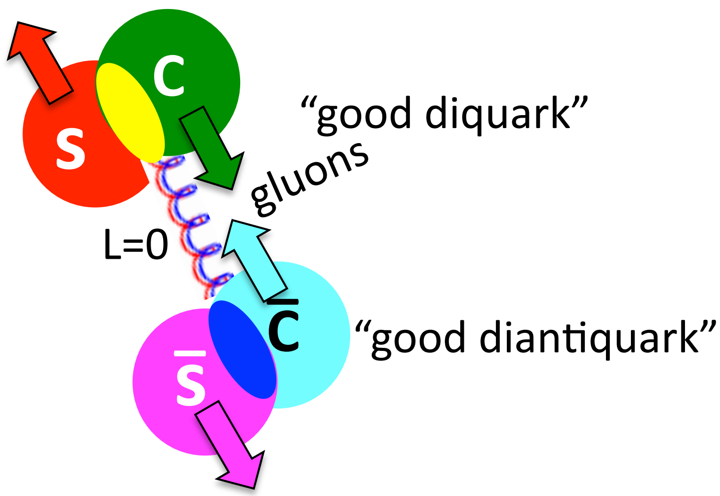
$[cs][\bar{c}\bar{s}] \rightarrow \omega J/\psi$ enhanced;
$\rightarrow D\bar{D}$ suppressed





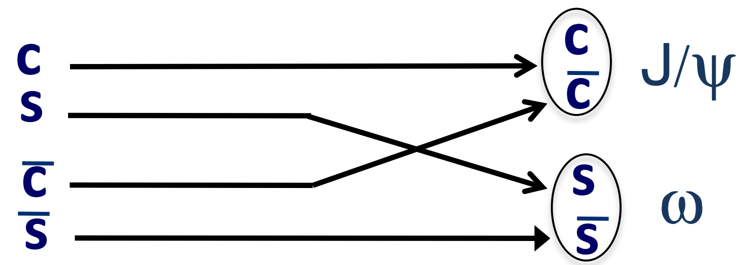
s & $\bar{s}$ have to annihilate

$[cs][\overline{cs}] \to \eta\eta_c$?

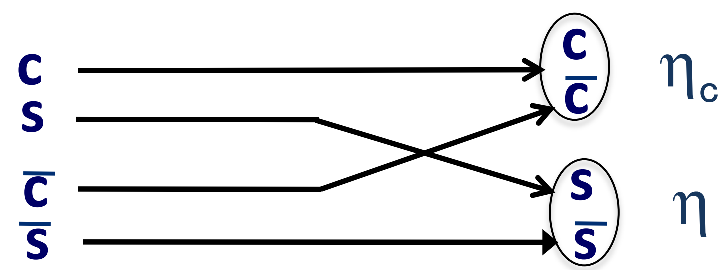


$$\text{Expect:} \quad \frac{Bf(X(3915) \to \eta_c \eta)}{Bf(X(3915) \to J/\psi\ \omega)} >> 1$$

OZI allowed decay processes



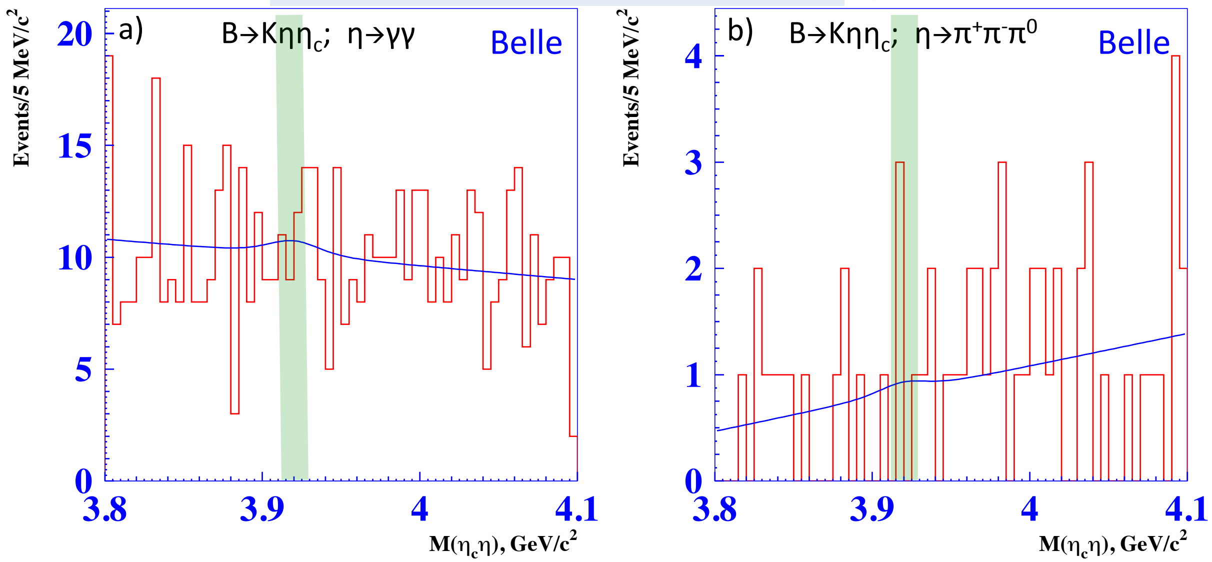
ω has a small (≈3%) $s\bar{s}$ content



η has a large (≈40%) $s\bar{s}$ content

X(3915)→$\eta_c\eta$

Vinokurova *et al* (Belle) JHEP06,132 ⟸ plus erratum



$$\mathcal{B}(B^+ \to K^+ X(3915)) \times \mathcal{B}(X \to \eta\eta_c) < 4.7 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+ X(3915)) \times \mathcal{B}(X \to \omega J/\psi) = 3.0^{+0.9}_{-0.7} \times 10^{-5}$$

$\Rightarrow$

$$\frac{Bf(X \to \eta_c \eta)}{Bf(X \to J/\psi\ \omega)} < 2$$

$Bf(X(3915) \to \eta_c \eta)$ is not much larger than $Bf(X(3915) \to J/\psi\ \omega)$

$\Rightarrow$ bad for the QCD tetraquark picture

X(3915) as a [cs][$\bar{c}\bar{s}$] tetraquark?

Lebed & Polosa, PRD 93, 094024

X(3915) = tetraquark ← not so bad

What is the X(3915)?

It is ***not*** the χ'_{c0} charmonium state

Belle recently found a much better χ'_{c0} candidate

It is ***not*** a threshold effect

18 MeV away from the nearest threshold (& a benign one at that)

It is ***not*** a good candidate for a $D_s\bar{D}_s$ molecule:

B.E. ≈ 18 MeV; ← needs a binding mechanism to produce this;

standard nuclear-physics-type forces do not work

It is ***not*** a $c\bar{c}$-gluon hybrid:

unless current (m_π≈400 MeV) LQCD mass calcs are wrong by ≈500 MeV

If it is a $[cs][\bar{c}\bar{s}]$ QCD tetraquark:

the X(3915)→$\eta\eta_c$ decay mode should be seen soon

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If it is a $[cs][\bar{c}\bar{s}]$ QCD tetraquark:

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Maybe in this case we'll learn something about " the original mechanism for the resonance"

to do list for the X(3915)

Separate J^{PC} analyses for $B \to K\omega J/\psi$ & $\gamma\gamma \to \omega J/\psi$ signals

is a single state responsible for the peaks the two production channels?

Establish the levels of *Bfs* for $X(3915) \to D\bar{D}$ and $X(3915) \to \eta\eta_c$

or set stringent upper limits

Hadronic production of the X(3915)?

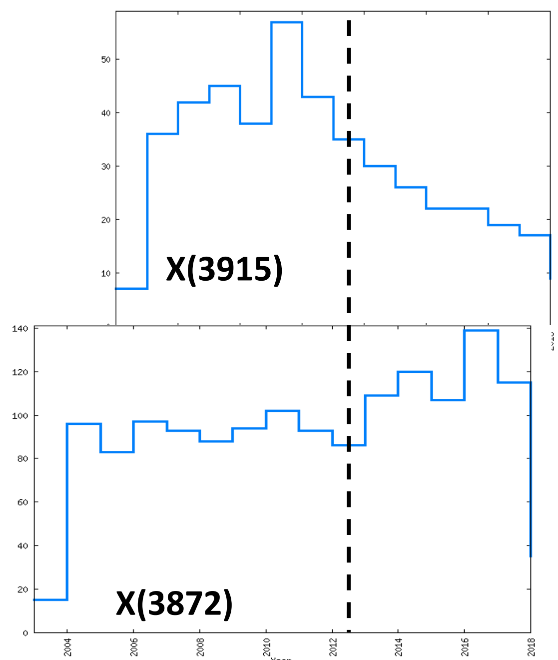
Search for $Y(4260) \to \gamma X(3915)$

$\hookrightarrow \omega J/\psi$

analogous to $Y(4260) \to \gamma X(3872)$

X(3915), the forgotten particle

in 2011, BaBar declared it to be the χ_{c0}', the
PDG acquiesced, & people forgot about it



Thursday's arXiv

1805.06276 [hep-ph]

Spectroscopy of the hidden-charm $[qc][\bar{q}\bar{c}]$ and $[sc][\bar{s}\bar{c}]$ tetraquarks

Muhammad Naeem Anwar,[1,2,*] Jacopo Ferretti,[1,†] and Elena Santopinto[3,‡]

[1] *CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

[2] *University of Chinese Academy of Sciences, Beijing 100049, China*

[3] *INFN, Sezione di Genova, via Dodecaneso 33, 16146 Genova, Italy*

?????

State	J^{PC}	$M_{\rm exp}$ (MeV)	Γ (MeV)	Observing Process	Experiment
$X(3872)$	1^{++}	3871.69 ± 0.17	< 1.7	$B^\pm \to K^\pm \pi^+\pi^- J/\psi$	Belle
$Z_c(3900)$	1^{+-}	3886.6 ± 2.4	28.1 ± 2.6	$e^+e^- \to \pi^+\pi^- J/\psi$	BESIII
$Y(4008)$	1^{--}	4008 ± 40	226 ± 44	$e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$	Belle
$Z_c(4020)^\pm$	1^{+-}	4024.1 ± 1.9	13 ± 5	$e^+e^- \pi^+\pi^- h_c$	BESIII
$X(4140)$	1^{++}	4146.8 ± 2.5	19^{+8}_{-7}	$\gamma\gamma \to \phi J/\psi$	CDF
$Z_c(4240)^\pm$	0^-	$4239 \pm 18^{+45}_{-10}$	$220 \pm 47^{+108}_{-74}$	$B^0 \to K^+\pi^-\psi(2S)$	LHCb
$Y(4260)$	1^{--}	4230 ± 8	55 ± 19	$e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$	BaBar
$X(4274)$	1^{++}	4273^{+19}_{-9}	56^{+14}_{-16}	$B^+ \to J/\psi\phi K^+$	CDF, LHCb
$Y(4360)$	1^{--}	4341 ± 8	102 ± 9	$e^+e^- \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$	Belle
$Z_c(4430)^\pm$	1^+	4478^{+15}_{-18}	181 ± 31	$B \to K\pi^\pm\psi(2S)$	Belle
$X(4500)$	0^{++}	4506^{+16}_{-19}	92 ± 29	$B^+ \to J/\psi\phi K^+$	LHCb
$Y(4630)$	1^{--}	4634^{+8}_{-7}	92^{+40}_{-24}	$e^+e^- \to \Lambda_c^+\Lambda_c^-$	Belle
$Y(4660)$	1^{--}	4643 ± 9	72 ± 11	$e^+e^- \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$	Belle
$X(4700)$	0^{++}	4704^{+17}_{-26}	120 ± 50	$B^+ \to J/\psi\phi K^+$	LHCb

Thank You