

Unresolved and under-appreciated



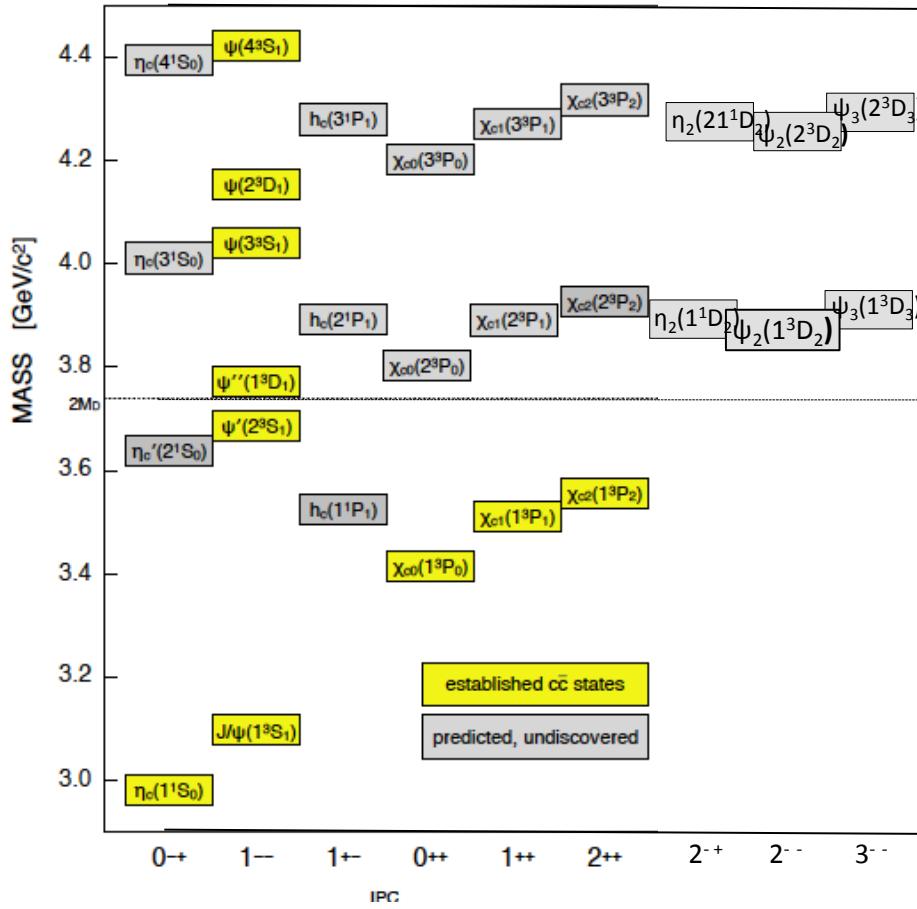
Stephen Lars Olsen UCAS



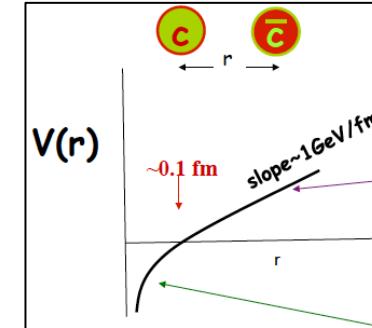
Exotic Hadrons & Flavor Physics, Stony Brook NY , May 28-June 1,2018

charmonium: pre B-factory

forty-plus years of work

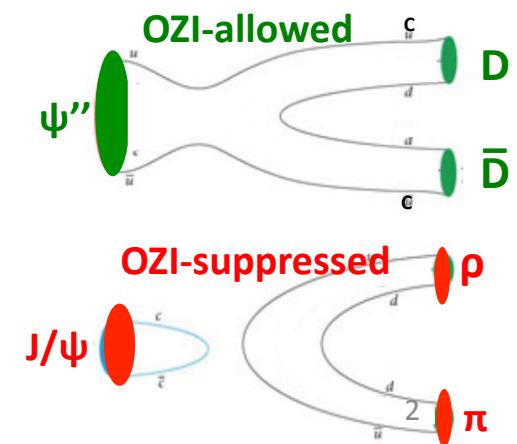


potential model works well

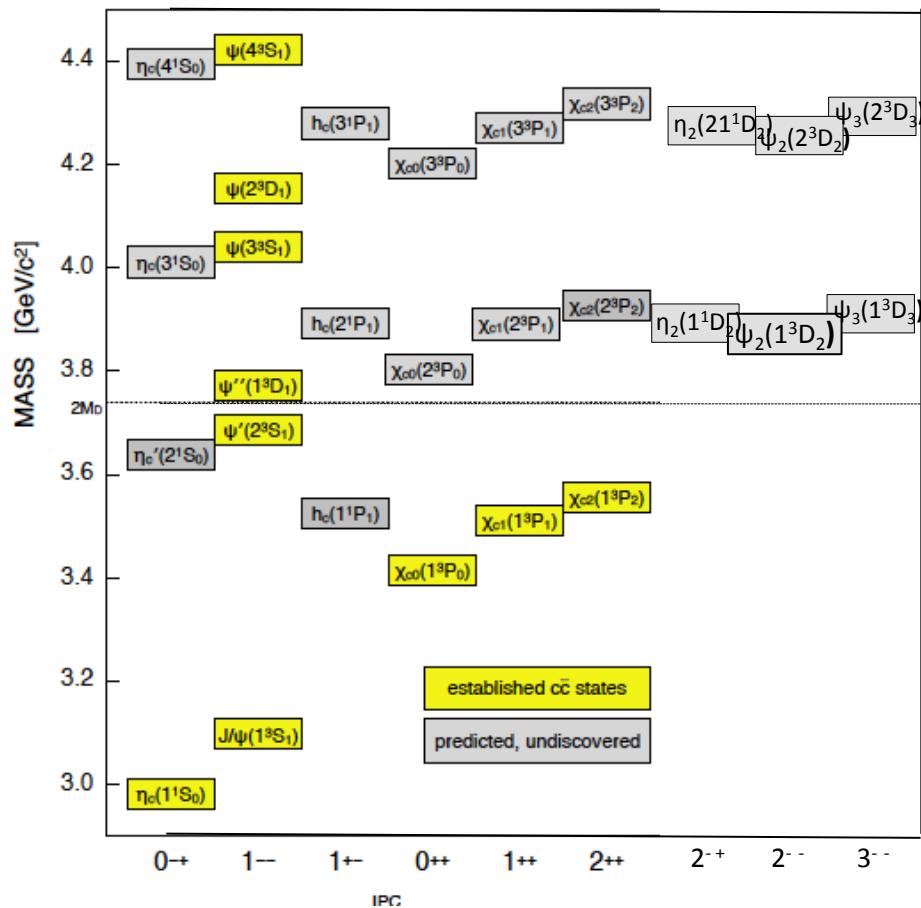


measured &
predicted masses agree

OZI-rule applies
no exceptions

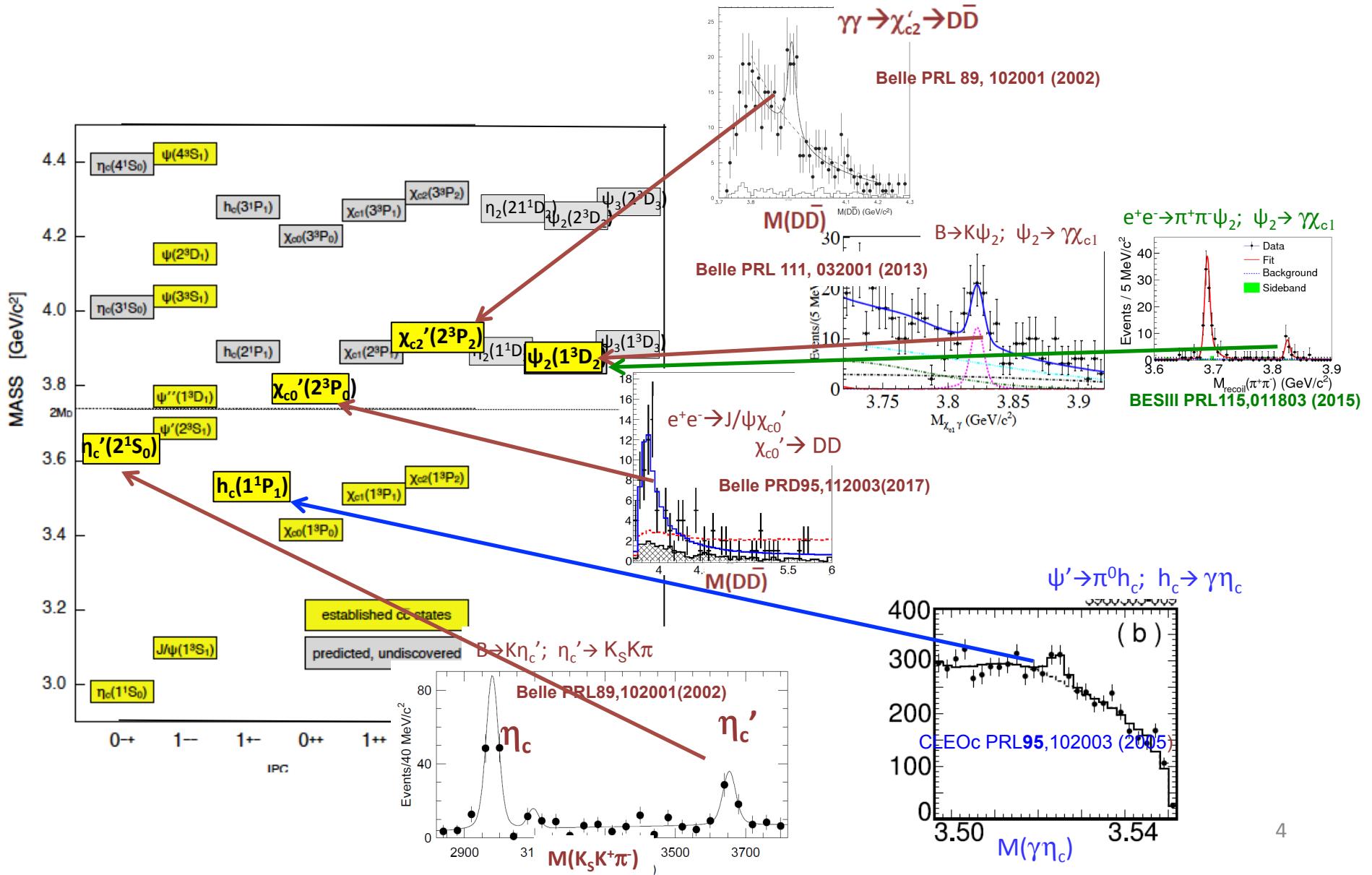


charmonium: pre B-factory plans for the B-factory era

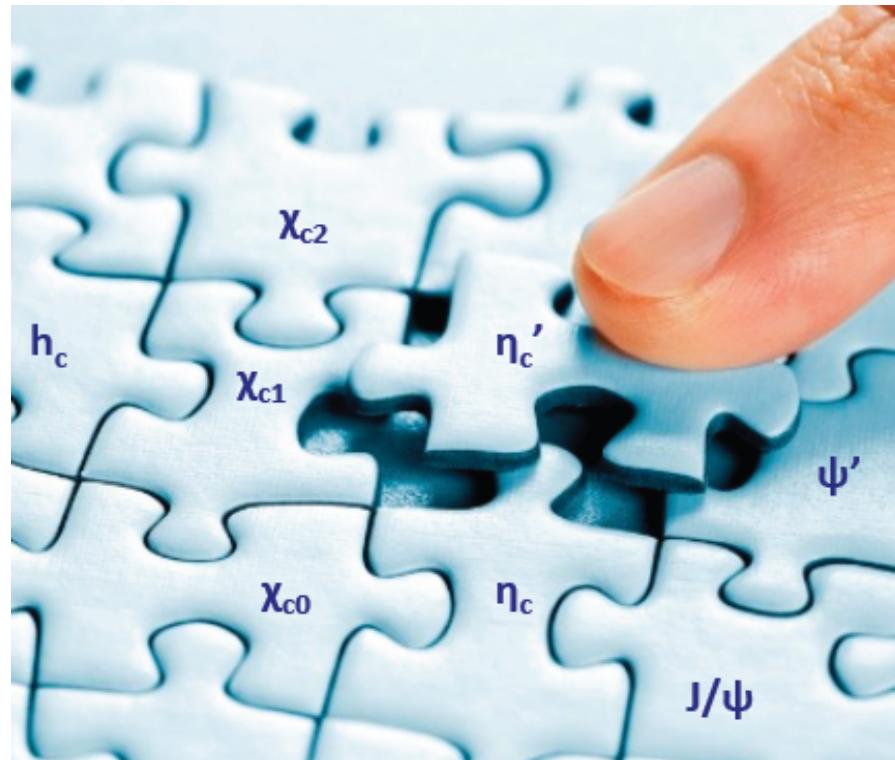


Turn the grey boxes into yellow ones

charmonium: post B-factory era

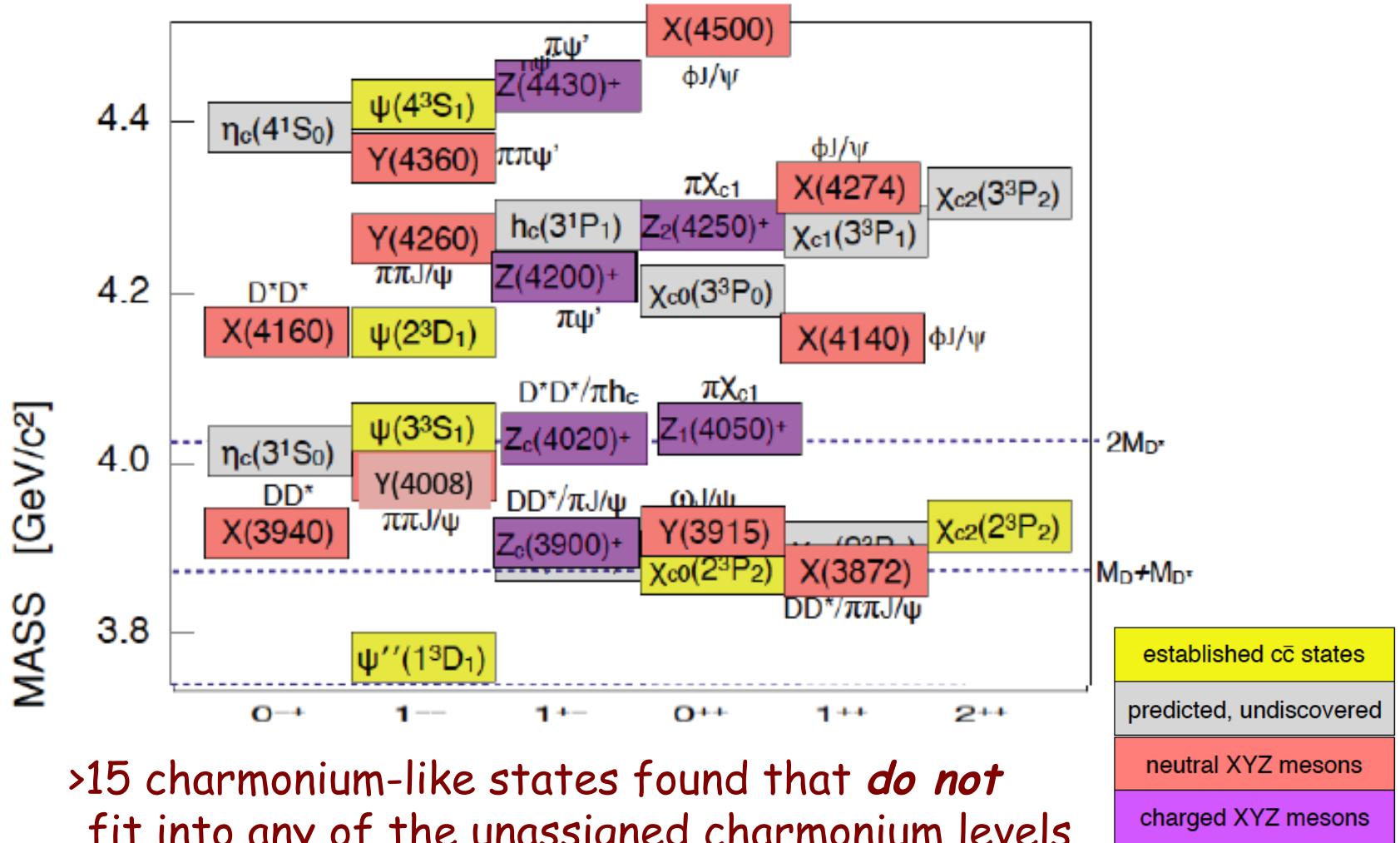


correct assignments “snap” into place

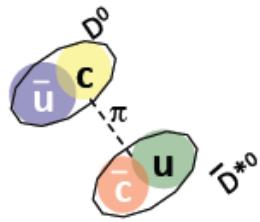


if you have to push hard, be careful ...

there are many others



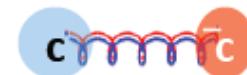
what are they?



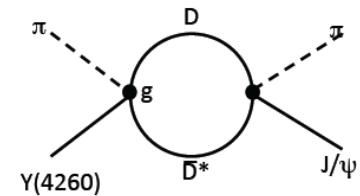
molecules?



QCD tetraquarks?

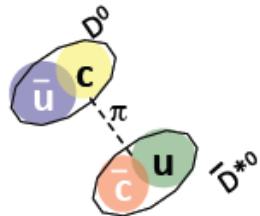


QCD hybrids?



threshold cusps?

Molecules

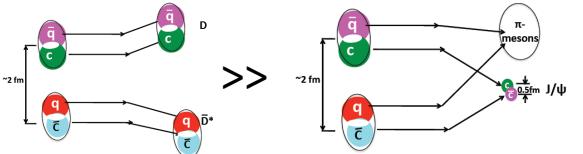


Karliner & Skwarnicki (PDG 2016):

masses near thresholds $d_{\text{rms}}^{-1} \approx a^{-1} = \sqrt{2\mu|BE|} < m_\pi \Rightarrow BE < \frac{m_\pi^2}{2\mu} \approx 10 \text{ MeV}$

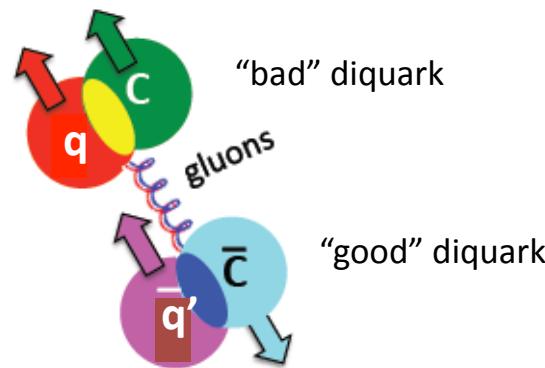
J^{PC} consistent with S-wave e.g.: $J^{PC} = 1^{++} \Leftarrow$ for $D\bar{D}^*$; $0^{++} \Leftarrow$ for $D\bar{D}$

fall-apart decays $>>$ hidden charm modes



no $0^- \oplus 0^-$ molecules

QCD tetraquarks



since spin force $\sim 1/m_Q$, “bad” diquarks are not so bad

Maiani et al., PRD 71, 014028 (2005)

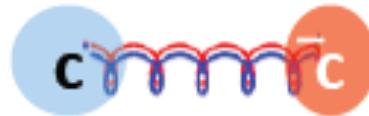
most masses and J^{PC} values are accessible for $[cq][\bar{c}\bar{q}']$

since QCD is flavor blind, $q \rightarrow u, d, s$ partner states allowed
(usually not seen)

“dynamical” diquarks: partner states suppressed
(predictability lost)

Brodsky, Hwang, Lebed, PRL 113, 112001 (2014)

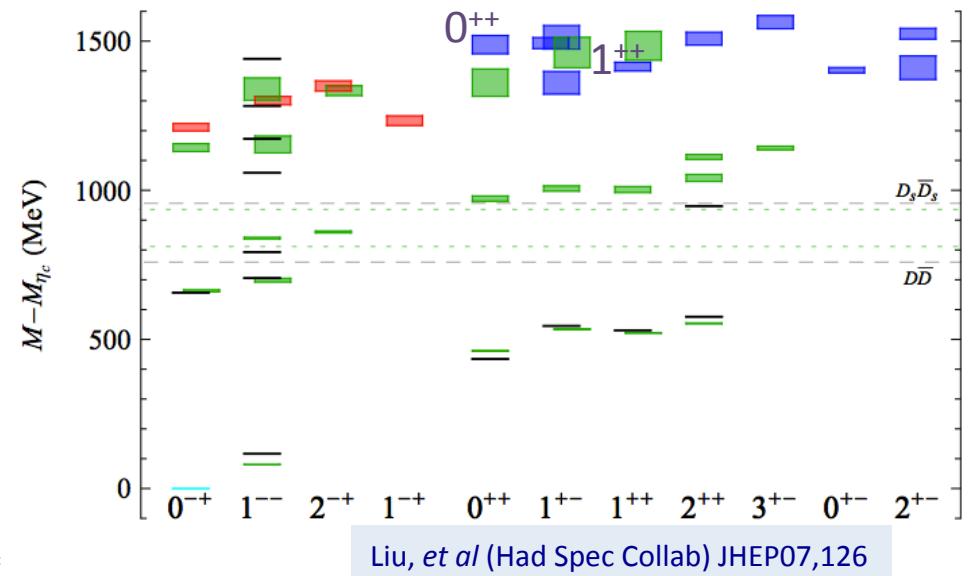
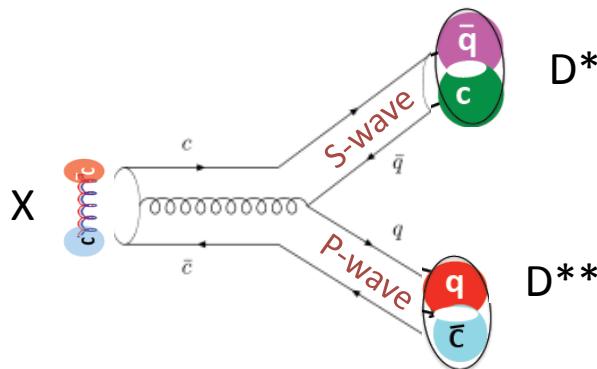
charmonium hybrids



LQCD ($m_\pi=400$ MeV) predicts high masses
(e.g.: $0^{++}\approx 4.5$ GeV; $1^{++}\approx 4.4$ GeV)

no charged states

decays to S-wave \oplus P-wave preferred



Thresholds cusps

at threshold: $\text{Im } T \propto g^2 \rho(s)$

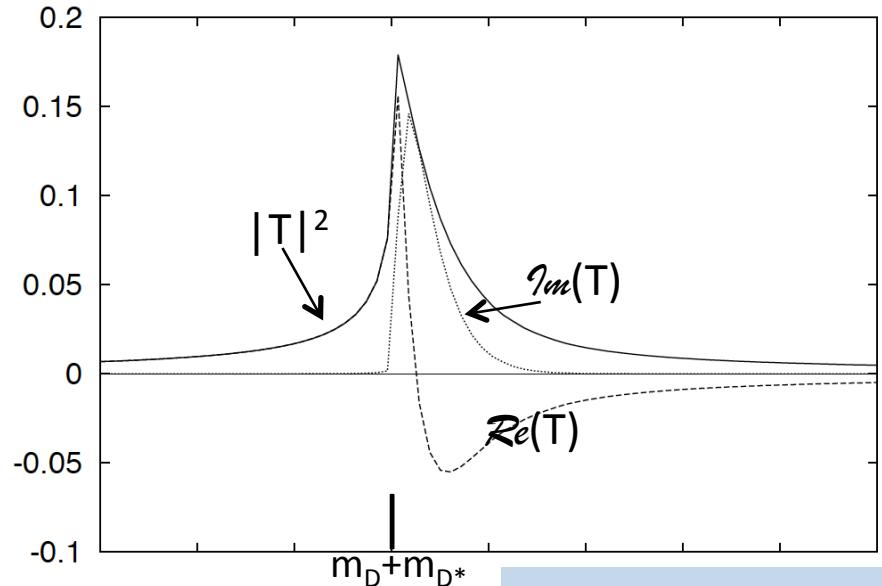
truncate with a form-factor:

$$\text{Im } T \propto g^2 \frac{2k}{\sqrt{s'}} FF(s')$$

use analyticity to get real part:

$$\text{Re } T \propto \frac{1}{\pi} P \int_{s_{thr}}^{M_Y^2} \frac{ds' \text{Im } T}{s' - s}$$

peaks just above threshold



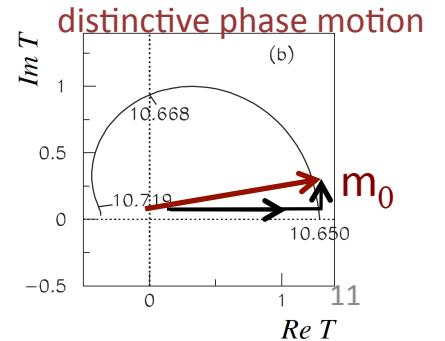
Bugg: EPL 96 11002 (2011)

similar widths for the $D\bar{D}^*$ ($B\bar{B}^*$) and $D^*\bar{D}^*$ ($B^*\bar{B}^*$) peaks

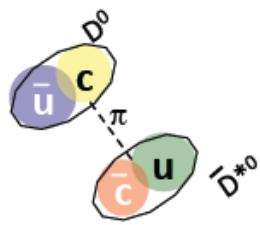
widths can depend on the decay channel

no signals in B meson decay

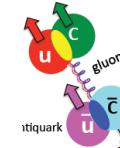
Swanson: PRD 91 034009 (2015)



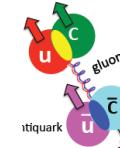
what are they?



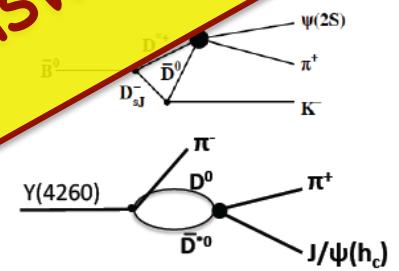
molecules?



QCD tetraquarks?



This question has been around for 16 years
and we still don't know the answer



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  Jan 1964

16 years ago

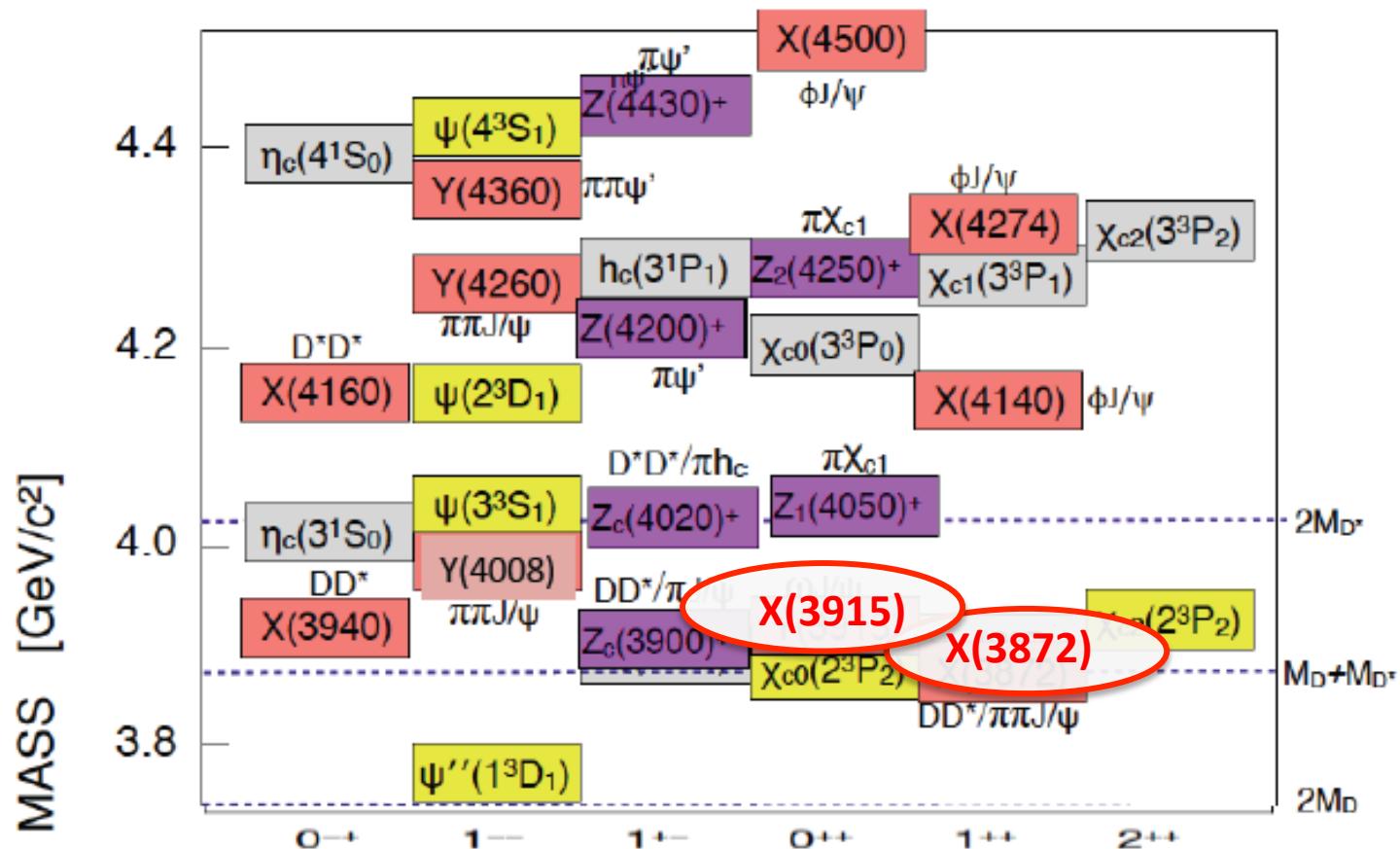
X(3872)

discovered -- *molecule? – diquark? – molecule? – diquark? – diquark? – molecule?* -- ????

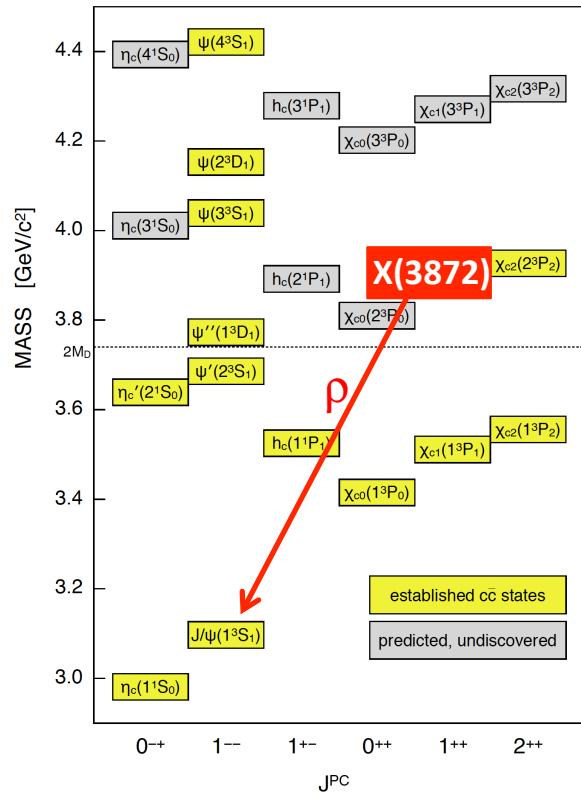
Aug. 2003  today

this talk

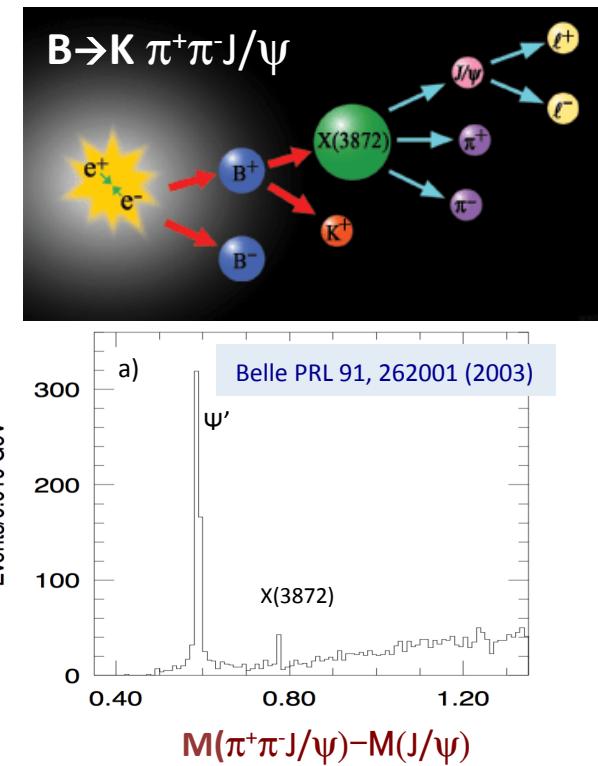
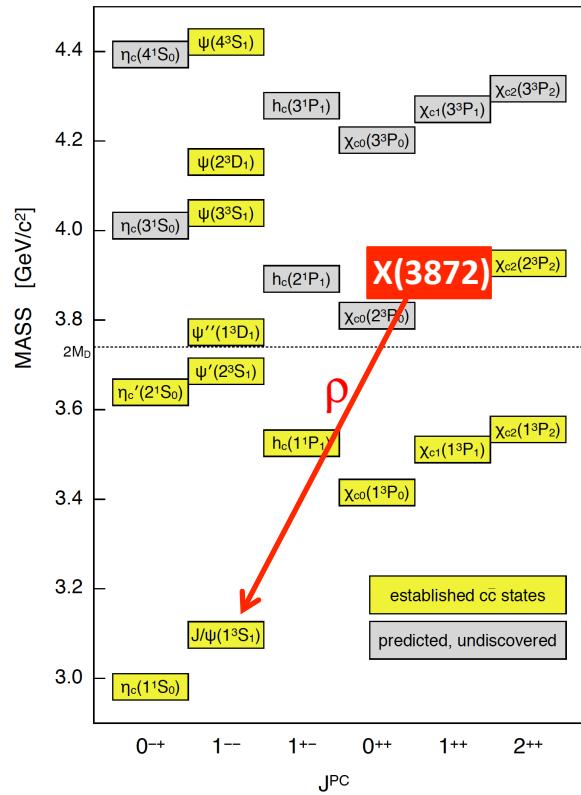
-- states not covered by others --



The X(3872)

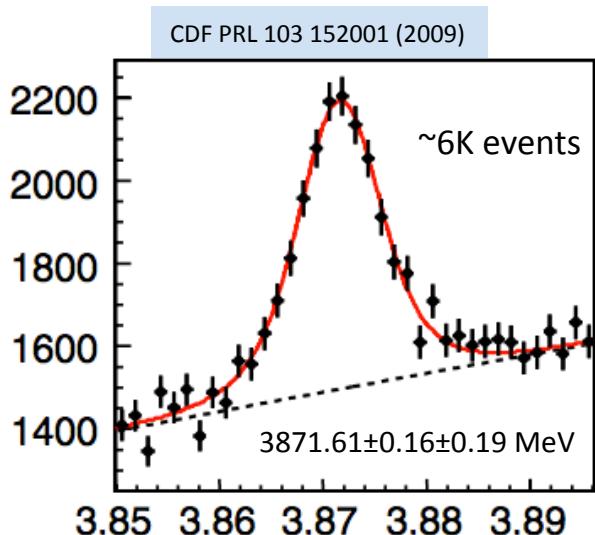


The X(3872)



mass and width

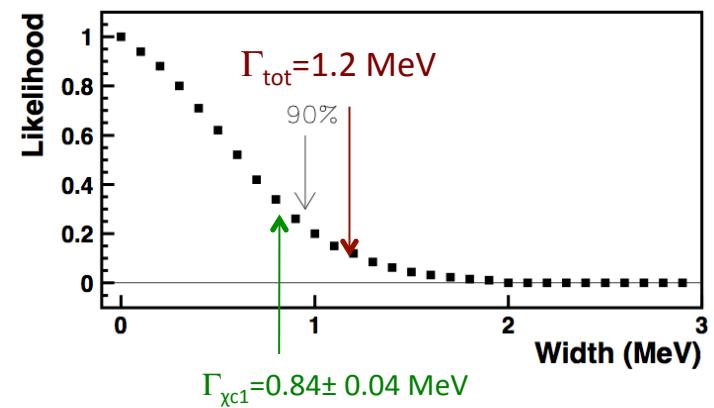
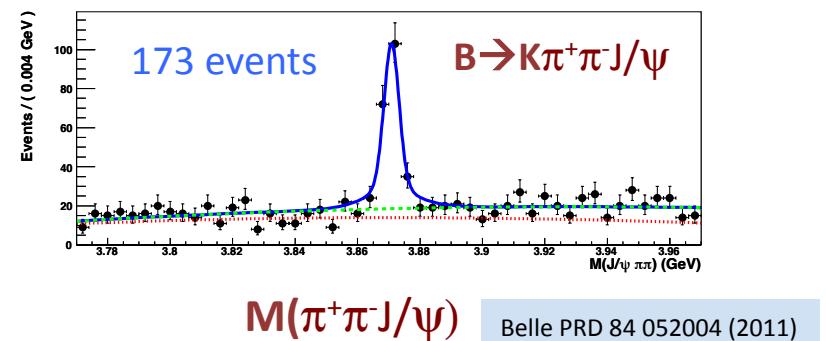
$X(3872)$ & $m_{D^0} + m_{D^{*0}}$
are indistinguishable



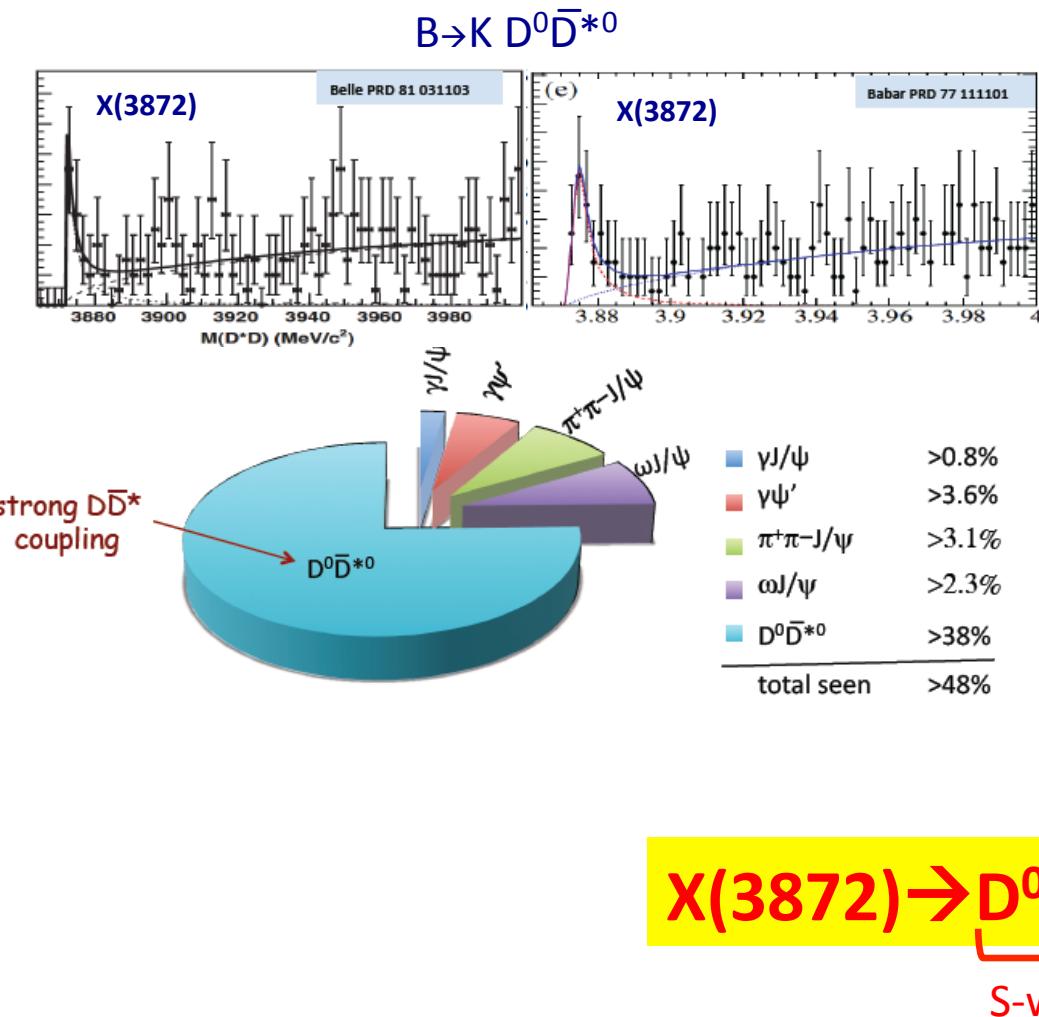
PDG17: $M_{X3872} = 3871.69 \pm 0.17$
 $m_{D^0} + m_{D^{*0}} = 3871.85 \pm 0.11$

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

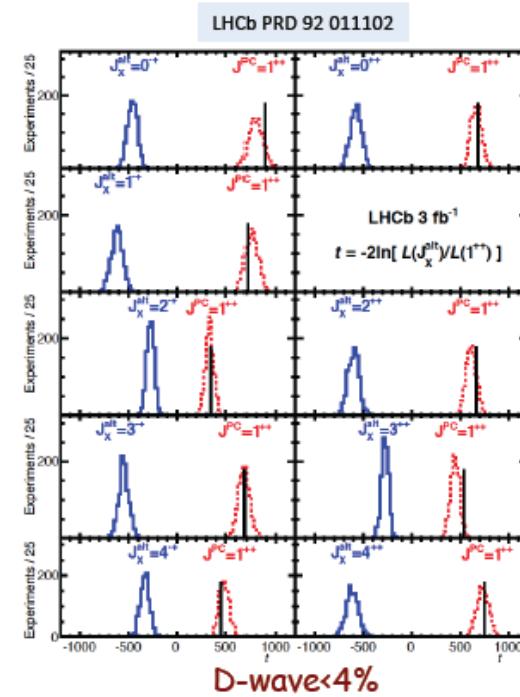
$\Gamma_{X(3872)}$ can't be much wider than $\Gamma_{\chi c1}$



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



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



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

S-wave

X(3872) *has* to be a “molecule”

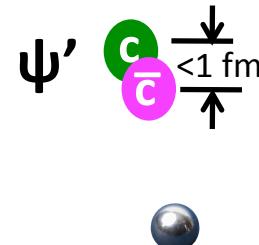
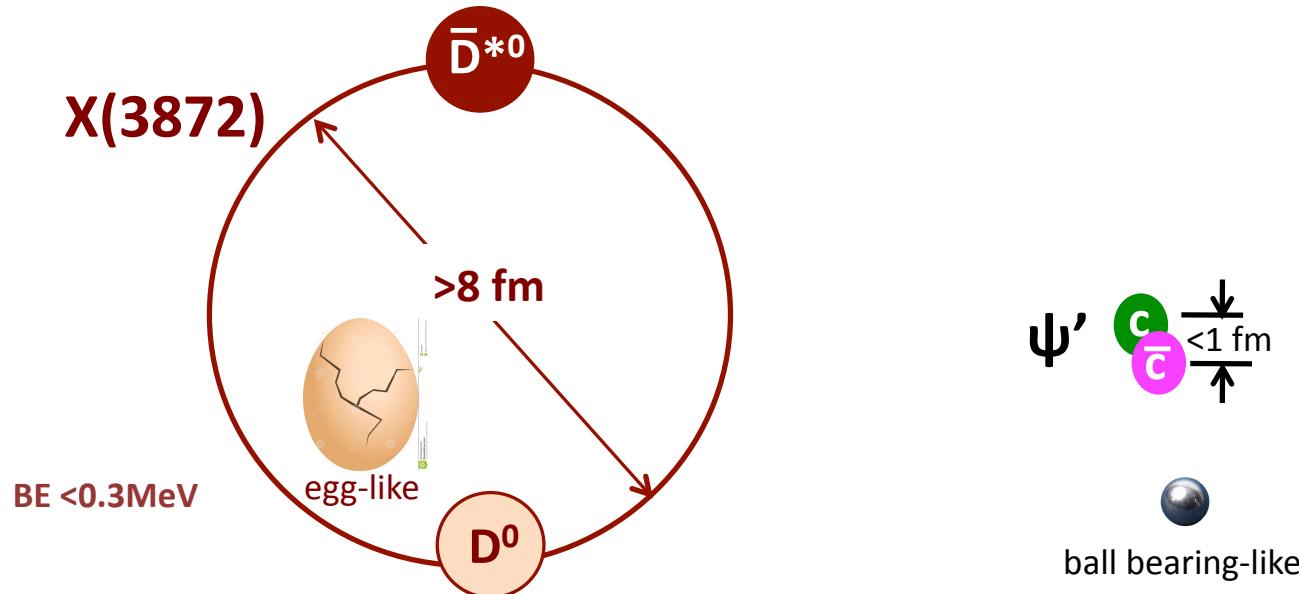
Independently of the original mechanism for the resonance, the strong coupling to $D\bar{D}^*$ in an S-wave & small “BE” imply unambiguously that the X(3872) must be either a molecule ($BE < 0$) or a virtual ($BE > 0$) $D\bar{D}^*$ state of size $\approx 1/\sqrt{2\mu_{D\bar{D}^*}|BE|} \geq 8 \text{ fm}$

PRD 76 094028

“scattering length”

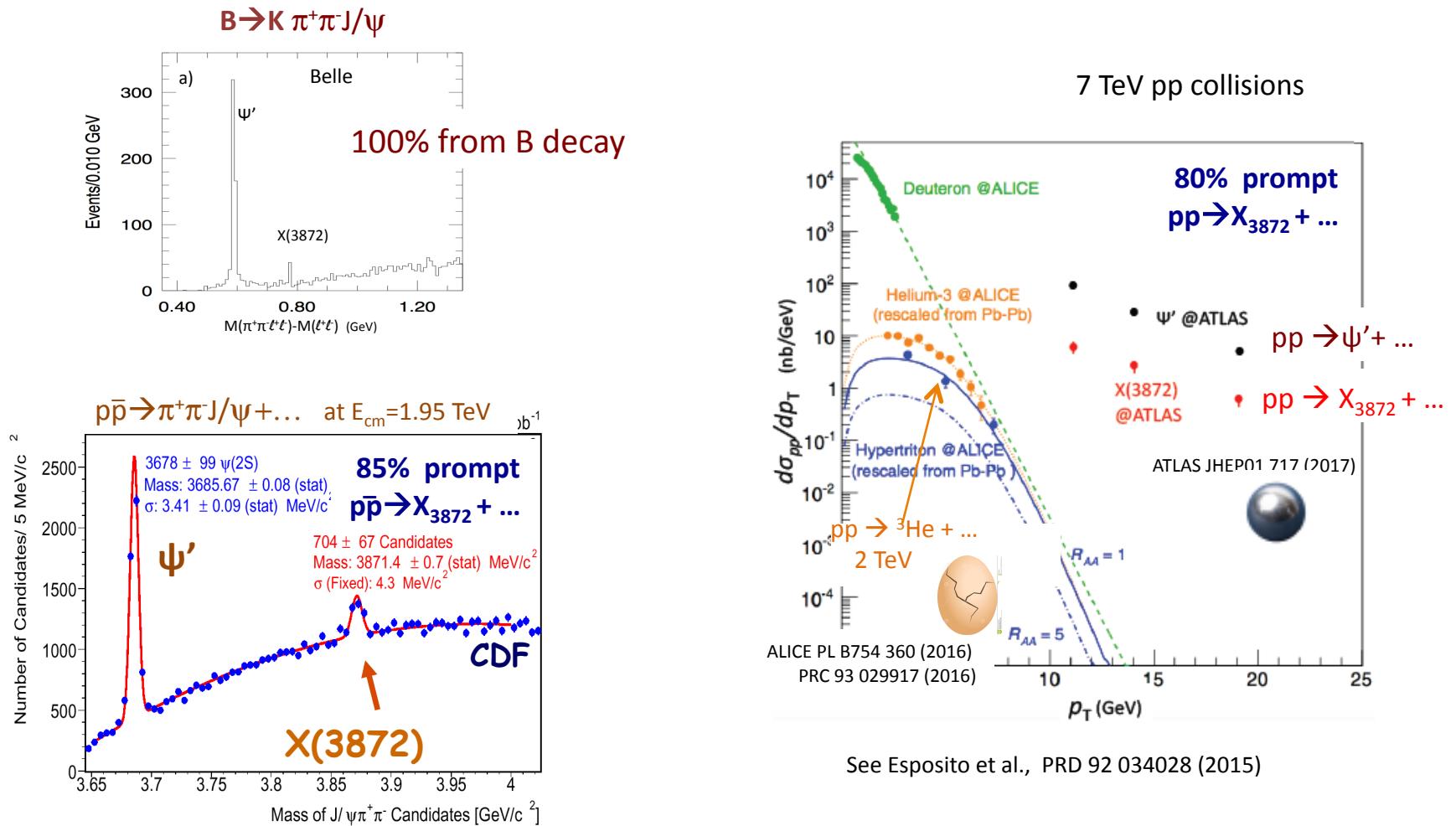


Eric Braaten

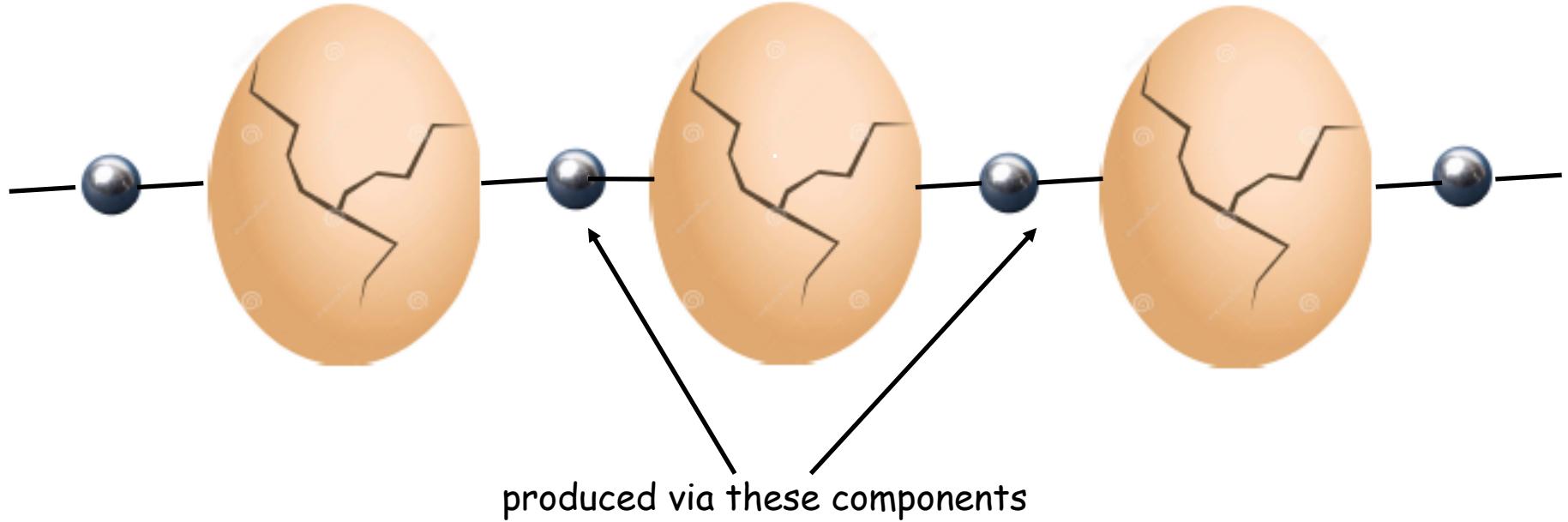


ball bearing-like

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

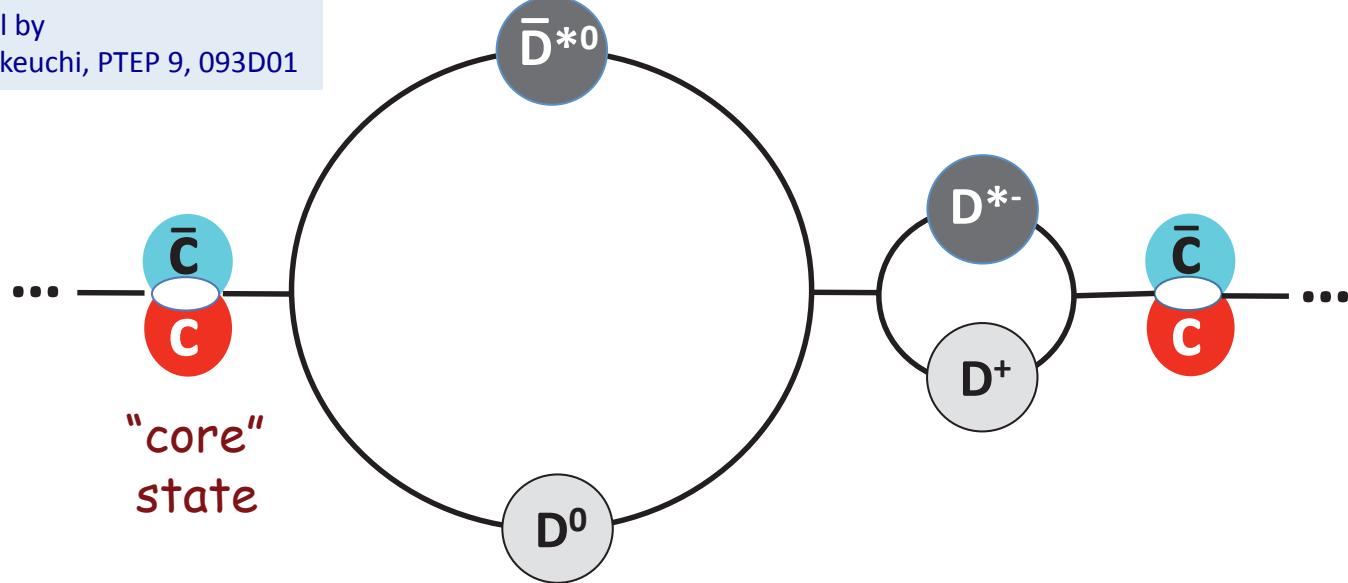


inescapable conclusion: QM mixture



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

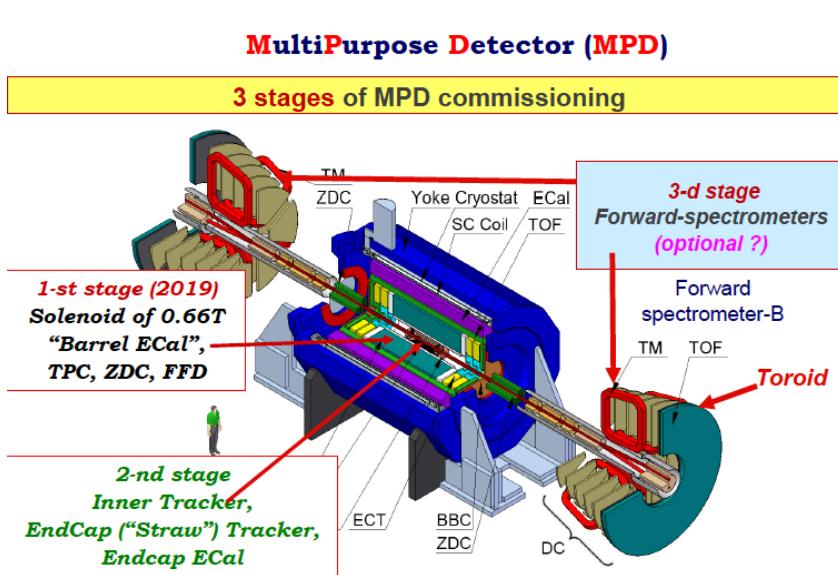
Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01



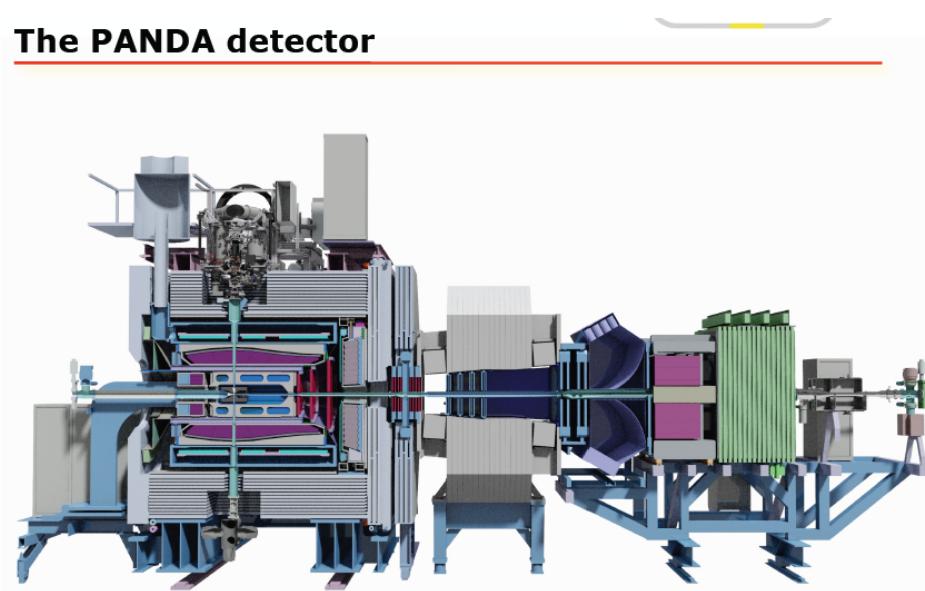
$$|X(3872)\rangle = 0.94|D^0\bar{D}^{*0}\rangle + 0.23|D^+\bar{D}^{*-}\rangle - 0.24|c\bar{c}\rangle$$

Probing the X(3872) in pp & pA

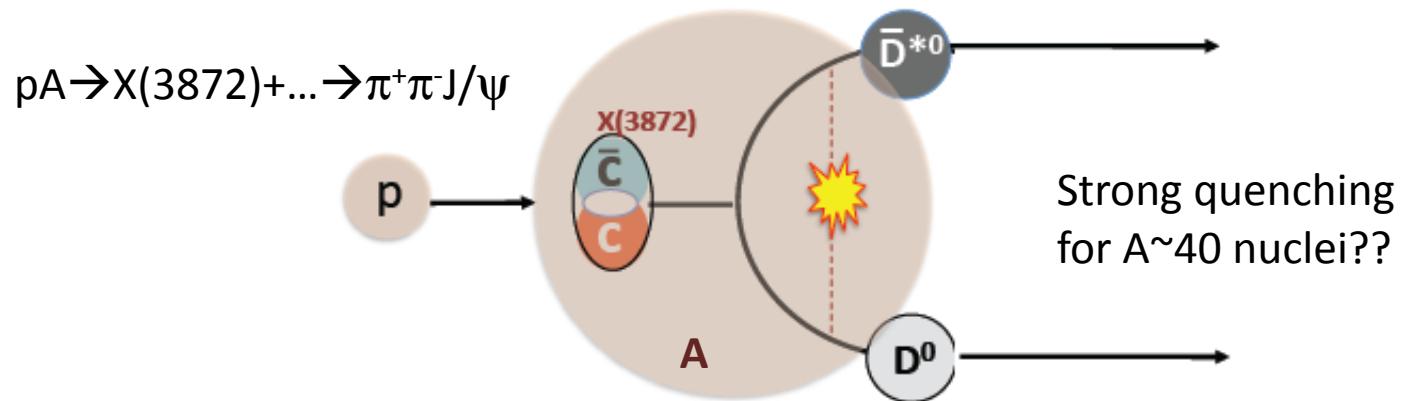
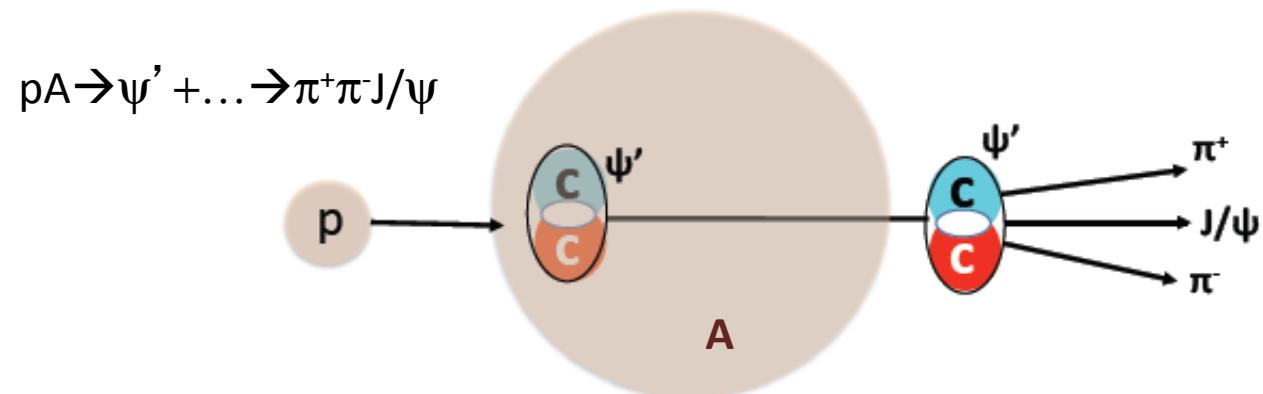
- at NICA and/or PANDA -



The PANDA detector



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



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

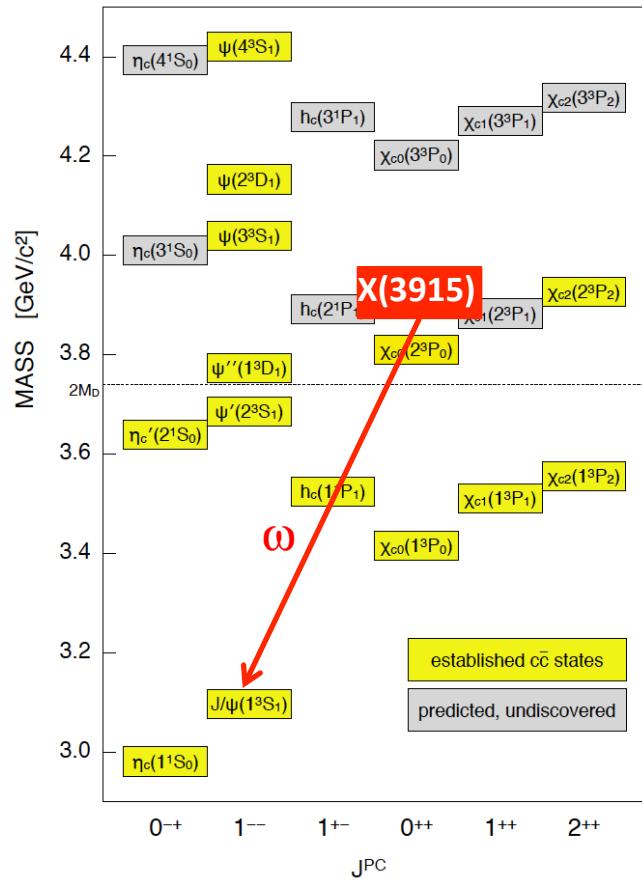
“original mechanism” = $c\bar{c}$ -core? ... $D\bar{D}^*$ molecule?



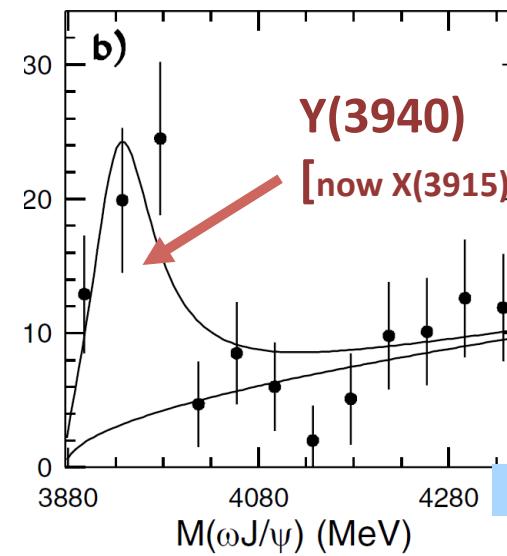
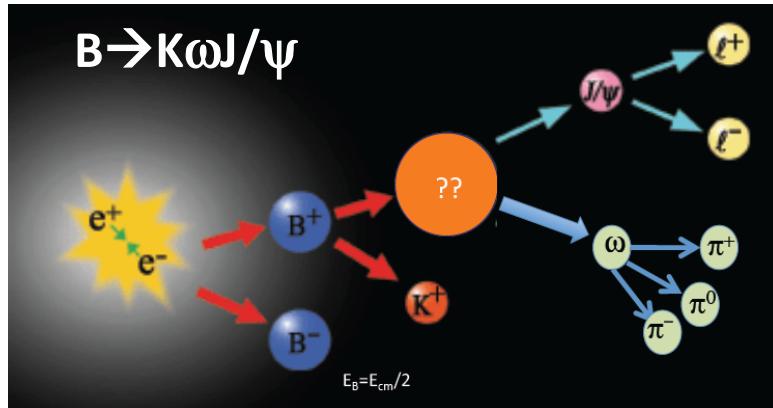
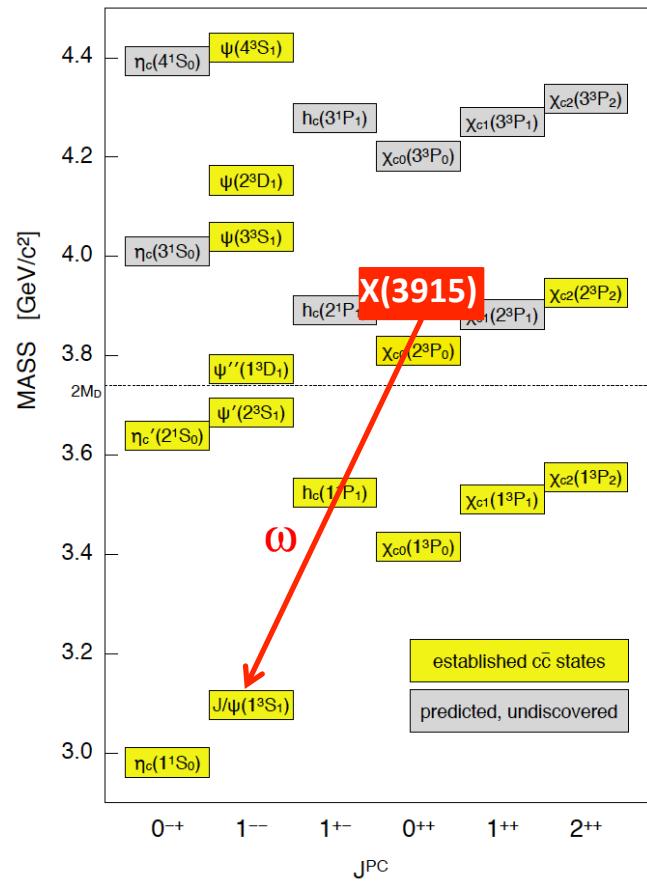
$c\bar{c}$ -core = χ_{c1}' ? ... diquark-dantiquark?



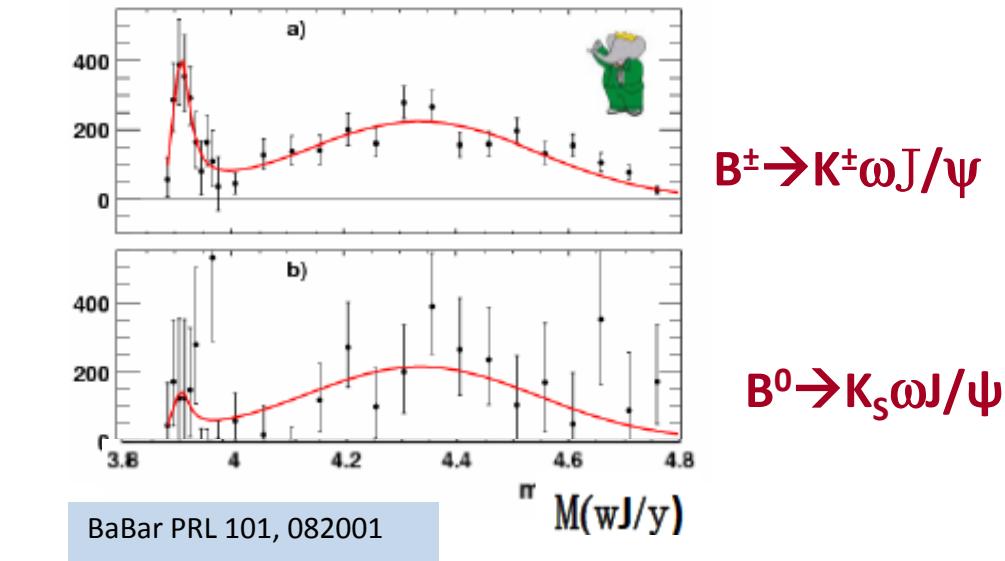
The X(3915)



The X(3915)



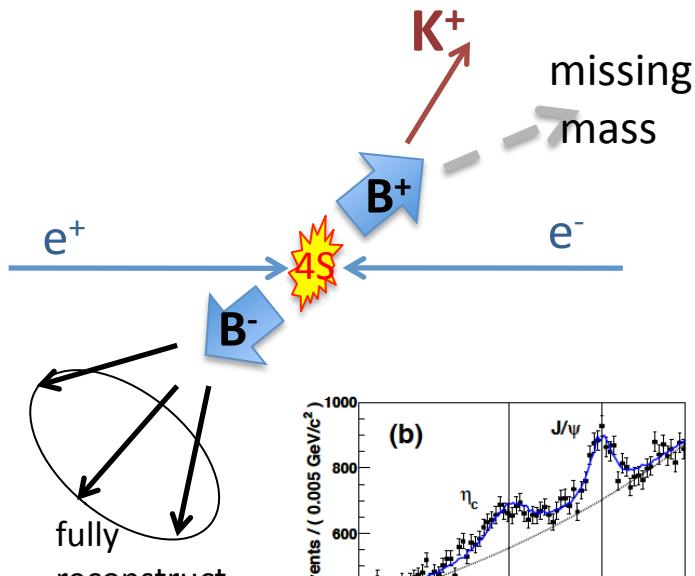
confirmed by BaBar



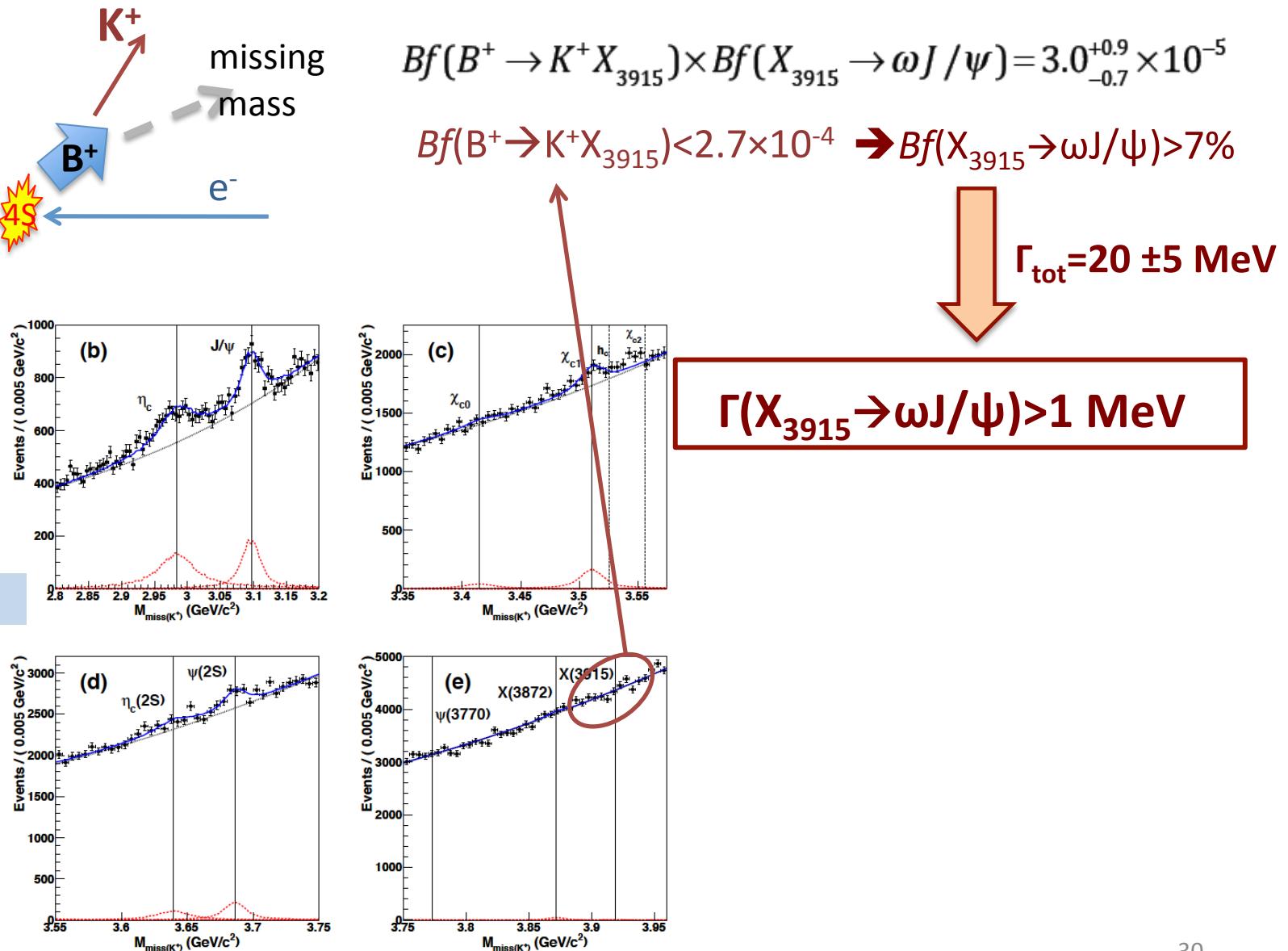
	Mass (MeV)	Γ (MeV)
Belle 253 fb ⁻¹	$3943 \pm 11(stat) \pm 13(syst)$	$87 \pm 22(stat) \pm 26(syst)$
BaBar 350 fb ⁻¹	$3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst)$	$33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst)$

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

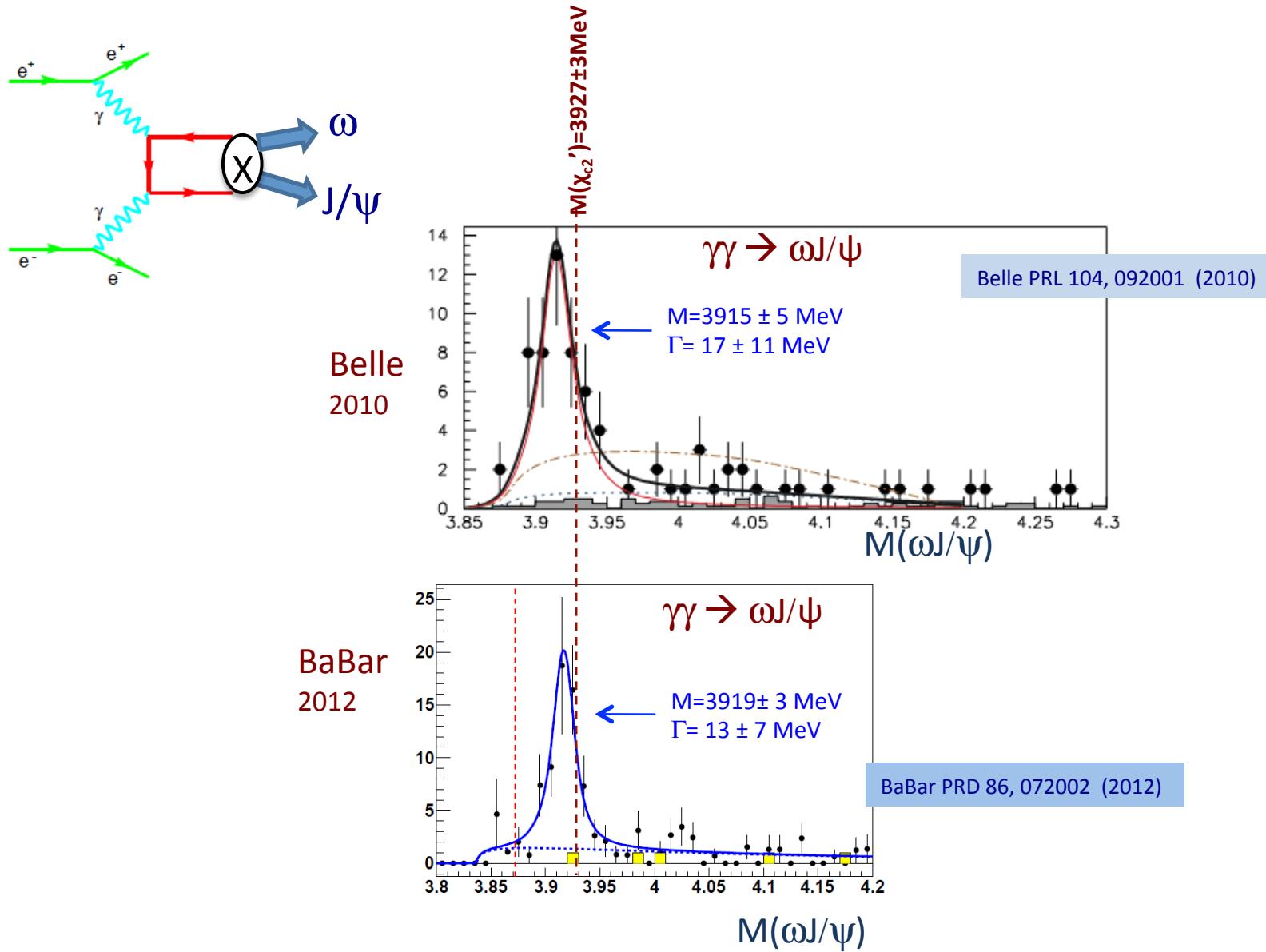
2018: lower limit on $\Gamma(X_{3915} \rightarrow \omega J/\psi)$



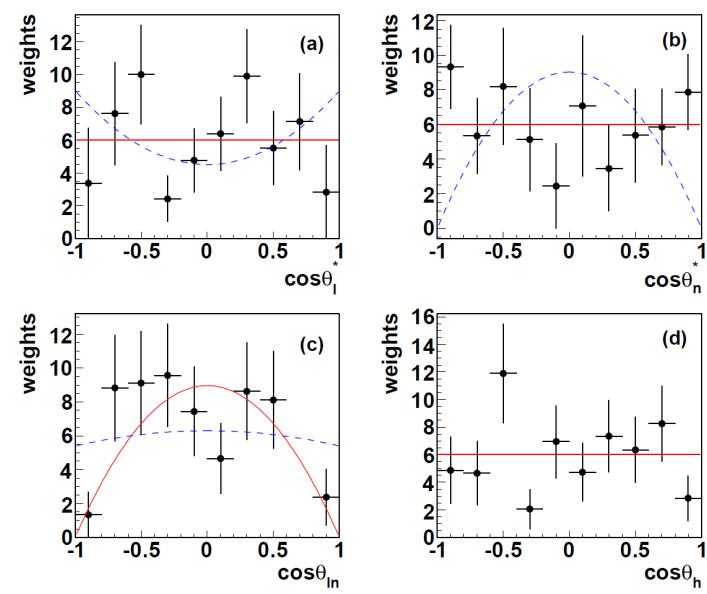
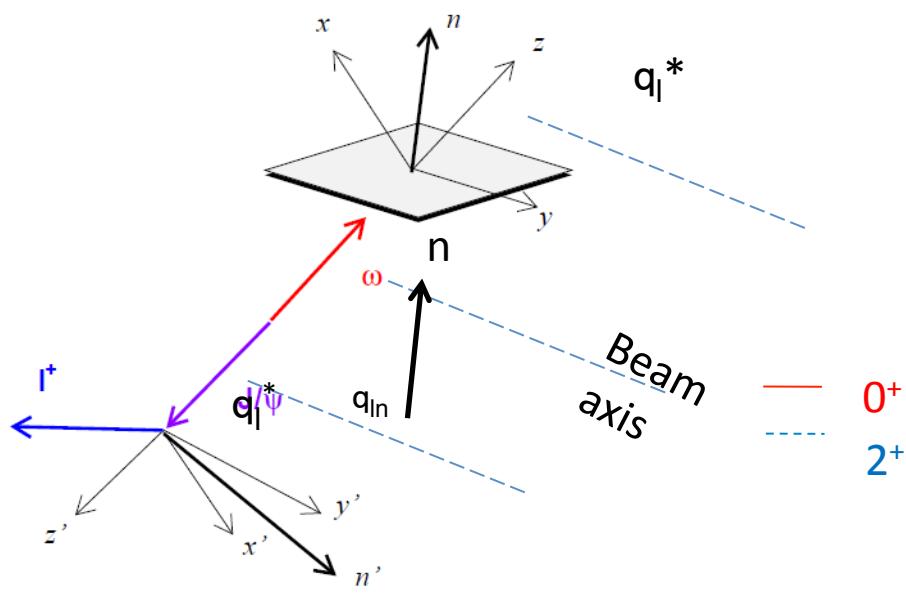
Belle PRD 97, 012005



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

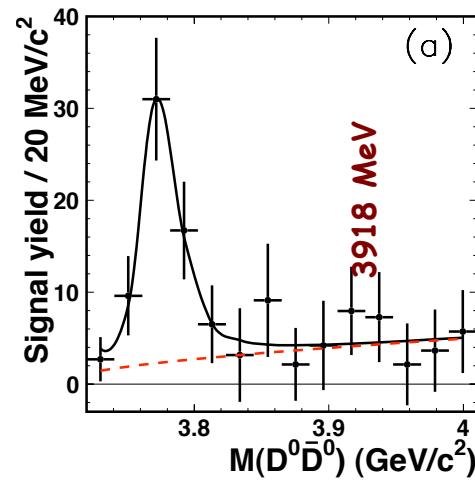
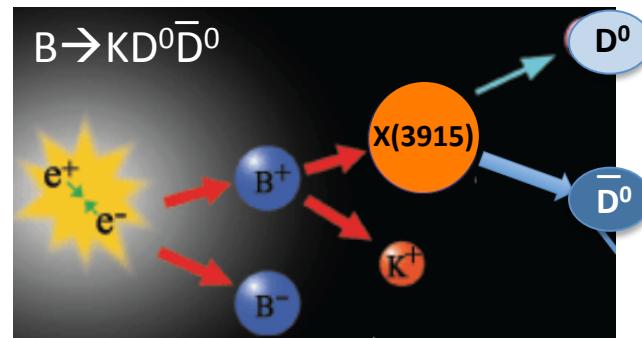


BaBar measurements prefer $J^{PC}=0^{++}$



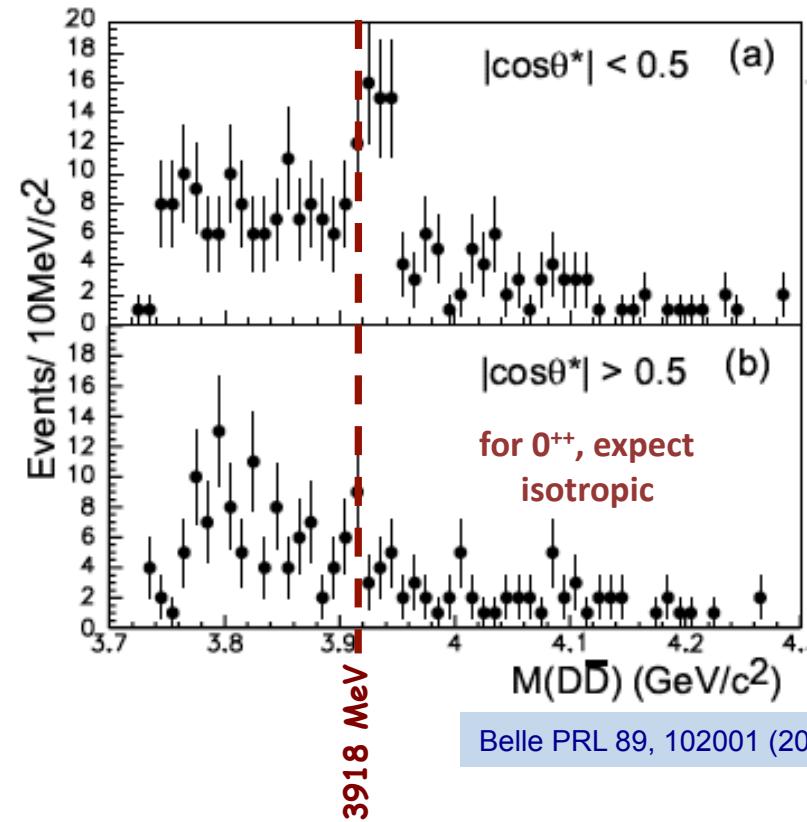
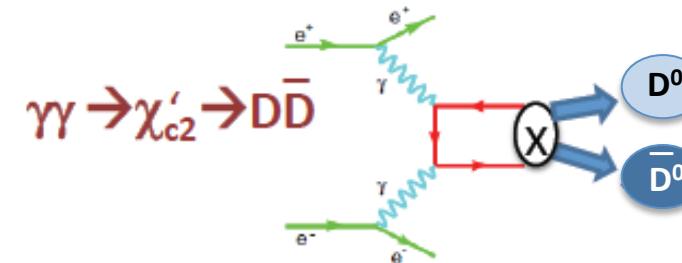
BaBar PRD 86, 072002 (2012)

no sign of $X(3915) \rightarrow D\bar{D}$?

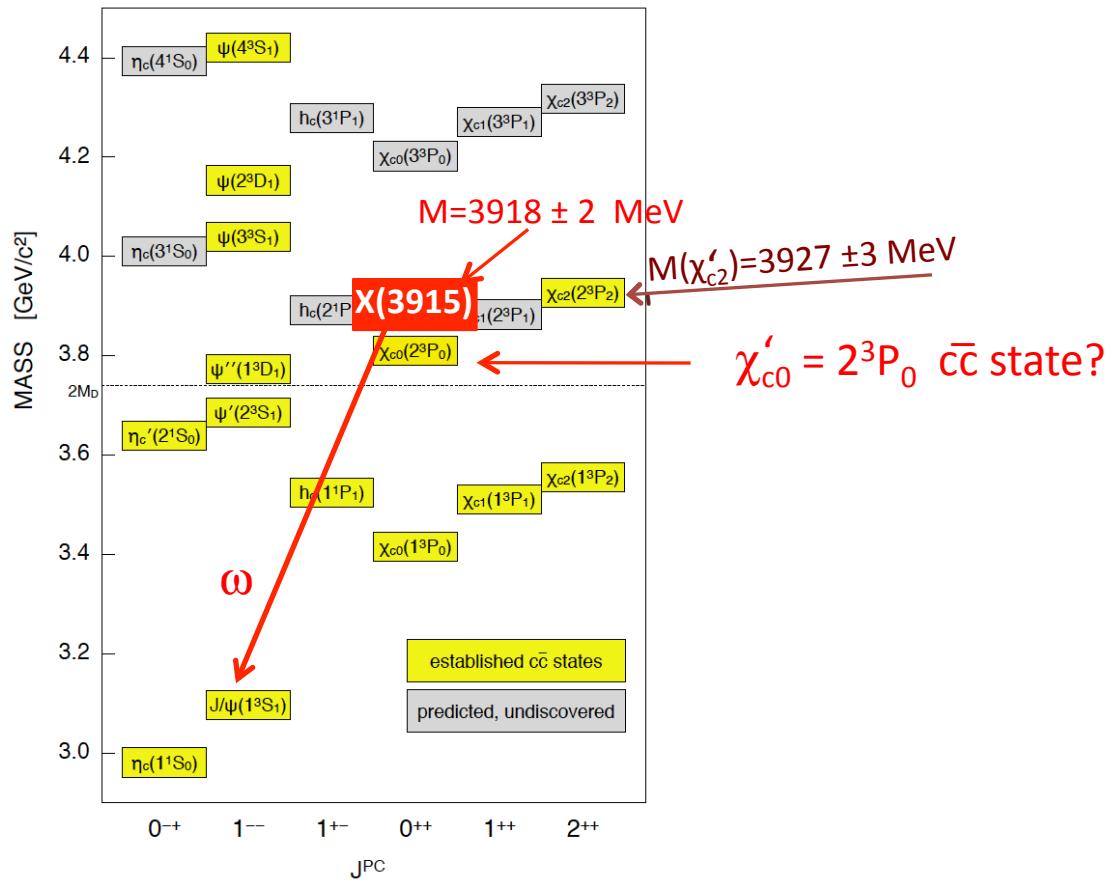


→ $\Gamma(X_{3915}) \rightarrow D\bar{D}) < 1 \text{ MeV}$

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

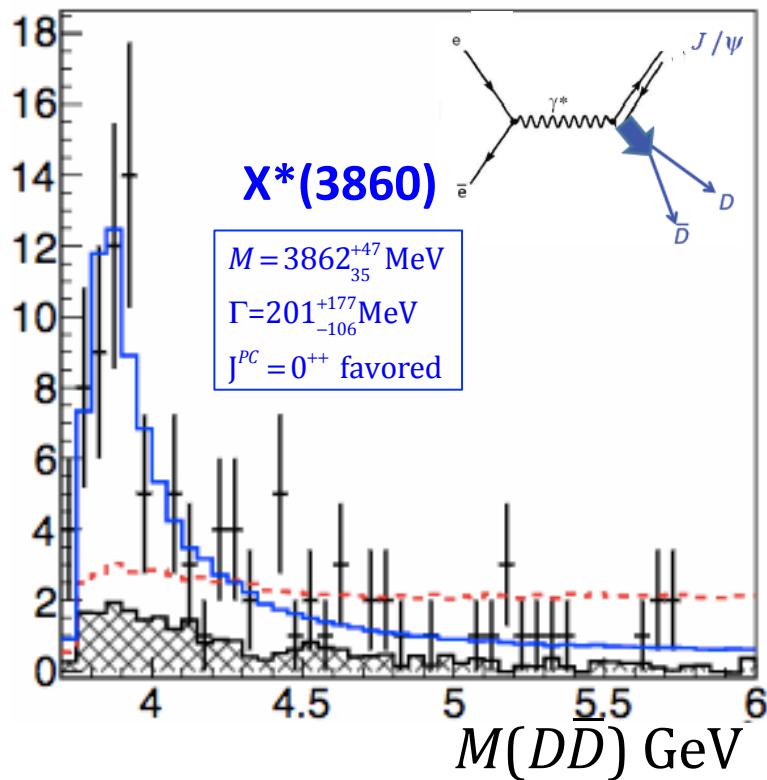


χ_{c0}' charmonium assignment for X(3915)?



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

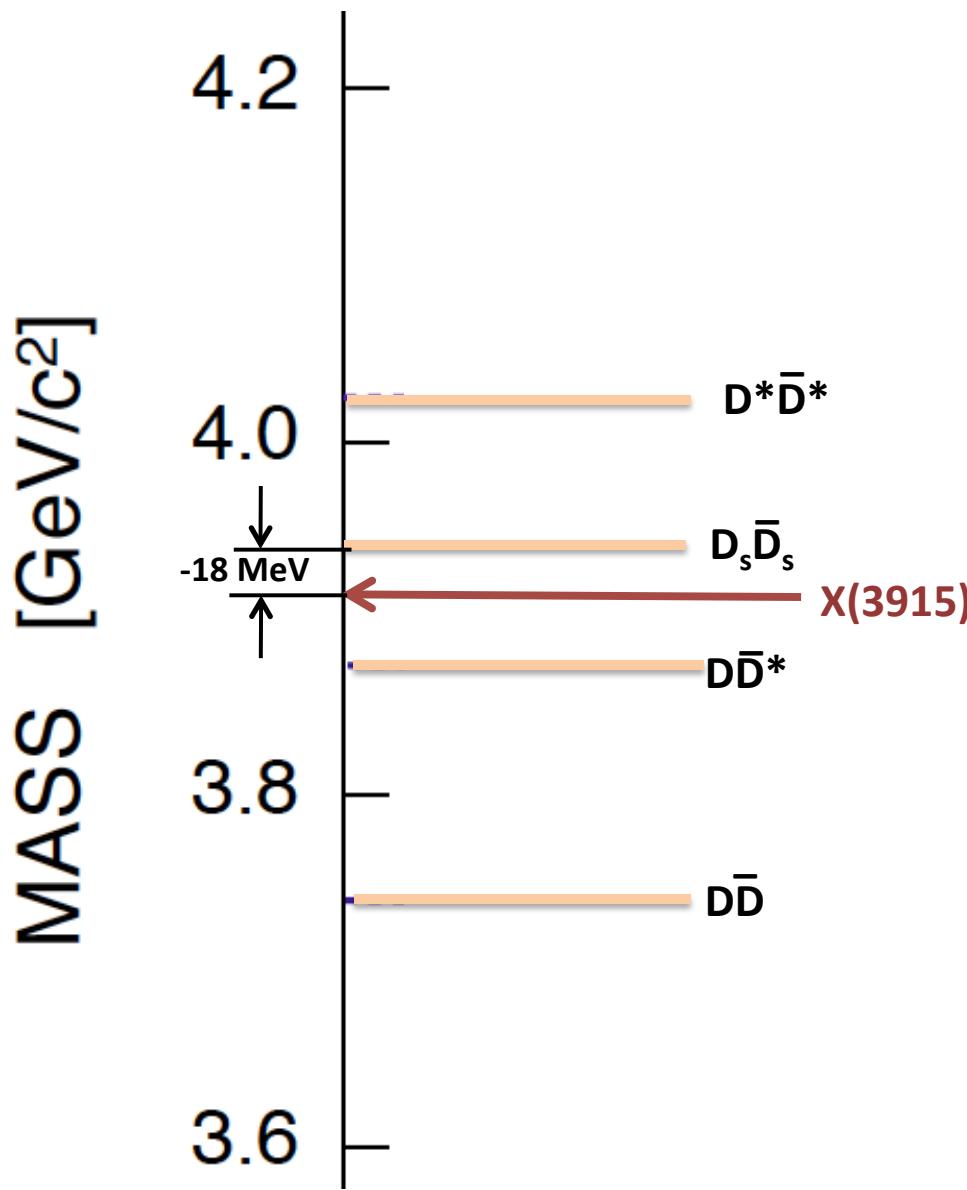
If $X(3915) \neq \chi_{c0}'$, what is it?

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

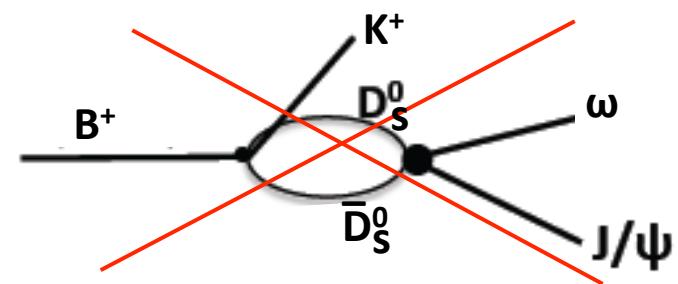
Mass is near $2m_{D_s}$ threshold: $M(X(3915)) = 2m_{D_s} - 18$ MeV

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

no nearby thresholds



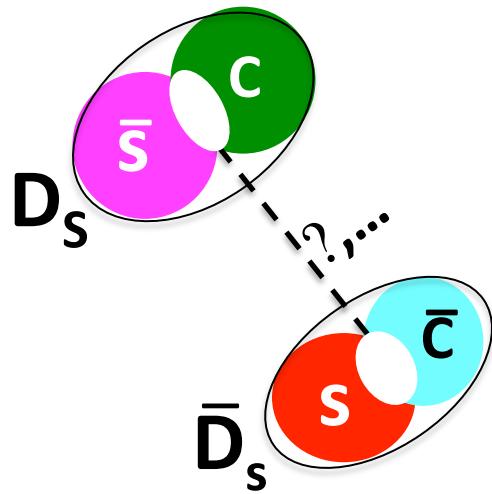
below $2m_{D_s}$ threshold
not a cusp, triangle
singularity, or the like



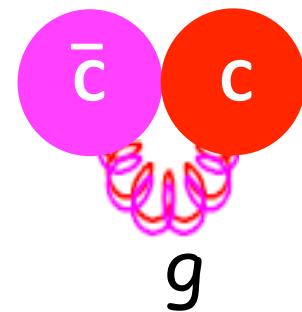
Possibilities

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

Li & Voloshin, PRD 91, 114014

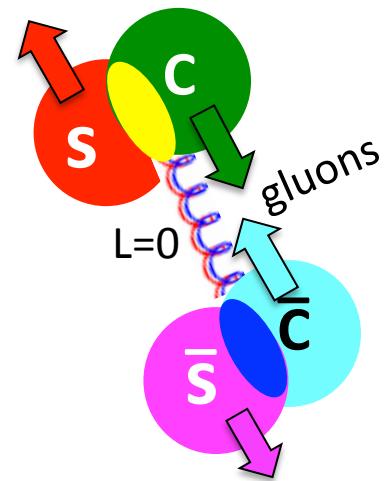


$c\bar{c}$ -gluon hybrid?



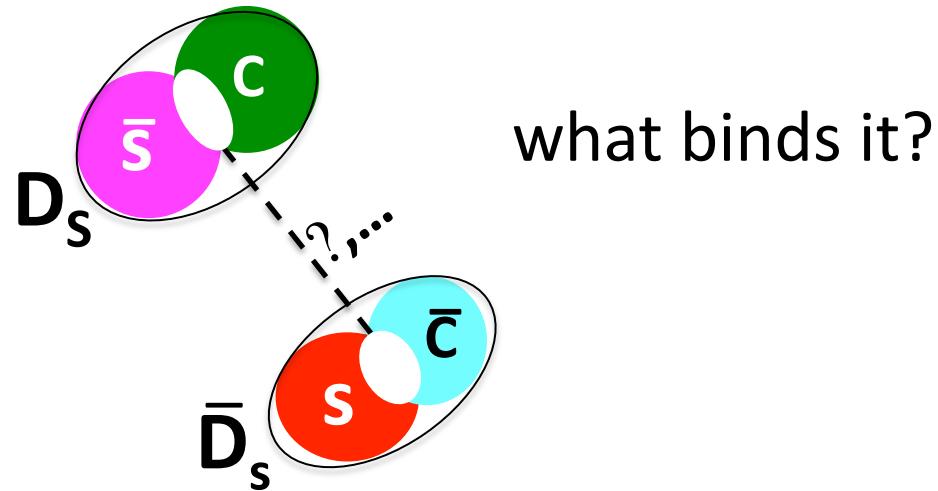
$[cs][\bar{c}\bar{s}]$ tetraquark?

Lebed & Polosa, PRD 93, 094024



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

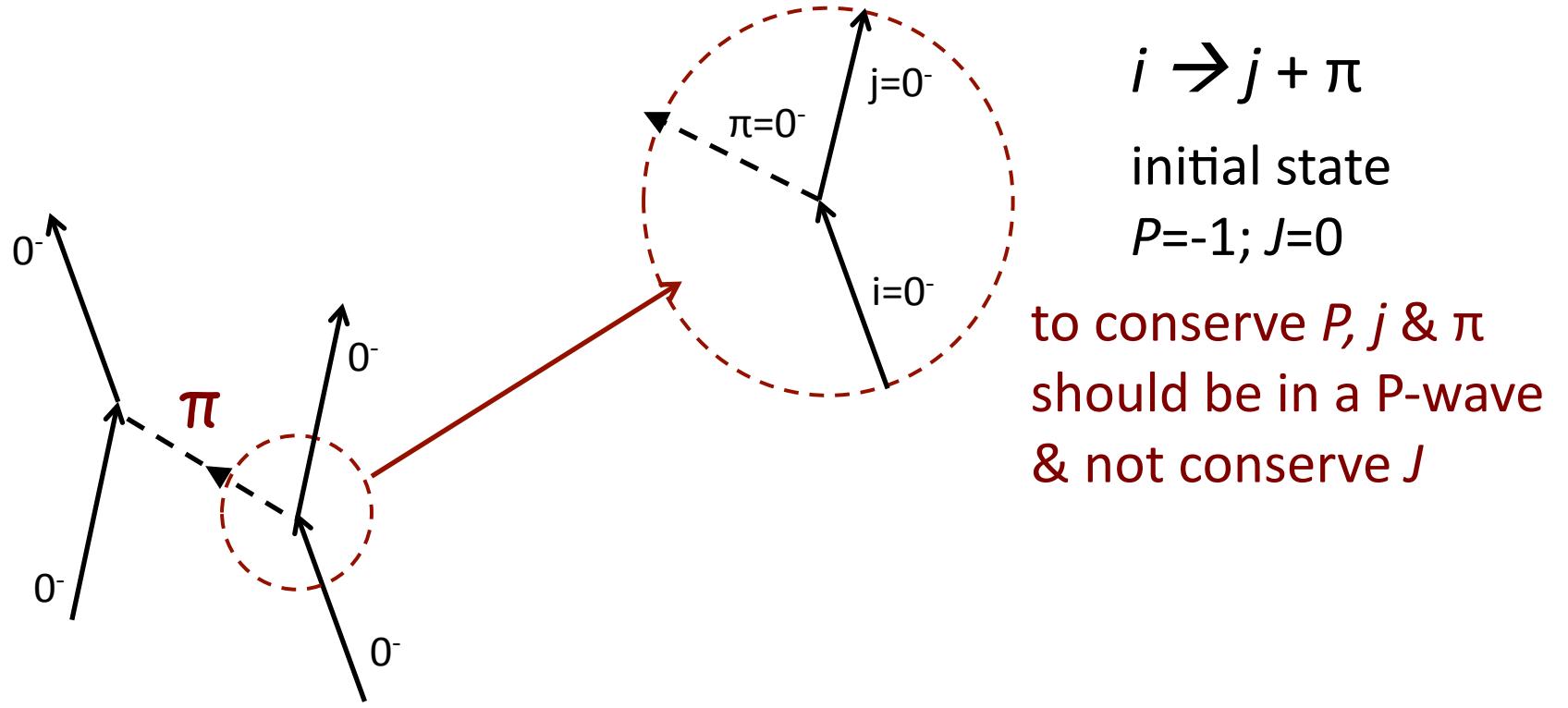
Li & Voloshin, PRD 91, 114014



$$"BE" = 2m_{D_s} - M_{X(3915)} \approx 18 \text{ MeV}$$

$$d_{\text{rms}} \approx \frac{1}{\sqrt{2\mu BE}} = 1 \text{ fm} \Leftarrow \langle m_\pi^{-1} \rangle$$

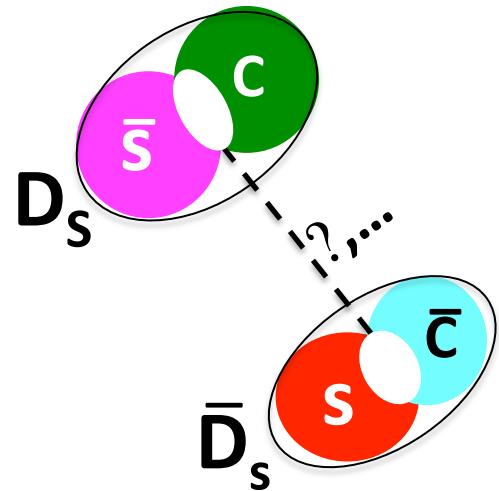
$0^- \leftrightarrow 0^- \pi$ -exchange violates Parity



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

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

Li & Voloshin, PRD 91, 114014



what binds it?

$$"BE" = 2m_{D_s} - M_{X(3915)} \approx 18 \text{ MeV}$$

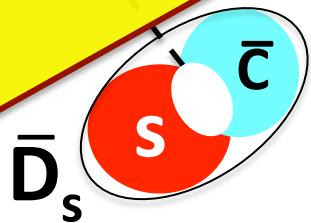
$$d_{\text{rms}} \approx \frac{1}{\sqrt{2\mu BE}} = 1 \text{ fm} \Leftarrow \langle m^{-1} \rangle$$

need a non- π -exchange
binding mechanism

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

Li & Voloshin, PRD 91, 114014

X(3915) is not a good candidate for a molecule
what binds it?

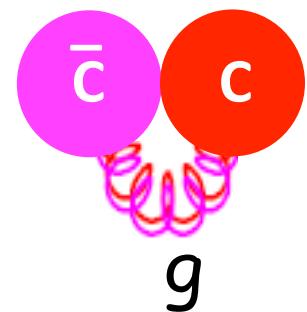


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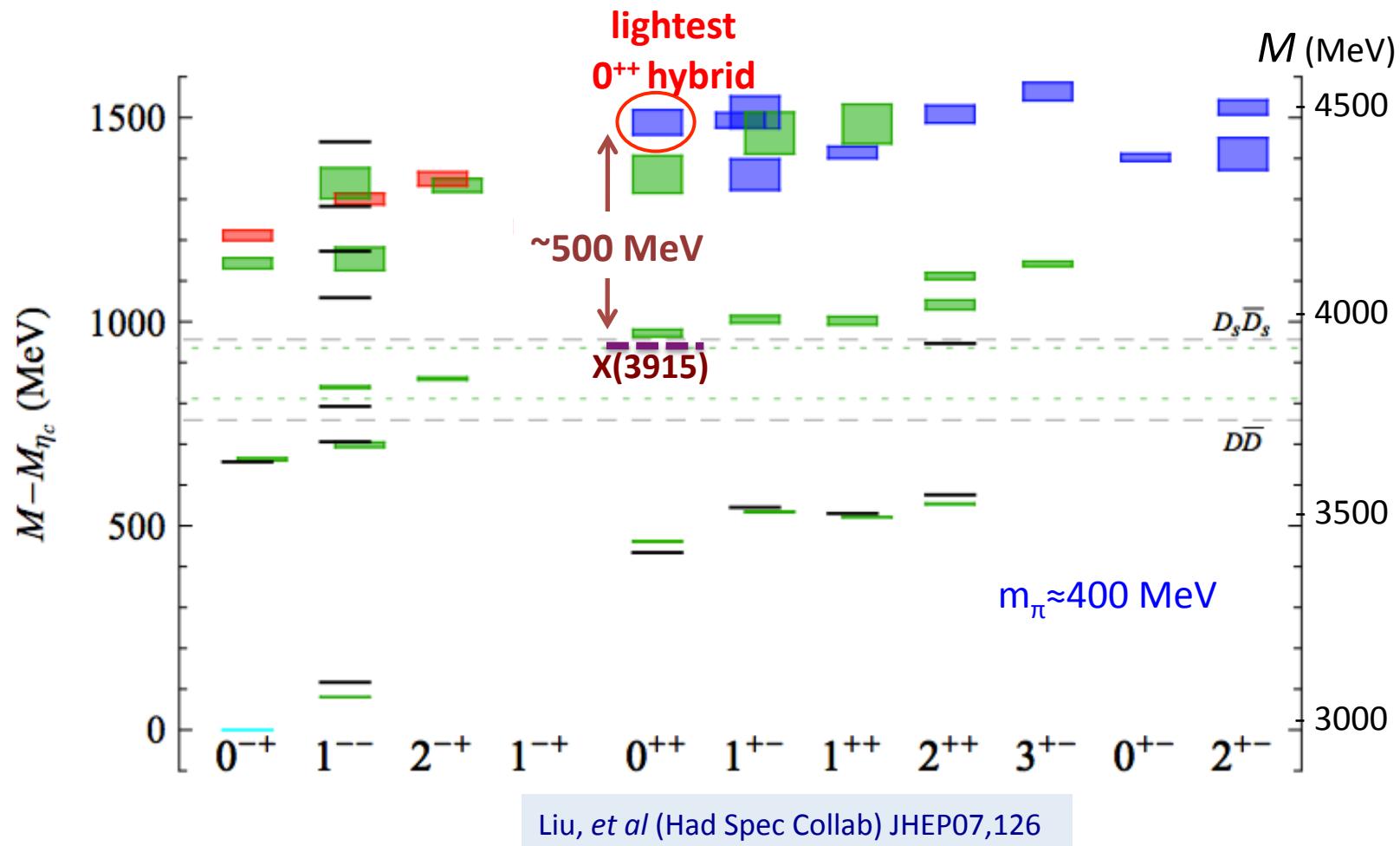
X(3915) as a $c\bar{c}$ -gluon hybrid?



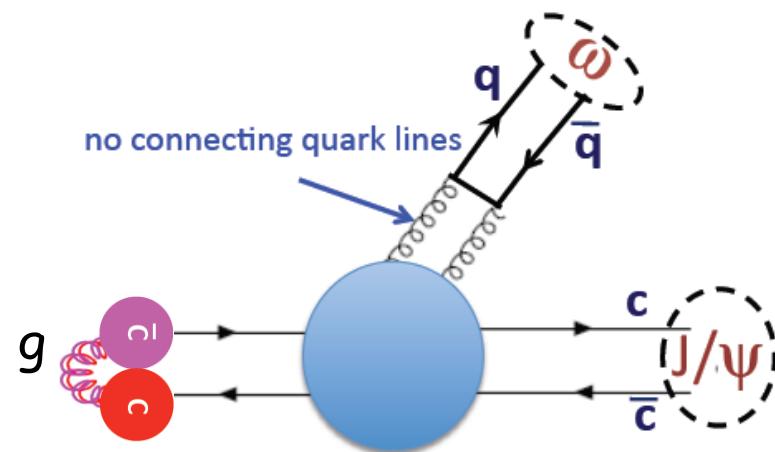
too light for $0^{++} c\bar{c}$ -hybrid?

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

-- Lattice QCD calculation --



$c\bar{c}$ -gluon $\rightarrow \omega J/\psi$ is OZI suppressed



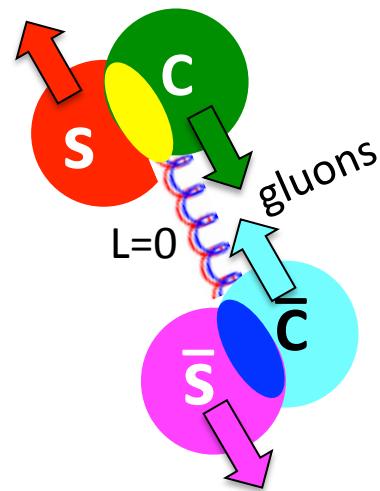
$$\Gamma(X_{3915} \rightarrow \omega J/\psi) > 1 \text{ MeV}$$

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

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

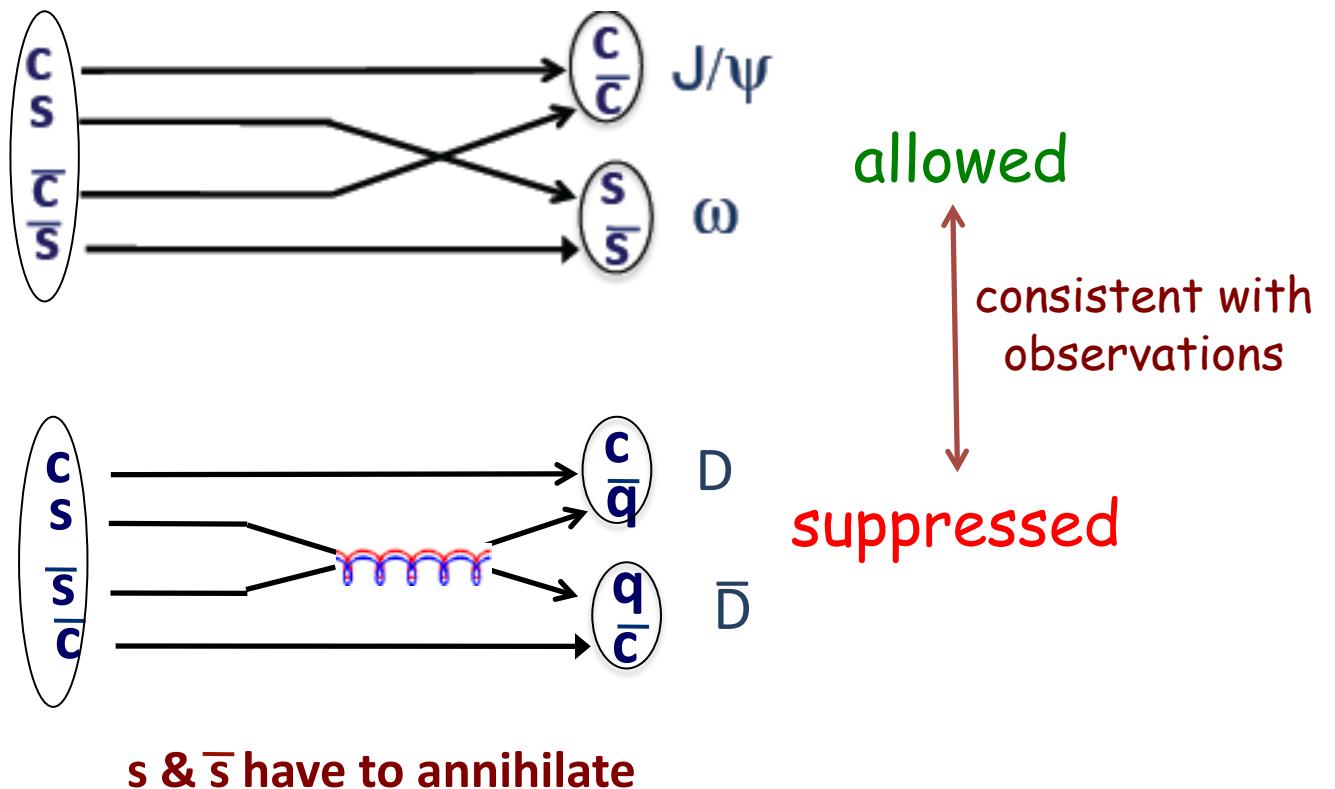
X(3915) as a $[cs][\bar{c}\bar{s}]$ tetraquark?

Lebed & Polosa, PRD 93, 094024

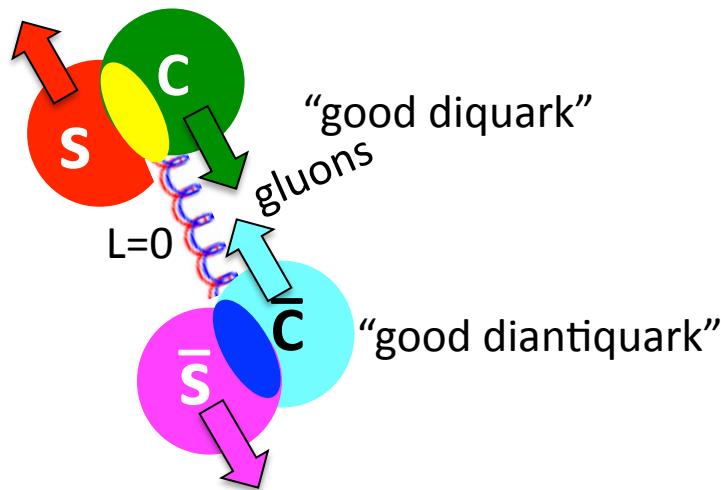


how would it decay?

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

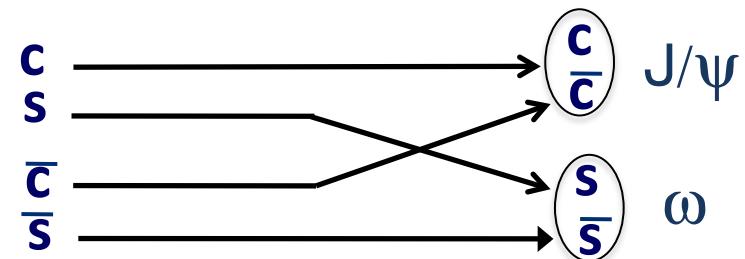


$[cs][\bar{c}\bar{s}] \rightarrow \eta\eta_c?$

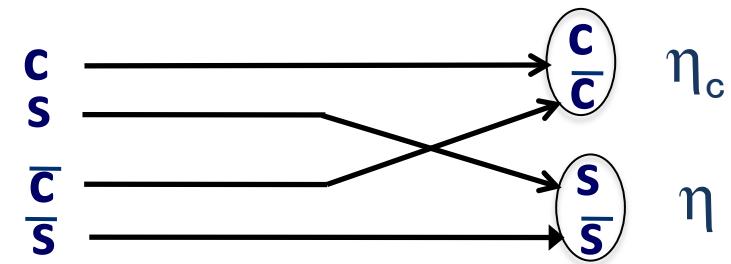


Expect: $\frac{Bf(X(3915) \rightarrow \eta_c \eta)}{Bf(X(3915) \rightarrow J/\psi \omega)} \gg 1$

OZI allowed decay processes

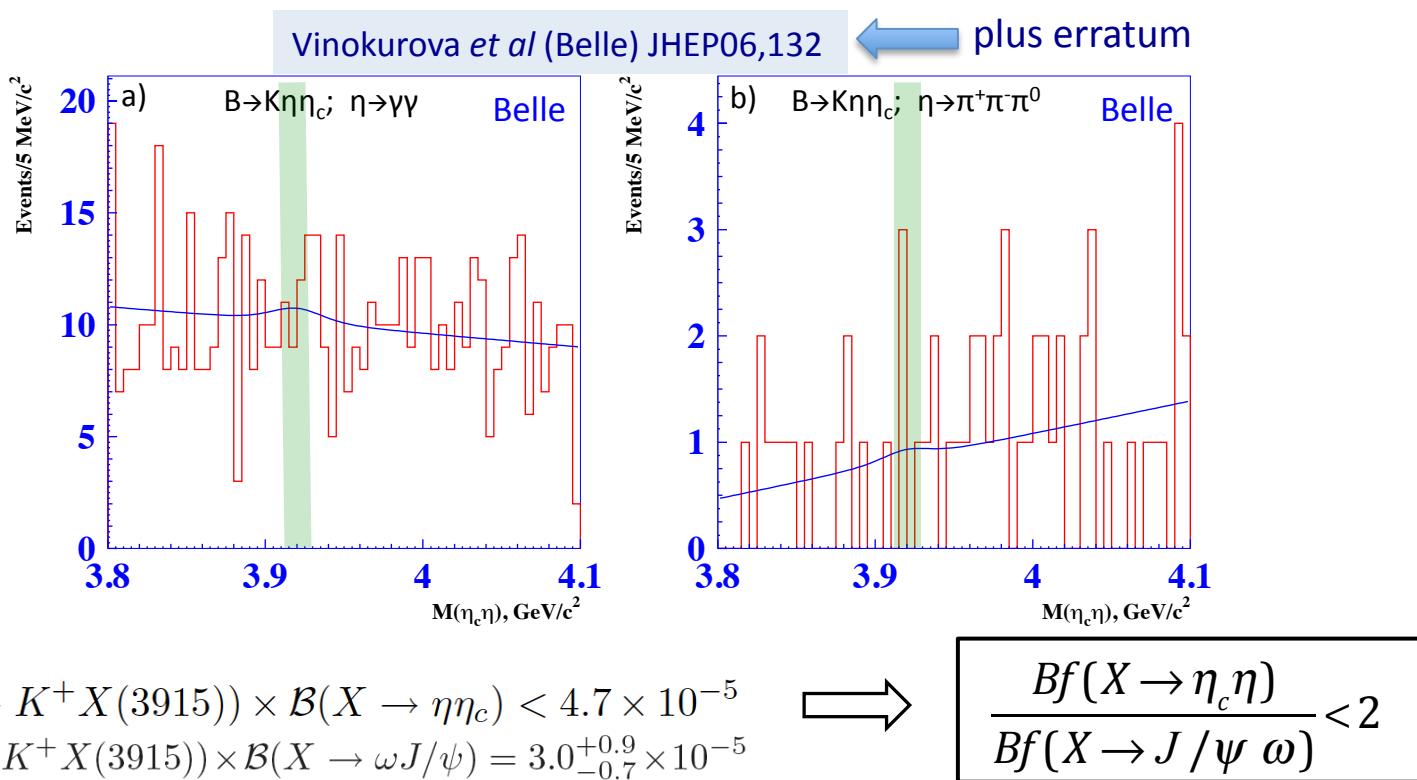


ω has a small ($\approx 3\%$) $s\bar{s}$ content



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

$X(3915) \rightarrow \eta_c \eta$



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

\Rightarrow not good 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



L=0 gluons

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.” \approx 18 MeV; ← needs a binding mechanism to produce this;

It is **not** a good candidate for a cc-gluon hybrid:

unless current ($m_\pi \approx 400$ MeV) LQCD mass calcs are wrong by ≈ 500 MeV

If it is a [cs][cs] QCD tetraquark:

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

What is the X(3915)?

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

It is **not** a good can-

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

standard nuclear-physics-type forces do not work

If it is not an $c\bar{c}$ -glueball hybrid:
mass current ($m_T \approx 400$ MeV) LQCD mass calcs are wrong by ≈ 500 MeV

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

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

to do list for the X(3915)

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

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

Establish the levels of Bfs for $X(3915) \rightarrow D\bar{D}$ and $X(3915) \rightarrow \eta\eta_c$
or set stringent upper limits

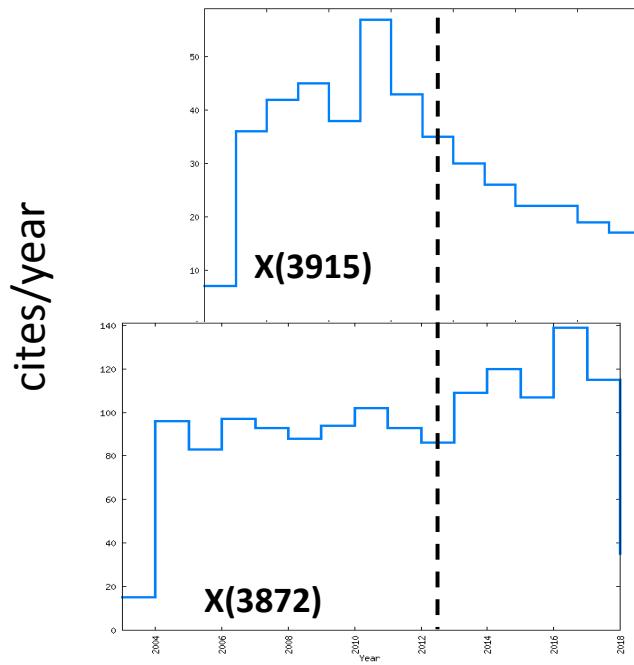
Hadronic production of the X(3915)?

Search for $Y(4260) \rightarrow \gamma X(3915)$
 $\downarrow \omega J/\psi$

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

X(3915), the forgotten particle

in 2011, BaBar declared it to be the χ_{c0}' , the PDG acquiesced, & it was promptly forgotten



last week's arXiv

1805.06276 [hep-ph]

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

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Chinese Academy of Sciences, Beijing 100190, China*

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

?????

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

Thank You