The XYZ mesons: what aren't they?

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"Phi 2 Psi Workshop 2019 " BINP Novosibirsk, Feb. 26 – Mar. 1, 2019

What a difference twenty years make:

phi-psi1999
Novosibirsk

Temp:-30C

BESI physics results with 7M J/ψ s, 4Mψ's plus 85 continuum events:
— most precise measurement of m_τ
— ρπ puzzle; ξ(2220)=glueball?; σ & κ mesons; …
— improved R values (15-20)% → (7-10)%: $a_{QED}(M_Z)$ for M_{Higgs} & $(g-2)_\mu$ for BNL831
— …

phi-psi 2019
Novosibirsk

Temp:-3C

BESIII physics results with 1.3B J/ψ, 450M ψ' events plus >100M continuum evts
— most precise measurements of f_D & f_{Ds}. ($|V_{cs}|$ & $|V_{cd}|$), m_τ, J/ψ & ψ' widths, …
— ultra precise R-values ((7-10)%→<1%) for FNAL & J-PARC $(g-2)_\mu$ experiments
— discoveries of $Z_c(3900)$ & $Z_c(4020)$; $Y(4260) \to \gamma X(3872)$; $X(3872) \to \pi^0\chi_{c1}$; …
— discovery of large Λ polarization in $J/\psi \to \Lambda\bar{\Lambda}$; CPV search in $\Lambda \to \pi^- p / \bar{\Lambda} \to \pi^+ \bar{p}$
— anomalous threshold jumps for $e^+e^- \to \Lambda\bar{\Lambda}$ & $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ (ala SND ($n\bar{n}$) & CMD($p\bar{p}$))
— anomalous $X(1835) \to \pi^+\pi^-\eta'$ lineshape at the $e^+e^- \to p\bar{p}$ threshold
— $a_0(980) \leftrightarrow f_0(980)$ mixing
— …

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~50M J/ψs & 10M ψ's will "close out" $E_{cm}<2m_D$ physics

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— $a_0(980)$ ←→ $f_0(980)$ mixing
— …

Can't have enough J/ψs; at least 10T needed for CPV tests

What a difference twenty years make:

phi-psi1999
Novosibirsk

Temp:-30C

BESI physics results with 7M J/ψ s, 4Mψ's plus 6[illegible] continuum events:
— most precise measurement of m[illegible]
— ρπ puzzle; ξ(2220)=glueball[illegible] & κ mesons; …
— improved R values (15-20)% → (7-10)%: $a_{QED}(M_Z)$ for M_{Higgs} & $(g-2)_\mu$ for BNL831
— …

~50M "outback" J/ψs & 10M ψ's will "close out" $E_{cm}<2m_D$ physics

phi-psi 2019
Novosibirsk

Temp:-3C

BESIII physics results with 1.3B J/ψ, 450M ψ' events plus 100M continuum evts
— most precise measurements of f_D & f_{Ds}; ($|V_{cs}|$ & $|V_{cd}|$), m_τ, J/ψ & ψ' widths, …
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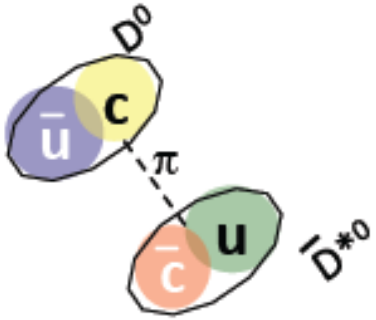
— $a_0(980)$ ←→ $f_0(980)$ mixing
— …

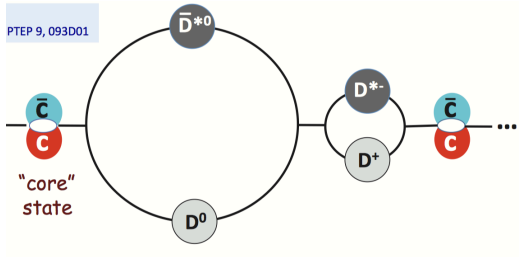
most exciting expt in particle physics

Can't have enough J/ψs; at least 10T needed for CPV tests

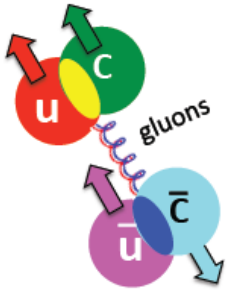
some proposed interpretations of the *XYZ* mesons?



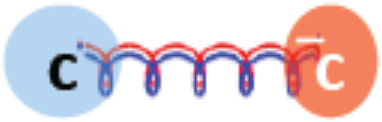
molecules?



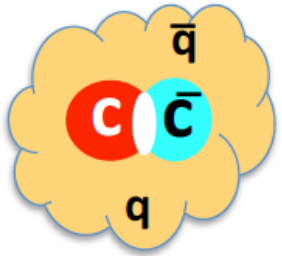
coupled channel system?



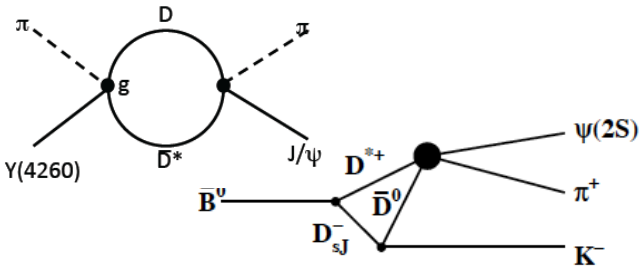
QCD tetraquarks?



QCD hybrids?

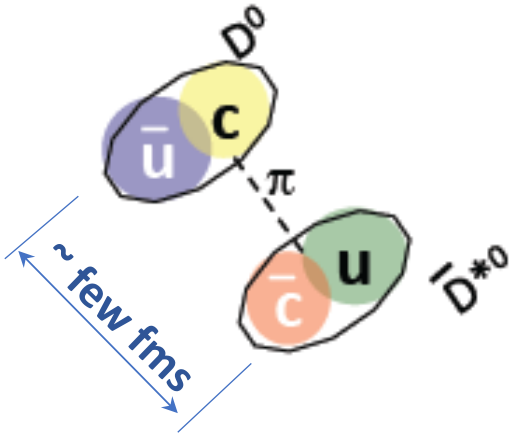


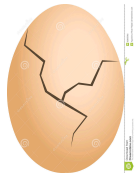
hadrocharmonium?



threshold effects?

deuteron-like molecules





egg-like

"Deusons"

Nils A. Tornqvist

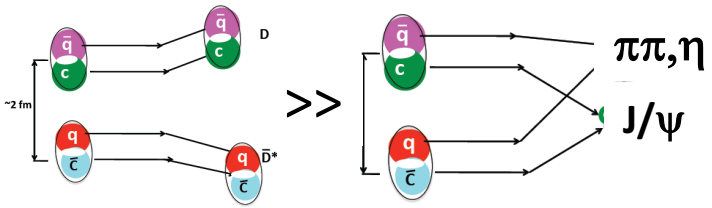
Karliner & Skwarnicki (PDG 2016):

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

Constituent mesons should be narrower than the molecule

J^{PC} consistent with S-wave $e.g.,\ J^{PC} = 1^{++}\ \mathrm{for}\ D\bar{D}^*;\ = 1^{--}\ \mathrm{for}\ D\bar{D}_1^{**}$

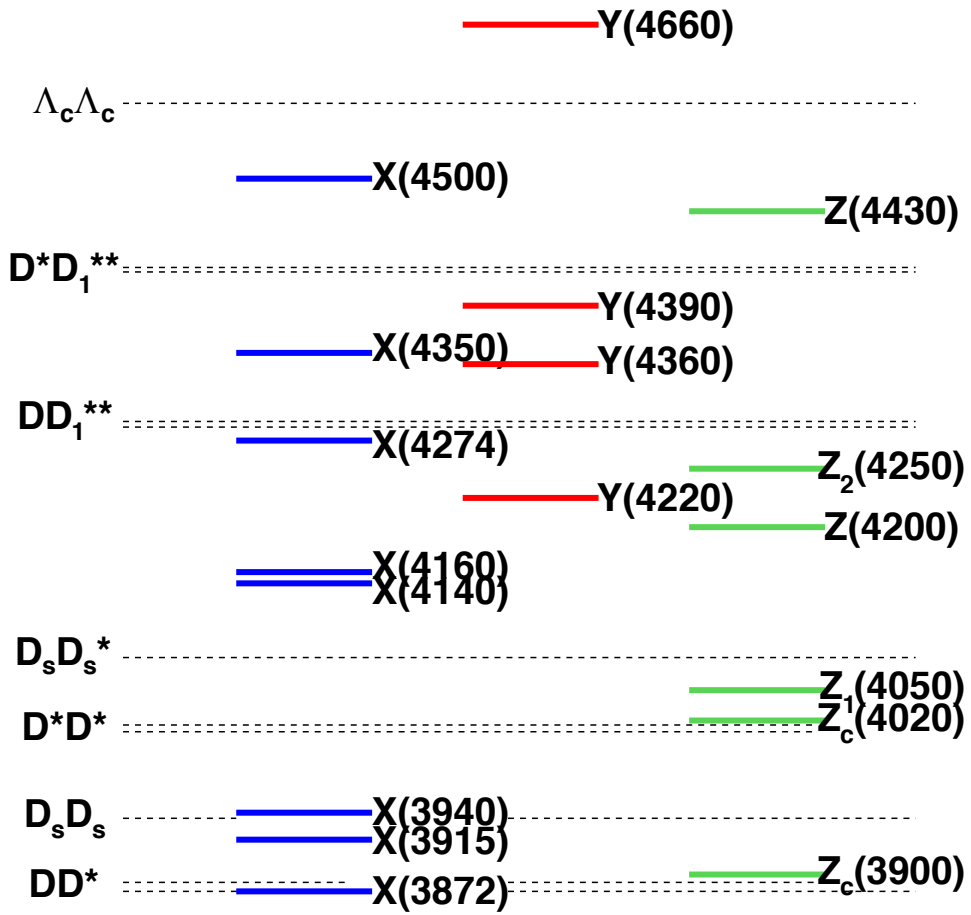
fall-apart decays >> hidden charm modes



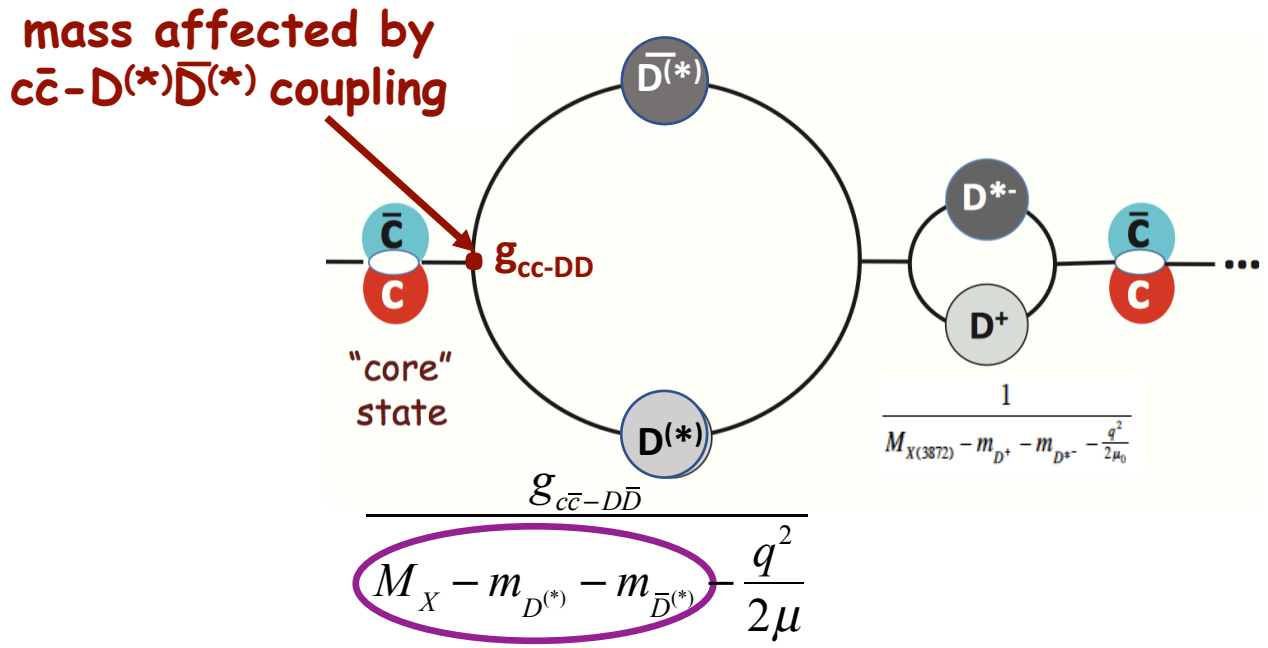
no $0^- \oplus 0^-$ molecules (one π-exchange forbidden)

XYZ mesons *vs* open-charm thresholds

-- aside from the X(3872), no apparent correlation --



coupled-channel system



If $M_X \rightarrow D^{(*)}\bar{D}^{(*)}$ threshold, propagator→ divergent and the coupling is amplified

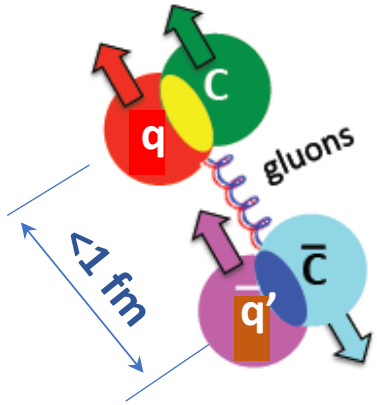
Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01

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

need a core cc̄ state strongly coupled to an S-wave $D^{(*)}\bar{D}^{(*)}$ system

close to a $D^{(*)}\bar{D}^{(*)}$ mass threshold

QCD tetraquarks



ball bearing-like

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

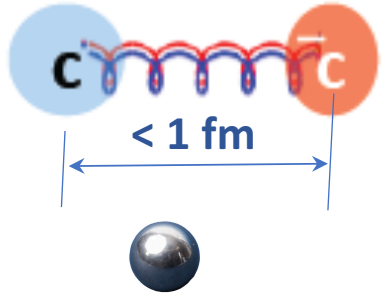
compact & tightly bound by the color force: BE = "∞"

since spin force ~ $1/m_Q$, "bad" diquarks are not so bad

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

QCD is flavor blind (q=u,d,s) ∴ tetraquark states should come in octets

charmonium hybrids

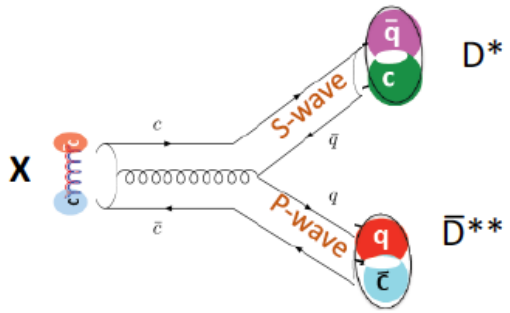


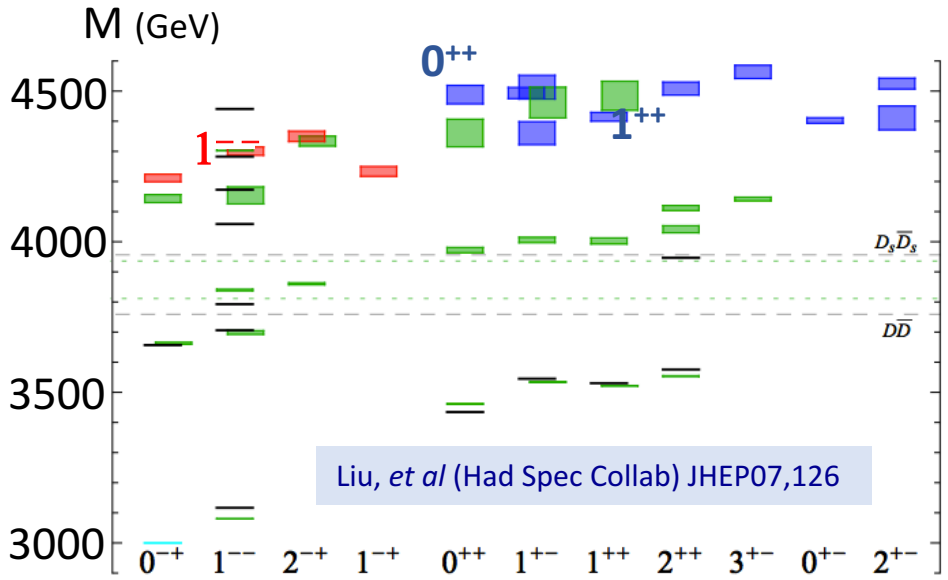
ball bearing-like

LQCD (m_π=400 MeV) predicts high masses
(e.g.: 1^{--}≈4.3 GeV; 0^{++}≈4.5 GeV; 1^{++}≈4.4 GeV)

no charged states

decays to S-wave ⊕ P-wave preferred



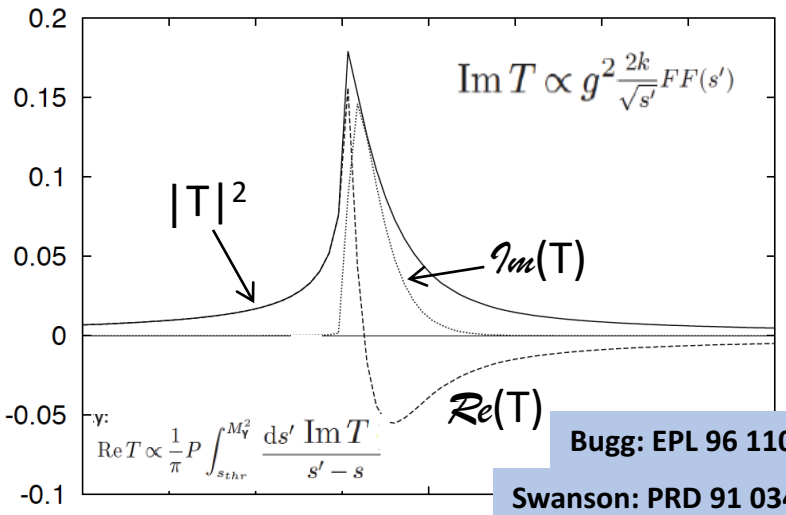


Liu, *et al* (Had Spec Collab) JHEP07,126

Page, Swanson, Szczepaniak, PRD 59, 034016 (1999)

Threshold effects

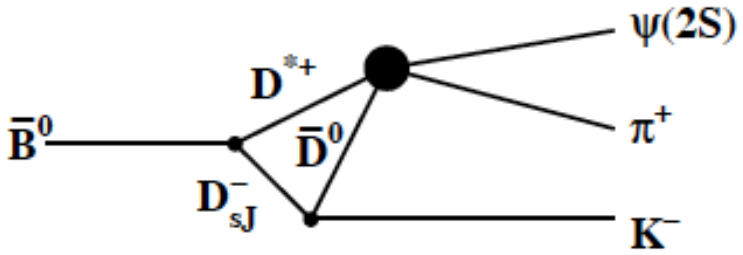
cusps



Bugg: EPL 96 11002 (2011)

Swanson: PRD 91 034009 (2015)

rescattering



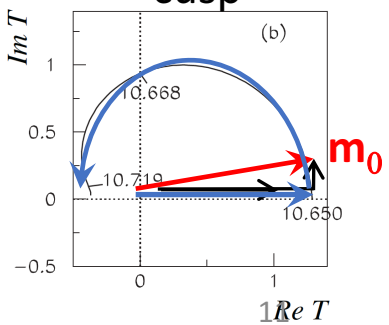
Landau: singular when loop particles are on the mass shell

Pakhlov & Uglov, PLB748,183 (2015)

peaks just above threshold: $a^{-1} = \sqrt{2\mu\delta E} < m_\pi \Rightarrow \delta E < \frac{m_\pi^2}{2\mu} \approx 10\ \mathrm{MeV}\ (\mathrm{for}\ 2\mu = m_D)$

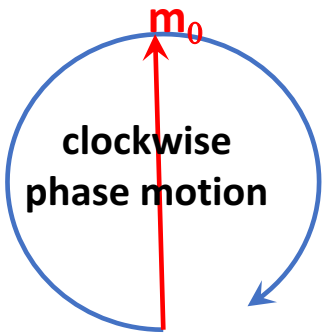
distinctive phase motion:

cusp

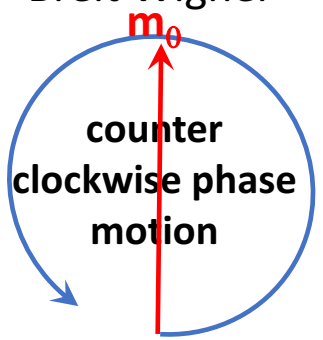


semi-circle

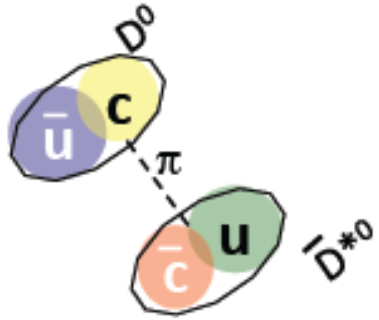
rescattering



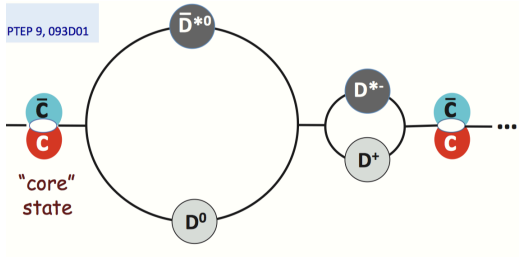
Breit Wigner



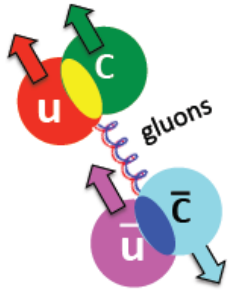
What are they?



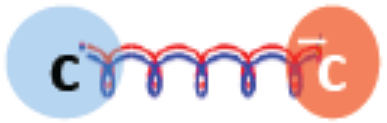
molecules?



coupled channel system?



QCD tetraquarks?



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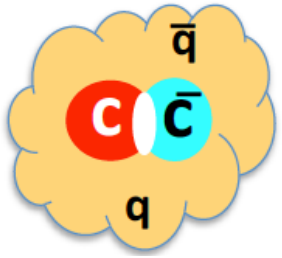

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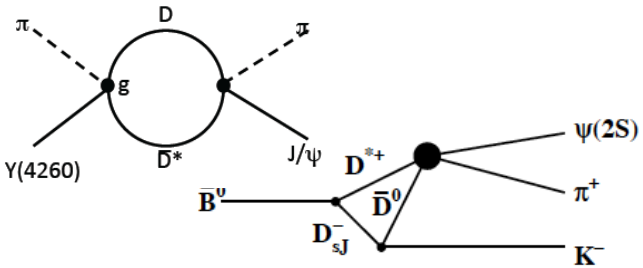
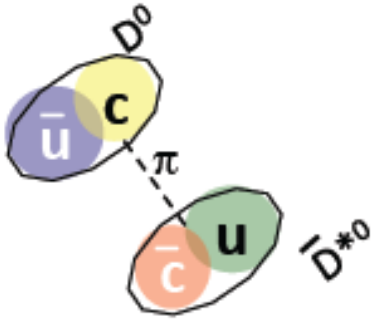


threshold effects?

~~What are they?~~

What aren't they?



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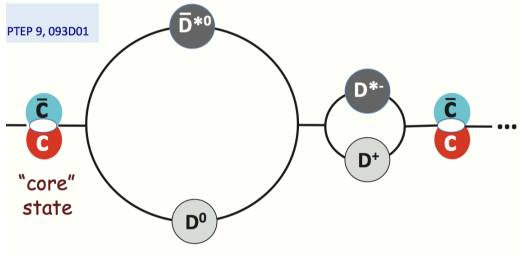

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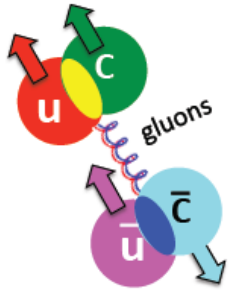

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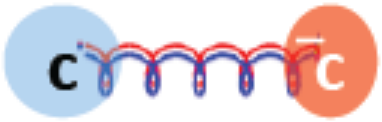

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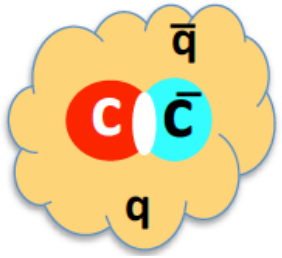

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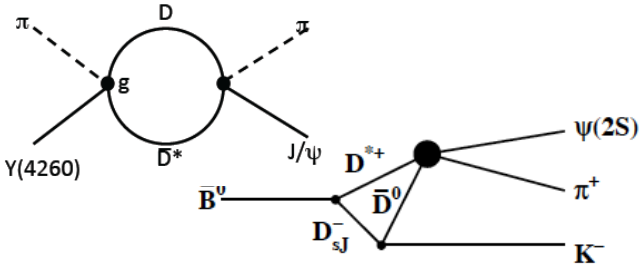
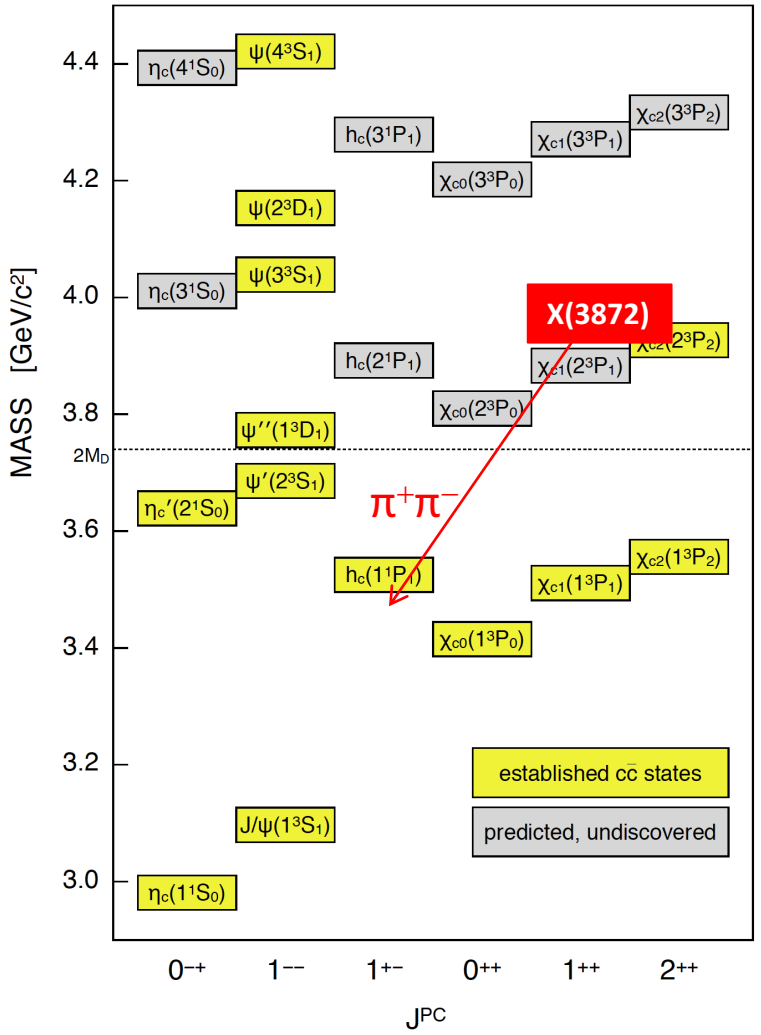


threshold effects?

X(3872)

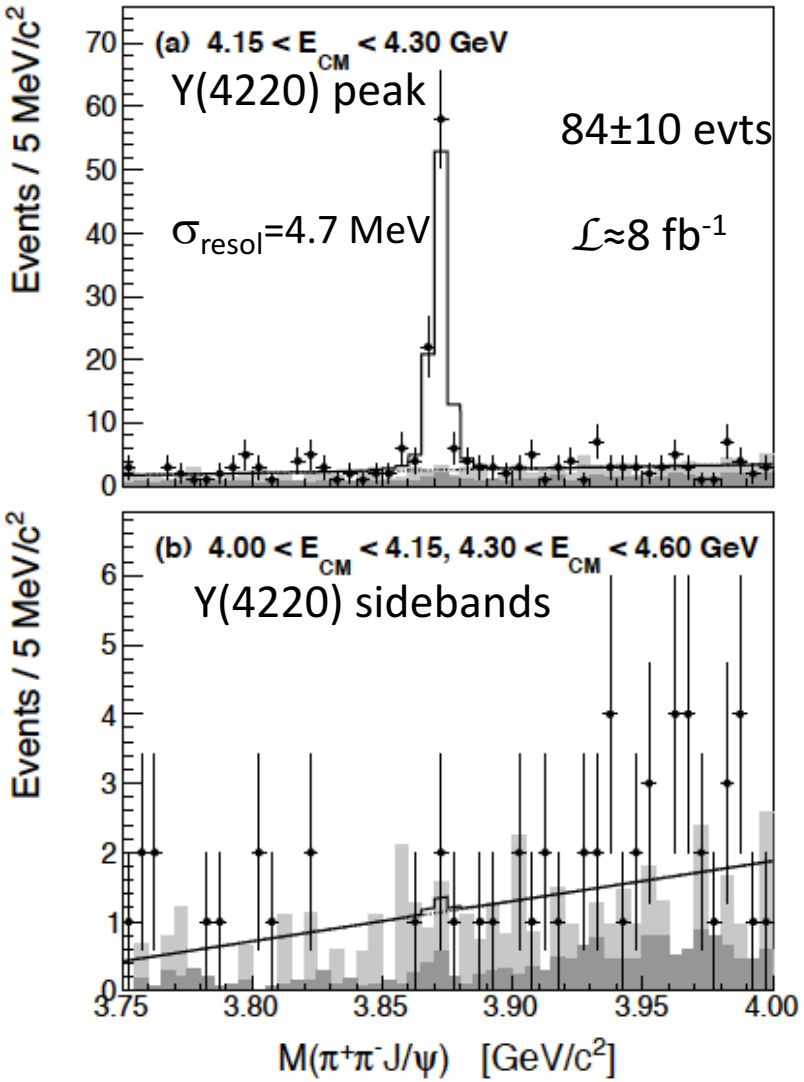
anything new?



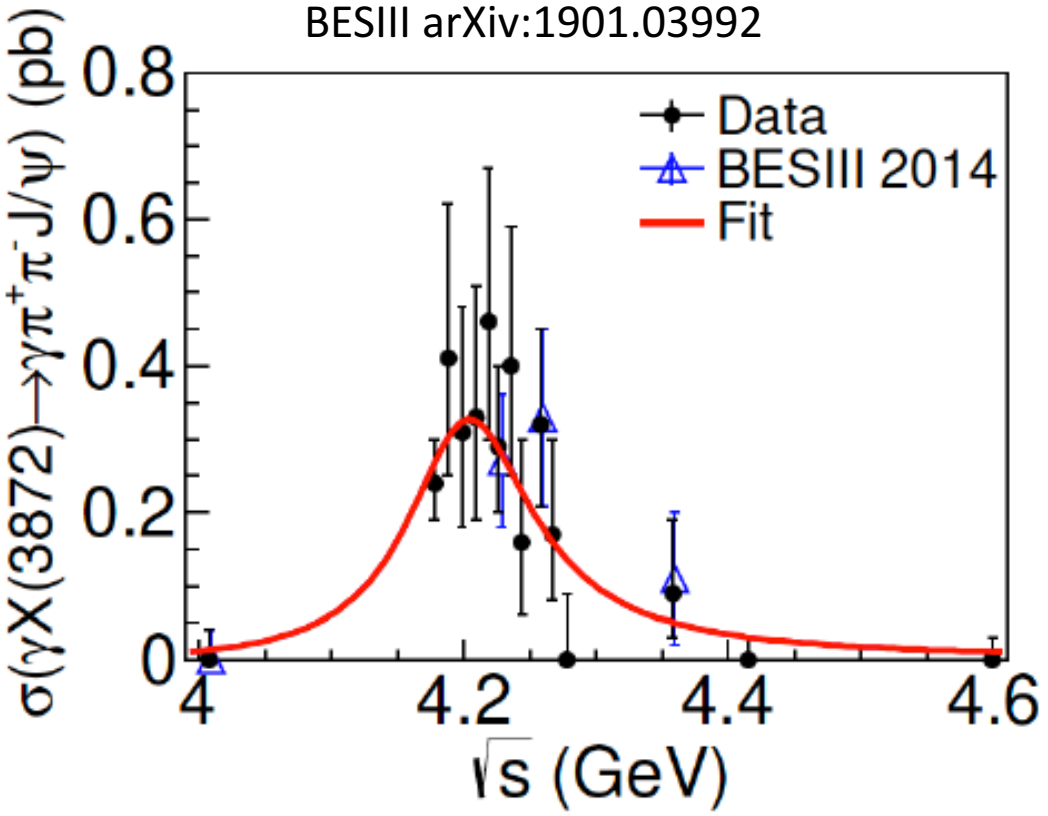
BESIII: new production mode

Y(4220)→γX(3872); X(3872)→$\pi^+\pi^-$J/ψ

e^+e^-→γ $\pi^+\pi^-$J/ψ



BESIII arXiv:1901.03992

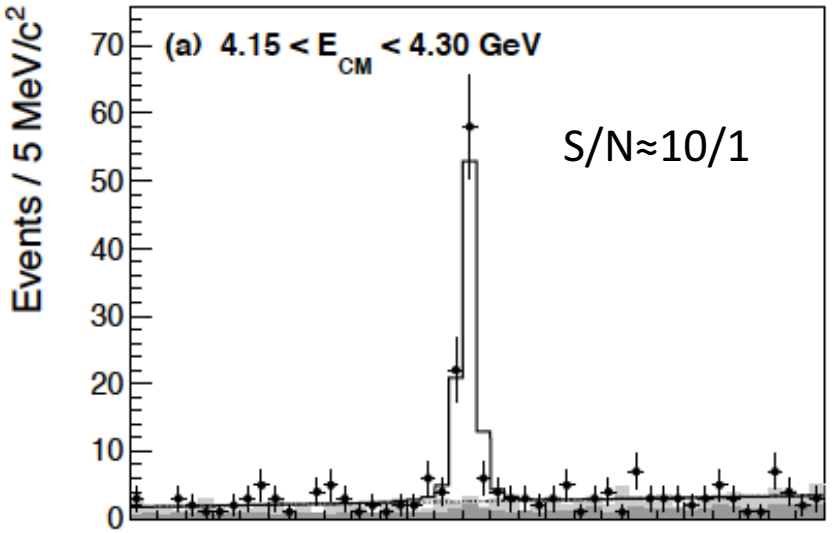


combinatoric-free channel for X(3872) studies

-- well suited for final states with $\gamma/\pi^0/\omega$ –

BESIII arXiv:1901.03992

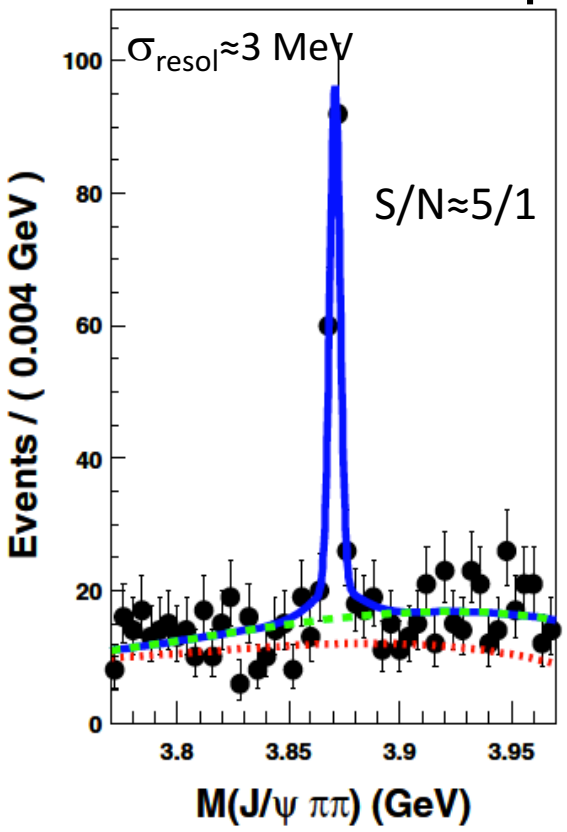
$e^+e^- \rightarrow \gamma\ \pi^+\pi^- J/\psi$



No combinatoric background!

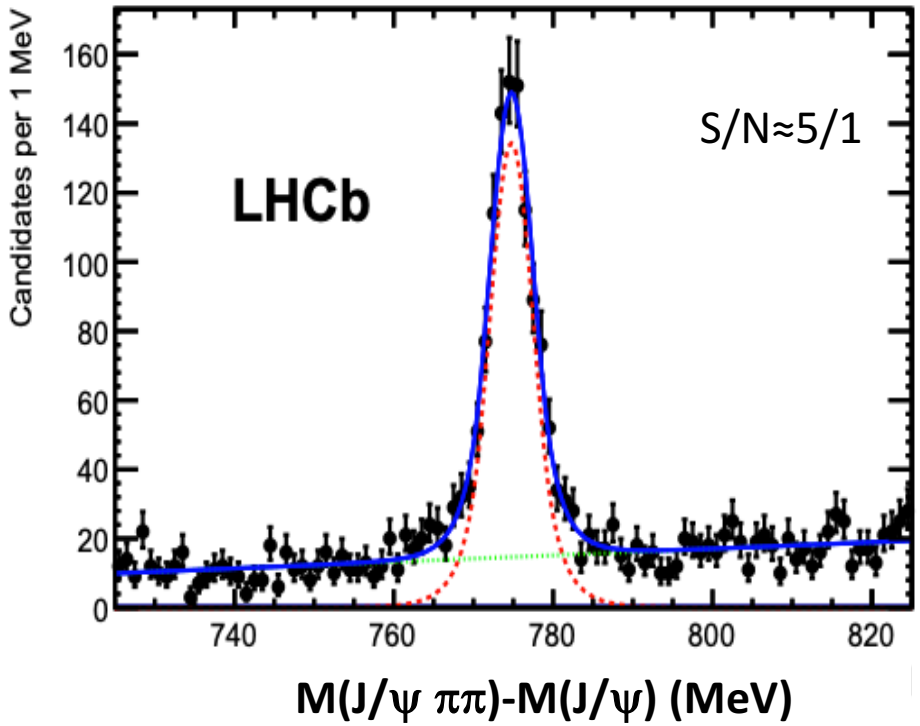
Belle PRD84,052004

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



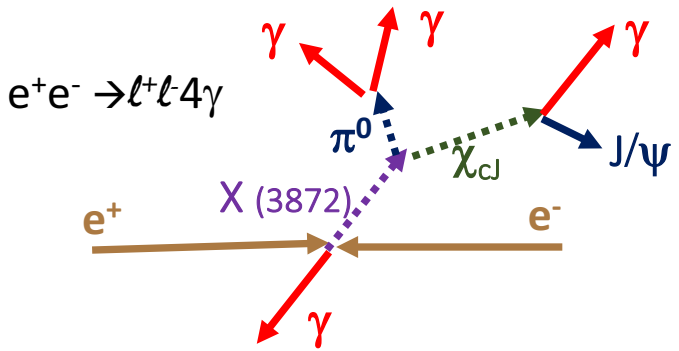
LHCb PRD92,01110

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

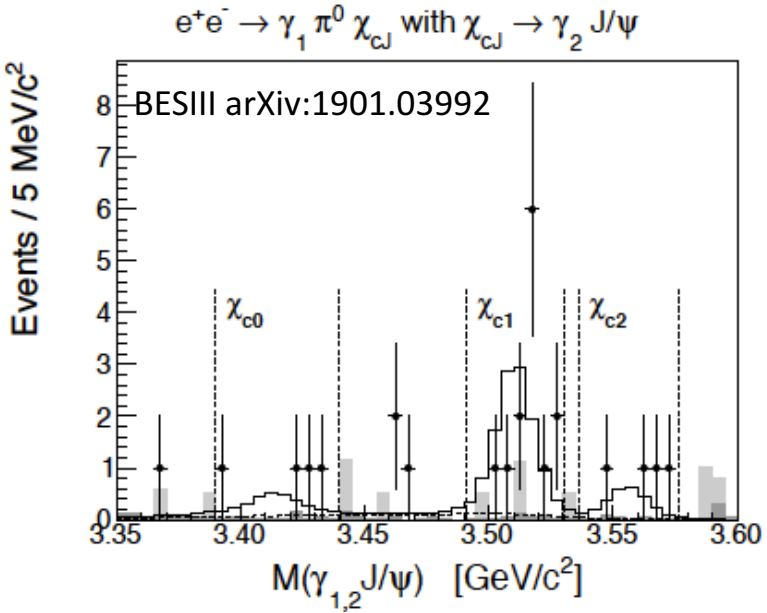


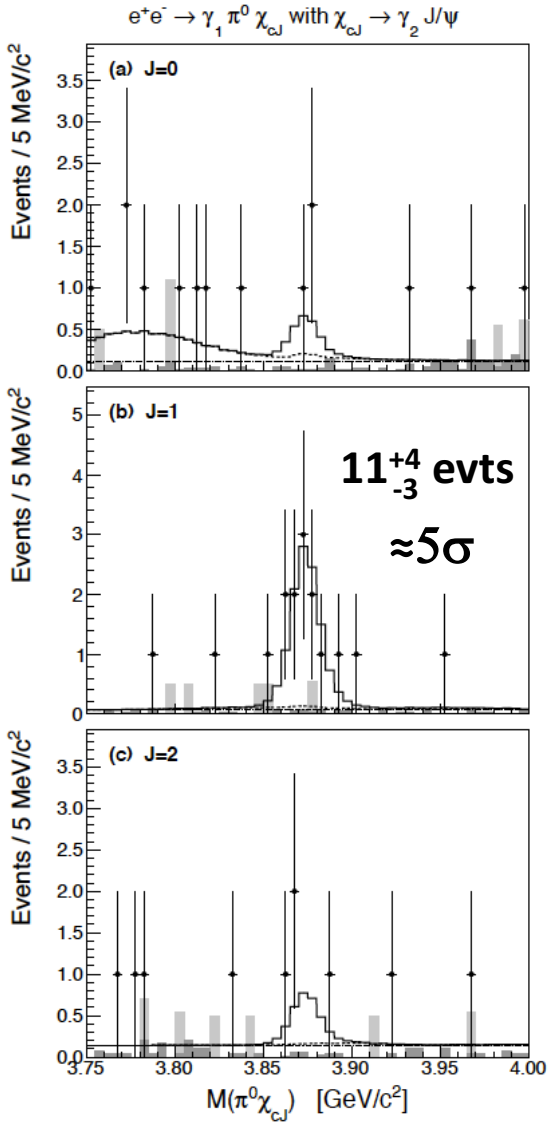
Y(4220)→γX(3872); X(3872)→$\pi^0\chi_{cJ}$; χ_{cJ}→γJ/ψ

4 γ-rays!



very low background



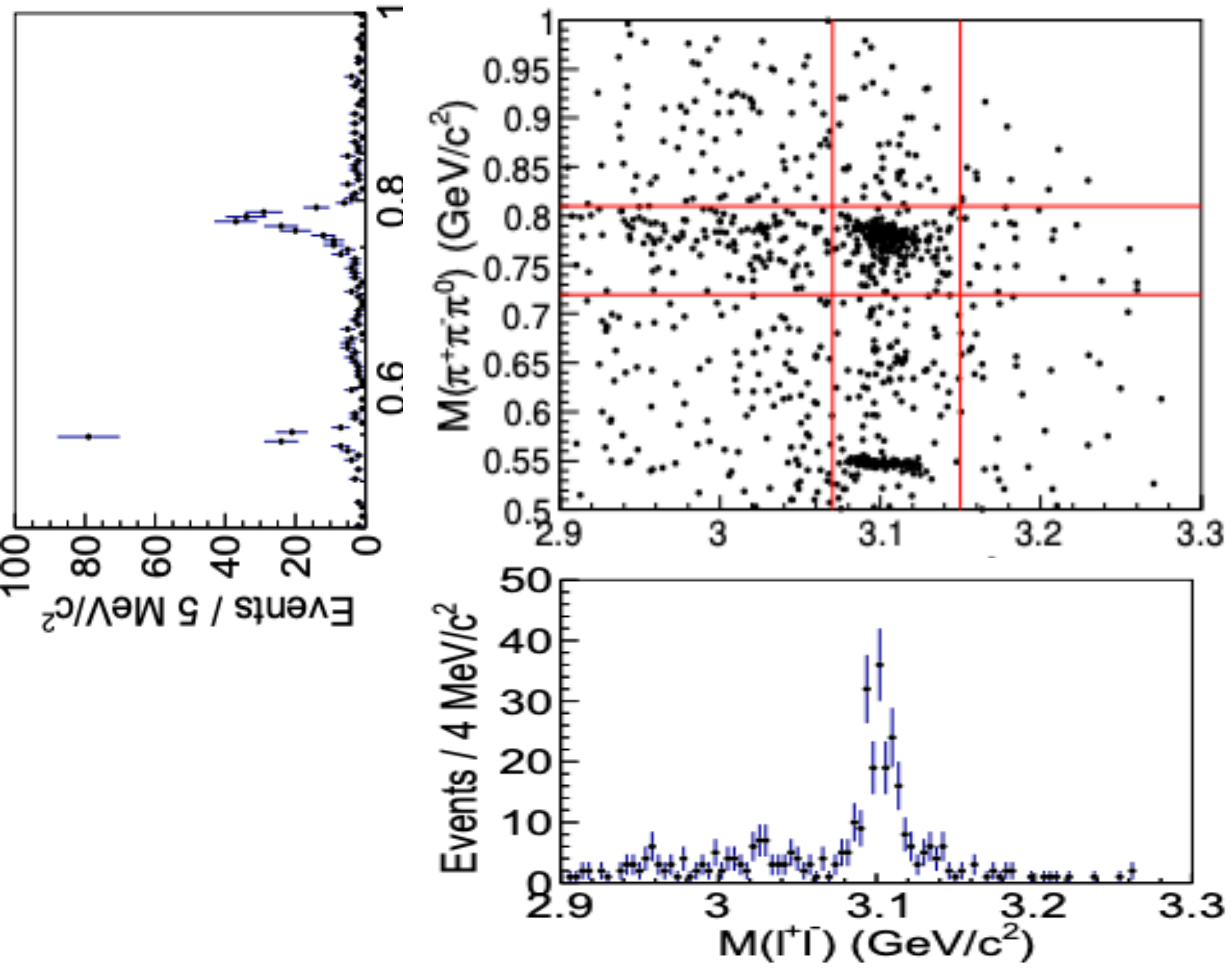


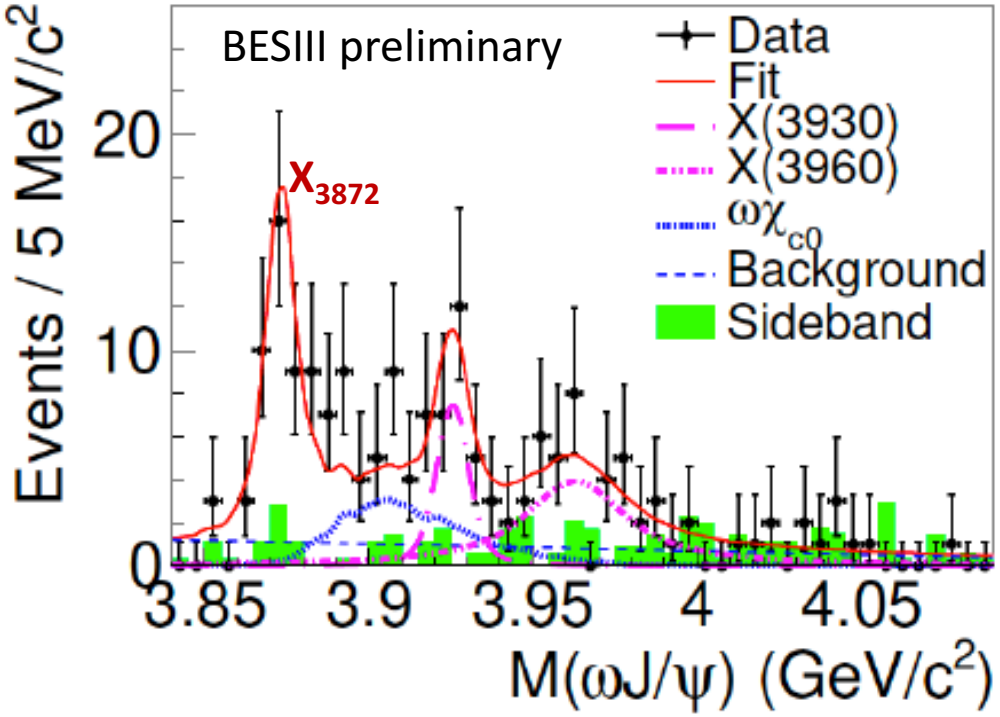
strongly suppressed for X(3872)=cc̄ state

$$\frac{Bf(X_{3872}\to\pi^0\chi_{c1})}{Bf(X_{3872}\to\pi^+\pi^- J/\psi)}=0.9^{+04}_{-0.3}$$

Y(4220)→γX(3872); X(3872)→ωJ/ψ

$e^+e^-\rightarrow\gamma\,\pi^+\pi^-\pi^0\,J/\psi$



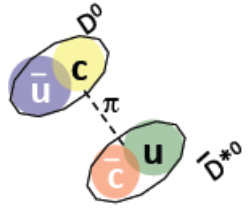


$$\frac{Bf(X_{3872}\rightarrow\omega J/\psi)}{Bf(X_{3872}\rightarrow\pi^+\pi^- J/\psi)}=1.6^{+0.5}_{-0.4}$$

PDG2018: 0.8±0.3

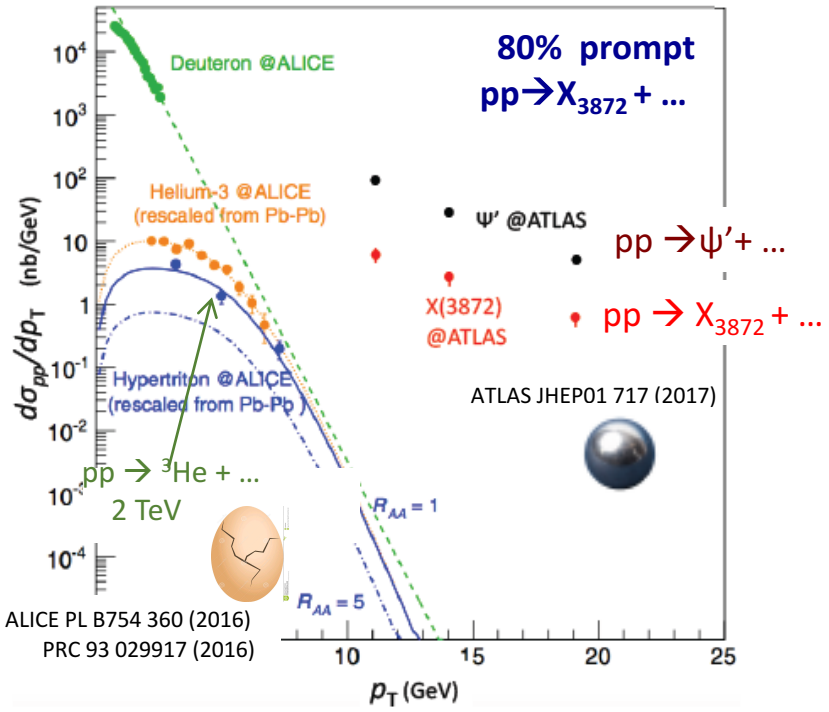
X(3872) = poster boy for $D^0\bar{D}^{*0}$ molecule

deuteronlike



But:

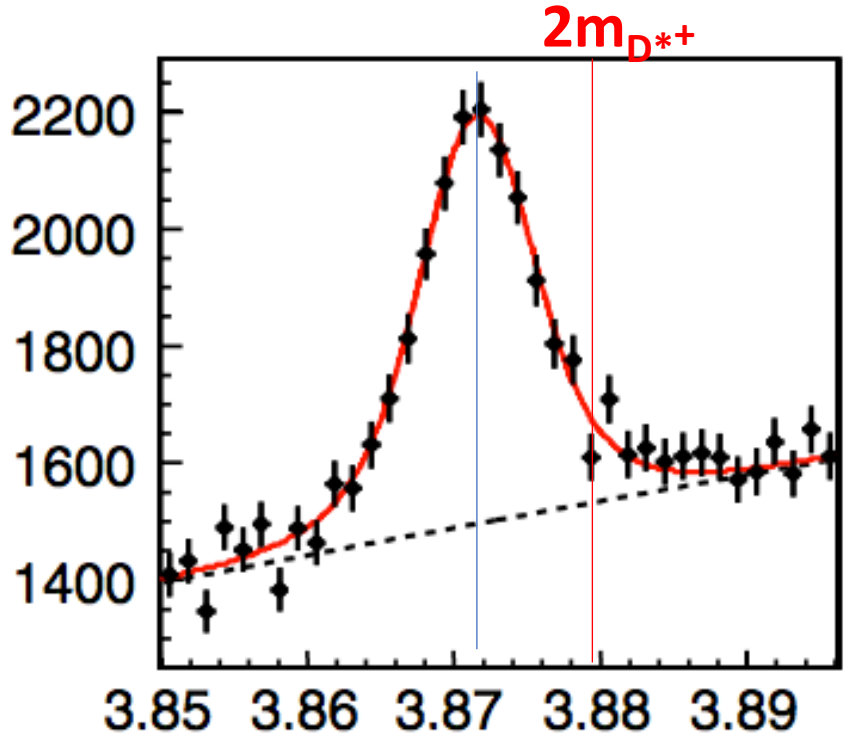
produced promptly in 7 TeV pp collisions



ALICE PL B754 360 (2016)
PRC 93 029917 (2016)

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

no sign of it in D^0/D^{*-} or D^+D^{*-}

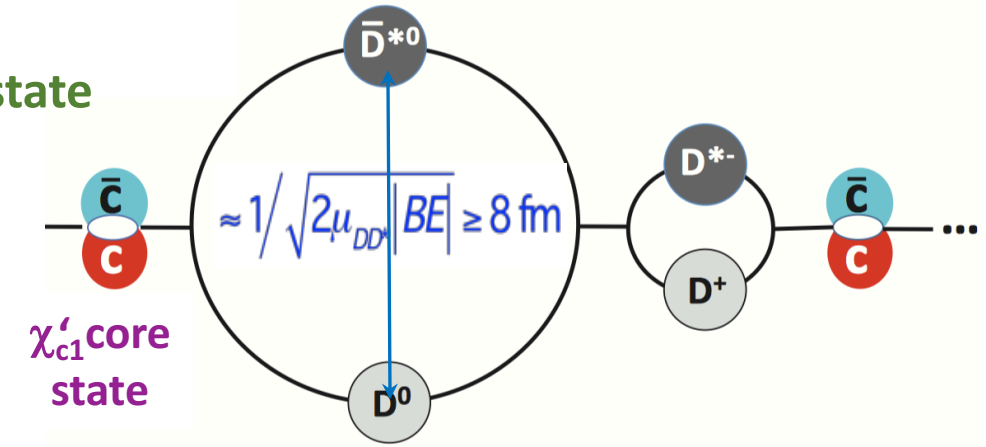


CDF PRL 103 152001 (2009)

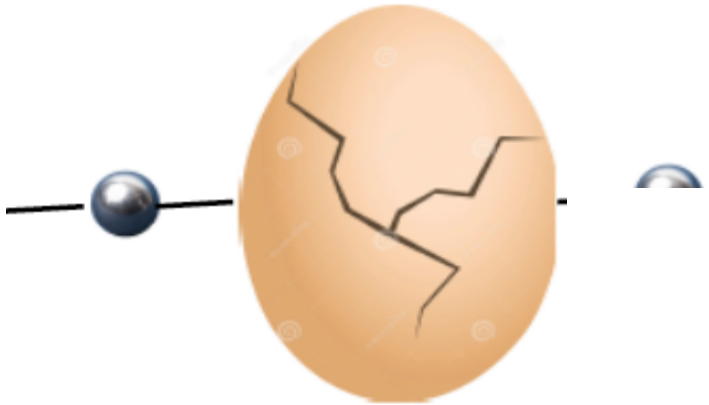
X(3872)=coupled channel state?

$D\bar{D}^* \oplus \chi_{c1}'$ coupled channel state

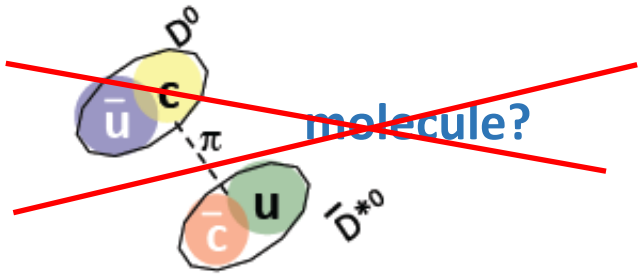
Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01



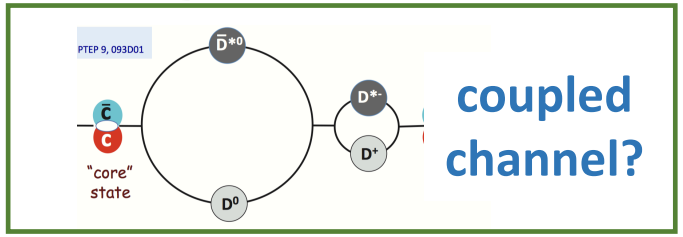
produced promptly via χ_{c1}' component



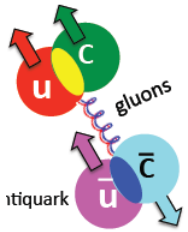
X(3872)



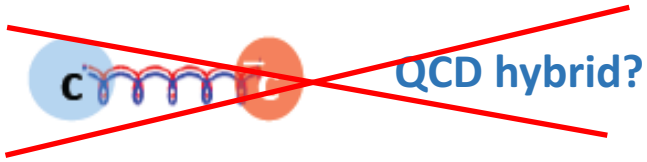
Produced promptly in HE pp collisions
no isopspin-related states are seen



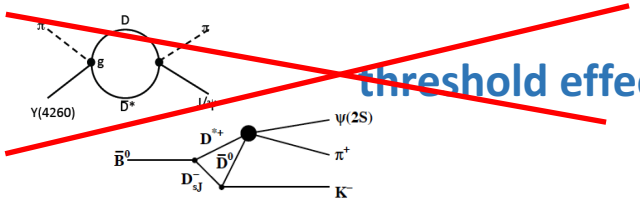
good description PTEP 9, 093D01 (2013)



PRD 71 014028 (2005)
no 1^{++} partner states seen

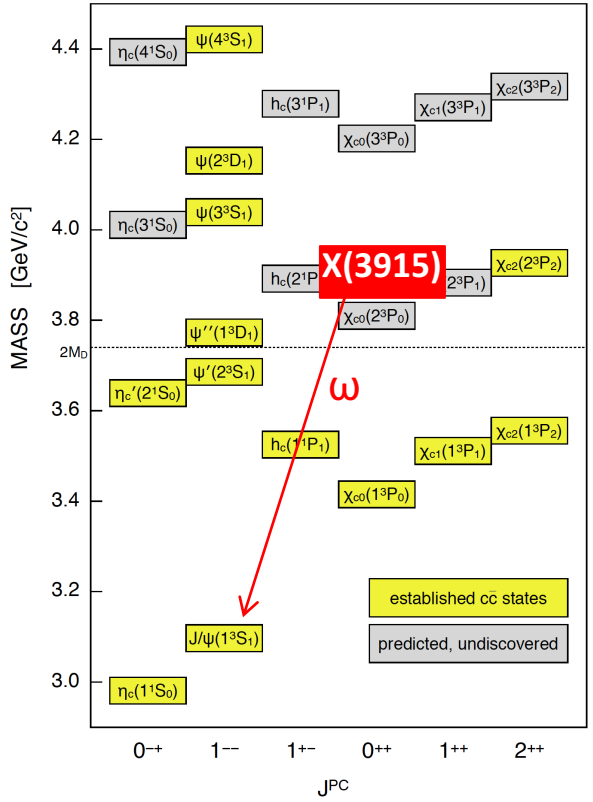


mass is 500 MeV below
LQCD's lightest 1^{++} hybrid



width is too narrow; mass
too close to threshold

X(3915)


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

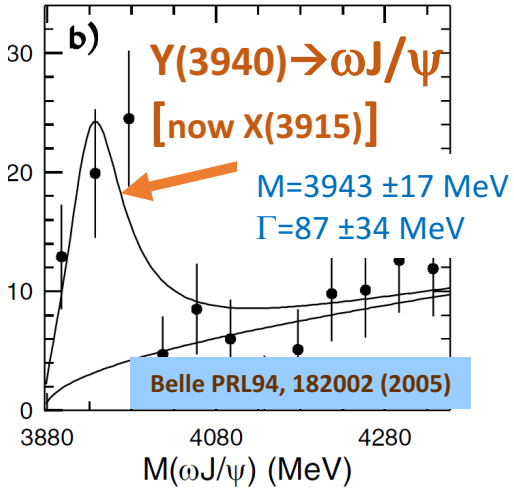
X(3915) -- seen in 2 production channels by 2 experiments --

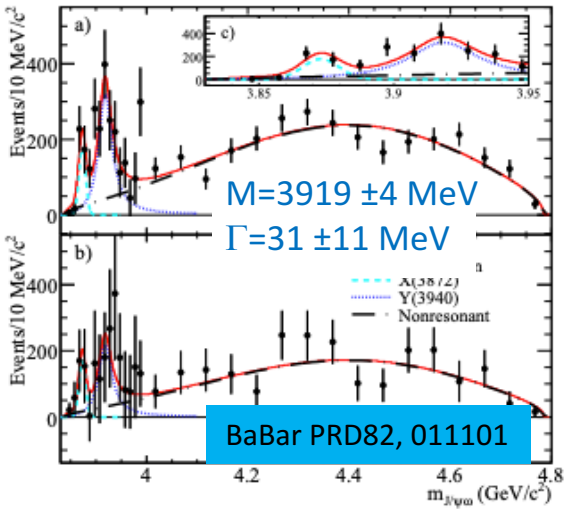
PDG 2018: $M_{X(3915)} = 3918 \pm 2$ MeV

$\Gamma_{X(3915)} = 20 \pm 5$ MeV

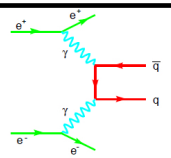
$M_{X(3915)}=2m_{D_s}-18$ MeV

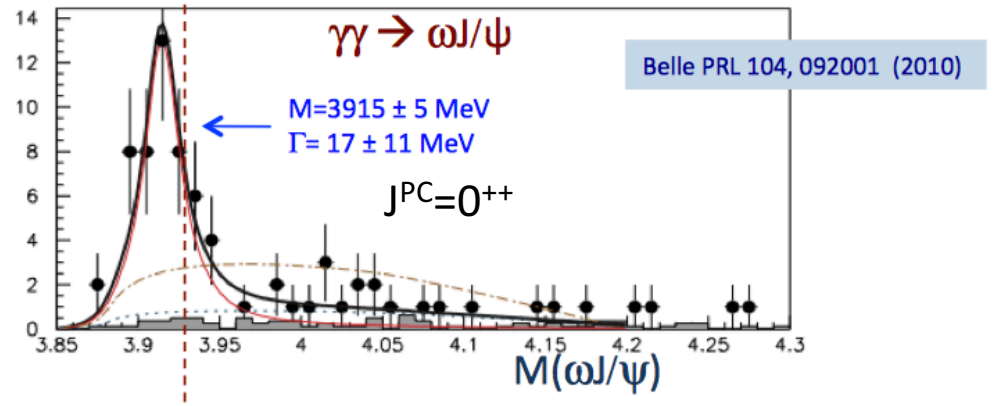
B→KωJ/ψ

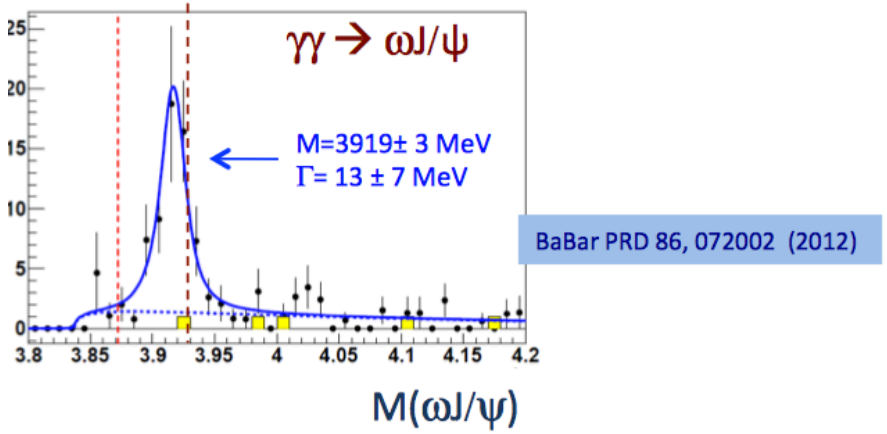




γγ→ωJ/ψ

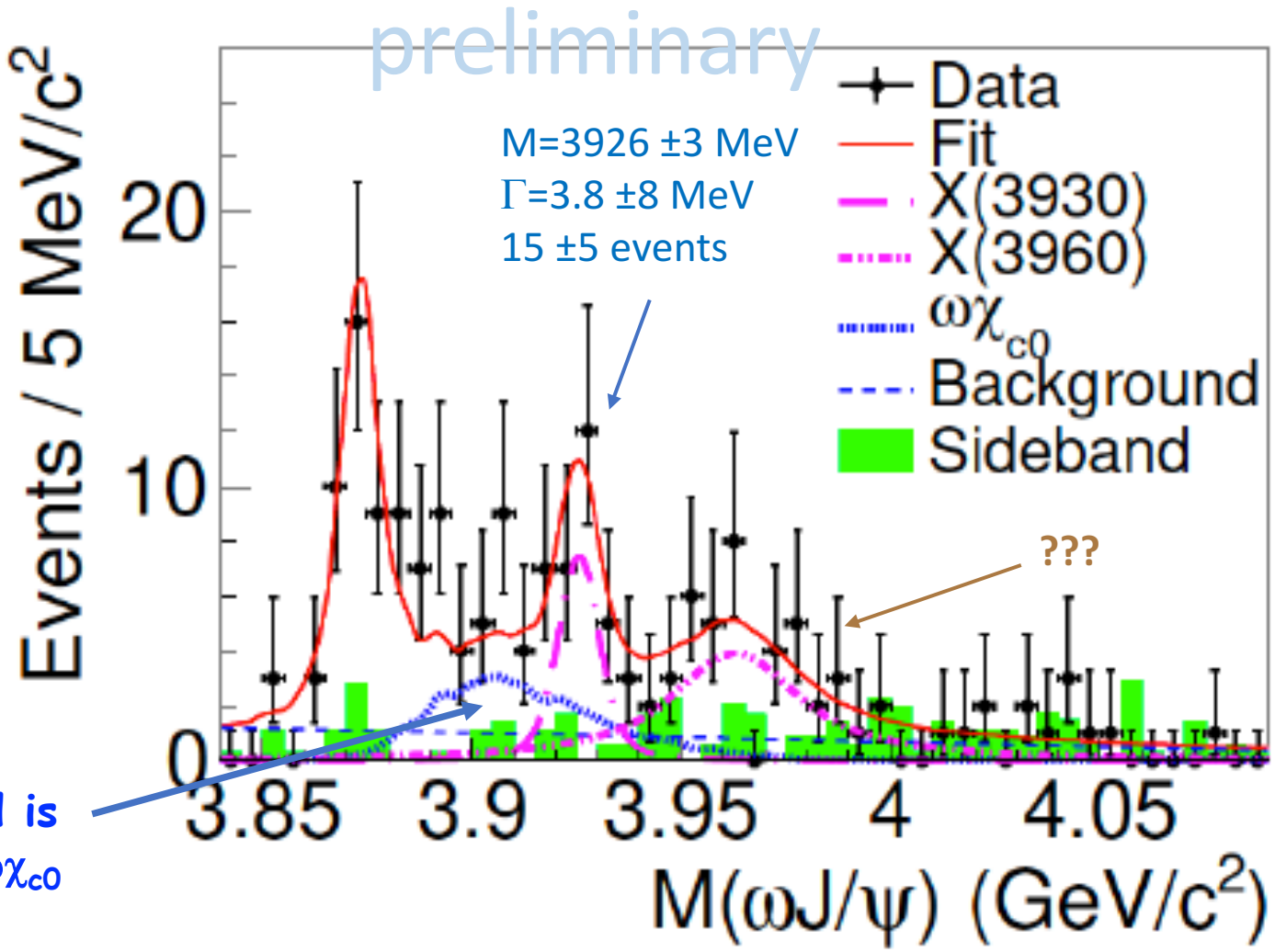






new production channel from BESIII

Y(4220)→γX(3915); X(3915)→ωJ/ψ

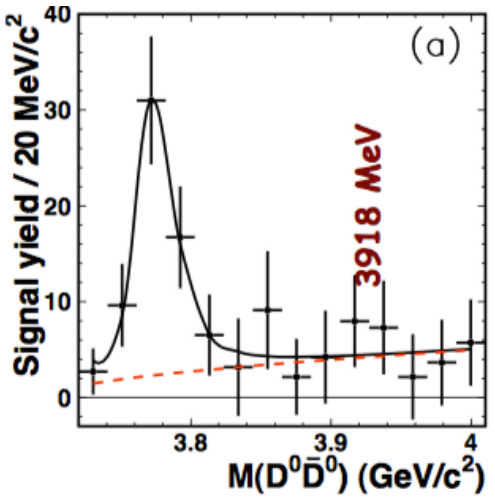


main background is physics: $e^+e^-\to\omega\chi_{c0}$

no sign of X(3915)→ $D\bar{D}$

-- in either B→K$D\bar{D}$ or γγ→$D\bar{D}$ --

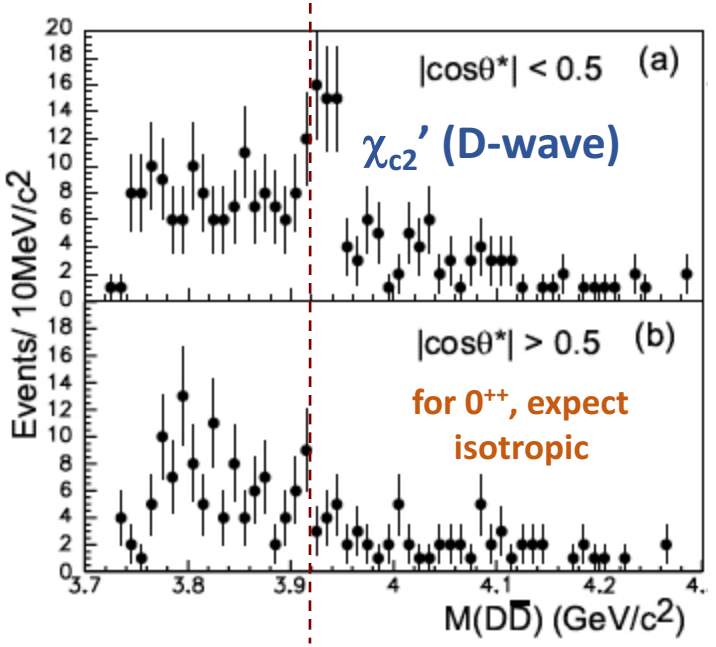
B→K$D\bar{D}$ (Belle)



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

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

γγ→K$D\bar{D}$ (Belle)



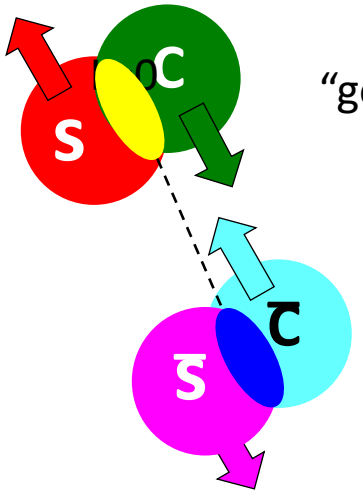
Belle PRL 89, 102001 (2002)

X(3915)→ωJψ/ is OZI-rule violating for a $c\bar{c}$ meson

$$\frac{Bf(X(3915)\to D^0\bar{D}^0))}{Bf(X(3915)\to \omega J/\psi))} < 1.2$$

SLO PRD91, 057501 (2015)

a $J^{PC}=0^{++}$ $cs\bar{c}\bar{s}$ tetraquark?

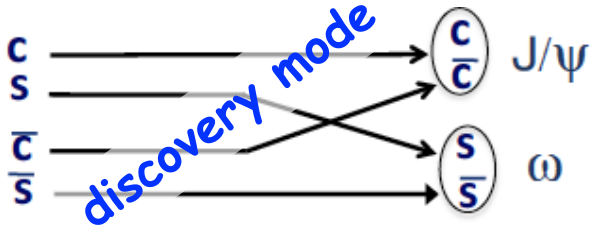


"good diquark"

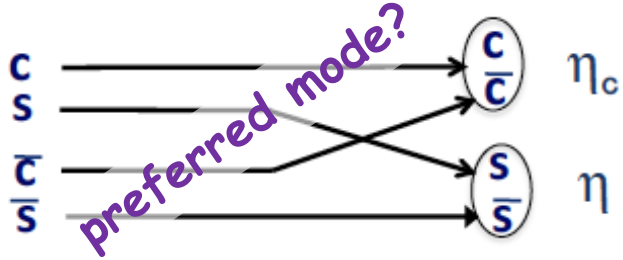
"good diantiquark"

no "fall-apart" decays to $D\bar{D}$

OZI-allowed decay processes:



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

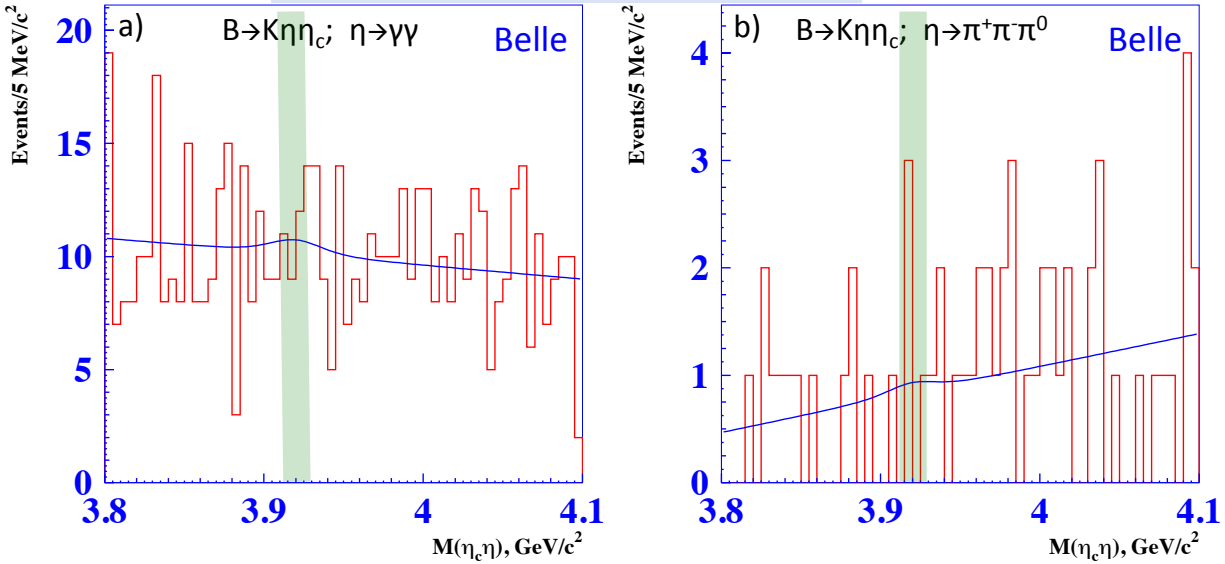


η has a large (≈40%) $s\bar{s}$ content

Expect: $\dfrac{Bf(X(3915)) \to \eta\eta_c}{Bf(X(S915)) \to \omega J/\psi} \gg 1$

No sign of X(3915)→$\eta_c\eta$

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

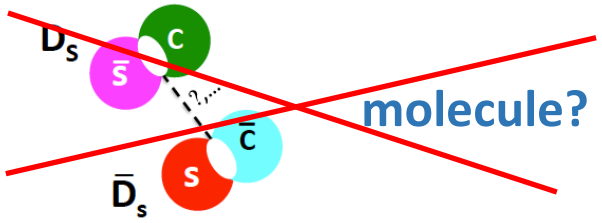


$$\mathcal{B}(B^+ \to K^+X(3915)) \times \mathcal{B}(X \to \eta\eta_c) < 4.7 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+X(3915)) \times \mathcal{B}(X \to \omega J/\psi) = 3.0^{+0.9}_{-0.7} \times 10^{-5}$$

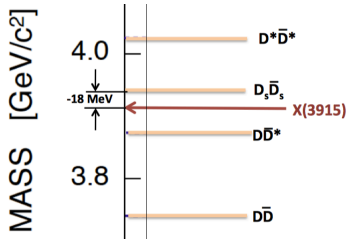
$$\frac{Bf(X \to \eta_c\eta)}{Bf(X \to J/\psi\ \omega)} < 2$$

not good for a tetraquark interpretation

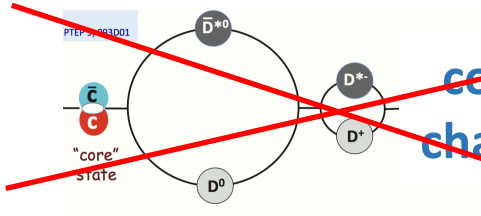
X(3915)



molecule?

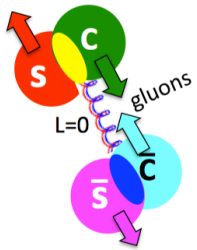


$D_s\bar{D}_s$ B.E. (≈18 MeV) large
$D^*\bar{D}^*$ B.E. (≈100 MeV) *very* large
π-exchange forbidden for $D_s\bar{D}_s$
but see: PRD91 114014 (2015)



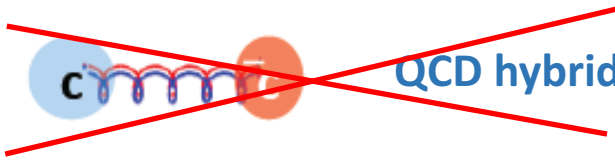
coupled channels?

no nearby $D\bar{D}$ threshold
no candidate $c\bar{c}$ core state



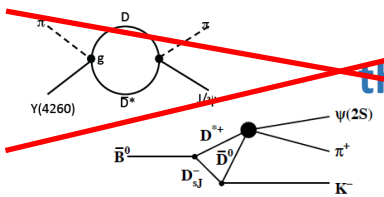
QCD tetraquark?

possible [cs][$\bar{c}\bar{s}$] tetraquark PRD93, 094024 (2016)
-- no sign of X(3915)→$\eta\eta_c$ or partner states



QCD hybrid?

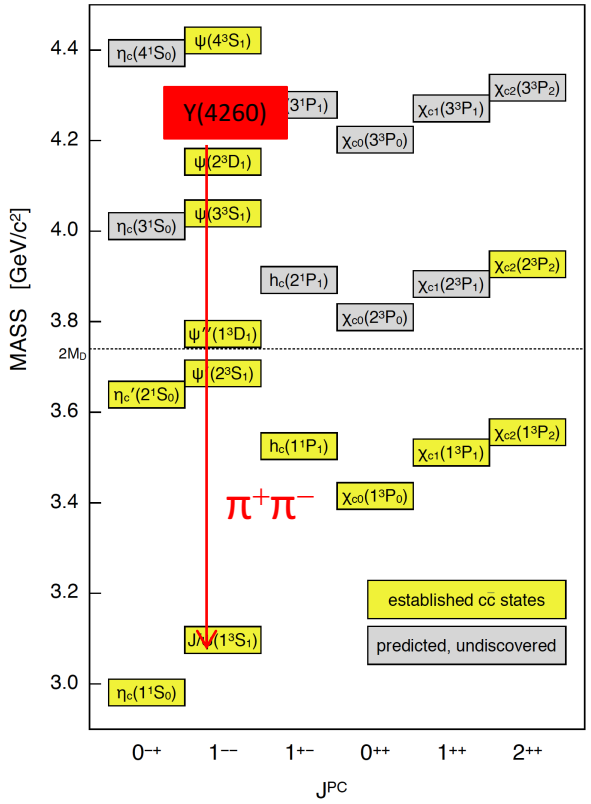
mass is 500 MeV below
LQCD's lightest 0^{++} hybrid



threshold effect?

mass is *below* the only
nearby threshold

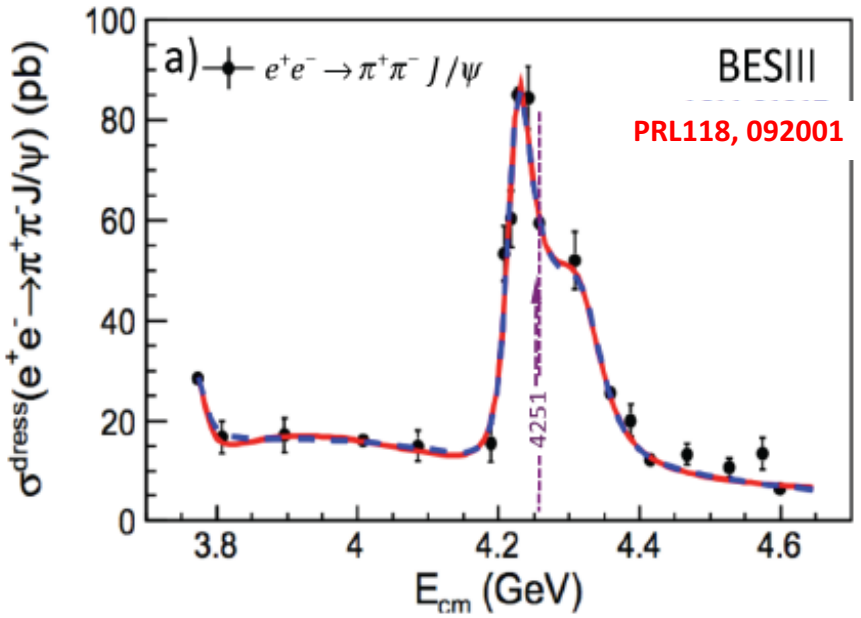
Y(4260)


MASS [GeV/c²]
4.4
4.2
4.0
3.8
2M_D
3.6
3.4
3.2
3.0
Y(4260)
ψ(4³S₁)
ηc(4¹S₀)
ψ(2³D₁)
ψ(3³S₁)
ηc(3¹S₀)
hc(2¹P₁)
ψ'(1³D₁)
ψ (2³S₁)
ηc'(2¹S₀)
hc(1¹P₁)
ψ(1³S₁)
ηc(1¹S₀)
χc2(3³P₂)
χc1(3³P₁)
χc0(3³P₀)
χc2(2³P₂)
χc1(2³P₁)
χc0(2³P₀)
χc2(1³P₂)
χc1(1³P₁)
χc0(1³P₀)
π⁺π⁻
established cc̄ states
predicted, undiscovered
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
JPC

Y(4260)→ππJ/ψ is 2 peaks

-- one at ≈4220 MeV & one at ≈4320 MeV --

2 peaks in $e^+e^- \to \pi^+\pi^- J/\psi$

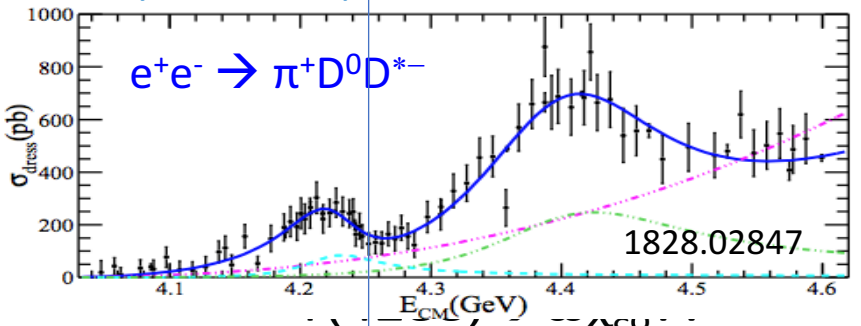


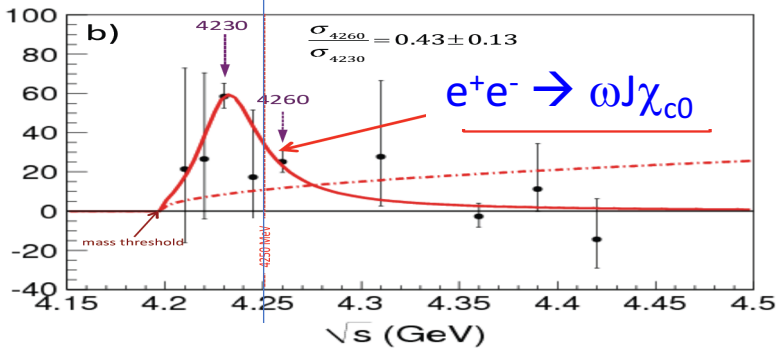
$M_1 = 4220 \pm 4$ MeV/c^2 $\quad M_2 = 4320 \pm 13$ MeV/c^2

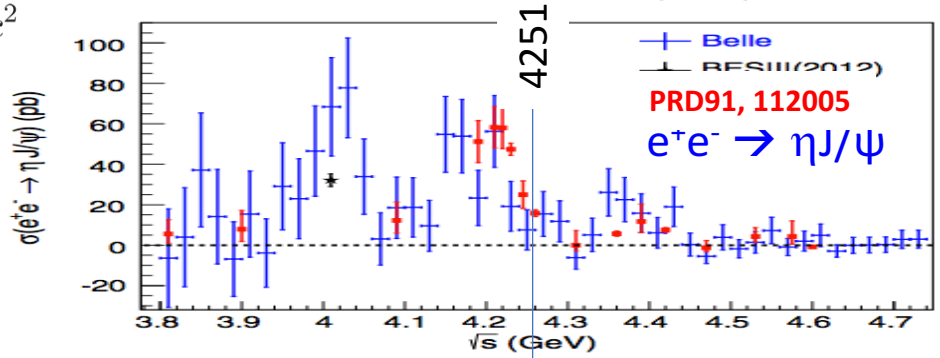
$\Gamma_1 = 44 \pm 5$ MeV $\quad \Gamma_2 = 101^{+27}_{-22}$ MeV

Not seen in B decays

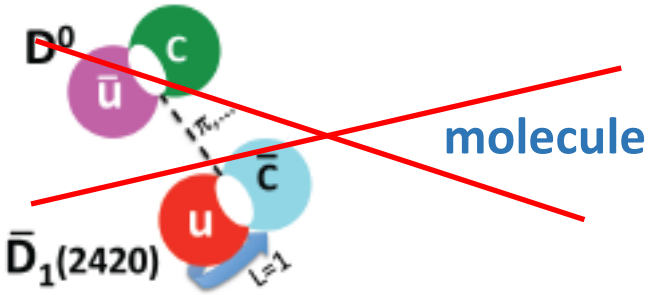
only the lower peak seen in other channels





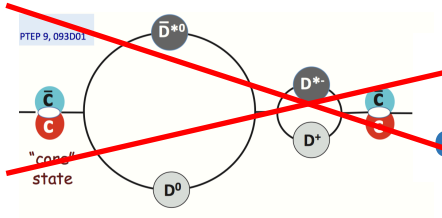


Y(4260)



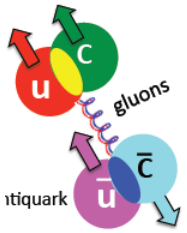
molecule?

$D\bar{D}_1(2460)$ BE (≈65 MeV) is very large
-- but see PRD 90, 074039



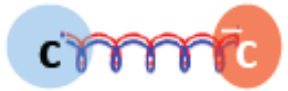
coupled channels?

no candidate $c\bar{c}$ state or nearby $D\bar{D}$ threshold
-- but see PRD 94, 054035



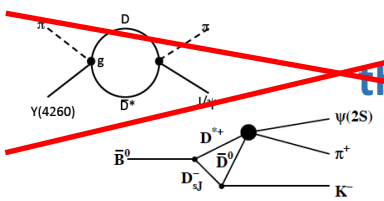
QCD tetraquark?

[cq][c̄q̄] tetraquark
-- but no partner states have been identified



QCD hybrid?

PLB 631 164 (2005)
only ≈65 MeV below LQCD's lightest 1^{--} hybrid



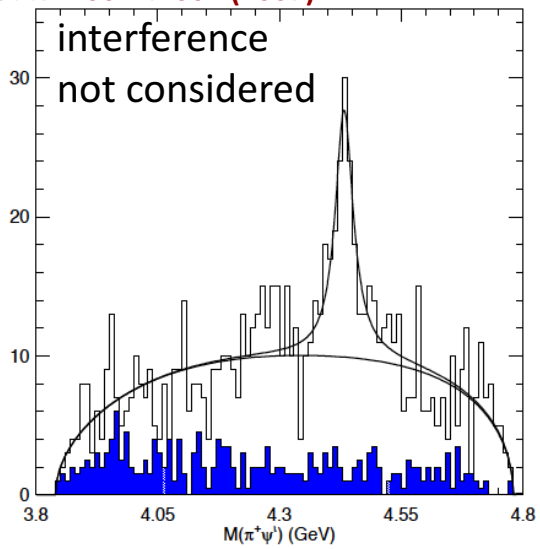
threshold effect?

mass is *below* the only relevant threshold

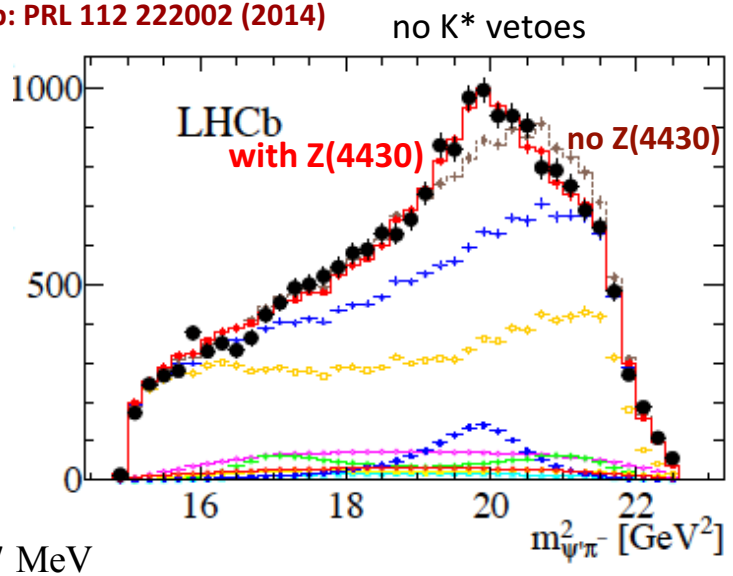
What about the charged Z states?

Z(4430) found by Belle; confirmed by LHCb

Belle: PRL 100 142001 (2007)



LHCb: PRL 112 222002 (2014)

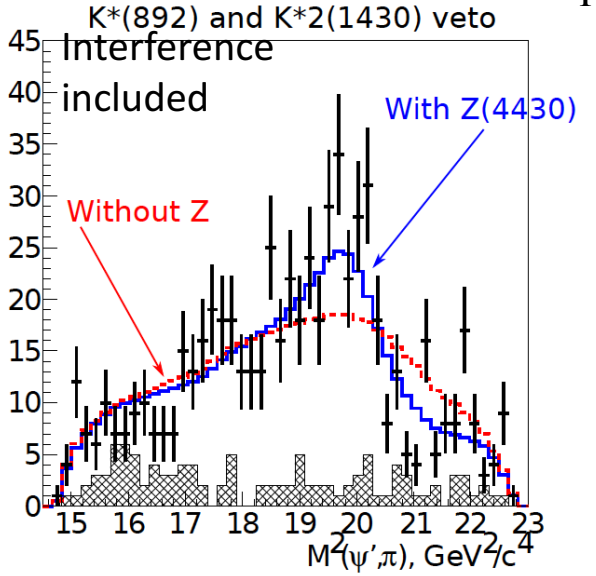


PDG 2018 average

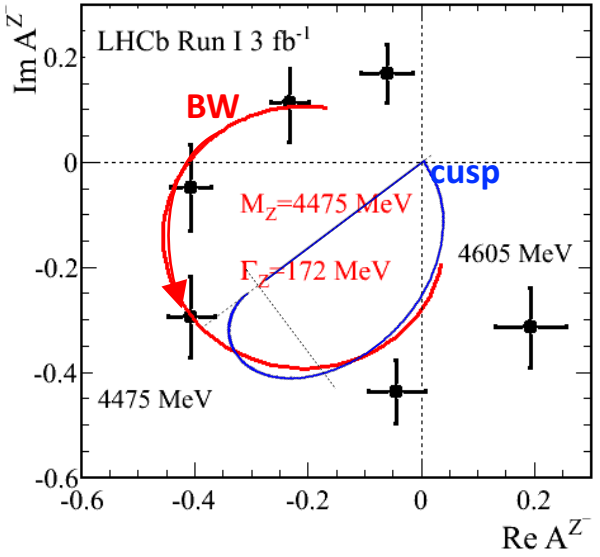
$$M(Z(4430)) = 4478 \pm 17 \text{ MeV}$$

$$\Gamma(Z(4430)) = 181 \pm 31 \text{ MeV}$$

Belle: PRD 88 074026 (2013)



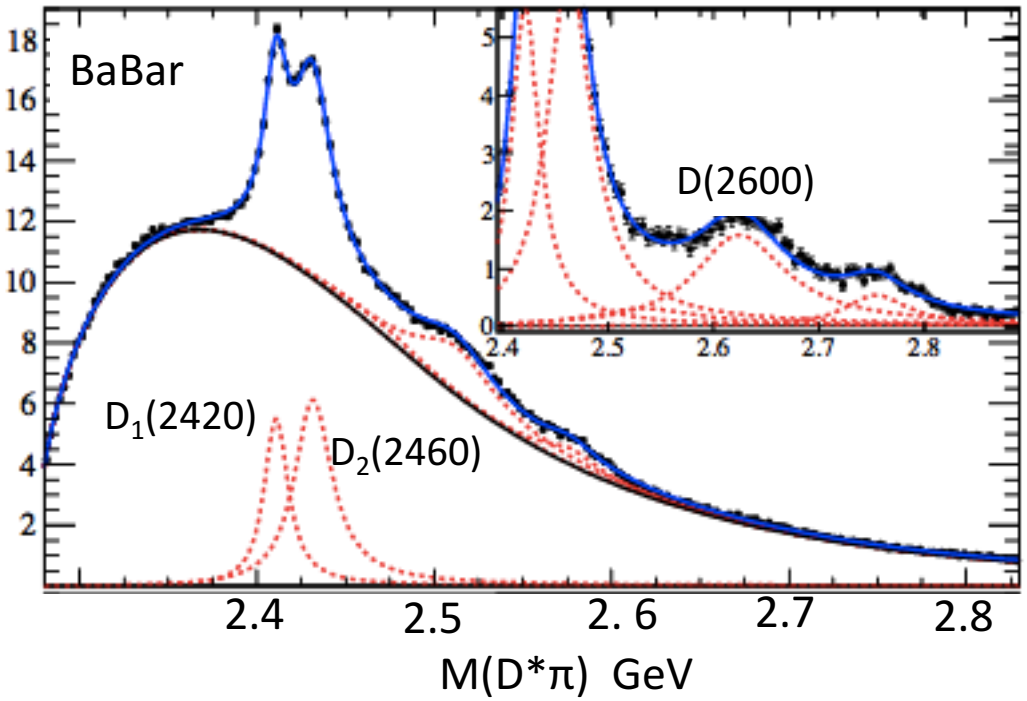
BW-like phase motion confirmed

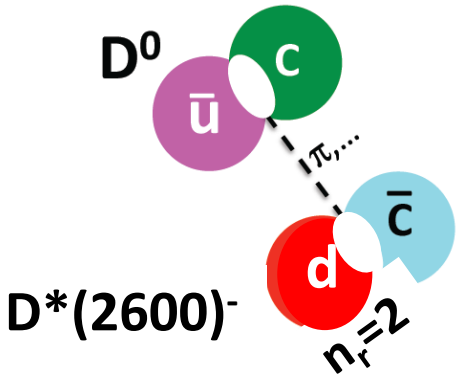


$D\bar{D}^*(2S)$ molecule

-- ($D^*(2S)$=radially excited D^*?) --

BaBar: Phys. Rev. D82, 111101



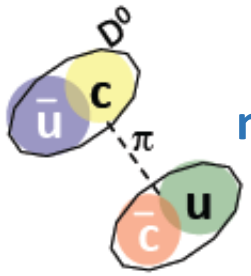


$$M(D(2600)) = 2609 \pm 4 \text{ MeV}$$

$$\Gamma(D(2600)) = 93 \pm 15 \text{ MeV}$$

"B.E."= $(m_{D^+} + m_{D^*(2S)}) - M_{Z(4430)} \approx 0 \pm 18$ MeV

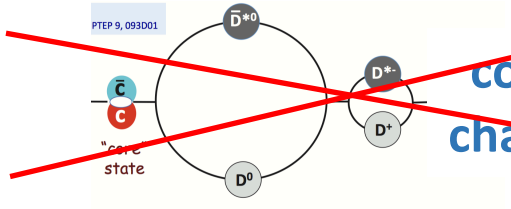
Z(4430)



molecule?

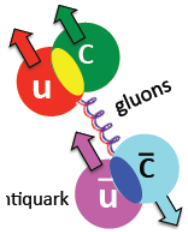
D*(2600)⁺

Γ(Z(4430)≈180 MeV & Γ(D*(2600)) ≈100 MeV
too short-lived for a molecule?



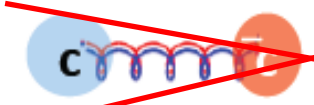
coupled channels?

no charged cc core states



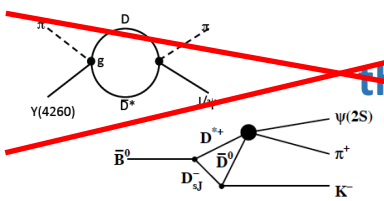
QCD tetraquark?

PRD 89 114010 (2012) / PRL 113, 112001 (2014)
no partner states seen



QCD hybrid?

no charged cc-gluon states

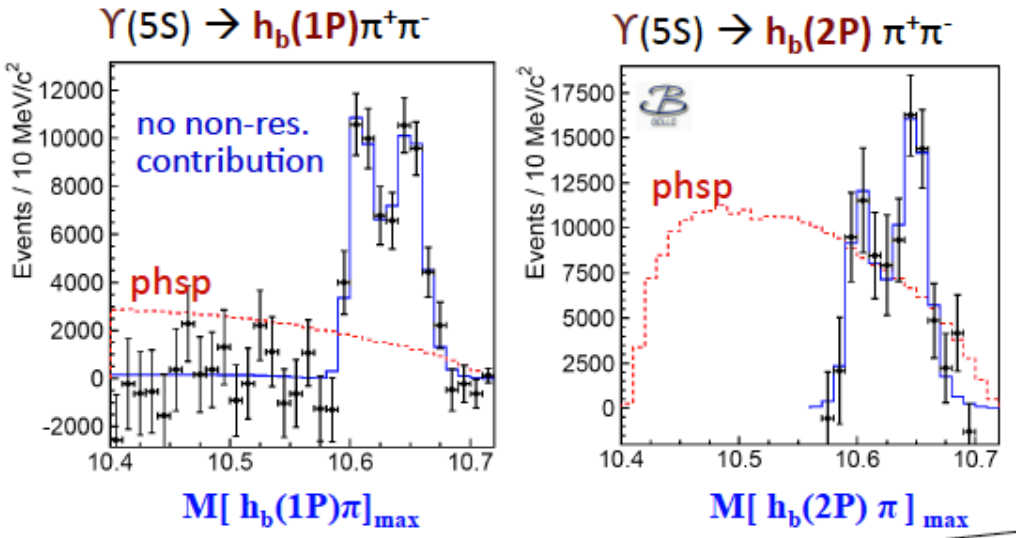


threshold effect?

Argand plot favors BW-like phase motion

Z_b states discovered by Belle

Belle: PRL108, 232001 (2012)

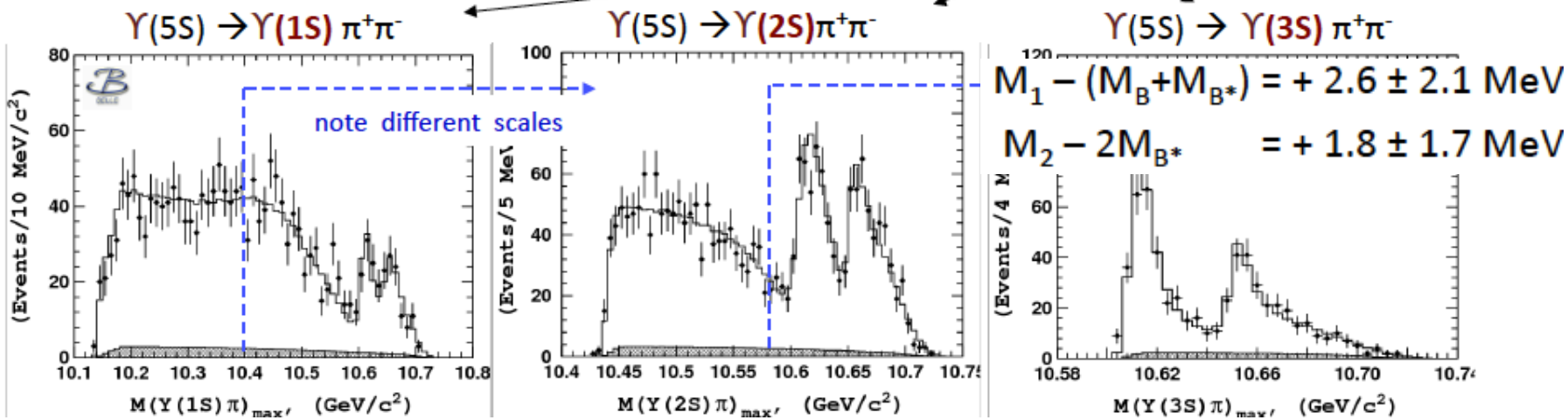


Z_1 & Z_2 are just above the BB* & B*B* thresholds

$M_1 - (M_B + M_{B^*}) = +2.6 \pm 2.1$ MeV

$M_2 - 2M_{B^*} = +1.8 \pm 1.7$ MeV

Dalitz plot analysis



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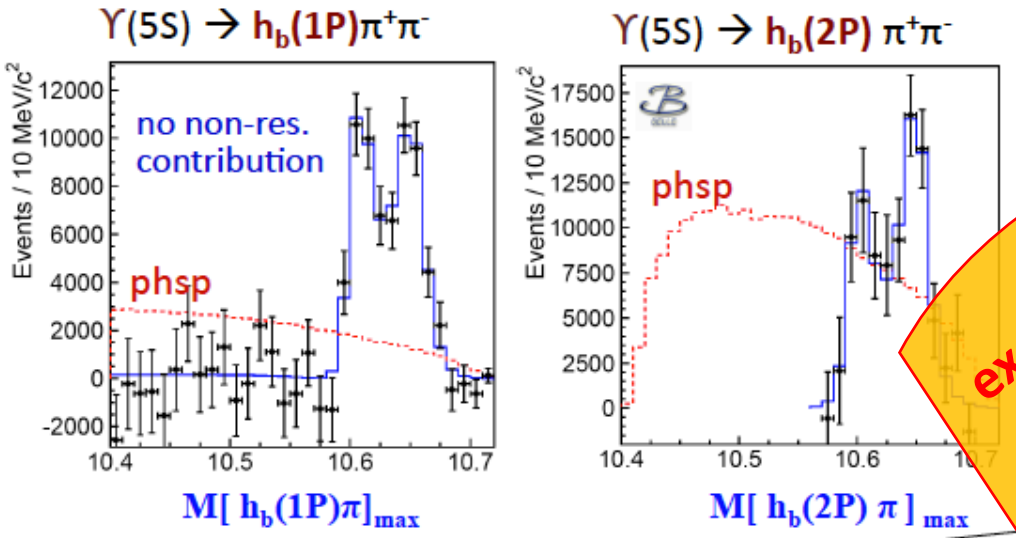


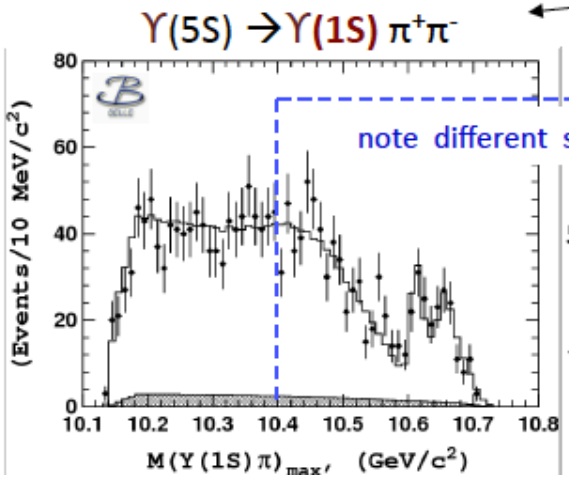
Z_1 & Z_2 are just above the BB^* & B^*B^* thresholds

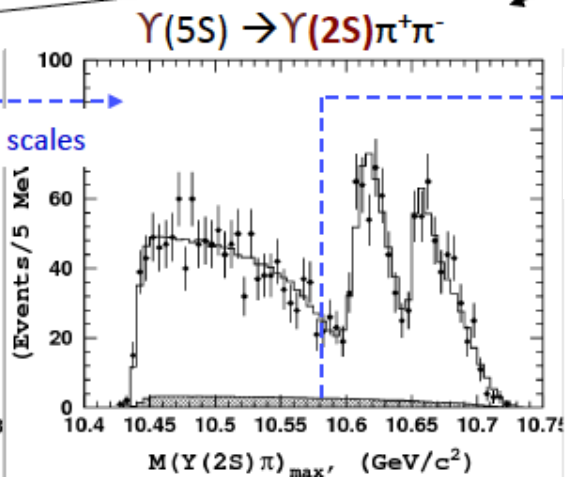
exactly where CUSP-like states are expected

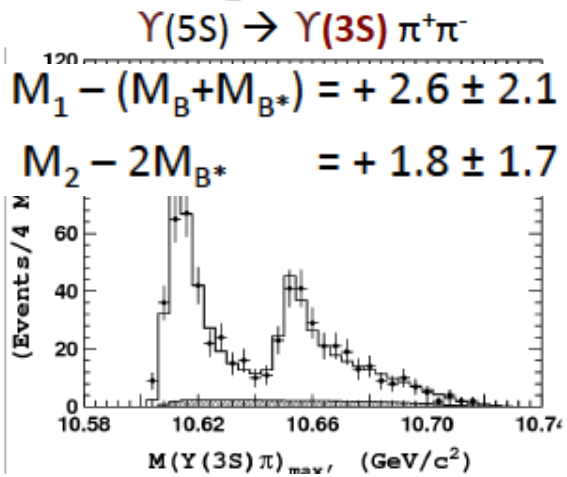
$M_1 - (M_B + M_{B^*}) = +2.6 \pm 2.1$ MeV

$M_2 - 2M_{B^*} = +1.8 \pm 1.7$ MeV

Dalitz plot analysis







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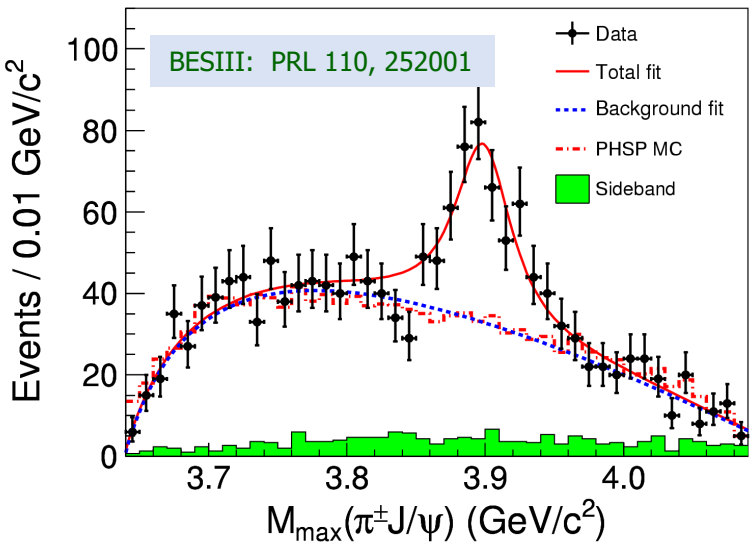
Z_c states discovered by BESIII & Belle

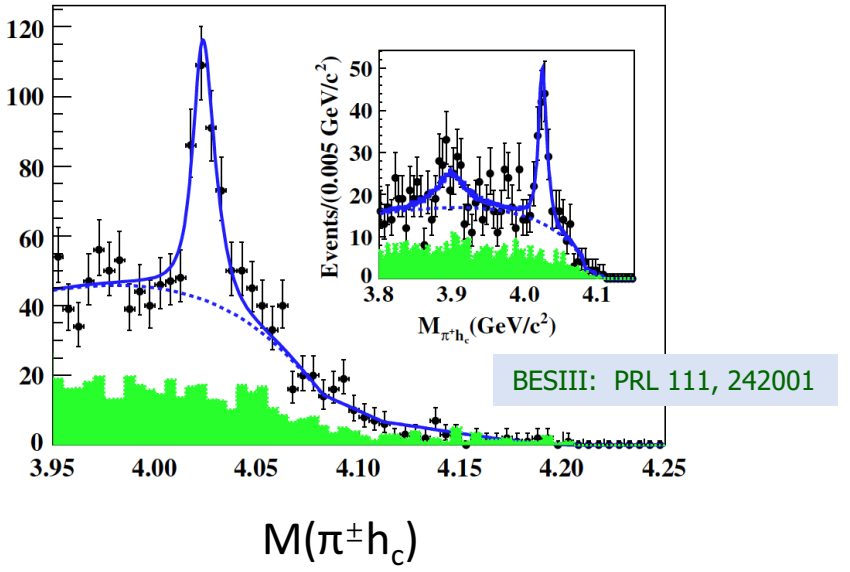
Y(4260)→$\pi^+\pi^- J/\psi$



12 ± 3 MeV above D^0D^{*-} thresh.

Also seen by Belle:
BESIII: PRL110, 252002

Y(4260)→$\pi^+\pi^- h_c$

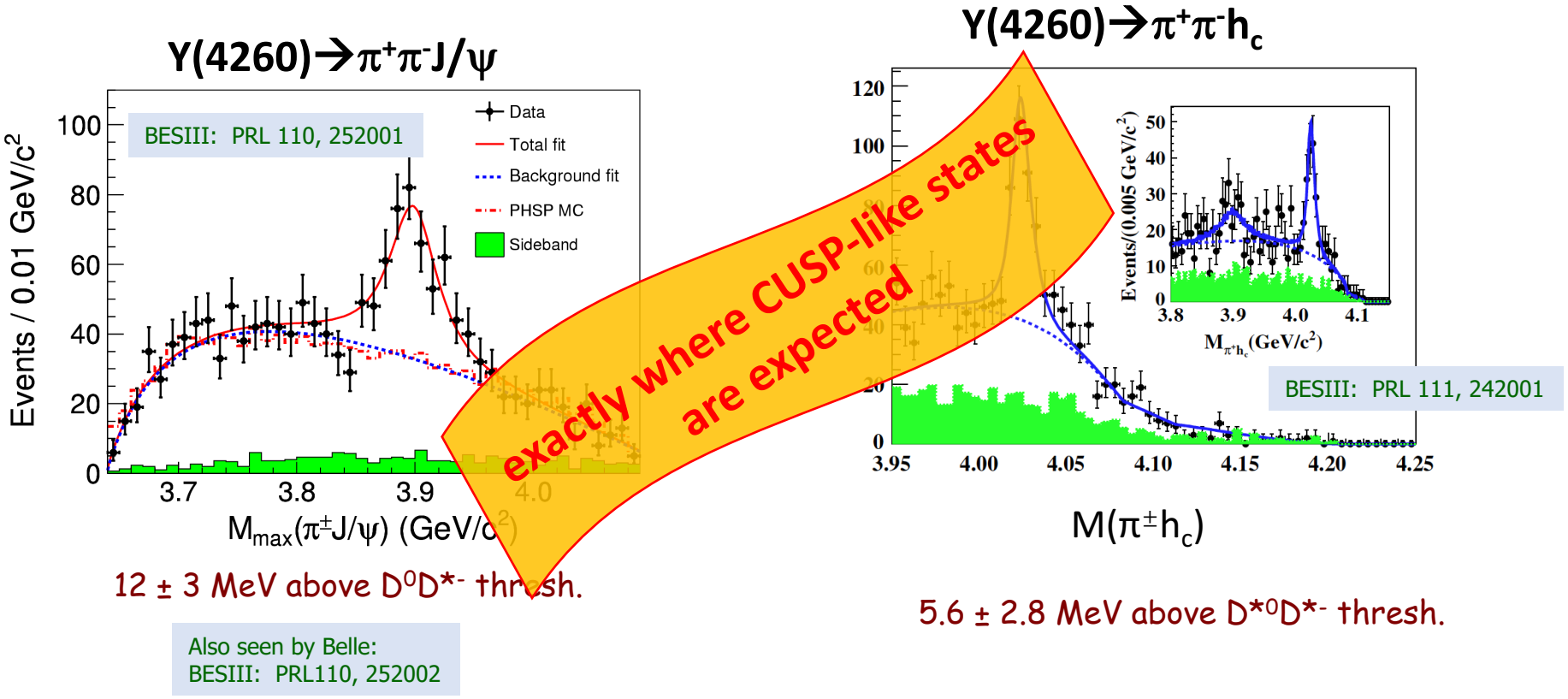


BESIII: PRL 111, 242001

5.6 ± 2.8 MeV above $D^{*0}D^{*-}$ thresh.

Not seen in B decays

Z_c states discovered by BESIII & Belle



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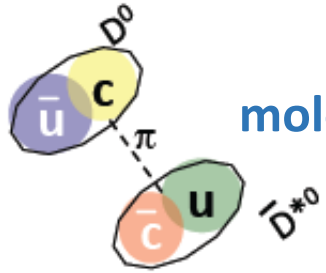
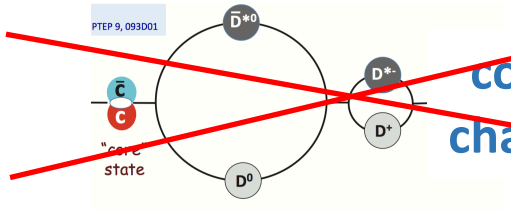
Not seen in B decays

$Z_c(3900/Z_c(4020)$ & $Z_1(10610)/Z_2(10650)$



molecules?

just *above* DD*/D*D* (BB*/B*B*) thresholds



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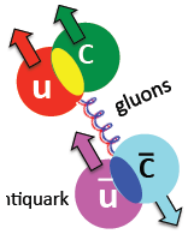
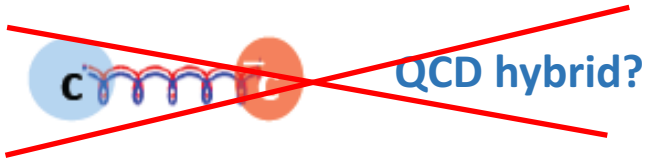


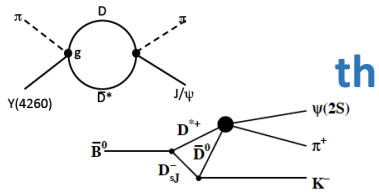
QCD tetraquark?

PRD87 111102 (2013)
no partner states seen



QCD hybrid?

no charged cc-gluon states



threshold effect?

very similar to expectations for cusps
EPL 96 11002 (2011) / PRD 91 034009 (2015)

-- Argand plots are needed

Scorecard

state	Molecule?	Coupled-channel	Tetraquark?	Hybrid?	Threshold effect?	Hadro-charmonium
X(3872)	problem with pp production	**Yes**	partners not seen	m≈500 MeV too low	narrow & at threshold	decays to both S- & P–wave $c\bar{c}$
X(3915)	no 1-π exchange allowed	no $c\bar{c}$ core or $D\bar{D}$ thresh.	partners not seen	m≈500 MeV too low	below threshold	
Y(4260) (Y(4220))?	$D \oplus \bar{D}_1(2420)$? B.E.≈65 MeV	no $c\bar{c}$ core or $D\bar{D}$ thresh.	partner not seen	m≈65 MeV too low	no nearby threshold	decays to both S=1 & S=0 $c\bar{c}$
Z(4430)	$D \oplus \bar{D}^*(2S)$? short lifetimes	no $c\bar{c}$ core state	partner not seen	electrically charged	below threshold	
$Z_c(3900)$ $Z_c(4020)$	≈5 MeV *above* DD* (D*D*) threshold	no $c\bar{c}$ core state	partner not seen	electrically charged	need Argand plot	
$Z_1(10610)$ $Z_2(10650)$	≈2MeV *above* BB* (B*B*) threshold	no $c\bar{c}$ core state	partner not seen	electrically charged	need Argand plot	

-- no single-size that fits all

-- only X(3872) has a clear assignment

Comments:

the X(3872) seems unique & not closely related to other XYZ states

QCD-tetraquarks can account for everything & predict nothing

a “deuson-like” bound molecule has not been seen

Y(4220) is the only XYZ hybrid possibility, but this assignment is very not compelling

Comments:

the X(3872) seems unique & not closely related to other XYZ states

QCD-tetraquarks can account for everything & predict nothing

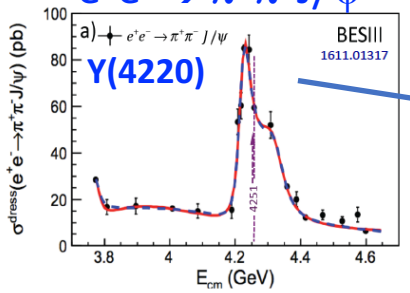
a "deuson-like" bound molecule has not been seen

Y(4220) is the only XYZ hybrid possibility, but this assignment is very not compelling

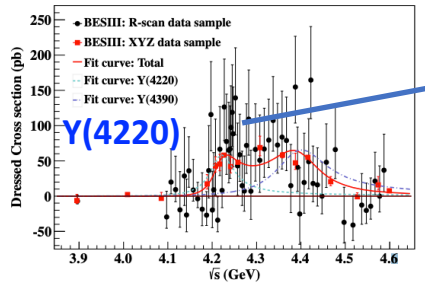
We need a new idea

SCT or STCF as an XYZ factory

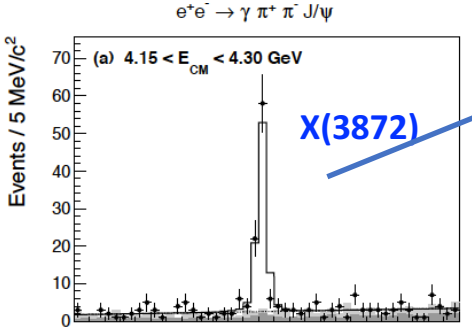
$e^+e^- \to \pi^+\pi^- J/\psi$



$e^+e^- \to \pi^+\pi^- h_c$



$e^+e^- \to \gamma\, \pi^+\, \pi^-\, J/\psi$



~10^8 Y(4220)→$\pi^+\pi^-$ J/ψ decays

+

~ 10^7 Z_c(3900)→π^+ J/ψ decays

+

~ 10^7 Y(4220)→$\pi^+\pi^-$ h_c decays

+

~ 10^6 Z_c(4020)→π^+ h_c decays

+

~ 10^5 X(3872)→$\pi^+\pi^-$ J/ψ decays

+

~ 10^4 X(3915)→ω J/ψ decays