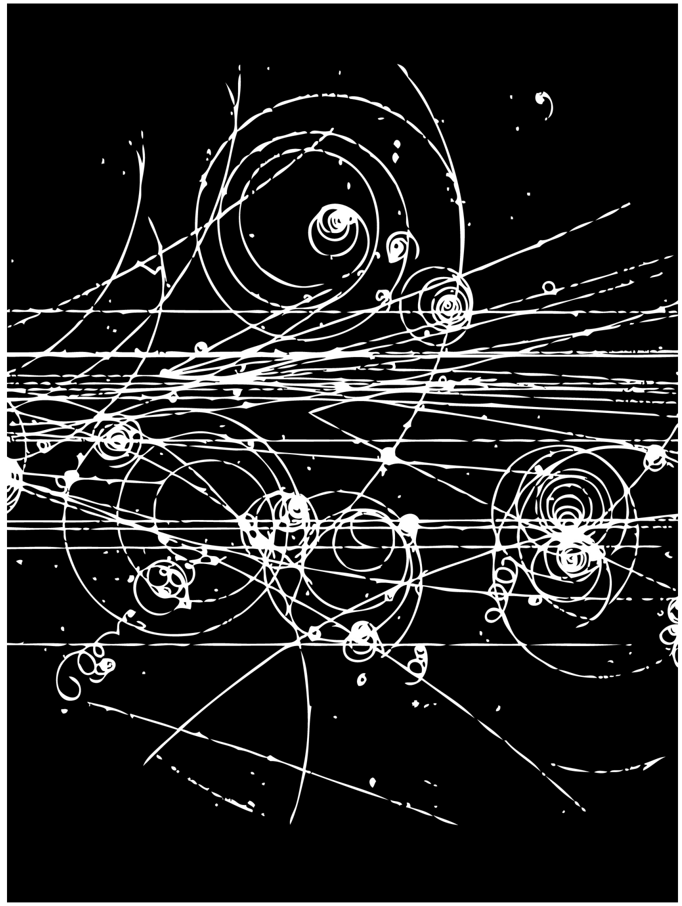
Hadron Spectroscopy



Stephen Lars Olsen
Institute for Basic Science (KOREA)
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UCAS Physics-department, June 20 – July 6, 2014

Summary (lecture 4)

- The quarkonium spectra are the strongest evidence that hadrons are composed of spin=1/2 constituent particles

- All of the charmonium states below the $M=2m_D$ "open charm" threshold have been found
  - most of the bottomonium states below $M=2m_B$ have been identified

- Above the $M=2m_D$ threshold, most of the 1^{--} states, but only three of the others (the χ_{c0}' , χ_{c2}' & ψ_{c2}) have been discovered.

- The masses of the assigned states match theory predictions
  - variations are less than ~50 MeV

- Transitions between quarkonium states are in reasonably good agreement with theoretical expectations

General comments

- The charmed and bottom "quarkonium systems" are relatively simple and reasonably well understood.
  - The "hydrogen atoms" of QCD.

- Let's try to use them to search for new and unpredicted phenomena.
  - If we find a meson that contains a $c\bar{c}$ ($b\bar{b}$) pair but doesn't fit into one of the remaining unassigned states, we have a candidate for an *exotic* hadron, the subject of the next lecture

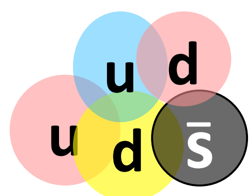
Lecture 5: are there other, non-$q\bar{q}$ meson and/or non-qqq baryon, spectroscopies?

Other possible "white" combinations of quarks & gluons:

Pentaquarks:

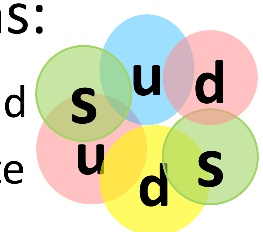
e.g. an S=+1 baryon

(only the anti-s quark has S=+1)



dibaryons:

tightly bound 6-quark state

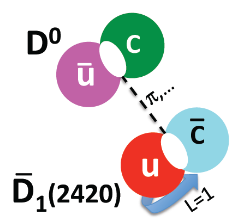


not a nuclear state

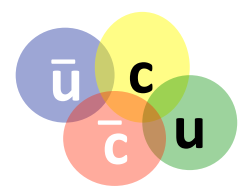
Glueballs:

gluon-gluon color singlet states

Tetraquark mesons

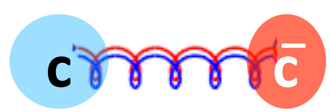


deuteron-like molecules

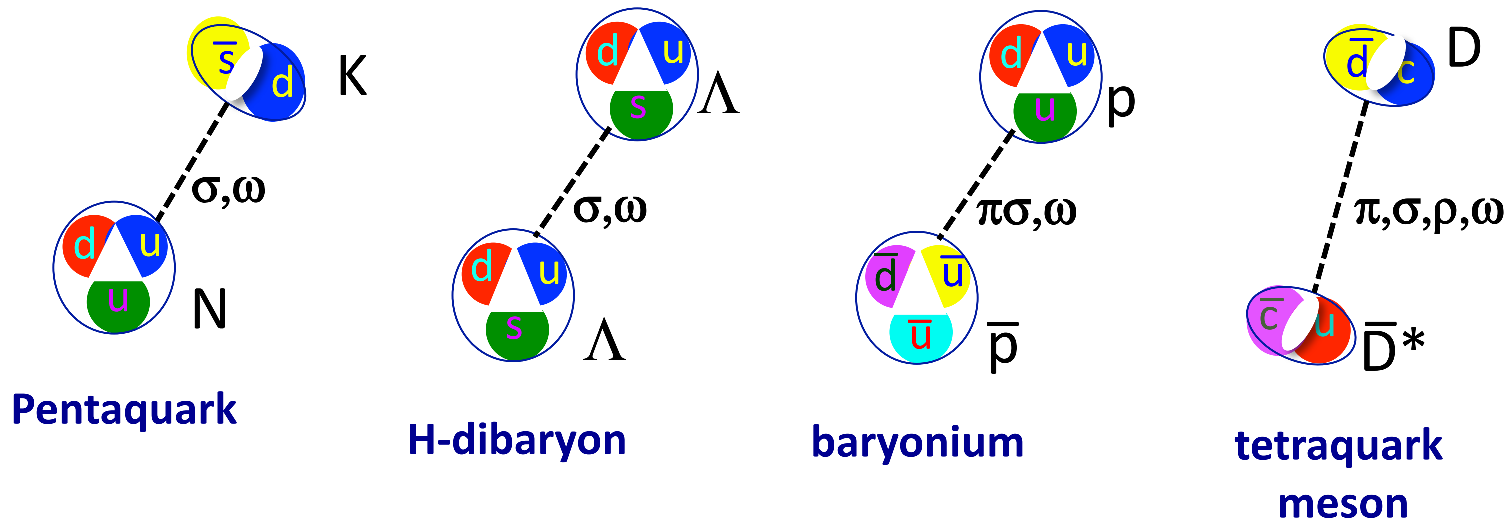


tightly bound diquark-diantiquarks

$q\bar{q}$-gluon hybrid mesons



multiquark states from “molecules”



“exotic” hadrons that nuclear theorists love

QCD diquarks?

PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

R. J. Jaffe†

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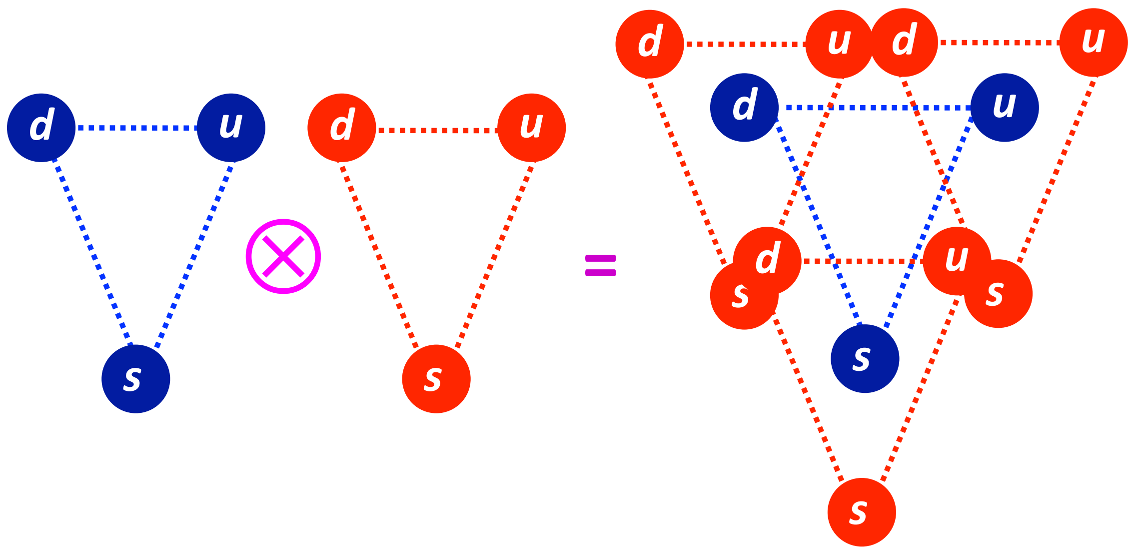
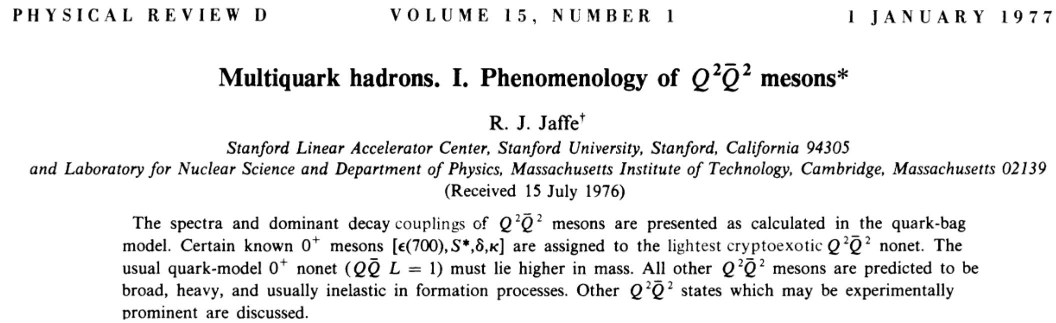
and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons [$\epsilon(700), S^*, \delta, \kappa$] are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L = 1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.



QCD diquarks?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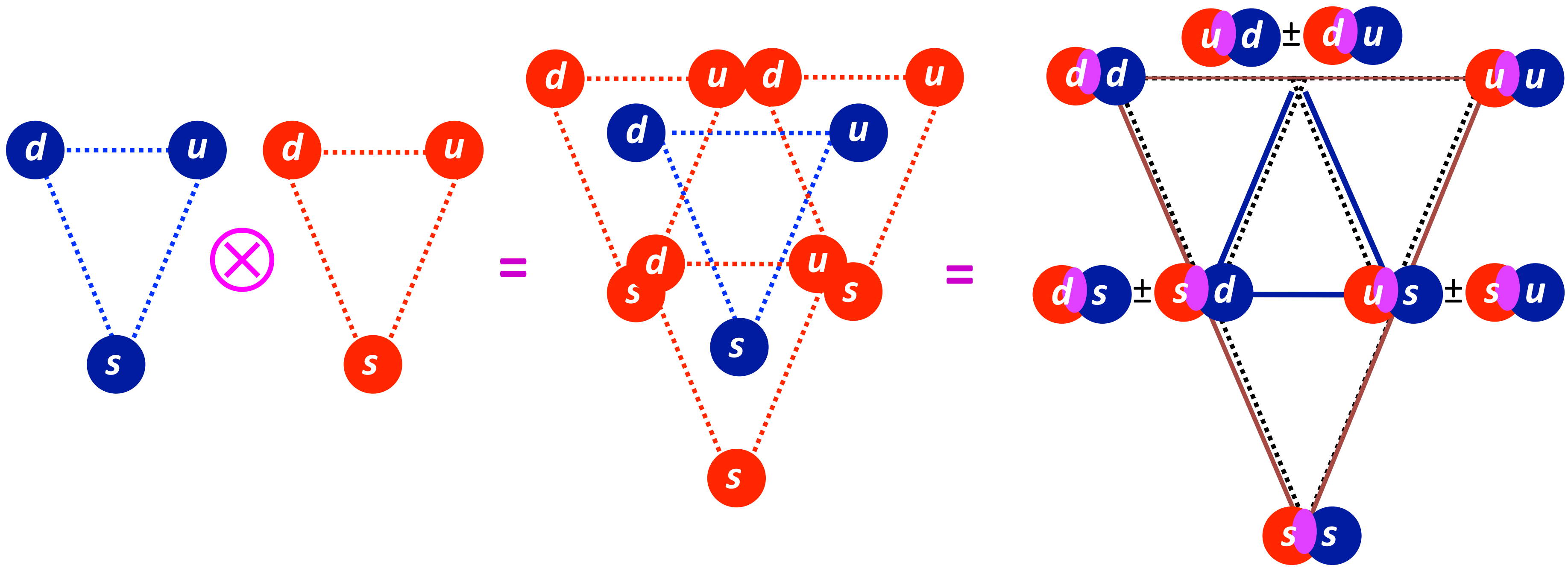


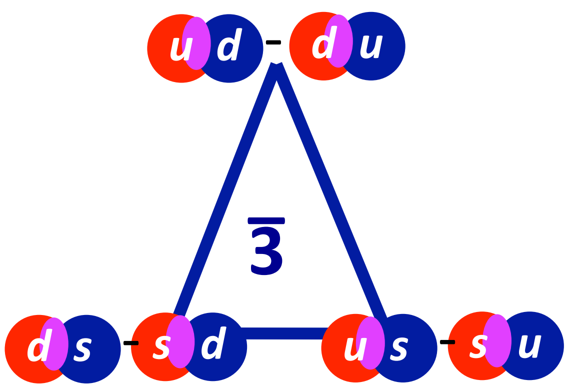
$$\color{blue}{3}\otimes\color{red}{3}=\color{magenta}{6}\oplus\color{magenta}{\bar{3}}$$

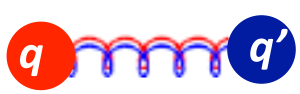
good diquarks

bad diquarks

anti-color anti-triplet

antisymm. in color
antisymm in flavor
must be Spin =0

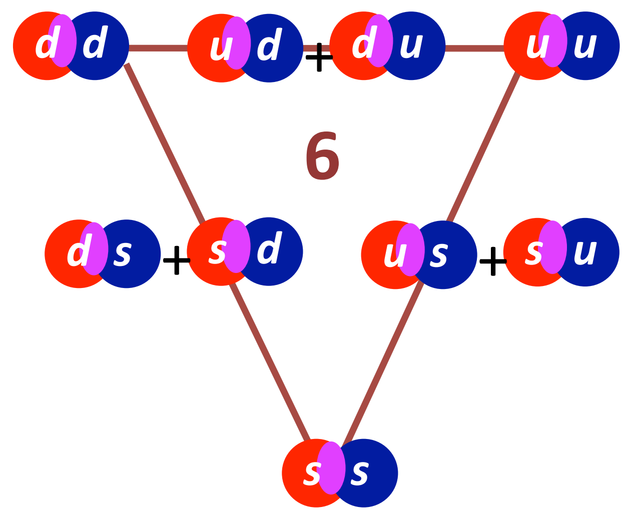




at very short distances, a “good” diquark is bound with ~ ½ the binding energy of a $q\bar{q}$ pair

anti-color sextet

antisymm. in color
symmetric in flavor
must be Spin =1



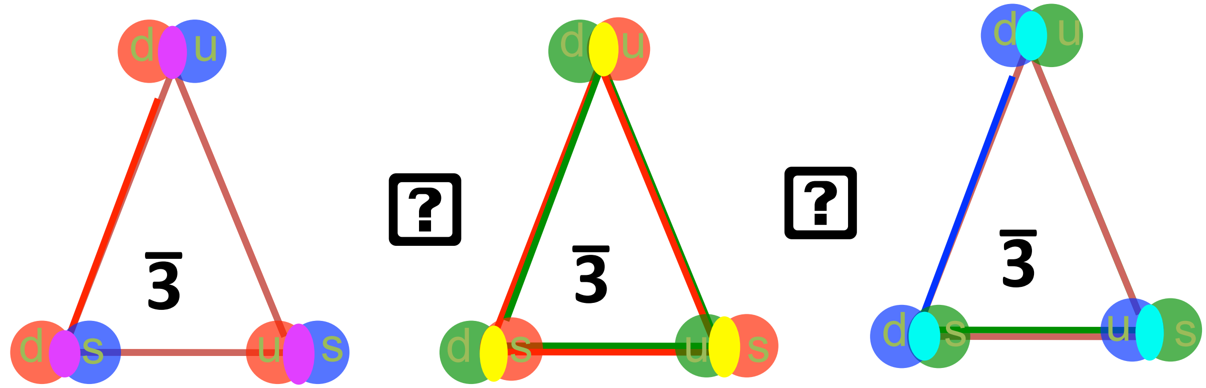
at very short distances, a “bad” diquark is not tightly bound

multiquark states from diquarks & diantiquarks

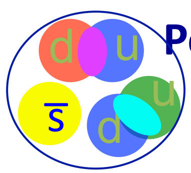
diquarks combine
like antiquarks

diantiquarks combine
like quarks

red-blue diquark | green-red diquark | blue-green diquark

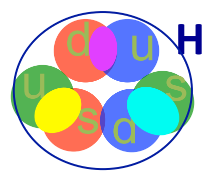


magenta (anti-green) **anti-triplet** | **yellow** (anti-blue) **anti-triplet** | **cyan** (anti-red) **anti-triplet**



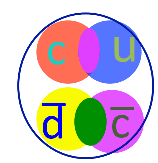
Pentaquark

magenta-cyan-yellow
color singlet 5-q state



H-dibaryon

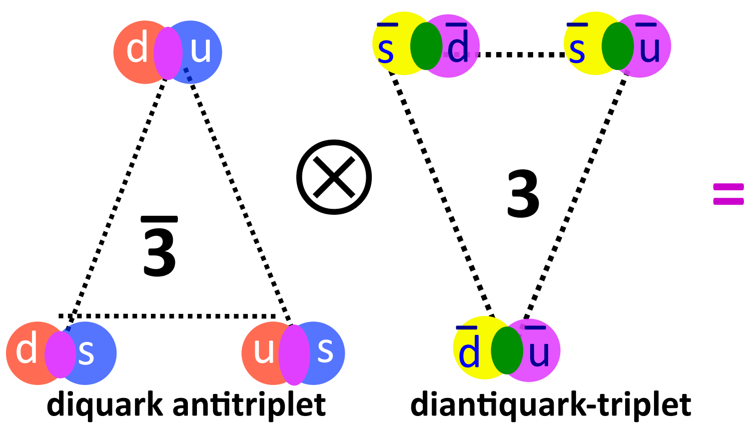
magenta-cyan-yellow
color singlet 6-q state

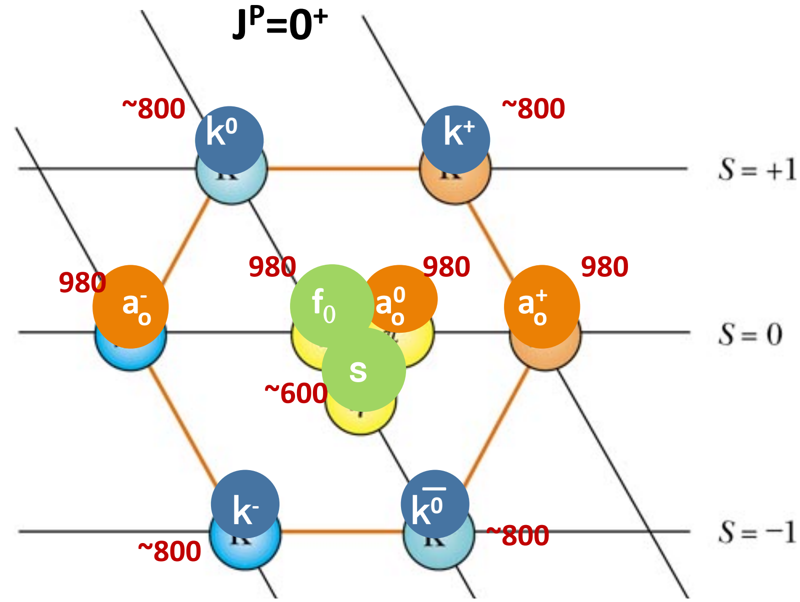


tetraquark meson

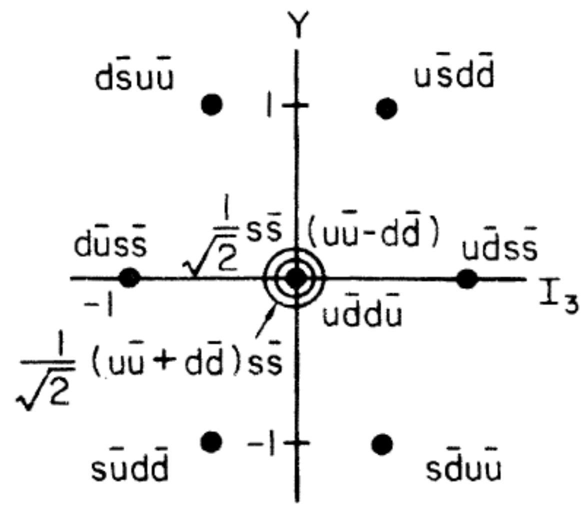
green-magenta (anti-green)
color singlet 4-q state

light scalars=diquarks⊗diantiquarks?





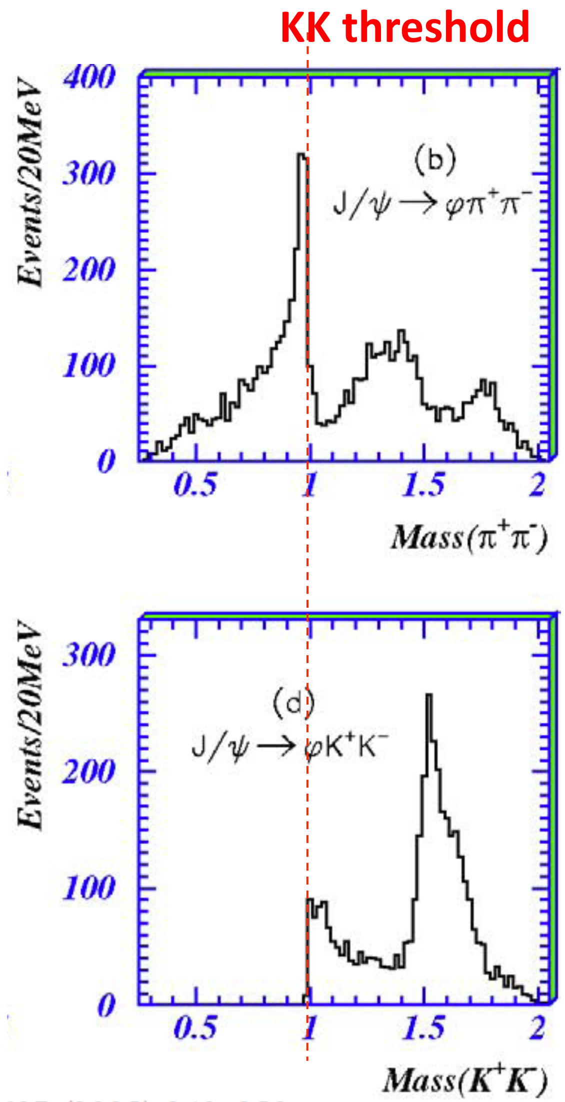
$$\bar{3}\otimes 3 = 8 \oplus 1$$

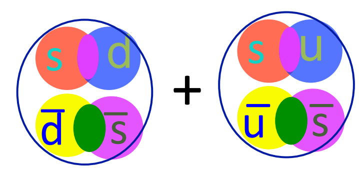


Is the $f_0(980)$ a $(su\bar{s}\bar{u}+sd\bar{s}\bar{d})$ state?

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

$J/\psi \to \varphi K^+K^-$





BES Collaboration / Physics Letters B 607 (2005) 243–253

BES sees an abrupt switch from f_0(980)→pp to f_0(980)→KK at threshold

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

Multiquark states have been discussed since the 1st page of the quark model

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Where are they??

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

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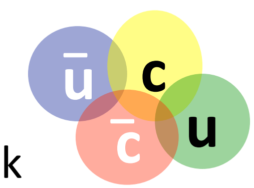
Are there multiquark mesons?

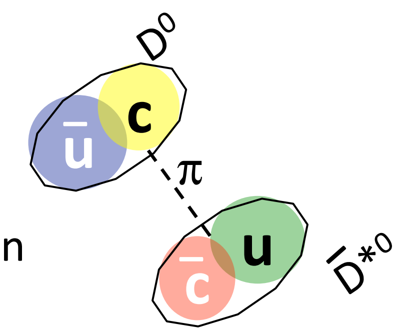
Possible non $q\bar{q}$ "white" combinations of quarks:

Tetraquark mesons

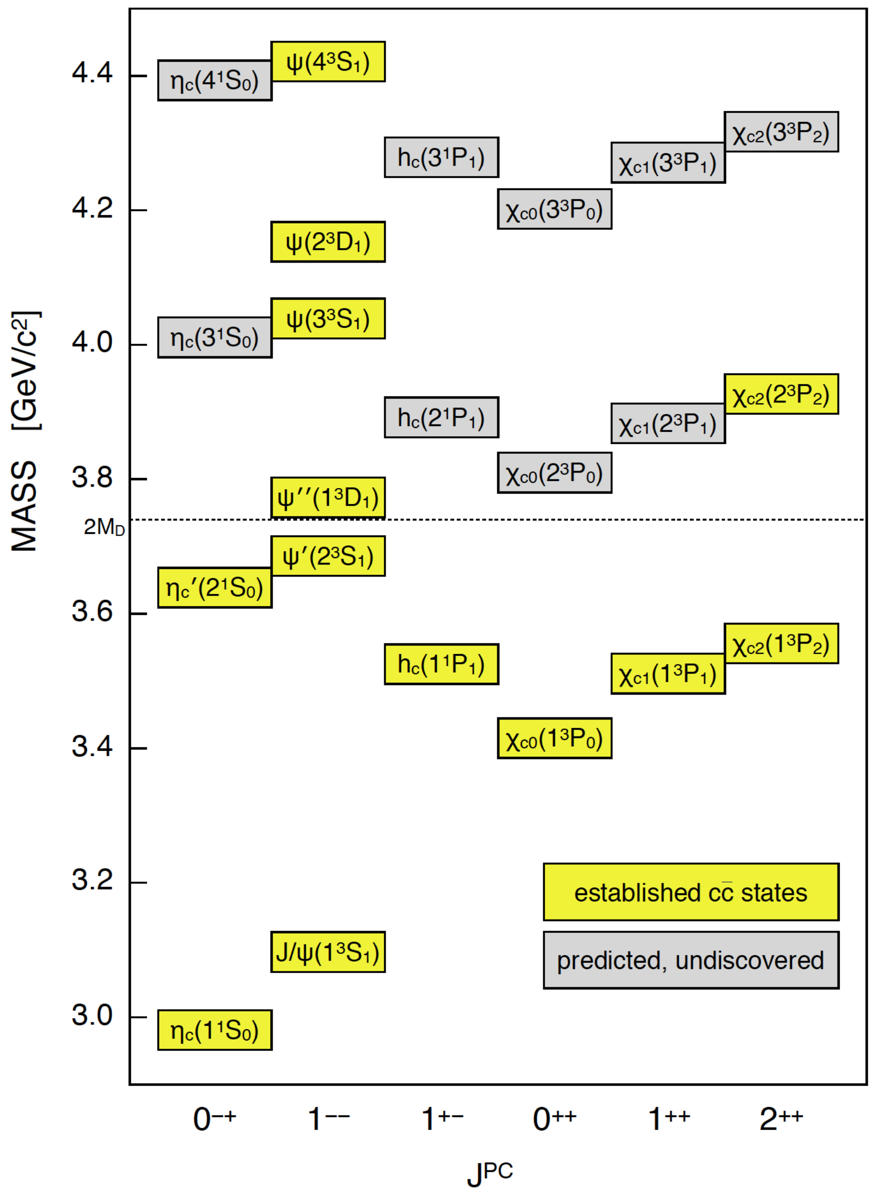
tightly bound
diquark-diantiquark



loosely bound
meson-antimeson
"molecule"



Charmonium spectrum

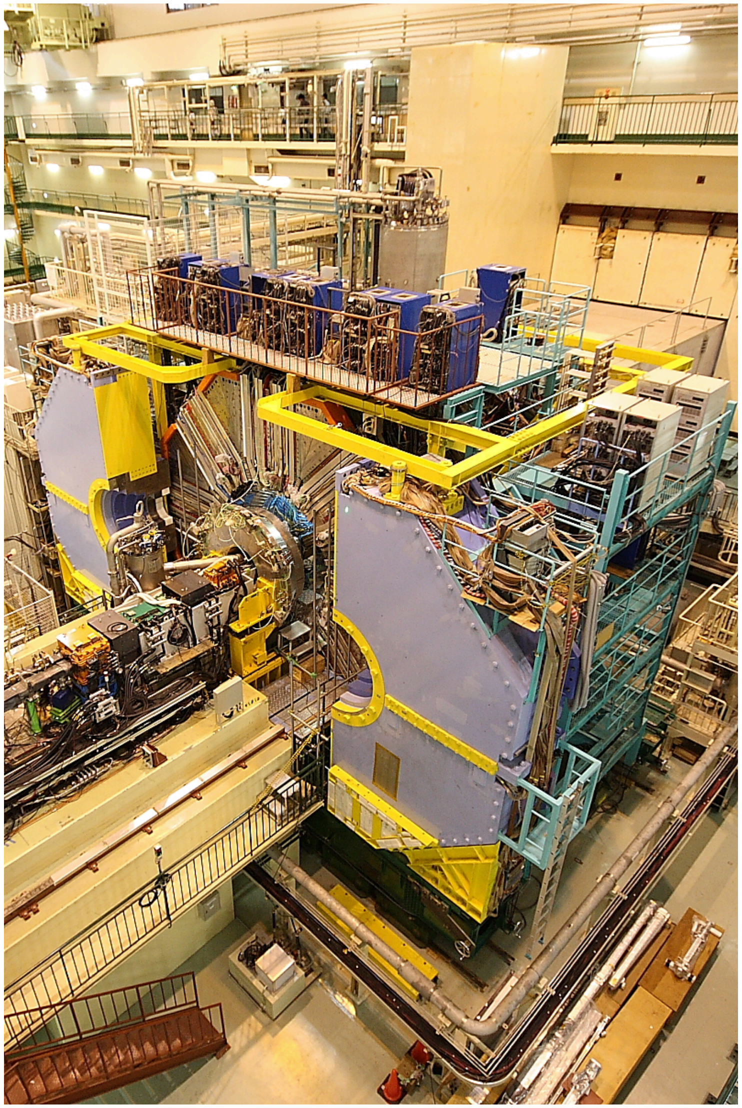


Any meson that decays to a c and $\bar{c}$ quark should fit in one of the (gray) unassigned states.

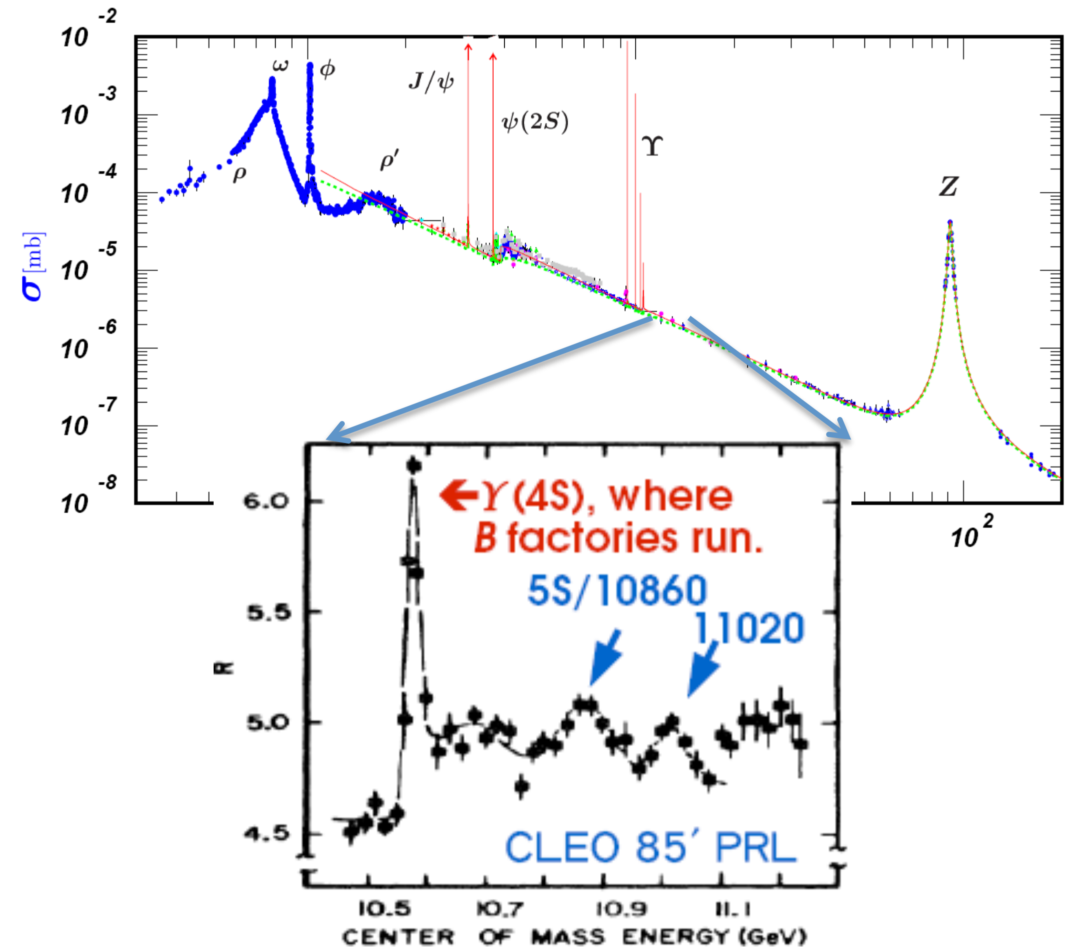
candidates for multi-quark states

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K + (J/\psi\pi^+\pi^-)$	Belle (157; 160), BaBar (78), LHCb (8; 17)
				$p\bar{p} \to (J/\psi\pi^+\pi^-) + ...$	CDF (26; 58; 60), D0 (30)
				$B \to K + (J/\psi\pi^+\pi^-\pi^0)$	Belle (36), BaBar (175)
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle (95; 202), BaBar (87)
				$B \to K + (J/\psi\gamma)$	BaBar (175), Belle (113), LHCb (6)
				$B \to K + (\psi'\gamma)$	BaBar (89), Belle (113), LHCb (13)
				$pp \to (J/\psi\pi^+\pi^-) + ...$	LHCb (6), CMS (141), ATLAS (2)
				$e^+e^- \to \gamma + (J/\psi\pi^+\pi^-) + ...$	BESIII (47)
$X(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K + (J/\psi\omega)$	Belle (158), BaBar (86; 175)
				$e^+e^- \to e^+e^- + (J/\psi\omega)$	Belle (333), BaBar (247)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0^{-+}(?)$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle (294)
				$e^+e^- \to J/\psi + (...)$	Belle (37)
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma + (J/\psi\pi^+\pi^-)$	Belle (352)
$X(4140)$	$4146.5^{+6.4}_{-5.3}$	83^{+27}_{-25}	1^{++}	$B \to K + (J/\psi\phi)$	CDF (25), CMS (143), D0 (32), LHCb (22; 24)
				$p\bar{p} \to (J/\psi\phi) + ...$	D0 (33)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0^{-+}(?)$	$e^+e^- \to J/\psi + (D^*\bar{D}^*)$	Belle (294)
$Y(4260)$	4222.0 ± 3.4	44.1 ± 4.7	1^{--}	$e^+e^- \to \gamma + (J/\psi\pi^+\pi^-)$	BaBar (76; 246), CLEO (213), Belle (262; 352)
				$e^+e^- \to (J/\psi\pi^+\pi^-)$	BESIII (56)
				$e^+e^- \to (\gamma X(3872))$	BESIII (47)
				$e^+e^- \to (\pi^- Z_c^+(3900))$	BESIII (42), Belle (262)
				$e^+e^- \to (\pi^- Z_c^+(4020))$	BESIII (43)
$X(4274)$	$4273.3^{+19.1}_{-9.0}$	56^{+14}_{-16}	1^{++}	$B \to K + (J/\psi\phi)$	CDF (27), CMS (143), LHCb (22; 24)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$(0/2)^{++}$	$e^+e^- \to e^+e^- + (J/\psi\phi)$	Belle (316)
$Y(4360)$	4346 ± 6	102 ± 10	1^{--}	$e^+e^- \to \gamma + (\psi'\pi^+\pi^-)$	BaBar (84; 248), Belle (342; 343)
$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-21}	0^{++}	$B \to K + (J/\psi\phi)$	LHCb (22; 24)
$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	$B \to K + (J/\psi\phi)$	LHCb (22; 24)
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma + (\Lambda_c^+\Lambda_c^-)$	Belle (297)
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to \gamma + (\psi'\pi^+\pi^-)$	Belle (342; 343), BaBar (84; 248)
$Z_c^{+,0}(3900)$	3886.6 ± 2.4	28.1 ± 2.6	1^{+-}	$Y(4260) \to \pi^{-,0} + (J/\psi\pi^{+,0})$	BESIII (42; 52), Belle (262)
				$Y(4260) \to \pi^{-,0} + (D\bar{D}^*)^{+,0}$	BESIII (45; 51)
$Z_c^{+,0}(4020)$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$Y(4260) \to \pi^{-,0} + (h_c\pi^{+,0})$	BESIII (43; 46)
				$Y(4260) \to \pi^{-,0} + (D^*\bar{D}^*)^{+,0}$	BESIII (44; 50)
$Z^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\pi^+)$	Belle (280), BaBar (245)
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^+	$B \to K + (J/\psi\pi^+)$	Belle (154)
				$B \to K + (\psi'\pi^+)$	LHCb (14; 45)
$Z^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K + (\chi_{c1}\pi^+)$	Belle (280), BaBar (245)
$Z^+(4430)$	4477 ± 20	181 ± 31	1^+	$B \to K + (\psi'\pi^+)$	Belle (153; 159; 281), LHCb (14; 15)
				$B \to K + (J\psi\pi^+)$	Belle (154)
$P_c^+(4380)$	4380 ± 30	205 ± 88	$(\frac{3}{2}/\frac{5}{2})^{\mp}$	$\Lambda_b^+ \to K + (J/\psi p)$	LHCb (16)
$P_c^+(4450)$	4449.8 ± 3.0	39 ± 20	$(\frac{5}{2}/\frac{3}{2})^{\pm}$	$\Lambda_b^+ \to K + (J/\psi p)$	LHCb (16)
$Y_b(10860)$	$10891.1^{+3.4}_{-3.8}$	$53.7^{+7.2}_{-7.8}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\pi^+\pi^-)$	Belle (149; 311)
$Z_b^{+,0}(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$Y_b(10860) \to \pi^{-,0} + (\Upsilon(nS)\pi^{+,0})$	Belle (120; 196; 235)
				$Y_b(10860) \to \pi^- + (h_b(nP)\pi^+)$	Belle (120)
				$Y_b(10860) \to \pi^- + (B\bar{B}^*)^+$	Belle (197)
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$Y_b(10860) \to \pi^- + (\Upsilon(nS)\pi^+)$	Belle (120; 196)
				$Y_b(10860) \to \pi^- + (h_b(nP)\pi^+)$	Belle (120)
				$Y_b(10860) \to \pi^- + (B^*\bar{B}^*)^+$	Belle (197)

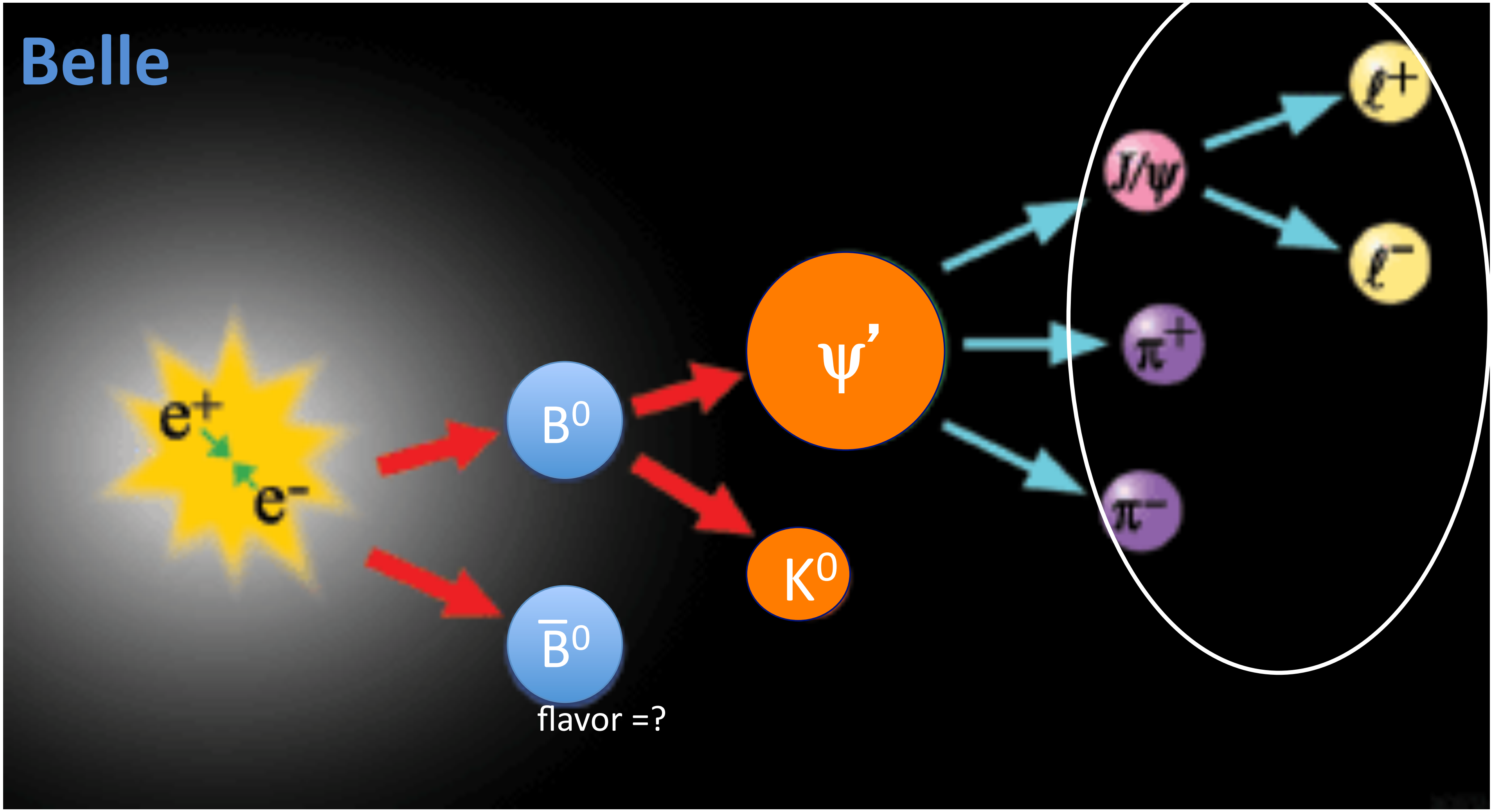
The Belle Experiment at KEK, Japan



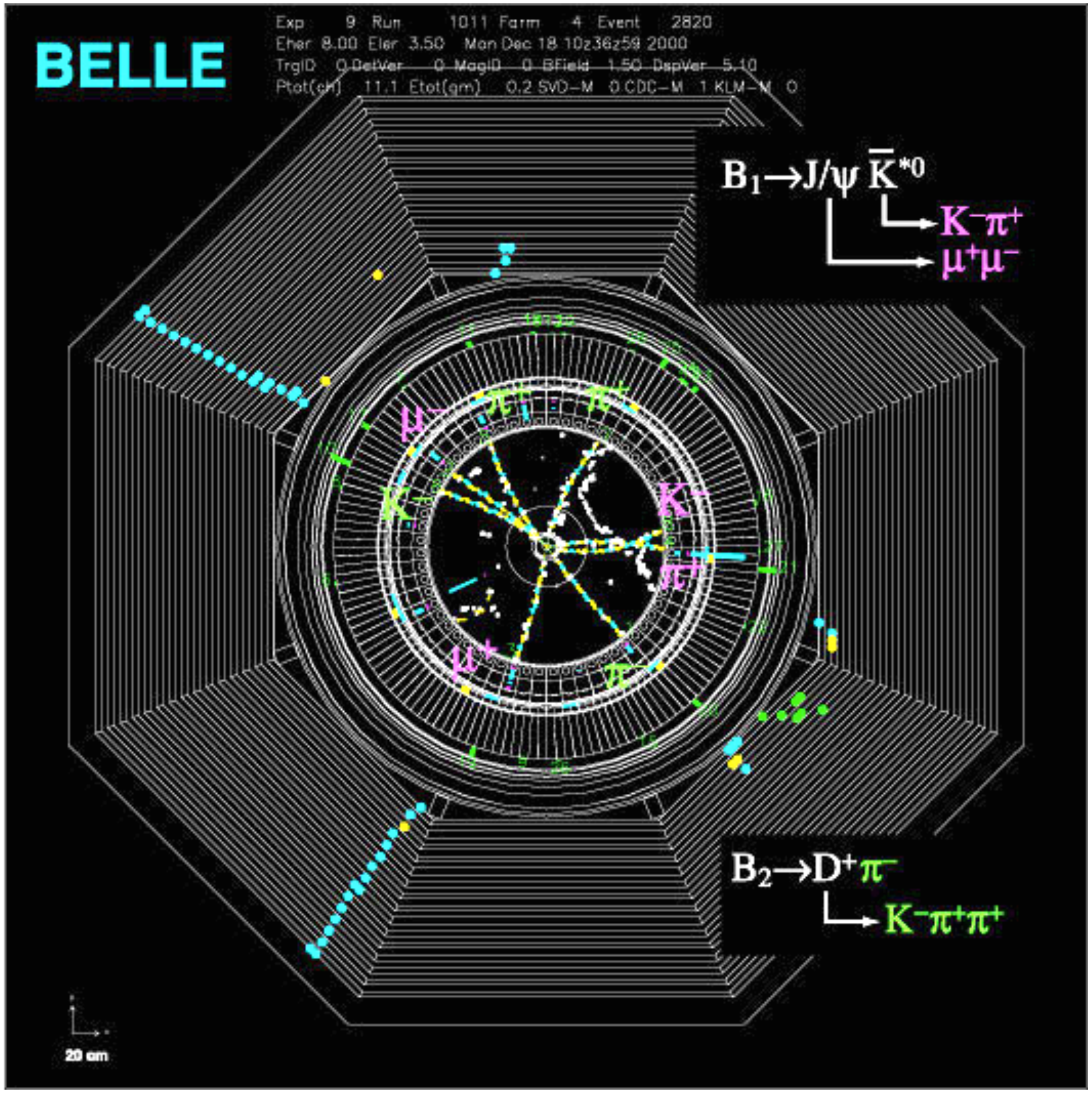
For studies of matter-antimatter asymmetries in B meson decays



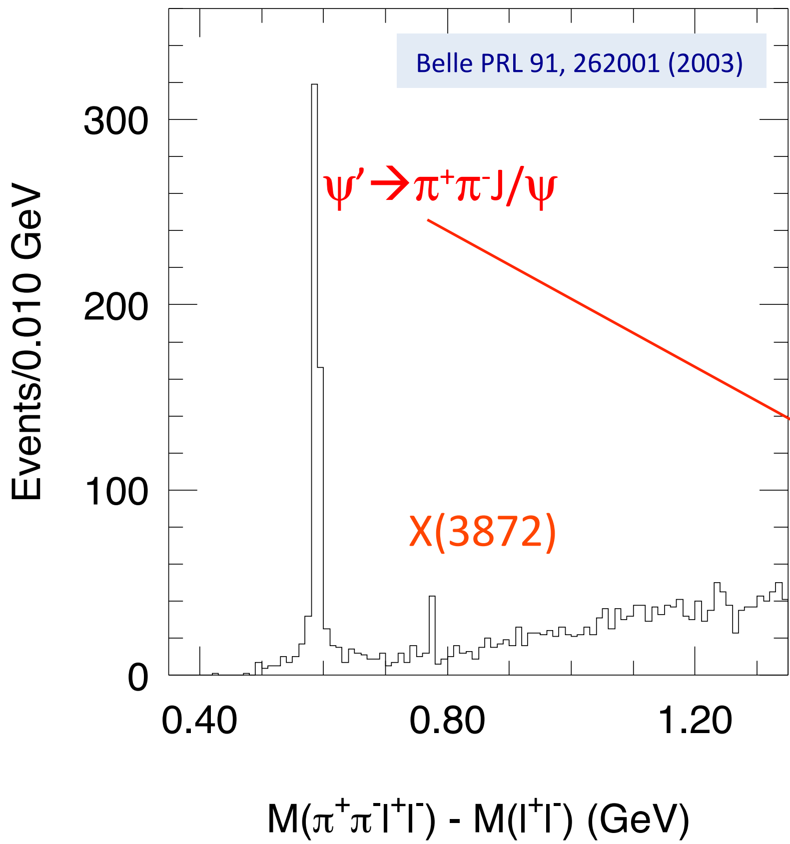
Select $B \rightarrow K\psi'$; $\psi' \rightarrow \pi^+\pi^- J/\psi$

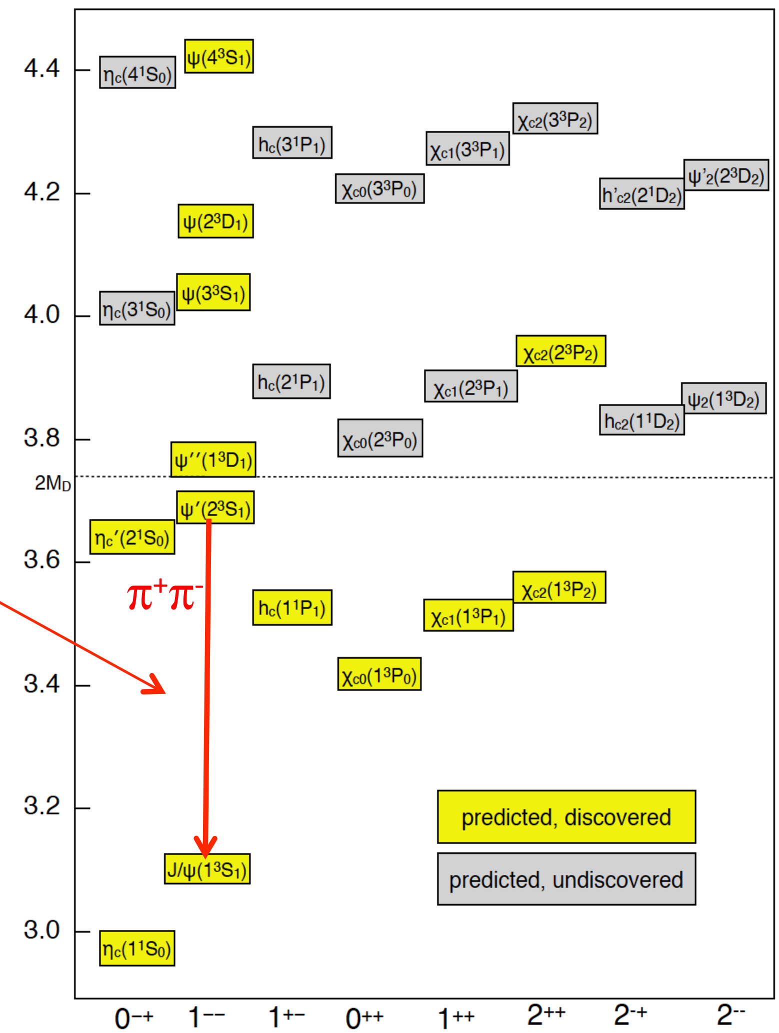


Event in the Belle Detector

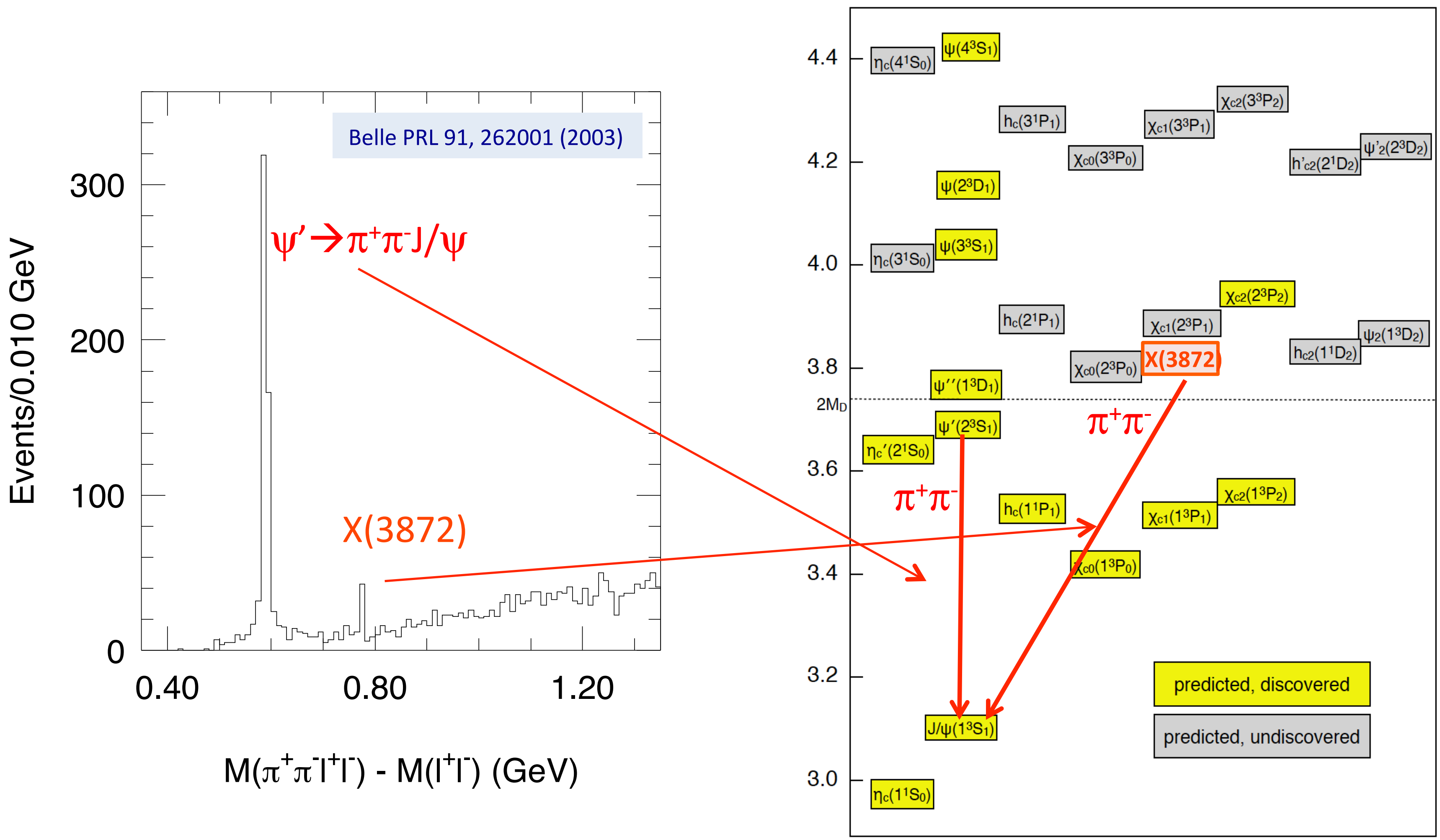


$M(\pi^+\pi^- J/\psi)$ from $B \rightarrow K\pi^+\pi^- J/\psi$



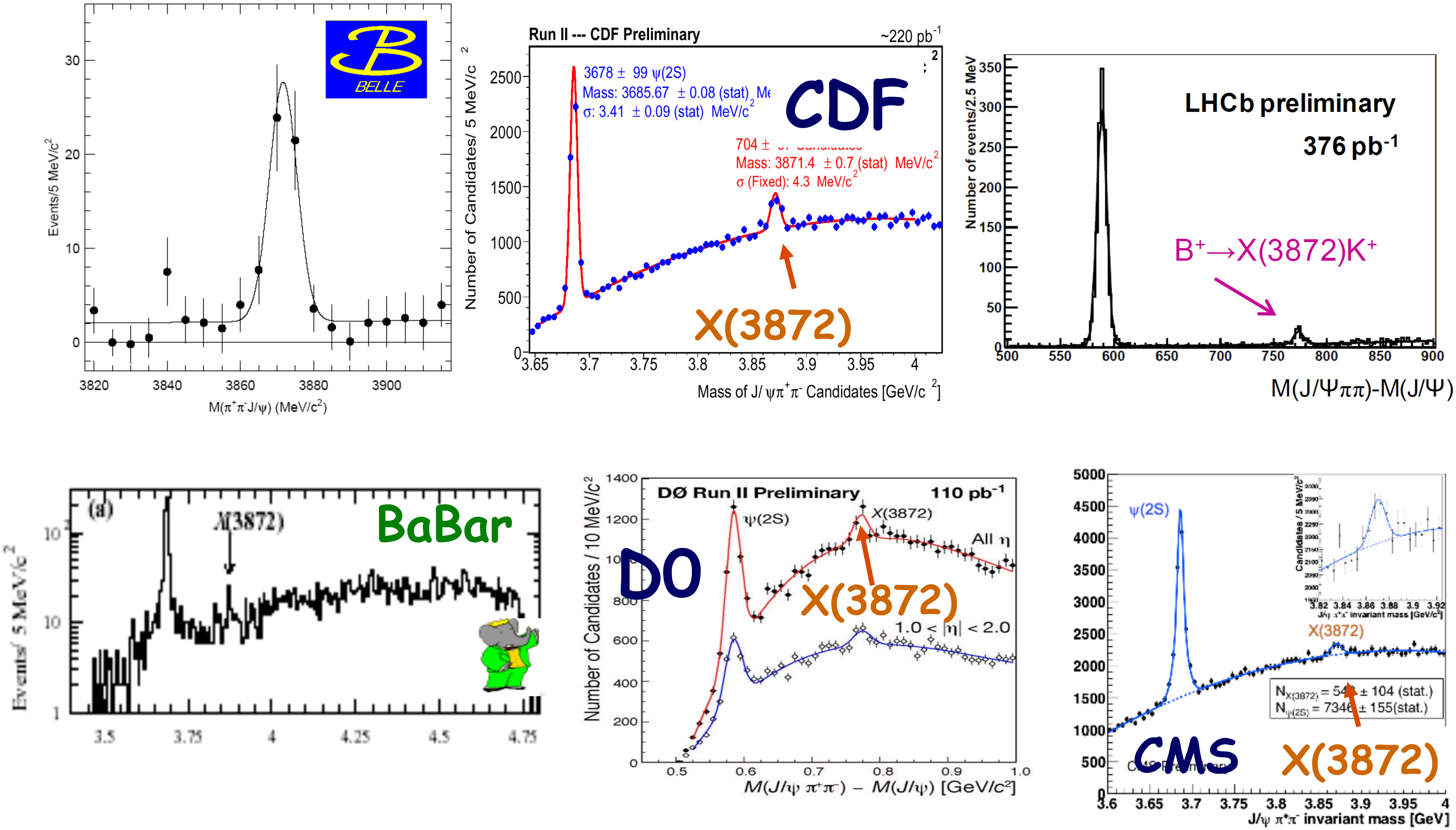


$M(\pi^+\pi^- J/\psi)$



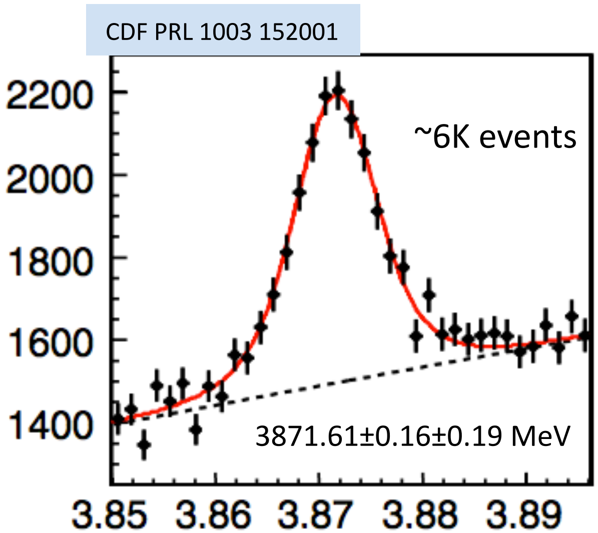
Belle PRL 91, 262001 (2003)
ψ′→π+π- J/ψ
X(3872)
Events/0.010 GeV
M(π+π-l+l-) - M(l+l-) (GeV)
0
100
200
300
0.40
0.80
1.20
ηc(4¹S0)
ψ(4³S1)
hc(3¹P1)
χc1(3³P1)
χc2(3³P2)
χc0(3³P0)
h′c2(2¹D2)
ψ′2(2³D2)
ψ(2³D1)
ηc(3¹S0)
ψ(3³S1)
χc2(2³P2)
hc(2¹P1)
χc1(2³P1)
ψ2(1³D2)
χc0(2³P0)
X(3872)
hc2(1¹D2)
ψ′′(1³D1)
2MD
ψ′(2³S1)
ηc′(2¹S0)
π+π-
π+π-
hc(1¹P1)
χc1(1³P1)
χc2(1³P2)
χc0(1³P0)
predicted, discovered
predicted, undiscovered
J/ψ(1³S1)
ηc(1¹S0)
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
0−+
1−−
1+−
0++
1++
2++
2−+
2−−

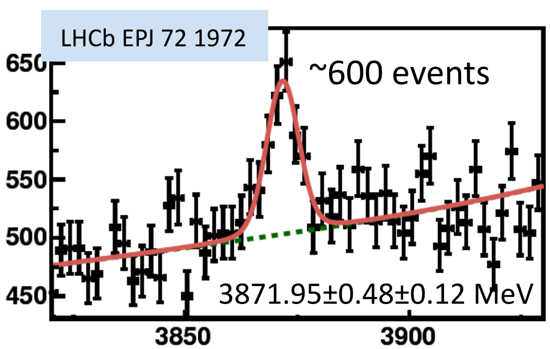
X(3872) is seen in many experiments



What is known about the X(3872)?

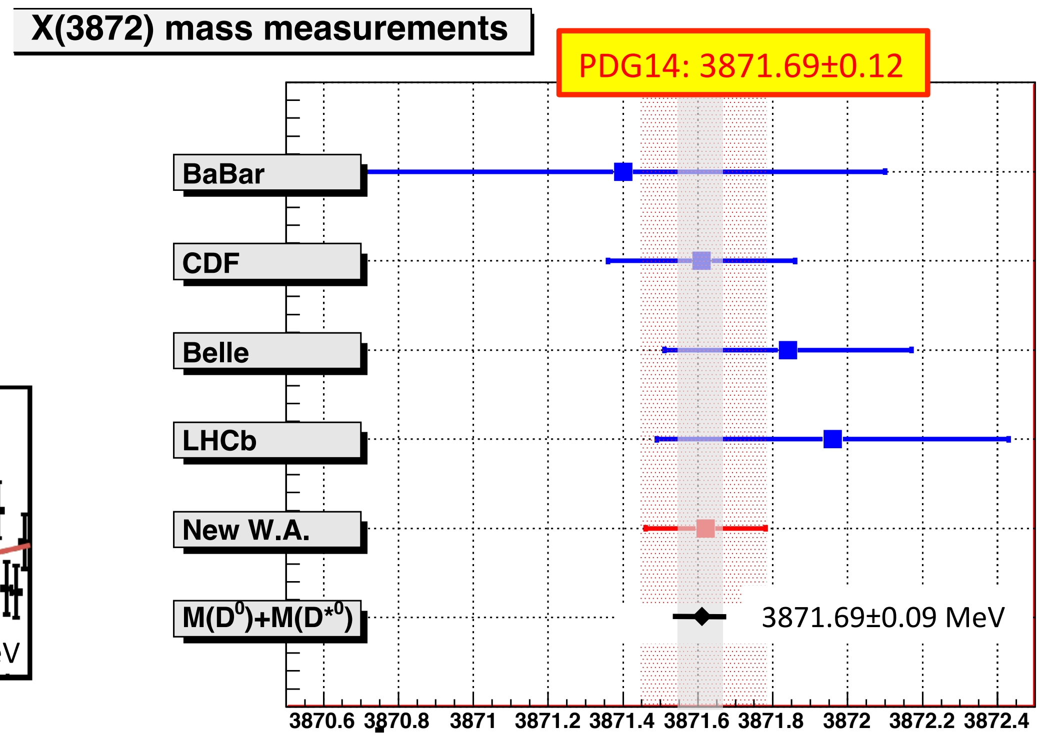
X(3872) Mass



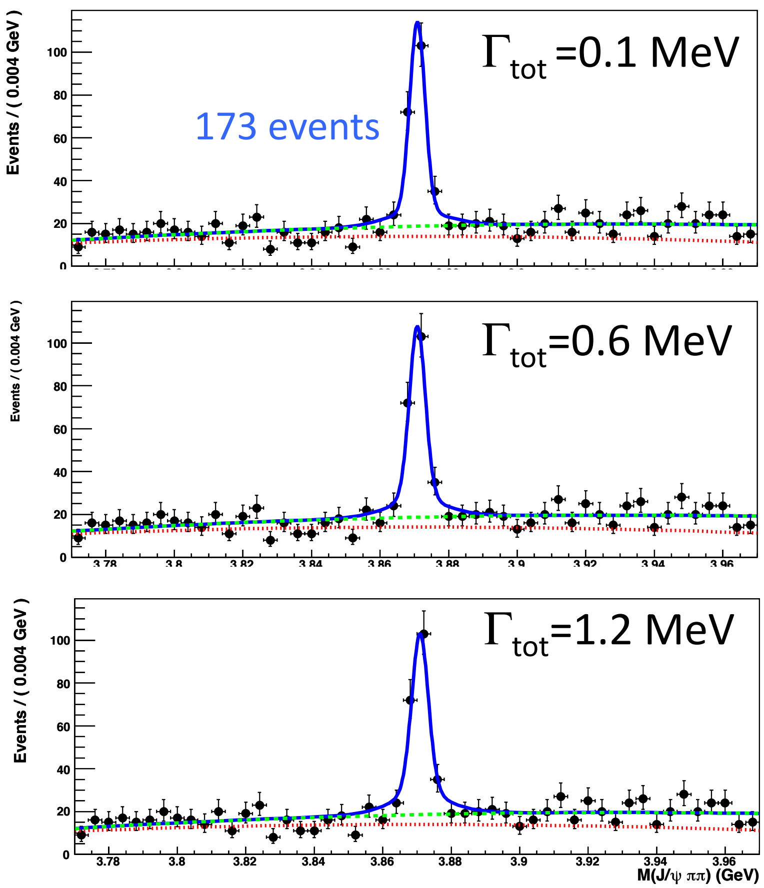


$M_{X(3872)}$ is indistinguishable from $m_{D0} + m_{D*0}$

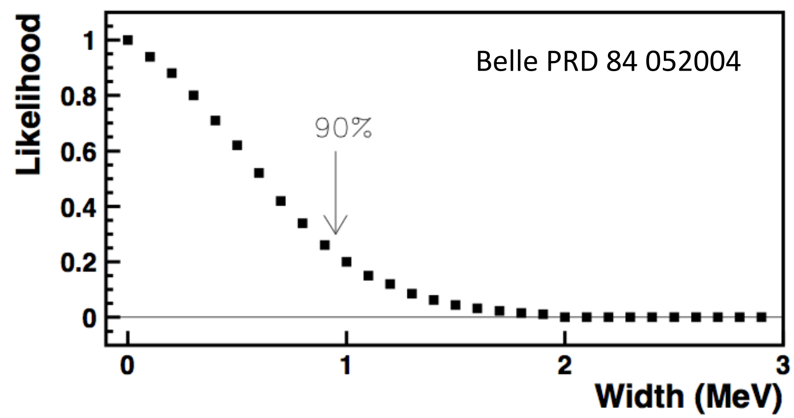
"B.E."=3 ± 193 keV



X(3872) width



$$\frac{1}{(m-m_0)^2+(\Gamma/2)^2}\otimes\exp\left(-\frac{(m-m_0)^2}{2\sigma^2}\right)$$

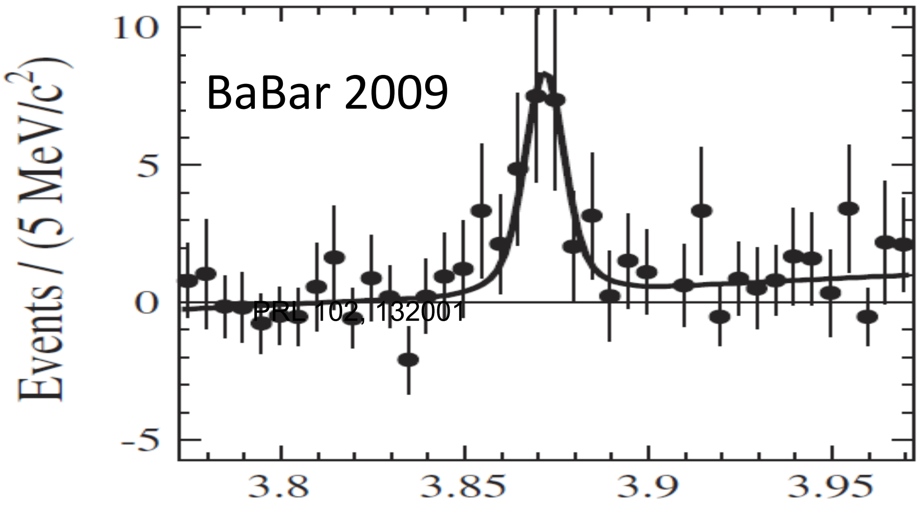


Γ_{tot}<1.2 MeV

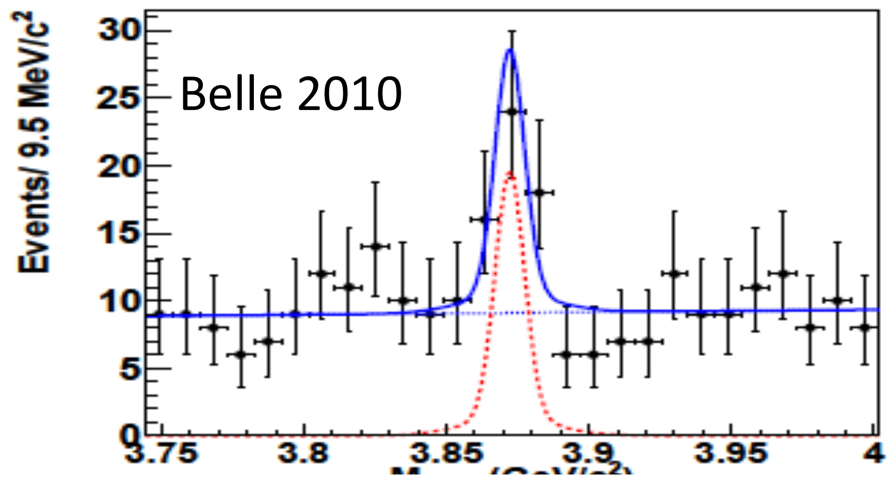
For comparison: $\Gamma_{\chi c1}$ = 0.84+0.04 MeV

X(3872)→ γJ/ψ is observed:

B→K γJ/ψ



M(γJ/ψ)



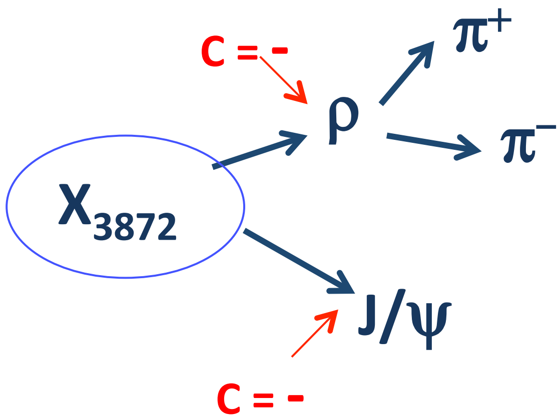
M(γJ/ψ)

$$C-\text{parity of the } X(3872)=(C_{\gamma}=-1)\times(C_{J/\psi}=-1)=+1$$

$C(X_{3872}) = +1$

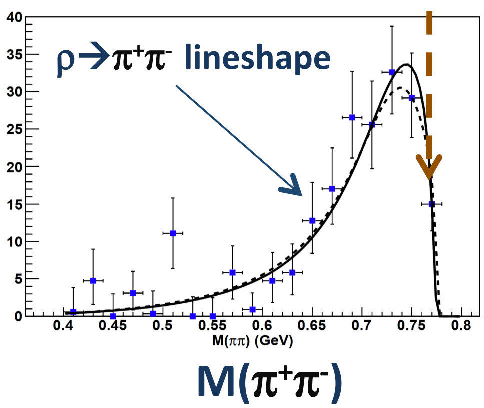
since $C(X_{3872}) = +$:

$\pi^+\pi^-$ system in $X_{3872} \rightarrow \pi^+\pi^- J/\psi$ must come from $\rho \rightarrow \pi^+\pi^-$

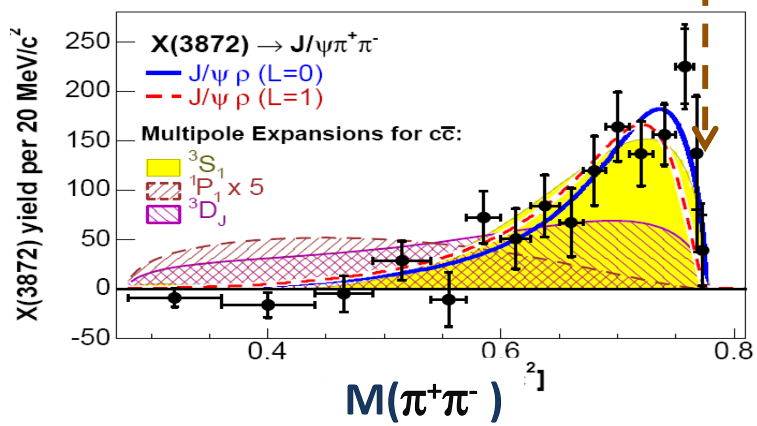


m_ρ=775 MeV is at kinematic limit

Belle agrees

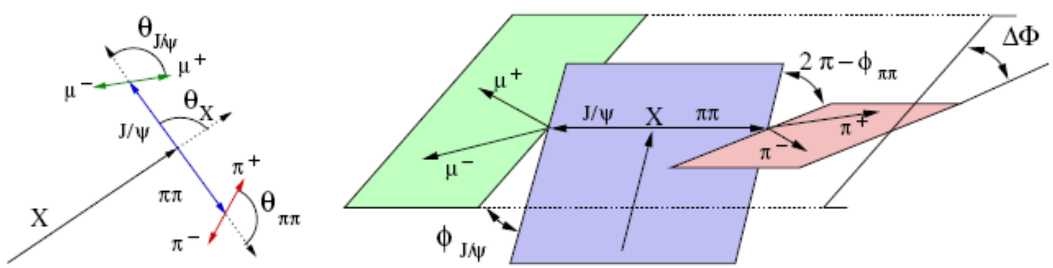


CDF agrees

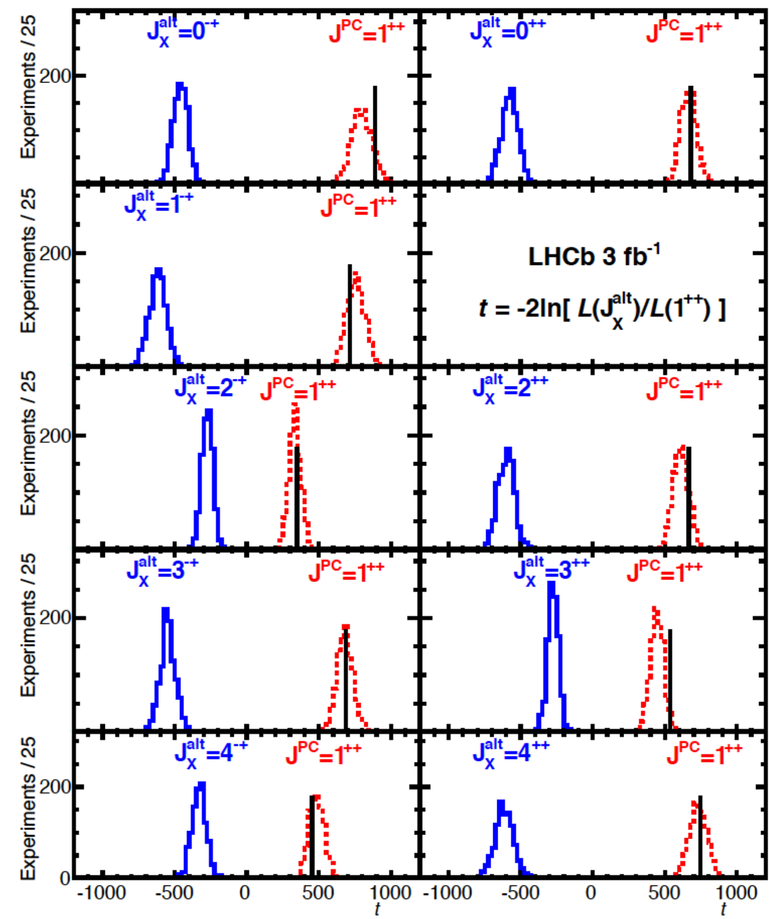


X(3872) J^{PC} values

Angular correlation analysis by LHCb:



LHCb PRD 92 011102



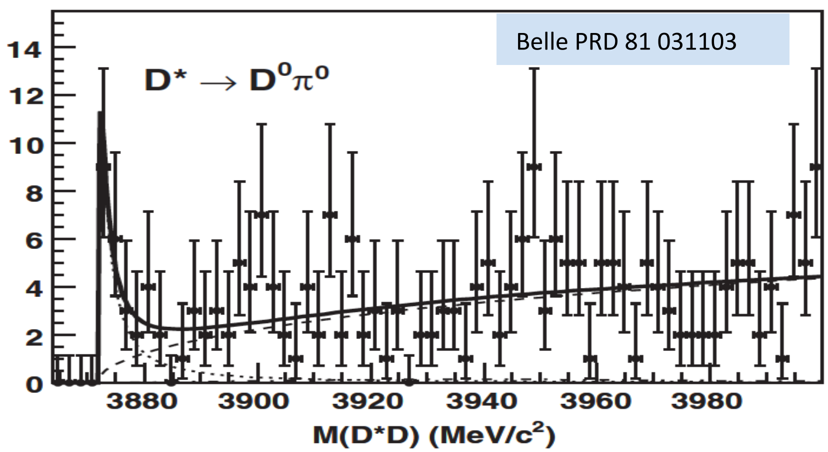
$J^{PC} = 1^{++}$

D-wave<4%

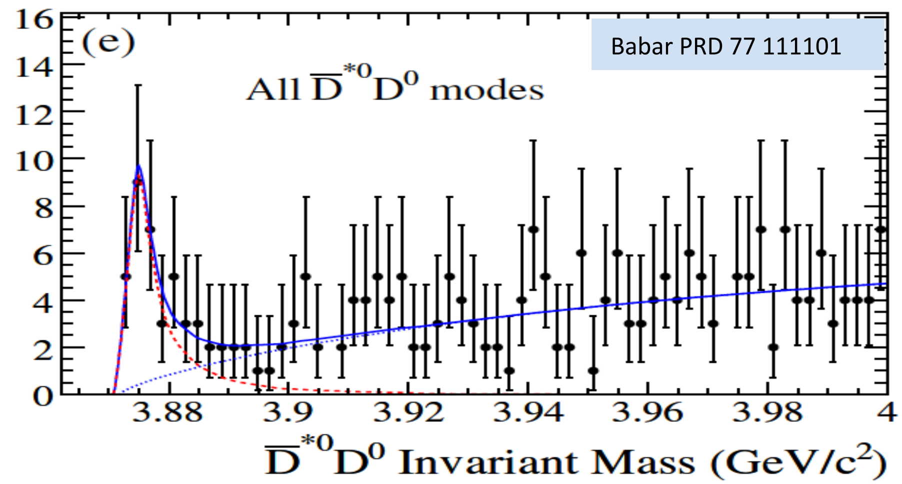
Strong coupling to $D\bar{D}^*$

$B^+ \rightarrow K^+ D^0 \bar{D}^{*0}$

Belle



BaBar



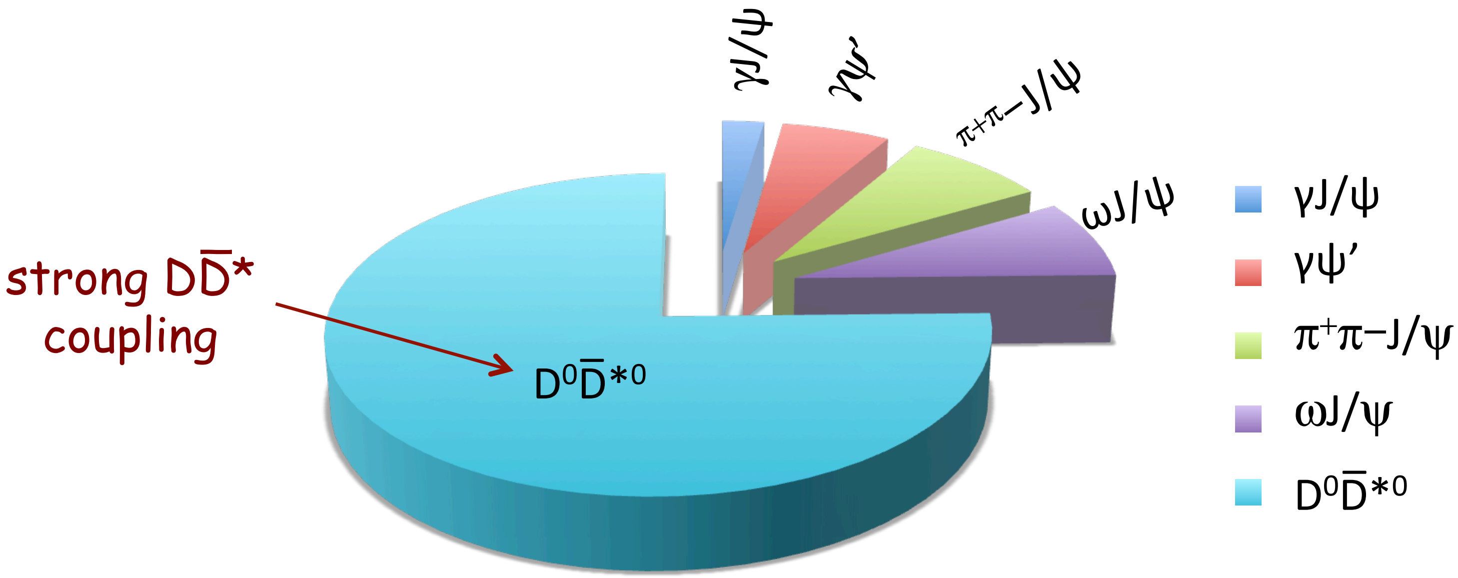
$Bf(X(3872) \rightarrow \underbrace{D^0\bar{D}^{*0}}_{\text{S-wave}}) = (10\pm3) \times Bf(X(3872) \rightarrow p+p\text{-}J/y)$

Braaten & Lu (PRD 76 094028):

Independently of the original mechanism for its existence, 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 $\approx 1/\sqrt{2m_D|BE|} \geq 7\,fm$

"scattering length"

X(3872) decay channels

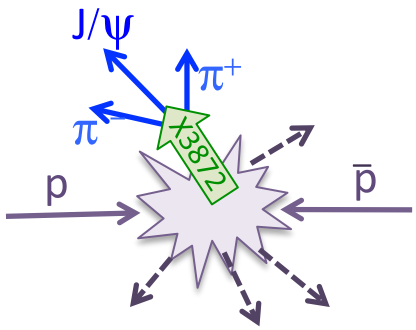


$\Gamma_{\text{"tot"}} \approx 15\ \Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi)$

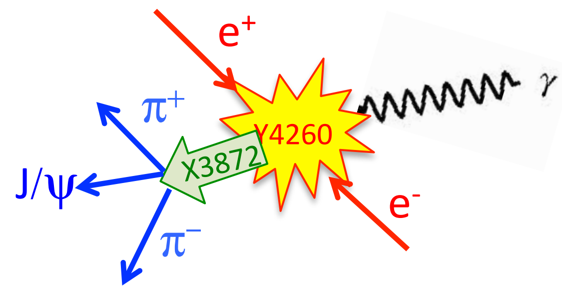
$\Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi) < 80$ keV

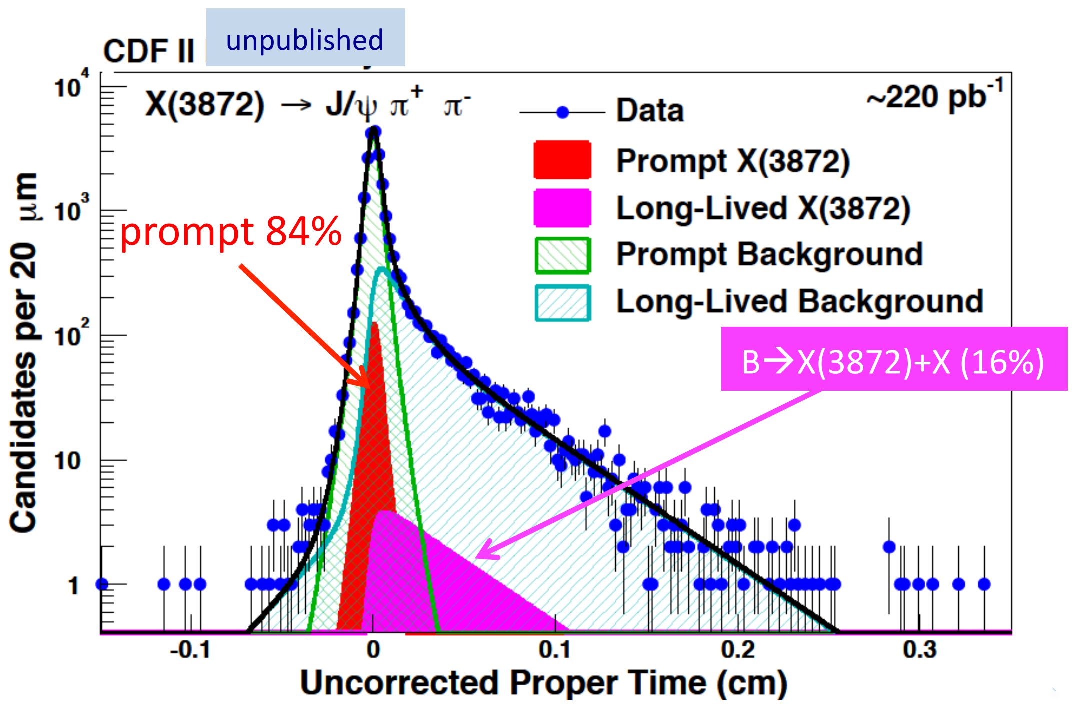
$\Gamma(X(3872) \rightarrow p\bar{p}) < 0.002\Gamma(\pi^+\pi^- J/\psi) < 160 eV$

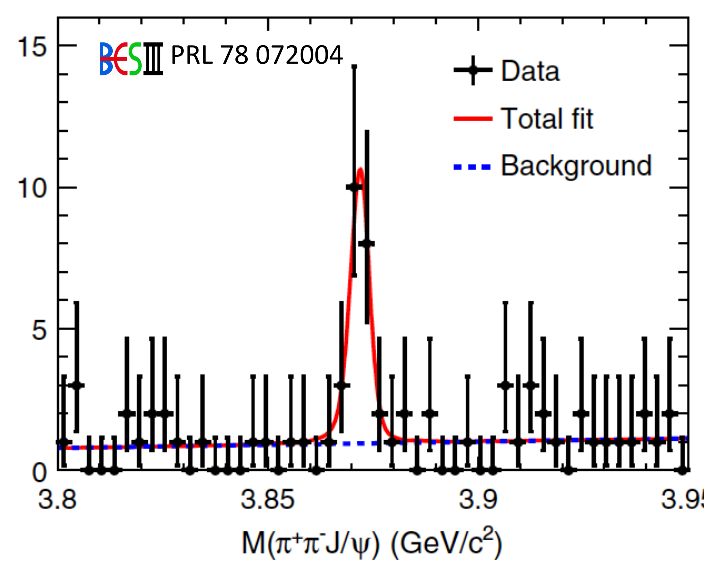
X(3872) production modes



- B-meson decays
- Prompt p̄p (& pp) collisions
- $e^+e^- \rightarrow \gamma X(3872)$

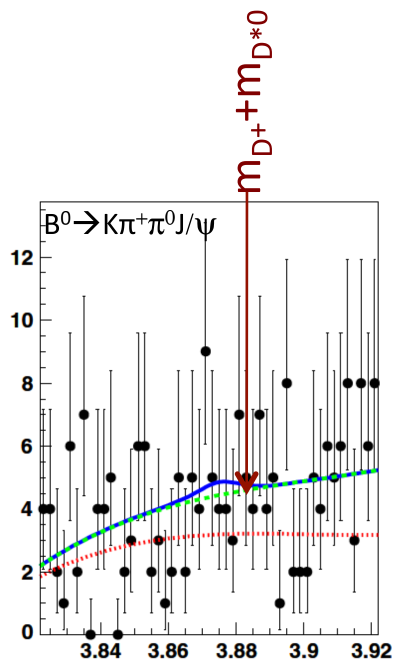




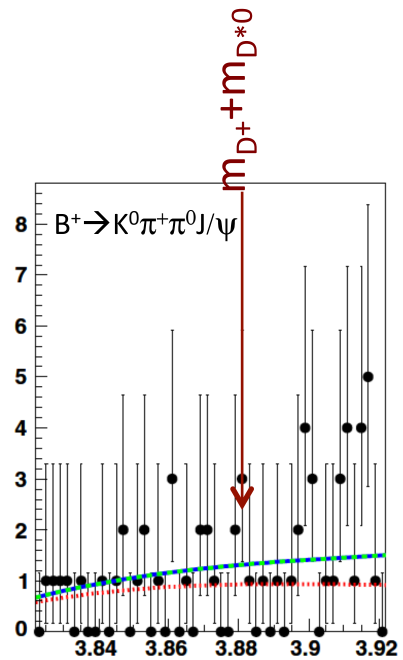


Isospin of the X(3872)

no sign of $X(3872)^+$ in $B \rightarrow K\pi^+\pi^0 J/\psi$



$M(\pi^+\pi^0 J/\psi)$ (GeV)

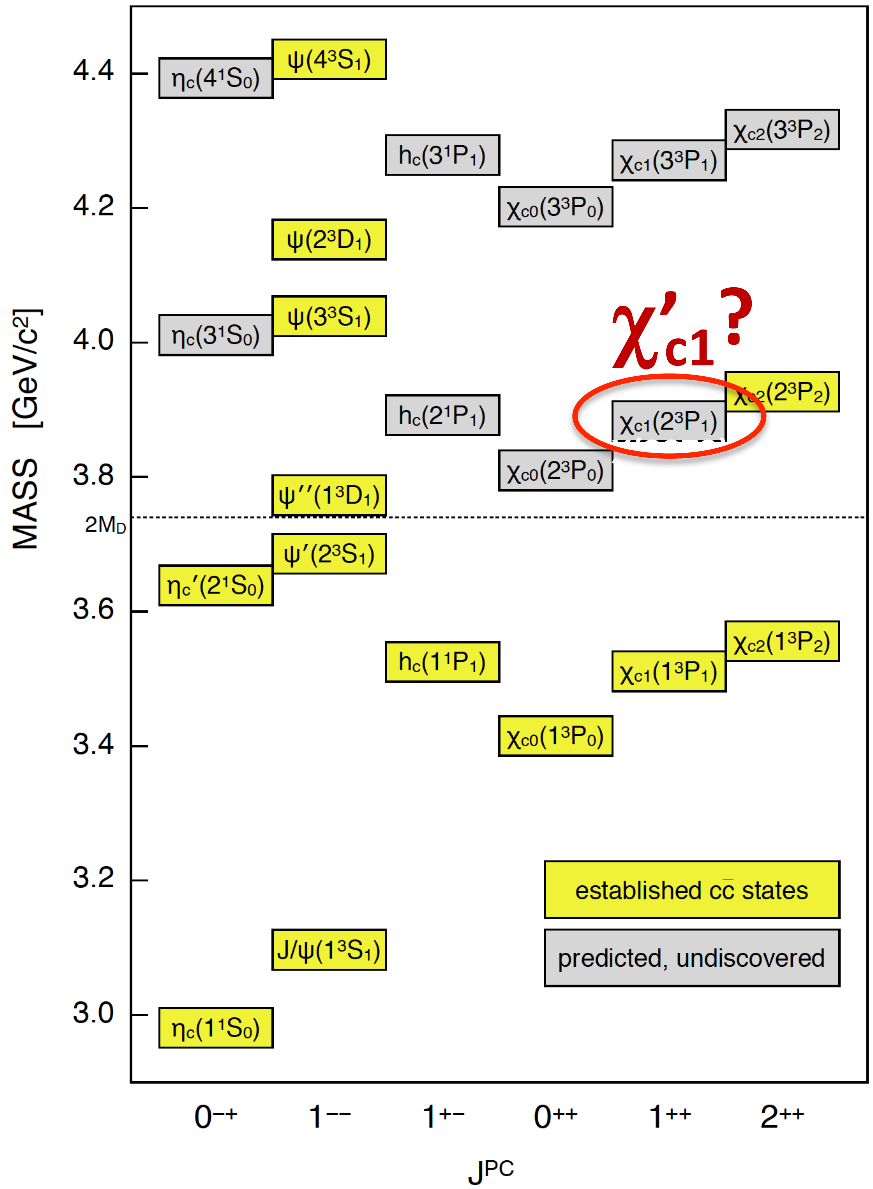


$M(\pi^+\pi^0 J/\psi)$ (GeV)

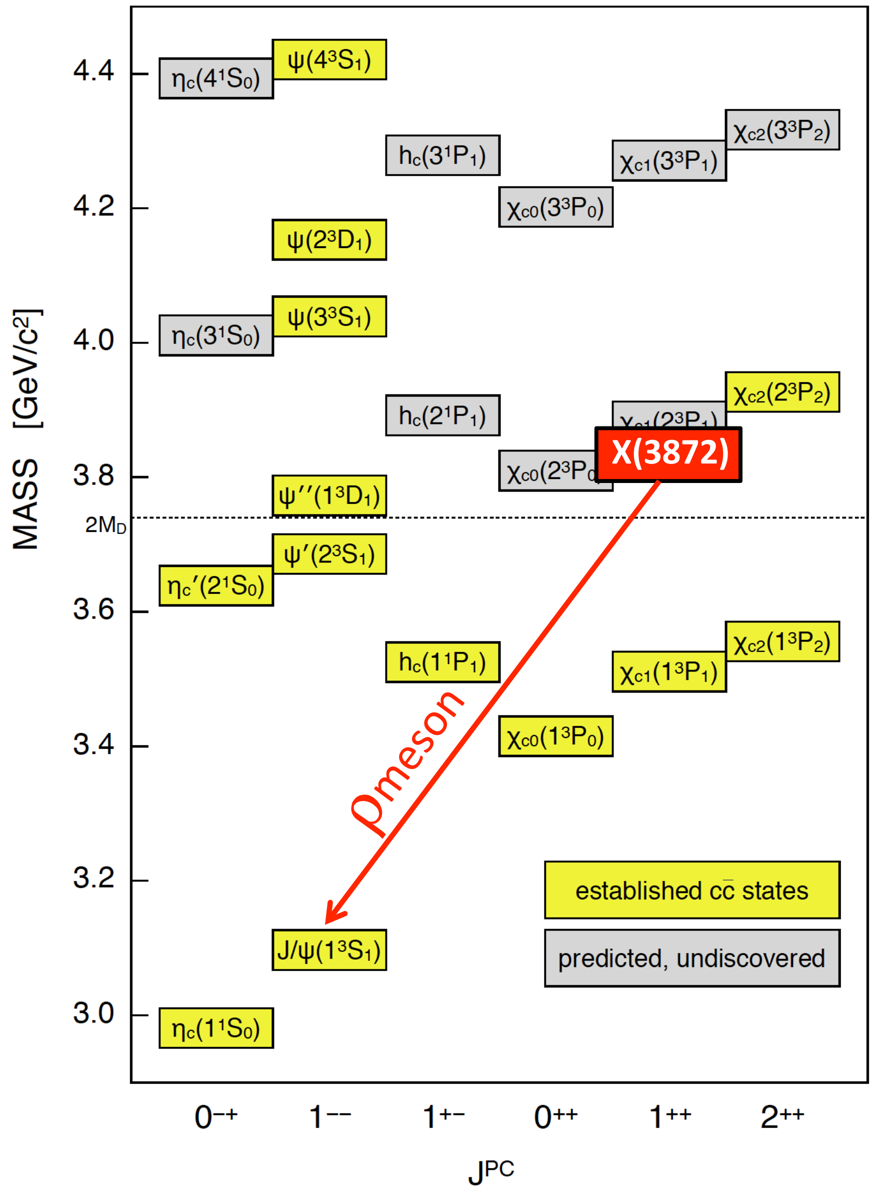
proviso: if $M(X^+) > m_{D^+}+m_{D^{*0}} \approx 3877$ MeV, $\Gamma(X^+)$ may be wide

BaBar PRD 71, 031501 Belle PRD 84, 052004(R)

Is the X(3872) the χ'_{c1} 1^{++} $c\bar{c}$ state?



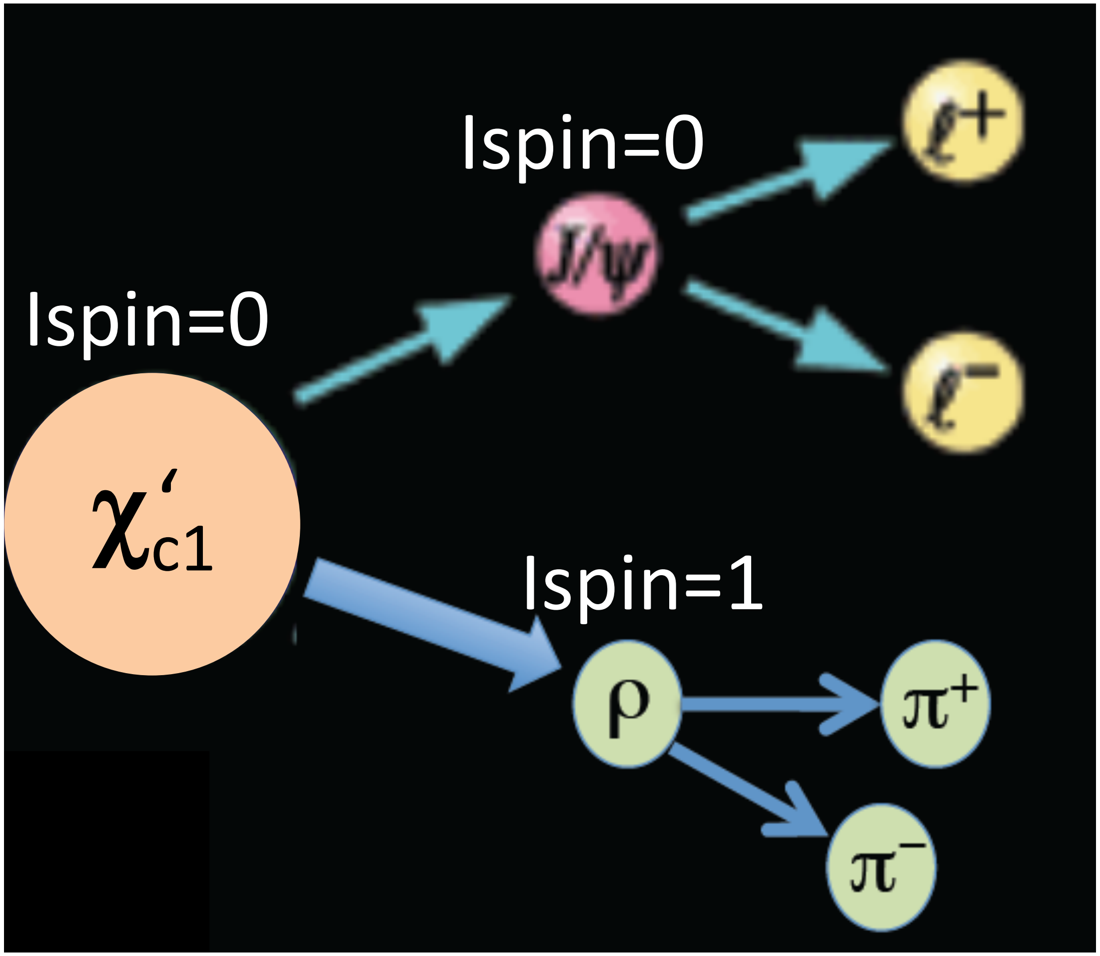
Is the X(3872) the χ'_{c1} 1^{++} $c\bar{c}$ state?



set by:
$M\chi'_{c2}$=3930 MeV

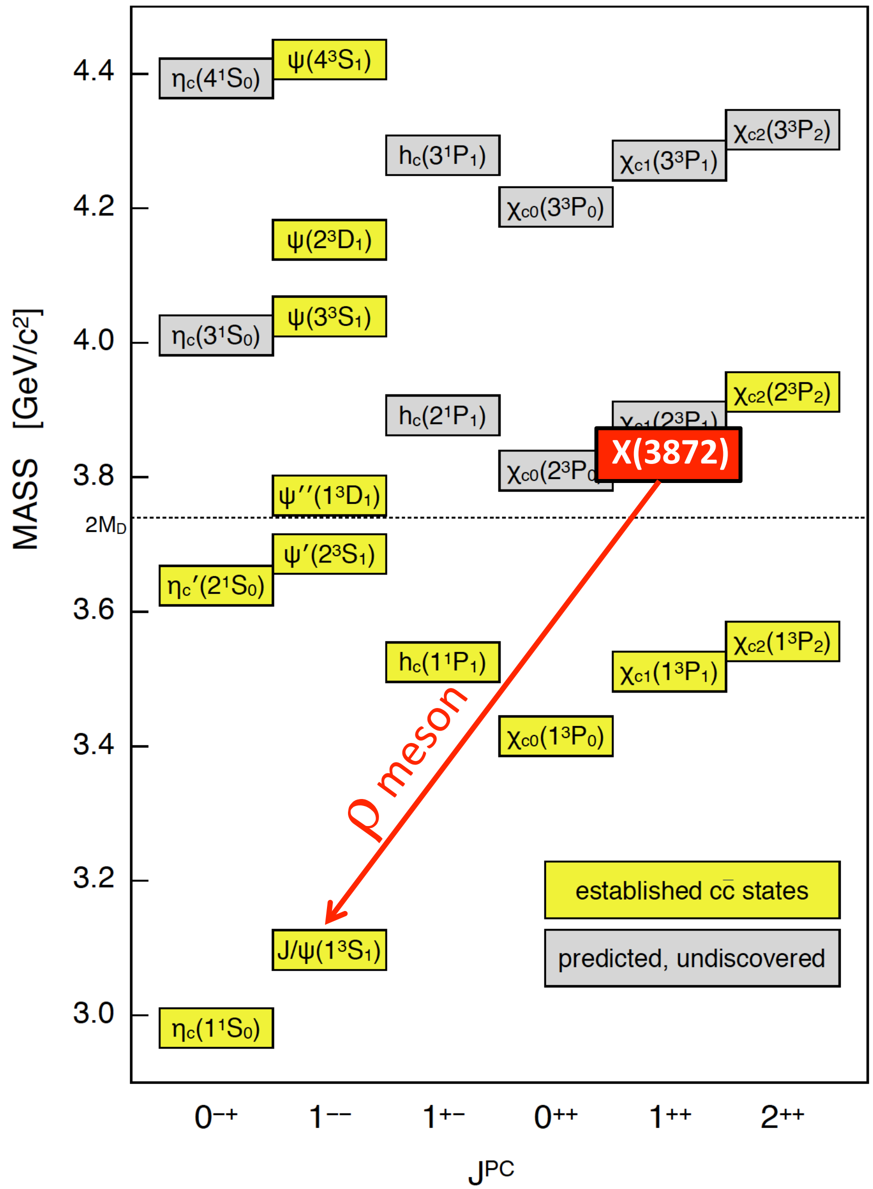
- Mass is too low?
  - 3872 *vs* 3905 MeV

$\chi_{c1}' \rightarrow \rho J/\psi$ violates Isospin



Initial Isospin=0 $\neq$ final Isospin =1

Is the X(3872) the χ'_{c1} 1^{++} $c\bar{c}$ state?



- Mass is too low?
  - 3872 *vs* 3905 MeV

- Inconsistent with Isospin conservation

Theory:

$\Gamma(\chi'_{c1} \to \gamma J/\psi)$ ~14 keV

Experiment:

$\Gamma(X \to \pi^+\pi^- J/\psi) = (3.4\pm1.2)\,\Gamma(X \to \gamma J/\psi)$

If $X(3872)=\chi'_{c1}$:

$\Gamma(\chi'_{c1} \to \pi^+\pi^- J/\psi) \approx 45$ keV;

~100x expectations for an Isospin-violating decay

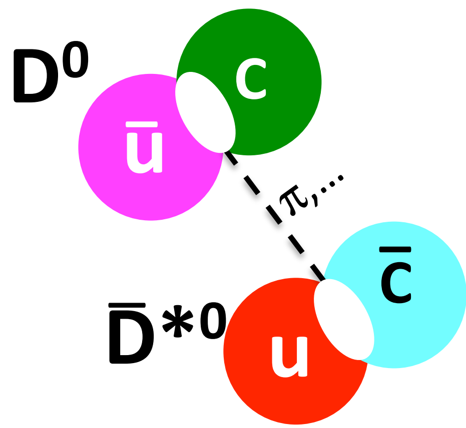
c.f.: $\Gamma(\psi' \to \pi^0 J/\psi) \approx 0.4$ keV

If not charmonium, what is it?

Models for the Y(3872)

D^0-$\bar{D}^{*0}$ molecule?

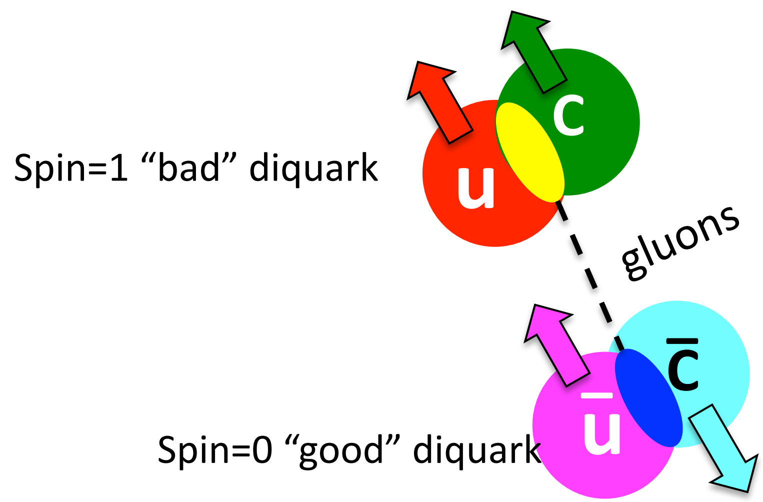
Lots of literature about this



Impossible to produce such an fragile extended object in prompt high energy hadron colliders at the rates reported by CDF & CMS

QCD diquark-diantiquark?

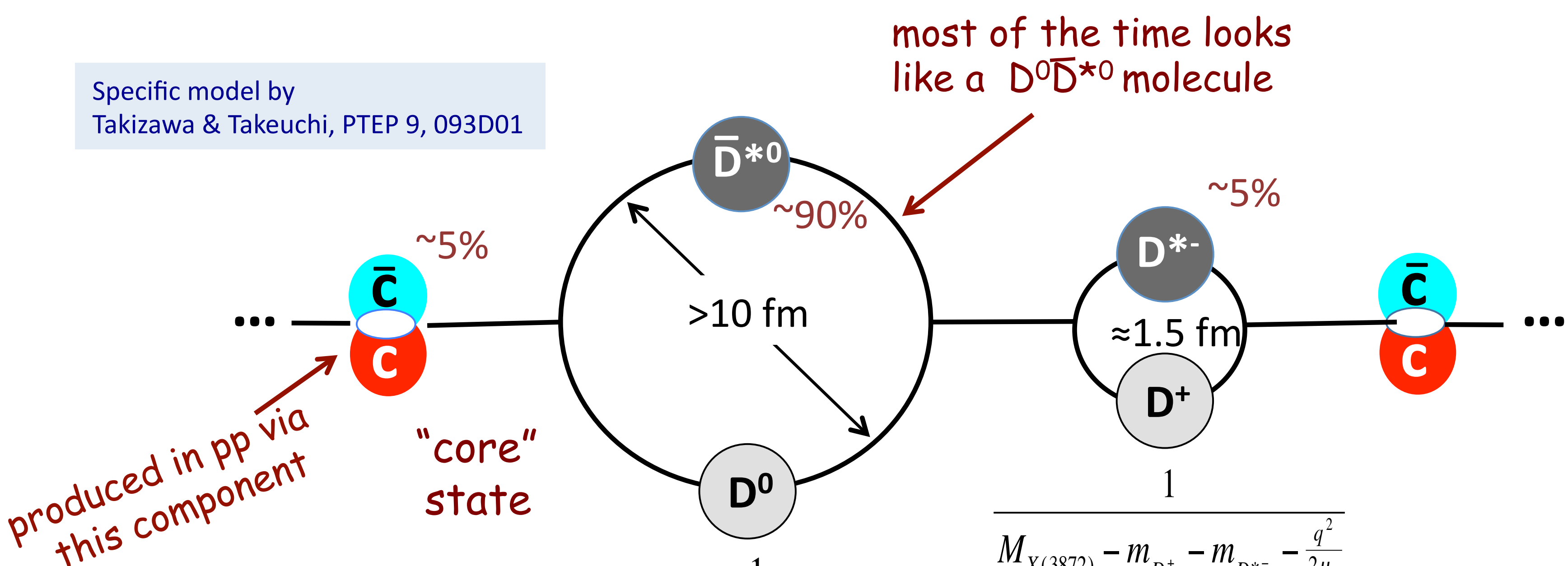
Maiani et al. PRD 71, 014028 (2005)



Predicts partner states (e.g., a nearby state with u→d) that have yet be seen.

Probably a mixture of $D\bar{D}^*$ & a $c\bar{c}$ “core”

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



$$\frac{1}{M_{X(3872)} - m_{D^0} - m_{D^{*0}} - \frac{q^2}{2\mu_0}}$$

$$|BE| < 0.2 \text{ MeV}$$

$$d_{\text{rms}}^{D^0\bar{D}^{*0}} > 10 \text{ fm}$$

$$\frac{1}{M_{X(3872)} - m_{D^+} - m_{D^{*-}} - \frac{q^2}{2\mu_0}}$$

$$|BE| \approx 8 \text{ MeV}$$

$$d_{\text{rms}}^{D^+D^{*-}} \simeq 1.5 \text{ fm}$$

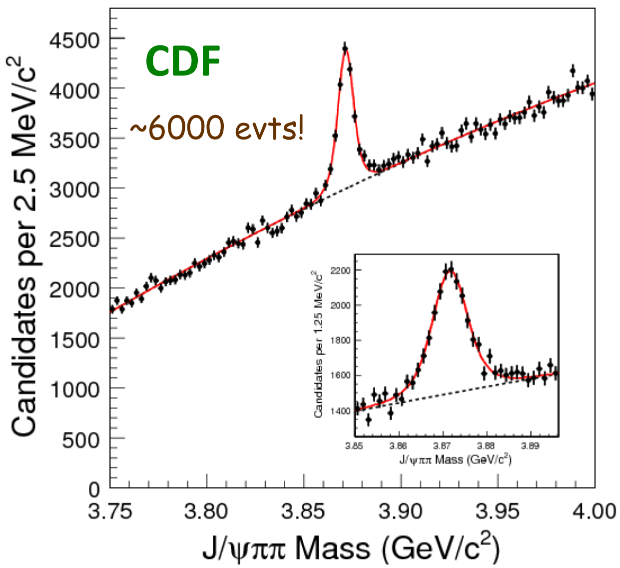
$$d_{\text{rms}} \approx \frac{1}{\sqrt{2\mu_D |BE|}}:$$

reduced mass

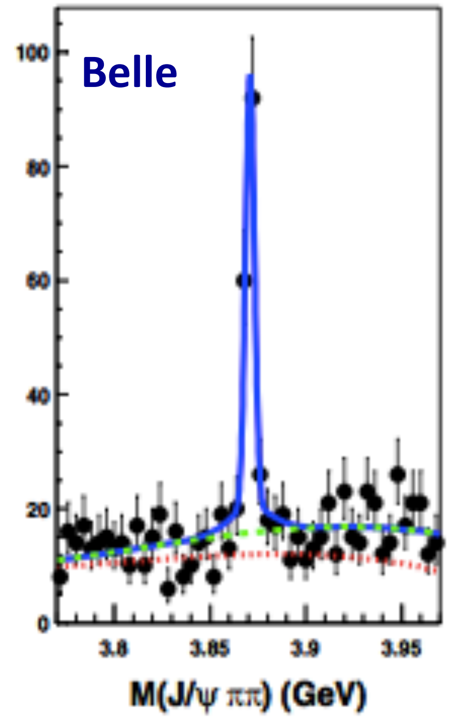
$|m_D+m_{D*}-m_{X3872}|$

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

recent results

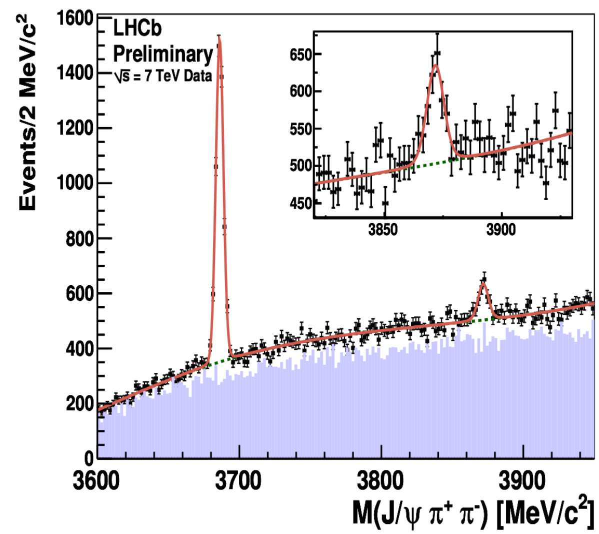


$M_X = 3871.61 \pm 0.16 \pm 0.19$ MeV



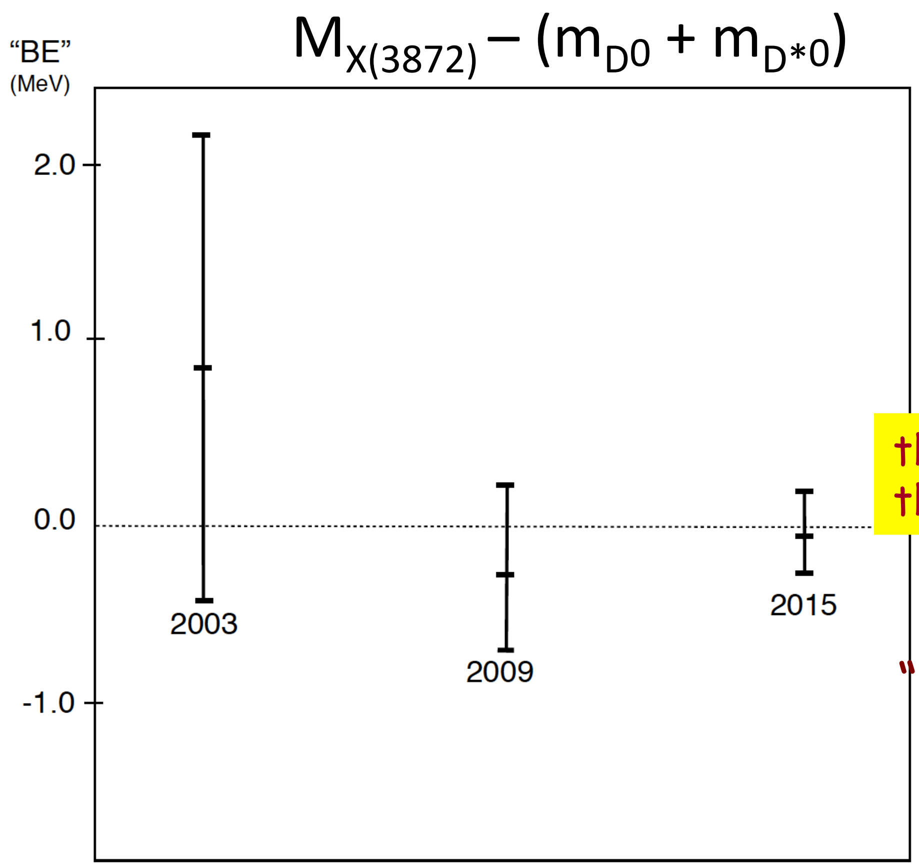
$M_X = 3871.85 \pm 0.27 \pm 0.19$ MeV

LHCb



$M_X = 3871.96 \pm 0.46 \pm 0.10$ MeV

X(3872) "Binding Energy"

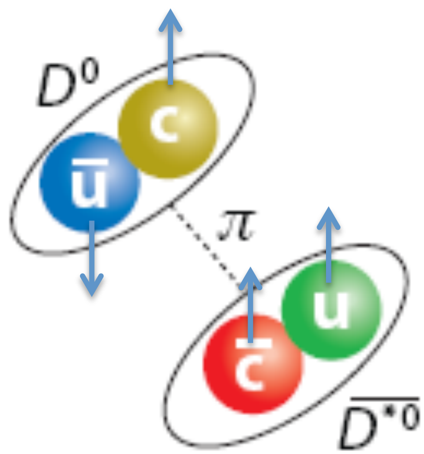


the better it is measured,
the closer it is to zero

"B.E."=3 ± 193 keV

Is this a "coincidence?...
or is the data telling us something?

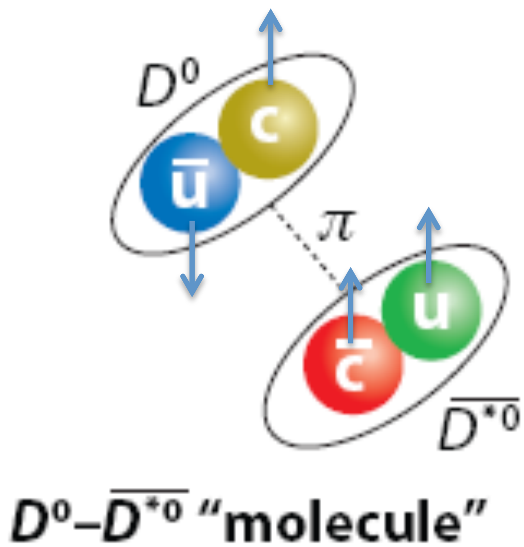
$D^0\bar{D}^{*0}$ molecule?



D^0–$\overline{D^{*0}}$ "molecule"

D^0-$\bar{D}^{*0}$ "Binding Energy" small
$\Delta m = 0.003 \pm 0.193$ MeV
…coincidence??

$D^0\bar{D}^{*0}$ molecule?



D^0-$\bar{D}^{*0}$ "Binding Energy" small
$\Delta m = 0.003 \pm 0.193$ MeV
...coincidence??

an "old" idea

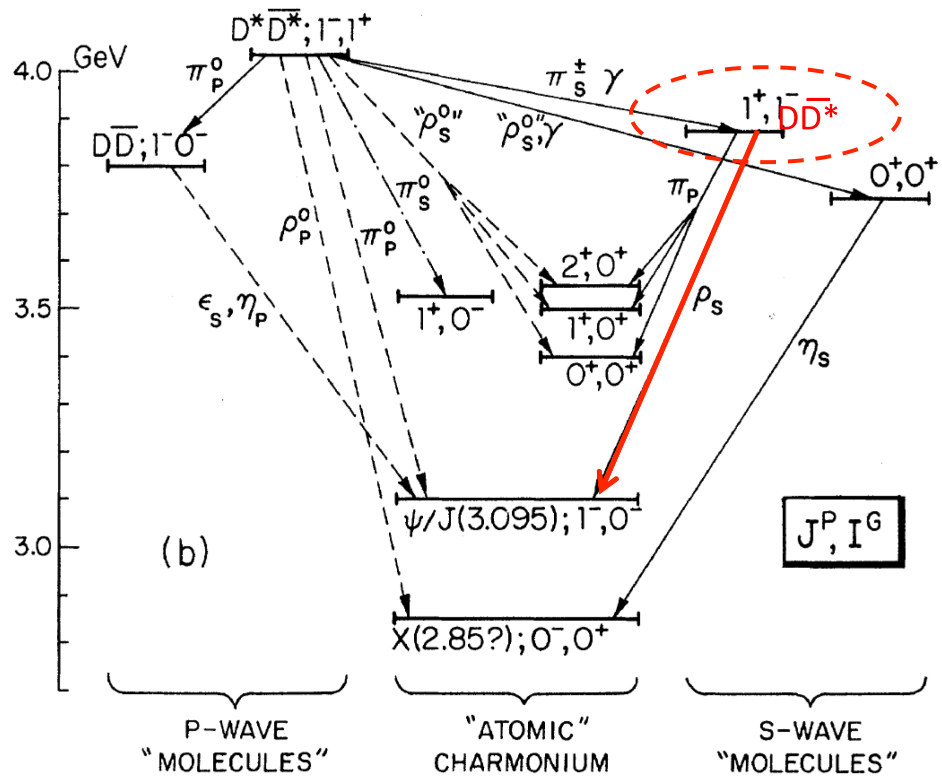
De Rujula, Glashow & Georgi (1976)

PRL 38, 317 (1976)

Molecular Charmonium: A New Spectroscopy?*

A. De Rújula, Howard Georgi,† and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 23 November 1976)

Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.



predictions:

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

$(D\bar{D}^*)_{mol} \rightarrow \rho J/\psi$

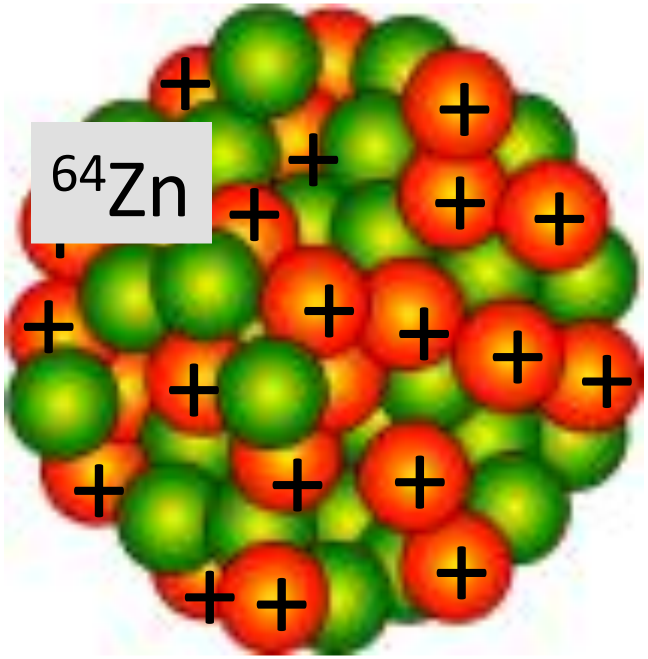
$\rho \rightarrow \pi^+\pi^-$

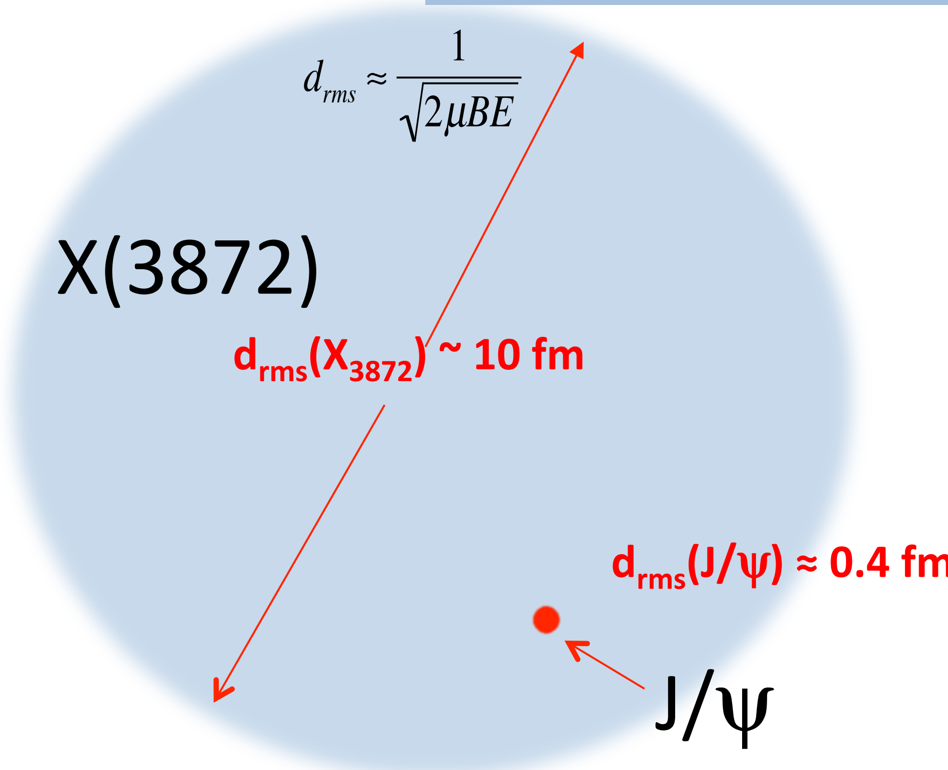
Also: L. Okun& M. Voloshin
JETP Lett. **23**, 333 (1974)

X(3872)-J/ψ relative sizes

E. Braaten, J. Stapleton PRD81, 0140189

d_{rms}(^{64}Zn nucleus)≈8 fm



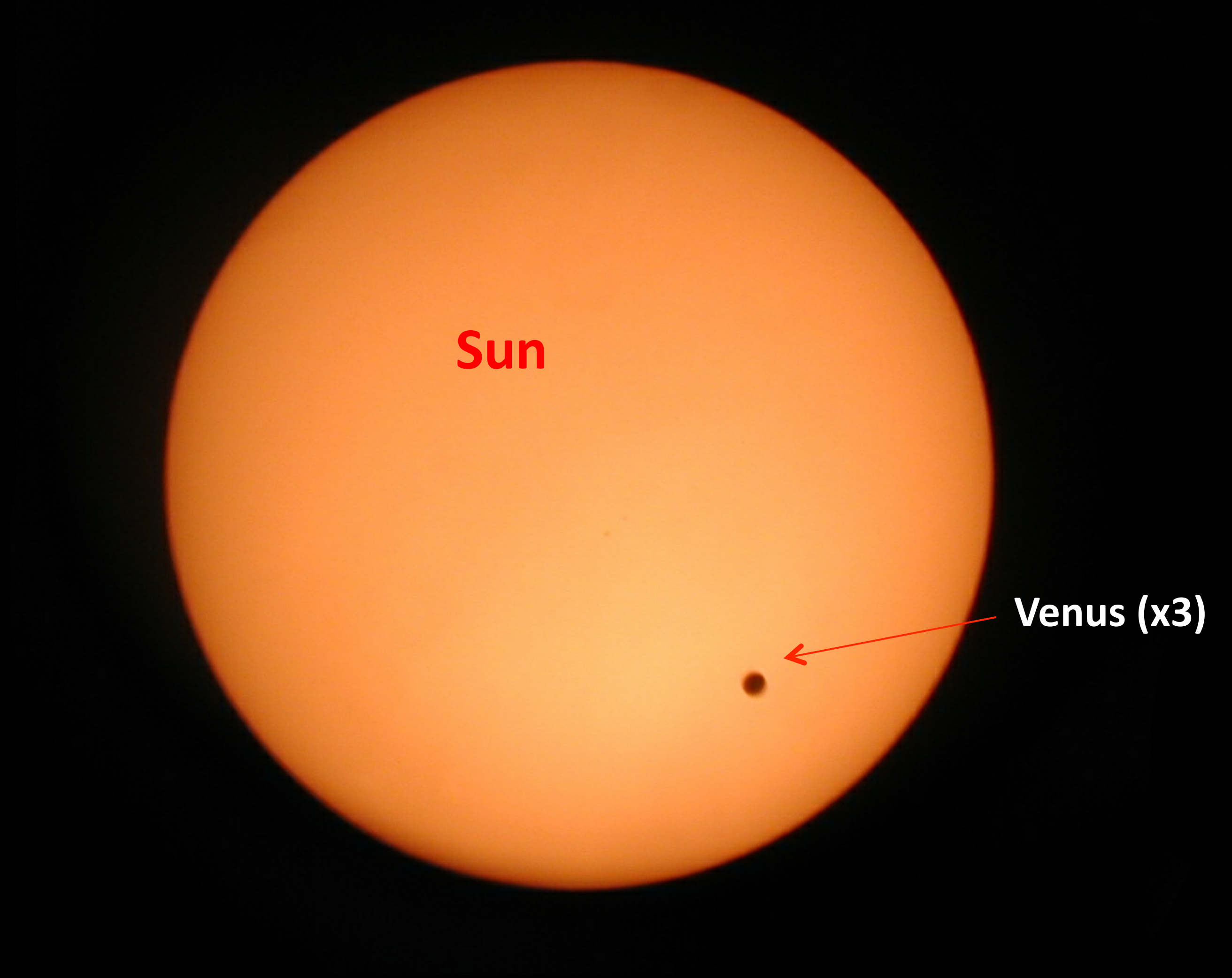


Volume(J/y) /Volume(X_{3872}) ≈ 10^{-4}

•How can such a fragile object be produced in H.E. pp collisions?

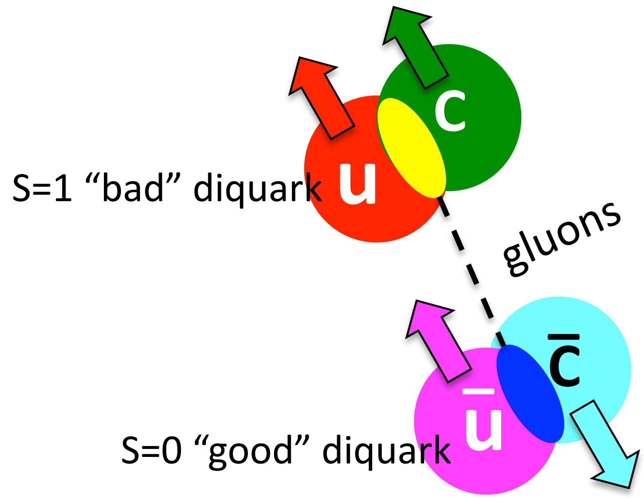
C. Bignamini *et al*, PRL 103, 162001: σ_{CDF}(meas)>3.1±0.7nb *vs* σ_{theory}(molecule)<0.11nb

Very different objects!



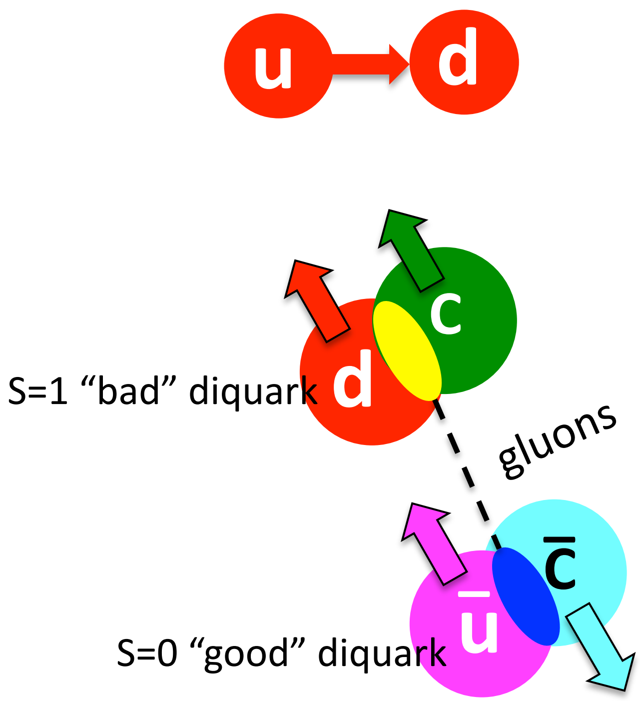
or a QCD tetraquark?

Maiani et al. PRD 71, 014028 (2005)

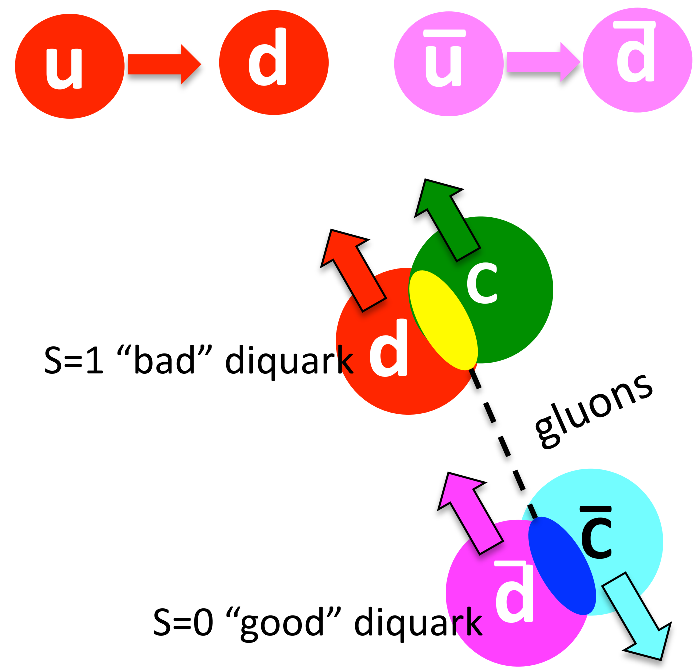


no sign of related tetraquarks

no charged partners of the X(3872)



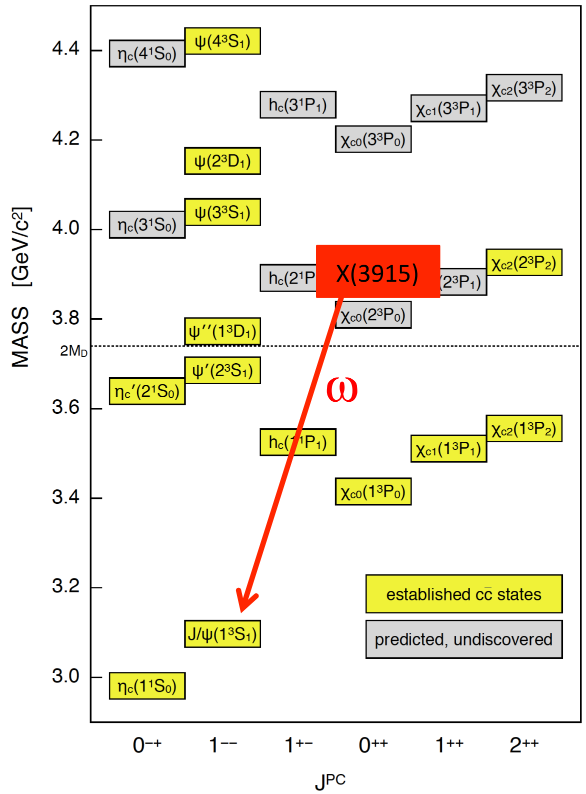
no nearby neutral X(3872) partners



after 14 years, we still don’t know

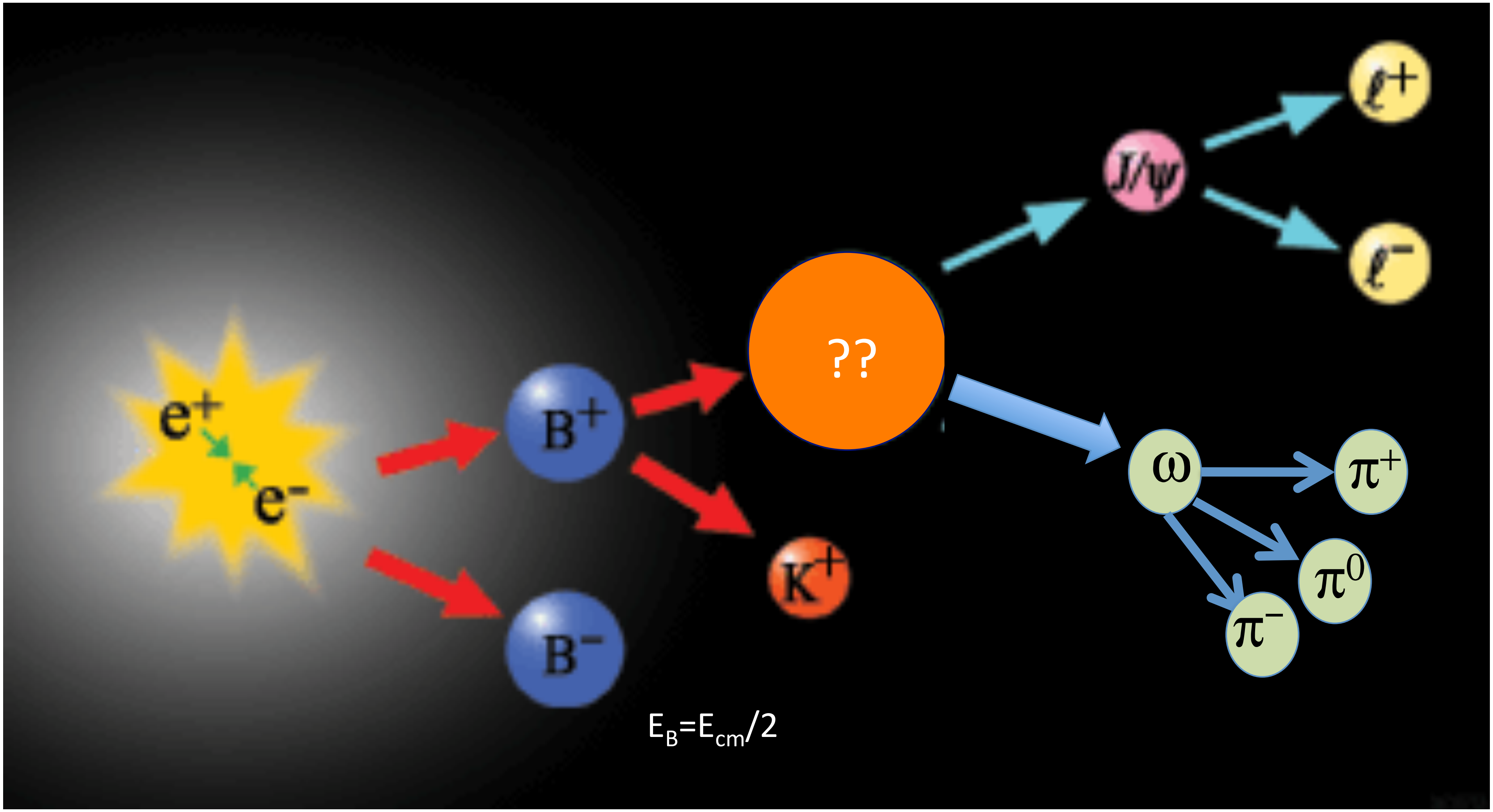
Search for other states

The X(3915)

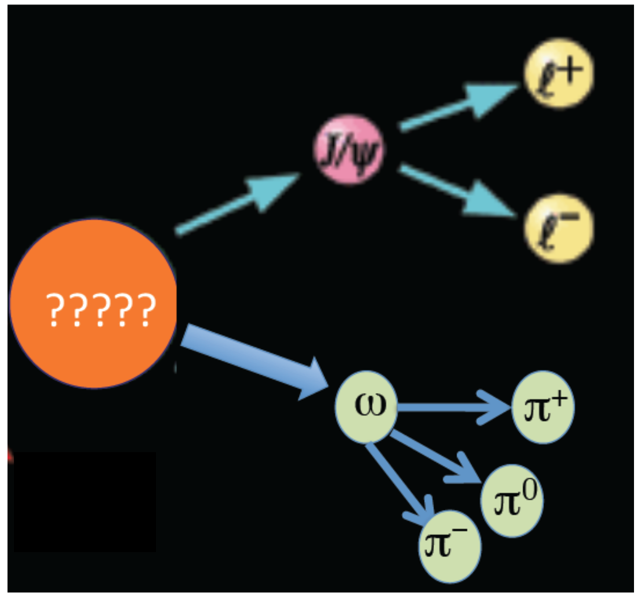


MASS [GeV/c²]
4.4
4.2
4.0
3.8
2MD
3.6
3.4
3.2
3.0
ηc(4¹S₀)
ψ(4³S₁)
hc(3¹P₁)
χc0(3³P₀)
χc1(3³P₁)
χc2(3³P₂)
ψ(2³D₁)
ηc(3¹S₀)
ψ(3³S₁)
X(3915)
χc2(2³P₂)
χc0(2³P₀)
ψ''(1³D₁)
ψ'(2³S₁)
ηc'(2¹S₀)
ω
hc(1¹P₁)
χc1(1³P₁)
χc2(1³P₂)
χc0(1³P₀)
established cc̄ states
predicted, undiscovered
J/ψ(1³S₁)
ηc(1¹S₀)
0⁻⁺
1⁻⁻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

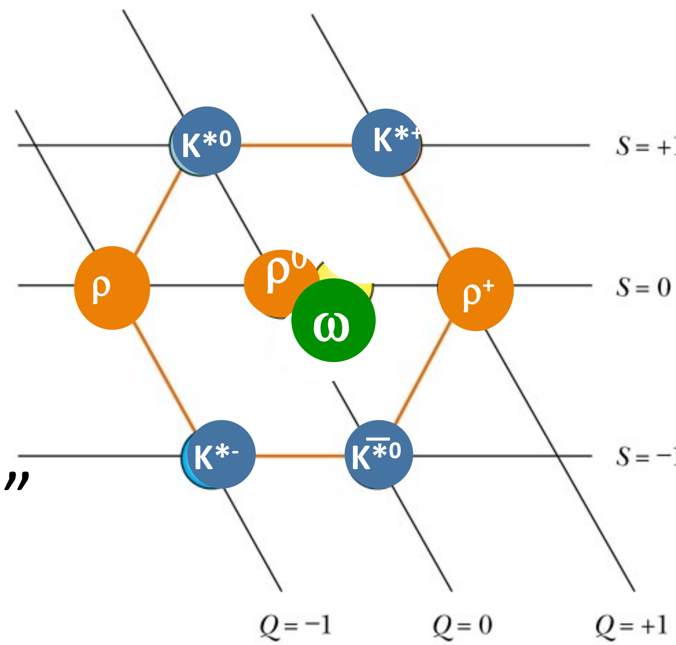
$B \rightarrow K??;\ ?? \rightarrow \omega J/\psi \rightarrow \pi^+\pi^-\pi^0 J/\psi$



Why ω J/ψ ?

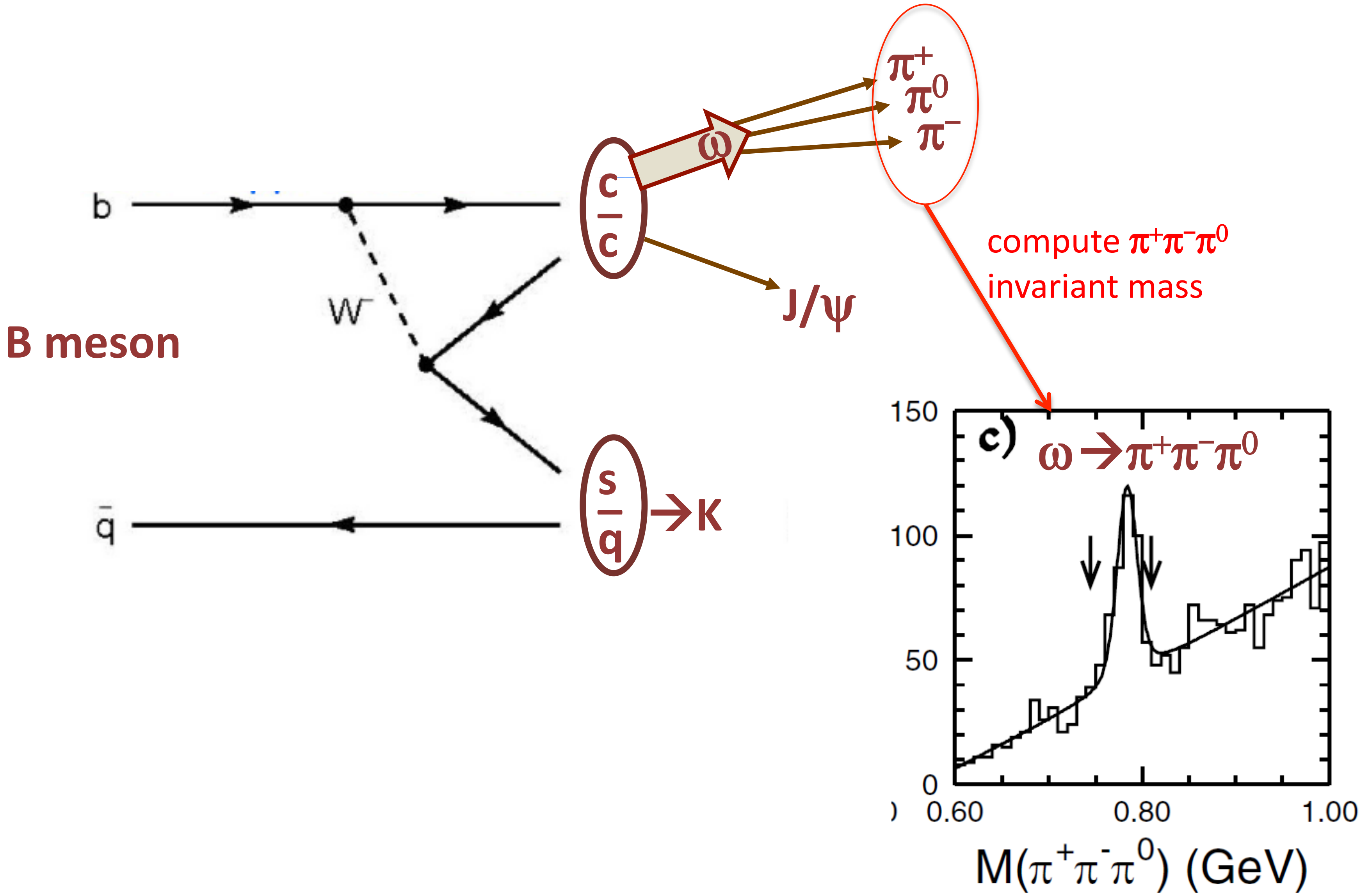


>> $\pi^+\pi^- \rightarrow \pi^+\pi^-\pi^0$ is the simplest next step experimentally

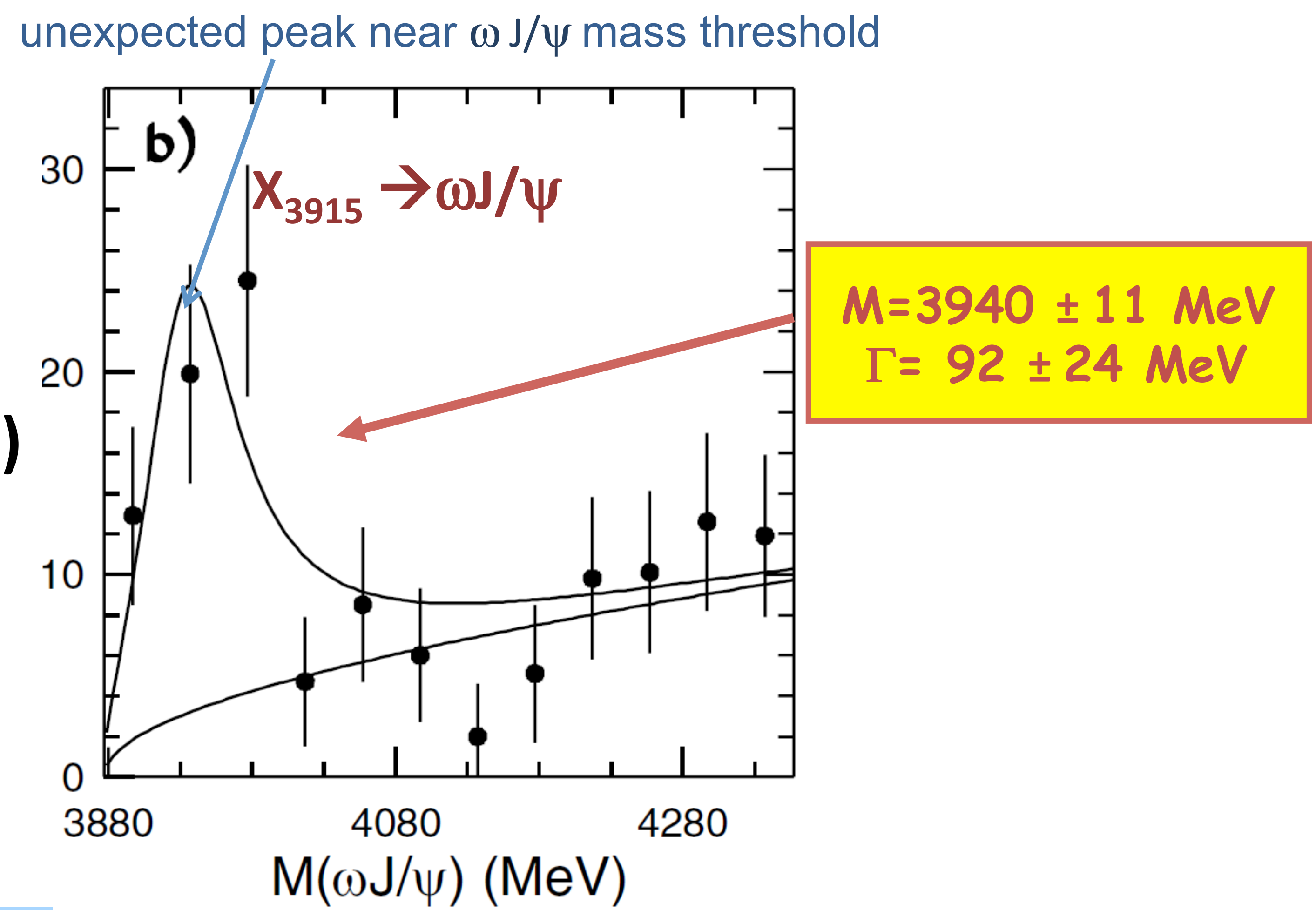


>> ω meson is the Isospin = 0 "brother" of the ρ meson

Study of B→KωJ/ψ decays



M(ω J/ψ)

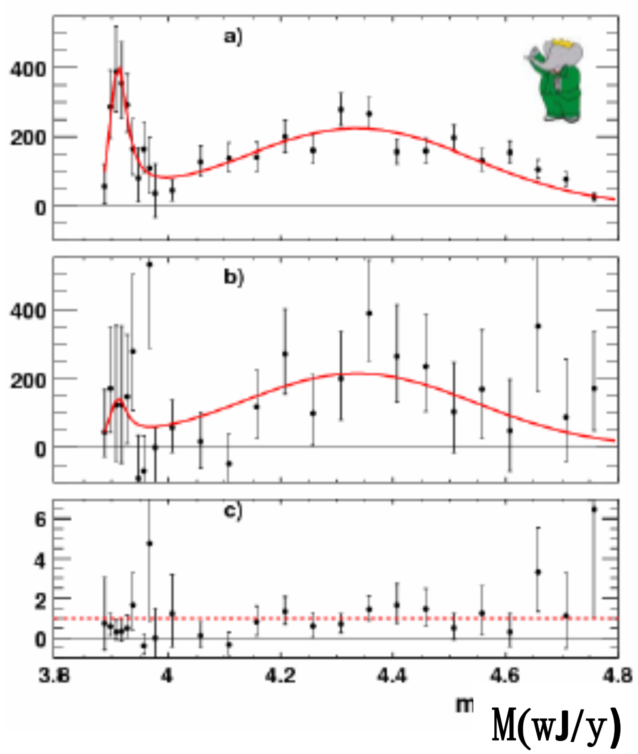


X(3915)

S.-K. Choi et al (Belle)
PRL94, 182002 (2005)

X(3915)→ωJ/ψ also seen by BaBar

BaBar PRL 101, 082001



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

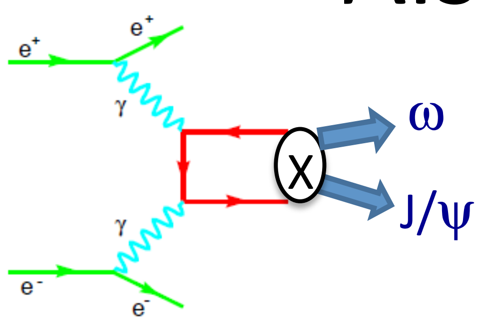
$B^0 \to K_s\omega J/\psi$

ratio

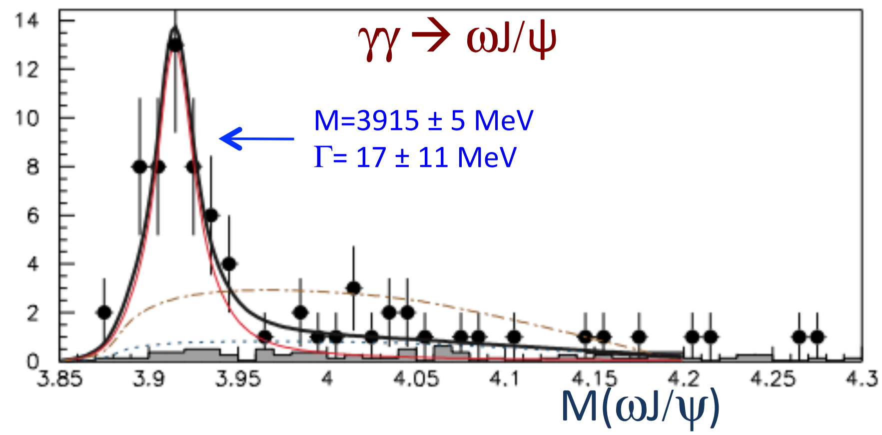
	Mass (MeV)	Γ (MeV)
Belle 253 fb^{-1}	$3943 \pm 11(stat) \pm 13(syst)$	$87 \pm 22(stat) \pm 26(syst)$
BaBar 350 fb^{-1}	$3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst)$	$33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst)$

Some discrepancy in M & Γ; general features agree

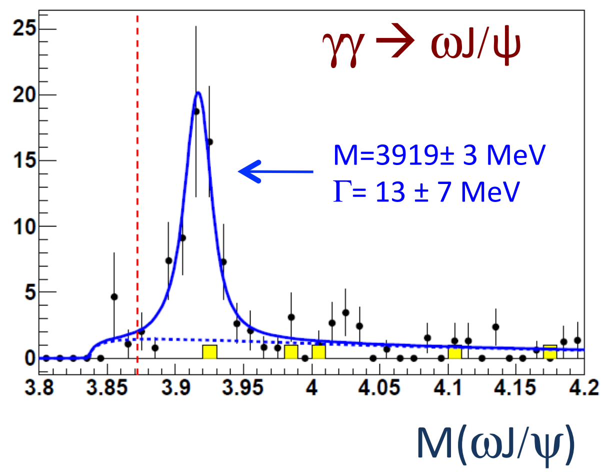
Also seen in $\gamma\gamma \rightarrow \omega J/\psi$



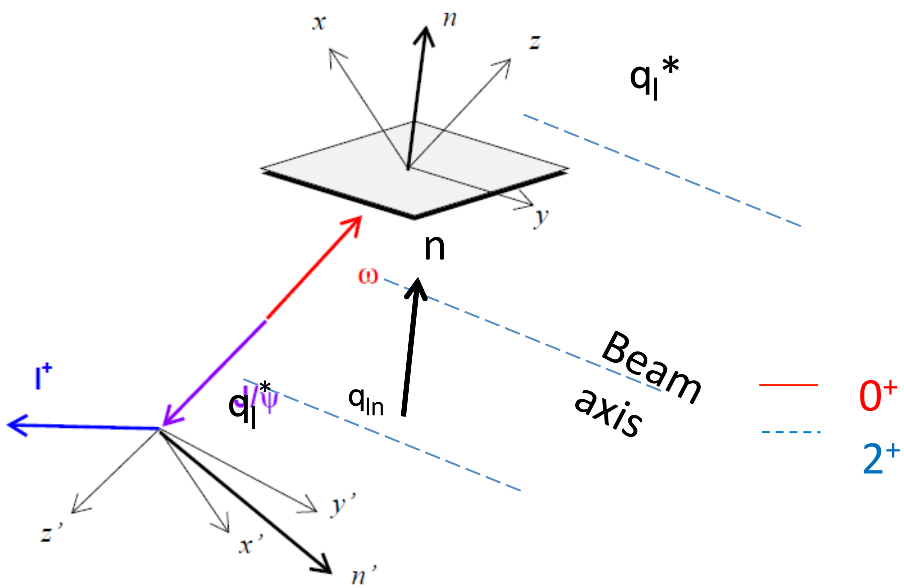
Belle
2010

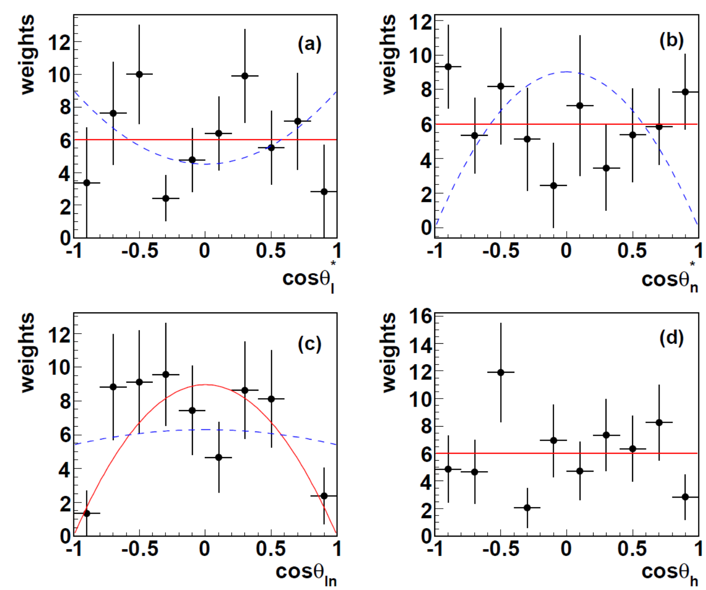


BaBar
2012



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

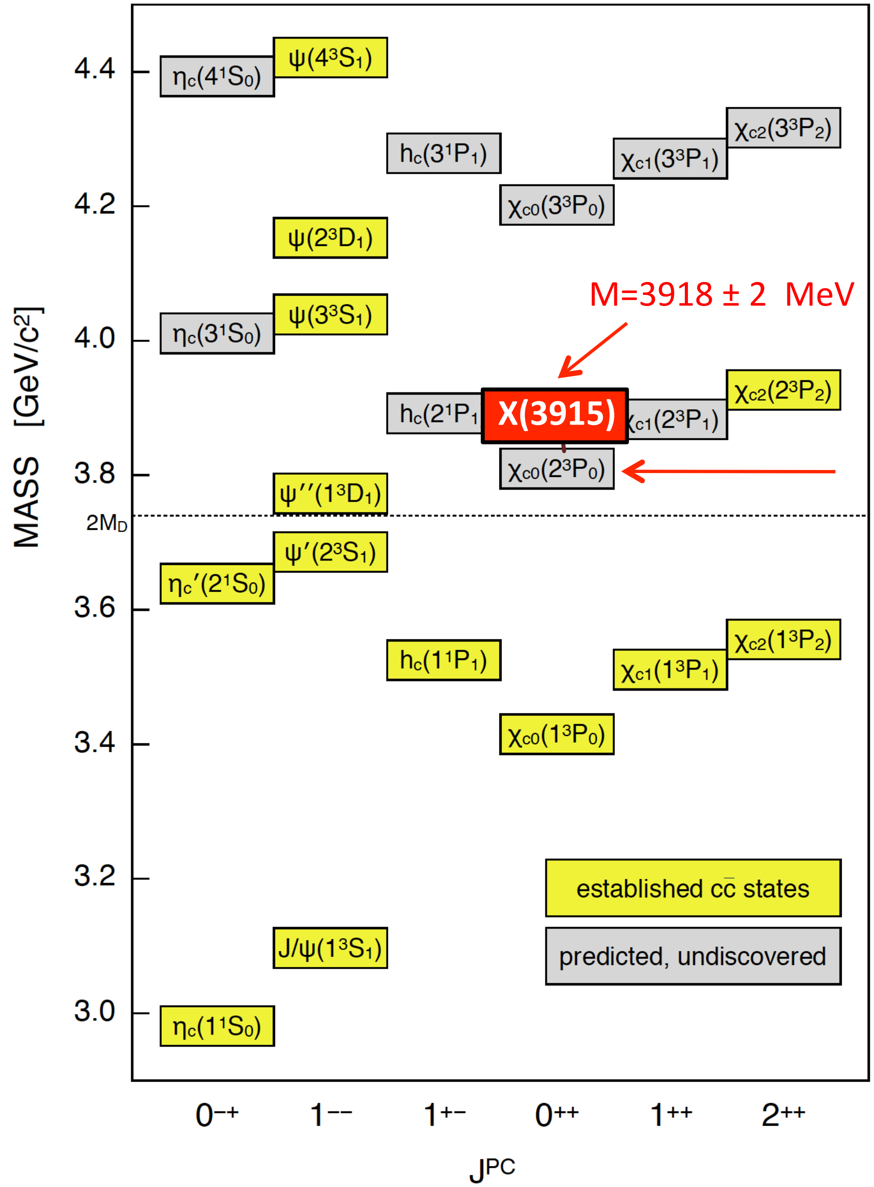




BaBar PRD 86, 072002 (2012)

arXiv:1207.2651

X(3915) = χ'_{c0} charmonium state?

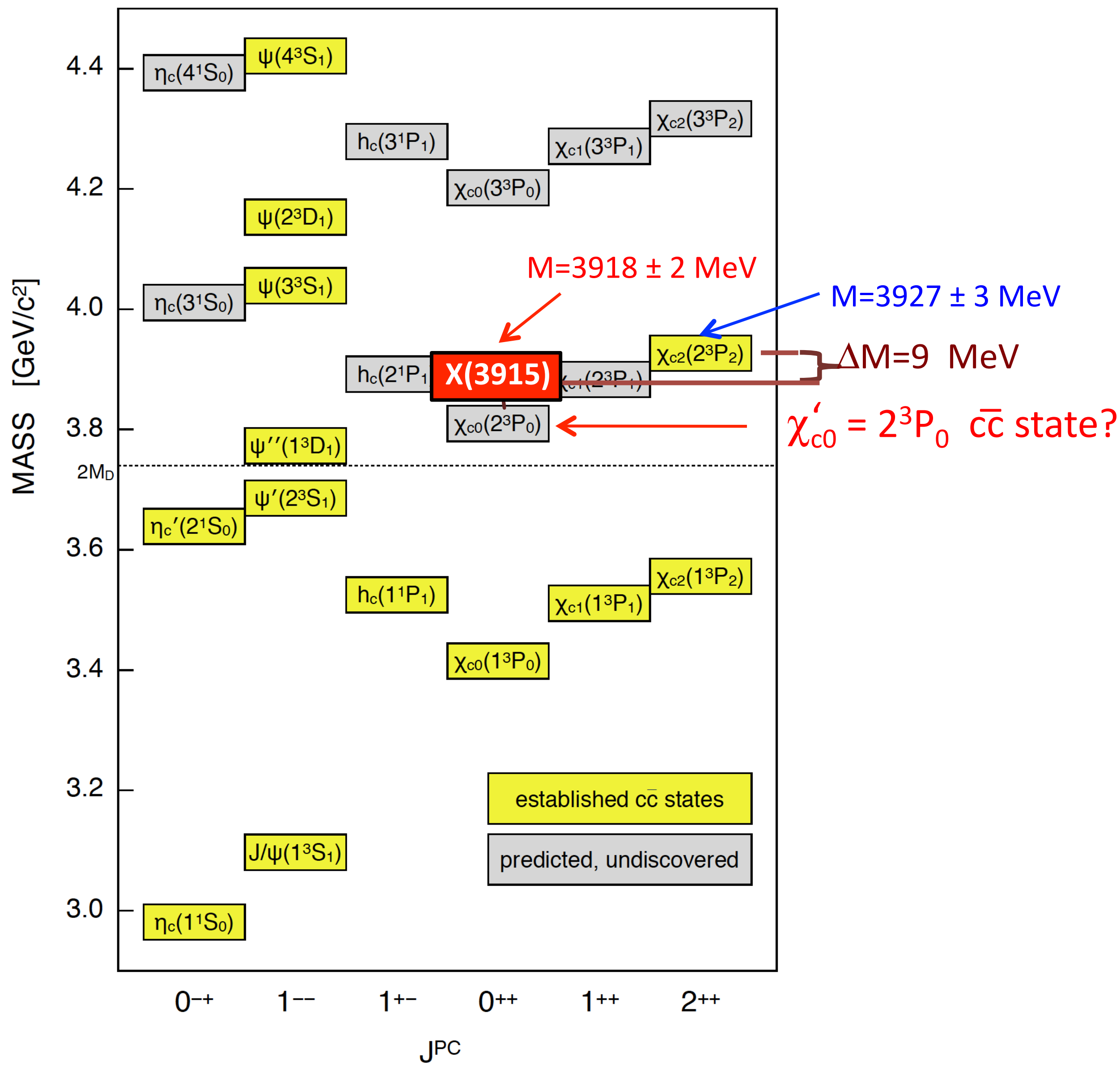


$\chi'_{c0} = 2^3P_0$ $c\bar{c}$ state?

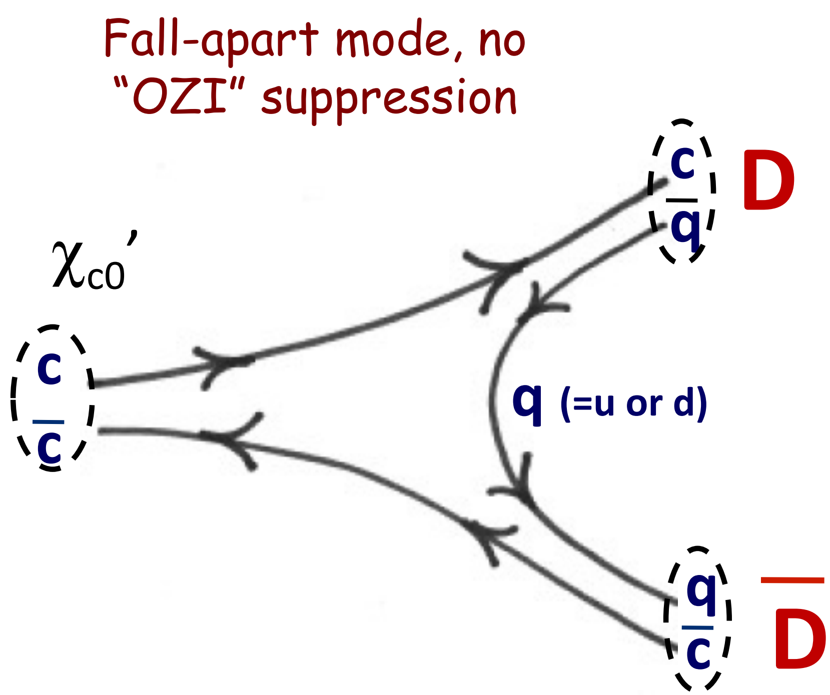
X(3915) = χ'_{c0} charmonium state?

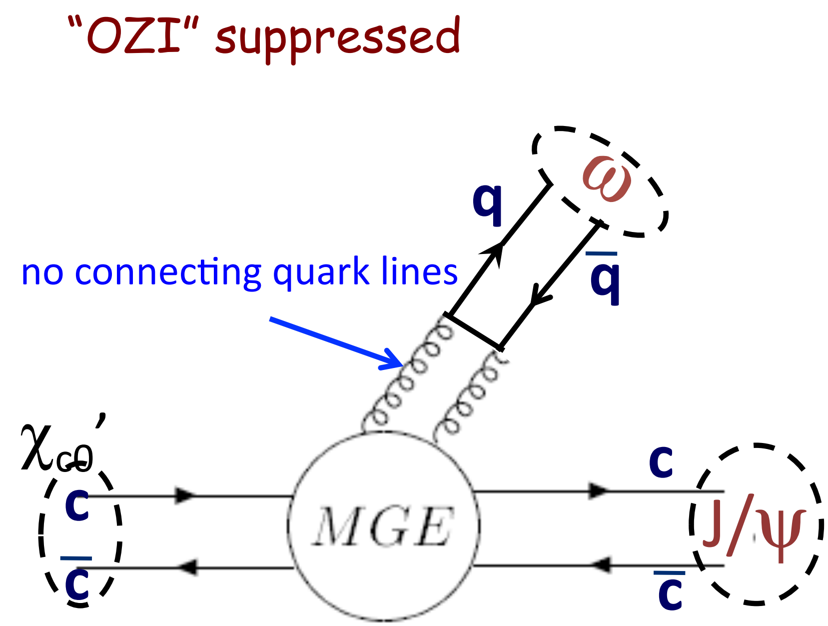
If X(3915) = χ'_{c0}:

- mass is to high:
  $M(\chi'_{c2})$-$M(\chi'_{c0}) \approx 9$ MeV
  $\approx 1/15^{th}$ the n=1 splitting:
  $M(\chi_{c2})$-$M(\chi_{c0})$=141 MeV



$\chi_{c0}' \rightarrow D\bar{D}$ should be huge & $\chi_{c0}' \rightarrow \omega J/\psi$ tiny





But: $Bf(X_{3915} \rightarrow D^0\bar{D}^0) < 1.2 \times Bf(X_{3915} \rightarrow \omega J/\psi)$

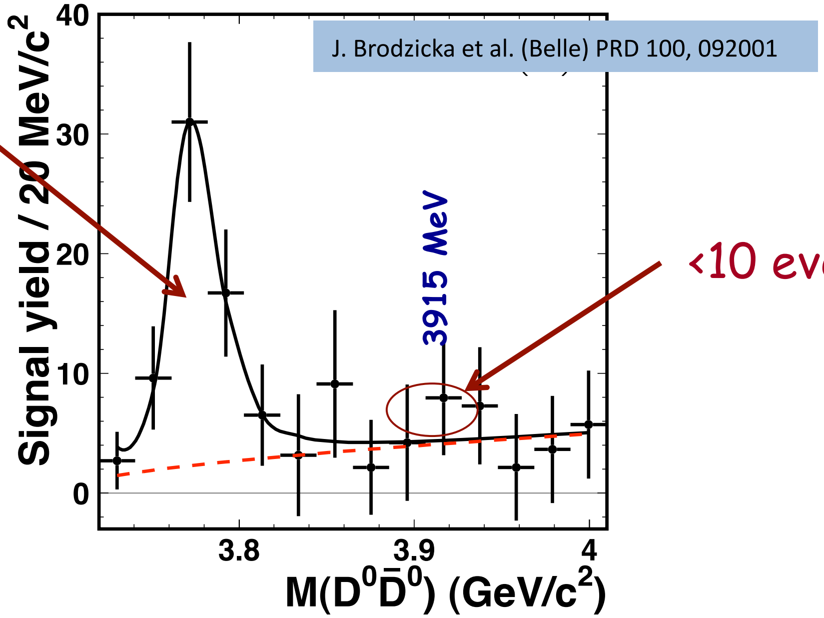
This strongly suggests that the X(3915) is a 4-quark state

Does X(3915) → D$\bar{D}$?

B→KD$^0\bar{D}^0$

B→Kψ(3770)
↳D$^0\bar{D}^0$
68+15 events

No signal near 3915:



<10 events

⇨ Γ(X(3915)→D$\bar{D}$) <1 MeV

charmonium theory: $\Gamma(\chi'_{c0}\rightarrow D\bar{D})$ > 30 MeV

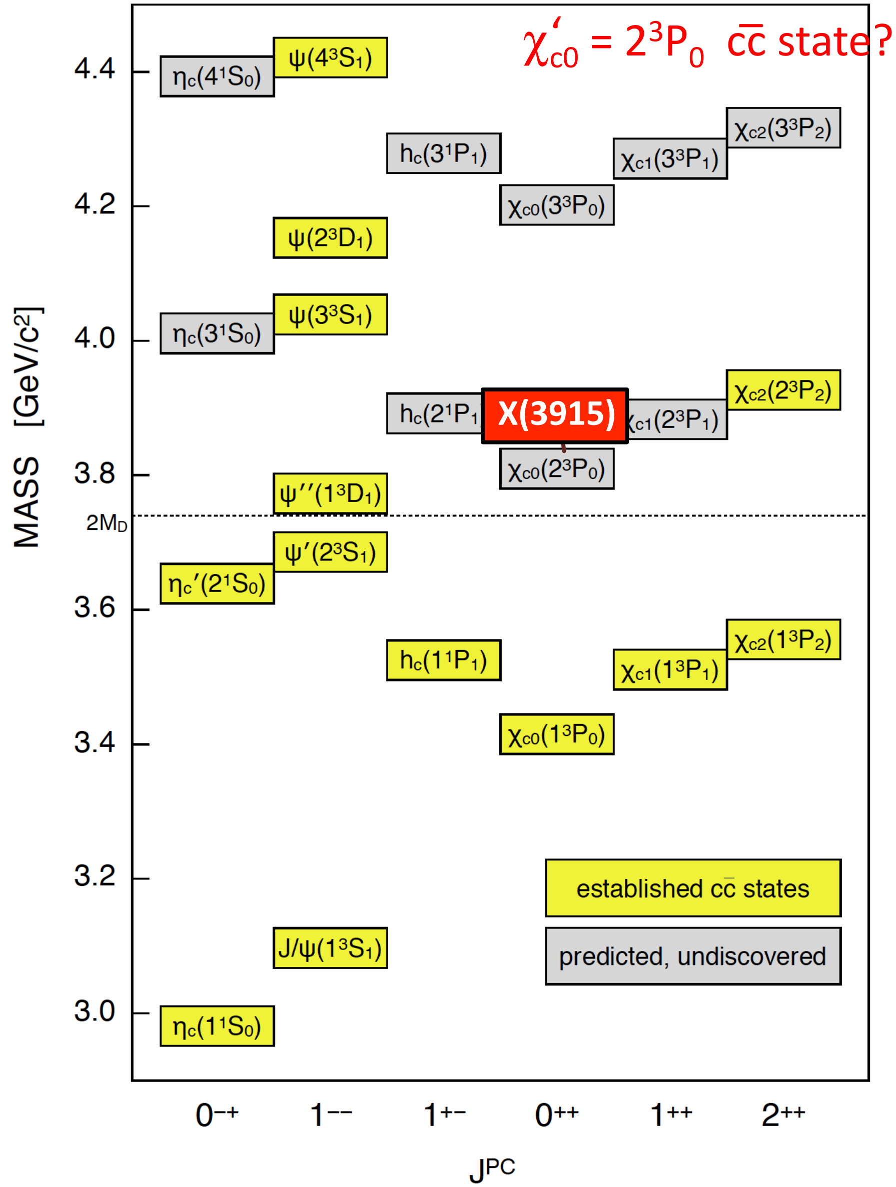
X(3915) = χ'_{c0} charmonium state?

If X(3915) = χ'_{c0}:

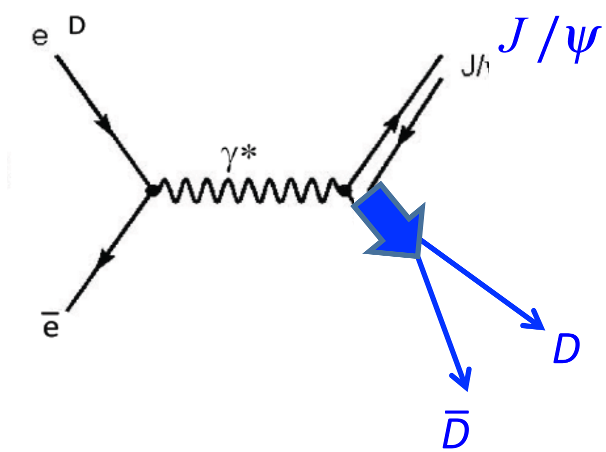
- mass is to high:
  $M(\chi'_{c2})$-$M(\chi'_{c0}) \approx 9$ MeV
  ≈1/15th the n=1 splitting:
  $M(\chi_{c2})$-$M(\chi_{c0})$=141 MeV

- X(3915)→$D\bar{D}$ not seen?
  theory predicts:
  $\Gamma(\chi'_{c0} \to D\bar{D}) \approx 30$ MeV
  my estimate:
  $\Gamma(Y(3940) \to D\bar{D}) < 1$ MeV

- $\Gamma(\chi'_{c0} \to \omega J/\psi) > 1$ MeV, too large for an OZI-suppressed charmonium transition.

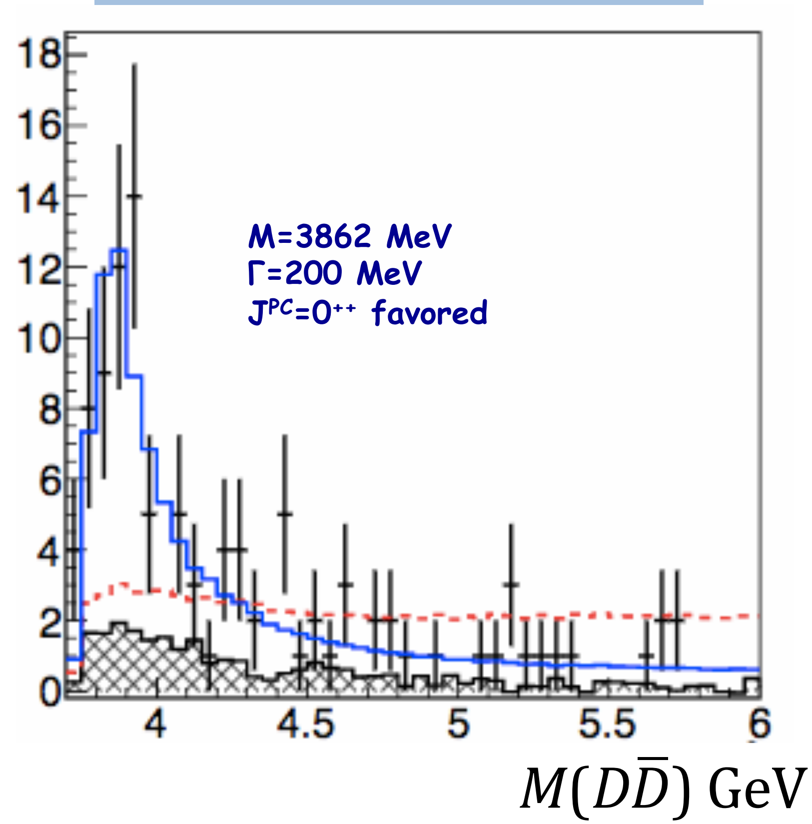


2017 news: Belle finds the "real" χ'_{c0}



$$e^+e^- \rightarrow J/\psi\ \chi'_{c0}$$
$$\hookrightarrow D\bar{D}$$

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



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

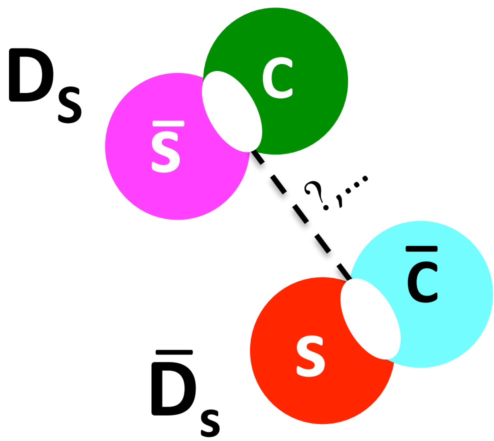
Mass is near $2m_{Ds}$ threshold: $M(X(3915)) = 2m_{Ds}$ -18 MeV

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

Possibilities

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

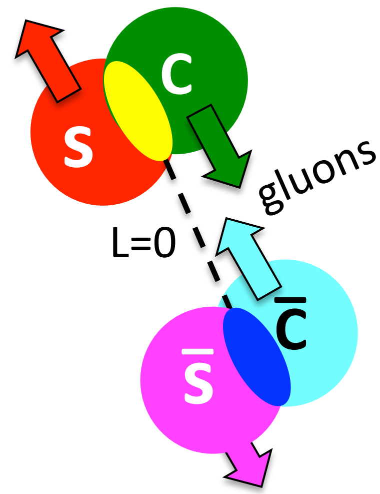
Li & Voloshin, PRD 91, 114014



what binds it?

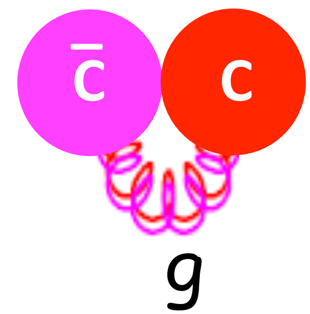
$[\bar{c}\bar{s}][cs]$ tetraquark?

Lebed & Polosa, PRD 93, 094024



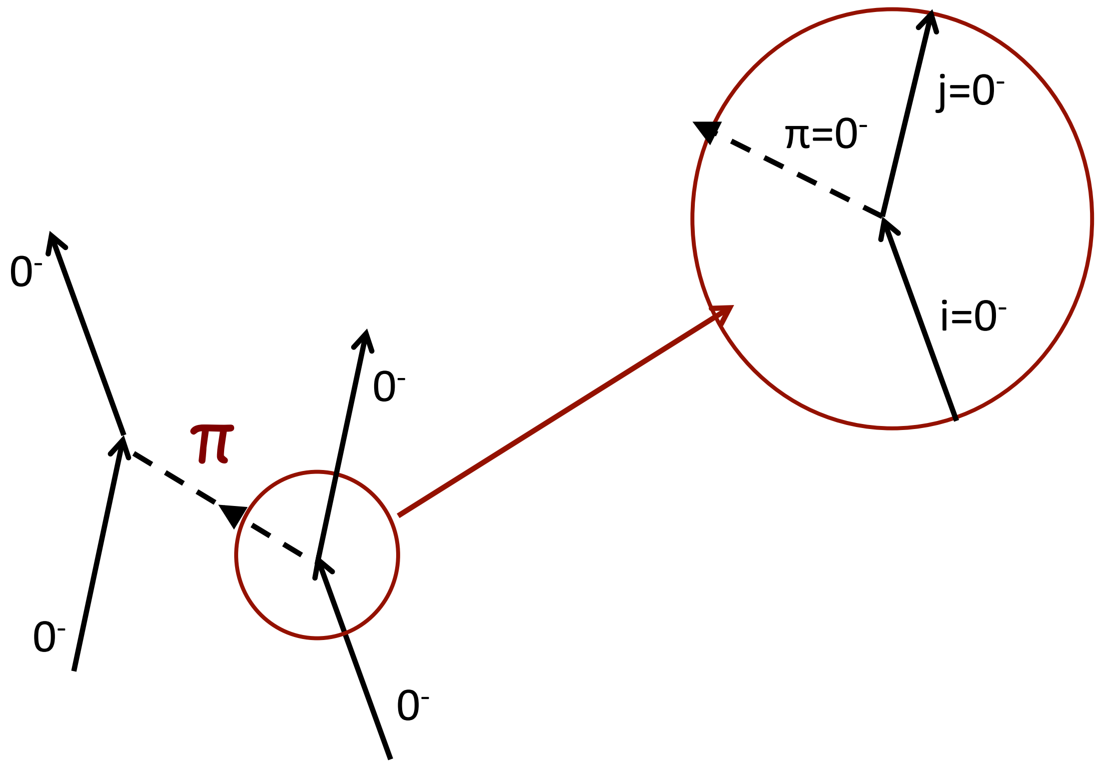
why not $X \rightarrow \eta\eta_c$?

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



too light for 0^{++} cc-hybrid

no pion exchange between 0^- and 0^-



$i \rightarrow j + \pi$

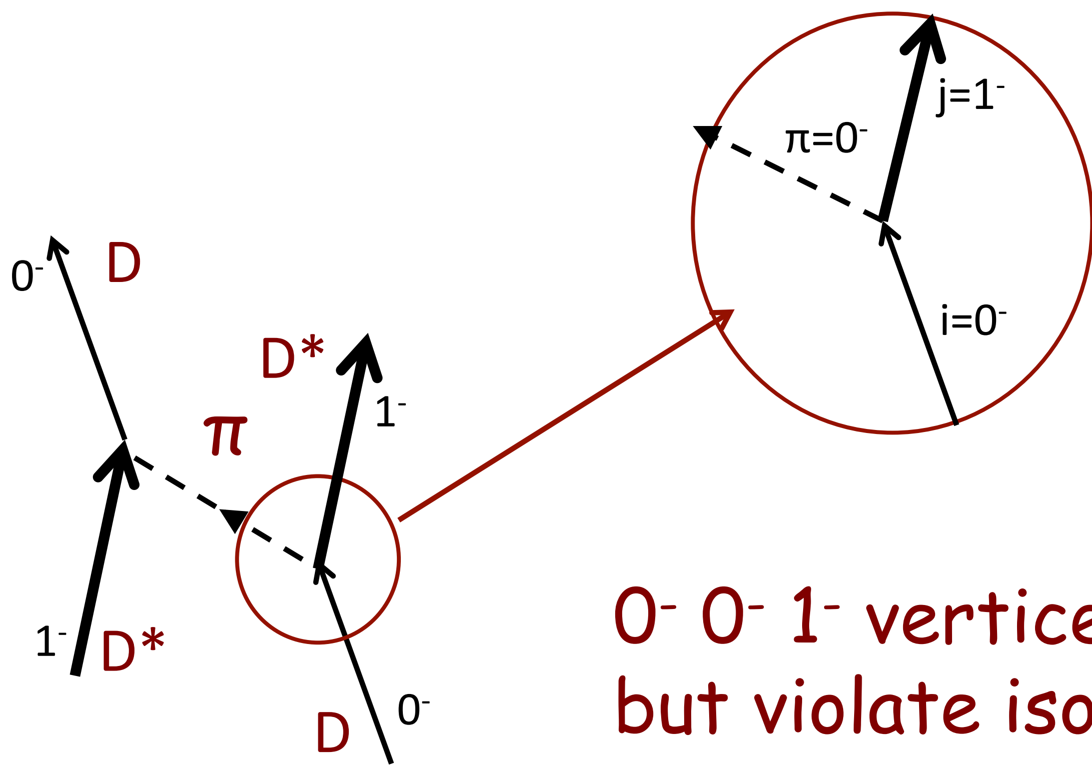
initial state

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

pion exchange between 0^- and 1^-



$i \rightarrow j + \pi$

initial state

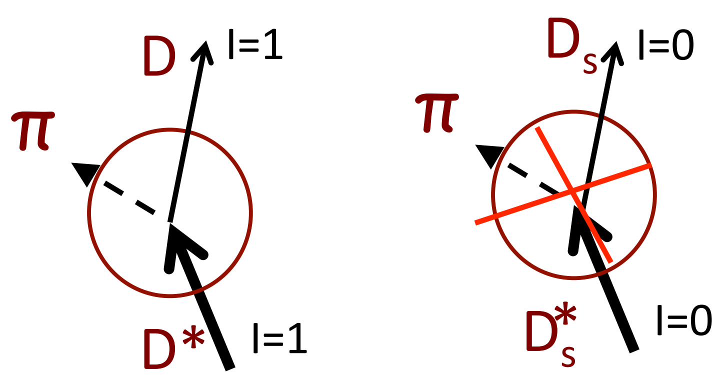
P=-1; J=0

to conserve P, j & π

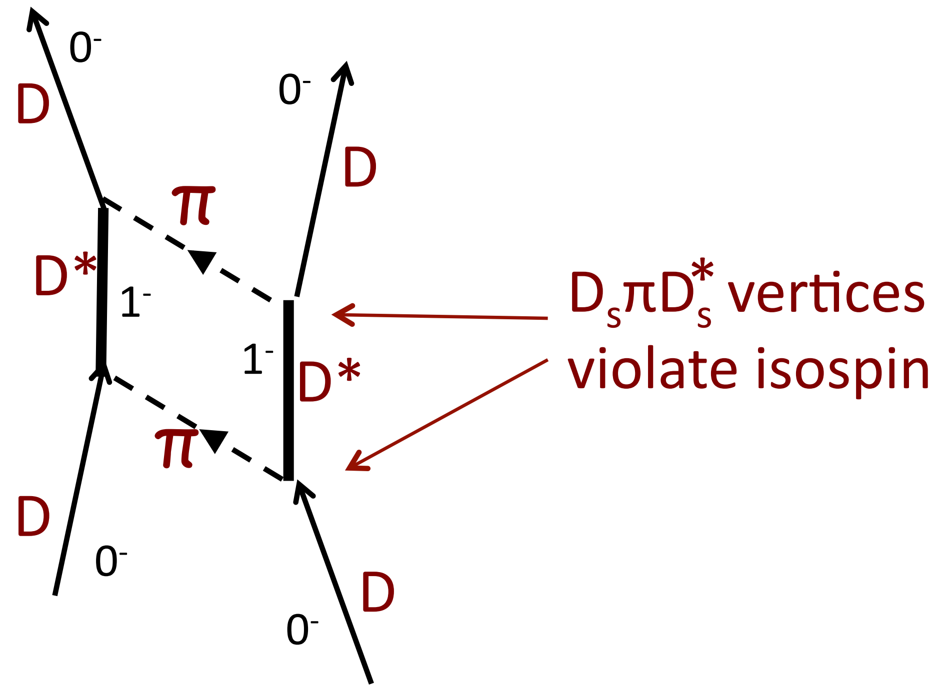
should be in a P-wave,

➔ OK for 0 → 1^- + π

0^- 0^- 1^- vertices are okay for DπD*, but violate isospin for $D_s \pi D_s^*$

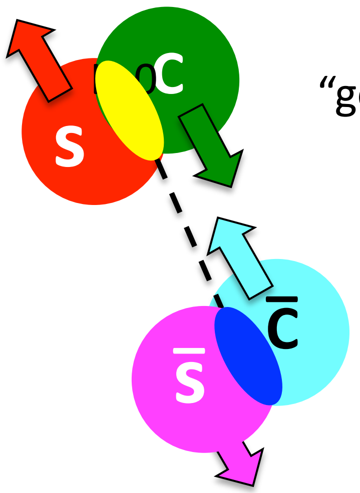


$\pi\pi$ exchange is OK for $D\bar{D}$, but not $D_s\bar{D}_s$



no plausible nuclear-physics-type force can bind $D_s\bar{D}_s$ into a "molecule"

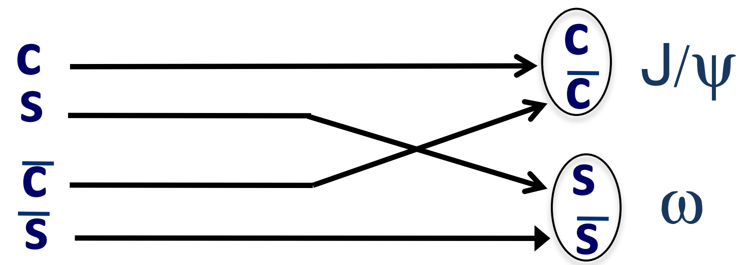
how does a $J^{PC}=0^{++}$, M=3915 MeV $cs\bar{c}\bar{s}$ tetraquark decay?



"good diquark"

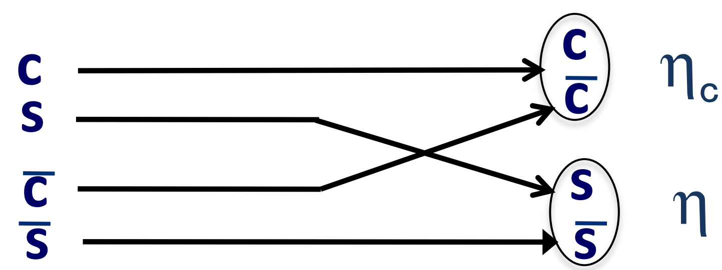
"good diantiquark"

OZI allowed decay processes



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

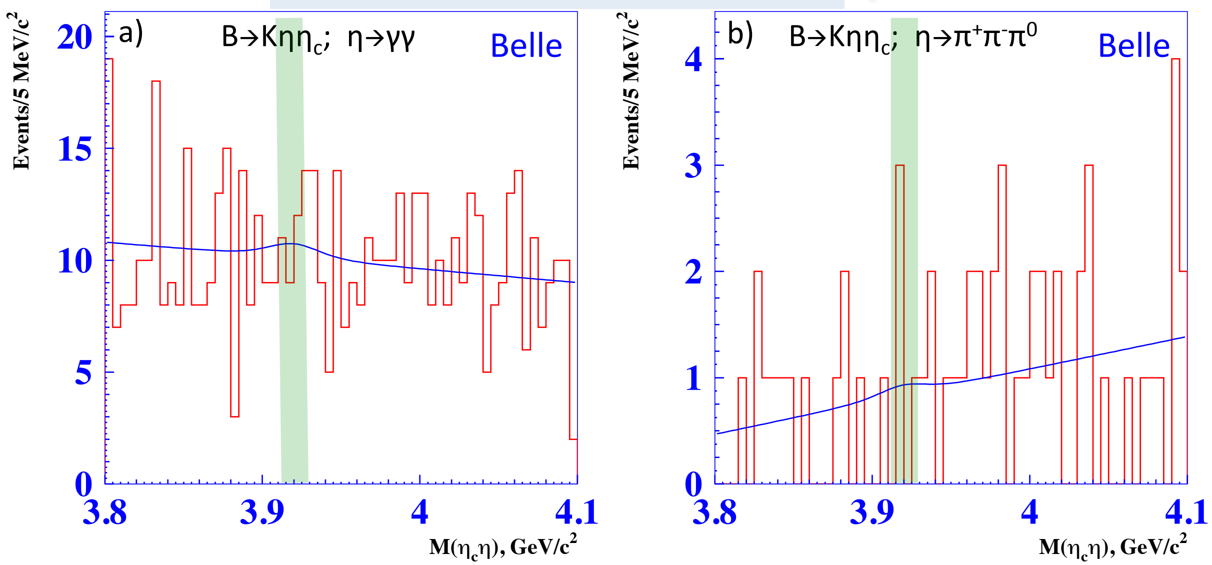
Expect: $$\frac{Bf(X(3915)\to\eta_c\eta)}{Bf(X(3915)\to J/\psi\ \omega)} \gg 1$$



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

X(3915)→$\eta_c\eta$

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

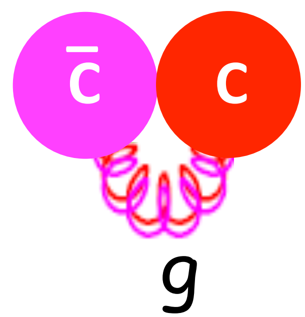


$$\mathcal{B}(B^+ \to K^+ X(3915)) \times \mathcal{B}(X \to \eta\eta_c) < 4.7 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+ X(3915)) \times \mathcal{B}(X \to \omega J/\psi) = 3.0^{+0.9}_{-0.7} \times 10^{-5}$$

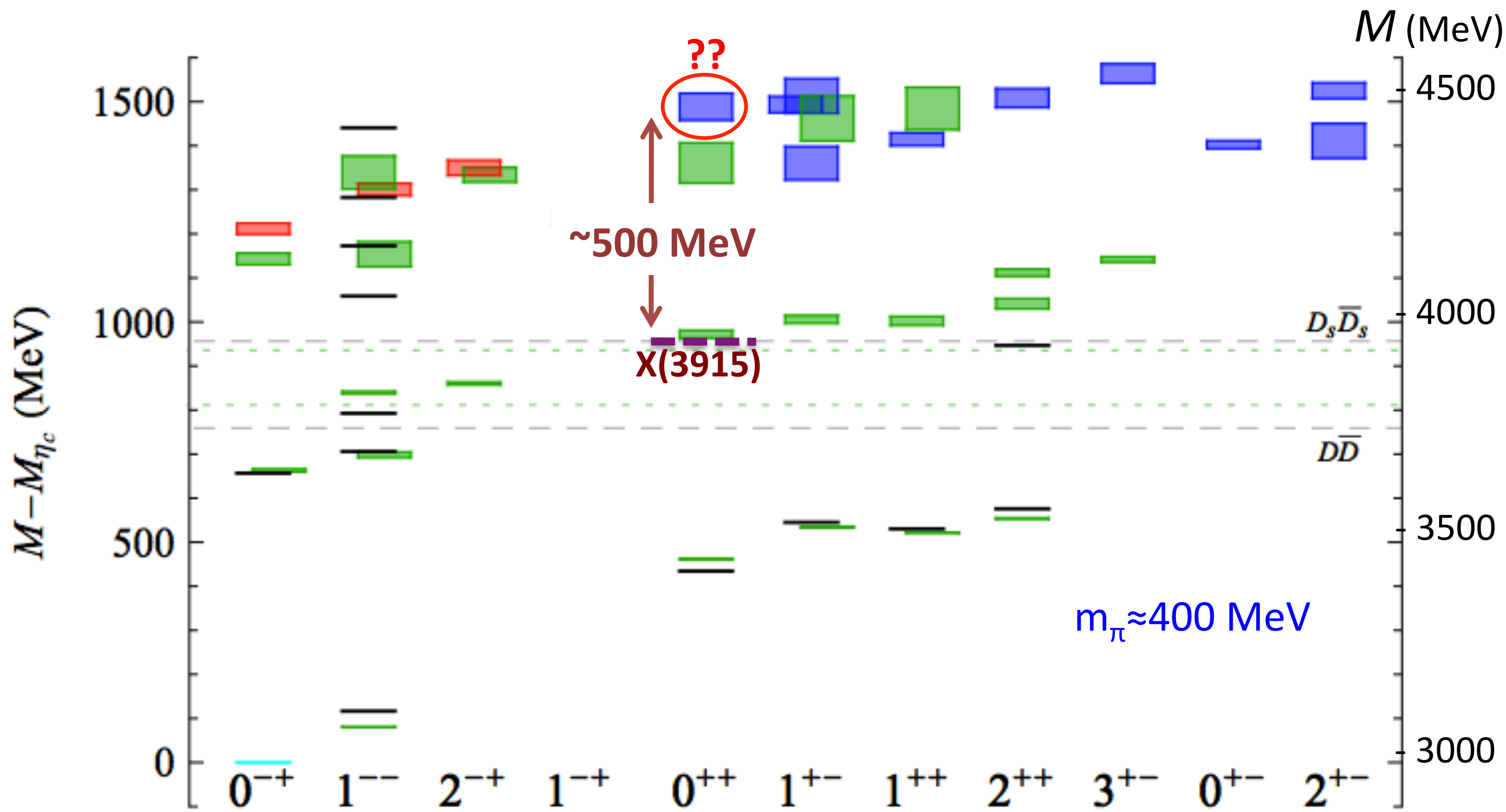
$$\Rightarrow \boxed{\frac{Bf(X \to \eta_c\eta)}{Bf(X \to J/\psi\ \omega)} < 2}$$

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

$\Rightarrow$ bad for the QCD tetraquark picture how about a $J^{PC}=0^{++}$ $c\bar{c}$-gluon hybrid?



0^{++} not a good match for a light hybrid



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

What is the X(3915)?

It is not a good candidate for the χ'_{c0}

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

If it is a $D_s\bar{D}_s(2420)$ molecule:

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

standard nuclear-physics type forces do not work

If it is a $c\bar{c}$-gluon hybrid:

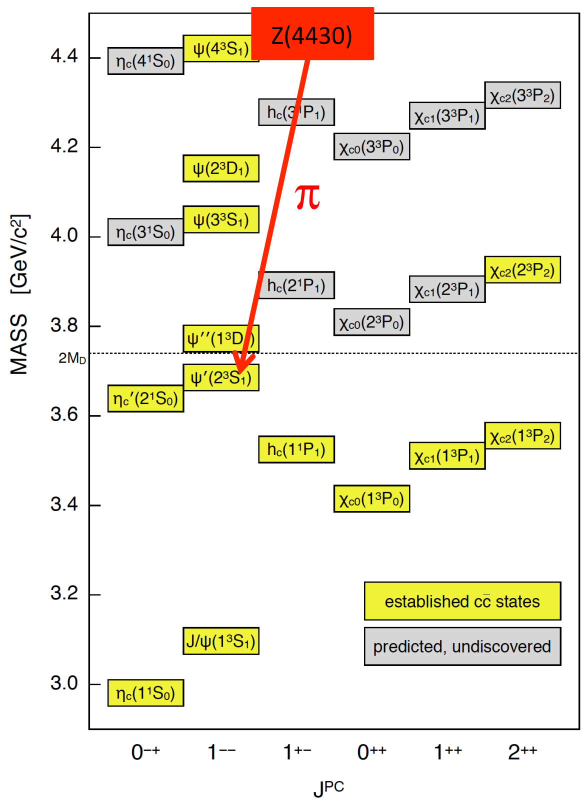
current (m_π≈400 MeV) LQCD mass calculation off by ≈500 MeV!

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

the $X(3915)\rightarrow\eta\eta_c$ decay mode should show up soon

It remains an intriguing puzzle

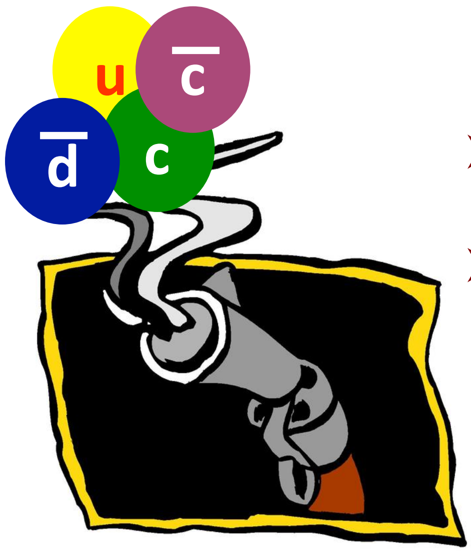
The Z(4430)



Z(4430)
π
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)
ηc(3¹S₀)
ψ(3³S₁)
hc(2¹P₁)
χc2(2³P₂)
χc1(2³P₁)
χc0(2³P₀)
ψ''(1³D₁)
ψ'(2³S₁)
ηc'(2¹S₀)
hc(1¹P₁)
χc2(1³P₂)
χc1(1³P₁)
χc0(1³P₀)
J/ψ(1³S₁)
ηc(1¹S₀)
established cc̄ states
predicted, undiscovered
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
JPC

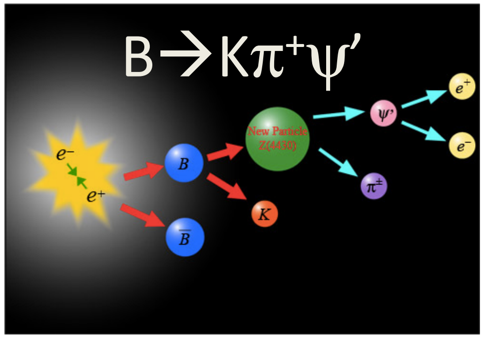
The $Z(4430)^+ \rightarrow \pi^+ \psi'$

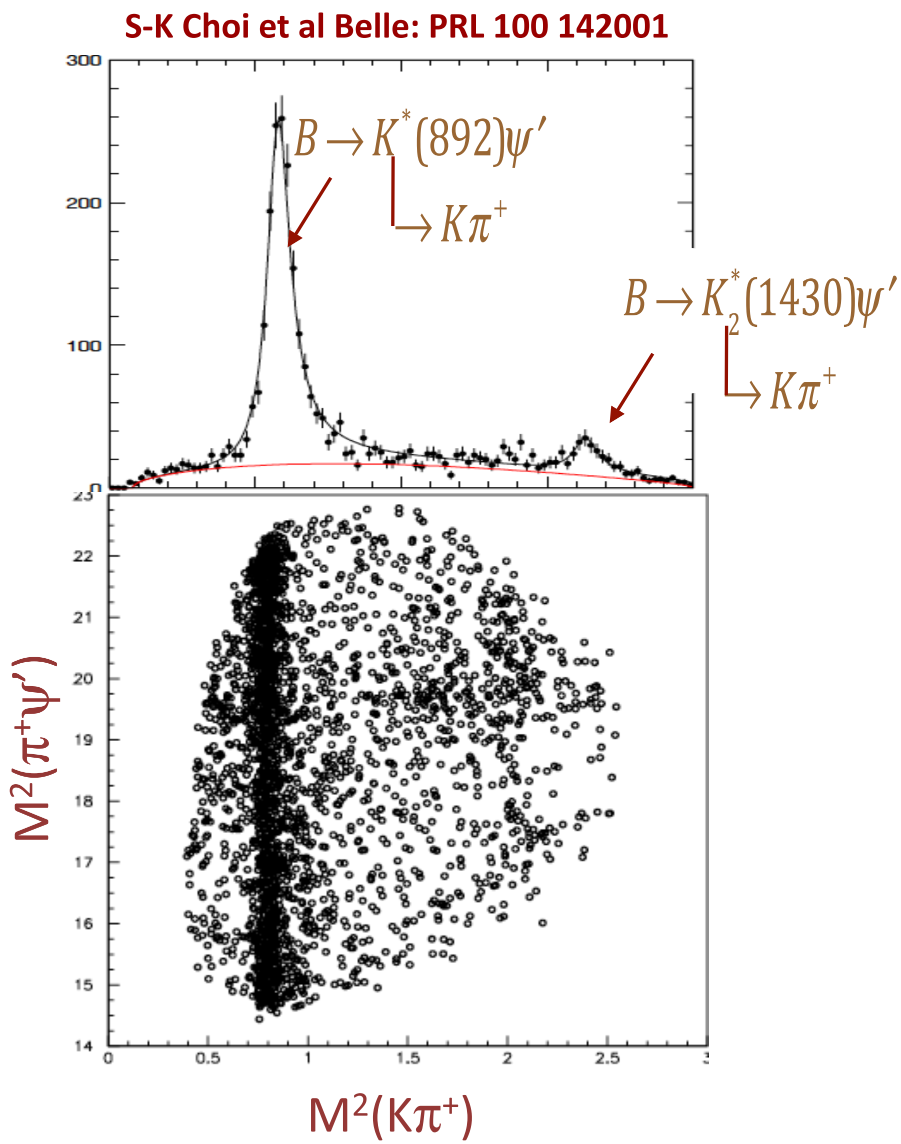
"smoking gun" evidence for a 4-quark meson



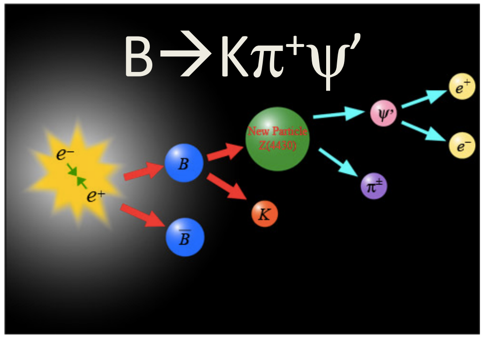
- decays to ψ' ➔ must contain $c\bar{c}$ pair
- electrically charged ➔ must contain $u\bar{d}$ pair

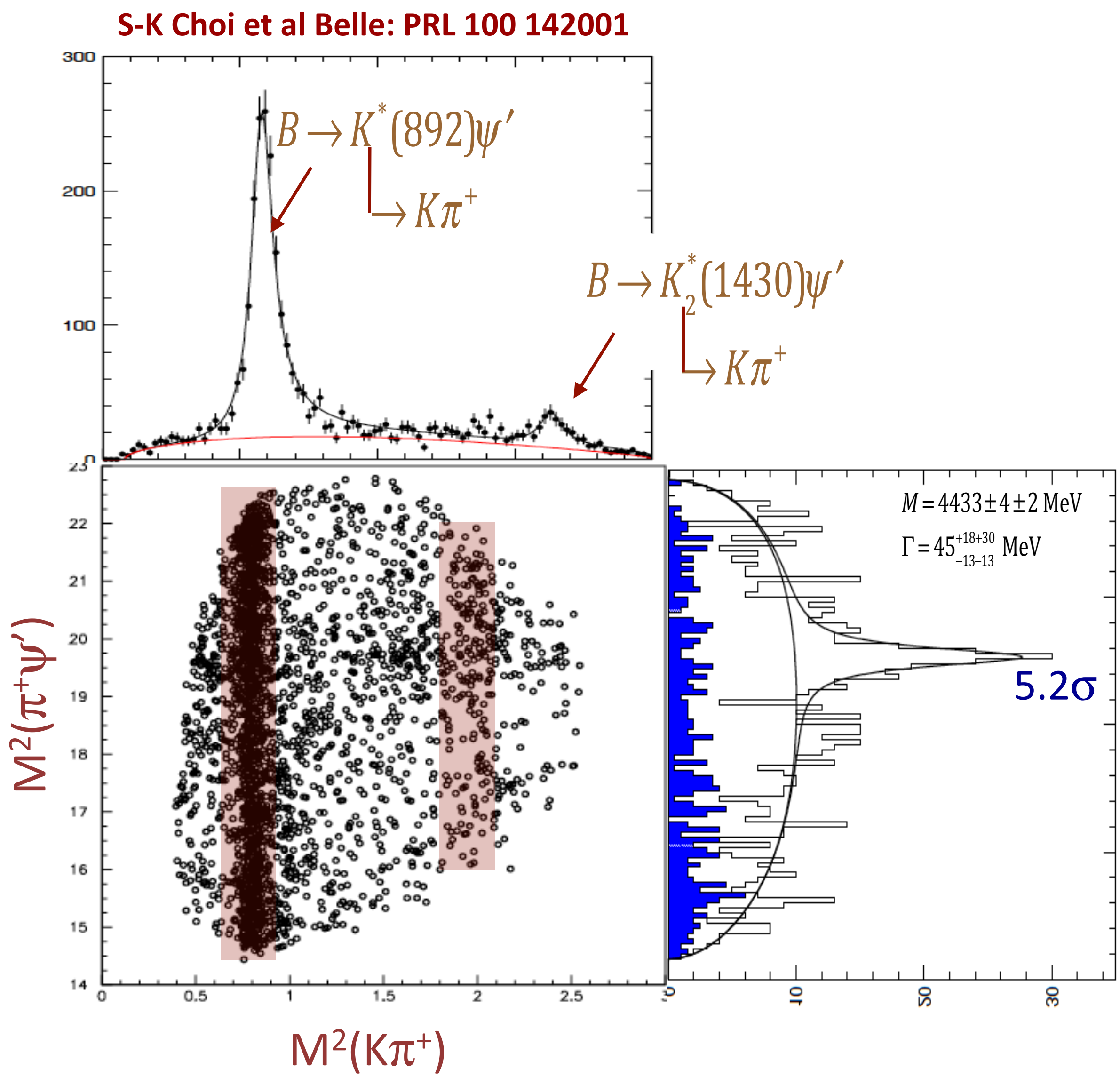
Found by Belle in 2007





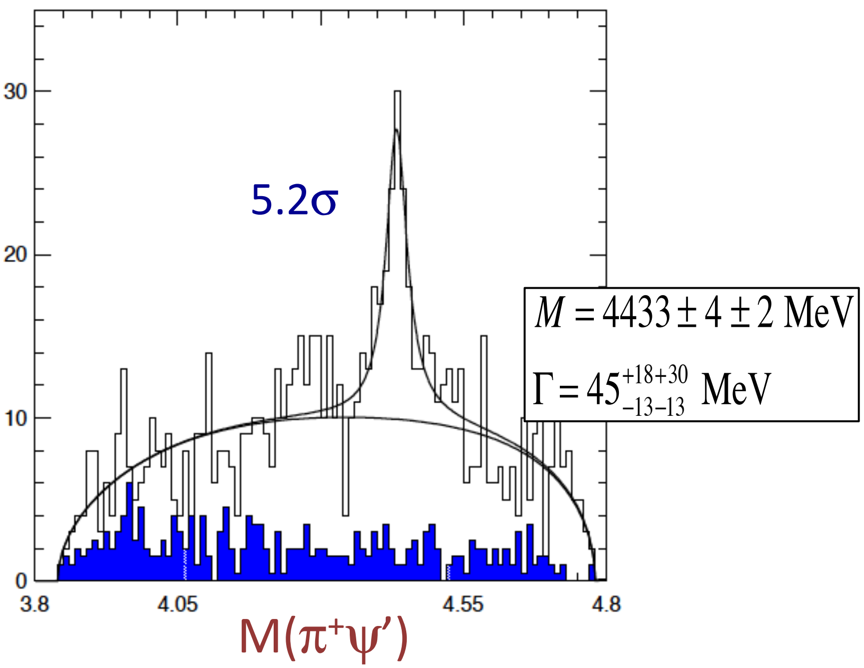
Found by Belle in 2007



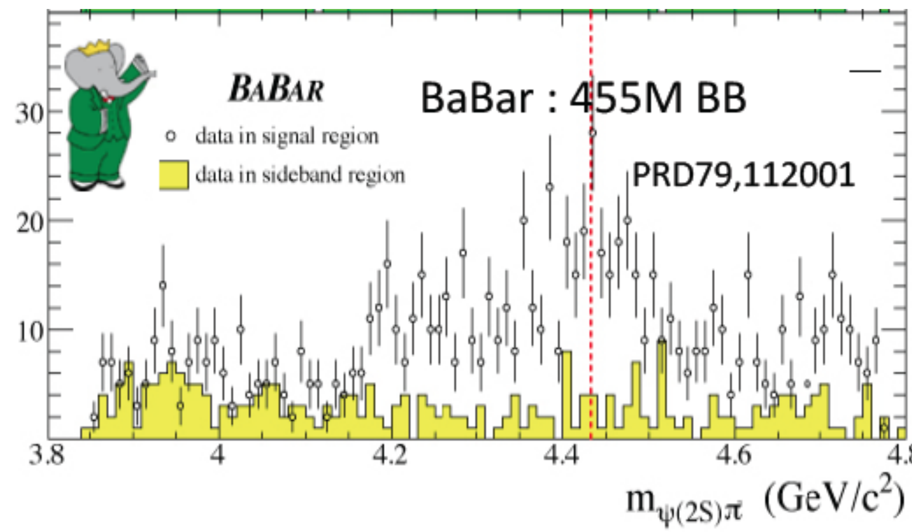


Not confirmed by BaBar

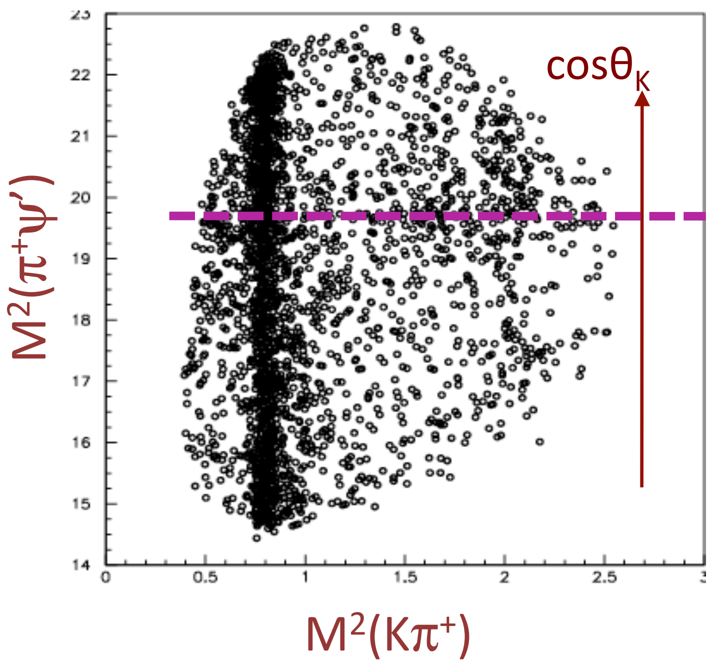
S-K Choi et al Belle: PRL 100 142001

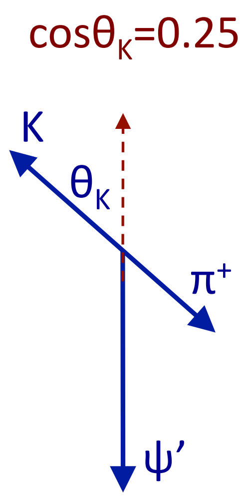


not confirmed by BaBar (only a 1.9σ "hint")

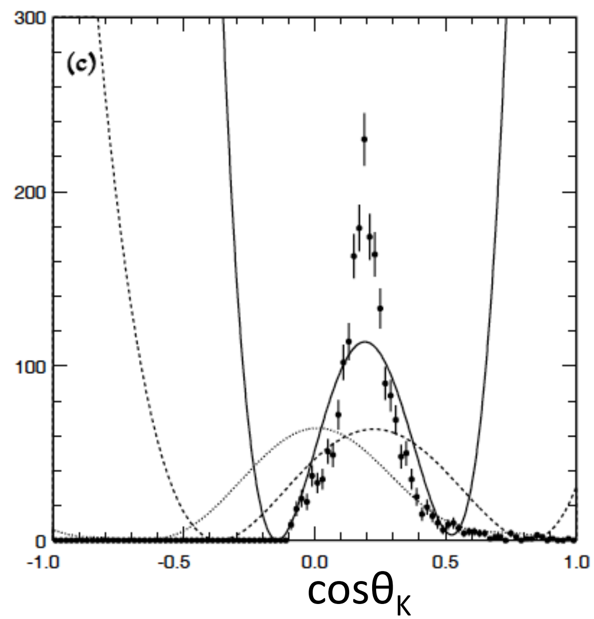


a “reflection” from the Kπ channel?





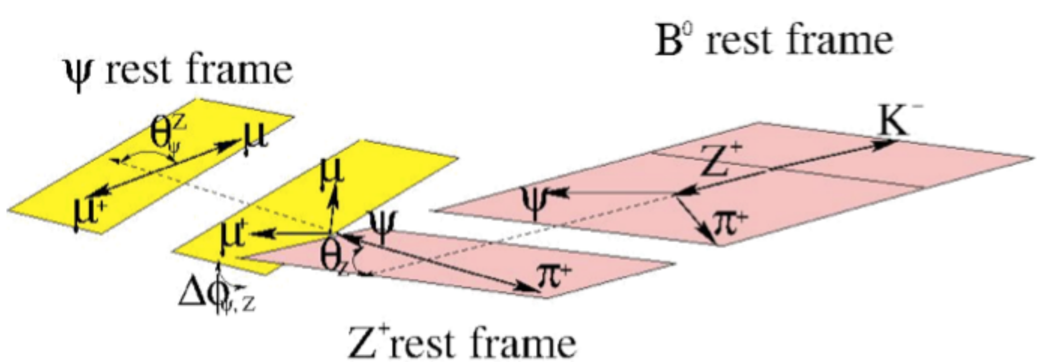
can you make a peak at cosθ=0.25
by interfering Kπ partial waves?



it can be done, but only by making
even larger structures elsewhere

not a reflection from the Kπ channel

2013: 4 dimensional Belle amplitude analysis

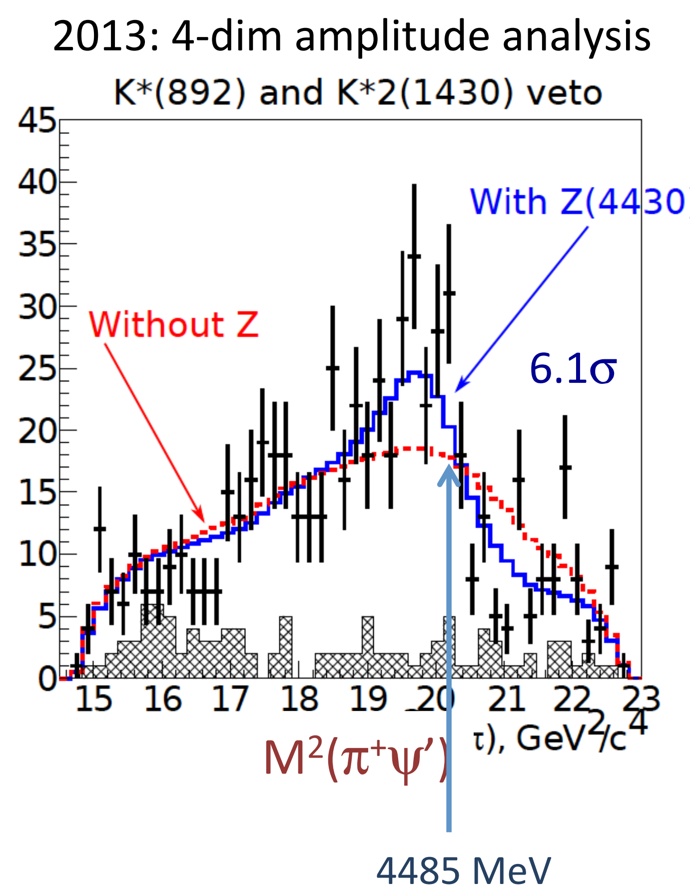


$$M^Z_{\Delta\lambda_\mu} = \sum_{\lambda_\psi=-1,0,1} A^{Z\to\psi\pi}_{\lambda_\psi} D^{J_Z}_{\lambda_\psi,\lambda_\psi}(0,\theta_Z,0)^* R(m_{\psi\pi} \mid M_Z,\Gamma_Z) D^1_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,Z},\theta_\psi^{\ Z},0)^*$$

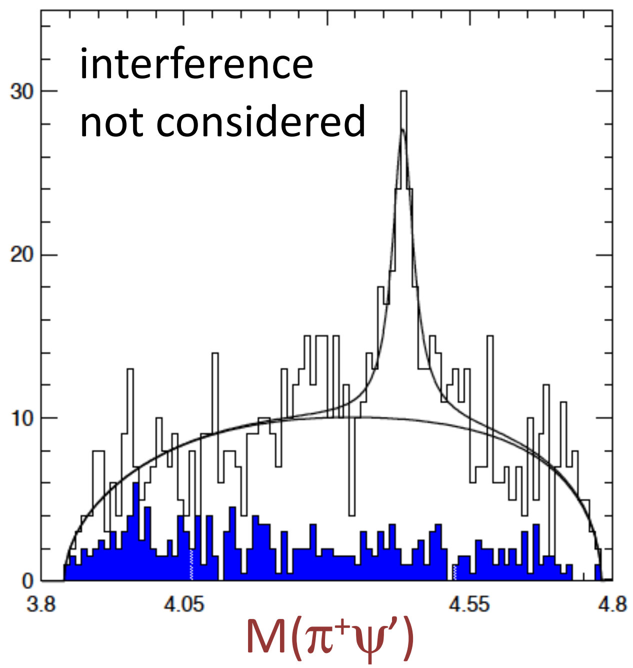
$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV}$$

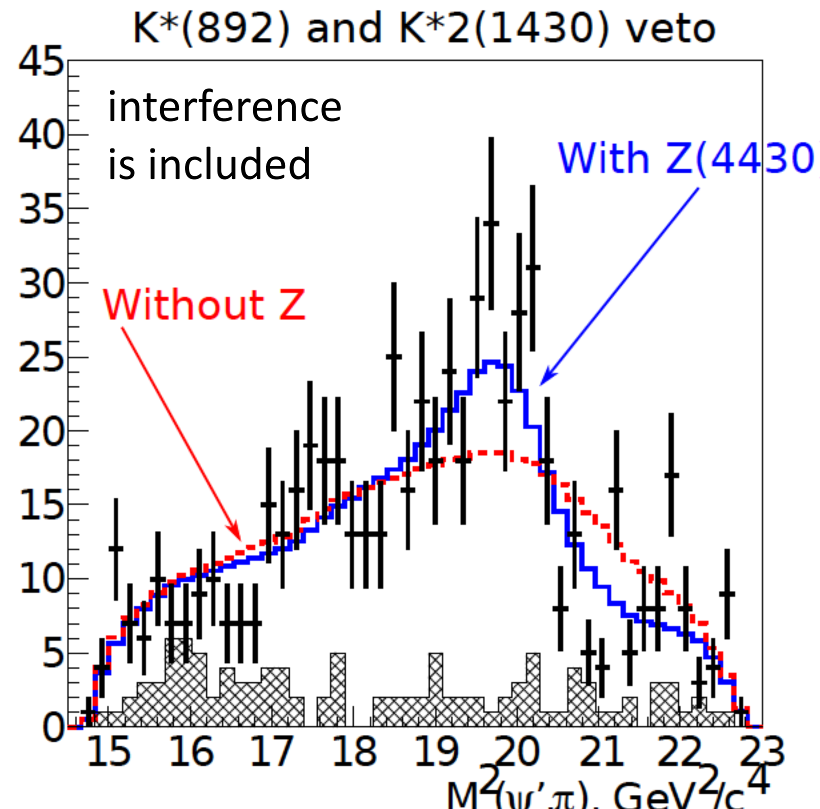
$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}$$

K Chilikin et al Belle: PRD 88 074026



2007 analysis *vs* 2013 analysis





$M = 4433 \pm 4 \pm 2$ MeV

$\Gamma = 45^{+18+30}_{-13-13}$ MeV

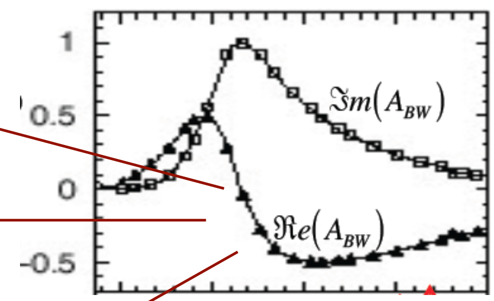
M & Γ increased

$M = 4485^{+22+28}_{-22-11}$ MeV

$\Gamma = 200^{+41+26}_{-46-35}$ MeV

BW resonance on a coherent background A_{bkg}

$$\left|BW + A_{\text{bkg}}\right|^2 = \left|BW\right|^2 + \left|A_{\text{bkg}}\right|^2 + 2\mathcal{Re}(A_{\text{bkg}} BW)$$



if $|BW|>>|A_{\text{bkg}}|$: $\quad \left|BW + A_{\text{bkg}}\right|^2 \approx \left|BW\right|^2 + 2\mathcal{Re}(A_{\text{bkg}} BW)$

if $|A_{\text{bkg}}|>> |BW|$: $\quad \left|BW + A_{\text{bkg}}\right|^2 \approx \left|A_{\text{bkg}}\right|^2 + 2\mathcal{Re}(A_{\text{bkg}} BW)$

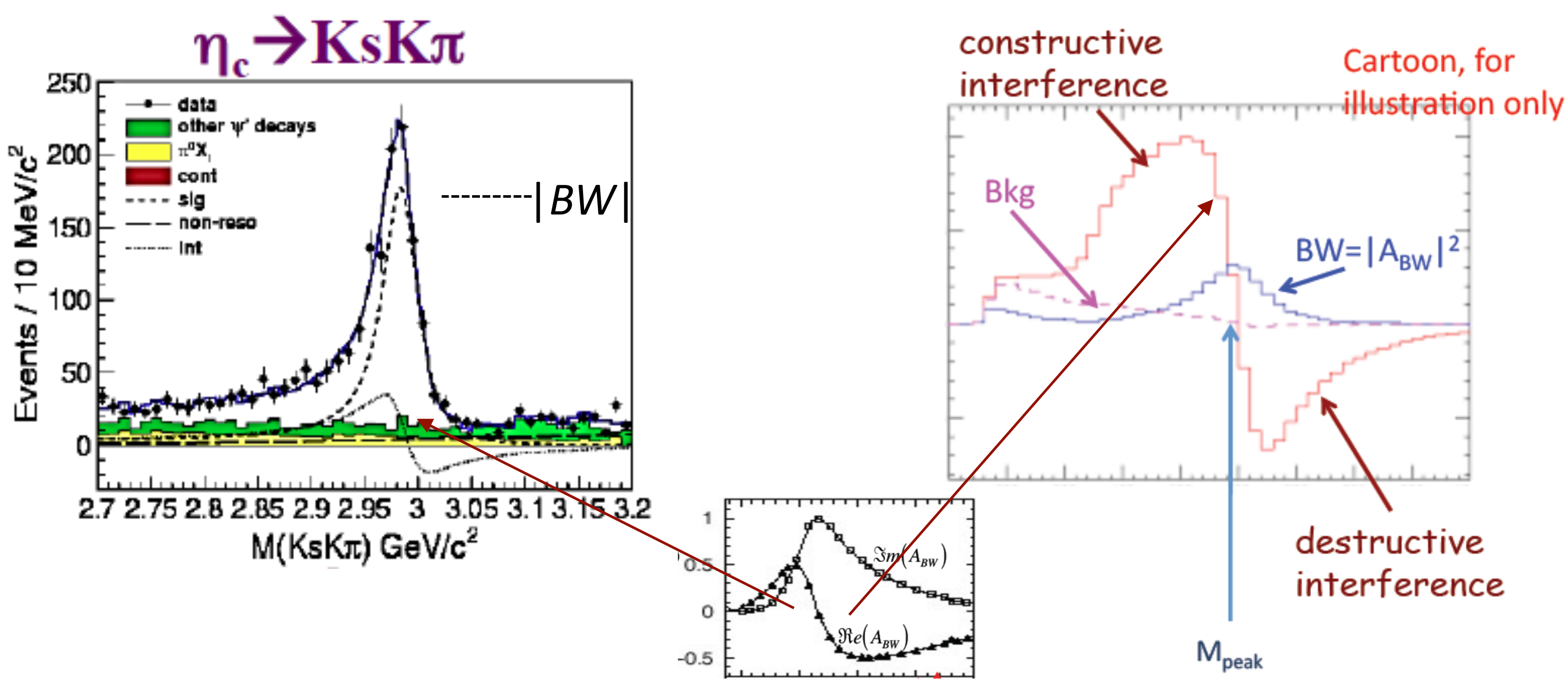
BW interfering with coherent background A_{bkg}

$|BW| >> |A_{\mathrm{bkg}}|$:

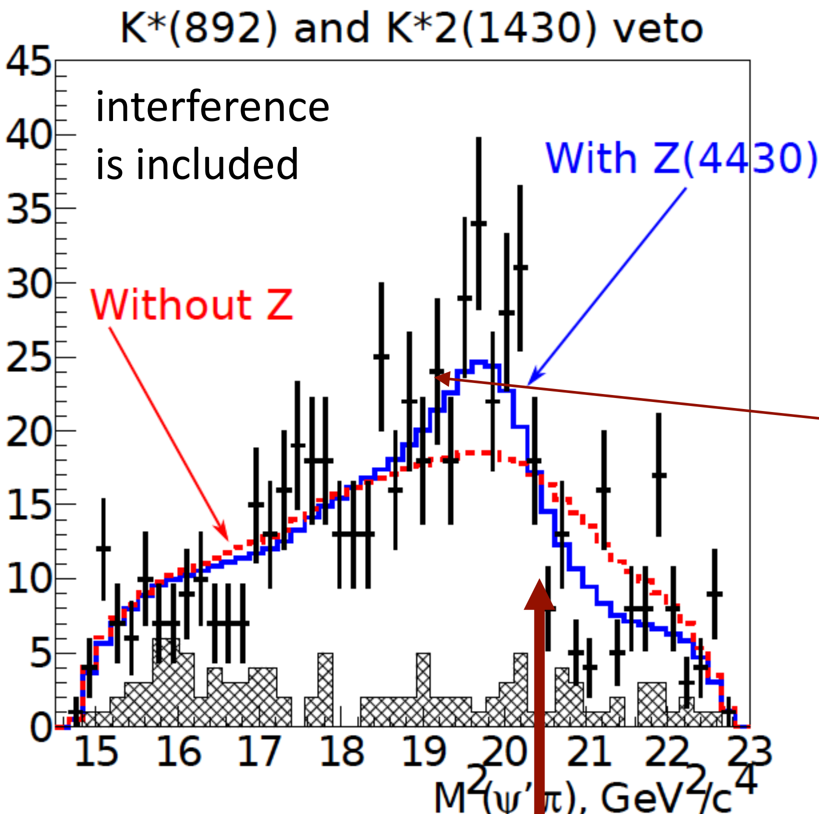
$$\left|BW + A_{\mathrm{bkg}}\right|^2 \approx \left|BW\right|^2 + 2\mathcal{Re}(A_{\mathrm{bkg}} BW)$$

$|A_{\mathrm{bkg}}| >> |BW|$:

$$\left|BW + A_{\mathrm{bkg}}\right|^2 \approx \left|A_{\mathrm{bkg}}\right|^2 + 2\mathcal{Re}(A_{\mathrm{bkg}} BW)$$



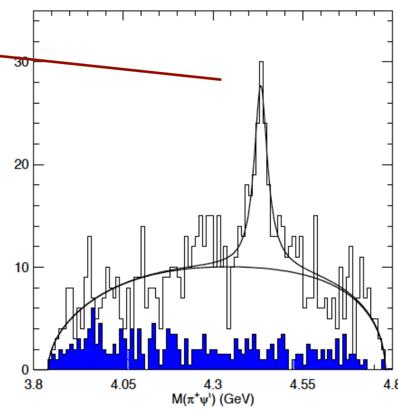
Z(4430) is an example of $A_{\mathrm{bkg}} \gg BW$



$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV}$$

$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}$$

peak of the BW amplitude is here



This peak is just the lower half of the BW,

that is why the 1st Belle paper got a lower mass and narrower width:

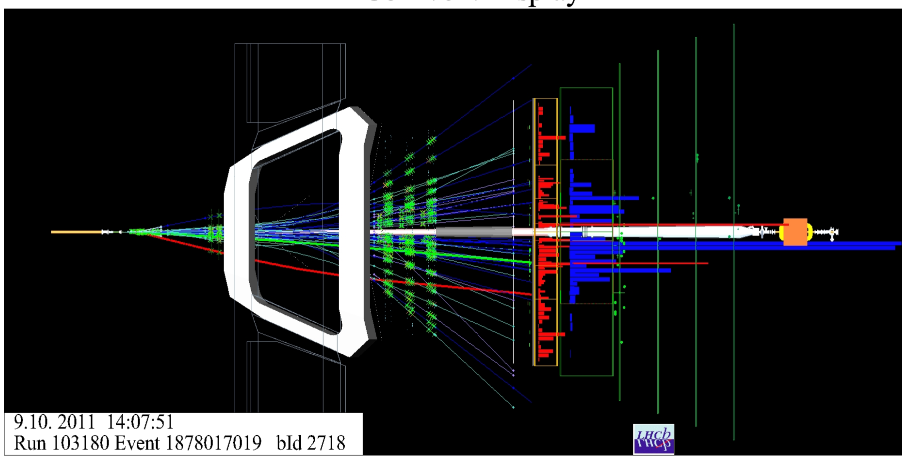
$$M = 4433 \pm 4 \pm 2\ \mathrm{MeV}$$

$$\Gamma = 45^{+18+30}_{-13-13}\ \mathrm{MeV}$$

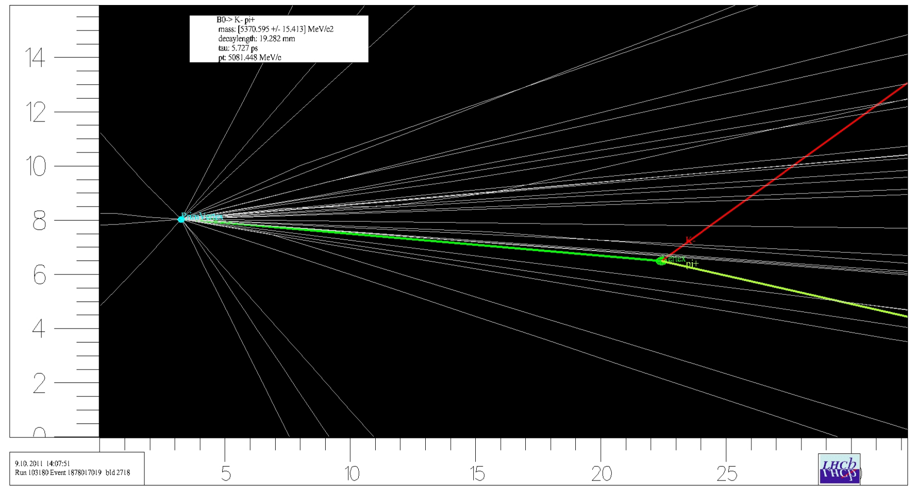
Z(4430) confirmed by LHCb

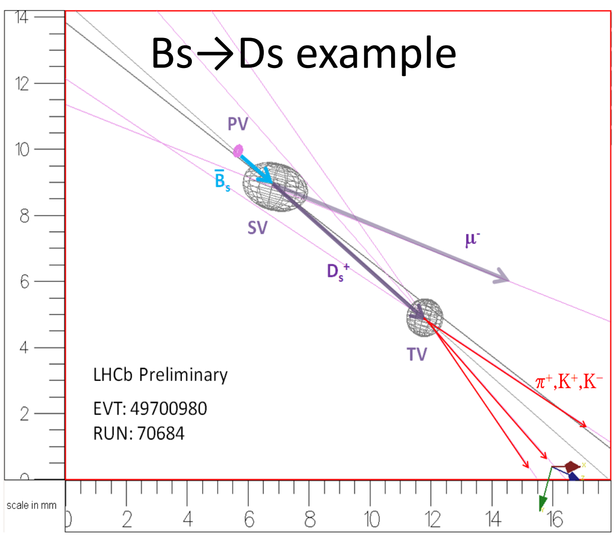
$$E_{\mathrm{cm}} = 8\ \text{TeV pp collisions: } pp \to B + X$$

LHCb Event Display



B→K$^+\pi^-$ example

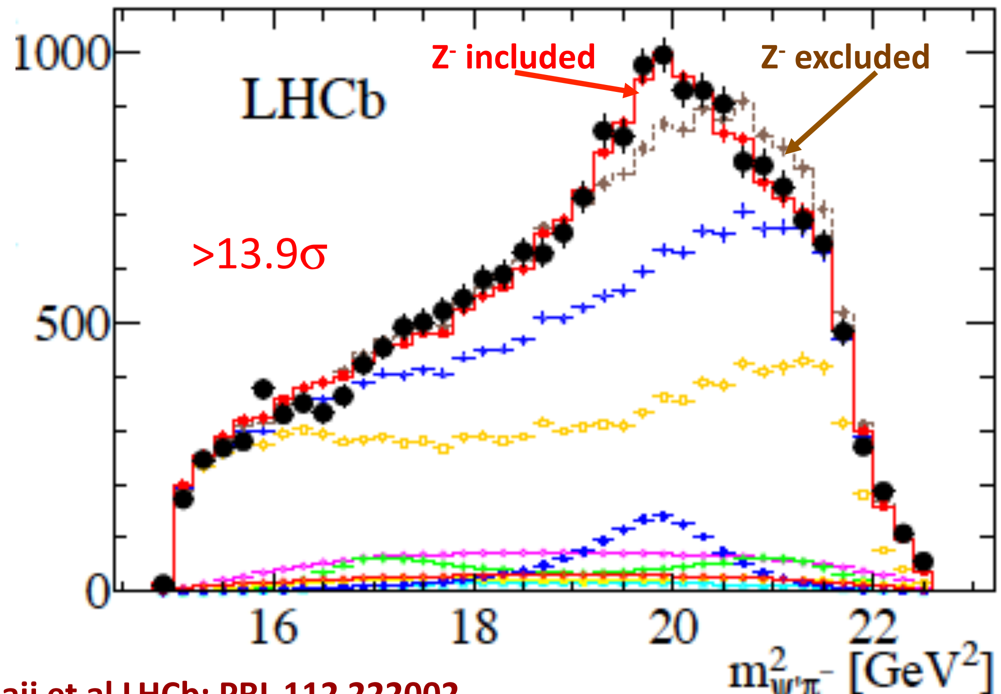




- Very large cross section in forward region in pp collision.
- ~2K B mesons /fb^{-1} wrt e^+e^- B-factories
- Flight length of bottom and charm hadrons ~5-10×σ_{vtx}

LHCb 4-dim analysis of B→$K^+\pi^-\psi'$

B→$K^+\pi^-\psi'$ 4-dim amplitude analysis



R. Aaij et al LHCb: PRL 112 222002

$J^P = 1^+$

$M = 4475 \pm 7^{+15}_{-25}$ MeV

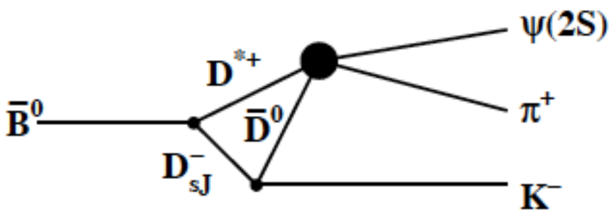
$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

Good agreement with Belle,
(with smaller errors)

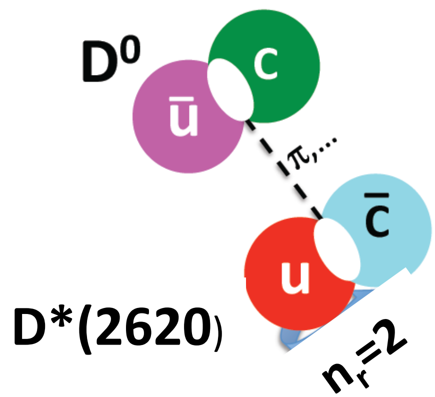
$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') \approx (3.4^{-1.1}_{-2.3}) \times 10^{-5}$$

What is the Z(4430)?

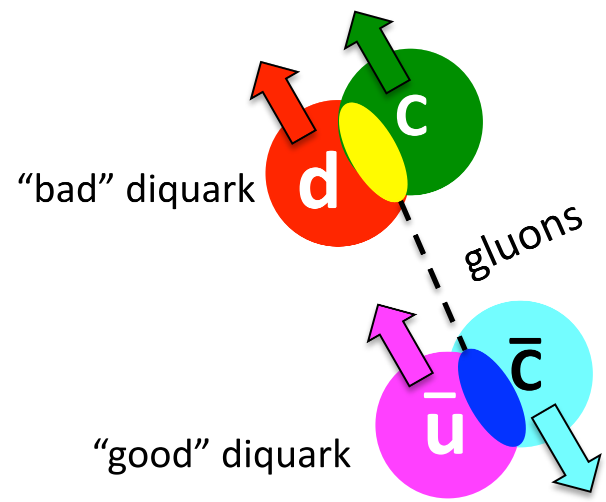
Kinematic effect due to $D^*\bar{D}$ rescattering?



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

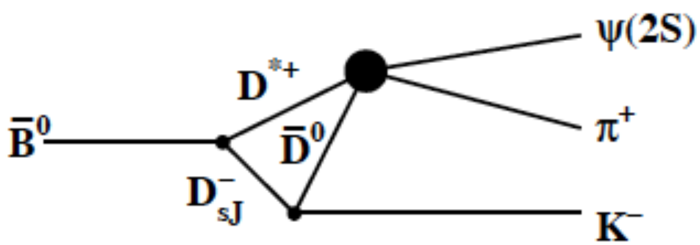


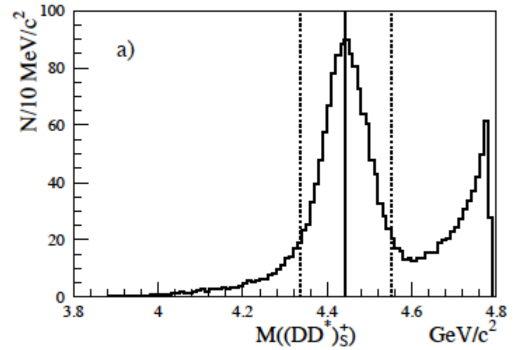
tetraquark formed with a radially excited diquark



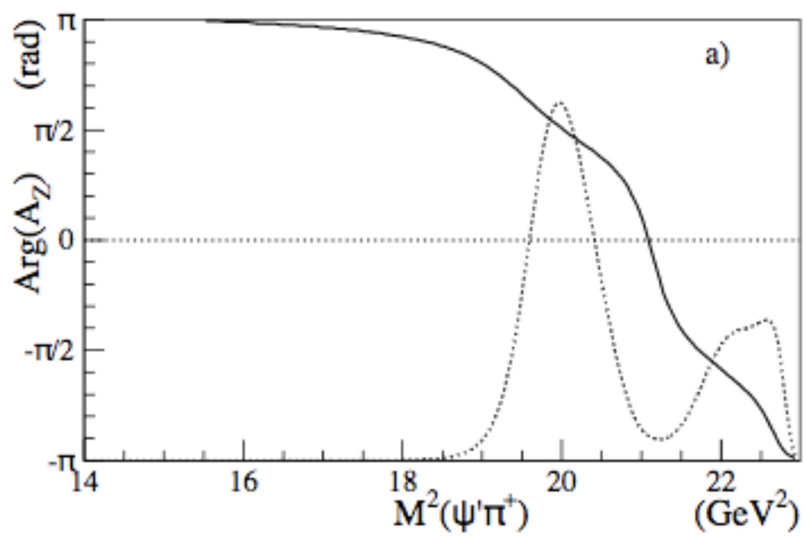
one of the diquarks is is in an n_r=2, radially excited state.

Rescattering process?





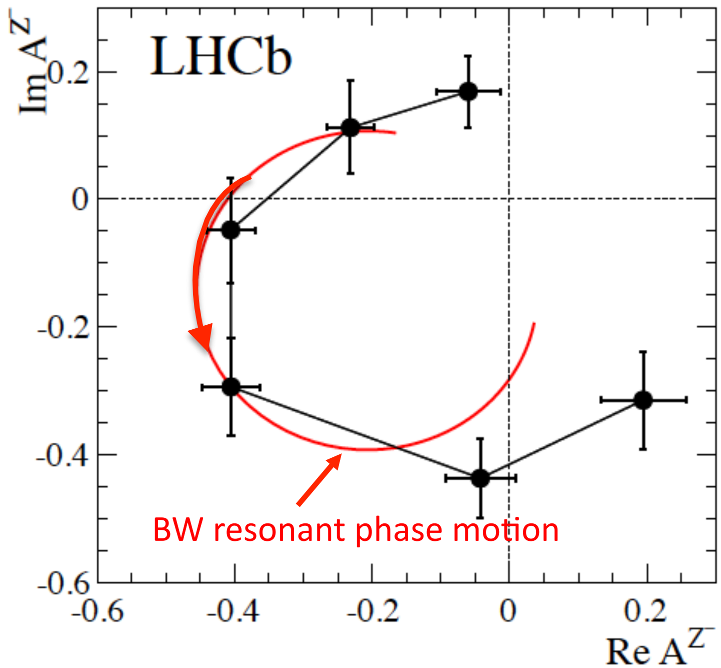
“Conventional” $\bar{D}_{sJ}=\bar{c}s$ resonance decaying to $\bar{D}K$, can produce a peak in the $\psi'\pi^+$ invariant mass. The phase motion of the $\bar{D}_{sJ}$ BW resonance amplitude produces (opposite) phase motion in the $\psi'\pi^+$ system.



Pakhlov &Uglov, PLB 183 (2015)

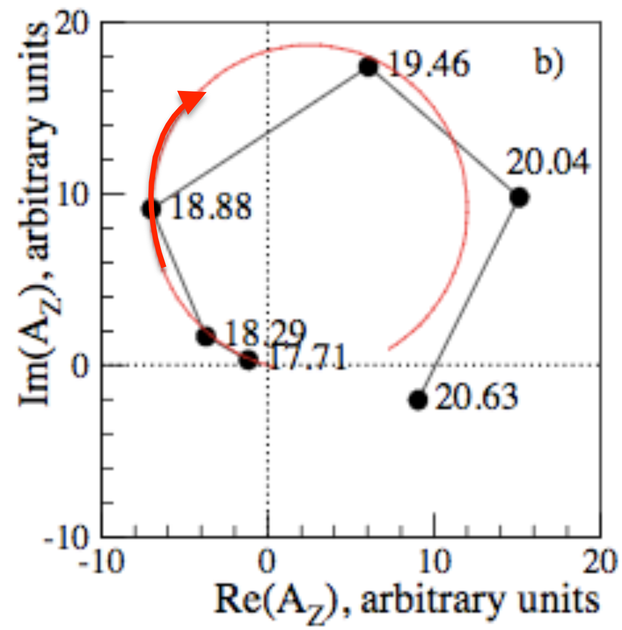
phase motion reported by LHCb

Model-ind. Argand plot



BW-like counter-clockwise phase motion is clearly established

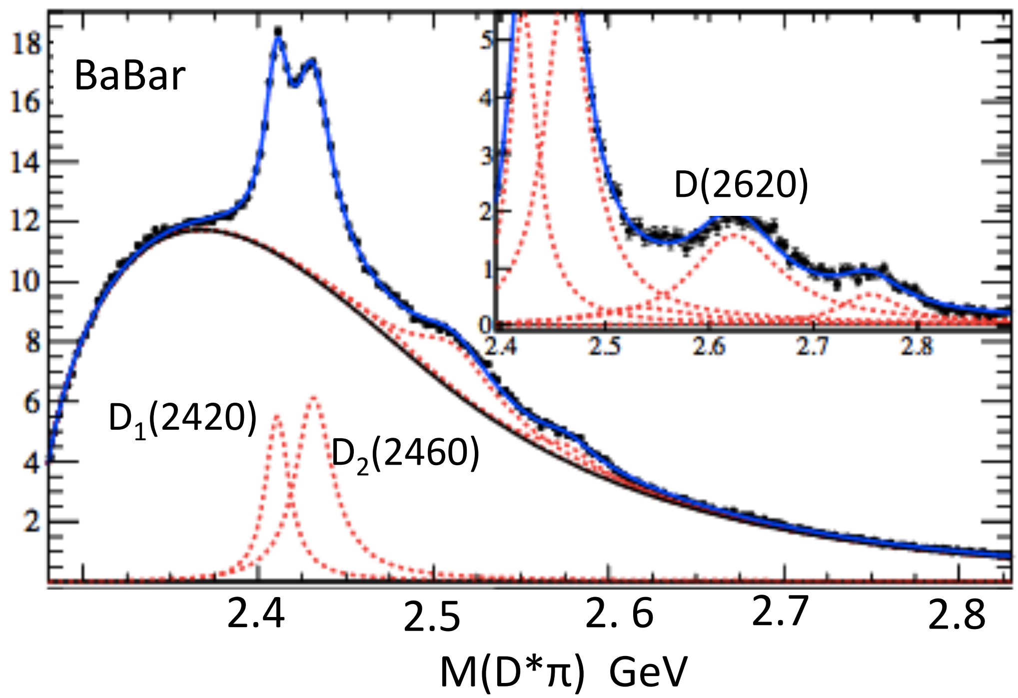
rescattering process predicts clockwise phase motion

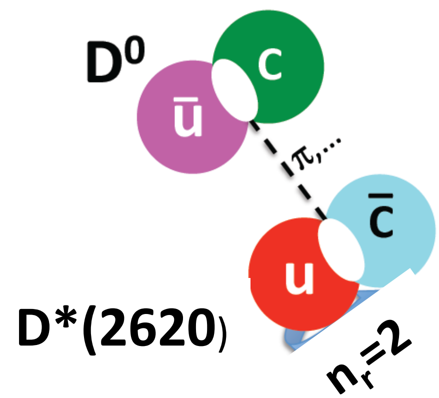


Pakhlov &Uglov, PLB 183 (2015)

D*(2S), radially excited D*?

BaBar: Phys. Rev. D82, 111101





binding energy: $m_D + M_{D^*(2620)} - M_{Z(4430)} = 20 \pm 30$ MeV

Z(4430)→πψ' favored over πJ/ψ

$$Bf(B^0 \to K^+ Z_{4430}^-) \times Bf(Z_{4430}^- \to \pi^- \psi') = (4.4 \pm 1.7) \times 10^{-5}$$

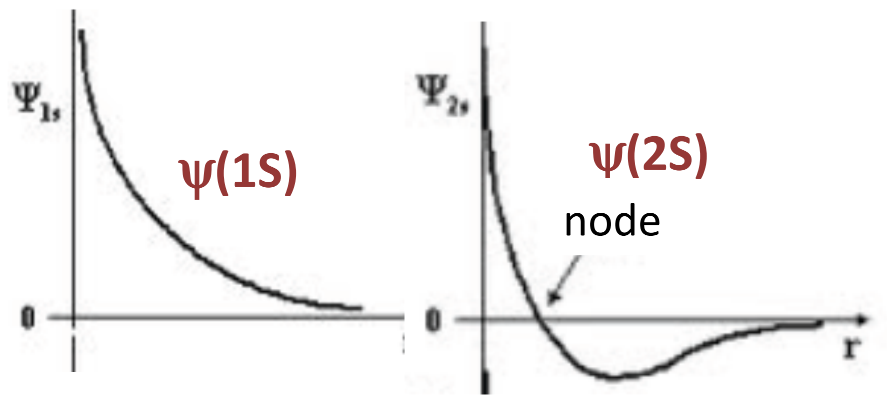
$$Bf(B^0 \to K^+ Z_{4430}^-) \times Bf(Z_{4430}^- \to \pi^- J/\psi) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}$$

$$\boxed{\frac{Bf(Z_{4430}^- \to \pi^- \psi')}{Bf(Z_{4430}^- \to \pi^- J/\psi)} \approx 8}$$

Z(4430) = radial excitation of Z_c(3900)?

$$\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$$

Radial Wave Functions

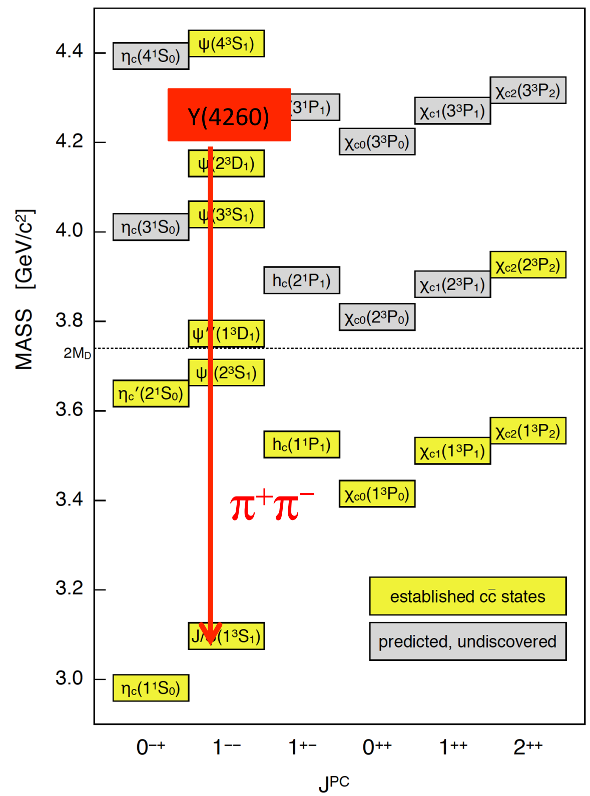


The $c\bar{c}$ part of the wave function of the Z(4430) likely has a node ➔ a radial excitation of the ground state: the Z_c(3900)?

$M(Z_c(4430))-M(Z_c(3900)) = 589 \pm 30$ MeV

$M(\psi') - M(J/\psi) = 589$ MeV

The Y(4260)

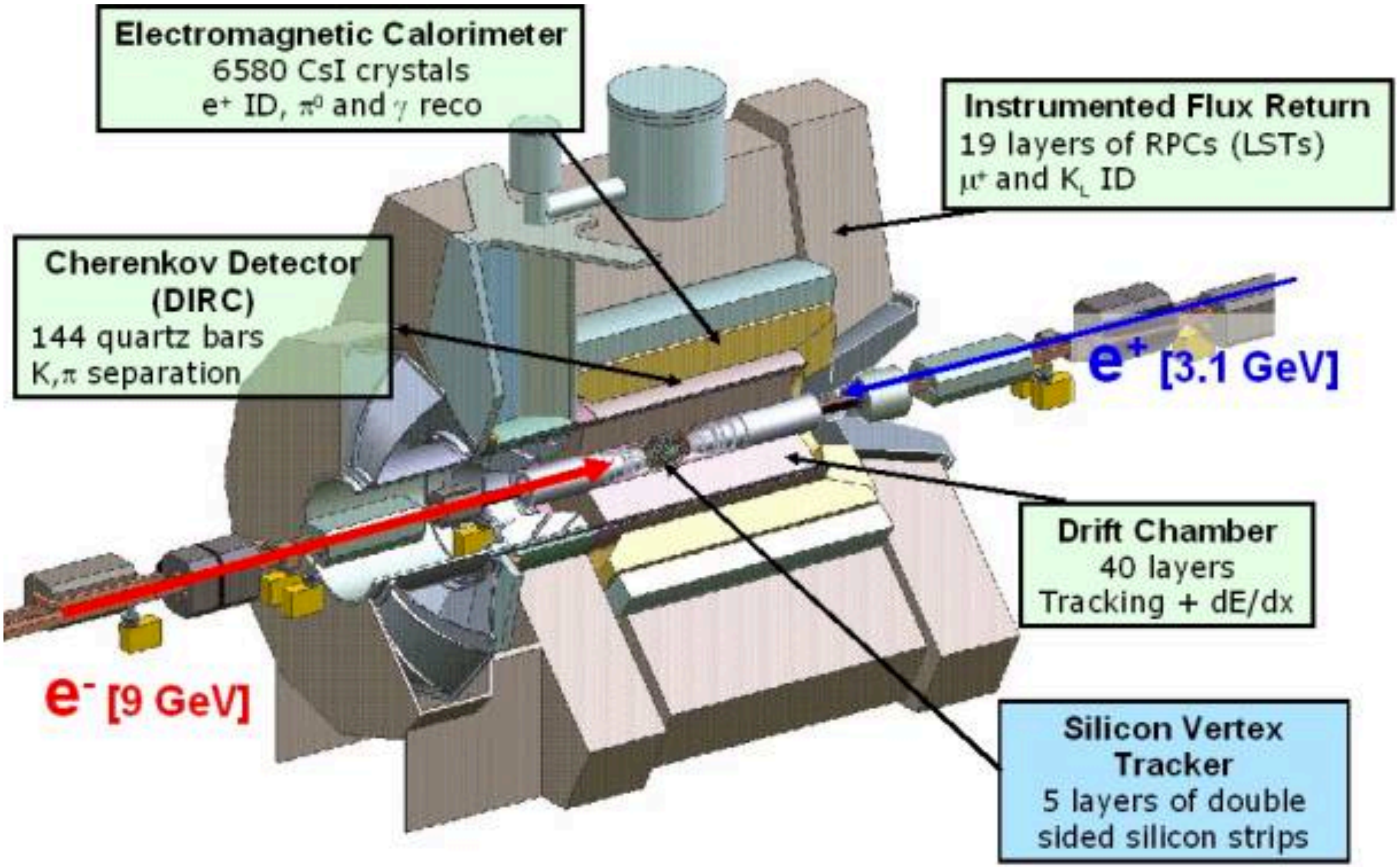


MASS [GeV/c²]
4.4
4.2
4.0
3.8
2MD
3.6
3.4
3.2
3.0
ηc(4¹S₀)
ψ(4³S₁)
Y(4260)
3¹P₁)
χc2(3³P₂)
χc1(3³P₁)
χc0(3³P₀)
ψ(2³D₁)
ψ(3³S₁)
ηc(3¹S₀)
hc(2¹P₁)
χc2(2³P₂)
χc1(2³P₁)
χc0(2³P₀)
ψ(1³D₁)
ψ(2³S₁)
ηc′(2¹S₀)
hc(1¹P₁)
χc2(1³P₂)
χc1(1³P₁)
χc0(1³P₀)
π⁺π⁻
established cc̄ states
predicted, undiscovered
J/ψ(1³S₁)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

The Y(4260)

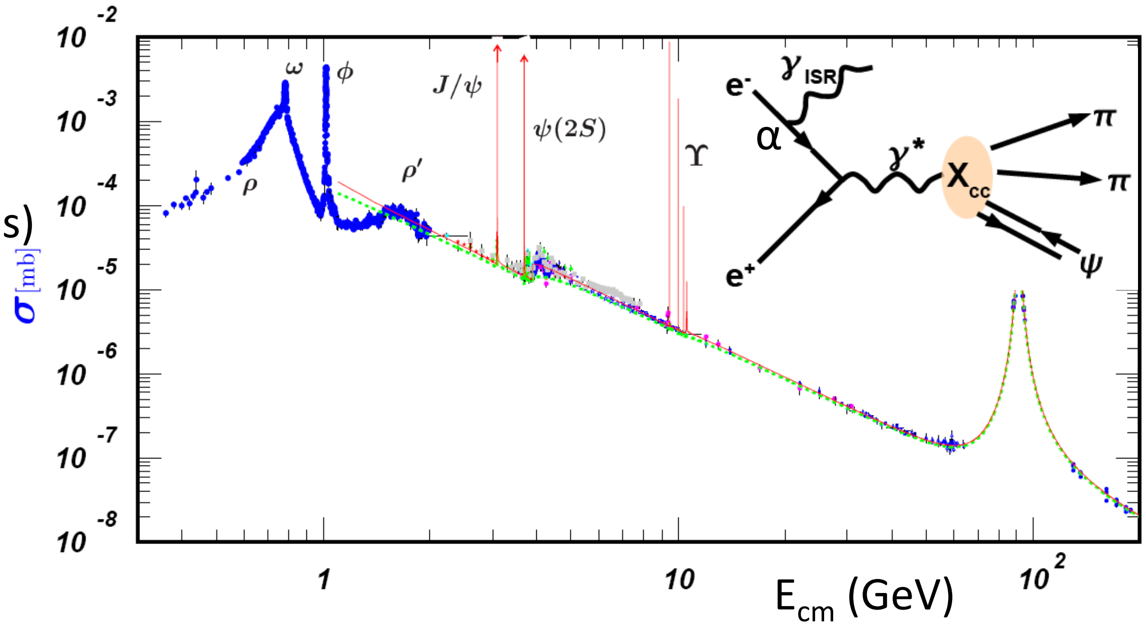
--discovered at Babar--

BaBar detector

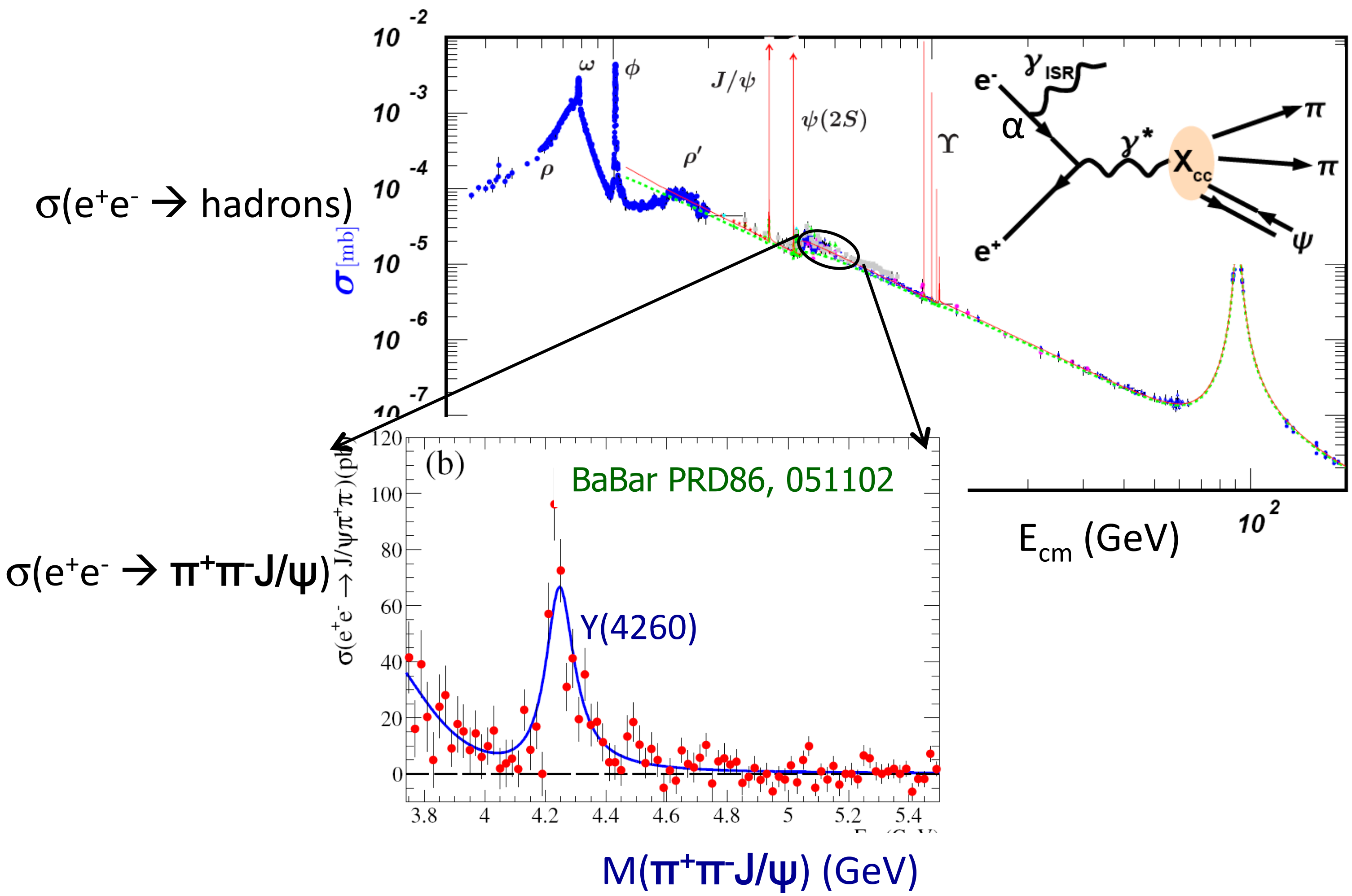


found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$

$\sigma(e^+e^- \rightarrow$ hadrons)



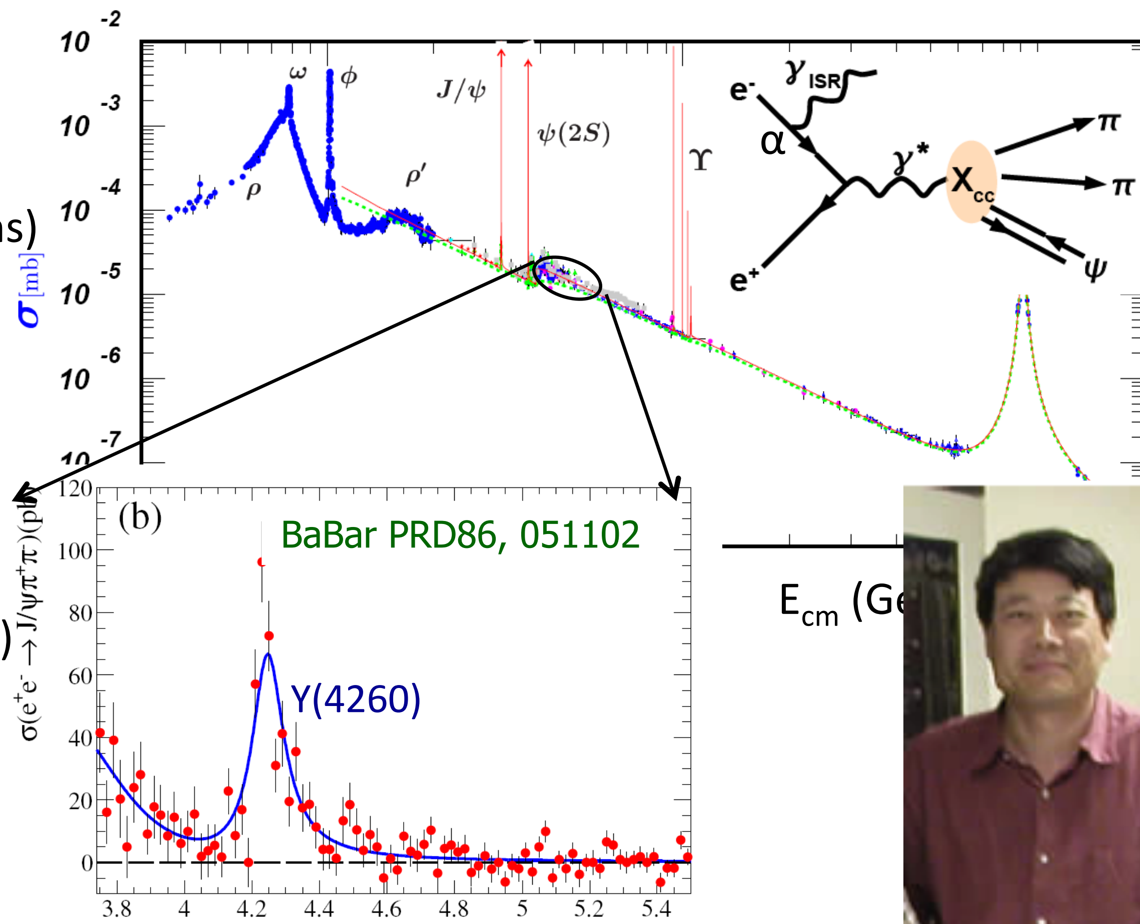
found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$



found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$

σ(e⁺e⁻ → hadrons)

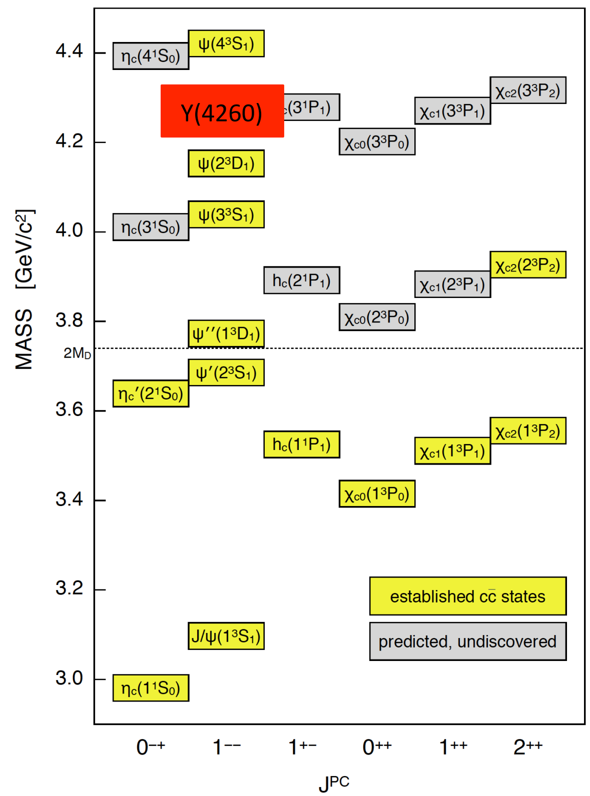
σ(e⁺e⁻ → π⁺π⁻J/ψ)

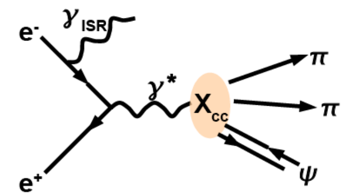


M(π⁺π⁻J/ψ) (GeV)

Xinchou Lou Shuwei Ye

What is the Y(4260)?

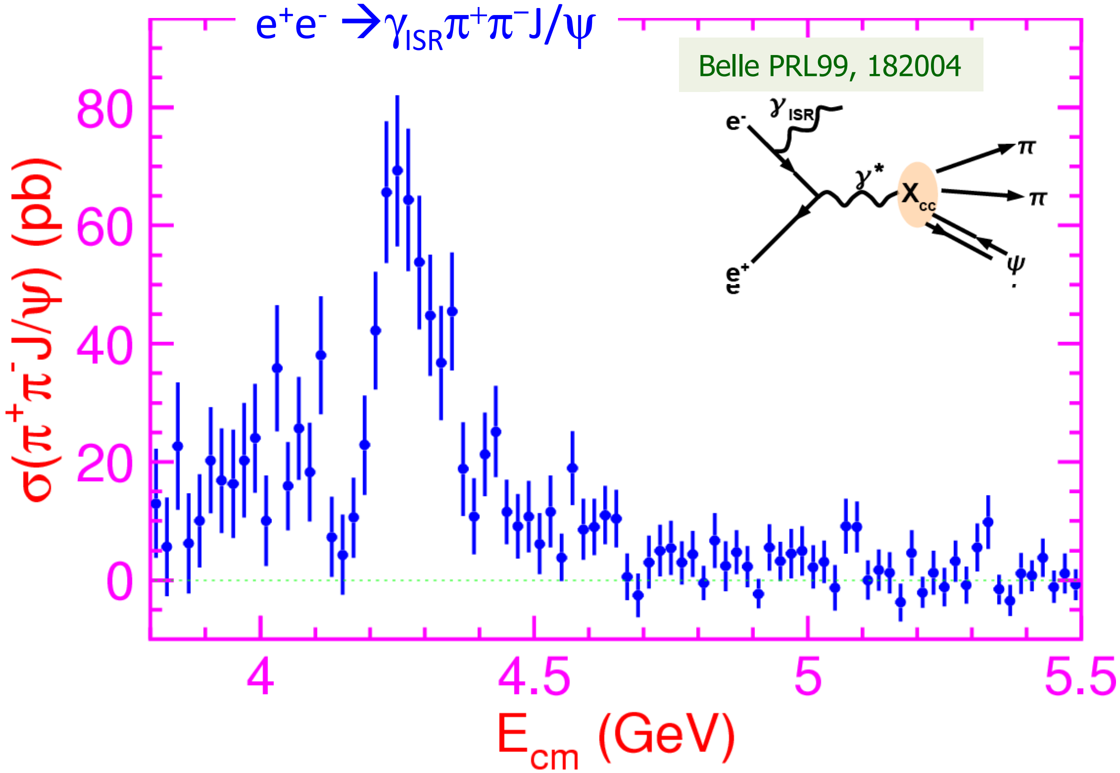




prod. mode ensures $J^{PC} = 1^{--}$

all the $J^{PC} = 1^{--}$ charmonium states below M=4500 MeV have already been assigned

Y(4260) → $\pi^+\pi^- J/\psi$ confirmed by Belle

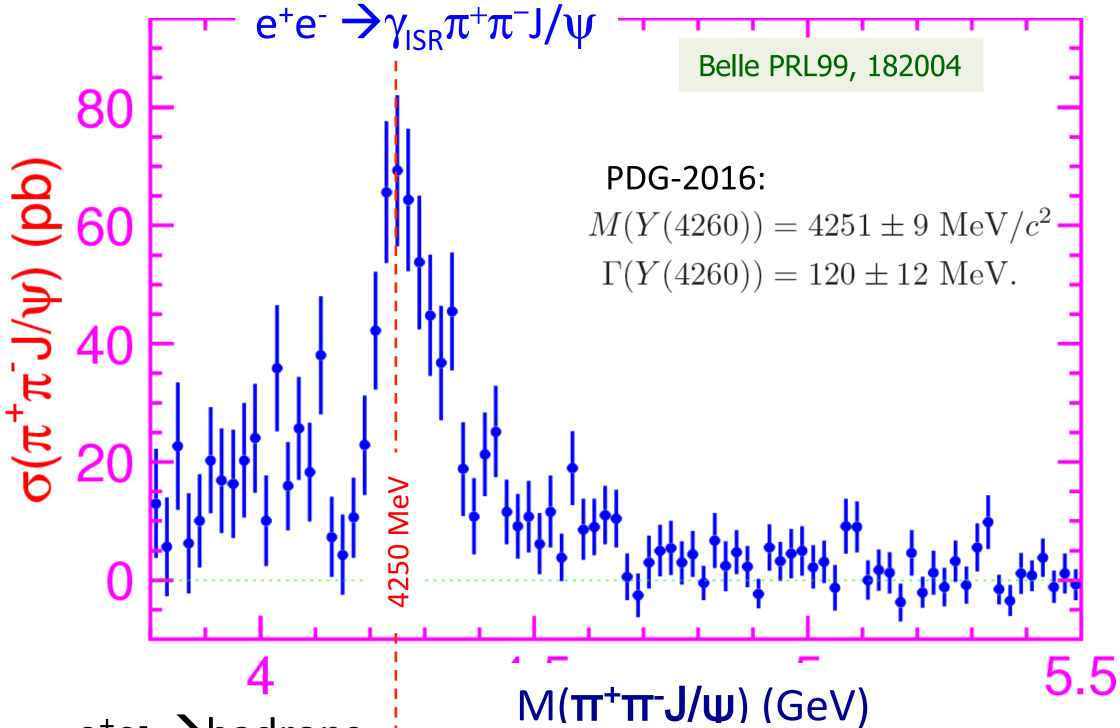


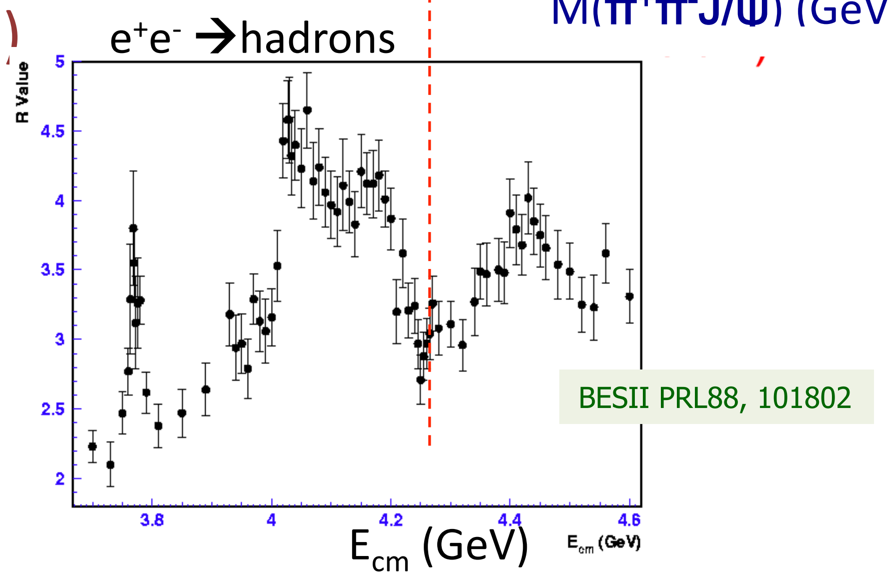
$Y(4260) \rightarrow \pi^+\pi^- J/\psi$ confirmed by Belle

no sign of $Y(4260) \rightarrow D^{(*)}\bar{D}^{(*)}$

$Y(4260)$ peak in $\sigma(\pi^+\pi^- J/\psi)$ occurs at a dip in $\sigma(D^{(*)}\bar{D}^{(*)})$

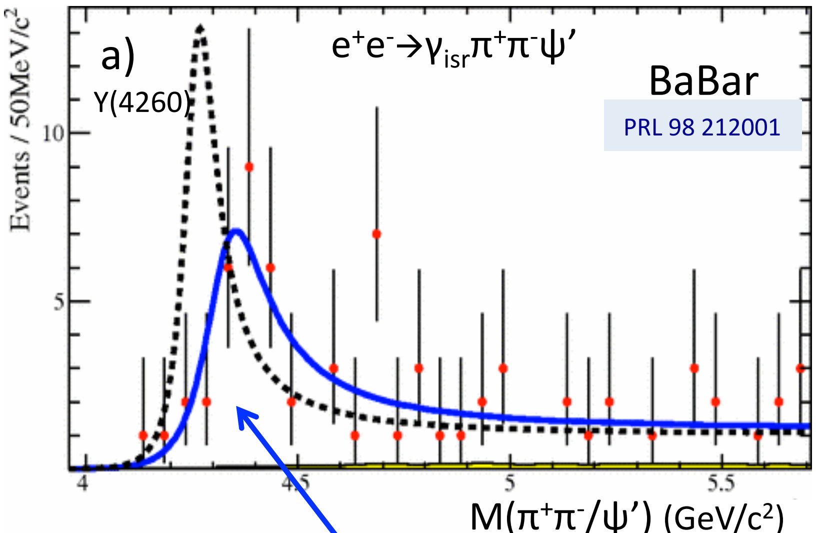
$\Gamma(\pi^+\pi^- J/\psi)$ is large, but should be OZI suppressed if $c\bar{c}$



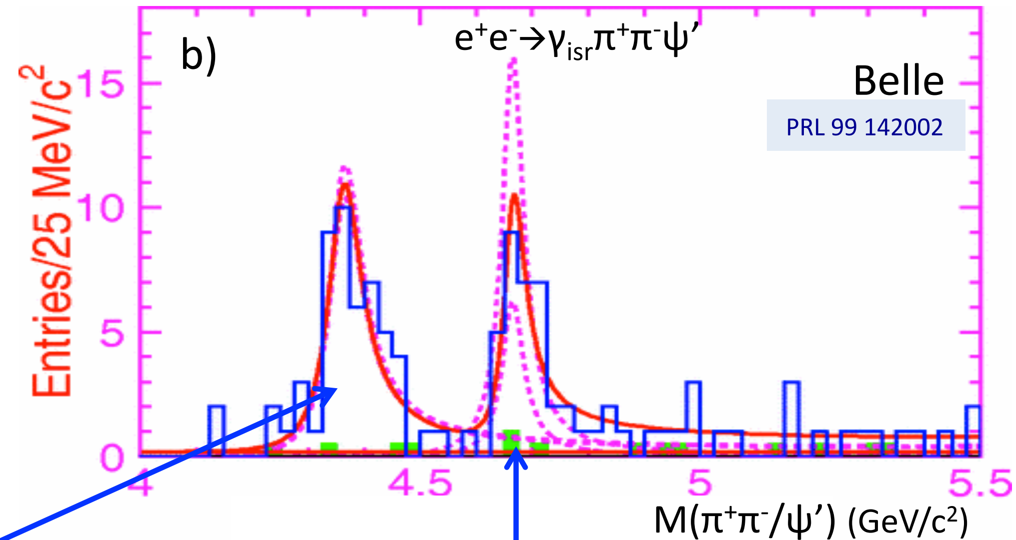


other resonances in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\psi'$

BaBar: another one in $\pi^+\pi^-\psi'$ (not the Y(4260))



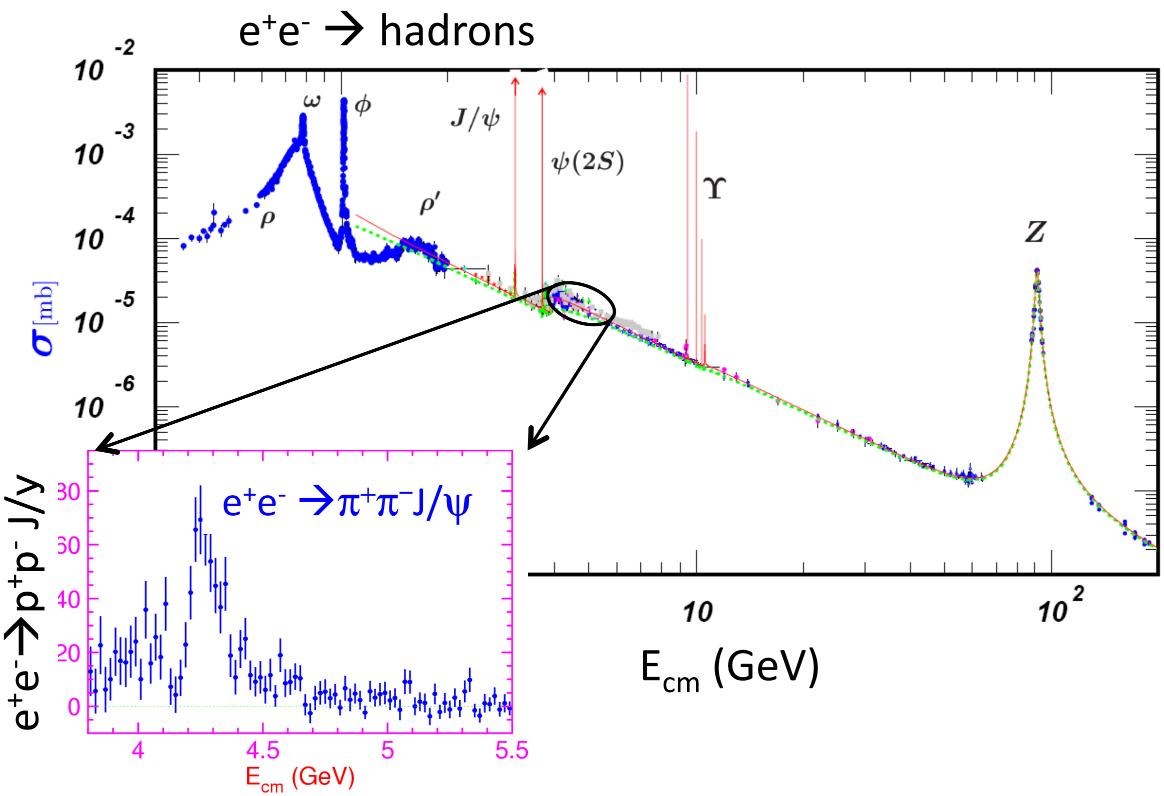
Belle: confirms the Y(4360) & finds another @ 4660



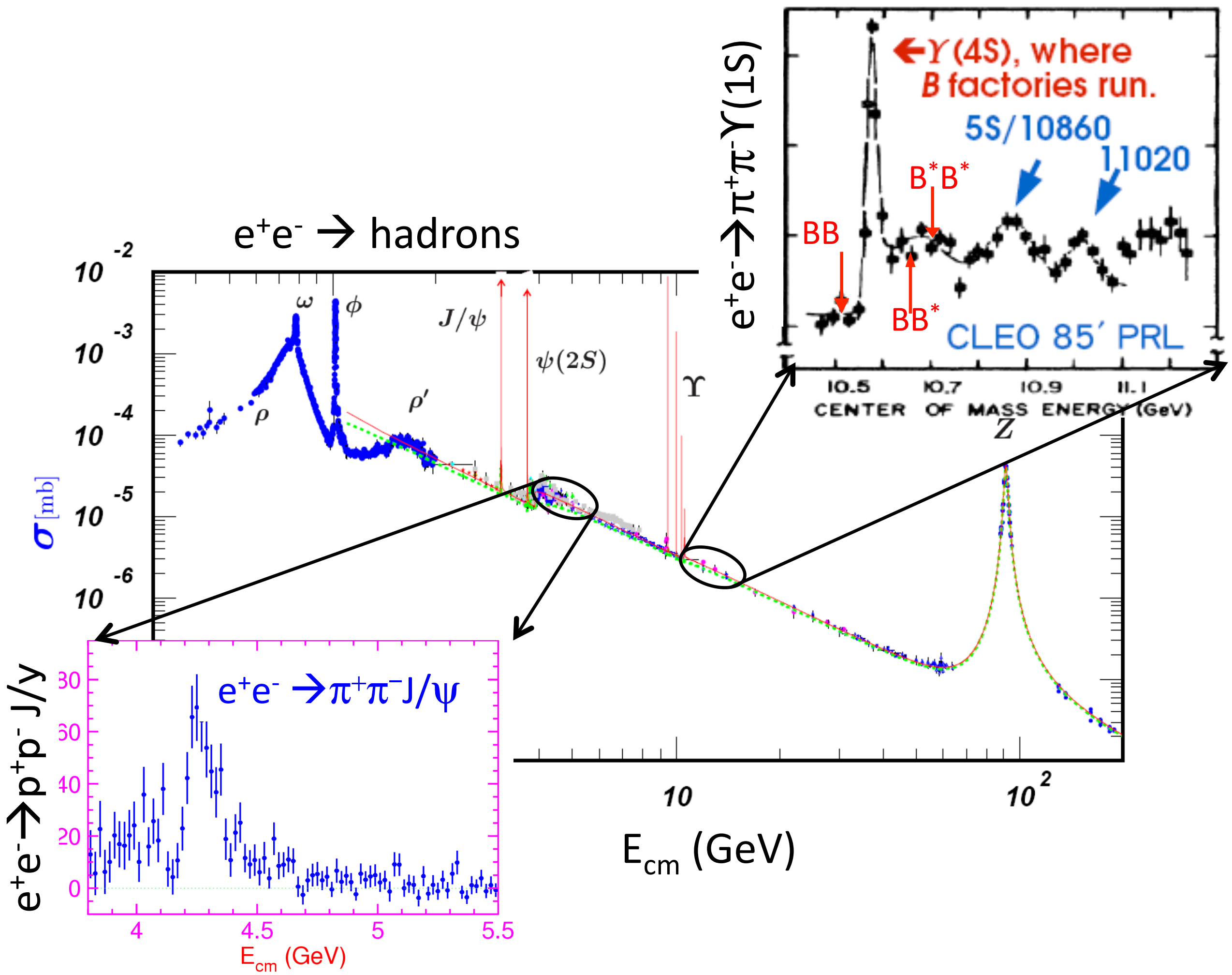
PDG-2016:
$$M(Y(4360)) = 4346 \pm 6 \text{ MeV}/c^2$$
$$\Gamma(Y(4360)) = 102 \pm 12 \text{ MeV}.$$

PDG-2016:
$$M(Y(4660)) = 4643 \pm 9 \text{ MeV}/c^2$$
$$\Gamma(Y(4660)) = 72 \pm 11 \text{ MeV}.$$

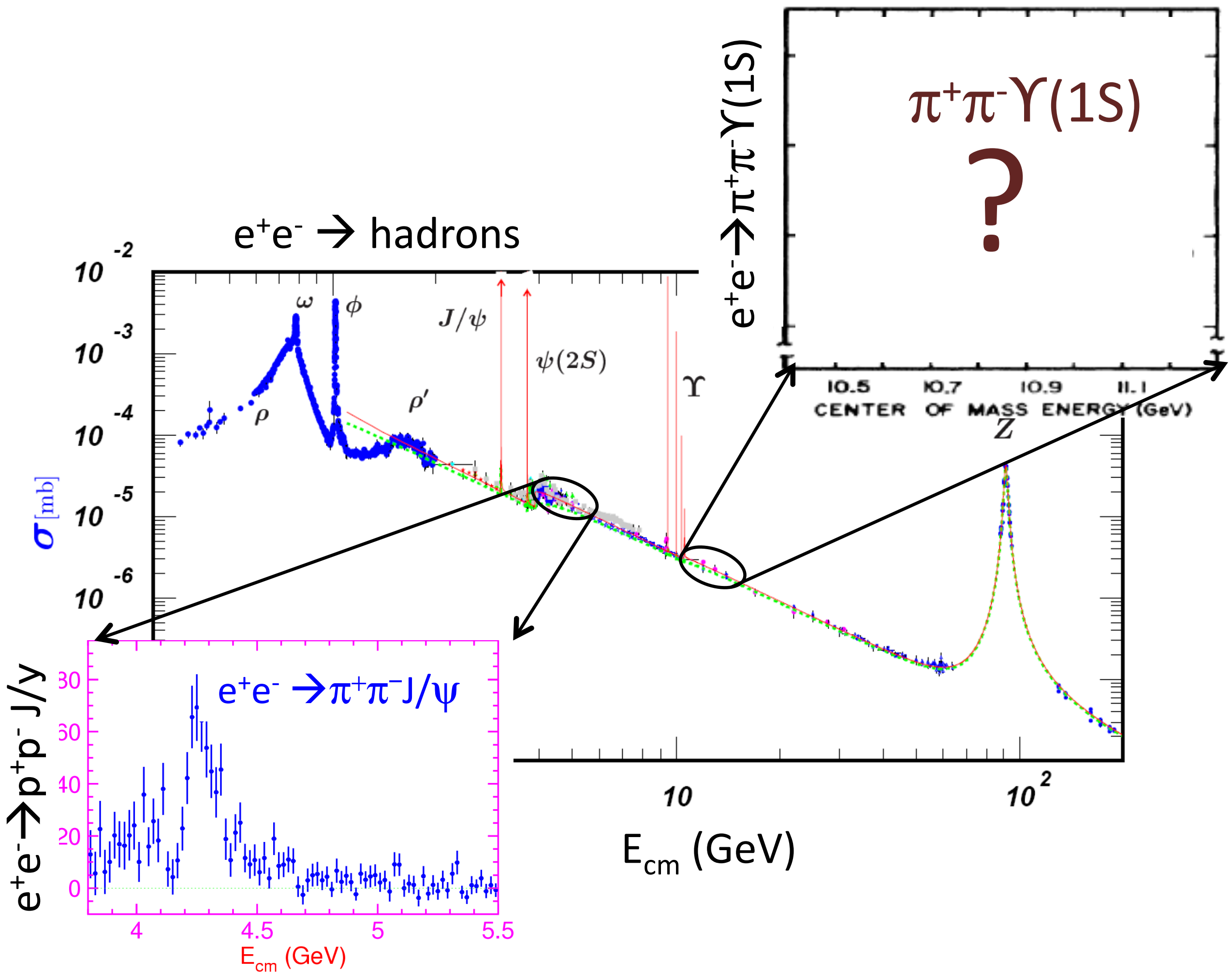
Is there a b-quark version of Y(4260)?



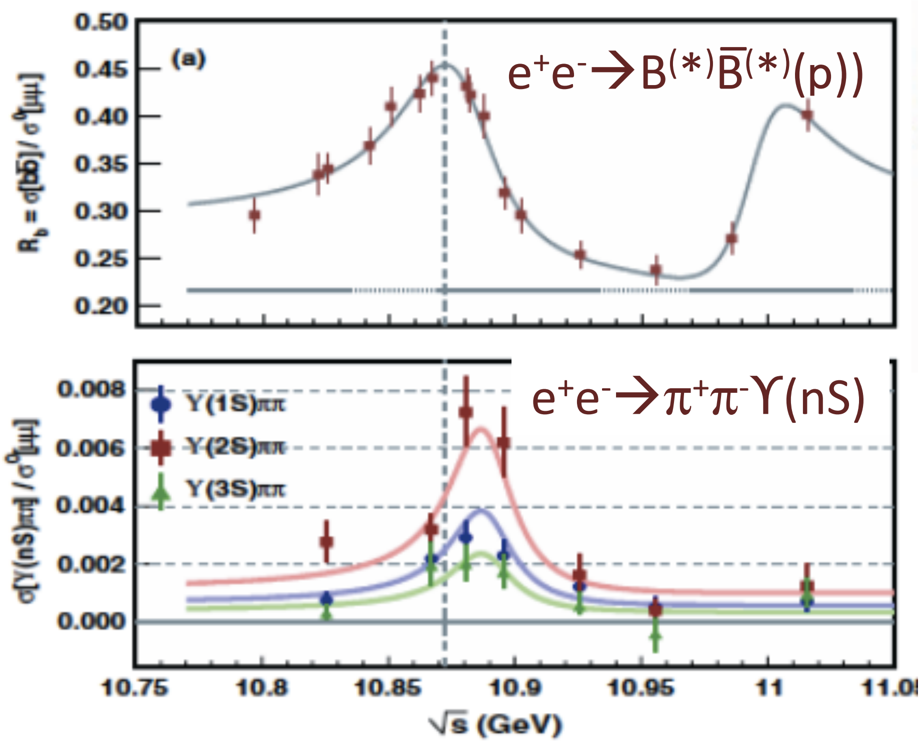
Is there a b-quark version of Y(4260)?



Is there a b-quark version of Y(4260)?



Yes



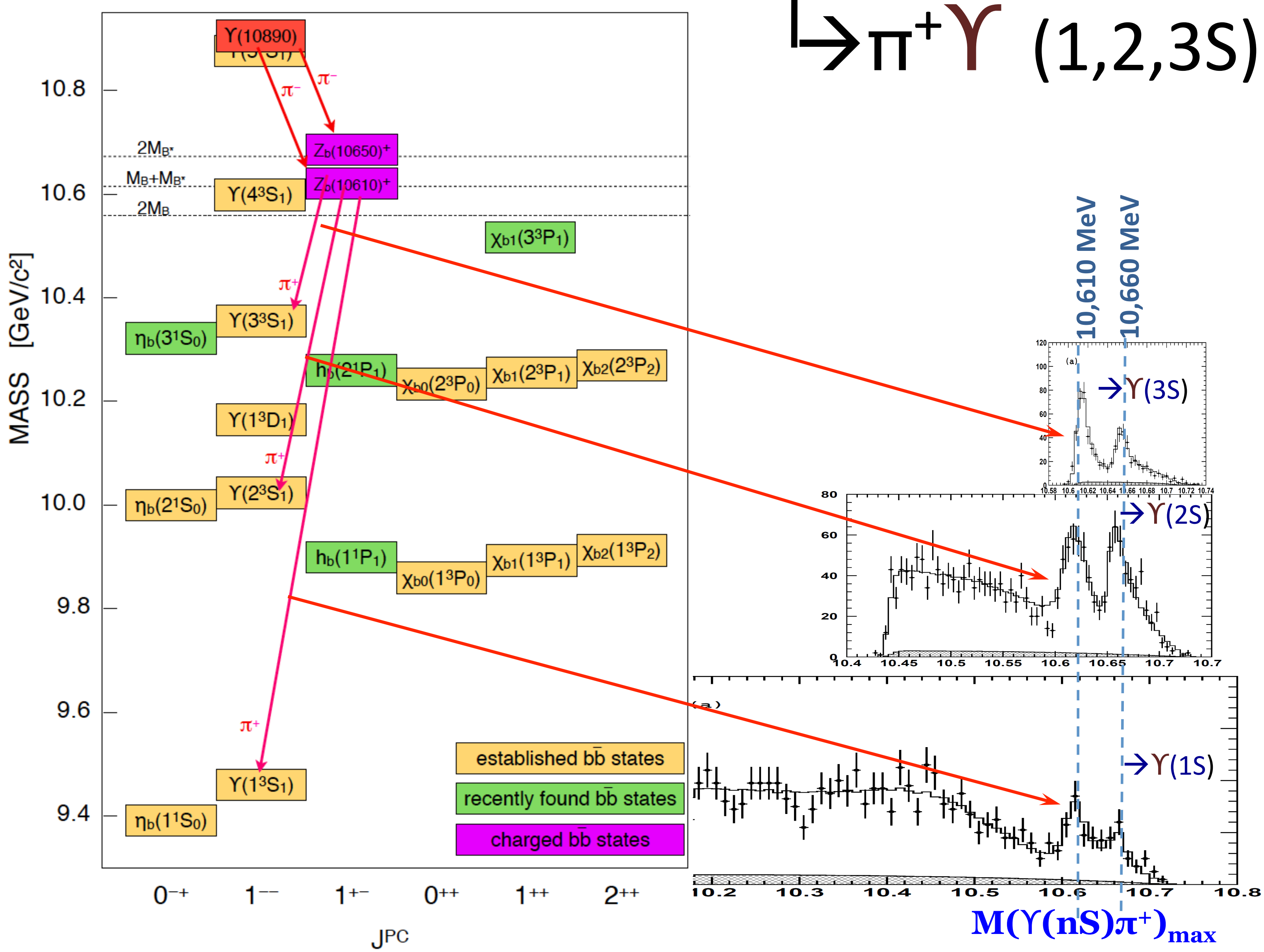
PRD82,091106(2010)

$\pi^+\pi^-\Upsilon(nS)$ rates are 100's of times larger than bottomonium expectations

"$\Upsilon(5S)$" $\rightarrow \pi^- Z_{b1,2}^{+}$

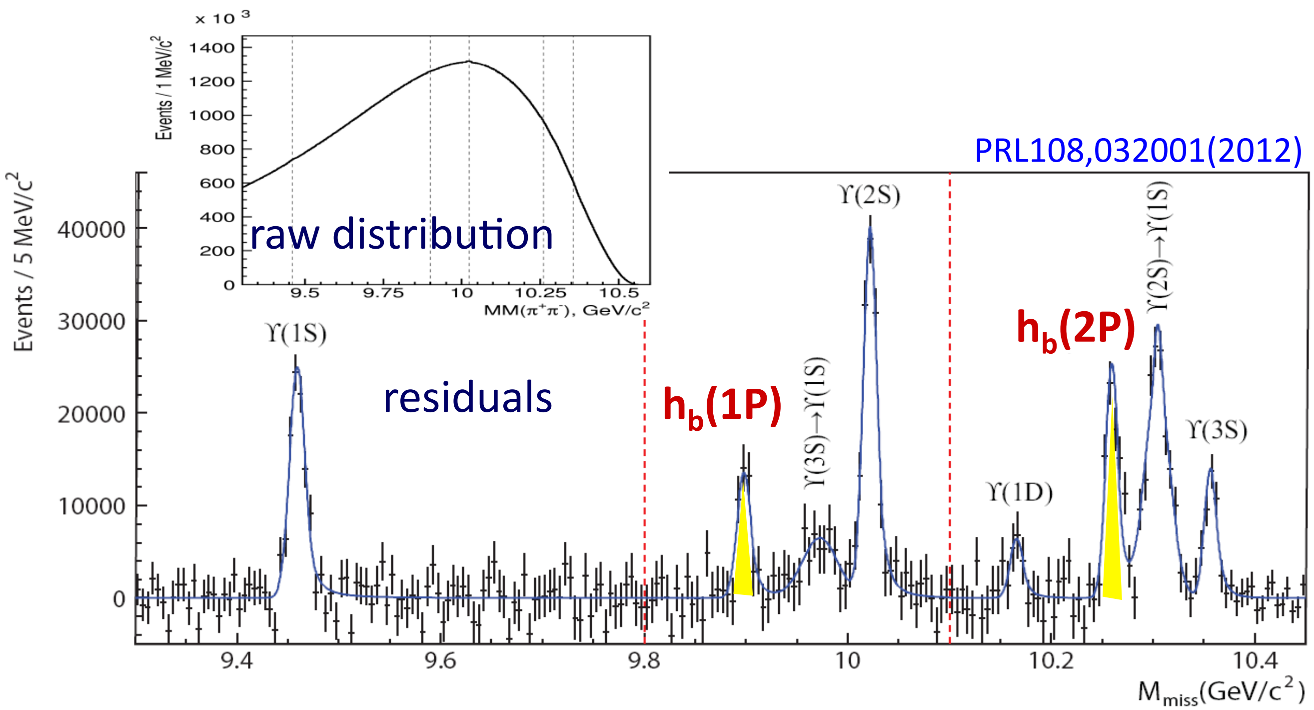
$\quad \rightarrow \pi^+ \Upsilon\ (1,2,3S)$

Belle PRL 108, 122001 (2012)
121.4 fb^{-1}

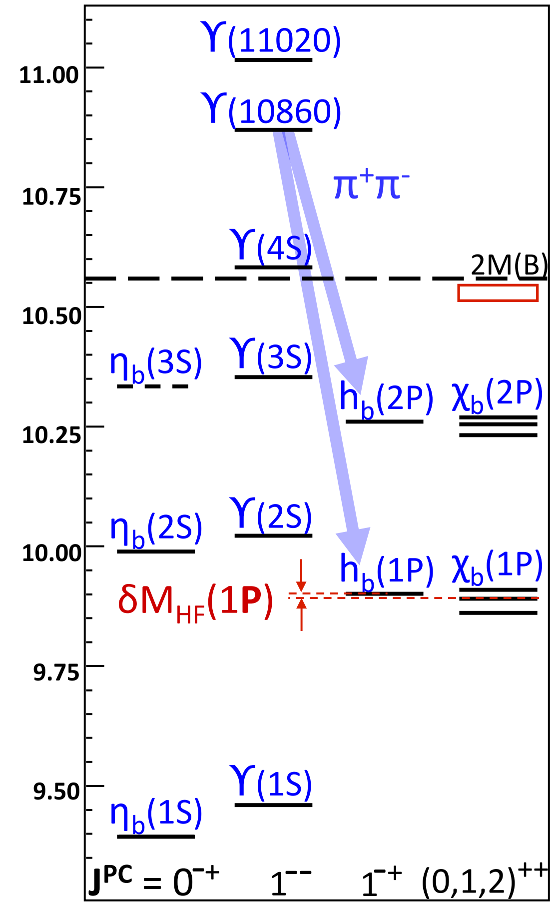


Observation of $h_b(1P,2P)$ at Belle

$e^+e^- \rightarrow \Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$ ← reconstructed, use $\mathbf{M_{miss}(\pi^+\pi^-)}$ $=\sqrt{(p_{e+e-} - p_{\pi+\pi-})^2}$



Belle arxiv:1205.6351



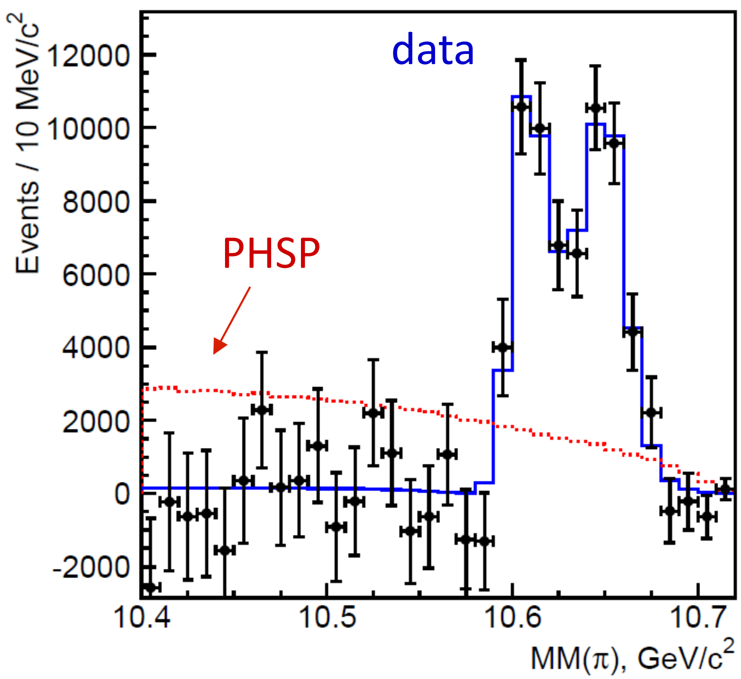
$\delta M_{HF}(\mathbf{1P}) = +0.8 \pm 1.1$ MeV
$\delta M_{HF}(\mathbf{2P}) = +0.5 \pm 1.2$ MeV

consistent with zero, as expected

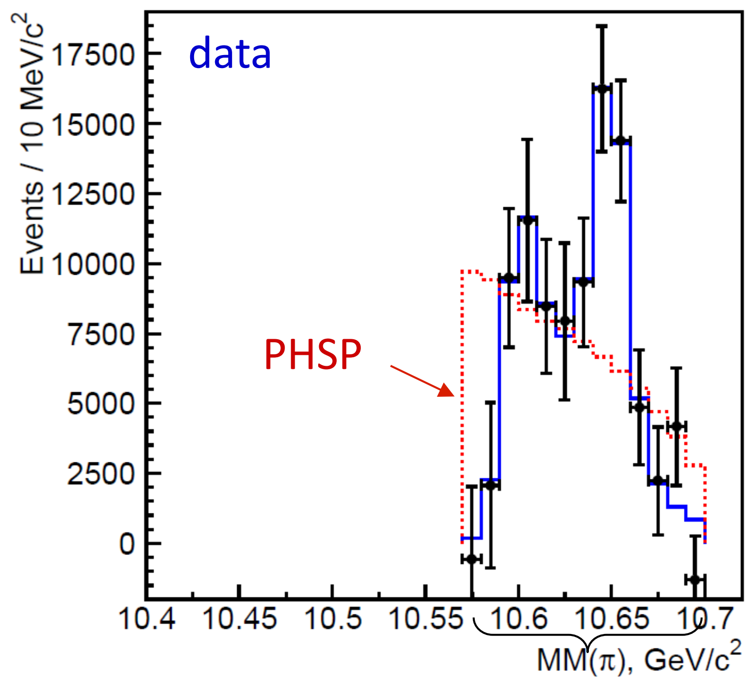
Large $h_b(1,2P)$ production rates

look at $M(\pi h_b(1P))$ and $M(\pi h_b(2P))$

two peaks



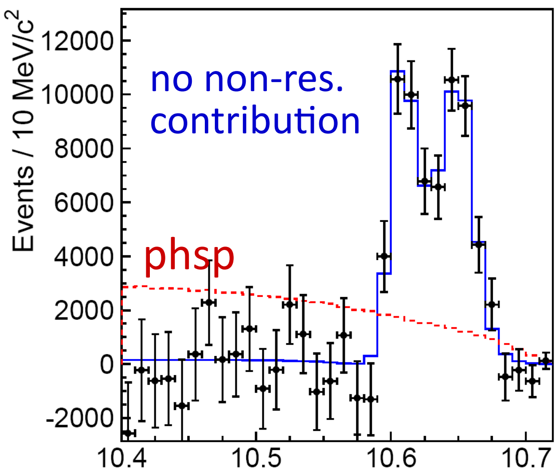
$M(\pi h_b(1P))$



$M(\pi h_b(2P))$

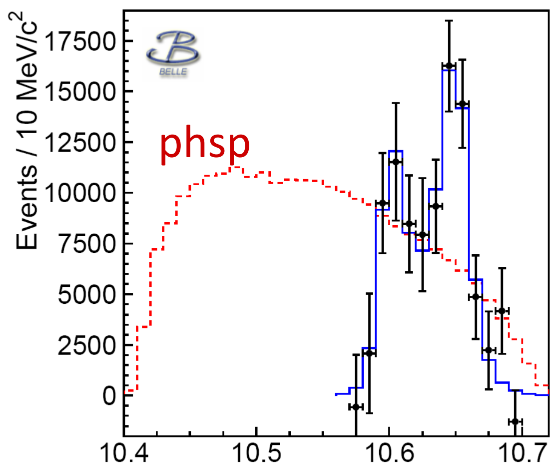
Resonant structure of $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$

$\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$



M[$h_b(1P)\pi$]$_{max}$

$\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$



M[$h_b(2P)\ \pi$]$_{max}$

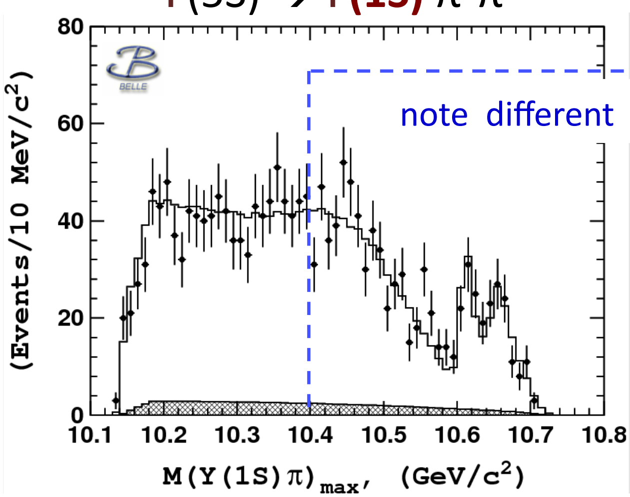
Two peaks are observed in all modes!

Belle: PRL108, 232001 (2012)

$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states

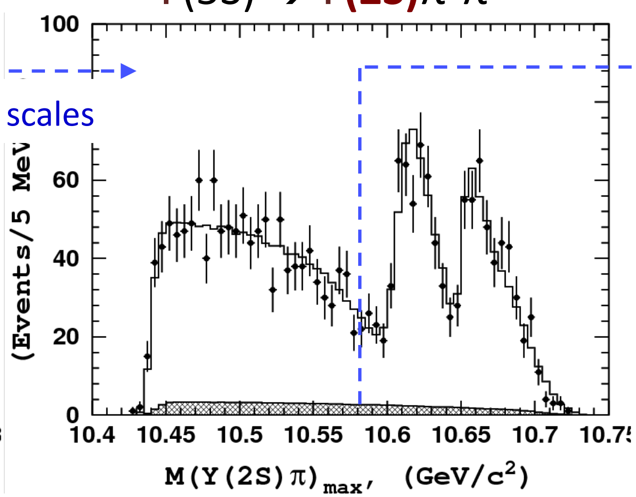
Dalitz plot analysis

$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$

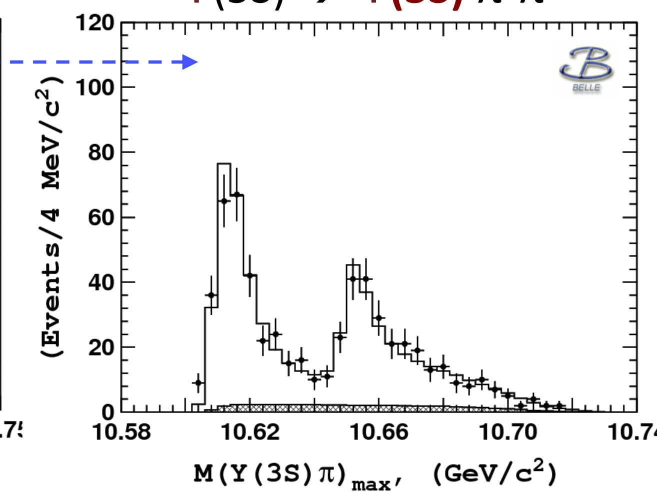


note different scales

$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$



$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$



Summary of Z_b parameters

Average over 5 channels

$M_1 = 10607.2 \pm 2.0$ MeV

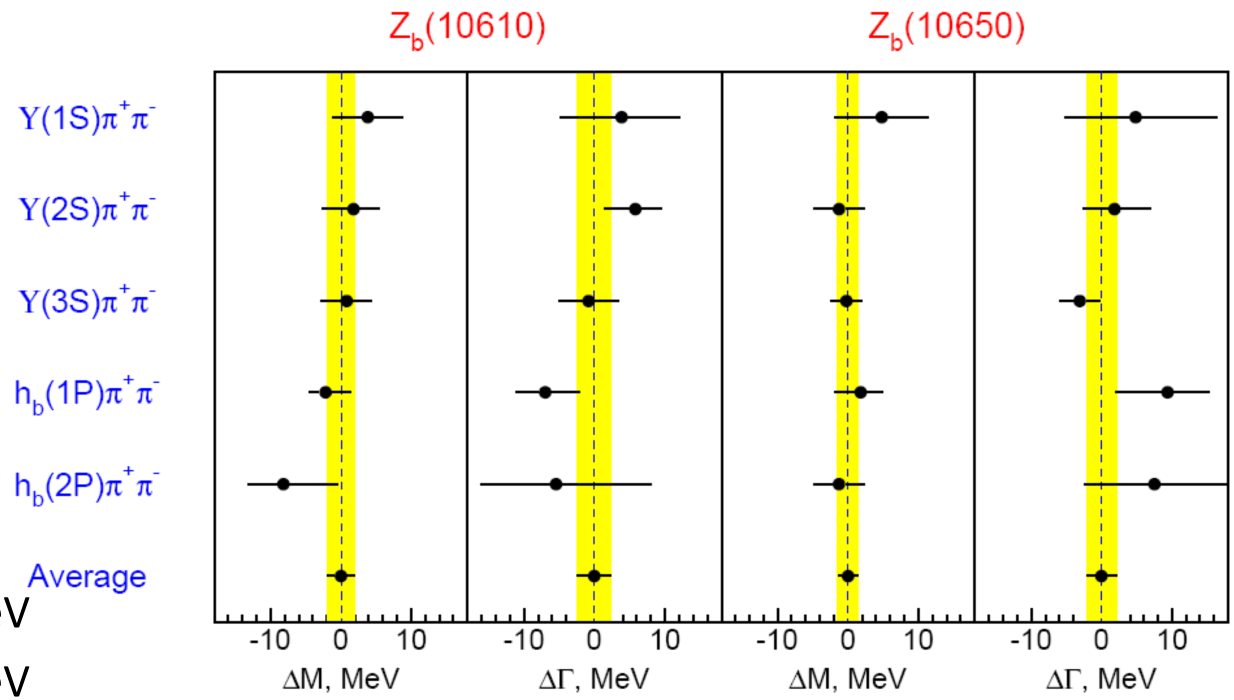
$\Gamma_1 = 18.4 \pm 2.4$ MeV

$M_2 = 10652.2 \pm 1.5$ MeV

$\Gamma_2 = 11.5 \pm 2.2$ MeV

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

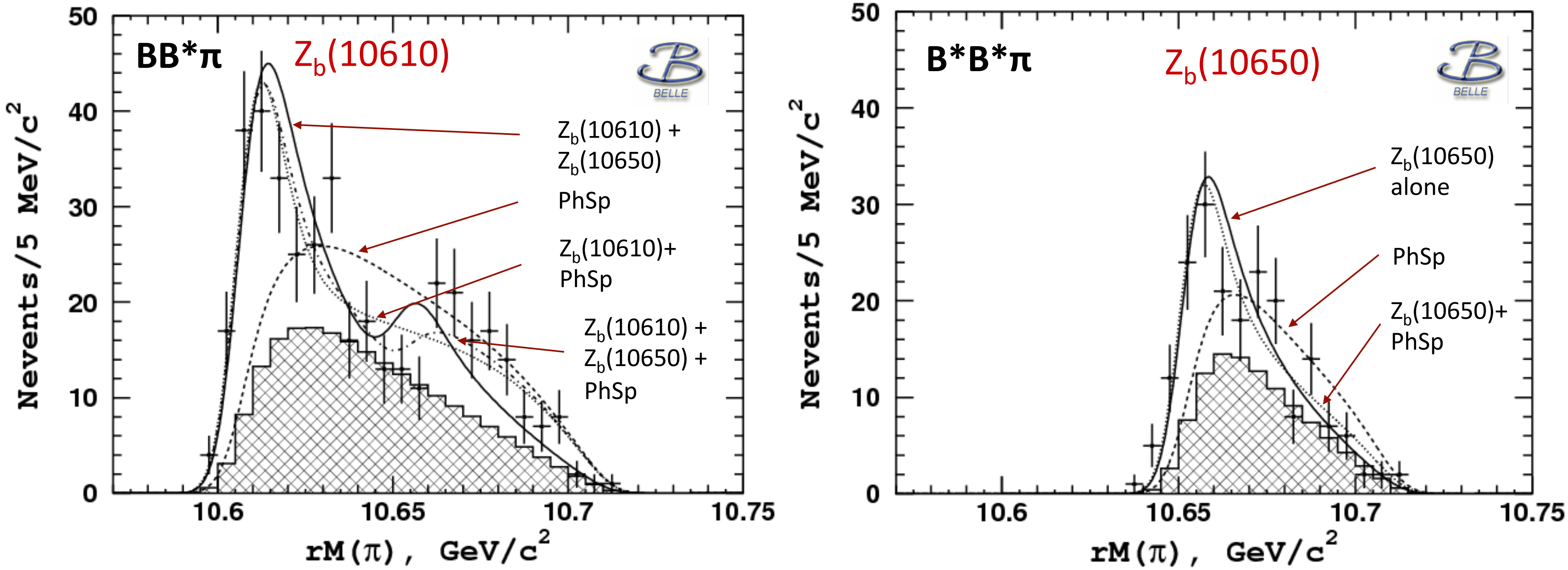
$M_2 - 2M_{B*} = +1.8 \pm 1.7$ MeV



$Z_b(10610)$ yield ~ $Z_b(10650)$ yield in every channel

Relative phases: 0^o for $\Upsilon\pi\pi$ and 180^o for $h_b\pi\pi$

$\Upsilon(5S)\rightarrow B^*B^{(*)}\pi$: Signal Region



points – right sign Bπ combinations (data);

lines – fit to data with various models (times PHSP, convolved with resolution function = Gaussian with σ=6MeV).

hatched histogram – background component

B*B*π signal is well fit to just Z_b(10650) signal alone

BB*π data fits (almost) equally well to a sum of Z_b(10610) and Z_b(10650) or to a sum of Z_b(10610) and non-resonant.

$\Upsilon(5S)\to B^*B^{(*)}\pi$: Results

Branching fractions of $\Upsilon(10680)$ decays (including neutral modes):
$BB\pi$ < 0.60% (90%CL)
$BB^*\pi$ = 4.25 ± 0.44 ± 0.69%
$B^*B^*\pi$ = 2.12 ± 0.29 ± 0.36%

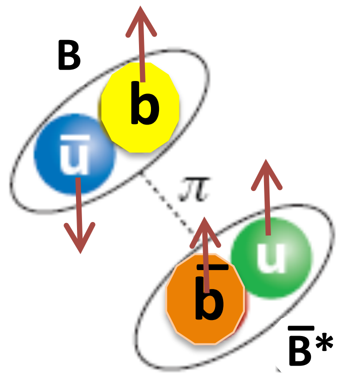
Assuming Z_b decays are saturated by the already observed $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and B(*)B* channels, one can calculate complete table of relative branching fractions:

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

B(*)B* channels dominate Z_b decays !

B-$\bar{B}$* & B*-$\bar{B}$* molecules??

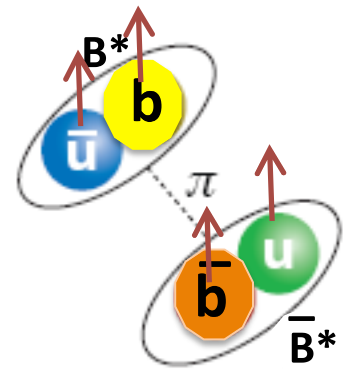
$Z_b(106010)^{\pm}$



B-$\bar{B}$* "molecule"

$M_{Z_b(106010)} - (M_B + M_{B^*}) = +3.6 \pm 1.8$ MeV

$Z_b(106050)^{\pm}$



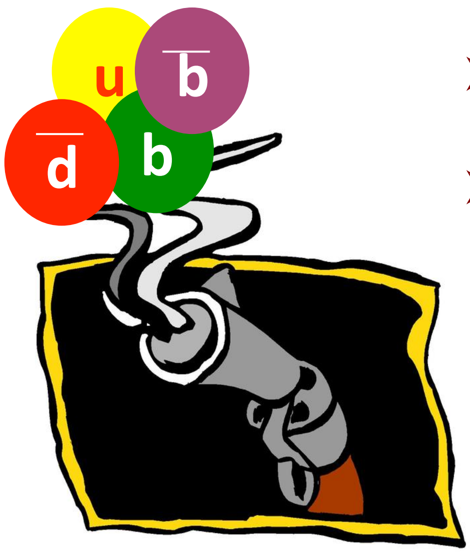
B*-$\bar{B}$* "molecule"

$M_{Z_b(106010)} - 2M_{B^*} = +3.1 \pm 1.8$ MeV

Slightly unbound threshold resonances??

Amplitude analyses: both states have $J^P = 1^+$

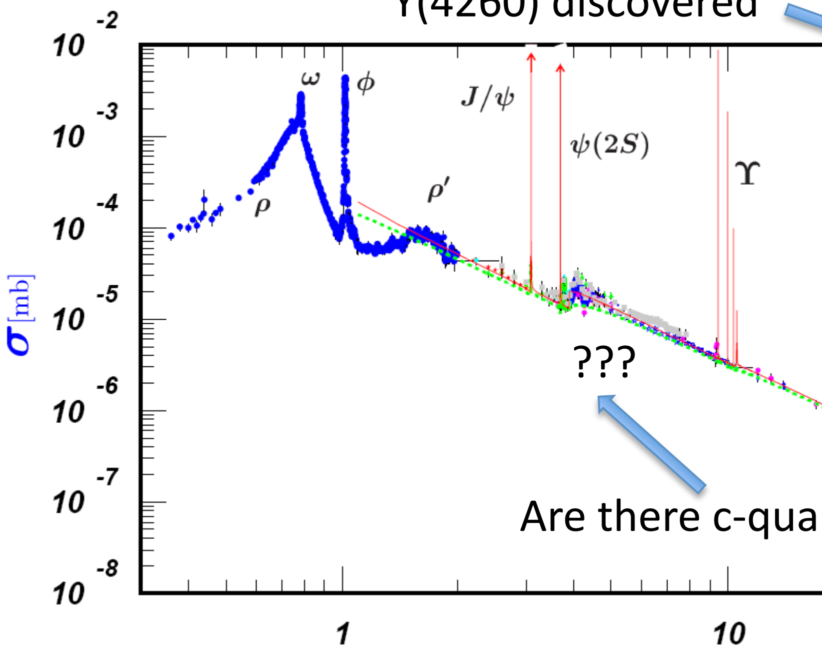
Z_{b1} & Z_{b2}, "smoking guns" for non-$q\bar{q}$ mesons



- decays to $\Upsilon(nS)$ & $h_b(nP)$ ➔ must contain $b\bar{b}$ pair
- electrically charged ➔ must contain $u\bar{d}$ pair

Are there c-quark versions of Z_b's

Y(4260) discovered



Is there a b-quark equivalent?

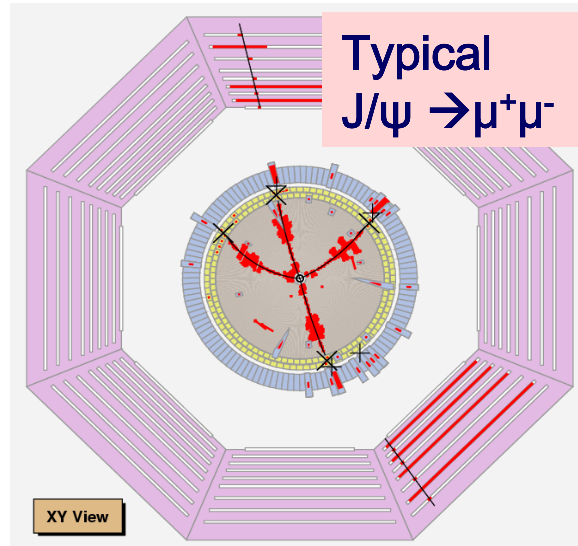
Yes, & it decays to Z_b states

Are there c-quark versions of Z_b's?

run BEPCII/BESIII as a Y(4260) factory

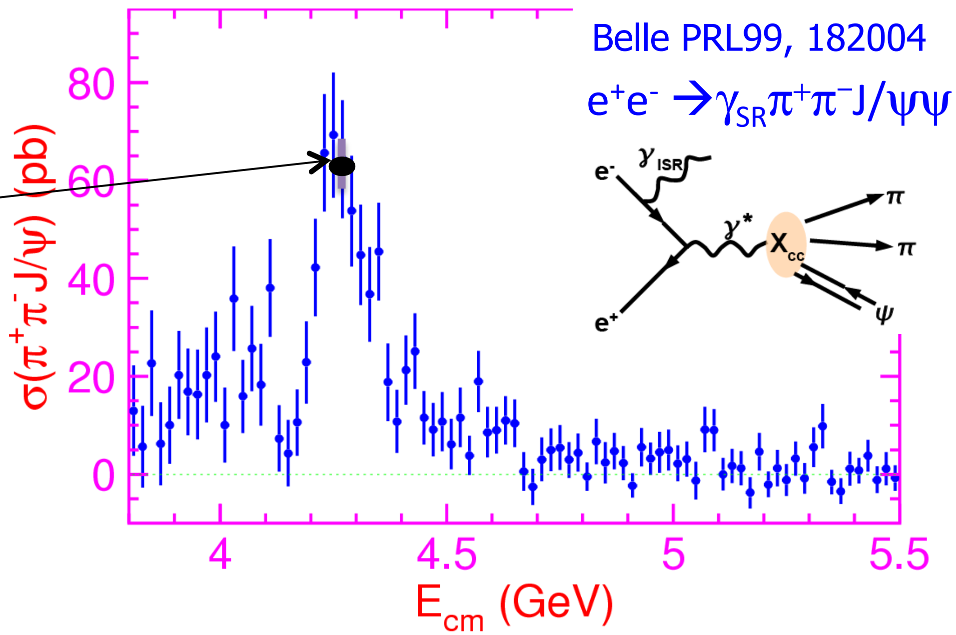
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$

$@E_{cm}$=4260 MeV

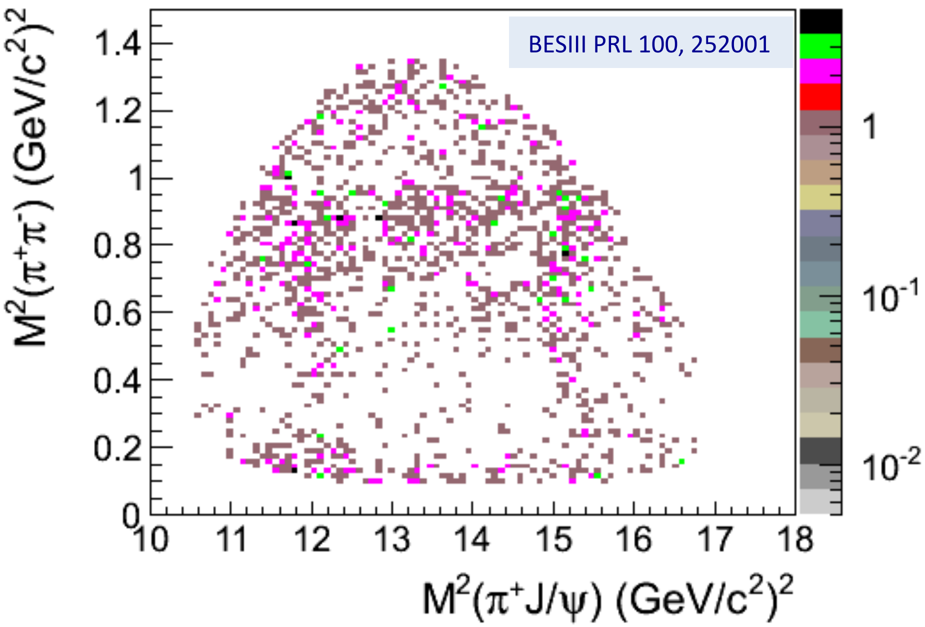


BESIII: PRL 110, 252001 (2013)

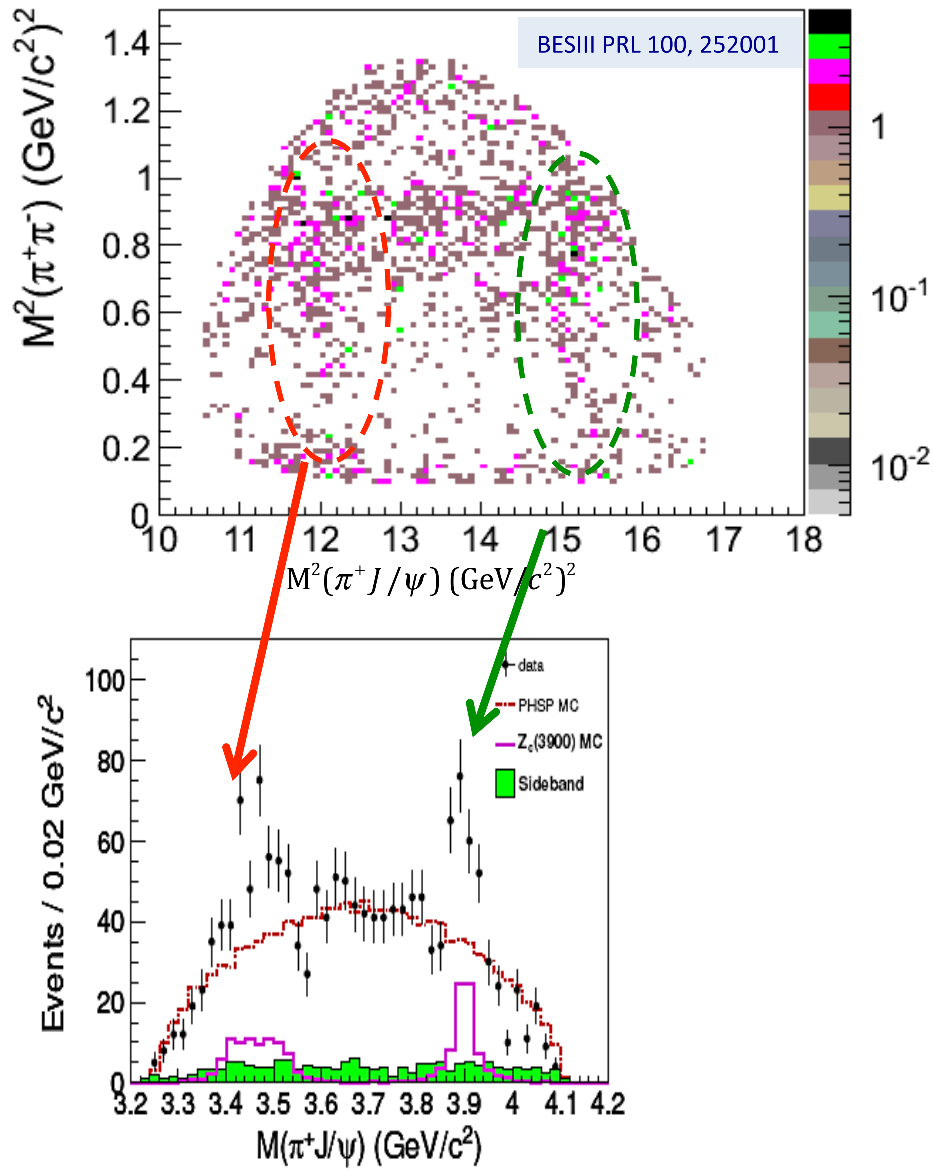
$\sigma\ (e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb



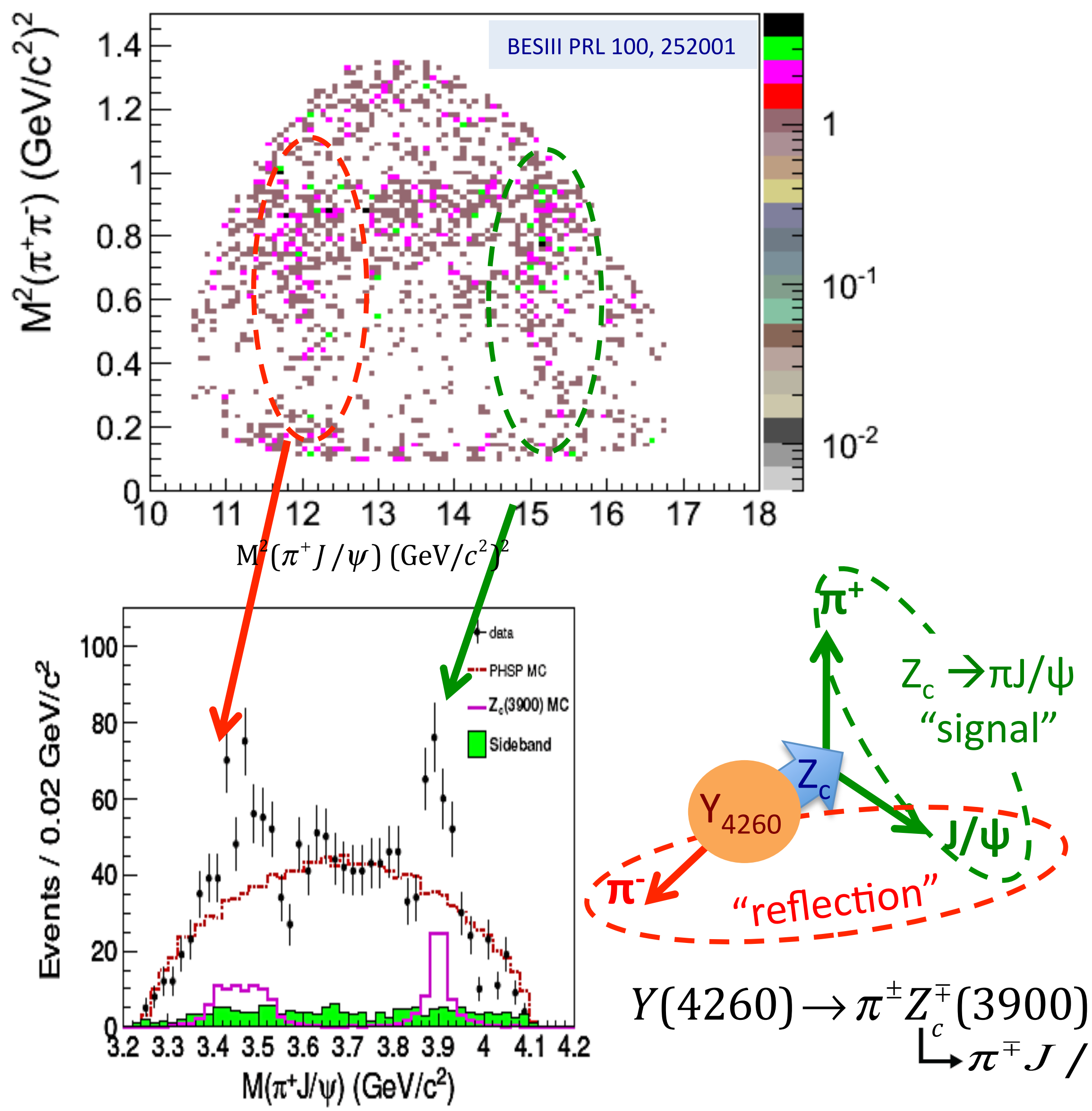
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ “Dalitz plot”



$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ “Dalitz plot”

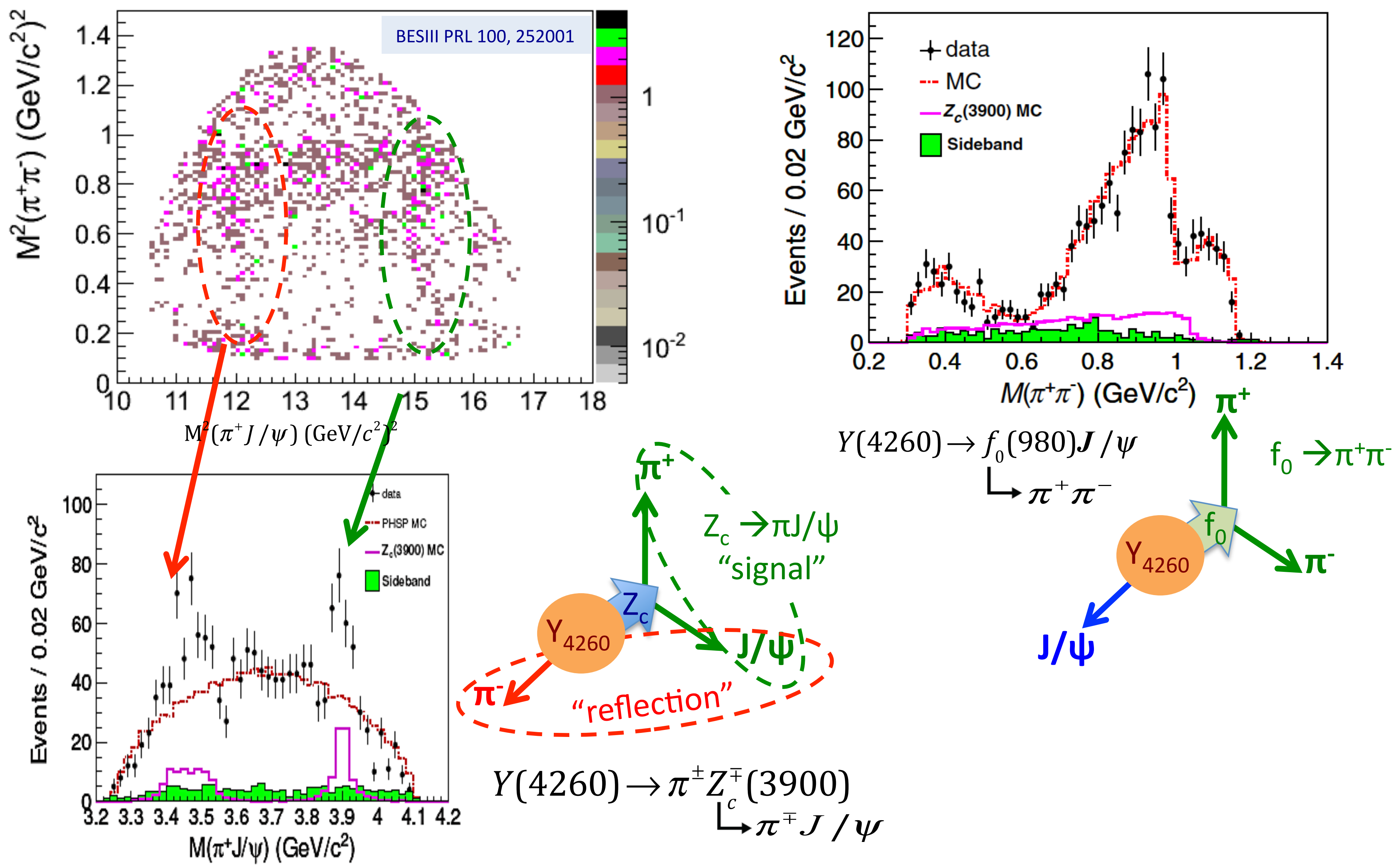


$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ "Dalitz plot"

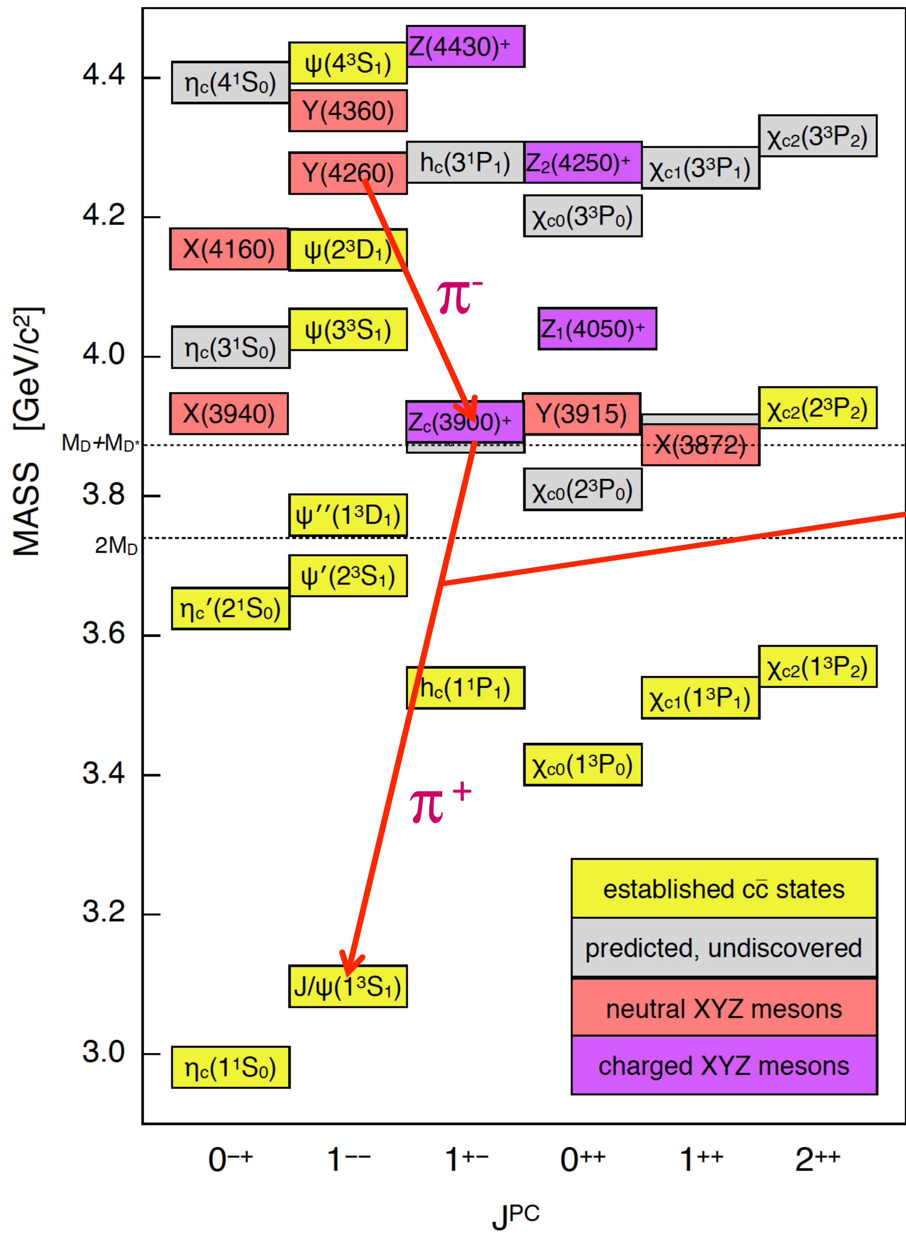


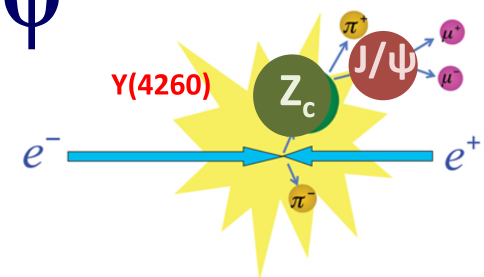
$$Y(4260) \rightarrow \pi^{\pm} Z_c^{\mp}(3900)$$
$$\hookrightarrow \pi^{\mp} J/\psi$$

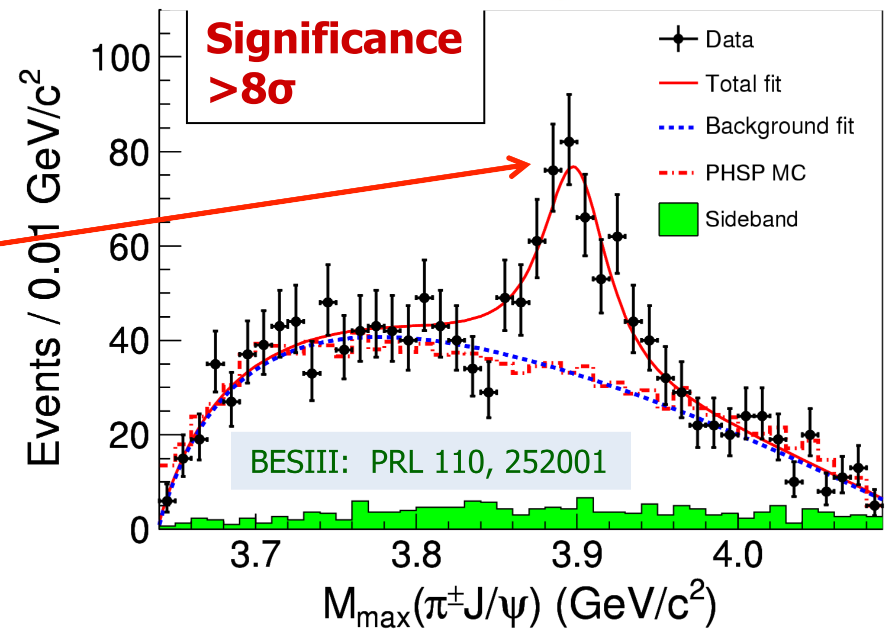
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ "Dalitz plot"



$Y(4260) \rightarrow \pi^- Z_c(3900)^+$
$\hookrightarrow \pi^+ J/\psi$

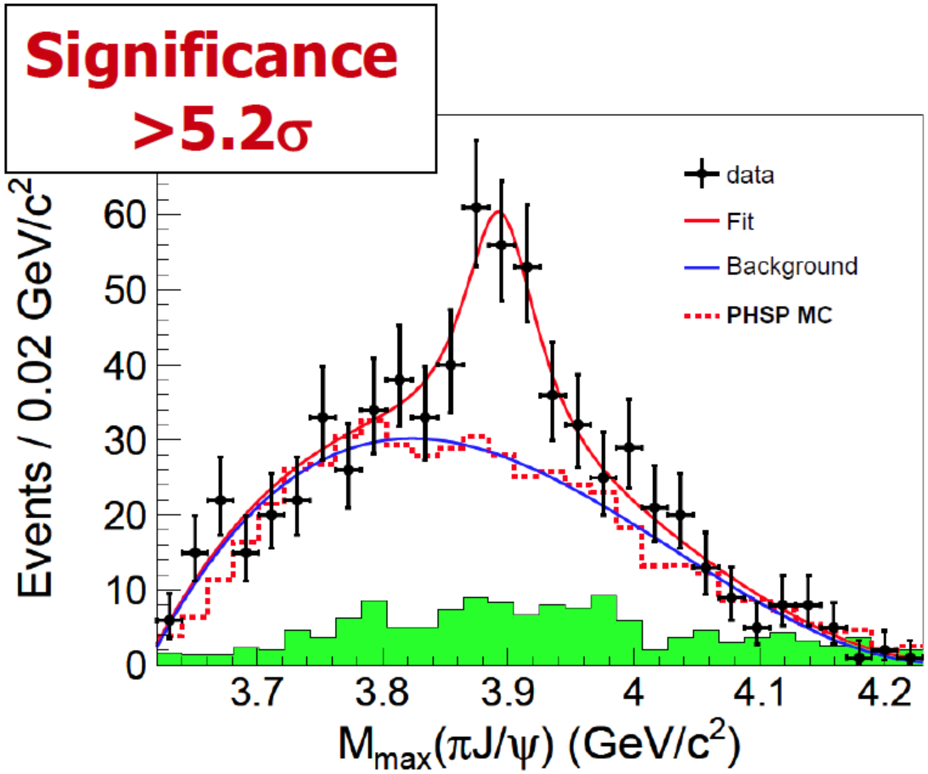






- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

$Z_c(3900)$ also seen by Belle



Mass = $(3894.5 \pm 6.6 \pm 4.5)$ MeV

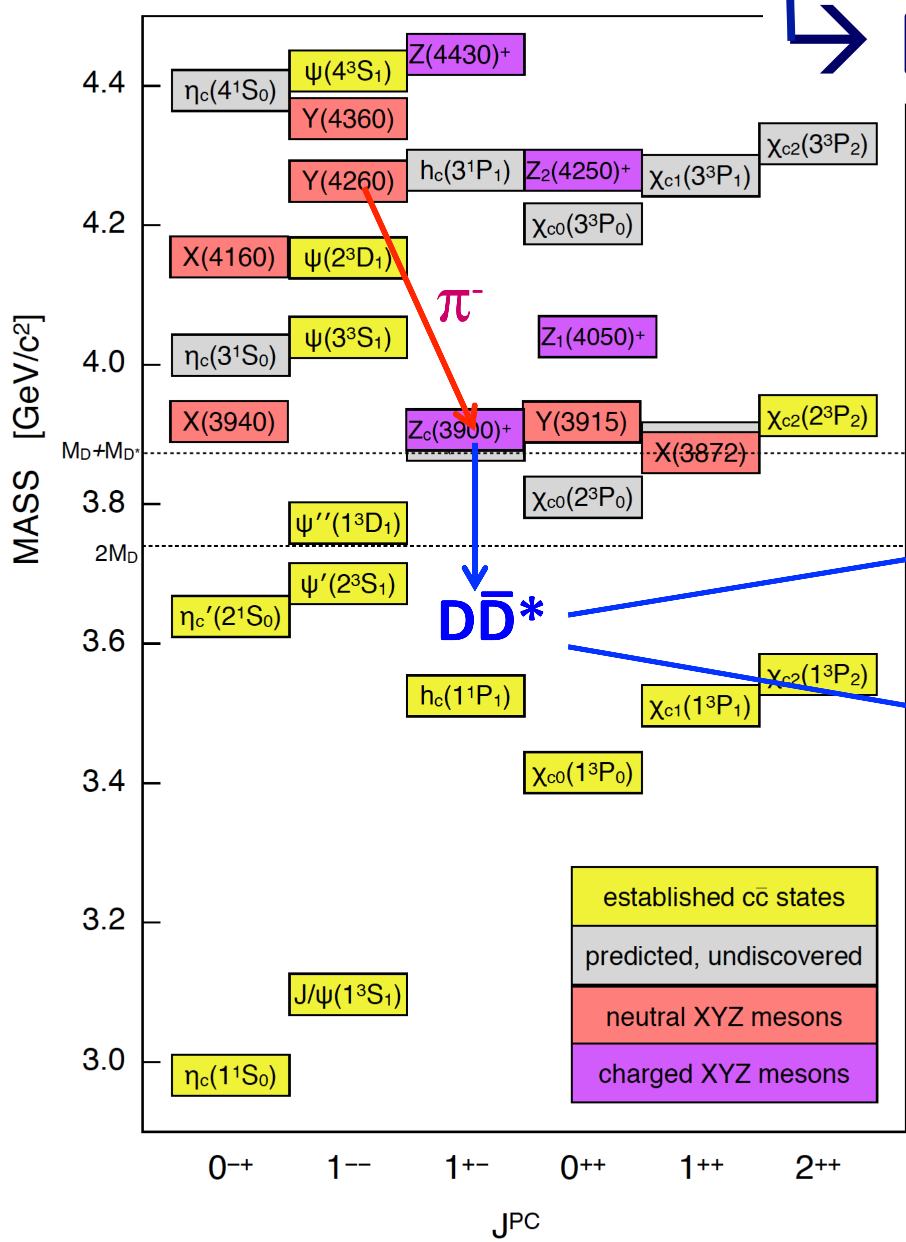
Width = $(63 \pm 24 \pm 26)$ MeV

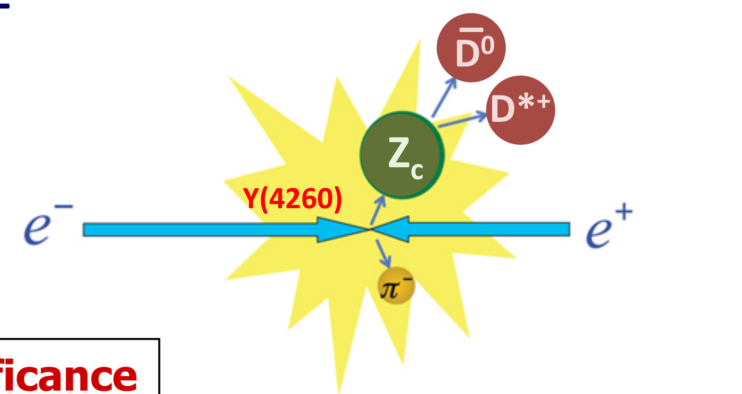
Fraction = $(29.0 \pm 8.9)\%$ (stat. err. only)

Belle: PRL 110, 252002

$Y(4260) \rightarrow \pi^- Z_c(3900)^+$

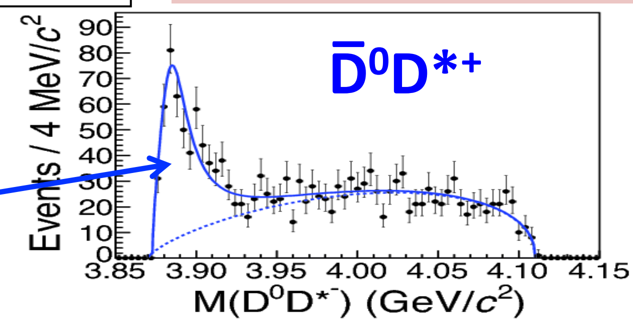
↳ $\bar{D}D^*$

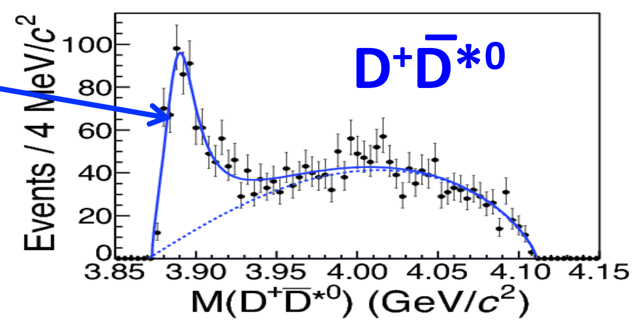




Significance >18σ

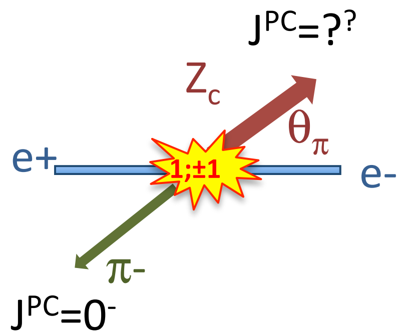
BESIII PRL 112, 022001 (last month)





- Mass = (3883.9 ±1.5 ±4.2) MeV
- Width = (24.8 ±3.3 ±11.0) MeV
- $D\bar{D}^*/\pi^+\pi^- J/\psi$ = 6.2 ± 1.1 ± 2.7

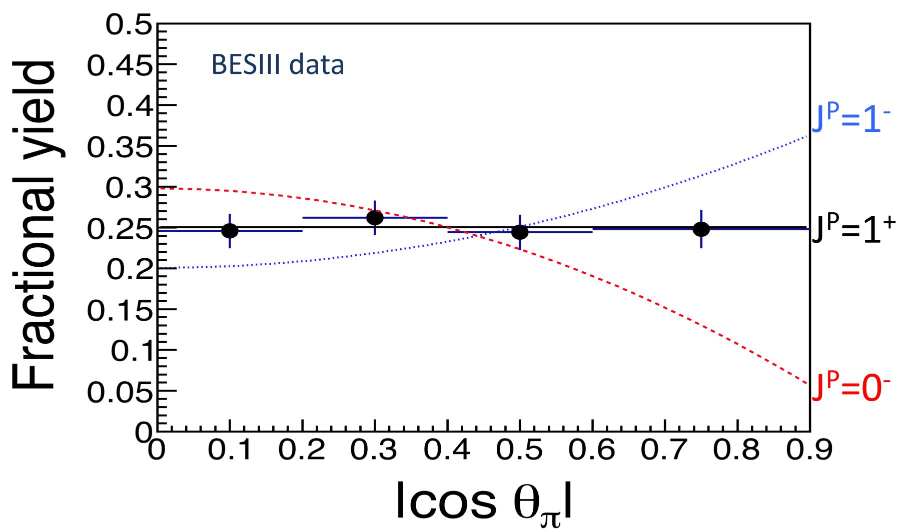
J^P of the $Z_c(3900)$?



initial state: $|J;J_z\rangle = |1;\pm1\rangle \; P=-1$

final state:

p	Z_c	$\|L;L_z\rangle\|S;S_z\rangle$	$dN/d\|\cos\theta\|$
0^-	0^+	forbidden by Parity	---
0^-	0^-	$\|1;\pm1\rangle\|0;0\rangle$	$\propto \sin^2\theta$
0^-	1^+	$\|0;0\rangle\|1;\pm1\rangle$	flat
0^-	1^-	$\|1;\pm1\rangle\|1;0\rangle - \|1;0\rangle\|1;\pm1\rangle$	$\propto 1+\cos^2\theta$



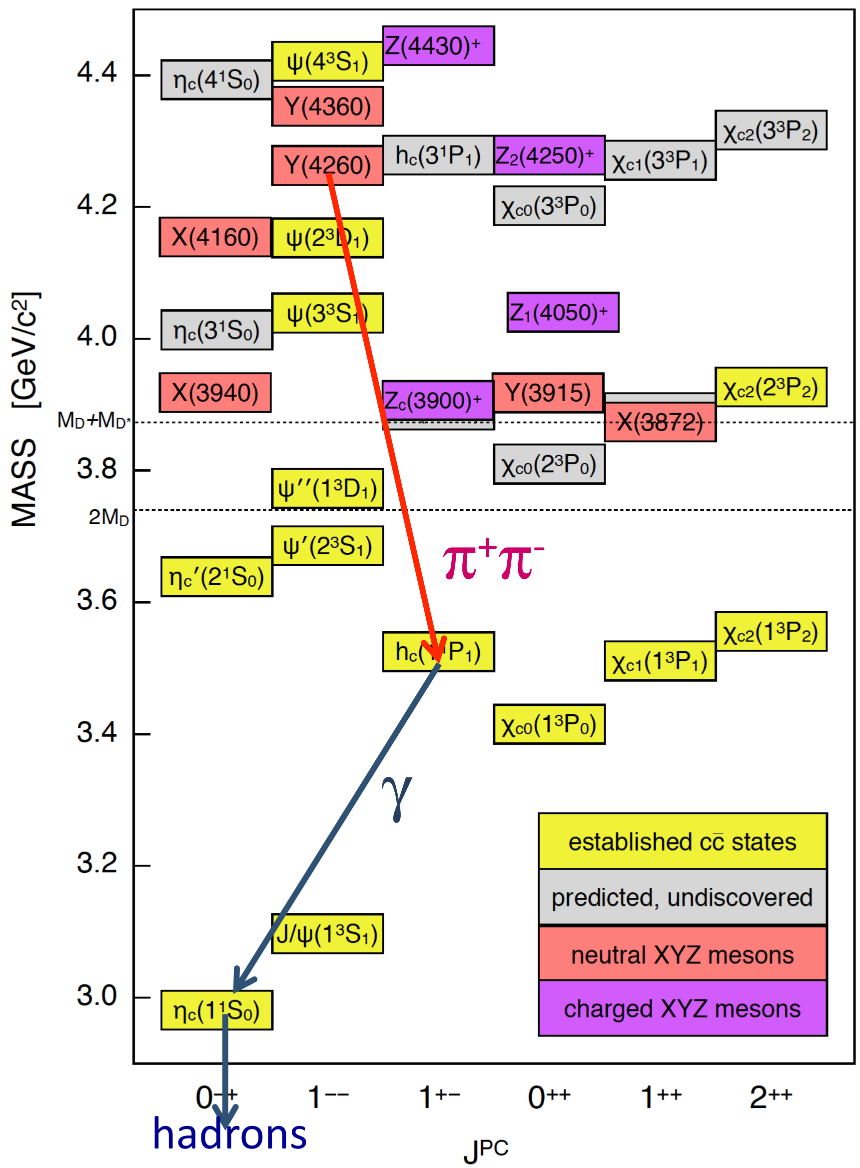
The data clearly establish $J^P=1^+$

Are there others?

Study Y(4260)→$\pi^+\pi^-$ h_c decays

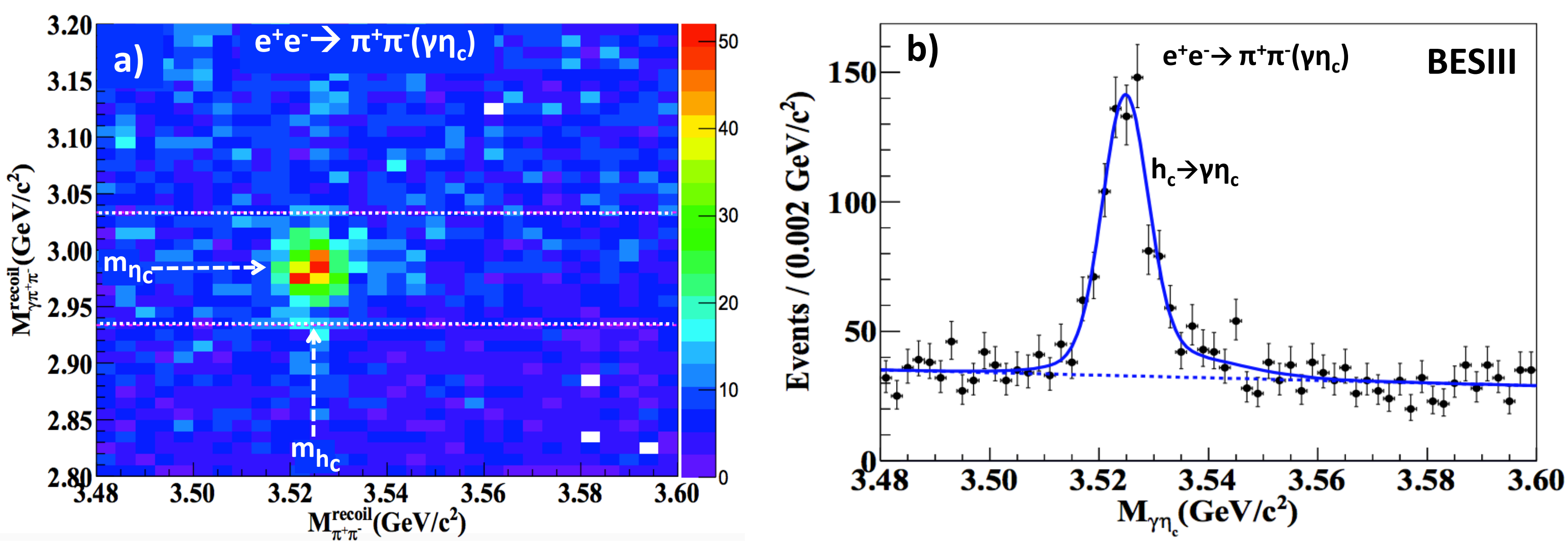
└→ $\gamma\eta_c$

16 channels



detecting h_c charmonium states at BESIII

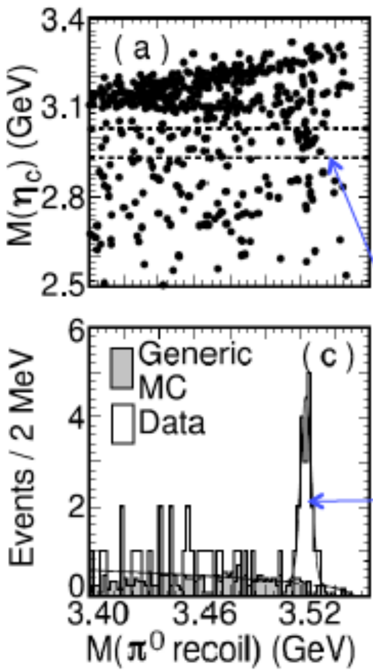
$$e^+e^- \to \pi^+\pi^- h_c$$
$$\hookrightarrow \gamma\eta_c$$
$$\hookrightarrow hadrons \Leftarrow \text{16 exclusive channels}$$



detecting h_c charmonium states at BESIII

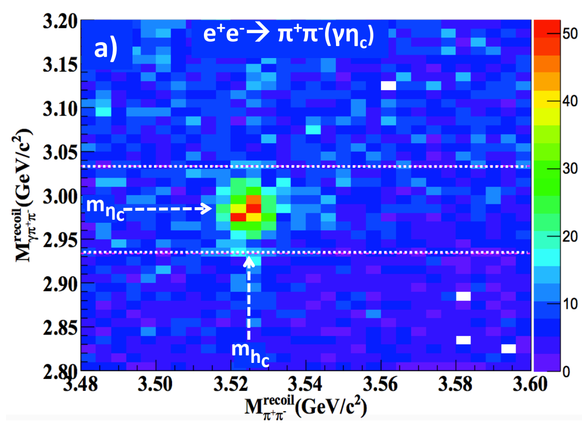
$$e^+e^- \to \pi^+\pi^- h_c$$
$$\hookrightarrow \gamma\eta_c$$
$$\hookrightarrow hadrons \;\Leftarrow 16 \text{ exclusive channels}$$

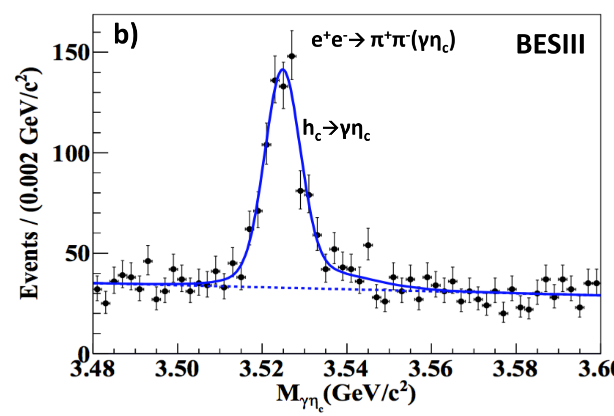
CLEO 2005 (20 evts)



CLEOII signal

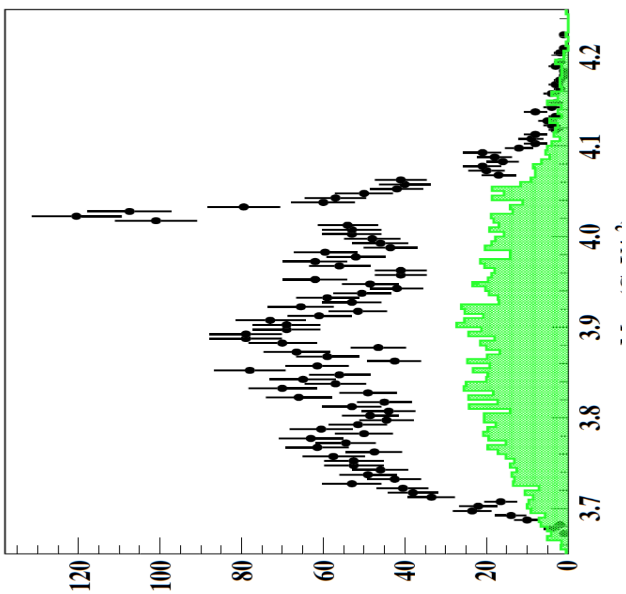
BESIII 2013 (1600 evts)

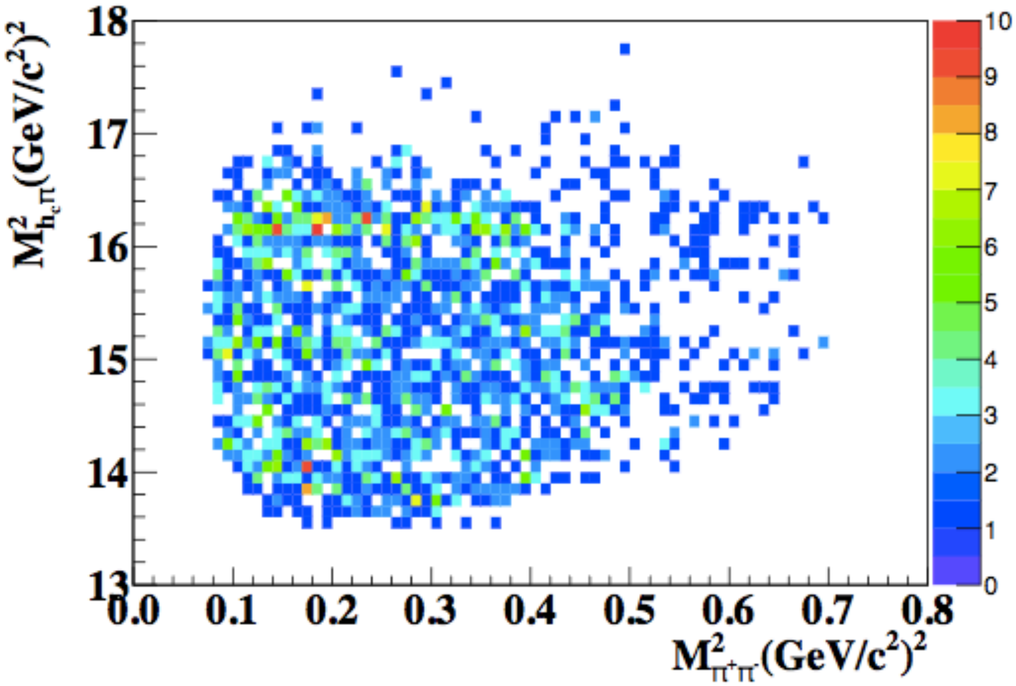




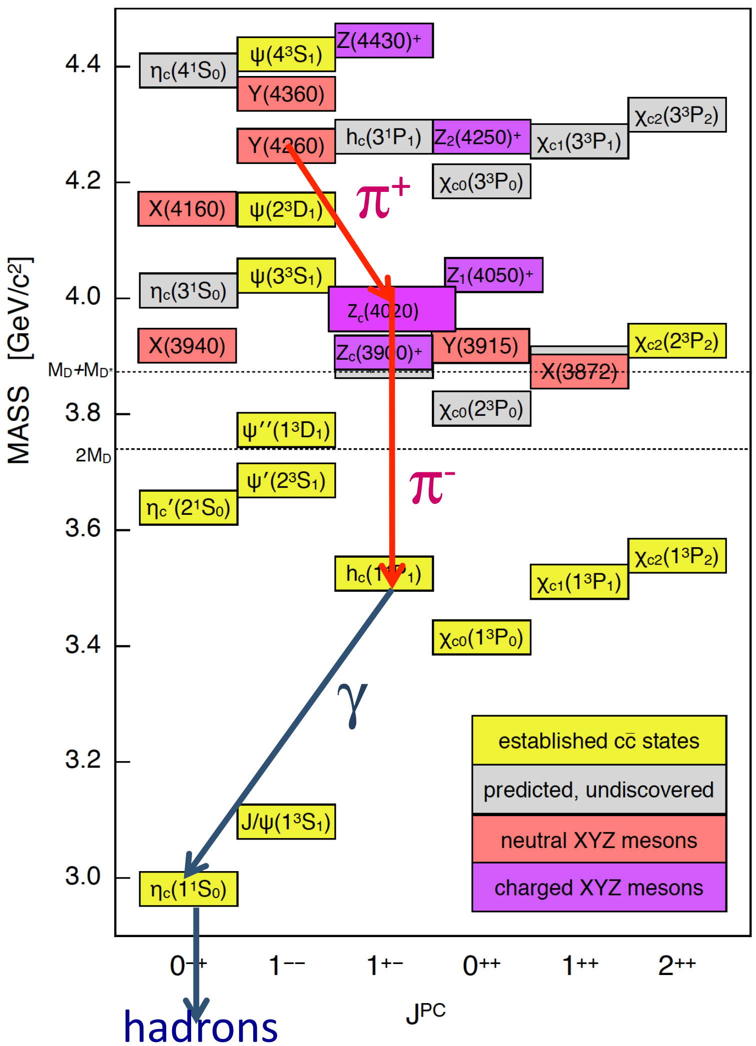
Y(4260)→$\pi^+\pi^-$ h_c Dalitz plot

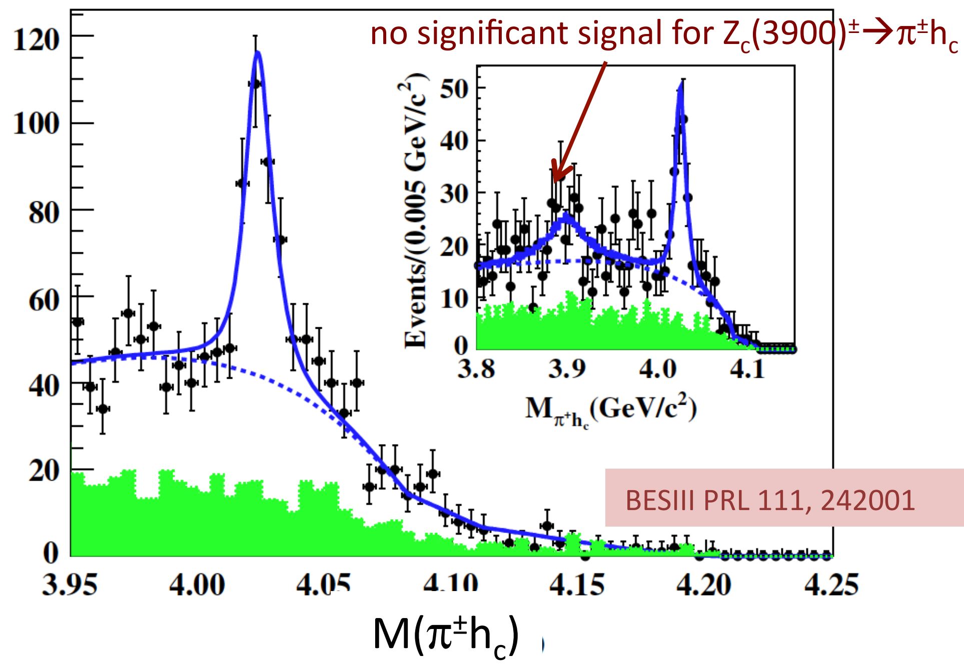
sharp peak, but at $M(\pi h_c)$ = 4020 MeV, not near ~3900 MeV





$Y(4260) \rightarrow \pi^+ Z_c(4020)^-$
$\hookrightarrow \pi^- h_c$





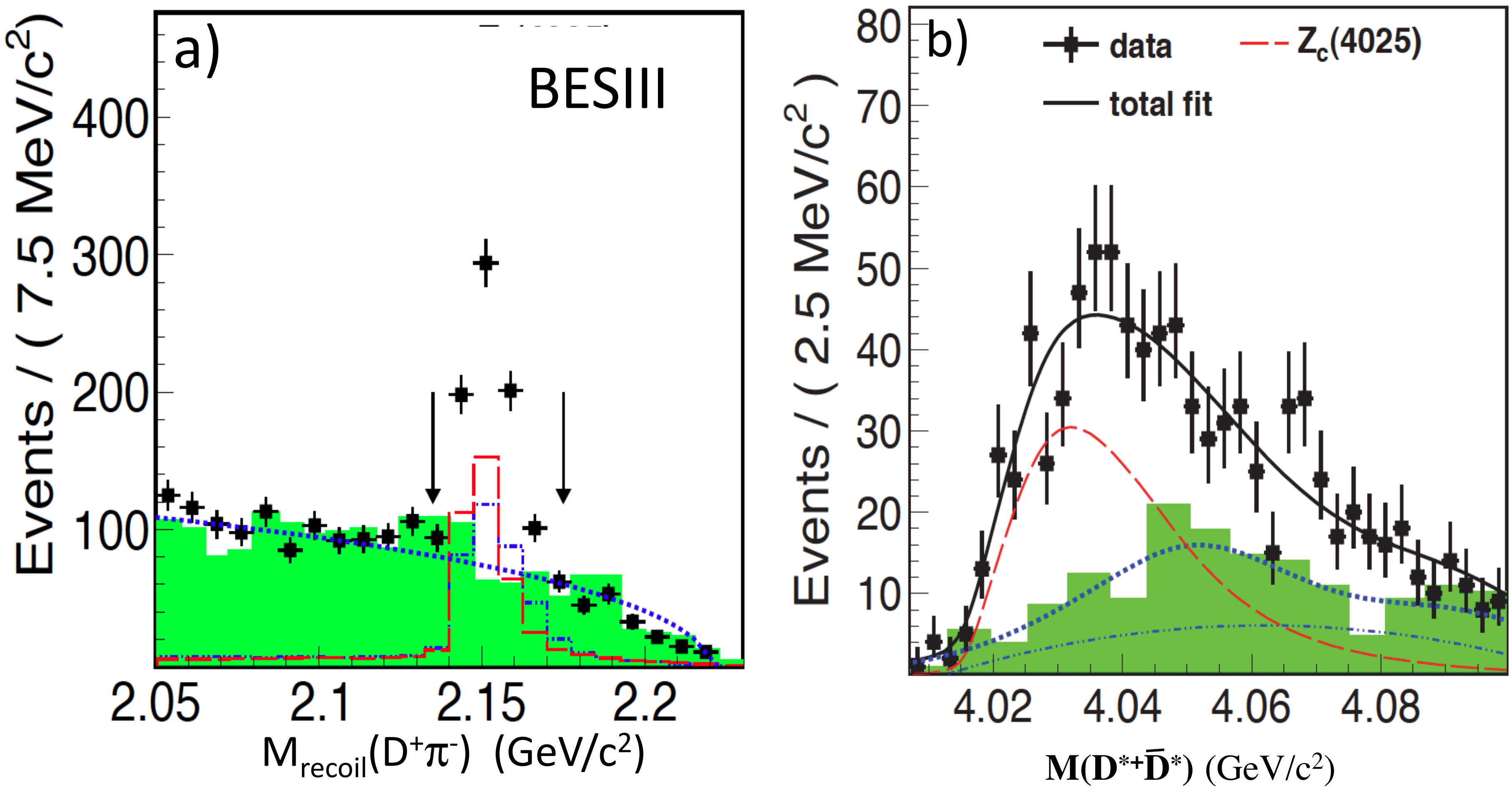
5.6 ± 2.8 MeV above $D^{*0}D^{*-}$ thresh.
= 4017.3 ±0.3 MeV

Fit results:
Mass = (4022.9 ±0.8 ±2.7) MeV
Width = (7.9 ±2.7 ±2.6) MeV
fraction = 0.18 ± 0.07

Observation of $Z_c(4020) \rightarrow D^*\bar{D}^*$

$$Y(4260) \rightarrow \pi^+ D^* \bar{D}^*$$
$$\hookrightarrow \bar{D}\,\pi$$

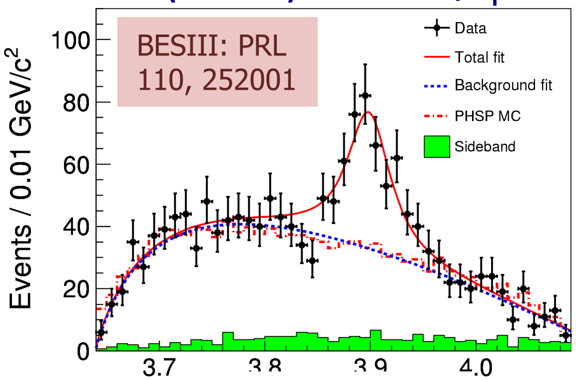
only detect bachelor π^+ and one $\bar{D}$ (or D)



Z_c states seen at BESIII

$Z_c(3900)$

Y(4260)→$\pi^+\pi^- J/\psi$

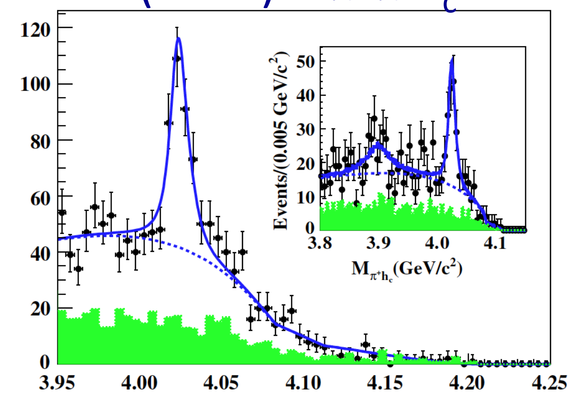


Belle: PRL 110, 252002

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

$Z_c(4020)$

Y(4260)→$\pi^+\pi^- h_c$

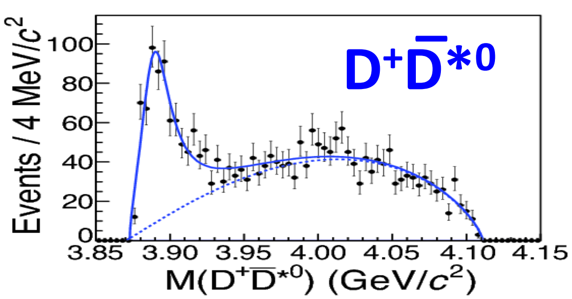


M($\pi^- h_c$)

BESIII PRL 111, 242001

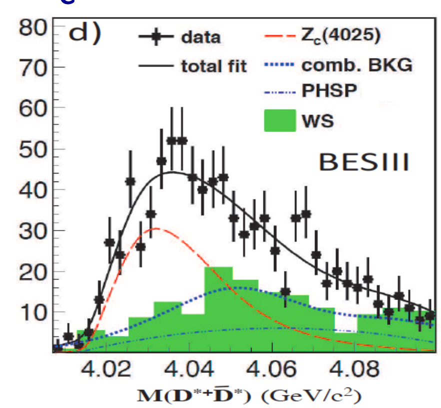
Both: $J^P=1^+$

$Z_c(3900)$ → $D\bar{D}^*$



BESIII PRL 112, 022001

$Z_c(4020)$ → $D^*\bar{D}^*$



BESIII PRL 112, 132001

Bottomonium-like vs Charmonium-like states

- Charged Upsilon-like structure
- Z_b are very close to $\bar{B}B^*$, $B^*\bar{B}^*$ threshold
- $I^G J^{P(C)} = 1^+ \, 1^{+\,(-)}$
- Observed both in the hidden-bottom modes: $\pi\Upsilon(1S,2S,3S)$, $\pi\, h_b(1P,2P)$ and open-bottom modes: $\bar{B}B^*$, $B^*\bar{B}^*$
- $B(^*)\bar{B}^*$ dominate Z_b decays with the branching ratio 86% and 73%

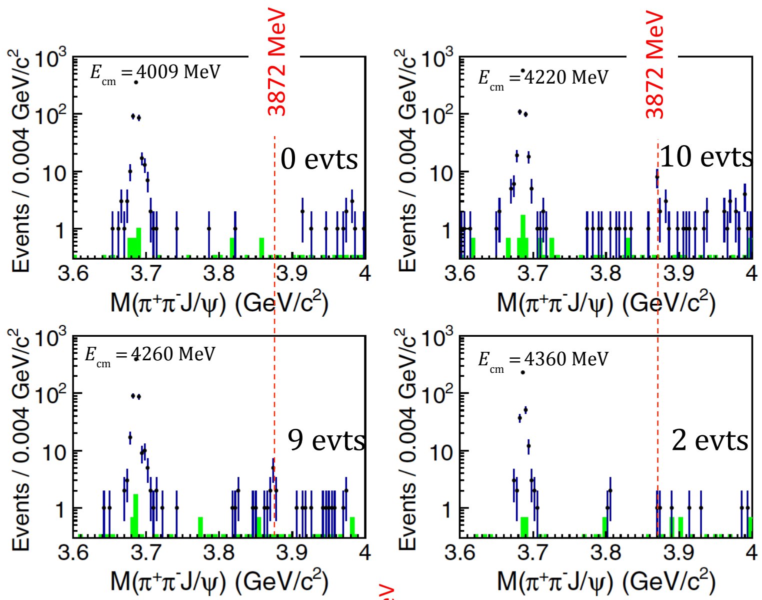
- Charged charmonium-like structure
- Z_c are very close to $\bar{D}D^*$, $D^*\bar{D}^*$ threshold
- $I^G J^{P(C)} = 1^+ \, 1^{+\,(-)}$
- Observed both in the hidden-charm modes: $\pi\, J/\psi$, $\pi\, h_c$ and open-charm modes: $\bar{D}D^*$, $D^*\bar{D}^*$
- $\bar{D}D^*$ dominates $Z_c(3900)$ decay

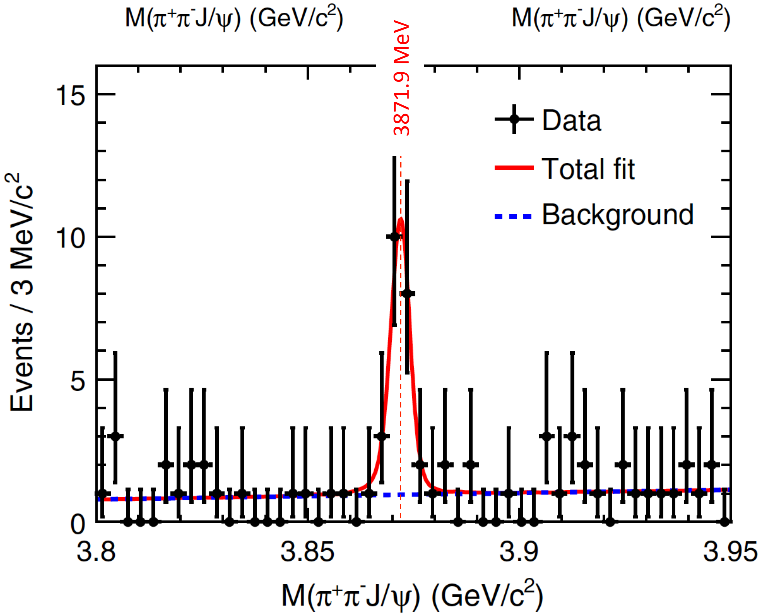
$$\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

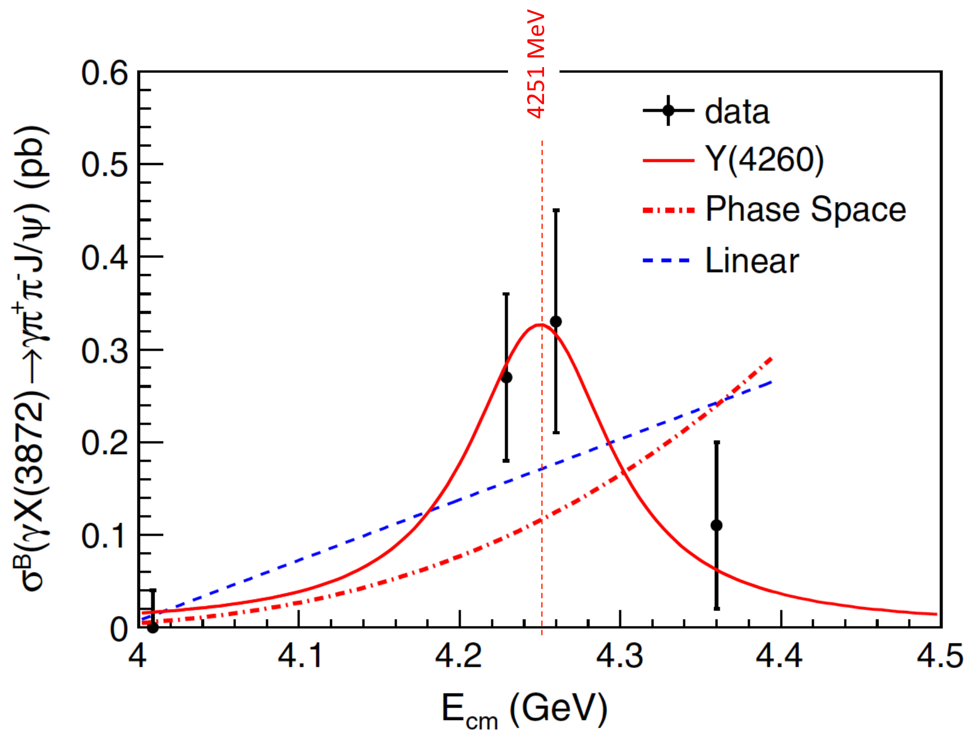
New this year:

other Y(4260) decay modes

Radiative decays? Y(4260)→$\gamma\pi^+\pi^- J/\psi$?





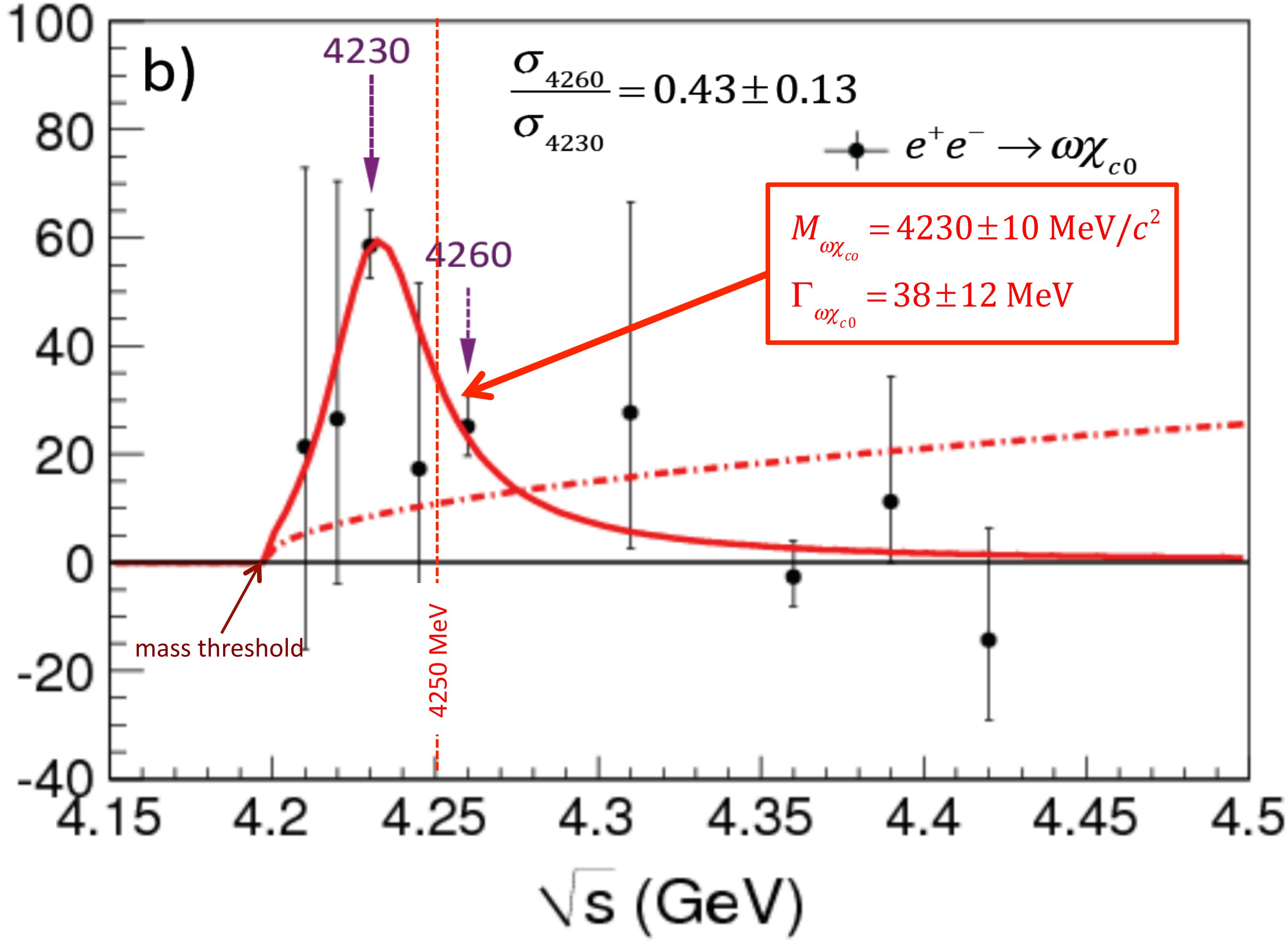


assuming *Bf*(X_{3872}→$\pi^+\pi^- J/\psi$)=5%:

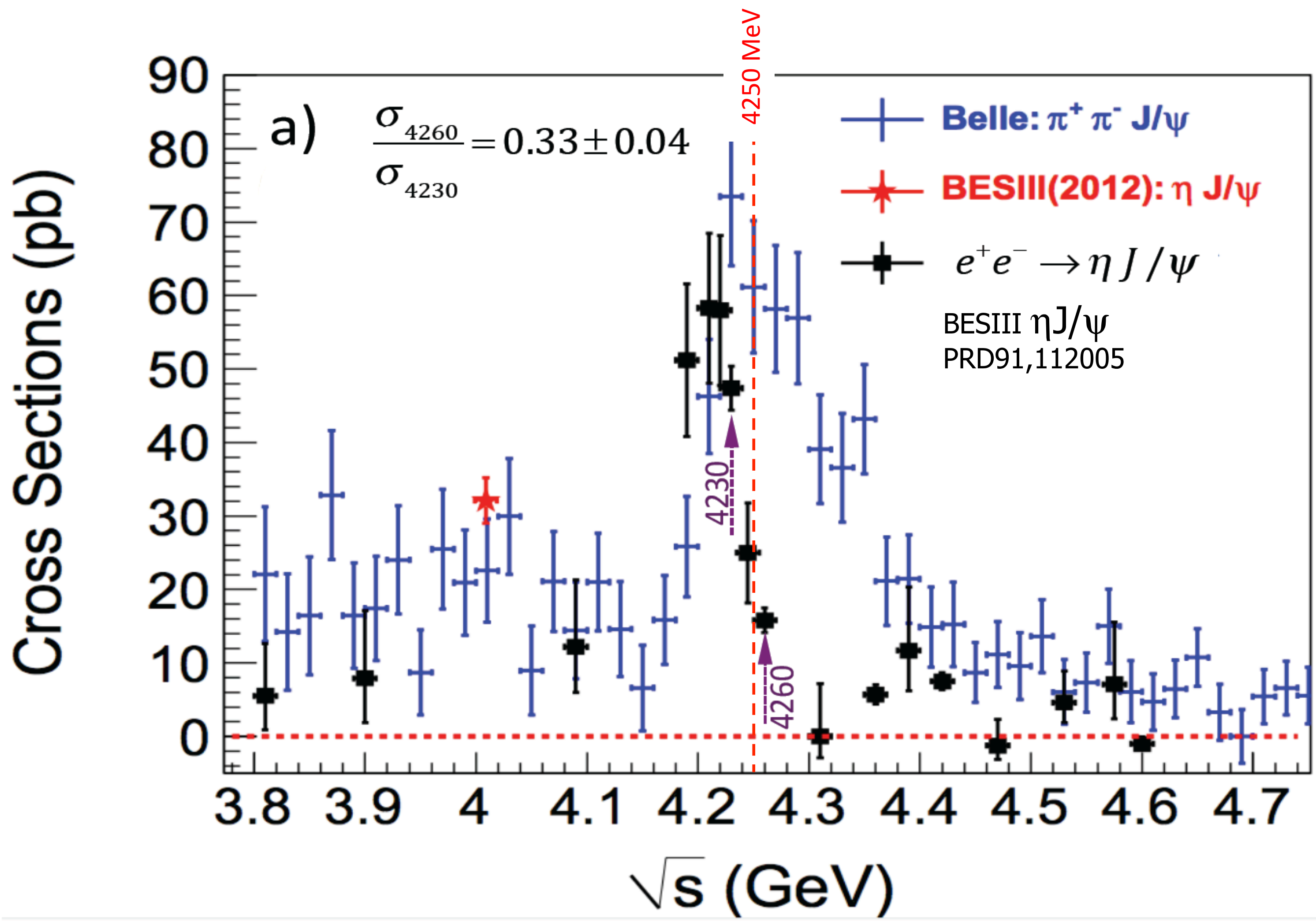
$$\frac{Bf(Y_{4260} \to \gamma X_{3872})}{Bf(Y_{4260} \to \pi^+\pi^- J/\psi)} \sim 0.1$$ ←not small!!

some commonality between X(3872) & Y(4260)?

$Y(4260) \to \omega\chi_{c0}$??

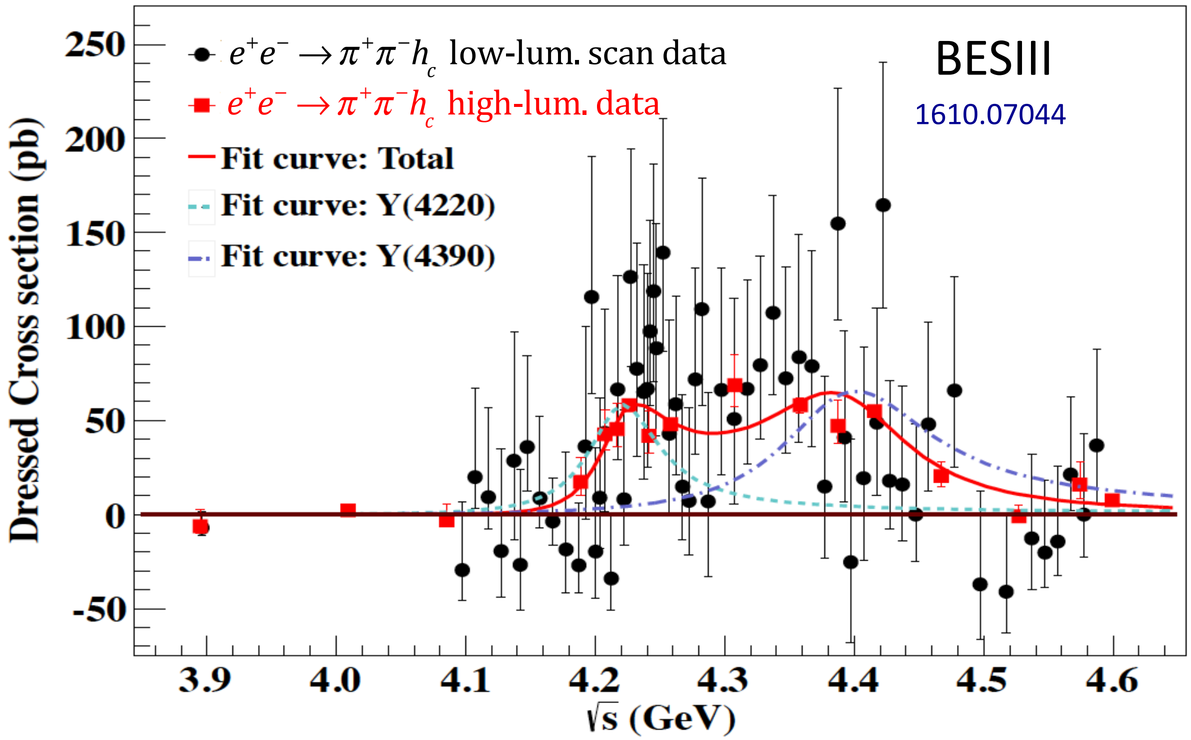


Y(4260)→ηJ/ψ ?



4250 MeV
a)
$\frac{\sigma_{4260}}{\sigma_{4230}} = 0.33 \pm 0.04$
Belle: $\pi^+\pi^-$ J/ψ
BESIII(2012): η J/ψ
$e^+e^- \to \eta J/\psi$
BESIII ηJ/ψ
PRD91,112005
4230
4260
Cross Sections (pb)
0
10
20
30
40
50
60
70
80
90
3.8
3.9
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
√s (GeV)

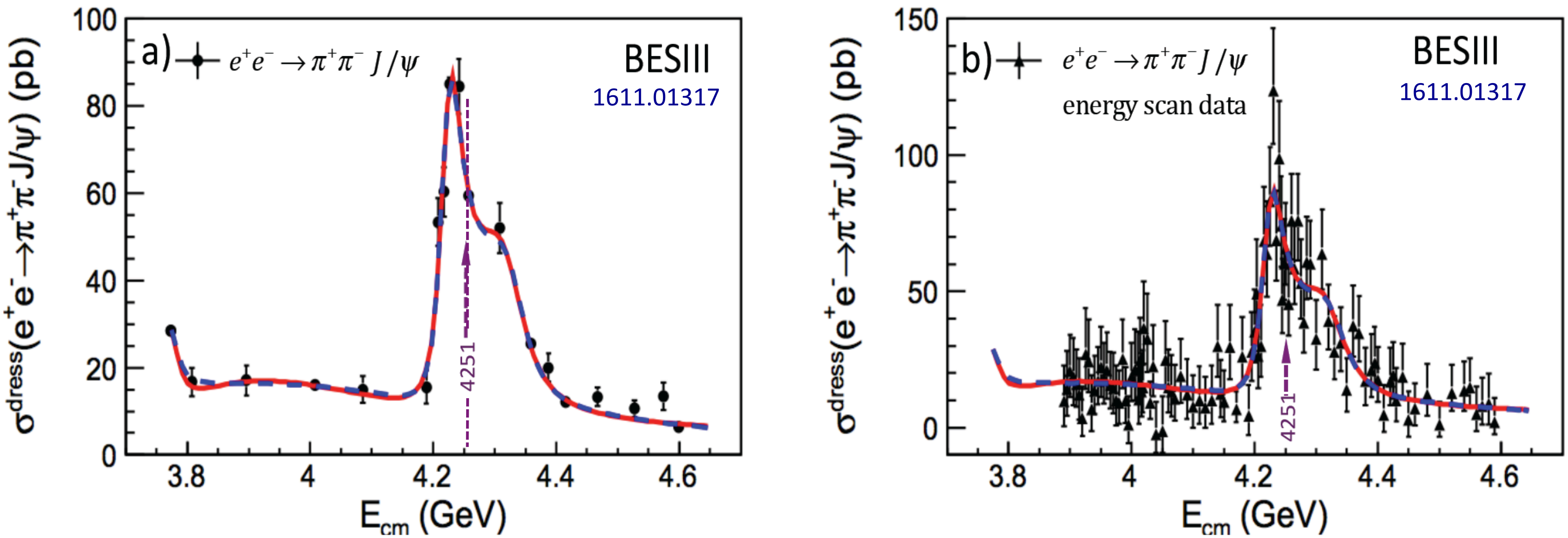
$e^+e^- \rightarrow \pi^+\pi^- h_c$



$$M_1 = 4218 \pm 4 \text{ MeV}/c^2 \qquad \Gamma_1 = 66 \pm 9 \text{ MeV}$$

$$M_2 = 4392 \pm 6 \text{ MeV}/c^2 \qquad \Gamma_2 = 140 \pm 16 \text{ MeV}$$

The Y(4260) is not a single BW resonance!

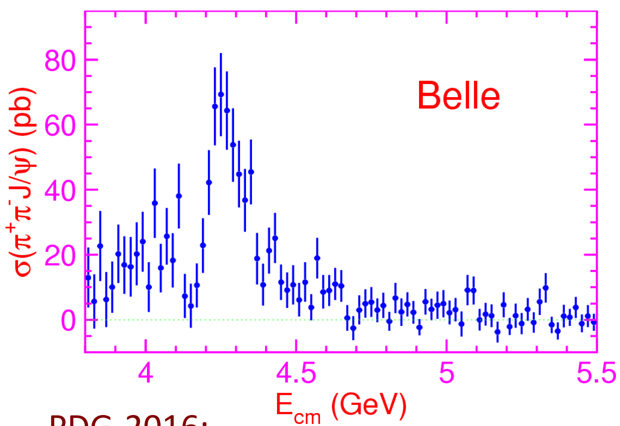


2 BW res. fit preferred over 1 BW res. fit by >7σ

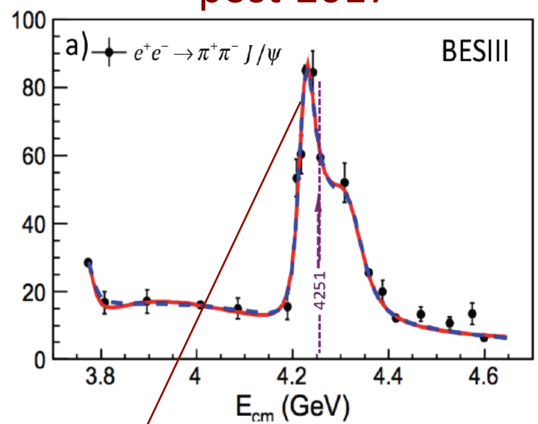
$$M_1 = 4220 \pm 4 \text{ MeV}/c^2 \qquad \Gamma_1 = 44 \pm 5 \text{ MeV}$$
$$M_2 = 4320 \pm 13 \text{ MeV}/c^2 \qquad \Gamma_2 = 101^{+27}_{-22} \text{ MeV}$$

Y(4260): mass → lower & width → narrower

pre-2017



post-2017



PDG-2016:

$$M(Y(4260)) = 4251 \pm 9\ \mathrm{MeV}/c^2 \xrightarrow{-31\ \mathrm{MeV}} M_1 = 4220 \pm 4\ \mathrm{MeV}/c^2$$

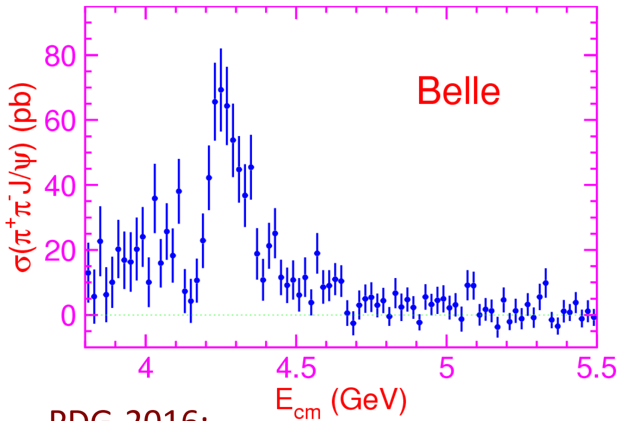
$$\underbrace{\Gamma(Y(4260)) = 120 \pm 12\ \mathrm{MeV}. \xrightarrow{\times 1/3} \Gamma_1 = 44 \pm 5\ \mathrm{MeV}}$$

Y(4220) decay modes:

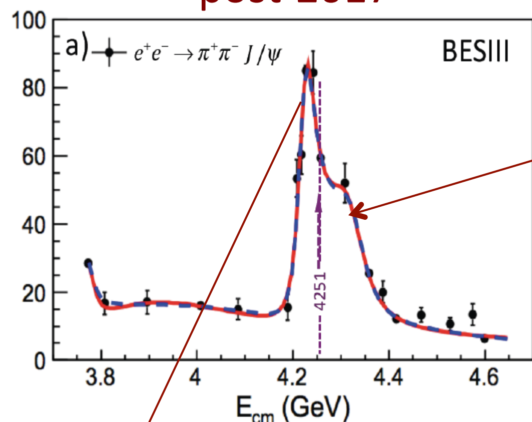
- $\pi^+\pi^- J/\psi$
  - $\pi Z_c(3900)$
  - $f_0(980)\ J/\psi$
- $\pi^+\pi^- h_c$
- $\omega\chi_{c0}$
- $\eta J/\psi$
- $\gamma X(3872)$
- $\pi D\bar{D}^*$

Y(4260): mass → lower & width → narrower

pre-2017



post-2017



what is the 2nd peak?

PDG-2016:

$$M(Y(4260)) = 4251 \pm 9\ \mathrm{MeV}/c^2 \xrightarrow{-31\ \mathrm{MeV}} M_1 = 4220 \pm 4\ \mathrm{MeV}/c^2$$

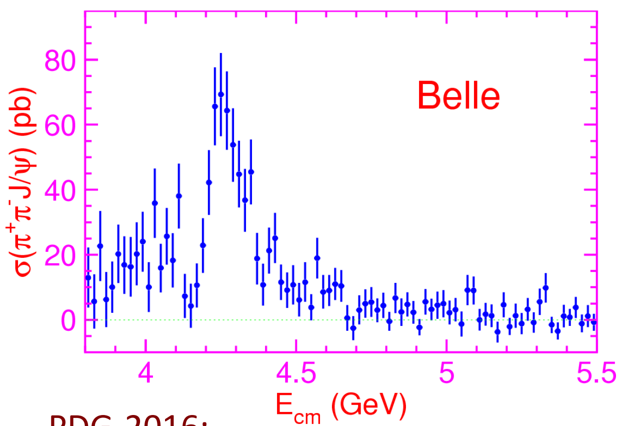
$$\Gamma(Y(4260)) = 120 \pm 12\ \mathrm{MeV}. \xrightarrow{\times 1/3} \Gamma_1 = 44 \pm 5\ \mathrm{MeV}$$

Y(4220) decay modes:

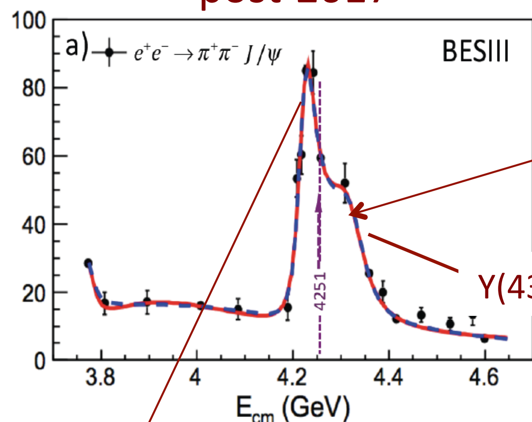
- $\pi^+\pi^- J/\psi$
  - $\pi Z_c(3900)$
  - $f_0(980)\ J/\psi$
- $\pi^+\pi^- h_c$
- $\omega\chi_{c0}$
- $\eta J/\psi$
- $\gamma X(3872)$
- $\pi D\bar{D}^*$

Y(4260): mass → lower & width → narrower

pre-2017

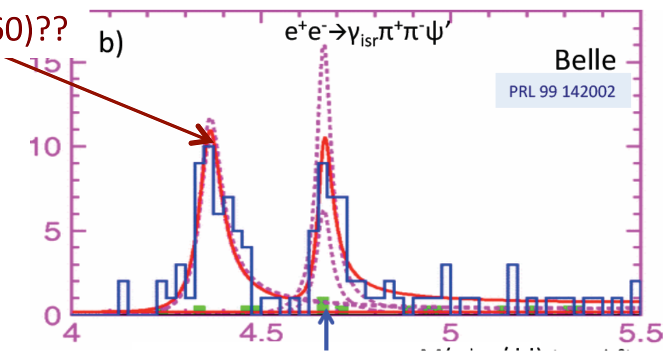


post-2017



what is the 2nd peak?

Y(4360)??



PDG-2016:

$M(Y(4260)) = 4251 \pm 9$ MeV$/c^2$ $\xrightarrow{-31\text{ MeV}}$ $M_1 = 4220 \pm 4$ MeV$/c^2$

$\Gamma(Y(4260)) = 120 \pm 12$ MeV. $\xrightarrow{\times 1/3}$ $\Gamma_1 = 44 \pm 5$ MeV

$M_2 = 4320 \pm 13$ MeV$/c^2$ $\xrightarrow{\delta M \approx -1.8\sigma}$ $M(Y(4360)) = 4346 \pm 6$ MeV$/c^2$

$\Gamma_2 = 101^{+27}_{-22}$ MeV $\xrightarrow{\text{spot on}}$ $\Gamma(Y(4360)) = 102 \pm 12$ MeV.

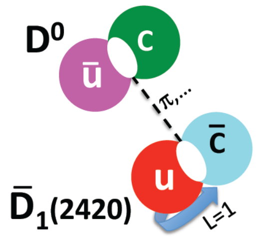
Y(4220) decay modes:
- $\pi^+\pi^-J/\psi$
  - $\pi Z_c(3900)$
  - $f_0(980)\ J/\psi$
- $\pi^+\pi^-h_c$
- $\omega\chi_{c0}$
- $\eta J/\psi$
- $\gamma X(3872)$
- $\pi D\bar{D}^*$

Y(4320) decay modes:
- $\pi^+\pi^-J/\psi$
- $\pi^+\pi^-\psi'$

What is the Y(4260)?

some proposed models

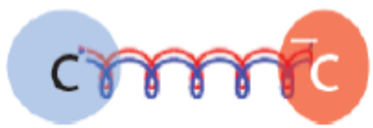
$D\bar{D}_1(2420)$ molecule



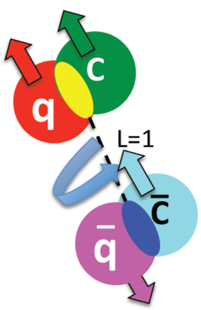
actually:

$$Y(4260) = \frac{1}{\sqrt{2}}\left[D\bar{D}_1(2420) \pm D_1(2420)\bar{D}\right]$$

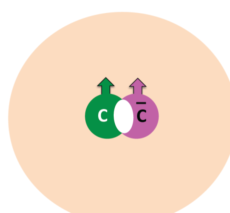
QCD $c\bar{c}$-gluon hybrid



QCD diquark-diantiquark
"tetra-quark"



"hadrocharmonium"



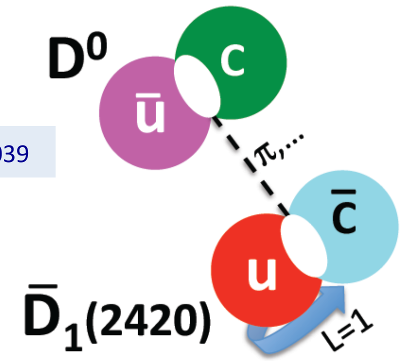
Models for the Y(4260) I

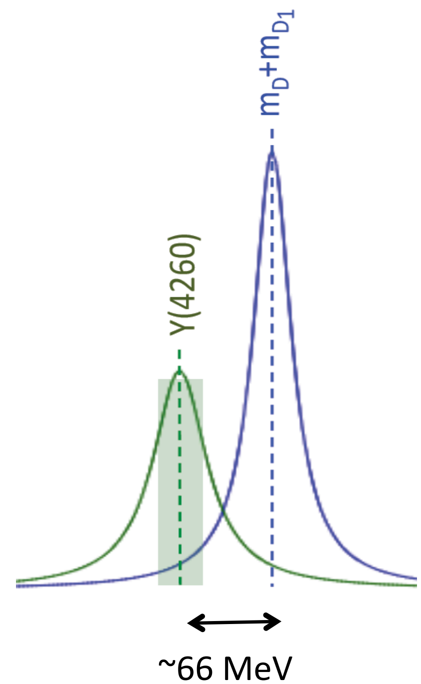
Molecule?

Ding PRD 79, 014001

Wang, Hanhart & Zhao PRL 111, 132002

Cleven, Wang, Guo, Hanhart, Meissner & Zhao PRD 90, 074039



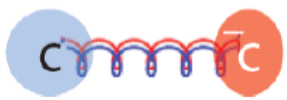


$D_1(2420)$ $J^P=1^+$
$M=2421.4 \pm 0.6$ MeV $\Gamma= 27.4 \pm 2.5$ MeV Decay: $D_1(2420) \rightarrow D^*\pi$ Y(4260) "B.E." ≈ 66 MeV

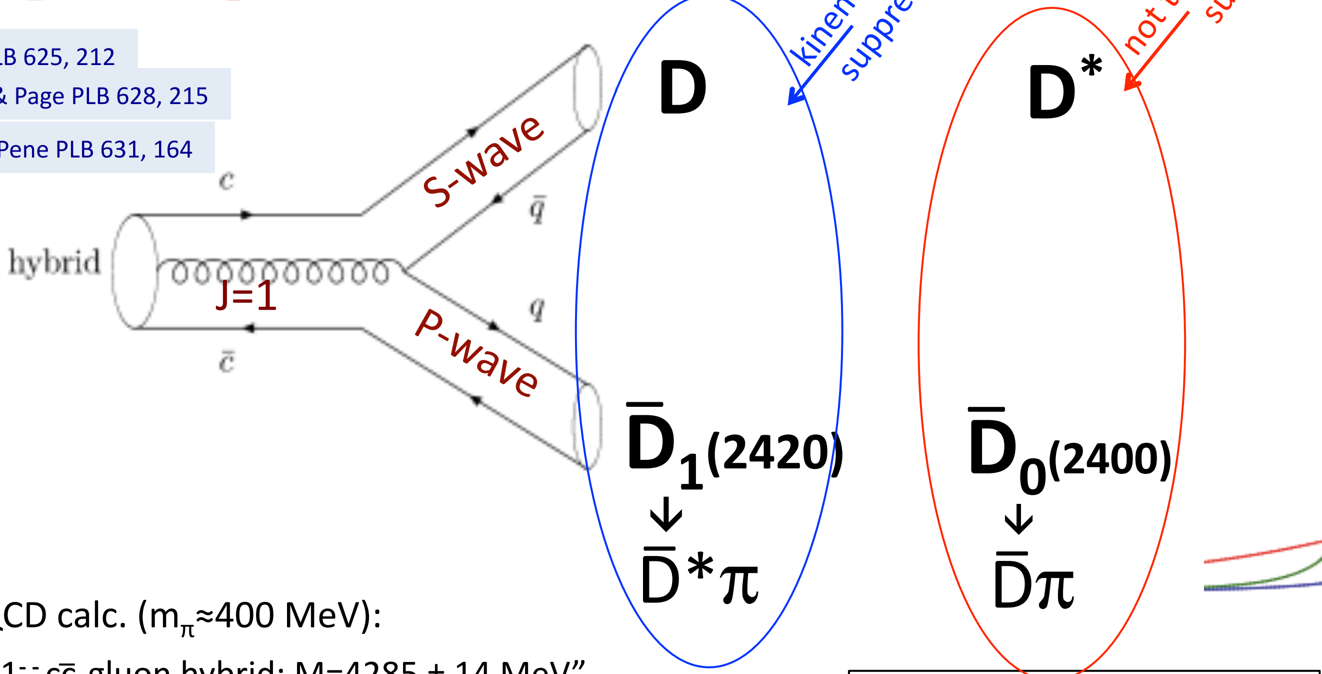
pre-2017: BE≈35 MeV

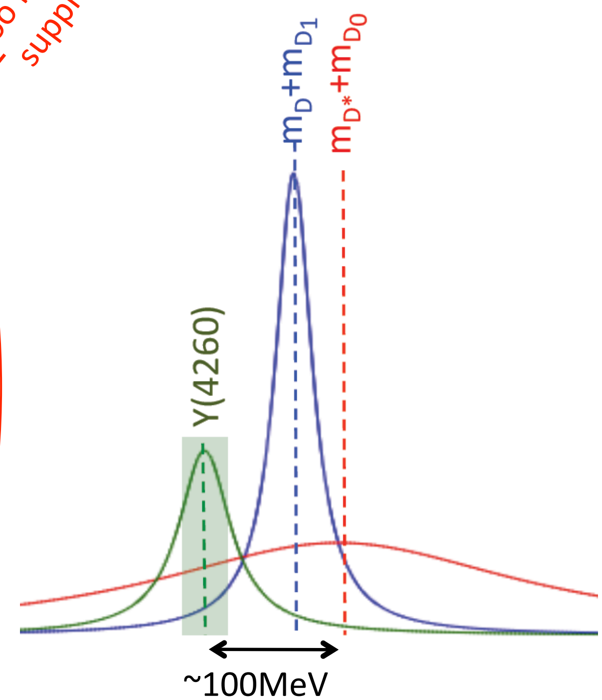
Models for the Y(4260) II

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



Zhu PLB 625, 212
Close & Page PLB 628, 215
Kou & Pene PLB 631, 164





2012 LQCD calc. ($m_\pi \approx 400$ MeV):

"Lowest 1^{--} $c\bar{c}$-gluon hybrid: M=4285 ± 14 MeV"

pre-2017: too high by ~35 MeV
post-2017: too high by ~65 MeV

Had. Spectr. Collab. JHEP07, 126

very broad
hard to see

$D_0(2400)$ $J^P=0^+$
M=2318 ± 29 MeV
Γ= 267 ± 40 MeV
Decay: $D_0(2400) \rightarrow D\pi$
Y(4260) "B.E." ≈ 100 MeV

Models for the Y(4260) III

QCD tetraquark?

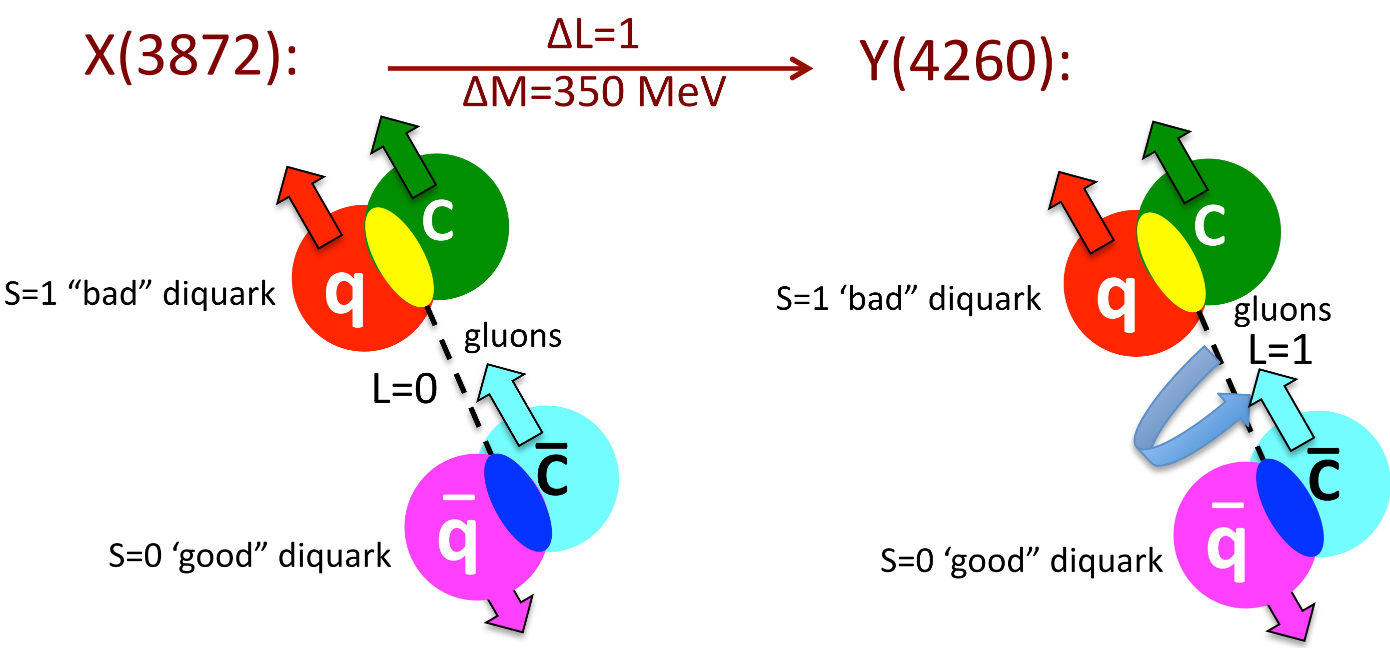
Maiani et al. PRD 89, 114010

L=1 excitation of the X(3872):

- naturally accounts for large Y(4260)→γX(3872) as an allowed E1 transition

- 350 MeV is a typical mass "penalty" for ΔL=1:

L=1	L=0	δM (MeV)
$D_1(2420)$	$D^*(2010)$	410
$D_{s1}(2460)$	$D_s(2110)$	350
$h_c(3525)$	J/ψ	430



Models for the Y(4260) IV

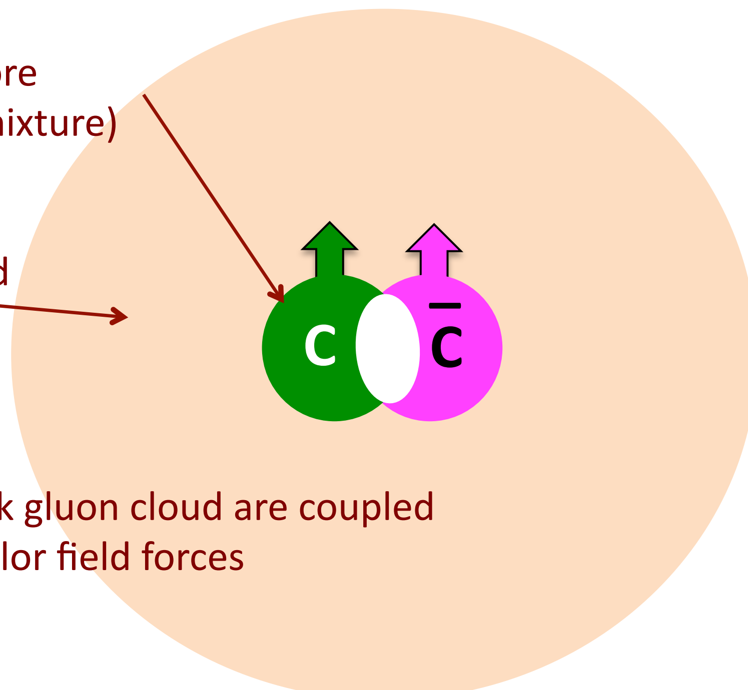
Hadrocharmonium?

Dubynskiy & Voloshin, PLB 666, 344

Li & Voloshin, Mod. Phys. Lett. A29, 1450060

color-singlet charmonium core
(for Y(4260) this a J/ψ + h_c mixture)

surrounding color-singlet cloud
of light quarks & gluons



charmonium core & light-quark gluon cloud are coupled
via Van-der-Waals–like color field forces

Y(4260) → J/ψ (or h_c)+ light-hadrons decays should be dominant,
--- decays to other charmonium states are suppressed

Testing Y(4260) models against data

- $D\bar{D}_1(2420)$ molecule:

expect a strong Y(4260) affinity for $D\bar{D}_1(2420)$-like final states

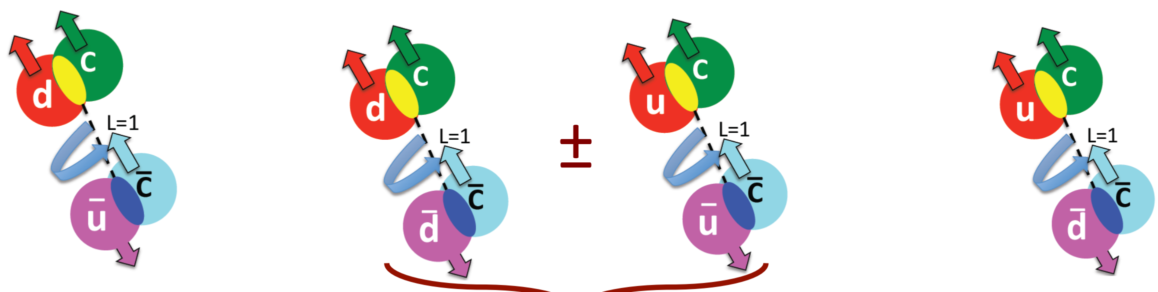
- $c\bar{c}$-gluon hybrid:

expect a strong Y(4260) affinity for $D^*\bar{D}_0(2400)$-like final states

- QCD tetraquark models:

expect partner states, including charged partners (likewise for the X(3872))

$Y^-(I=1;I_z=-1)$



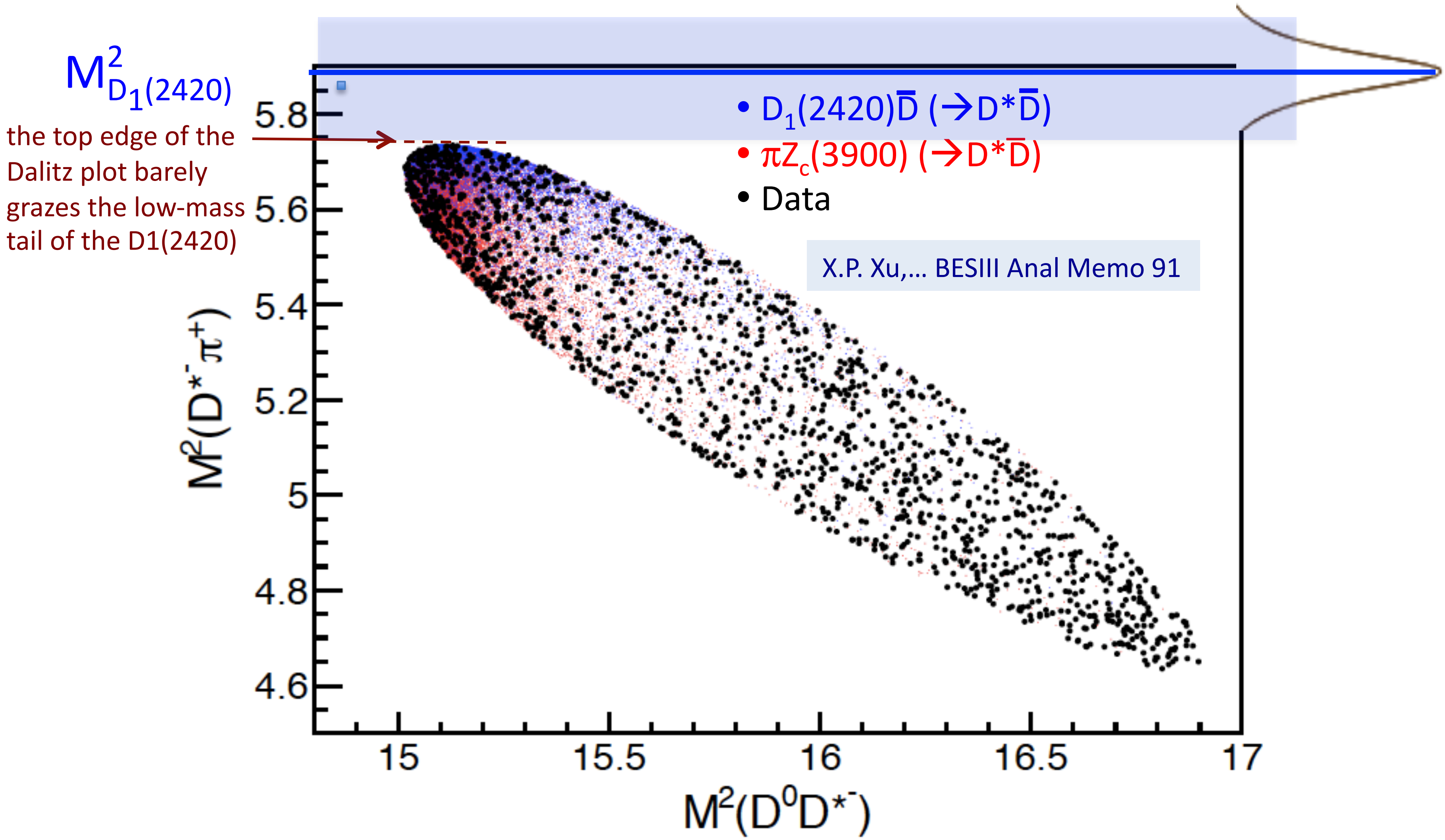
$Y^+(I=1;I_z=+1)$

+: $Y^0(I=1;I_z=0)$
-: $Y^0(I=0;I_z=0)$

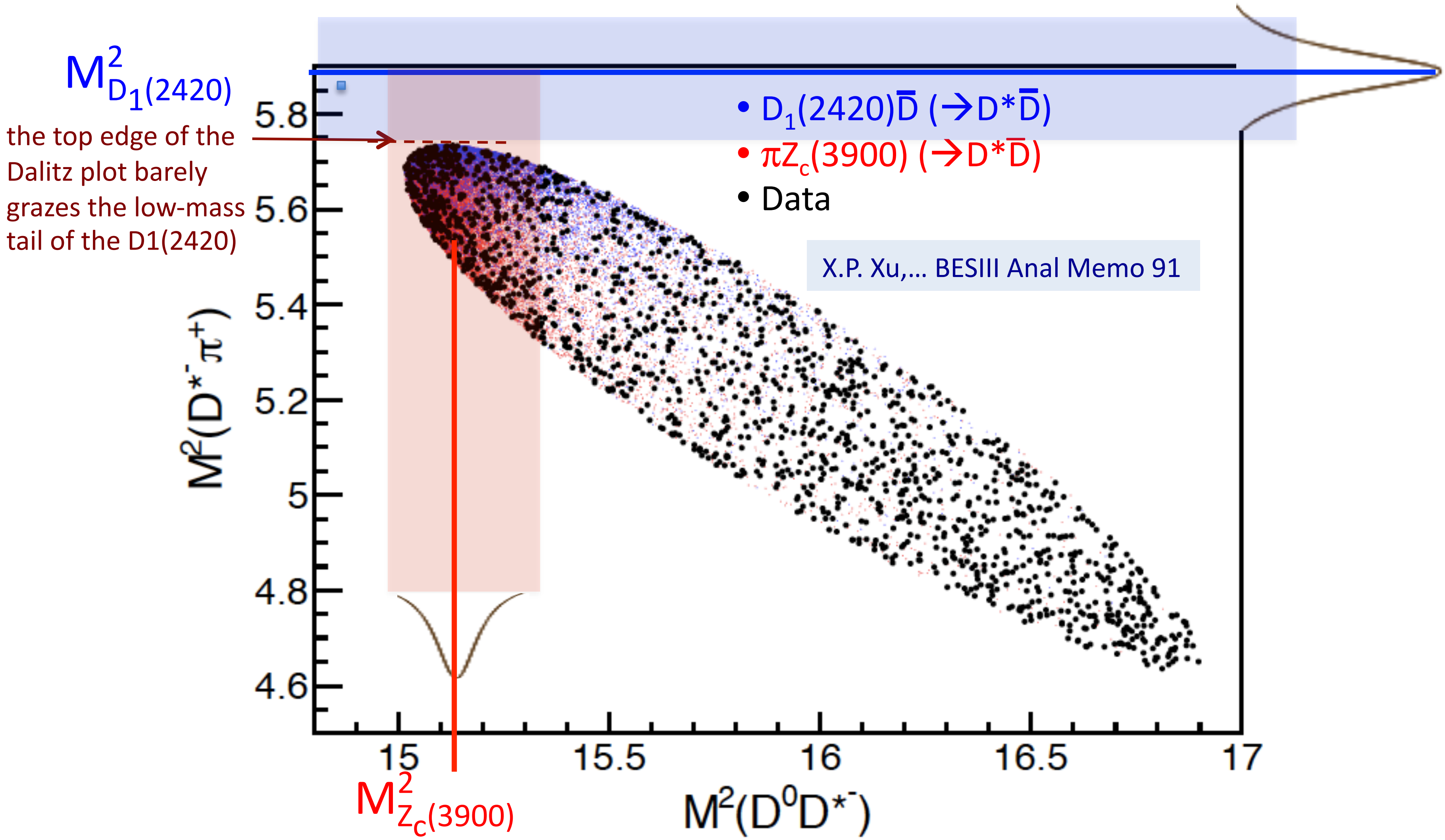
- hadrocharmonium model:

expect $Bf(Y(4260) \to \pi\pi\, J/\psi) >> Bf(Y(4260) \to \omega\, \chi_{c0})$

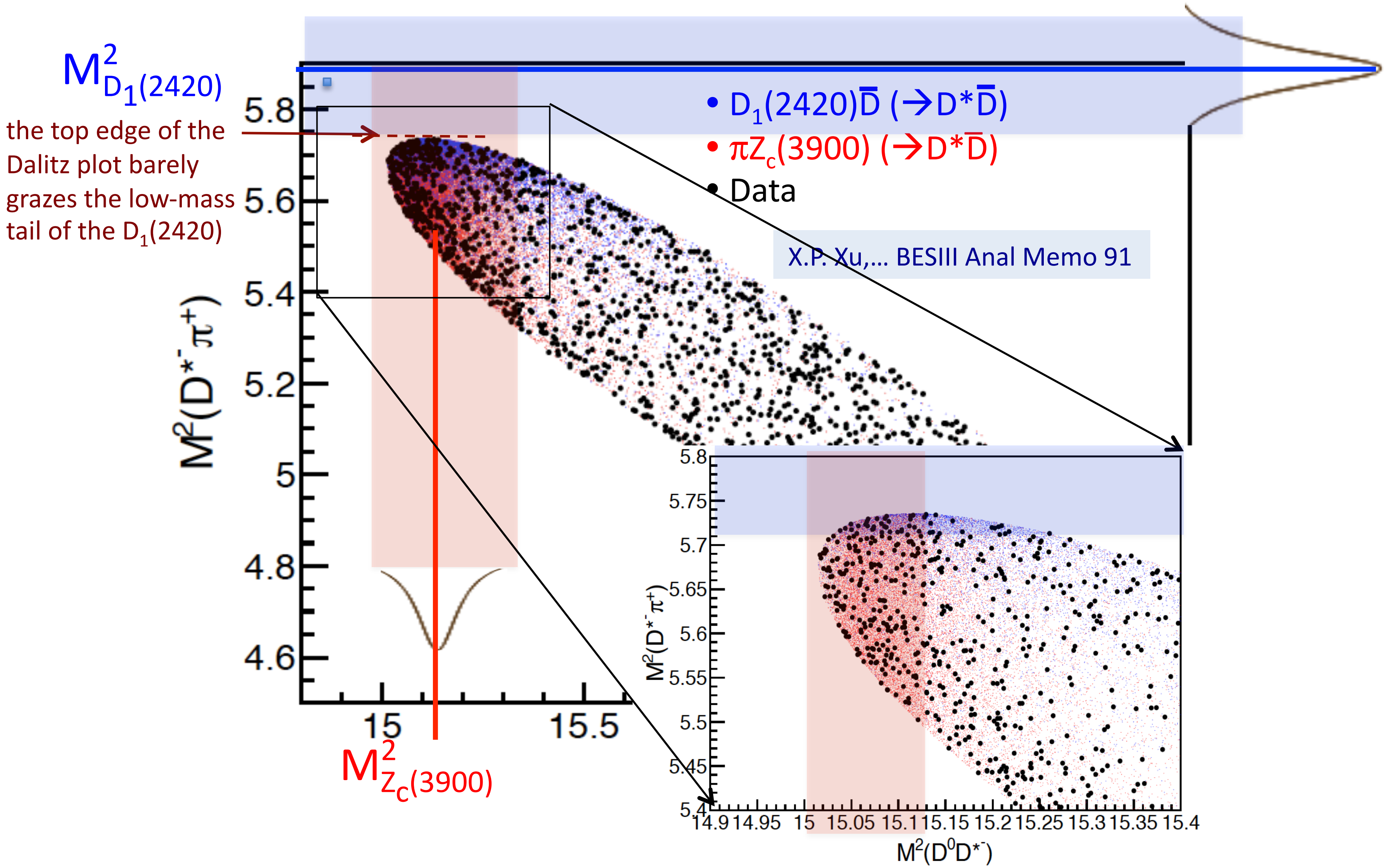
$e^+e^- \to \pi D\bar{D}^*$ @ E_{cm}=4260 MeV Dalitz plot



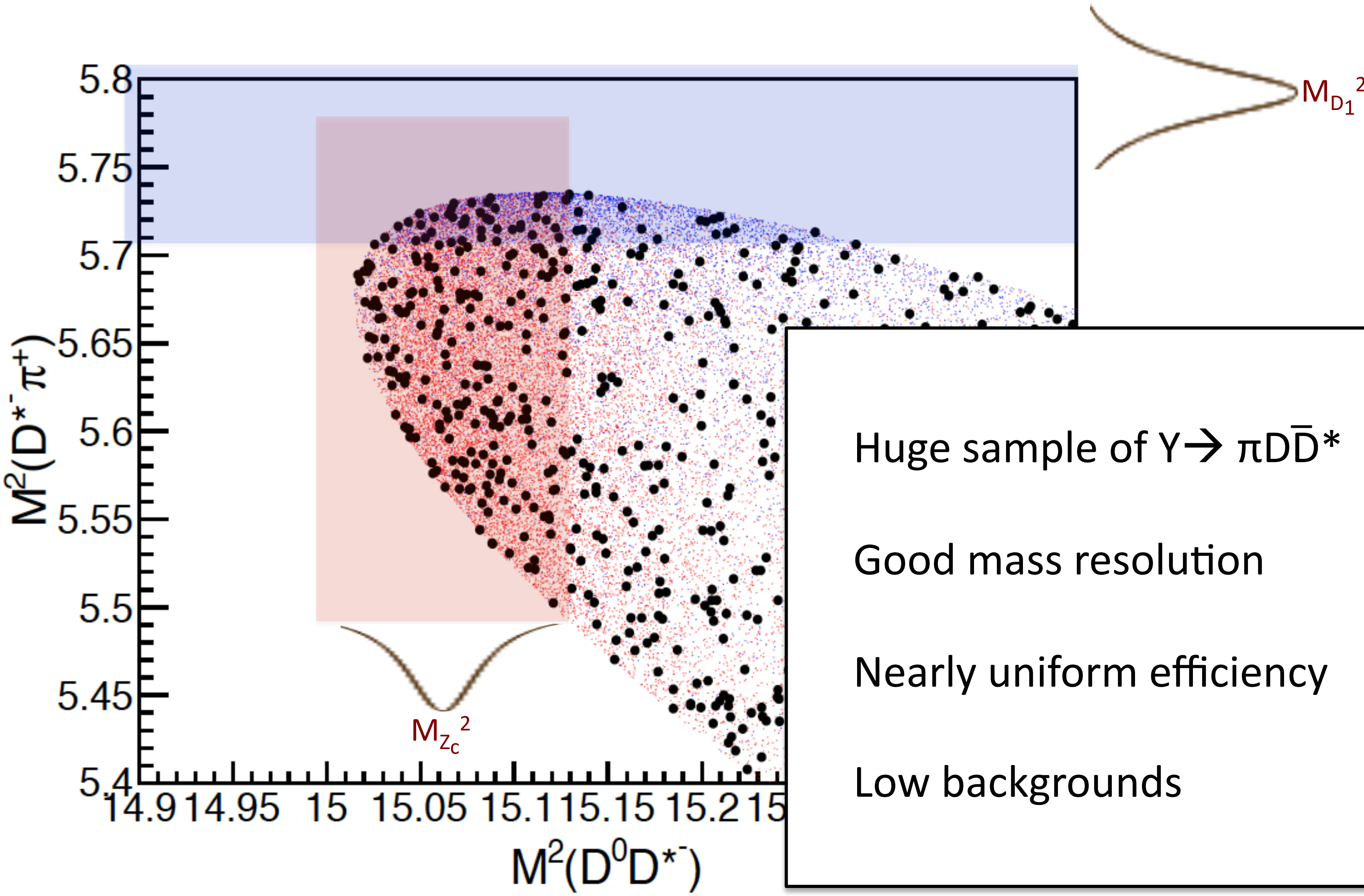
$e^+e^- \to \pi D\bar{D}^*$ @ E_{cm}=4260 MeV Dalitz plot



$e^+e^- \to \pi D\bar{D}^*$ @ E_{cm}=4260 MeV Dalitz plot

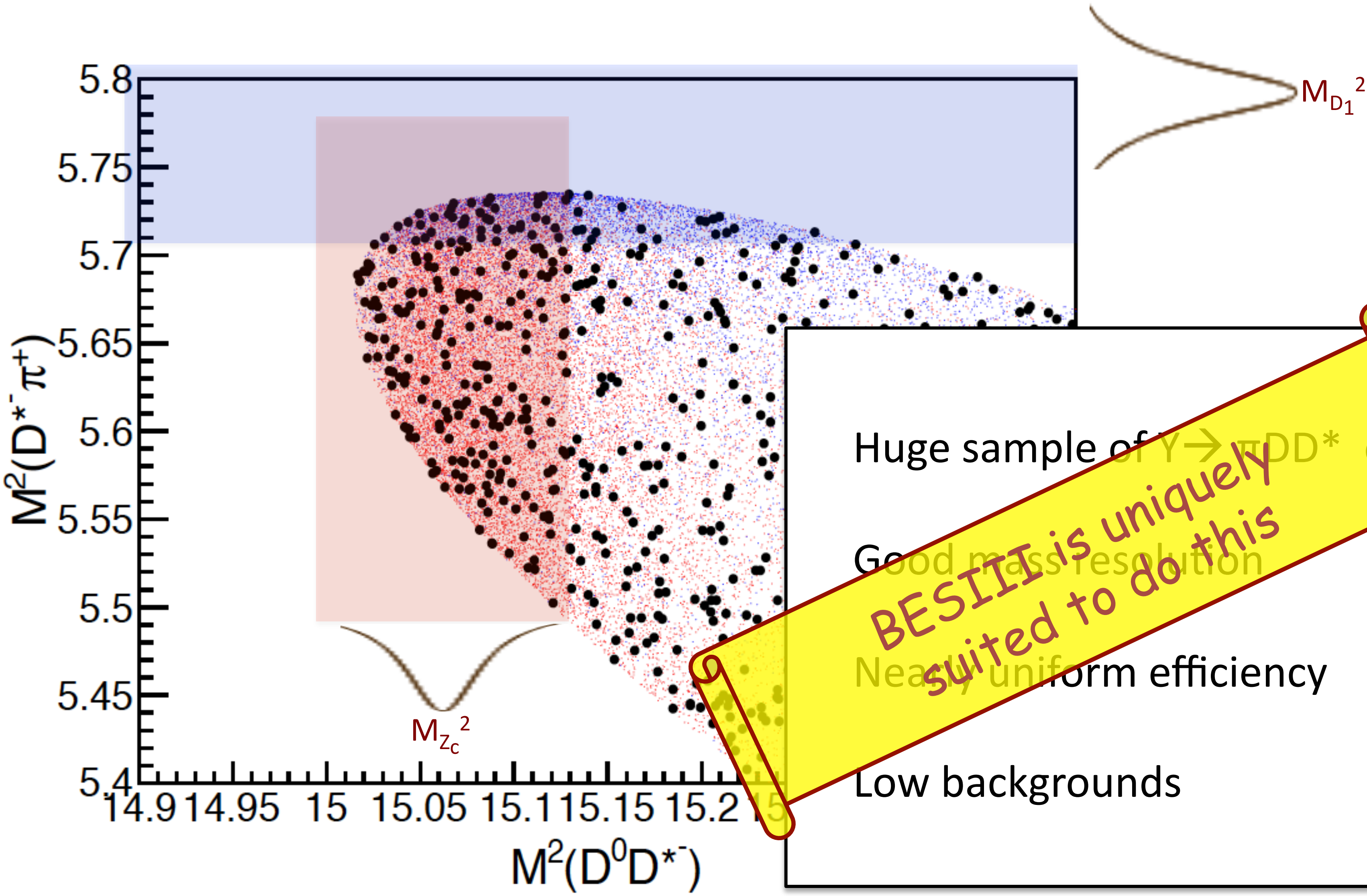


What is needed



- Huge sample of $Y \rightarrow \pi D\bar{D}^*$ evts
- Good mass resolution
- Nearly uniform efficiency
- Low backgrounds

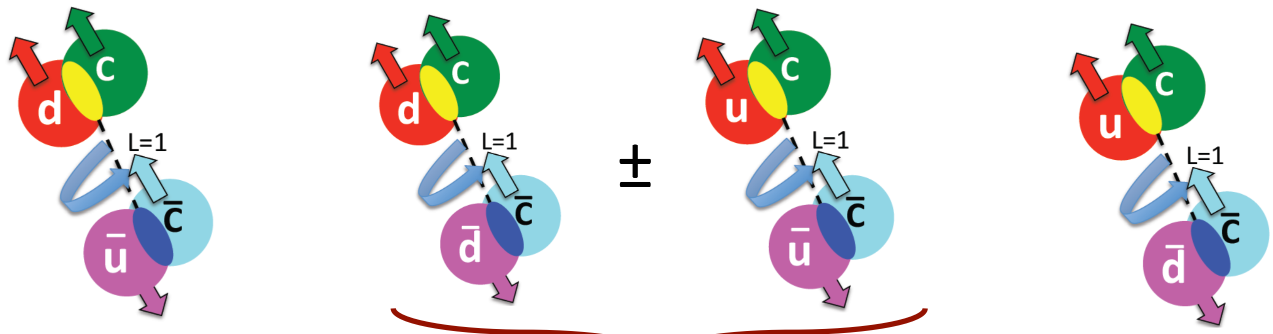
What is needed



- Huge sample of $Y \rightarrow \pi D D^*$ evts
- Good mass resolution
- Nearly uniform efficiency
- Low backgrounds

BESIII is uniquely suited to do this

Partner states?



$Y^-(I=1;I_z=-1)$ +: $Y^0(I=1;I_z=0)$ $Y^+(I=1;I_z=+1)$

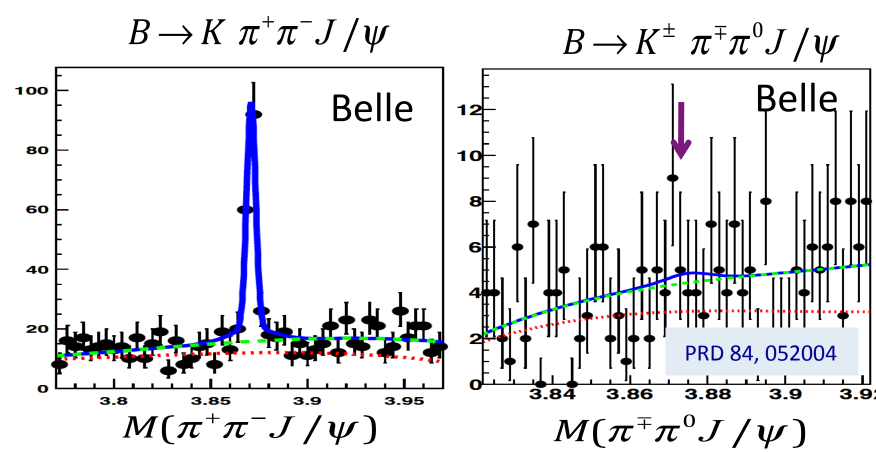
I=1, 1^{--} states have not been seen

—need to look at $\pi J/\psi$ or $\pi\psi'$—

-: $Y^0(I=0;I_z=0)$

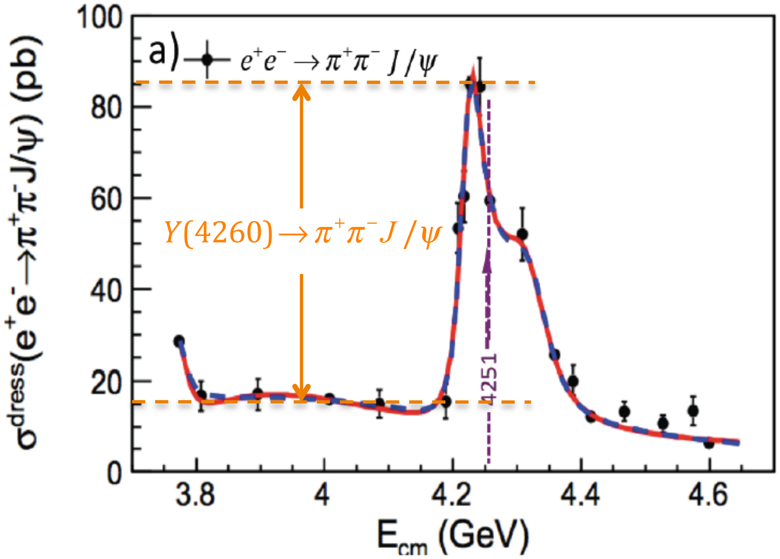
Y(4260)?

(same for X(3872). BaBar & Belle searches for B→K"$X^\pm$"; "$X^\pm$"→ $\rho^\pm$ J/ψ found nothing):

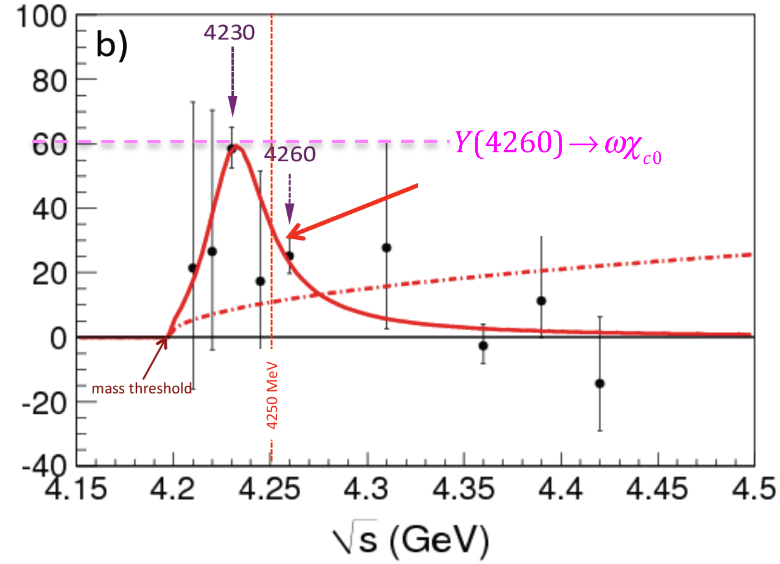


$Bf(Y(4260)\rightarrow\pi\pi J/\psi)$ *vs* $Bf(Y(4260)\rightarrow\omega\chi_{c0})$

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



$e^+e^- \to \omega\chi_{c0}$



$Bf(Y(4260) \to \pi^+\pi^- J/\psi) \approx Bf(Y(4260) \to \omega\chi_{c0}) \Leftarrow$ within a factor of ~ 2

$\cancel{Bf(Y(4260) \to \pi^+\pi^- J/\psi) \gg Bf(Y(4260) \to \omega\chi_{c0})} \Leftarrow$ not the case

What is the Y(4260)?

The Y(4260) mass is lower and width narrower than previously thought

"Y(4260)" → Y(4220)?

If it is a $D\bar{D}_1$(2420) molecule:

B.E. ≈ 66 MeV ← too large??

"affinity" to $D\bar{D}_1$(2420) should be high

If it is a $c\bar{c}$-gluon hybrid:

its mass is ~65 MeV below current (m_π≈400 MeV) LQCD predictions ← not so bad?

"affinity" to $D\bar{D}_0$(2400) should be high

If it is a QCD diquark–diantiquark tetraquark:

it should have Isospin- & $SU_F(3)$-multiplet partner states ← not seen

If it is hadrocharmonium:

decays to non-J/ψ(h_c) charmonium states should be suppressed ← they aren't

BESIII is well suited to further investigate this intriguing puzzle ← a "Y(4260)" factory

Big job/opportunity for BESIII

Summary

The study of the spectrum of hadrons has taught us lots of physics
- -- discovery of flavor
- -- prediction of quarks
- -- etc.

After 70 years of research, the hadron spectrum is not well understood

There are many interesting puzzles, with new ones appearing every year

We need a major breakthrough or a new revolutionary idea

The BESIII experiment is well suited to make such a major breakthrough

Thank you for your attention and interesting questions & comments