Spectroscopy of Exotic States

Stefano Spataro

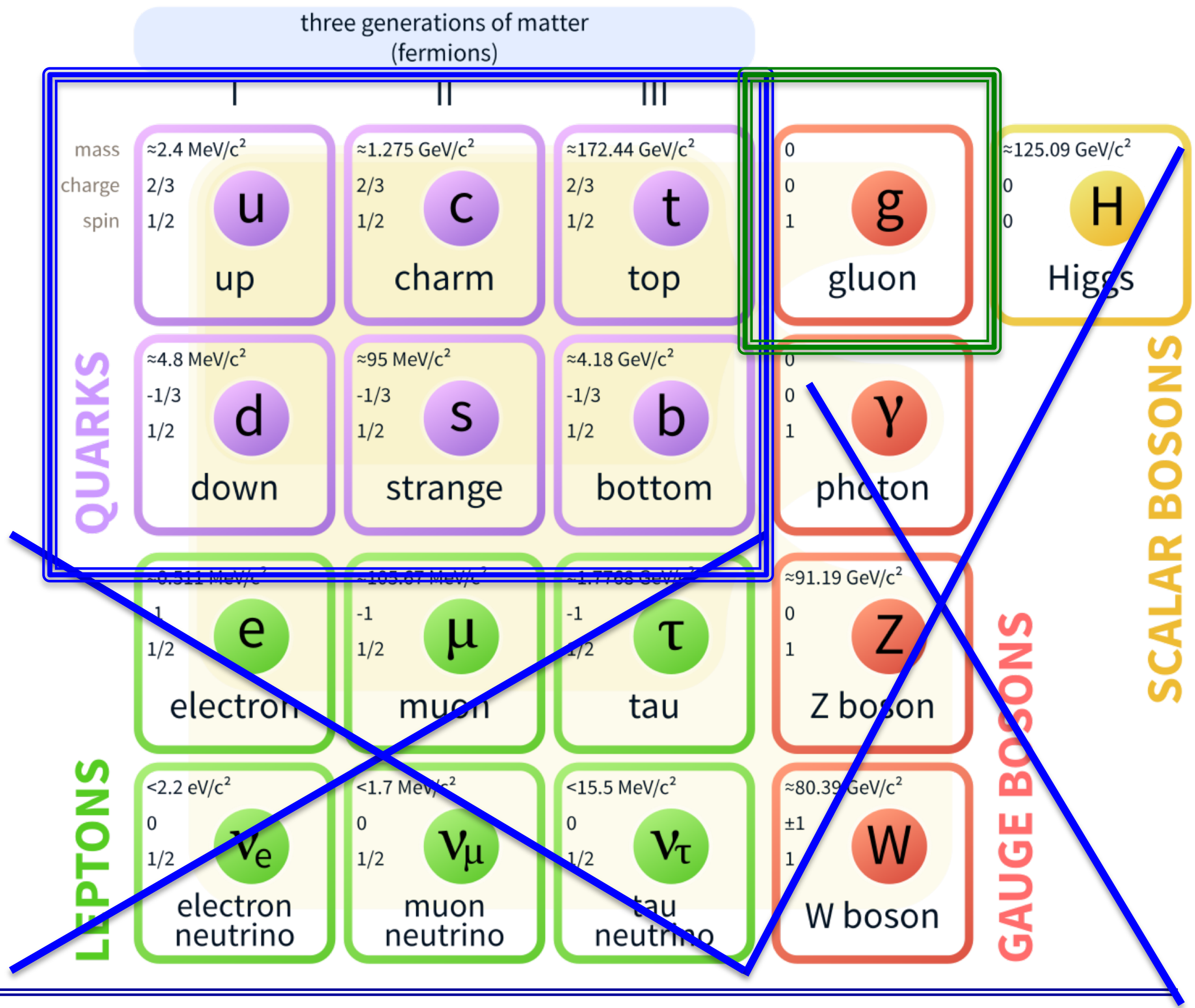
UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

INFN
ISTITUTO NAZIONALE DI FISICA NUCLEARE
Sezione di Torino

What is a Hadron?

Hadrons are particles which undergo strong interaction

Particles
made of quarks
(but also gluons)



Quantum Chromo Dynamics

$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j \left(i\gamma^\mu D_\mu + m_j \right) q_j$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

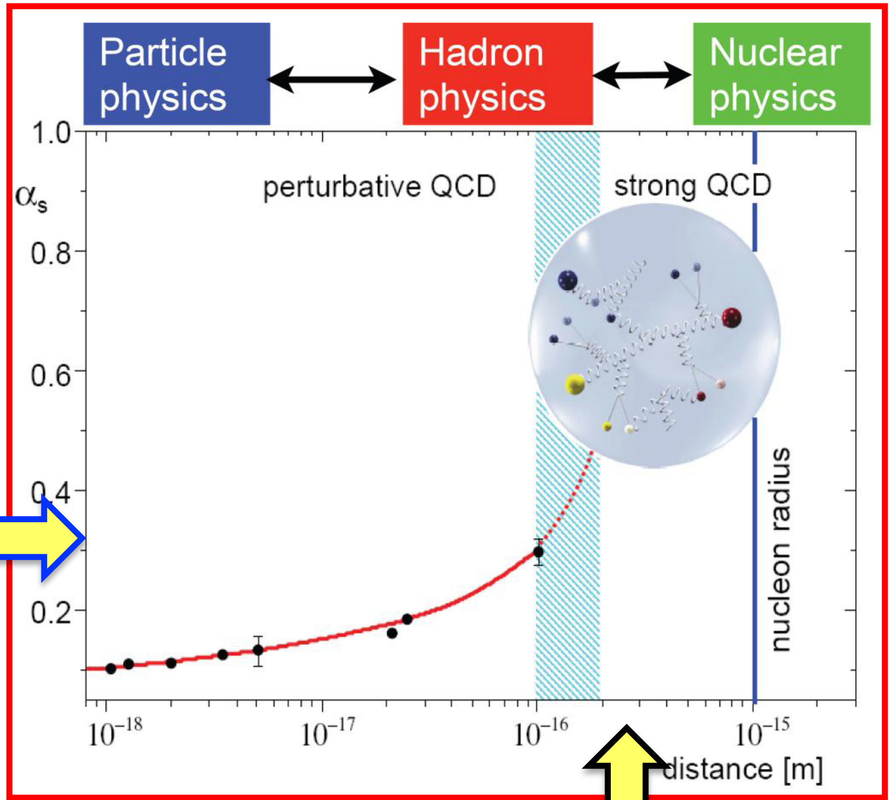
and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

That's it!

QCD gives a complete description of the strong interaction

but it leads to equations hard to solve

The QCD Running Coupling



At small distances (high Q) the interaction is mild

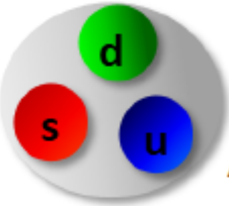
asymptotic freedom

perturbative theory can be used

At large distances (energies below Λ_{QCD}) the interaction is intense and perturbative theory cannot be used

confinement

Real Hadrons are color singlet

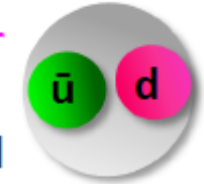


Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

π=ūd

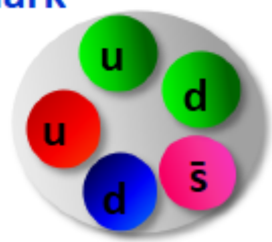


Other possible combinations of quarks and gluons : **eXoTiC**

artistic illustration

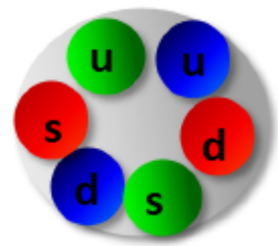
Pentaquark

S= +1 Baryon



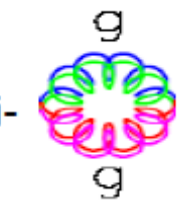
H di-Baryon

Tightly bound 6 quark state



Glueball

Color-singlet multi-gluon bound state

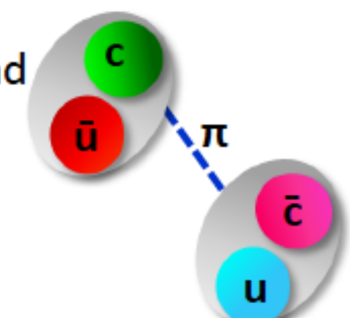


Tetraquark

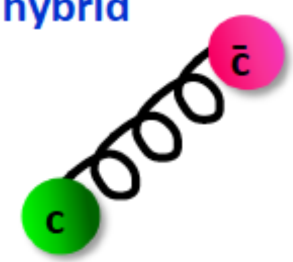
Tightly bound diquark & anti-diquark

Molecule

loosely bound meson-antimeson "molecule"



qq̄ -gluon hybrid mesons



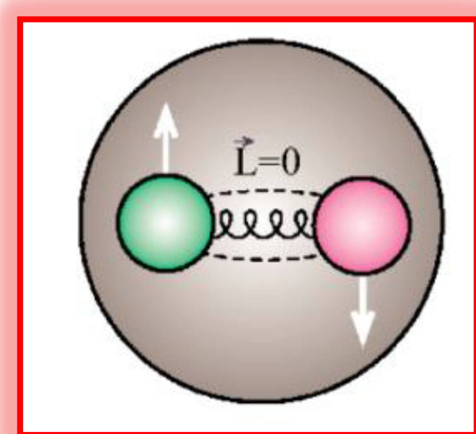
quark-antiquark spectroscopy is the best way to study the quark model

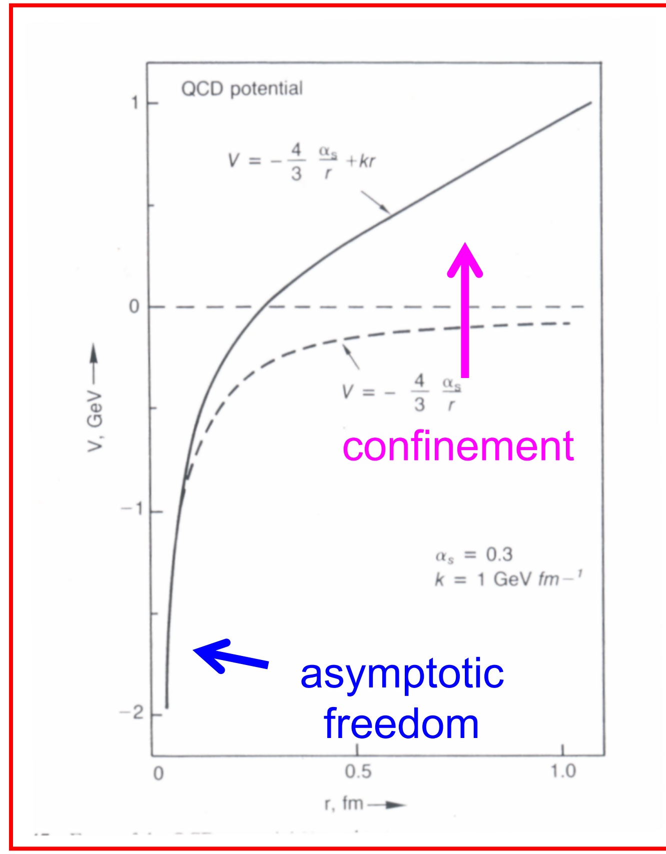
Heavy Quarkonium

$\bar{c}c$ system
$M_c \sim 1.5$ GeV/c^2

$\bar{b}b$ system
$M_b \sim 4.5$ GeV/c^2

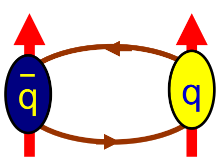
non-relativistic potential model





Heavy Quarkonium states can be calculated !!

similarity with positronium

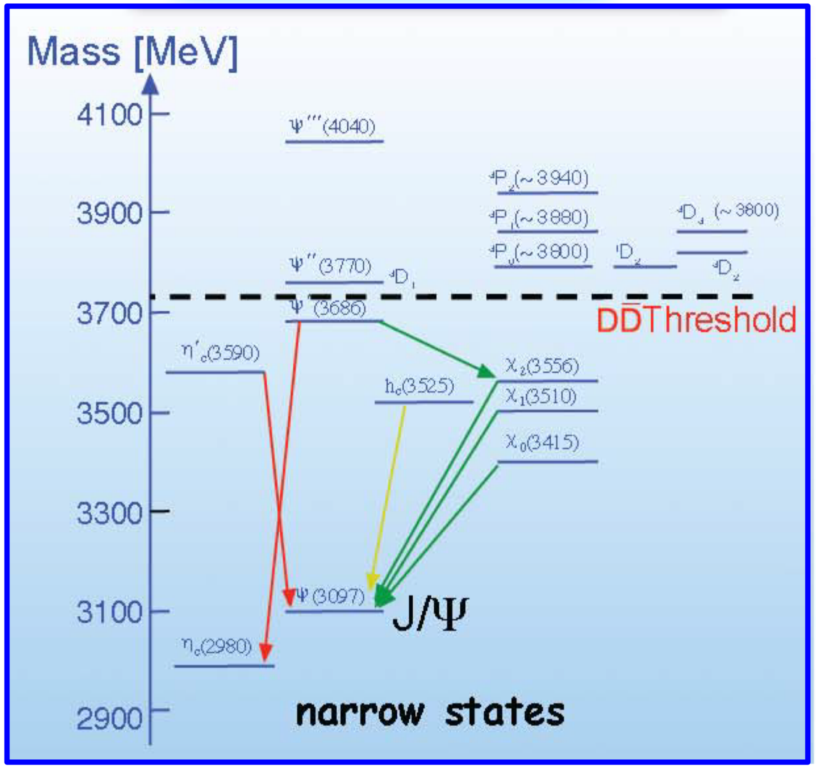


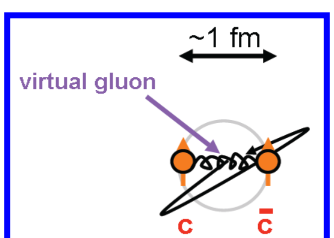
0^{++} ~~0^{+-}~~ 0^{-+} ~~0^{--}~~ 1^{++} 1^{+-} ~~1^{-+}~~ 1^{--} 2^{++} ~~2^{+-}~~ 2^{-+} 2^{--} 3^{++} 3^{+-} ~~3^{-+}~~ 3^{--} …

Note that not all the quantum numbers J^{PC} are allowed in the traditional quark model

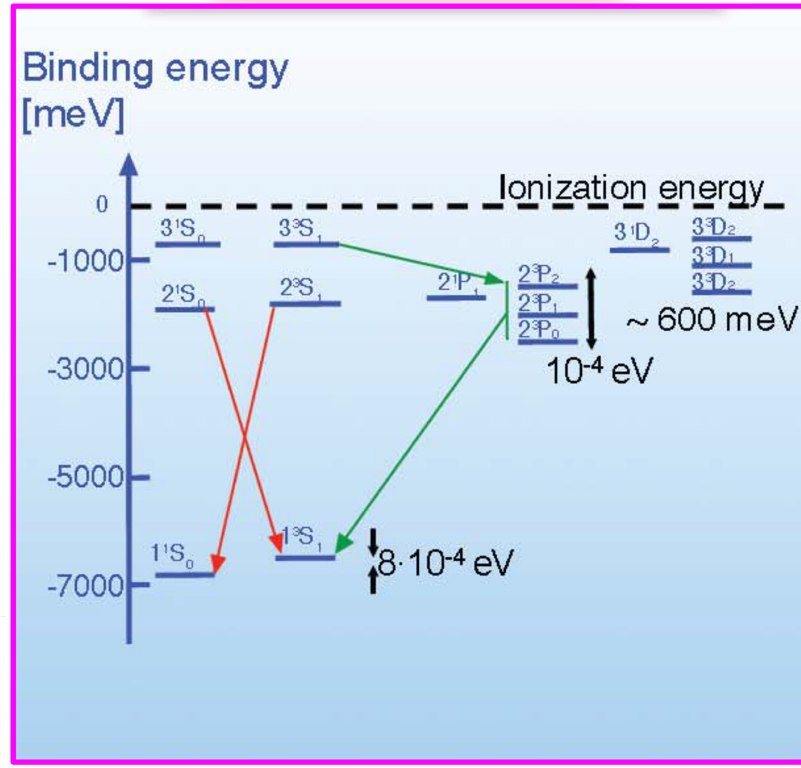
Analogy with QED

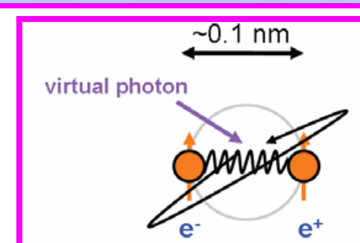
Charmonium



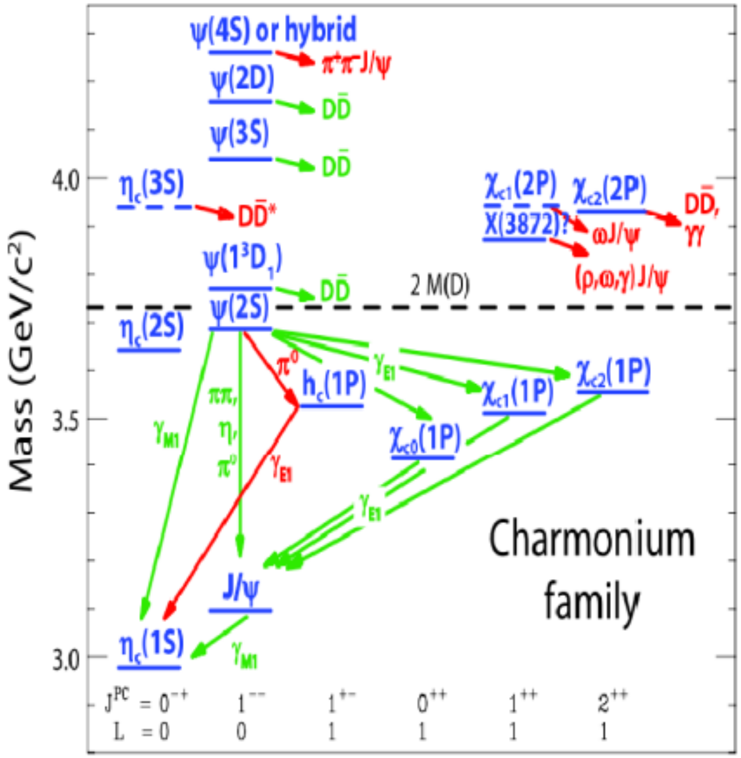


Positronium





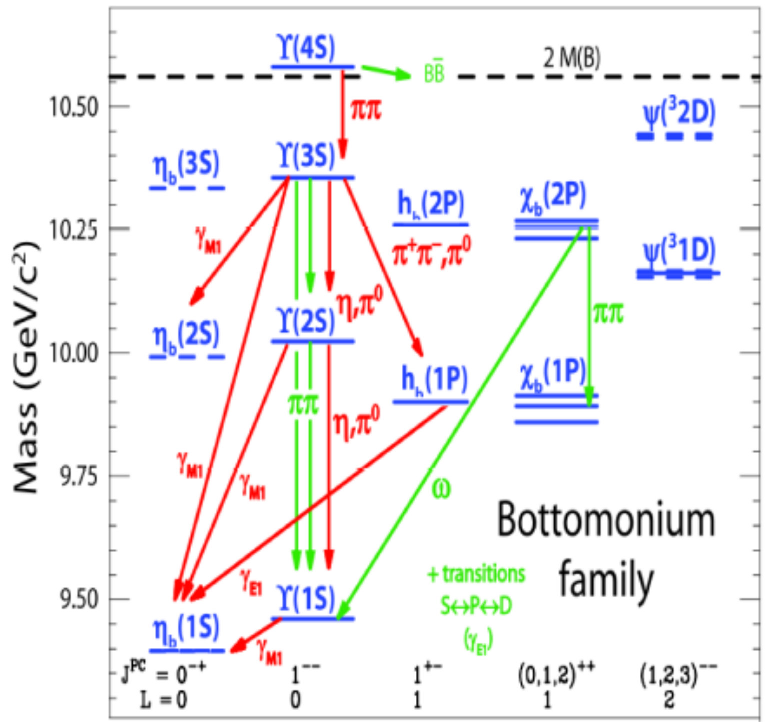
Charmonium vs Bottomonium



2M(D) – M(ψ') = 52.3 MeV

2M(B) – M(Υ(3S)) = 203.1 MeV
2M(B) – M(Υ(2S)) = 535.3 MeV

Richer spectrum below threshold



Next slides will show Charmonium examples, mostly valid also for Bottomonium

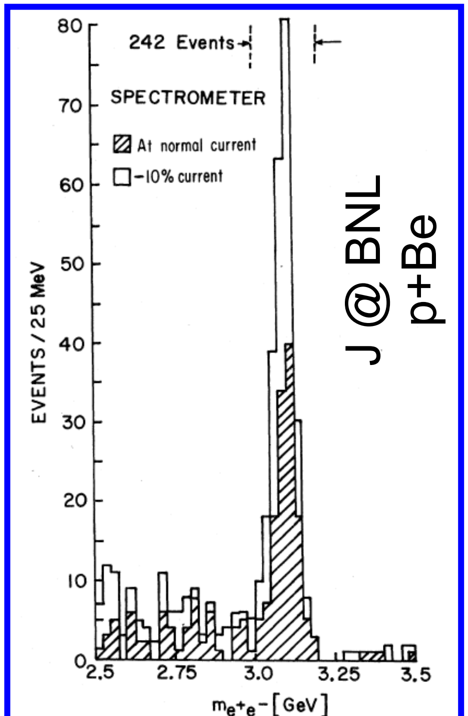
Charmonium history

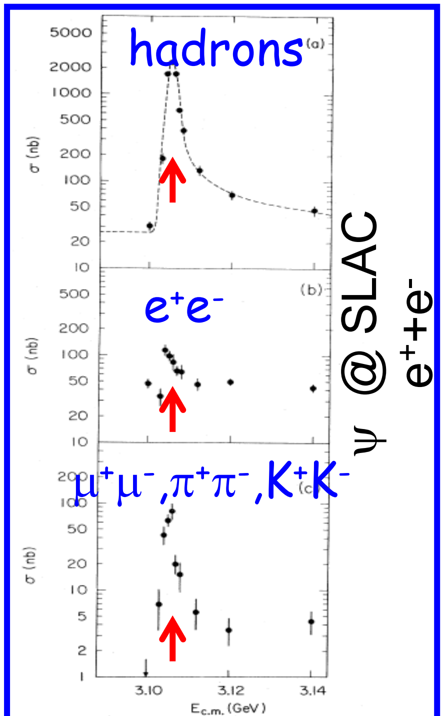
J/ψ discovered at the same time (1974) at SLAC and BNL

and called with different names

J.E. Augustin *et al.*, Mark I, Phys. Rev. Lett. 33, 1406–1408 (psi)

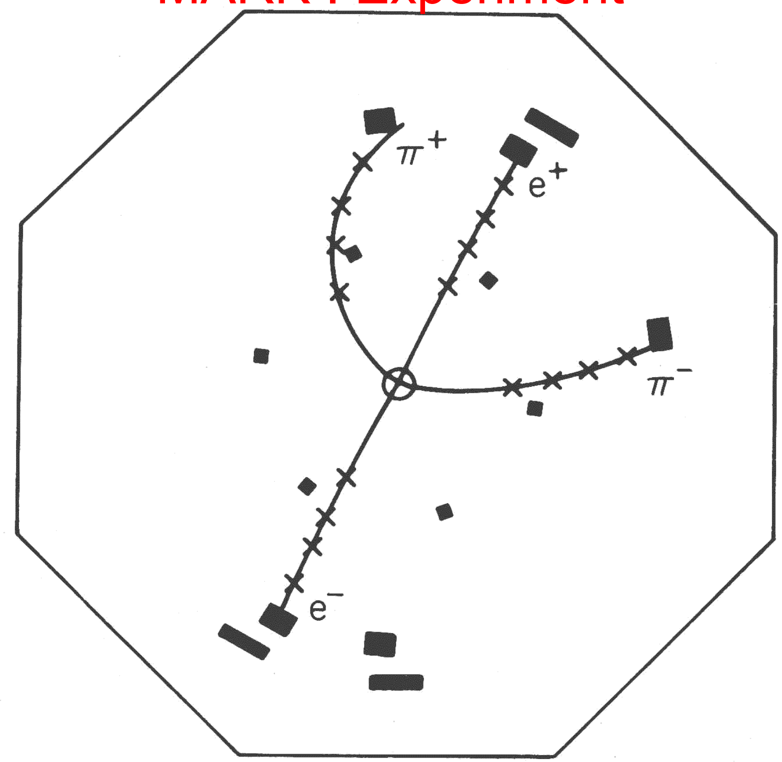
J.J. Aubert *et al.*, BNL, Phys. Rev. Lett. 33, 1404–1406 (J)





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

MARK I Experiment



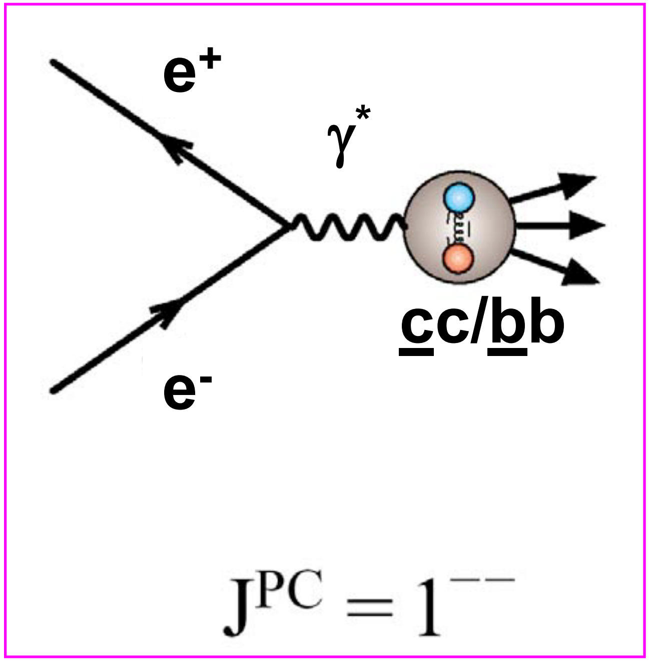
Phys. Rev. Lett. 34, 1181–1183 (1975)

in the paper J/ψ called ψ(3095)

Quarkonium in e^+e^- collisions

Direct Formation

allowed only $J^{PC} = 1^{--}$ states

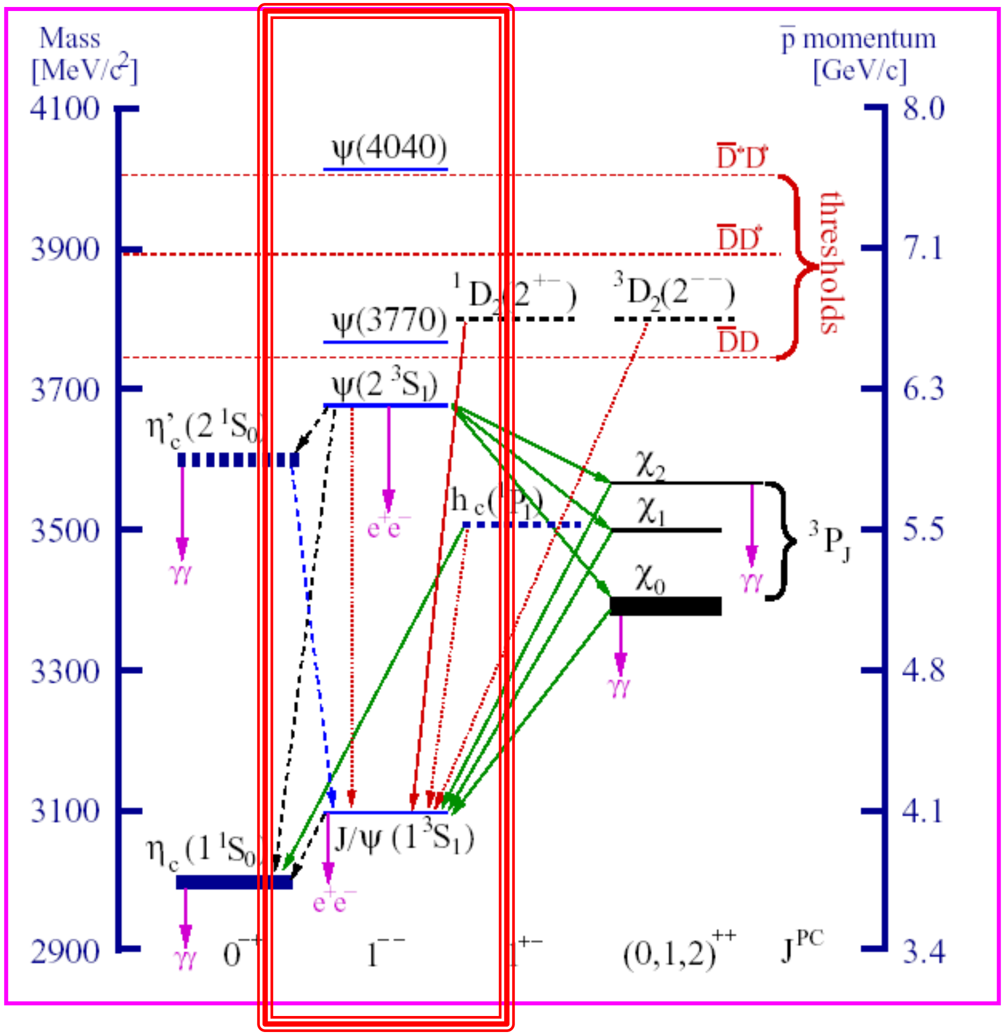


Charm factories

Crystal Ball, CLEO-C, BES

Beauty factories

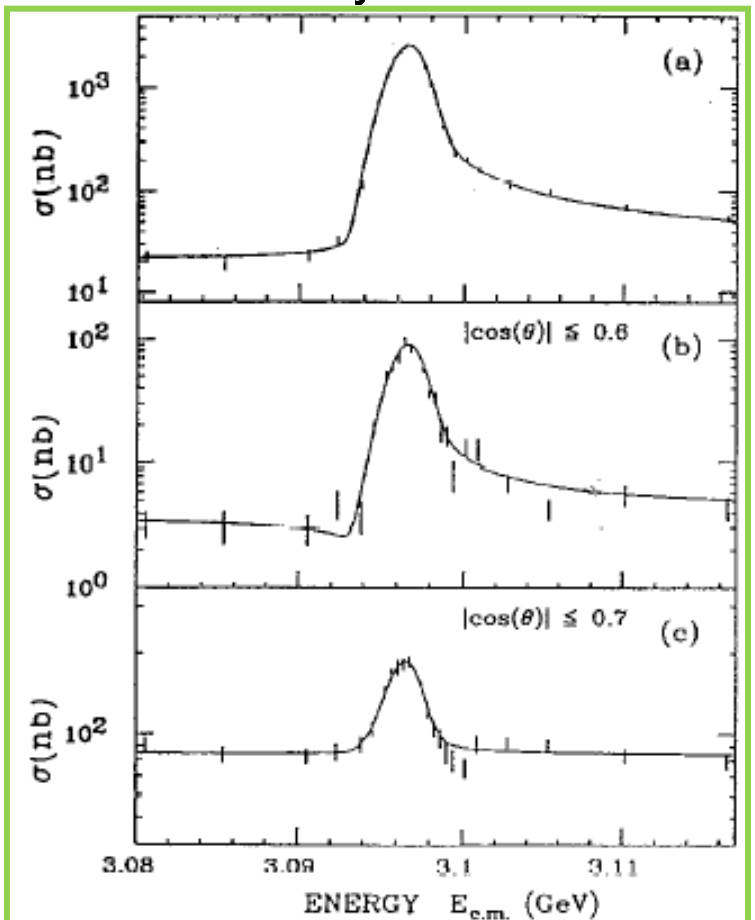
Belle, Babar



Charmonium formation in charm factories

J/Ψ

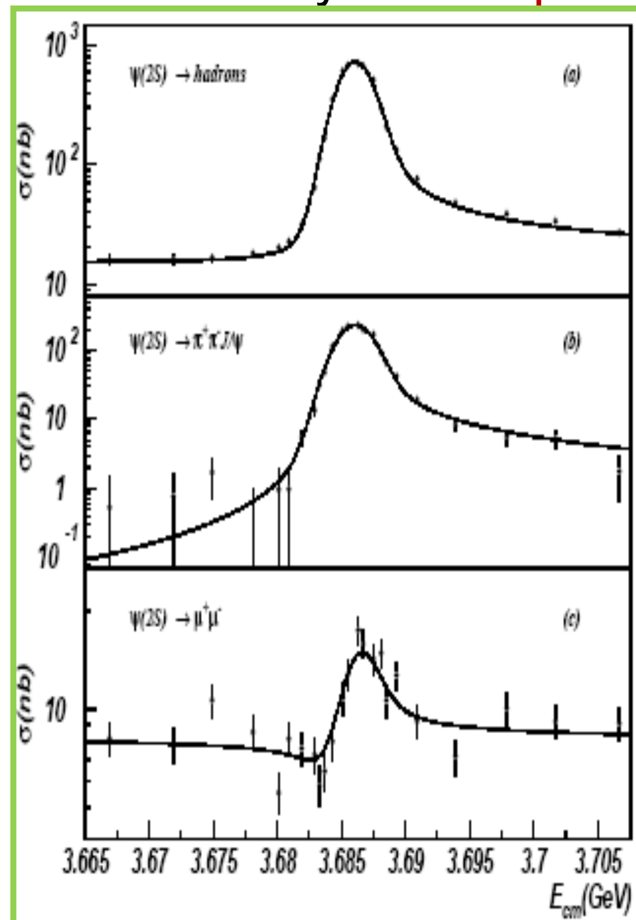
Phys. Lett. B355 (1995) 374
Energy points : 23
Total luminosity : 82.28/nb



BES data

Ψ(2S)

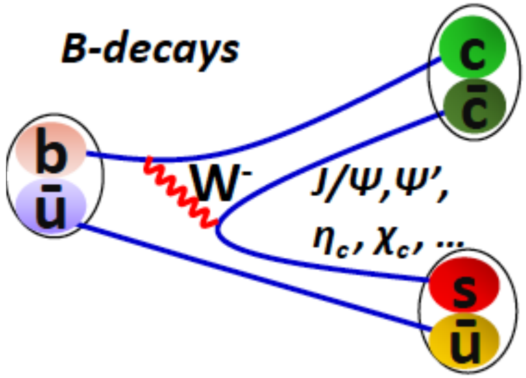
Phys. Lett. B550 (2002) 24
Energy points : 24
Total luminosity : 1.149/pb



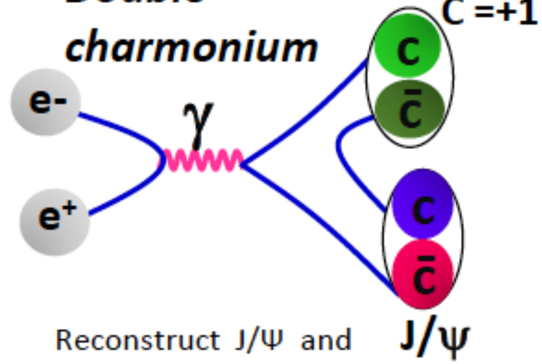
OLD RESULTS, UPDATED BY BESIII

Measuring Charmonium in B-factories

B-decays

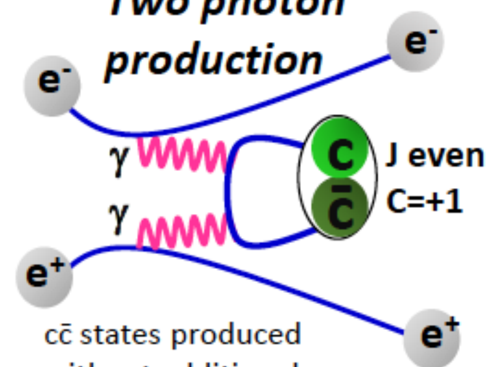


Double charmonium



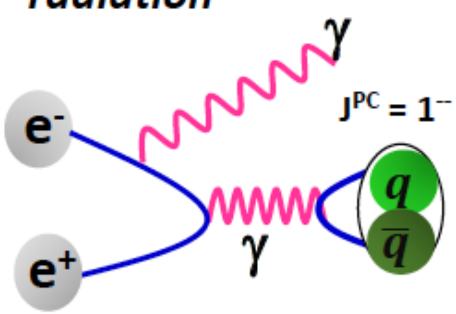
Reconstruct J/Ψ and look at recoil mass

Two photon production



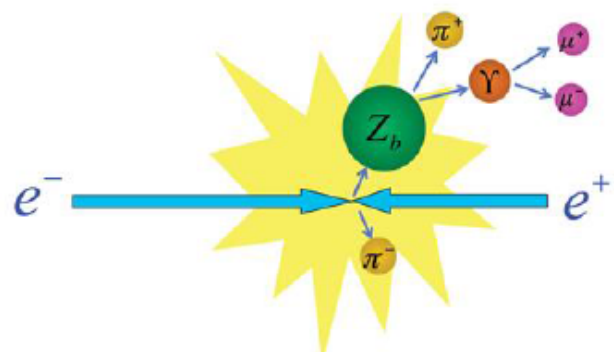
cc̄ states produced without additional hadrons.

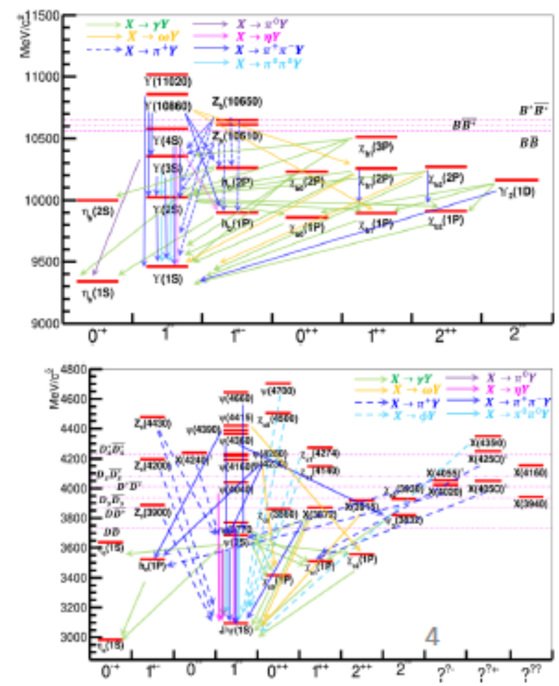
Initial state radiation



Annihilation at smaller energy.

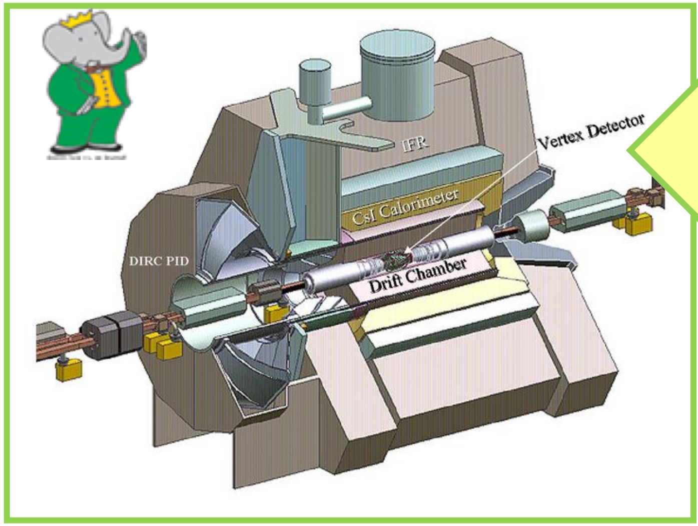
Quarkonium decay/transitions





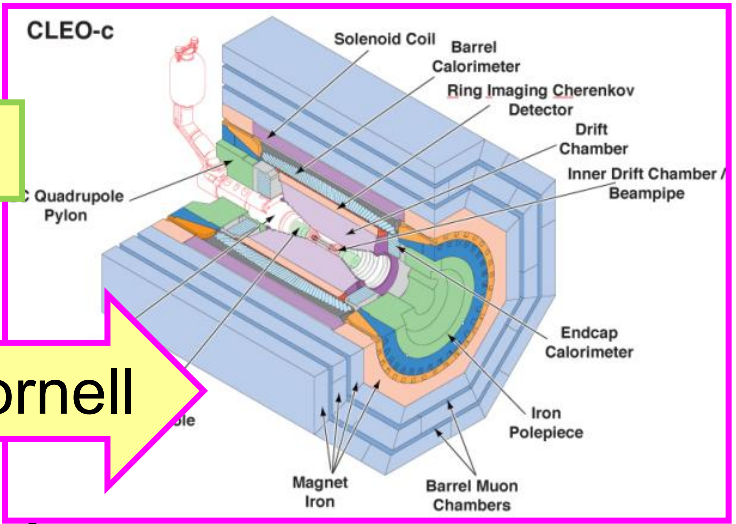
How to measure Charmonium?

First experimental technique: e^+e^- colliders



BaBar @ SLAC

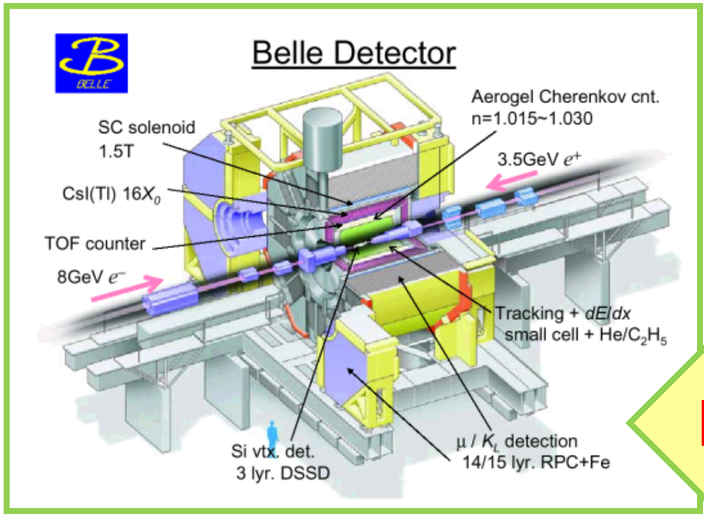
B factory



CLEO @ Cornell

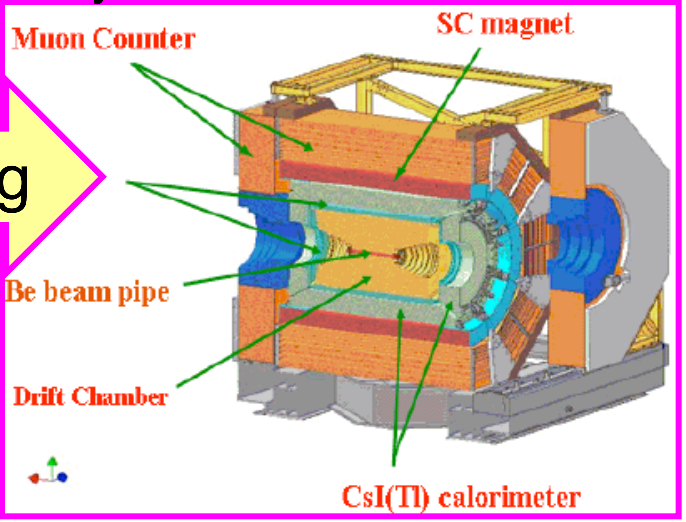
B factory

CLEO-C→Charm factory



BES @ Beijing

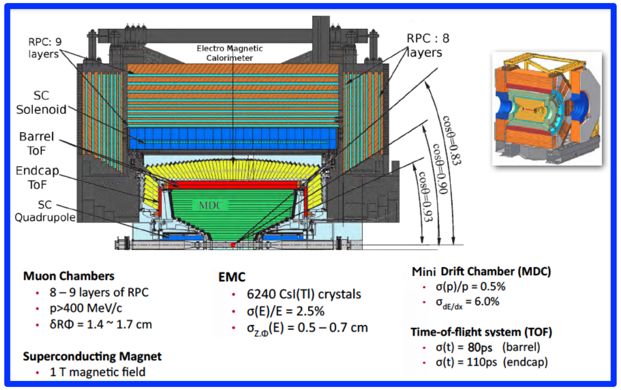
Charm factory



Belle @ KEKB

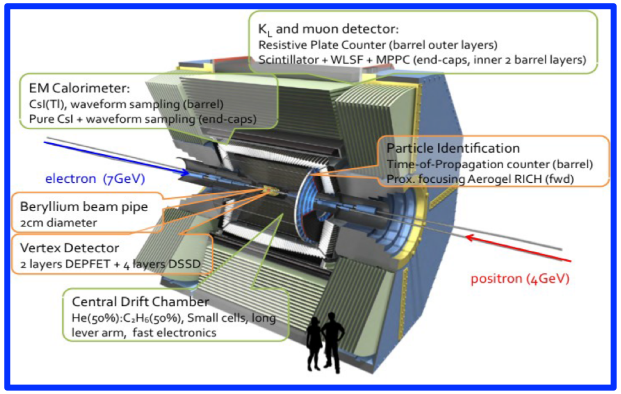
B factory

The current major spectroscopy players



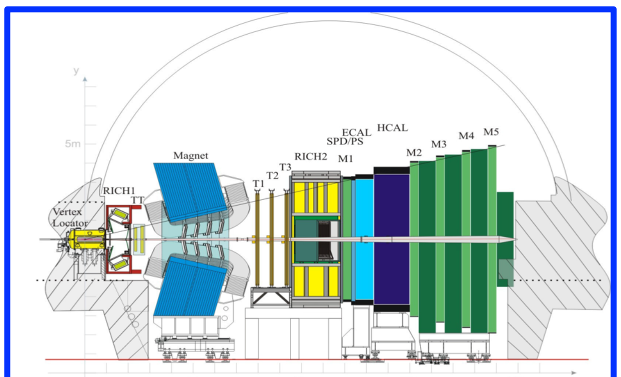
BESIII

- ✓ Charm factory
- ✓ Active in Beijing since 2008
- ✓ You will see a lot of results from here



Belle II

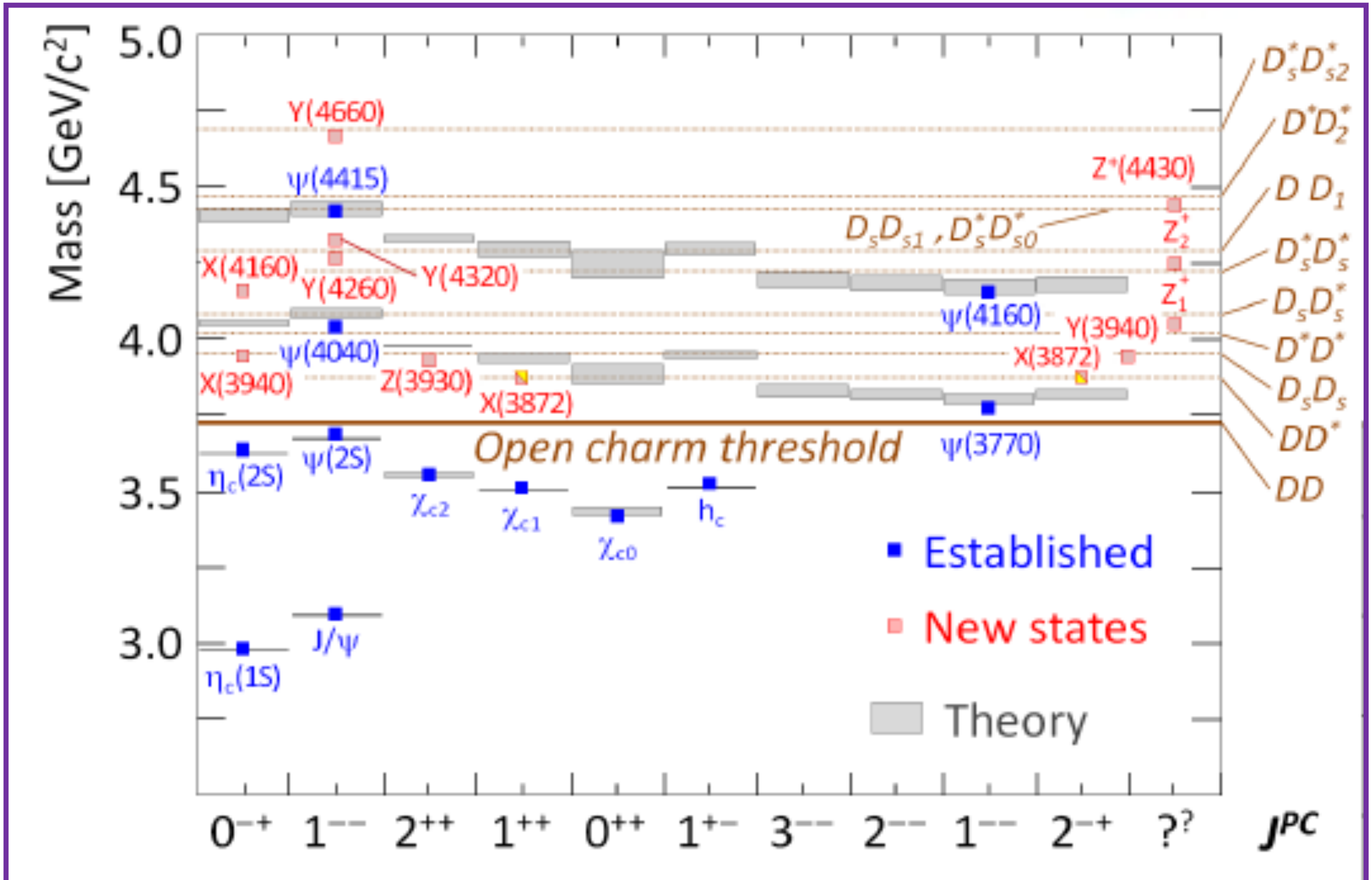
- ✓ Beauty factory
- ✓ Phase 2 commissioning in 2018 has ended
- ✓ Starting phase 3 in 2019



LHCb

- ✓ LHC: p p collisions (hadroproduction)
- ✓ New interesting results from the latest years

The current Charmonium status



New Quarkonium-like resonances

The exotic alphabet

Y – 1^{--} states in e^+e^- collisions

Z – charged states

X – all the remaining cases

NEW

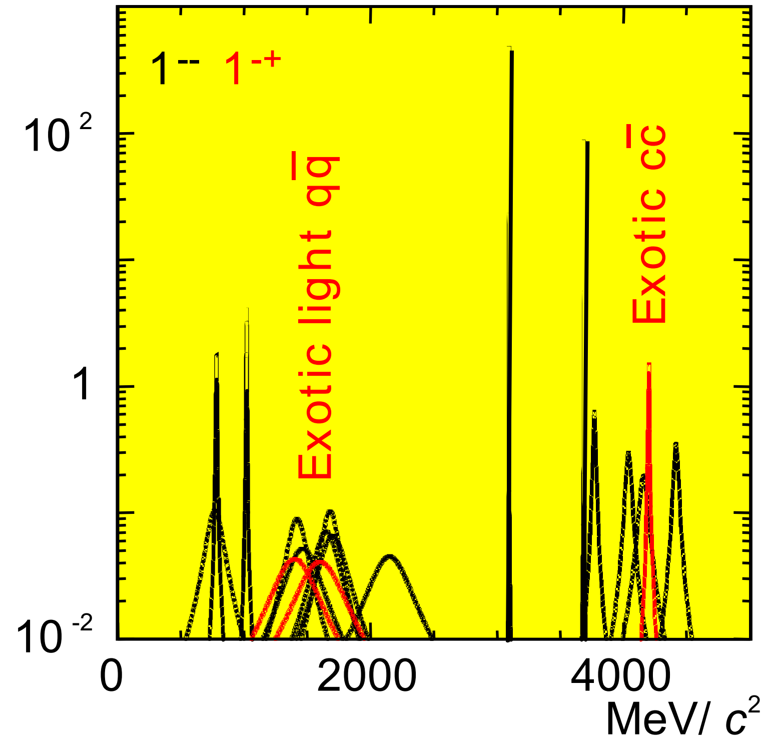
P – Pentaquark Candidates

Particle	$I^G J^{PC}$	Mass [MeV]	Width [MeV]	Production and Decay
$X(3823)$ $(\psi_2(1D))$	(0^-2^{--})	3822.2 ± 1.2 [176]	< 16	$B \to KX;\, X \to \gamma\chi_{c1}$ $e^+e^- \to \pi^+\pi^- X;\, X \to \gamma\chi_{c1}$
$X(3872)$	0^+1^{++}	3871.69 ± 0.17 [176]	< 1.2	$B \to KX;\, X \to \pi^+\pi^- J/\psi$ $B \to KX;\, X \to D^{*0}D^0$ $B \to KX;\, X \to \gamma J/\psi, \gamma\psi(2S)$ $B \to KX;\, X \to \omega J/\psi$ $B \to K\pi X;\, X \to \pi^+\pi^- J/\psi$ $e^+e^- \to \gamma X;\, X \to \pi^+\pi^- J/\psi$ pp or $p\bar{p} \to X$ + any.; $X \to \pi^+\pi^- J/\psi$
$Z_c(3900)$	1^+1^{+-}	3886.6 ± 2.4 [176]	28.1 ± 2.6	$e^+e^- \to \pi Z;\, Z \to \pi J/\psi$ $e^+e^- \to \pi Z;\, Z \to D^* D$
$X(3915)$	0^+0^{++}	3918.4 ± 1.9 [176]	20 ± 5	$\gamma\gamma \to X;\, X \to \omega J/\psi$
$Y(3940)$				$B \to KX;\, X \to \omega J/\psi$
$Z(3930)$ $(\chi_{c2}(2P))$	0^+2^{++}	3927.2 ± 2.6 [176]	24 ± 6	$\gamma\gamma \to Z;\, Z \to DD$
$X(3940)$		$3942^{+7}_{-6} \pm 6$ [41]	$37^{+26}_{-15} \pm 8$	$e^+e^- \to J/\psi + X;\, X \to DD^*$
$Y(4008)$	1^{--}	$3891 \pm 41 \pm 12$ [23]	$255 \pm 40 \pm 14$	$e^+e^- \to Y;\, Y \to \pi^+\pi^- J/\psi$
$Z_c(4020)$	$1^+?^{?-}$	4024.1 ± 1.9 [176]	13 ± 5	$e^+e^- \to \pi Z;\, Z \to \pi h_c$ $e^+e^- \to \pi Z;\, Z \to D^* D^*$
$Z_1(4050)$	$1^-?^{?+}$	$4051 \pm 14^{+20}_{-41}$ [133]	82^{+21+47}_{-17-22}	$B \to KZ;\, Z \to \pi^\pm\chi_{c1}$
$Z_c(4055)$	$1^+?^{?-}$	$4054 \pm 3 \pm 1$ [148]	$45 \pm 11 \pm 6$	$e^+e^- \to \pi^+ Z;\, Z \to \pi^\pm\psi(2S)$
$Y(4140)$	0^+1^{++}	$4146.5 \pm 4.5^{+4.6}_{-2.8}$ [125]	$83 \pm 21^{+21}_{-14}$	$B \to KY;\, Y \to \phi J/\psi$ pp or $p\bar{p} \to Y$ + any.; $Y \to \phi J/\psi$
$X(4160)$		$4156^{+25}_{-20} \pm 15$ [41]	$139^{+111}_{-61} \pm 21$	$e^+e^- \to J/\psi + X;\, X \to D^* D^*$
$Z_c(4200)$	1^+1^{+-}	4196^{+31+17}_{-29-13} [46]	$370^{+70+70}_{-70-132}$	$B \to KZ;\, Z \to \pi^\pm J/\psi$
$Y(4230)$	0^-1^{--}	$4230 \pm 8 \pm 6$ [149]	$38 \pm 12 \pm 2$	$e^+e^- \to Y;\, Y \to \omega\chi_{c0}$
$Z_c(4240)$	1^+0^{--}	$4239 \pm 18^{+45}_{-10}$ [138]	$220 \pm 47^{+108}_{-74}$	$B \to KZ;\, Z \to \pi^\pm\psi(2S)$
$Z_2(4250)$	$1^-?^{?+}$	$4248^{+44+180}_{-29-35}$ [133]	$177^{+54+316}_{-39-61}$	$B \to KZ;\, Z \to \pi^\pm\chi_{c1}$
$Y(4260)$	0^-1^{--}	4251 ± 9 [176]	120 ± 12	$e^+e^- \to Y;\, Y \to \pi\pi J/\psi$
$Y(4274)$	0^+1^{++}	$4273.3 \pm 8.3^{+17.2}_{-3.6}$ [125]	$52 \pm 11^{+8}_{-11}$	$B \to KY;\, Y \to \phi J/\psi$
$X(4350)$	$0^+?^{?+}$	$4350.6^{+4.6}_{-5.1} \pm 0.7$ [170]	$13^{+18}_{-9} \pm 4$	$\gamma\gamma \to X;\, X \to \phi J/\psi$
$Y(4360)$	1^{--}	4346 ± 6 [176]	102 ± 10	$e^+e^- \to Y;\, Y \to \pi^+\pi^-\psi(2S)$
$Z_c(4430)$	1^+1^{+-}	4478^{+15}_{-18} [176]	181 ± 31	$B \to KZ;\, Z \to \pi^\pm J/\psi$ $B \to KZ;\, Z \to \pi^\pm\psi(2S)$
$X(4500)$	0^+0^{++}	$4506 \pm 11^{+12}_{-15}$ [125]	$92 \pm 21^{+21}_{-20}$	$B \to KX;\, X \to \phi J/\psi$
$X(4630)$	1^{--}	4634^{+8+5}_{-7-8} [150]	92^{+40+10}_{-24-21}	$e^+e^- \to X;\, X \to \Lambda_c\bar{\Lambda}_c$
$Y(4660)$	1^{--}	4643 ± 9 [176]	72 ± 11	$e^+e^- \to Y;\, Y \to \pi^+\pi^-\psi(2S)$
$X(4700)$	0^+0^{++}	$4704 \pm 10^{+14}_{-24}$ [125]	$120 \pm 31^{+42}_{-33}$	$B \to KX;\, X \to \phi J/\psi$
$P_c(4380)$		$4380 \pm 8 \pm 29$ [35]	$205 \pm 18 \pm 86$	$\Lambda_b \to KP_c;\, P_c \to pJ/\psi$
$P_c(4450)$		$4449.8 \pm 1.7 \pm 2.5$ [35]	$39 \pm 5 \pm 19$	$\Lambda_b \to KP_c;\, P_c \to pJ/\psi$
$X(5568)$		$5567.8 \pm 2.9^{+0.9}_{-1.9}$ [175]	$21.9 \pm 6.4^{+5.0}_{-2.5}$	$p\bar{p} \to X$ + anything; $X \to B_s\pi^\pm$
$Z_b(10610)$	1^+1^{+-}	10607.2 ± 2.0 [176]	18.4 ± 2.4	$e^+e^- \to \pi Z;\, Z \to \pi\Upsilon(1S,2S,3S)$ $e^+e^- \to \pi Z;\, Z \to \pi h_b(1P,2P)$ $e^+e^- \to \pi Z;\, Z \to BB^*$
$Z_b(10650)$	1^+1^{+-}	10652.2 ± 1.5 [176]	11.5 ± 2.2	$e^+e^- \to \pi Z;\, Z \to \pi\Upsilon(1S,2S,3S)$ $e^+e^- \to \pi Z;\, Z \to \pi h_b(1P,2P)$ $e^+e^- \to \pi Z;\, Z \to B^* B^*$
$Y_b(10888)$	0^-1^{--}	10891 ± 4 [176]	54 ± 7	$e^+e^- \to Y;\, Y \to \pi\pi\Upsilon(1S,2S,3S)$ $e^+e^- \to Y;\, Y \to \pi\pi h_b(1P,2P)$

Exotic States in Charm sector

Why not al lower energies?

- At low energy high state density
- Mixing and broad widths complicate the interpretation

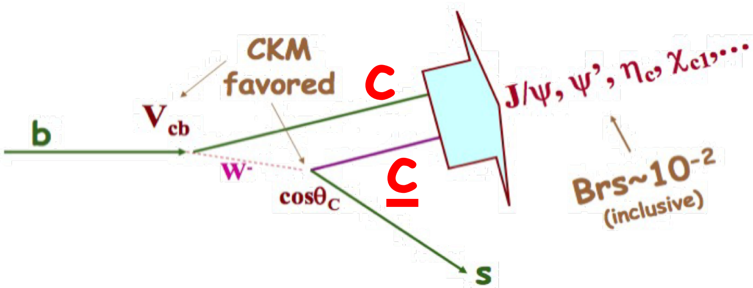


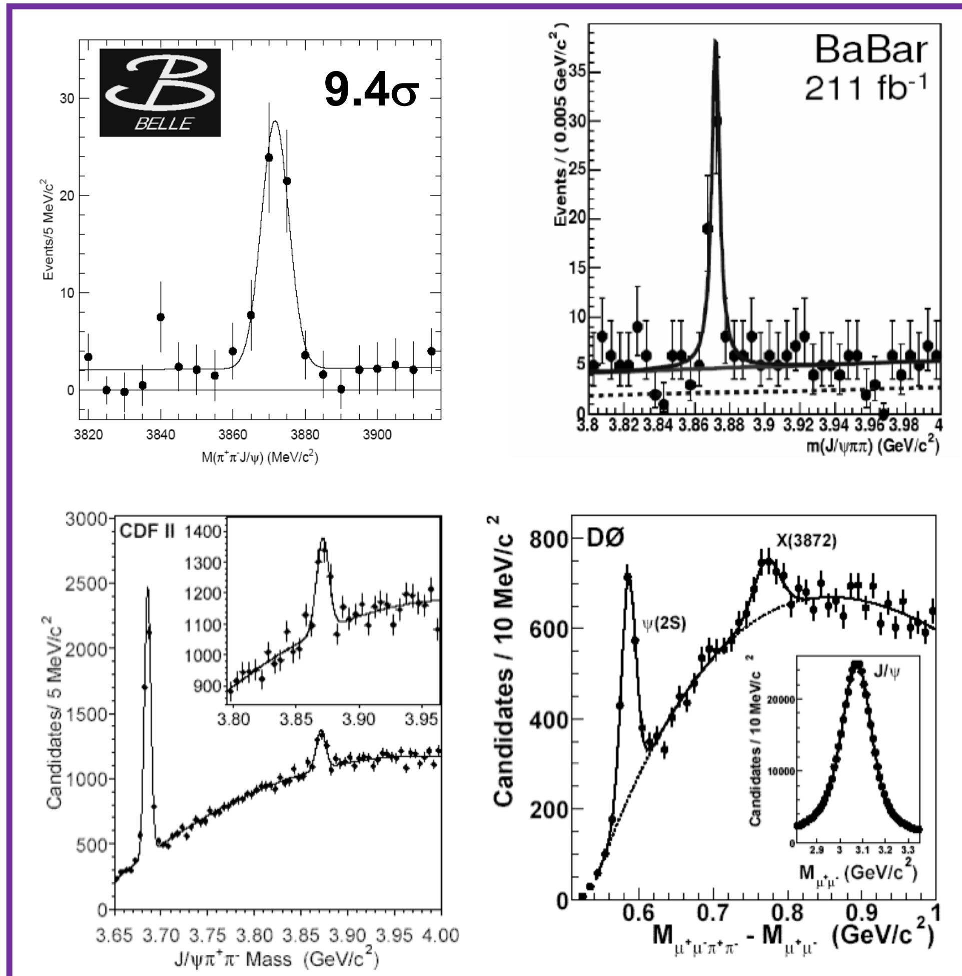
- At high energy less states can mix
- Narrower states because open charm decays forbidden/suppressed below $D\underline{D}^*_J$ threshold

Everything started from X(3872)

Year:	Search for this:	Find this:
2003	$B \to K\psi(2S)$ $\hookrightarrow \pi^+\pi^- J/\psi$	$B \to K\psi(2S)$, X(3872) $\hookrightarrow \pi^+\pi^- J/\psi$

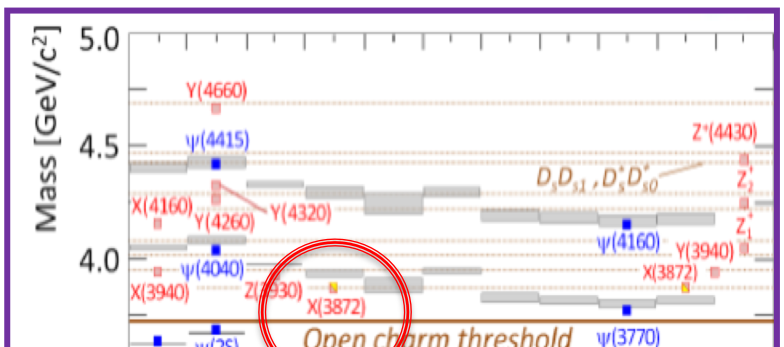
Belle, Phys. Rev. Lett.91(2003)262001
CDF-II, Phys. Rev. Lett.93(2004)072001
D0, Phys. Rev. Lett.93(2004)162002
BaBar, Phys. Rev. D71(2005)071103





very narrow state

Conflicting with quark model

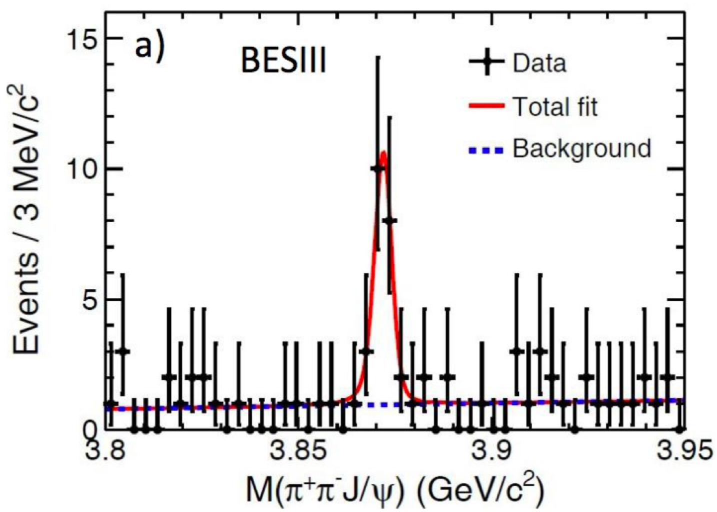


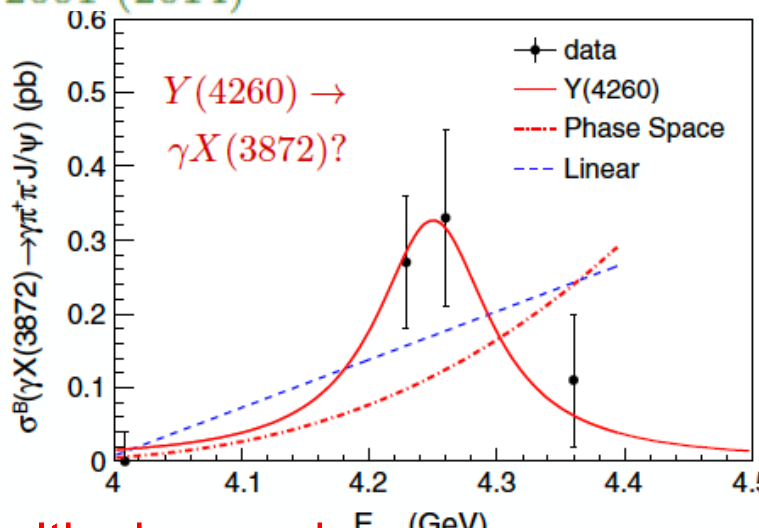
What we know about X(3872)

- ✓ Very close do the D^0D^{*0} threshold $M(X) - M(D^0\bar{D}^{*0}) = 0.01 \pm 0.18$ MeV
- ✓ Very narrow $\Gamma(X) < 1.2$ MeV
- ✓ $J^{PC} = 1^{++}$ (from LHCb)
- ✓ Charged partner not found – iso-singlet state?
- ✓ Large isospin breaking $B(X\to\rho J/\psi) \simeq B(X\to\omega J/\psi)$
- ✓ Produced in B decays, in hadron collisions, in $e^+e^-\to Y(4260)\to\gamma X(3872)$?

$$e^+e^- \to \gamma X;\ X \to \pi^+\pi^- J/\psi \text{ at BESIII}$$

PRL 112, 092001 (2014)



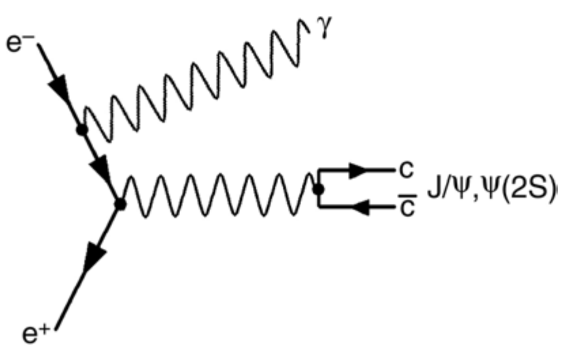


- ➢ Favorite interpretation: molecule mixed with charmonium
- ➢ Other options are not ruled out

After X(3872) comes Y(4260)

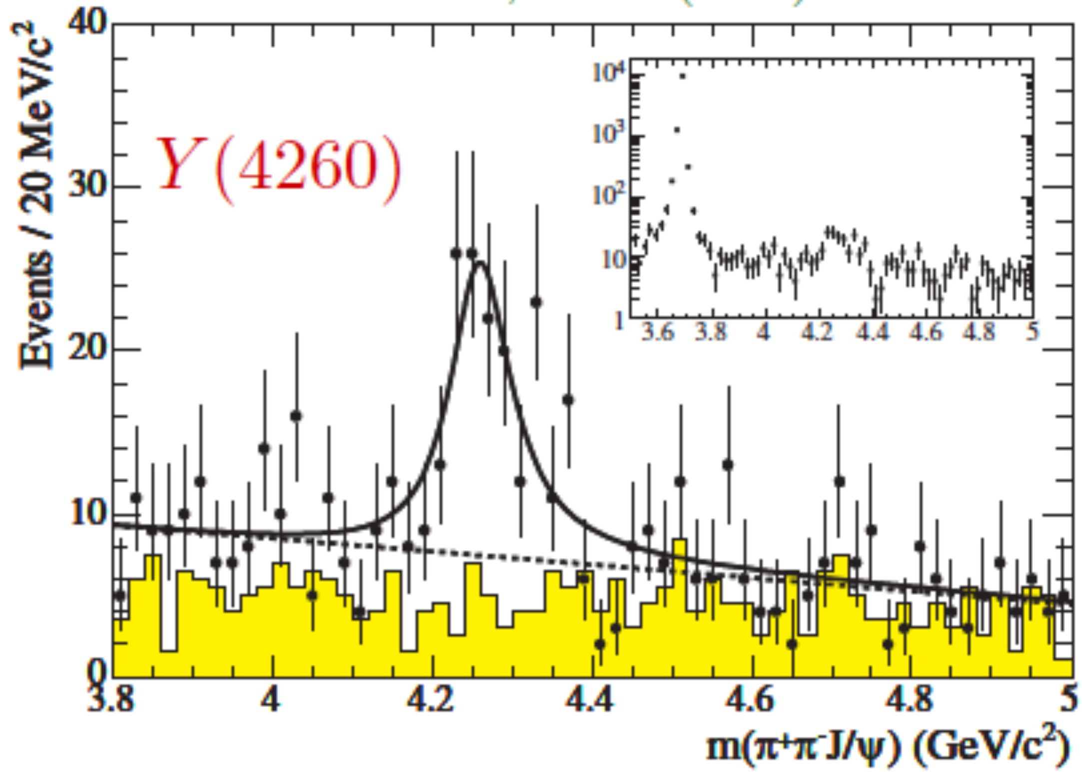
Year:	*Search for this:*	*Find this:*
2005	$e^+e^- \to X(3872)$ ↳ $\pi^+\pi^- J/\psi$	$e^+e^- \to Y(4260)$ ↳ $\pi^+\pi^- J/\psi$

In Initial State Radiation

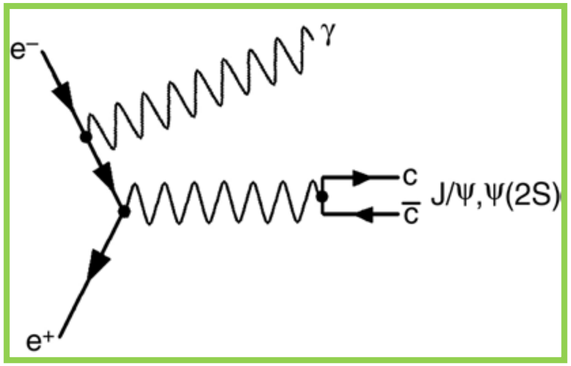


$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BaBar

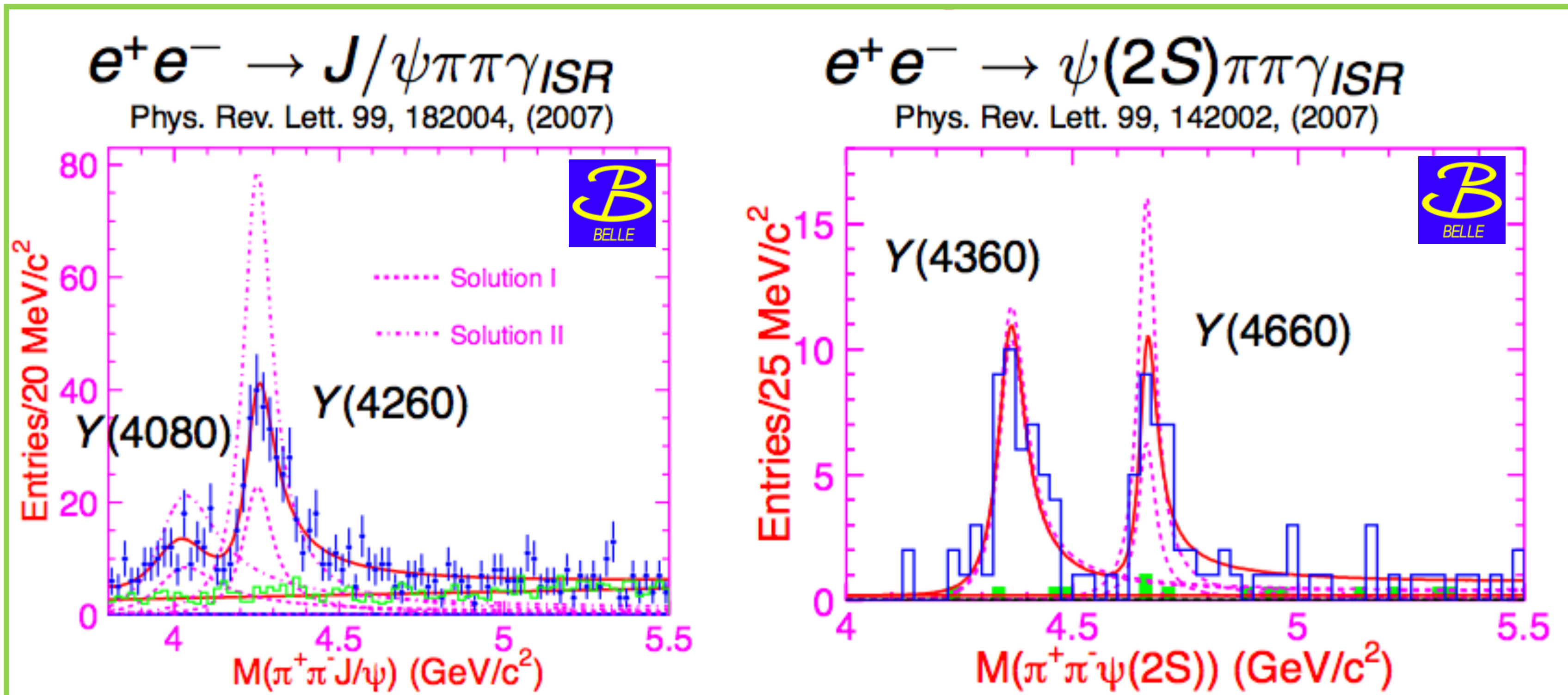
PRL95,142001 (2005)



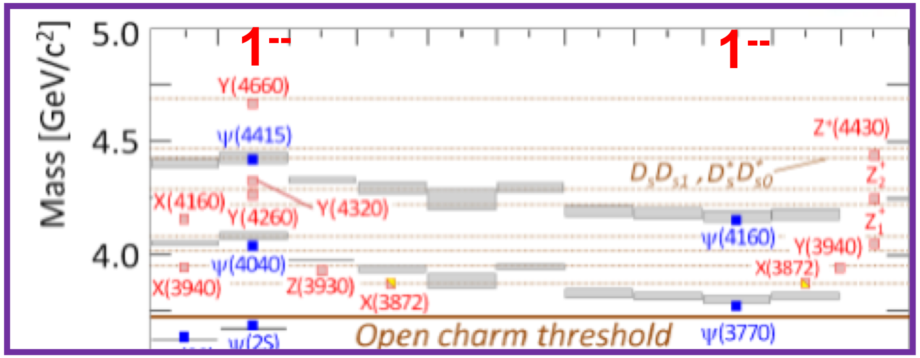
Y from Initial State Radiation

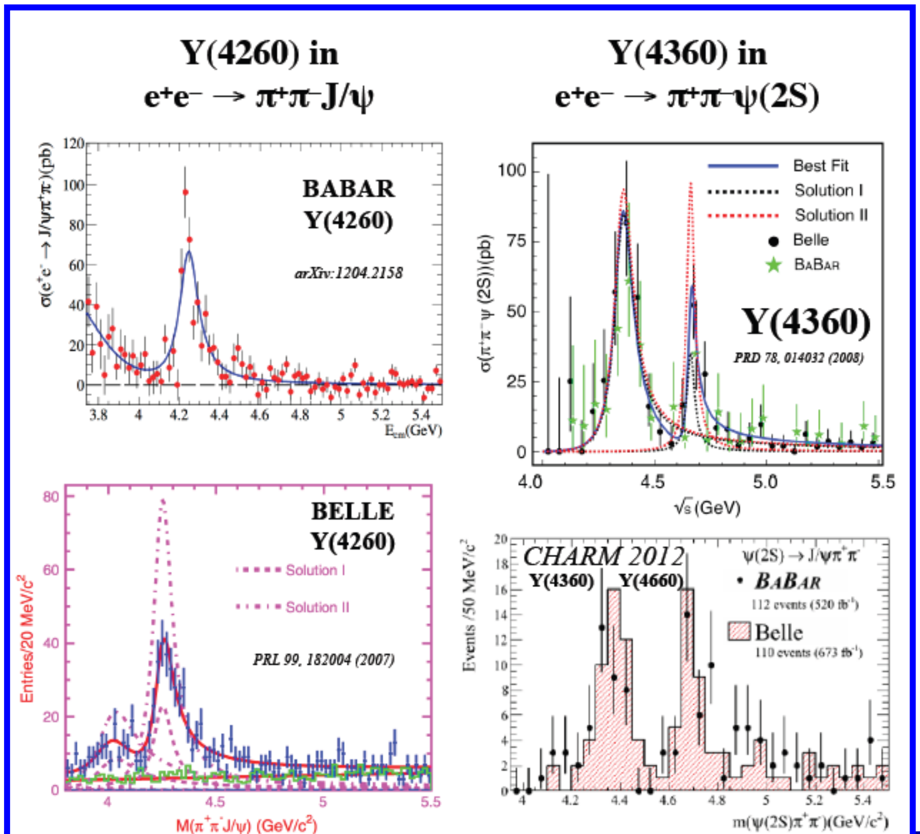


- A photon is radiated before annihilation
- Lower center-of-mass energy
- Only $J^{PC} \rightarrow 1^{--}$ states
- R scan



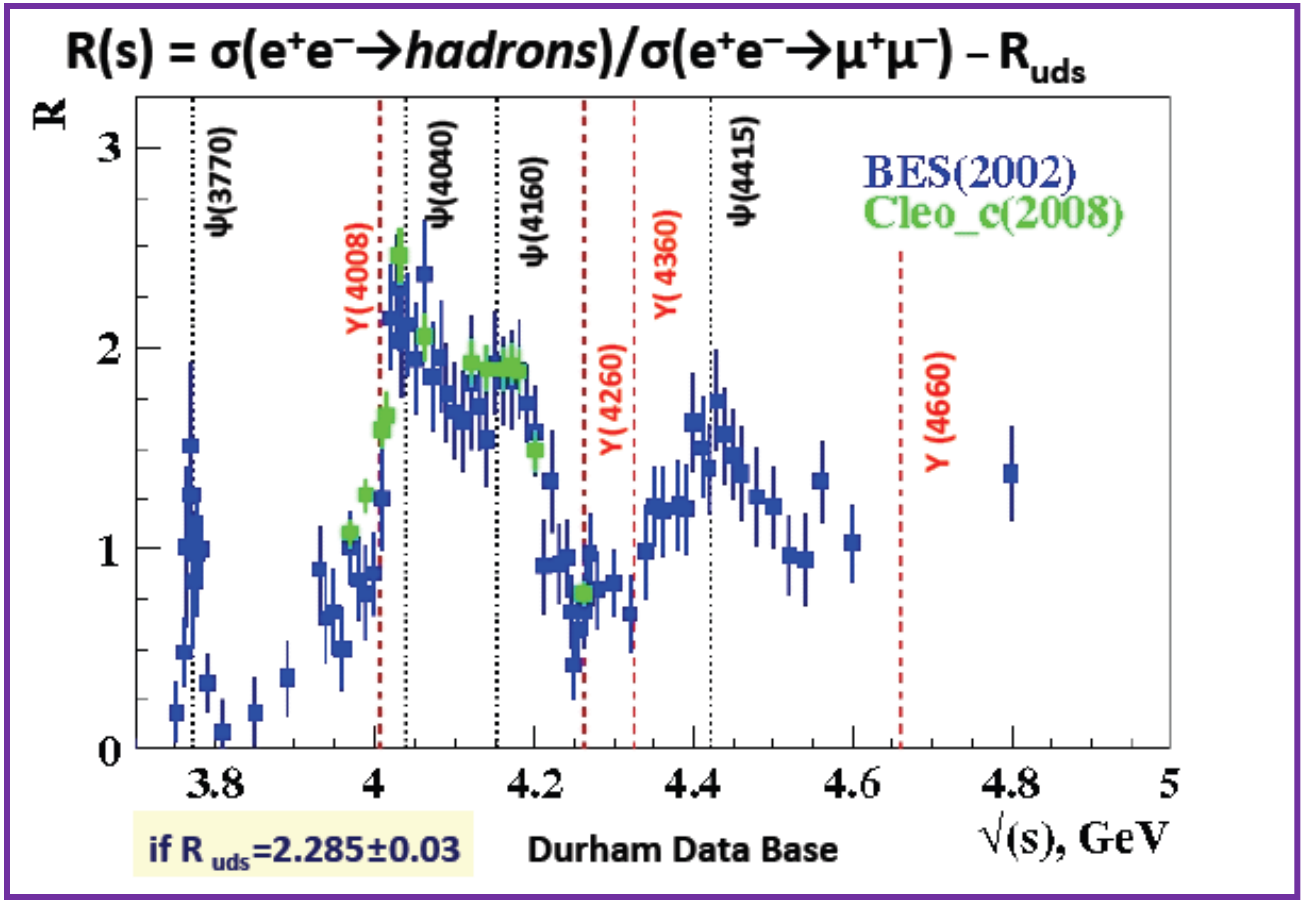
Y "exotic" resonances





- Inconsistent with all 1^{--} quark model states
- Very suppressed open charm decays
- Candidates for exotic matter
  - ? Hybrids?
  - ? Tetraquark?
  - ? Hadronic molecules?
- Well established
- Experimentally easy to produce using e^+e^- collisions

R scan in the charmonium region

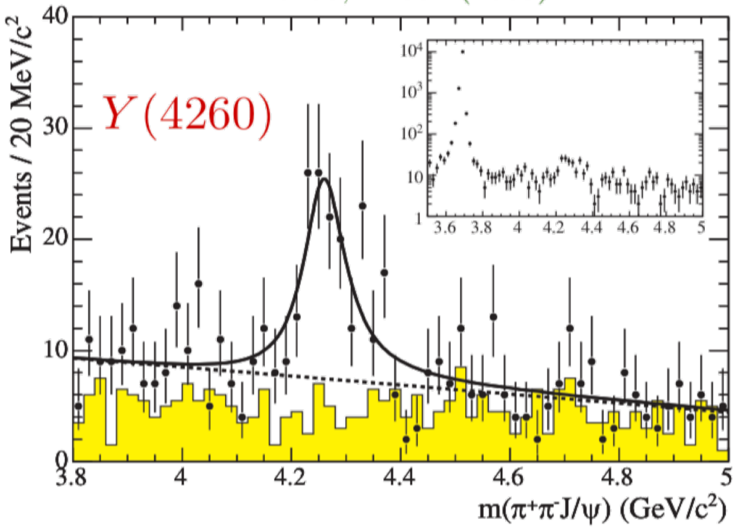


Y(4260)/Y(4360) is a dip in inclusive cross section

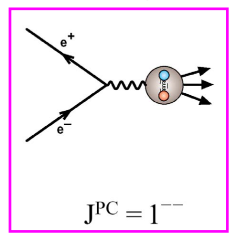
Surprises from Y production in BESIII

$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BaBar

PRL95,142001 (2005)

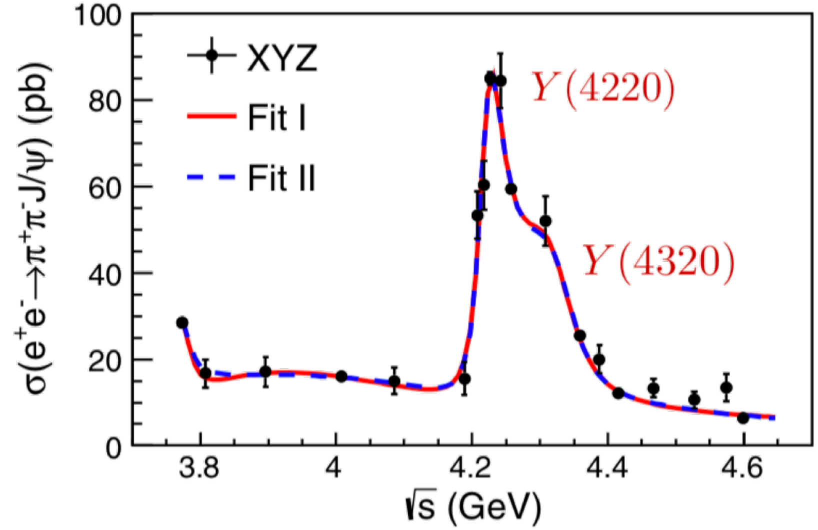


From ISR to direct production



$e^+e^- \to Y; Y \to \pi^+\pi^- J/\psi$ at BESIII

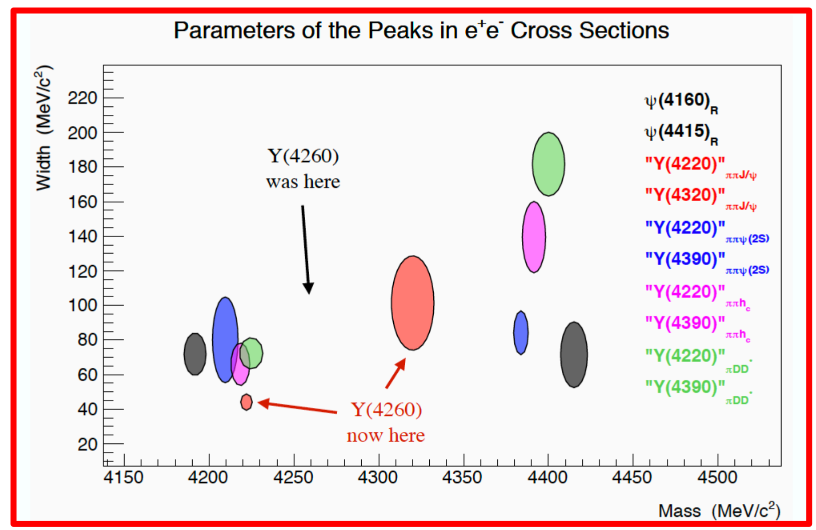
PRL118,092001 (2017)



Increasing statistics and precision

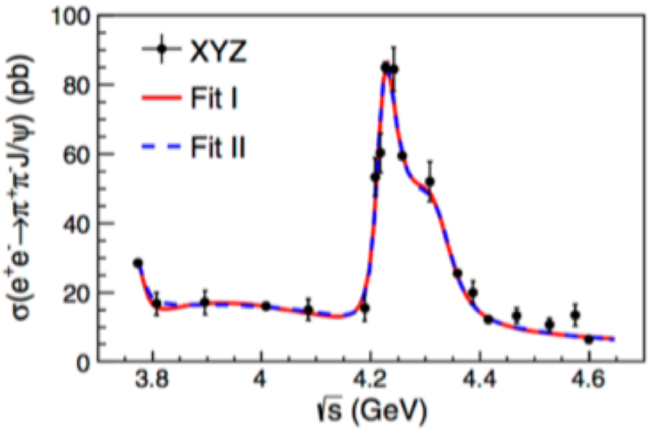
Y(4260) is not a single peak!

- ✓ No Y(4008) seen by Belle
- ✓ Narrower Y(4220)
- ✓ Broader Y(4320)

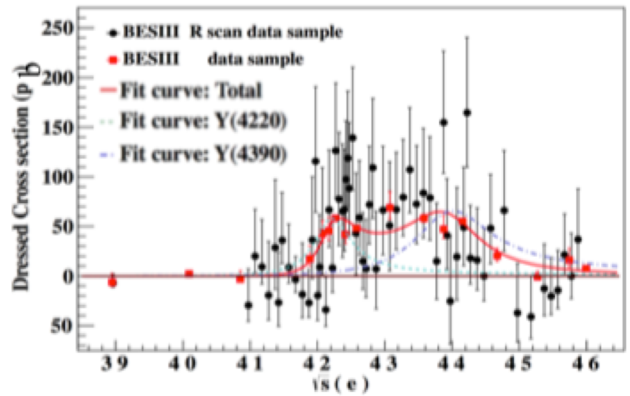


Summing up different decays

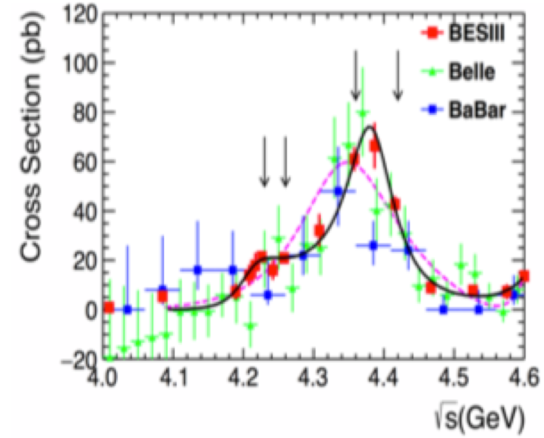
$e^+e^- \to J/\psi\pi^+\pi^-$



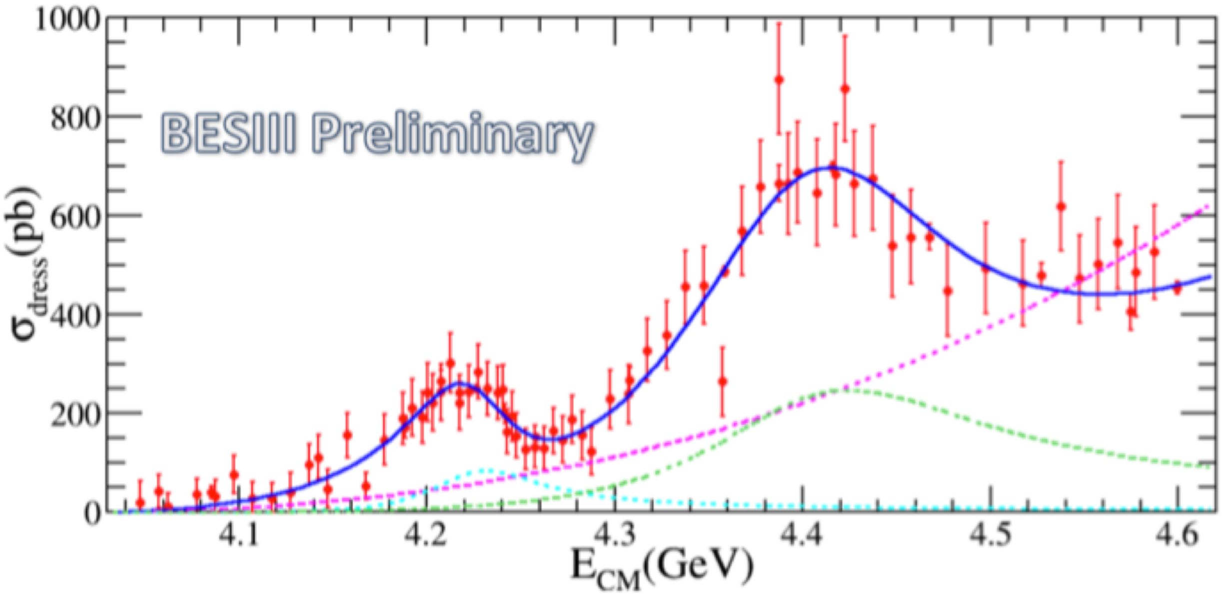
$e^+e^- \to h_c\pi^+\pi^-$



$e^+e^- \to \psi(2S)\pi^+\pi^-$



$e^+e^- \to D^0D^{*-}\pi^+$

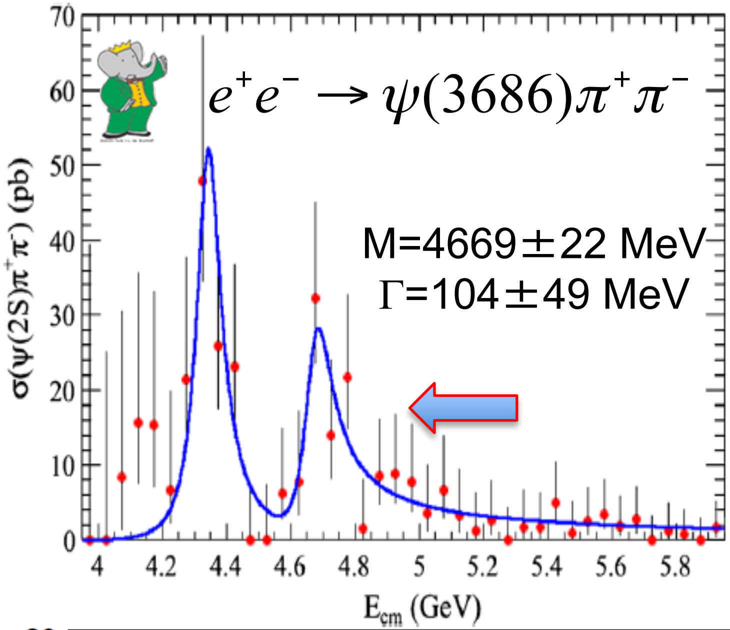


Y(4220):
- $M=(4224.8\pm5.6\pm4.0)\,\mathrm{MeV/c^2}$
- $\Gamma=(72.3\pm9.1\pm0.9)\,\mathrm{MeV/c^2}$

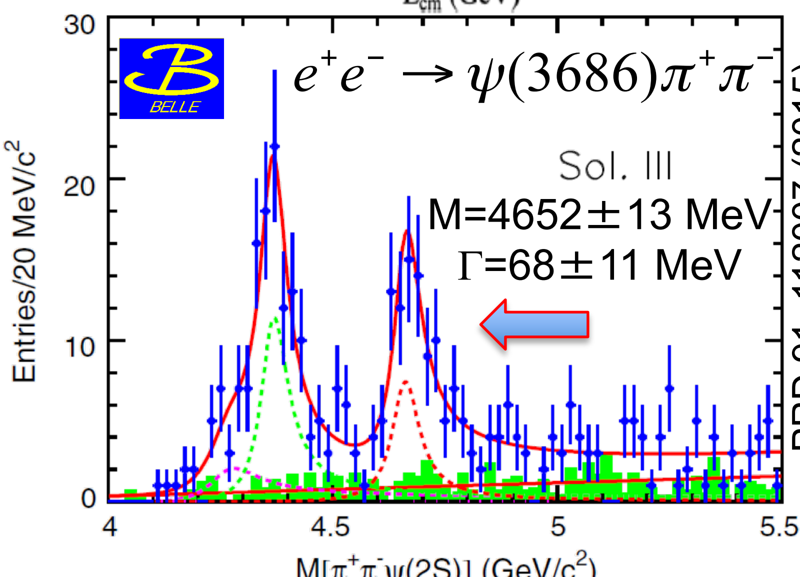
Y(4390):
- $M=(4400.1\pm9.3\pm2.1)\,\mathrm{MeV/c^2}$
- $\Gamma=(181.7\pm16.9\pm7.4)\,\mathrm{MeV/c^2}$

=> Consistent with structures observed in $h_c\pi\pi$, $\psi(2S)\pi\pi$, also $J/\psi\pi\pi$

Something interesting from Y(4660)



PRD 89, 111103(R) (2014)



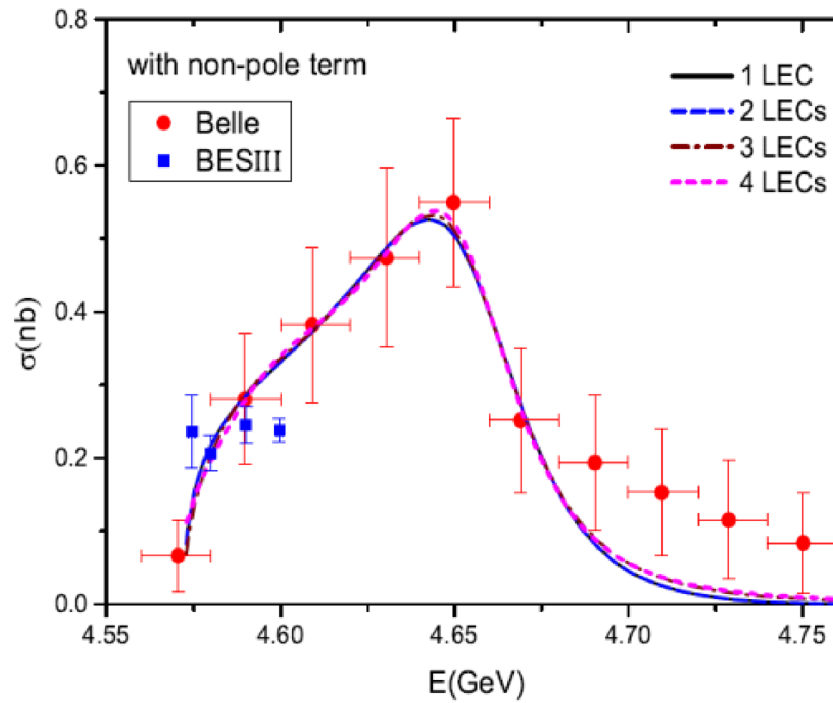
PRD 91, 112007 (2015)

$$e^+e^- \to \Lambda_c\bar{\Lambda}_c$$

just above threshold

Belle PRL 101, 172001 (2008)

BESIII PRL 120, 132001 (2018)



Belle and BESIII data do not agree so much…

Y(4660) cross section values

$e^+e^- \to \psi(3686)\pi^+\pi^-$ $\sigma_{peak} \sim 0.04$ nb

$e^+e^- \to \Lambda_c\bar{\Lambda}_c$ $\sigma_{peak} \sim 0.55$ nb

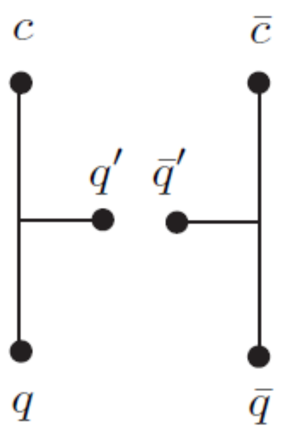
Y(4660) baryonic coupling ≥ 10 mesonic coupling

Unexpected !

Is there another mesonic decay with larger BR than ψ(3686)ππ?

or

Y(4660) is a charmed baryonium ?



Faccini et al. (also Maiani et al.):

hidden charm tetraquark (charmed baryonium) decay

mostly a light quark pair popping up from the vacuum

and falling apart as a charmed baryon pair

arXiv:0911.2178(2017) - PRD72(2005)9031502 - NPB 123(1977)507 - NPB79(1974)365

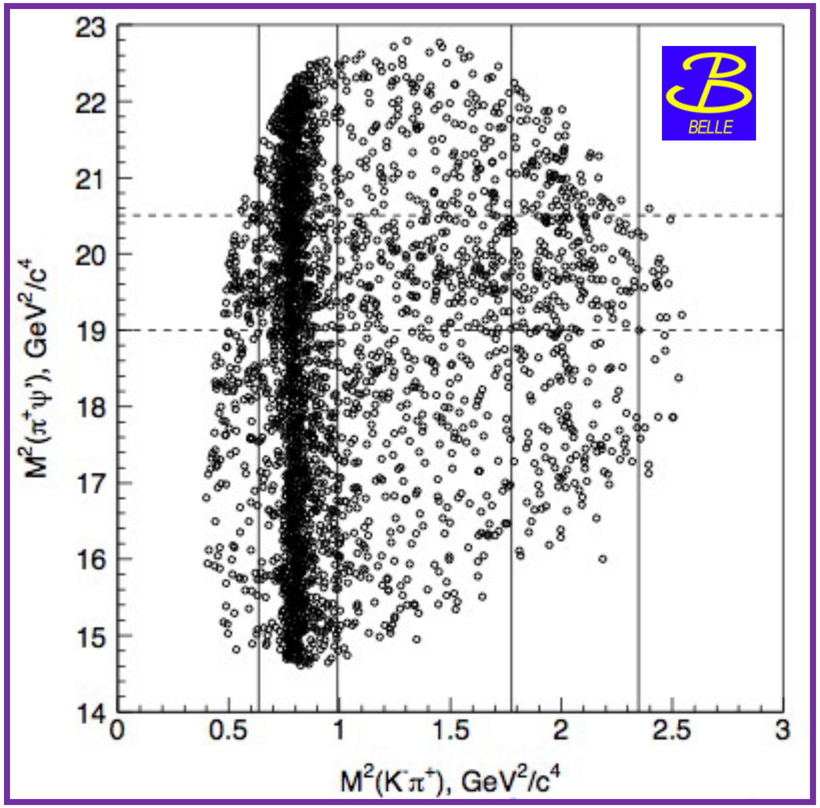
After X and Y, time for Z

Year:	*Search for this:*	*Find this:*
2008	$B \to K\pi^{\pm}\psi(2S)$	$B \to KZ_c(4430)^{\pm}$ $\hookrightarrow \pi^{\pm}\psi(2S)$

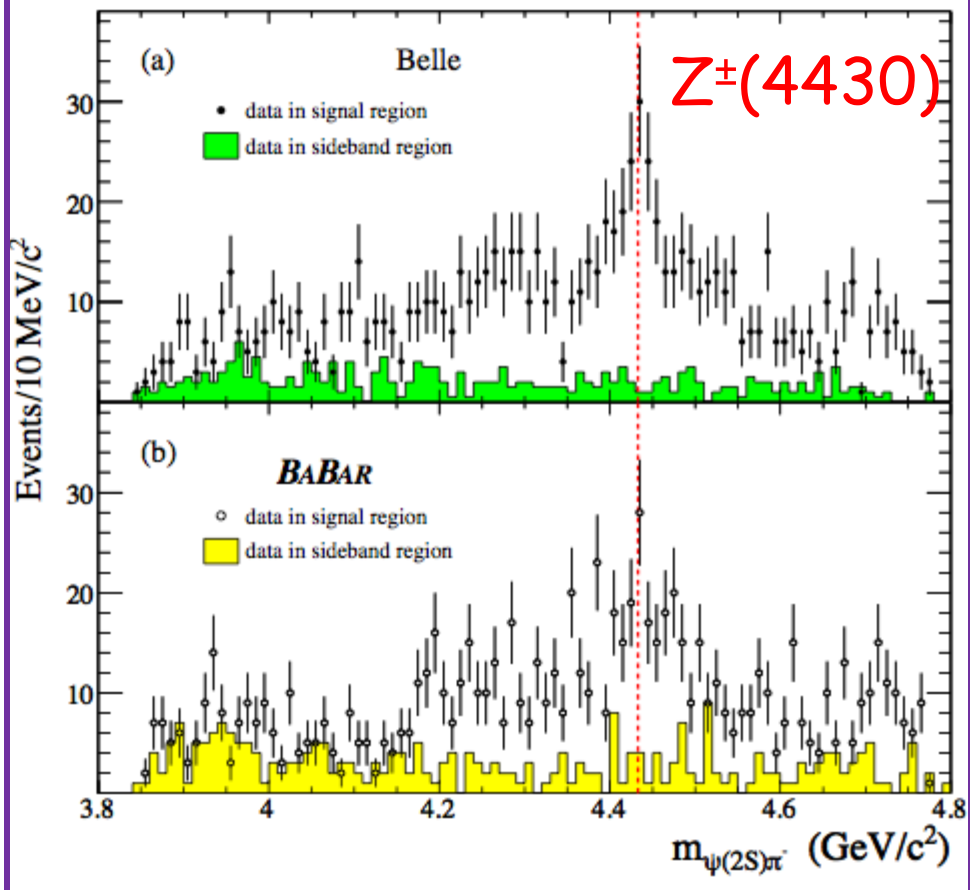
$$M = 4433^{+15}_{-12}\ {}^{+19}_{-13}\ \text{MeV}$$
$$\Gamma = 107^{+86}_{-43}\ {}^{+74}_{-56}\ \text{MeV}$$

First charged charmonium state

PRL 100, 142001 (2008)

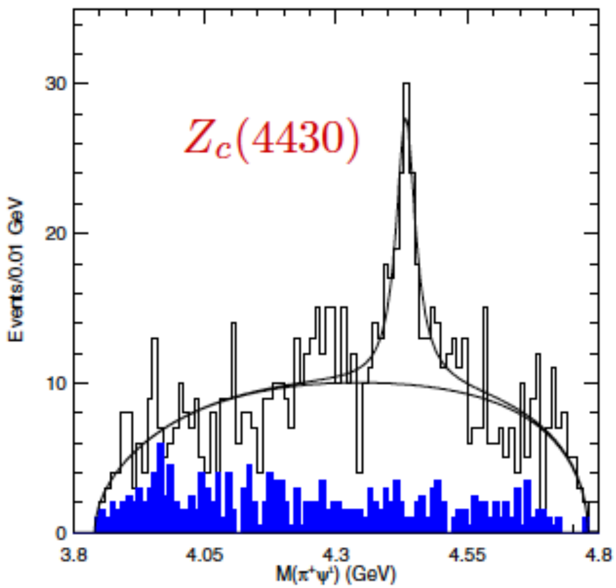


$B \to K\ \psi'\ \pi^{\pm}$ Dalitz plot



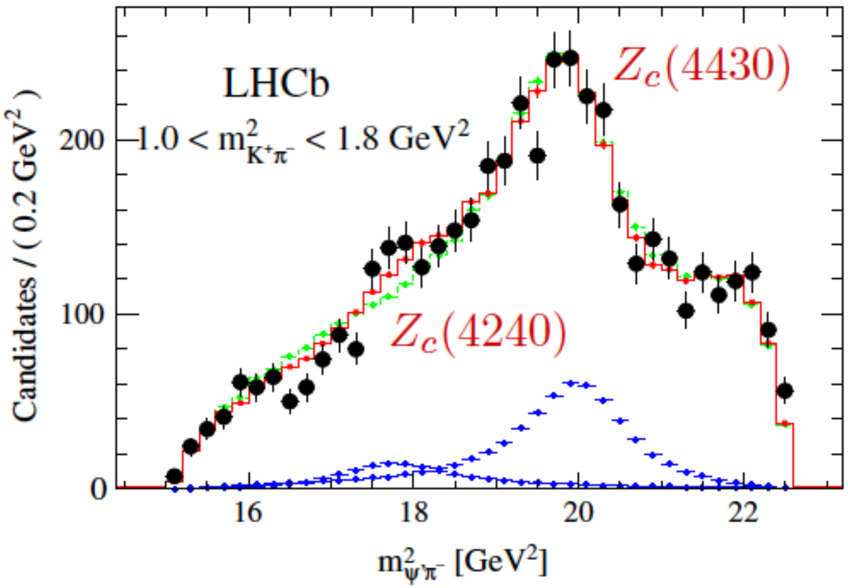
$Z_c(4430)$ nowadays

$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at Belle
PRL100,142001 (2008)

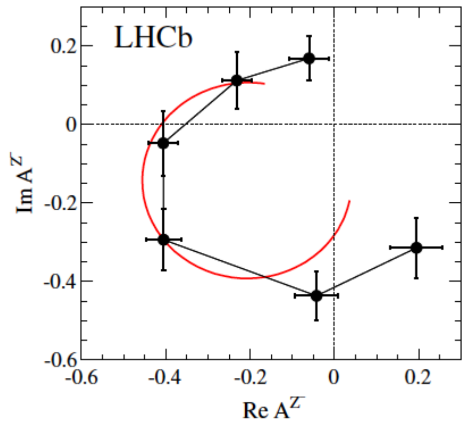


Confirmed by LHCb

$B \to KZ; Z \to \pi^{\pm}\psi(2S)$ at LHCb
PRL112,222002 (2014)

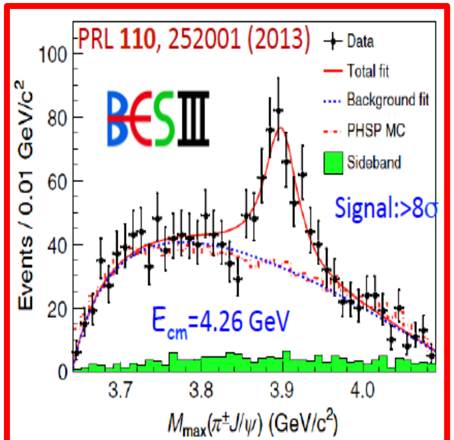


Spin parity 1^+

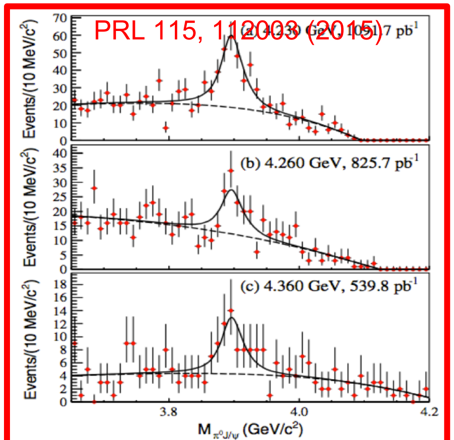


More Charged Charmonium-like States

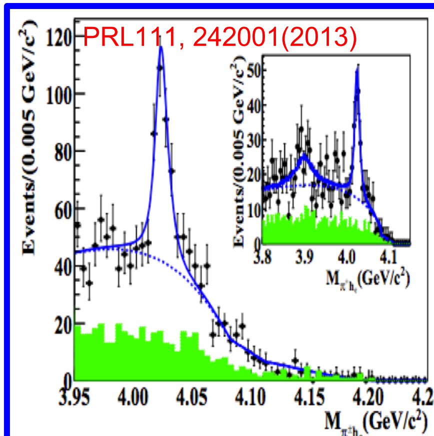
BESIII



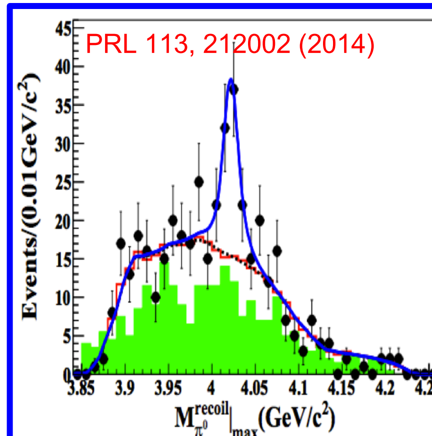
$e^+e^- \to \pi^-\pi^+ J/\psi$



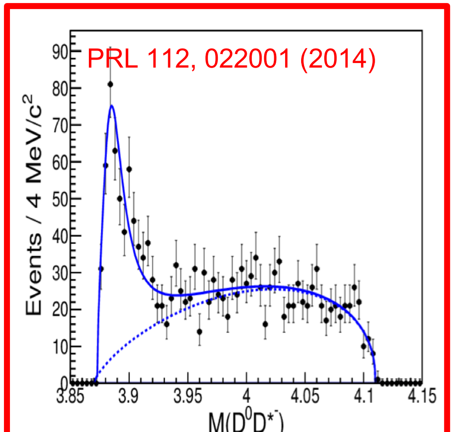
$e^+e^- \to \pi^\circ\pi^\circ J/\psi$



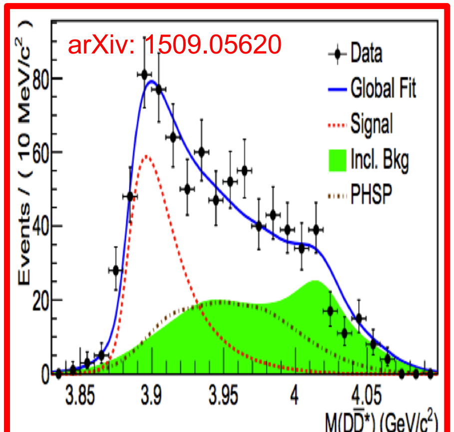
$e^+e^- \to \pi^-\pi^+ h_c$



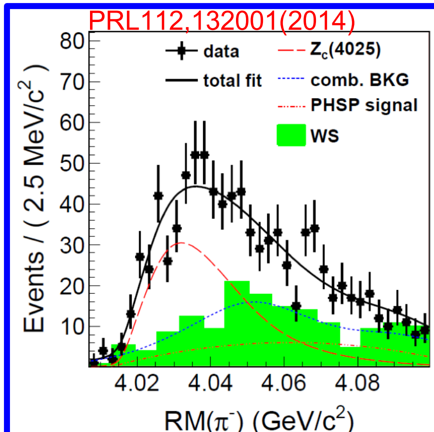
$e^+e^- \to \pi^\circ\pi^\circ h_c$



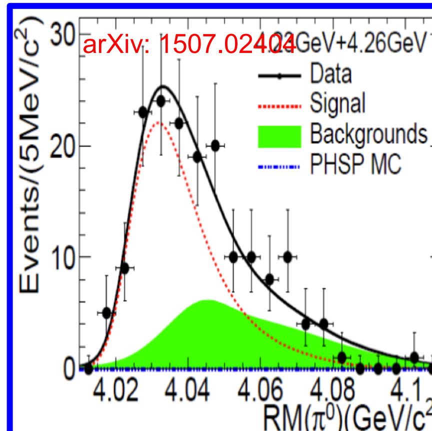
$e^+e^- \to \pi^\pm(D\underline{D}^*)^\mp$



$e^+e^- \to \pi^\circ(D\underline{D}^*)^\circ$



$e^+e^- \to \pi^\pm(D^*\underline{D}^*)^\mp$



$e^+e^- \to \pi^\circ(D^*\underline{D}^*)^\circ$

$Z_c(3900)^+$? $Z_c(3900)^\circ$? $Z_c(4020)^+$? $Z_c(4020)^\circ$?

$Z_c(3900)$, $Z_c(4020)$

- ✓ States observed in open-charm and pion decays with compatible masses
- ✓ Two isospin triplets in two different decay modes?
- ✓ Strongly coupling $D\underline{D}^*, D^*\underline{D}^*$
- ✓ Molecule state? We need at least 4 quarks…
- ✓ $Z_c(3900)$: J^P favors 1^+
- ✓ Are they coming from Y decays?

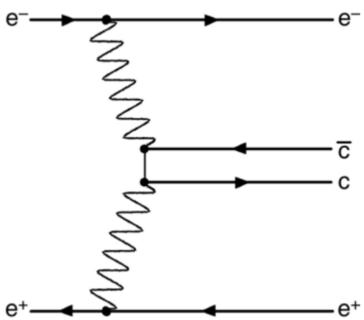
⇩

This could suggest us that X Y and Z are similar objects

More open questions than answers

We need more data (as usual)

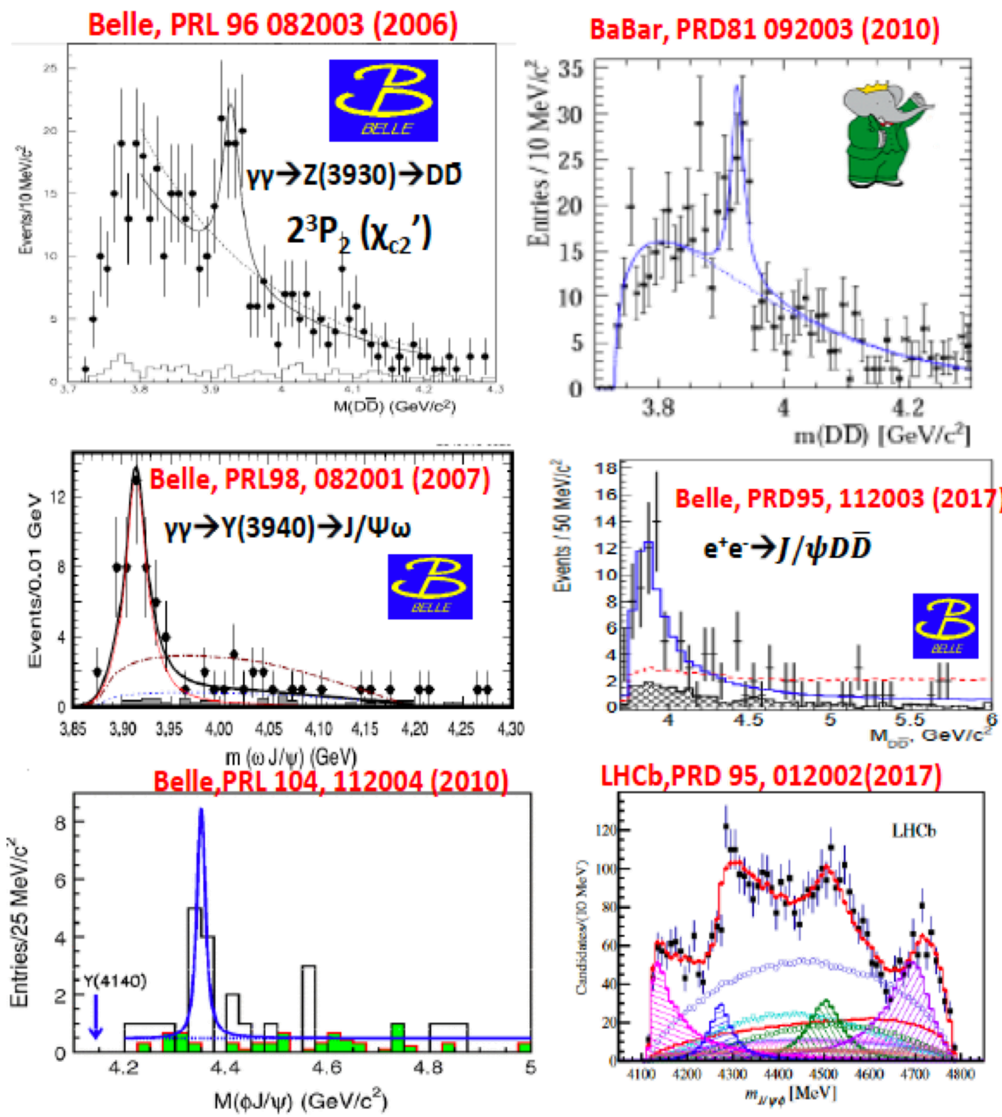
Two-photon exotic production



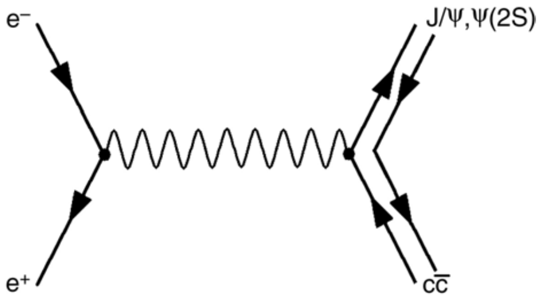
Study of $\chi_{c2}(3930)$ using $\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$
Mass and width precision study.

X(3915) (thought to be $\chi_{c0}(2P)$) was discovered in two photon process.
Currently, $\chi_{c0}(2P)$ has been suggested to be recently found X(3860) in $J/\psi D\bar{D}$.

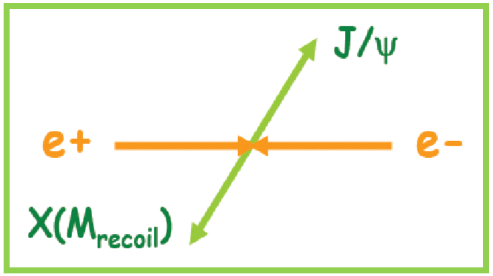
Belle observed X(4350) in $\gamma\gamma \rightarrow J/\psi\phi$.
Recently, LHCb did amplitude analysis of $B \rightarrow J/\psi\phi K$, found several structures Y(4140), Y(4274), X(4500), X(4700) but not X(4350) (?)

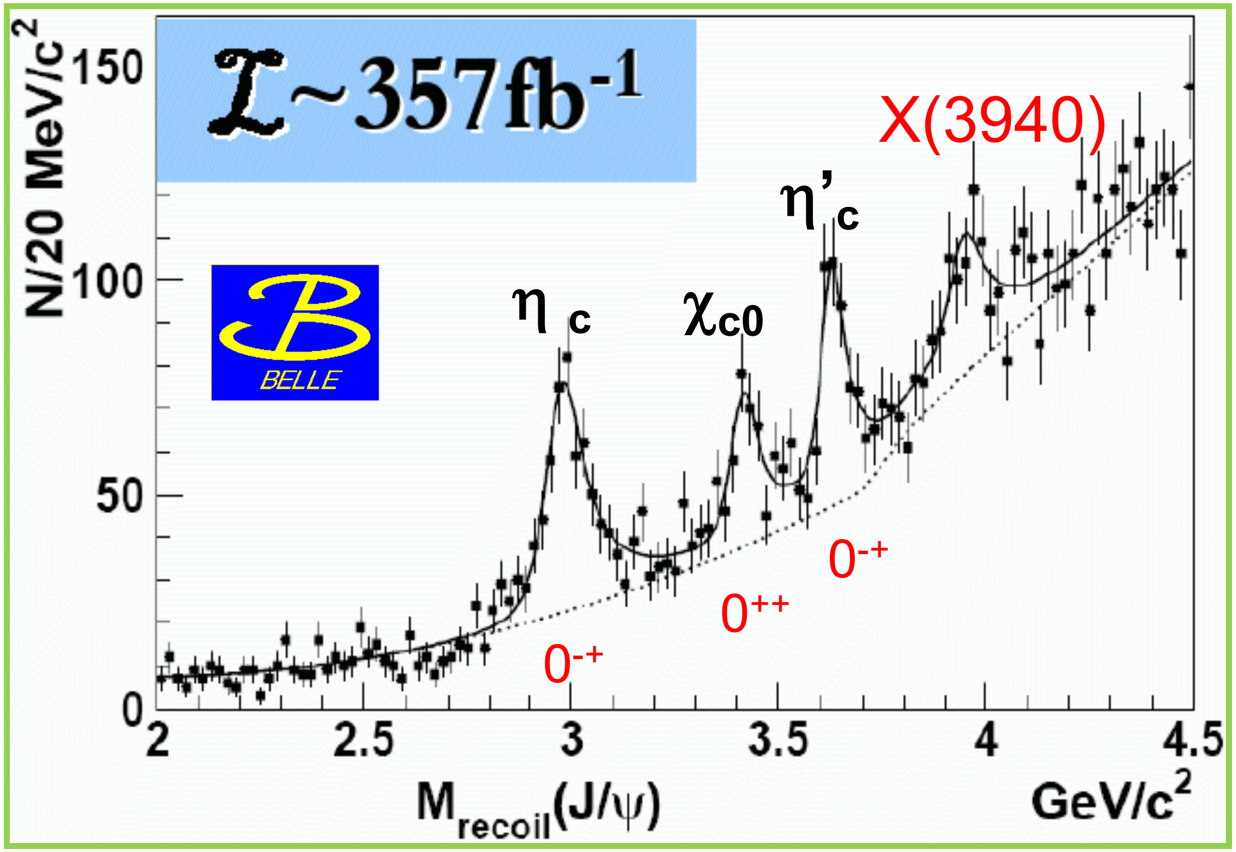


Double charmonium production



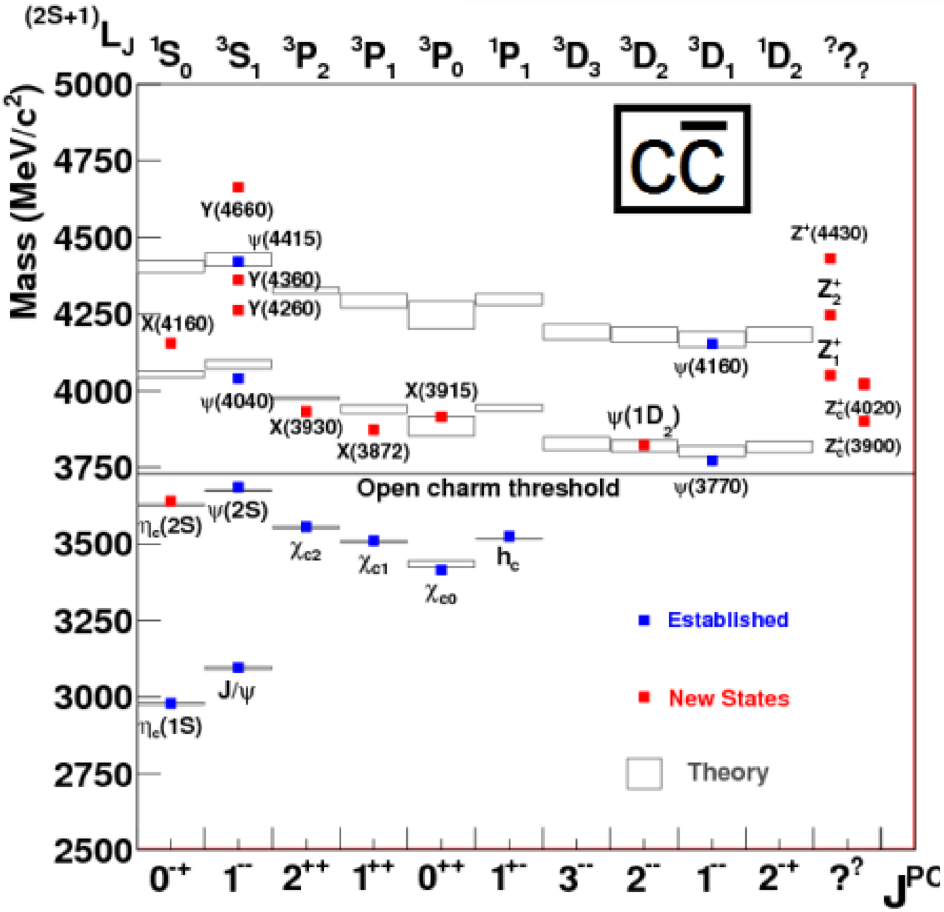
Cross sections about one order of magnitude larger than theoretical prediction of NRQCD

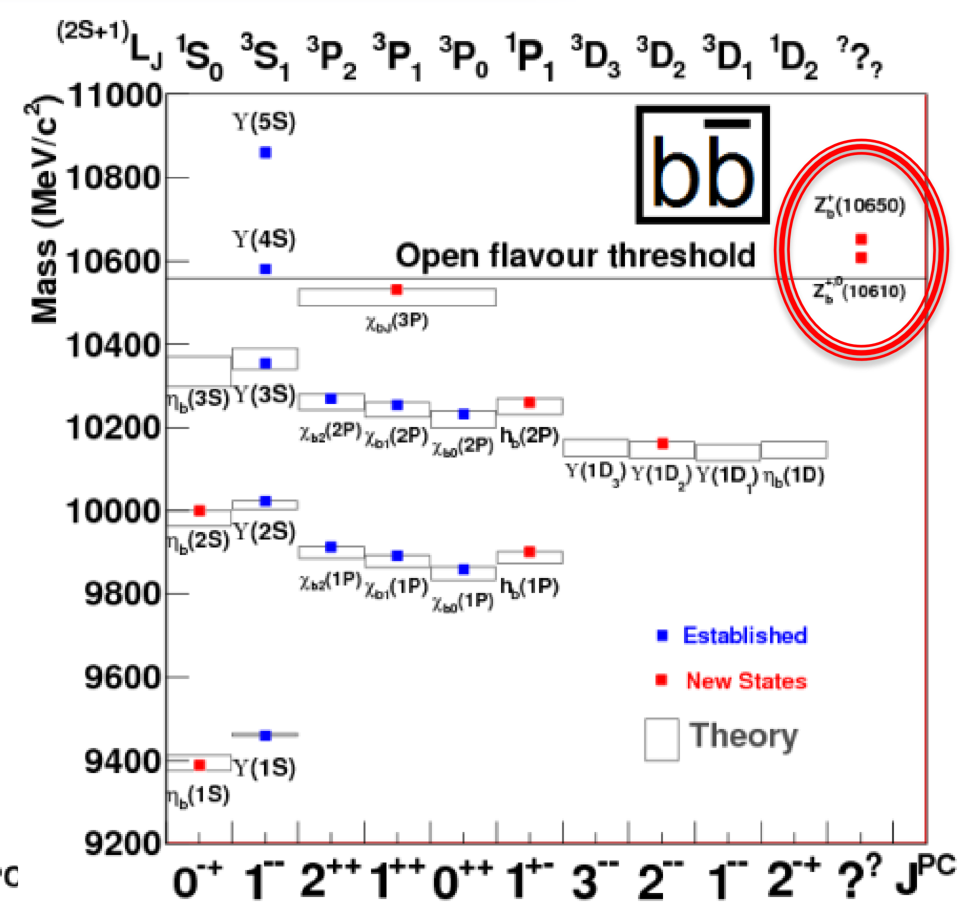




PRL 98, 082001 (2007)

Exotics in Bottomonium range?

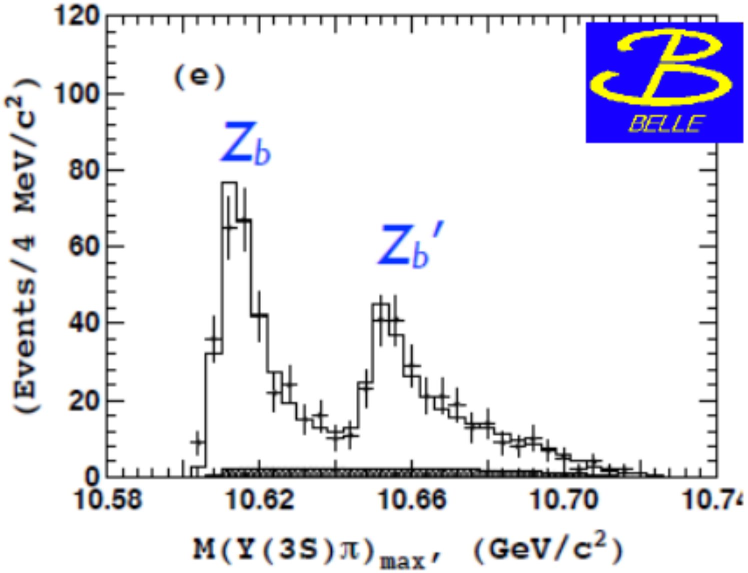




So far a reduced mass range was explored above open b threshold

Two exotic states: $Z^{+}_{b}(10610)$ $Z^{+,0}_{b}(10650)$

Charged Bottomonium-like States



- $Z_b^+(10610)$ and $Z_b^+(10650)$
- Discovered by Belle in 2011 in $\pi^+\pi^-$ transitions from Υ(5S).
- Both decay to $\Upsilon(nS)\pi^+$ and $h_b(nP)\pi^+$
  5σ evidence for neutral isospin partner of $Z_b^+(10610)$.
- Minimal quark content $b\bar{b}u\bar{d}$

The $Z_b^+(10610)$ and $Z_b^+(10650)$ lie very close to the BB* and B*B* thresholds, respectively.
Molecular states ?

Something new could come in the next years from Belle II data at Y(5S) and Y(6S)

Scan above Υ(4S)?

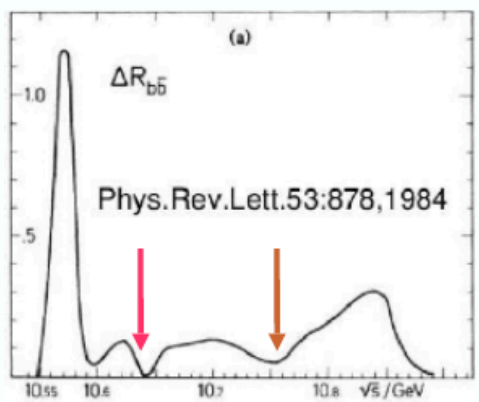
Where to run for $\int L dt \sim 10\ fb^{-1}$?

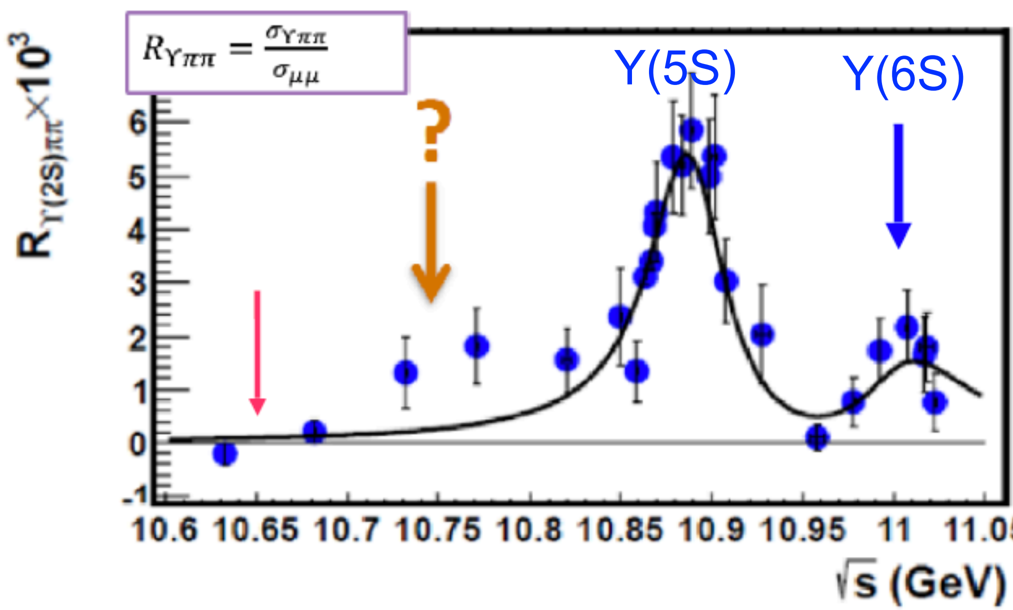
⇒ E = **10.65** GeV
Dip in R_b, just on B*B* threshold

⇒ E = **10.75** GeV
On the first $Z_b\pi$ threshold, above R_b drop at 10.74 where a bump is observed in R_Υ

Dip in R, new exotic states like in charm case?

Note: features predicted by theory (coupled channel model)



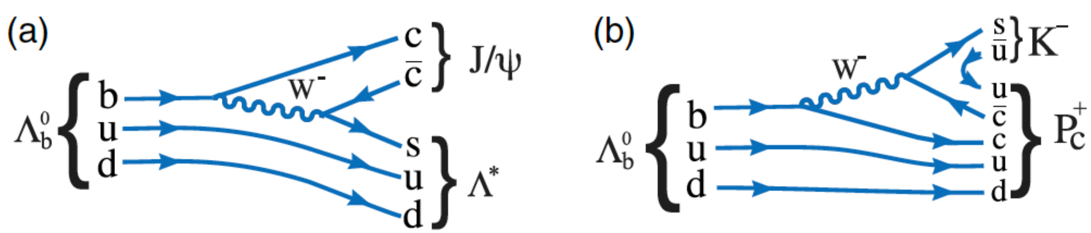


Pentaquark?

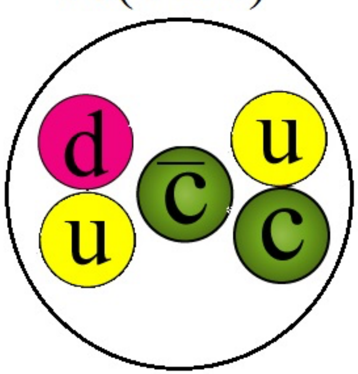
Selected for a Viewpoint in *Physics*
PRL **115**, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

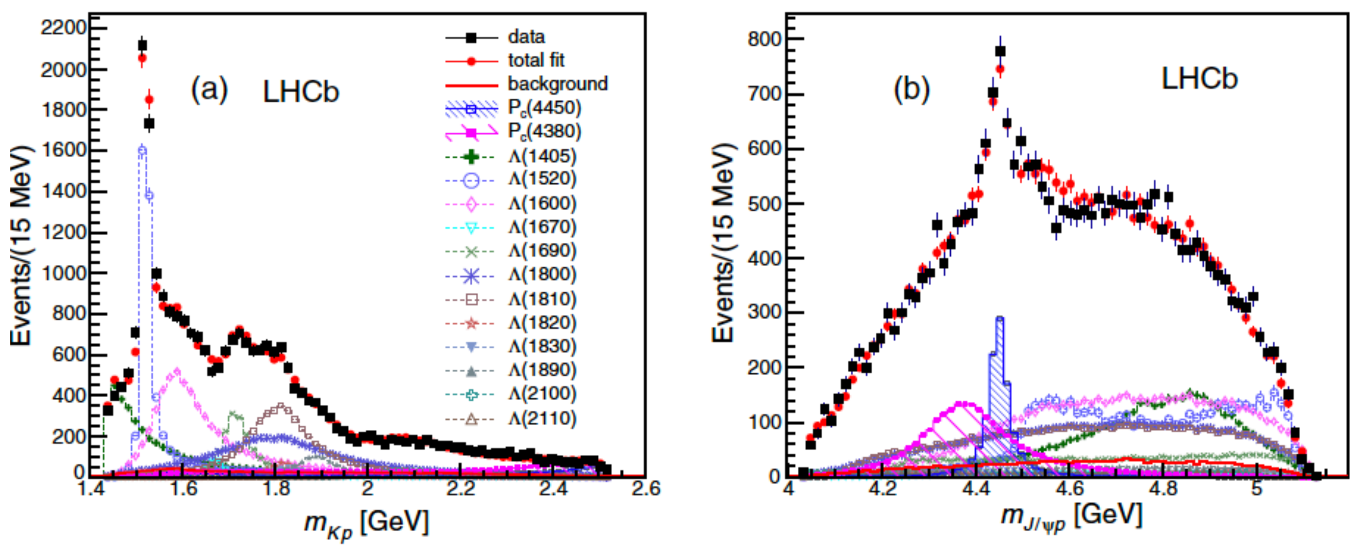
R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)



Pc(4450)

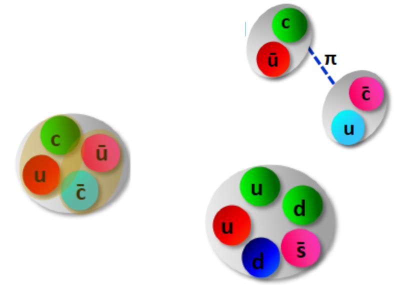


Pc(4380)

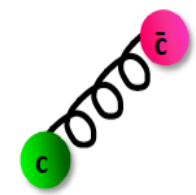


Possible Theoretical Interpretations

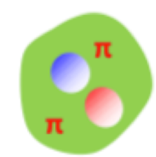
- Multiquark states
  - Molecular states: two loosely bound charm meson
  - Tetraquark: tightly bound four-quark state
  - Pentaquark: tightly bound five-quark state



- Hybrids
  - States with excited gluonic degree of freedom



- Hadro-charmonium
  - Charmonium states coated by excited light-hadron matter



- Threshold effects
  - Virtual states at threshold
  - Masses shifted by nearby $D^{(*)}D^{(*)}$, $B^{(*)}B^{(*)}$ threshold
- Rescattering
  - Two D(B)-mesons, produced closely, exchange quarks

Trying to conclude

Hadron spectroscopy is an important tool to understand the strong interaction

The recent analyses tell us that the scenario is far from being solved, still a lot to study and to understand

Many new states have been found with puzzling nature

Still not fully understood, in spite of the best efforts from all the experiments

BESIII, Belle2 and LHCb experiments will play a crucial role in disentangling the scenarios

The next years will be very exciting!