Exotic hadronic states XYZ

Yu-Ping Guo

(KPH, Mainz University)

International School of Nuclear Physics

37th Course

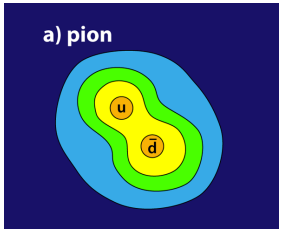
Probing Hadron Structure with lepton and Hadron Beams

Erice-Sicily September 16-24, 2015

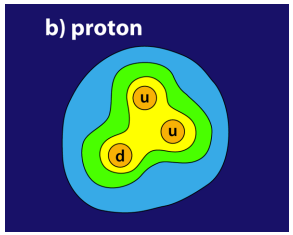
Hadrons

- Quark model:

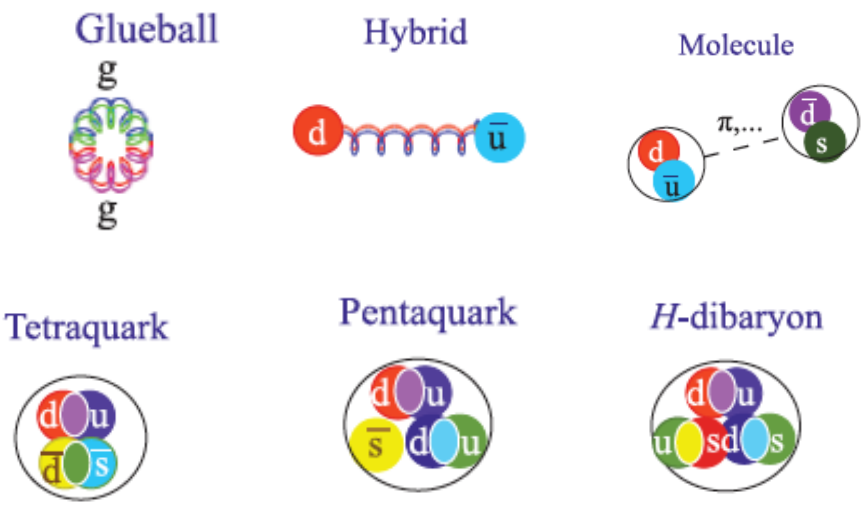
Mesons



Baryons



- Exotic hadrons:
  - Glueball
  - Hybrid
  - Multiquark state
  - Molecule
  - …



Static Quark Anti-quark Potential

- Coulomb-like + linear potential

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br$$

At small distance: one-gluon exchange dominate

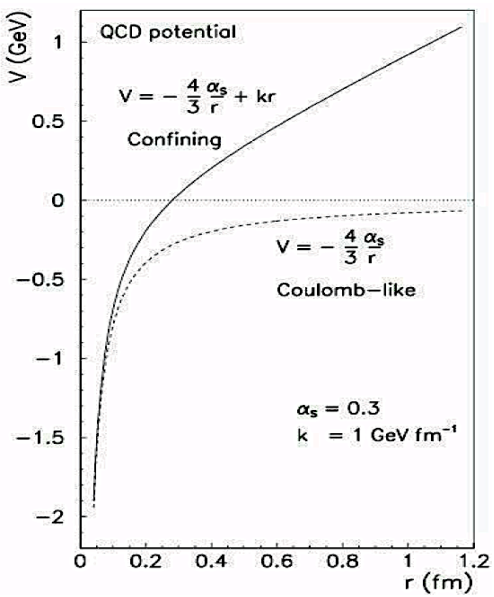
At large distance: confinement

spin-spin $+ \frac{32\pi\alpha_s}{9m_c^2}\vec{S}_c \cdot \vec{S}_{\bar{c}}\,\delta(\vec{x})$

Mass splitting

spin-orbit tensor $+ \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$

[PRD 72, 054026 (2005)]

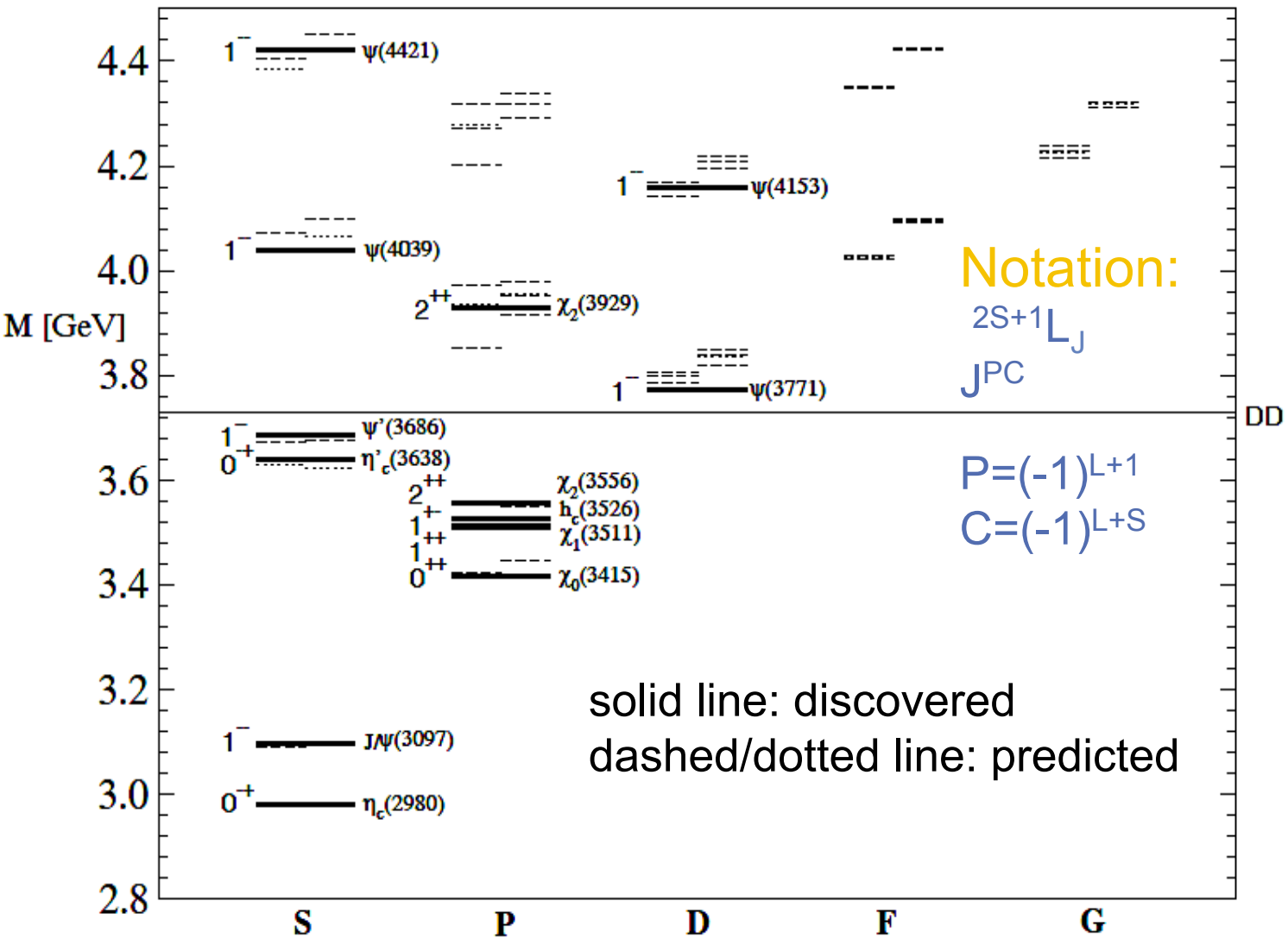


- Solve Schrödinger equation
  (heavy quark mass, $m_q >> \Lambda_{QCD}$, non-relativistic)
  → states in the spectroscopy

k is the string constant of QCD string between quark and anti-quark

Charmonium Spectroscopy

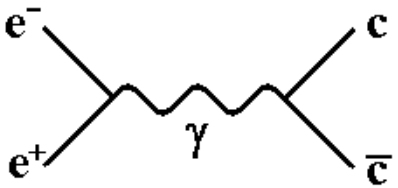
[PRD 72, 054026 (2005)]



Z(4430) 1^+
Z(4050)
Z(4250)
Z(4200) 1^+
Z_c(3900)
Z_c(3885) 1^+
Z_c(4020)
Z_c(4025)
X(3872) 1^{++}
X(3915) 0^{++}
X(3940)
Y(3940)
Y(4140)
X(4350) $0/2^{++}$
Y(4008) 1^{--}
Y(4260) 1^{--}
Y(4360) 1^{--}
Y(4660) 1^{--}

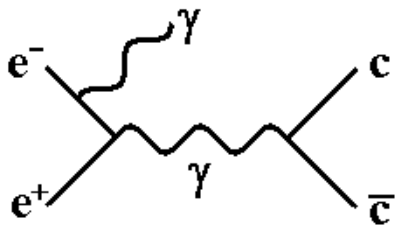
Charmonium Production

Direct Production



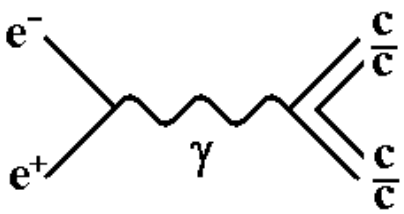
$J^{PC}=1^{--}$

Initial State Radiation



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

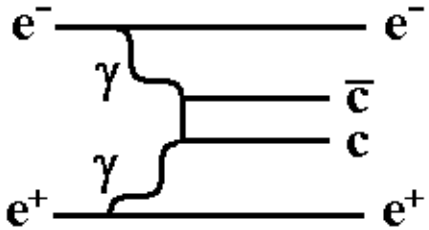
Double Charmonium Production



J/ψ, $\psi(2S)$

C=+

Two Photon Production

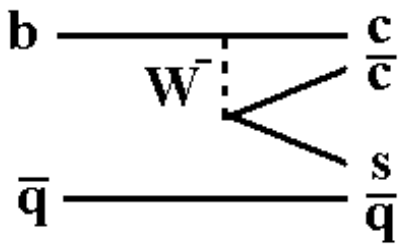


untagged case:

$J^{PC}=0^{\pm+}, 2^{\pm+}$

Charmonium Production

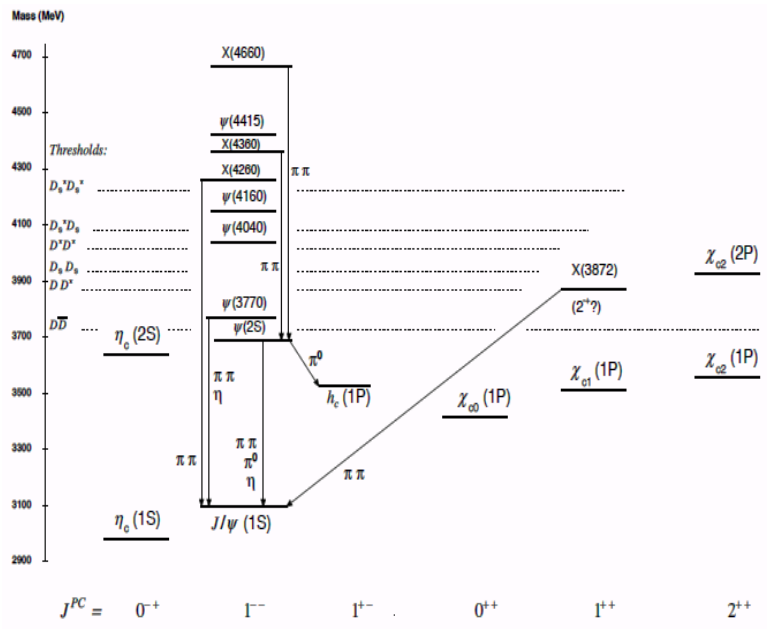
B-meson Decays



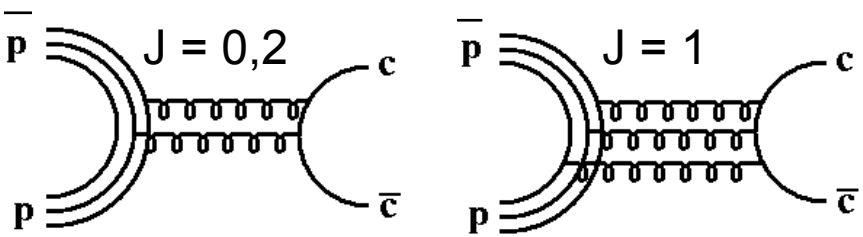
$J^{PC}=0^{-+},1^{--},1^{++}$

$K^{(*)}$

Charmonium Transitions

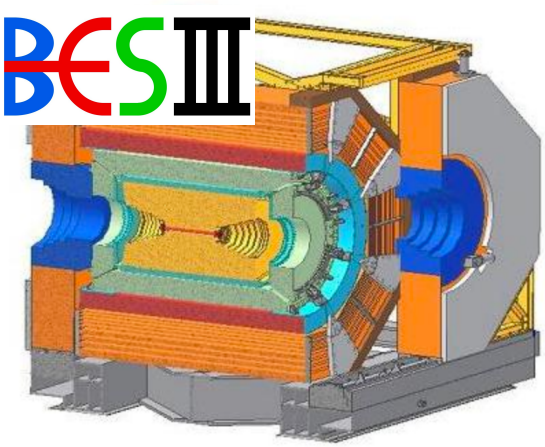


pp-bar Annihilation

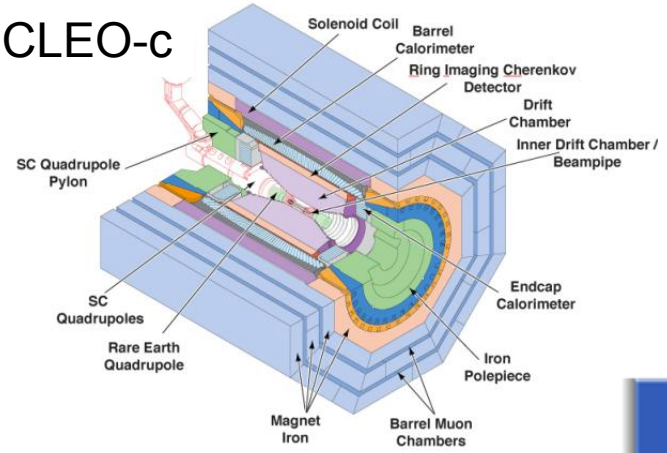


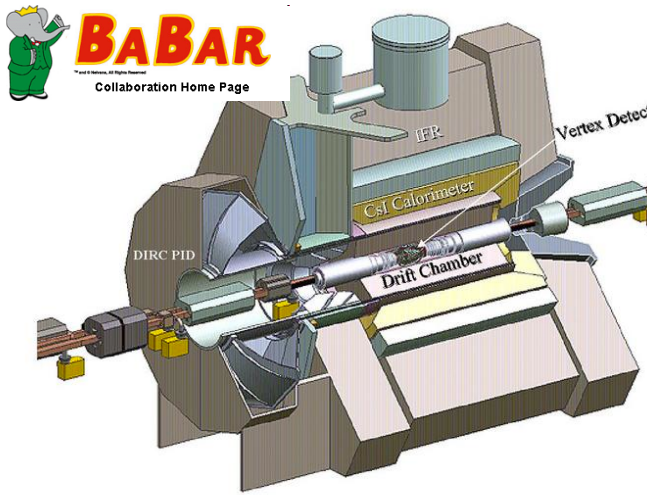
All quantum numbers

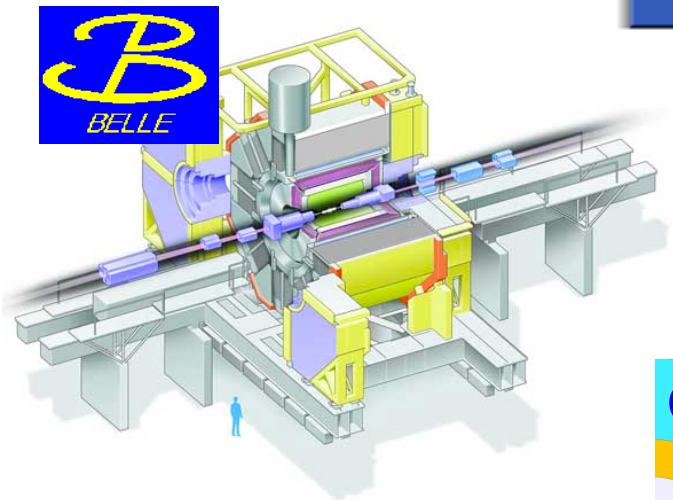
Experiments



CLEO-c





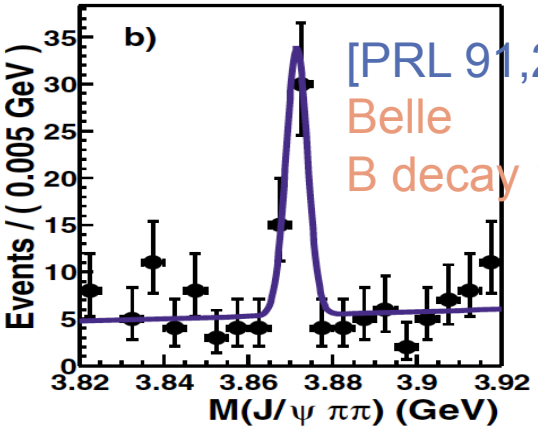


...

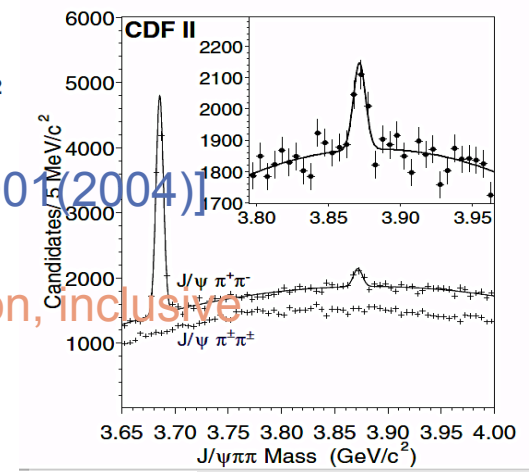
X(3872)

Discovery

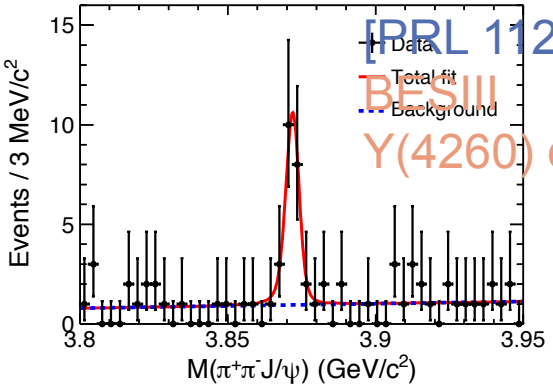
- First observation:
  $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}J/\psi$
- Production:
  - B meson decays (Belle, BaBar, LHCb)
  - pp(-bar) annihilation (CDFII, D0, LHCb, CMS)
  - Vector charmonium(-like) transition (BESIII)
- Decay:
  - $\pi^{+}\pi^{-}J/\psi$, $\pi^{+}\pi^{-}\pi^{0}J/\psi$, $D^{0}D^{0}\pi^{0}$, $D^{0}D^{*0}$, $\gamma J/\psi$, $\gamma\psi'$



[PRL 91,262001(2003)]
Belle
B decay 152M



[PRL93,072001(2004)]
CDF-II
pp annihilation, inclusive
220 pb^{-1}



[PRL 112, 092001 (2014)]
BESIII
Y(4260) decay

Mass and Width Measurement

- Mass: 3871.69±0.17 MeV/c^2
  - Close to D^0D^{*0} threshold: 3871.80±0.17 MeV/c^2
    "binding energy": -0.11±0.24 MeV/c^2, large radius
  - Only measurements from $\pi^+\pi^-J/\psi$ are used

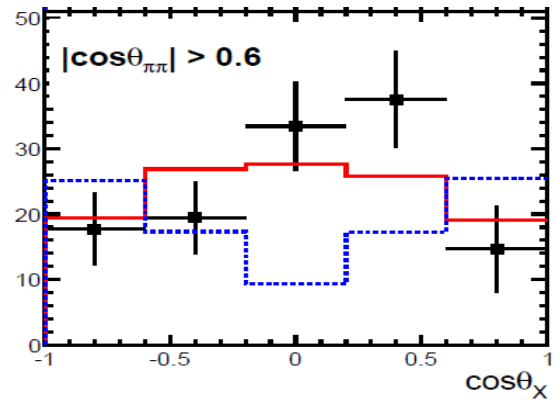
Mass (MeV/c^2)	Experiments	Note
3871.9±0.7±0.2	BESIII	Y radiatve transition [PRL 112 092001]
3871.95±0.48±0.12	LHCb	pp annihilation [EPJC 73 2462]
3871.85±0.27±0.19	Belle	B^+,B^0 decay [PRL 107 091803]
3871.61±0.16±0.19	CDFII	pp-bar annihilation [PRL 103 152001]
3871.4±0.6±0.1	BaBar	B^+ decay [PRD 77 011102]
3868.7±1.5±0.4	BaBar	B^0 decay [PRD 77 011102]
3871.8±3.1±3.0	D0	pp-bar annihilation [PRL 93 162002]

- Width: <1.2 MeV [PRD 84, 052004 (2011) Belle]

Quantum Number

- Decay into $\gamma J/\psi$: C=+ state
- CDFII narrow it to 1^{++} or 2^{-+} [PRL 98,132002 (2007)]
  - Use helicity-amplitude analysis, compare angular distribution
- LHCb: 2^{-+} rejected > 8σ

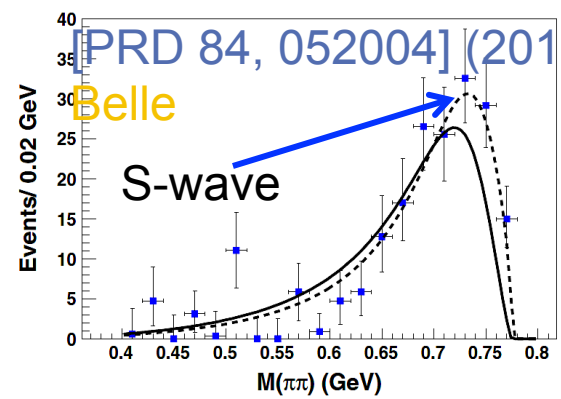
  [PRL 110, 222001 (2013)] $1fb^{-1}$



- $\pi\pi$ in $X(3872) \rightarrow \pi^+\pi^- J/\psi$ decay:
  - Dominant contribution: ρ^0 (CDF, Belle)
  - Isospin of X(3872) 0 or 1

    0: $X(3872) \rightarrow \rho J/\psi$ isospin violate

    1: charged partner not found, large $X(3872) \rightarrow \omega J/\psi$ branching fraction



What's X(3872)

arXiv: 1411.7738

- As conventional charmonium
  - $J^{PC}=1^{++}$, $2^3 P_1$ state $\chi_{c1}(2P)$
  - Potential model predicted mass: 3925 MeV (NR)/ 3953 MeV (GI), 50~70 MeV higher
  - Decay to $\rho J/\psi$ isospin and OZI violating process
- As Molecule:
  - Small binding energy, large radius
  - Production characteristics in pp(-bar) collision similar to $\psi(2S)$ [D0: PRL 93, 162002 (2004)] [LHCb: EPJC 72, 1972 (2012)] [CMS: JHP 1304, 154 (2013)]
  - Ratio of $X(3872)\rightarrow\gamma J/\psi$ to $X(3872)\rightarrow\pi^+\pi^- J/\psi$:
    - 0.24±0.05 [BaBar: PRL 102 132001 (2009)] [PRL 107 091803 (2011)]
    - Consistent with molecule calculation when D^+D^{*-} and $D_S^+D_S^{*-}$ included [PRD 86(11) 113007 (2012)]

What's X(3872)

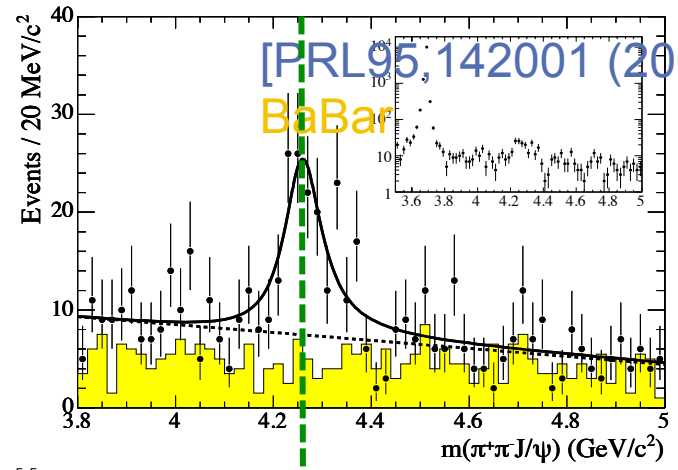
- As Molecule (cont.):
  - Ration of X(3872)→$\gamma J/\psi$ to X(3872)→$\gamma\psi(2S)$:
    - 2.31±0.57 [BaBar: PRL 102 132001 (2009)] [LHCb: NPB 886 665 (2014)]
    - Pure DD* assignment failed at this point
- As tetraquark:
  - Two states in B^+ and B^0 decays [PRL99, 182003 (2007)]
    - Not confirmed by Belle and BaBar [PRD 84 052004 (2011)] [PRD 71 031501 (2005)] (−0.71 ± 0.96 ± 0.19) MeV
- As mixture of difference configurations
  - $|X(3872)\rangle = c_1|cc\rangle + c_2|DD^*\rangle$

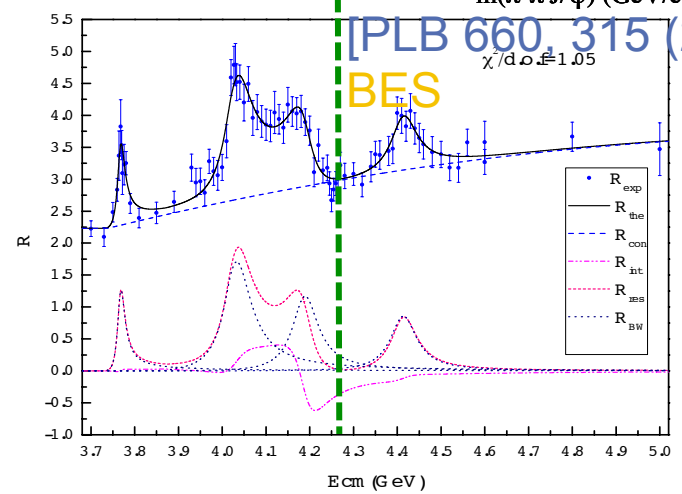
[EPJC 73(3): 2351] [PTEP 9 093D01]

Y STATES
1^{--}

Discovery

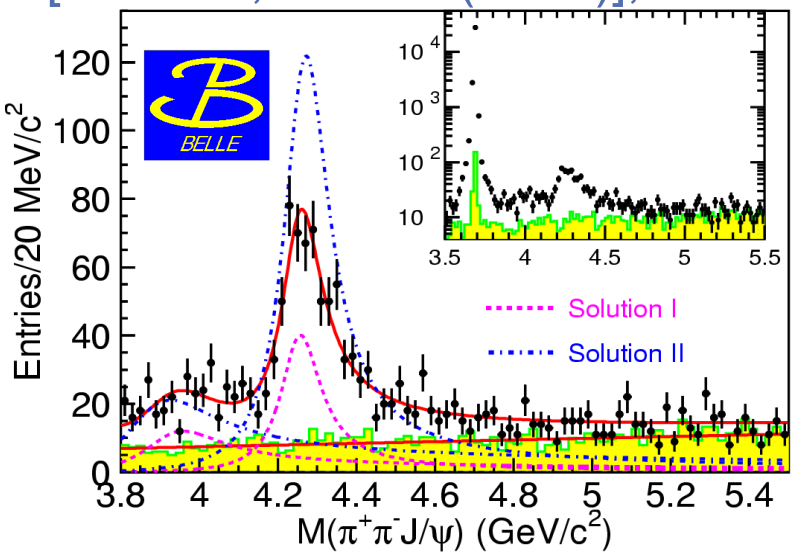
- First state - Y(4260), discovered in ISR process at BaBar
  - $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$
  - M > 4 GeV above DD threshold
  - Not observed in inclusive hadron cross section
  - Not observed in open charm pair cross section
  - Confirmed by CLEO and Belle
- Quantum number: 1^{--}



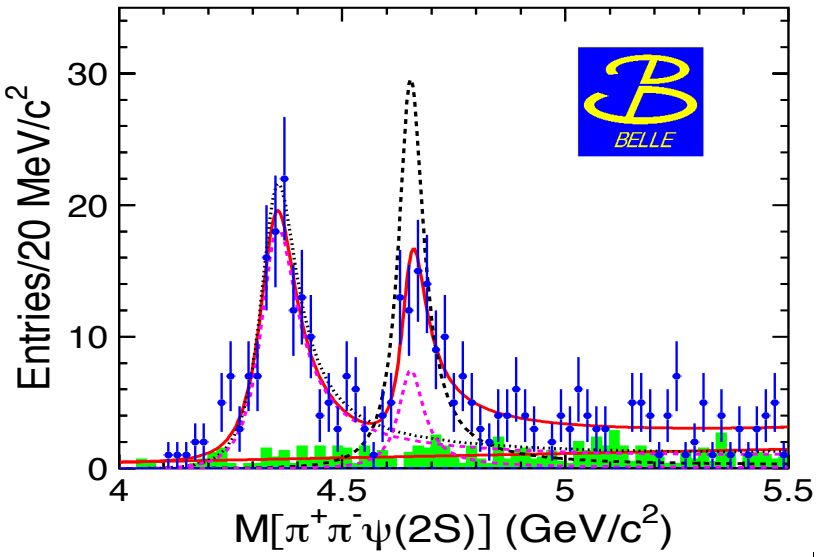


Y Family from ISR

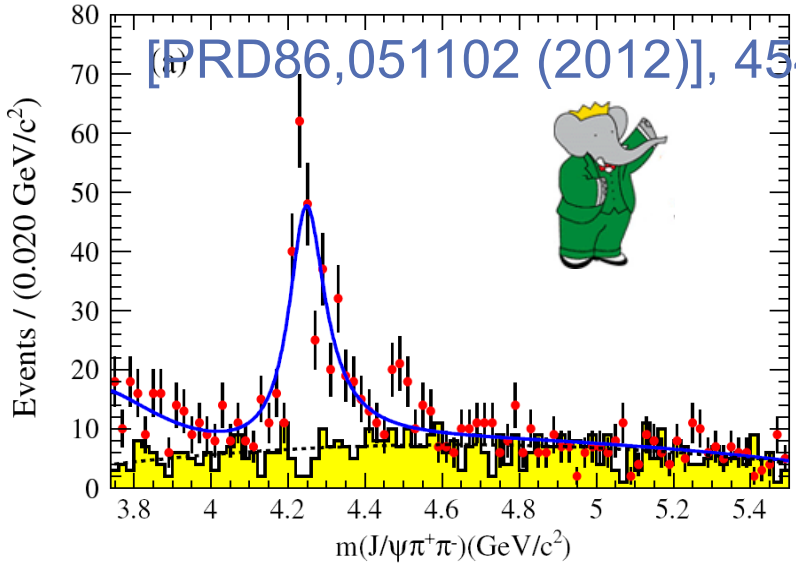
[PRL110,252002 (2013)], 967 fb^{-1}



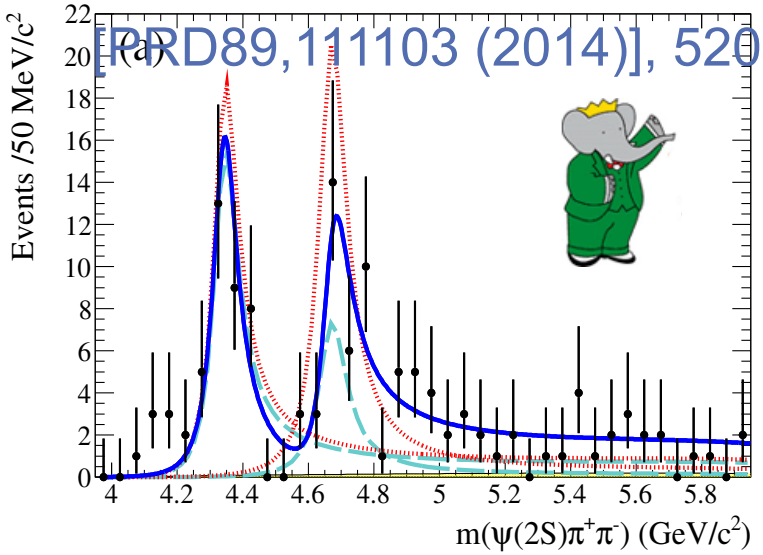
[PRD 91,112007 (2014)], 980 fb^{-1}



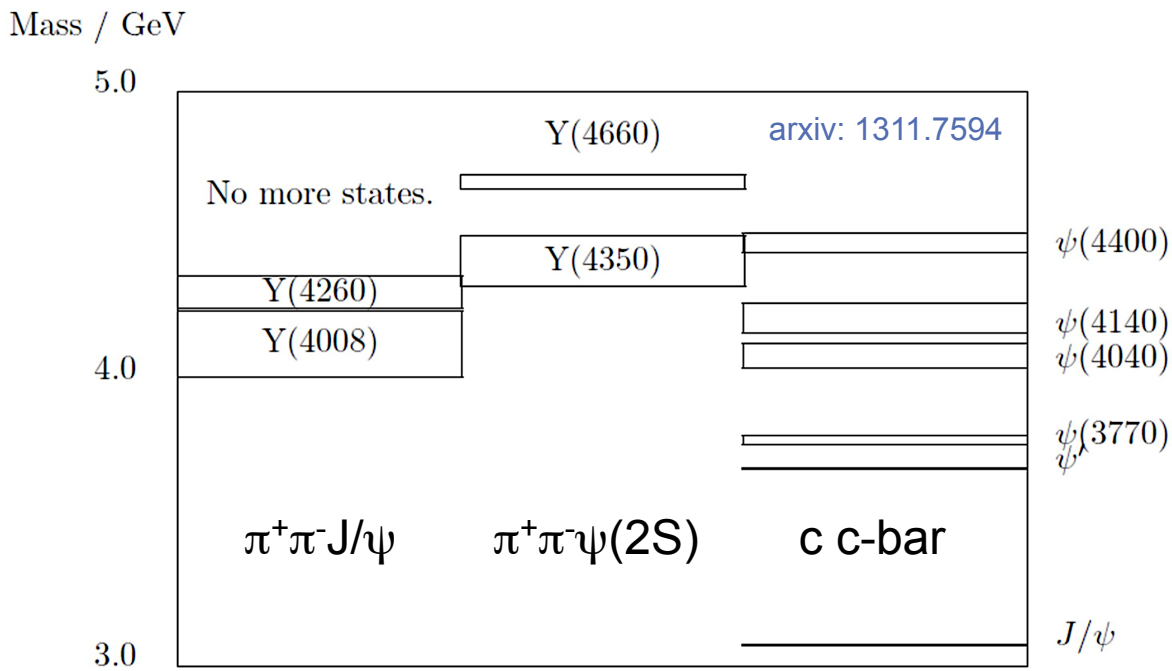
[PRD86,051102 (2012)], 454 fb^{-1}



[PRD89,111103 (2014)], 520 fb^{-1}

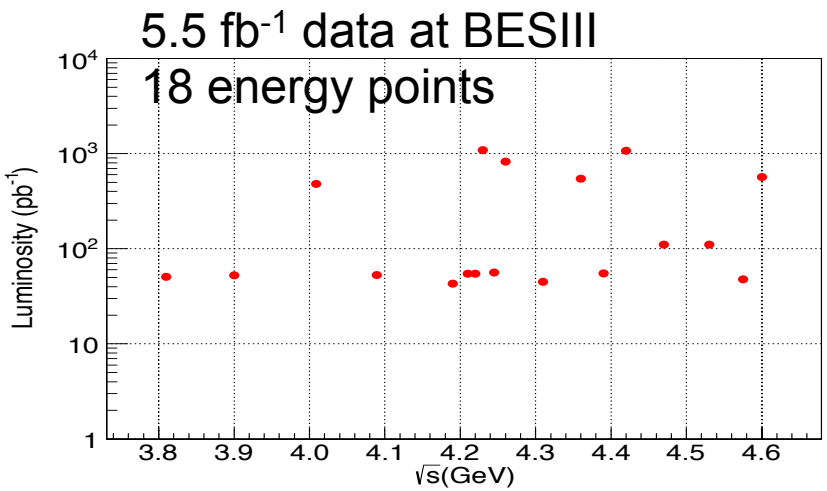


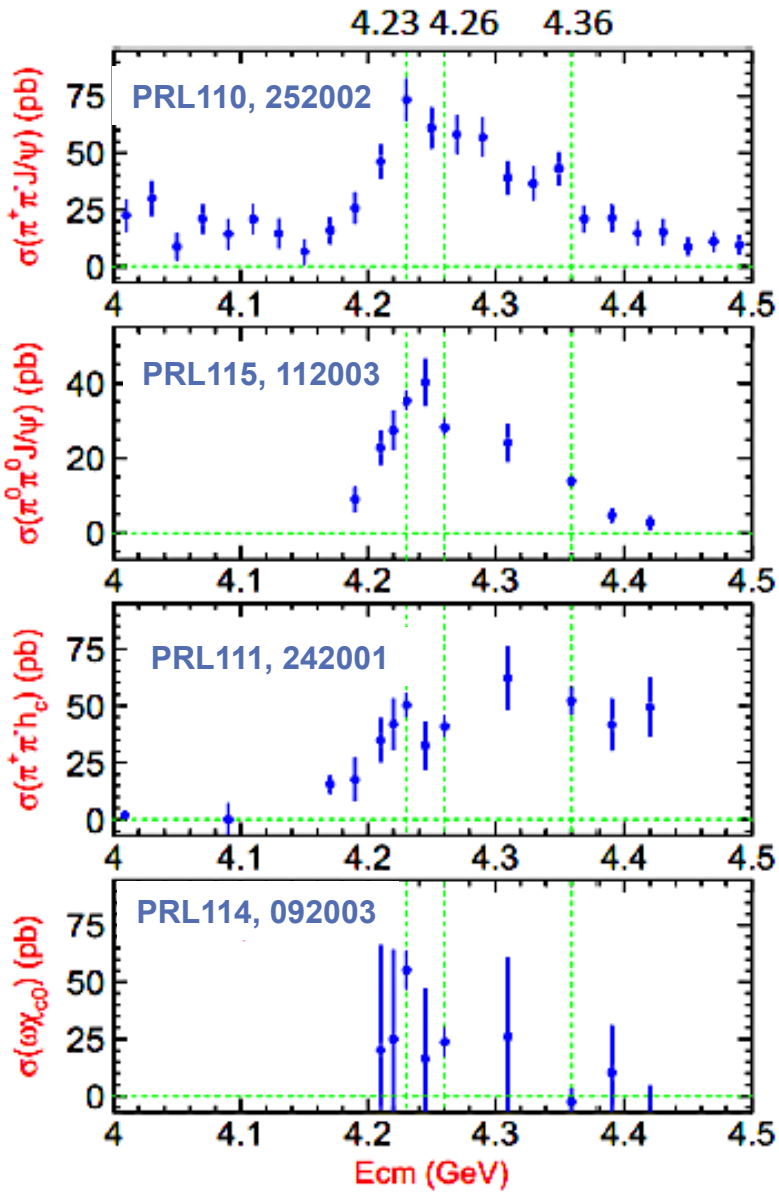
Over Population 1^{--} States



- Above charm threshold, 5 expected, 7 observed
  - No mixing with ψ states
  - No mixing among final states
    - Y(4260) only to $\pi^+\pi^-J/\psi$ (small hint 2.4σ in $\pi^+\pi^-\psi(2S)$)
    - Y(4360) and Y(4660) only to $\pi^+\pi^-\psi(2S)$

New Information from Scan



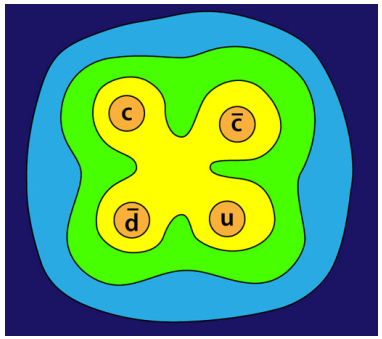


- Cross section VS E_{cms}
  - $\pi^0\pi^0 J/\psi$
  - $\pi^{+,0}\pi^{-,0}h_c$
  - $\omega\chi_{c0}$
- Information limited due to small statistics
- Maybe exist fine structure of Y(4260)??

What's Y States

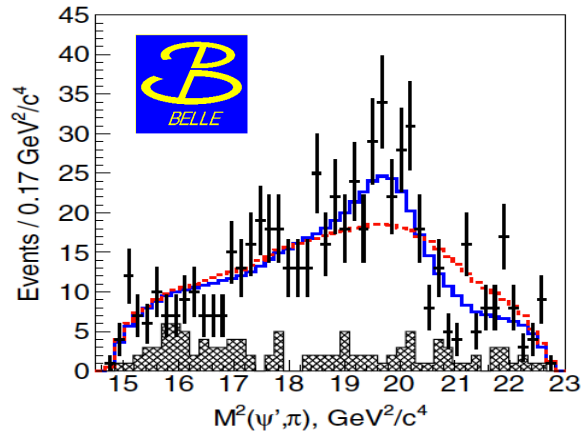
- As conventional charmonium
  - $J^{PC}=1^{--}$
  - No candidates from potential model prediction in nearby mass
  - Missing from open charm production cross section
  - Missing from inclusive hadron cross section
- As charmonium hybrid
  - Predicted mass ~4.2 GeV [PRD78, 056003 (Guo); 094504 (Dudek)]
  - Decay to DD_1 should be large, need experimental result [PLB 628 215]
- Other configurations:
  - Hadrocharmonium, molecule, terequark, threshold effect

Z_c^+ STATES

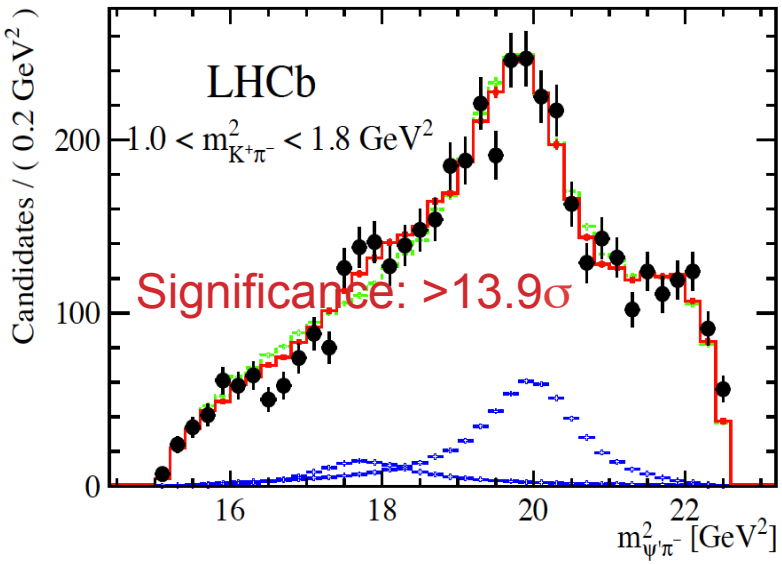


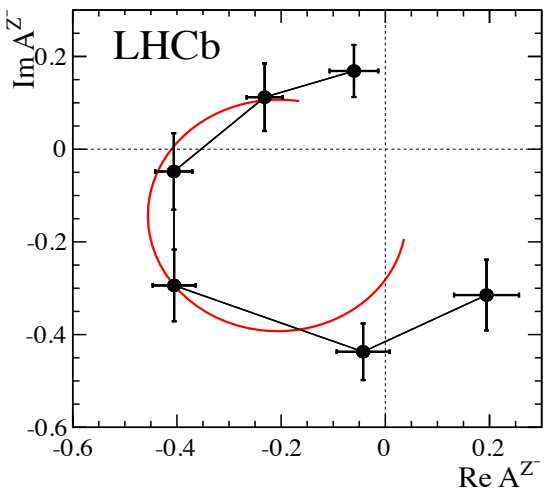
Z(4430)

- First observation: [PRL100, 142001 (2008)]
  - Belle, $B \to K\pi^{\pm}\psi(2S)$, 605 fb^{-1} data at $\Upsilon(4S)$
  - Fit to the mass spectrum of $\pi^{\pm}\psi(2S)$, 6.5σ
- Not confirmed by BaBar, found data can be explained by K^* reflections: [PRD79, 112001 (2009)]
  - Two dimensional analysis, 413 fb^{-1} data at $\Upsilon(4S)$
- Updated Belle results: [PRD80, 031104(R) (2009)] [PRD88, 074026 (2013)]
  - Two dimensional analysis using same data as first publication
  - Four dimensional amplitude analysis, 711 fb^{-1} $\Upsilon(4S)$, Z(4430) favor 1^+
  - Larger width, higher mass



Confirmation of Z(4430)





25176±174 $B^0 \rightarrow \psi' K^+\pi^-$, $\psi' \rightarrow \mu^+\mu^-$

[PRL 112 , 222002] 3 fb^{-1}

Four dimensional analysis:
$\Phi=(M^2_{K\pi'}, M^2_{\psi'\pi}, \theta_{\psi'}, \varphi)$

Mass and width consistent with Belle latest result

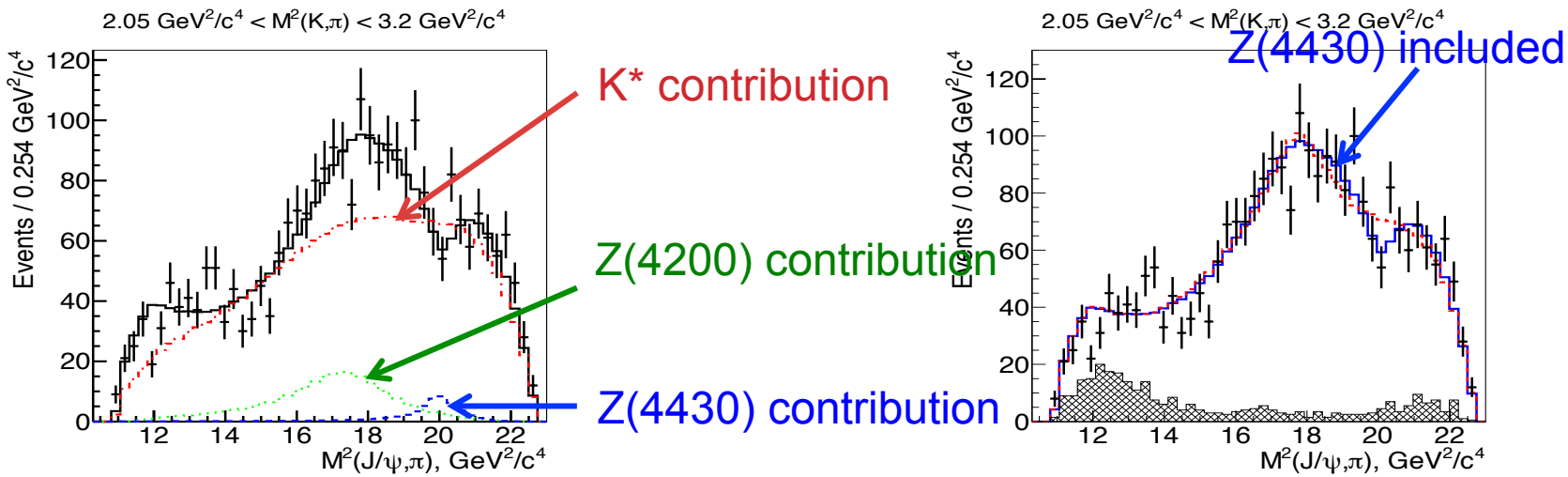
$J^P=1^+$

Second peak: $4239\pm18^{+45}_{-10}$ MeV/c^2
$220\pm47^{+108}_{-74}$ MeV

Argand diagram
resonance behavior character

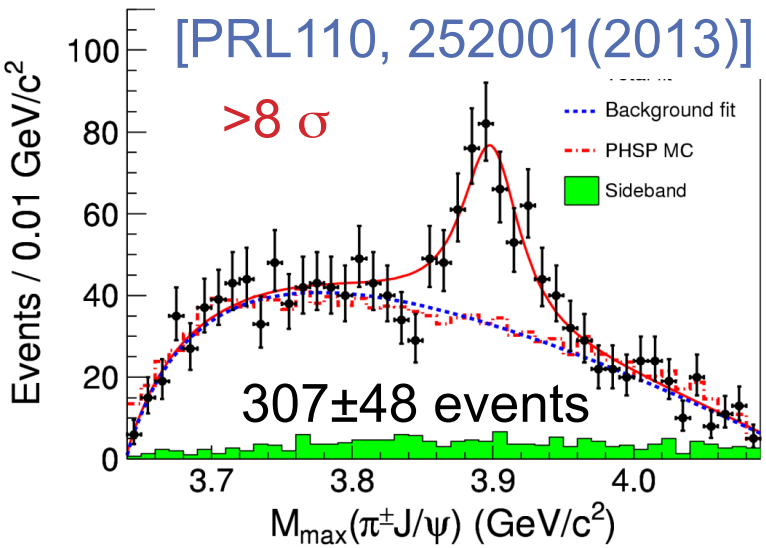
Z(4430) in $\pi J/\psi$

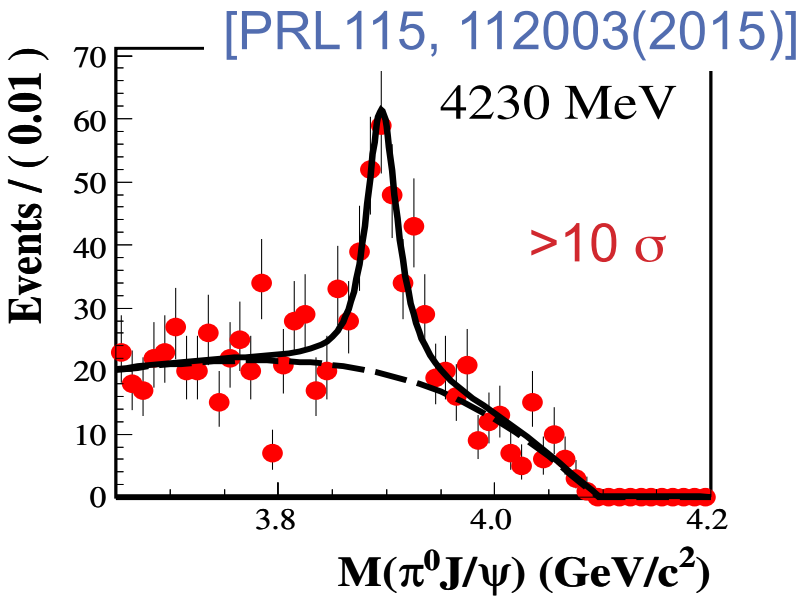
- Belle $\bar{B}^0 \rightarrow K^-\pi^+ J/\psi$, $J/\psi \rightarrow l^+l^-$ [PRD 90, 112009 (2014)]
  - 711 fb^{-1} data at $\Upsilon(4S)$, 29990±190±50 signal events
  - Four dimensional analysis:
    $\Phi=(M^2_{K\pi}, M^2_{\psi\pi}, \theta_\psi, \varphi)$
- $Z(4200)^+$ observed
  - $J^P = 1^+$
  - Global significance: 6.2 σ
- Evidence of $Z(4430)^+$
  - Global significance: 4.0 σ
- Argand diagram shows resonance character

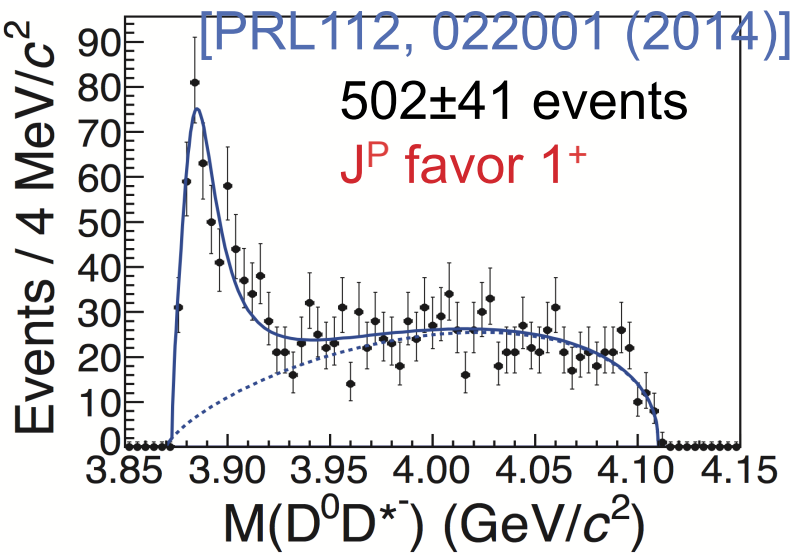


Z_c States from Y s

Iso-triplet







$Z_c(3900)^{\pm,0}$

- BESIII, Belle, CLEO-c data

$Z_c(3885)^{\pm}$

- BESIII: single and double D-tag

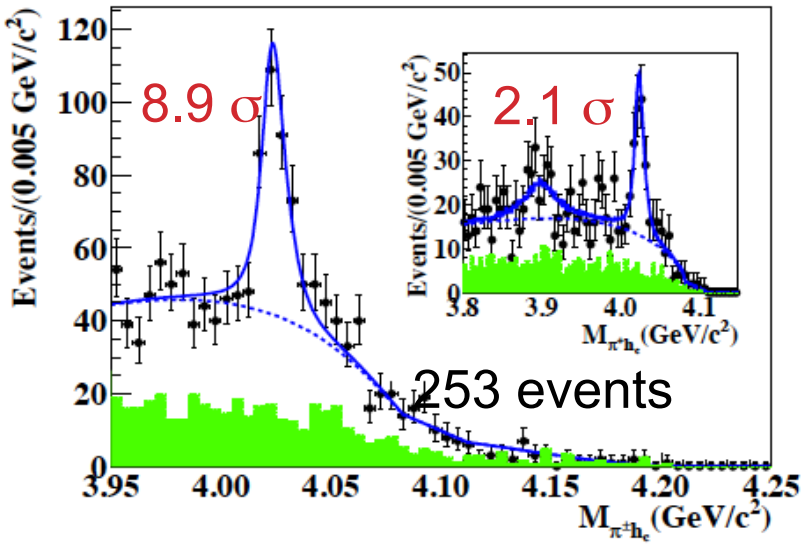
482±84 for ψ(3770)

$$\frac{\Gamma(Z_c(3885)\to DD^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)} = 6.2\pm1.1\pm2.7$$

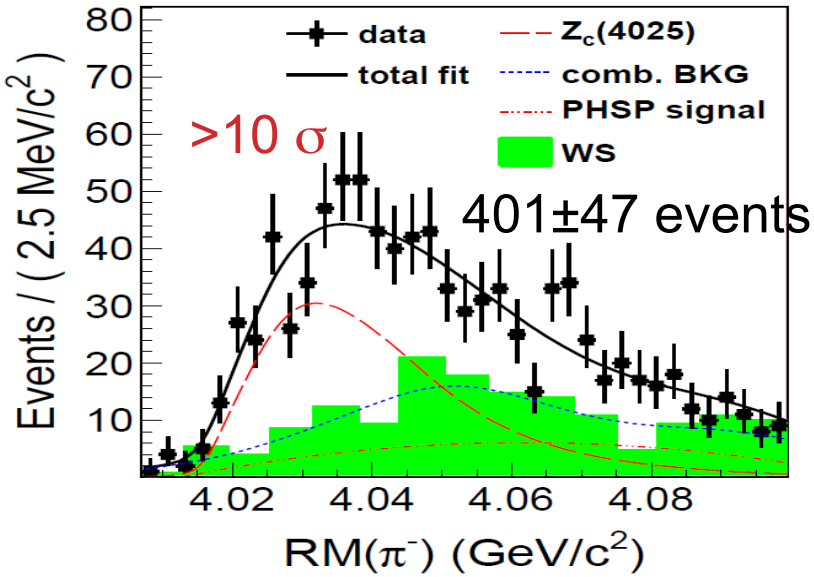
Z_c States from Y s

Iso-triplet

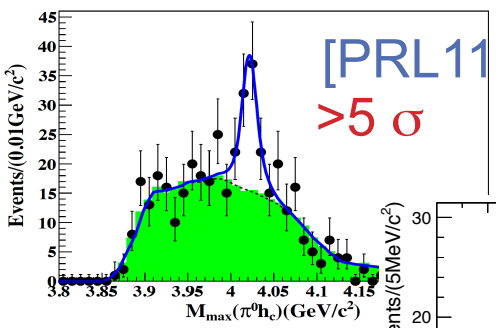
[PRL111, 242001 (2013)]



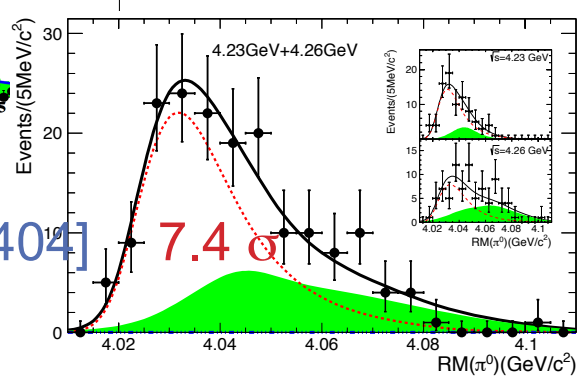
[PRL112, 132001 (2014)]



[PRL113, 212002 (2014)]



[arXiv:1507.02404]



$Z_c(4020)^{\pm,0}/Z_c(4025)^{\pm,0}$

- BESIII, need confirmation

$$\frac{\Gamma(Z_c(4025)\to D^*\bar{D}^*)}{\Gamma(Z_c(4020)\to\pi h_c)} = 12\pm5$$

Summary of Z_c States

State	Mass (MeV/c^2)	Width (MeV)	Note
$Z_c(3900)^{\pm,0}$	3899.0±3.6±4.9	46±10±20	BESIII, $\pi^{\pm}J/\psi$
	3894.5±6.6±4.5	63±24±26	Belle, $\pi^{\pm}J/\psi$
	3886±4±2	37±4±8	CLEO-c*, $\pi^{\pm}J/\psi$
	3883.9±1.5±4.2	24.8±3.3±11.0	BESIII, DD* single tag
	3884.3±1.2±1.5	23.8±2.1±2.6	BESIII, DD* double tag
	3904±9±5	--	CLEO-c*, π^0J/ψ
	3894.8±2.3±2.7	29.6±8.2±8.2	BESIII, π^0J/ψ
$Z_c(4020)^{\pm,0}$ BESIII	4022.9±0.8±2.7	7.9±2.7±2.6	$\pi^{\pm}h_c$
	4026.3±2.6±2.7	24.8±5.6±7.7	$(D^*D^*)^{\pm}$, single tag
	4023.6±2.3±3.9	-	π^0h_c
	$4025.5^{+2.0}_{-4.7}\pm3.1$	23.0±6.0±1.0	$(D^*D^*)^0$, double tag
Z(4430)	$4485\pm22^{+28}_{-11}$	$200^{+41}_{-46}{}^{+26}_{-35}$	Belle, $\pi^-\psi(2S)$
	$4475\pm7^{+15}_{-25}$	$172\pm13^{+37}_{-34}$	LHCb, $\pi^-\psi(2S)$
Z(4200)	$4196^{+31}_{-29}{}^{+17}_{-13}$	$370+70^{+70}_{-132}$	Belle, π^-J/ψ
Z(4050)	$4051\pm14^{+20}_{-41}$	$82^{+21}_{-17}{}^{+47}_{-22}$	Belle, $\pi^+\chi_{c1}$
Z(4250)	$4248^{+44}_{-29}{}^{+180}_{-35}$	$177^{+54}_{-39}{}^{+316}_{-61}$	Belle, $\pi^+\chi_{c1}$

What's Z_c states

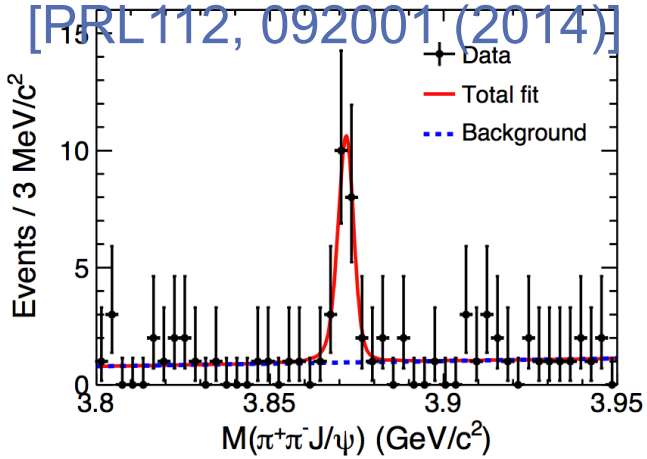
- Experimental information:
  - At least four quarks
  - Mass close charm meson pair threshold
  - Product in two pattern:
    - B meson decay
    - Y states: isospin triplet states (similar states in bottomonium system, Z_b states)
    - No mixing between them
- Possible of Z_c
  - Molecule
  - Tetraquark
  - Threshold effect
  - Hadrocharmonium

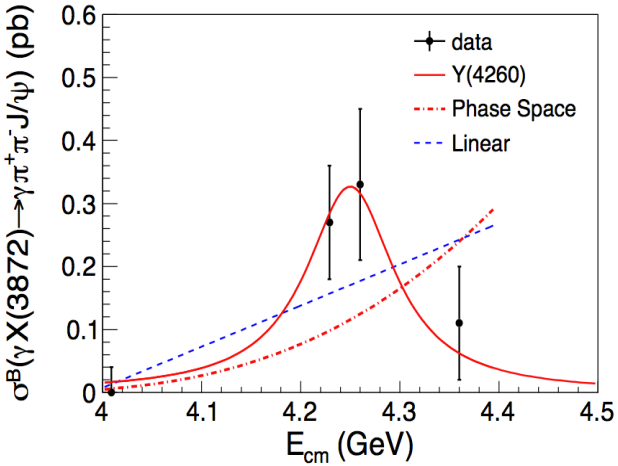
Connection between XYZ

- Y → Z
  - Z_c states are produced from Y states above 4 GeV
  - Z_c cross section vs E_{cms} measurement

- Y → X
  - $e^+e^- \rightarrow \gamma X(3872)$

[PRL112, 092001 (2014)]





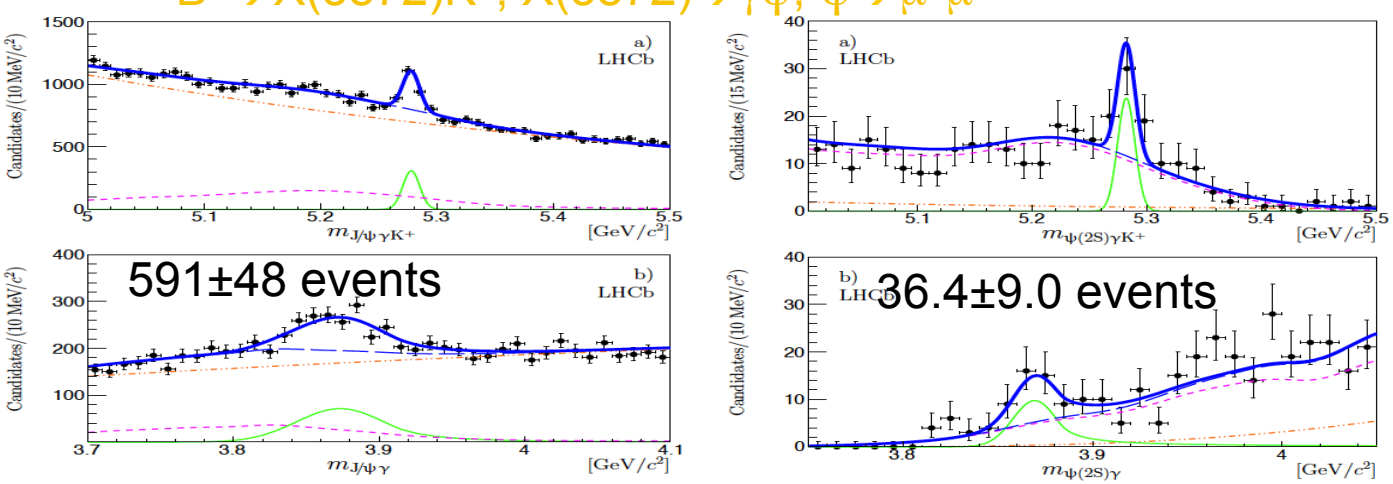
Summary

- Great progress in exotic hadrons in the past decades
  - Properties of X(3872) measurements: mass, quantum number, production and decays
  - Overpopulation of 1^{--} states above 4 GeV
  - Unexplained 1^{+} (probably) states discovered
  - Building relations between exotic states
- Theoretical progress
  - Better understanding of threshold structures
  - Systematic analysis of various processes from difference scenarios

THANK YOU

X(3872) Radiative Decays

- Ratio of X(3872)→γψ(2S) to γJ/ψ:
  - Theoretical predictions:
    - Pure DD* molecule: (3-4)×10^{-3};Charmonium: 1.2-15; Mixture: 0.5-5
  - Experimental measurements:
    - BaBar: 3.4±1.4, 3.5σ [PRL102, 132001 (2009)]
    - Belle: <2.1 @ 90% C.L [PRL107, 091803 (2011)]
    - LHCb: 2.46±0.64±0.29, 4.4σ [NPB 886, 665 (2014)]
      $B^+ \to X(3872)K^+$, $X(3872) \to \gamma\psi$, $\psi \to \mu^+\mu^-$

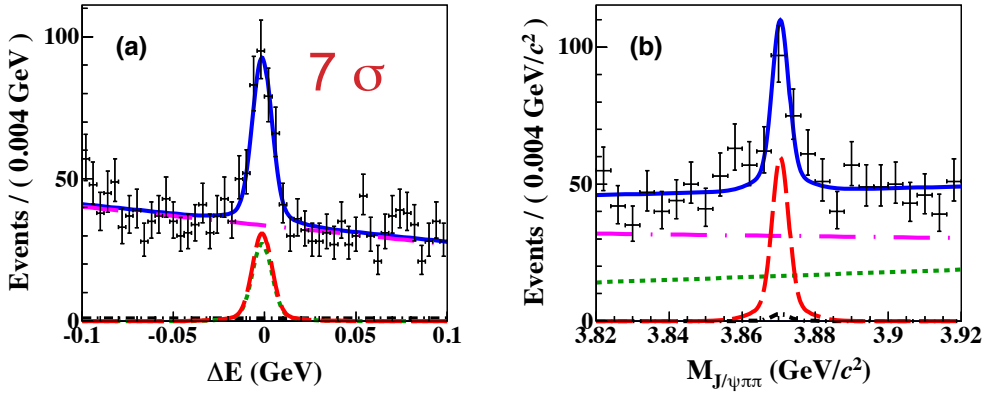


X(3872) in B→X(3872)Kπ

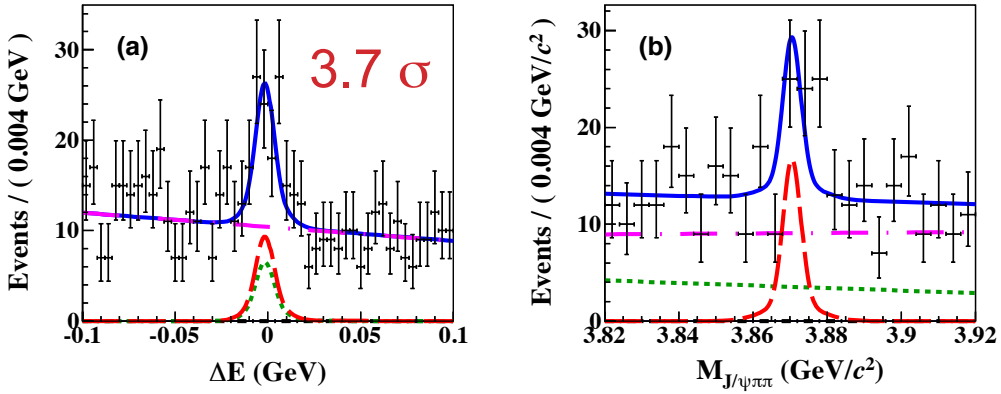
711 fb^{-1} data, 2D fit

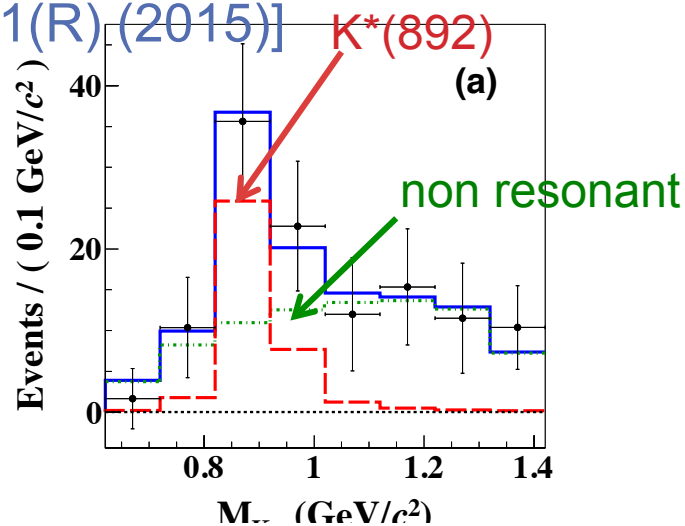
[PRD91, 051101(R) (2015)]

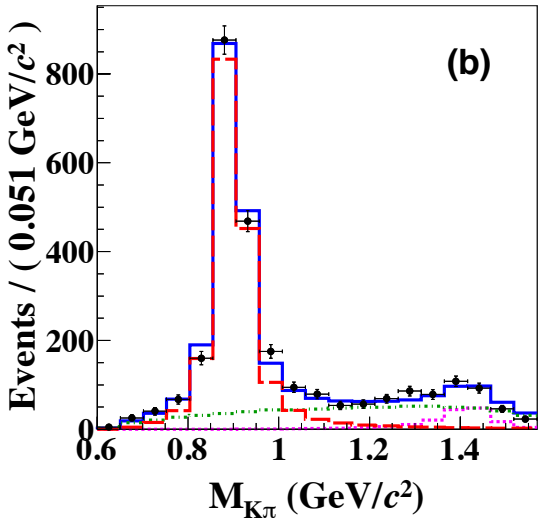
$B^0 \to X(3872)(K^+\pi^-)$ $(7.9\pm1.3\pm0.4)\times10^{-6}$



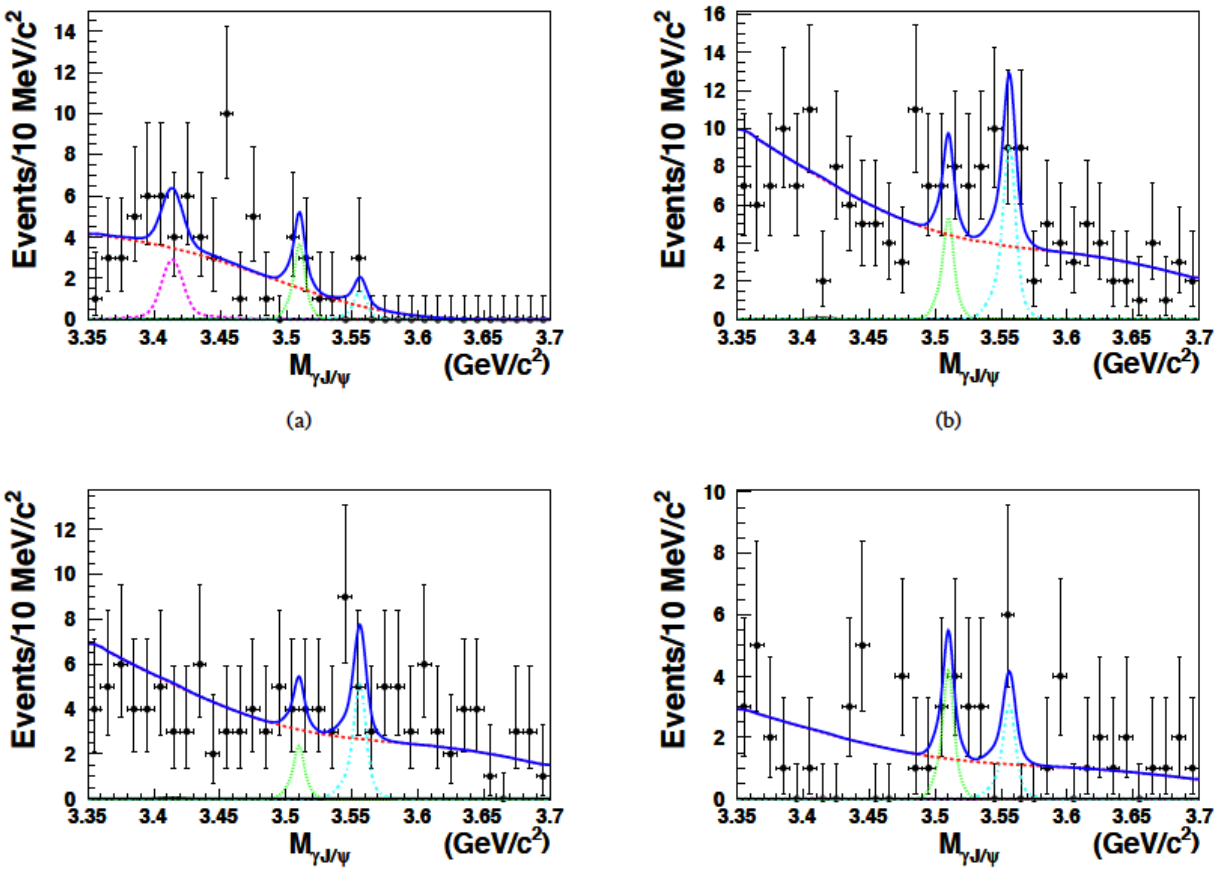
$B^+ \to X(3872)(K^0\pi^+)$ $(10.6\pm3.0\pm0.9)\times10^{-6}$







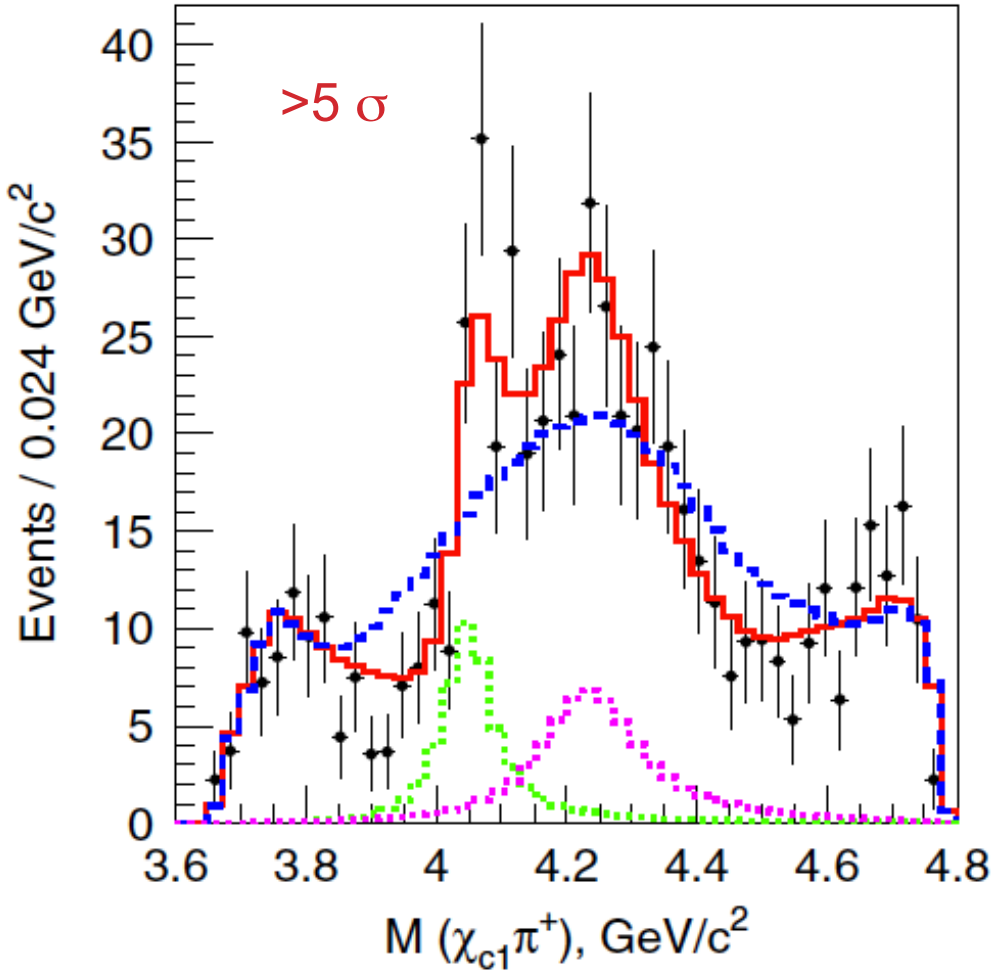
Y to $\gamma\chi_{cJ}$



Z(4050) and Z(4250)

$B^0 \to K^+\pi^-\chi_{c1}$ 605 fb^{-1}

[PRD78, 072004 (2008)]



$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$