# EXOTIC HEAVY HADRONS

## (EXPERIMENTAL RESULTS)

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# What is Exotic?

In the constituent quark model hadrons are classified:

- Mesons: quark-antiquark
- Baryons: 3 quarks

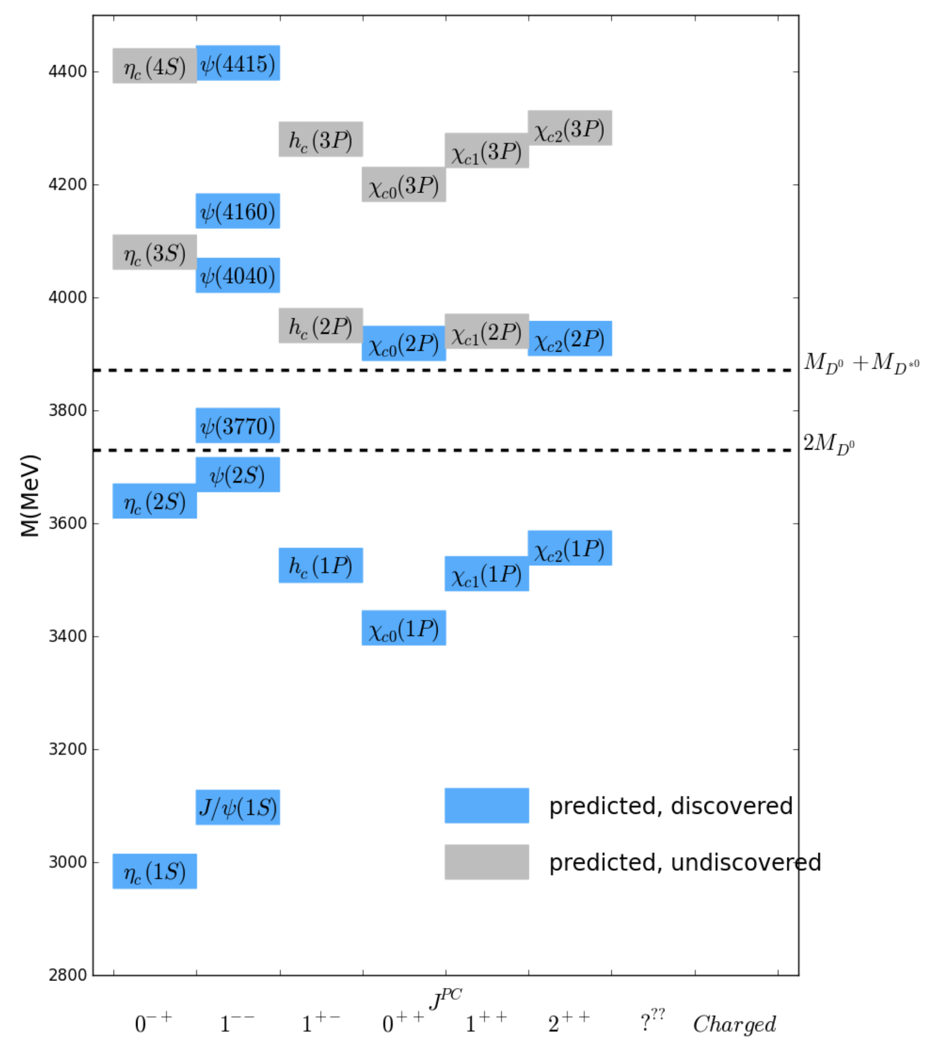
Many models predict an existence of hadrons of more complex structure with $N_{quarks} \neq 2,3$:

- Tetraquark: tightly bound diquark & anti-diquark
- Molecule: loosely bound meson-antimeson "molecule"
- Pentaquarks: 5 quarks
- H di-Baryon: Tightly bound of 6 quark state
- Glueball: Color-singlet multi-gluon bound state
- Hybrids: qqg hybrid mesons

Exotics are named *X, Y, Z, G*, ….currently all are *X* in PDG

# Introduction

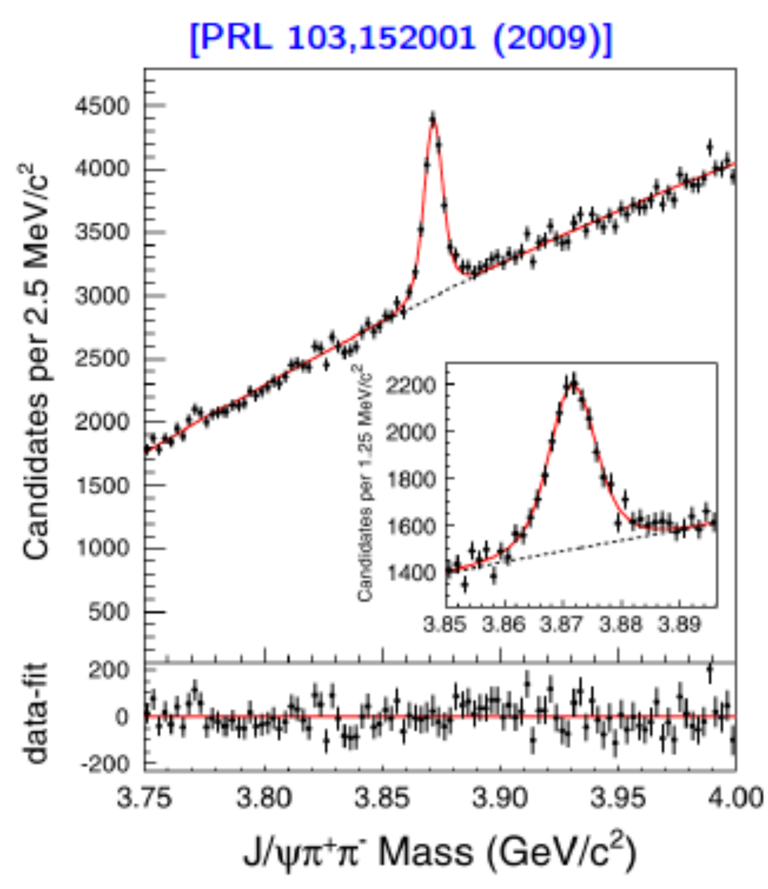
- All charmonium states below the $D\bar{D}$ threshold have been observed
- Charmonium states above the $D\bar{D}$ or $D\bar{D}^*$ threshold can decay into $D\bar{D}$ and $D\bar{D}^*$ final states
- Many predicted states still not observed
- Everything seemed understood and well established up to 2003…



# X(3872)

The X(3872) exotic-meson was discovered in 2003 by the Belle collaboration in the $B \to KX(3872)$ with $X(3872) \to J/\psi\pi^+\pi^-$

- ⊛ Promptly confirmed by BaBar, CDF, D0
- ⊛ Observed also in $J/\psi\omega, \gamma J/\psi, \gamma\psi(2S), D^0\bar{D}^{*0}$
- ⊛ Quantum number constrained to $1^{++}$ or $2^{-+}$ by CDF
- ⊛ Width is surprisely narrow ($< 1.2$ MeV)
- ⊛ Mass is not near to any of the predicted $c\bar{c}$ states
- ⊛ Mass is roughly equal to $m(D^0) + m(D^{*0})$
- ⊛ High production rate in $p\bar{p}$ collisions



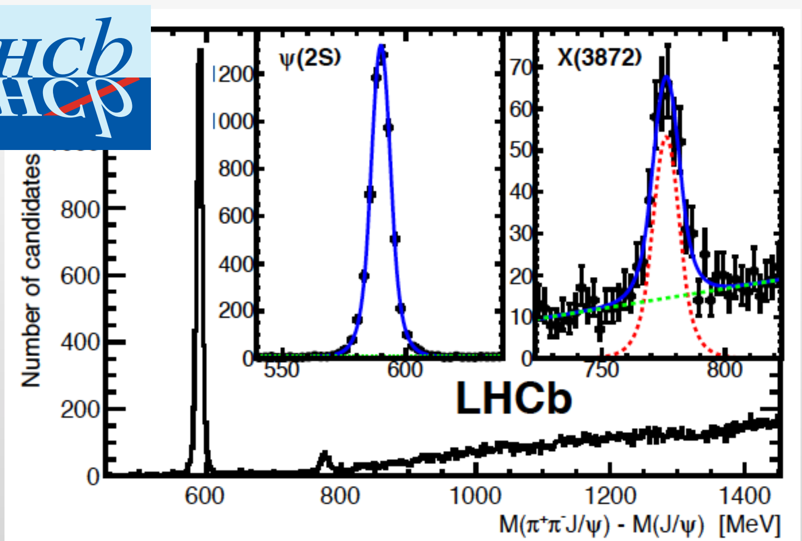

After 10 years the nature of X(3872) remains uncertain:

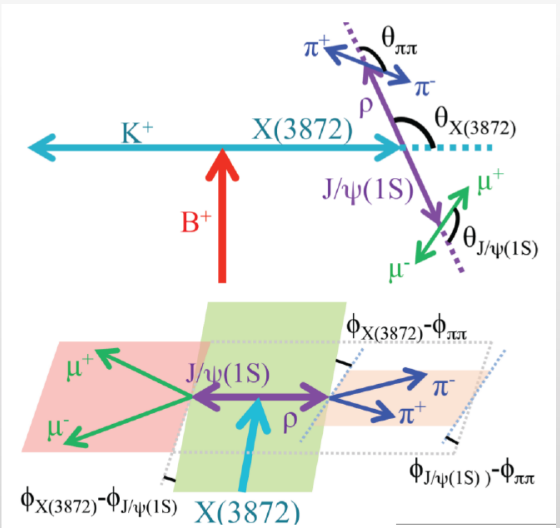
- ⊛ Conventional $c\bar{c}$ state? $\chi_{c1}(2^3P_1)$ $(J^{PC} = 1^{++})$?$\eta_{c2}(1^1D_2)$ $(J^{PC} = 2^{-+})$?
- ⊛ $D^{*0}\bar{D}^0$ bound state or tetraquark state $(J^{PC} = 1^{++})$?

New experimental inputs requested: quantum numbers, precision measurement of mass and width, production mechanism

# X(3872) Quantum Numbers

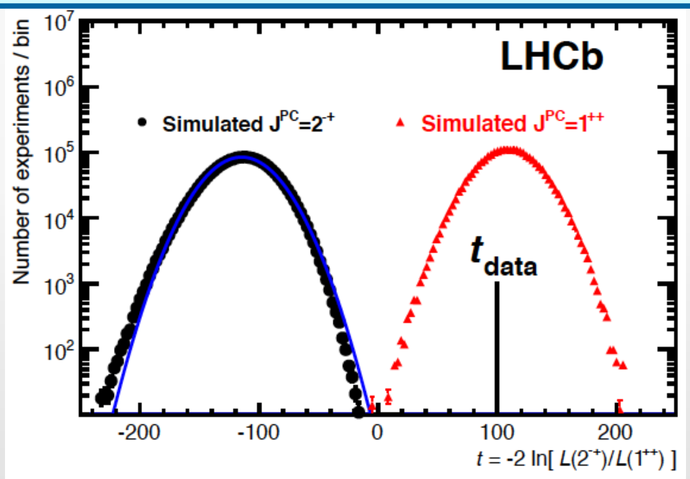
- Observation of the $X(3872) -> J/\psi\gamma$ decay $\Rightarrow$ **C=+**. BaBar [PRL 102 132001] and Belle[PRL 107 091803]
- CDF: $2292 \pm 113$ $p\bar{p} \to X(3872) + anything$ events. Unknown X(3872) polarization (only 3 angles).Quantum numbers constrained to $1^{++}$ or $2^{-+}$. [PRL 98, 132002 (2007)]
- Belle: $173 \pm 16$ $B \to KX(3872)$ events. 1D analysis carried out (Not enough events to bin in 5D). $1^{++}$ or $2^{-+}$ could not be distinguished. [hep-ex/0505038]
- LHCb: $313 \pm 26$ $B^+ \to K^+X(3872)$, 5D analysis: all angular correlations used to measure X(3872) $J^{PC}$ [PRL 110, 222001 (2013)]



# X(3872) Quantum Numbers

- Likelihood-ratio test to discriminate between the $1^{++}$ and the $2^{-+}$ assignments
- Simulated experiments, each with the number of signals and background events as in the real experiment
- The two spin hypotheses are completely separated
  - $t > 0$ implies $1^{++}$ favoured
  - $t < 0$ implies $2^{-+}$ favoured
- Data favour the $1^{++}$ over the $2^{-+}$ hypothesis at $8.4\sigma$

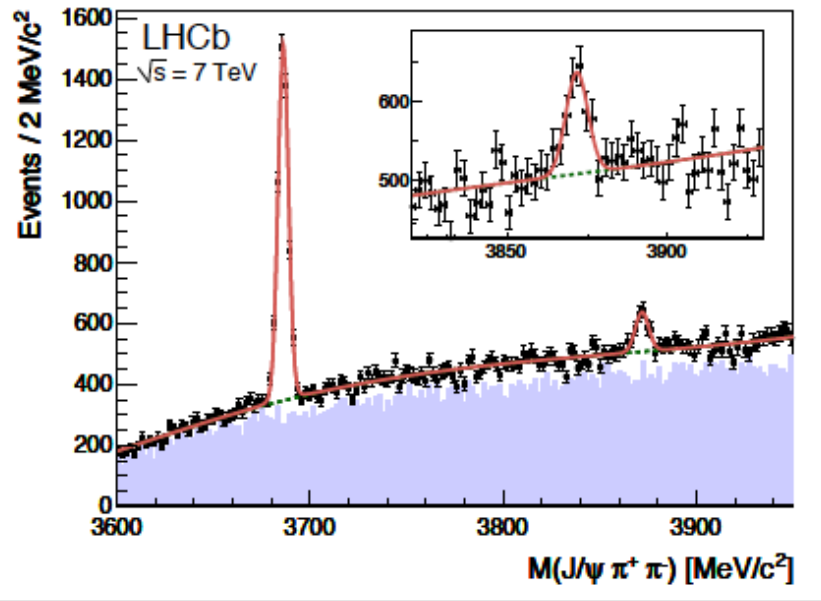



- Conventional charmonium interpretation of the X(3872) is fading
- Exotic interpretation is favoured!

# X(3872) AND $D^0$ MASS MEASUREMENTS

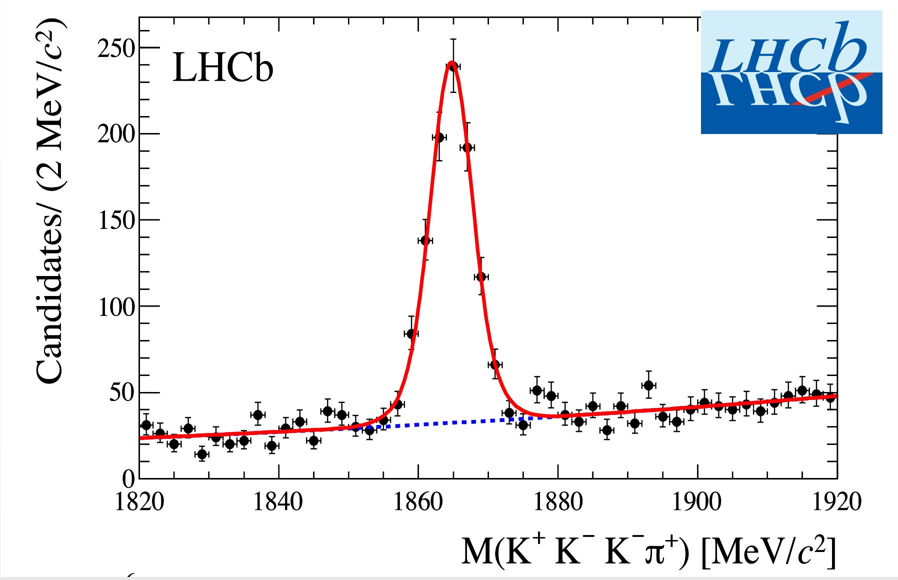
If X(3872) is a $\bar{D}^0 D^{*0}$ bound state $\Rightarrow m(X(3872)) < m(D^0) + m(D^{*0})$

**Eur. Phys. J. C. 72 (2012) 1972**



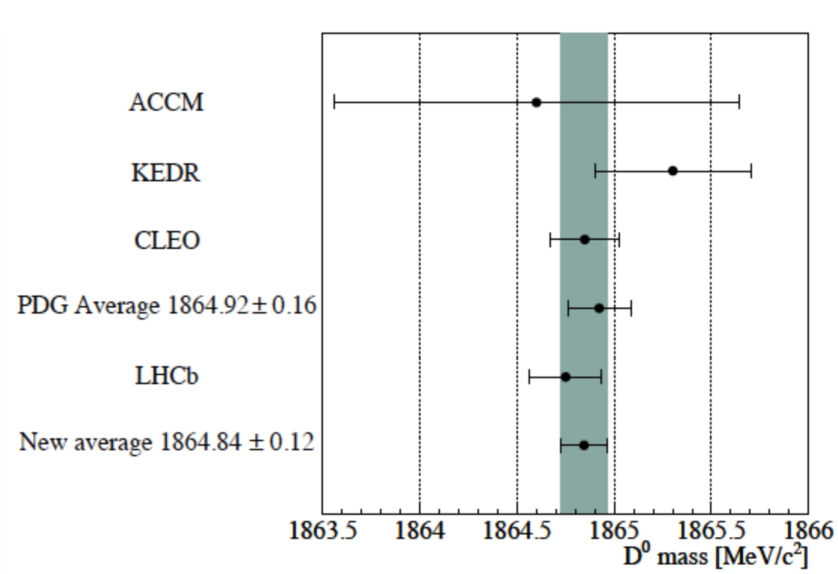

$m(X(3872)) = 3871.95 \pm 0.48 \pm 0.12\,\mathrm{MeV/c^2}$

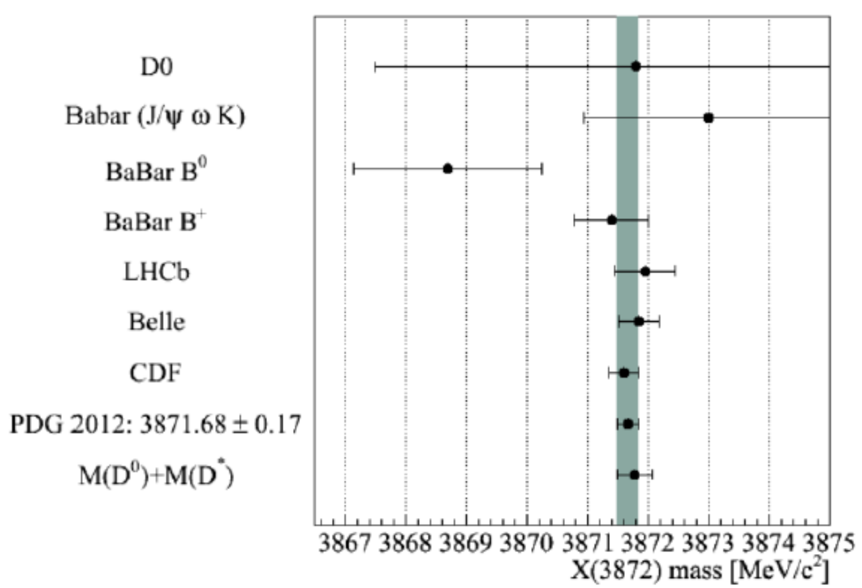
**JHEP 06 (2013) 065**




$m(D^0) = 1864.75 \pm 0.15 \pm 0.11\,\mathrm{MeV/c^2}$

# Binding Energy



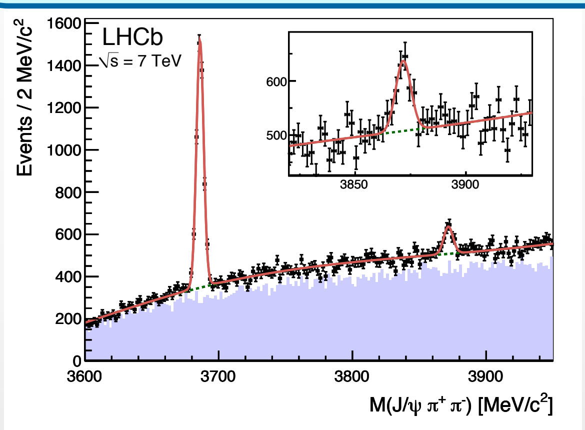



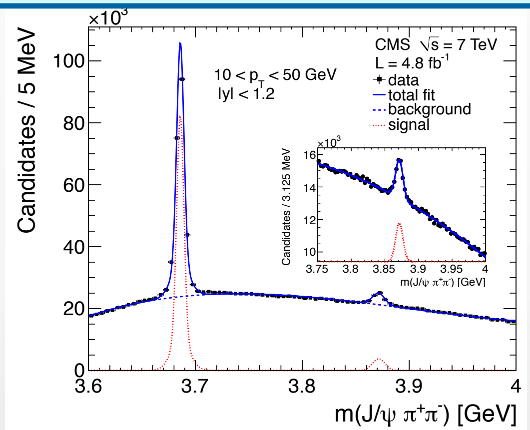

$$
\begin{aligned}
E_B &= m(D^0 D^{*0}) - m(X(3872)) \\
&= 2m(D^0) + \Delta m(D^{*0} - D^0) - m(X(3872)) \\
&= 0.09 \pm 0.28\,\mathrm{MeV/c^2}
\end{aligned}
$$

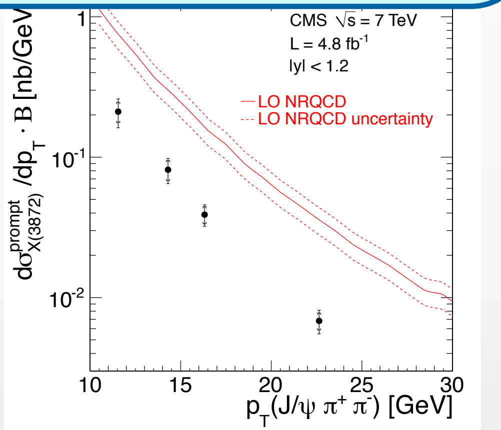
**The result reinforces the conclusion that if the X(3872) state is a molecule, it is extremely loosely bound**

# X(3872) Production

- X(3872) production in hadron collisions reported by CDF [PRL93, 072001 (2004)], D0 [PRL93, 162002 (2004)], LHCb [EPJC72, 1972 (2012)] and CMS [JHEP 1304, 154 (2013)].
- X(3872) reconstructed in the $J/\psi\pi^+\pi^-$ decay mode, in the central region (CMS, $|y| < 1.2$) or in the forward region (LHCb, $2.5 < y < 4.5$)




$$\text{LHCb}: \sigma_{X(3872)} \times BR(X(3972) \to J/\psi\pi^+\pi^-)^{[2.5<y<4.5, p_T>5\text{GeV}]} = 5.4 \pm 1.3 \pm 0.8\,\text{nb}$$

$$\text{CMS}: \sigma_{X(3872)} \times BR(X(3972) \to J/\psi\pi^+\pi^-)^{[|y|<1.2, p_T>10\text{GeV}]} = 1.06 \pm 0.11 \pm 0.15\,\text{nb}$$

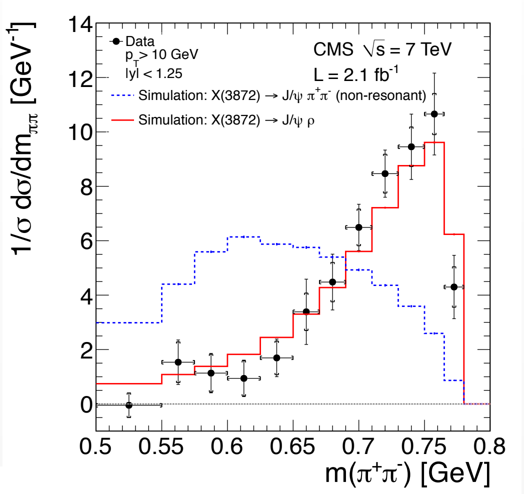
@ $\sqrt{s} = 7$ TeV

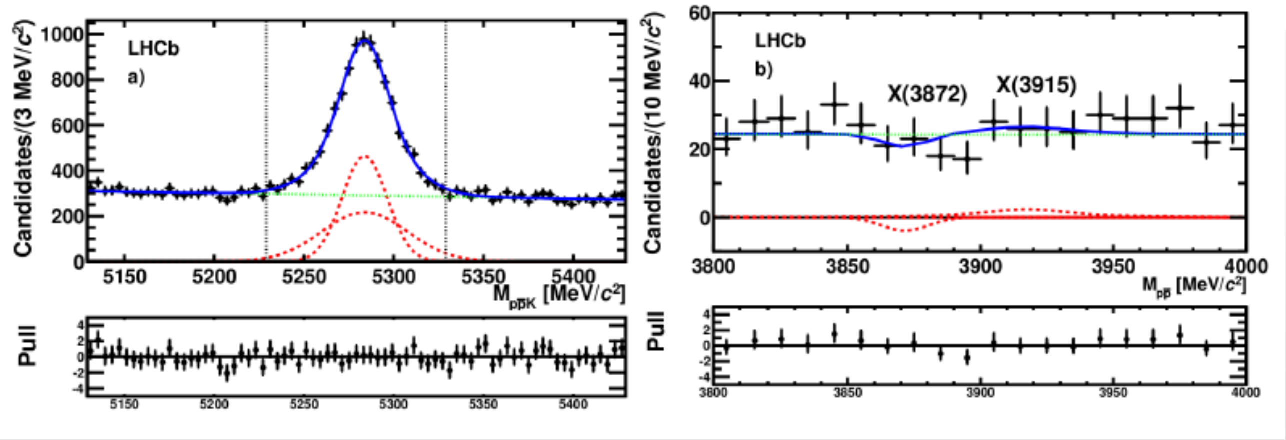
CMS: Fraction of X(3872) from $B = (26.0 \pm 2.4 \pm 1.6)\%$

"Predictions" actually larger than the measured rate

# X(3872) Decay

- CMS: $\pi^+\pi^-$ spectrum in $X(3872) \to J/\psi\pi^+\pi^-$ decays, consistent with $\rho^0$ [JHEP 1304, 154 (2013)]
- LHCb: search for $X(3872) \to p\bar{p}$ decays in $B^+ \to K^+ p\bar{p}$ [EPJC73, 2642 (2013)]

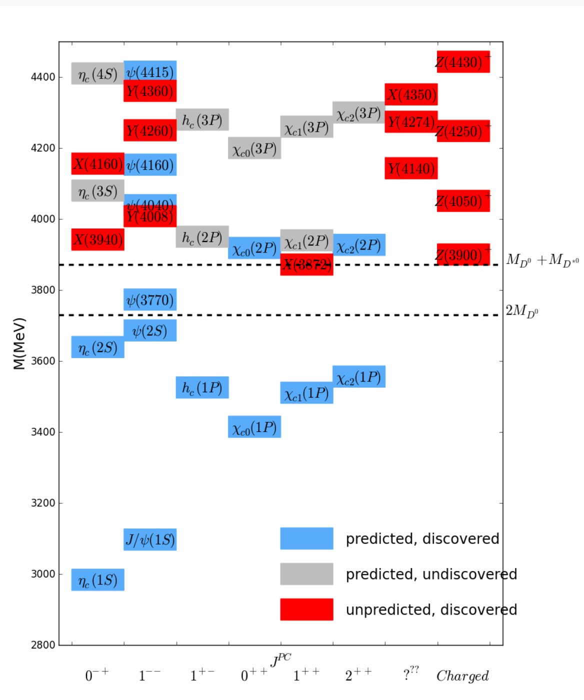



$$\frac{BR(X(3872) \to p\bar{p})}{BR(X(3872) \to J/\psi\pi^+\pi^-)} < 2.0 \times 10^{-3}$$

# The Exotic Particle Zoo

- The X(3872) has been the first unexpected quarkonia candidate
- Many other states observed in the years after
- Most of them need to be confirmed
- Large uncertainties on masses and widths
- The list is getting longer: $Z_b^+$, $Z_c^+$




$\chi_{c0}(2P)$

| State | $m$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode) | Experiment (#$\sigma$) | Year | Status |
|---|---|---|---|---|---|---|---|
| $X(3872)$ | $3871.52\pm0.20$ | $1.3\pm0.6$ | $1^{++}$ | $B\to K(\pi^+\pi^-J/\psi)$ | Belle [85, 86] (12.8), BABAR [87] (8.6) | 2003 | OK |
| | | $(<2.2)$ | | $p\bar{p}\to(\pi^+\pi^-J/\psi)+\cdots$ | CDF [88–90] (np), DØ [91] (5.2) | | |
| | | | | $B\to K(\omega J/\psi)$ | Belle [92] (4.3), BABAR [93] (4.0) | | |
| | | | | $B\to K(D^{*0}\bar{D}^0)$ | Belle [94, 95] (6.4), BABAR [96] (4.9) | | |
| | | | | $B\to K(\gamma J/\psi)$ | Belle [92] (4.0), BABAR [97, 98] (3.6) | | |
| | | | | $B\to K(\gamma\psi(2S))$ | BABAR [98] (3.5), Belle [99] (0.4) | | |
| $X(3915)$ | $3915.6\pm3.1$ | $28\pm10$ | $0/2^{?+}$ | $B\to K(\omega J/\psi)$ | Belle [100] (8.1), BABAR [101] (19) | 2004 | OK |
| | | | | $e^+e^-\to e^+e^-(\omega J/\psi)$ | Belle [102] (7.7) | | |
| $X(3940)$ | $3942^{+9}_{-8}$ | $37^{+27}_{-17}$ | $?^{?+}$ | $e^+e^-\to J/\psi(D\bar{D}^*)$ | Belle [103] (6.0) | 2007 | NC! |
| | | | | $e^+e^-\to J/\psi\,(\ldots)$ | Belle [54] (5.0) | | |
| $G(3900)$ | $3943\pm21$ | $52\pm11$ | $1^{--}$ | $e^+e^-\to\gamma(D\bar{D})$ | BABAR [27] (np), Belle [21] (np) | 2007 | OK |
| $Y(4008)$ | $4008^{+121}_{-49}$ | $226\pm97$ | $1^{--}$ | $e^+e^-\to\gamma(\pi^+\pi^-J/\psi)$ | Belle [104] (7.4) | 2007 | NC! |
| $Z_1(4050)^+$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | ? | $B\to K(\pi^+\chi_{c1}(1P))$ | Belle [105] (5.0) | 2008 | NC! |
| $Y(4140)$ | $4143.4\pm3.0$ | $15^{+11}_{-7}$ | $?^{?+}$ | $B\to K(\phi J/\psi)$ | CDF [106, 107] (5.0) | 2009 | NC! |
| $X(4160)$ | $4156^{+29}_{-25}$ | $139^{+113}_{-65}$ | $?^{?+}$ | $e^+e^-\to J/\psi(D\bar{D}^*)$ | Belle [103] (5.5) | 2007 | NC! |
| $Z_2(4250)^+$ | $4248^{+185}_{-45}$ | $177^{+321}_{-72}$ | ? | $B\to K(\pi^+\chi_{c1}(1P))$ | Belle [105] (5.0) | 2008 | NC! |
| $Y(4260)$ | $4263\pm5$ | $108\pm14$ | $1^{--}$ | $e^+e^-\to\gamma(\pi^+\pi^-J/\psi)$ | BABAR [108, 109] (8.0) | 2005 | OK |
| | | | | | CLEO [110] (5.4) | | |
| | | | | | Belle [104] (15) | | |
| | | | | $e^+e^-\to(\pi^+\pi^-J/\psi)$ | CLEO [111] (11) | | |
| | | | | $e^+e^-\to(\pi^0\pi^0J/\psi)$ | CLEO [111] (5.1) | | |
| $Y(4274)$ | $4274.4^{+8.4}_{-6.7}$ | $32^{+22}_{-15}$ | $?^{?+}$ | $B\to K(\phi J/\psi)$ | CDF [107] (3.1) | 2010 | NC! |
| $X(4350)$ | $4350.6^{+4.6}_{-5.1}$ | $13.3^{+18.4}_{-10.0}$ | $0,2^{++}$ | $e^+e^-\to e^+e^-(\phi J/\psi)$ | Belle [112] (3.2) | 2009 | NC! |
| $Y(4360)$ | $4353\pm11$ | $96\pm42$ | $1^{--}$ | $e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$ | BABAR [113] (np), Belle [114] (8.0) | 2007 | OK |
| $Z(4430)^+$ | $4443^{+24}_{-18}$ | $107^{+113}_{-71}$ | ? | $B\to K(\pi^+\psi(2S))$ | Belle [115, 116] (6.4) | 2007 | NC! |
| $X(4630)$ | $4634^{+9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $e^+e^-\to\gamma(\Lambda_c^+\Lambda_c^-)$ | Belle [25] (8.2) | 2007 | NC! |
| $Y(4660)$ | $4664\pm12$ | $48\pm15$ | $1^{--}$ | $e^+e^-\to\gamma(\pi^+\pi^-\psi(2S))$ | Belle [114] (5.8) | 2007 | NC! |
| $Y_b(10888)$ | $10888.4\pm3.0$ | $30.7^{+8.9}_{-7.7}$ | $1^{--}$ | $e^+e^-\to(\pi^+\pi^-\Upsilon(nS))$ | Belle [37, 117] (3.2) | 2010 | NC! |

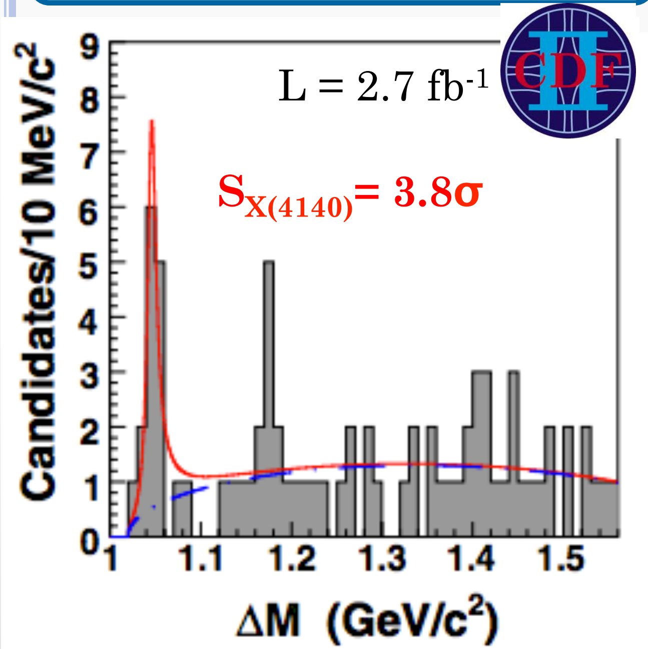
Eur. Phys. J. C71:1534, 2011

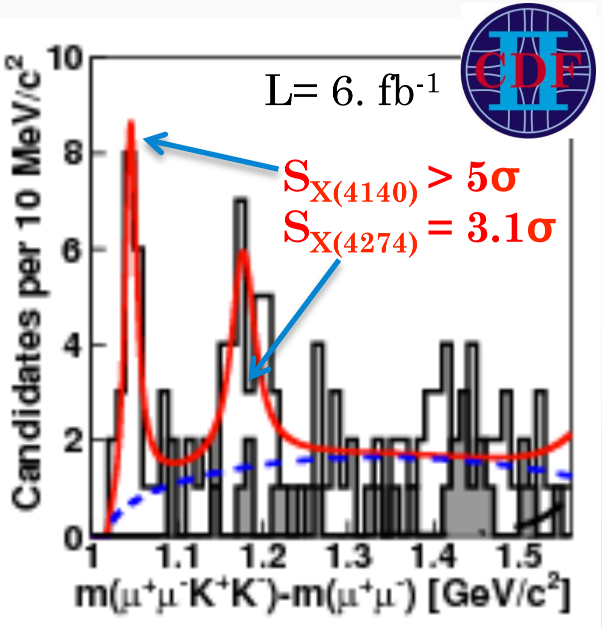
# X(4140) AND X(4274)

Evidence/"Observation" in $B^+ \rightarrow J/\psi\ \phi\ K^+$

**PRL 102, 242002 (2009)**

**arXiv: 1101.6058 (2011)**




**X(4140)**

$m = 4143.0^{+2.9}_{-3.0} \pm 0.6$ MeV
$\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV

**X(4274)**

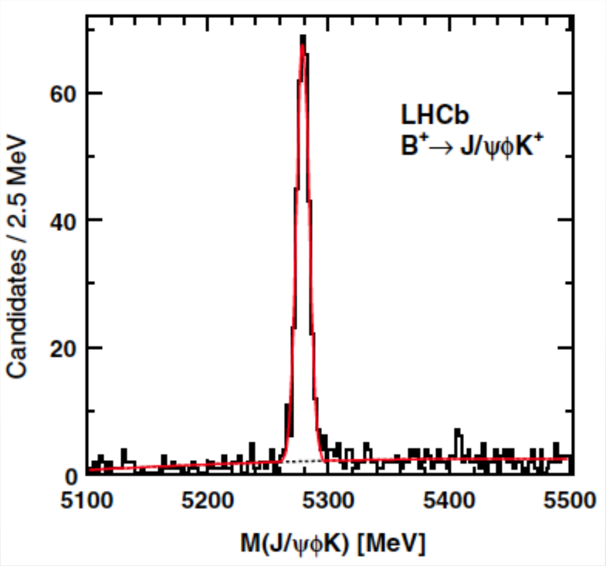
$m = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV
$\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$ MeV

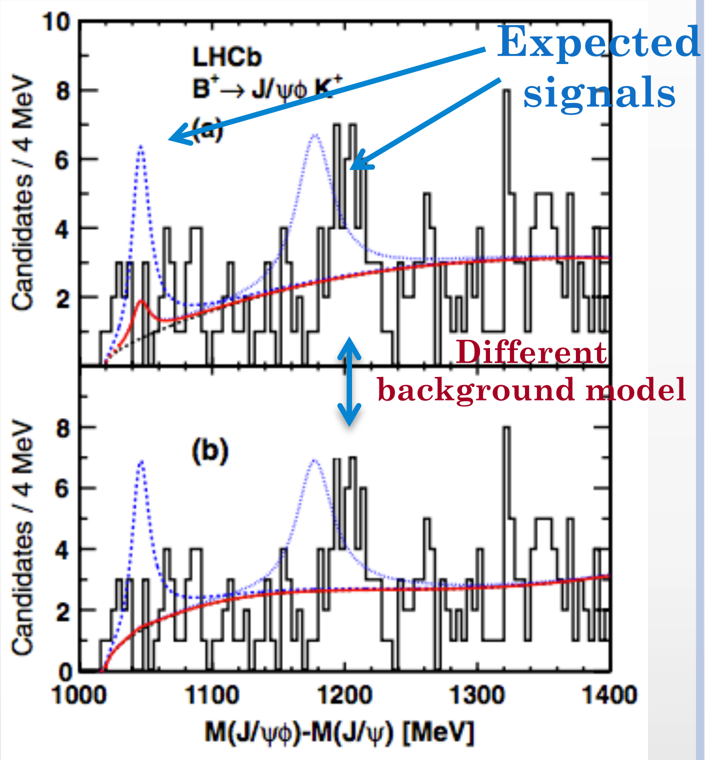
**Charmonium states with $m_X >> D_{(s)}^{(*)} D_{(s)}^{(*)}$ should decay easily into D mesons. The narrow widths hint that their nature is different: meson-meson, hybrid, tetraquark, etc..**

# SEARCH FOR X(4140) AT LHCB

**PRD 85, 091103(R) (2012)**

- 0.37 $fb^{-1}$ analyzed (~1/8 of the recorded data sample)
- (Almost) background free $B^+ \to J/\psi\ \phi\ K^+$ sample. 382 ± 22 events




- According to the CDF results, 35 ± 11 X(4140) signal candidates and 53 ± 19 X(4274) signal candidates expected
- No narrow structure is observed near the threshold
- The LHCb results disagree at $2.4\sigma$ level with the CDF measurement

**LHCb(90%) C.L.**

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.07.$$

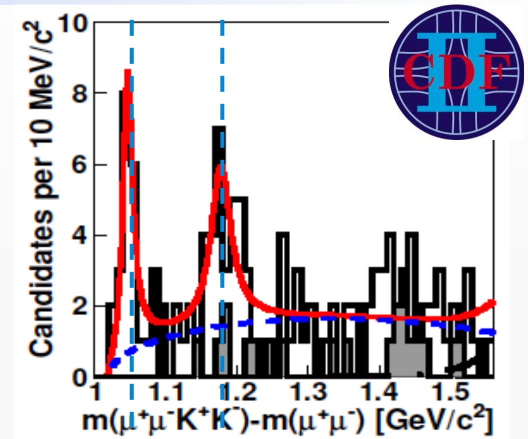
$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.08$$

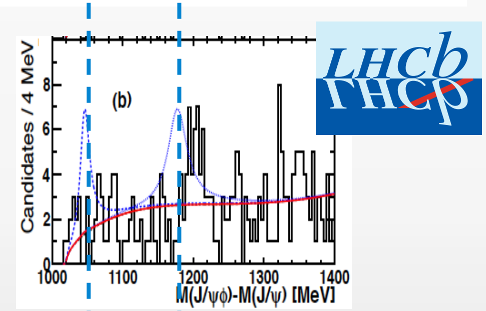
# X(4140) RESULTS: COMPARISON

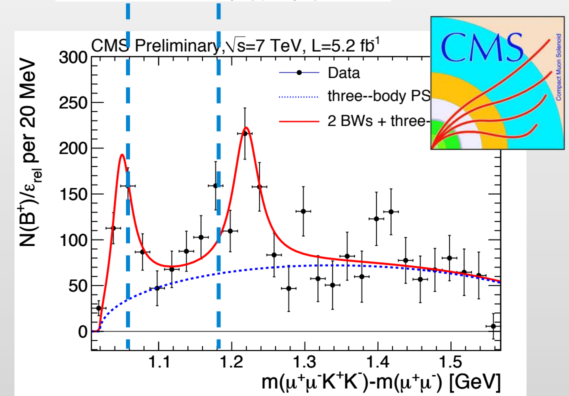
- CMS has reported observation/ evidence of peaks in J$\psi$ $\phi$ with a larger sample of $B^+ \rightarrow J/\psi\ \phi\ K^+$
- The width of structure near the threshold (not yet quoted) looks wider
- The mass of the X(4274) is 3.8$\sigma$ in disagreement with CDF measurement

X(4140) and X(4274) still to be confirmed

An amplitude analysis would help to show the resonance nature of these peaks



# $Z_c(4430)^+$

- Charged structure observed in the $\psi(2S)\pi^+$ in $B^{0(+)} \to \psi(2S)\pi^+K^{-(0)}$ decays($6.4\sigma$) by Belle[PRL 100, 142001 (2008)].

$$M = 4433 \pm 4(stat) \pm 2(syst)$$
$$\Gamma = 45^{+18}_{-13}(stat)^{+30}_{-13}(syst)$$

- Clear signature of exotic:

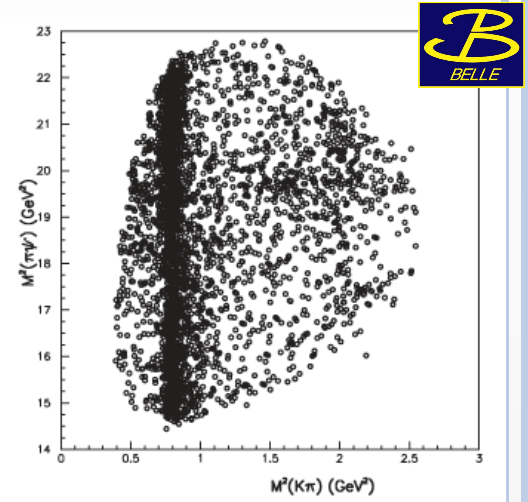
  Decay to charmonium: contains a $c\bar{c}$ pair

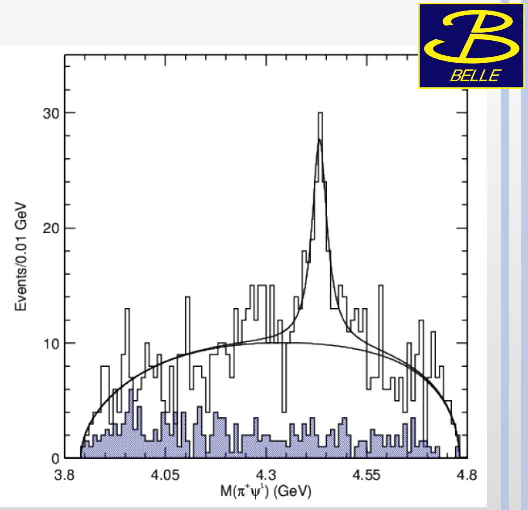
  Has electric charge: has 2 more light quarks $N_{quarks} >= 4$!

  Tetraquark, $D^*D_1$ molecule?

- Later Belle re-analysed their data with a 2D "Dalitz" technique. Integration over 2 angles $\Rightarrow$ 2 remaining variable: $M^2(\psi(2S)\pi^+)$ and $M^2(K^-\pi^+)$ $\Rightarrow$ No interferences between the different $\psi(2S)$ helicity states.($6.4\sigma$)[PHYS. REV. D 80, 031104(R) (2009)]

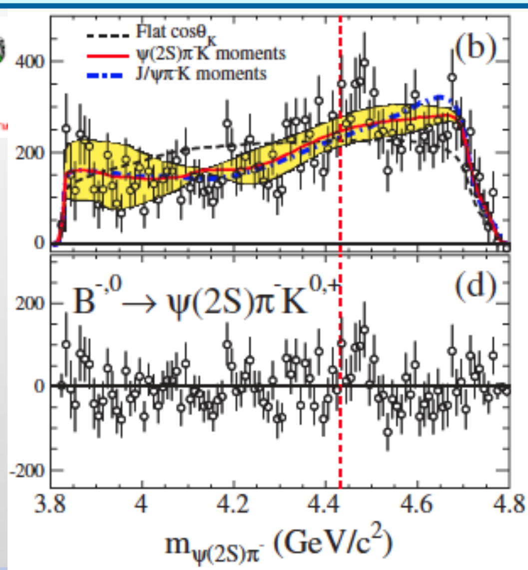
$$M = 4443^{+15}_{-12}(stat)^{19}_{-13}(syst)$$
$$\Gamma = 107^{+86}_{-43}(stat)^{+74}_{-56}(syst)$$

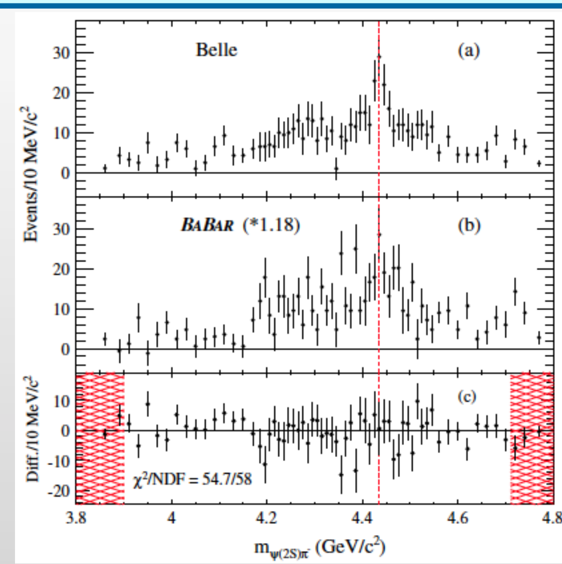


# $Z_c(4430)^+$

- Dalitz plot is dominated by mass and angular distribution structures in the $K\pi$ system
- Investigation the extent to which reflection of the $K\pi$ mass and angular structures are able to reproduce the $\psi(2S)\pi$ mass distributions
- Representation the $K\pi$ angular distribution in terms of a Legendre polynomial expansion (S, P and D waves) [PRD 79, 112001 (2009)]
- Belle and BABAR mass distributions are statistically consistent.
- $Z(4430)^+$ not confirmed (nor excluded)



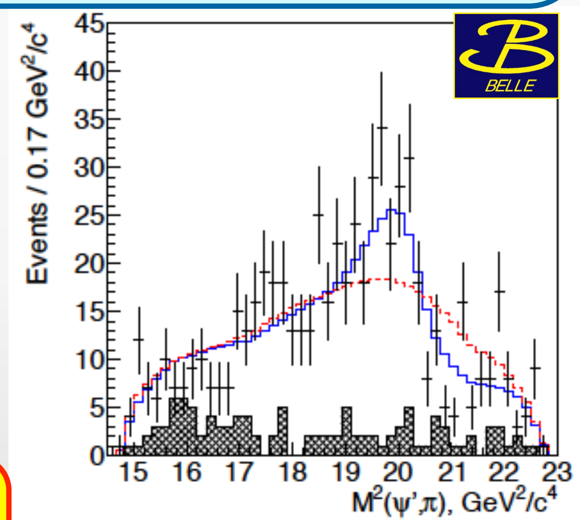



# $Z_c(4430)^+$

- Recently Belle presented results of a full 4D amplitude analysis[arXiv:1306.4894]
- The preferred assignment of the quantum numbers of the $Z(4430)^+$ is $1^+$
- The $0^-$ hypothesis is not excluded

$0^+ \not\rightarrow 1^- \, 0^-$

| $J^P$ | $0^-$ | $1^-$ | $1^+$ | $2^-$ | $2^+$ |
|---|---|---|---|---|---|
| Mass, MeV$/c^2$ | $4470 \pm 20$ | $4482 \pm 4$ | $4500 \pm 12$ | $4545 \pm 2$ | $4367 \pm 2$ |
| Width, MeV | $139 \pm 36$ | $10.9 \pm 0.3$ | $126 \pm 20$ | $11.2 \pm 0.6$ | $9.1 \pm 0.6$ |
| Significance | $4.4\sigma$ | $1.2\sigma$ | $6.1\sigma$ | $2.3\sigma$ | $2.6\sigma$ |




$$M = 4470^{+26}_{-30}(stat)^{+83}_{-23}(syst)$$

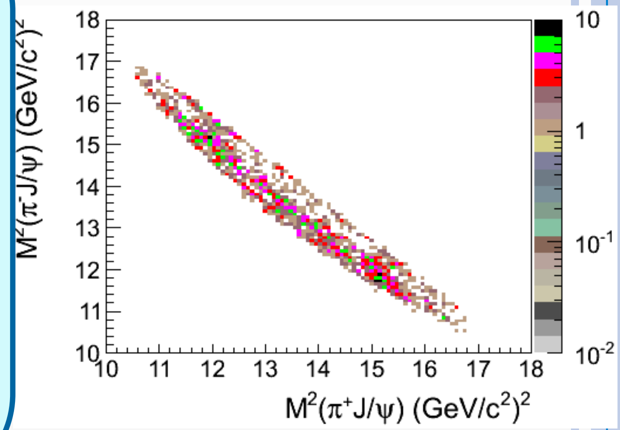
$$\Gamma = 139^{+52}_{-39}(stat)^{+17}_{-32}(syst)$$

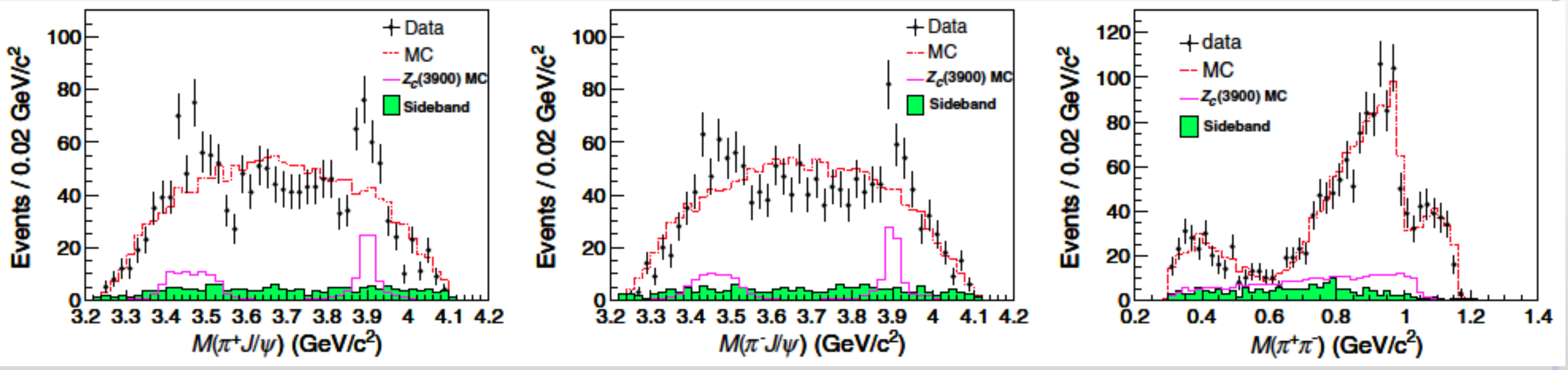
$$M = 4500^{+14}_{-13}(stat)^{+16}_{-9}(syst)$$

$$\Gamma = 126^{+30}_{-26}(stat)^{+3}_{-26}(syst)$$

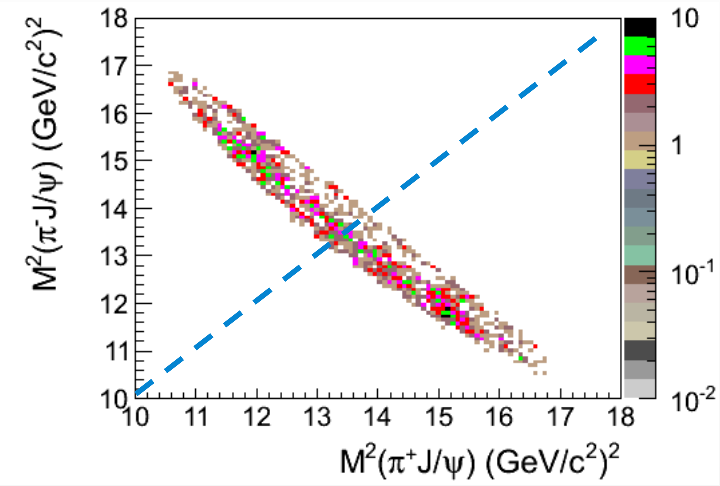
# $Z_c(3900)^+$

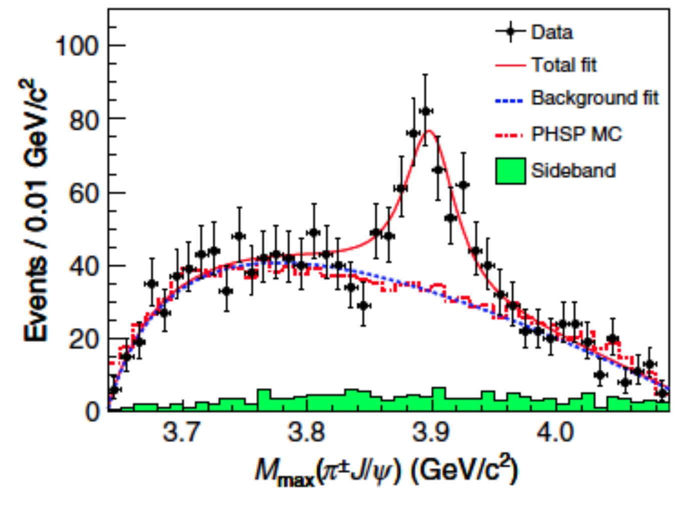
- $e^+e^- \to \pi^+\pi^- J/\psi$ at 4.26 GeV (peak of the Y(4260) cross section)[PRL 110, 252001 (2013)]
- Structures observed in the $\pi^+\pi^-$ and $\pi J/\psi$ mass spectra
- Reflections of the $\pi\pi$ mass spectrum, that includes the $f_0(500)$, $f_0(980)$ and non-resonant S-wave, can't cope peaking structures in $\pi J/\psi$
- The reflection of the $Z_c(3900)^+$ itself is observed!



# $Z_c(3900)^+$

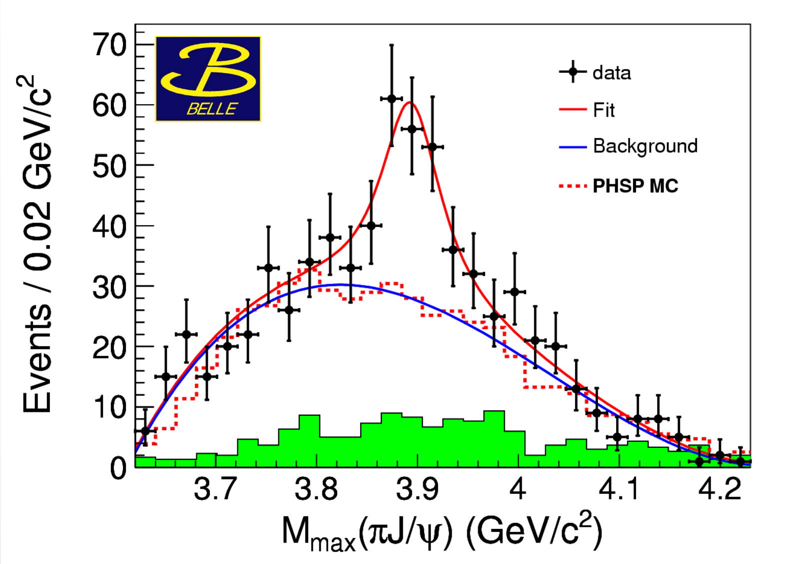



- S-wave Breit-Wigner with efficiency correction
- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

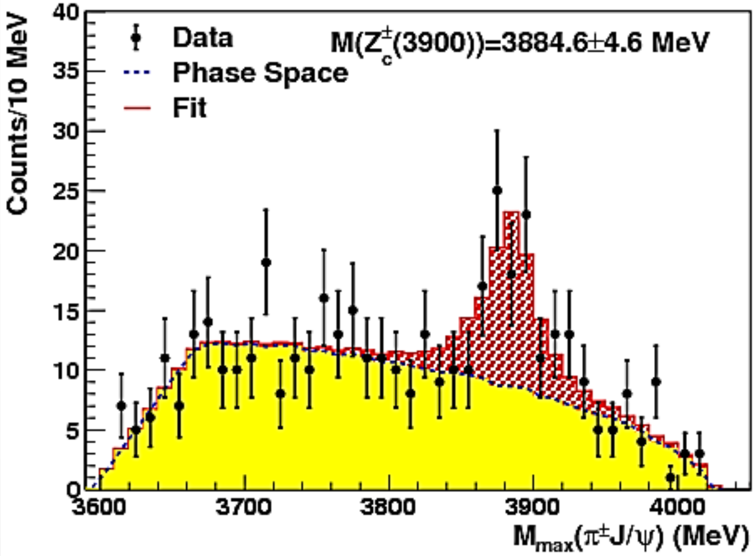
# $Z_c(3900)^+$ : CONFIRMATION

Belle with ISR in Y(4260) decays: [PRL110, 252002 (2013)]




- M = 3894.5±6.6±4.5 MeV
- Γ = 63±24±26 MeV
- 159 ± 49 events
- >5.2σ

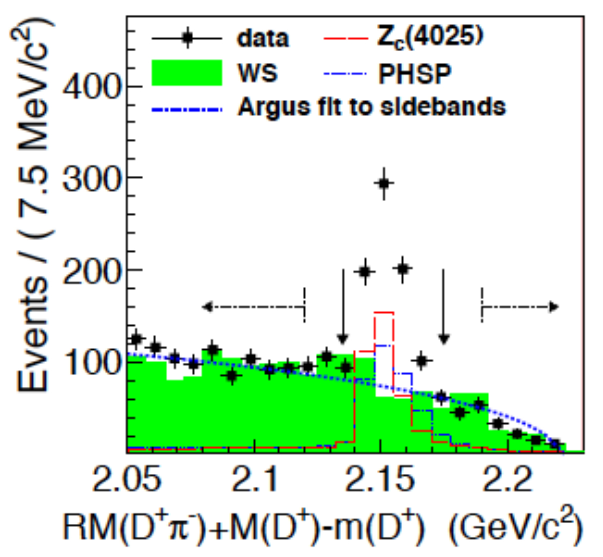
CLEOc data at 4.17 GeV: [arxiv:1304.3036]

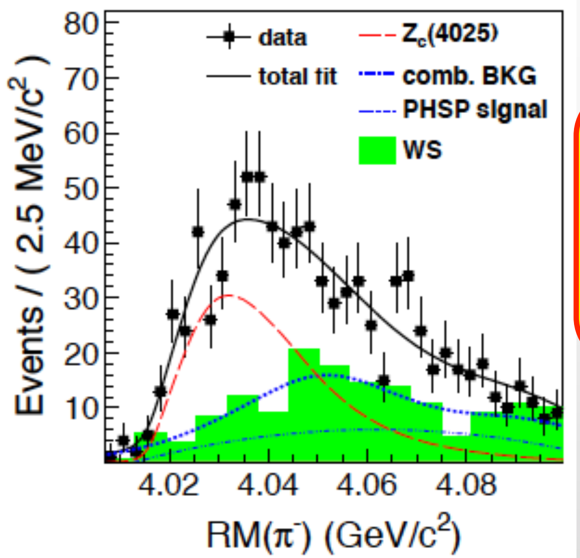



- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events
- 6.1σ
- Neutral partner also observed in $J/\psi\pi^0$

# $Z_c(4025)^+$

- $e^+e^- \to (D^*\bar{D}^*)^+\pi^-$ at 4.26 GeV (peak of the Y(4260) cross section)[arXiv:1308.2760]
- Partial reconstruction technique is used. The $e^+e^- \to (D^*\bar{D}^*)^+\pi^-$ signal identified in the recoil $D^+\pi^-$ mass spectrum ($RM(X) = |p_{e^+e^-} - p_X|$)
- Structure observed in the $\pi^-$ recoil mass spectrum
- $\sqrt{s} = 4.26\,\text{GeV} << $ the production thresholds $D^{**}\bar{D}^*$




- M = 4026.3±2.6±3.7 MeV
- Γ = 24.8±5.6±7.7 MeV
- 401 ± 48 events
- >10σ

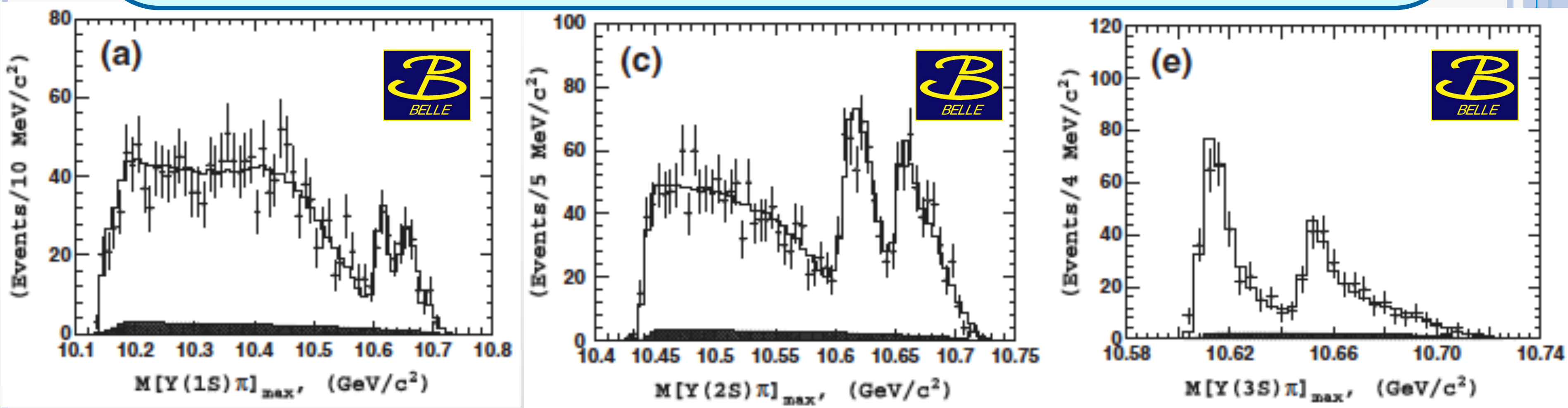
BESIII has presented the observation of a $Z_c(4020)^+ \to h_c\,\pi^+$ (Changzheng Yuan at Lepton-Photon 2013)
Is it the same state? More studies are needed

# $Z_B(10610)^+$ AND $Z_B(10650)^+$

- Belle reported the observation of two charged bottomonium-like states in 5 different decay modes [PRL 108, 122001 (2012)]:

$$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^- \; (n = 1, 2, 3)$$
$$\Upsilon(5S) \to h_b(mP)\pi^+\pi^- \; (m = 1, 2)$$

- $B^*\bar{B}$ and $B^*\bar{B}^*$ bound states?
- $J^P = 1^+$ favoured




- M = 10607.2±2.0 MeV
- Γ = 18.4±2.4 MeV

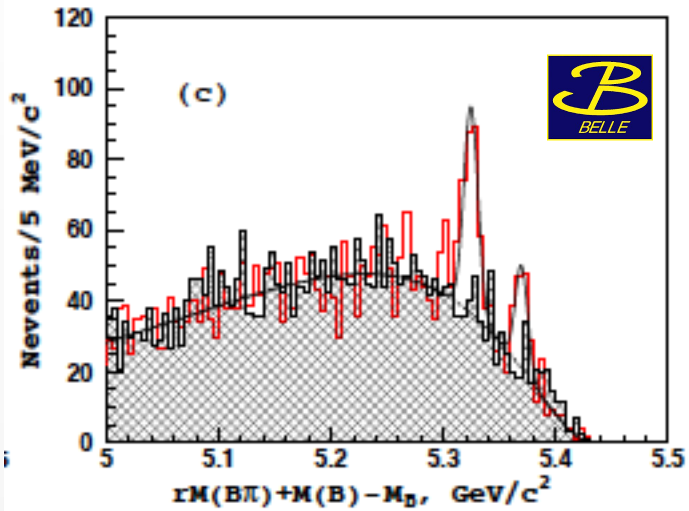
- M = 10652.2±1.5 MeV
- Γ = 11.5±2.2 MeV

# $Z_B(10610)^+$ AND $Z_B(10650)^+$

- $Z_b$'s observed also in [arXiv:1209.6450]:

$$\Upsilon(5S) \to (B^*\bar{B}^*)^+\pi^-$$

- $B^*\bar{B}$ and $B^*\bar{B}^*$ are the dominant decay modes



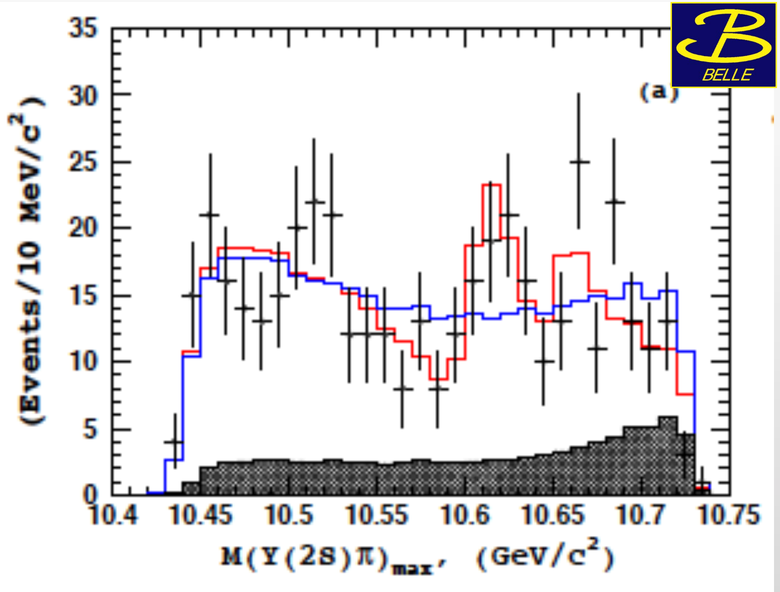

| Channel | Fraction, % | |
|---|---|---|
| | $Z_b(10610)$ | $Z_b(10650)$ |
| $\Upsilon(1S)\pi^+$ | $0.32 \pm 0.09$ | $0.24 \pm 0.07$ |
| $\Upsilon(2S)\pi^+$ | $4.38 \pm 1.21$ | $2.40 \pm 0.63$ |
| $\Upsilon(3S)\pi^+$ | $2.15 \pm 0.56$ | $1.64 \pm 0.40$ |
| $h_b(1P)\pi^+$ | $2.81 \pm 1.10$ | $7.43 \pm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

# $Z_B(10610)^0$

- Evidence of the neutral partner $Z_b(10610)^0$ in Dalitz plot analysis [arXiv:1207.4345]:

  $\Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0$

- No evidence of $Z_b(10650)^0$ (Consistent with the available statistics)



# Conclusions

- Experimental analysis of quarkonia states is a very active field of particle physics.

- The existence of most of the exotic states has to be proven/confirmed but relevant progress have been made recently:
  - ✓ The quantum number $J^{PC}=1^{++}$ for the X(3872) favors an exotic interpretation.
  - ✓ First confirmation of a charged $Z_c(3900)^+$

- Many results based on a subset of the available data samples. Huge potential for improving precision and sheding light on the nature of some exotics