

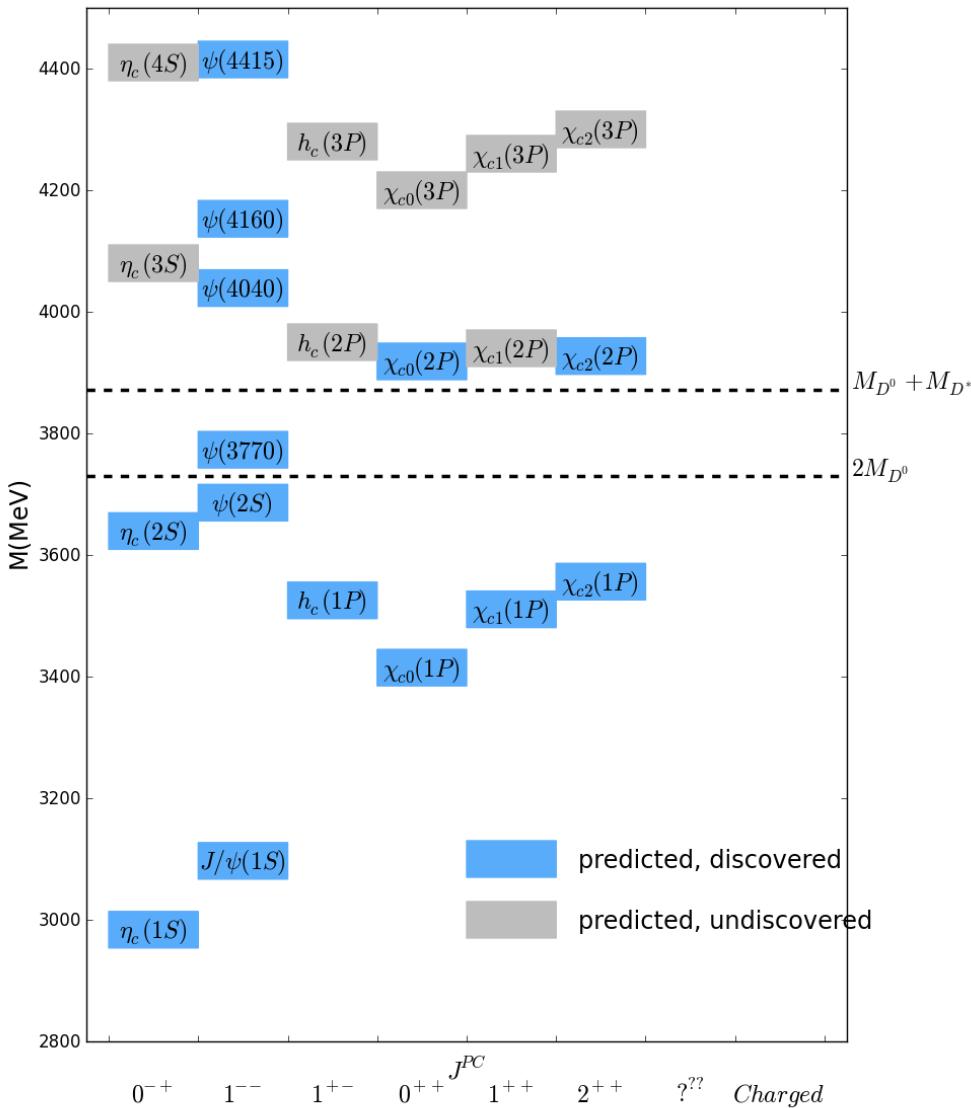
X,Y,Z at the LHC and e^+e^- colliders

Patrick Robbe (LHCb Collaboration), LAL Orsay, 2 Sep 2013

Outline

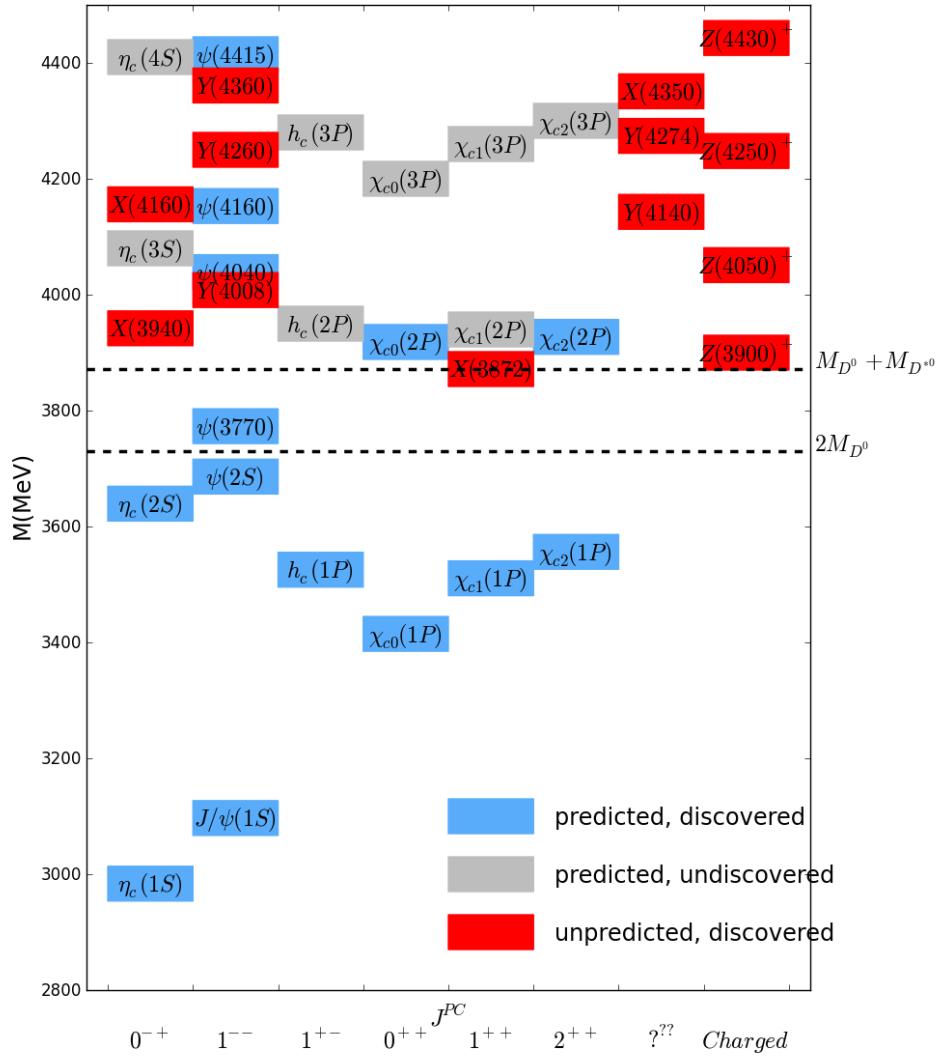
- Introduction
- A lot of experimental activities, concentrate on:
 - Area where LHC experiments contribute:
 - Study of the X(3872)
 - Study of the X(4140)
 - $Z_c(3900)^+$ at BESIII

Charmonium



- Charmonium ($c\bar{c}$) spectrum J^{PC} :
 - $J = S + L$
 - $P = (-1)^{L+1}$ (spatial parity)
 - $C = (-1)^{L+S}$ (charge parity)
- Observed states match very well predicted states, most recently discovered: $h_c(1P)$, $\chi_{c0}(2P)$
- All states below open charm threshold (8) observed
- 6 states above threshold
- Everything seems understood and well established...

X, Y, Z exotics



- After 2003, many new unexpected states discovered:
 - They decay with a charmonium in the final state or to 2 charmed hadrons
 - But they cannot be obviously associated with a predicted charmonium state.
- Some of them have not been confirmed, or don't have well measured properties, but for sure some of them are not conventional charmonia (charged states)
- They can be produced by different mechanisms (B decay, ISR, hadron collisions, ...) so can be studied by different experiments: important to confirm them and measure unambiguously their properties and decay modes.
- Interpretation not yet established: hybrid, tetraquarks, molecules, ...

X(3872)

- First exotic observed, studied now in details:

- Mass = 3871.68 ± 0.17 MeV [PDG], Width < 1.2 MeV
 - $J^{PC} = 1^{++}$ [NEW LHCb]

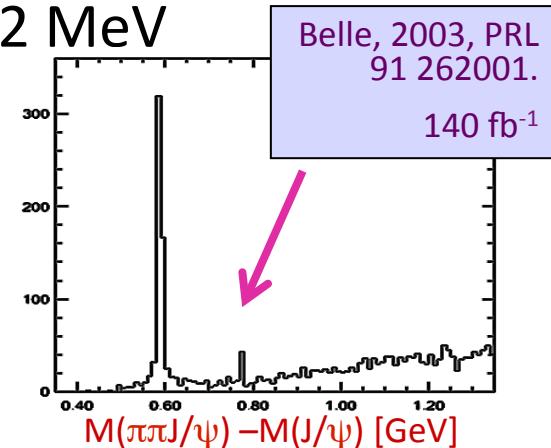
- Production:

- In B decays, rate of $B^+ \rightarrow X(3872) K^+$ similar to other charmonium, $B \rightarrow X(3872) K^*$ smaller compared to conventional charmonium.
 - In $p p / p \bar{p}$ collisions

- Decays: open charm ($\sim 50\%$), charmonium ($J/\psi \pi^+ \pi^-$, ...)

- But interpretation not clear:

- Loosely bound $D^0 D^{*0}$ molecule [Tornqvist (2004), Voloshin (2004), Swanson (2004), Braaten (2004), Close & Page (2005)]
 - Mixture of χ_{c1}' and $D^0 D^{*0}$ bound state [Meng, Gao, Chao (2005)]
 - Many other possibilities
 - Need of experimental inputs

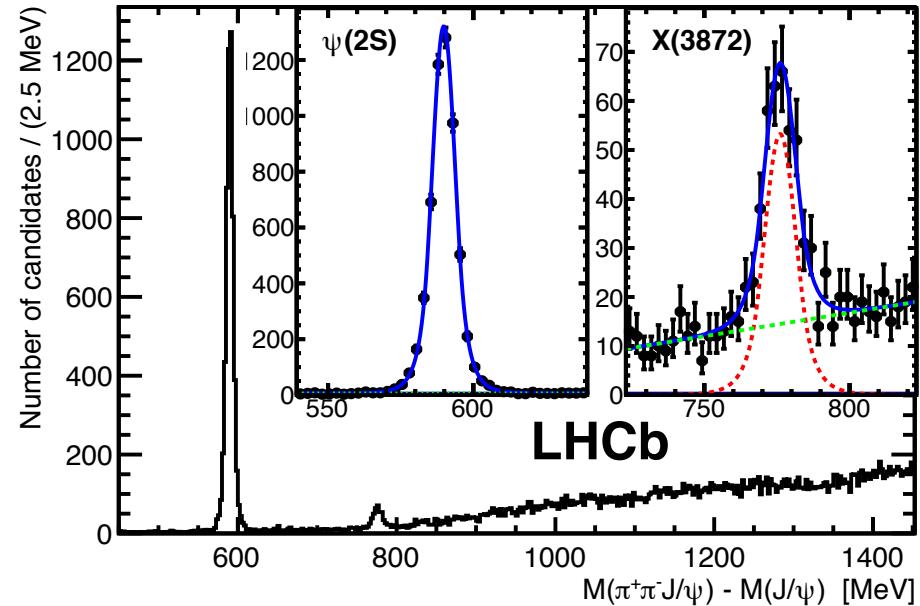
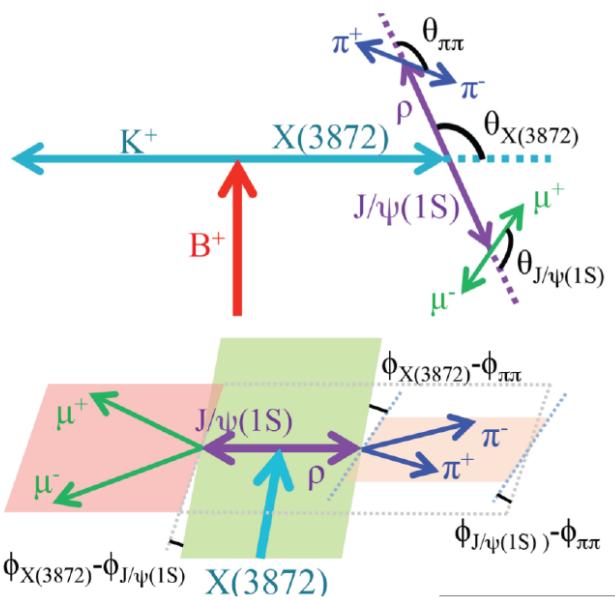


X(3872) quantum numbers

- Observation of $X(3872) \rightarrow J/\psi \gamma$ [BaBar PRD74 (2006) 071101, BELLE PRL107 (2011) 091803]
 - C=+
- Spin-parity possibilities reduced to 1^{++} and 2^{-+} by CDF [PRL 98, 132002 (2007)] and BELLE [hep-ex/0505038] measurements.
- Important observable to confirm exotic nature of X(3872):
 - $M_{X(3872)}$ close to two unobserved conventional charmonium states [Eichten, Lane, Quigg, PRD69, 094019 (2004)]:
 - $\chi_{c1}(2P)$ [1^{++}]
 - $\eta_{c2}(1D)$ [2^{-+}]

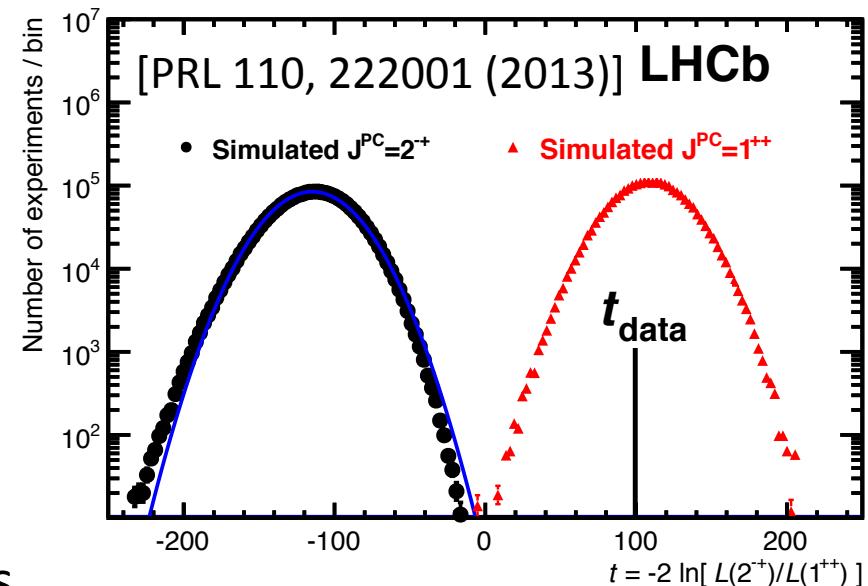
X(3872) quantum numbers

- **LHCb:** Use $B^+ \rightarrow X(3872) K^+$ decays, with $X(3872) \rightarrow J/\psi \pi^+ \pi^-$, $J/\psi \rightarrow \mu^+ \mu^-$ [PRL 110, 222001 (2013)]
- In 1fb^{-1} of data, 313 ± 26 signal events (and 5642 ± 76 $B^+ \rightarrow \psi(2S) K^+$ control channel)
- 5-dimension angular analysis to benefit from all angular correlations and constraints in the B^+ decay chain.



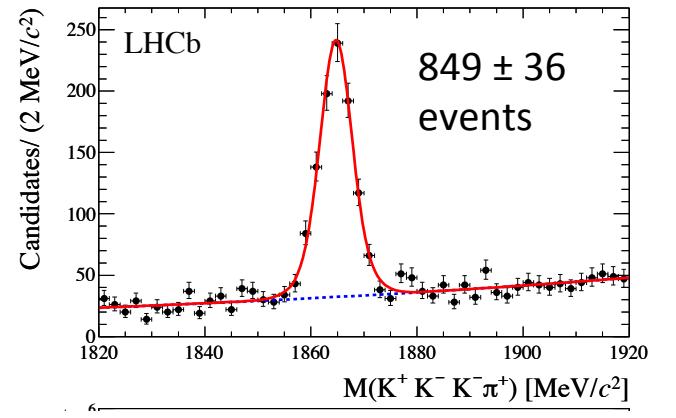
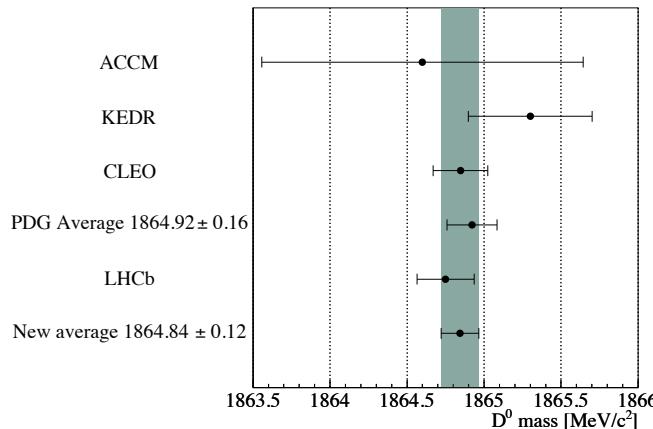
X(3872) quantum numbers

- Likelihood ratio between 1^{++} and 2^{-+} hypotheses
- 2^{-+} hypothesis rejected at $>8\sigma$.
- This result favours the exotic explanation of the X(3872):
 - Conventional $\eta_{c2}(1D)$
 - ruled out
 - Conventional $\chi_{c1}(2P)$
 - still possible
 - but expected mass higher by 100 MeV and small $X(3872) \rightarrow J/\psi \gamma$ ratio
 - very disfavoured hypothesis
 - 1^{++} expected from tetraquark and molecular models



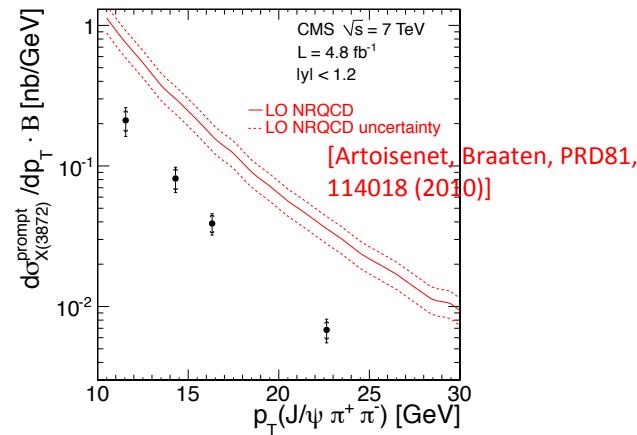
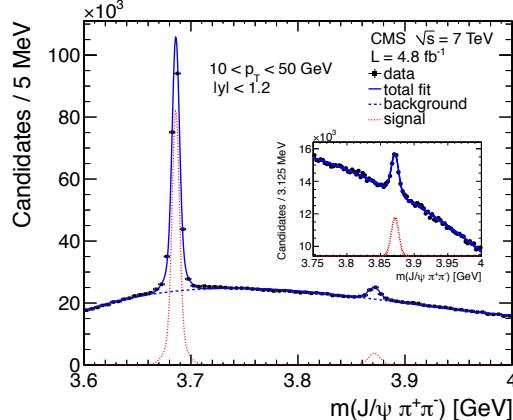
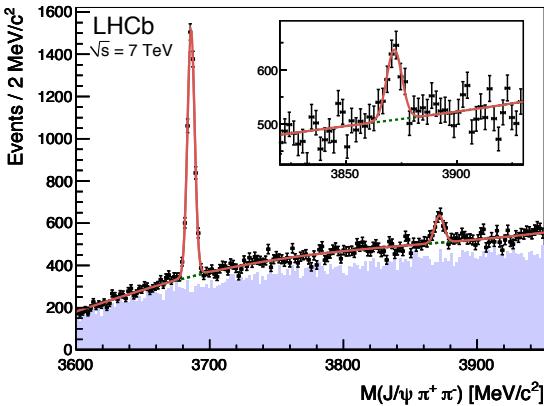
X(3872) mass

- Interpretation as bound $D^0 D^{*0}$ molecule model requires comparison between X(3872) mass and $M(D^0) + M(D^{*0})$. If molecule, X(3872) mass should be below threshold.
- Precise D^0 mass determination from LHCb [JHEP06, 065 (2013)]
 - From $D^0 \rightarrow K^- K^+ \pi^+$ decays
- Using PDG averages of ΔM and X(3872):
 - $M_{X(3872)} - (M_{D^0} + M_{D^{*0}}) = -0.09 \pm 0.28$ MeV.
 - Require improved X mass measurements to distinguish from threshold



X(3872) production

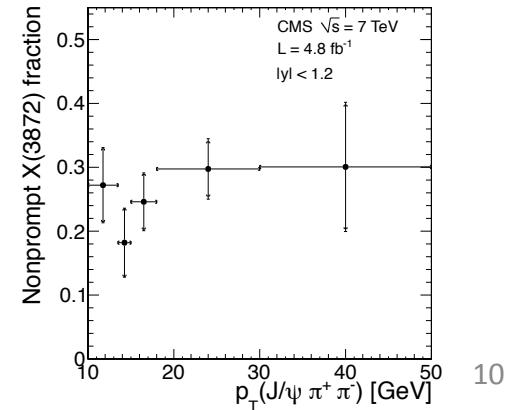
- X(3872) production in hadron collisions reported by CDF [PRL93, 072001 (2004)], D0 [PRL93, 162002 (2004)], [LHCb](#) [EPJC72, 1972 (2012)] and [CMS](#) [JHEP 1304, 154 (2013)].
- X(3872) reconstructed in the $J/\psi \pi^+ \pi^-$ decay mode, in the central region (CMS, $|y|<1.2$) or in the forward region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



LHCb: $\sigma_{\text{inclusive}} B(X(3872) \rightarrow J/\psi \pi^+ \pi^-) [2.5 < y < 4.5, p_T > 5 \text{ GeV}] = 4.7 \pm 1.1 \pm 0.7 \text{ nb}$

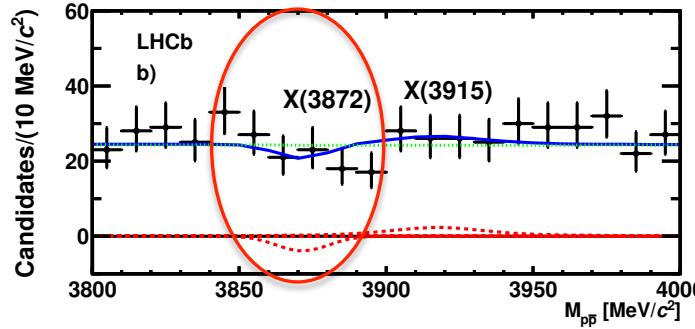
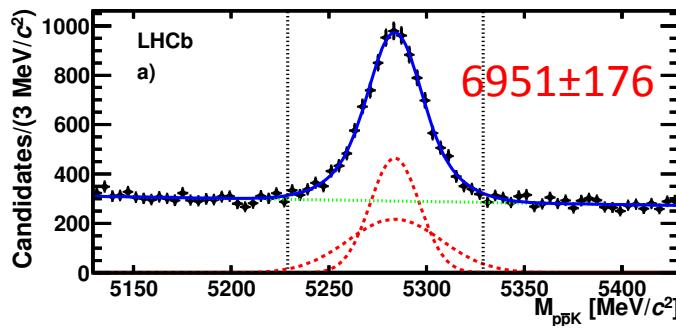
CMS: $\sigma_{\text{inclusive}} B(X(3872) \rightarrow J/\psi \pi^+ \pi^-) [|y| < 1.2, p_T > 10 \text{ GeV}] = 1.06 \pm 0.11 \pm 0.15 \text{ nb}$

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



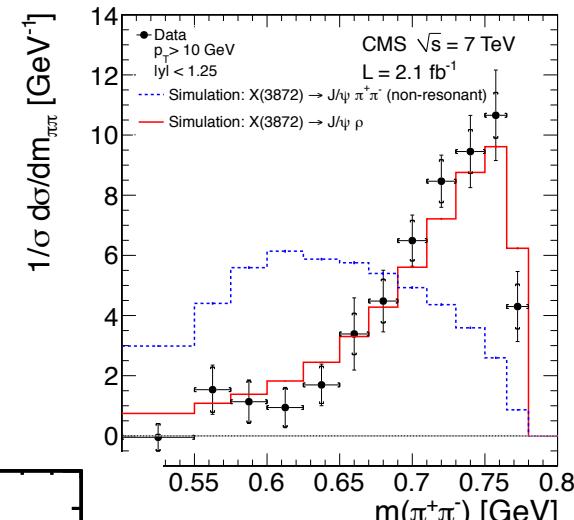
X(3872) decay

- CMS: $\pi^-\pi^+$ spectrum in $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ decays, consistent with ρ^0 [JHEP 1304, 154 (2013)]
- LHCb: search for $X(3872) \rightarrow p\bar{p}$ decays, in $B^+ \rightarrow K^+ p\bar{p}$ with 1 fb^{-1} [EPJC73, 2642 (2013)]



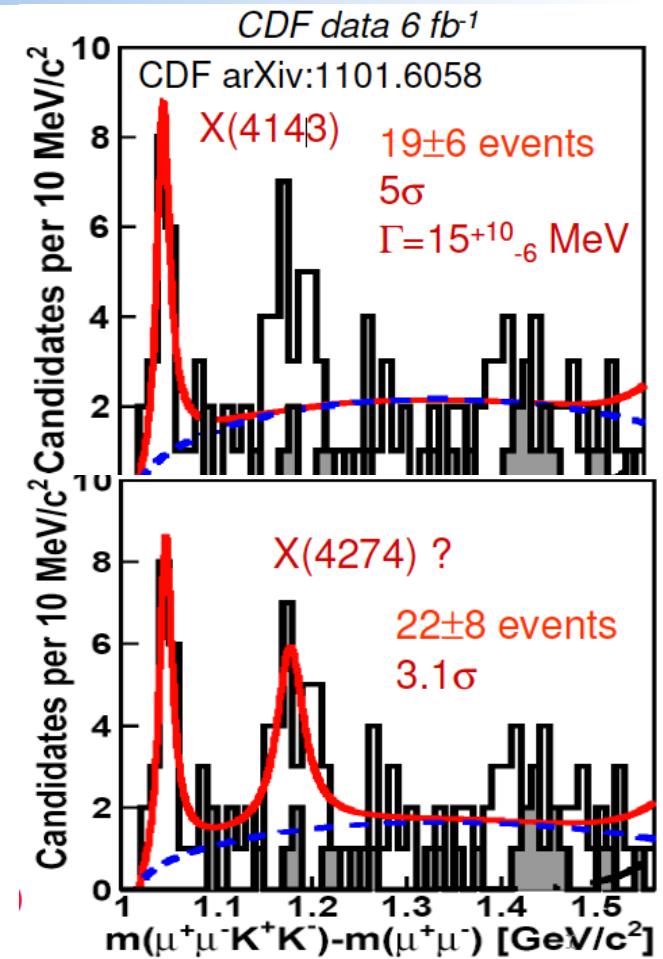
- Upper limit:

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



X(4140)

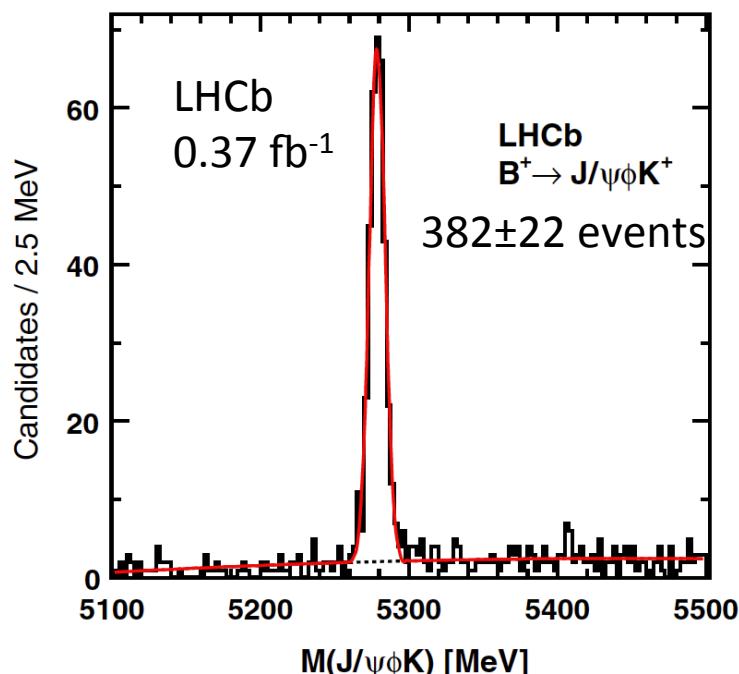
- CDF observed a narrow ($J/\psi \phi$) structure in $B^+ \rightarrow J/\psi \phi K^+$ decays (with $\phi \rightarrow K^+K^-$, $J/\psi \rightarrow \mu^+\mu^-$) [PRL102, 242002 (2009)]
 - Called X(4140):
 $M=4143.2 \pm 3 \pm 0.6$ MeV
 - 19 ± 6 events for a total of
 115 ± 12 $B^+ \rightarrow J/\psi \phi K^+$
 - Necessarily exotic since it is narrow and above the DD threshold
 - [$c\bar{s}c\bar{s}$] tetraquark ?
 - Hint of a second structure:
X(4274)



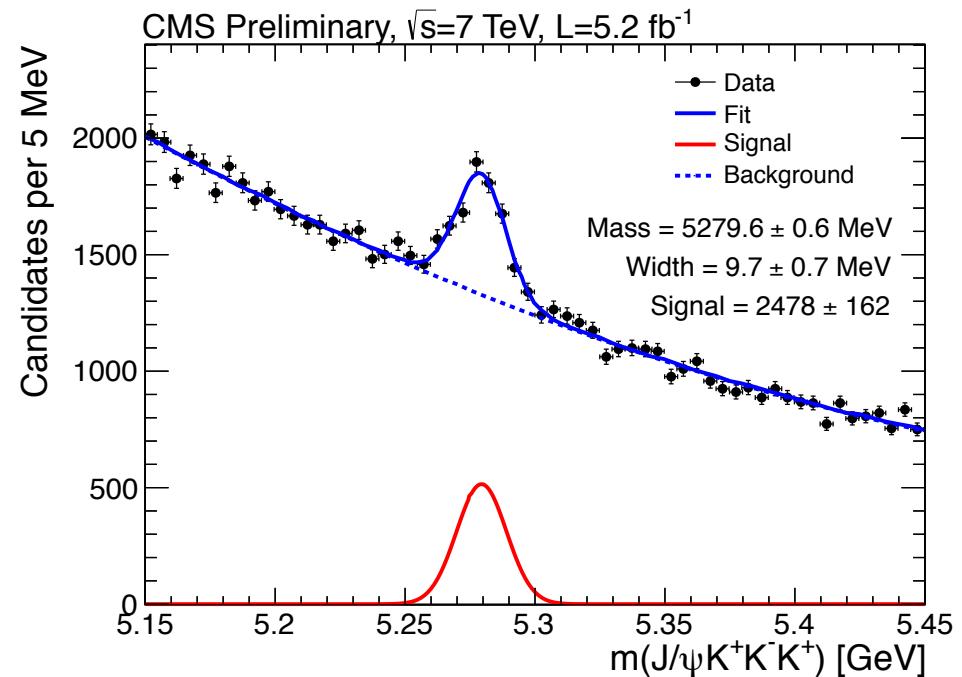
$$\frac{\mathcal{B}(B^+ \rightarrow X(4140)K^+) \times \mathcal{B}(X(4140) \rightarrow J/\psi \phi)}{\mathcal{B}(B^+ \rightarrow J/\psi \phi K^+)} = 0.149 \pm 0.039 \pm 0.024_{12}$$

X(4140)

- In multibody decays like $B^+ \rightarrow J/\psi \phi K^+$, reflexions from intermediate resonances or threshold effects can cause apparent structures: crucial to confirm all exotic states by a different experiment.
- Analysis of the same decay by LHCb and CMS, with larger statistics:



[PRD85, 091103 (2012)]

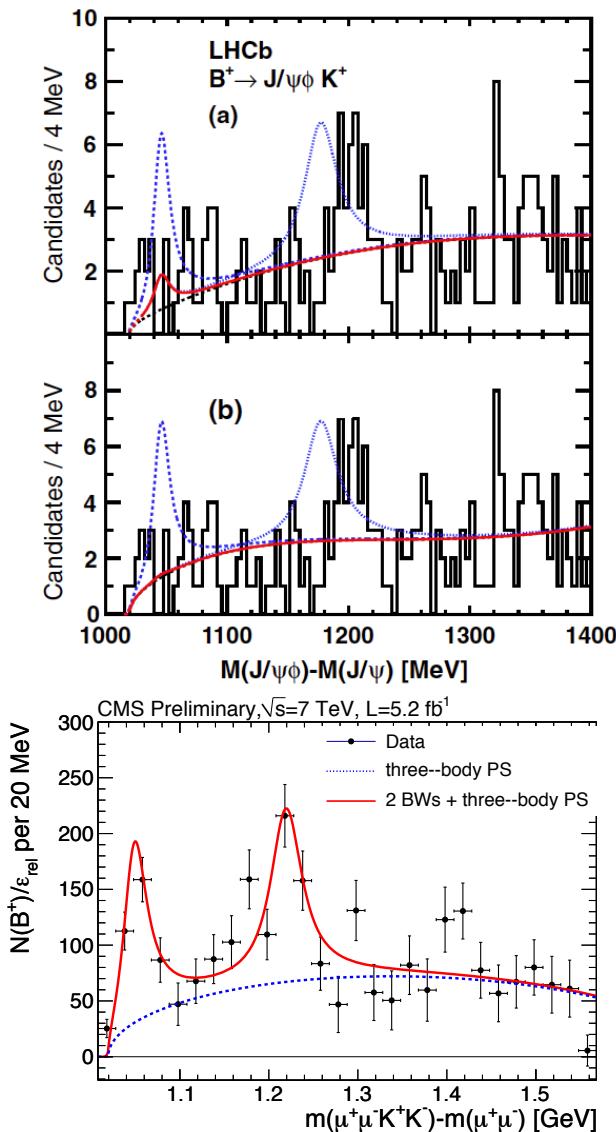


X(4140)

- **LHCb:** no observation of the X(4140) and X(4274) [PRD85, 091103 (2012)]
- Fit with $\Gamma=15$ MeV, 2.4σ disagreement with CDF result.

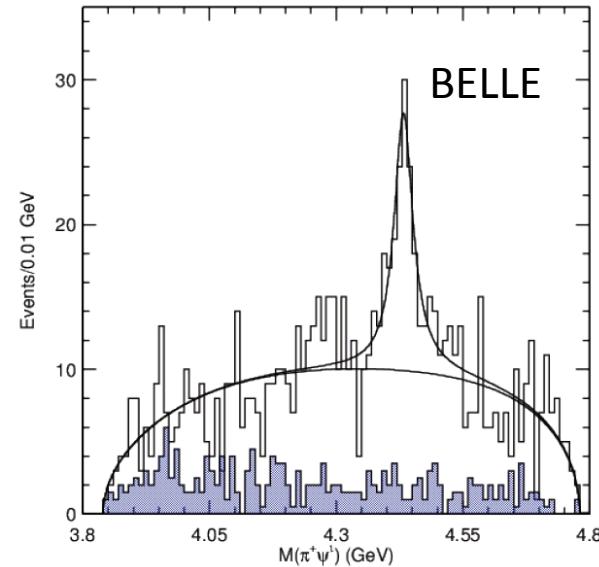
$$\frac{\mathcal{B}(B^+ \rightarrow X(4140)K^+) \times \mathcal{B}(X(4140) \rightarrow J/\psi \phi)}{\mathcal{B}(B^+ \rightarrow J/\psi \phi K^+)} < 0.07$$

- **CMS:** $>5\sigma$ observation of a near-threshold structure ($>3\sigma$ of the second one) [Preliminary]
- $M_{X(4140)} = 4148.2 \pm 2.0 \pm 4.6$ MeV
- More data needed to conclude



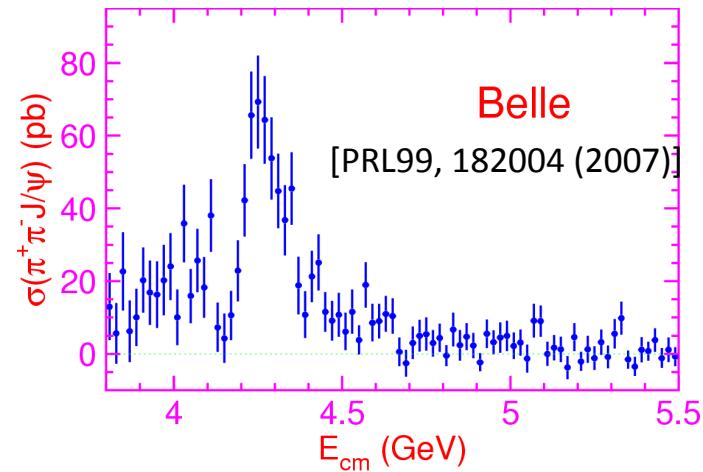
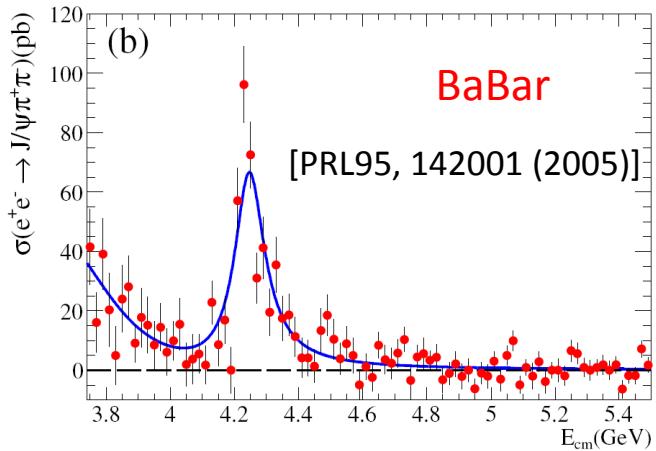
$Z_c(4430)^+$: charged exotics

- Charged structure seen in $B^+ \rightarrow [\psi(2S) \pi^-] K^+$ by BELLE [PRL100, 142001], but not confirmed (nor excluded) by BaBar .
- Clear signature of exotic:
 - Decay to charmonium: contains a $\bar{c}c$ pair
 - Has electric charge: has 2 more light quarks, $N_{\text{quarks}} \geq 4$!
 - $[cd\bar{c}\bar{u}]$ tetraquark, D^*D_1 molecule ?
- Needs confirmation.



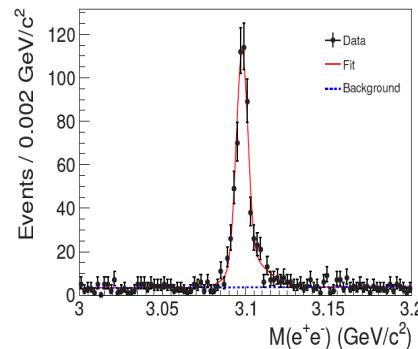
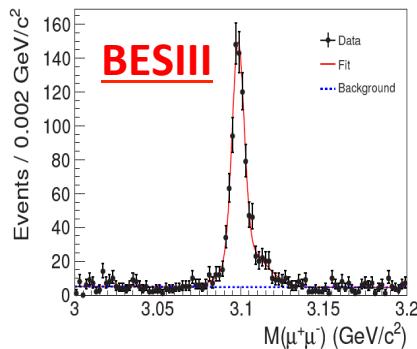
$Z_c(3900)^+$: charged exotics

- BESIII: reconstruct $\Upsilon(4260) \rightarrow J/\psi \pi^+ \pi^-$ running at $\sqrt{s}(e^+e^-)=4.26$ GeV.
- Vector exotic state already seen at B factories through ISR production and CLEO:



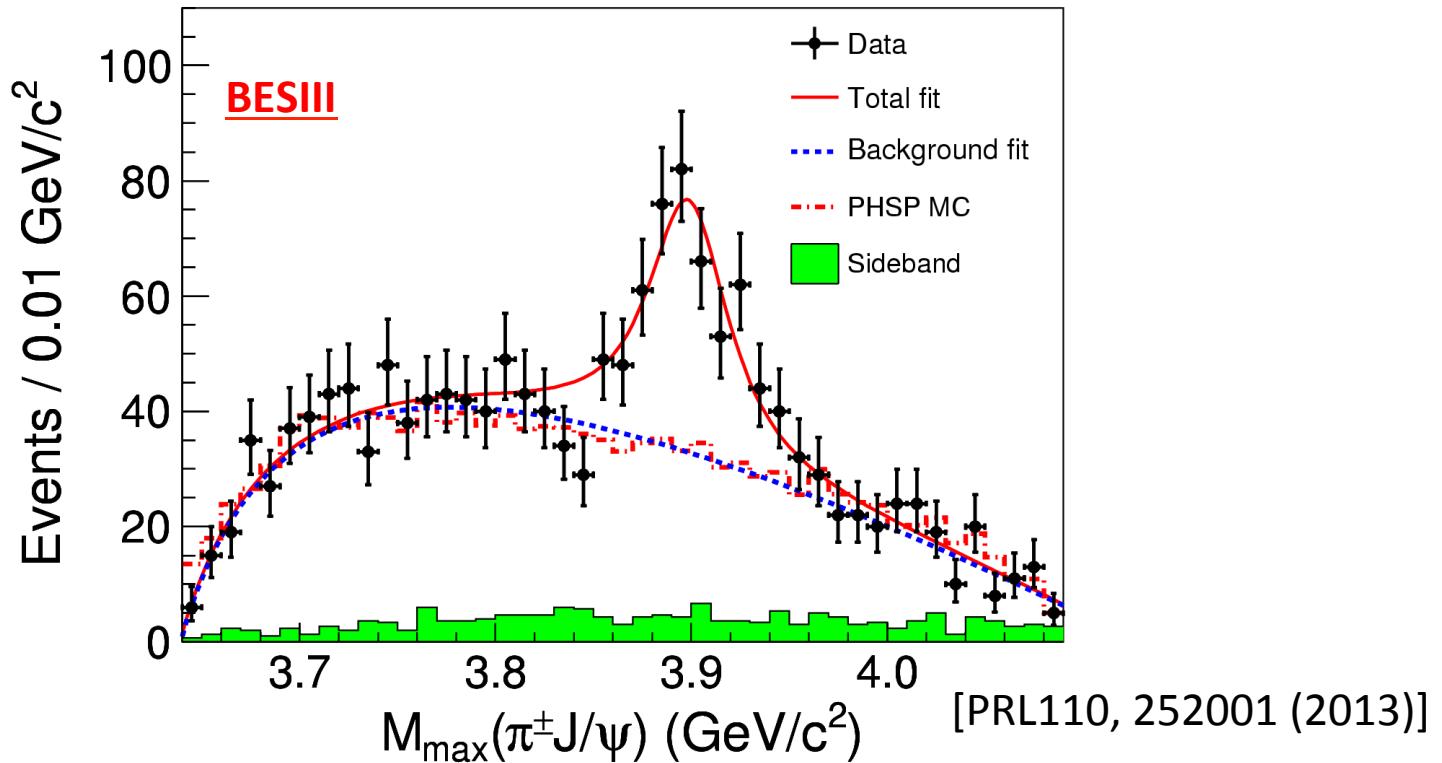
- LHCb: non-observation of $\Upsilon(4260) \rightarrow \mu^+\mu^-$ decays in $B^+ \rightarrow K^+\mu^+\mu^-$ decays [LHCb-PAPER-2013-039]
- BESIII: Reconstruct J/ψ with muons or electrons, very clean sample, with cross-section in good agreement with BaBar and BELLE results [PRL110, 252001 (2013)].

882 ± 33
 $J/\psi \rightarrow \mu^+\mu^-$



595 ± 28
 $J/\psi \rightarrow e^+e^-$

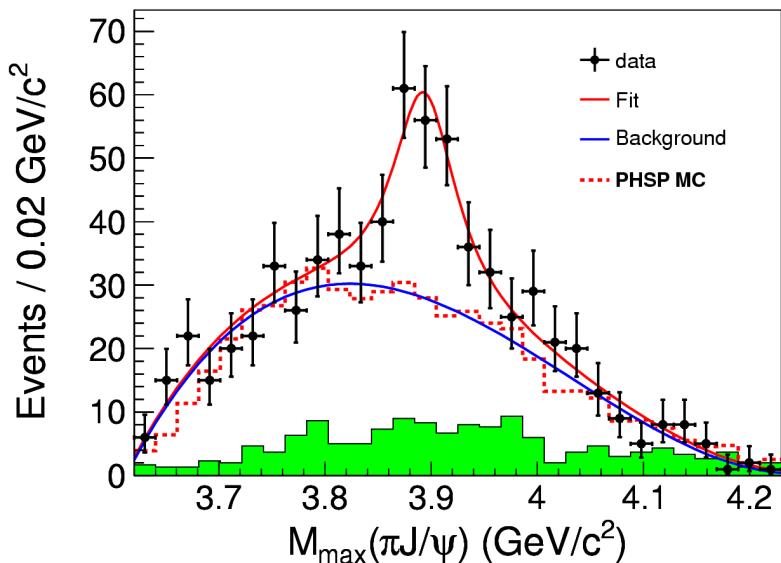
$Z_c(3900)^+$: charged exotics



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

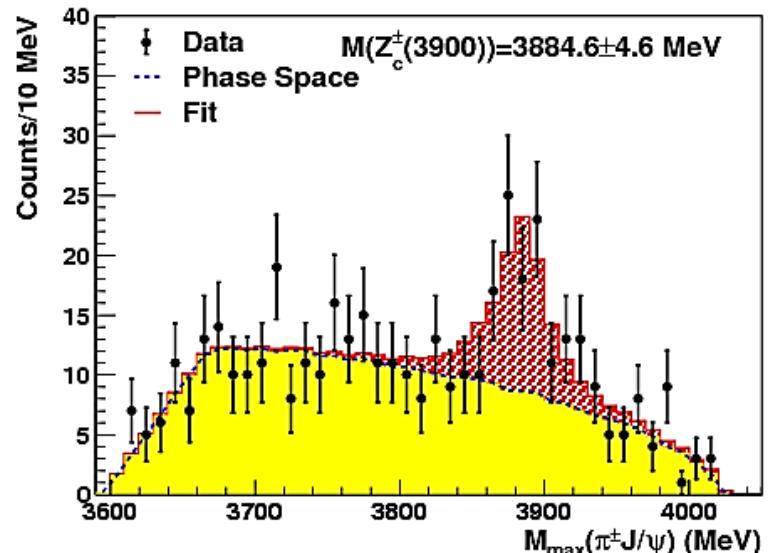
$Z_c(3900)^+$: confirmation

Belle with ISR in $\Upsilon(4260)$ decays:
[PRL110, 252002 (2013)]



- $M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$
- $\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$
- $159 \pm 49 \text{ events}$
- $> 5.2\sigma$

CLEOc data at 4.17 GeV:
[arxiv:1304.3036]



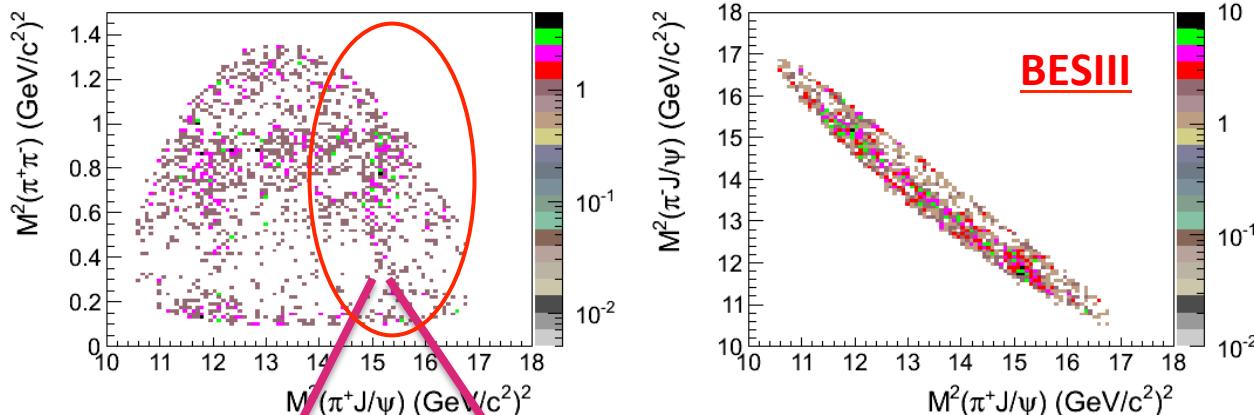
- $M = 3885 \pm 5 \pm 1 \text{ MeV}$
- $\Gamma = 34 \pm 12 \pm 4 \text{ MeV}$
- $81 \pm 20 \text{ events}$
- 6.1σ

Conclusions

- Experimental analysis of charmonium-like exotics states is a very active field of particle physics.
- Growing contributions from LHC experiments, which will become even more important in the future.
- New states continue to be observed at e^+e^- colliders, including the first charged confirmed state (growing importance of BESIII data: observation of $Z_c(4024)^+$ in π recoil mass spectrum in 4.26 GeV collisions during the summer [arxiv:1308.2760])

$Z_c(3900)^+$: charged exotics

- Dalitz plot of $J/\psi \pi^+ \pi^-$: one structure (plus the corresponding reflections observed)



[PRL110, 252001 (2013)]

