BESIII Studies of Exotic Quark States

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On behalf of the BESIII Collaboration

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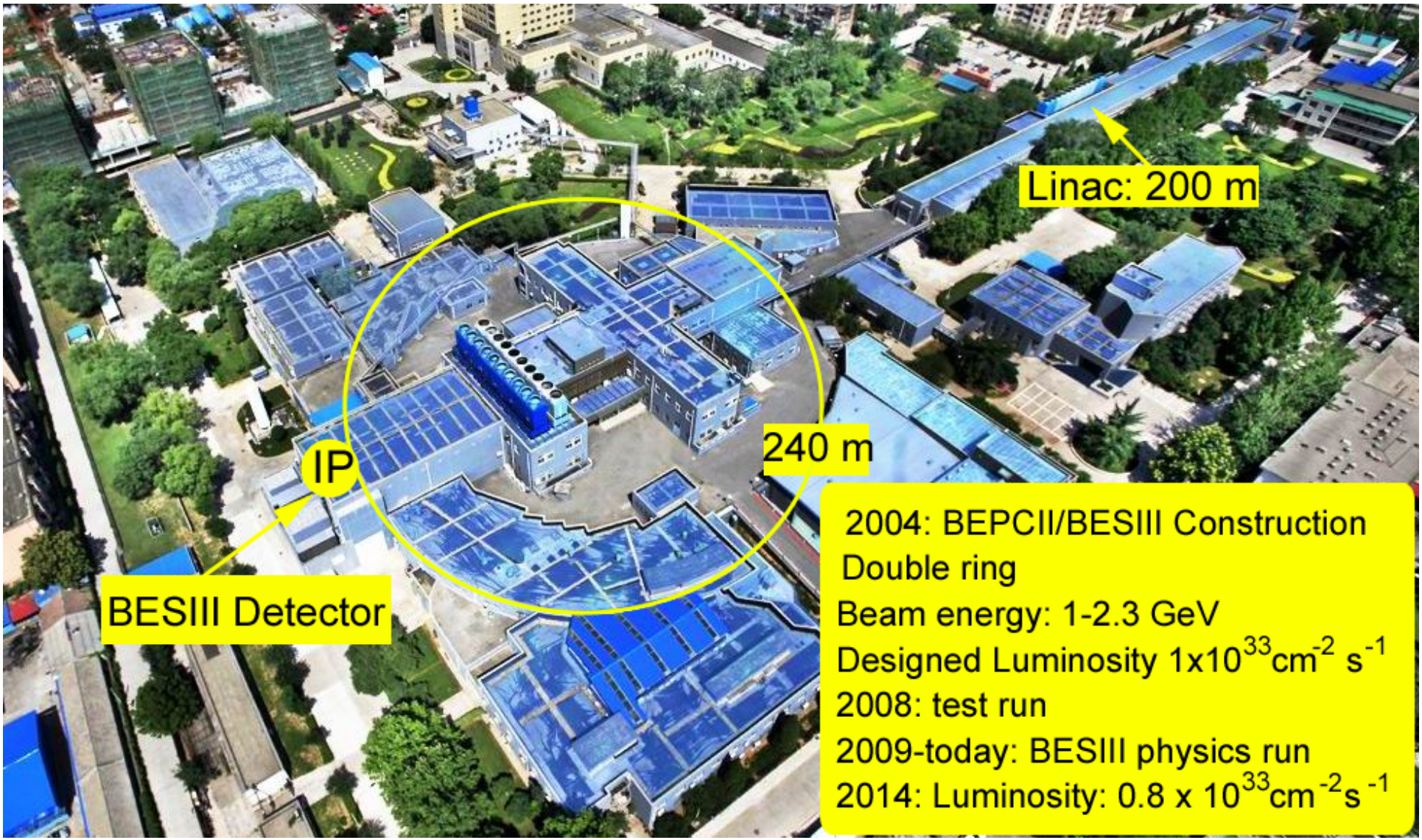
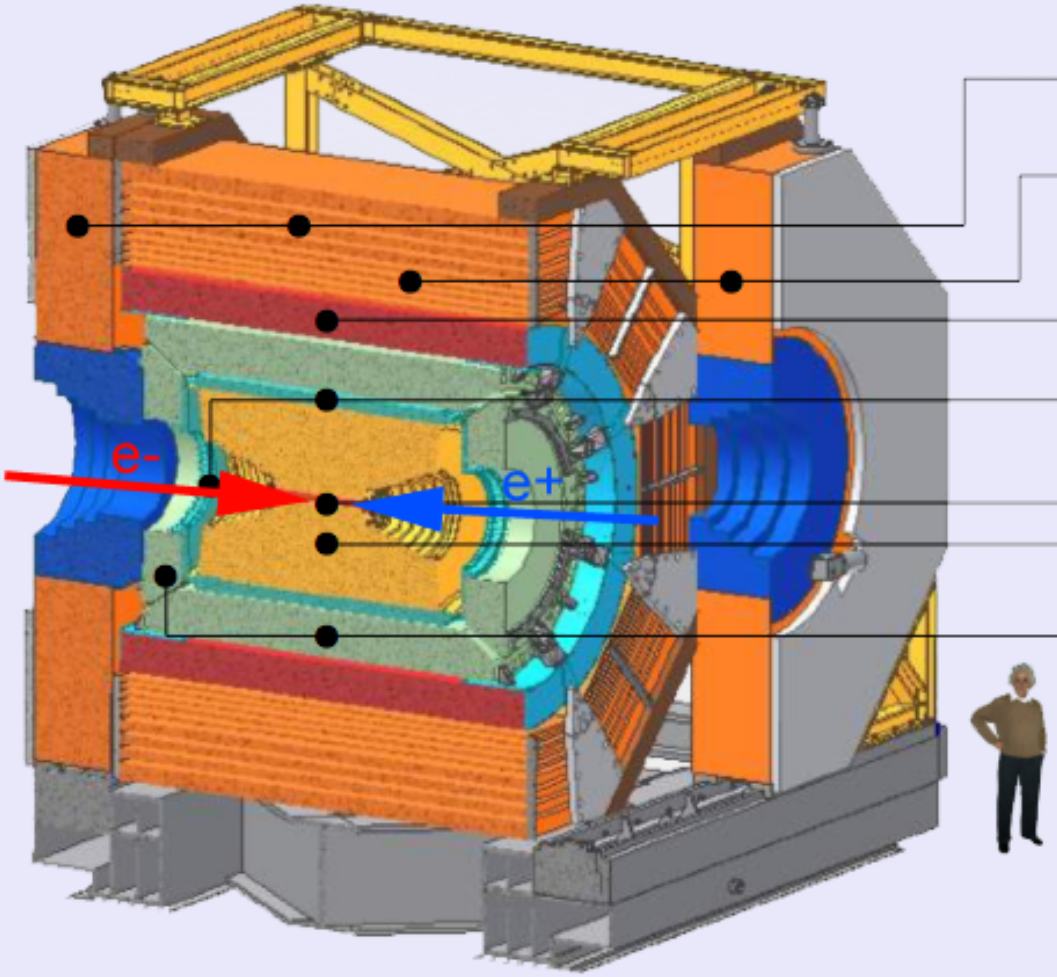
Outline

- The BESIII experiment
- Charmonium spectrum
  - The X, Y, Z states
- Conclusion

Beijing Electron Positron Collider II



The BESIII detector



- Magnet yoke
- RPC (9/8 layers Barrel/Endcaps)
- SC magnet, 1 Tesla
- TOF (scintillators), 90 ps
- Be beam pipe
- MDC, 120μm
- CsI(Tl) calorimeter, 2.5% at 1 GeV

Data samples

Data sample	E_{cm}	Years
1.3×10^9	J/ψ at 3.097 GeV	2009 (0.225×10^9) + 2012
0.5×10^9	$\psi(2S)$ at 3.686 GeV	2009 (0.106×10^9) + 2012
2.92 fb^{-1}	$\psi(3770)$ at 3.773 GeV	2010+2011
0.5 fb^{-1}	$\psi(4040)$ at 4.009 GeV	2011
0.024 fb^{-1}	τ mass scan at around 3.554 GeV	2011
1.9 fb^{-1}	Y(4260) at 4.23 GeV and 4.26 GeV	2013
0.5 fb^{-1}	Y(4360) at 4.36 GeV	2013
0.5 fb^{-1}	Y(4260) and Y(4360) scan	2013
0.8 fb^{-1}	R scan, 104 energy points between 3.85 and 4.59 GeV	2014
1.0 fb^{-1}	at 4.42 GeV	2014
0.1 fb^{-1}	at 4.47 GeV and 4.53 GeV for line shape	2014
0.04 fb^{-1}	at 4.575 GeV (around the threshold of Lambda Charm)	2014
0.5 fb^{-1}	at 4.60 GeV	2014

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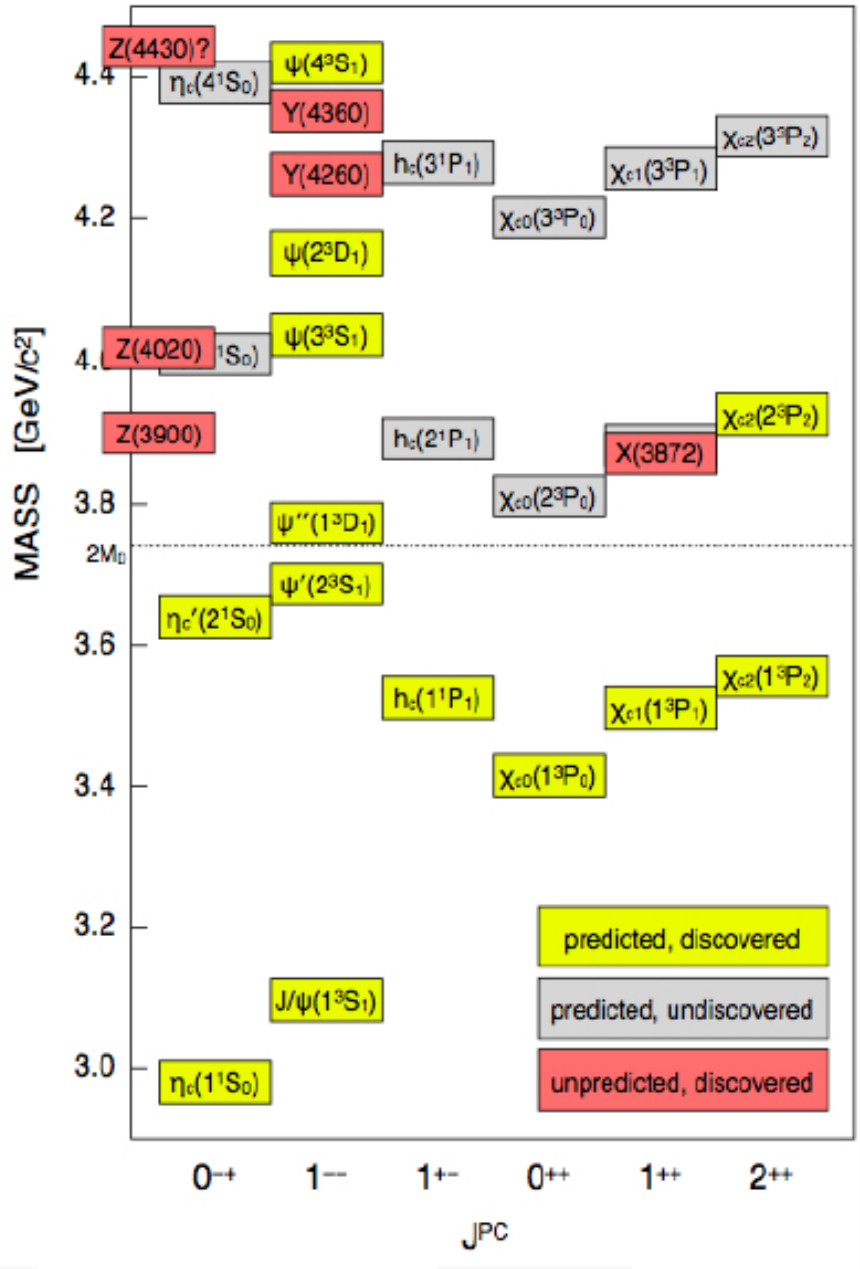
Charmonium spectroscopy

Charmonium spectrum



- Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory.
- Many unexpected states have been reported above the $D\bar{D}$ threshold (XYZ). Several exotic hypotheses as to their nature: tetraquarks, hadronic molecules, hybrids, glueballs, hadro-quarkonia.

X states:

- charmonium-like states with $J^{PC} \neq 1^{--}$
- Observed in B decays, pp and $p\bar{p}$ collisions

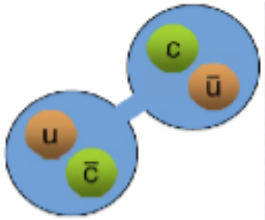
Y states:

- charmonium-like states with $J^{PC} = 1^{--}$
- Observed in direct e^+e^- annihilation or in ISR

Z states:

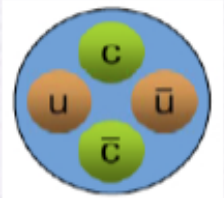
- charmonium-like states carrying electric charge
- Must contain at least a $c\bar{c}$ and a light $q\bar{q}$ pair

Exotic charmonium-like states interpretation



Molecular state:
loosely bound state of a pair of mesons.
The dominant binding mechanism should be pion exchange. Being weakly bound, mesons tend to decay as if they were free.

NA Tornqvist PLB 590, 209 (2004)
ES Swanson PLB 598,197 (2004)
E Braaten & T Kusunoki
PRD 69 074005 (2004)
CY Wong PRC 69, 055202 (2004)
MB Voloshin PLB 579, 316 (2004)
F Close & P Page PLB 578,119 (2004) .....



Tetraquark:
Bound state of four quarks, i.e. diquark-antidiquark
Strong decays proceed via rearrangement processes.

L Maiani et al PRD 71,014028 (2005)
T-W Chiu & TH Hsieh PRD 73, 111503 (2006)
D Ebert et al PLB 634, 214 (2006)
...

Distinctive features of multi-quark picture with respect to charmonium:
- prediction of many new states
- possible existence of states with non-zero charge, strangeness or both.

Charmonium hybrids
States with an excited gluonic degree of freedom
Lattice and model predictions for the lowest lying hybrid:
m ~4200 MeV

P Lacock et al (UKQCD) PLB 401, 308 (1997)
SL Zhu PLB 625, 212 (2005)
FE Close, PR Page PLB 628, 215 (2005)
E Kou, O Pene PLB 631, 164 (2005)
...

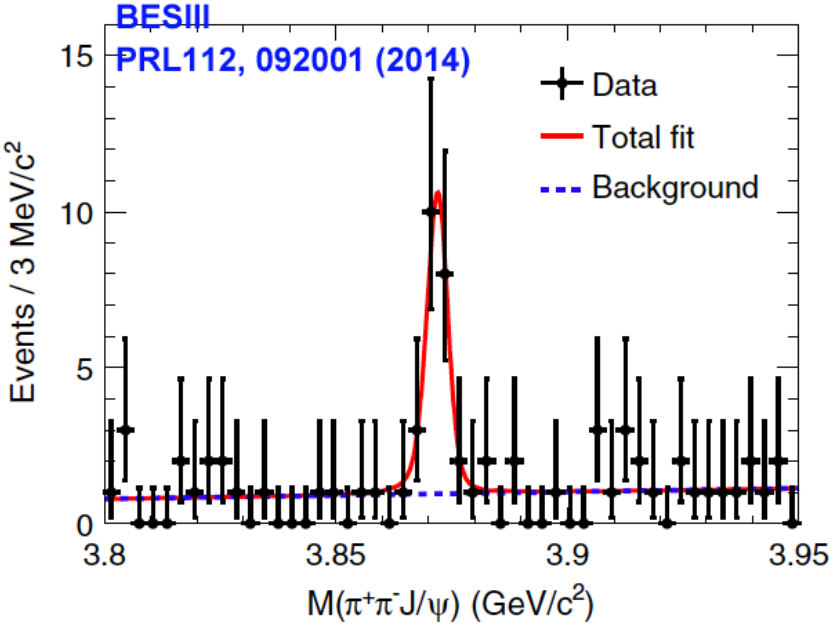
Conventional charmonium

C Meng & KT Chao PRD 75, 114002 (2007)
W Dunwoodie & V Ziegler PRL 100 062006 (2008)
O Zhang, C Meng & HQ Zheng arXiv:0901.1553
...

THE X STATES

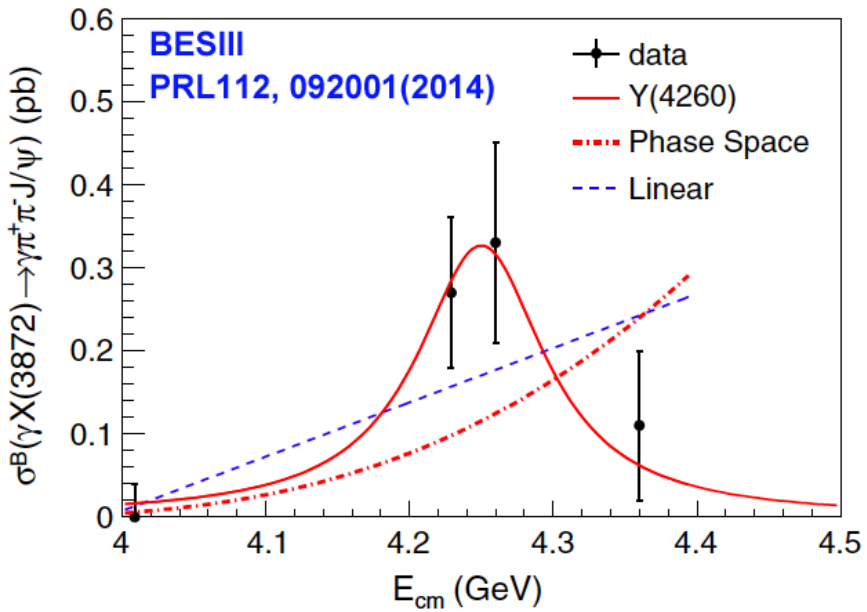
Observation of $e^+e^- \to \gamma X(3872)$ - PRL 112, 092001(2014)

- The X(3872) was discovered by Belle in $J/\psi\pi^+\pi^-$, PRL 110,252002(2013). $J^{PC} = 1^{++}$
- BESIII: Study of $e^+e^- \to \gamma X(3872)$, $X(3872) \to J/\psi\pi^+\pi^-$ at center of mass energies from 4.009 to 4.420 GeV.



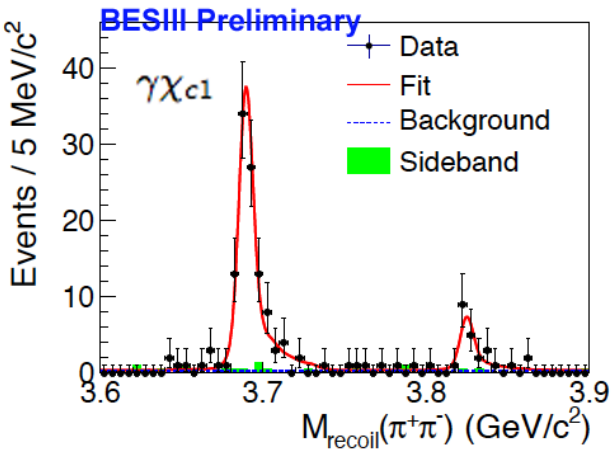
- The X(3872) is observed with significance 6.3σ
- m=3871.9±0.7±0.2 MeV/c^2
- Γ <2.4 MeV at 90% CL

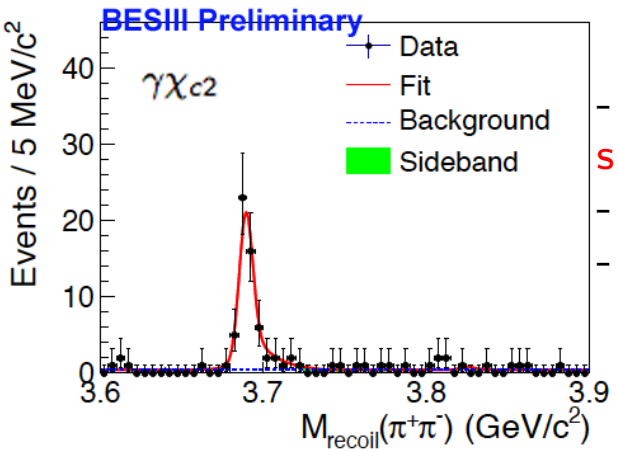
- Study of the energy dependent cross section
- The fit with a Y(4260) resonance gives a better description of the data ($\chi^2/ndf = 0.49/3$ at 90% CL)
- These observations strongly support the existence of the radiative transition process $Y(4260) \to \gamma X(3872)$



Observation of $e^+e^- \to \pi^+\pi^- X(3823)$ - Preliminary results

- The X(3823) was discovered by Belle in $B \to \chi_{c1}\gamma K$, PRL 111,032001(2013). Mass and width consistent with the missing $\psi(1^3D_2)$ state
- BESIII: Study of $e^+e^- \to \pi^+\pi^- X(3823)$, $X(3823) \to \gamma\chi_{c1,c2}$ at center of mass energies from 4.19 to 4.6 GeV, with 4.67 fb^{-1}.

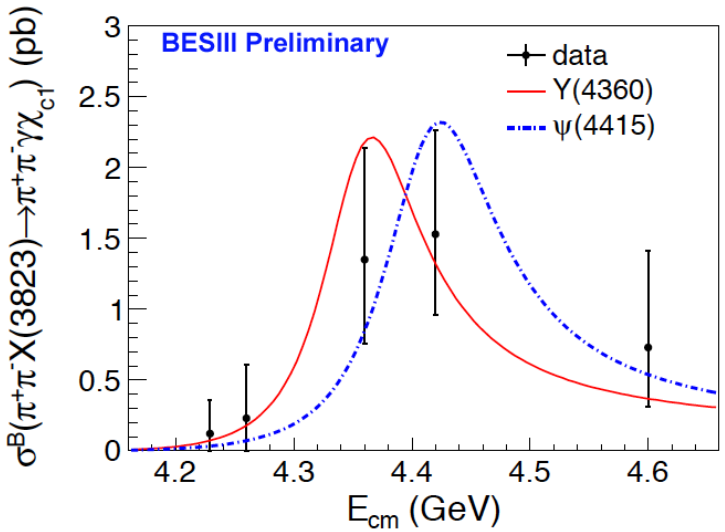




- The X(3823) is observed with significance 6.2σ in $\chi_{c1}\gamma$
- m=3821.7$\pm$1.3$\pm$0.7 MeV/c^2
- Γ <16 MeV at 90% CL

- Study of the energy dependent cross section
- The fit with the Y(4360) and $\psi(4415)$ gives a good description of the data

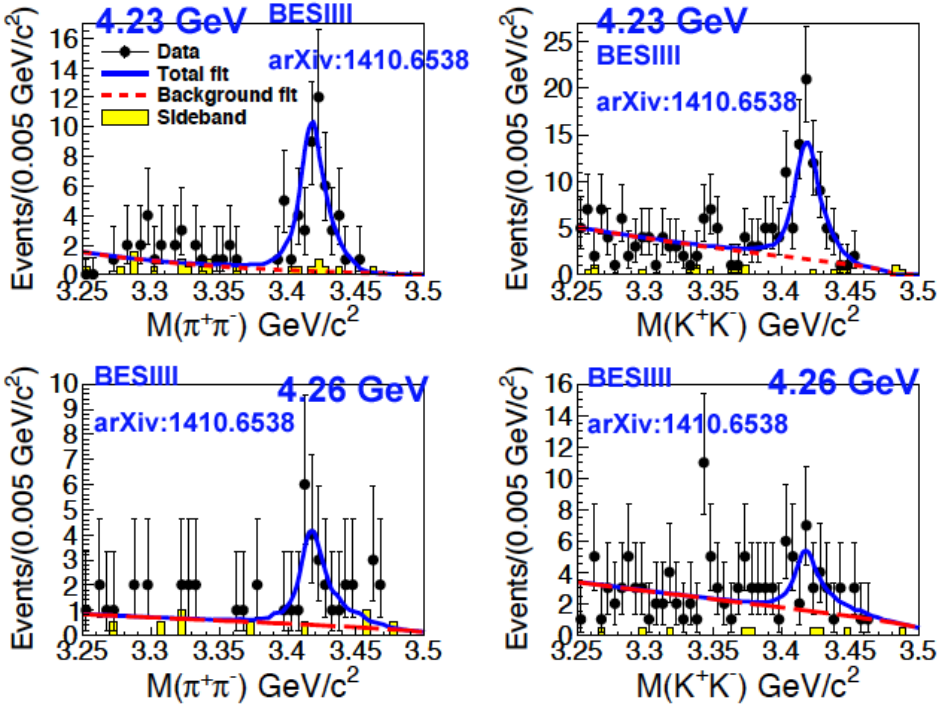
- The X(3823) is a good candidate for the $\psi(1^3D_2)$ charmonium state



THE Y STATES

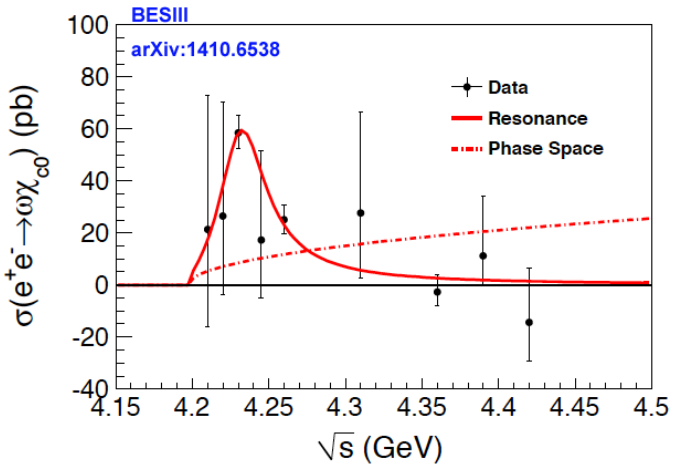
Observation of $e^+e^- \to \omega\chi_{c0}$ - arXiv:1410.6538 (accepted by CPC)

- Study of $e^+e^- \to \omega\chi_{cJ}$ at center of mass energies from 4.21 to 4.42 GeV (L=1fb^{-1} at 4.23 GeV; 0.8 fb^{-1} at 4.26 GeV).
- $\omega \to \pi^+\pi^-\pi^0$; $\chi_{c0} \to \pi^+\pi^-$ and K^+K^-; $\chi_{c1,2} \to \gamma J/\psi$



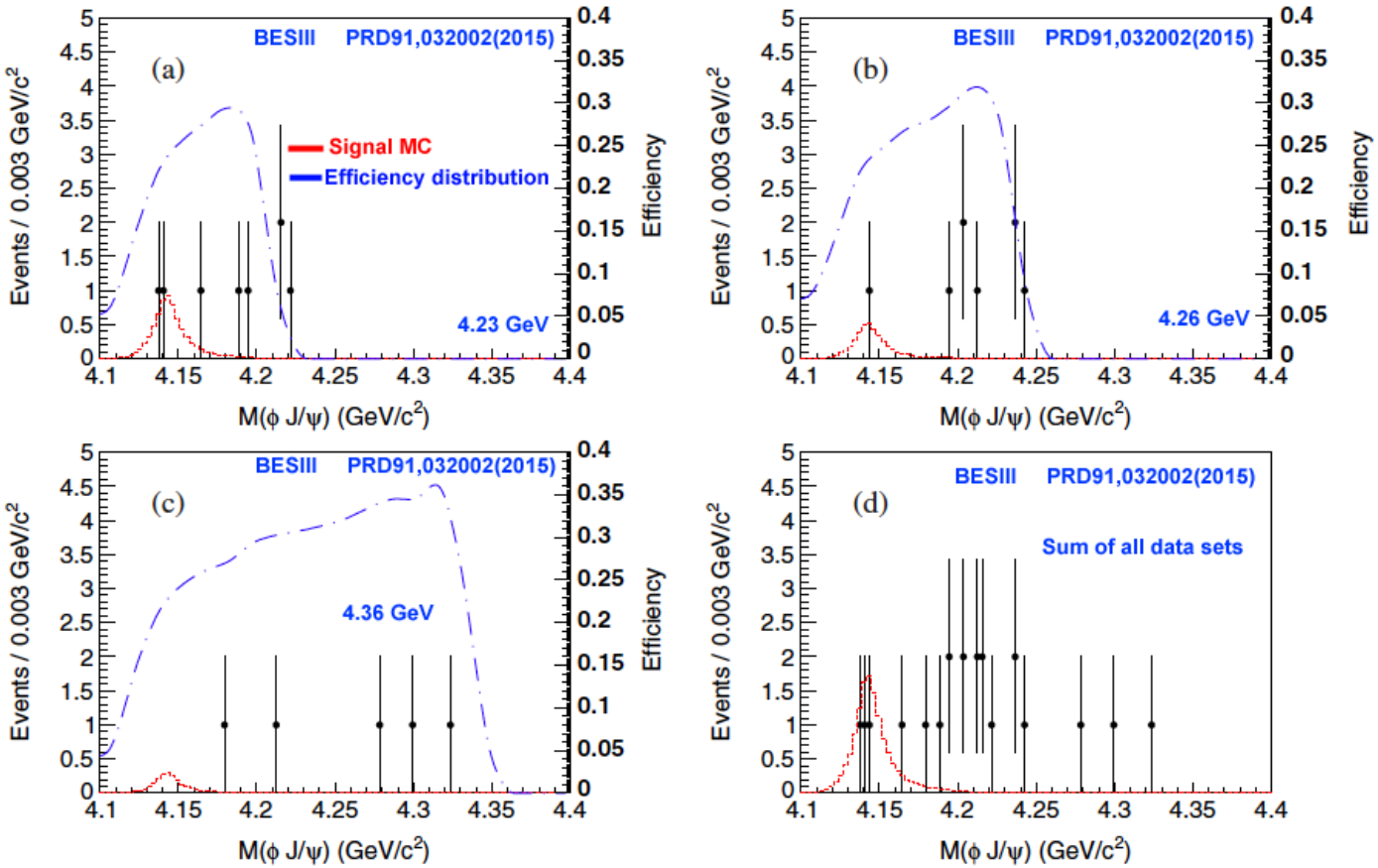
- The process $e^+e^- \to \omega\chi_{c0}$ is observed for the first time
- $\sigma(e^+e^- \to \omega\chi_{c0}) = 55.4 \pm 6.0 \pm 5.9$ pb at 4.23 GeV
- $\sigma(e^+e^- \to \omega\chi_{c0}) = 23.7 \pm 5.3 \pm 3.5$ pb at 4.26 GeV
- $e^+e^- \to \omega\chi_{c1,c2}$ signals are not significant

- Study of the energy dependent cross section
- Incosistent with the line shape of the Y(4260) observed in $e^+e^- \to J/\psi\pi^+\pi^-$
- Assuming the $\omega\chi_{c0}$ signal comes from a single resonance:
- m=4230±8±6 MeV/c^2; Γ=38±12±2 MeV
- Significance $> 9\sigma$



Search for the Y(4140) via $e^+e^- \to \gamma\phi J/\psi$ - PRD91,032002 (2015)

- The Y(4140) was discovered by CDF in $B^+ \to \phi J/\psi K^+$, PRL102,242002 (2009). Not observed by Belle and LHCb.
- BESIII: Search for $Y(4140)$ decays into $\phi J/\psi$ through the process $e^+e^- \to \gamma\phi J/\psi$ with 1094 pb^{-1} at 4.23 GeV, 827 pb^{-1} at 4.26 GeV and 545 pb^{-1} at 4.36 GeV



Search for the Y(4140) via $e^+e^- \to \gamma\phi J/\psi$ - PRD91,032002 (2015)

$\sigma^B \cdot \mathcal{B} = \sigma(e^+e^- \to \gamma Y(4140)) \cdot \mathcal{B}(Y(4140) \to \phi J/\psi)$:
at 4.23 GeV: <0.35 pb at 90% CL
at 4.26 GeV: <0.28 pb at 90% CL
at 4.36 GeV: <0.33 pb at 90% CL

Compared with X(3872) production PRL 112, 092001:

$\sigma^B \cdot \mathcal{B} = \sigma(e^+e^- \to \gamma X(3872)) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$:
at 4.23 GeV: $0.27 \pm 0.09 \pm 0.02$ pb
at 4.26 GeV: $0.33 \pm 0.12 \pm 0.02$ pb

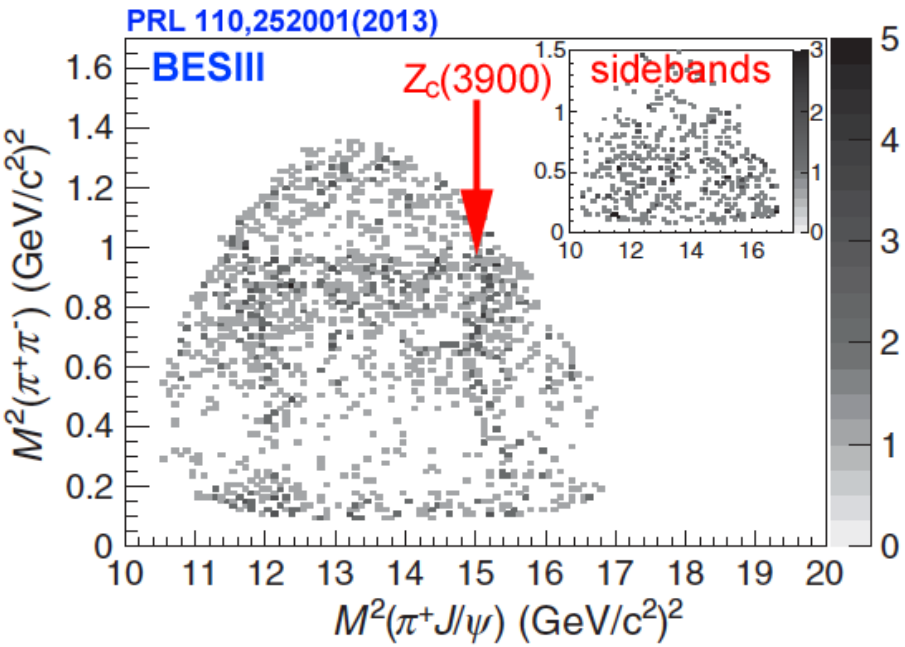
They are of the same order of magnitude!

Considering $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$=5% arXiv:0910.3138
and $\mathcal{B}(Y(4140) \to \phi J/\psi) = 30\%$ PRD80, 054019 (molecular calculation)

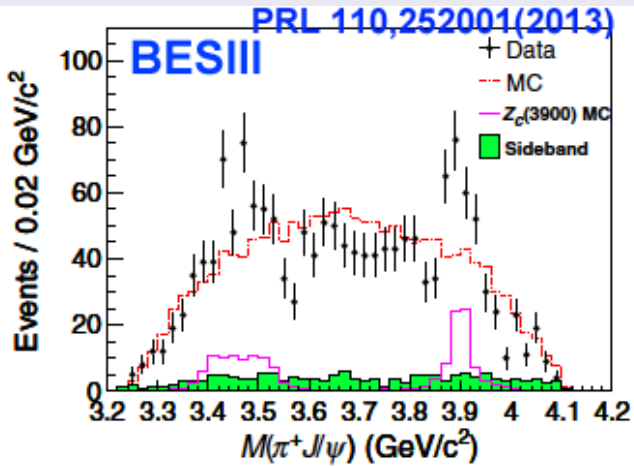
$\frac{\sigma^B(e^+e^- \to \gamma Y(4140))}{\sigma(e^+e^- \to \gamma X(3872))} \leq 0.1$ at 4.23 and 4.26 GeV

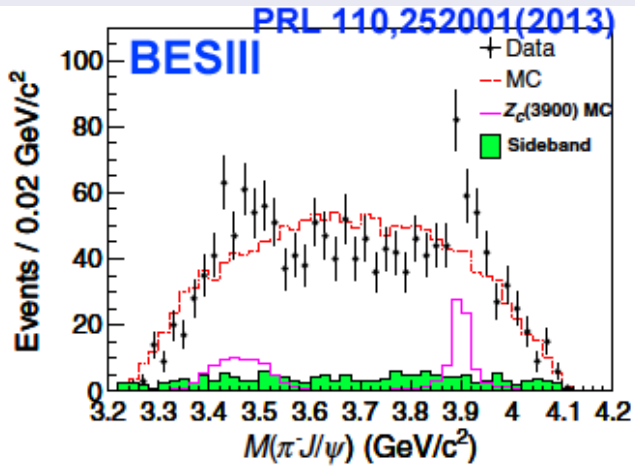
THE Z STATES

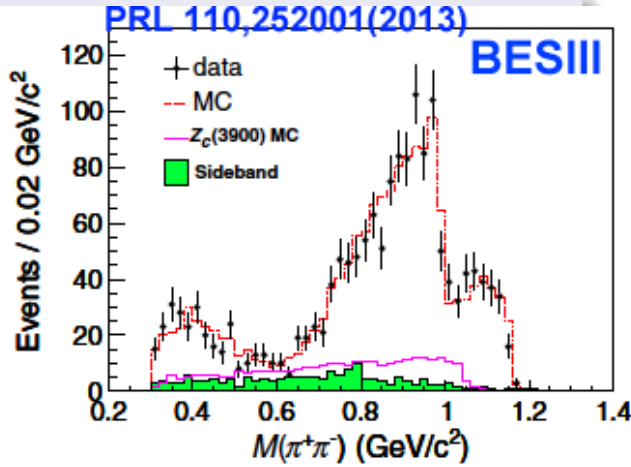
Discovery of the $Z_c(3900)^{\pm}$ - PRL 110, 252001 (2013)



- Study of the $e^+e^- \to \pi^+\pi^- J/\psi$ process at the center of mass energy of 4.260 GeV using a 525 pb^{-1}
- Measured Born cross section is $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$=(62.9±1.9±3.7) pb
- Dalitz plot of events in the J/ψ signal region shows structures in the $\pi^+\pi^-$ system and evidence for an exotic charmoniumlike structure in the $\pi^{\pm} J/\psi$ system at 3.9 GeV

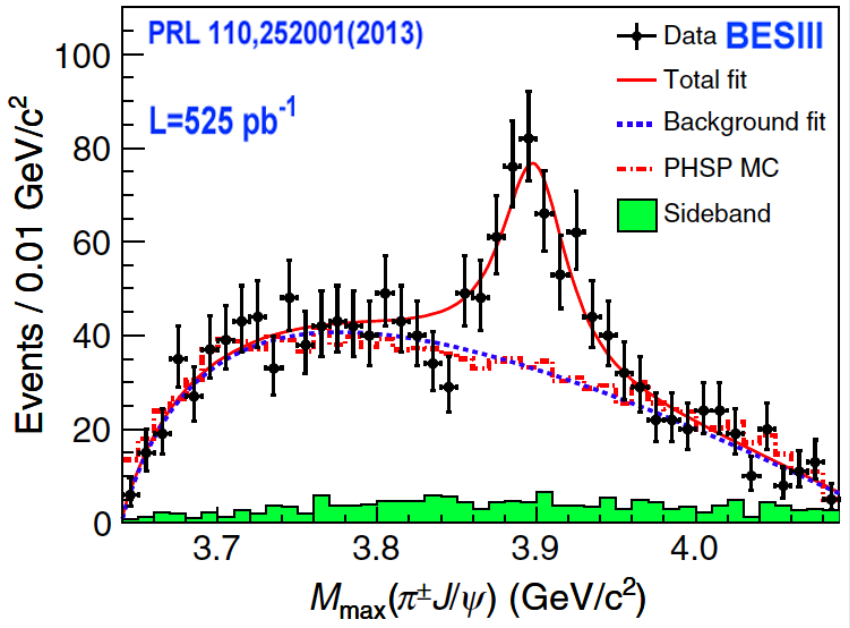






Discovery of the $Z_c(3900)^{\pm}$ - PRL 110, 252001 (2013)

- Choosing the heavier J/ψ combination per events removes reflection at 3.45 GeV/c^2
- Unbinned maximum likelihood fit to the $\pi^{\pm} J/\psi$ invariant mass distribution

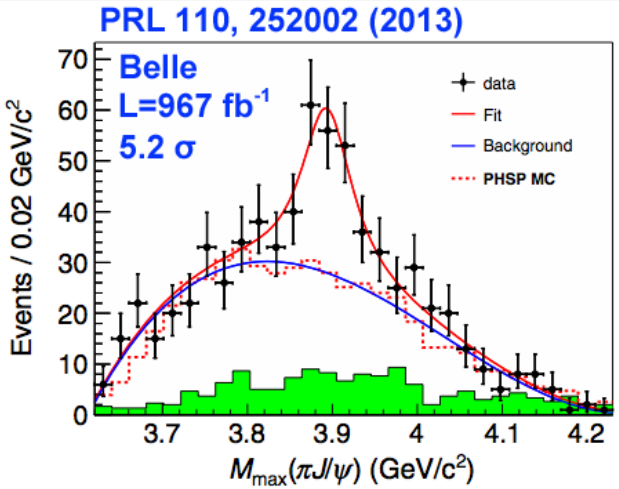


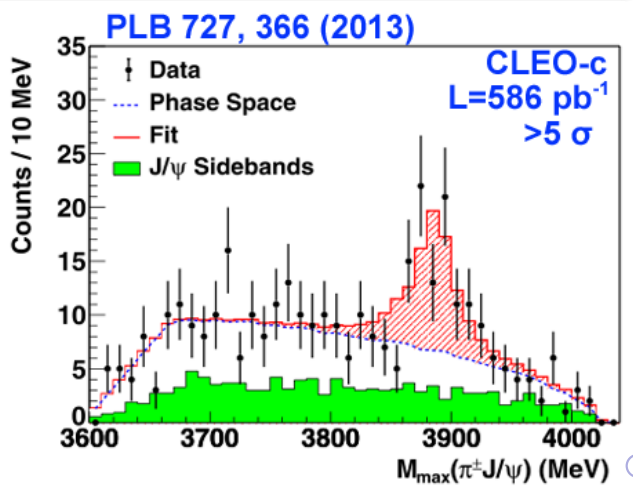
- Significance greater than 8σ
- m=(3899.0±3.6±4.9) MeV/c^2
- Γ= (46±10±20) MeV
- Mass close to the $D\bar{D}^*$ threshold
- Decays to $J/\psi \rightarrow$ contains $c\bar{c}$
- Electric charge $\rightarrow$ contains $u\bar{d}$
- 4-quark state?!

$$\frac{\sigma(e^+e^- \rightarrow \pi^{\pm} Z_c(3900)^{\mp} \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} = (21.5 \pm 3.3 \pm 7.2)\%$$

Belle: $e^+e^- \rightarrow \gamma_{ISR} J/\psi\pi^+\pi^-$
m=(3894.5±6.6±4.5) MeV/c^2
Γ=(63±24±26) MeV

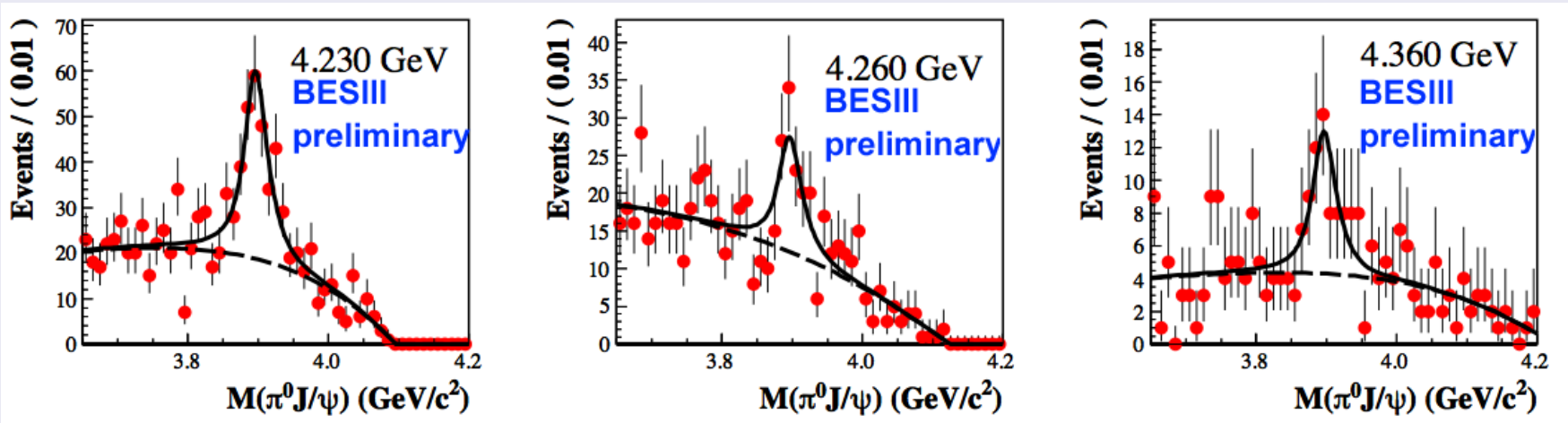
CLEO-c: $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ at 4.17 GeV
m=(3886±4±2) MeV/c^2
Γ=37±4±8) MeV

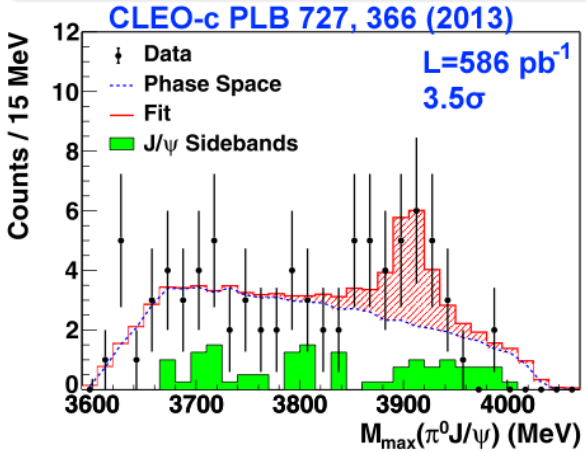




Search for a neutral $Z_c(3900)$ isospin partner - Preliminary results

- Observation of the $Z_c(3900)^0$ decaying into $J/\psi\pi^0$ in $e^-e^- \to \pi^0\pi^0 J/\psi$ using 2.5 fb^{-1} data sample
- Simultaneous fit to the $J/\psi\pi^0$ invariant mass distributions for the three data samples: $\sqrt{s}$ =4.230 GeV, 4.260 GeV, 4.360 GeV
- m=3894.8±2.3±2.7 MeV/c^2; Γ=29.6±8.2±8.2 MeV; Significance greater than 10σ



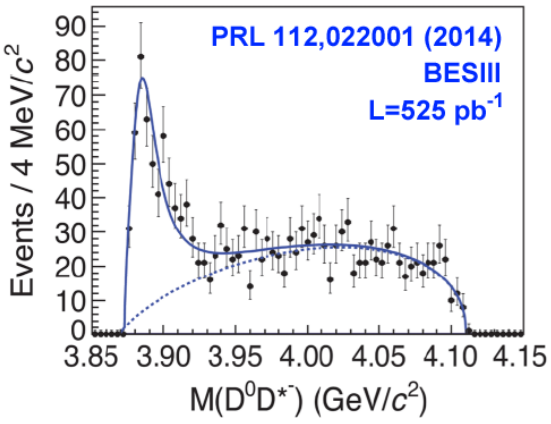


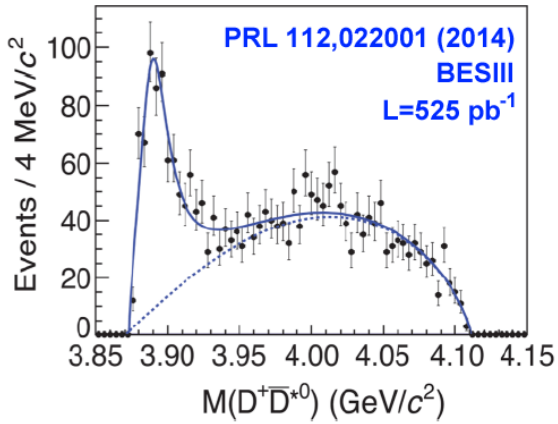
- First evidence by CLEO-c
- $e^+e^- \to J/\psi\pi^+\pi^-$ at 4.17 GeV
- m=3904±4±5 MeV/c^2
- Γ=37 (Fixed) MeV
- Significance 3.7σ

Isospin triplet is established!

Observation of $Z_c(3885)^{\pm}$ in $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$ using single D tag method - PRL 112, 022001 (2014)

- Study of the $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$ at $\sqrt{s}$=4.26 GeV using a 525 pb^{-1}
- Single D tag method: Reconstruction of the π and one final state D meson; the presence of the $\bar{D}^*$ is inferred from energy-momentum conservation.
- $D^0 \to K^-\pi^+$; $D^+ \to K^-\pi^+\pi^-$





- Enhancement at $D\bar{D}^*$ threshold in both channels - Significance $> 18\sigma$
- Fit function:Breit-Wigner+smooth threshold function
- m=(3883.9±1.5±4.2) MeV/c^2
- Γ=(24.8±3.3±11.0)MeV
- $\sigma \times \mathcal{B}$=(83.5±6.6±22.0) pb

Parameters similar to $Z_c(3900)$. A J^P quantum number determination for the $Z_c(3900)$ needed

Fit to angular distribution favours $J^P = 1^+$

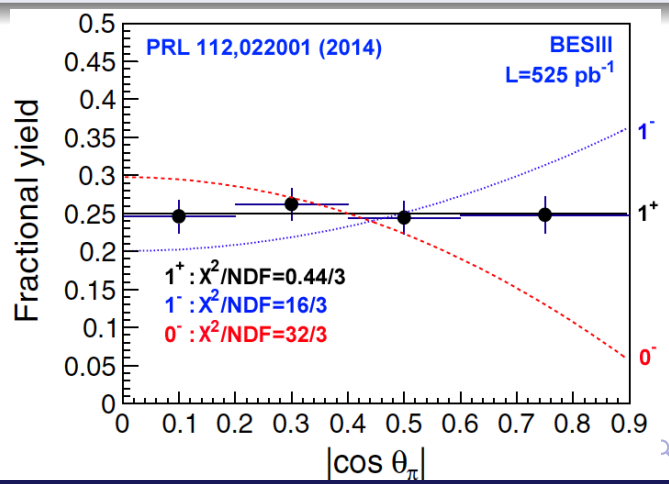
If this is $Z_c(3900)^{\pm}$, the ratio of partial decay widths is:

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

This ratio is much smaller than typical values for decays of conventional charmonium states above the open charm threshold:

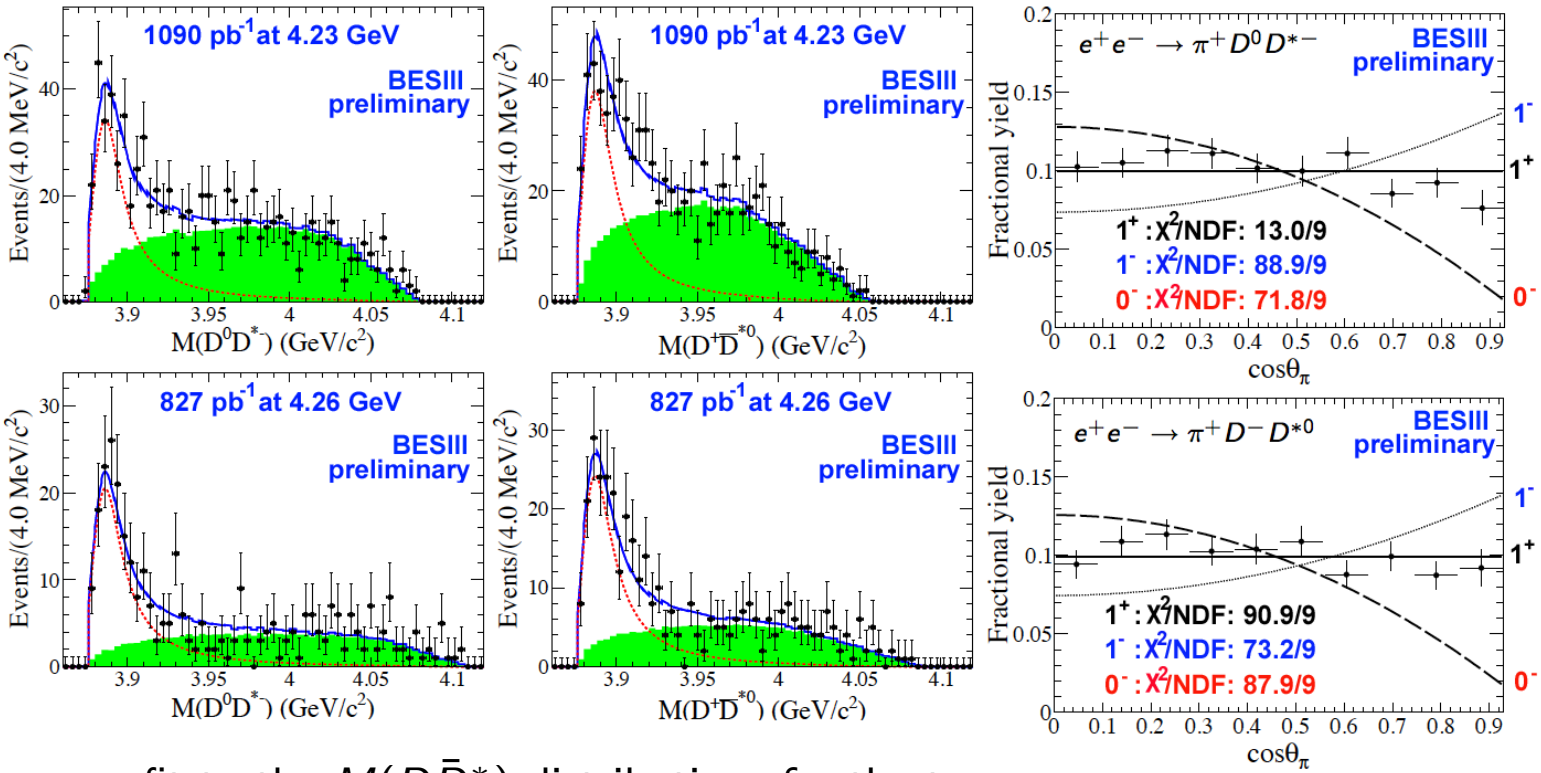
$$\frac{\Gamma(\psi(3770)\to D\bar{D})}{\Gamma(\psi(3770)\to \pi^+\pi^- J/\psi)} = 482 \pm 84$$

This suggests the influence of very different dynamics in the Y(4260)-$Z_c(3900)$ system



Confirmation of $Z_c(3885)^{\pm}$ in $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$ using double D tag method - Preliminary results

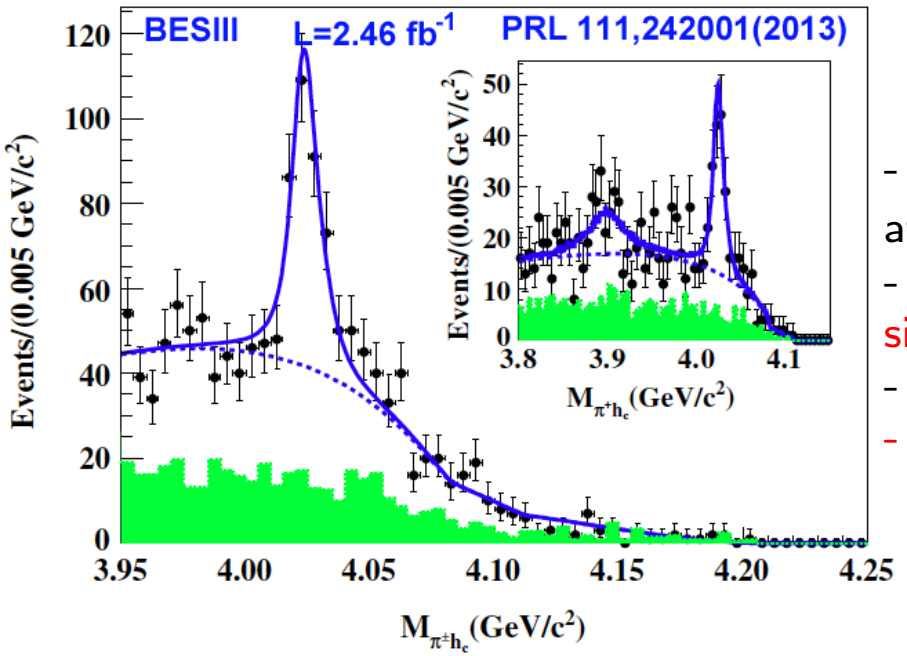
- Combined study of the processes $e^+e^- \to \pi^+ D^0 D^{*-}$ ($\pi^+ D^0 \bar{D}^0$-tag.) and $e^+e^- \to \pi^+ D^- D^{*0}$ ($\pi^+ D^- D^0$-tag.) using 1090 pb^{-1} at $\sqrt{s}$ =4.23 GeV and 827 pb^{-1} at $\sqrt{s}$=4.26 GeV.
- Double tag method: reconstruction of the bachelor π and $D\bar{D}$ pair: this allows to use more D decays modes and effectively suppresses background.



- Simultaneous fit to the $M(D\bar{D}^*)$ distributions for the two processes.
- m=3884.3$\pm$1.2$\pm$1.5 MeV/c^2; Γ=23.8$\pm$2.1$\pm$2.5 MeV; Significance $> 10\sigma$
- The angular distribution is consistent with $J^P = 1^+$.
- The measured mass, width and quantum numbers are consistent with single D tag results.

Observation of $Z_c(4020)^{\pm}$ in $e^+e^- \to \pi^+\pi^- h_c$ - PRL 111, 242001(2013)

-Study of $e^+e^- \to \pi^+\pi^- h_c$ at center of mass energies from 3.90 to 4.42 GeV.
- $h_c \to \gamma\eta_c$; η_c reconstructed in 16 hadronic decay modes



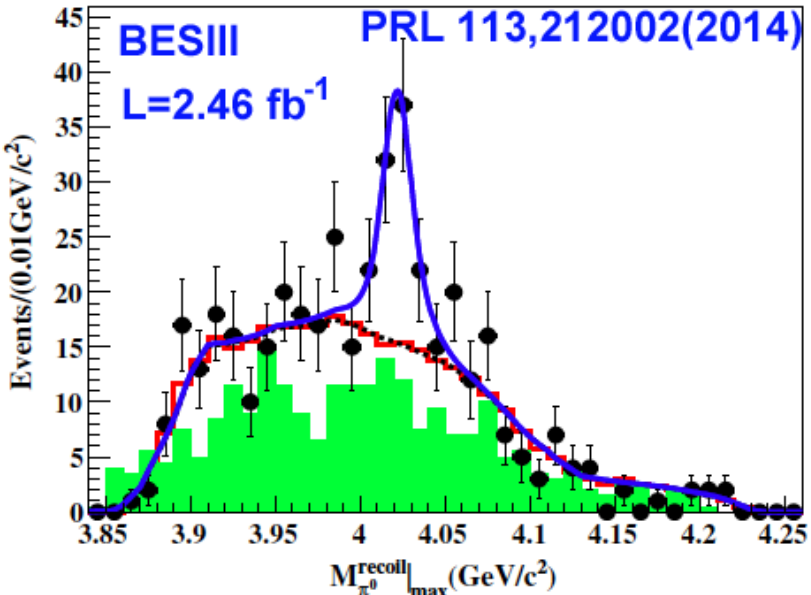
- Simultaneous fit to the $M_{\pi^\pm h_c}$ distributions at 4.23, 4.26 and 4.36 GeV using 2.46 fb^{-1}.
- A structure, $Z_c(4020)^{\pm}$ is observed with significance $> 8.9\sigma$
- m=4022.9±0.8±2.7 MeV/c^2
- Γ=7.9±2.7±2.6 MeV

- $\sigma(e^+e^- \to \pi^\pm Z_c(4020)^\mp \to \pi^+\pi^- h_c) = 8.7 \pm 1.9 \pm 2.8 \pm 1.4$ pb at 4.23 GeV
- $\sigma(e^+e^- \to \pi^\pm Z_c(4020)^\mp \to \pi^+\pi^- h_c) = 7.4 \pm 1.7 \pm 2.1 \pm 1.2$ pb at 4.26 GeV
- $\sigma(e^+e^- \to \pi^\pm Z_c(4020)^\mp \to \pi^+\pi^- h_c) = 10.3 \pm 2.3 \pm 3.1 \pm 1.6$ pb at 4.36 GeV

Observation of $Z_c(4020)^0$ in $e^+e^- \to \pi^0\pi^0 h_c$ - PRL 113, 212002(2014)

-Study of $e^+e^- \to \pi^0\pi^0 h_c$ at center of mass energies of 4.23, 4.26 and 4.36 GeV using 2.46 fb^{-1}.

- $h_c \to \gamma\eta_c$; η_c reconstructed in 16 hadronic decay modes



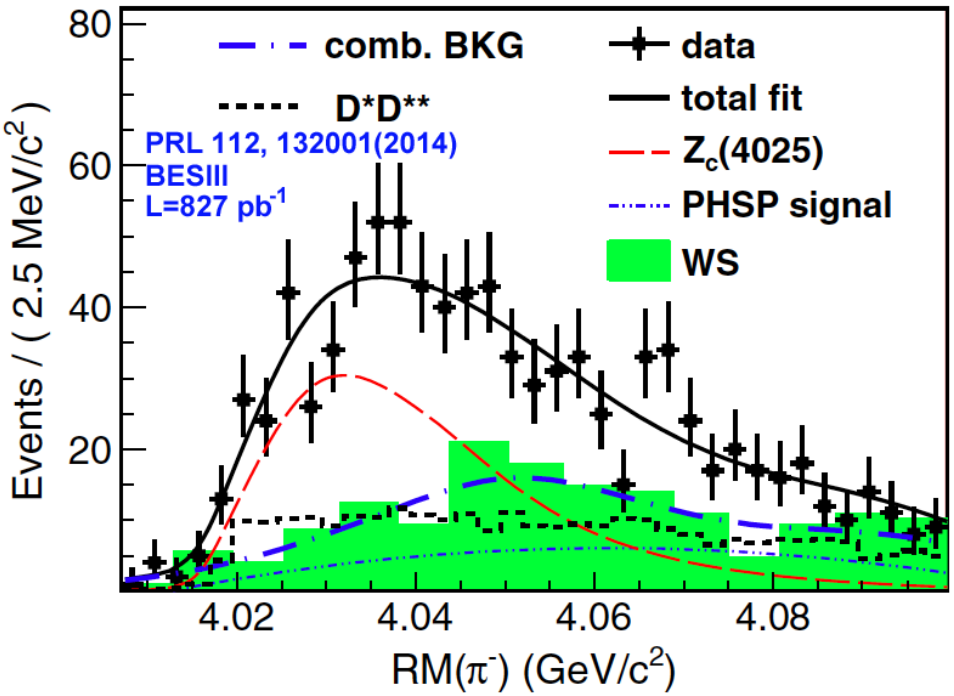
- Simultaneous fit to the $M_{\pi^0}^{recoil}$ distributions.
- A structure, $Z_c(4020)^0$ is observed with significance $> 5\sigma$
- m=4023.9$\pm$2.2$\pm$3.8 MeV/c^2
- Width is fixed to be the same as its charged partner
- Another isospin triplet is established!

- $\sigma(e^+e^- \to \pi^0 Z_c(4020)^0 \to \pi^0\pi^0 h_c) = 6.5 \pm 2.2 \pm 0.7 \pm 1.0$ pb at 4.23 GeV
- $\sigma(e^+e^- \to \pi^0 Z_c(4020)^0 \to \pi^0\pi^0 h_c) = 8.5 \pm 2.9 \pm 1.1 \pm 1.3$ pb at 4.26 GeV
- $\sigma(e^+e^- \to \pi^0 Z_c(4020)^0 \to \pi^0\pi^0 h_c) = 9.9 \pm 4.1 \pm 1.3 \pm 1.5$ pb at 4.36 GeV

The combined ratio $\mathcal{R}_{\pi Z_c(4020)} = \frac{\sigma(e^+e^- \to \pi^0 Z_c(4020)^0 \to \pi^0\pi^0 h_c)}{\sigma(e^+e^- \to \pi^\pm Z_c(4020)^\mp \to \pi^+\pi^- h_c}$=0.99$\pm$0.31 with is well within 1σ of the expectation of isospin symmetry 1.0

Observation of $Z_c(4025)^{\pm}$ in $e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp}$ - PRL 112, 132001(2014)

-Study of $e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp}$ at 4.26 GeV using 827 pb^{-1}.
- Only the bachelor π^-, the D^+ decaying from $D^{*+} \to D^+\pi^0$ and at least one soft π^0 from $D^{*+} \to D^+\pi^0$ or $\bar{D}^{*0} \to \bar{D}^0\pi^0$ decay are reconstructed.



- Unbinned maximum likelihood fit to the $M^{recoil}_{\pi^-}$ distribution.
- A structure, $Z_c(4025)^+$ is observed with significance 13σ
- m=4026.3±2.6±3.7 MeV/c^2
- Γ=24.8±5.6±7.7 MeV

To validate the establishment of $Z_c(4025)$ a rigorous spin analysis is required based on a larger data sample.

Conclusion

- Quarkonium spectroscopy is a very interesting field, many new exotic states have been discovered in recent years;
- Still many missing pieces need to be found to have the full picture;
- In 2012, BESIII has started a dedicated program toward understanding X, Y, Z states.

THANKS FOR YOUR ATTENTION!

BACKUP SLIDES