HADRON SPECTROSCOPY AT BESIII

Light hadrons and XYZ states

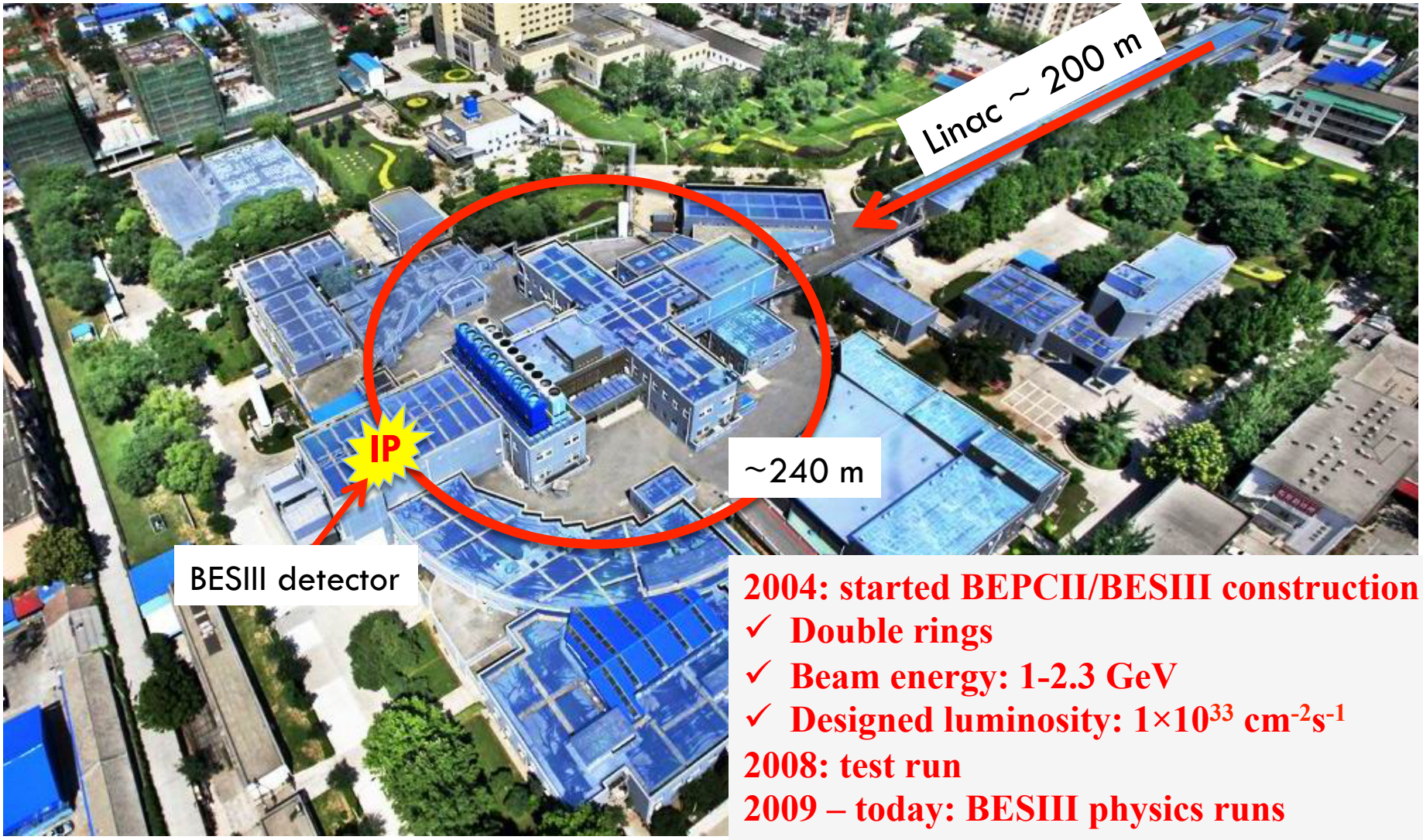
Isabella Garzia, INFN-Sezione di Ferrara
On behalf of the BESIII Collaboration

50th Anniversary Meeting, La Thuille - 19-26 March, 2016

OUTLINE

- ✓ INTRODUCTION: The BESIII experiment
  - BEPCII and the BESIII detector
  - The BesIII dataset and physics programme
- ✓ Physics highlights
  - Light hadron spectroscopy: X(18??) states
  - Charmonium-like states: XYZ states
- ✓ Summary and Conclusions

Beijing Electron Positron Collider II



2004: started BEPCII/BESIII construction

- ✓ **Double rings**
- ✓ **Beam energy: 1-2.3 GeV**
- ✓ **Designed luminosity: 1×10^{33} cm^{-2}s^{-1}**

2008: test run

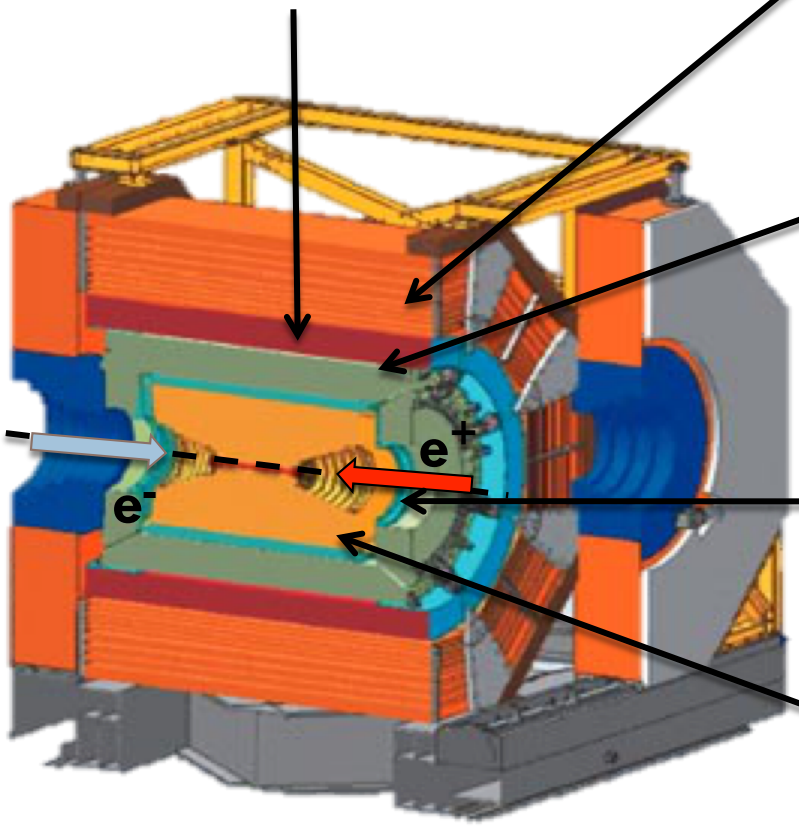
2009 – today: BESIII physics runs

The BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)

Superconducting solenoid (1T)

RPC Muon Detector
8 layers (end caps) + 9 layers (barrel)
$\Delta\Omega/4\pi$=93%



Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} = (6\ mm)/E^{1/2}$ @ 1 GeV

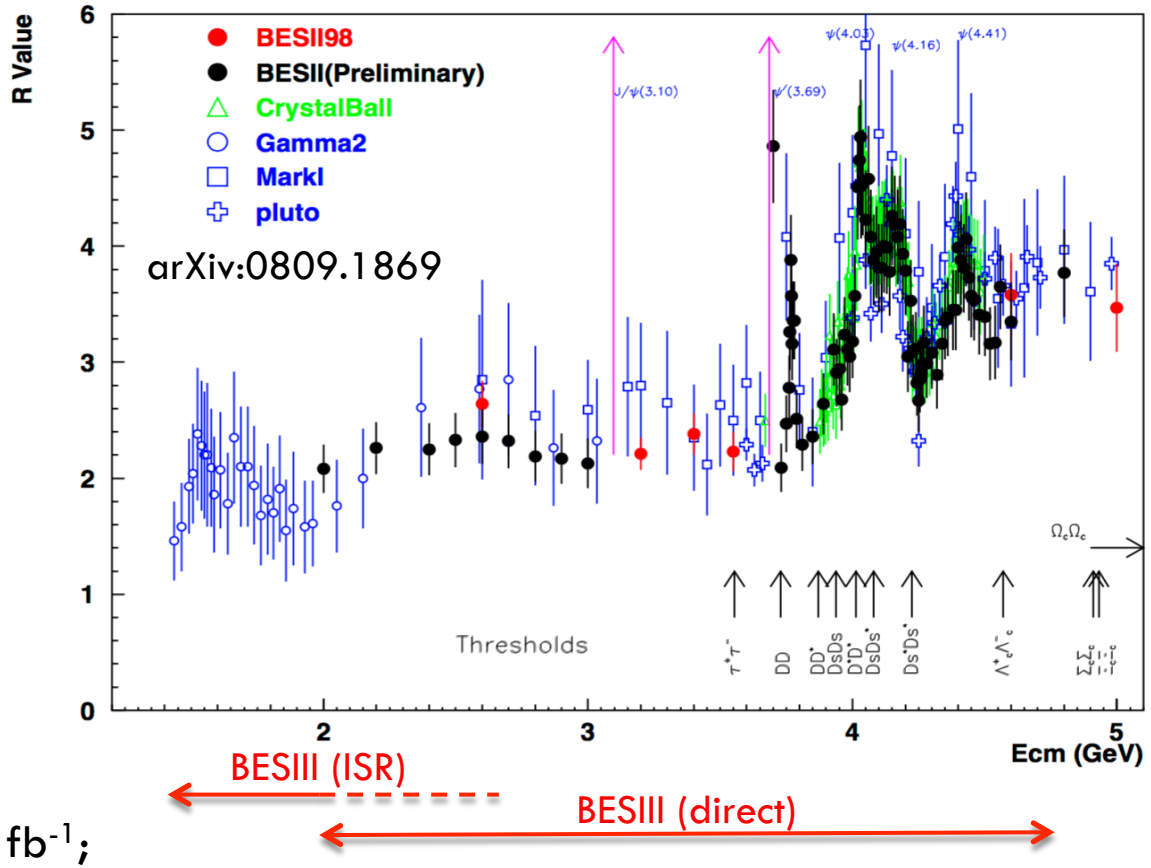
Time of Flight
$\sigma_t = 90$ ps (barrel)
$\sigma_t = 120$ ps (end caps)

Drift Chamber
$\sigma_{r\phi} = 130\ \mu m$ (single wire)
$\sigma_{pt}/p_t = 0.5\ \%$ @ 1 GeV

The BESIII data set

From 2009 to 2014/2015:

- **1.3×10^9 J/ψ**
- **5×10^8 ψ(2S)**
- 2.9 fb^{-1} @ ψ_{3770}
- 0.5 fb^{-1} @ ψ_{4040}
- 2.3 fb^{-1} @ 4230/4260 MeV
- 0.5 fb^{-1} @ 4360 MeV
- 0.5 fb^{-1} @ 4600 MeV
- 1 fb^{-1} @ ψ_{4415}
- 0.1 fb^{-1} @ 4470/4530 MeV
- 0.04 fb^{-1} around Λ_c threshold
- 1 fb^{-1} @ 4420 MeV
- R scan:
  - 2-3 GeV, 19 points, ~0.5 fb^{-1};
  - 3.85-4.59 GeV, 104 points, ~0.8 fb^{-1}



MORE:

- 3554 MeV 24 pb^{-1} τ mass; 4100-4400 MeV 0.5 fb^{-1} coarse scan
- On-going data taking

http://bes3.ihep.ac.cn/datasets/datasets.htm

Selected results

Mesons spectroscopy

- X(1860) in $J/\psi \to \gamma p\bar{p}$
- X(1835) in $J/\psi \to \gamma\pi^-\pi^+\eta'$
- X(1560) and X(1835) in $J/\psi \to \gamma K_S^0 K_S^0 \eta$
- X(1835) line shape and study and connection with X(pp)

XYZ states

- $e^+e^- \to \pi^-\pi^+ X(3823) \to \pi^-\pi^+\gamma\chi_c$
- Z_c states

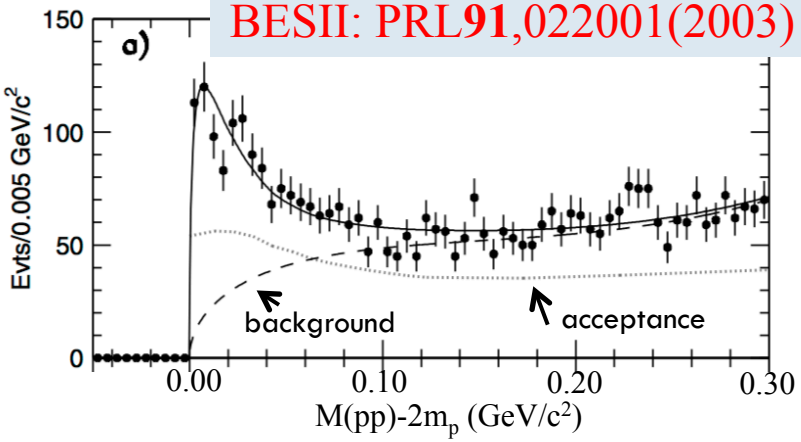
Many others results not covered in this talk

- Y(2175) resonance and search for X(1835) and X(1870) in $J/\psi \to \eta\phi\pi^-\pi^+$ (PRD91,052017)
- $e^+e^- \to \gamma X(3872) \to \gamma J/\psi\pi^-\pi^+$ (PRL 112, 092001)
- $e^+e^- \to \omega\chi_{CJ}$ (PRL 114, 092003 and PRD 93, 011102)
- $e^+e^- \to \eta J/\psi$ (PRD 91, 112005)
- Search for Y(4140) $\to J/\psi\phi$ (PRD 91, 032002)
- $Z_c(3900)^\pm \to \omega\pi^\pm$ (PRD 92, 032009)
- Search for isospin violating decay Y(4260) $\to J/\psi\eta\pi^0$ (PRD 92, 012008)
- …

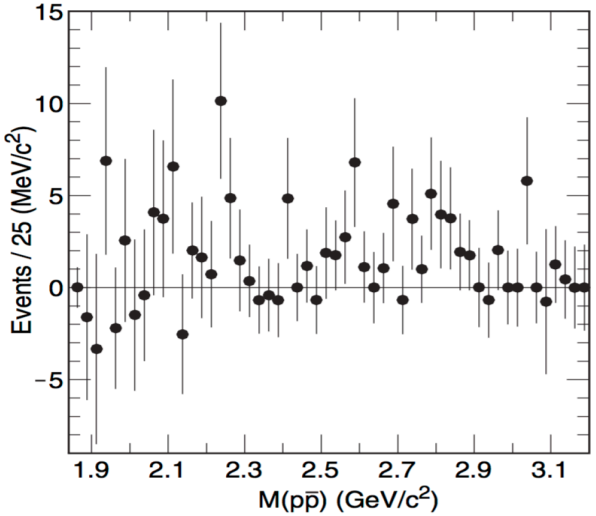
$J/\psi \to \gamma p\bar{p}$: threshold enhancement in $p\bar{p}$ mass

- Enhancement observed more than 10 years ago at BESII and confirmed by CLEO-c [PRD82,092002]
- What about its nature ?
- No similar structures observed in related channels:

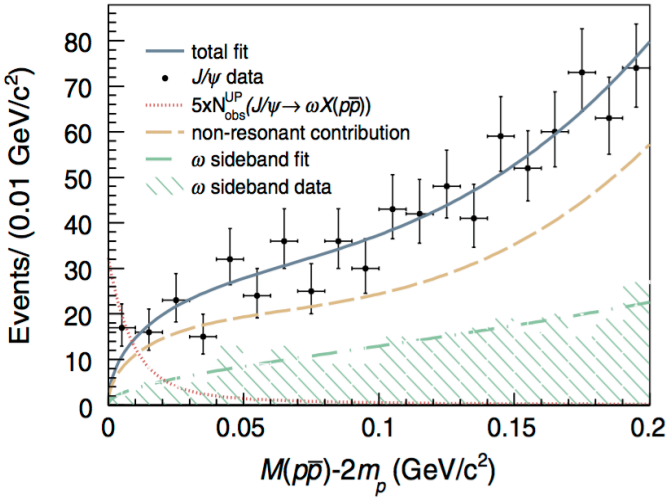
BESII: PRL**91**,022001(2003)



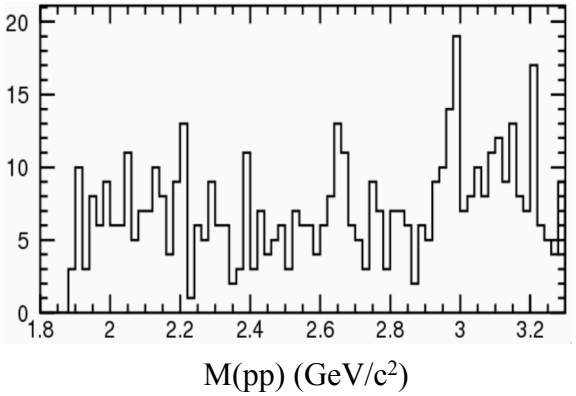
CLEO, $\Upsilon(1S) \to \gamma p\bar{p}$
PRD 73, 032001



BESIII, $J/\psi \to \omega p\bar{p}$
PRD 87, 112004

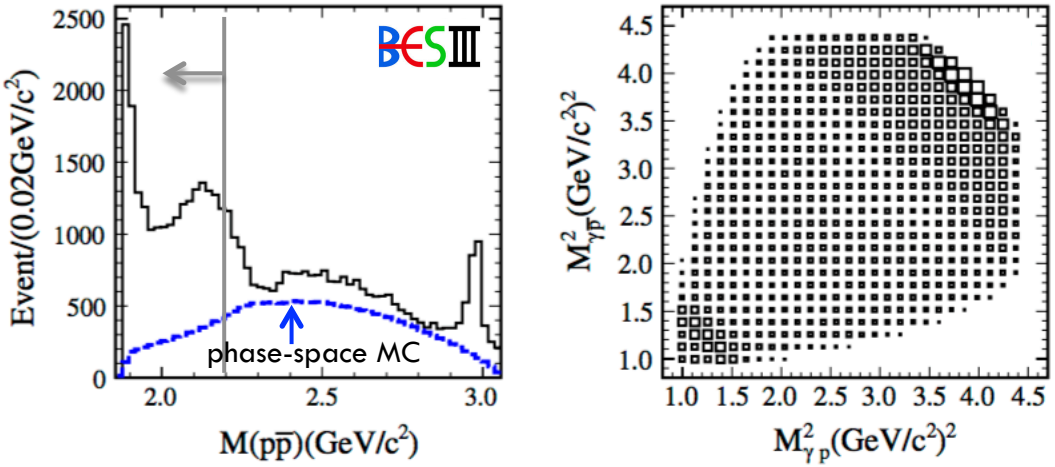


BES, $\psi' \to \gamma p\bar{p}$
PRL 99, 011802



BESIII $J/\psi \to \gamma p\bar{p}$

BESIII: PRL**108**,112003(2012)



PWA analysis for the region below 2.2 GeV using 225M J/ψ decays

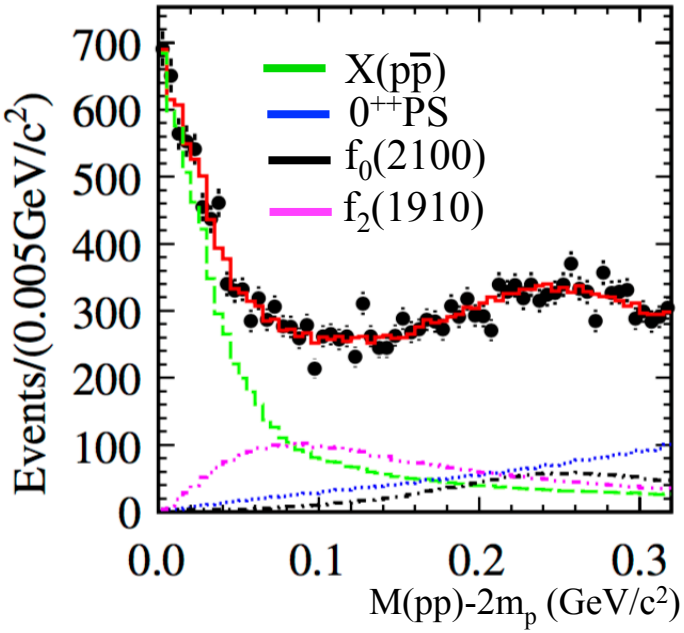
- Four components included in the PWA fit: X($p\bar{p}$), $f_2(1910)$, $f_0(2100)$ and 0^{++} phase space
- Intermediate resonances described by Breit-Wigner propagators
- $f_2(1910)$ and $f_0(2100)$ parameters fixed at the PDG values

- Statistical significance of the X($p\bar{p}$) component > 30 σ, 5 σ for the other components
- The 0^{-+} assignment is better than other J^{PC}

$$M = 1832^{+19}_{-5}(\text{stat})\ ^{+18}_{-17}(\text{syst}) \pm 19(\text{model})\ \text{MeV}/c^2$$

$$\Gamma = 13 \pm 39(\text{stat})\ ^{+10}_{-13}(\text{syst}) \pm 4(\text{model})\ \text{MeV}/c^2$$

$$BR_{[J/\psi \to \gamma X] \times BR[X \to pp]} = (9.0^{+0.4}_{-1.1}(\text{stat})^{+1.5}_{-5.0}(\text{syst}) \pm 2.3(\text{model})) \times 10^{-5}$$



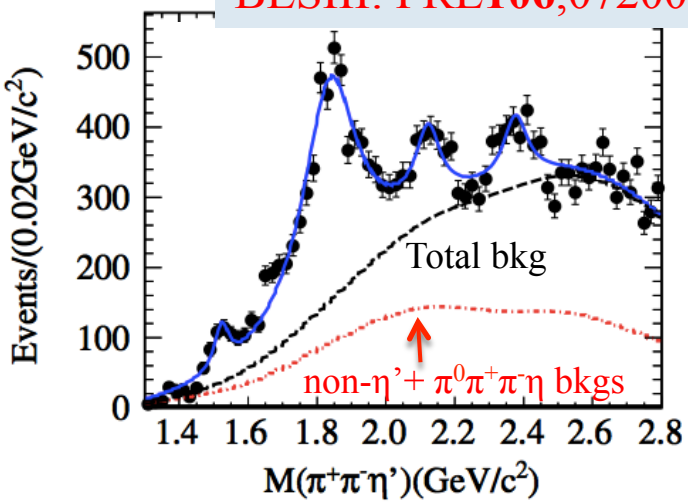
$X(1835)$ in $J/\psi \to \gamma \pi^-\pi^+\eta'$

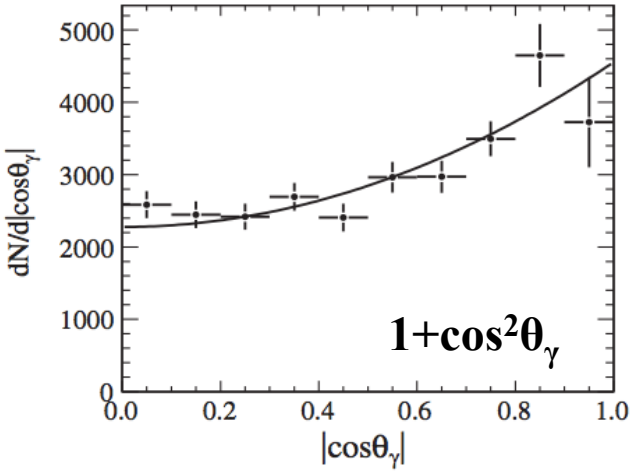
- X(1835) was first observed at BES, and then confirmed at BESII [PRL95,262001]
- Two additional structures observed at BESIII
- Many interpretation: $p\bar{p}$ bound state? Glueballs? Radial excitation of the η' meson
  - Needed higher statistic

- BESIII $J/\psi \to \gamma \pi^-\pi^+\eta'$: PRL **106**, 072002
  - 225M J/ψ events
  - $\eta' \to \gamma \pi^-\pi^+$ and $\eta' \to \eta\,_{\gamma\gamma}\pi^-\pi^+$
  - 4 resonances (BW⊗Gauss)+non-resonant $\eta'\pi^-\pi^+$ (from MC) + non-η' and $\pi^-\pi^+\pi^0\eta'$ bkgs

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$
$f_1(1510)$	1522.7 ± 5.0	48 ± 11
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0
$X(2120)$	2122.4 ± 6.7	83 ± 16
$X(2370)$	2376.3 ± 8.7	83 ± 17

BESIII: PRL**106**,072002





- The polar angle distribution of the photon in the J/ψ center-of-mass system supports $J^{PC}=0^{-+}$ → need PWA analysis to determine spin-parity assignment

$X(1835)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

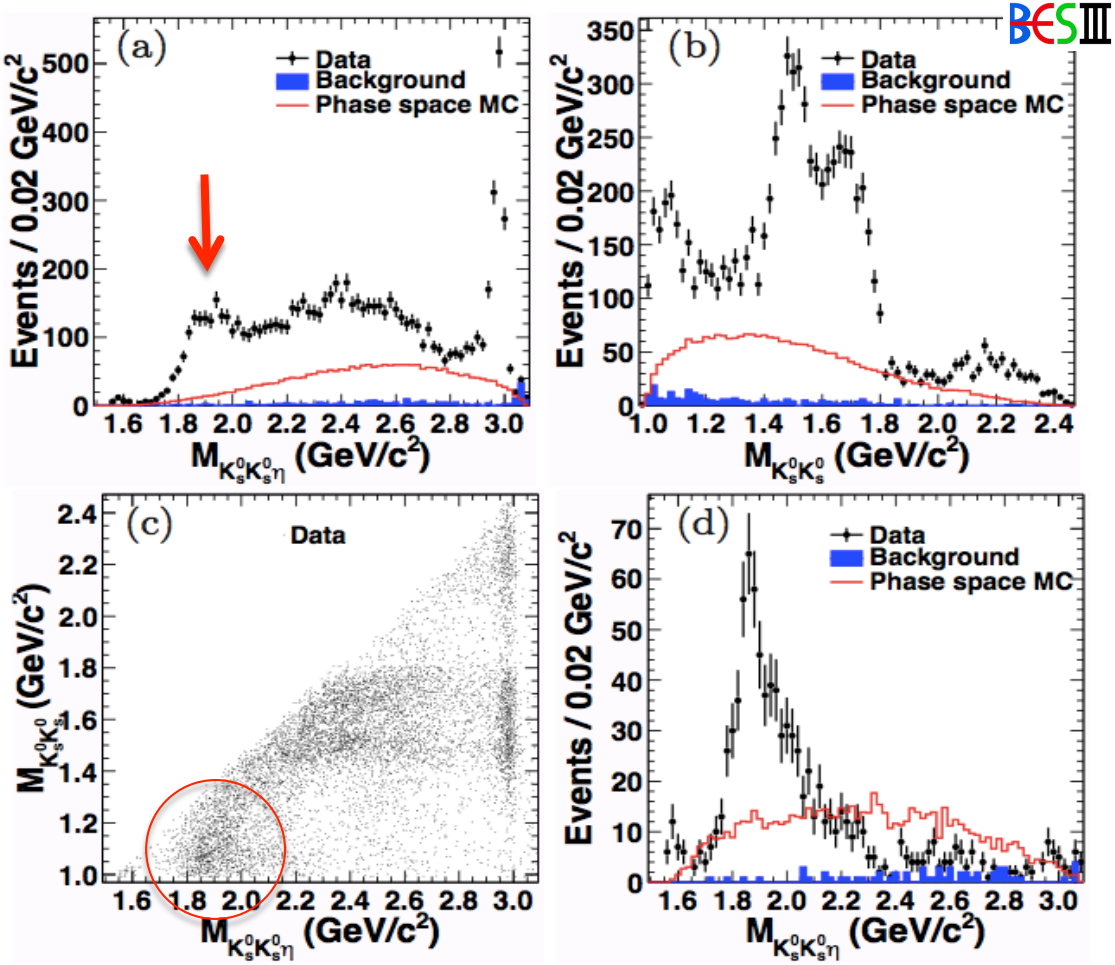
BESIII: PRL**115**,091803

$J/\psi \to \gamma K^0_S K^0_S \eta$ provides a clear environment

- $K^0_S K^0_S \eta$ and $\pi^0 K^0_S K^0_S \eta$ bkgs are forbidden by exchange symmetry and CP conservation

- 1.3×10^9 J/ψ events
- (a) Structure around 1.85 GeV/c^2
- (b) Strong enhancement near the $K^0_S K^0_S$ threshold interpreted as the $f_0(980)$
- (c) Strong correlation between the $f_0(980)$ and the structure near 1.85 GeV/c^2
- (d) $M(K^0_S K^0_S)$<1.1 GeV/c^2 ➔ the structure near 1.85 GeV/c^2 became more pronounced

PWA of events with $M(K^0_S K^0_S)$<1.1 GeV/c^2 and $M(K^0_S K^0_S \eta)$<2.8 GeV/c^2



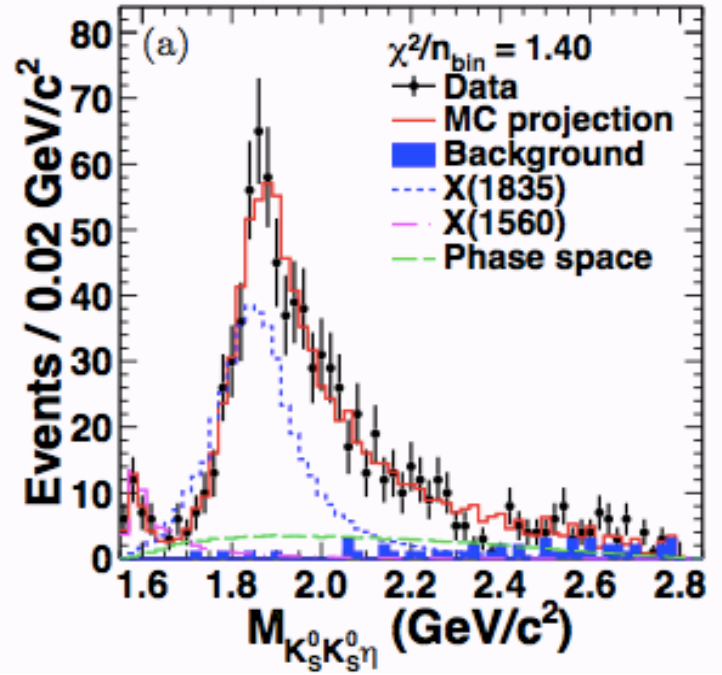
$J/\psi \to \gamma K_S^0 K_S^0 \eta$: PWA results

BESIII: PRL**115**,091803

Final fit results: the data can be best described with three components: X(1835)→$f_0(980)\,\eta$, X(1560)→$f_0(980)\,\eta$, and a non-resonant $f_0(1500)\,\eta$ component

- The X(1560) component improves the fit quality when interference with the X(1835) is allowed
- Several fits with different J^{PC} hypothesis
- **$J^{PC} = 0^{-+}$** for X(1835), X(1560), and non-resonant component
- $J^{PC} = 1^{++}$ for non-resonant component cannot be excluded

Mass and width of X(1835) consistent with PRL**106**



$M = 1844 \pm 9\,(stat)\,{}^{+16}_{-25}(syst)$ MeV/c^2 $\quad \Gamma = 192^{+20}_{-17}(stat)\,{}^{+62}_{-43}(syst)$ MeV $\quad (>12.9\,\sigma)$

$BR = (3.3^{+0.33}_{-0.30}(stat)\,{}^{+1.96}_{-1.29}(syst)) \times 10^{-5}$

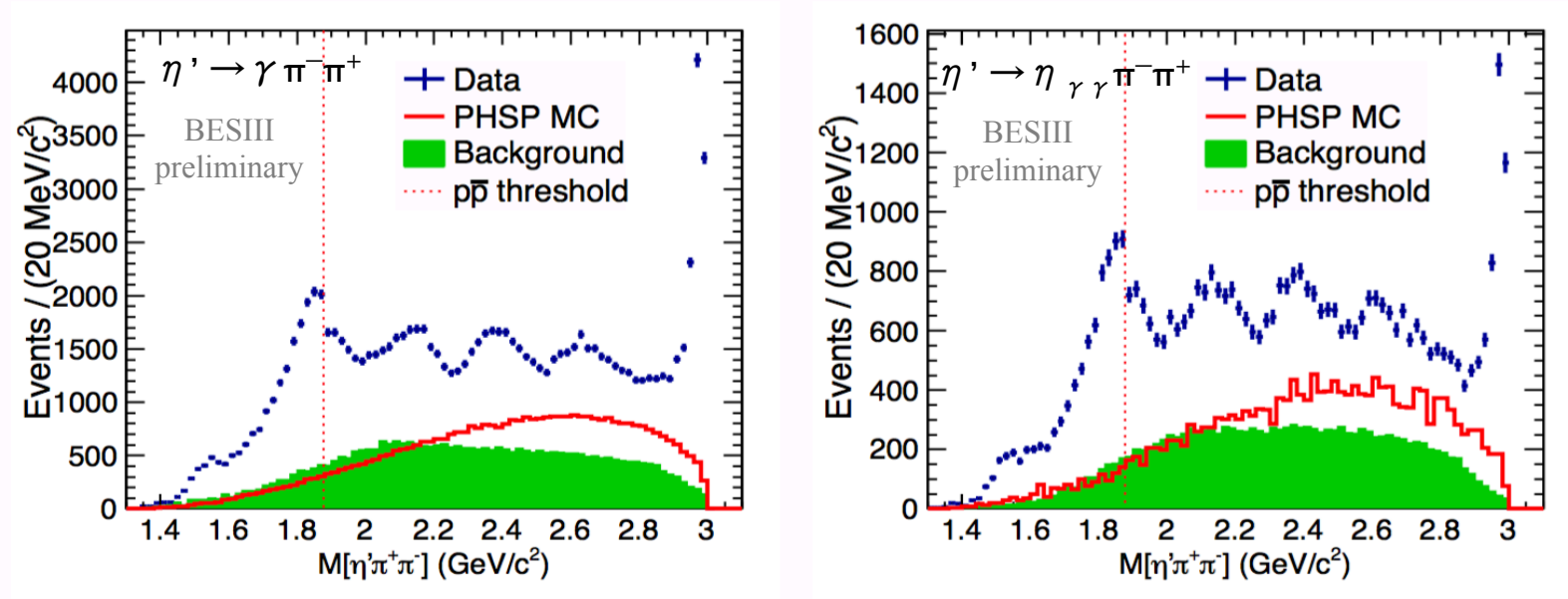
$M = 1565 \pm 8\,(stat)^{+0}_{-63}(syst)$ MeV/c^2 $\quad \Gamma = 45^{+14}_{-13}(stat)^{+21}_{-28}(syst)$ MeV $\quad (>8.9\,\sigma)$

New: connection between X(1835) and X($p\bar{p}$)

BESIII preliminary

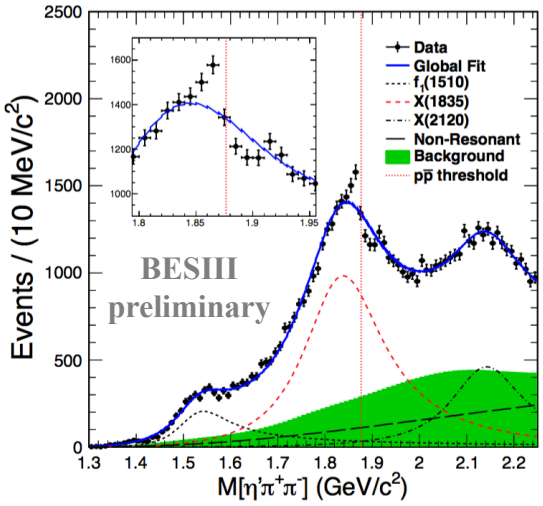
If the X(1835) is a pp bound state, the $\eta'\pi^-\pi^+$ line shape at the $p\bar{p}$ threshold would be affected by the opening of the X(1835) $\rightarrow p\bar{p}$ decay mode

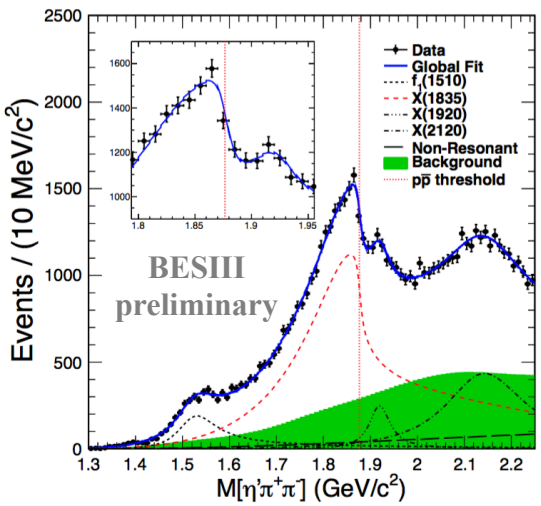
- 1.09×10^9 J/ψ events collected in 2012
- $\eta' \rightarrow \gamma\pi^-\pi^+$ and $\eta' \rightarrow \eta_{\gamma\gamma}\pi^-\pi^+$
- Clear peaks of X(1835), X(2120), X(2370), η_c, and a structure near 2.6 GeV/c^2

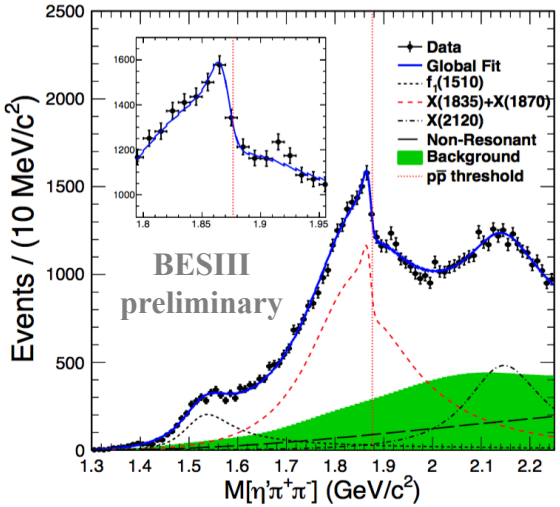


Significant distortion of the $\eta'\pi^-\pi^+$ line shape near the $p\bar{p}$ mass threshold

Connection between X(1835) and X(pp): Fit results







- Three efficiency-corrected Breit-Wigner functions
- Simple BW function fails in describing the $\eta'\pi^-\pi^+$ line shape near the threshold

MODEL 1

Threshold structure caused by the opening of additional decay mode

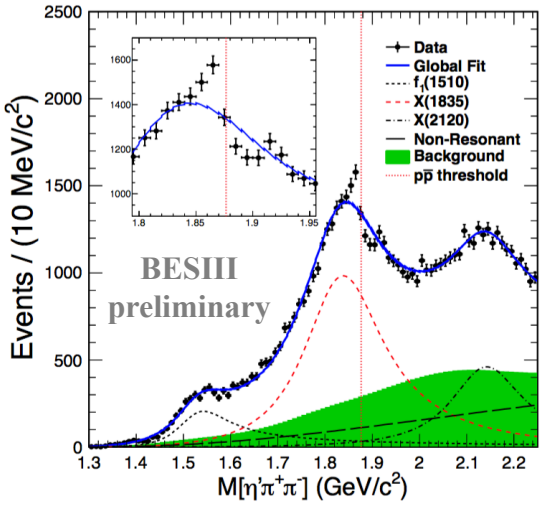
- Flatté formula for the shape (Phys.Lett.B**63**, 224)
- An additional BW resonance (X(1920)) is needed ($5.7\,\sigma$)

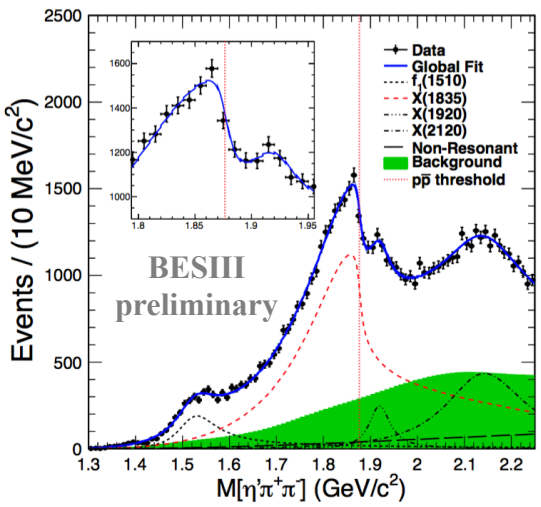
MODEL 2

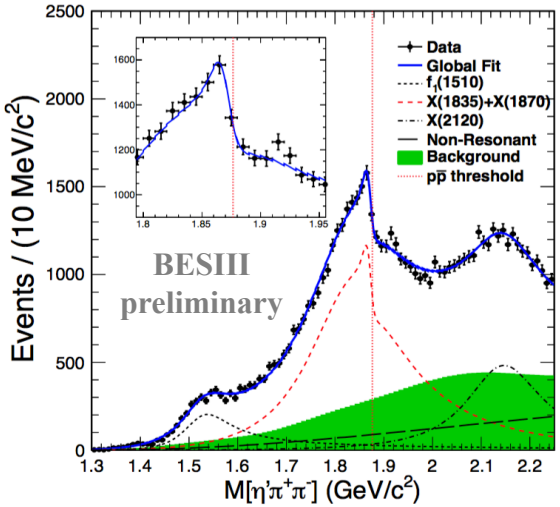
Interference between two resonances

- Use coherent sum of two BW amplitudes for the line shape: X(1835) and a narrow resonance called X(1870)
- X(1920) not significant

Connection between X(1835) and X(pp): Fit results

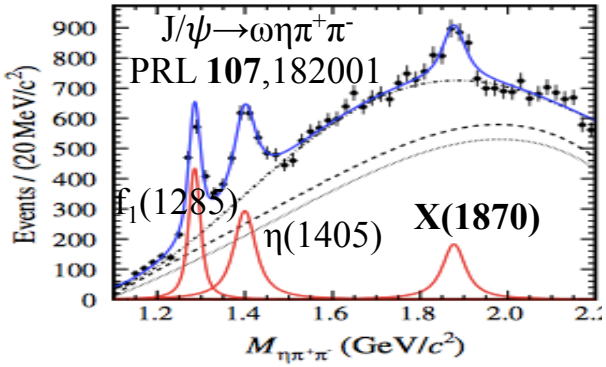


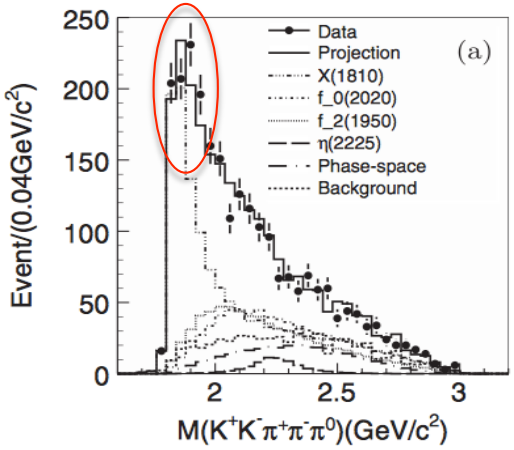




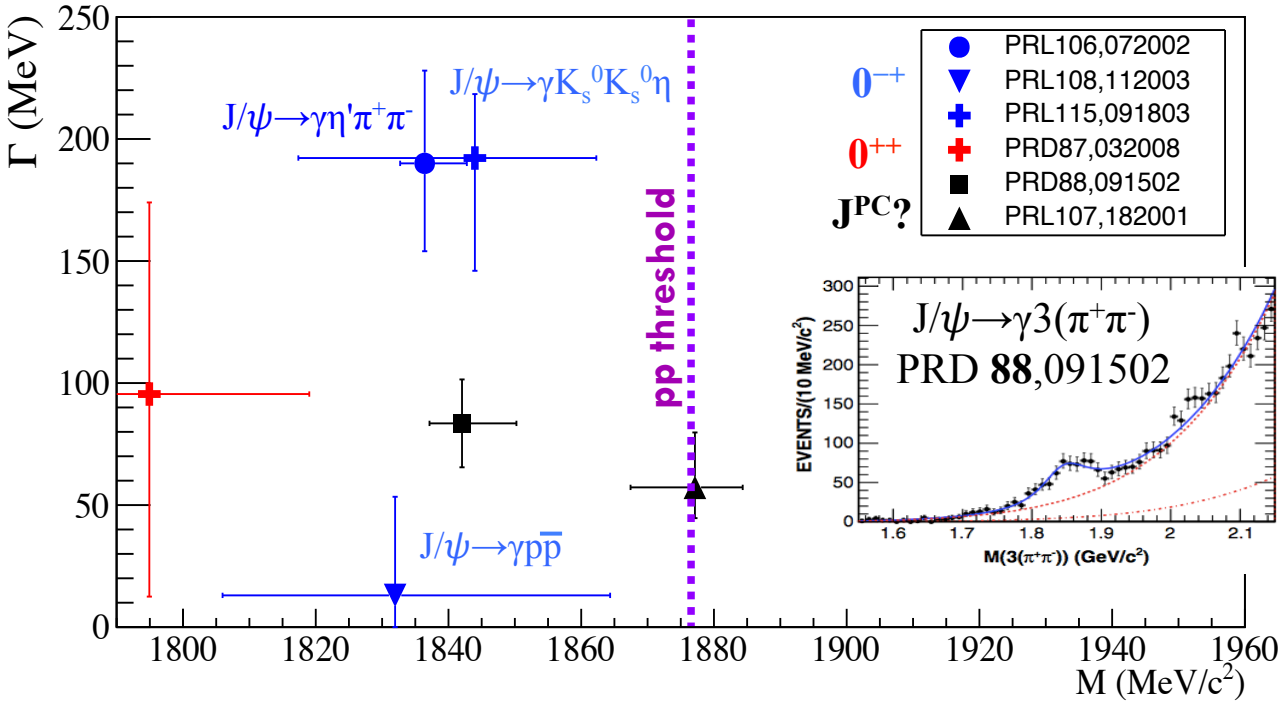
- The two models used to describe the data (Flatté and two interfering resonances) give almost equal fit quality
- MODEL 1: significance of $g_{pp}/g_0 > 0$ larger than $7\,\sigma$ (g_{pp}/g_0=ratio between the coupling strength to the $p\bar{p}$ channel and the summation of all the other channels)
- MODEL 2: significance for the X(1870) larger than $7\,\sigma$
- Both fits support the existence of one of
  - Broad state with strong coupling to $p\bar{p}$
  - Narrow state just below the $p\bar{p}$ mass threshold
- Study of the line shape for other decay modes, e.g. $\gamma\, p\bar{p}$, $\gamma\, K^0_S K^0_S\, \eta$ …

Other BESIII observations





J/ψ→γωϕ
PRD 87,032008
>30σ



X states near proton-antiproton threshold

- X(pp̄) in agreement with X(1835), while its width is significantly different
- **Are they the same particles?**
- **More studies are needed to answer this question**

XYZ States

Below DD threshold: all the states have been observed and described by the $c\bar{c}$ potential model

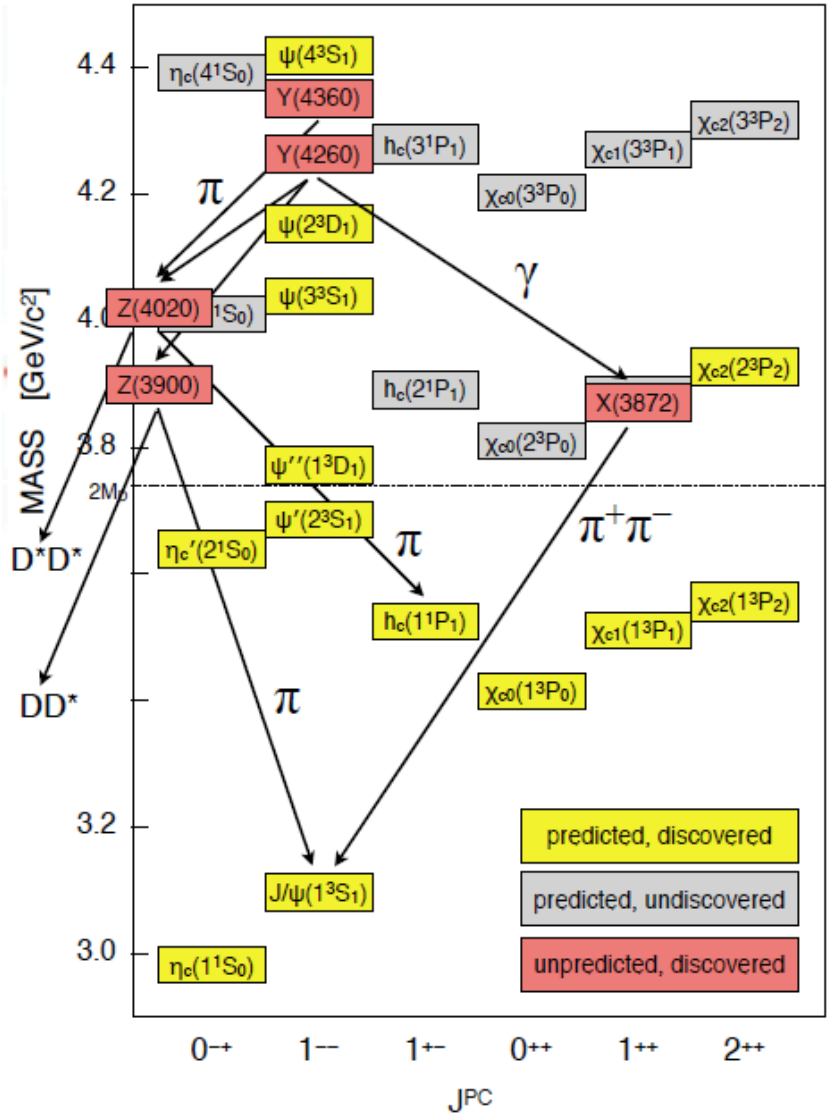
Above the threshold: more complex situation

- only a few of the predicted states above the threshold have been found
- Many new states have been observed with properties that are not consistent with the expectation for charmonium: X, Y, Z

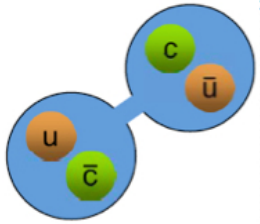
X states: charmonium-like states with $J^{PC} \neq 1^{--}$; Observed in B decays, proton-proton, and proton-antiproton collisions.

Y states: charmonium-like states with $J^{PC} = 1^{--}$; Observed in direct e^+e^- annihilation or initial state ration (ISR).

Z states: charmonium-like states **carrying electric charge**; must contain at least $c\bar{c}$ and a light $q\bar{q}$ pair



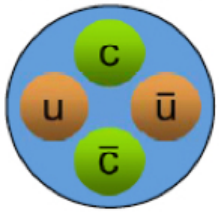
Nature of the XYZ states



Molecular state

Loosely bound state of a pair of mesons. The dominant binding mechanism should be pions exchange

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) …..



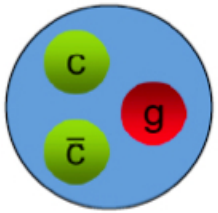
Tetraquark

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)
…

Bound state of four quarks, i.e. diquark-antidiquark

Distinctive feature of multi-quark picture with respect to charmonium:

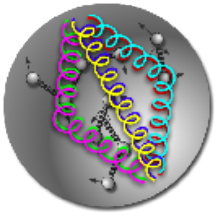
- Prediction of many new states
- Possible existence of new states with nonzero charge, strangeness, or both



Charmonium hybrids

Bound states with a pair of quarks and one excited gluon; Lattice and model predictions found that the lowest charmonium hybrids lies around 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)
…

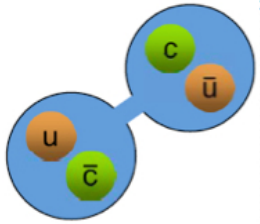


Glueball

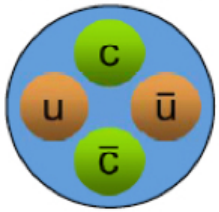
Bound states of gluons

Heavy quarkonium: progress, puzzles, and opportunities
N. Brambilla et. All, Eur.Phys.J.C71:1534,2011

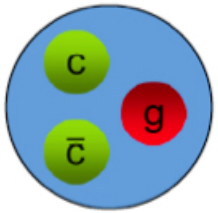
Nature of the XYZ states



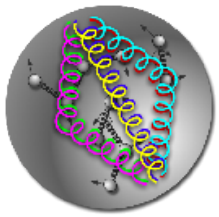
1) Establish the spectrum: search for more X, Y, and Z states, determine masses, widths, quantum numbers, and investigates the decays



2) Build connections: look for transitions between different states (i.e. radiative transitions)

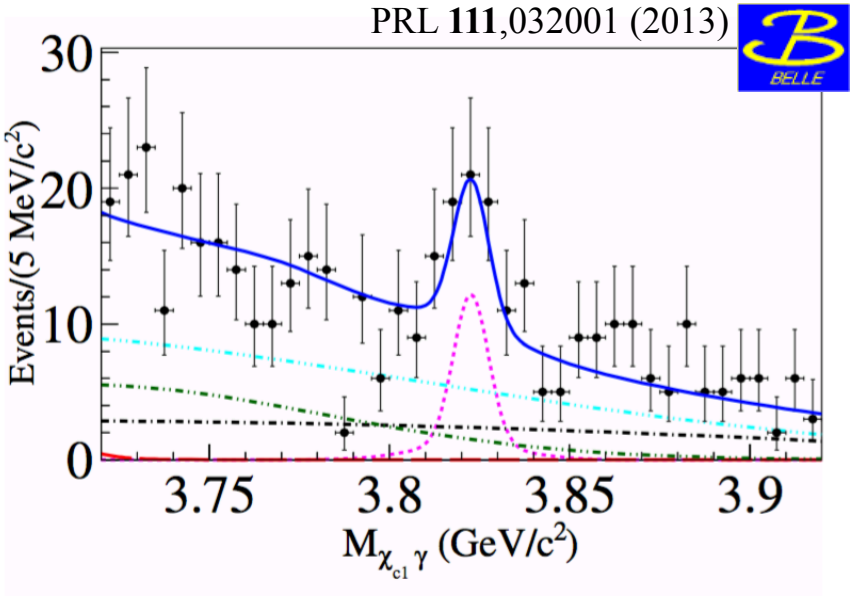


BESIII dedicated program started in 2012



Conventional $c\bar{c}$ state: X(3823)

- X(3823) first observed by Belle in $B^{\pm} \to K \gamma \chi_{c1}$
- 3.8 σ evidence
- Mass and width compatible with ψ_2 state (1^3D_2)
- E705 (PRD50,4258(1994)) report a candidate for the ψ_2 state with a significance of 2.8 σ



BESIII analysis uses 5 large data sets ($\mathcal{L}_{tot}$~4.7 fb^{-1}) at the center-of-mass energies 4.23, 4.26, 4.36, 4.42, 4.6 GeV

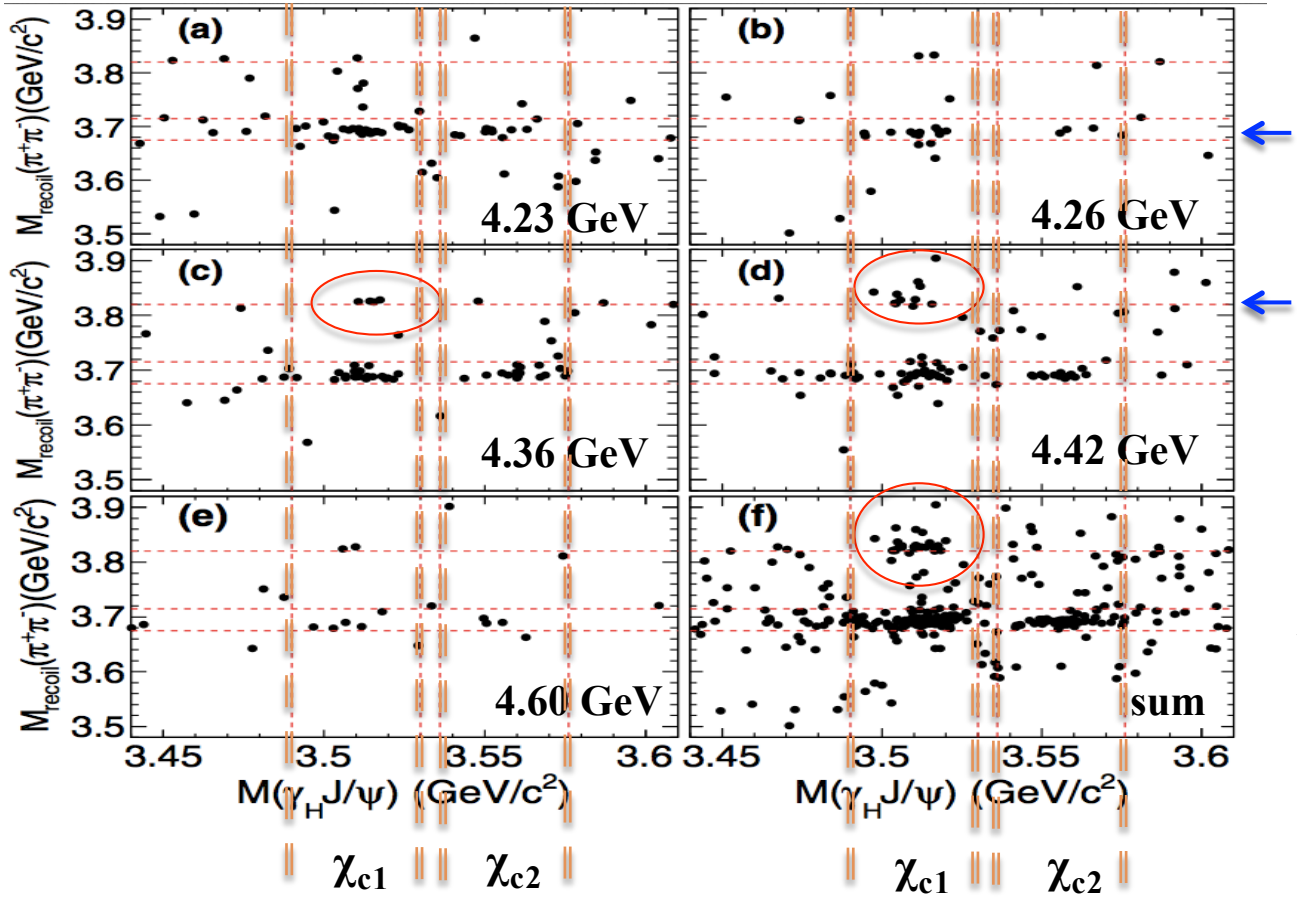
- Reconstructed in $\chi_{c1,c2} \to \gamma J/\psi \to \gamma \ell^+\ell^-$

BESII: PRL**115**,011803(2015)

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^- \gamma\chi_{c1}$

BESII: PRL**115**,011803(2015)

Two dimensional scatter plot is used to investigate the possible existence of resonances that may decay to $\chi_c\gamma$ states: $M_{reco}(\pi^+\pi^-)=\sqrt{(P_{e+e}-P_{\pi+}-P_{\pi-})^2}$ vs. $M(\gamma_H J/\psi)$, where γ_H refers to the higher energy photon



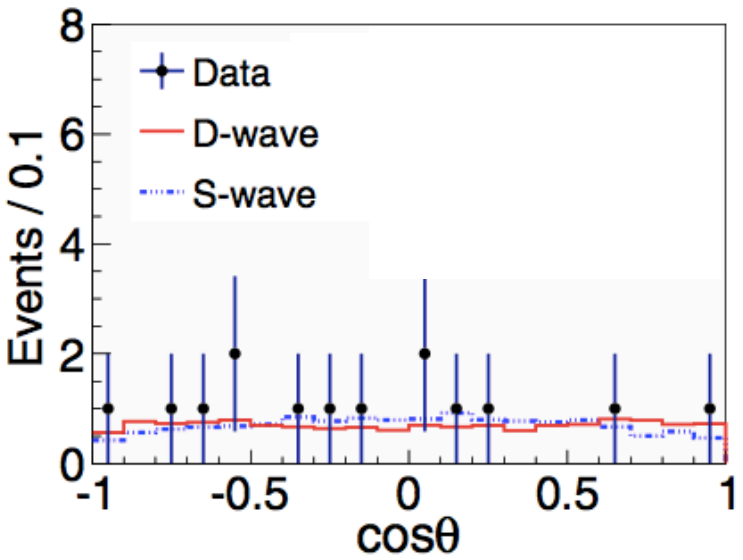
$e^+e^- \to \pi^+\pi^-\psi' \to \pi^+\pi^-\gamma\chi_c$ signals are evident in almost the data sets

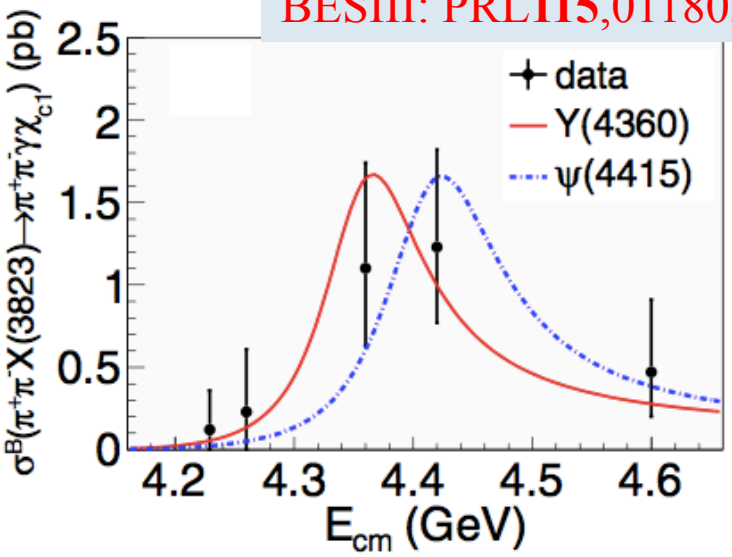
Accumulation near 3.82 GeV/c^2 are evident in the $\gamma\chi_{c1}$ signal region

Remaining backgrounds from $e^+e^- \to (\eta'/\gamma\omega)J/\psi$, with $\eta'/\omega \to \gamma\pi^+\pi^-$ or $\gamma\pi^+\pi^-$, and $\pi^+\pi^-\pi^+\pi^-$ ($\pi^0\gamma\gamma$)

$e^+e^- \to \pi^+\pi^- X(3823) \to \pi^+\pi^- \gamma \chi_{c1}$

BESIII: PRL**115**,011803(2015)





- M=3821.7 ± 1.3 ± 0.7 MeV/c^2 and Γ <16 MeV (90% C.L.)
- Significance = 6.2 σ ($\gamma\chi_{c1}$ channel)
- The X(3823) is a good candidate for the ψ_2 charmonium state with $J^{PC}=2^{--}$
  - assuming $\pi^+\pi^-$ system in S-wave ➔ $1+\cos^2\theta$ for spin 2
  - Mass and width are ~ agreement with potential model prediction for 1^3D_2
  - not enough statistics to distinguish between D- and S- wave hypothesis
- The fit of the energy-dependent cross section for the process is compatible with both Y(4360) and $\psi(4415)$ line shapes

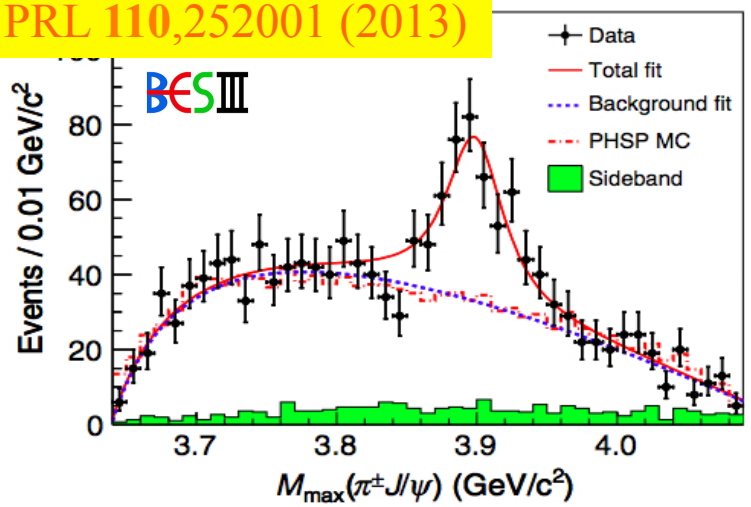
Discovery of $Z_c(3900)$

Study of the $e^+e^- \to \pi^+\pi^- J/\psi$ process at the c.m. energy of 4.26 GeV using 525 pb^{-1}

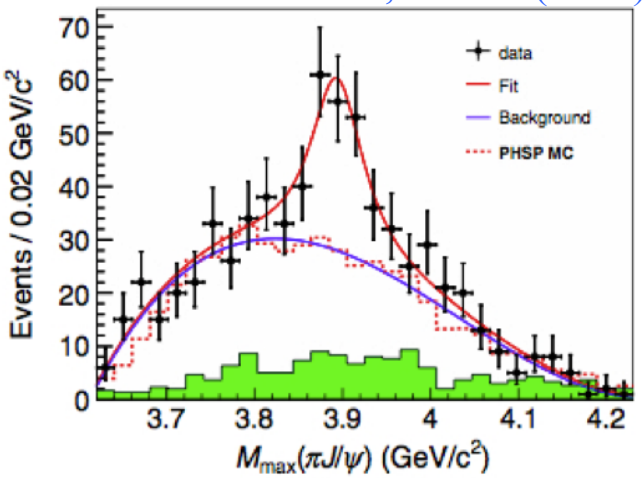
- Reflection effect removed by choosing the heavier J/ψ combination per event ($M_{max}(\pi^\pm J/\psi)$)
- Significance greater than **8 σ**
- **M = (3899.0 ± 3.6 ± 4.9) MeV/c^2 and Γ = (46 ± 10 ± 20) MeV**
- Mass very close to the DD^* threshold
- It couples to charmonium ($c\bar{c}$), has electric charge (contains ud) ➔ at least 4 quark

What is its nature?

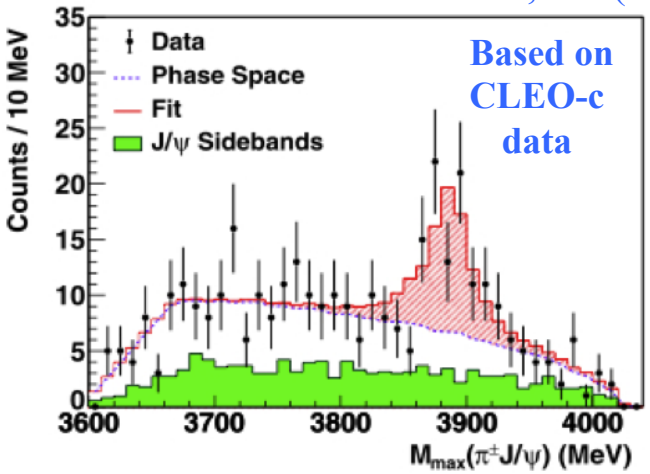
PRL 110,252001 (2013)



BELLE: PRL **110**,252002 (2013)



Northwestern Uni.: PLB **727**, 366(2013)



BELLE

$e^+e^- \to \gamma_{ISR} J/\psi\pi^+\pi^-$

M=(3894.5±6.6±4.5)MeV/c^2

Γ=(63±24±26) MeV

NWU (CLEO-c data)

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

$\sqrt{s}$=4.17 GeV

M=(3886±4±2)MeV/c^2

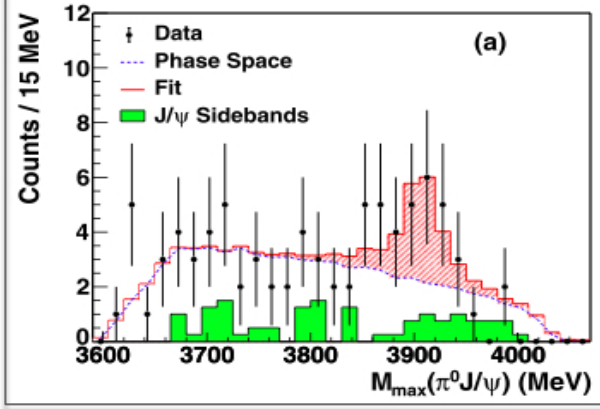
Γ=(37±4±8) MeV

Search for a neutral $Z_c(3900)$ isospin partner

Study of $e^+e^- \to \pi^0\pi^0 J/\psi$ process

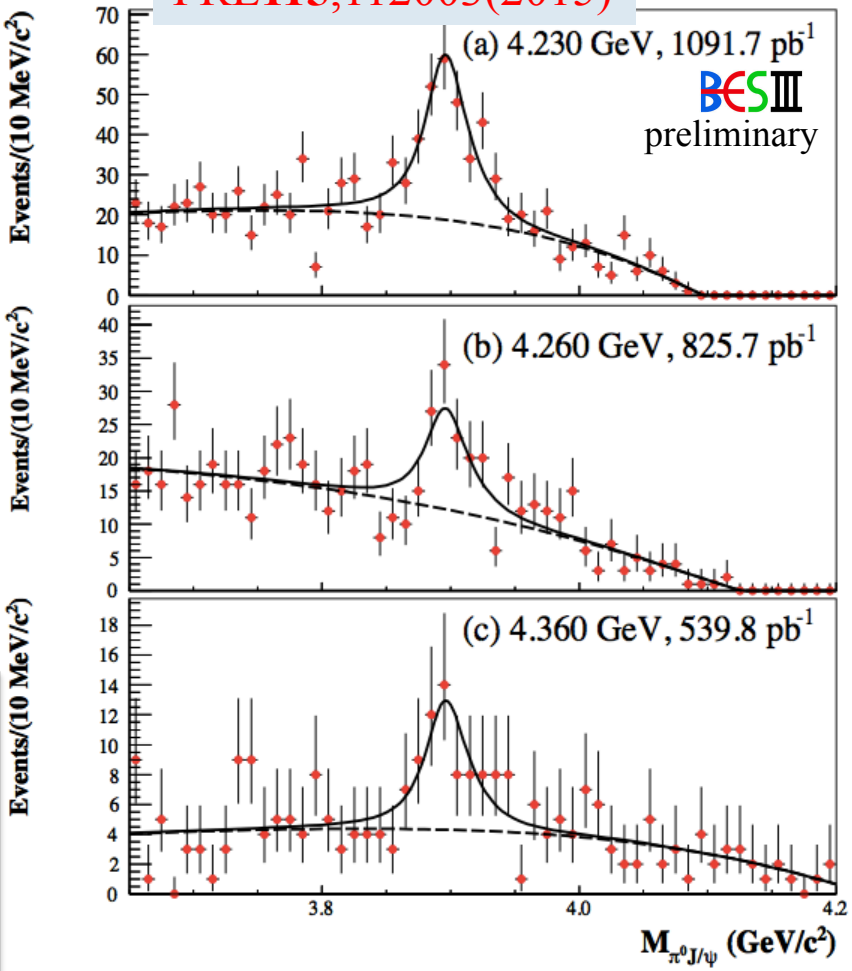
- Data sample of 2809.4 pb^{-1} distributed over the c.m. energy range from 4.190 to 4.420 GeV
- New structure ($Z_c(3900)^0$) observed in the $\pi^0 J/\psi$ mass spectra
- **Isospin triplet established:** the measured Born cross sections are about half of those for $e^+e^- \to \pi^+\pi^- J/\psi$ [PRL**110**,252002], consistent with isospin symmetry expectation

NWU, based on CLEO-c data: PLB 727, 366 (2013)



First evidence:
M = 3904±10 MeV/c^2
Γ = 37 MeV (fixed)
Significance 3.5 σ

PRL**115**,112003(2015)

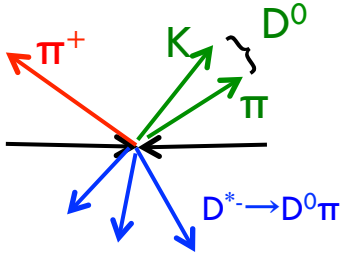


M = (3894.8 ± 2.3 ± 3.2) MeV/c^2
Γ = (29.6± 8.2 ± 8.2) MeV
Significance >10 σ

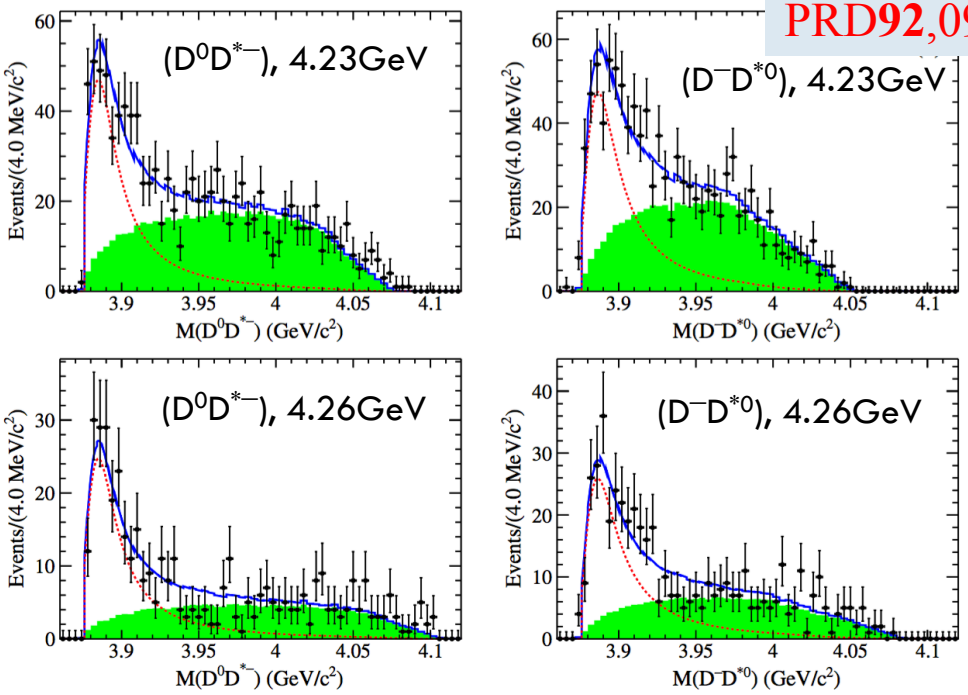
$Z_c(3885)^{\pm}$ in $e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$

The $Z_c(3900)$ lies close to the DD* threshold ➔ it is interesting to investigate this region

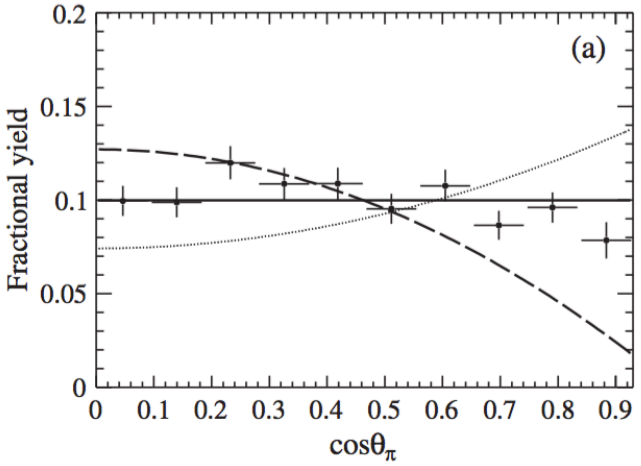
- $\mathcal{L}$~1092 pb^{-1} @ 4.23 GeV and ~826 pb^{-1} @ 4.26 GeV
- **Double tag method: reconstruction of the bachelor π and D pair**



PRD**92**,092006(2015)



- The data agree well with $J^P=1^+$ quantum numbers



$M_{pole} = (3881.7 \pm 1.6 \pm 1.6)$ MeV/c^2 $\Gamma_{pole} = (26.6 \pm 2.0 \pm 2.1)$ MeV

$\sigma \times \mathcal{B} = (108.4 \pm 6.9 \pm 8.8)$ pb

Significance >10σ

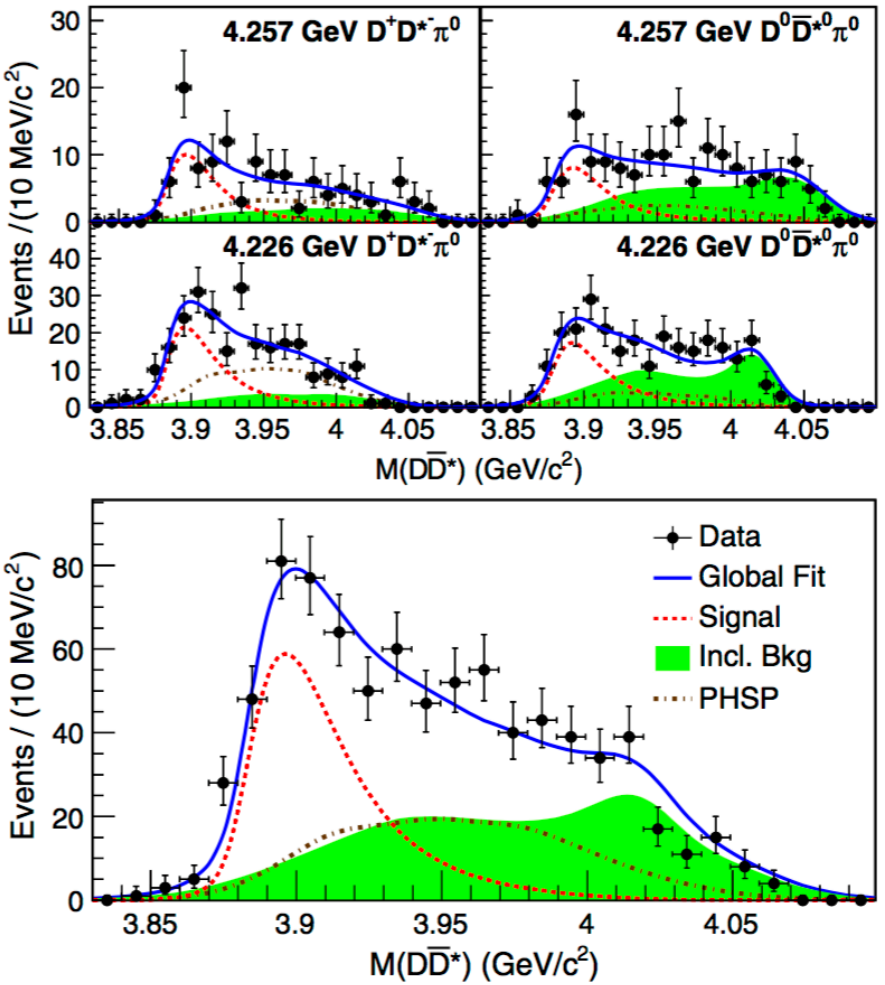
$Z_c(3885)^0$ in $e^+e^- \to (D\bar{D}^*)^0\pi^0$

- $\mathcal{L}$~1092 pb^{-1} @ 4.23 GeV and ~826 pb^{-1} @ 4.26 GeV
- Simultaneous fit to both charge combinations in the two datasets
- Significance $> 10\,\sigma$
- Pole parameters of the relativistic BW extracted **(c)**

State	$m_{\rm pole}(\mathrm{MeV}/c^2)$	$\Gamma_{\rm pole}(\mathrm{MeV})$	
$Z_c(3885)^+$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$	**(a)**
$Z_c(3885)^+$	$3881.7 \pm 1.6 \pm 2.1$	$26.6 \pm 2.0 \pm 2.3$	**(b)**
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	**(c)**

- Born cross section consistent with half of the charged channel
- Favours the assumption that $Z_c(3885)^0$ is the neutral isospin partner of $Z_c(3885)^+$

PRL**115**,222002(2015)



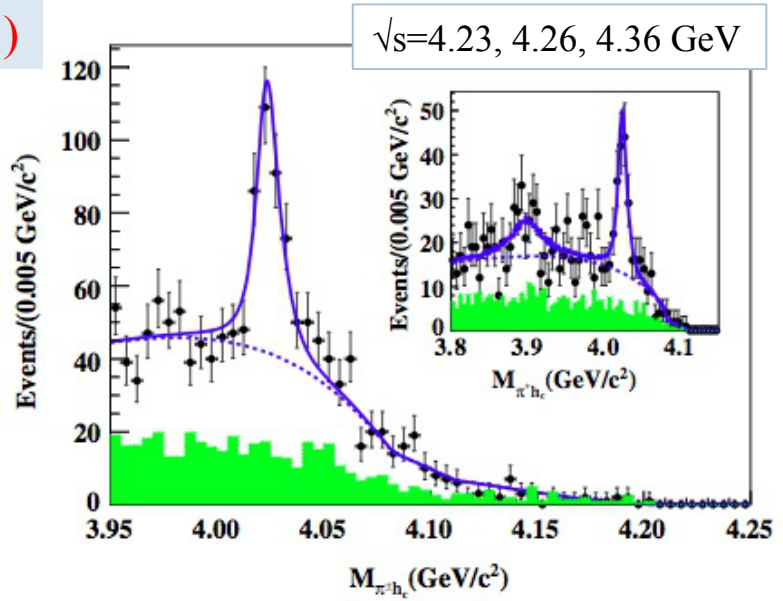
(a) PRL**112**,022001(2014)
(b) PRD**92**,092006 (2015)

$Z_c(4020)^{\pm,0}$: study of $e^+e^- \to h_c\pi^+\pi^-$, and $h_c\pi^0\pi^0$

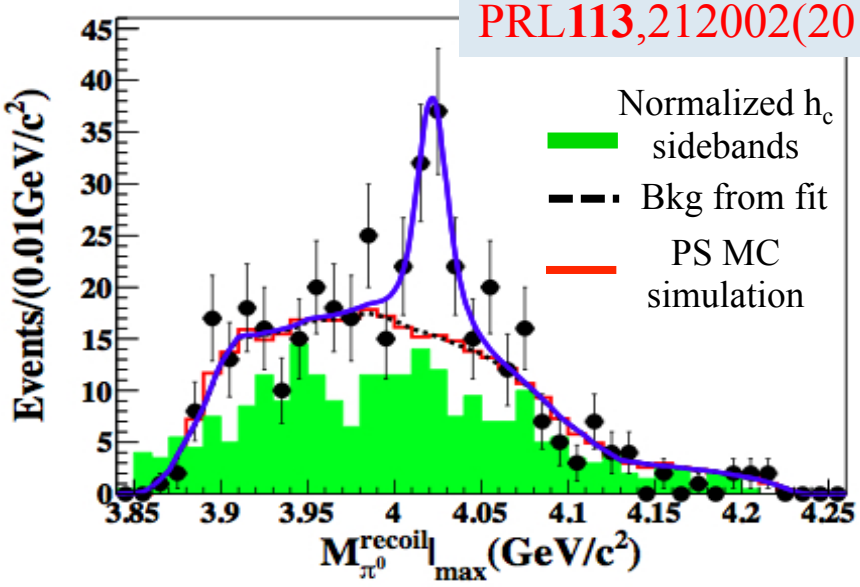
PRL**111**,242001(2013)

- 13 center-of-mass energies from 3.9 to 4.42 GeV
- Reconstruction of $h_c \to \gamma\ \eta_c$ including 16 exclusive hadonic η_c decay modes
- Narrow state very close to the $(D^*\bar{D}^*)^{\pm}$ threshold

- $M = (4022.9 \pm 0.8 \pm 2.7)$ MeV/c^2
- $\Gamma = (7.9 \pm 2.7 \pm 2.6)$ MeV
- Significance $>8.9\,\sigma$
- Significance of $2.1\,\sigma$ for $Z_c(3900)^+$



PRL**113**,212002(2014)



- √s=4.23, 4.26, and 4.36 GeV
- 16 exclusive hadonic η_c decay modes

- $M = (4023.9 \pm 2.2 \pm 3.8)$ MeV/c^2
- Γ = fixed to be the same as its charged partner
- Significance $>5\,\sigma$

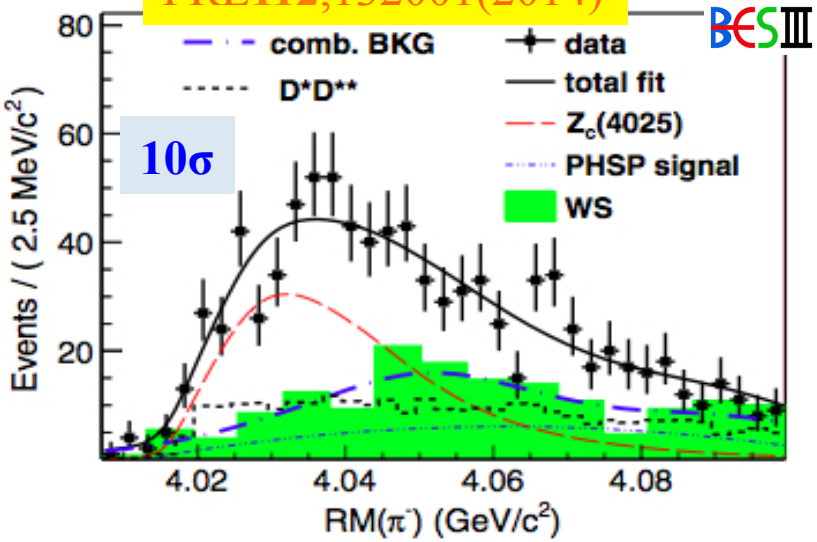
- Ratios of Born cross section for neutral and charged modes agree with isospin symmetry

Another isospin triplet is established!

$Z_c(4025)^{\pm,0}$: study of $(D^*\bar{D}^*)^{\pm 0}$ system

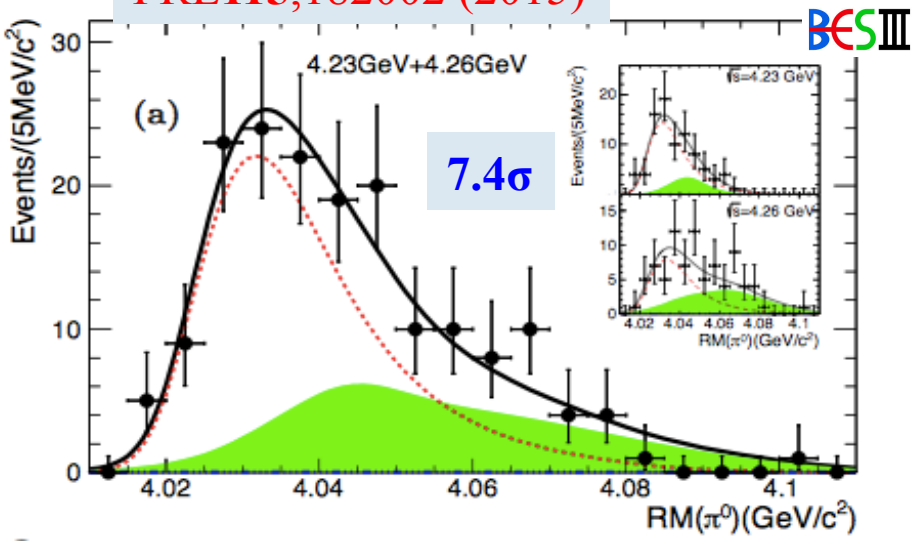
- Study the $e^+e^- \to D^{*+}\bar{D}^{*0}\pi^-$ and $D^{*-}\bar{D}^{*0}\pi^+$ at $\sqrt{s}$=4.26 GeV (827 pb^{-1}), and $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$ at $\sqrt{s}$=4.26 GeV (827 pb^{-1}) and at $\sqrt{s}$=4.23 GeV (1092 pb^{-1})
- Partial reconstruction technique: bachelor pion and one $D^{*\pm}$ reconstruction
- Fit to the π recoiling mass spectra

PRL**112**,132001(2014)



$Z_c(4025)^{\pm}$: $M = (4026.3 \pm 2.6 \pm 3.7)$ MeV/c^2
$\Gamma = (24.8 \pm 5.6 \pm 7.7)$ MeV

PRL**115**,182002 (2015)



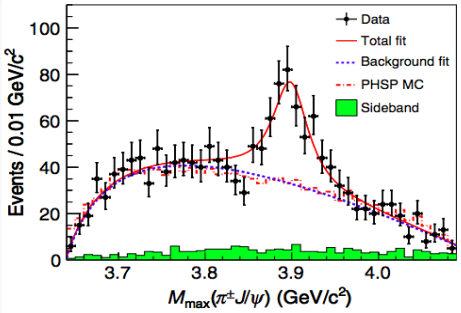
$Z_c(4025)^0$: $M = (4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c^2
$\Gamma = (23.0 \pm 6.0 \pm 1.0)$ MeV

- Enhancement cannot be explained by three-body non-resonant processes
- $Z_c(4025)^0$ is a good candidate to be the isospin partner of $Z_c(4025)^{\pm}$
- Parameter very similar to $Z_c(4020)$ ➔ needed rigorous spin analysis

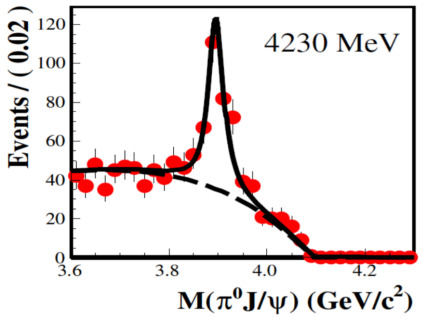
Summary: all Z_cs from BESIII

$e^+e^- \to \pi^{+(0)}\pi^{-(0)}J/\psi$

$Z_c(3900)^\pm$

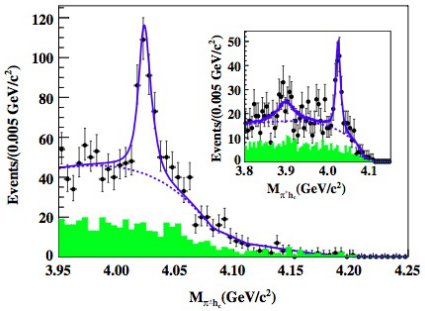


$Z_c(3900)^0$

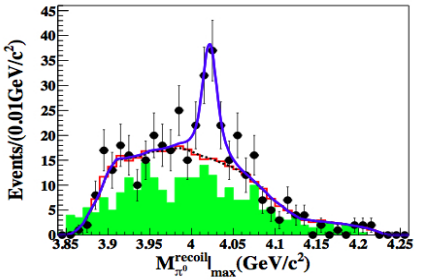


$e^+e^- \to \pi^{+(0)}\pi^{-(0)}h_c$

$Z_c(4020)^\pm$

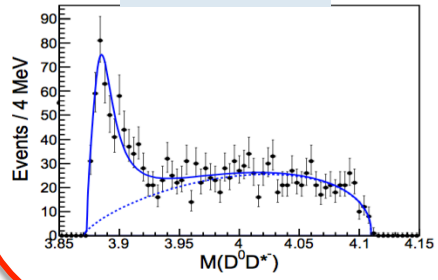


$Z_c(4020)^0$

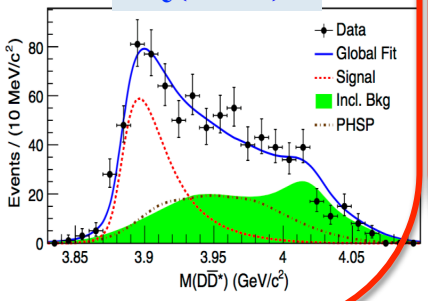


$e^+e^- \to (D\bar{D}^*)^{\pm(0)}\pi^{\mp(0)}$

$Z_c(3885)^\pm$

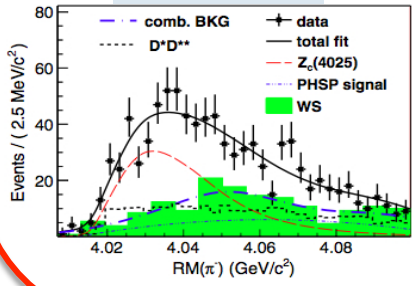


$Z_c(3885)^0$

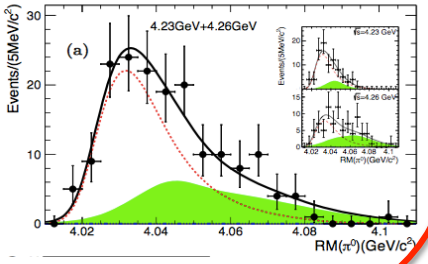


$e^+e^- \to (D^*\bar{D}^*)^{\pm(0)}\pi^{\mp(0)}$

$Z_c(4025)^\pm$



$Z_c(4025)^0$



- Nature of these states? Isospin triplets?
- Different decay channels of the same states observed?
- Other decay modes?

Conclusions

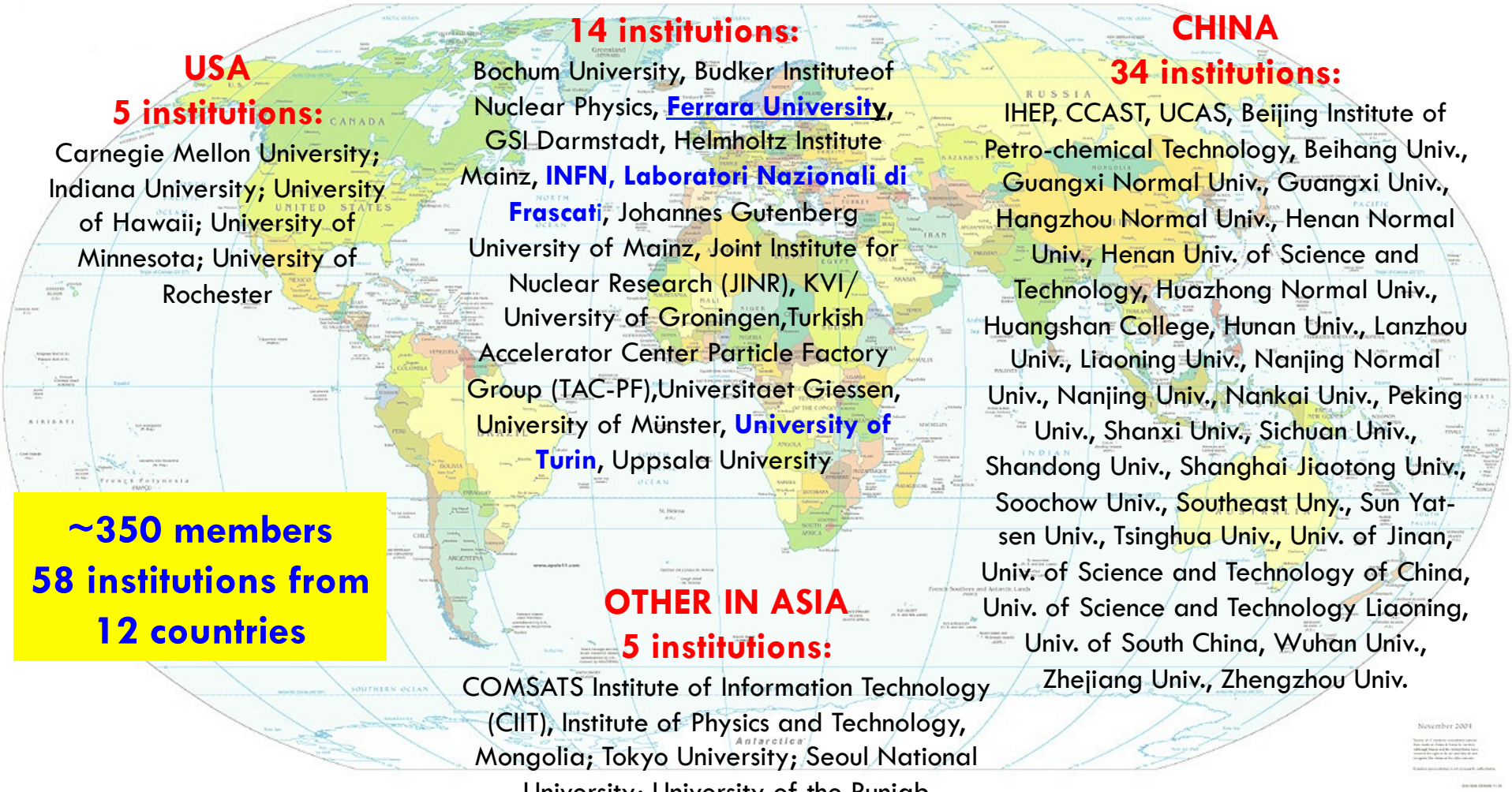
- BESIII is successfully operating since 2008, and continues to take data
- Excellent laboratory to study hadron spectroscopy, complementary to scattering and photo production experiments
  - High statistics
  - Low backgrounds
- Many interesting results have been obtained, and only a small part are covered in this talk
- A lot of work must be done
  - Clarify the nature of the XYZ states
  - Observation of transition between these states
  - More detailed studies: PWA, other decay modes, …

FUTURE

- More data will be collected
- Higher luminosity expected from BEPCII
- More detailed studies will be done

Back-up slides

The BESIII Collaboration



USA
5 institutions:

Carnegie Mellon University; Indiana University; University of Hawaii; University of Minnesota; University of Rochester

EUROPE
14 institutions:

Bochum University, Budker Instituteof Nuclear Physics, Ferrara University, GSI Darmstadt, Helmholtz Institute Mainz, INFN, Laboratori Nazionali di Frascati, Johannes Gutenberg University of Mainz, Joint Institute for Nuclear Research (JINR), KVI/ University of Groningen,Turkish Accelerator Center Particle Factory Group (TAC-PF),Universitaet Giessen, University of Münster, University of Turin, Uppsala University

CHINA
34 institutions:

IHEP, CCAST, UCAS, Beijing Institute of Petro-chemical Technology, Beihang Univ., Guangxi Normal Univ., Guangxi Univ., Hangzhou Normal Univ., Henan Normal Univ., Henan Univ. of Science and Technology, Huazhong Normal Univ., Huangshan College, Hunan Univ., Lanzhou Univ., Liaoning Univ., Nanjing Normal Univ., Nanjing Univ., Nankai Univ., Peking Univ., Shanxi Univ., Sichuan Univ., Shandong Univ., Shanghai Jiaotong Univ., Soochow Univ., Southeast Uny., Sun Yat-sen Univ., Tsinghua Univ., Univ. of Jinan, Univ. of Science and Technology of China, Univ. of Science and Technology Liaoning, Univ. of South China, Wuhan Univ., Zhejiang Univ., Zhengzhou Univ.

OTHER IN ASIA
5 institutions:

COMSATS Institute of Information Technology (CIIT), Institute of Physics and Technology, Mongolia; Tokyo University; Seoul National University; University of the Punjab

~350 members
58 institutions from 12 countries

http://bes3.ihep.ac.cn

BESIII physics programme

Light hadron physics

- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- two-photon physics
- Form factors

XYZ meson physics

- Y(4260), Y(4360) properties
- $Z_c(3900)^+$, …

QCD and τ

- Precision R measurement
- τ decay

Charm physics

- Semi-leptonic form factors
- Decay constants f_D and f_{Ds}
- CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
- D^0-$\overline{D}^0$ mixing, CPV
- Strong phases

Charmonium physics

- Precision spectroscopy
- Transitions and decays

Precision mass measurements

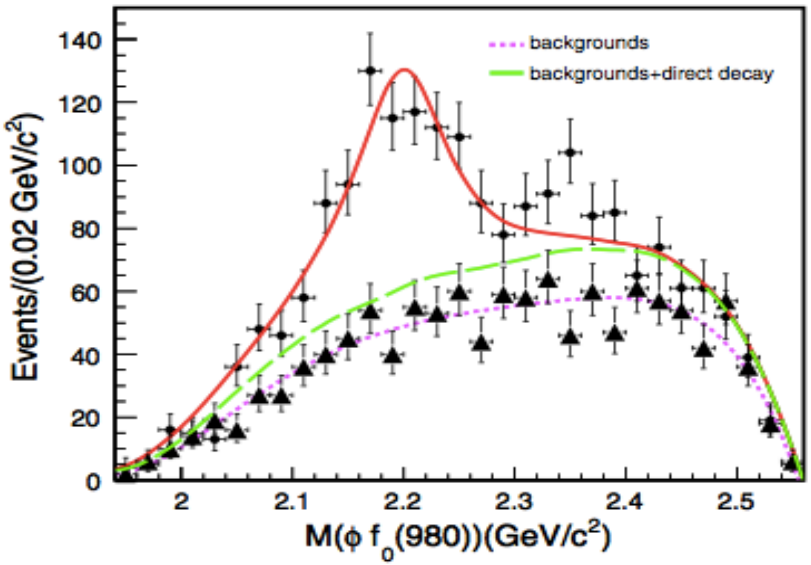
- τ mass
- D, D^* mass

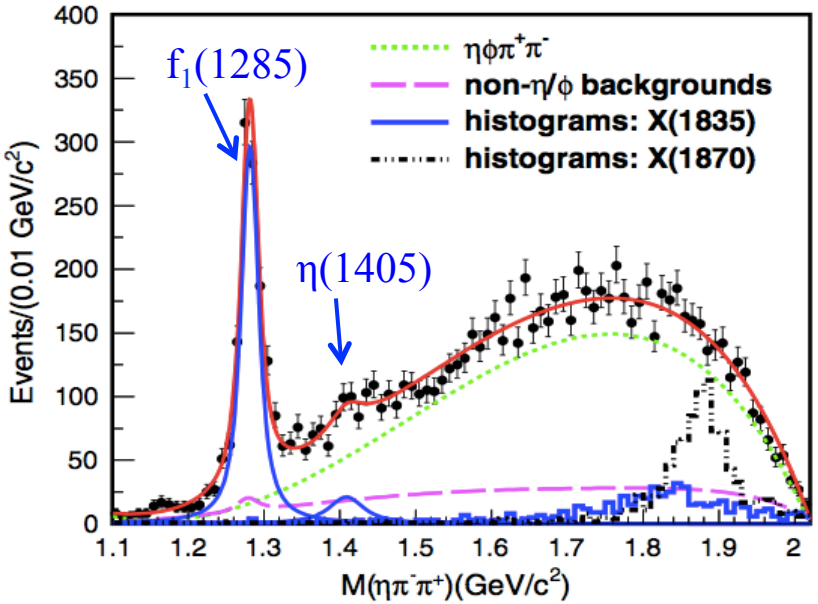
Study of $J/\psi \to \eta \phi \pi^+ \pi^-$

BESIII: PRD**91**,052017

- Study based on 2.25×108 J/ψ events
- Unbinned maximum likelihood fit is performed to the $\phi f_0(980)$ invariant mass distribution
- No interference between Y(2175) and direct three-body decay of $J/\psi \to \eta \phi f_0(980)$
- Y(2175) resonance observed with a significance greater than **10** σ

$M=2200 \pm 6 \pm 5$ MeV/c^2, $\Gamma = 104 \pm 15 \pm 15$ MeV





ηππ mass spectrum recoiling against the ϕ:

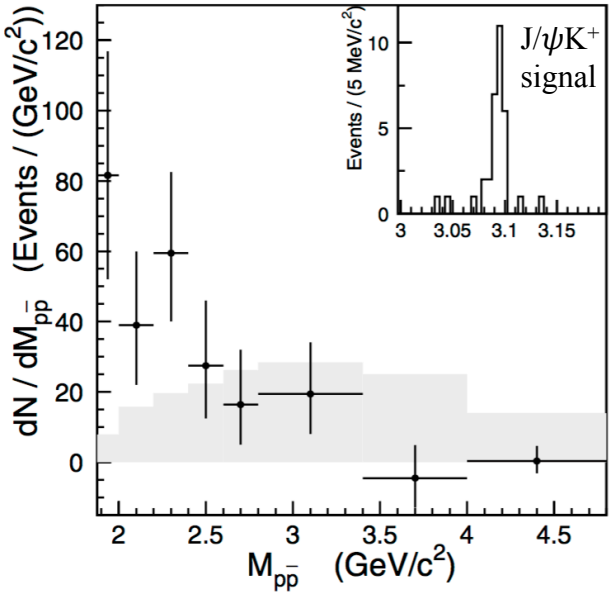
- Fit includes contributions from the $f_1(1285)$ and η(1405) signals, the $J/\psi \to \eta \phi \pi\pi$ decay, and backgrounds from non-η and non-ϕ processes
- No evidence of X(1835) and X(1870) states

$\mathcal{B}(J/\psi \to \phi f_1 \to \phi \eta \pi\pi) = (1.20 \pm 0.06 \pm 0.14) \times 10^{-4}$

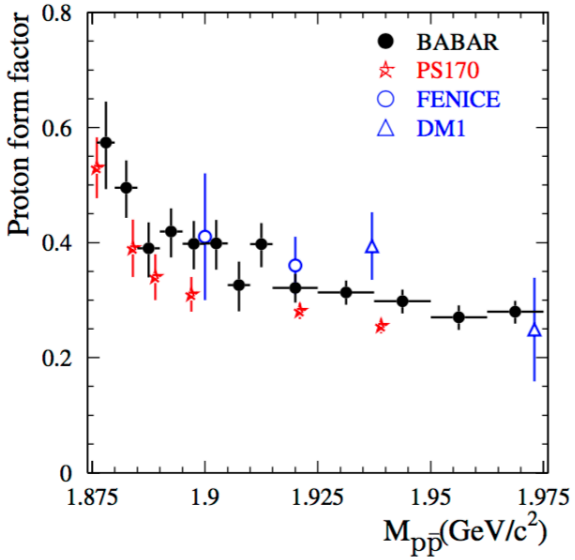
$\mathcal{B}(J/\psi \to \phi \eta(1405) \to \phi \eta \pi\pi) = (2.01 \pm 0.58 \pm 0.82) \times 10^{-5}$

ppbar enhancement in other reactions

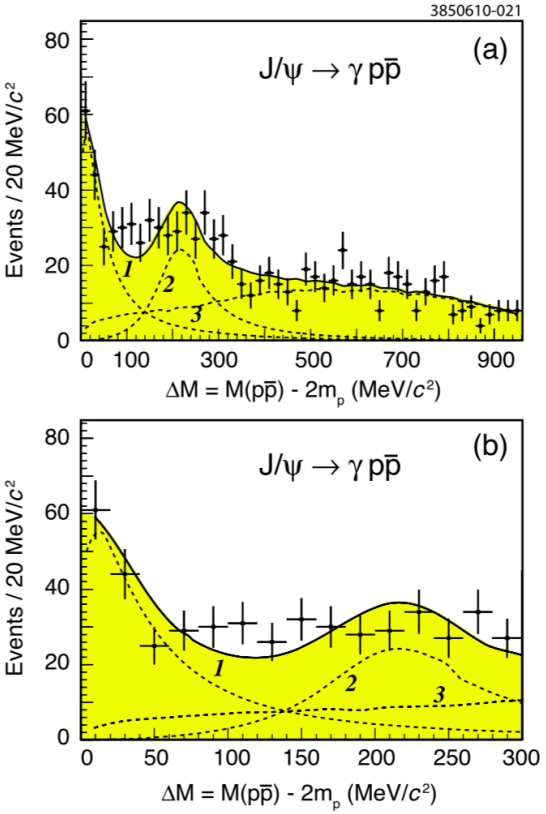
Belle: PRL**88**, 181803
$B^+ \to p\bar{p}K^+$



BaBar: PRD**73**, 012005
$e^+e^- \to \gamma p\bar{p}$ar

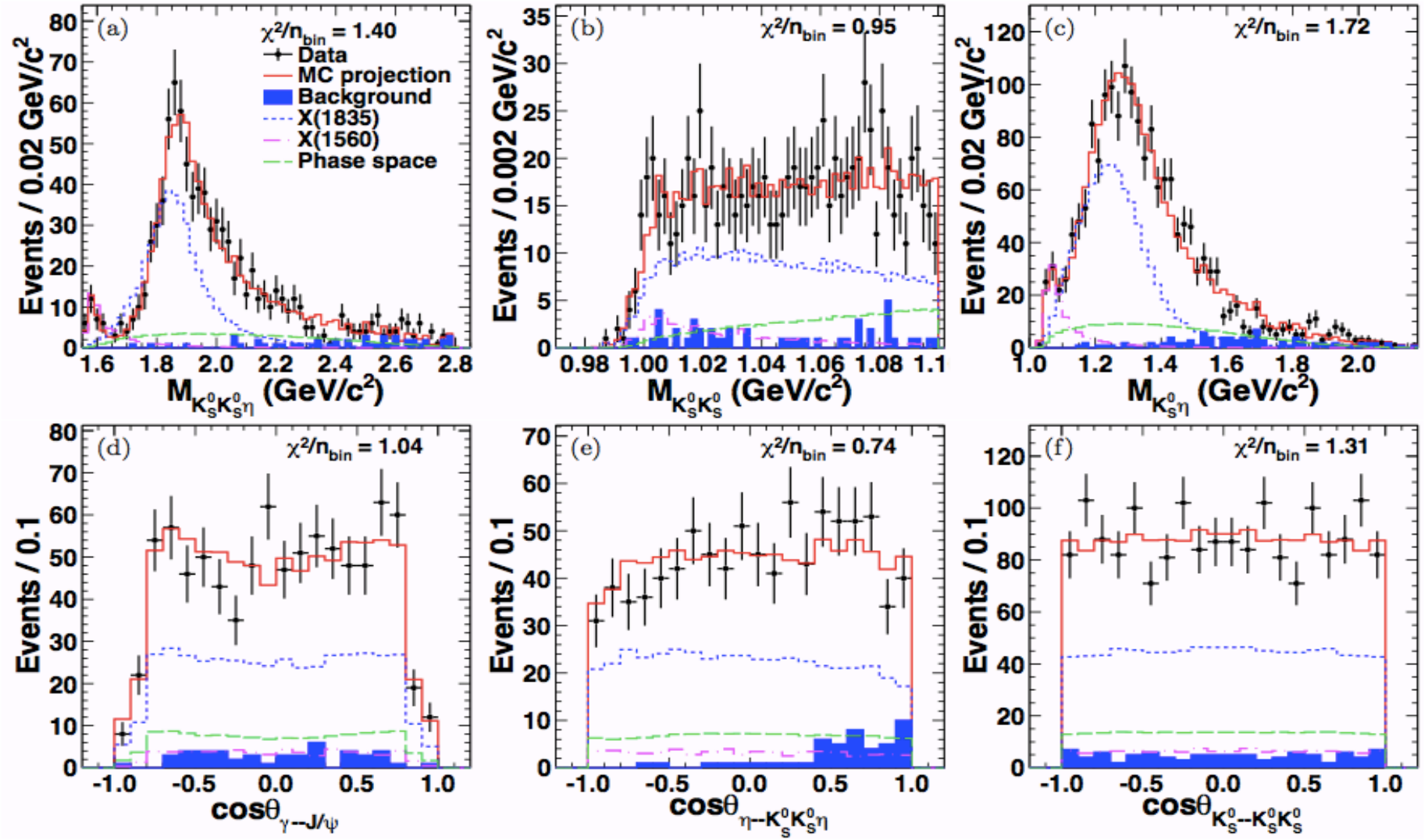


CLEO: PRD**82**, 092002
$\psi' \to \pi^+\pi^- J/\psi$



- Enhancement also seen in other B decays
- FSI? Sub-threshold resonance?
- Not enough statistic to draw any conclusion

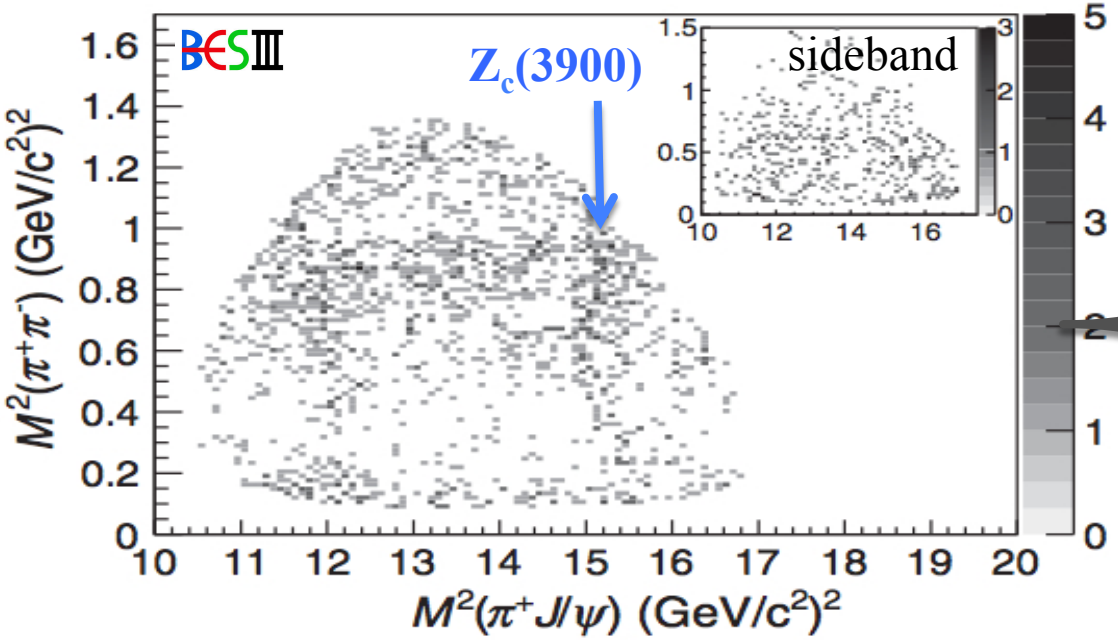
$J/\psi \to \gamma K_S^0 K_S^0 \eta$: PWA results



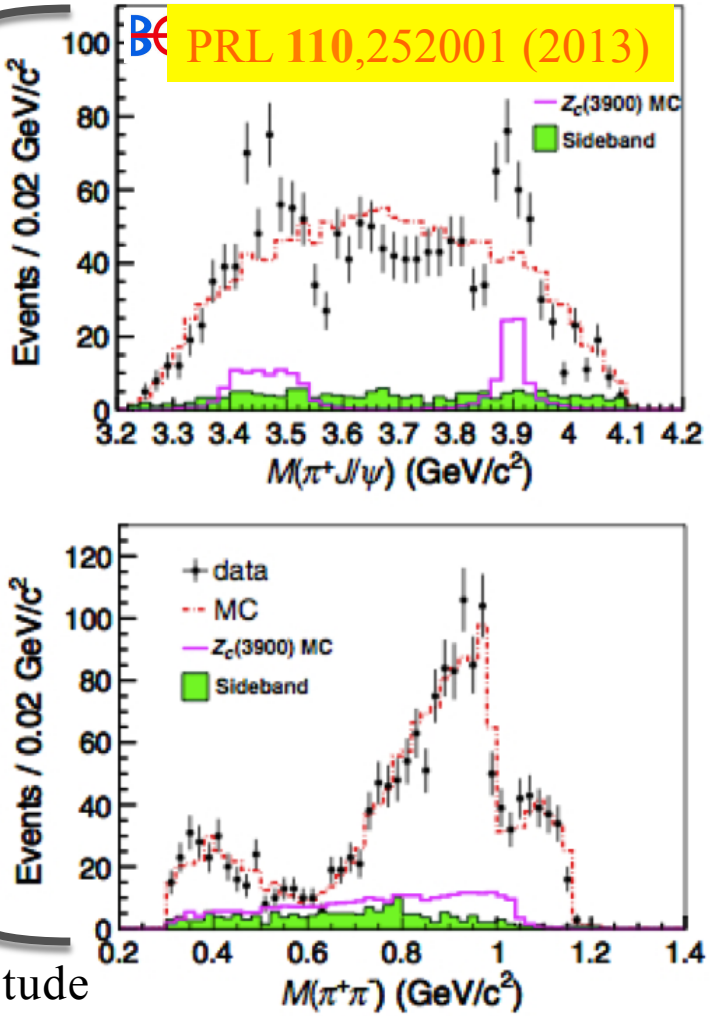
Discovery of $Z_c(3900)$

Study of the $e^+e^- \to \pi^+\pi^- J/\psi$ process at the c.m. energy of 4.26 GeV using 525 pb^{-1}

- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb
- Study the substructures in the $Y(4260) \to \pi^+\pi^- J/\psi$
  - Dalitz plot analysis: structures in the $\pi^+\pi^-$ and $J/\psi\pi^+$ systems



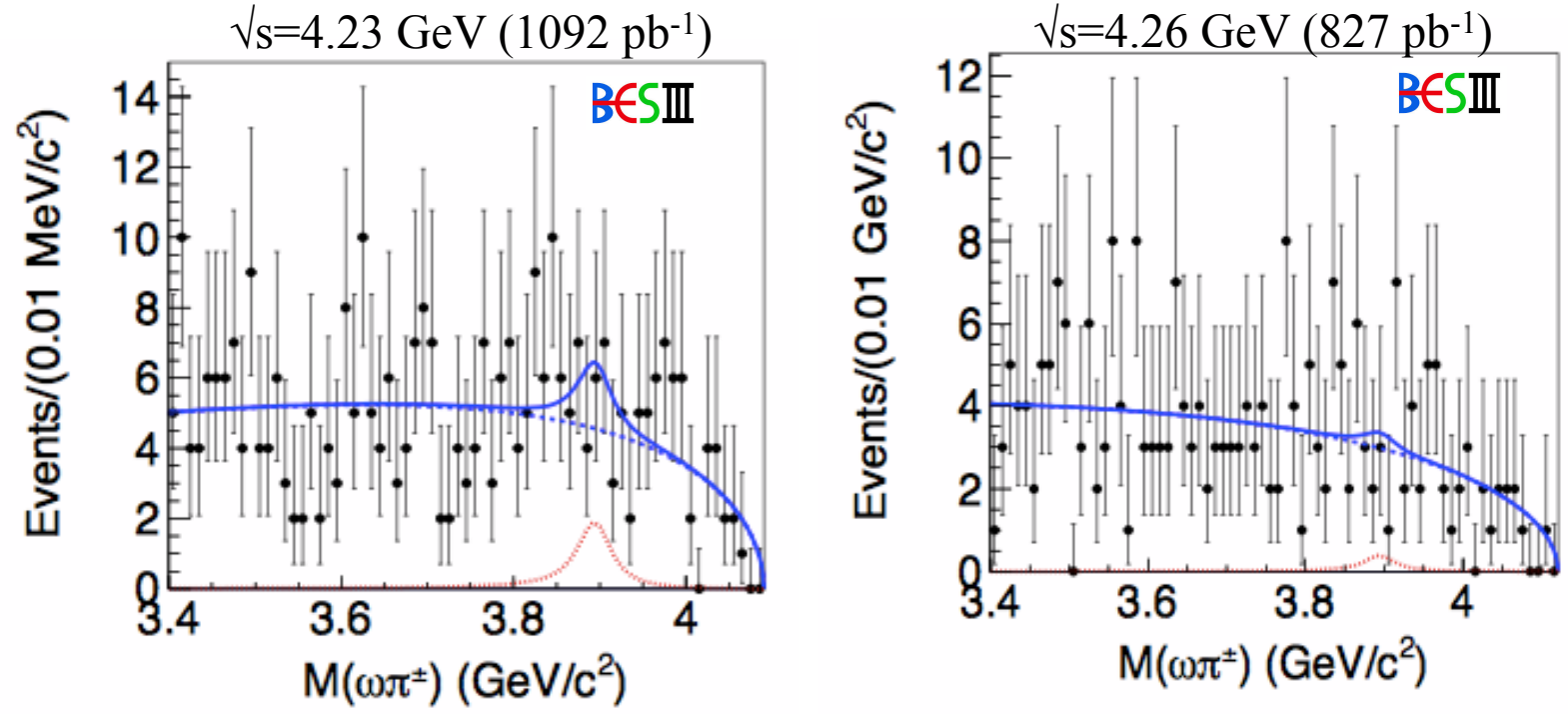
PRL 110,252001 (2013)



MC includes $\sigma(500)$, $f_0(980)$, and non-resonant $\pi^+\pi^-$ amplitude

Search of $Z_c(3900) \to \omega\pi$ in $e^+e^- \to \omega\pi^+\pi^-$

BESIII, PRD **92**, 032009 (2015)



No $Z_c(3900)$ signal is observed

- As $\pi\omega$ is a typical light hadron decay mode, the non-observation of this decay mode may indicates that the annihilation of ccbar in $Z_c(3900)^{\pm}$ is suppressed

Y states: $e^+e^- \to \eta J/\psi$

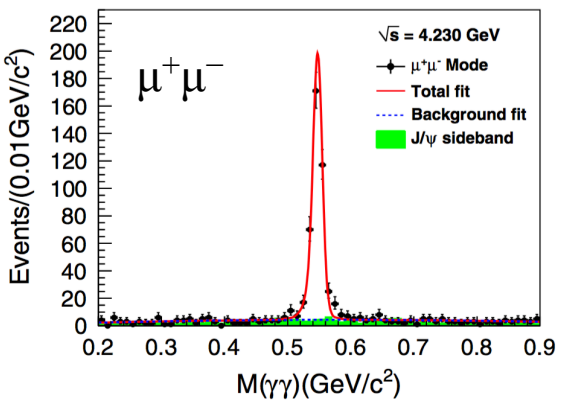
PRD**91**,112005(2015)

Several non conventional charmoniumlike Y states have been observed in recent years

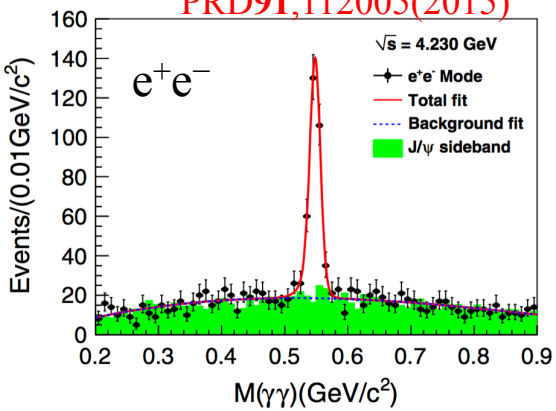
- The study of hadronic transitions to J/ψ allows to probe their properties
- BESIII analysis: $e^+e^- \to \eta(\pi^0)J/\psi$ from 3.81 to 4.60 GeV (17 c.m. points)

Clear η signal observed (no significant for π^0)

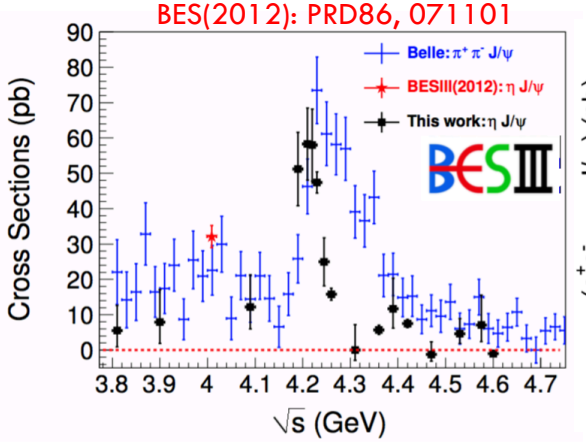
- Unbinned maximum likelihood fit
- Signal: signal MC shape ⊗ Gaussian function
- BKG: 2th-order Chebishev



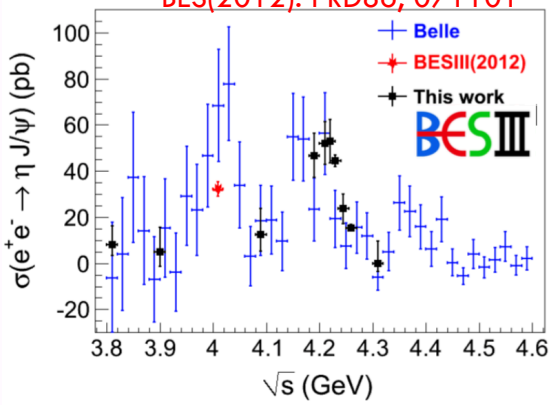
PRD**91**,112005(2015)



Belle: PRL99, 182004
BES(2012): PRD86, 071101



Belle: PRL99, 182004
BES(2012): PRD86, 071101



- Good agreement with Belle $\gamma_{ISR}\eta J/\psi$
- Better precision
- Cross section peaks around 4.2 GeV
- Different shape if compared to Belle $\pi^-\pi^+ J/\psi$ data
- Different dynamic at work in $e^+e^- \to \eta J/\psi$ and $e^+e^- \to \pi^-\pi^+ J/\psi$

$Z_c(3885)$: study of $(D\bar{D}^*)^{\pm}$ system

PRL112,022001(2014)

The $Z_c(3900)$ mass is 24 MeV/c^2 above the $D\bar{D}^*$ mass threshold

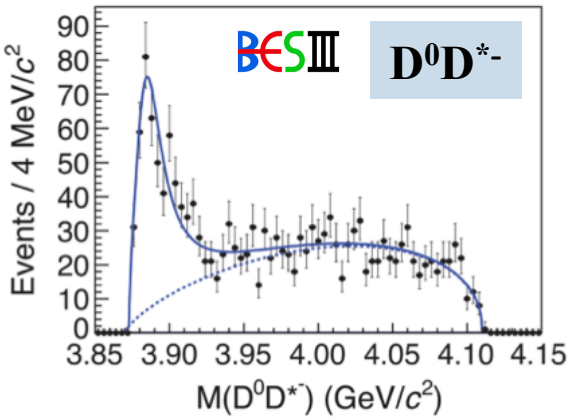
- Study the $e^+e^- \to D^0D^{*-}\pi^+$ and $D^+D^{*0}\pi^-$ at $\sqrt{s}$=4.26 GeV (525 pb^{-1})
- Partial reconstruction technique: detection of the bachelor $\pi^{\pm}$ and one D-meson final state ($D^0 \to K\pi$ and $D^+ \to K^-\pi^+\pi^+$)
- Presence of D^* inferred from energy momentum conservation

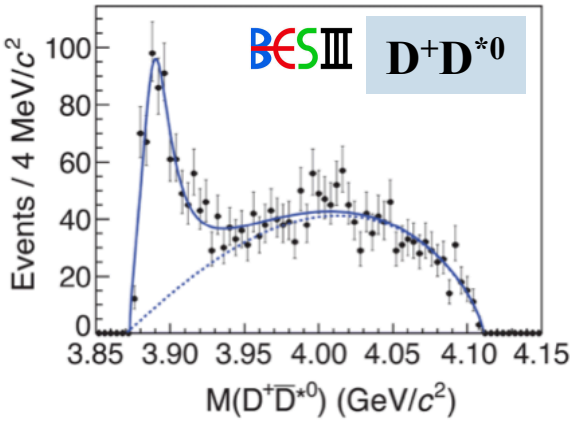
$M = (3883.9 \pm 1.5 \pm 4.2)$ MeV/c^2

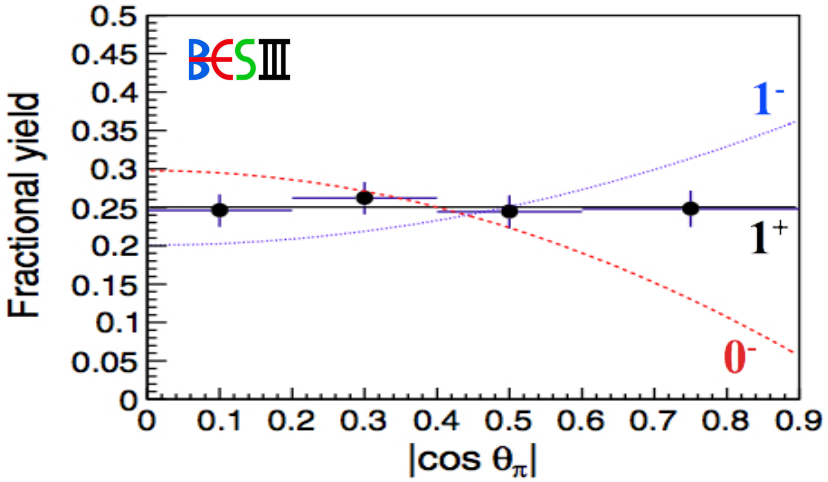
$\Gamma = (24.8 \pm 3.3 \pm 11.0)$ MeV

$\sigma \times \mathcal{B} = (83.5 \pm 6.6 \pm 22.0)$ pb

Significance >18σ







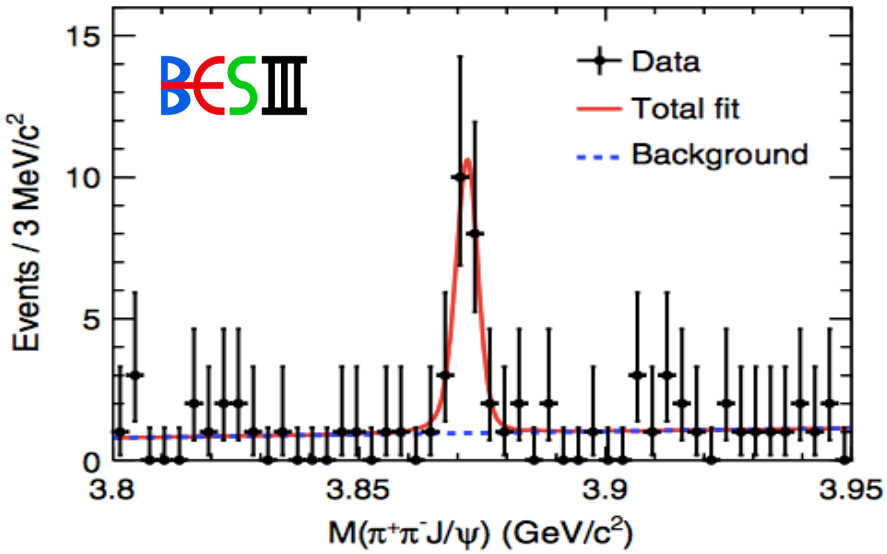
$$\frac{\mathcal{B}(Z_c(3885) \to D\bar{D}^*)}{\mathcal{B}(Z_c(3900) \to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$

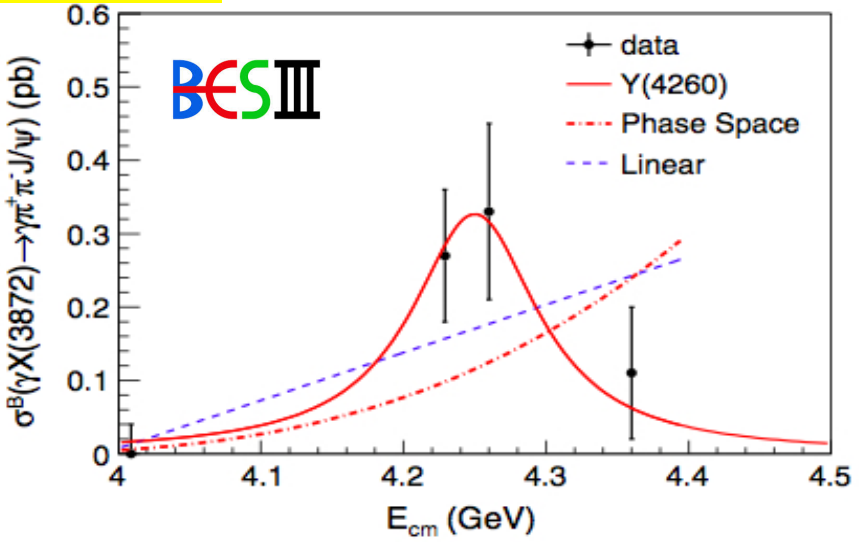
$$\frac{\mathcal{B}(\psi(3770) \to D\bar{D})}{\mathcal{B}(\psi(3770) \to J/\psi\pi^+\pi^-)} = 482 \pm 84$$

Open charm decay are suppressed w.r.t. conventional charmonium states➔ different dynamics in the Y(4260)-Z_c(3900) system

Observation of $e^+e^- \to \gamma X(3872)$

PRL112,092001 (2014)





Significance = 6.3 σ
N = 20.1 $\pm$ 4.5 events
M = 3871.9 $\pm$ 0.7 $\pm$ 0.2 MeV
Γ consistent with detector resolution

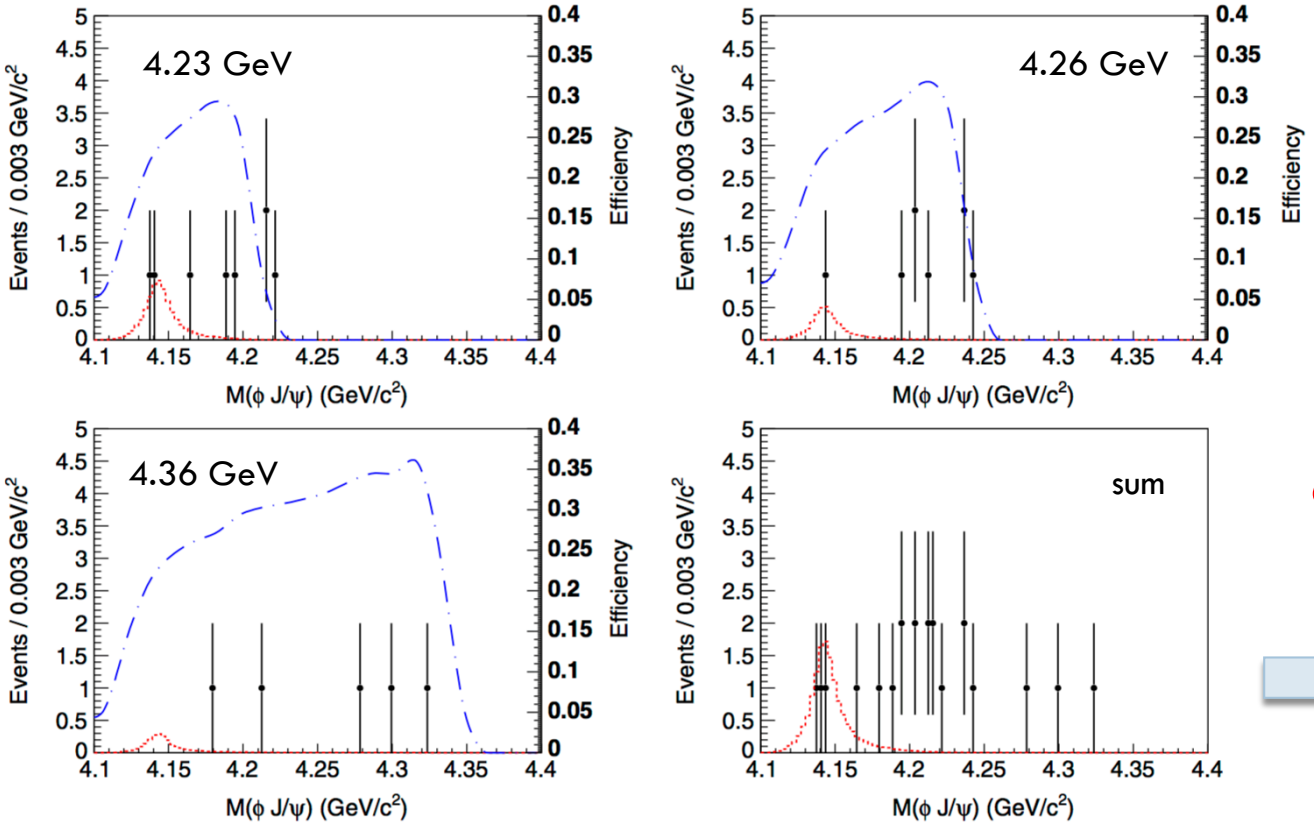
The resonant contribution with Y(4260) line shape provides a better description of the data than either a linear continuum or a E1-transition phase space distribution

The Y(4260)$\to \gamma$ X(3872) could be another previously unseen decay mode of the Y(4260) resonance

Search for $Y(4140) \to J/\psi\phi$

Observed by CDF in the decay $B^+ \to \phi J/\psi K^+$ with a significance $> 5\sigma$

- Not confirmed by Belle (PRL104), BaBar (PRD91), and LHCb (PRD85)
- Enhancement observed recently by CMS (PLB734), and D0 (PRD89)
- It is the first charmoniumlike state decaying into two vector mesons
- C=+1 ⇒ search in radiative transition of Y(4260) (or other 1^{--} states)



PRD**91**,112005(2015)

- Large BESIII samples from 4.23-4.36 GeV (tot. 2.47fb^{-1})

$e^+e^- \to \gamma\phi J/\psi$

$J/\psi \to e^+e^-, \mu^+\mu^-$

$\phi \to K^+K^-, K_SK_L, \pi^+\pi^-\pi^0$

Combined distributions of the six modes

Search for $Y(4140) \to J/\psi\phi$

PRD**91**,112005(2015)

No significant signal found @ BESIII

- Place upper limit (UL) on $\sigma(e^+e^- \to \gamma Y(4140)) \times \mathcal{B}(Y(4140) \to \phi J/\psi)$ @ 90% C.L.

$\sqrt{s}$ (GeV)	Luminosity (pb-1)	$\sigma^B \cdot \mathcal{B}$(Y(4140)) (pb) (*)	$\sigma^B \cdot \mathcal{B}$(X(3872)) (pb) PRL**112**, 092001
4.23	1094	< 0.35	0.27 ± 0.09
4.26	827	< 0.28	0.33 ± 0.12
4.36	545	< 0.33	0.11 ± 0.09

(*)Systematic errors included

UL of the same order of magnitude as $\sigma(e^+e^- \to \gamma X(3872)) \times \mathcal{B}((X(3872) \to J/\psi\pi^+\pi^-)$

Assuming:

- $\mathcal{B}((X(3872) \to J/\psi\pi^+\pi^-) \sim 5\%$ (arXiv:0910.3138)
- $\mathcal{B}((Y(4140) \to \phi J/\psi) \sim 30\%$ (using partial width of $Y(4140) \to \phi J/\psi$ calculated under the molecular hypothesis (PRD**80**, 054019) and the total width measured by CDF (arXiv:1101.6058))

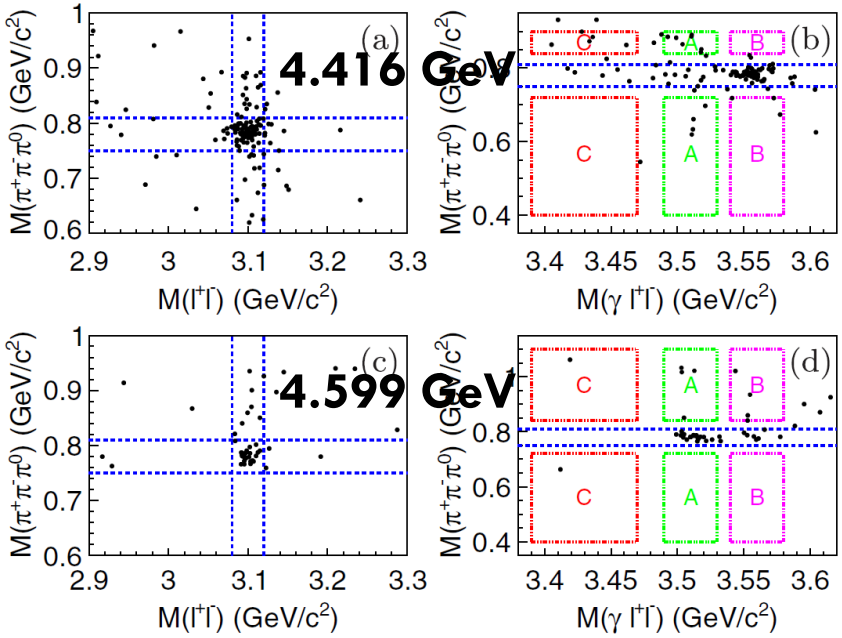
$$\frac{\sigma[e^+e^- \to \gamma Y(4140)]}{\sigma[e^+e^- \to \gamma X(3872)]} < 0.1$$

@ 4.23 and 4.26 GeV

First observation of $e^+e^- \to \omega \chi_{c1,2}$

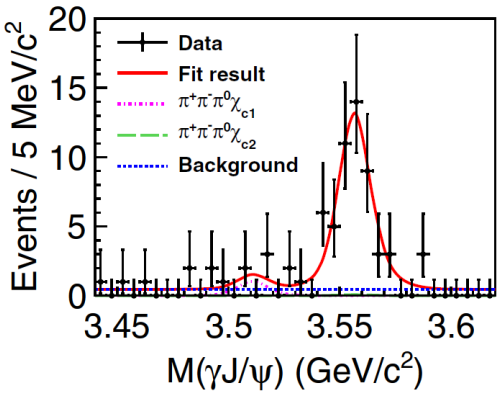
PRD93,011102(R) (2016)

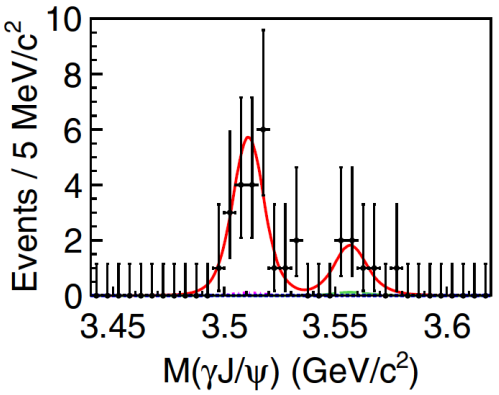
Clear and signal

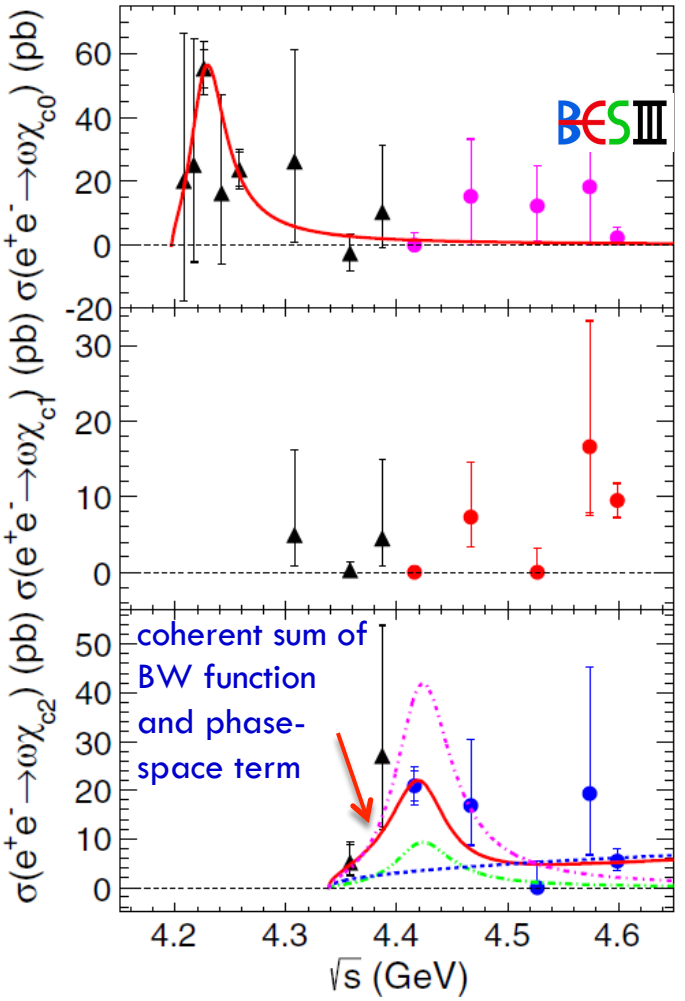


5 data samples with GeV

Fit to distribution







Different line shape for $\omega\chi_{cJ}$: different production mechanism