



中国科学院高能物理研究所  
*Institute of High Energy Physics*  
*Chinese Academy of Sciences*

# New Observations on Light Hadron Spectroscopy at BESIII

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**ICHEP2010, Paris, Jul 22-28, 2010**

# Outline

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- Introduction
- $p\bar{p}$  mass threshold study in  $J/\psi$  and  $\psi'$  radiative decays
- Confirmation of X(1835) and observation of two new resonances in  $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$
- Observation of X(1870) in  $J/\psi \rightarrow \omega\eta\pi^+\pi^-$
- Summary

# Introduction

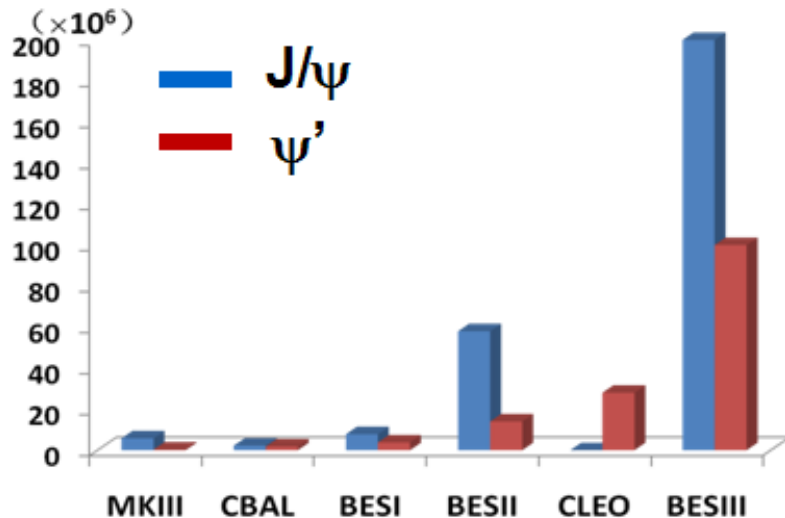
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- **Multi-quark states, glueballs and hybrids have been searched for experimentally for a very long time, but none have been established.**
- **However, during the past a few years, a lot of unexpected experimental evidence for hadrons cannot (easily) be explained by the conventional quark model.**

**For example, at BESII:**

- **$p\bar{p}$  threshold enhancement was observed in  $J/\psi \rightarrow \gamma p\bar{p}$**
- **X(1835) was observed in  $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$**

# The BEPCII/BESIII Project



## Double-ring collider

Designed Luminosity:  $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

Record Luminosity :  $3.2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

Beginning of 2004, construction starts

Apr. 14, 2009: ~106 M ψ' events

(42.3 pb<sup>-1</sup> at 3.65 GeV)

July 28, 2009: ~226 M J/ψ events

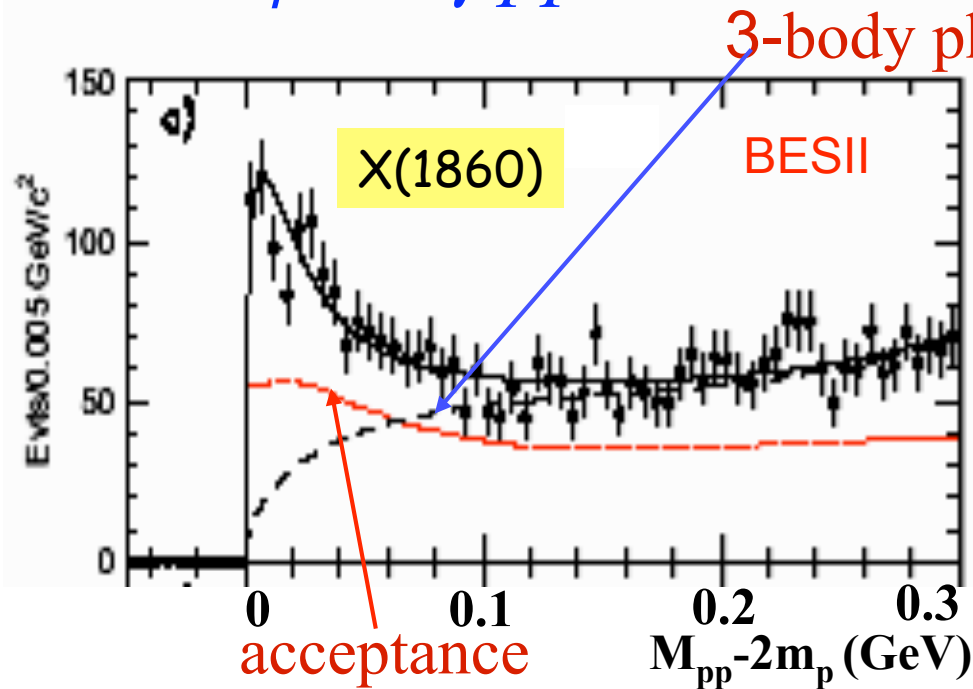
We have opportunities to confirm the existence of  $p\bar{p}$  threshold enhancement and X(1835) at BESIII... **and for new observations!**

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**$p\bar{p}$  mass threshold study  
in  $J/\psi$  and  $\psi'$  radiative decays**

# Observation of $p\bar{p}$ mass threshold enhancement @ BESII

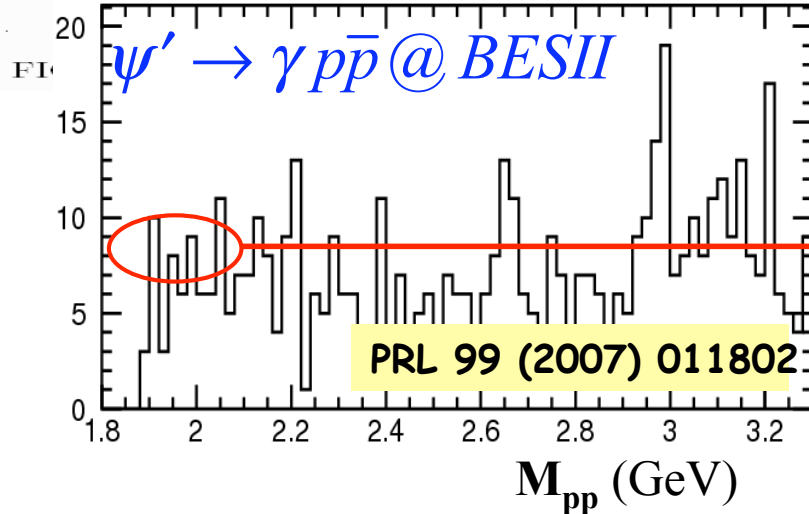
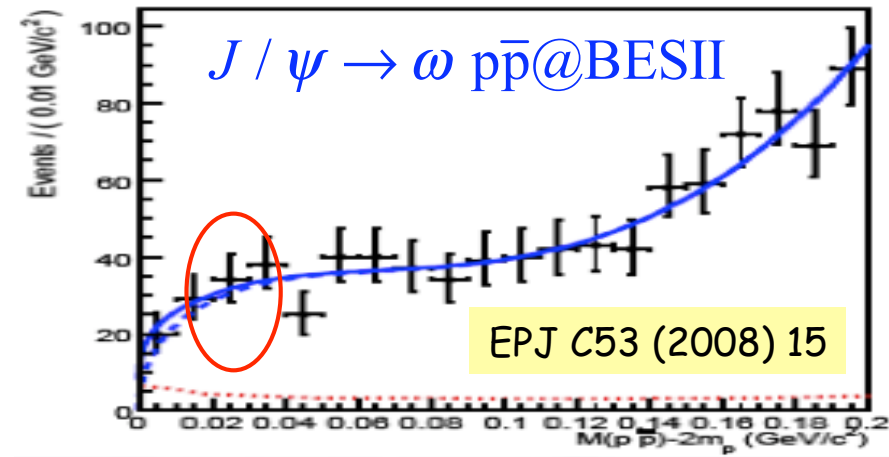
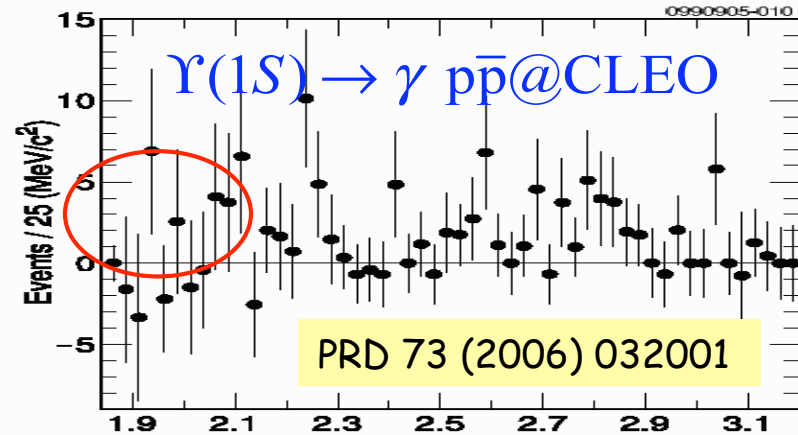
$$J/\psi \rightarrow \gamma p\bar{p}$$



## theoretical speculation:

- $p\bar{p}$  bound state (baryonium)
- FSI effect
- .....

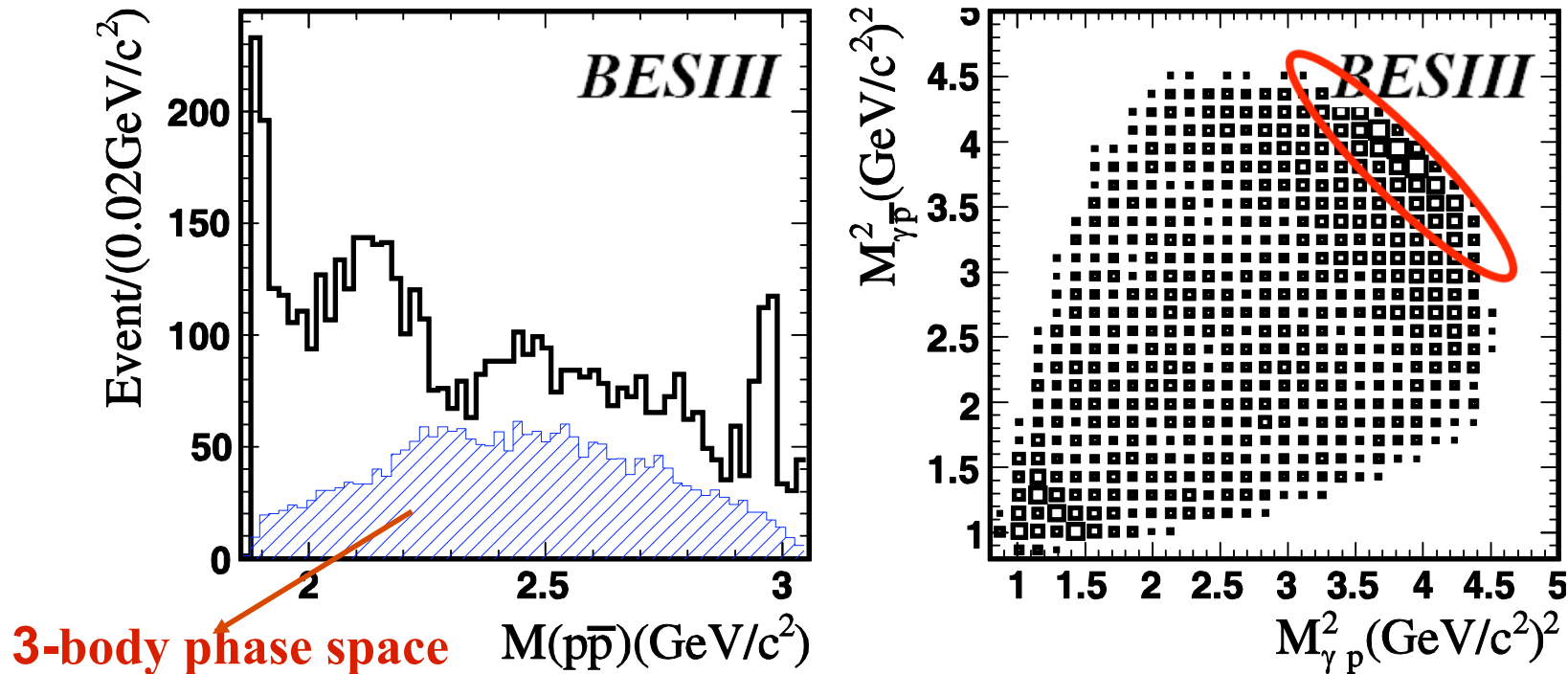
# Several non-observations



**No significant narrow strong enhancement near threshold (~2σ if fitted with X(1860))**

# $p\bar{p}$ Mass Spectrum and Dalitz Plot

$$\psi' \rightarrow \pi^+ \pi^- J / \psi, J / \psi \rightarrow \gamma p\bar{p}$$

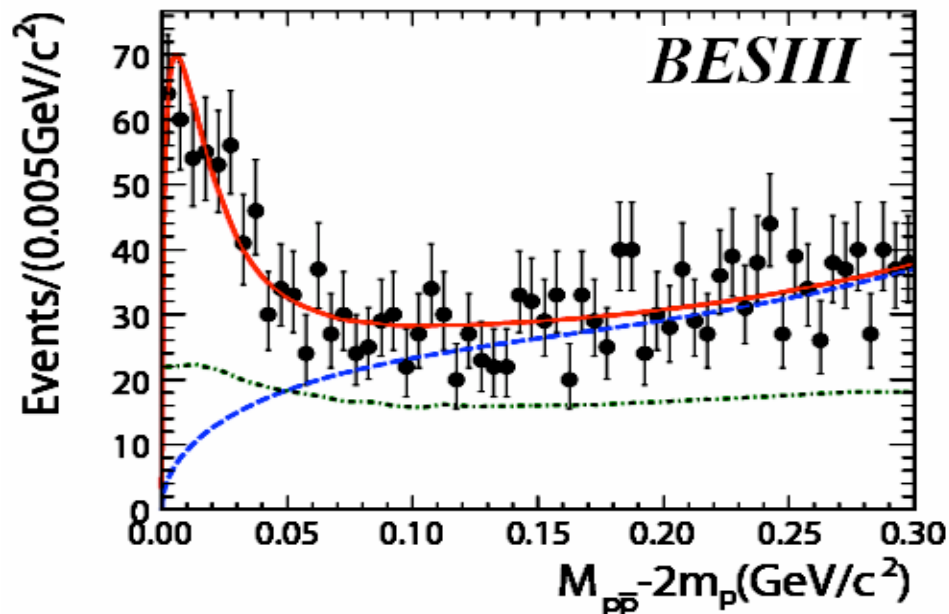


➤ Narrow threshold enhancement is evident in  $p\bar{p}$  mass spectrum.



# Mass spectrum fitting

$\psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma p \bar{p}$

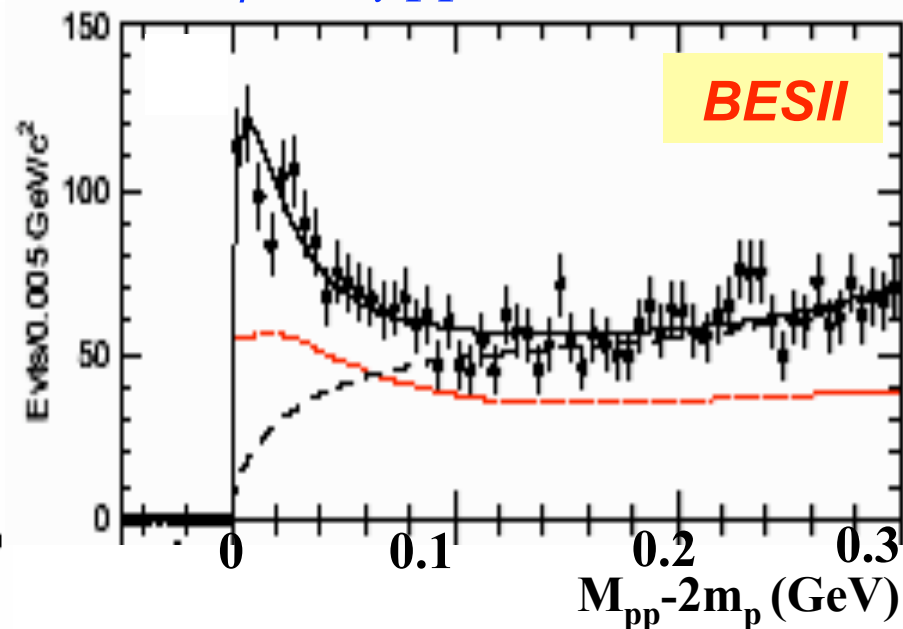


$$M = 1861^{+6}_{-13} \text{ } ^{+7}_{-26} \text{ MeV}/c^2$$

$$\Gamma < 38 \text{ MeV}/c^2 \text{ (90\% CL)}$$

Chinese Physics C 34, 421 (2010)

$J/\psi \rightarrow \gamma p \bar{p}$



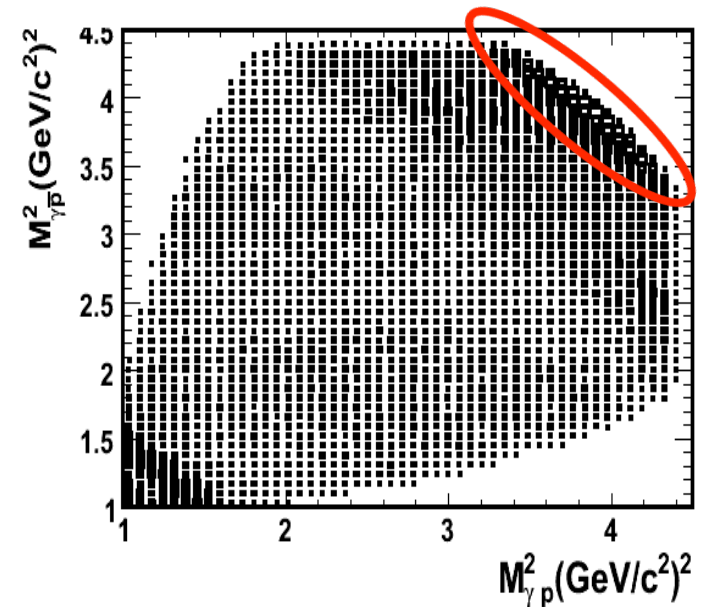
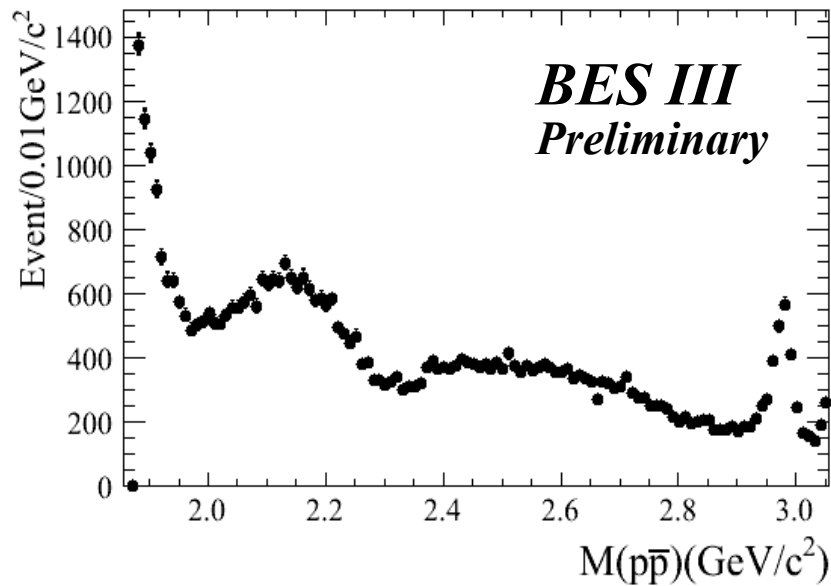
$$M = 1859^{+3}_{-10} \text{ } ^{+5}_{-25} \text{ MeV}/c^2$$

$$\Gamma < 30 \text{ MeV}/c^2 \text{ (90\% CL)}$$

PRL 91 (2003) 022001

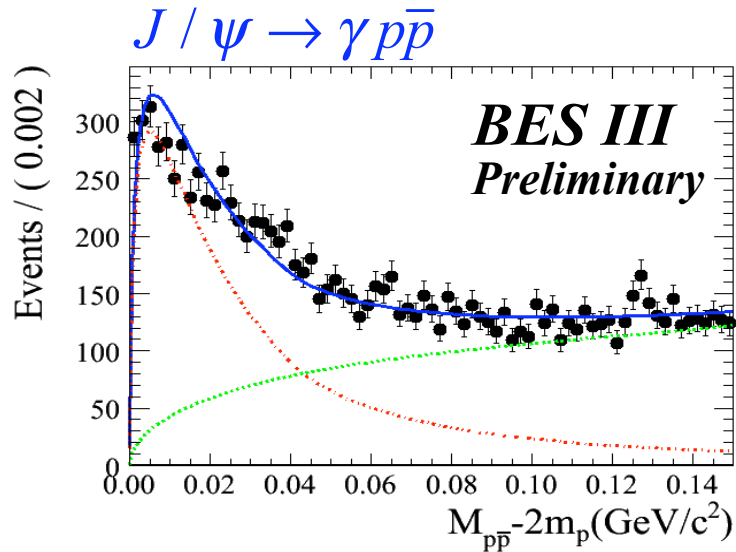
# $p\bar{p}$ invariant mass spectrum and Dalitz plot

$$J/\psi \rightarrow \gamma p\bar{p}$$



**Significant narrow threshold enhancement exists**

# Mass spectrum fitting

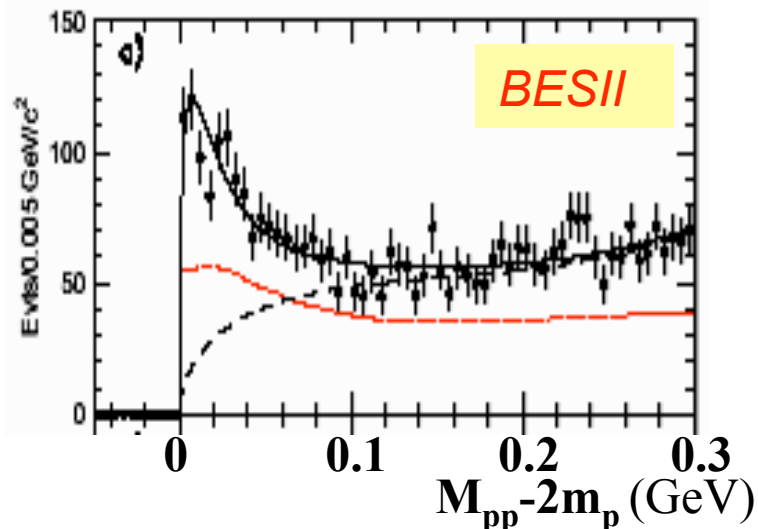


Fit result:

$$\text{Mass} = 1861.6 \pm 0.8 \text{ MeV} / c^2$$

$$\Gamma < 8 \text{ MeV} (90\% \text{ CL})$$

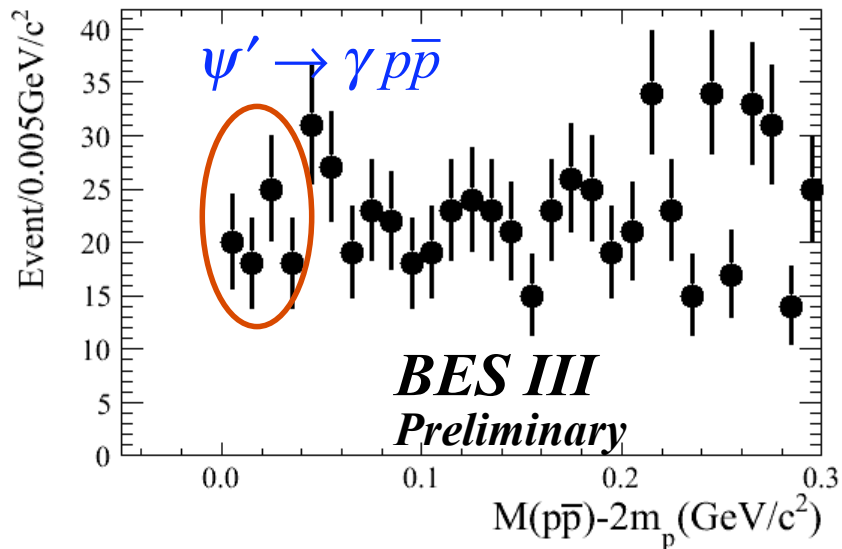
Study on more sophisticated fits, such as including FSI, is ongoing



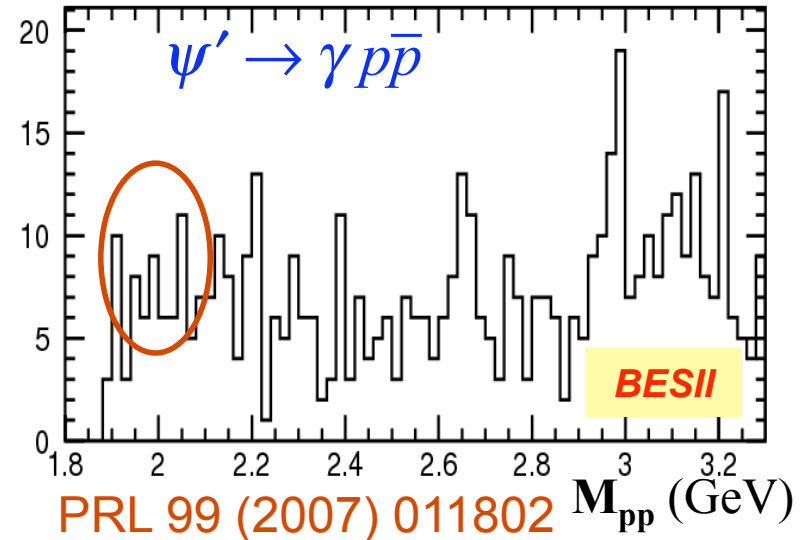
$$M = 1859^{+3}_{-10} \text{ MeV}/c^2$$

$$\Gamma < 30 \text{ MeV}/c^2 (90\% \text{ CL})$$

# $p\bar{p}$ threshold mass spectrum in $\psi'$ radiative decay



No obvious narrow threshold enhancement



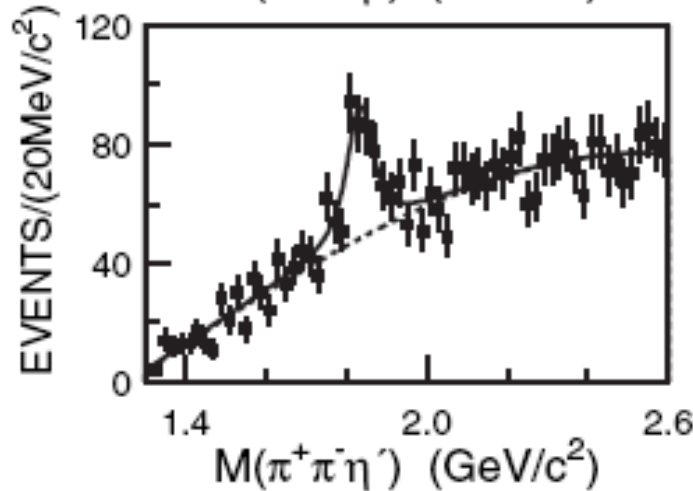
No significant narrow strong enhancement near threshold ( $\sim 2\sigma$  if fitted with X(1860))

Pure FSI interpretation of the narrow and strong  $p\bar{p}$  mass threshold enhancement is disfavored.

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Confirmation of  $X(1835)$  and  
observation of two new resonances in  
 $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$

# Observation of X(1835) in $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$ at BESII



*BESII result* (Stat. sig.  $\sim 7.7\sigma$ ):

$$M = 1833.7 \pm 6.1(\text{stat}) \pm 2.7(\text{syst}) \text{MeV}$$

$$\Gamma = 67.7 \pm 20.3(\text{stat}) \pm 7.7(\text{syst}) \text{MeV}$$

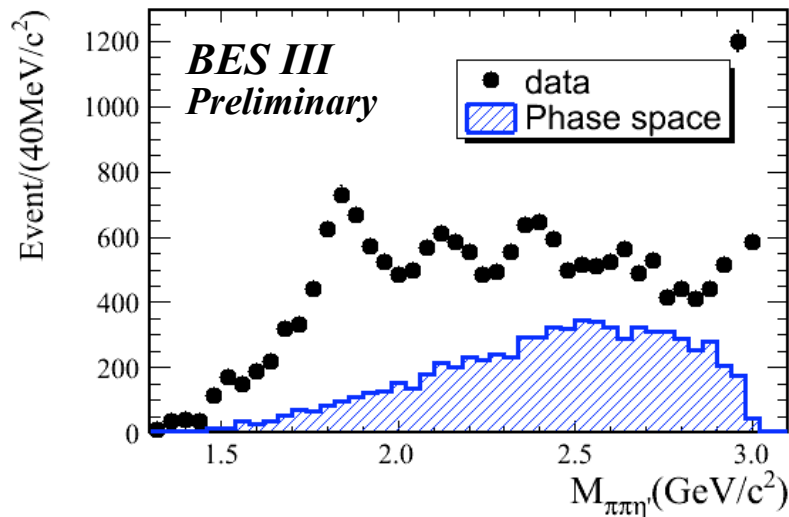
**PRL 95,262001(2005)**

- Confirmation of X(1835) is necessary with high statistic data sample.
- LQCD predicts the  $0^{++}$  glueball mass is  $\sim 2.3\text{GeV}$ .
- A  $0^{++}$  glueball may have similar decay property as  $\eta_c$  (the main  $\eta_c$  decay mode is  $\pi\pi\eta'$ ).

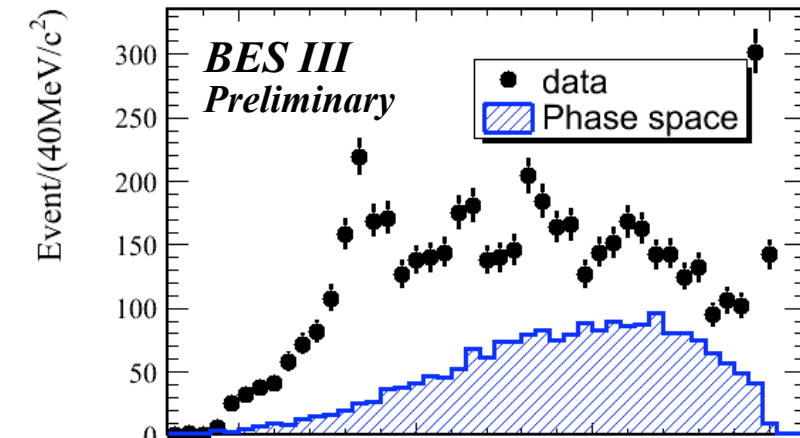
→ It is important and interesting to study  $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$

# Mass spectrum of $\pi^+\pi^-\eta'$

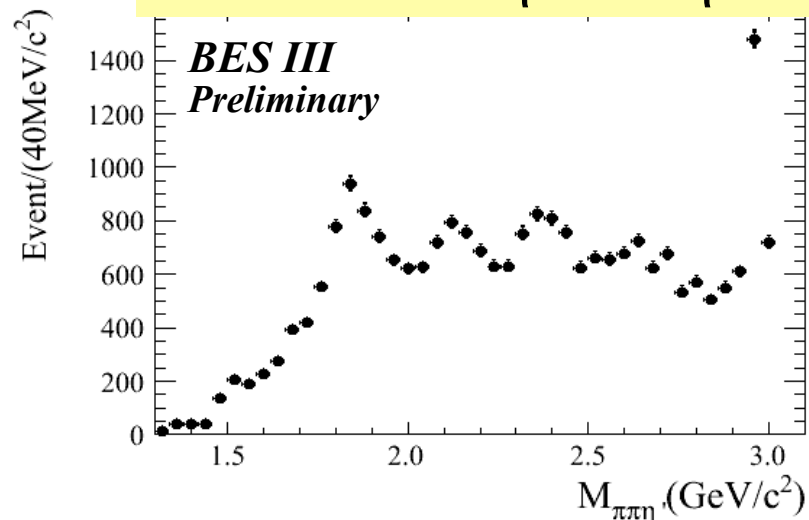
$\eta' \rightarrow \gamma\rho$



$\eta' \rightarrow \pi\pi\eta$



Combination for  $\eta'$  to  $\pi^+\pi^-\eta$  and  $\gamma\rho$

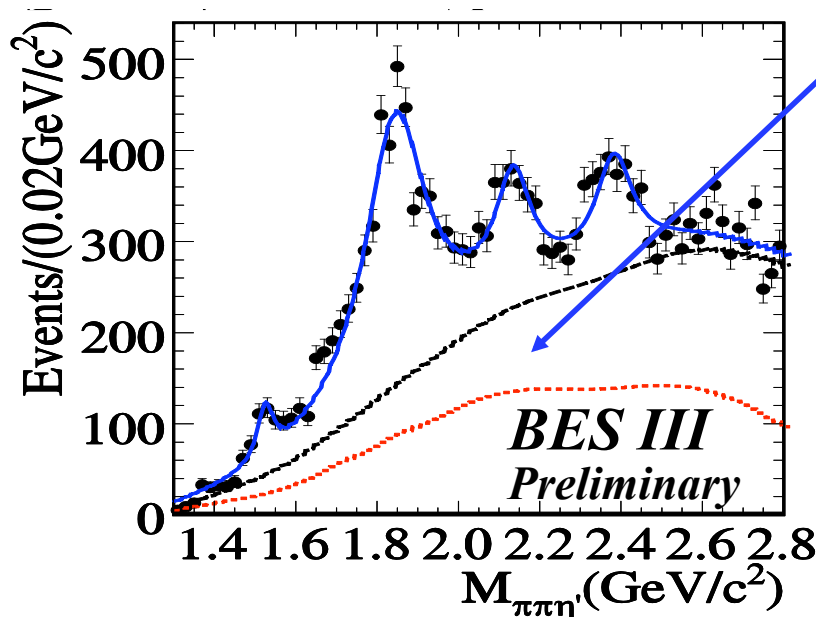


- $X(1835)$  and  $\eta_c$  are evident.
- Two additional structures at  $M \sim 2.1 \text{ GeV}$  and  $2.3 \text{ GeV}$
- There maybe some  $f_1(1510)$ .

# Fitting for the combined mass spectrum

- Fitting with four resonances (acceptance weighted BW ⊗ gauss)
- Three background components:
  - ① Contribution from non- $\eta'$  events estimated by  $\eta'$  mass sideband
  - ② Contribution from  $J/\psi \rightarrow \pi^0 \pi^+ \pi^- \eta'$  with re-weighting method
  - ③ Contribution from “PS background”

$$f_{bkg}(x) = (x - m_0)^{1/2} + a_0(x - m_0)^{3/2} + a_1(x - m_0)^{5/2}, \quad m_0 = 2m_\pi + m_{\eta'}$$



Red line: estimated contribution of ①+ ②  
 Black line: total background

resonance	$M$ ( MeV/ $c^2$ )	$\Gamma$ ( MeV/ $c^2$ )	Stat. sig.
X(1835)	$1838.1 \pm 2.8$	$179.5 \pm 9.1$	$> 25\sigma$
X(2120)	$2124.8 \pm 5.6$	$101 \pm 14$	$> 7.2\sigma$
X(2370)	$2371.0 \pm 6.4$	$108 \pm 15$	$> 6.7\sigma$

Stat. sig. is conservatively estimated:  
 fit range, background shape,  
 contribution of extra resonances



- 
- **X(1835) resonance is confirmed at BESIII, but the width is significantly larger than that measured at BESII with one resonance in the fit.**
  - **Two new resonances, X(2120) and X(2370), are observed with significances larger than  $7.2\sigma$  and  $6.7\sigma$  respectively.**
  - **PWA is needed not only to determine the spin-parities of above three resonances, but also to make more precise measurements on masses, widths and BRs by considering possible interferences among them.**

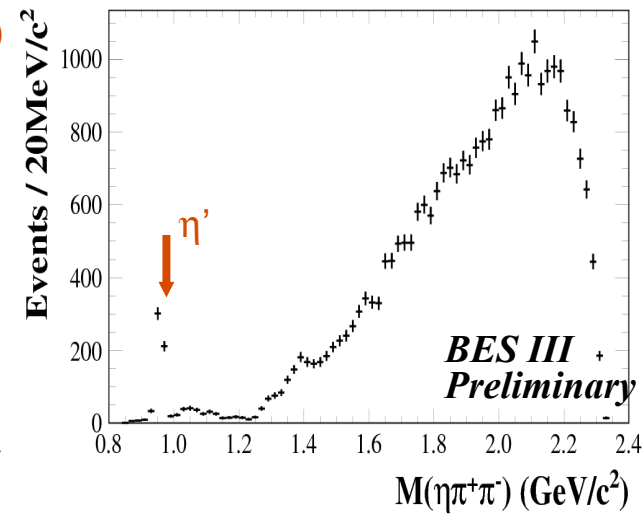
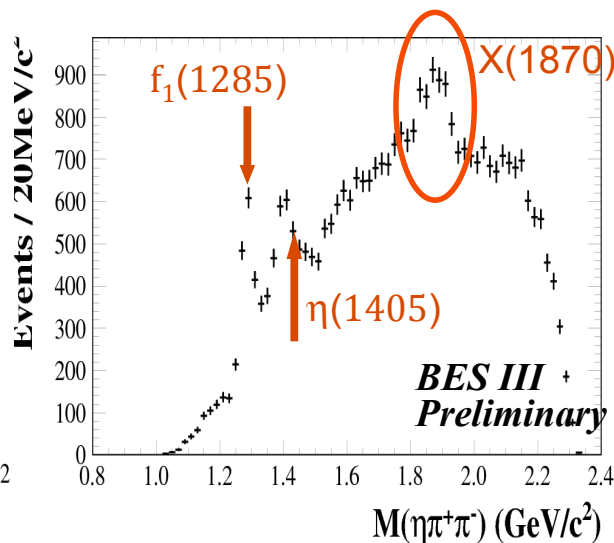
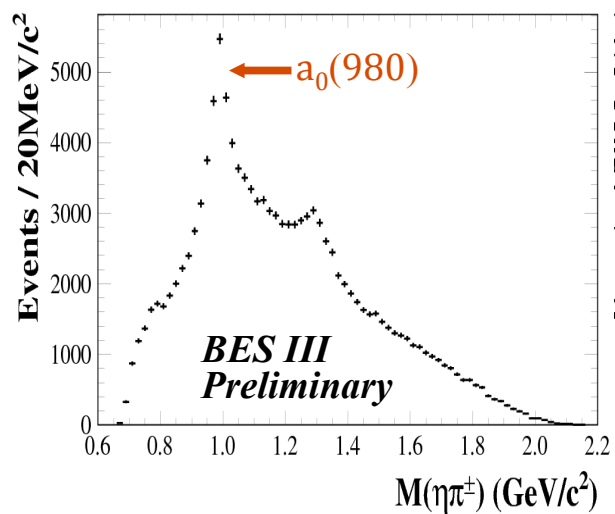
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Observation of  $X(1870) \rightarrow a_0(980)\pi$  in  
 $J/\psi \rightarrow \omega \pi^+ \pi^- \eta$

# Analysis of $J/\psi \rightarrow \omega \pi^+ \pi^- \eta$ @ BESIII

• With  $a_0(980)$ :

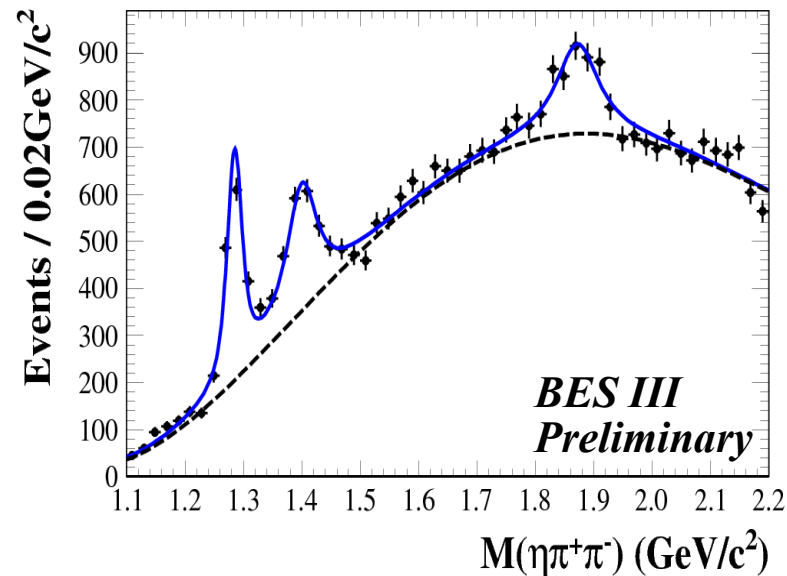
• Veto  $a_0(980)$ :



The  $f_1(1285)$ ,  $\eta(1405)$  and  $X(1870)$  primarily decay via  $a_0(980)\pi^\pm$

# Mass spectrum fitting

- Fitting with three resonances (acceptance weighted BW  $\otimes$  Gauss)
- Background component described by Polynomial function



Fit result (*stat. sig.*  $\sim 7.7\sigma$ )

$$M = 1873 \pm 11 \text{ MeV}$$

$$\Gamma = 82 \pm 19 \text{ MeV}$$

Whether the X(1870) is the X(1835) or  $\eta_2(1870)$ , or a new resonance, needs further study.

# Summary

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- $X(1860) \rightarrow p\bar{p}$  is confirmed in  $J/\psi$  radiative decay, and no obvious similar structure is observed in  $\psi'$  radiative decay.
- $X(1835) \rightarrow \pi^+\pi^-\eta'$  is confirmed in  $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ , and two new resonances,  $X(2120)$  and  $X(2370)$  are observed with significances larger than  $7.2\sigma$  and  $6.7\sigma$  respectively.
- A new process  $J/\psi \rightarrow \omega X(1870) \rightarrow \omega a_0 \pi$  is observed.
- Whether or not the  $X(1860)$ ,  $X(1835)$  and  $X(1870)$  are the same resonance, still needs further study.

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Thank You

# Summary on the previous experimental results

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- The strong and narrow  $p\bar{p}$  mass threshold enhancement has only been observed in  $J/\psi$  radiative decay, not in any other place so far.
- Any model trying to interpret the mass threshold enhancement should also answer why it is not observed in other places, especially in  $\psi(2S)$  and  $Y(1S)$  radiative decays as well as in  $J/\psi \rightarrow \omega p\bar{p}$  process.

# Mass spectrum fitting method

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## ■ Fit function:

- signal: acceptance weighted S-wave BW

function: 
$$BW(M) \propto \frac{q^{(2l-1)}k^3}{(M^2 - M_0^2)^2 + M^2\Gamma^2}$$

- q : the proton momentum in cms of ppb
- k : the photon momentum
- k: the ppb orbital angular momentum

- background shape: 
$$f_{bkg}(\delta) = \delta^{1/2} + a_1\delta^{3/2} + a_2\delta^{5/2}$$

$a_1$  and  $a_2$  are obtain from a fit to an uniform phase space MC sample



# $p\bar{p}$ threshold enhancement @ CLEOc

➤ CLEO-c does fit the same as BES and obtains:

$$M(R_{\text{thr}}) = 1861^{+6}_{-16} \text{ (MeV)}, \quad \Gamma(R_{\text{thr}}) = 0^{+32}_{-0} \text{ (MeV)},$$

$$B_1(J/\psi \rightarrow \gamma R_{\text{thr}}) \times B_2(R_{\text{thr}} \rightarrow p\bar{p}) = (5.9^{+2.8}_{-3.2}) \times 10^{-5}$$

agrees with BESII results

[PRL91(2003)022011].

➤ CLEO-c fits with three contributions:

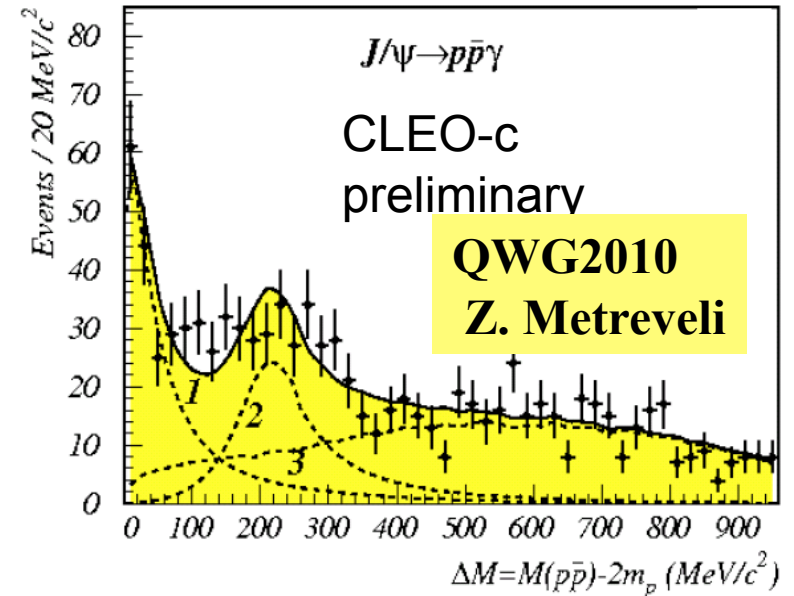
$$R_{\text{thr}} + f_0(2100) + \text{PS}$$

(1)                      (2)                      (3)

$$M(R_{\text{thr}}) = 1837^{+10}_{-12} \text{ } ^{+9}_{-7} \text{ (MeV)},$$

$$\Gamma(R_{\text{thr}}) = 0^{+44}_{-0} \text{ (MeV)}, \quad \text{CL} = 26.1\%$$

$$B_1(J/\psi \rightarrow \gamma R_{\text{thr}}) \times B_2(R_{\text{thr}} \rightarrow p\bar{p}) = (11.4^{+4.3}_{-3.0} \text{ } ^{+4.2}_{-2.6}) \times 10^{-5}$$



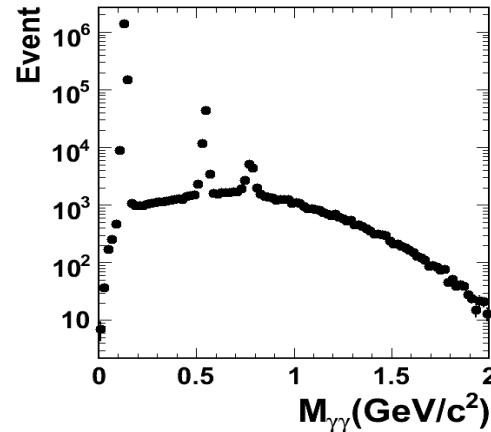
The central value of the mass is close to the sub-threshold resonance mass reported by BES with  $M(R) = 1833.7 \pm 6.1 \pm 2.7$  (MeV), observed in  $J/\psi \rightarrow \gamma R, R \rightarrow \pi^+ \pi^- \eta'$  [PRL 95 (2005) 262001].

**BES considered these (2) and (3) as systematic errors.**

# Event selection for $J/\psi \rightarrow \gamma\pi^+\pi^-\eta' (\eta' \rightarrow \gamma\rho, \rho \rightarrow \pi^+\pi^-)$

## Initial selection criteria:

- $N_{\text{charged}}=4, N_{\gamma} \geq 2$
- $N_{\pi} > 2$
- Kinematic fit(4C):  
 $\chi_{4C}^2(\gamma\pi^+\pi^-\pi^+\pi^-) < 40$   
 $\chi_{4C}^2(\gamma\pi^+\pi^-\pi^+\pi^-) < \chi_{4C}^2(\gamma K^+K^-\pi^+\pi^-)$



$$J/\psi \rightarrow \pi^0\pi^+\pi^-\pi^+\pi^-$$

$$J/\psi \rightarrow \eta\pi^+\pi^-\pi^+\pi^-$$

$$J/\psi \rightarrow \omega\pi^+\pi^-\pi^+\pi^- (\omega \rightarrow \gamma\pi^0)$$

## Final selection criteria:

- Reduce background from  $\pi^0\pi^+\pi^-\pi^+\pi^-$ :

$$|m_{\gamma\gamma} - m_{\pi}| < 0.04\text{GeV}$$

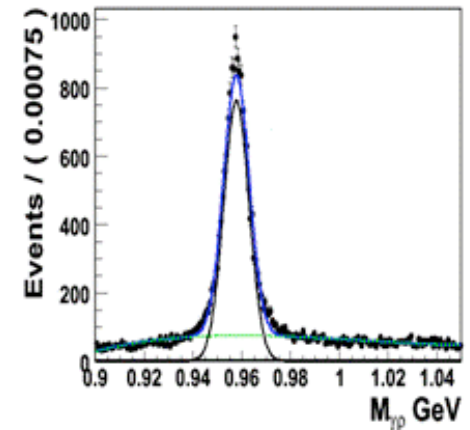
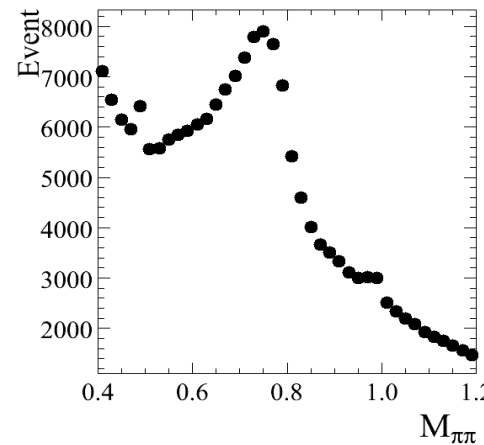
$$|m_{\gamma\gamma} - m_{\eta}| < 0.03\text{GeV}$$

$$0.72\text{GeV} < m_{\gamma\gamma} < 0.82\text{GeV}$$

Selection for  $\rho$  and  $\eta'$  signal:

- $|M_{\pi\pi} - m_{\rho}| < 0.2\text{GeV}$

$$|M_{\gamma\rho} - m_{\eta'}| < 0.018\text{GeV}$$



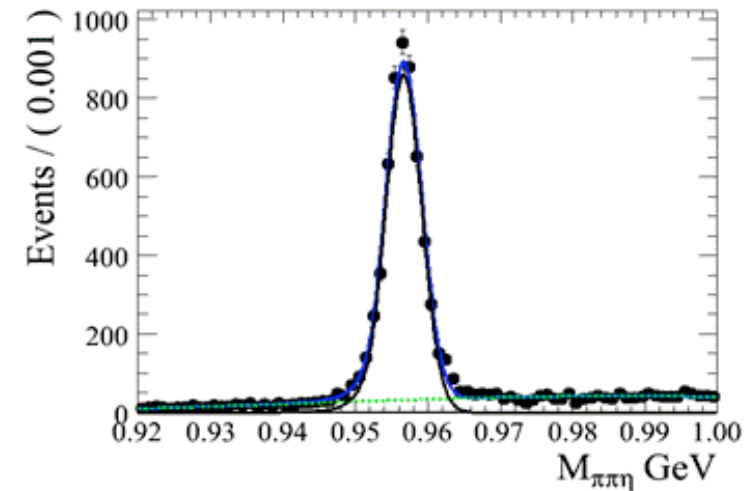
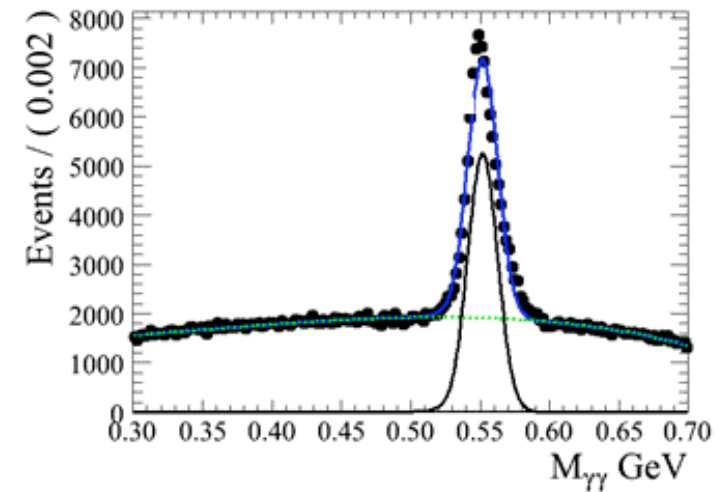
# Event selection for $J / \psi \rightarrow \gamma \pi^+ \pi^- \eta' (\eta' \rightarrow \pi^+ \pi^- \eta)$

## ■ Initial selection criteria:

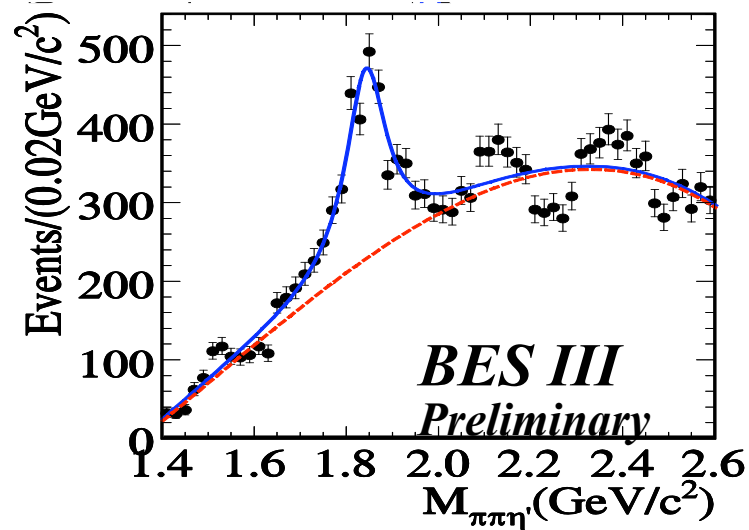
- $N_{\text{charged}}=4, N_{\gamma} \geq 2$
- $N_{\pi} > 2$
- Kinematic fit(4C,5C):  
 $\chi_{4C}^2(\gamma\gamma\pi^+\pi^-\pi^+\pi^-) < 40$   
 $\chi_{5C}^2(\gamma\eta\pi^+\pi^-\pi^+\pi^-) < 40$

## ■ Final selection criteria:

- selection for  $\eta$  and  $\eta'$  signal:  
 $|M_{\gamma\gamma} - m_{\eta}| < 0.03 \text{ GeV}$   
 $|M_{\pi\pi\eta} - m_{\eta'}| < 0.01 \text{ GeV}$

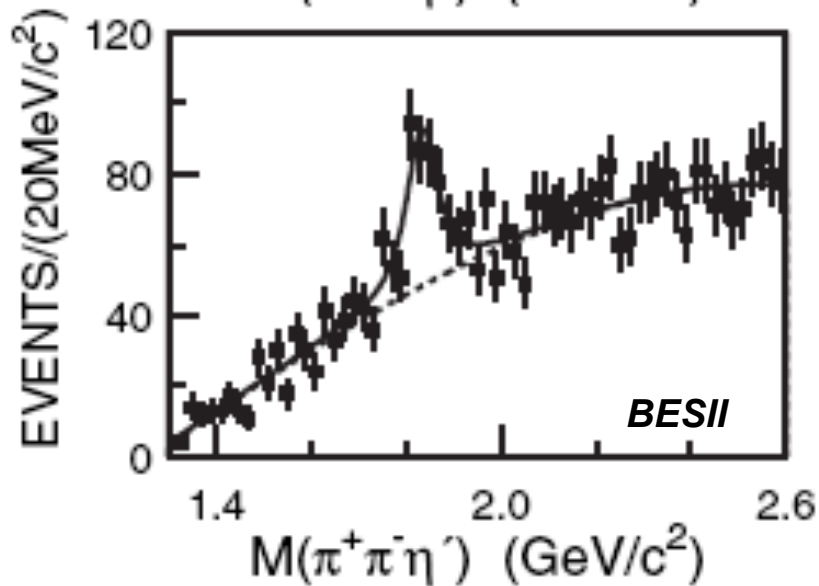


# Fitting for the combined mass spectrum



Fitting with one resonance as BESII

Fit result (Stat. sig.  $\sim 20\sigma$ ):  
 $M = 1839.9 \pm 3.0(\text{stat}) \text{ MeV}$   
 $\Gamma = 104.5 \pm 10.5(\text{stat}) \text{ MeV}$

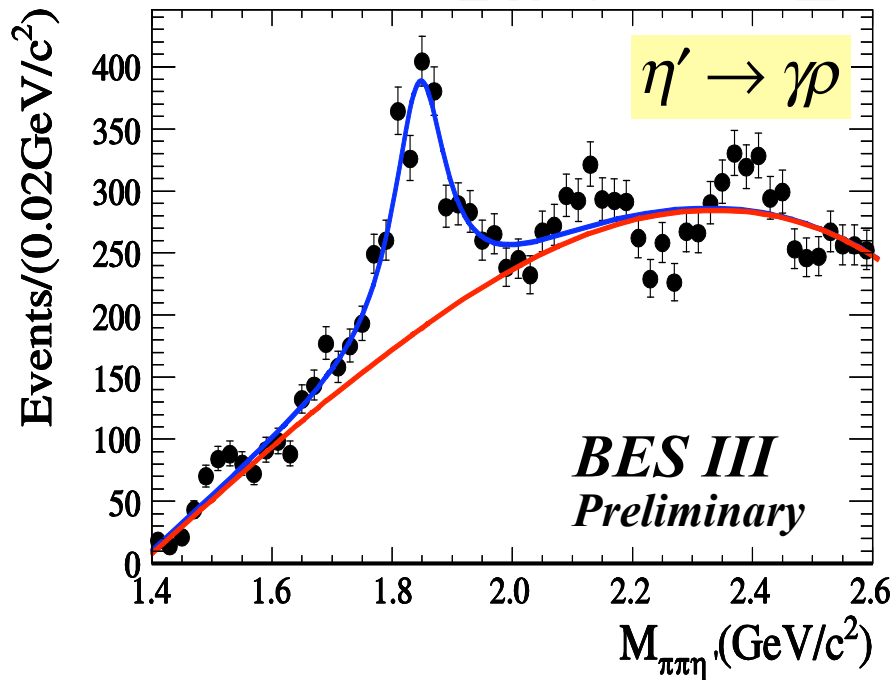


*BESII* result (Stat. sig.  $\sim 7.7\sigma$ ):  
 $M = 1833.7 \pm 6.1(\text{stat}) \pm 2.7(\text{syst}) \text{ MeV}$   
 $\Gamma = 67.7 \pm 20.3(\text{stat}) \pm 7.7(\text{syst}) \text{ MeV}$

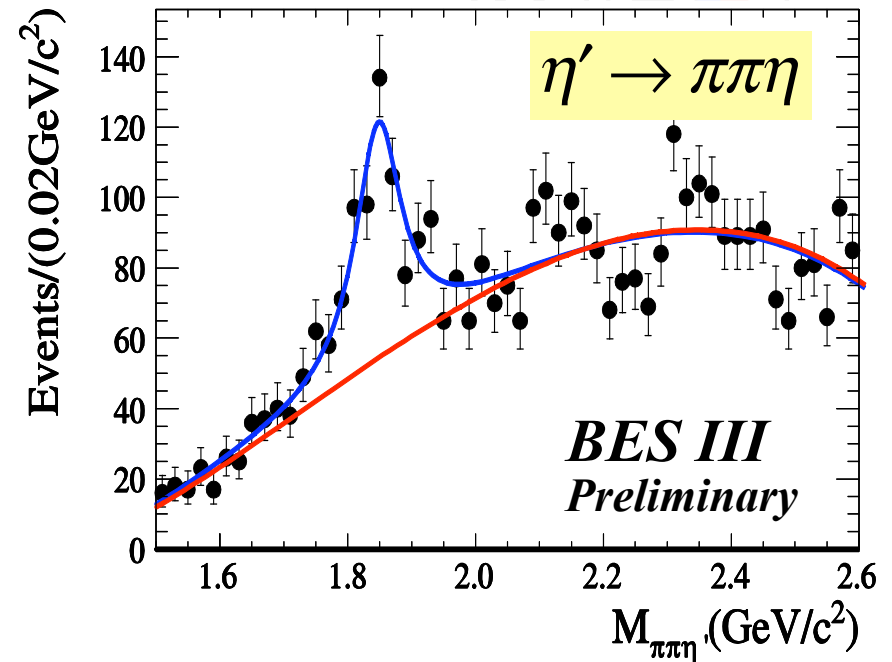
**X(1835) confirmed by BESIII**

# Mass spectrum of $\pi^+\pi^-\eta'$

Fit with one resonances + polynomial background:



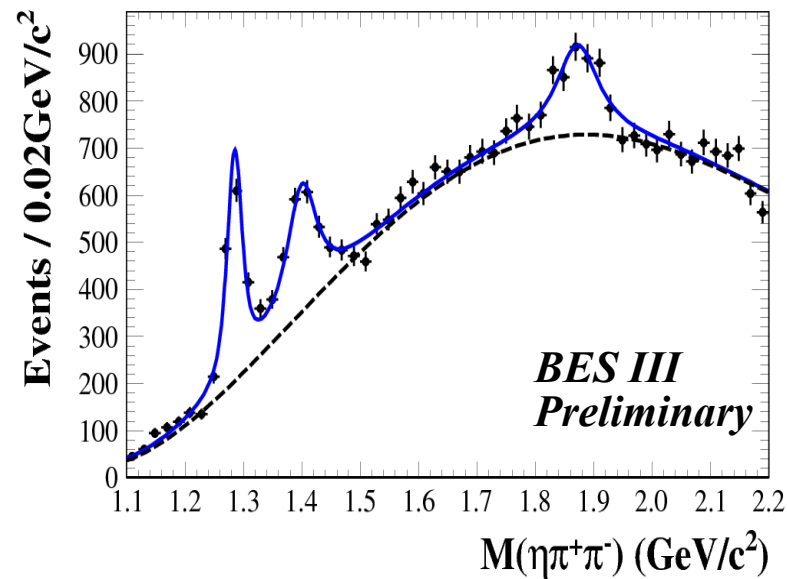
Stat. sig.  $\sim 18\sigma$



Stat. sig.  $\sim 9\sigma$

# Mass spectrum fitting

- Fitting with three resonances (acceptance weighted BW  $\otimes$  Gauss)
- Background component described by Polynomial function



resonance	$M(\text{ MeV}/c^2)$	$\Gamma(\text{ MeV}/c^2)$
$f_1(1285)$	$1285.0 \pm 1.0$	$20.9 \pm 2.9$
$\eta(1405)$	$1400.2 \pm 2.5$	$56.5 \pm 8.4$
$X(1870)$	$1872.7 \pm 10.6$	$81.5 \pm 18.6$