The J/ψ and ψ' Radiative Decays

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Outline

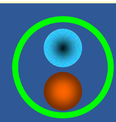
- Introduction
- J/ψ and ψ' radiative decays
- Summary

New forms of hadrons

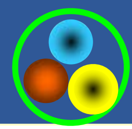
- **Hadrons consist of 2 or 3 quarks：**

Naive Quark Model：

Meson（ $q\ \bar{q}$ ）



Baryon（q q q）



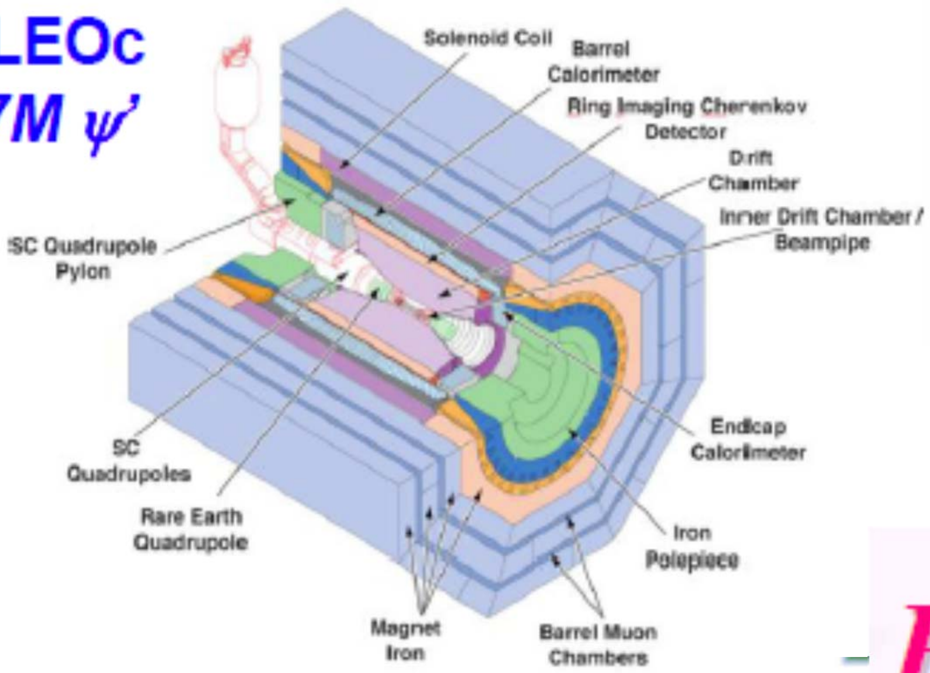
- **QCD predicts the new forms of hadrons:**
  - **Multi-quark states： Number of quarks >＝ 4**
  - **Hybrids： $q\bar{q}g$， qqqg …**
  - **Glueballs： gg， ggg …**

- **None of the non-qqbar or non-qqq states is established experimentally.**

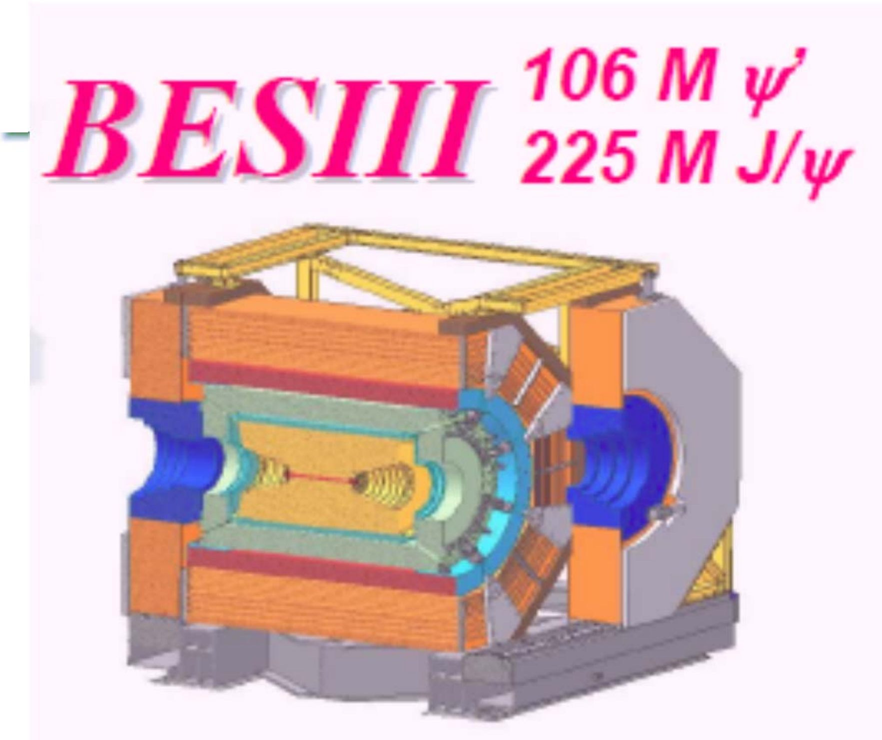
- **Search for new hadrons and systematic study of the spectroscopy – a way of understanding the internal structure of hadrons.**

- **Radiative decays of the charmonium states provide good lab.**

CLEOc
27M ψ'



Stopped running in 2008



Started physics run from 2009.

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Search for exotic 1^{-+} states in $\eta'\pi$

- VES (1993): 37 GeV $\pi^- N \to \eta'\pi^- N$ (PLB 313, 276 (1993))

  Found a P-wave resonant – exotic 1^{-+} in $\eta'\pi$ system:

- E852 (2001): 18 GeV $\pi^- p \to \eta'\pi^- p$ (PLB 563, 3997 (2001))

  Found $a_2(1700)$+exotic $\pi_1(1600)$

- COMPASS (2008 data): 190 GeV $\pi^- p \to \eta'\pi^- p$ (T. Schlueter Hadron2011 talk)

  Evidence for $a_4(2040)$ found, but resonant P-wave cannot be confirmed.

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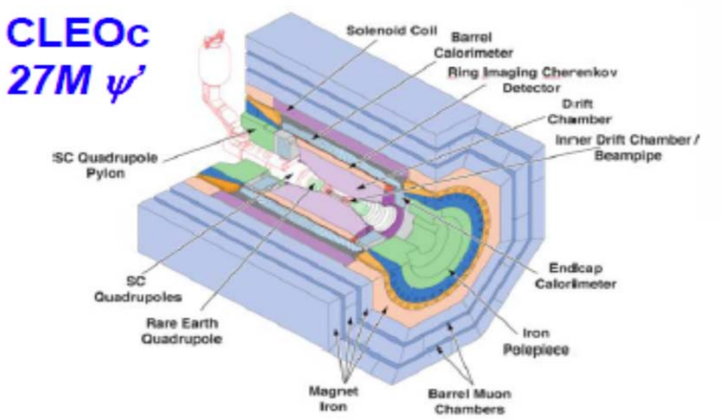
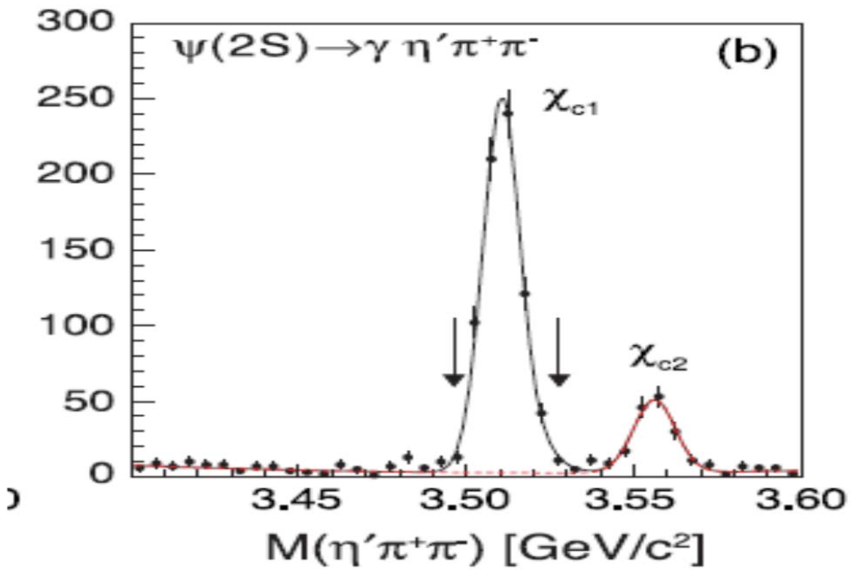
Evidence for $\pi_1(1600)$ in $\chi_{c1}\to\eta'\pi^+\pi^-$ at CLEO-c

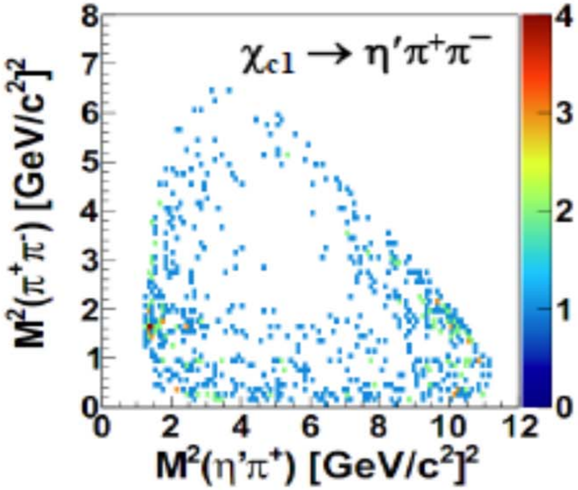
arXiv: 1109.5843, PRD

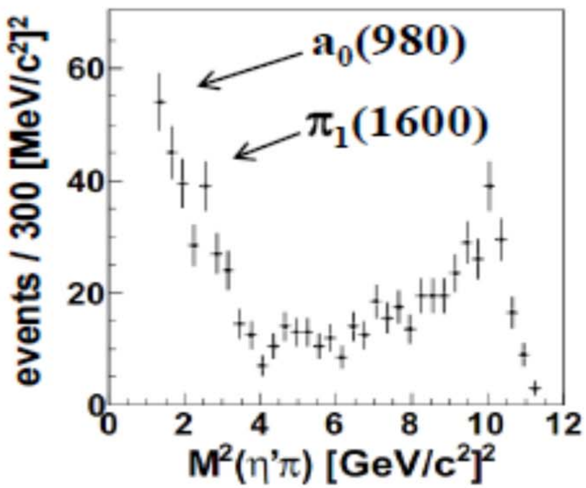


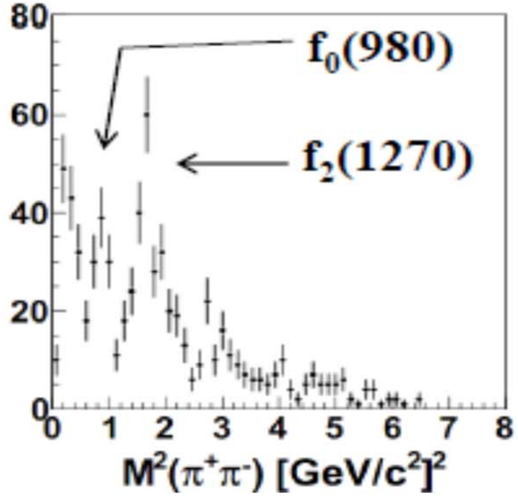


χ_{c1} produced in $\psi(2S)\to\gamma\chi_{c1}$

Signal purity: 94.6% (1.3%)





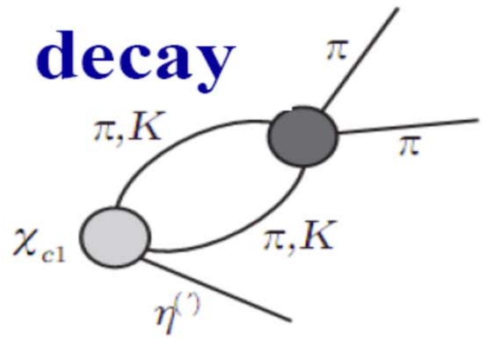


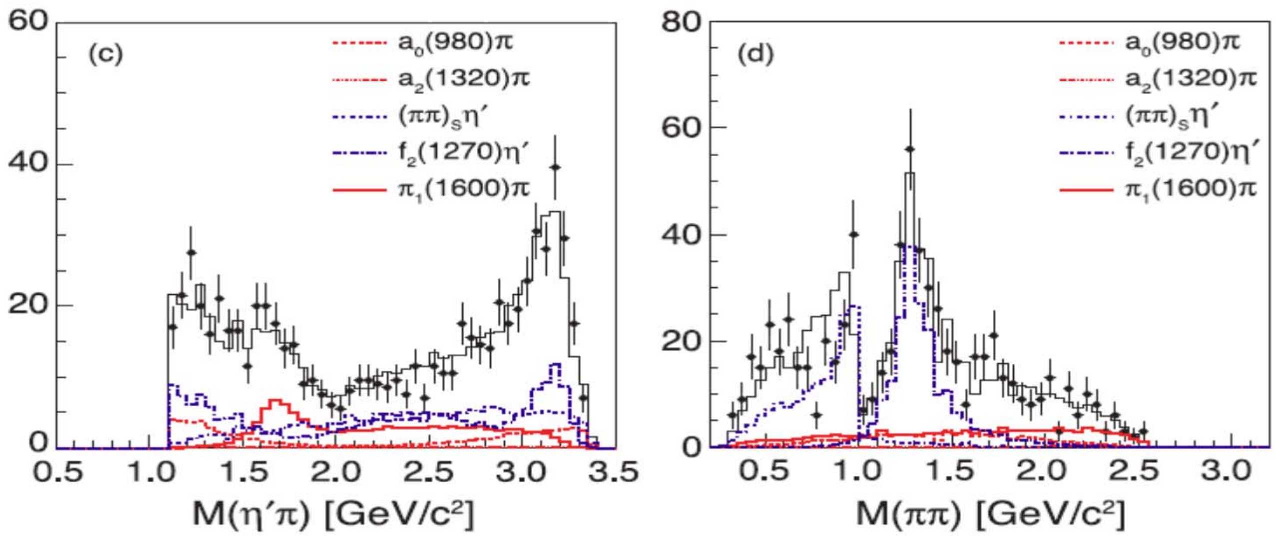
A full amplitude analysis with isobar model :

BW for most of resonances

Flatte: $a_0(980)$

$\pi\pi$-S wave : KK, $\pi\pi$ scattering



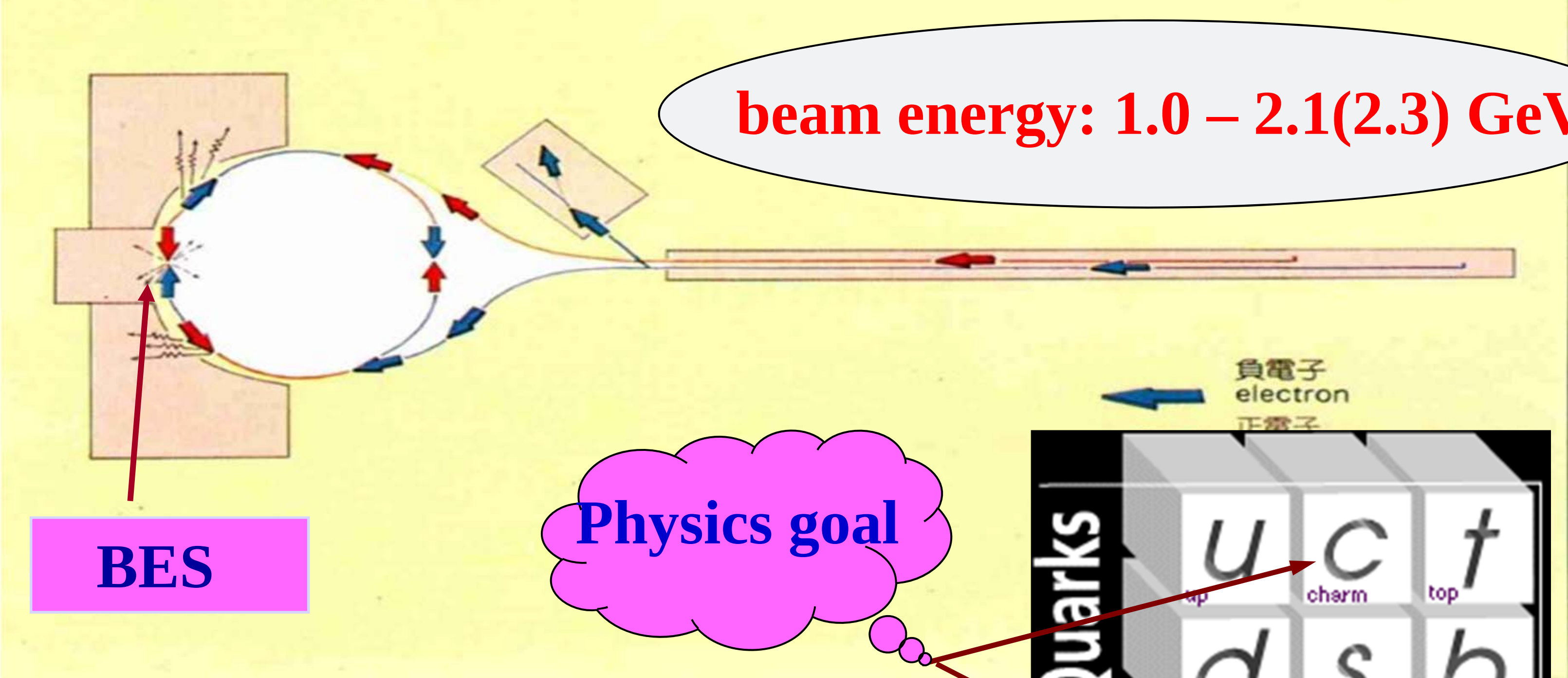


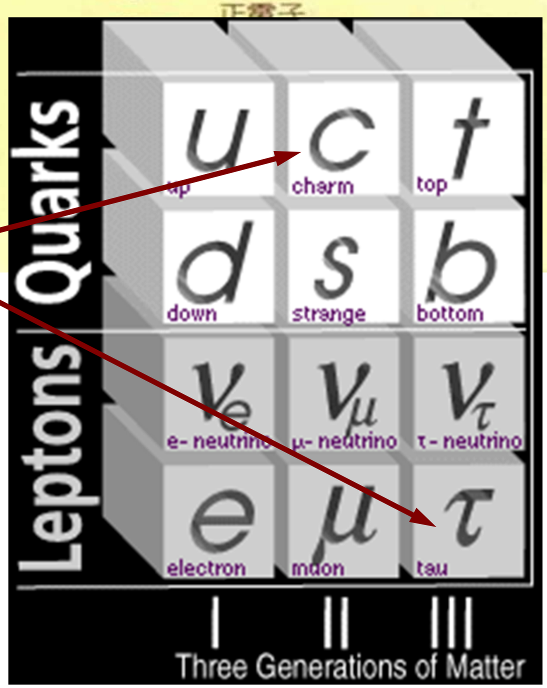
Assuming BW shape for 1^{-+} :

$M=1670\pm30\pm20$ MeV/c^2 , $\Gamma=240\pm50\pm60$ MeV

Significance > 4.0 σ (different models)

（BEPC/BES）

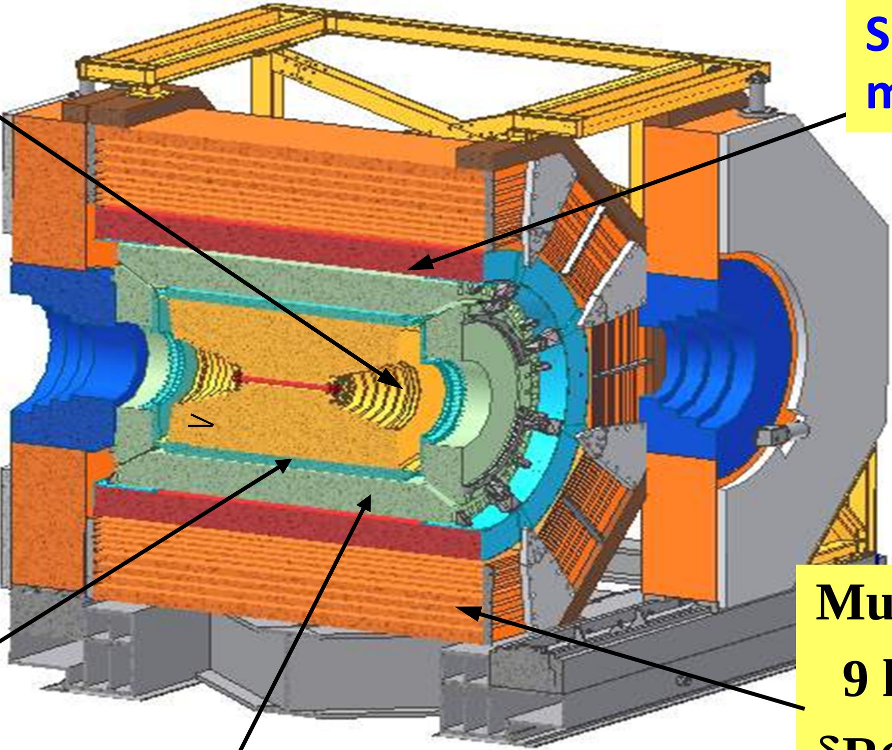




1-2.3GeV e+ e- collisions produce charmonium states （J/ψ， ψ(2S), χ_{cJ} and ψ(3770) etc.), charm mesons and τ lepton.

The BESIII Detector

NIM A614 (2010)



Drift Chamber (MDC)
$\sigma P/P$ (%) = 0.5%(1GeV)
$\sigma_{dE/dx}$ (%) = 6%

Super-conducting magnet (1.0 Tesla)

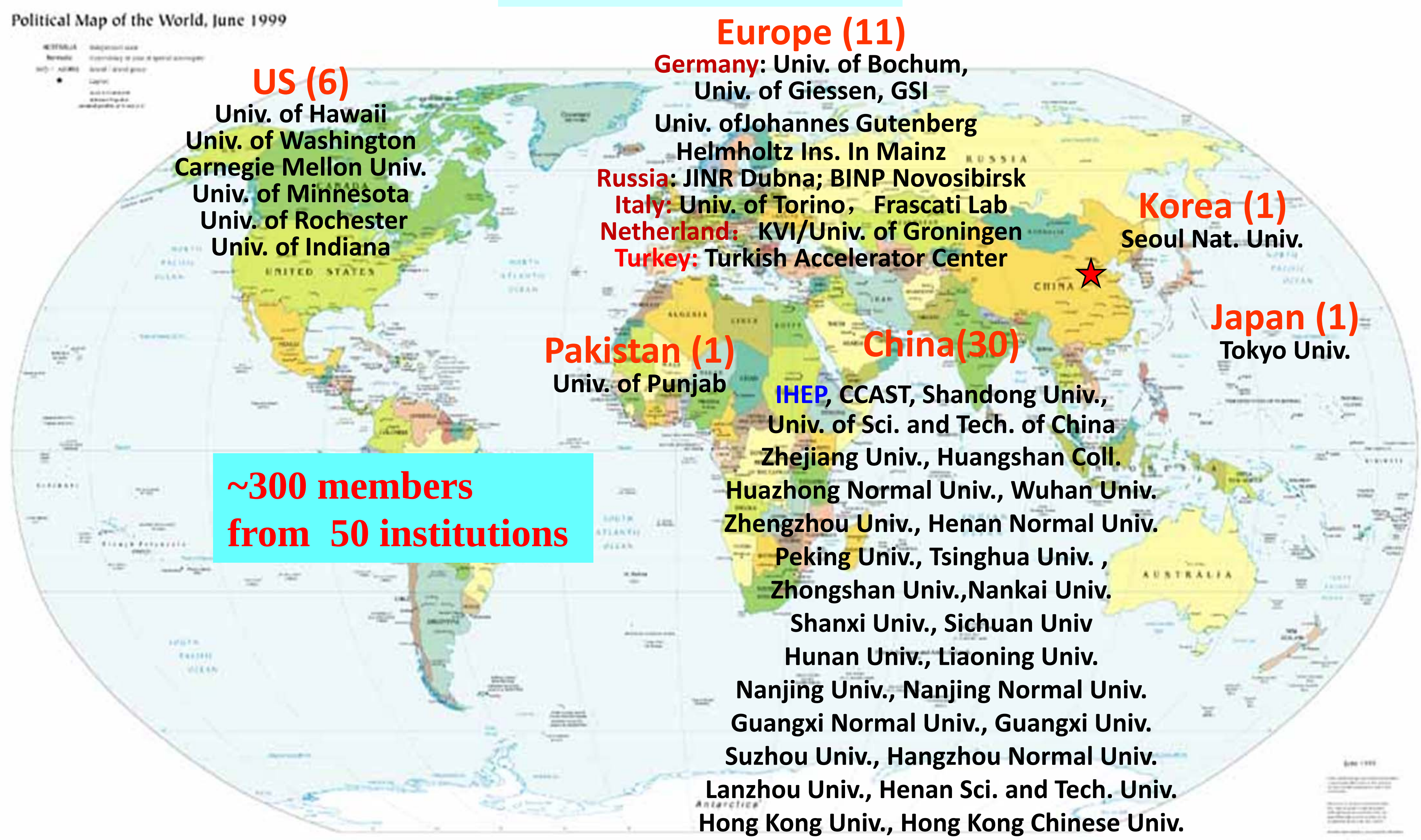
Time Of Flight (TOF)
σ_T: 90 ps Barrel
110 ps endcap

Muon Counter
9 layers RPC
$\delta R\Phi$=1.4 cm~1.7 cm

EMC: $\sigma E/\sqrt{E}$(%) = 2.5 % (1 GeV)
(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

The BESIII Collaboration

http://bes3.ihep.ac.cn



US (6)
Univ. of Hawaii
Univ. of Washington
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Europe (11)
Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. ofJohannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino， Frascati Lab
Netherland: KVI/Univ. of Groningen
Turkey: Turkish Accelerator Center

Korea (1)
Seoul Nat. Univ.

Japan (1)
Tokyo Univ.

Pakistan (1)
Univ. of Punjab

China(30)
IHEP, CCAST, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ.
Shanxi Univ., Sichuan Univ
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Hong Kong Univ., Hong Kong Chinese Univ.

~300 members
from 50 institutions

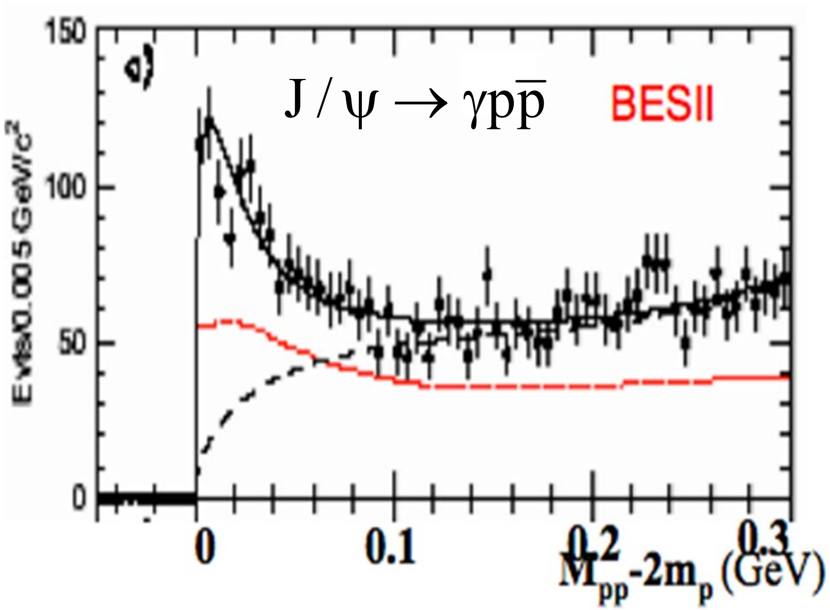
BESIII commissioning

- July 19, 2008: first e^+e^- collision event in BESIII
- Nov. 2008: ~ 14M $\psi(2S)$ events for detector calibration
- 2009: 106M $\psi(2S)$ 4*CLEOc
  225M J/ψ 4*BESII
- 2010: 900 pb^{-1} $\psi(3770)$
- 2011: 1800 pb^{-1} $\psi(3770)$ } 3.5*CLEOc
  470 pb^{-1} @ 4.01 GeV
- 2012: $\psi(2S)$: ~0.4 billion,
- @J/ψ since April 5, ~0.7 billion (peak lum. $2.7X10^{32}$)

Peak luminosity reached $6.5 X 10^{32}$ @3770 MeV

$p\bar{p}$ enhancement at threshold

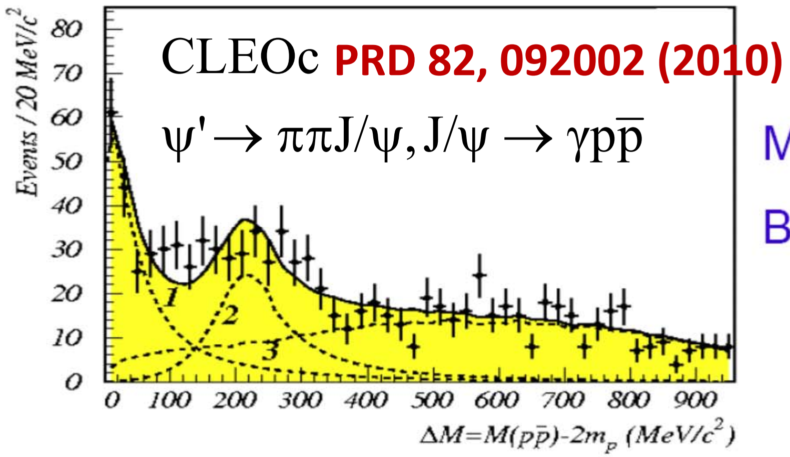
- Observed at BESII in 2003
  - M=$1859^{+3}_{-10}{}^{+5}_{-25}$ MeV
  - Width < 30 MeV (90% CL)
  - Agree with spin zero expectation



Phys. Rev. Lett., 91, 022001

- Possibilities
  - Conventional meson?
  - $p\bar{p}$ bound state/ multiquark/ glueball/ …

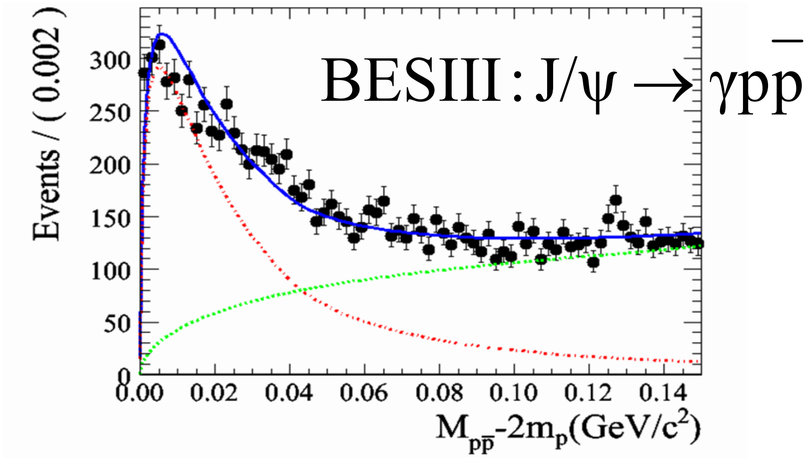
■ Confirmed by CLEOc and BESIII

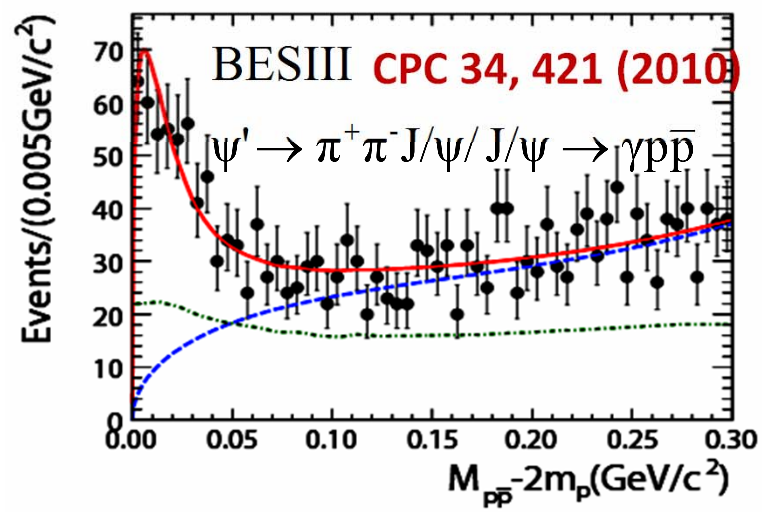


➢ **fit with one resonance as BES did:**

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

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

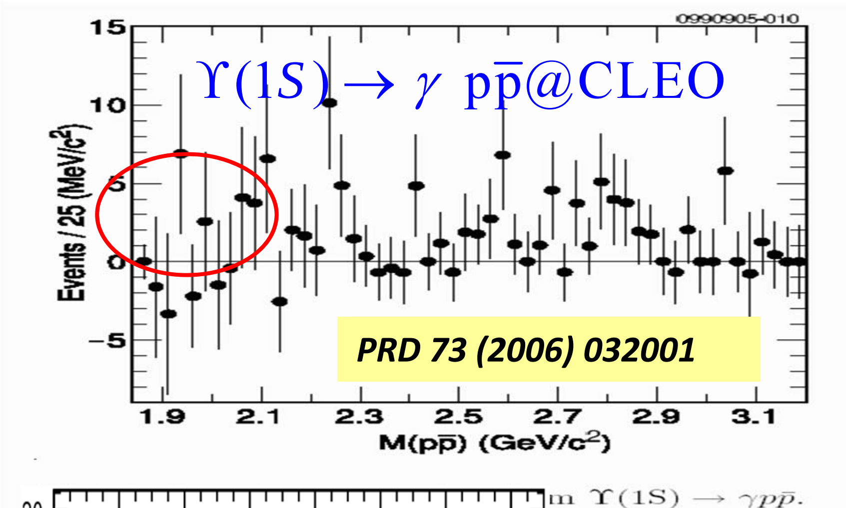


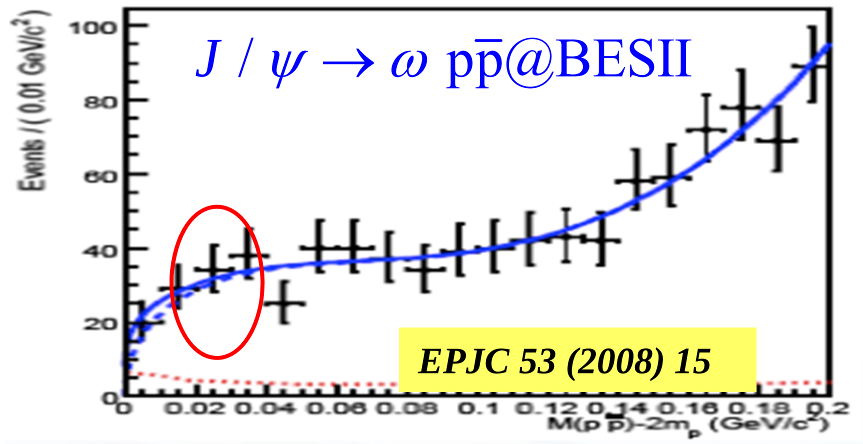


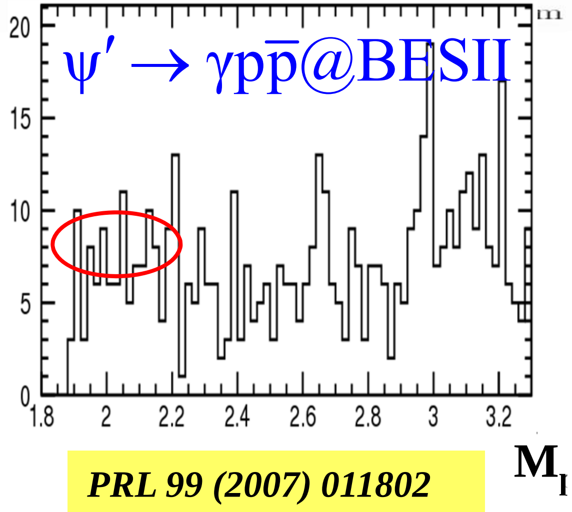
$M = 1861^{+6}_{-13}{}^{+7}_{-26}$ MeV/c²

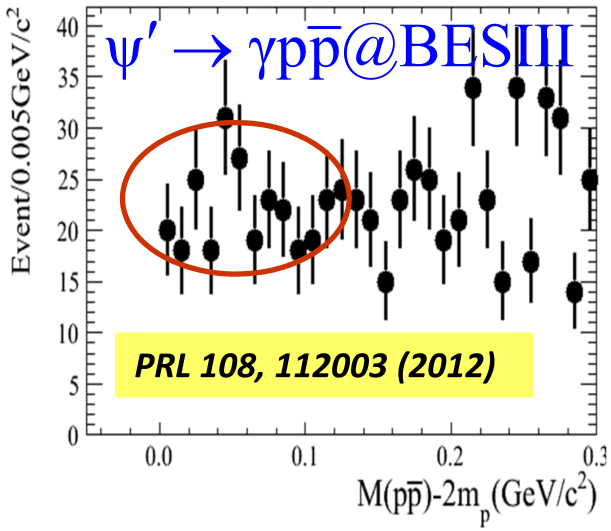
$\Gamma < 38$ MeV/c² (90% CL)

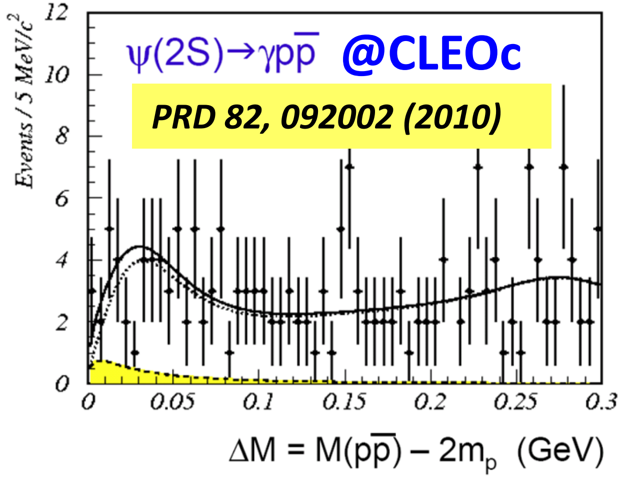
No significant narrow threshold enhancement observed here:





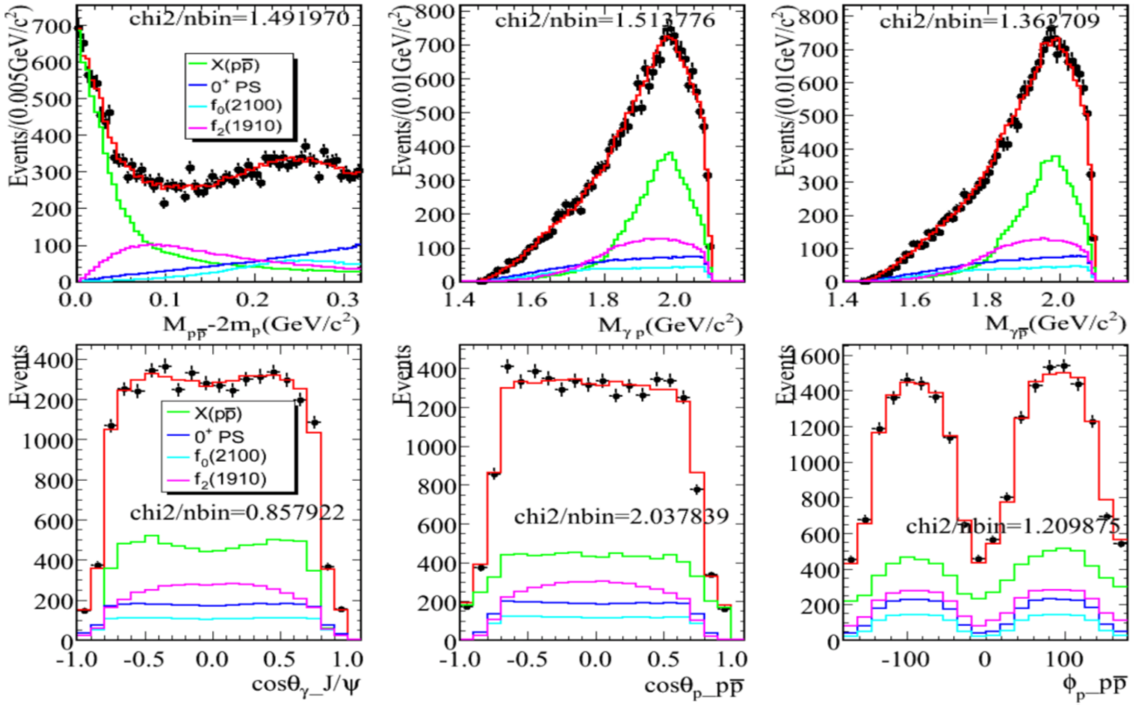






PWA of $J/\psi \to \gamma p\bar{p}$ @ BESIII

Phys. Rev. Lett. 108, 112003 (2012)



$f_0(2100)$ / $f_2(1910)$ fixed to PDG.
Signif. of X(ppbar) >>30σ

- The fit with a BW and S-wave FSI(I=0) factor can well describe ppb mass threshold structure.
- It is much better than that without FSI effect, and Δ2lnL=51 ⇒ 7.1σ.

$$J^{PC} = 0^{-+}$$

$$M = 1832^{+10}_{-5}(\text{stat.})^{+18}_{-17}(\text{syst.}) \pm 19(\text{model})\ \text{MeV}/c^2$$

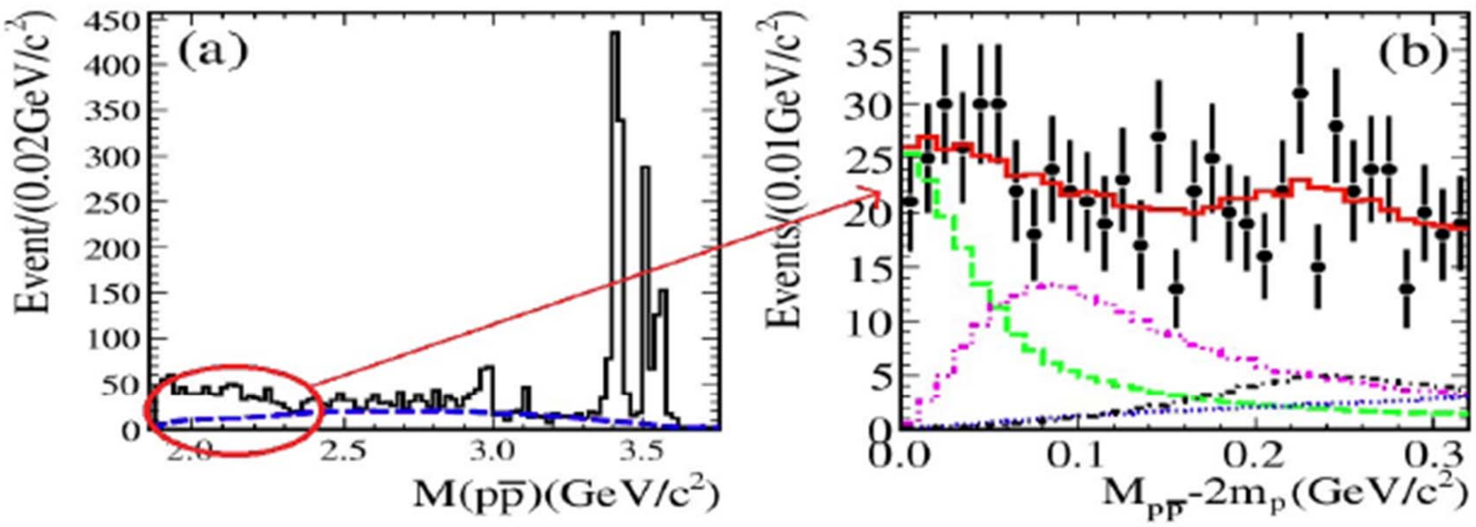
$$\Gamma = 13 \pm 39(\text{stat.})^{+10}_{-13}(\text{syst.}) \pm 4(\text{model})\ \text{MeV}/c^2 (\Gamma < 60\text{MeV}/c^2\ @\ 90\text{C.L.})$$

$$Br(J/\psi \to \gamma X)Br(X \to p\bar{p}) = (9.0^{+0.4}_{-1.1}(\text{stat.})^{+1.5}_{-5.0}(\text{syst.}) \pm 2.3(\text{model})) \times 10^{-5}$$

- Different FSI models → Model dependent uncertainty

PWA of $\psi' \to \gamma p\bar{p}$ @ BESIII

Phys. Rev. Lett. 108, 112003 (2012)



$Br(\psi(2S) \to \gamma X)Br(X \to p\bar{p}) =$
$(4.57 \pm 0.36(stat.)^{+1.23}_{-4.07} \pm 1.28(model)) \times 10^{-6}$

The production ratio R:

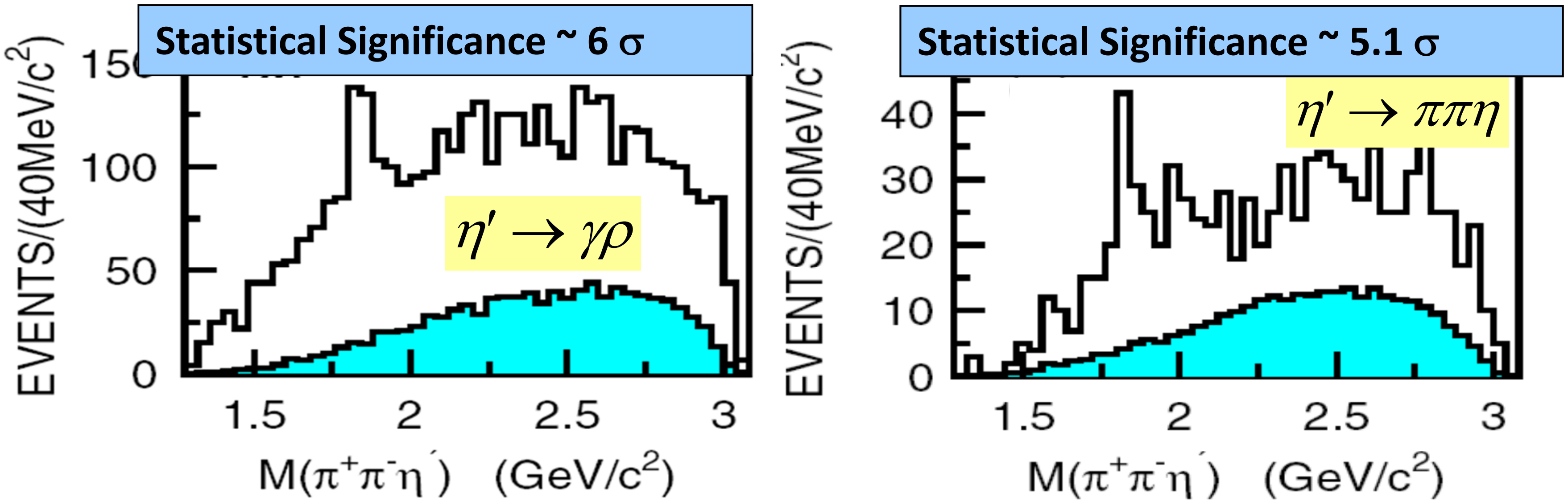
$R = \frac{Br(\psi(2S)\to\gamma X(p\bar{p}))}{Br(J/\psi\to\gamma X(p\bar{p}))} = (5.08^{+0.71}_{-0.45}(stat.)^{+0.67}_{-3.58}(syst.) \pm 0.12(model))\%$

Suppressed compared with 12% rule!

X(1835) in $\eta'\pi^+\pi^-$

$J/\psi \to \gamma\pi^+\pi^-\eta'$ @ BESII

PRL 95,262001(2005)



M=1833.7±6.1(stat)±2.7(syst)MeV

Γ=67.7±20.3(stat)±7.7(syst)MeV

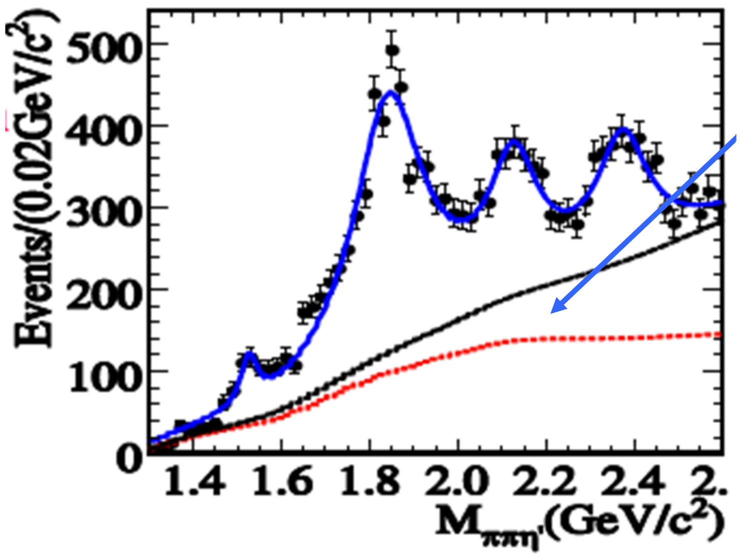
Theoretical interpretation:

- **pp̄ bound state, η excitation ....**
- **Are X(pp̄) and X(1835) from the same source?**

X(1835) in J/ψ→γπ⁺π⁻η' at BESIII PRL 108, 112003

- **Fit with four resonances** (acceptance weighted BW⊗ gaussian)
- **Three background components:**
  ① Contribution from non-η' events estimated by η' mass sideband
  ② Contribution from $J/\psi \to \pi^0\pi^+\pi^-\eta'(\eta' \to \gamma\rho)$ with re-weighting method
  ③ Contribution from "PS background"

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



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

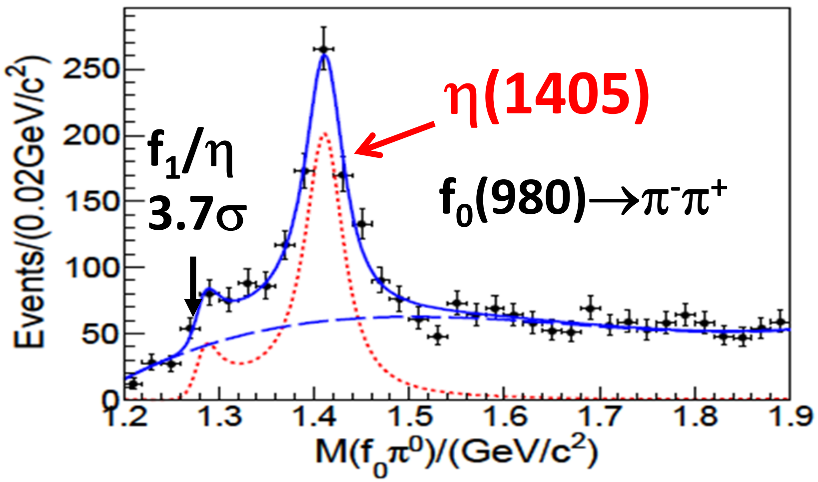
resonance	$M(\text{ MeV}/c^2)$	$\Gamma(\text{ MeV}/c^2)$	significance
X(1835)	1836.5 ± 3.0	190.1 ± 9.0	$>> 20\sigma$
X(2120)	2122.4 ± 6.7	84 ± 16	$> 7.2\sigma$
X(2370)	2376.3 ± 8.7	83 ± 17	$> 6.4\sigma$

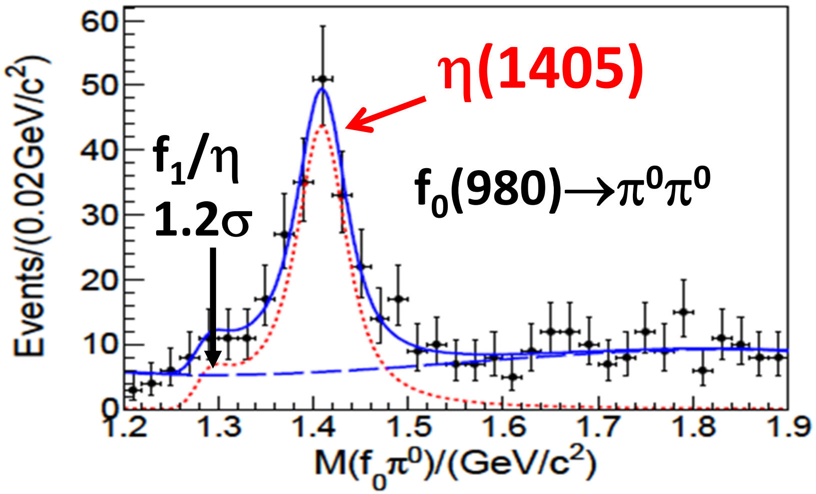
PWA is needed, inference among the resonances needs to be considered.

Study of $J/\psi \to \gamma 3\pi$

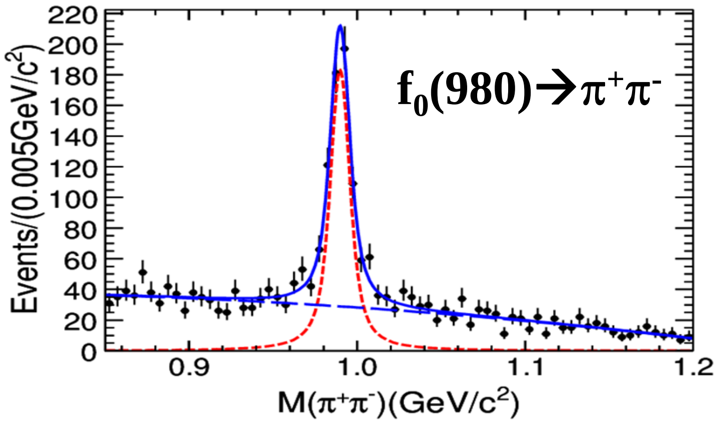
arXiv:1201:2737
accepted by PRL

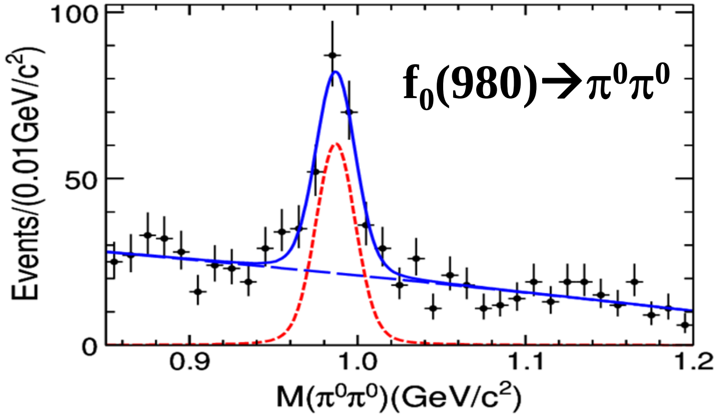
First observed: $\eta(1405) \to f_0(980)\pi^0$ (isospin breaking)





Narrow $f_0(980)$





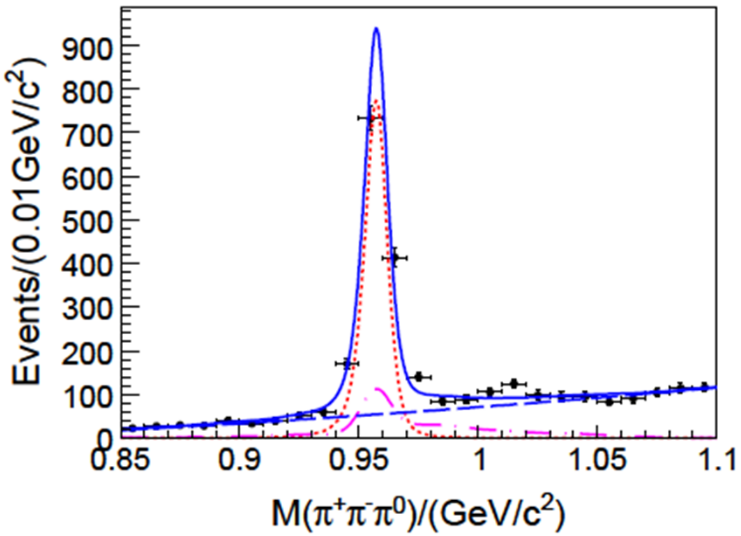
$M = 989.9 \pm 0.4$ MeV
$\Gamma = 9.5 \pm 1.1$ MeV

$M = 987.0 \pm 1.4$ MeV
$\Gamma = 4.6 \pm 5.1$ MeV

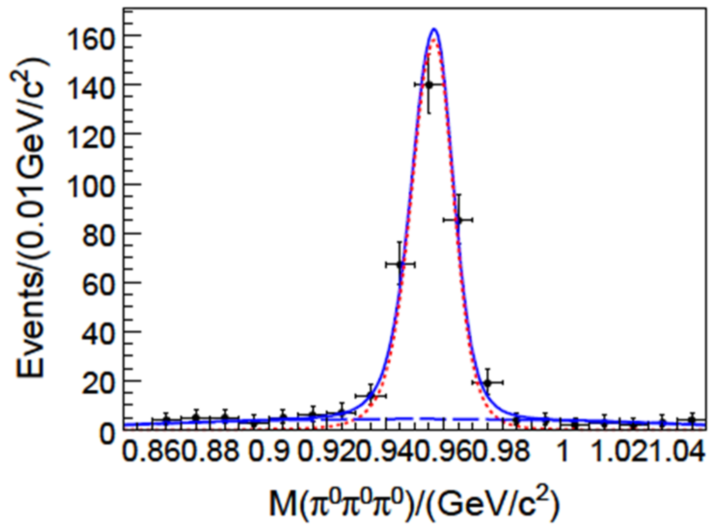
Isospin violation: $\eta' \to 3\pi$

arXiv:1201:2737
accepted by PRL

$J/\psi \to \gamma\eta' \to \pi^+\pi^-\pi^0$



$J/\psi \to \gamma\eta' \to \pi^0\pi^0\pi^0$



Large Isospin breaking: $\eta(1405)\to f_0(980)\pi^0$

arXiv:1201:2737
accepted by PRL

$$\frac{BR(\eta(1405)\to f_0(980)\pi^0)}{BR(\eta(1405)\to a_0(980)\pi)}\approx(17.9\pm4.2)\%$$

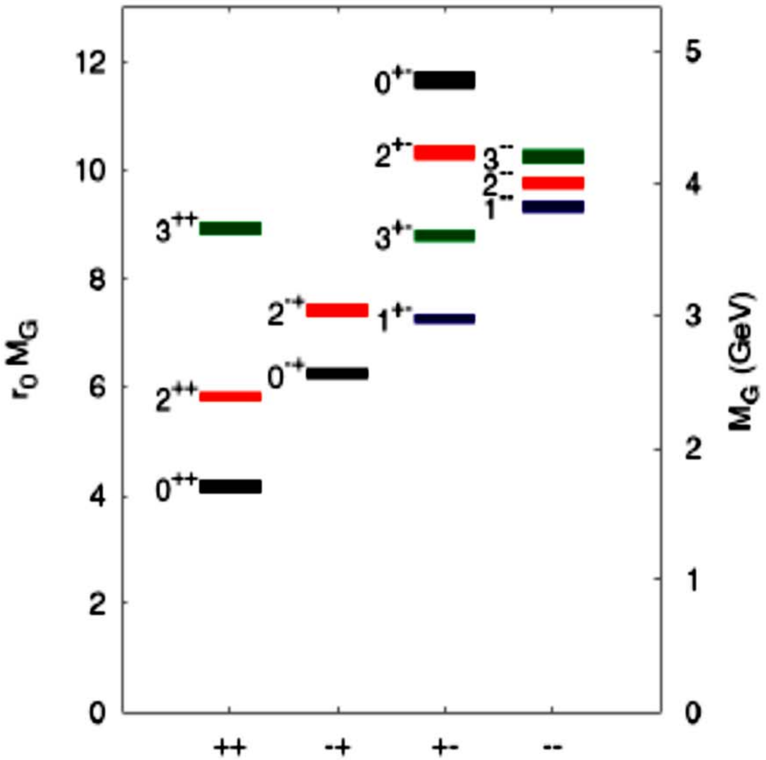
Theoretical explanation: effect of Triangle Singularity?
J.J.Wu et al., PRL 108, 081803(2012)

Isospin breaking: $\eta'\to 3\pi$

$$\frac{BR(\eta'\to\pi^+\pi^-\pi^0)}{BR(\eta'\to\pi^+\pi^-\eta)}\approx0.9\%$$

$$\frac{BR(\eta'\to\pi^0\pi^0\pi^0)}{BR(\eta'\to\pi^0\pi^0\eta)}\approx1.6\%$$

- Lattice QCD predicts the 0^{++} scalar glueball mass in the range 1.5 - 1.7 GeV.



Spectrum from quenched LQCD

Y. Chen *et al.* PRD73:014516,2006 (updates Morningstar & Peardon, '99)

0^{++} : 1710 ± 50 ± 80

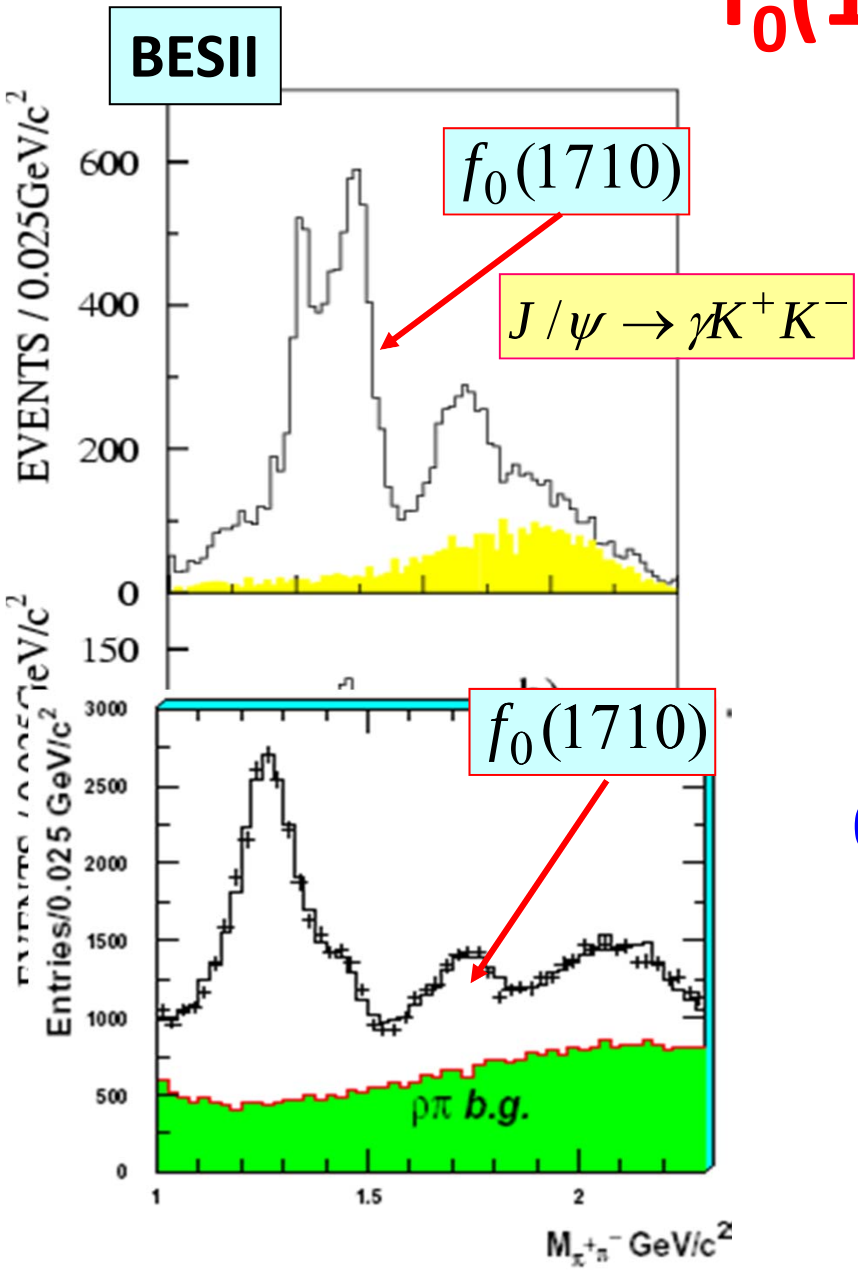
Also:
1611 ± 30 ± 160 Michael '98
1550 ± 50 ± ? Bali et al. '93

$f_0(1500)$ and $f_0(1710)$ are good candidates.

$f_0(1710)$: a long history of uncertainty.

Process	Collaboration	M(MeV)	Γ(MeV)	J^{PC}
$J/\psi \to \gamma\eta\eta$	CBAL(82)	1640 ± 50	220^{+100}_{-70}	2^{++}
$\pi^- p \to K^0_s K^0_s n$	BNL(82)	1771^{+77}_{-53}	200^{+156}_{-9}	0^{++}
$\pi^- N \to K^0_s K^0_s n$	FNAL(84)	1742 ± 15	57 ± 38	——
$\pi^- p \to \eta\eta N$	GAMS(86)	1755 ± 8	< 50	0^{++}
$J/\psi \to \gamma K^+ K^-$	MARKIII(87)	1720 ± 14	130 ± 20	2^{++}
$J/\psi \to \gamma K\bar{K}$ $\gamma\pi^+\pi^-$	DM2(88)	1707 ± 10 1698 ± 15	166 ± 33 136 ± 28	——
$pp \to ppK^+K^-$ $ppK^0_S K^0_S$	WA76(89)	1713 ± 10 1706 ± 10	181 ± 30 104 ± 30	2^{++}
$J/\psi \to \gamma K\bar{K}$	MARKIII(91)	1710 ± 20	186 ± 30	0^{++}
$p\bar{p} \to \pi^0\eta\eta$	E760(93)	1748 ± 10	264 ± 25	$(even)^{++}$
$J/\psi \to \gamma 4\pi$	MARKIII data D. Bugg *et al.*(95)	1750 ± 15	160 ± 40	0^{++}
$J/\psi \to \gamma K^+ K^-$	BES(96)	$1696 \pm 5^{+9}_{-34}$ $1781 \pm 8^{+10}_{-31}$	$103 \pm 18^{+30}_{-11}$ $85 \pm 24^{+22}_{-19}$	2^{++} 0^{++}
$J/\psi \to \gamma K\bar{K}$	MARKIII data W. Dunwoodie(97)	1704^{+16}_{-23}	124^{+52}_{-44}	0^{++}
$pp \to p_f(K^+K^-)p_s$	WA102(99)	1730 ± 15	100 ± 25	0^{++}
$pp \to p_f(\pi^+\pi^-)p_s$	WA102(99)	1750 ± 25	105 ± 34	0^{++}
$pp \to K^+K^-\pi^+\pi^-$	WA102(99)	1710 ± 16	126 ± 24	0^{++}
$pp \to p_f(K^+K^-)p_s$	WA76(99)	1710 ± 25	105 ± 34	0^{++}
$pp \to p_f\eta\eta p_s$	WA102(00)	1698 ± 18	120 ± 26	0^{++}
$J/\psi \to \gamma 4\pi$	BES(00)	1740^{+20}_{-25}	135^{+40}_{-25}	0^{++}

$f_0(1710)$



PWA analysis shows one scalar in 1.7 GeV region

$$M = 1740 \pm 4^{+10}_{-25} \ \text{MeV}$$

$$\Gamma = 166^{+5+15}_{-8-10} \ \text{MeV}$$

BESII: PRD 68 (2003) 052003

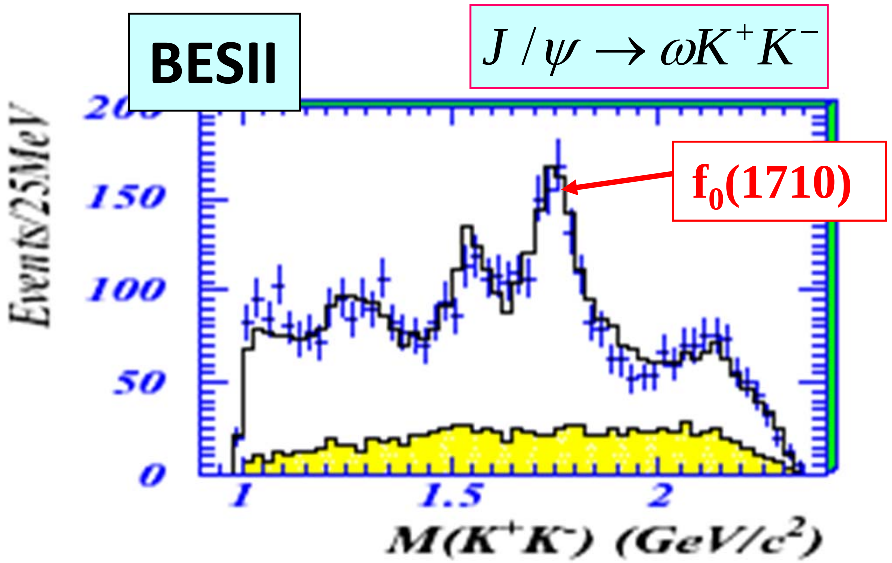
0^{++} is strongly favored in $\pi\pi$.

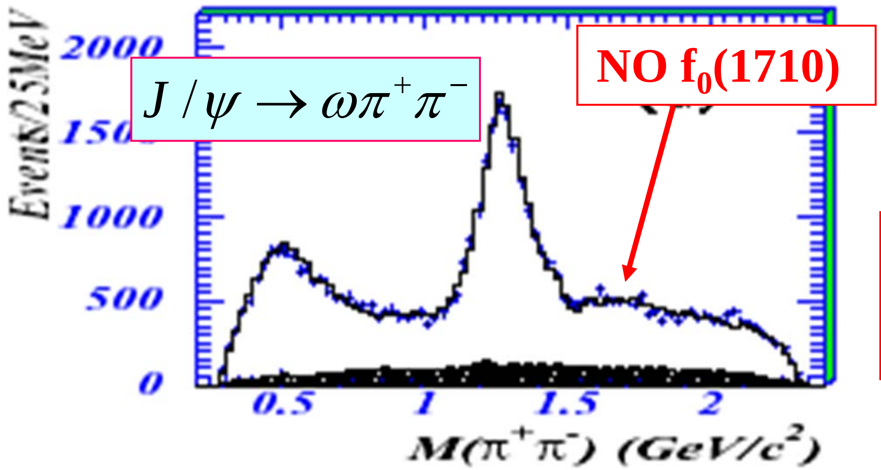
$$M = (1765^{+4}_{-3} \pm 11) \ \text{MeV}$$

$$\Gamma = (145 \pm 8 \pm 23) \ \text{MeV}$$

BESII: PRD 68 (2003) 052003

$f_0(1710)$





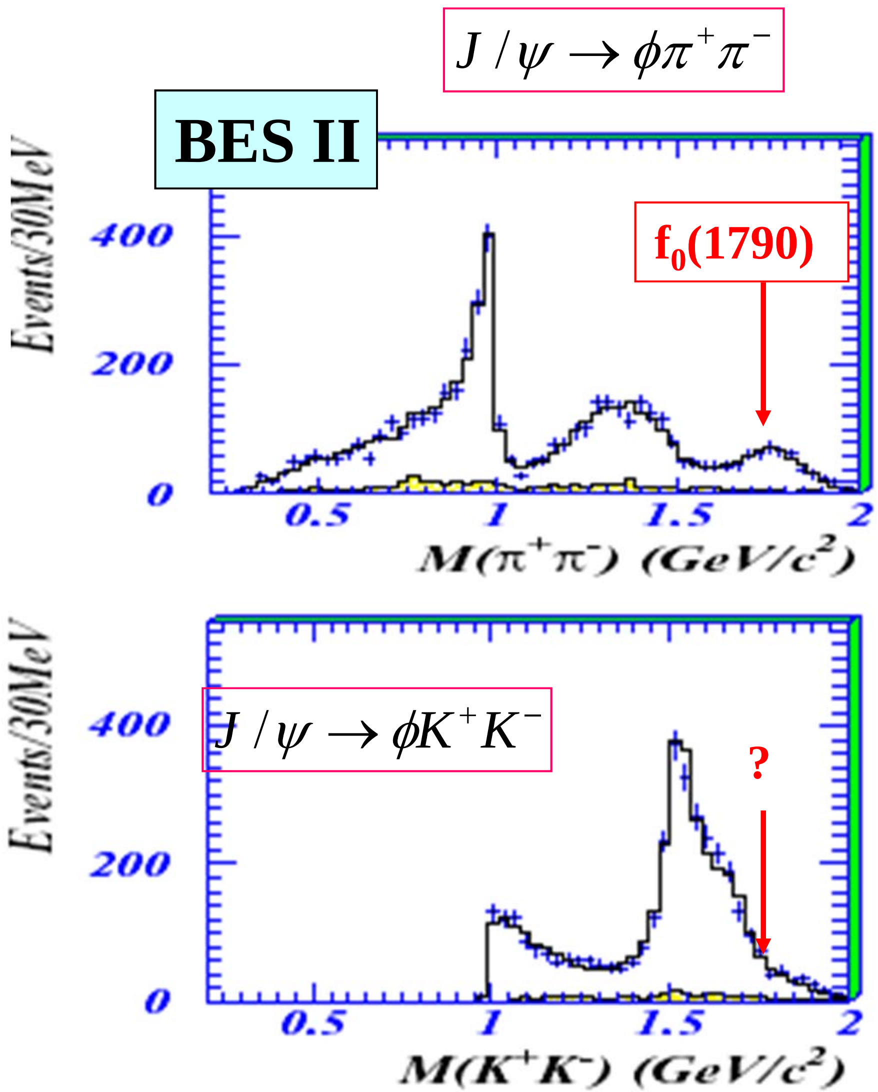
- **Clear $f_0(1710)$ peak in $J/\psi \to \omega KK$.**

$$M = 1740 \pm 30 \ MeV$$
$$\Gamma = 125 \pm 20 \ MeV$$

- **No $f_0(1710)$ observed in $J/\psi \to \omega\pi\pi$!**

$$\frac{BR(f_0(1710) \to \pi\pi)}{BR(f_0(1710) \to K\bar{K})} < 0.13 \quad @95\%CL$$

$f_0(1790)$?



- **A bump at around 1790 MeV is observed in $J/\psi \to \phi\pi\pi$.**

$$M = 1790^{+40}_{-30} \quad MeV$$
$$\Gamma = 270^{+60}_{-30} \quad MeV$$

- **No evident peak in $J/\psi \to \phi KK$. If $f_0(1790)$ were the same as $f_0(1710)$, we would have:**

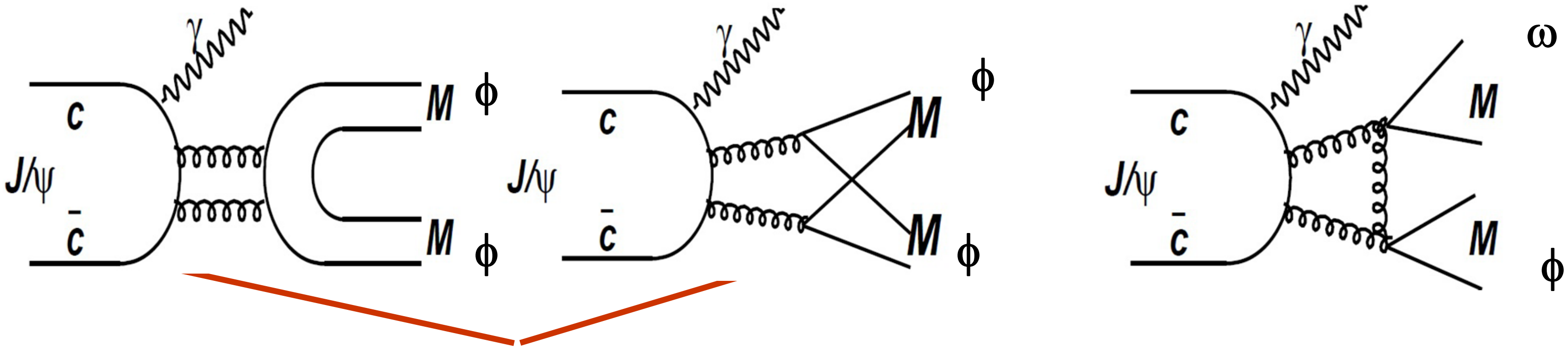
$$\frac{BR(f_0(1790) \to \pi\pi)}{BR(f_0(1710) \to K\bar{K})} \sim 1.5$$

Inconsistent with what we observed in $J/\psi \to \omega\pi\pi$, ωKK

$$\frac{BR(f_0(1710) \to \pi\pi)}{BR(f_0(1710) \to K\bar{K})} < 0.13 \quad @95\%CL$$

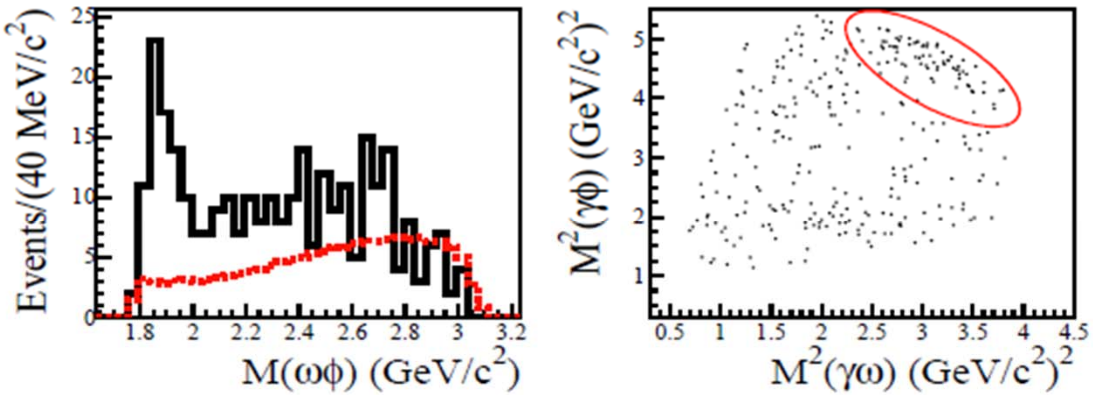
→ $f_0(1790)$ **a new scalar ?**

ωϕ threshold enhancement in $J/\psi \to \gamma\omega\phi$



$J/\psi \to \gamma\phi\phi, \phi \to K^+K^-$ **(OZI)** $J/\psi \to \gamma\omega\phi$ **(DOZI)**

BESII



$M = 1812^{+19}_{-26} \pm 18 \text{ MeV/c}^2$

$\Gamma = 105 \pm 20 \pm 28 \text{ MeV/c}^2$

J^{PC} favors 0^{++} over 0^{-+} and 2^{++}

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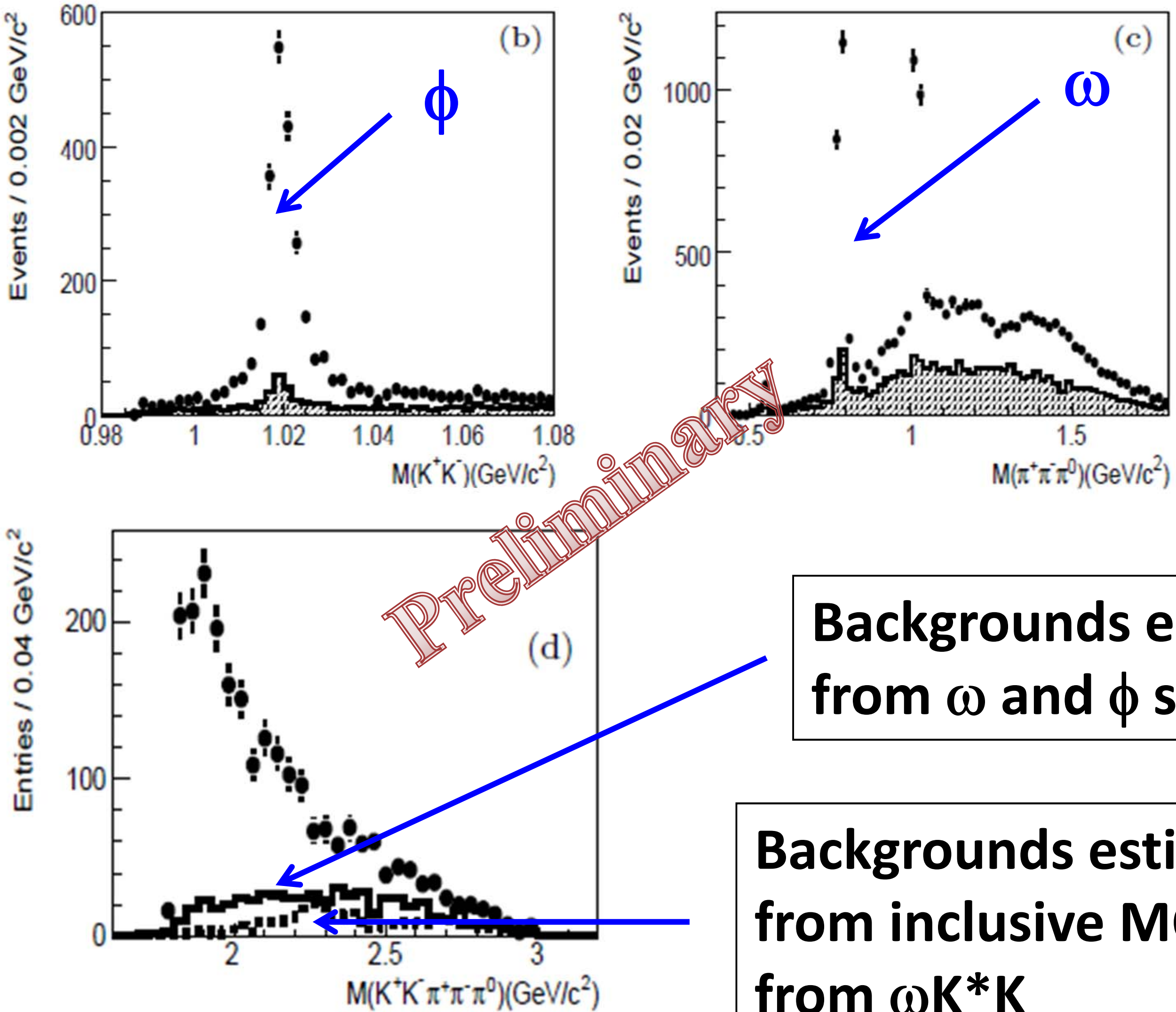
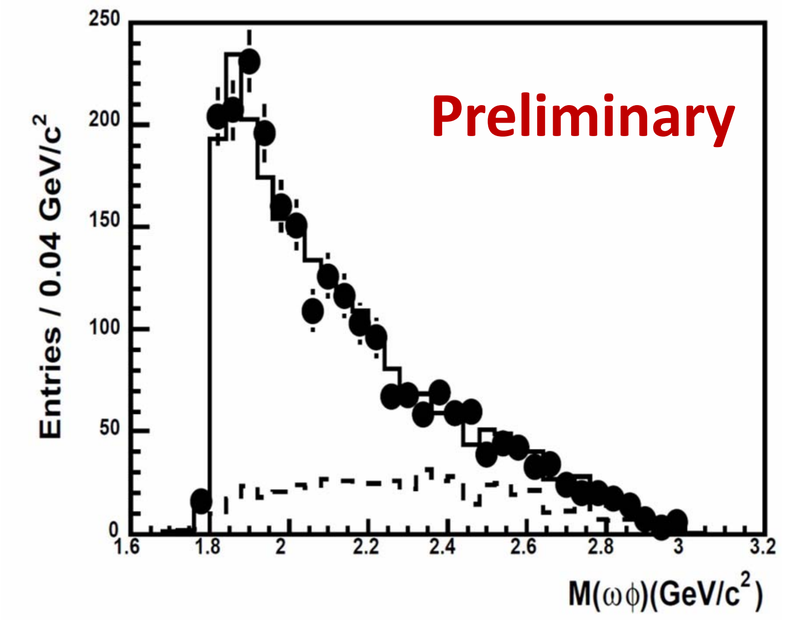
$J/\psi \to \gamma\omega\phi$ @ BESIII

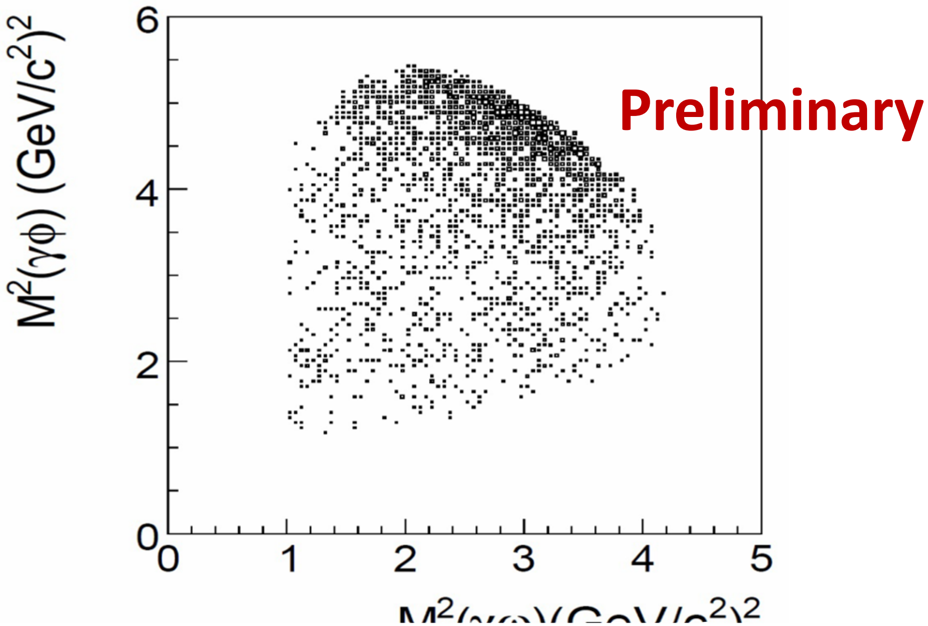


Backgrounds estimated from ω and ϕ sidebands

Backgrounds estimated from inclusive MC -- mainly from ωK^*K

Preliminary PWA results at BESIII:





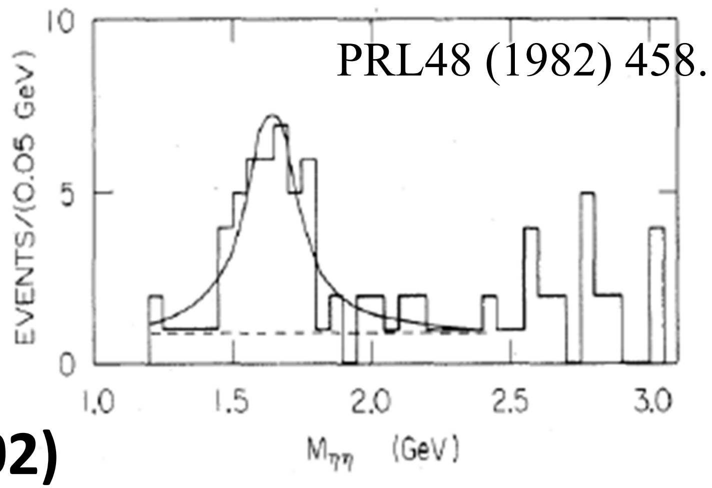
Resonance	J^{PC}	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	Significance
$X(1810)$	0^{++}	1795 ± 7	95 ± 10	$> 30\sigma$
$f_2(1950)$	2^{++}	1944	472	$> 10\sigma$
$f_0(2020)$	0^{++}	1992	442	$> 10\sigma$
$\eta(2225)$	0^{-+}	2240	1903	6.4σ

Preliminary

Is X(1810) the f_0(1710)/f_0(1790) or new state?

Study of ηη system

- First observed $f_0(1710)$ from
- J/ψ radiative decays to ηη
  by Crystal Ball in 1982.

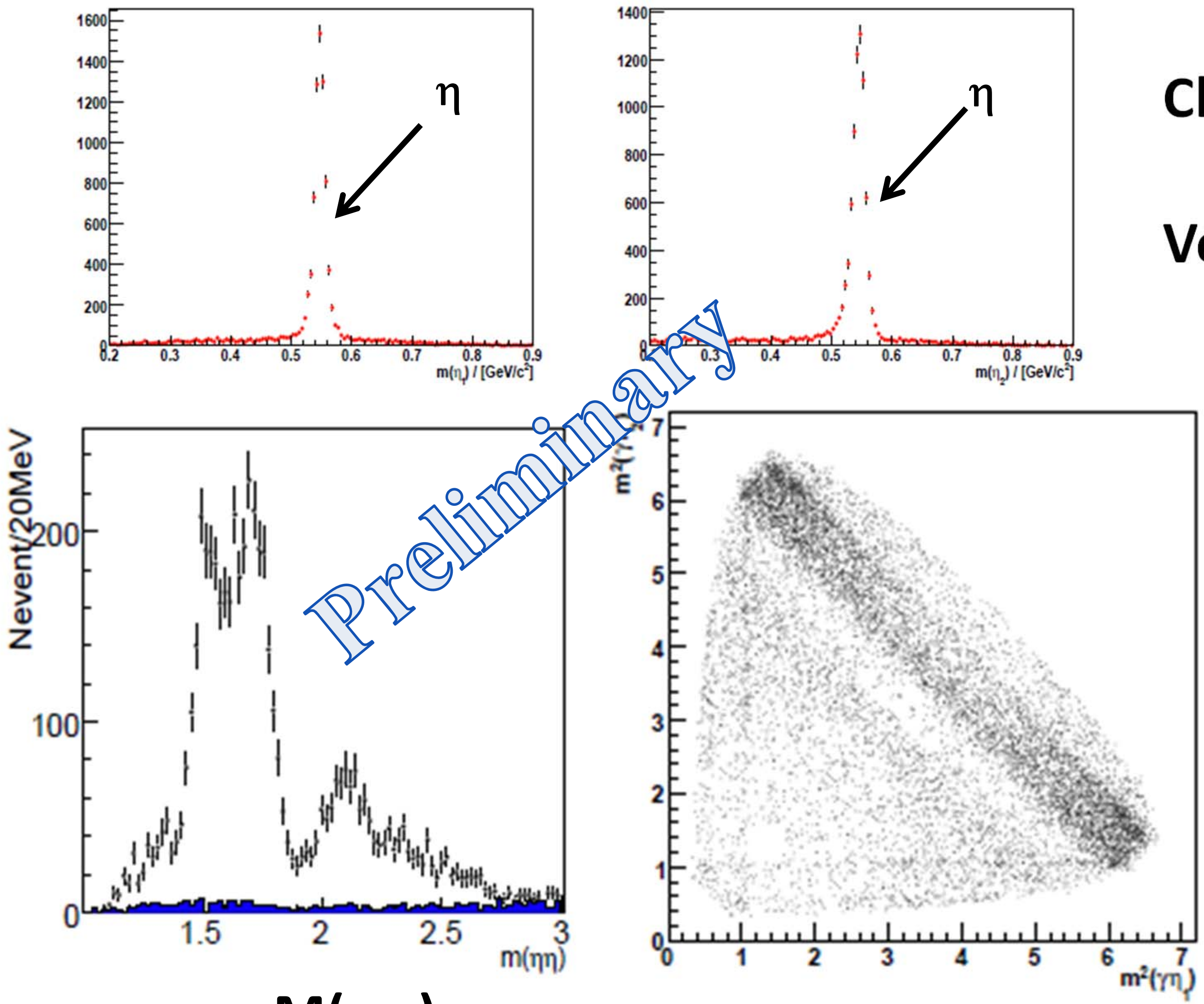


- Crystal Barrel Collaboration (2002)
  analyzed the three final states $\pi^0\pi^0\pi^0$, $\eta\pi^0\pi^0$ and $\pi^0\eta\eta$ with K matrix formalism. Found a 2^{++} (~1870), but no $f_0(1710)$.

- E835 (2006): ppbar → $\pi^0\eta\eta$, found $f_0(1500)$ and $f_0(1710)$.

- WA102 and GAMS all identified $f_0(1710)$ in ηη.

J/ψ→γηη @ BESIII

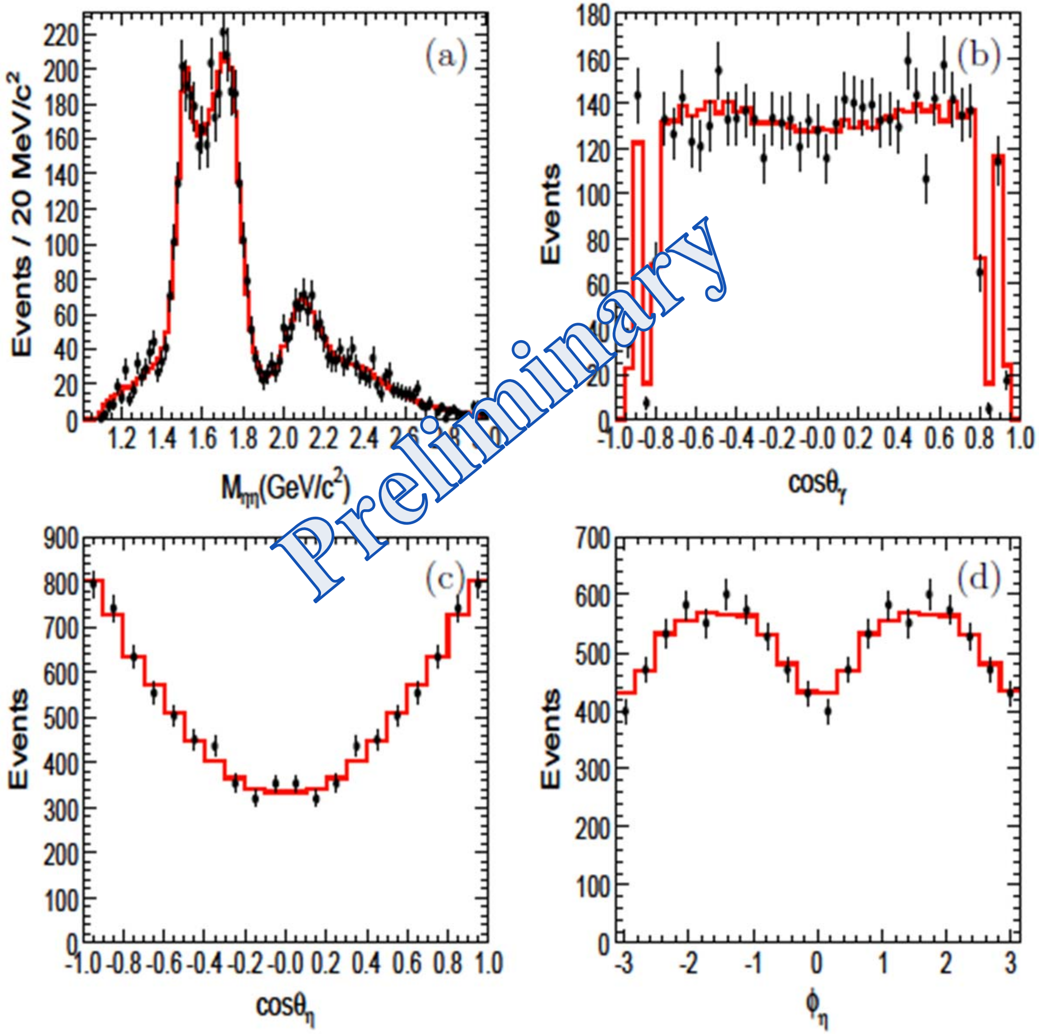


M(ηη)

Clear resonances

Very low BG level

Preliminary PWA results of $J/\psi \to \gamma\eta\eta$



- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2 σ)
- f2'(1525) is the dominant tensor

Preliminary PWA results of J/ψ→γηη

Resonance	Mass(MeV/c^2)	Width(MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+20}_{-15-74}	$136^{+41+8}_{-26-100}$	$(1.61^{+0.29+0.41}_{-0.32-1.28}) \times 10^{-5}$	8.2 σ
$f_0(1710)$	1759^{+6+14}_{-6-25}	172^{+10+31}_{-10-15}	$(2.35^{+0.07+1.23}_{-0.07-0.72}) \times 10^{-4}$	25.0 σ
$f_0(2100)$	2081^{+13+23}_{-13-34}	273^{+27+65}_{-24-18}	$(9.9[illegible]^{+0.57+5.52}_{-0.52-2.21}) \times 10^{-5}$	13.9 σ
$f_2'(1525)$	1513^{+5+3}_{-5-10}	75^{+12+15}_{-10-7}	$([illegible].41^{+0.43+1.22}_{-0.50-1.23}) \times 10^{-5}$	11.0 σ
$f_2(1810)$	1822^{+29+61}_{-24-54}	$229^{+52+64}_{-42-[illegible]}$	$(5.38^{+0.60+3.31}_{-0.67-2.24}) \times 10^{-5}$	6.4 σ
$f_2(2340)$	$2362^{+31+139}_{-30-59}$	$334^{+[illegible]+[illegible]64}_{-[illegible]-99}$	$(5.58^{+0.61+1.93}_{-0.65-1.81}) \times 10^{-5}$	7.6 σ

Summary

- 1 billion J/ψ data will come soon at BESIII
- Still a long and hard way to understand the light hadron spectroscopy. Need data from different experiments. Need a global analysis?

Thank you!