Light hadron spectroscopy at BESIII

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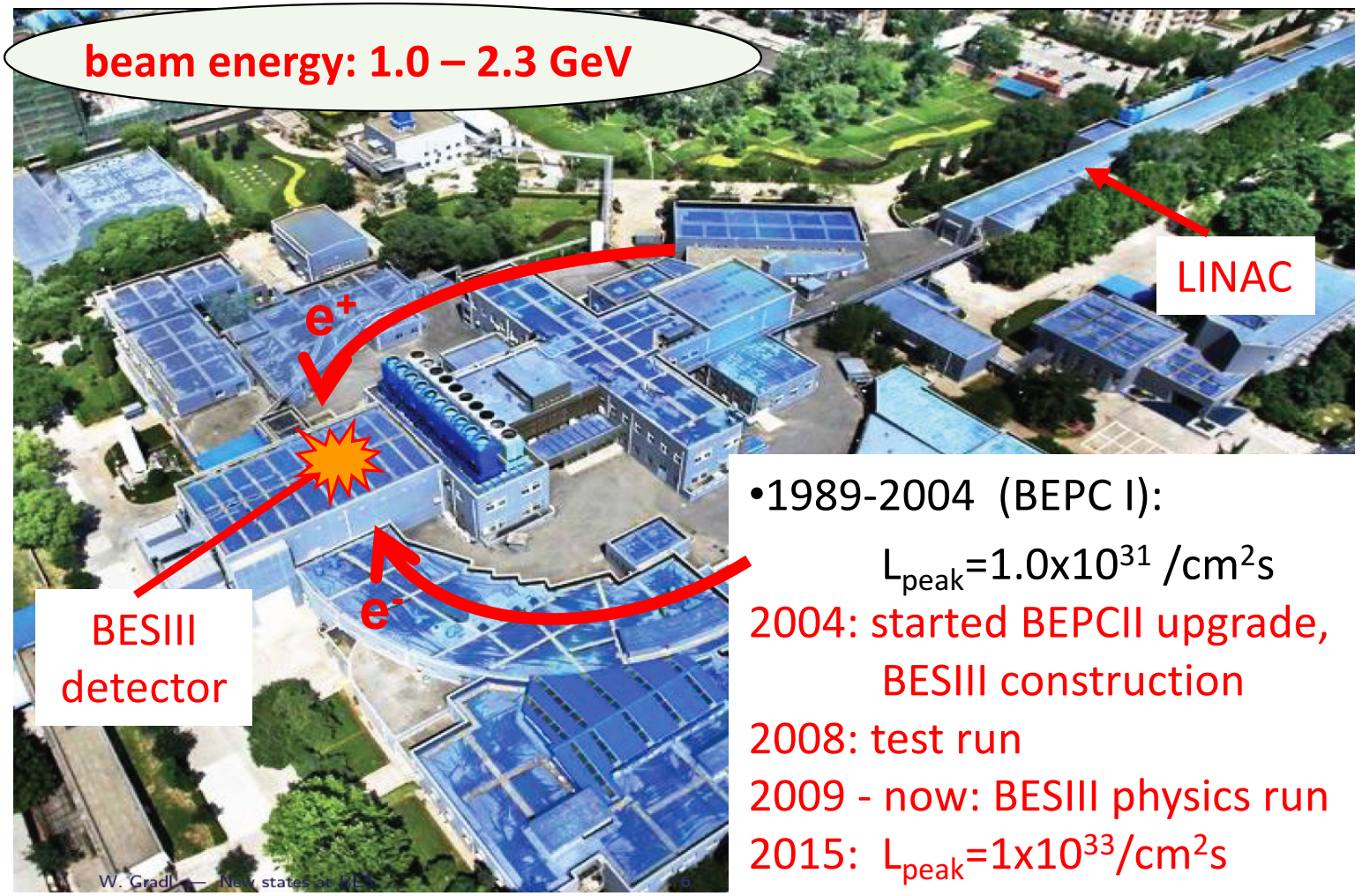
Outline

- BEPCII and BESIII
- Selected topics on Light Hadron spectroscopy
  - Light Meson spectroscopy
    - **X(1835) and X($p\bar{p}$)**
    - $J/\psi \to \gamma\eta K_S^0 K_S^0$
    - **$J/\psi \to \gamma\eta'\pi^+\pi^-$**
  - Glueball Searches
    - **PWA of $J/\psi \to \gamma\eta\eta$**
    - **MIPWA of $J/\psi \to \gamma\pi^0\pi^0$**
    - **PWA of $J/\psi \to \gamma\phi\phi$**
  - Exotic Search
    - **$\chi_{c1} \to \eta\pi^+\pi^-$**
- Summary

Beijing Electron Positron Collider II (BEPCII)



•1989-2004 (BEPC I):

$L_{peak}=1.0\times10^{31}$ /cm^{2}s

2004: started BEPCII upgrade, BESIII construction

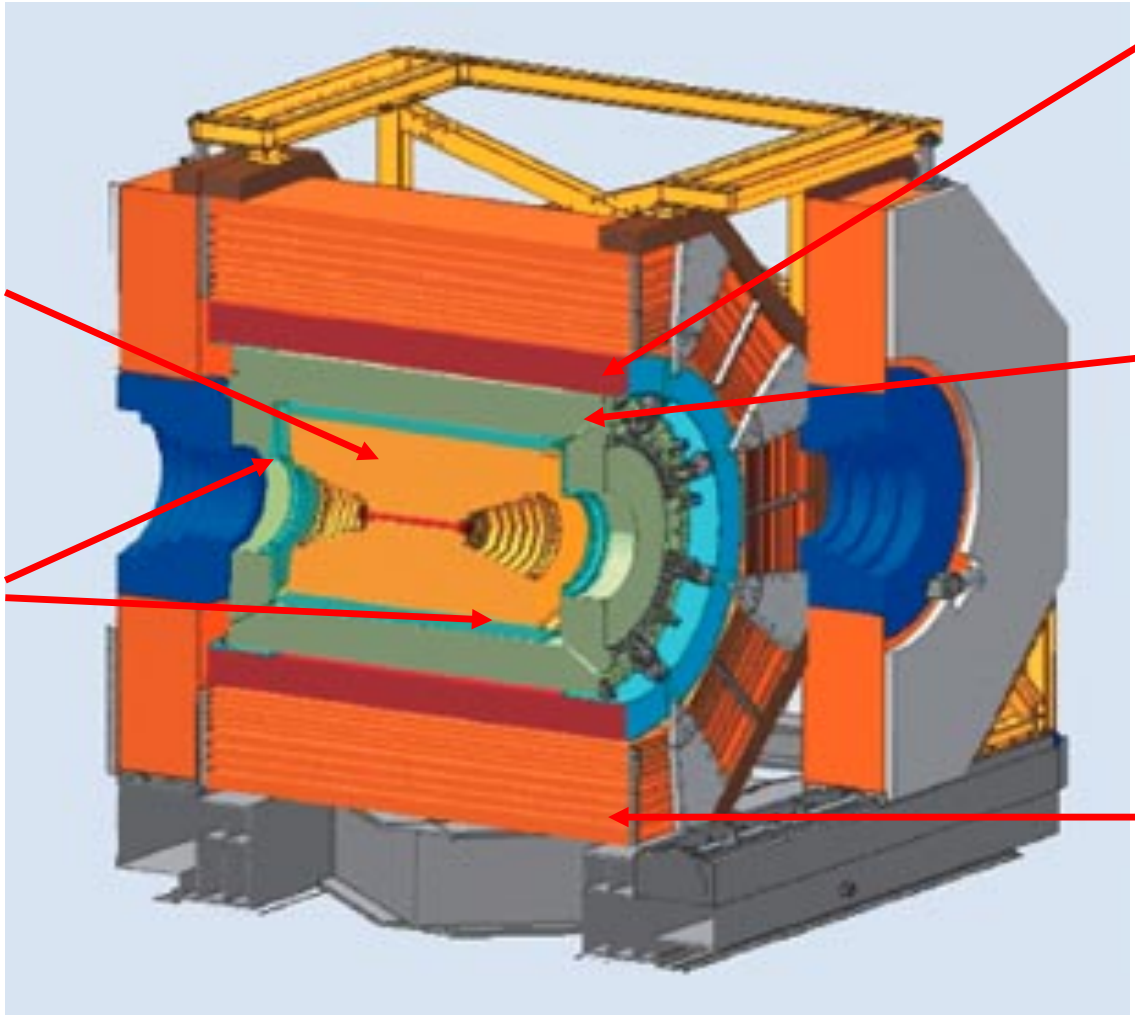
2008: test run

2009 - now: BESIII physics run

2015: $L_{peak}=1\times10^{33}$/cm^{2}s

Detector

Nucl. Instrum. Meth. A **614**, 345 (2010)



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

Time of Flight (TOF)
σ_T: 90 ps (barrel)
60 ps (endcap)

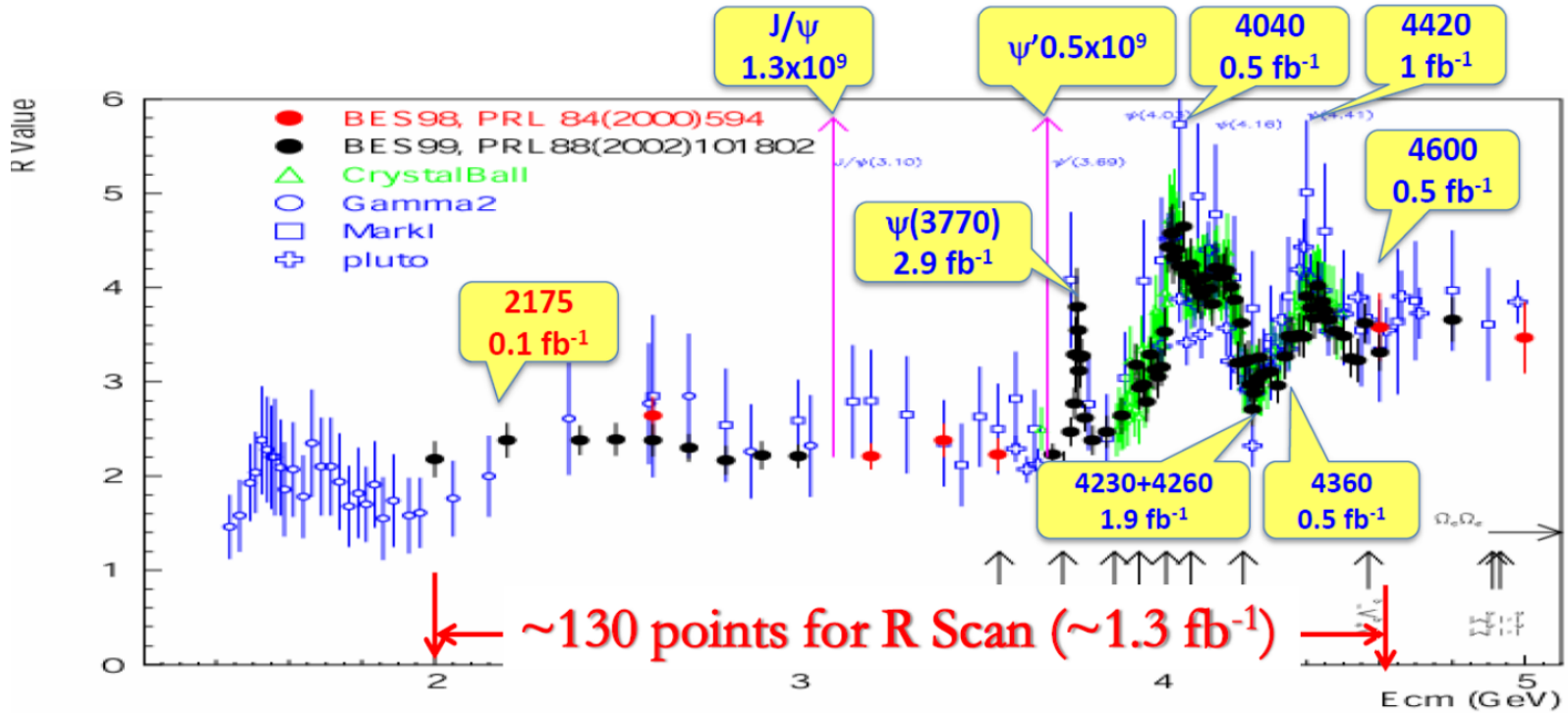
Acceptance: 93% 4π

Super-Conducting Magnet
1.0 T (2009)
0.9 T(2012)

Electromagnetic Calorimeter (EMC)
CsI (Tl)
$\sigma_E/\sqrt{E} = 2.5\%$ (1 GeV)
$\sigma_{z,\varphi} = 0.5$ - 0.7 cm$/\sqrt{E}$

μ Counter (MUC)
8 - 9 layers RPC
$\delta_{R\Phi} = 1.4$ cm ~ 1.7 cm

Data Collected at BESIII



World largest J/ψ, ψ(3686), ψ(3770), …

produced directly from e^+e^- collision — ideal factory to study hadron spectroscopy

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    - **$J/\psi \to \gamma\eta'\pi^+\pi^-$**
  - Glueball Searches
    - PWA of $J/\psi \to \gamma\eta\eta$
    - MIPWA of $J/\psi \to \gamma\pi^0\pi^0$
    - PWA of $J/\psi \to \gamma\phi\phi$
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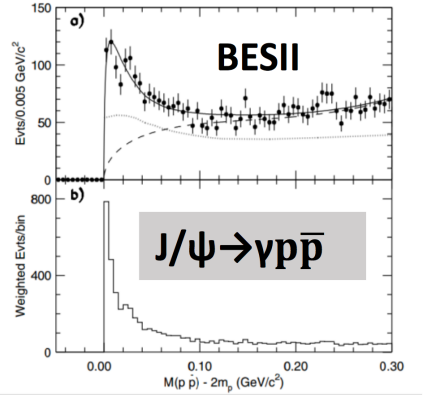
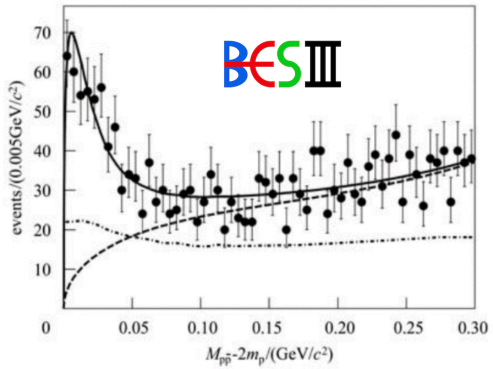
$X(p\bar{p})$

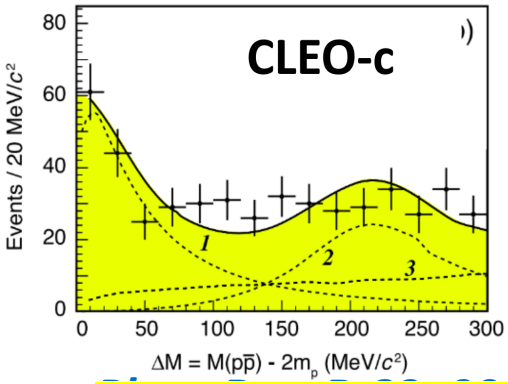
- Discovered by BESII in $J/\psi \to \gamma p\bar{p}$
- Confirmed by BESIII and CLEO-c in $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \gamma p\bar{p}$
- Confirmed by BESIII in $J/\psi \to \gamma p\bar{p}$ and its J^{pc} determined by PWA
  - $J^{pc} = 0^{-+}$
  - $M = 1832^{+19}_{-5}\ ^{+18}_{-17} \pm 19\ MeV/c^2$
  - $\Gamma = 13 \pm 39^{+10}_{-13} \pm 4\ MeV/c^2$
  - $B(J/\psi \to \gamma X)\cdot B(X \to p\bar{p}) = 9.0^{+0.4}_{-1.1}\ ^{+1.5}_{-5.0} \pm 2.3 \times 10^{-5}$



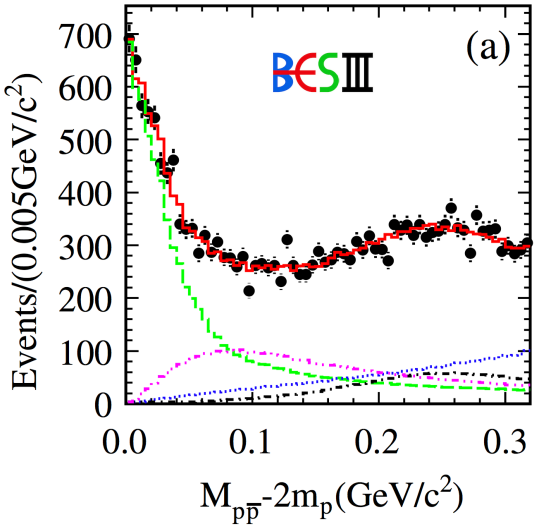
Phys. Rev. Lett. 91, 022001 (2003)



Chin. Phys. C 34, 421 (2010)



Phys. Rev. D 82, 092002 (2010)

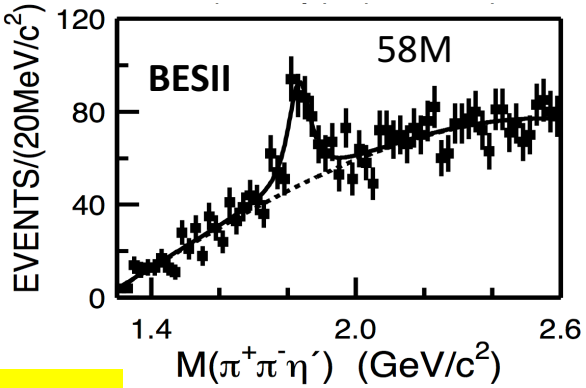


Phys. Rev. Lett. 108, 112003 (2012)

X(1835)

- Discovered by BESII in $J/\psi \to \gamma\eta'\pi^+\pi^-$
- Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi^+\pi^-$ with two η' decays
  - $M = 1836.5^{+19}_{-5} \pm 3.0^{+5.6}_{-2.1}\ MeV/c^2$
  - $\Gamma = 190 \pm 9^{+38}_{-36}\ MeV/c^2$
  - Angular distribution is consistent with 0^-
  - Observed two additional structures > 2 GeV/c^2

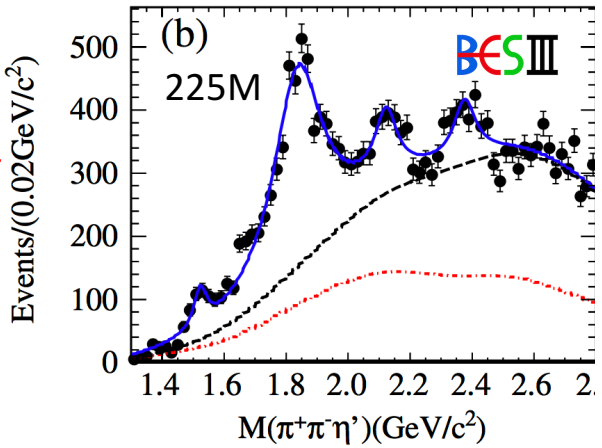
Phys. Rev. Lett. 95, 262001 (2005)

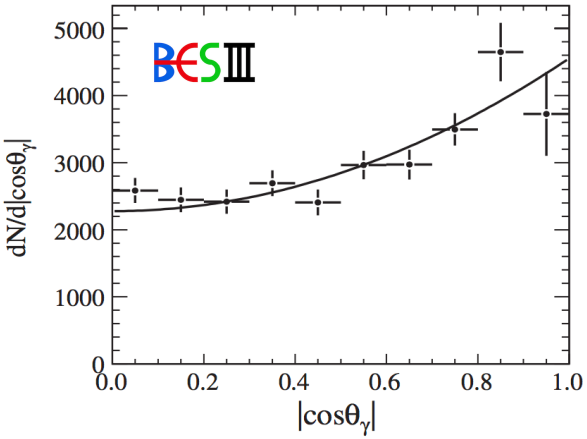


Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	N_{event}
$f_1(1510)$	1522.7 ± 5.0	48 ± 11	230 ± 37
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0	4265 ± 131
$X(2120)$	2122.4 ± 6.7	83 ± 16	647 ± 103
$X(2370)$	2376.3 ± 8.7	83 ± 17	565 ± 105

Phys. Rev. Lett. 106, 072002 (2011)

> 5.7σ
> 20σ
>7.2σ
>6.4σ

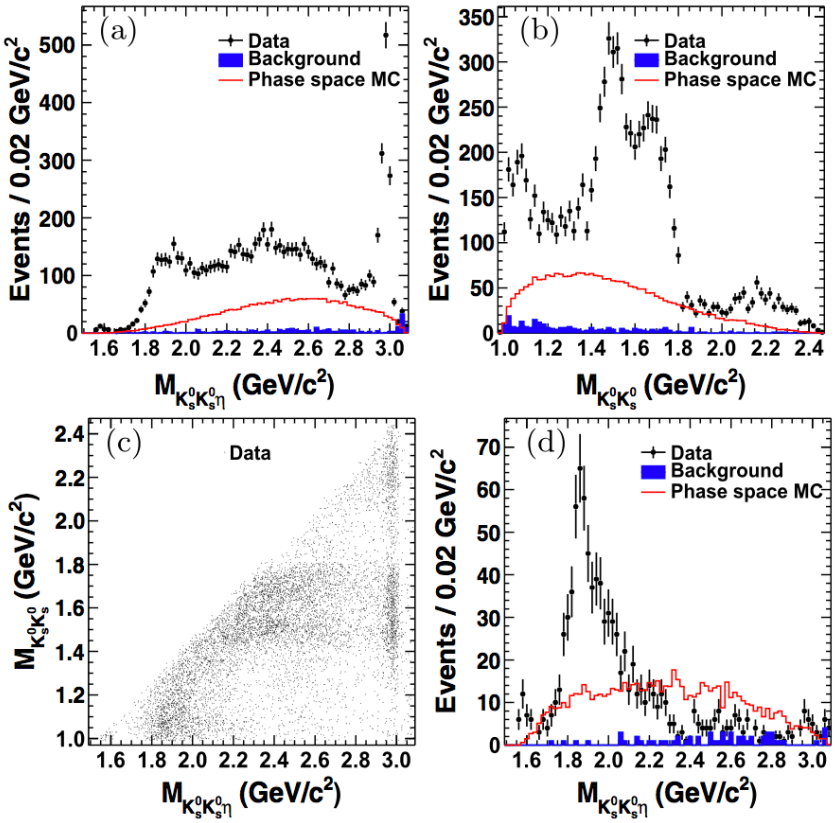




Observation of X(1835) in $J/\psi \to \gamma\eta K_S^0 K_S^0$

Phys. Rev. Lett. 115, 091803 (2015)

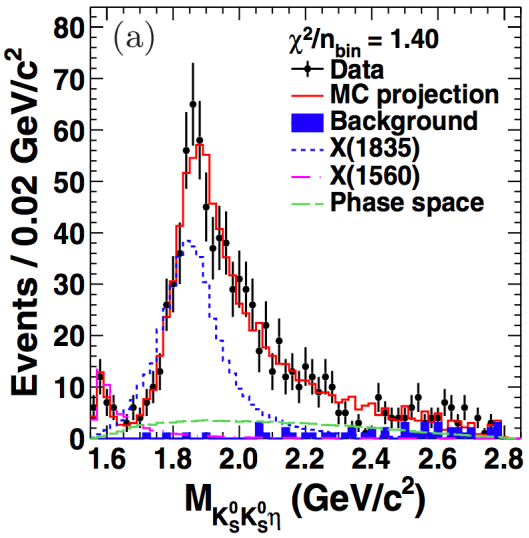
- 1.3×10^9 J/ψ events collected in 2009 and 2012
- Clear structure on mass spectrum of $K_S^0 K_S^0\eta$ around 1.85 GeV/c^2
- Strongly correlated to $f_0(980)$
- PWA for events :
  - M($K_S^0 K_S^0$) < 1.1 GeV/c^2
  - M($K_S^0 K_S^0\ \eta$) < 2.8 GeV/c^2



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

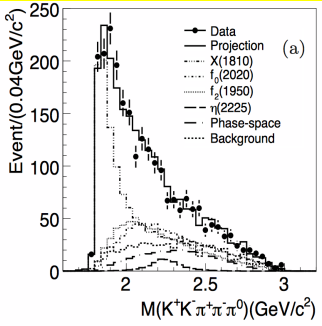
- X(1835)
  - J^{pc} determined to be 0^{-+}
  - $X(1835) \to \eta K_S^0 K_S^0$ (> 12.9 σ), dominated by $f_0(980)$ production
  - $M = 1844 \pm 9^{+16}_{-25}\ MeV/c^2$
  - $\Gamma = 192^{+20+62}_{-17-43}\ MeV/c^2$
  - $B(J/\psi \to \gamma X(1835)) \cdot B(X(1835) \to \eta K_S^0 K_S^0) = (3.31^{+0.33+1.96}_{-0.30-1.29}) \times 10^{-5}$
  - Consistent with X(1835) parameters obtained from $J/\psi \to \gamma\eta'\pi^+\pi^-$
- X(1560)
  - $J^{pc} = 0^{-+}; X(1560) \to \eta K_S^0 K_S^0$ (> 8.9 σ)
  - $M = 1565 \pm 8^{+0}_{-63}\ MeV/c^2$
  - $\Gamma = 45^{+14+21}_{-13-28}\ MeV/c^2$
  - Consistent with $\eta(1405)/\eta(1475)$ within 2.0 σ

Phys. Rev. Lett. 115, 091803(2015)

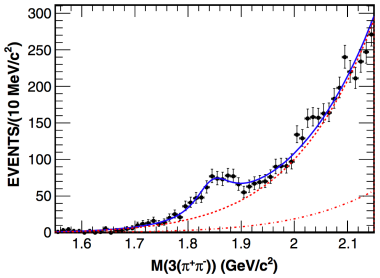


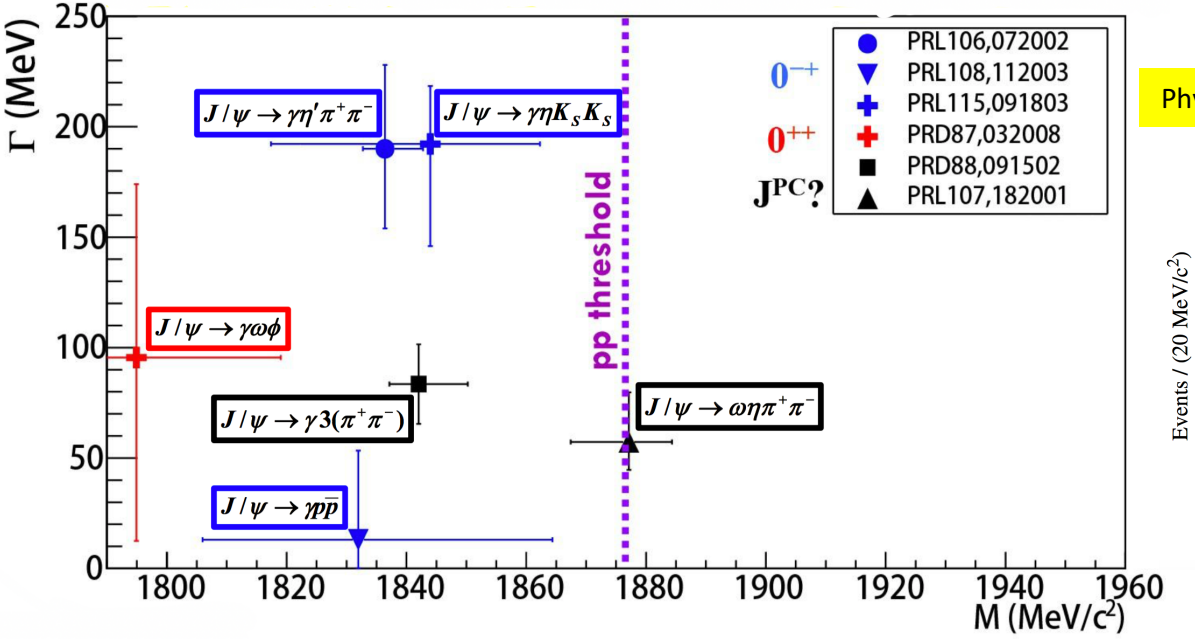
X(1835) and X($p\bar{p}$)

Phys. Rev. D 87, 032008 (2012)

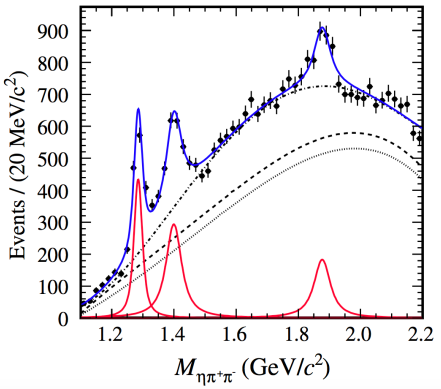


Phys. Rev. D 88, 091502 (2013)





Phys. Rev. Lett. 107, 182001 (2011)

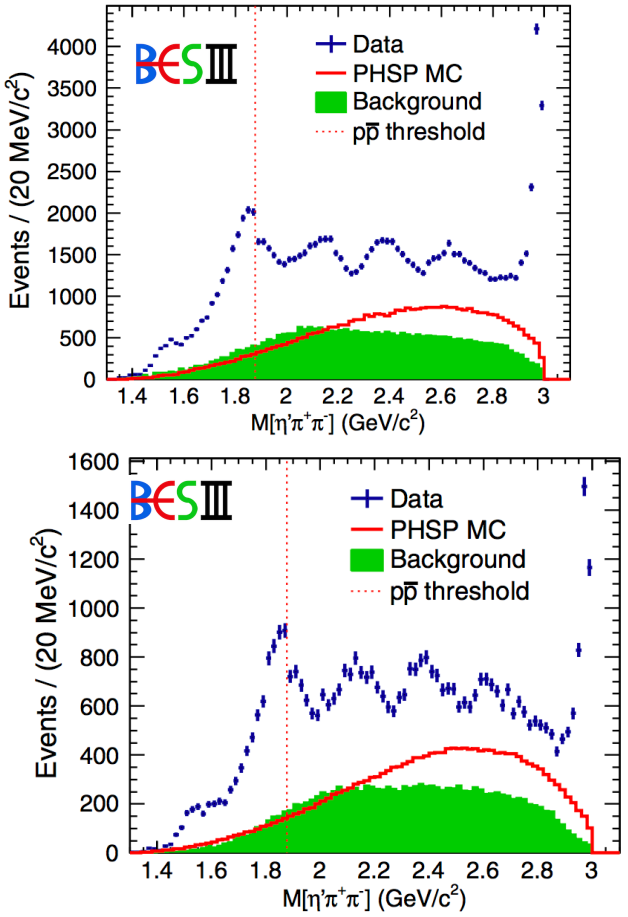


- Any relations?
- What is the role of the $p\bar{p}$ threshold (and other thresholds)?
- Patterns in the production and decay modes

Anomalous line shape of $\eta'\pi^+\pi^-$ near the $\mathbf{p\bar{p}}$ mass threshold in $\mathbf{J/\psi \to \gamma\eta'\pi^+\pi^-}$

Phys. Rev. Lett. 117, 042002 (2016)

- Use 1.09 $\times 10^9$ J/ψ events collected by BESIII in 2012
- Two decay modes of η'
  - $\eta' \to \gamma\pi^+\pi^-$
  - $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$
- Clear peaks of X(1835), X(2120), X(2370), η_c and a structure near 2.6 GeV/c^2
- A significant distortion of the $\eta'\pi^+\pi^-$ line shape near the $\mathbf{p\bar{p}}$ mass threshold



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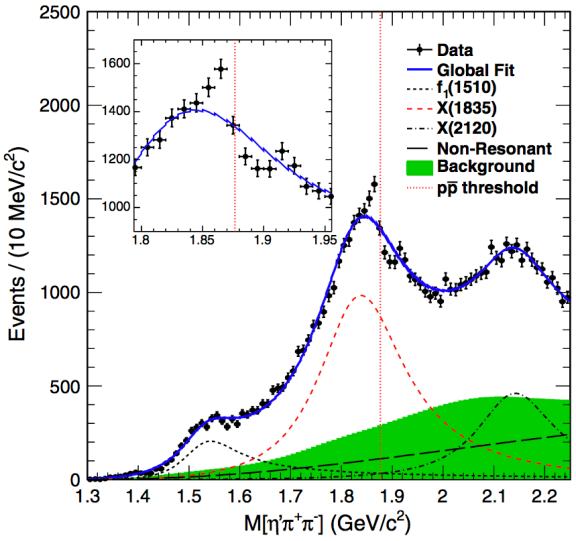
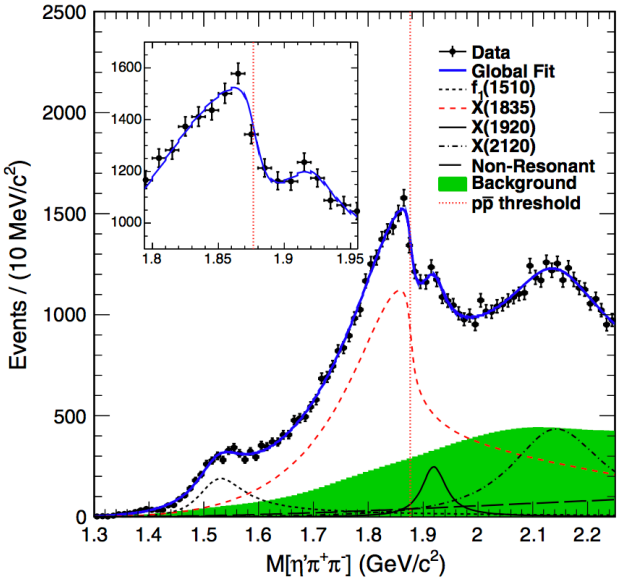
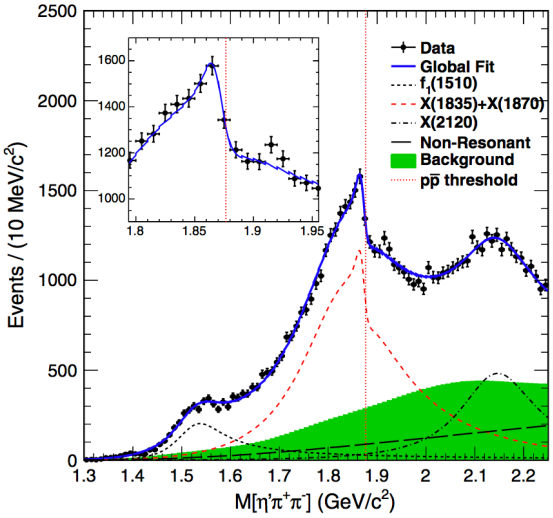
Phys. Rev. Lett. 117, 042002 (2016)



- A simple Breit-Wigner function to describe the X(1835) lineshape fails near the $p\bar{p}$ mass threshold.

- Model 1: Flatt$\acute{e}$ lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at ~1920 MeV/c^2

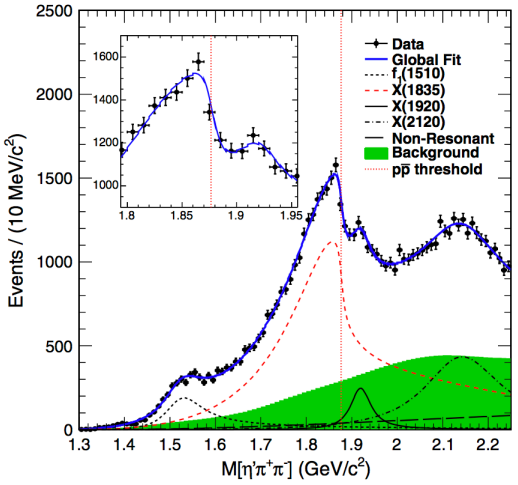


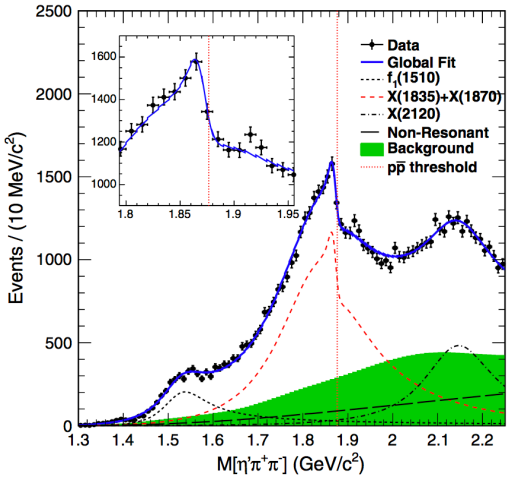


- Model 2: coherent sum of X(1835) Breit-Wigner and one additional narrow Breit-Wigner at ~1870 MeV/c^2

Anomalous line shape of $\eta'\pi^+\pi^-$ near the $p\bar{p}$ mass threshold in $J/\psi \to \gamma\eta'\pi^+\pi^-$

- Both models fit the data well with almost equally good quality
  - Cannot distinguish them with current data
  - Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold
  - Support the existence of a $p\bar{p}$ molecule-like state or bound state
- To understand the nature of the state(s)
  - Take more data
  - Study line shapes in other related decay channels





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    - $\mathbf{X(1835)}$ **and** $\mathbf{X(p\bar{p})}$
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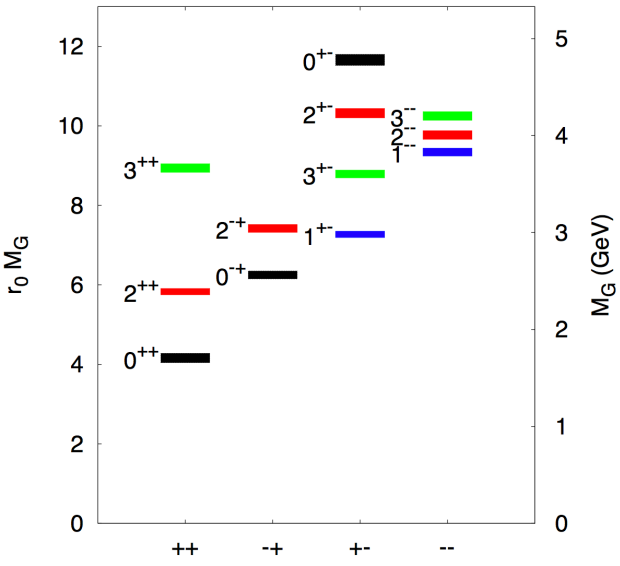
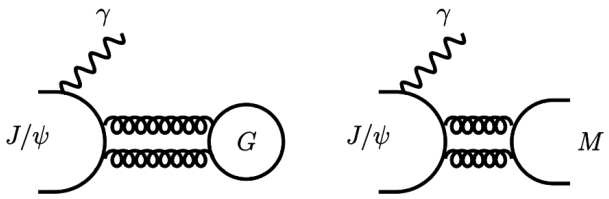
Glueballs

- Formed by gluon-gluon interaction
  - Predicted by QCD
  - Lattice QCD prediction
    - 0^{++} ground state: 1~2 GeV/c^2
    - 2^{++} ground state: 2.3~2.4 GeV/c^2
    - 0^{-+} ground state: 2.3~2.6 GeV/c^2
- Experimentally, some candidates, but not established
  - $f_0(1370), f_0(1500), f_0(1710), f_J(2220), \ldots$
- J/ψ radiative decays are believed to be an ideal place to search for glueballs

Phys. Rev. D 73, 014516 (2006)



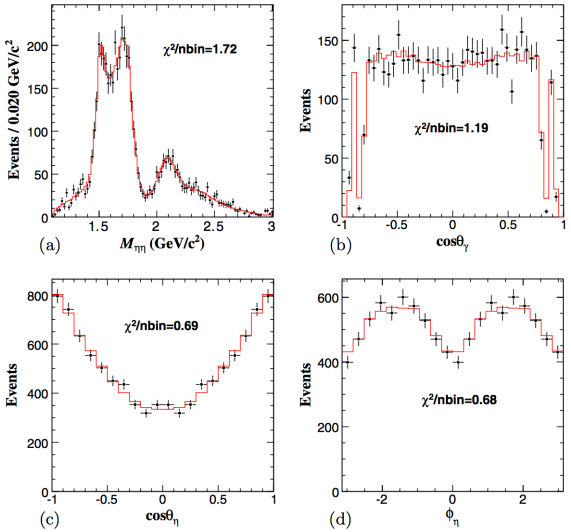


PWA of $J/\psi \to \gamma\eta\eta$

- Use 225 $\times 10^6$ J/ψ events collected by BESIII in 2009
- $f_0(1700)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4 σ and 7.6 σ)
- No evidence for $f_J(2220)$

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+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ

Phys. Rev. D 87, 092009 (2013)

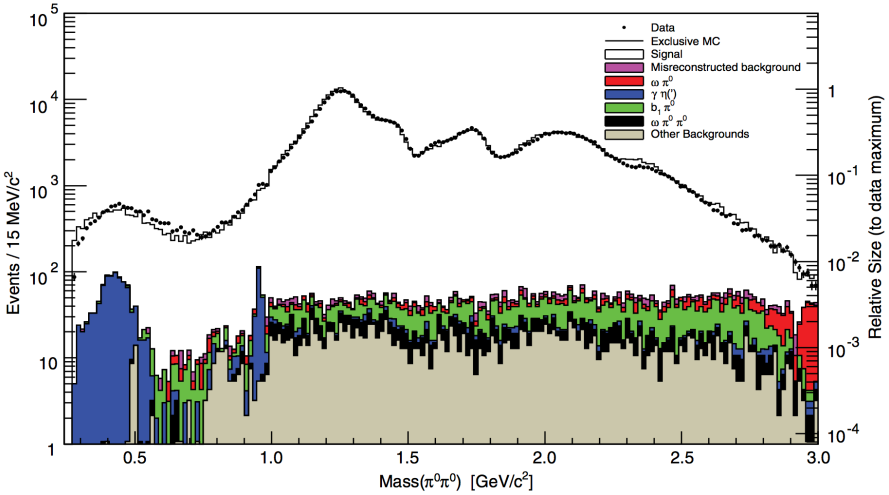


- Br. of $f_0(1700)$ and $f_0(2100)$ are ~ 10 X larger than than of $f_0(1500)$
- Possible large overlap with LQCD predictions of 0^+Glueball (PRL 110 021601)

Model Independent PWA of $J/\psi \to \gamma\pi^0\pi^0$

- Use 1.3 $\times 10^9$ J/ψ events collected by BESIII in 2009 and 2012
- $\pi^0\pi^0$ system
  - Only significant 0^{++} and 2^{++} contributions
  - Larger statistics and more open channels than $\eta\eta$ system
  - Many broad and overlapping resonances (parameterization challenging)
  - Model independent PWA

Phys. Rev. D 92, 052003 (2015)

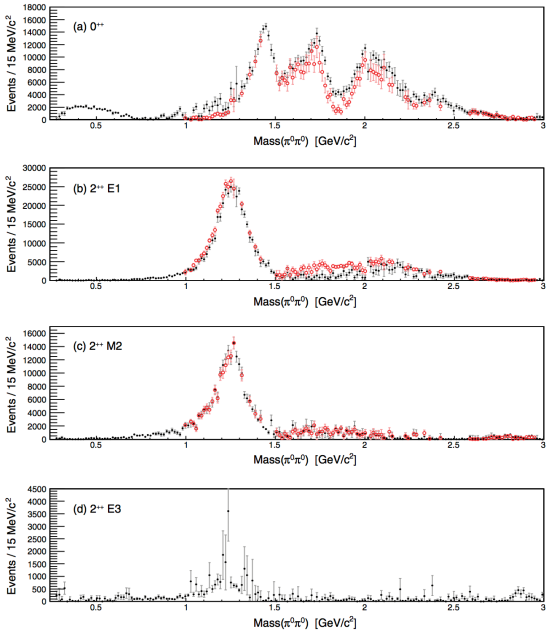


- More than 440,000 reconstructed events
- Background level ~1.8%

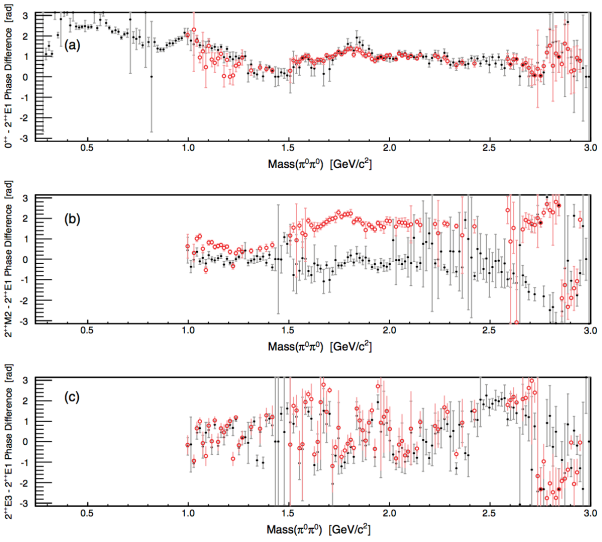
Model Independent PWA of $J/\psi \to \gamma\pi^0\pi^0$

- Extract amplitudes in each M($\pi^0\pi^0$) mass bin
- Significant features of the scalar spectrum includes structures near 1.5, 1.7 and 2.0 $\mathbf{GeV}/c\mathbf{2}$
- 2^{++} dominated by $f_2(1270)$
- Multi-solution problem in MIPWA is usually unavoidable.
- Model Dependent PWA of global PWA fit is still needed to extract resonance parameters.

Extracted Intensity



Relative Phase



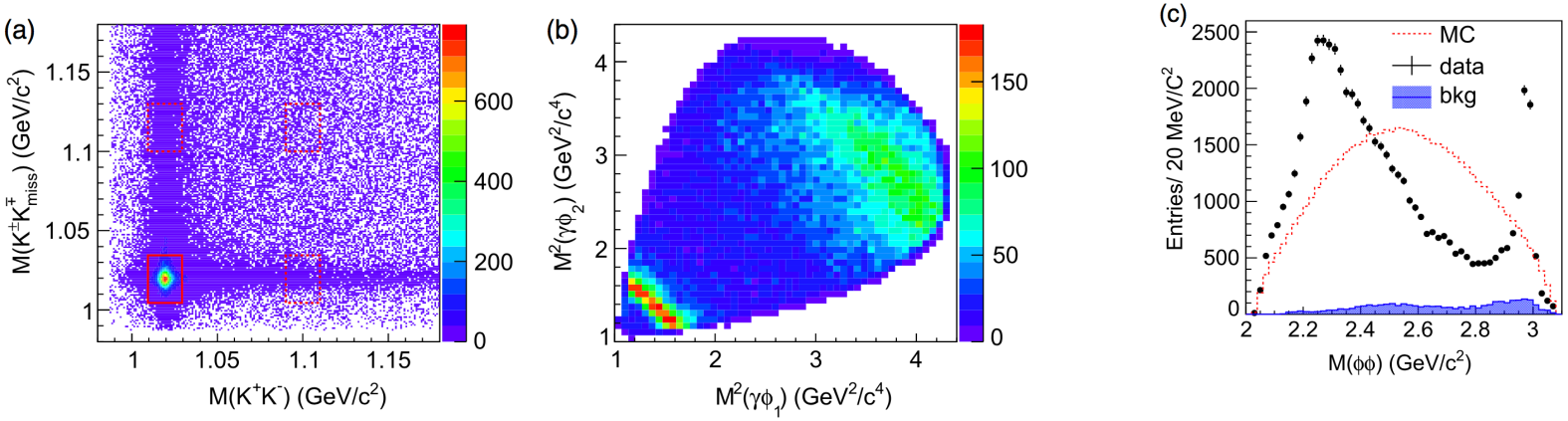
- **Nominal Solution**
- **Ambiguous Solution**

Phys. Rev. D 92, 052003 (2015)

PWA of $J/\psi \to \gamma\phi\phi$

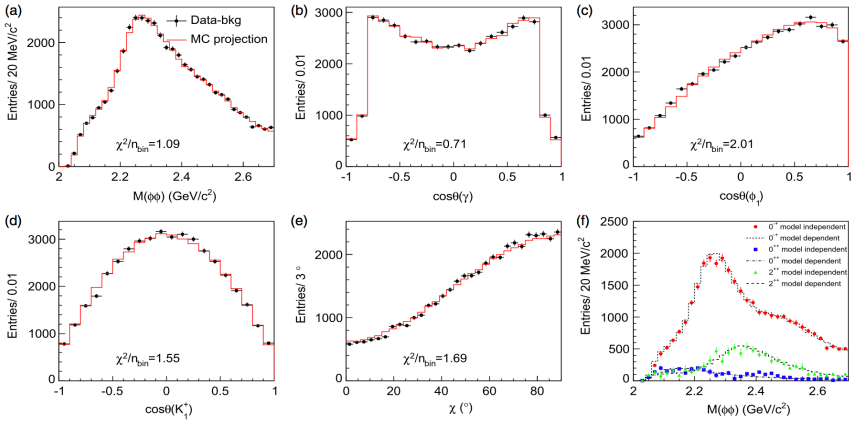
Phys. Rev. D 93, 112011 (2016)

- Besides $\eta(2225)$, little known on the pseduoscalar above 2 GeV
- New ressults help to map out the psedoscalar excitations and search for 0^{-+} glueball
- Use 1.3 $\times 10^9$ J/ψ events collected by BESIII in 2009 and 2012
- PWA procedure
  - Covariant tensor formalism
  - Data-driven background subtraction
  - Resonances are parameterized by relativistic Breit-Wigner with constant width
  - Resonances with significance $> 5\sigma$ are selected as components in solution



PWA of $J/\psi \to \gamma\phi\phi$

Phys. Rev. D 93, 112011 (2016)



Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	11σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

- Dominant contribution from pseudoscalars
  - $\eta(2225)$ is confirmed
  - $\eta(2100)$ and X(2500) are observed with large sig.
- Three tensor states
  - $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ are observed
  - Strong production of $f_2(2340)$ is compatible with LQCD prediction for tensor glueball
- Well consistent with the results from Model Independent PWA

Outline

- BEPCII and BESIII
- Selected topics on Light Hadron spectroscopy
  - Light Meson spectroscopy
    - $\mathbf{X(1835)}$ **and** $\mathbf{X(p\bar{p})}$
    - $J/\psi \to \gamma\eta K_S^0 K_S^0$
    - $\mathbf{J/\psi \to \gamma\eta'\pi^+\pi^-}$
  - Glueball Searches
    - **PWA of** $J/\psi \to \gamma\eta\eta$
    - **MIPWA of** $J/\psi \to \gamma\pi^0\pi^0$
    - **PWA of** $J/\psi \to \gamma\phi\phi$
  - Exotic Search
    - $\boldsymbol{\chi_{c1} \to \eta\pi^+\pi^-}$
- Summary

Exotics ($J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}$,…)

- J^{PC} exotic particles: beyond the naïve quark model
- Easily to distinguish from others due to the exotic J^{PC}
- Theoretically, LQCD predicts the lightest hybrid with exotic 1^{-+} is between 1.8 and 1.9 GeV, the Bag model also predicts an exotic 1^{-+} around or above 1.4 GeV
- Experimentally, $\pi_1(1400), \pi_1(1600)$ were observed in πp reaction decay to η / η' / ρ+π

Amplitude Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$

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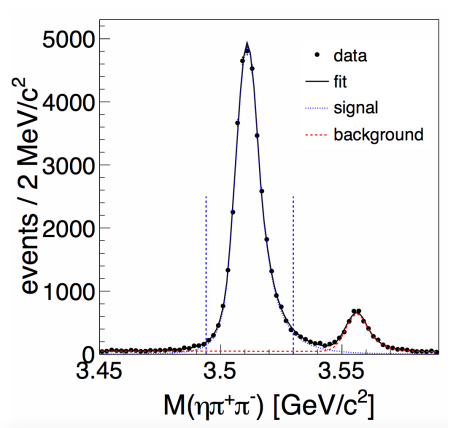
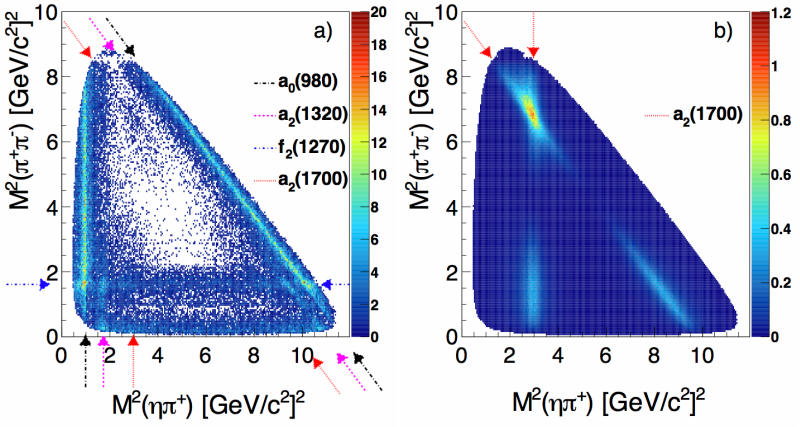
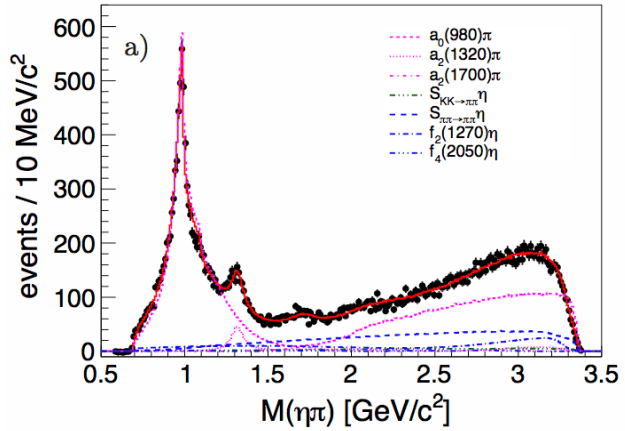
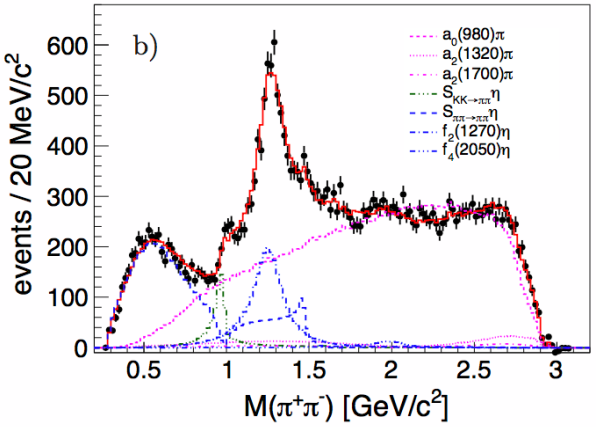
- χ_{c1} provides another suitable place to look for 1^{-+}
  - $\pi_1(1600)$ studied in χ_{c1} decays by CLEO-c
  - Only $\pi_1(1400)$ reported decaying to $\eta\pi$
- World largest χ_{c1} sample (~ 35K) from 448.0×10^6 $\psi(3686)$events
  - $\psi(3686) \to \gamma\, \chi_{c1} \to \gamma\, \eta\pi^+\pi^-$
  - Search for exotic meson with 1^{-+} in $\eta\pi, \eta'\pi$ and $\pi\pi$ final states





Amplitude Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$





Decay	$\mathcal{F}$ [%]	Significance [σ]	$\mathcal{B}(\chi_{c1} \to \eta\pi^+\pi^-)$ [10^{-3}]
$\eta\pi^+\pi^-$	...	...	$4.67 \pm 0.03 \pm 0.23 \pm 0.16$
$a_0(980)^+\pi^-$	$72.8 \pm 0.6 \pm 2.3$	> 100	$3.40 \pm 0.03 \pm 0.19 \pm 0.11$
$a_2(1320)^+\pi^-$	$3.8 \pm 0.2 \pm 0.3$	32	$0.18 \pm 0.01 \pm 0.02 \pm 0.01$
$a_2(1700)^+\pi^-$	$1.0 \pm 0.1 \pm 0.1$	20	$0.047 \pm 0.004 \pm 0.006 \pm 0.002$
$S_{K\bar{K}}\eta$	$2.5 \pm 0.2 \pm 0.3$	22	$0.119 \pm 0.007 \pm 0.015 \pm 0.004$
$S_{\pi\pi}\eta$	$16.4 \pm 0.5 \pm 0.7$	> 100	$0.76 \pm 0.02 \pm 0.05 \pm 0.03$
$(\pi^+\pi^-)_S\eta$	$17.8 \pm 0.5 \pm 0.6$	...	$0.83 \pm 0.02 \pm 0.05 \pm 0.03$
$f_2(1270)\eta$	$7.8 \pm 0.3 \pm 1.1$	> 100	$0.36 \pm 0.01 \pm 0.06 \pm 0.01$
$f_4(2050)\eta$	$0.6 \pm 0.1 \pm 0.2$	9.8	$0.026 \pm 0.004 \pm 0.008 \pm 0.001$
Exotic candidates			U.L. [90% C.L.]
$\pi_1(1400)^+\pi^-$	0.58±0.20	3.5	< 0.046
$\pi_1(1600)^+\pi^-$	0.11±0.10	1.3	< 0.015
$\pi_1(2015)^+\pi^-$	0.06±0.03	2.6	< 0.008

- Most dominant two-body structure is from $a_0(980)\pi$
- Observation of nonzero $a_0(980)$ coupling to the $\eta'\pi$
- Observed $\chi_{c1} \to a_2(1700)\pi$ for the first time ($> 17\sigma$)
- Measured upper limits for $\pi_1(1^{-+})$ in 1.4-2.0 GeV/c^2 region

Summary

- **Highlights of latest results in light hadron spectroscopy from BESIII**
  - **Observation of X(1835) in $J/\psi \to \gamma\eta K_S^0 K_S^0$**
    - **New decay mode of X(1835) $\to \eta K_S^0 K_S^0$ and J^{pc} determined to be 0^{-+}**
  - **Observation of anomalous $\eta'\pi^+\pi^-$ line shape near $p\bar{p}$ mass threshold**
    - **Support the existence of $p\bar{p}$ bound state or molecule-like state**
  - **Partial wave analysis of $J/\psi \to \gamma\eta\eta$**
    - **Strong production of $f_0(1700)$ and $f_0(2100)$**
  - **Model independent PWA of $J/\psi \to \gamma\pi^0\pi^0$**
    - **Useful information for 0^{++} and 2^{++} components**
  - **Partial wave analysis of $J/\psi \to \gamma\phi\phi$**
    - **Many 0^{-+}, 2^{++} mesons observed**
  - **Amplitude Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$**
    - **Clear evidence for $a_2(1700)$ in χ_{c1} decays and upper limit for π_1**
- **More results come soon with BESIII continuing data taking**

Thanks for your attention!