Light Meson Spectroscopy at BESIII

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On Behalf of the BESIII Collaboration

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Outline

- BEPCII and BESIII
- Light Meson Spectroscopy at BESIII
- Summary

BEPCII and BESIII

Beam energy: 1.0 ~ 2.3 GeV

Luminosity: 1.0×10^{33} $cm^{-2}s^{-1}$
(reached in April 5th, 2016)

2004: BEPCII upgrade,
BEPCIII construction

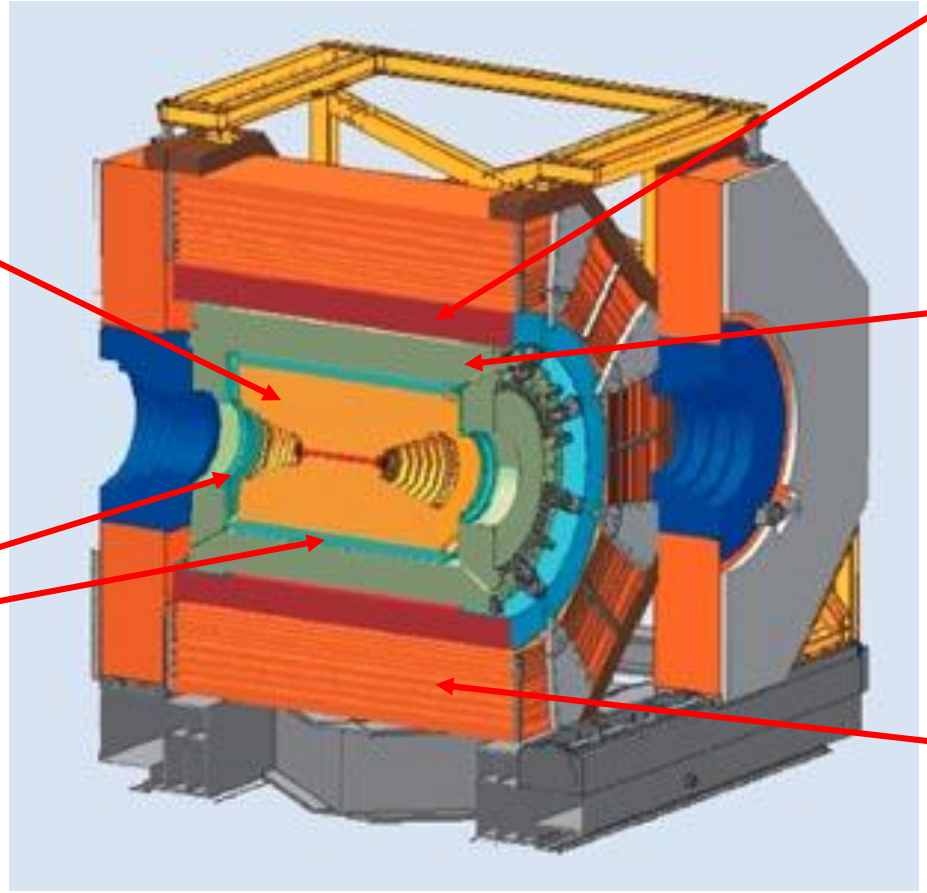
2008: test run

2009 ~ now: physics run

BEPCII and BESIII

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

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

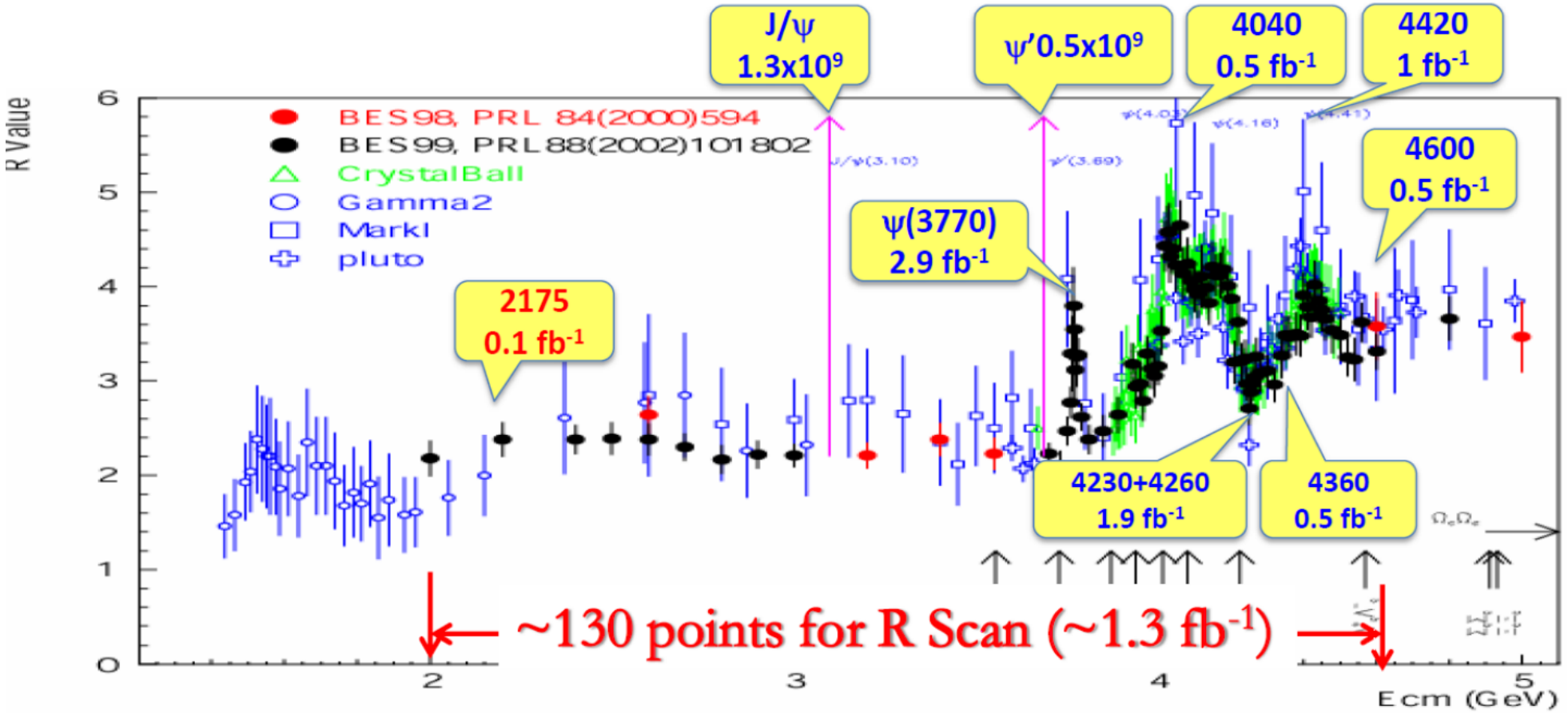


Super-Conducting Magnet
1.0 T (2009)
0.9 T(2012)

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

BEPCII and BESIII



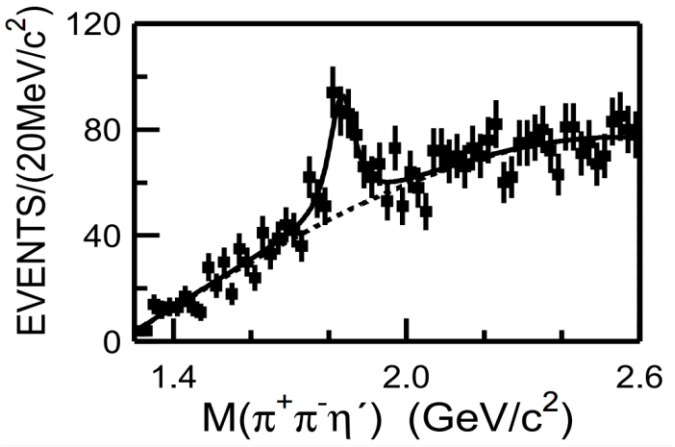
World largest J/ψ, ψ(3686), ψ(3770), …
Produced directly from e^+e^- collision

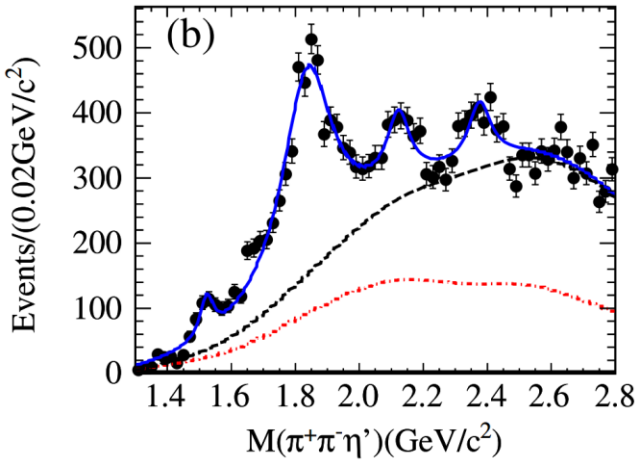
Light Meson Spectroscopy at BESIII

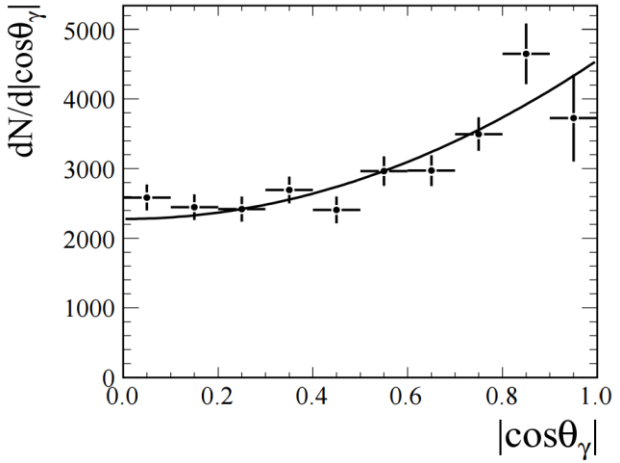
- Light meson spectroscopy plays an important role in testing the QCD theory
- J/ψ decays is an ideal place to study light meson spectroscopy
- BESIII collected the largest J/ψ sample (~1.3 billion events) in the world
  - 225 million in 2009
  - 1086 million in 2012
- Recent progress in light meson spectroscopy at BESIII
  - Observation of X(1835) in $J/\psi\to\gamma K_S K_S\eta$
  - Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold in $J/\psi\to\gamma\eta'\pi^+\pi^-$
  - Model independent partial wave analysis of $J/\psi\to\gamma\pi^0\pi^0$
  - Partial wave analysis of $J/\psi\to\gamma\phi\phi$

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

- X(1835)
  - Discovered by BESII in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi^+\pi^-$
    - ✓ $M = 1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/c^2
    - ✓ $\Gamma = 190 \pm 9^{+38}_{-36}$ MeV/c^2
    - ✓ Angular distribution is consistent with 0^-

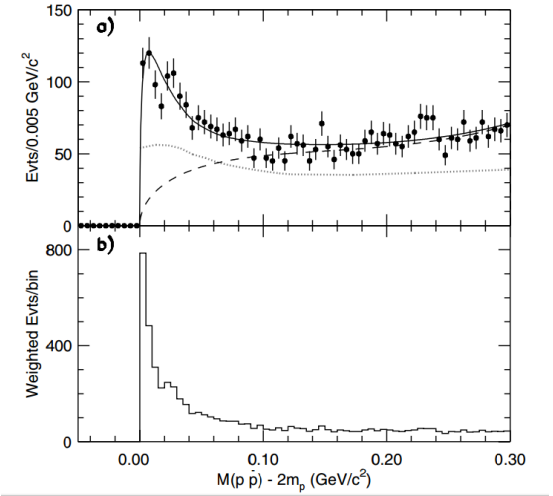


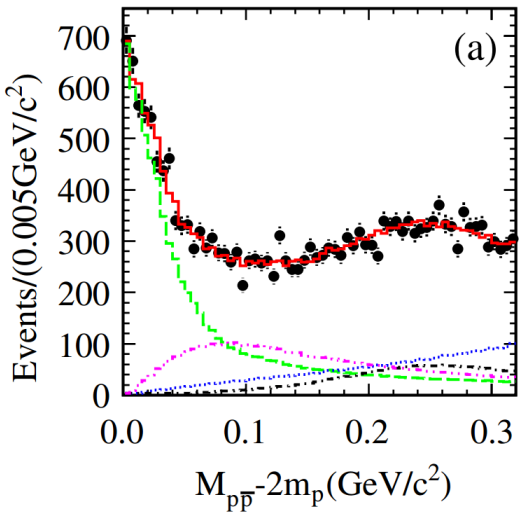


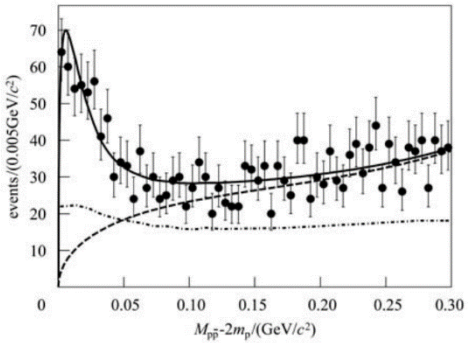


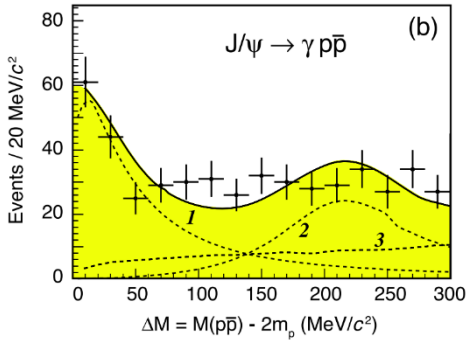
X(1835) and X(pp̄)

- X(pp̄)
  - Discovered by BESII in J/ψ→γpp̄
  - Confirmed by BESIII and CLEO-c in ψ(3686)→π⁺π⁻J/ψ, J/ψ→γpp̄
  - Confirmed by BESIII in J/ψ→γpp̄
    - ✓ 0^{-+}
    - ✓ Not from FSI
    - ✓ $M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19\ \mathrm{MeV}/c^2$
    - ✓ $\Gamma = 13 \pm 19\ \mathrm{MeV}/c^2$ ($< 76\ \mathrm{MeV}/c^2$ @ 90% C.L.)









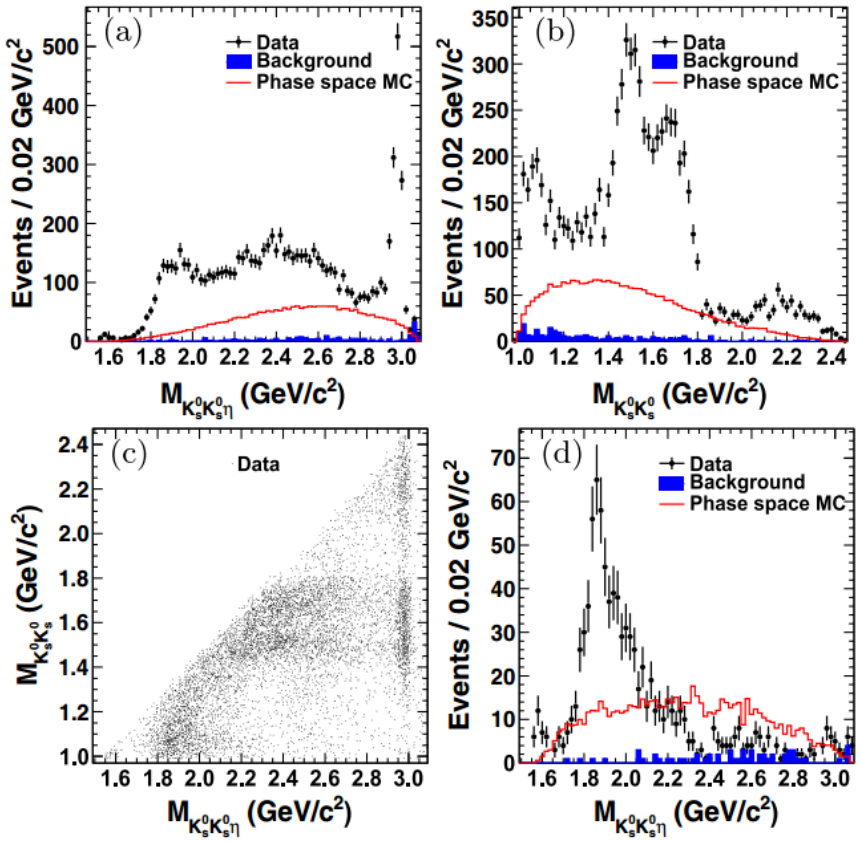
X(1835) and X($p\bar{p}$)

X(1835)	X($p\bar{p}$)
$M = \mathbf{1836.5 \pm 3.0^{+5.6}_{-2.1}}$ MeV/c^2	$M = \mathbf{1832^{+19}_{-5}\,{}^{+18}_{-17} \pm 19}$ MeV/c^2
$\Gamma = 190 \pm 9^{+38}_{-36}$ MeV/c^2	$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 MeV/c^2 @ 90% C.L.)
Probably 0^{-+}	**0^{-+}**
η' excitation? glueball? …	$p\bar{p}$ bound state? …
SAME state?	

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

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

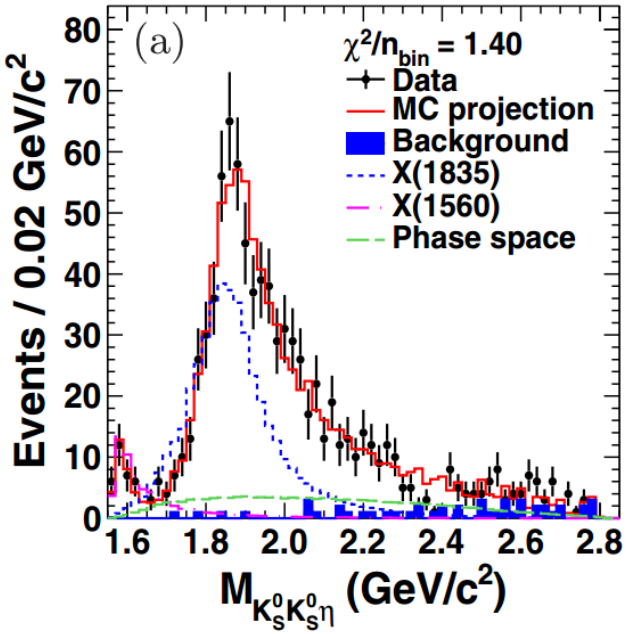
PRL 115, 091803 (2015)



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

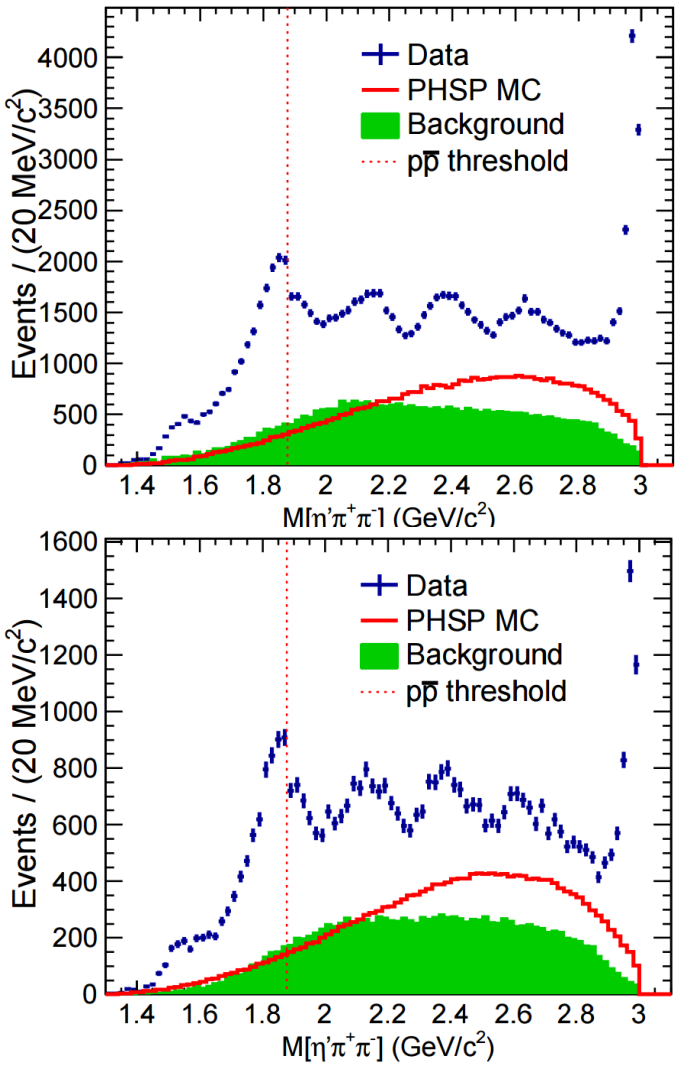
PRL 115, 091803 (2015)

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



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

- Use 1.09×10^9 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 $p\bar{p}$ mass threshold**

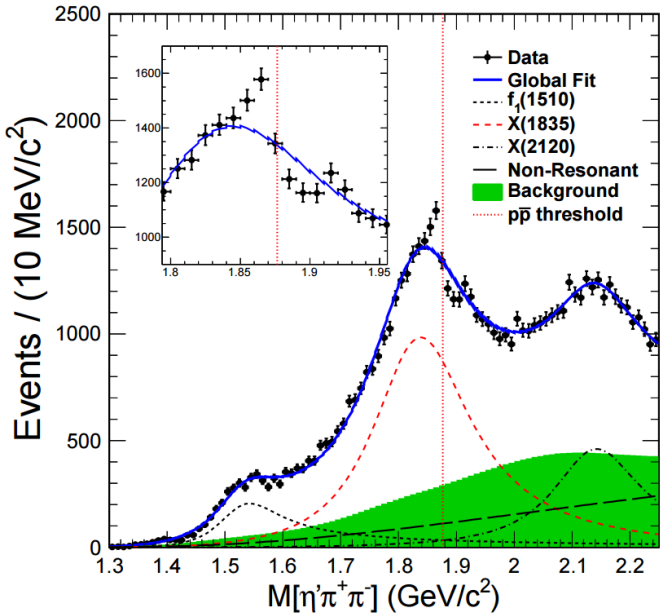


arXiv:1603.09653v2

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

arXiv:1603.09653v2

- Simultaneous fits to two η' decay modes
- Simple Breit-Wigner function fails in describing the $\eta'\pi^+\pi^-$ line shape near the $p\bar{p}$ mass threshold
- Two typical circumstances where an abrupt distortion of a resonance's line shape shows up
  - **Threshold structure caused by the opening of an additional $p\bar{p}$ decay mode**
    - Use the Flatté formula for the line shape
  - **Interference between two resonances**
    - Use coherent sum of two Breit-Wigner amplitudes for the line shape



$\log\mathcal{L} = 630503.3$

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

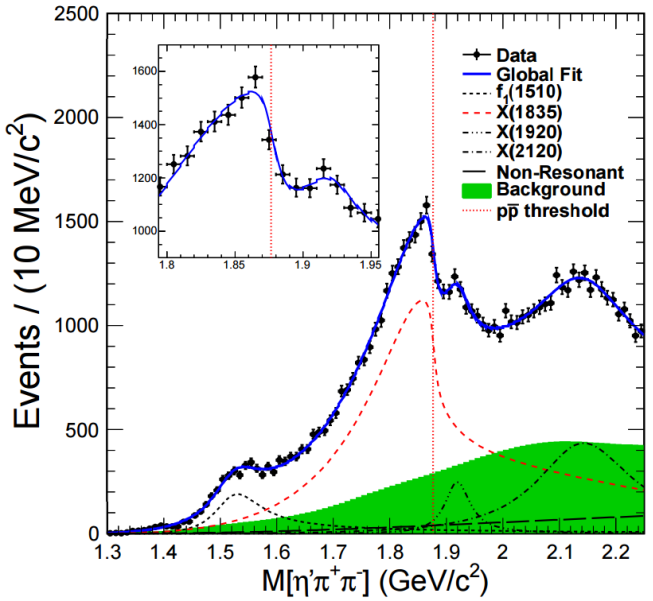
arXiv:1603.09653v2

- Use the Flatté formula for the line shape
  - $T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i\sum_k g_k^2\rho_k}$
    - $\sum_k g_k^2\rho_k \simeq g_0^2(\rho_0 + \frac{g_{p\bar{p}}^2}{g_0^2}\rho_{p\bar{p}})$
    - $g_{p\bar{p}}^2/g_0^2$ is the ratio between the coupling strength to the $p\bar{p}$ channel and the summation of all other channels

The state around 1.85 GeV/c^2	
$\mathcal{M}$ (MeV/c^2)	$1638.0\ ^{+121.9\ +127.8}_{-121.9\ -254.3}$
g_0^2 ((GeV/c^2)^2)	$93.7\ ^{+35.4\ +47.6}_{-35.4\ -43.9}$
$g_{p\bar{p}}^2/g_0^2$	$2.31\ ^{+0.37\ +0.83}_{-0.37\ -0.60}$
M_{pole} (MeV/c^2) *	$1909.5\ ^{+15.9\ +9.4}_{-15.9\ -27.5}$
Γ_{pole} (MeV/c^2) *	$273.5\ ^{+21.4\ +6.1}_{-21.4\ -64.0}$
Branching Ratio	$(3.93\ ^{+0.38\ +0.31}_{-0.38\ -0.84}) \times 10^{-4}$

* The pole nearest to the $p\bar{p}$ mass threshold

A $p\bar{p}$ molecule-like state?



$\log\mathcal{L}$ = 630549.5

Significance of $g_{p\bar{p}}^2/g_0^2$ being non-zero is larger than 7σ

X(1920) is needed with 5.7σ

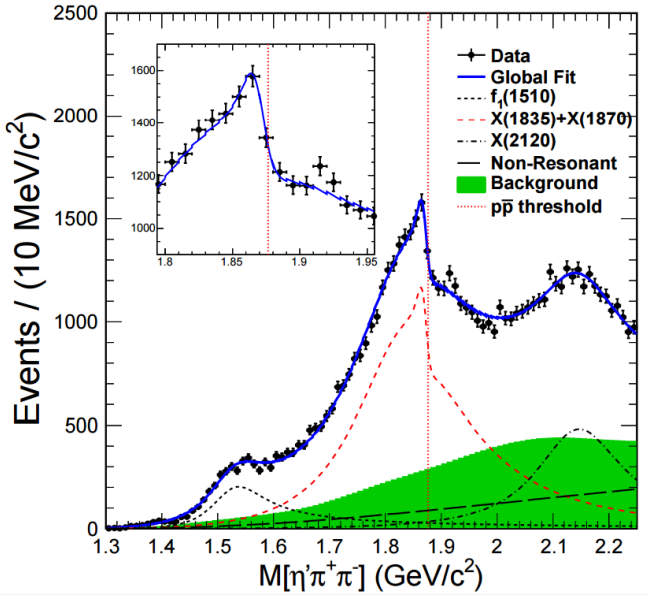
Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold in $J/\psi\to\gamma\eta'\pi^+\pi^-$

arXiv:1603.09653v2

- Use coherent sum of two Breit-Wigner amplitudes
  - $T = \frac{\sqrt{\rho_{out}}}{M_1^2 - s - iM_1\Gamma_1} + \frac{\beta\cdot e^{i\theta}\cdot\sqrt{\rho_{out}}}{M_2^2 - s - iM_2\Gamma_2}$

X(1835)	
M (MeV/c^2)	$1825.3\ ^{+2.4\ +17.3}_{-2.4\ -2.4}$
Γ (MeV/c^2)	$245.2\ ^{+14.2\ +4.6}_{-12.6\ -9.6}$
B.R. (constructive interference)	$(3.01\ ^{+0.17\ +0.26}_{-0.17\ -0.28}) \times 10^{-4}$
B.R. (destructive interference)	$(3.72\ ^{+0.21\ +0.18}_{-0.21\ -0.35}) \times 10^{-4}$
X(1870)	
M (MeV/c^2)	$1870.2\ ^{+2.2\ +2.3}_{-2.3\ -0.7}$
Γ (MeV/c^2)	$13.0\ ^{+7.1\ +2.1}_{-5.5\ -3.8}$
B.R. (constructive interference)	$(2.03\ ^{+0.12\ +0.43}_{-0.12\ -0.70}) \times 10^{-7}$
B.R. (destructive interference)	$(1.57\ ^{+0.09\ +0.49}_{-0.09\ -0.86}) \times 10^{-5}$

A $p\bar{p}$ bound state?



log$\mathcal{L}$ = 630540.3

Significance of X(1870) is larger than 7σ

X(1920) is not significant

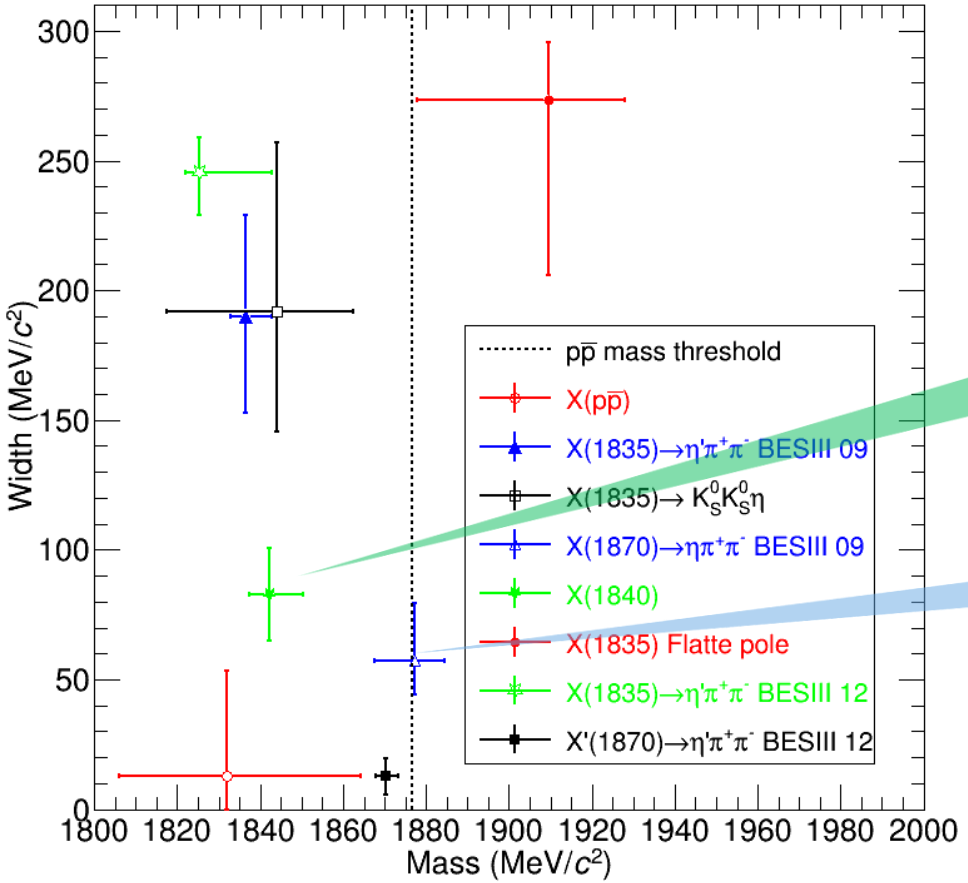
Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold in $J/\psi\to\gamma\eta'\pi^+\pi^-$

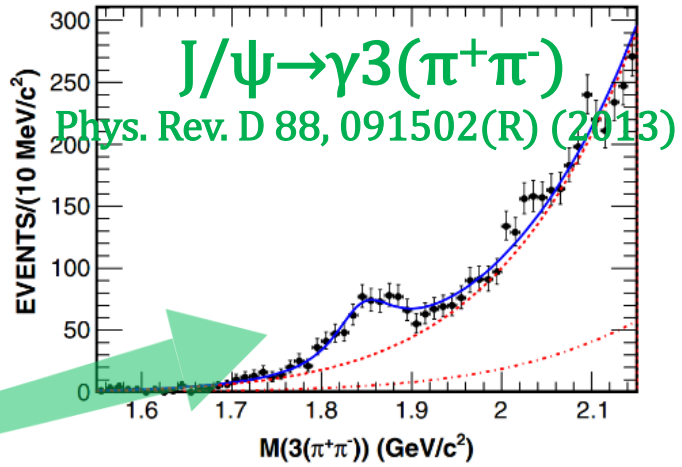
- A significant distortion of the $\eta'\pi^+\pi^-$ line shape near the $p\bar{p}$ mass threshold is observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$
  - Simple Breit-Wigner function fails in describing the line shape near the $p\bar{p}$ mass threshold
- Two models have been used
  - MODEL I: threshold structure due to the opening of the $p\bar{p}$ decay mode
    - Use the Flatté formula
    - **Strong $p\bar{p}$ coupling, with significance larger than 7σ**
    - **$M_{pole} = 1909.5\ ^{+15.9\ +9.4}_{-15.9\ -27.5}\ MeV/c^2$**
    - **$\Gamma_{pole} = 273.5\ ^{+21.4\ +6.1}_{-21.4\ -64.0}\ MeV/c^2$**
  - MODEL II: interference between two resonances
    - Use coherent sum of two Breit-Wigner amplitudes
    - **A narrow resonance below the $p\bar{p}$ mass threshold, with significance larger than 7σ**
    - **$M = 1870.2\ ^{+2.2\ +2.3}_{-2.3\ -0.7}\ MeV/c^2$**
    - **$\Gamma = 13.0\ ^{+7.1\ +2.1}_{-5.5\ -3.8}\ MeV/c^2$**

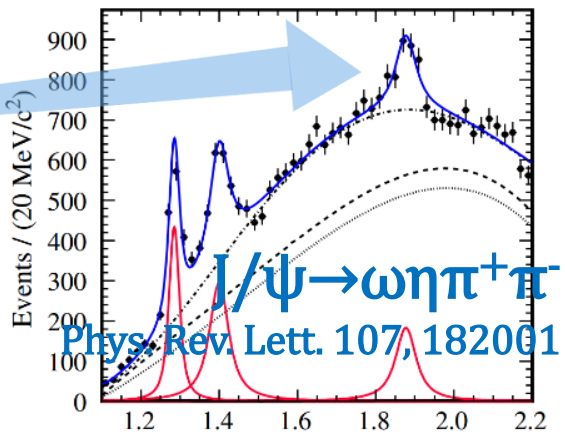
Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold in $J/\psi\to\gamma\eta'\pi^+\pi^-$

- 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 elucidate further the nature of the state
  - More J/ψ data
  - Study line shapes in other decay modes
    - $J/\psi\to\gamma p\bar{p}$
    - $J/\psi\to\gamma K_S K_S\eta$
    - ...

Structures around 1.8 GeV/c^2



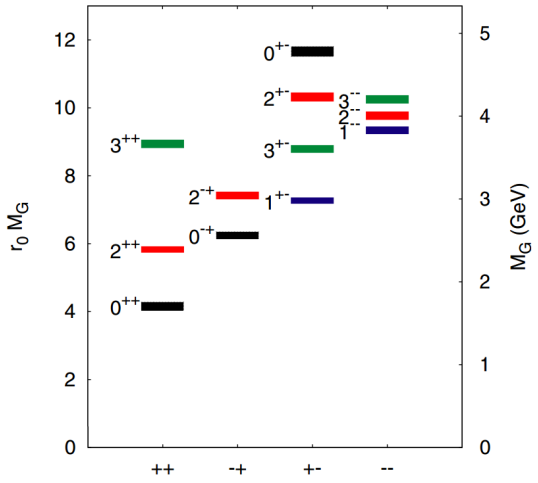


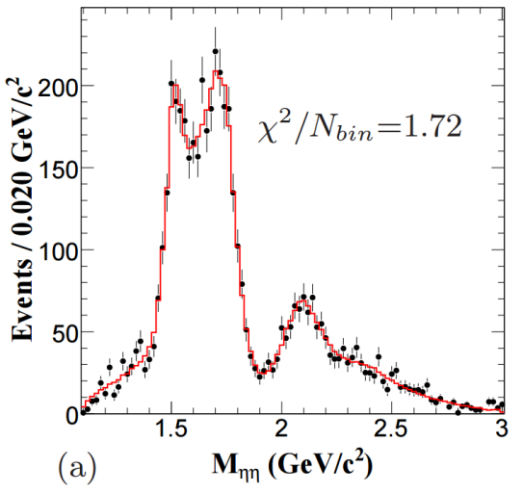


- J^{PC} of X(1840) and X(1870): PWA
- Search and study those states in more channels

Glueball

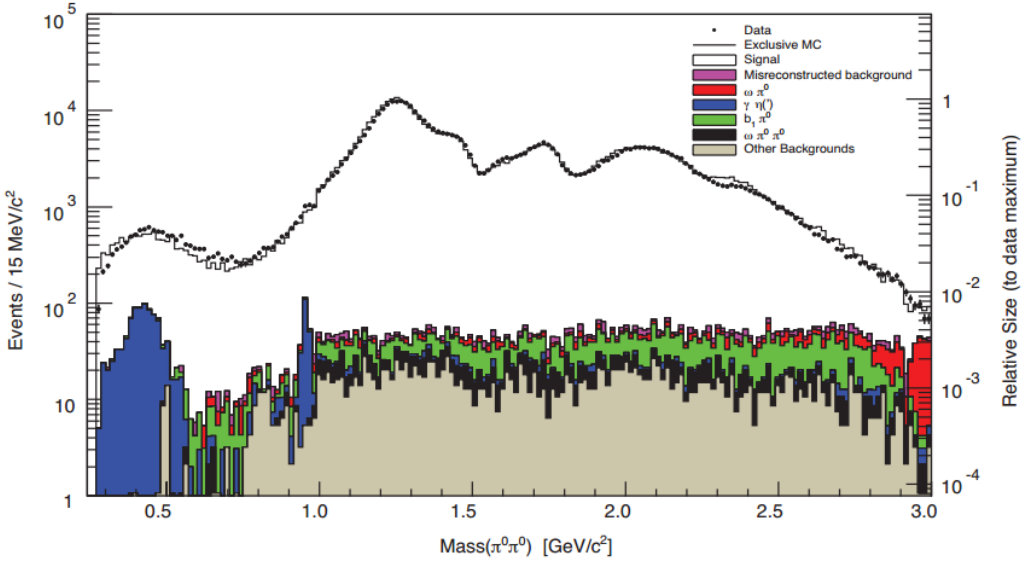
- Predicted by QCD
- Not established in experiment
- LQCD prediction
  - 0^{++} ground state: 1~2 GeV/c^2
  - 2^{++} ground state: 2.3~2.4 GeV/c^2
  - 0^{-+} ground state: 2.3~2.6 GeV/c^2
- J/ψ→γPP, γVV, …
  - J/ψ→γηη Phys. Rev. D. 87, 092009 (2013)





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

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

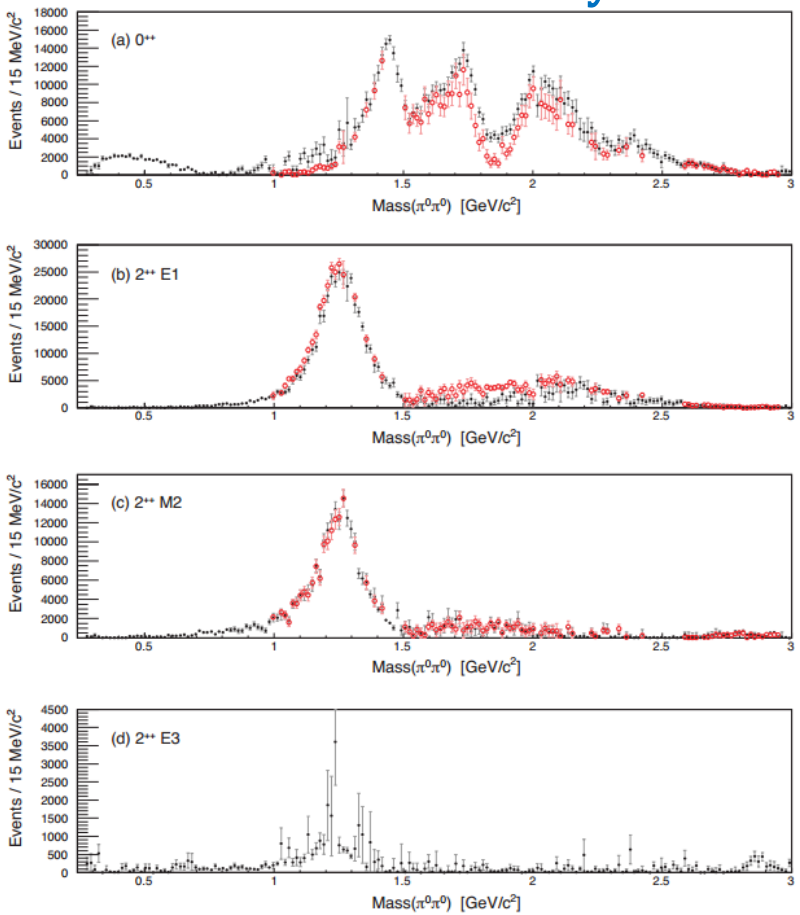


✓ More than 440,000 reconstructed events
✓ Background level ~ 1.8%

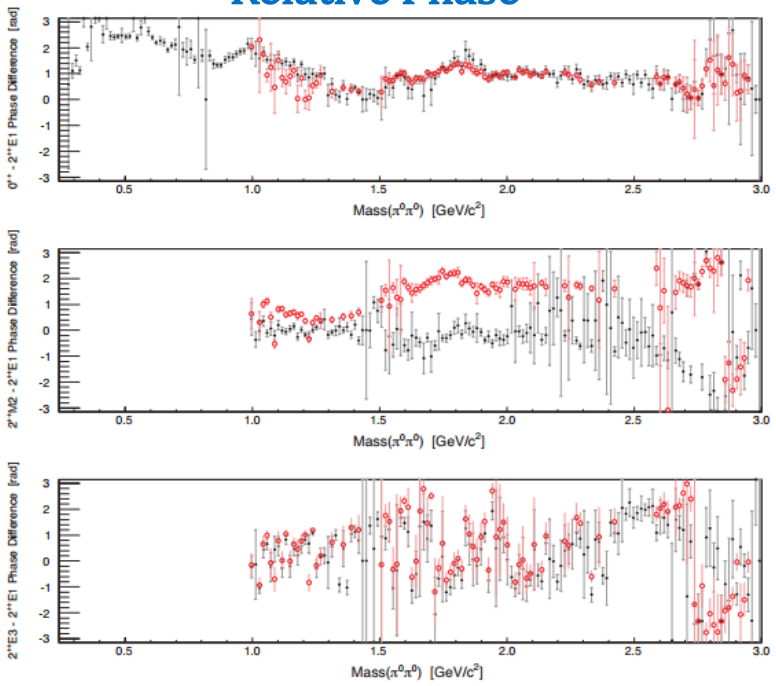
Phys. Rev. D 92, 052003 (2015)

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

Extracted Intensity



Relative Phase



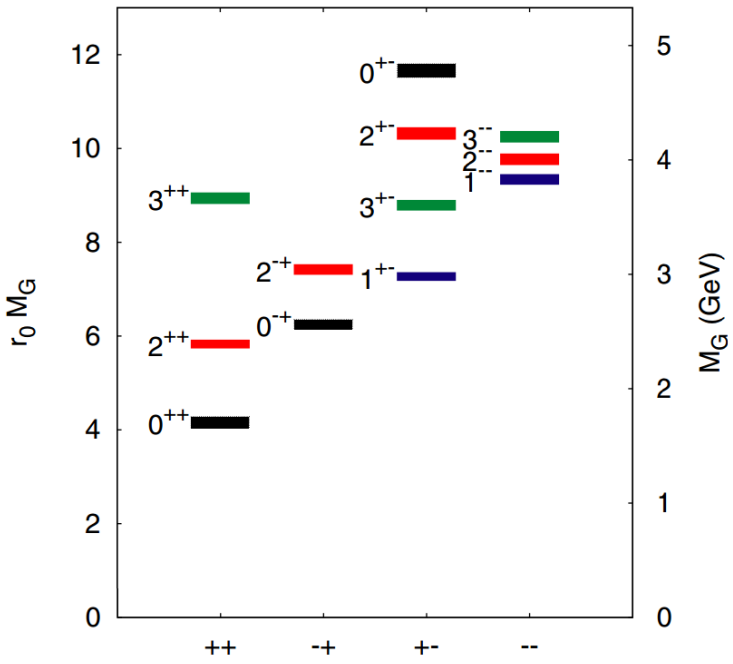
- **Nominal Solution**
- **Ambiguous Solution**

- ✓ A piecewise function that describes the dynamics of the $\pi^0\pi^0$ system is determined as a function of $M(\pi^0\pi^0)$
- ✓ Significant features of the scalar spectrum includes structures near 1.5, 1.7 and 2.0 GeV/c^2
- ✓ Ambiguities present above $K\bar{K}$ threshold

Phys. Rev. D 92, 052003 (2015)

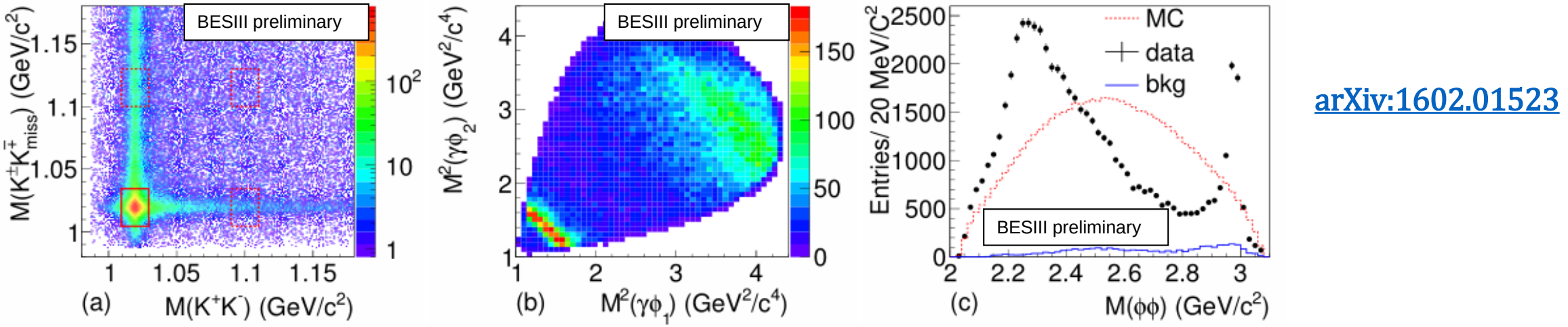
PWA of J/ψ→γϕϕ

- Lattice QCD predictions:
  - Ground state of 2^{++} glueball in 2.3 ~2.4 GeV/c^2
  - Ground state of 0^{-+} glueball in 2.3~2.6 GeV/c^2
- Structures in ϕϕ spectrum:
  - Pseudoscalar state η(2225) was observed in J/ψ→γϕϕ
  - For higher 0^{-+} mass states above 2 GeV/c^2, very little is known.
  - Broad 2^{++} structures decaying to ϕϕ were reported around 2.3 GeV in π^-N reactions and in $p\bar{p}$ central collisions



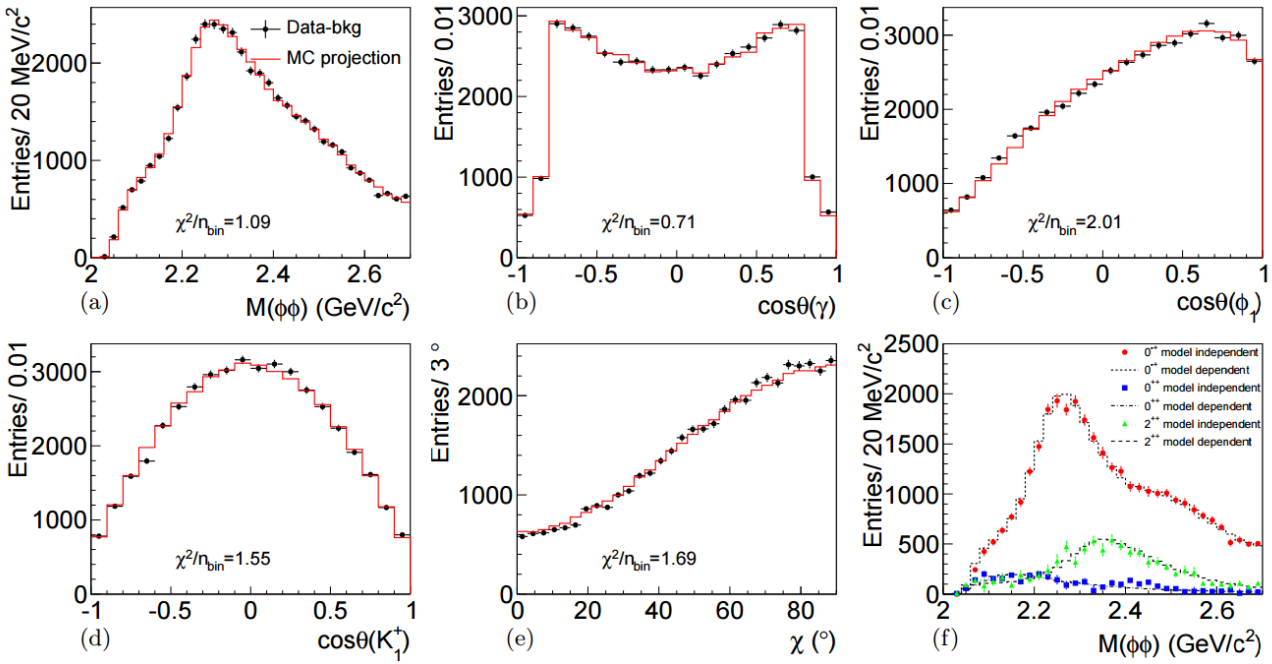
PWA of J/ψ→γϕϕ

- Use 1.3×10^9 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



arXiv:1602.01523

PWA of J/ψ→γϕϕ



Resonance	M(MeV/c^2)	Γ(MeV/c^2)	B.F.($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+18}_{-5-11}	185^{+12+44}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28.1σ
$\eta(2100)$	2050^{+30+77}_{-24-26}	$250^{+36+187}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	21.5σ
X(2500)	2470^{+15+63}_{-19-23}	230^{+64+53}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2102	211	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24.2σ
$f_2(2010)$	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	$(1.91 \pm 0.07^{+0.72}_{-0.69})$	10.7σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

arXiv:1602.01523

Pesudoscalar:
η(2225) confirmed
η(2100) and X(2500)

Dominant

Tensor:
$f_2(2010)$, $f_2(2300)$, $f_2(2340)$: stated in $\pi^- p$ reaction; strong $f_2(2340)$ production.

- ✓ **Well consistent with the results from Model-independent PWA**
- ✓ **Helpful for mapping out the pseudoscalar excitations and searching for a 0^{-+} glueball**

Summary

- Many interesting results in light meson spectroscopy from BESIII
  - Observation of X(1835) in $J/\psi\to\gamma K_S K_S \eta$
    - **J^{PC} of X(1835) is determined: 0^{-+}**
  - Observation of anomalous $\eta'\pi^+\pi^-$ line shape near $p\bar{p}$ mass threshold in $J/\psi\to\gamma\eta'\pi^+\pi^-$
    - **Support the existence of a $p\bar{p}$ bound state or molecule-like state**
  - Sophisticated model independent partial wave analysis of $J/\psi\to\gamma\pi^0\pi^0$
  - Partial wave analysis of $J/\psi\to\gamma\phi\phi$
- More results are expected in the future!

Thank you!