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Hadron Spectroscopy at BESIII

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On Behalf of the BESIII Collaboration

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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

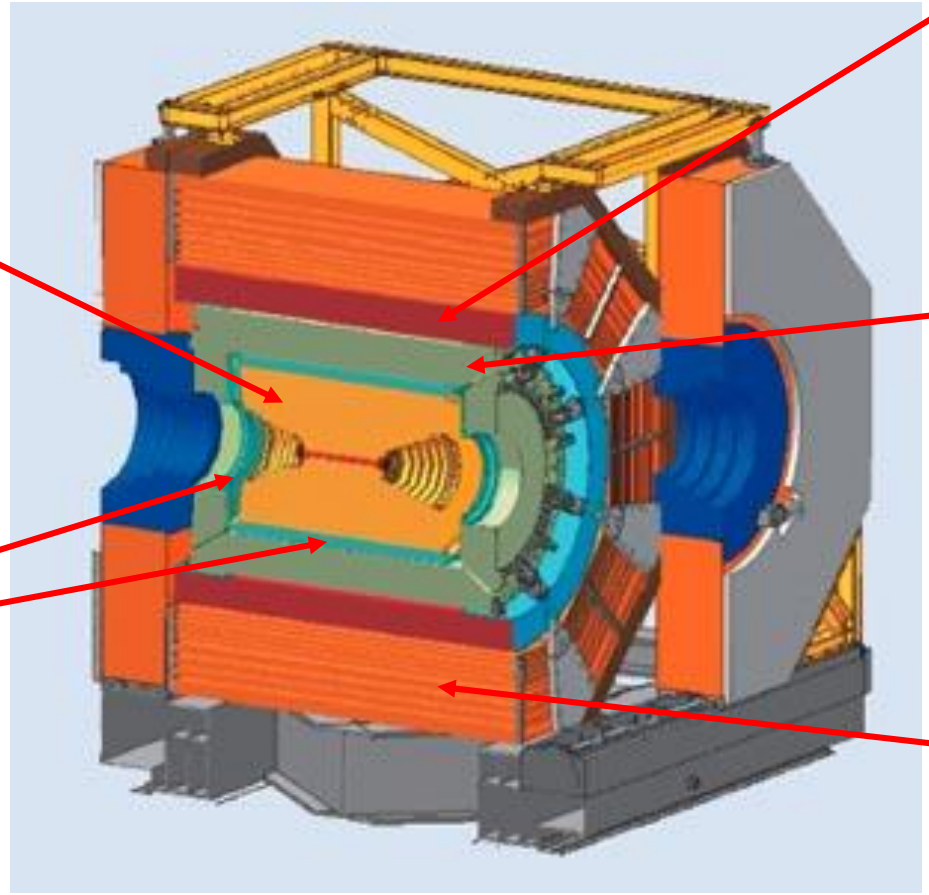
2008: test run

2009 ~ now: physics run

BESIII Detector

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

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

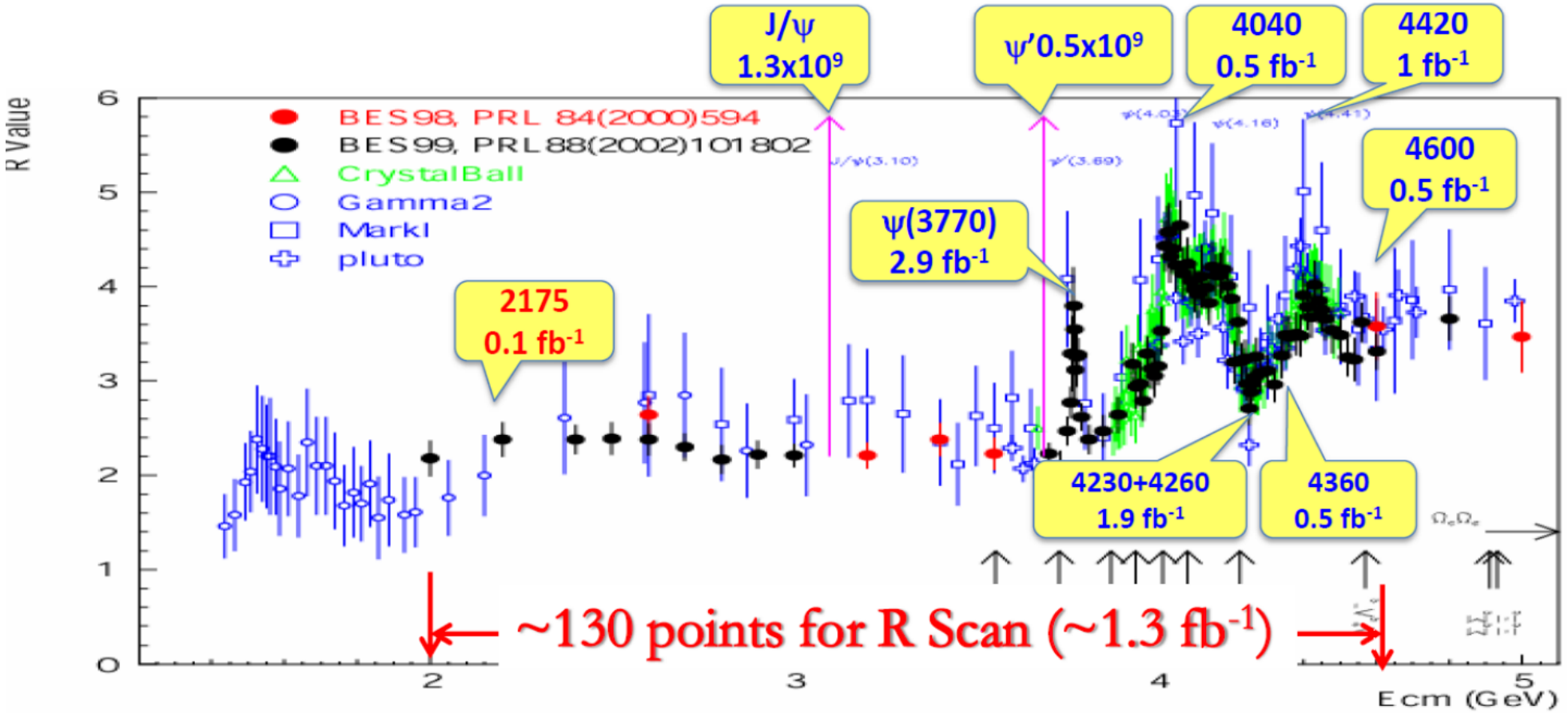


Electromagnetic Calorimeter (EMC)
CsI (Tl)
$\sigma_E/\sqrt{E} = 2.5\%$ (1 GeV)
$\sigma_{z,\varphi} = 0.5$ - $0.7\ cm/\sqrt{E}$

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

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

Data Collected at BESIII



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

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

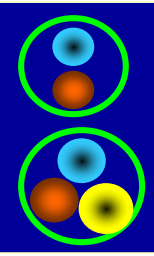
Multi-quark State, Glueball and Hybrid

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

Naive Quark Model：

Meson（ $q\ \bar{q}$ ）

Baryon（$q\ q\ q$）



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

Lots of candidates, but new forms of hadrons have not been established yet!

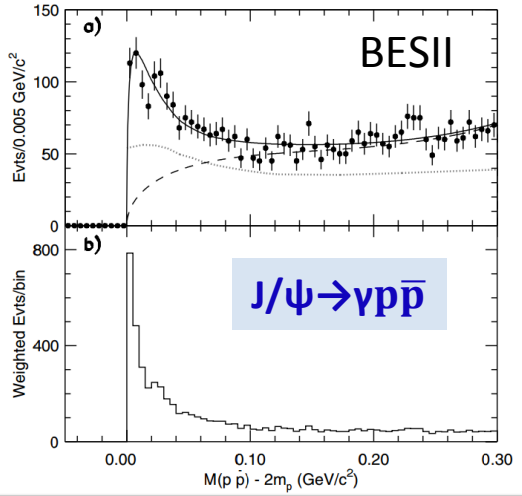
Highlights of latest results on searching for new forms of hadrons at BESIII

- **X($p\bar{p}$) and X(1835)**
  - New decay mode of X(1835) →$K_S K_S \eta$ and determinating J^{PC} of X(1835)
  - Anomalous $\eta'\pi^+\pi^-$ mass line shape near $p\bar{p}$ mass threshold —— connection between X($p\bar{p}$) and X(1835)
- **Glueball Searches**
  - Model independent partial wave analysis of $J/\psi \to \gamma\pi^0\pi^0$
  - Partial wave analysis of $J/\psi \to \gamma\phi\phi$
- **Z_c Structures**
  - Observation of $Z_c(3900)/Z_c(3885)$, $Z_c(4020)/Z_c(4025)$
  - Non-observation of $Z_c(3900) \to \omega\pi$

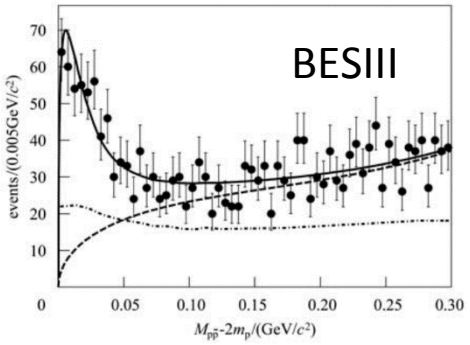
X(pp̄)

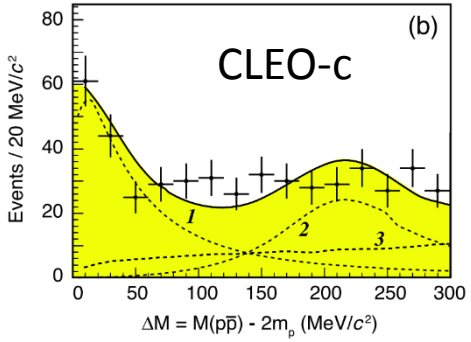
- **Discovered by BESII in J/ψ→γpp̄**
- **Confirmed by BESIII and CLEO-c in ψ(3686)→π⁺π⁻J/ψ, J/ψ→γpp̄**
- **Confirmed by BESIII in J/ψ→γpp̄ and its J^{PC} determined by PWA**
  - ✓ 0^{-+}
  - ✓ $M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19\ \mathrm{MeV/c^2}$
  - ✓ $\Gamma = 13 \pm 19\ \mathrm{MeV/c^2}$ ($< 76\ \mathrm{MeV/c^2}$ @ 90% C.L.)

PRL 91, 022001 (2003)



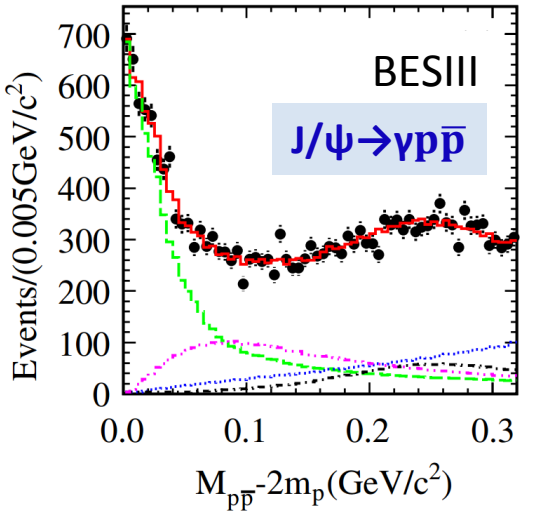
ψ(3686)→π⁺π⁻J/ψ, J/ψ→γpp̄





Chinese Phys. C34, 421 (2010)

PRD 82, 092002 (2010)

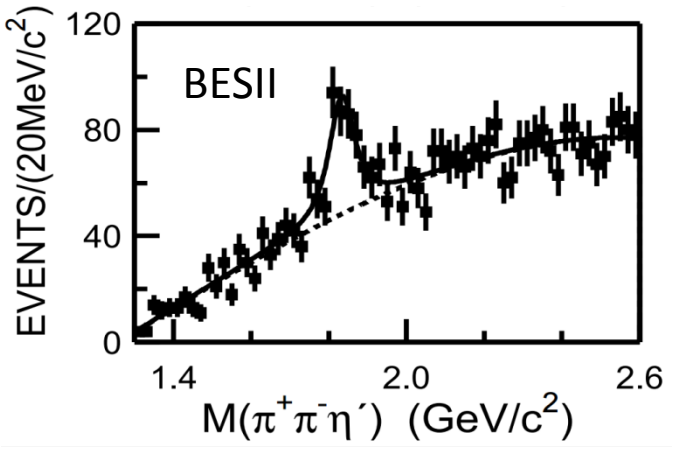


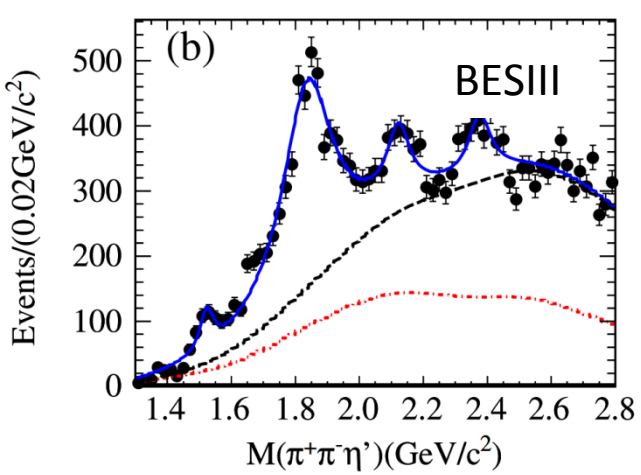
PRL 108, 112003 (2012)

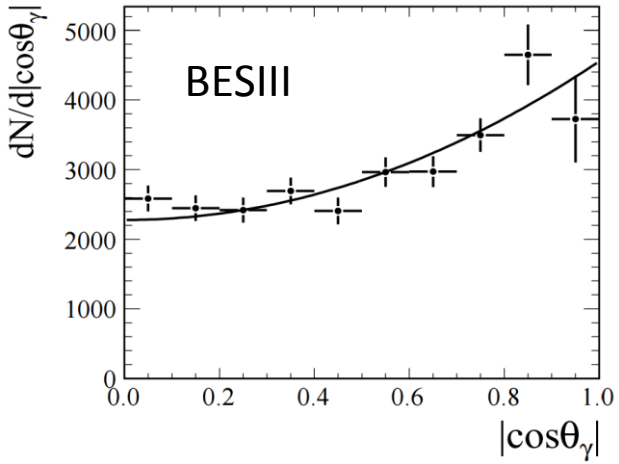
X(1835)

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

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





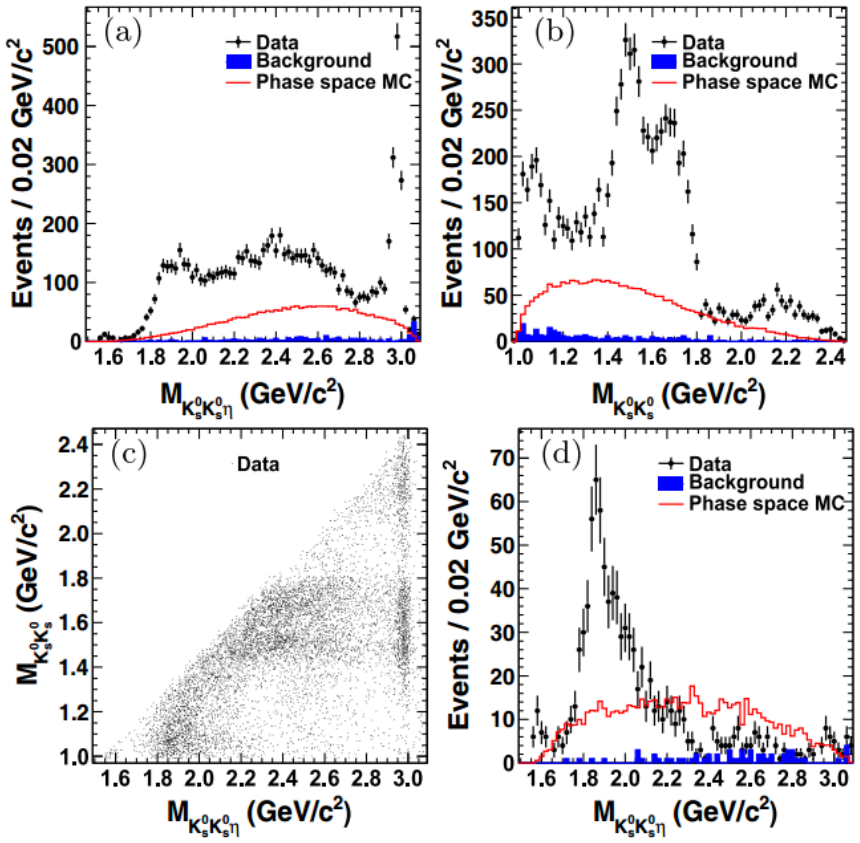


Phys. Rev. Lett. 106, 072002 (2011)

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

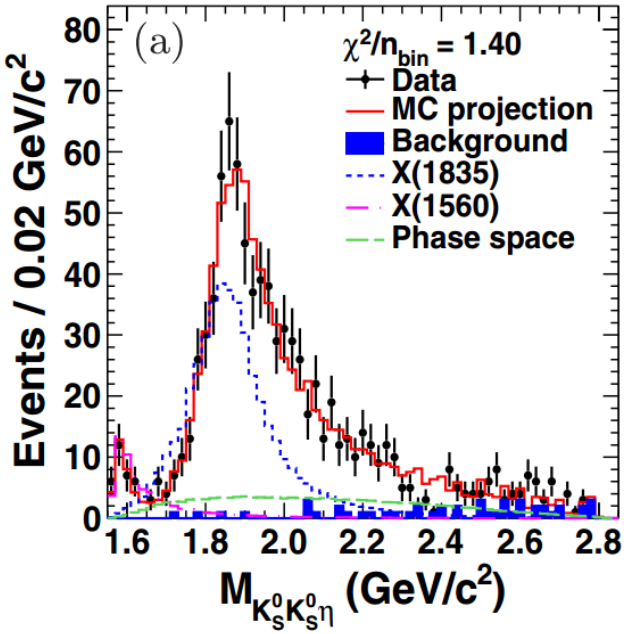
PRL 115, 091803 (2015)



New decay mode of X(1835) →$K_SK_S\eta$ and determination J^{PC} of X(1835)

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

PRL 115, 091803 (2015)



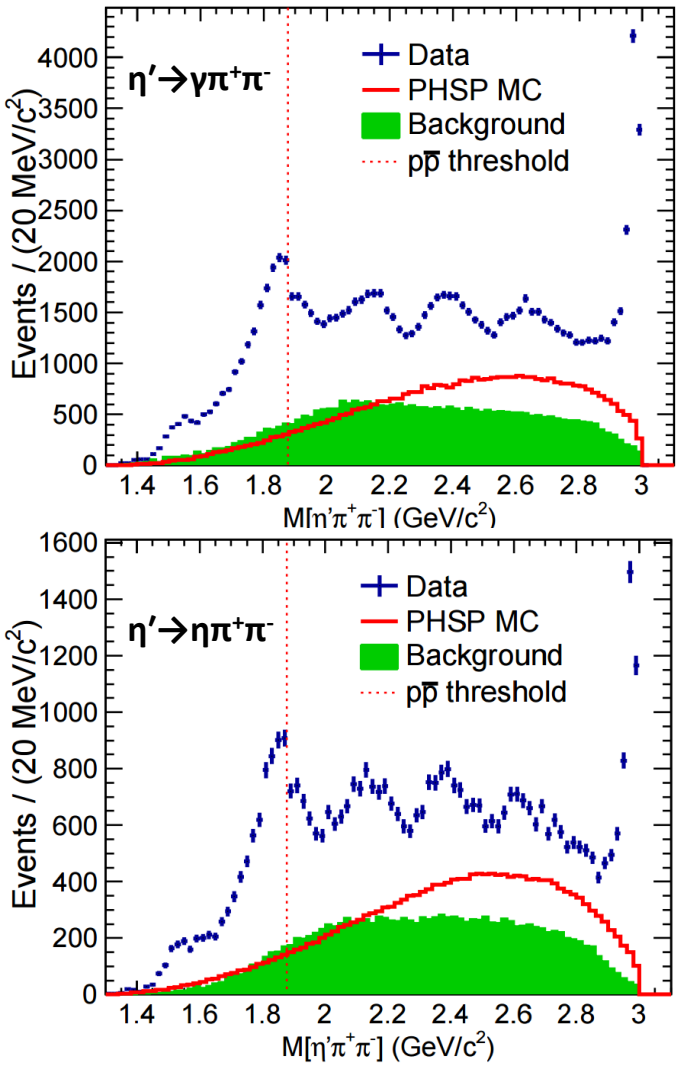
X(1835) and X($p\bar{p}$)

X(1835)	X($p\bar{p}$)
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2	$M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2	$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 MeV/c^2 @ 90% C.L.)
0^{-+}	0^{-+}
$p\bar{p}$ bound state? η' excitation? glueball? …	 $p\bar{p}$ bound state? …
The SAME state?	

Anomalous line shape of $\eta'\pi^+\pi^-$ near the $p\bar{p}$ 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

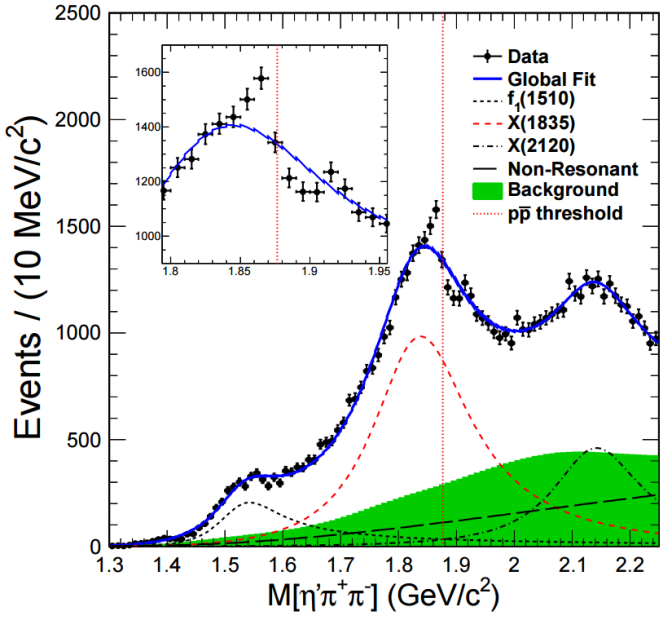
PRL 117, 042002 (2016)



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

- 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 with one very narrow close to threshold
    - Use coherent sum of two Breit-Wigner amplitudes for the line shape

PRL 117, 042002 (2016)



$\log\mathcal{L} = 630503.3$

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

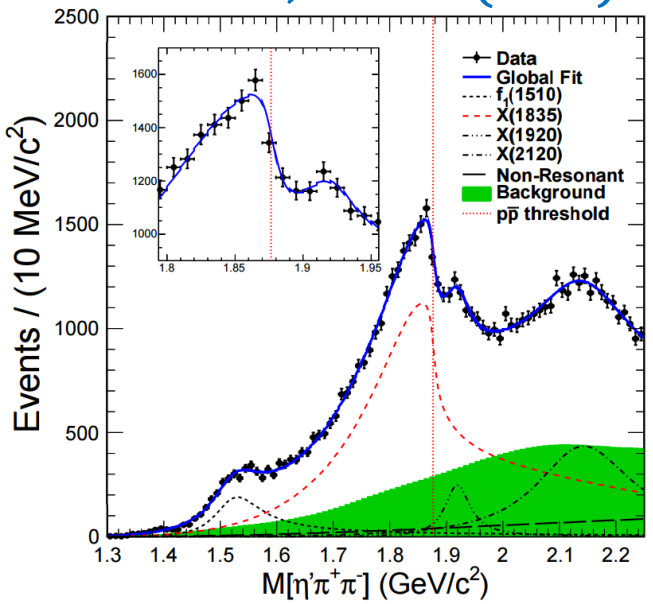
- **Use the Flatté formula for the line shape**
  - $T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i\sum_k g_k^2\rho_k}$
    - $\sum_k g_k^2\rho_k \simeq g_0^2(\rho_0 + \frac{g_{p\bar{p}}^2}{g_0^2}\rho_{p\bar{p}})$
    - $g_{p\bar{p}}^2/g_0^2$ is the ratio between the coupling strength to the $p\bar{p}$ 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)	$93.7\ ^{+35.4\ +47.6}_{-35.4\ -43.9}$
$\mathbf{g_{p\bar{p}}^2/g_0^2}$	$\mathbf{2.31\ ^{+0.37\ +0.83}_{-0.37\ -0.60}}$
$\mathbf{M_{pole}}$ **(MeV/c^2) ***	$\mathbf{1909.5\ ^{+15.9\ +9.4}_{-15.9\ -27.5}}$
$\mathbf{\Gamma_{pole}}$ **(MeV/c^2) ***	$\mathbf{273.5\ ^{+21.4\ +6.1}_{-21.4\ -64.0}}$
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?

PRL 117, 042002 (2016)



$\log\mathcal{L}$ = 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

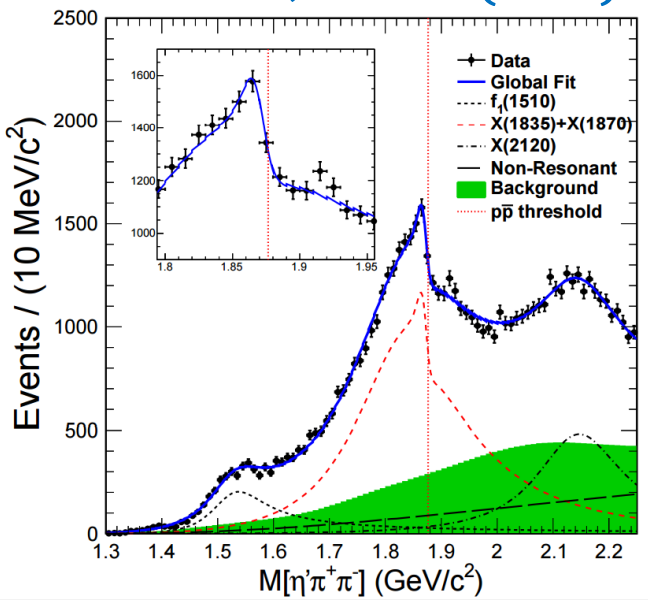
Anomalous line shape of $\eta'\pi^+\pi^-$ near the $p\bar{p}$ mass threshold in $J/\psi\to\gamma\eta'\pi^+\pi^-$ — Model II

- **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)	$\mathbf{1870.2\ ^{+2.2\ +2.3}_{-2.3\ -0.7}}$
Γ (MeV/c^2)	$\mathbf{13.0\ ^{+7.1\ +2.1}_{-5.5\ -3.8}}$
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?

PRL 117, 042002 (2016)



$\log\mathcal{L}$ = 630540.3

Significance of narrow X(1870) is larger than 7σ

X(1920) is not significant

Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold —— connection between X(1835) and X($p\bar{p}$)

- **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)**
  - **More J/ψ data to distinguish two models**
  - **Study line shapes in other decay modes**
    - **$J/\psi\to\gamma p\bar{p}$**
    - **$J/\psi\to\gamma K_S K_S \eta$**
    - **…**

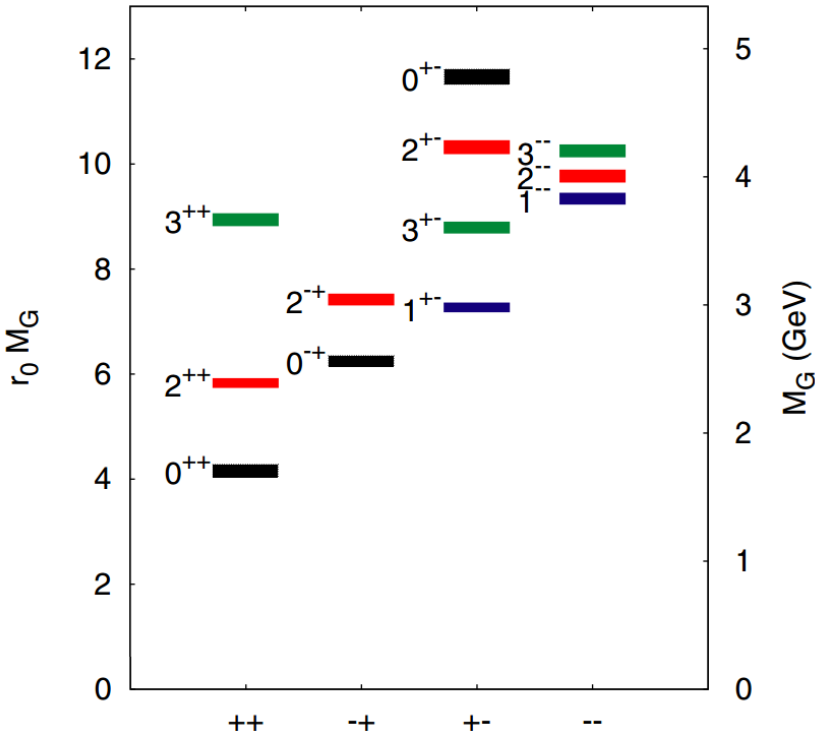
Glueballs

- Unique particle formed by non-Abel Gauge self-interactions

→ Direct test of 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

- J/ψ radiative decays are believed to be an ideal place to search for glueballs.

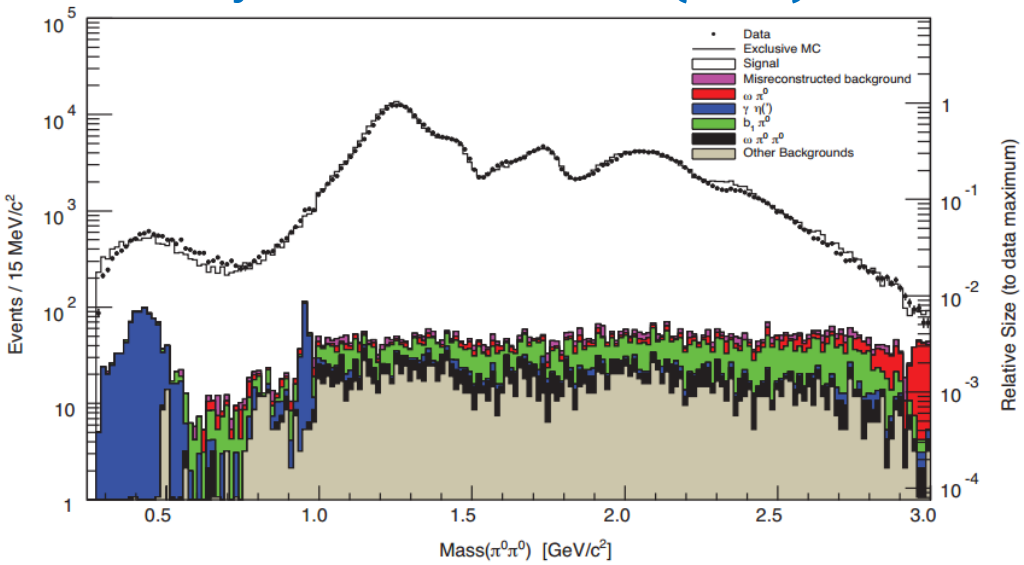


Model Independent PWA of $J/\psi \to \gamma\pi^0\pi^0$

- Use 1.3×10^9 J/ψ events collected by BESIII in 2009 and 2012

- $\pi^0\pi^0$ system
  - Very clean and larger statistics
  - Many broad and overlapping resonances (parameterization challenging)
  - Model independent PWA (MIPWA)

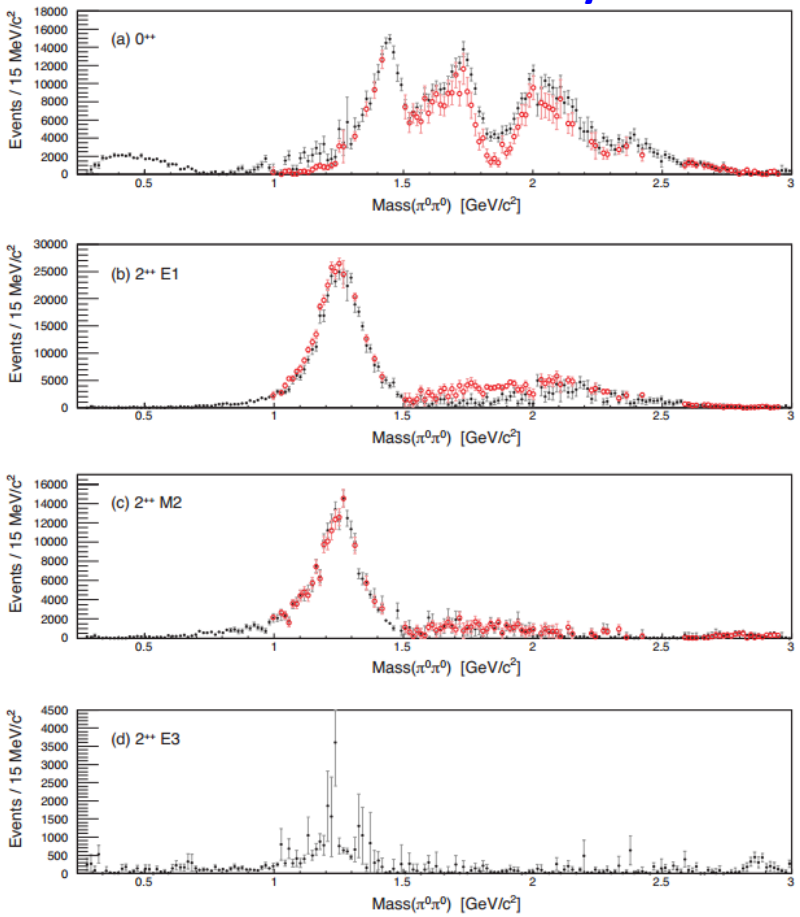
Phys. Rev. D 92, 052003 (2015)



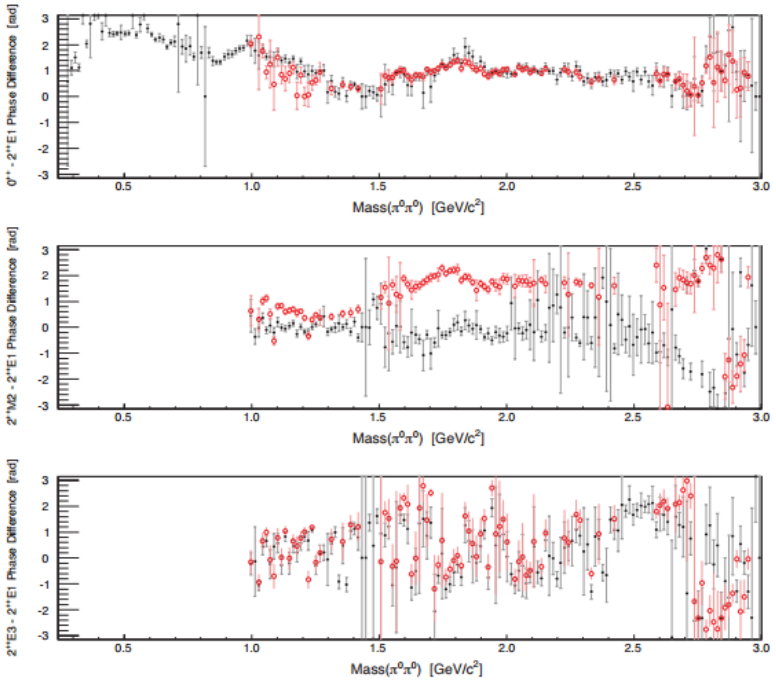
✓ More than 440,000 reconstructed events
✓ Background level ~ 1.8%

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

Extracted Intensity



Relative Phase



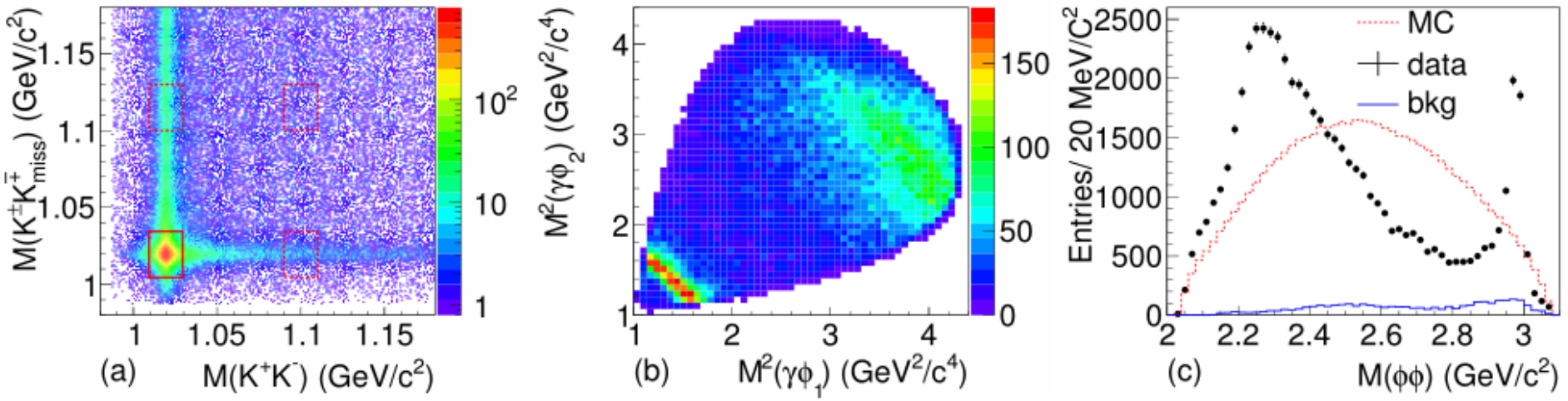
- Solution 1
- Solution 2

Phys. Rev. D 92, 052003 (2015)

- ✓ 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 GeV/c^2
- ✓ Multi-solution problem in MIPWA is usually unavoidable.
- ✓ Only Model Dependent PWA of global PWA fit can rigerously extract resonance parameters, but cross-check between MDPWA and MIPWA is helpful.

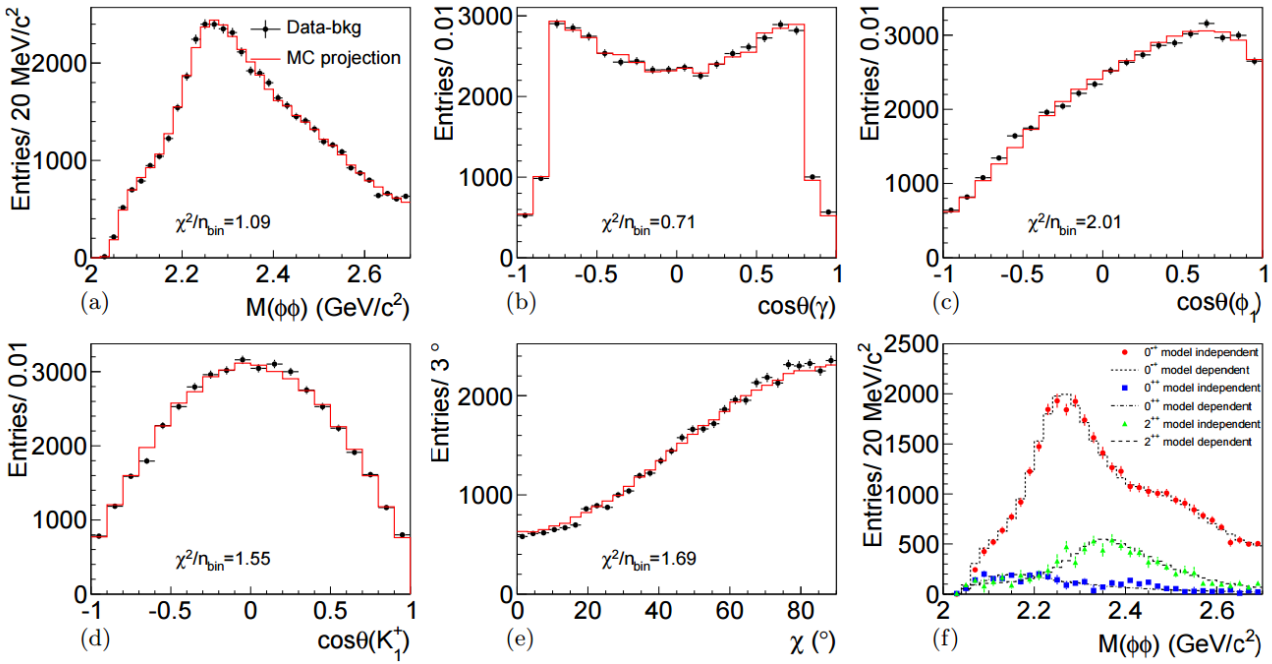
PWA of J/ψ→γϕϕ

- Use 1.3×10^9 J/ψ events collected by BESIII in 2009 and 2012
- PWA procedure (applied to most published BESIII PWA results)
  - Covariant tensor formalism
  - Data-driven background subtraction
  - Resonances are parameterized by relativistic Breit-Wigner with constant width
  - Resonances with significance > 5 σ are selected as components in solution



Phys. Rev. D 93, 112011 (2016)

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

Phys. Rev. D 93, 112011 (2016)

Pesudoscalar:

η(2225) confirmed

η(2100) and X(2500)

Dominant

Tensor:

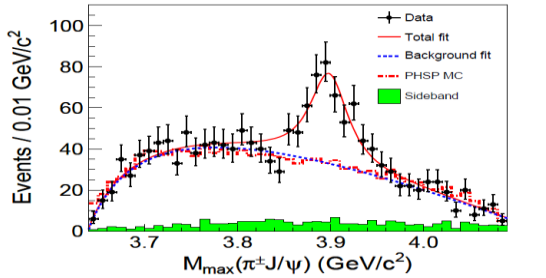
$f_2(2010)$, $f_2(2300)$, $f_2(2340)$:

strong $f_2(2340)$ production

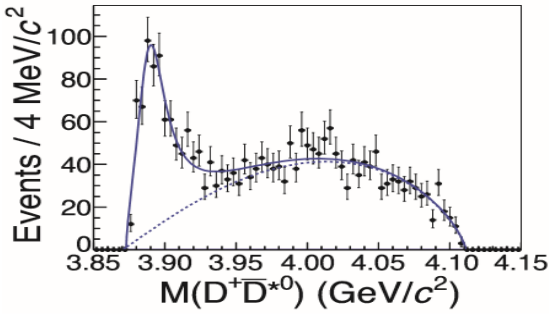
—— tensor glueball candidate?

✓ **Well consistent with the results from Model-independent PWA**

Summary of Z_c structures observed at BESIII

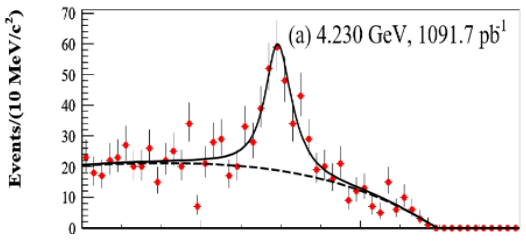


$e^+e^- \to \pi^+ \pi^- J/\psi$

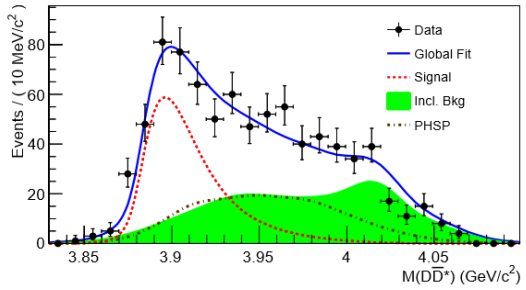


$e^+e^- \to \pi^+ (D\bar{D}^*)^-$

$Z_c(3900)^{\pm}$?

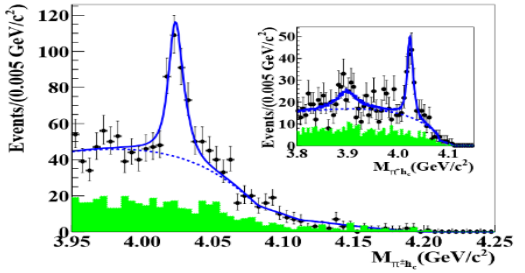


$e^+e^- \to \pi^0 \pi^0 J/\psi$

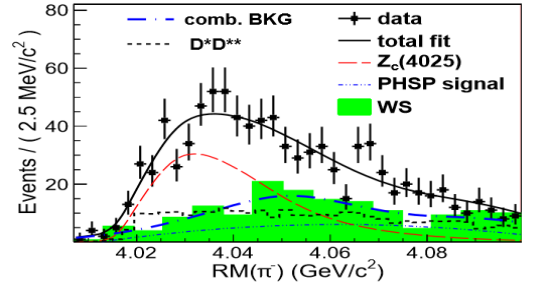


$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

$Z_c(3900)^0$?

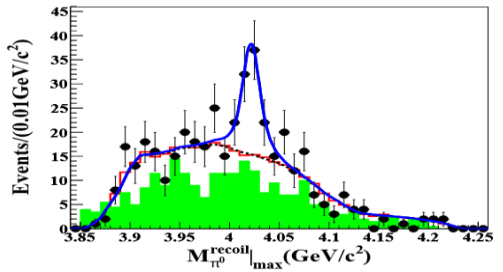


$e^+e^- \to \pi^+ \pi^- h_c$

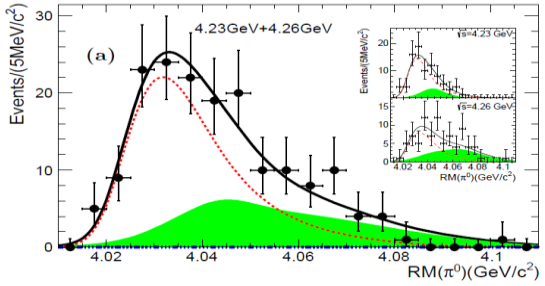


$e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$

$Z_c(4020)^{\pm}$?



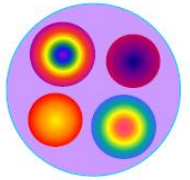
$e^+e^- \to \pi^0 \pi^0 h_c$



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

$Z_c(4020)^0$?

- If these structures are real QCD states, charged Z_c decays into $\pi^{+/-} J/\psi$ ($\pi^{+/-} h_c$) → at least four valence quarks to satisfy charge=$\pm$1 and strong couplings to ccbar components.



BESIII: a summary of Z_c observations

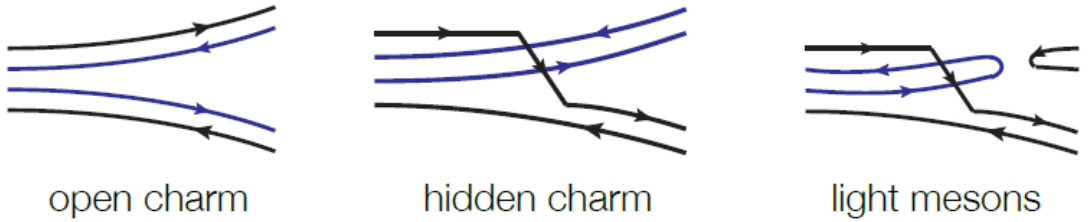
Zc	Mass (MeV/c^2)	Width (MeV)	Decay	Process	[Ref]
$Z_c(3900)^{\pm}$	$3899.0\pm3.6\pm4.9$	$46\pm10\pm20$	$\pi^{\pm}J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$	[1]
$Z_c(3900)^0$	$3894.8\pm2.3\pm2.7$	$29.6\pm8.2\pm8.2$	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$	[2]
$Z_c(3885)^{\pm}$	$3883.9\pm1.5\pm4.2$ Single D tag	$24.8\pm3.3\pm11.0$ Single D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$	[3]
	$3881.7\pm1.6\pm2.1$ Double D tag	$26.6\pm2.0\pm2.3$ Double D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$	[4]
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7}\pm8.4$	$35^{+11}_{-12}\pm15$	$(D\bar{D}^*)^0$	$e^+e^- \to (D\bar{D}^*)^0\pi^0$	[5]
$Z_c(4020)^{\pm}$	$4022.9\pm0.8\pm2.7$	$7.9\pm2.7\pm2.6$	$\pi^{\pm}h_c$	$e^+e^- \to \pi^+\pi^- h_c$	[6]
$Z_c(4020)^0$	$4023.9\pm2.2\pm3.8$	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$	[7]
$Z_c(4025)^{\pm}$	$4026.3\pm2.6\pm3.7$	$24.8\pm5.6\pm7.7$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$	[8]
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm3.1$	$23.0\pm6.0\pm1.0$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$	[9]

[1] PRL 110,252001; [2] PRL 115, 112003; [3] PRL 112, 022001; [4] PRD 92, 092006
[5] PRL 115, 222002; [6] PRL110, 252001; [7] PRL 113,212002; [8] PRL 112, 132001
[9] PRL 115, 182002

- Charged and neutral Z_c's are consistent with isospin triplets expectations.
- Mass and widths of $Z_c(3900)$ and $Z_c(3885)$ (also $Z_c(4020)$ and $Z_c(4025)$) are consistent within $2\sigma \rightarrow$ the same states?

Nature of Z_c?

- If these structures are real QCD states, charged Z_c decays into $\pi^{+/-}$ J/ψ ($\pi^{+/-}h_c$) → at least four valence quarks to satisfy charge=±1 and strong couplings to ccbar components. → e.g., likely to be $D\bar{D}^*$ molecular state.
- Other possible non-resonant interpretations:
  - Threshold Cusps? (PRD91, 034009 (2015))
  - Threshold effect from ATS (Anomalous Triangle Singularity: PLB753 (2016) 297-302)
- It is noticed that, so far, at least 4 LQCD groups have tried to find Z_c states in their calculations, but all failed.
- Light hadron decays: If observed, threshold effect can be excluded.

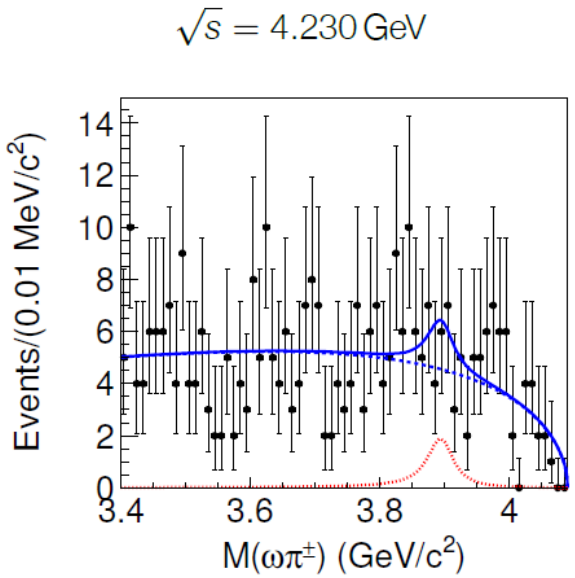


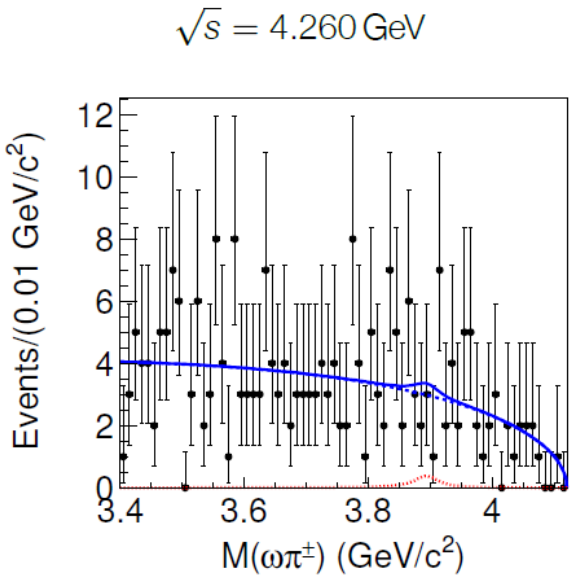
could also happen to threshold effect!

No threshold effect!

→Naiive expectations from η_c decays, the partial width to an exclusive light hadron mode is typically ~500 keV.

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





Phys. Rev. D92, 032009 (2015)

- **No significant $Z_c \to \omega\pi$ is observed:**
  $\sigma(e^+e^- \to \pi Z_c(3900) \to \pi(\omega\pi)) < 0.26$ pb @ 4.23 GeV
  $\sigma(e^+e^- \to \pi Z_c(3900) \to \pi(\omega\pi)) < 0.18$ pb @ 4.26 GeV

Compared to sum of $Z_c^+ \to J/\psi\pi^+$ and $Z_c^+ \to (D\bar{D}^*)^+$:

$$\Gamma(Z_c^+ \to \omega\pi^+) < 0.2\%\Gamma_{\text{tot}}$$ ~60keV

ccbar annihilation of Z_c decays is suppressed → threshold effect cannot be ruled out.

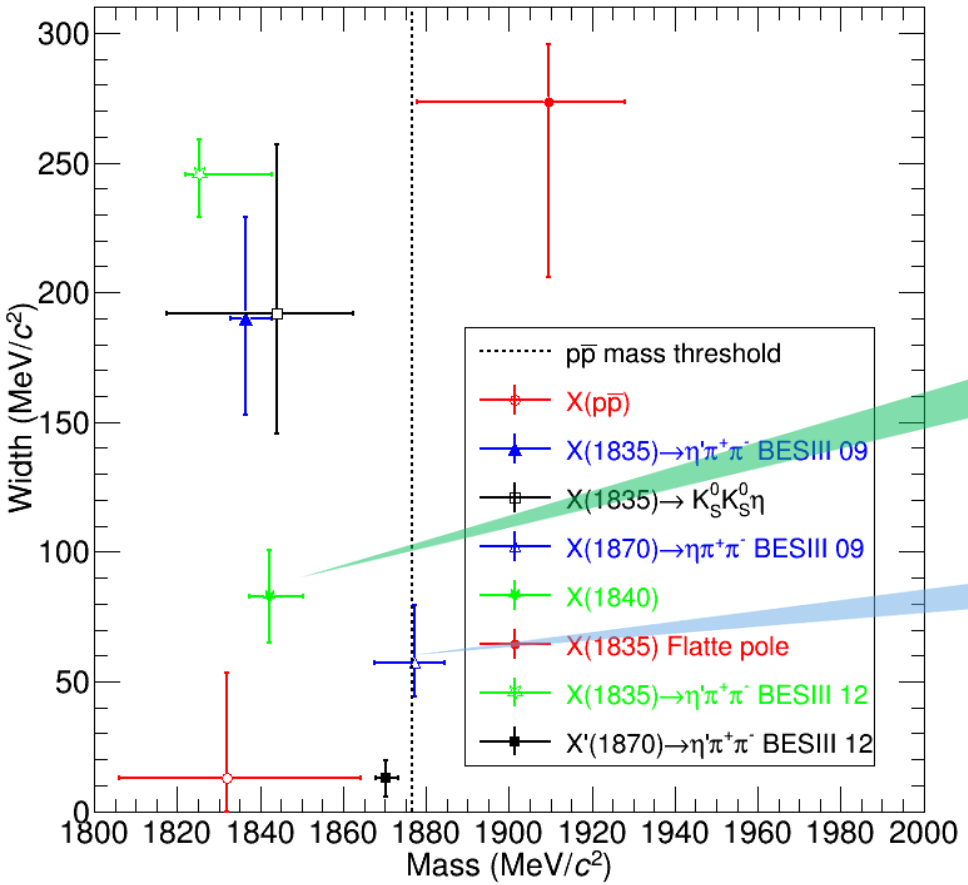
Summary

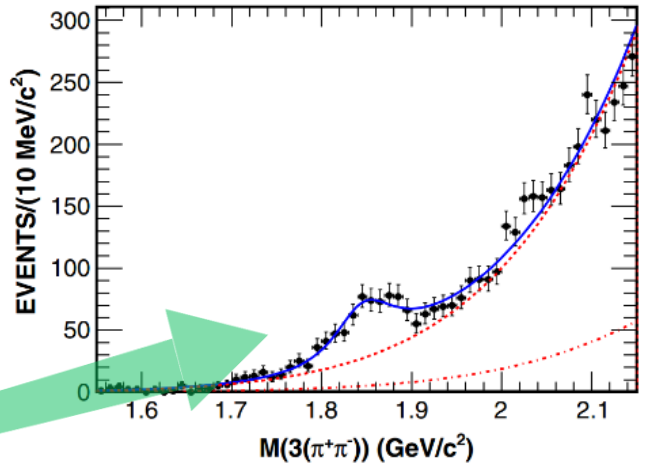
- **Highlights of latest results on searching for new forms of hadrons at BESIII:**
  - **Observation of X(1835) in $J/\psi \to \gamma K_S K_S \eta$**
    - **New decay mode of X(1835)→ $K_S K_S \eta$ and J^{PC} of X(1835) determined: 0^{-+}**
  - **Observation of anomalous $\eta'\pi^+\pi^-$ line shape 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**
  - **Model independent partial wave analysis (MIPWA) of $J/\psi \to \gamma\pi^0\pi^0$**
    - **Useful information for 0^{++}, 2^{++} components; multi-solution problem exists in MIPWA.**
  - **Partial wave analysis of $J/\psi \to \gamma\phi\phi$**
    - **Many 0^{-+}, 2^{++} mesons observed —— any glueball candidates?**
  - **Observation of $Z_c(3900)/Z_c(3885)$, $Z_c(4020)/Z_c(4025)$ structures**
    - **If real QCD states, they should contain at least 4 quarks.**
    - **Threshold effect needs to be excluded first.**
- **More results are expected in the future!**

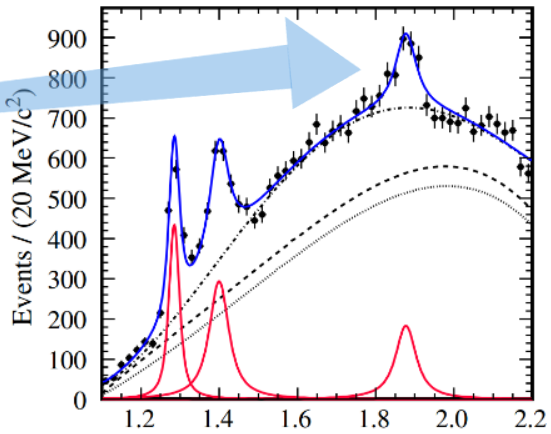
Thank you!

backup

Structures around 1.8 GeV/c^2







$J/\psi\to\gamma 3(\pi^+\pi^-)$
Phys. Rev. D 88, 091502(R) (2013)

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

$J/\psi\to\omega\eta\pi^+\pi^-$
Phys. Rev. Lett. 107, 182001 (2011)