Light quark spectroscopy at BESIII

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(on behalf of BESIII Collaboration)

The Flavor Physics and CP Violation conference 2016 in Pasadena, California, USA

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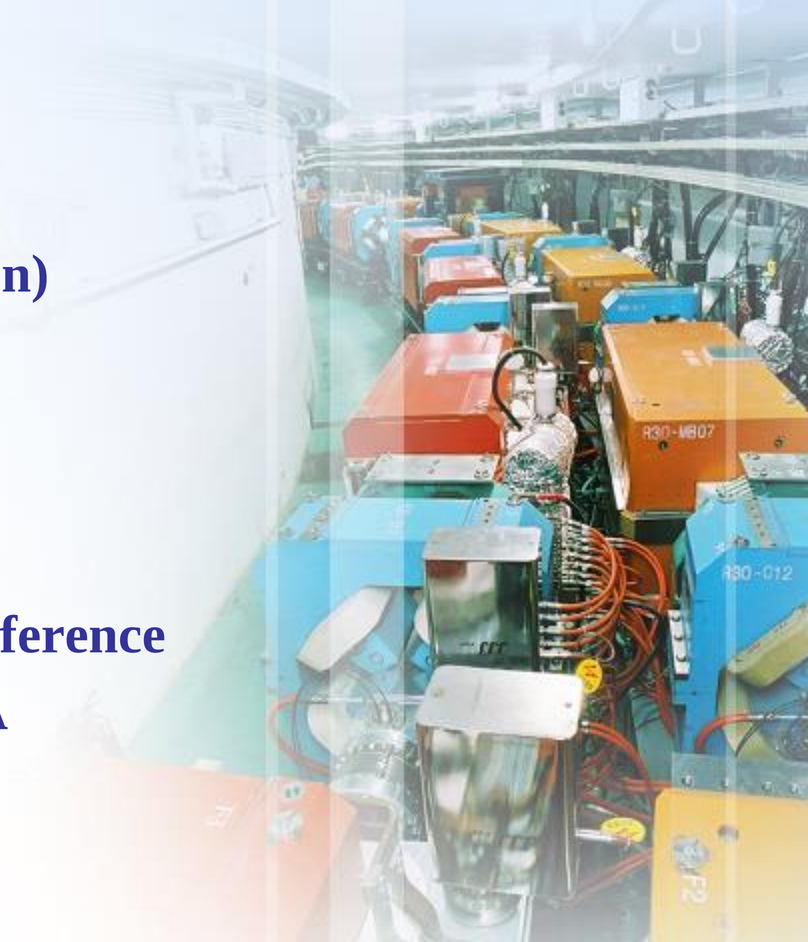
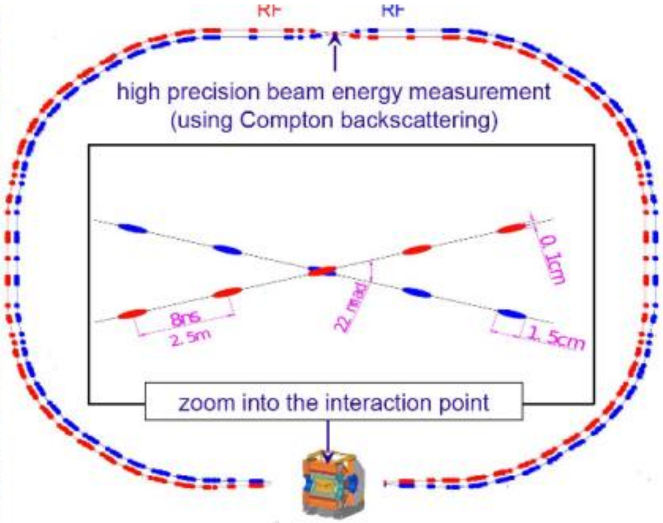


OUTLINE

- BESIII/BEPCII and BESIII physics
- Selected topics on light quark spectroscopy
  - X(1835) and mass enhancement
  - Model independent PWA of $J/\psi \to \gamma \pi^0 \pi^0$
  - PWA of $J/\psi \to \gamma \phi \phi$
  - Amplitude analysis of $\chi_{C1} \to \eta \pi^+ \pi^-$
- Conclusion and outlook

BESIII at BEPCII



Symmetric electron-positron collider BEPC II

- Energy range: $\sqrt{s}$ = 2.0-4.6 GeV
- Design luminosity: 1×10^{33} $cm^{-2}s^{-1}$ (at $\psi(3770)$)
- Energy spread: $\sim5\times10^{-4}$
- Operating since March 2008
- Achieved luminosity: 1×10^{33} $cm^{-2}s^{-1}$

BESIII Detector

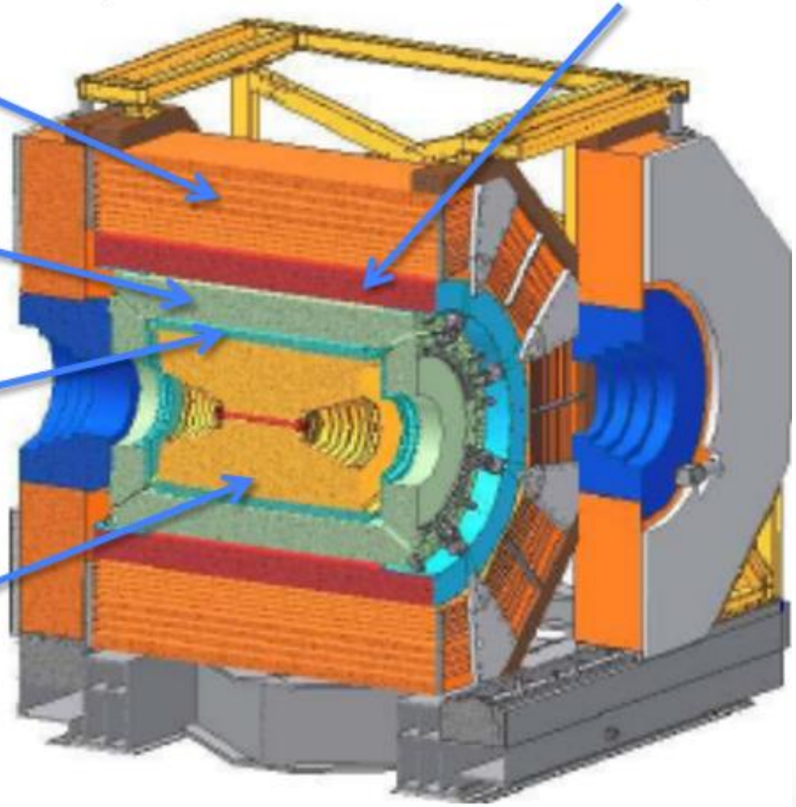
RPC Muon Detector
8 layers (end caps), 9 layers (barrel)
$\delta R_{\phi} = 1.4 - 1.7\,\mathrm{mm}$

Electromagnetic
CsI(TI) Calorimeter
$\sigma_E/E < 2.5\%/\sqrt{E}$
$\sigma_{z,\phi} = 0.5 - 0.7\,\mathrm{cm}/\sqrt{\mathrm{E}}$

Time of Flight System
$\sigma_t = 80\,\mathrm{ps}$ (barrel)
$\sigma_t = 110\,\mathrm{ps}$ (end caps)

Drift Chamber
$\sigma_{(dE/dx)} = 6\%$
$\sigma_{p_t}/p_t = 0.5\%$

Superconducting
Solenoid (1 T)



The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.

BESIII Physics

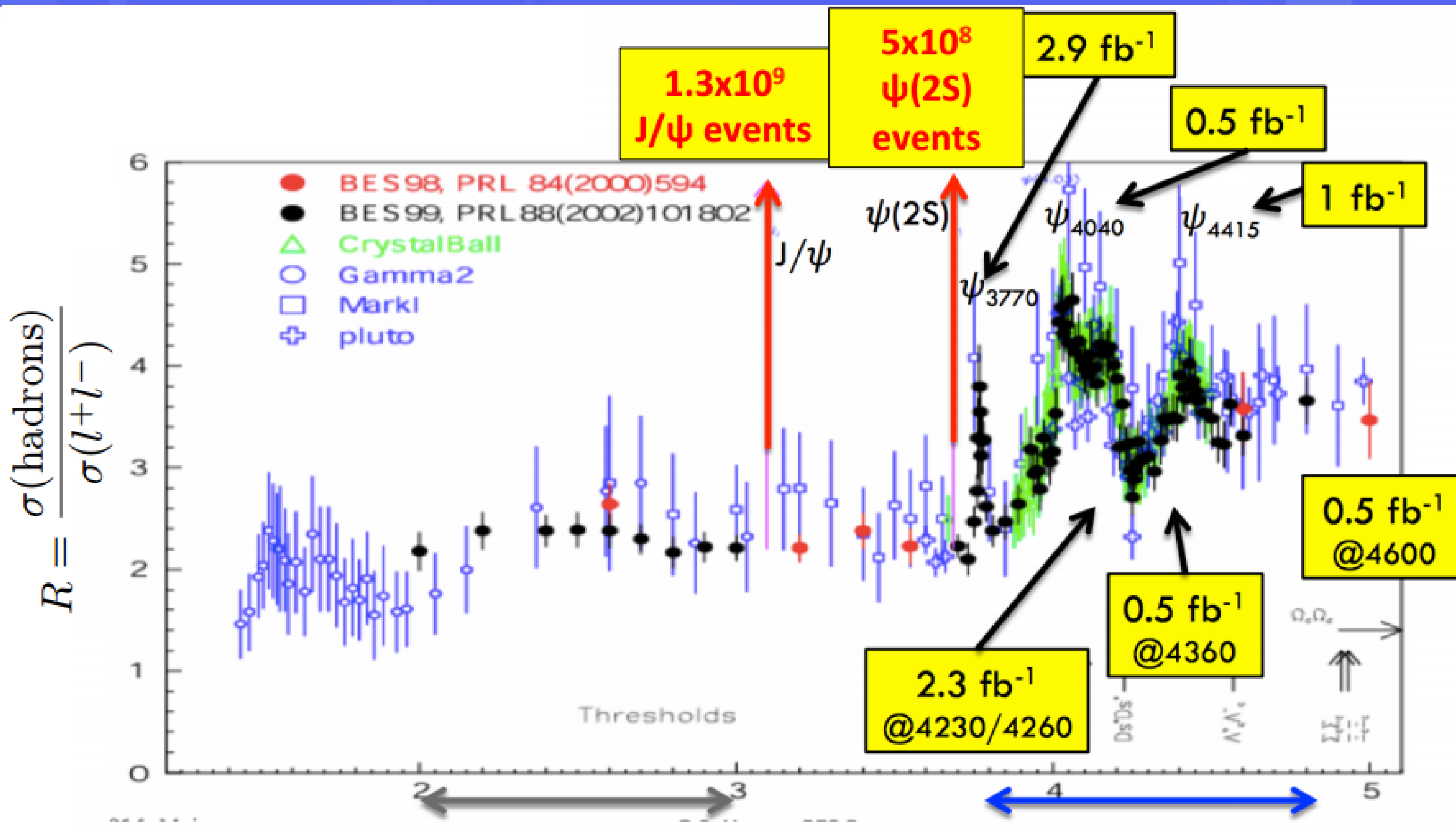
- Light Hadrons
  - Meson and baryon spectroscopy
  - Search for exotic hadrons, e.g. glueballs, hybrids, tetraquarks
  - Light meson decays ($\eta^{(\prime)}$, ω)

- Charmonium Physics
  - X, Y, and Z states
  - Decays and transitions

- Open Charm Physics
  - D meson decays
  - $D\bar{D}$ mixing
  - CP violation in the charm sector

- And many further topics
  - e.g. tau and two-photon physics

Data samples



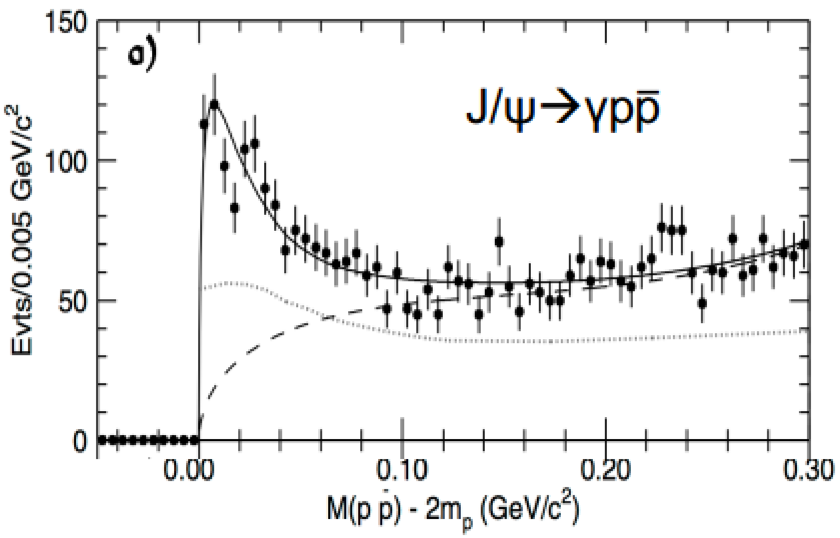
R scan: 2-3 GeV, 19 points, ~0.5 fb^{-1}; 3.85-4.59 GeV, 104 points, ~0.8 fb^{-1}

plus 24/pb at τ mass threshold and
0.5/fb in the region 4100-4400 MeV

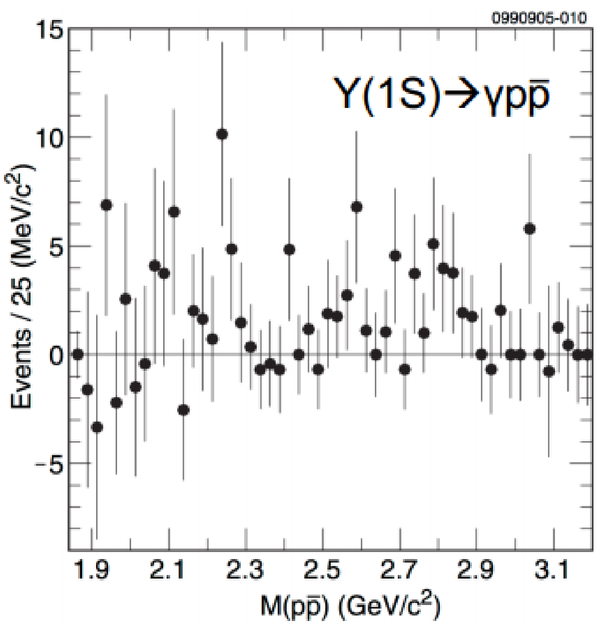
Enhancement of $p\bar{p}$ threshold

- Enhancement at $p\bar{p}$ threshold observed in $J/\psi \to \gamma p\bar{p}$ by BESII (2003) and confirmed by CLEOc (2010)
- Enhancement not observed in related channel: $\Upsilon(1S) \to \gamma p\bar{p}$
- Nature yet unclear
  - baryonium, multiquark state, FSI effect ?

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



CLEOc, Phys. Rev. D73, 032001 (2006)



Radiative J/ψ and ψ′ decays into $p\bar{p}$

- Partial Wave Analysis of $J/\psi \to \gamma p\bar{p}$ and $\psi' \to \gamma p\bar{p}$ in the mass region $m_{p\bar{p}} < 2.2$ GeV/c^2

  $J/\psi \to \gamma p\bar{p}$: Significant contributions of $X(p\bar{p})$, $f_2(1920)$, $f_0(2100)$, and non-resonant 0^{++} $p\bar{p}$ wave

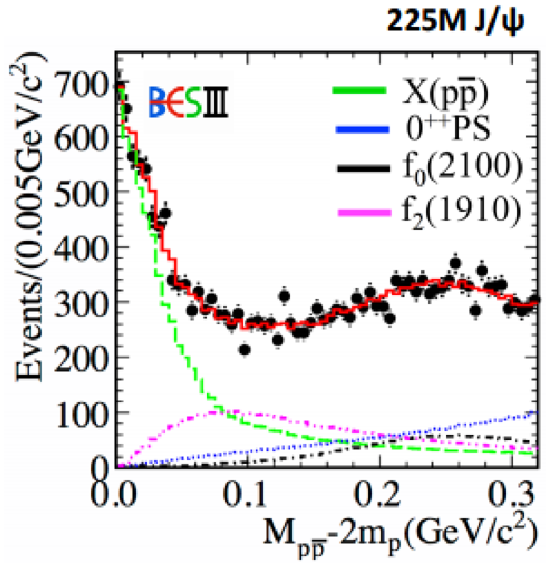
  → Structure at threshold $X(p\bar{p})$: $J^{PC} = 0^{-+}$
  Breit-Wigner parameterization:

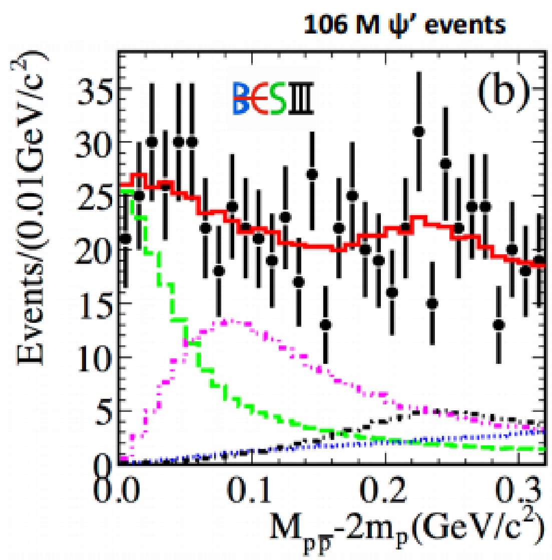
$$M = 1832^{+19}_{-5}(\text{stat})\ ^{+18}_{-17}(\text{syst}) \pm 19(\text{model})\ \text{MeV}/c^2$$

$$\Gamma = 13 \pm 39(\text{stat})\ ^{+10}_{-13}(\text{syst}) \pm 4(\text{model})\ \text{MeV}/c^2$$

$$BR_{[J/\psi \to \gamma X]} \times BR_{[X \to pp]} = (9.0^{+0.4}_{-1.1}(\text{stat})^{+1.5}_{-5.0}(\text{syst}) \pm 2.3(\text{model})) \times 10^{-5}$$

- $\psi' \to \gamma p\bar{p}$: $X(p\bar{p})$ production is suppressed by a factor of ~20 over production in $J/\psi \to \gamma p\bar{p}$





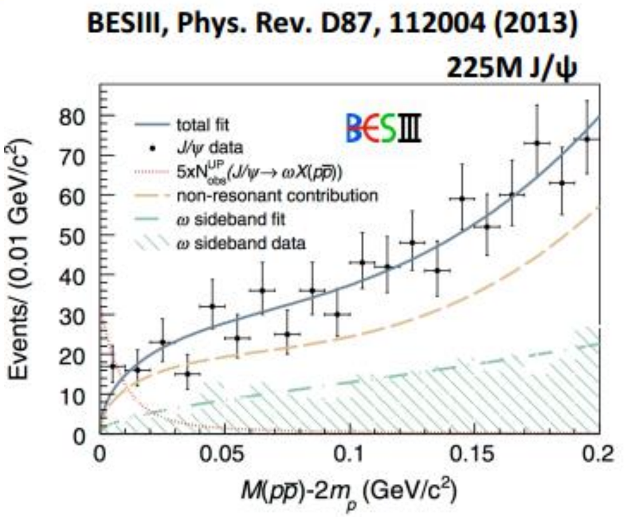
Hadronic J/ψ decays into ω p p̄ and ϕ p p̄

Study of J/ψ→ωpp̄ and J/ψ→Φpp̄ may shed further light on the nature of X(pp̄)

- **J/ψ→ω p p̄**

  B(J/ψ → ωX(pp̄) → ωpp̄)
  <3.7×10^{-6} (95% CL)

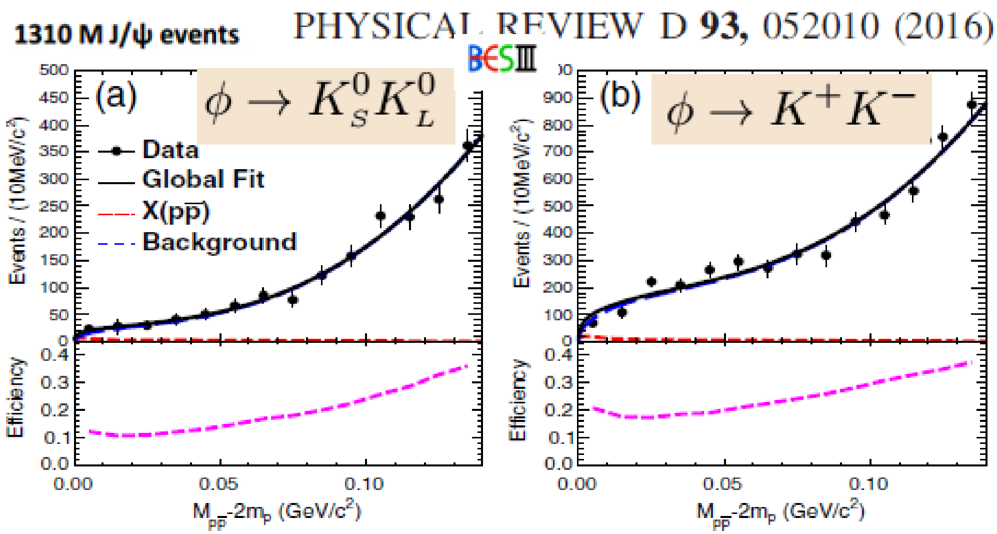
  >10x suppressed compared to J/ψ →γX(pp̄)→γpp̄



- **J/ψ→ϕ p p̄**

  B(J/ψ→ΦX(pp̄)→Φpp̄)
  <2×10^{-7} (90% CL)

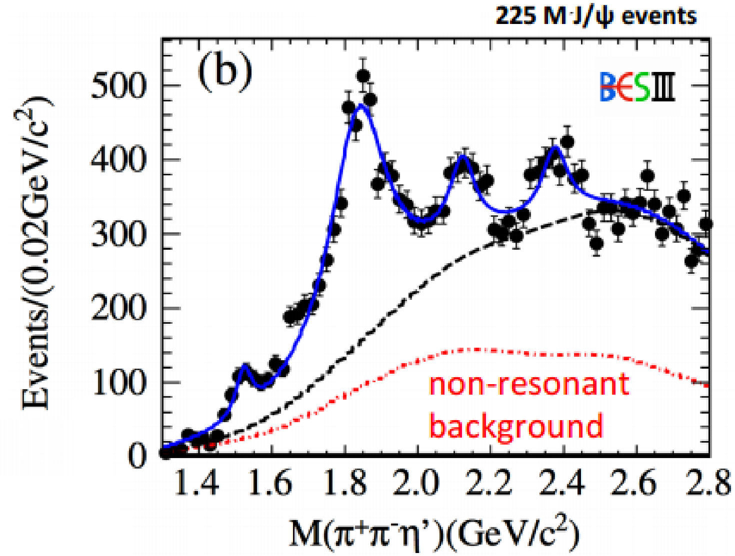
  >100x suppressed compared to J/ψ → γX(pp̄)→γpp̄



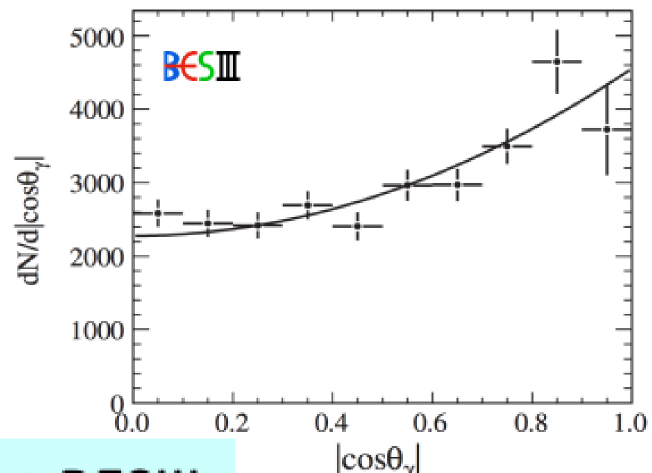
X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$

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

- X(1835) previously observed at BES and BESII
- Nature unclear, interpretations include glueball, $\bar{p}p$ bound state, excited η meson
- Confirmed at BESIII with two additional structures above 2 GeV/c^2



Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	
$f_1(1510)$	1522.7 ± 5.0	48 ± 11	$>5.7\sigma$
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0	$>20\sigma$
$X(2120)$	2122.4 ± 6.7	83 ± 16	$>7.2\sigma$
$X(2370)$	2376.3 ± 8.7	83 ± 17	$>6.4\sigma$



X(1835) angular distribution consistent with pseudoscalar, but other spin-parity assignments not exclude

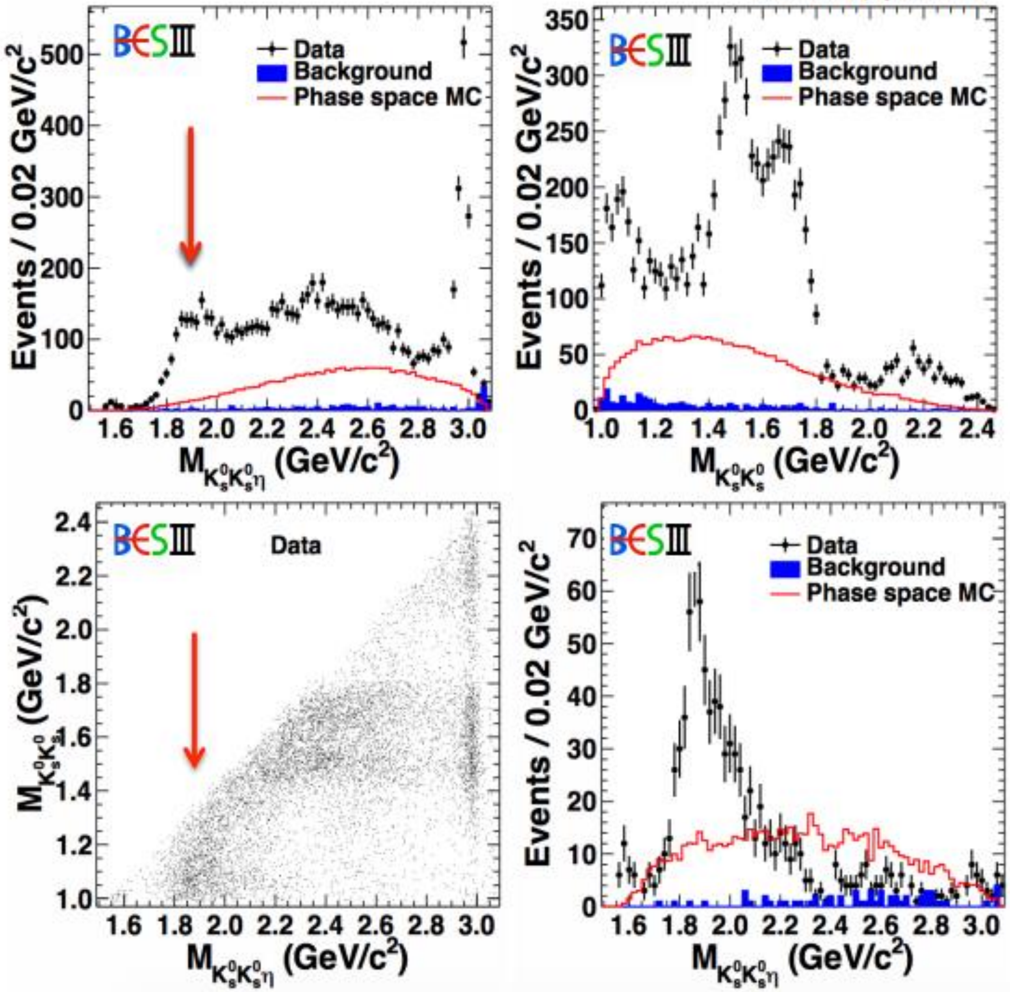
Systematic studies of X(1835) ongoing at BESIII

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

- Structure in invariant $K_S K_S \eta$ mass at ~1.85 GeV/c^2
- Strong correlation with enhancement at $K_S K_S$ mass threshold (interpretated as $f_0(980)$)
- Structure in $K_S K_S \eta$ is enhanced for $m(K_S K_S)$<1.1 GeV/c^2

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

1310 M J/ψ events



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

- Partial wave analysis for $m(K_SK_S)<1.1$ GeV/c^2 and $m(K_SK_S\eta)<2.8$ GeV/c^2

- Two resonant pseudoscalar components (Breit-Wigner parameterization) required in best fit hypothesis

$X(1835) \to f_0(980)\eta$ (>12.9σ)

$$m = 1844 \pm 19^{+16}_{-25}\ \mathrm{MeV}/c^2$$

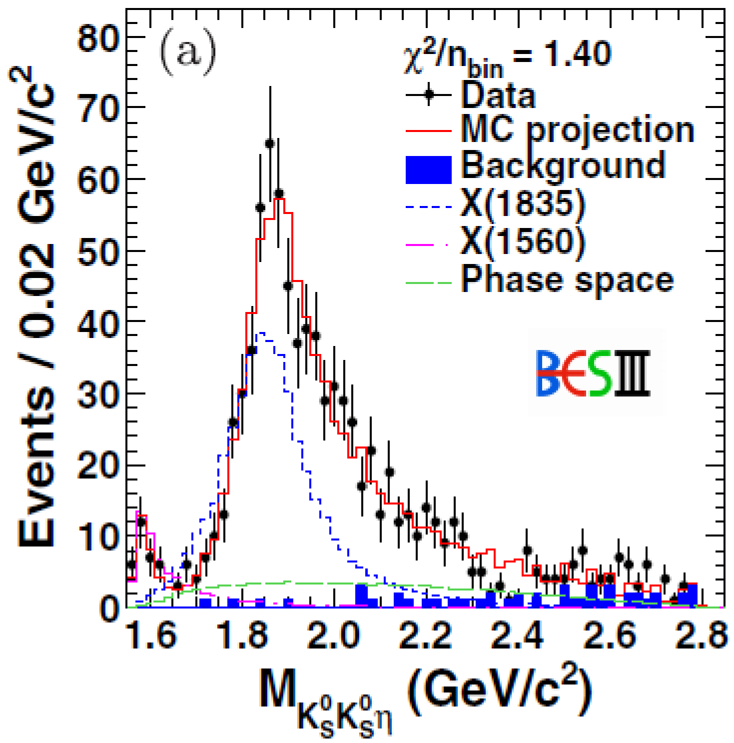
$$\Gamma = 192^{+20+62}_{-17-43}\ \mathrm{MeV}$$

$X(1560) \to f_0(980)\eta$ (>8.9σ)

$$m = 1565 \pm 8^{+0}_{-63}\ \mathrm{MeV}/c^2$$

$$\Gamma = 45^{+14+21}_{-13-28}\ \mathrm{MeV}$$

BESIII, Phys. Rev. Lett. 115, 091803 (2015)　　1310 M J/ψ events



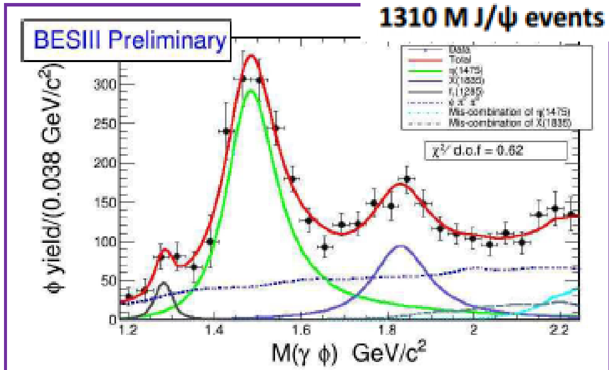
consistent with those of η(1405)/η(1475) within 2σ and more further study is need

X(1835) in $J/\psi \to \gamma\gamma\phi$

preliminary

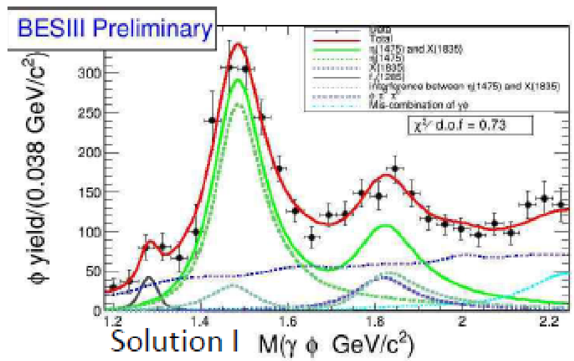
- A comparison of the decay rate for $X \to \gamma V$ ($V=\rho,\phi,\omega$) can provide information on the flavor content of X(1835)
- f1(1285) , η(1405)/η(1475) and X(1835) are evident by fitting $M(\gamma\phi)$

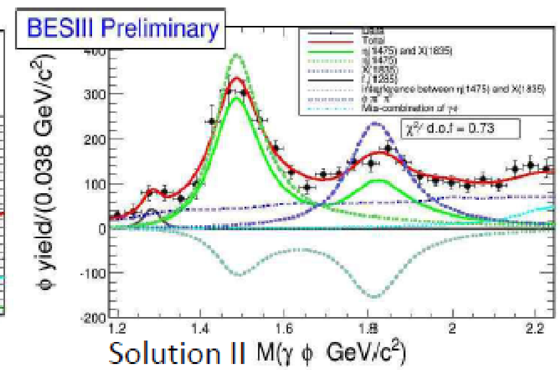
1310 M J/ψ events



Assuming no interference

	Mass (MeV/c²)	Γ(MeV/c²)
η(1405/1475)	1475±7±16	132±15±23
X(1835)	1826±13±29	148±39±31





Interference between η(1405/1475) and X(1835)

	Mass (MeV/c²)	Γ(MeV/c²)
η(1405/1475)	1479±11±21	133±35±20
X(1835)	1812±59±42	161±47±24

	Mass (MeV/c²)	Γ(MeV/c²)
η(1405/1475)	1479±11±16	132±36±31
X(1835)	1813±61±45	160±81±43

$M(\eta(1405))=(1408\pm1.8)\mathrm{MeV}/c^2$; $\Gamma(\eta(1405))=(51.0\pm2.9)\mathrm{MeV}/c^2$
$M(\eta(1475))=(1476\pm4)\mathrm{MeV}/c^2$; $\Gamma(\eta(1475))=(85\pm9)\mathrm{MeV}/c^2$
$M(X(1835))=(1835.7^{+5.0}_{-3.2})\mathrm{MeV}/c^2$; $\Gamma(X(1835))=(99\pm50)\mathrm{MeV}/c^2$
PDG Value

X(1835) and other states in $J/\psi \to \gamma\gamma\phi$

preliminary

- X(1835) is first observed in $\gamma\phi$ final state, more studies are needed to make sure the nature of X(1835).
- The structure in $\gamma\phi$ favors $\eta(1475)$.

  One state assumption: the ratio between $\gamma\rho$ and $\gamma\phi$ final states is a little larger than the prediction in Ref[1].

  Two states assumption: $\eta(1475)$ probably contains the $s\bar{s}$ component.

- Assuming $\eta(1405)$ and $\eta(1475)$ belong to one meson [1]:
  $\Gamma(\eta(1405/1475)\to\gamma\rho):\Gamma(\eta(1405/1475)\to\gamma\phi) = 3.8 : 1$
- Assuming $\eta(1405/1475)$ is glueball[2]:
  $\Gamma(\eta(1405/1475)\to\gamma\rho):\Gamma(\eta(1405/1475)\to\gamma\phi) = 1 : 1$

The partial width relationship of $\gamma\rho$ and $\gamma\phi$ final states

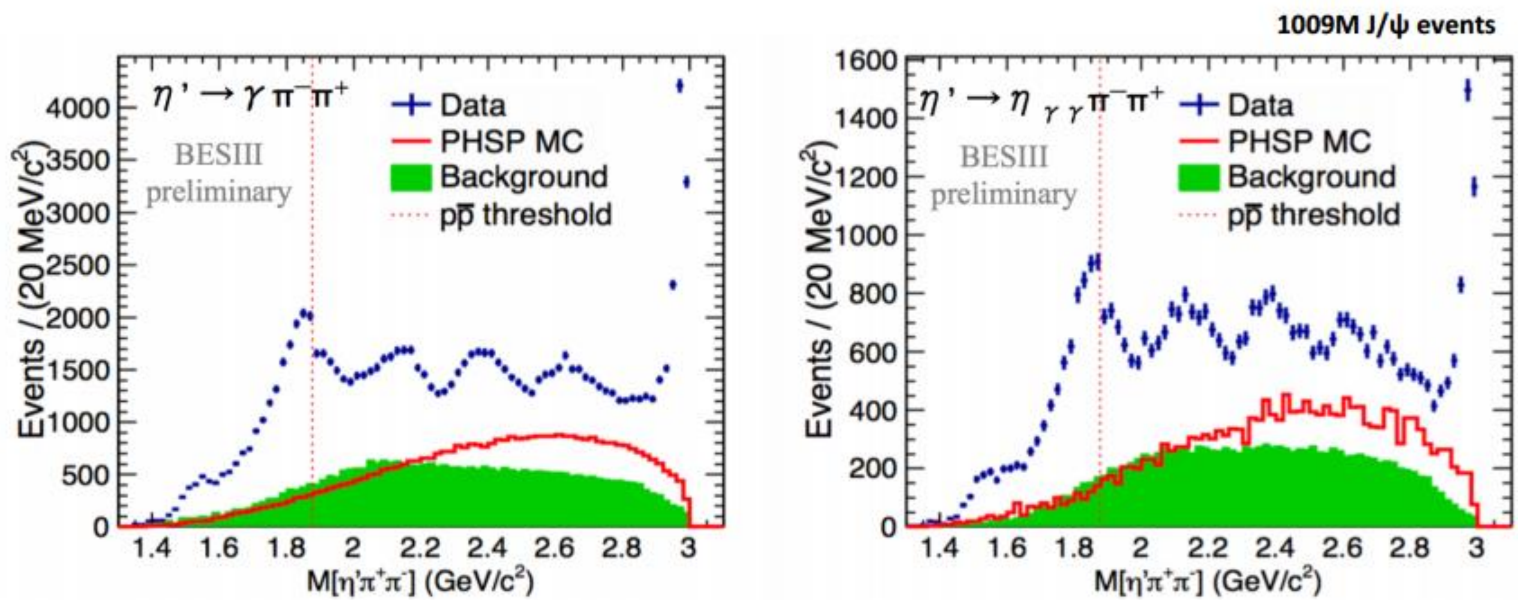
BESIII preliminary

	No interference	Interference between $\eta(1405/1475)$ and X(1835)	
		Solution 1	Solution 2
$\Gamma(f_1(1285)\to\gamma\rho)$[3]:$\Gamma(f_1(1285)\to\gamma\phi)$	$(116.6\pm77.5):1$	$(128.8\pm96.7):1$	$(129.3\pm99.8):1$
$\Gamma(\eta(1405/1475)\to\gamma\rho)$[4]:$\Gamma(\eta(1405/1475)\to\gamma\phi)$	$(9.8\pm2.0):1$	$(6.6\pm2.1):1$	$(9.9\pm2.8):1$

[1] X. G. Wu et, al. Phys. Rev. D **87**, 014023.
[2] L. Kopke and N. Wermes Phys. Rep. **174** , 67.
[3] BES Collaboration Phys. Lett. B **594**, 47.
[4] Particle Data Group Chin. Phys. C **38**, 090001.

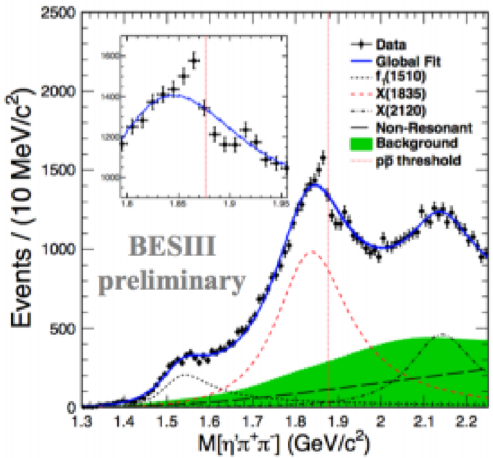
Connection of X(p $\bar{p}$) and X(1835)

- If X(1835) couples to $p\bar{p}$ the lineshape would be affected at the $p\bar{p}$ threshold
- Update of $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ analysis with 1.09×10^9 J/ψ events
  - Using $\eta' \rightarrow \eta\pi^+\pi^-$ and $\eta \rightarrow \gamma\pi^+\pi^-$
  - X(1835), X(2120), X(2370) and η_c signals; structure at ~2600 MeV/c^2

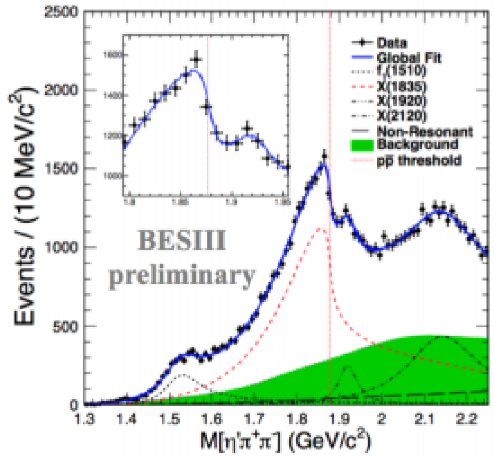


Drop of the X(1835) lineshape at the $p\bar{p}$ threshold !

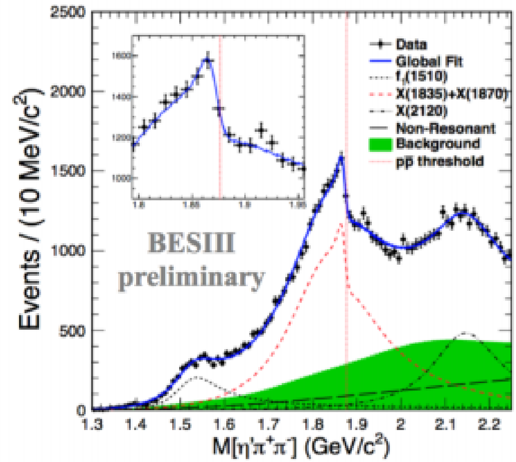
Connection of X($p\bar{p}$) and X(1835)



Parameterization with single Breit-Wigner fails to describe the data



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

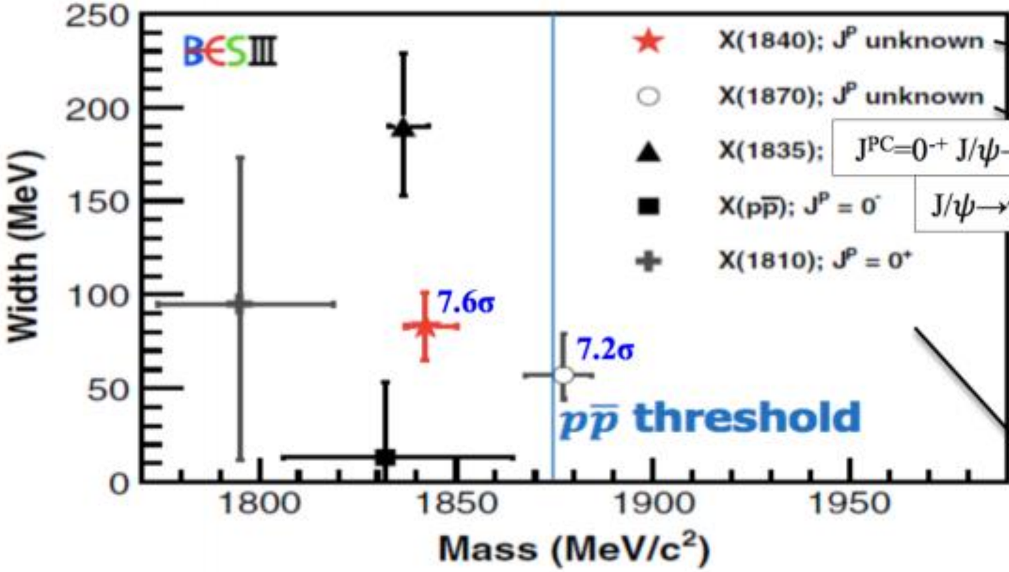


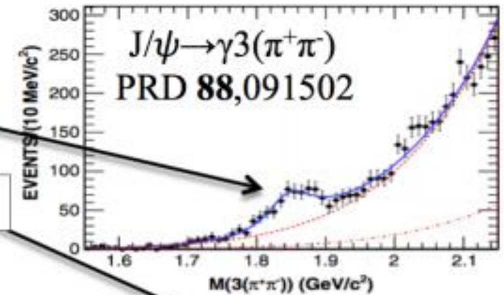
Model 2:
Coherent sum of X(1835) Breit-Wigner and one additional, narrow Breit-Wigner at ~1870 MeV/c^2

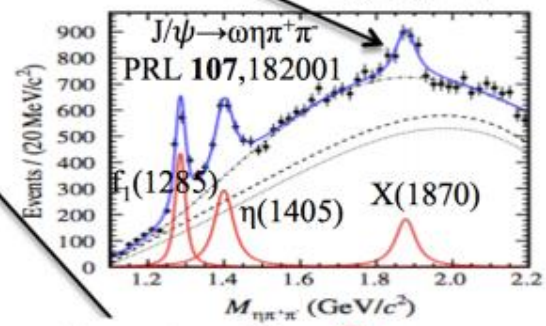
Model 1 and 2 yield almost equal fit quality
Both fits suggest two resonances:

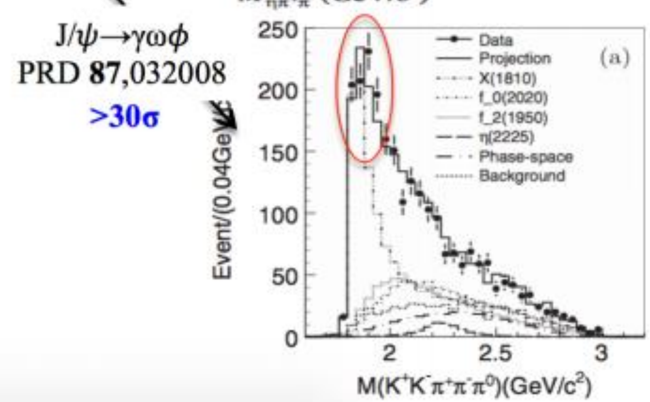
- one broad resonance below threshold
- one narrow state very close to $p\bar{p}$ threshold

Further study of X(p $\bar{p}$) threshold and X(1835)









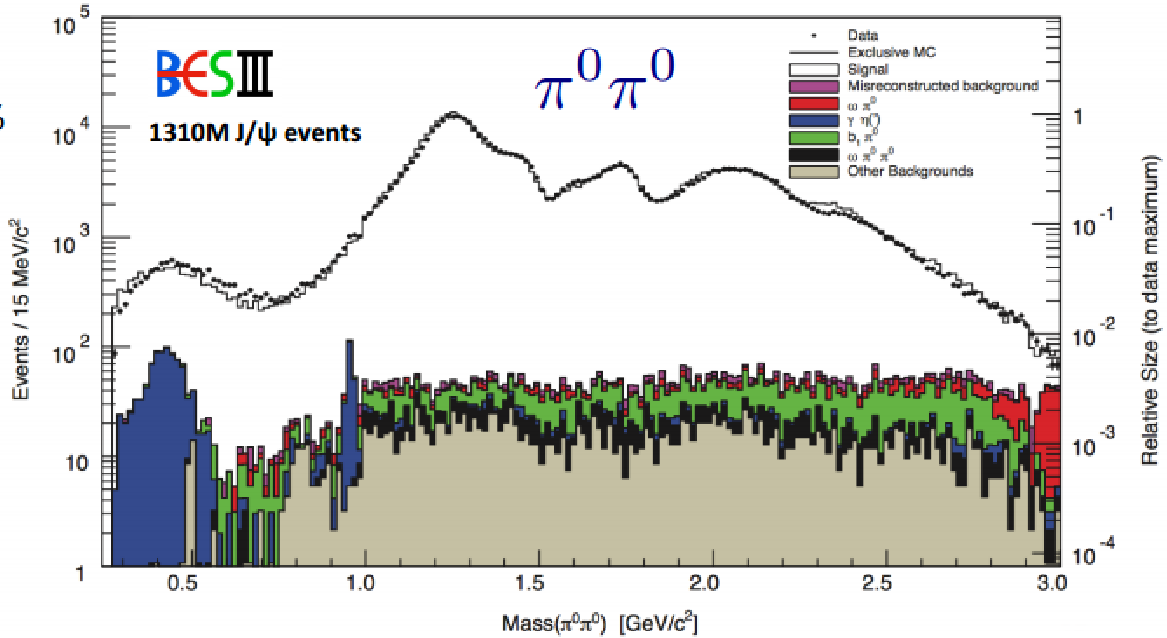
- Same origin?
- Further investigations required to clarify
  - J^{PC} not determined for all structures
  - Coupled channel analysis including various final states and production mechanisms

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

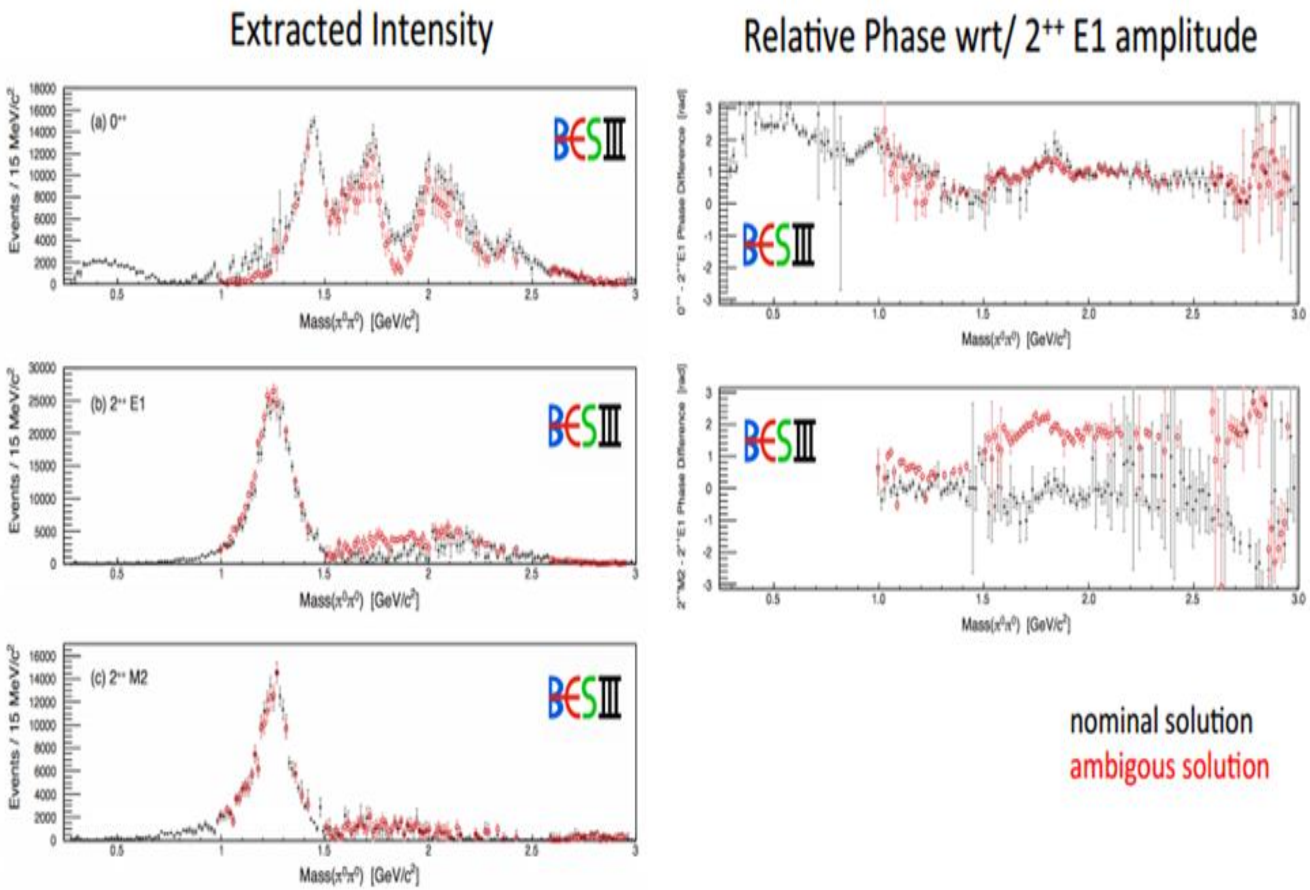
- Radiative J/ψ decays into two pseudoscalar mesons
  - Search for scalar and tensor glueballs (predicted at ~1.5 to ~2 GeV/c^2)
- $\pi^0\pi^0$ system: only significant 0^{++} and 2^{++} contributions
  - Many broad and overlapping resonances, many open channels
    → complex structure, parameterization challenging
  - Model Independent Partial Wave Analysis

>440k reconstructed events at a background level of 1.8%

BESIII, Phys.Rev. D92 052003 (2015)



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



BESIII, Phys.Rev. D92 052003 (2015)

- ✓ 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 below 1.5, near 1.7 and 2.0GeV/c^2
- ✓ 2^{++} amplitude indicates a dominant contribution from $f_2(1270)$
- ✓ Ambiguities present above $K\bar{K}$ threshold

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

BESIII preliminary

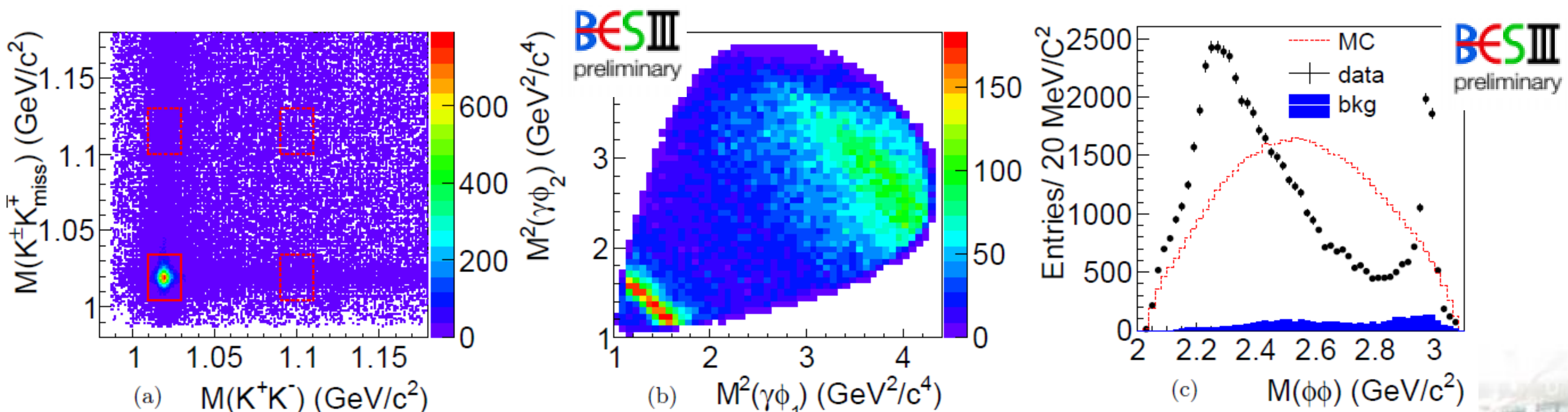
- Lattice QCD predictions:
  - Ground state of 2^{++} glueball in 2.3 ~2.4 GeV/c^2
  - Ground state of 0^{-+} glueball in 2.3~2.6 GeV/c^2

- Structures in $\phi\phi$ spectrum:
  - Pseudoscalar state $\eta(2225)$ was observed in $J/\psi \to \gamma\phi\phi$
  - For higher 0^{-+} mass states above 2 GeV/c^2, very little is known.
  - Broad 2^{++} structures decaying to $\phi\phi$ were reported around 2.3 GeV in $\pi^{-}N$ reactions and in $p\bar{p}$ central collisions

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

arXiv:1602.01523

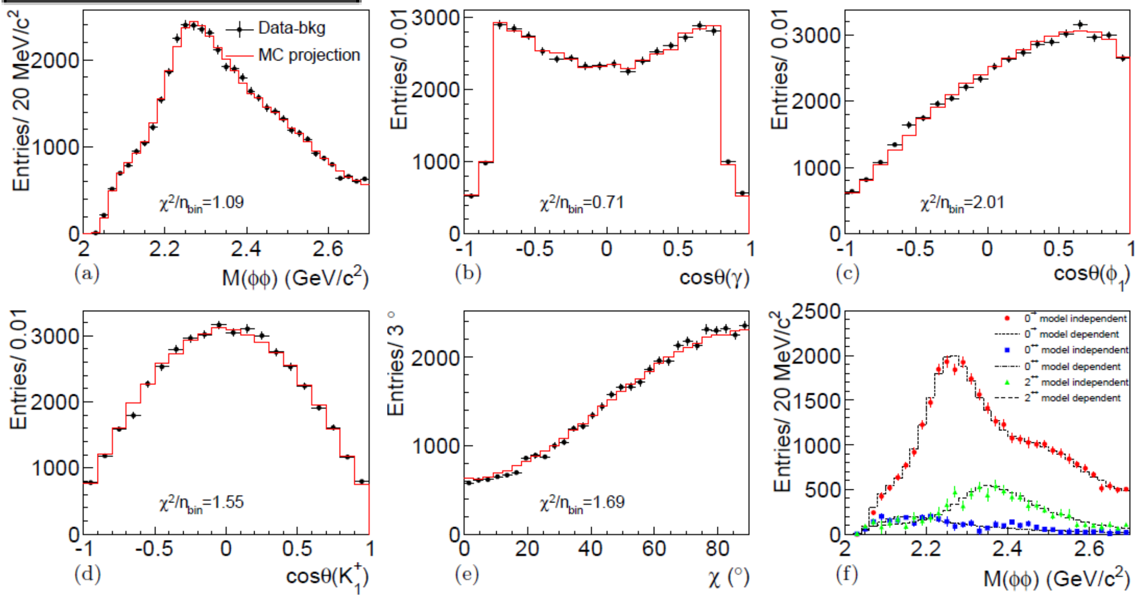
- Use 1.3×10^9 J/ψ events collected by BESIII in 2009 and 2012
- PWA procedure
  - ✓ Covariant tensor formalism
  - ✓ Data-driven background subtraction
  - ✓ Resonances parameterized by relative Breit-Wigner with constant width
  - ✓ Resonance with significance >5σ are selected as components in solution



PWA of J/ψ→γΦΦ

arXiv:1602.01523

BESIII preliminary



- Pesudoscalar: η(2225), dominant η(2100) and X(2500)
- Tensor: $f_2(2010)$, $f_2(2300)$, $f_2(2340)$: stated in π-p reaction; strong $f_2(2340)$ production

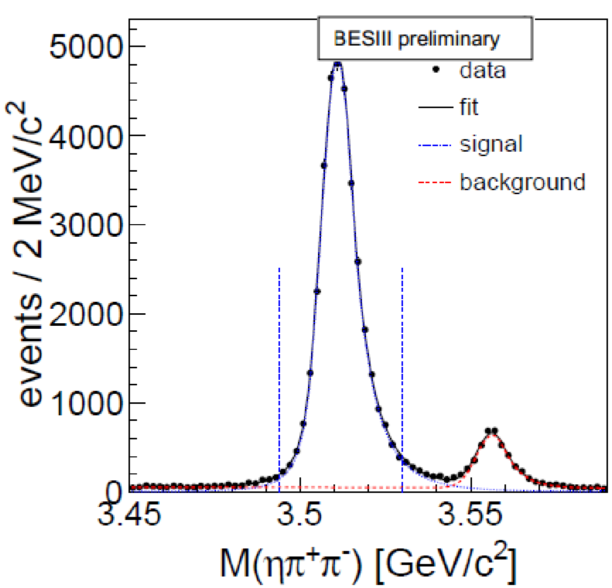
Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	B.F.$(\times 10^{-4})$	Sig.
$\eta(2225)$	$2216^{+4}_{-5}{}^{+21}_{-11}$	$185^{+12}_{-14}{}^{+43}_{-17}$	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	$28\ \sigma$
$\eta(2100)$	$2050^{+30}_{-24}{}^{+75}_{-26}$	$250^{+36}_{-30}{}^{+181}_{-164}$	$(3.30 \pm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

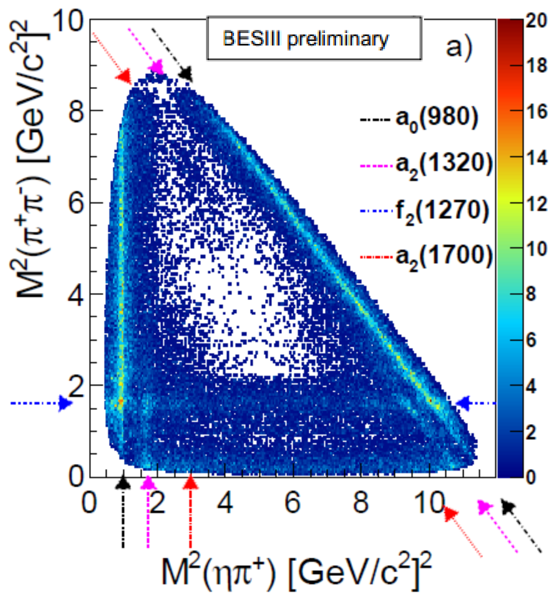
fixed to PDG

The new experimental results are helpful for mapping out the pseudoscalar excitations and searching for a 0^{-+} glueball

Amplitude Analysis of $\chi_{C1} \to \eta\pi^+\pi^-$

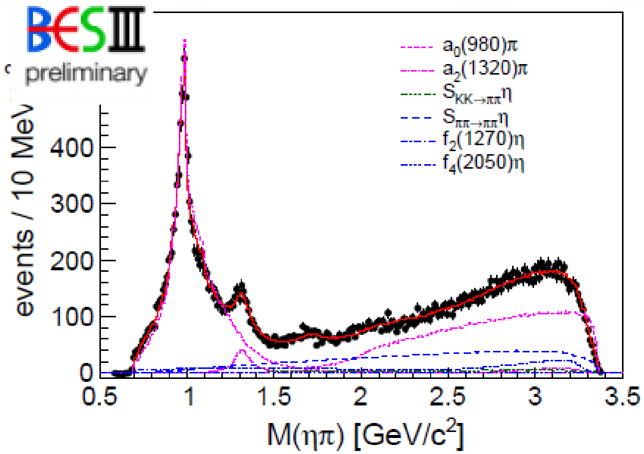
- $\chi_{C1} \to \eta\pi^+\pi^-$ is suitable to look for 1^{-+} exotics
  - ✓ $\pi_1(1600)$ was studied in χ_{c1} decays by CLEO-c
  - ✓ only $\pi_1(1400)$ was reported in $\eta\pi$ final state
- Further study of $a_0(980)$ and $a_2(1700)$ in $\eta\pi$ final state

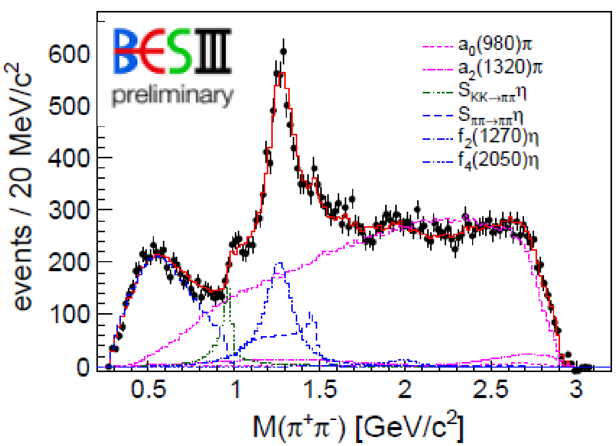




- ✓ Two body structures $a_0(980)$, $a_2(1320)$ and $f_2(1270)$ are evident similar to previous analysis
- ✓ The events in the upper left corner are compatible with $a_2(1700)$ hypothesis

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





Decay	$\mathcal{B}(\chi_{c1} \to \eta\pi^+\pi^-)$ $[10^{-3}]$	
$\eta\pi^+\pi^-$	$4.676 \pm 0.030 \pm 0.232 \pm 0.158$	
$a_0(980)^+\pi^-$	$3.422 \pm 0.033 \pm 0.193 \pm 0.115$	
$a_2(1320)^+\pi^-$	$0.181 \pm 0.009 \pm 0.017 \pm 0.006$	
$a_2(1700)^+\pi^-$	$0.049 \pm 0.005 \pm 0.007 \pm 0.002$	
$S_{KK}\eta$	$0.114 \pm 0.006 \pm 0.014 \pm 0.004$	
$S_{\pi\pi}\eta$	$0.761 \pm 0.019 \pm 0.05 \pm 0.026$	
$(\pi^+\pi^-)_S\eta$	$0.829 \pm 0.020 \pm 0.049 \pm 0.028$	
$f_2(1270)\eta$	$0.368 \pm 0.012 \pm 0.056 \pm 0.012$	
$f_4(2050)\eta$	$0.026 \pm 0.004 \pm 0.008 \pm 0.001$	
Exotic candidates		U.L. [90% C.L.]
$\pi_1(1400)$	0.58 ± 0.20	< 0.046
$\pi_1(1600)$	0.11 ± 0.10	< 0.015
$\pi_1(2015)$	0.06 ± 0.03	< 0.008

- ✓ Clear evidence for $a_2(1700)$ in χ_{c1} decays
- ✓ First measurement of $g_{\eta'\pi}$ using $a_0(980) \to \eta\pi$ line shape
- ✓ Upper limits for $\pi_1(1^{-+})$ in 1.4 - 2.0 GeV$/c^2$ region are measured

Conclusion and outlook

- **Many interesting results in light quark spectroscopy from BESIII**
  - ✓ **Systematic studies to understand X(1835) and other structures observed near ppbar threshold**
    - X(1835) nature unclear: $p\bar{p}$ bound state, glueball, excited η meson?
  - ✓ **Sophisticated model independent partial wave analysis of $J/\psi \to \gamma\pi^0\pi^0$**
  - ✓ **PWA of $J/\psi \to \gamma\phi\phi$**
  - ✓ **Amplitude Analysis of $\chi_{C1} \to \eta\pi^+\pi^-$**
- **Expect more important results from BESIII**