LIGHT HADRON SPECTROSCOPY @ BESIII

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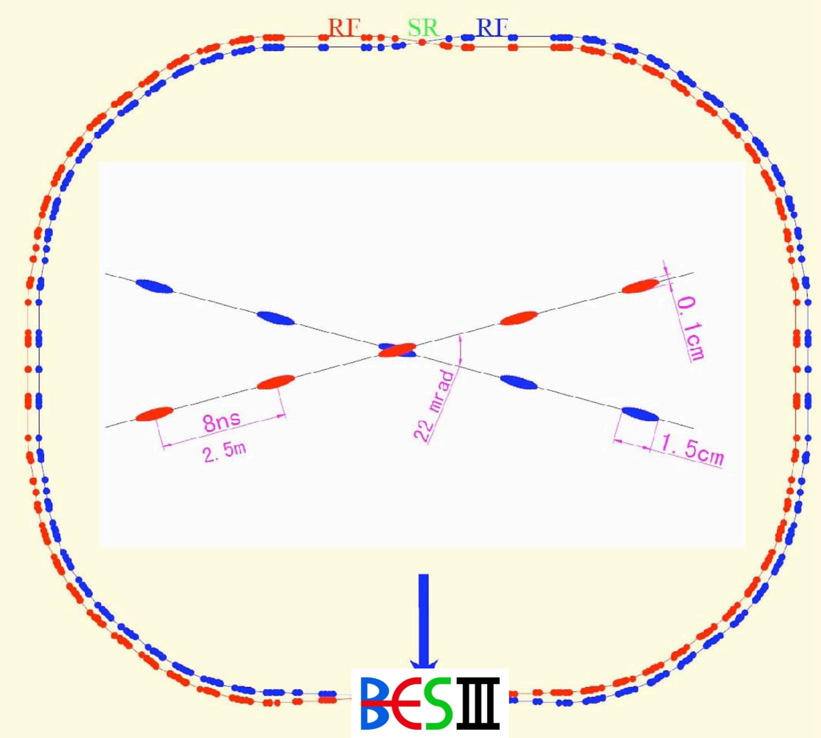
EUROPEAN PHYSICAL SOCIETY HEP2017

Outline

- Introduction to BESIII and BEPCII
- Highlights of light hadron spectroscopy:
  - ✿X states @ $p\bar{p}$ mass threshold
  - ✿PWA in charmonia decays
- Summary and conclusions

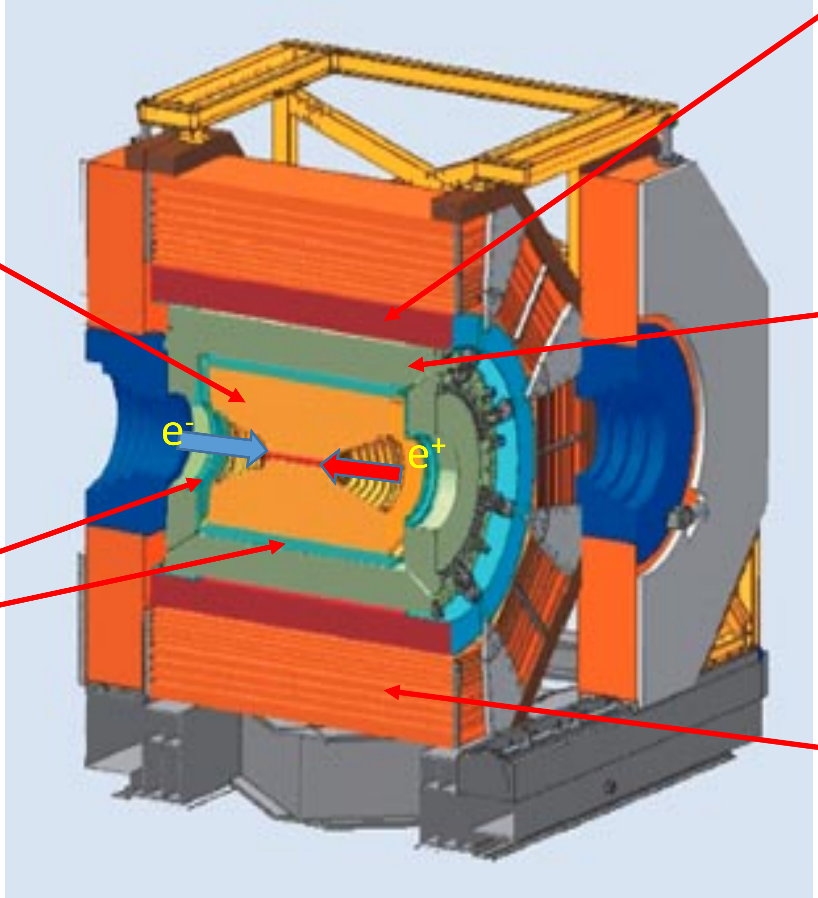
BEPCII: a τ-charm factory



Upgrade of BEPC (started 2004,
first collisions July 2008)
Beam energy 1 . . . 2.3 GeV
Optimum energy 1.89 GeV
Single beam current 0.91 A
Crossing angle: ±11 mrad

Design luminosity: $10^{33}\,cm^{-2}\,s^{-1}$
Achieved in in April 5th, 2016
Beam energy measurement by
Laser compton backscattering
$\Delta E/E \approx 5 * 10^{-5}$ (50 keV at τ threshold)

BESIII: The 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)
$\sigma_{z,\varphi} = 0.5 - 0.7\ \mathrm{cm}/\sqrt{E}$

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

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

93% of 4π acceptance

NIM A614, 345 (2010)

BESIII: the collaboration

US (6)

Univ. of Hawaii
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana
Univ. of Washington

Europe (13)

Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. di Torino, Univ. di Ferrara, LNF Frascati
Netherland : KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

Pakistan (2)

Univ. of Punjab
COMSAT CIIT

China(31)

IHEP, CCAST, GUCAS, 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., Univ. of South China
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.
Beihang Univ., Beijing Petrol Chemical Univ.

400 members
53 institutions
11 nations

BESIII: The physics program

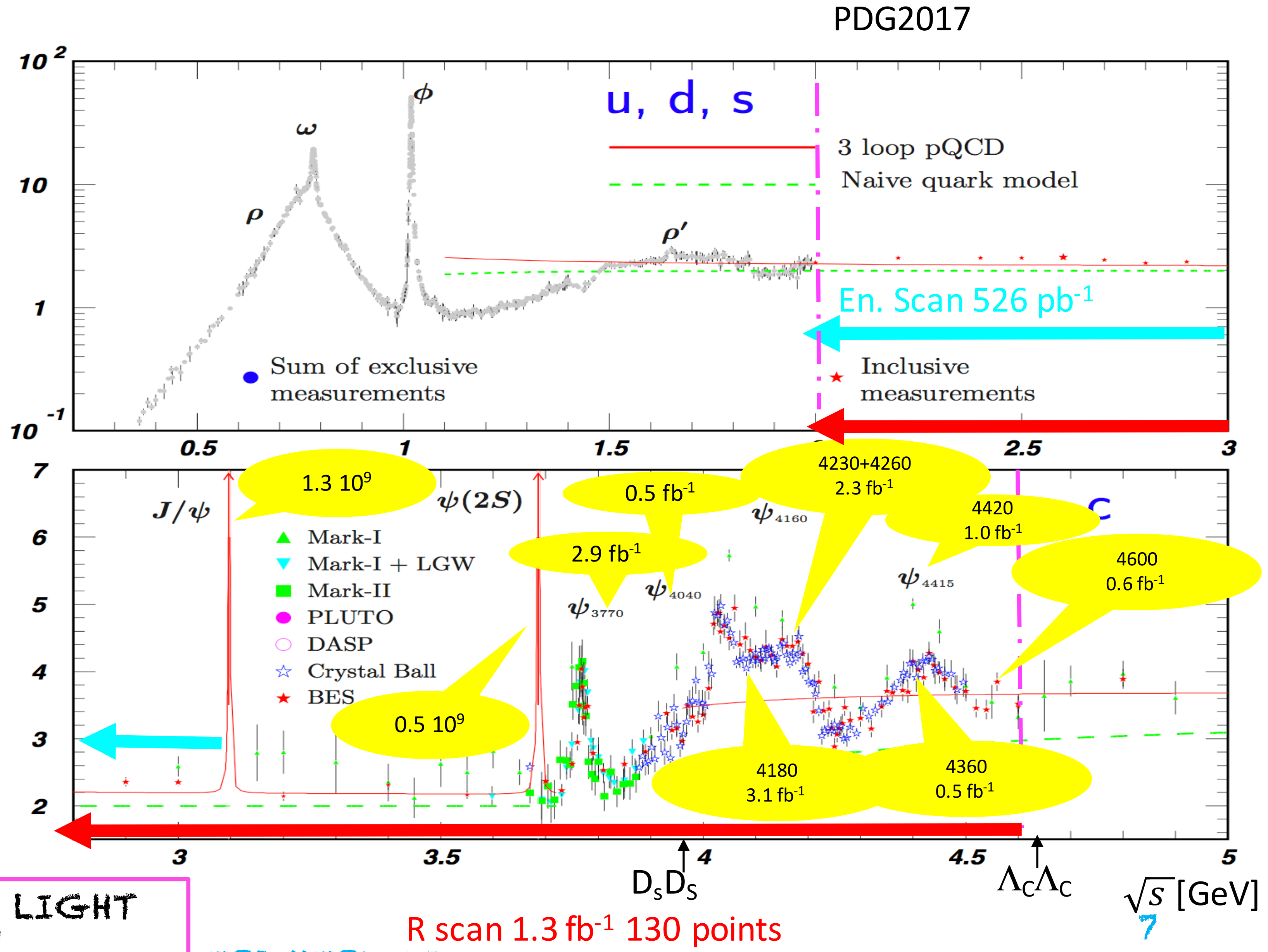
- Light Hadrons
  - Meson and baryon spectroscopy
  - Search for exotic hadrons
  - Light meson decays
- Charmonium Physics
  - X, Y, and Z states
  - Decays and transitions
- Open Charm Physics
  - D meson decays
  - mixing
  - CP violation in the charm sector

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

BESIII: Data Samples

$$R_{had} = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

World largest samples of J/ψ, ψ(2S), ψ(3770) directly produced in e^+e^- collisions



MORE:
Coarse scan 4100-4400 MeV/c²;
0.04 fb⁻¹ around Λ_c threshold;
Data taking on-going

IDEAL ENVIRONMENT TO STUDY LIGHT HADRON SPECTROSCOPY!!

Hadrons: conventional and exotic

- Conventional hadrons consist of 2 or 3 quarks
  - Meson: two quarks
  - Baryon: three quarks

But QCD allows other forms of hadrons:

- ✓ Multi-quark state: > 3 quarks
- ✓ Glueball: gg, ggg, …
- ✓ Hybrid: qqg, qqqg, …
- ✓ molecule: bound state of more then 2 hadrons

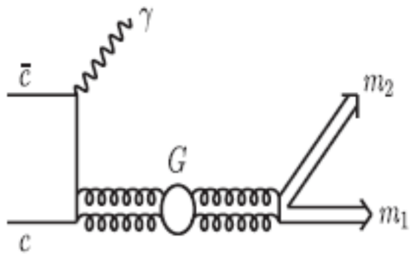
} Lots of candidates but not established yet

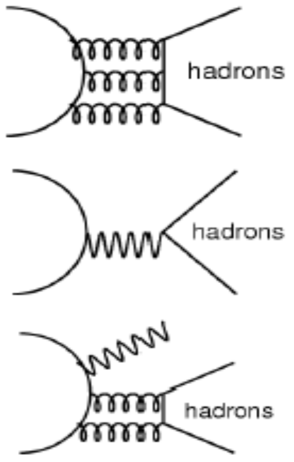
<u>Searching for new forms of hadrons provide test of QCD</u>

Light Hadron Spectroscopy

- Motivation:
  - Establish spectrum
  - Search for exotic hadrons

<u>BESIII advantages?</u>
Charmonium decays can be used (high statistics)
- Gluon rich processes
- Kinematics favorable
- Clean environment, no combinatorial bkg
- J^{PC} and Isospin filters in strong decays compared to hadron colliders





Why J/ψ decays are mostly used?

- ➢ J/ψ production cross section is high and the BR of hadrons in J/ψ decays higher than ψ′ decays ("12% rule").
- ➢ Large phase space to 1-3 GeV hadrons in J/ψ decays
- ➢ Production BR of exotic hadrons expected to be larger or similar to the one for conventional hadrons in J/ψ decays.

Hunting Glueballs

→ Direct test of QCD

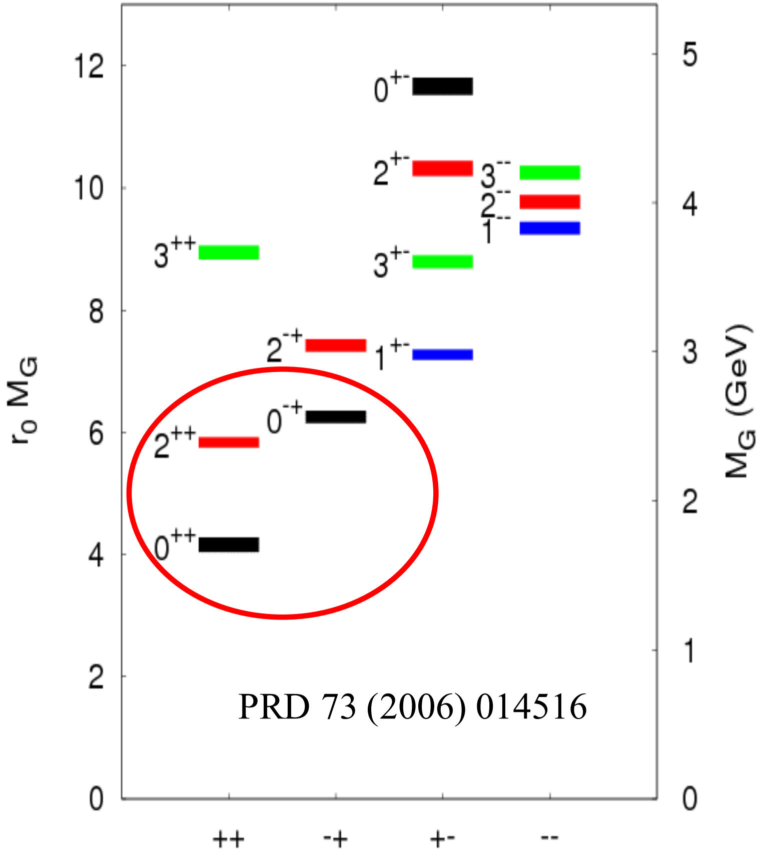
- Lattice QCD prediction
  - 0^{++} ground state: 1~1.7 GeV/c^2
  - 2^{++} ground state: 2.3~2.4 GeV/c^2
  - 0^{-+} ground state: 2.3~2.6 GeV/c^2

They can mix with ordinary $q\bar{q}$ states

J/ψ radiative decays are gluon-rich environment (large BR forseen): an ideal place to search for glueballs.

Systematic experimental studies needed:
- Map of the resonances
- Study of the production patterns ($J/\psi \to \gamma/\omega/\phi + X$)
- Study of the decay patterns

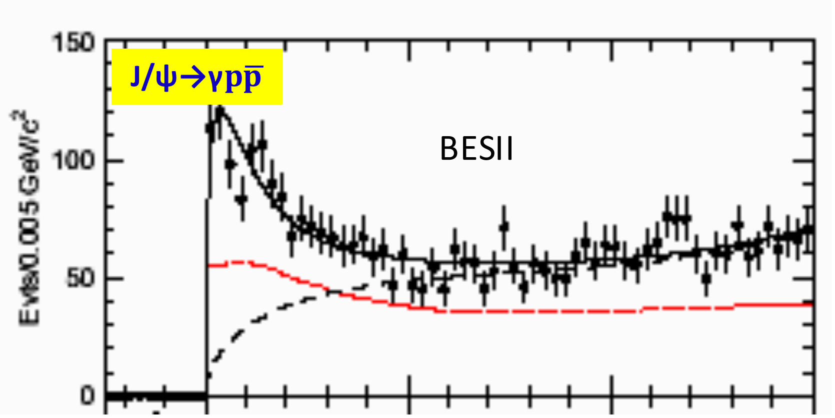
Glueballs from quenched LQCD



X states @ $p\bar{p}$ mass threshold

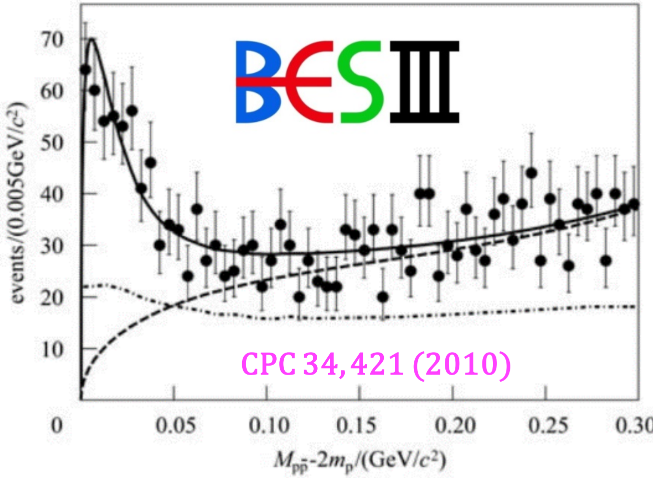
The $p\bar{p}$ threshold enhancement

- Observed by BESII in $J/\psi \to \gamma p\bar{p}$ more than 10 years ago

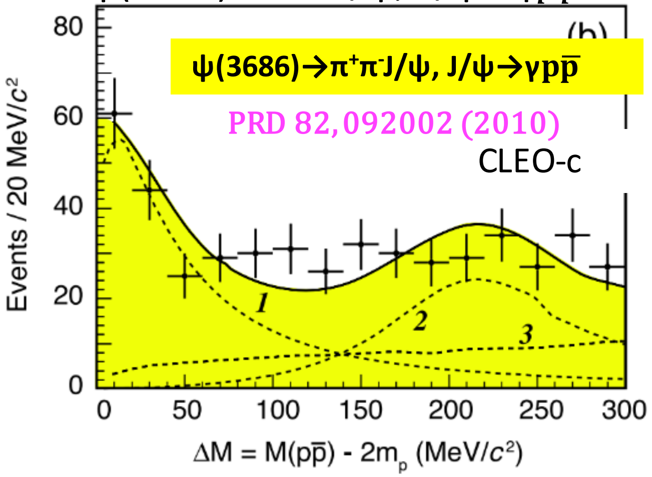


PRL 91,022001 (2003)

- Confirmed by BESIII and CLEO-c in $\psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma p\bar{p}$



CPC 34,421 (2010)



PRD 82,092002 (2010)

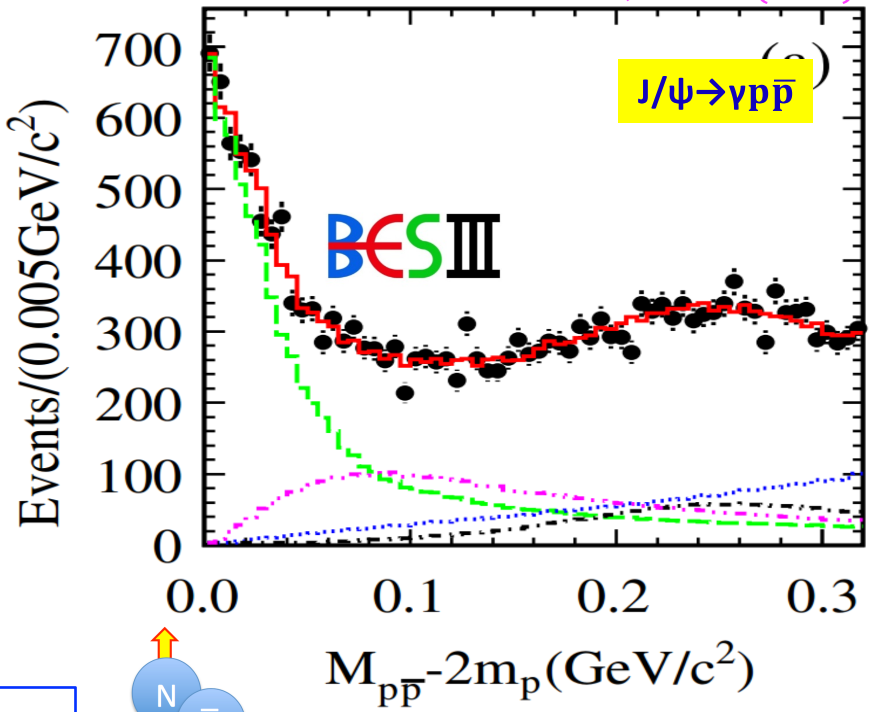
Confirmed by BESIII in $J/\psi \to \gamma p\bar{p}$ (PWA below 2.2GeV/c²)

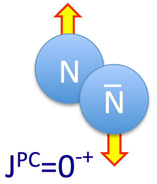
✓ $X(p\bar{p}) \to J^{PC} = 0^{-+}$ (>30 σ) with BW parametrization

✓ $M = 1832^{+19}_{-5}{}^{+18}_{-17}(syst) \pm 19$ (Model) MeV/c²

✓ $\Gamma = 13 \pm 39(stat)^{+10}_{-13}(syst) \pm 4$ (Model) MeV/c² (< 76 MeV/c² @ 90% C.L.)

✓ PWA: 4 contributions included: $X(p\bar{p})$, $f_2(1910)$, $f_0(2100)$, non-resonant 0^{++} contribution, FSI)





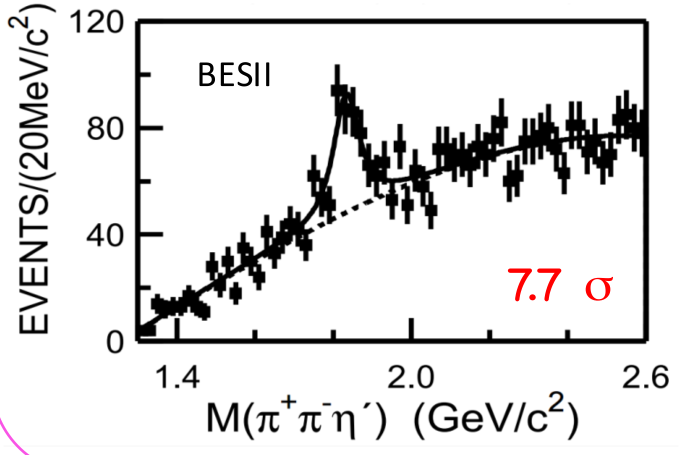
PRL 108,112003 (2012)

No similar structure observed in related channels
(e.g. $\Upsilon(1S) \to \gamma p\bar{p}$, $\psi' \to \gamma p\bar{p}$)

nature of these states? $p\bar{p}$ bound state?
look into the subthreshold energy region.

X(1835)

- Discovery by BESII in $J/\psi \to \gamma\eta'\pi^+\pi^-$ in 2005



(58M J/ψ)

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

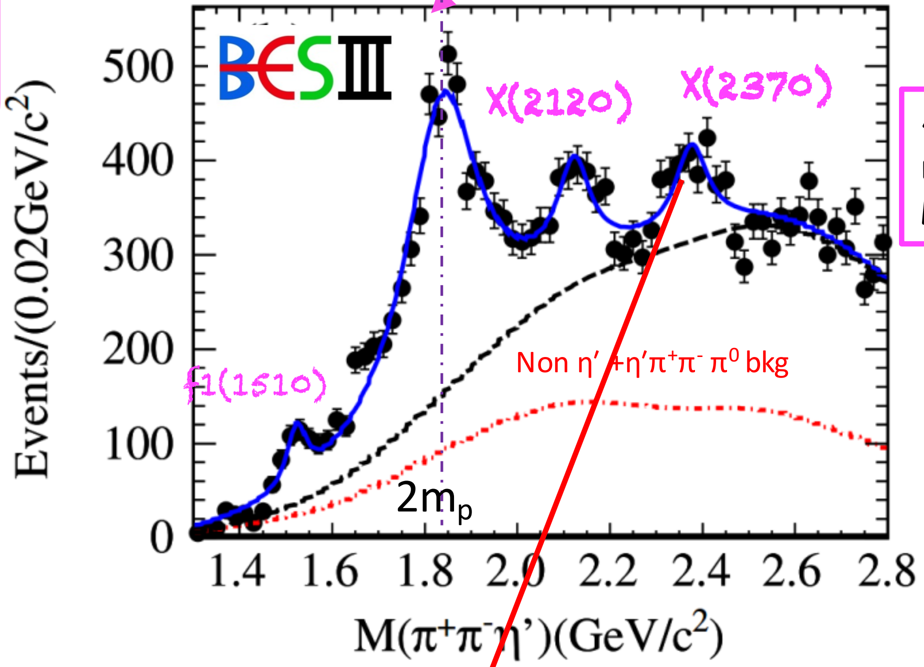
- Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi^+\pi^-$

(230M J/ψ)

✓ $M = 1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/c^2
✓ $\Gamma = 190 \pm 9^{+38}_{-36}$ MeV/c^2

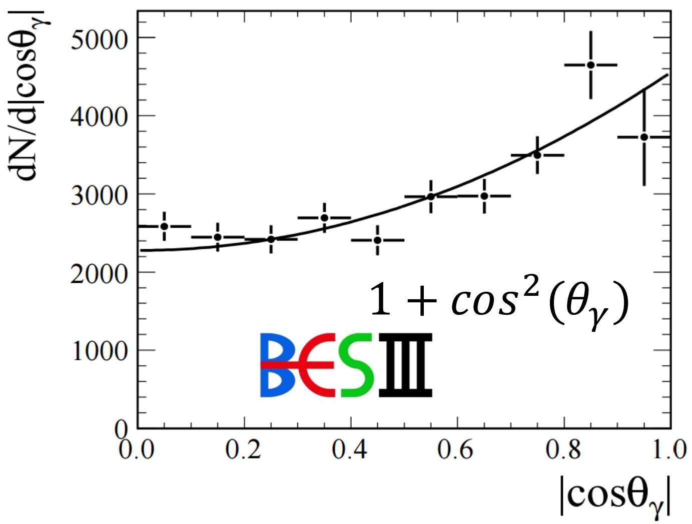
$>20\sigma$

$\eta' \to \gamma\rho$ ($\rho \to \pi^+\pi^-$)
$\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$



4 resonances (BW ⊗ GAUSS) + non resonant contribution (from MC)+ Non η′ + η′π⁺π⁻ π⁰ bkg

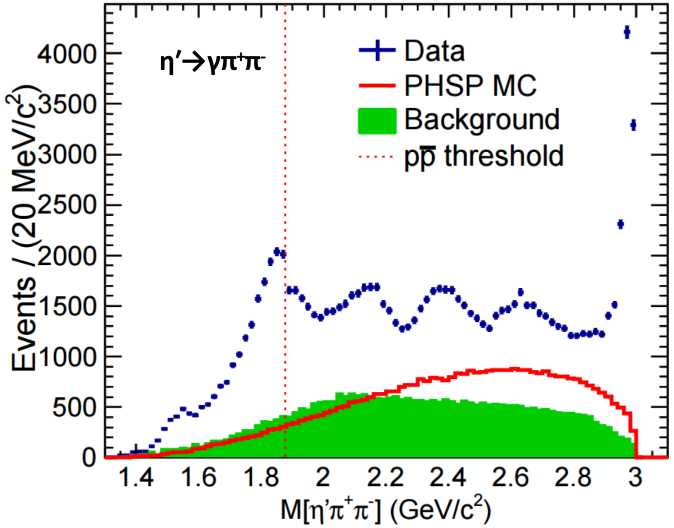
Phys. Rev. Lett. 106, 072002 (2011)

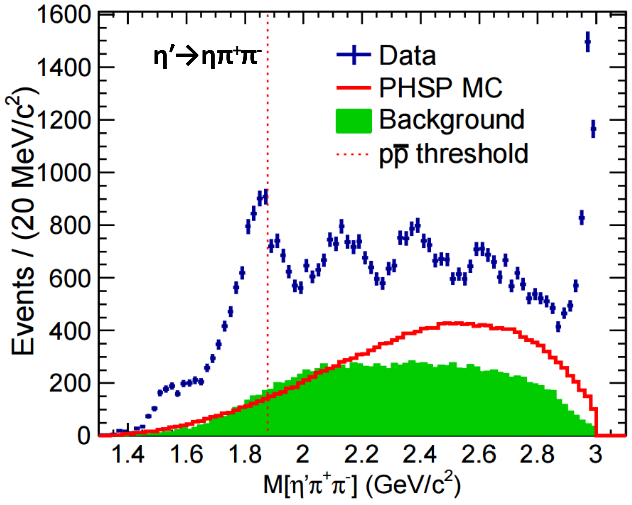


✓ **Angular distribution is consistent with 0⁻**

LQCD predicts the glueball mass of 0^{-+} is ~2.3GeV. For 0^{-+} glueball, it may have similar property as η_c (the main decay mode is $\pi\pi\eta'$).

X(1835) in J/ψ→γη′π⁺π⁻ (I)





PRL 117, 042002 (2016)

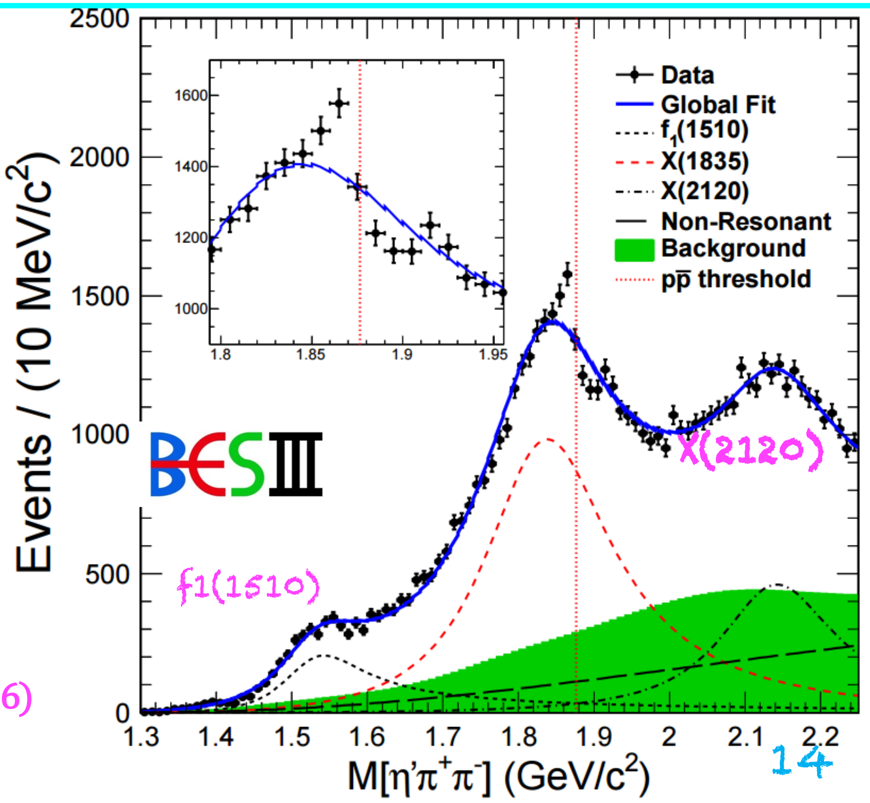
1.09×10^9 J/ψ (2012)

- Two decay modes of η′
  - η′→γπ⁺π⁻
  - η′→ηπ⁺π⁻, η→γγ

Clear peaks of X(1835), X(2120), X(2370), η_c, and a structure near 2.6 GeV/c^2

A significant and anomalous distortion of the η′π⁺π⁻ line shape close to the $p\bar{p}$ mass threshold as expected for a $p\bar{p}$ bound state

Simultaneous fits for the two η′ decay modes: simple BW function fails description near the $p\bar{p}$ mass threshold



PRL 117, 042002 (2016)

X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$: fit of the Lineshape

Threshold structure caused by the opening of additional $p\bar{p}$ decay mode (Flatté formula)

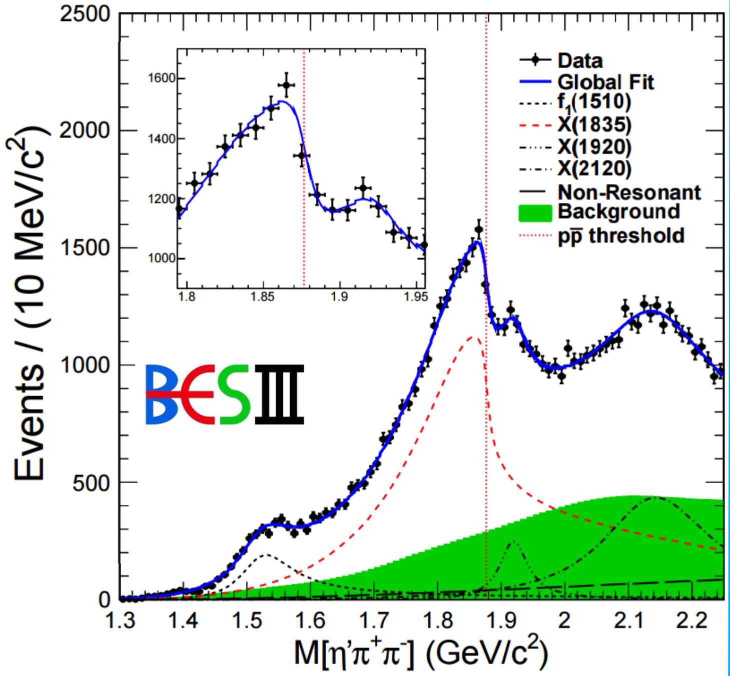
$$T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i\sum_k g_k^2 \rho_k}; \quad \sum_k g_k^2 \rho_k \simeq g_0^2\left(\rho_0 + \frac{g_{p\bar{p}}^2}{g_0^2}\rho_{p\bar{p}}\right)$$

S.M. Flatté PLB 63, 224 (1976)

coupling to $p\bar{p}$ channel

coupling to everything else

Fitting results	
$\mathcal{M}$ (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	$(3.93^{+0.38\,+0.31}_{-0.38\,-0.84})\times10^{-4}$



PRL 117, 042002 (2016)

An additional resonance, "X(1920)", is needed with 5.7σ

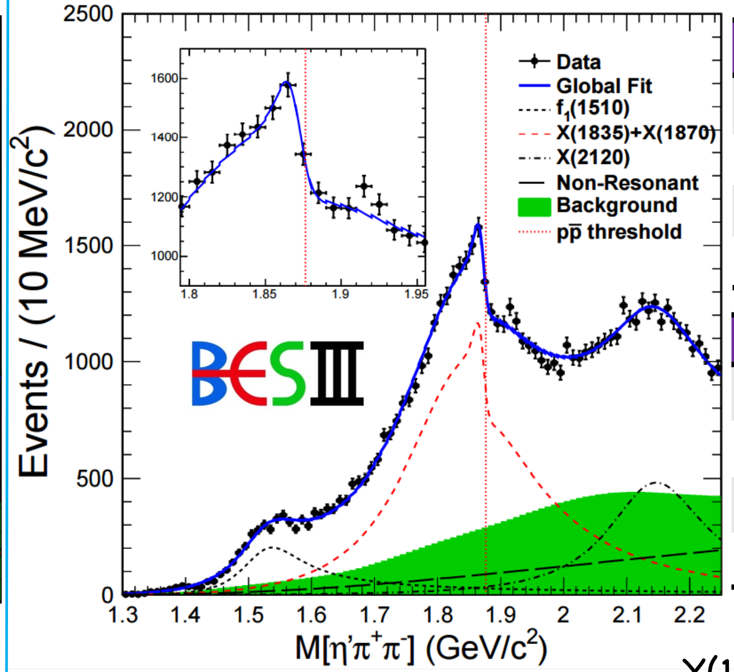
Significance of $g_{p\bar{p}}^2/g_0^2$ being non-zero is larger than 7σ

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

Interference between X(1835) and another very narrow resonance close to threshold:

$$T = \frac{\sqrt{\rho_{out}}}{M_1^2 - s - iM_1\Gamma_1} + \frac{\beta \cdot e^{i\theta} \cdot \sqrt{\rho_{out}}}{M_2^2 - s - iM_2\Gamma_2}$$

Coherent sum of two BW



FIRST RESONANCE: X(1835)	
M(MeV/c²)	$1825.3^{+2.4\,+17.3}_{-2.4\,-2.4}$
Γ(MeV/c²)	$245.2^{+14.2\,+4.6}_{-12.6\,-9.6}$
B.R. (c. I.)	$(3.01^{+0.17\,+0.26}_{-0.17\,-0.28})\times10^{-4}$
B.R. (d. I.)	$(3.72^{+0.21\,+0.18}_{-0.21\,-0.35})\times10^{-4}$

SECOND RESONANCE: X(1870)	
M(MeV/c²)	$1870.2^{+2.2\,+2.3}_{-2.3\,-0.7}$
Γ (MeV/c²)	$13.0^{+7.1\,+2.1}_{-5.5\,-3.8}$
B.R. (CI)	$(2.03^{+0.12\,+0.43}_{-0.12\,-0.70})\times10^{-7}$
B.R. (DI)	$(1.57^{+0.09\,+0.49}_{-0.09\,-0.86})\times10^{-5}$

X(1920) is not significant

Significance of narrow X(1870) is larger than 7σ,
M = $2m_p$-6.3±16 MeV/c²

Is it a $p\bar{p}$ bound state?

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

Both models fit the data well, both suggest two structures:

- a broad state and a narrow state very close to $p\bar{p}$ mass threshold,
- a $p\bar{p}$ molecule-like state or bound state?

Whatever the X(1835) is, it has large coupling to $p\bar{p}$!

- To understand the nature of this exotic state
  - Larger data sample needed
  - Study other decay modes
    - $J/\psi \to \gamma p\bar{p}$ (seen before)
    - $J/\psi \to \gamma K_S K_S \eta$
    - …

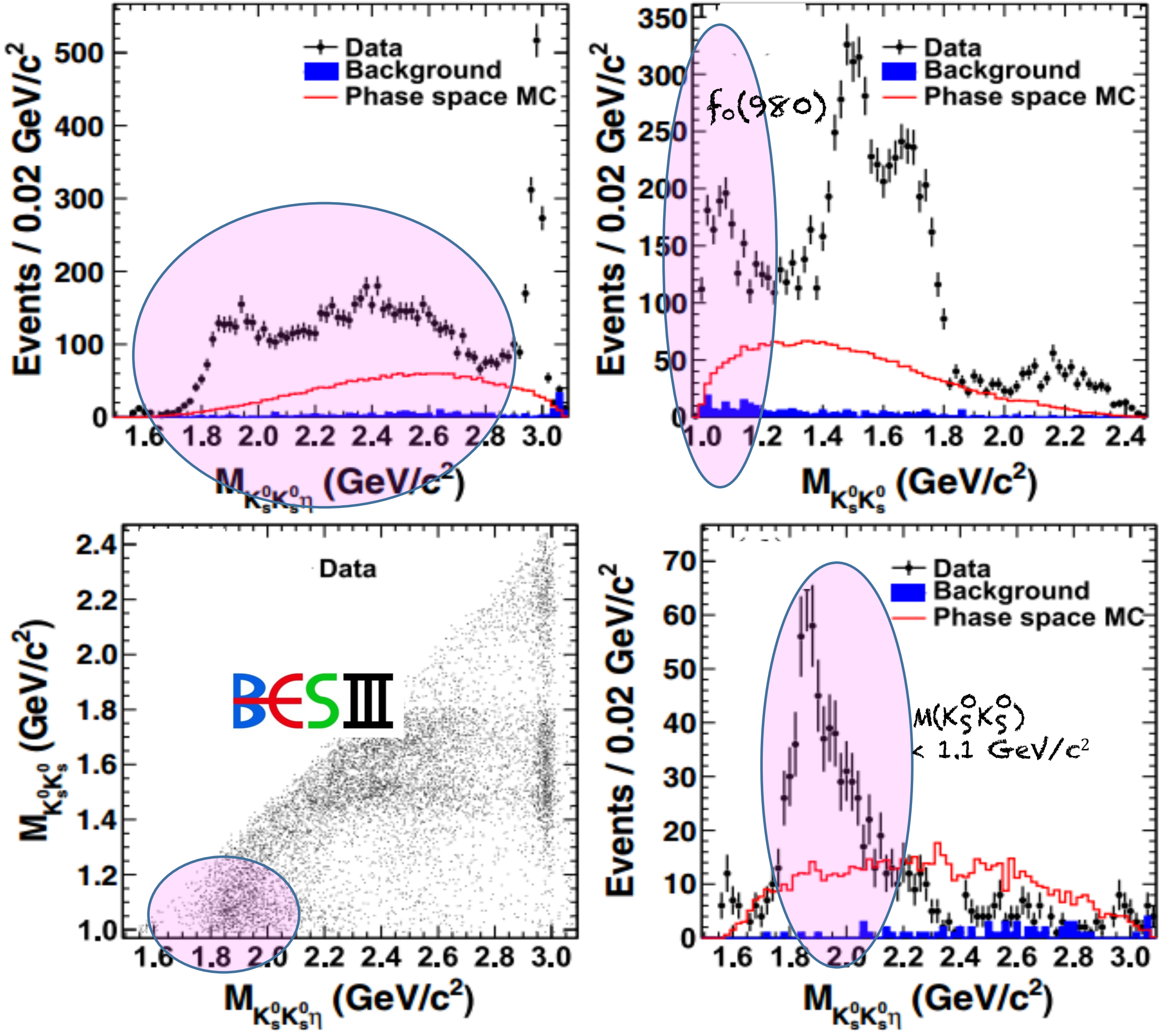
X(1835) in $J/\psi \to \gamma \eta K_S^0 K_S^0$

Search for new decay modes to understand X(1835) nature

1.3×10^9 J/ψ events (2009 and 2012)

Clean environment: $\eta K_S^0 K_S^0$ and $\eta\pi^0 K_S^0 K_S^0$ bkg forbiddden

- Clear structure on mass spectrum of $K_S K_S \eta$ @1.85 GeV/c^2, strongly correlated to $f_0(980)$
- PWA for $M(K_S^0 K_S^0) < 1.1$ GeV/c^2 and $M(K_S^0 K_S^0 \eta) < 2.8$ GeV/c^2 to determine spin parity



PRL 115, 091803 (2015)

X(1835)

$J^{PC}=0^{-+}$; $X(1835)\to K_S^0 K_S^0 \eta$ (>12.9σ) , dominated by $f_0(980)$ production

$$M = 1844 \pm 9^{+16}_{-25} \frac{\text{MeV}}{c^2}$$
$$\Gamma = 192^{+20+62}_{-17-43} \text{MeV}/c^2$$

Consistent with X(1835) parameters obtained from $J/\psi \to \gamma\eta'\pi^+\pi^-$, mass consistent and width larger than $X(p\bar{p})$

$\mathcal{B}(J/\psi\to\gamma X(1835)) \cdot \mathcal{B}(X(1835)\to K_S K_S \eta) = (3.31^{+0.33+1.96}_{-0.30-1.29})\times 10^{-5}$

+

X(1560).

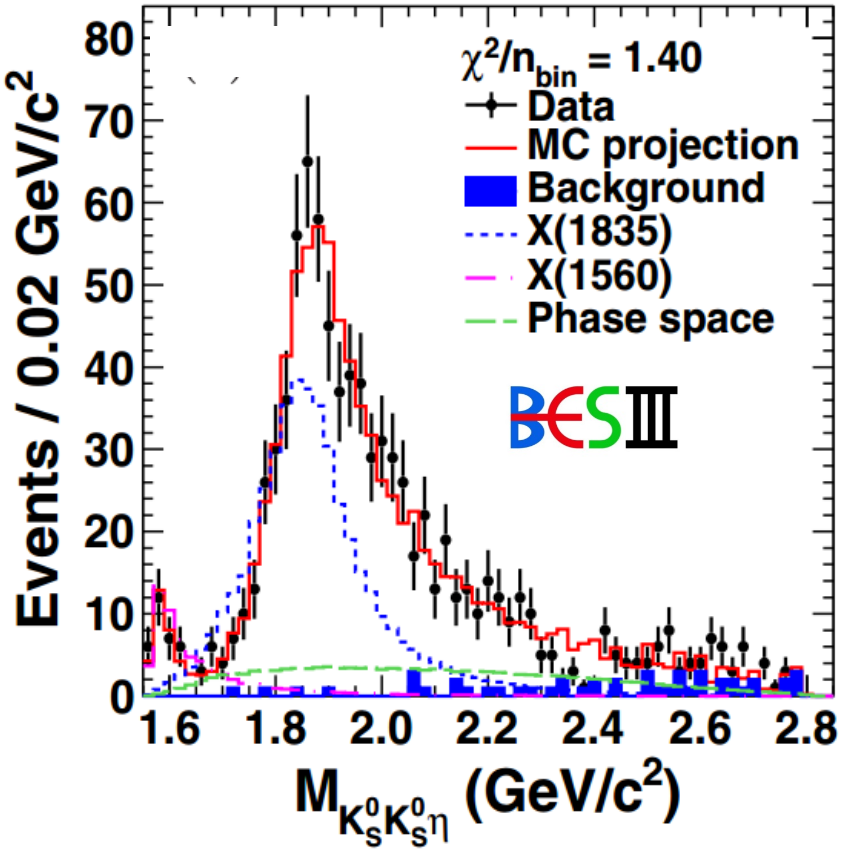
$J^{PC}=0^{-+}$; $X(1560)\to K_S^0 K_S^0 \eta$ (> 8.9σ)

$$M = 1565 \pm 8^{+0}_{-63} \frac{\text{MeV}}{c^2}$$
$$\Gamma = 45^{+14+21}_{-13-28} \text{MeV}/c^2$$

Consistent with η(1405)/η(1475) within 2.0σ

Interference allowed in PWA

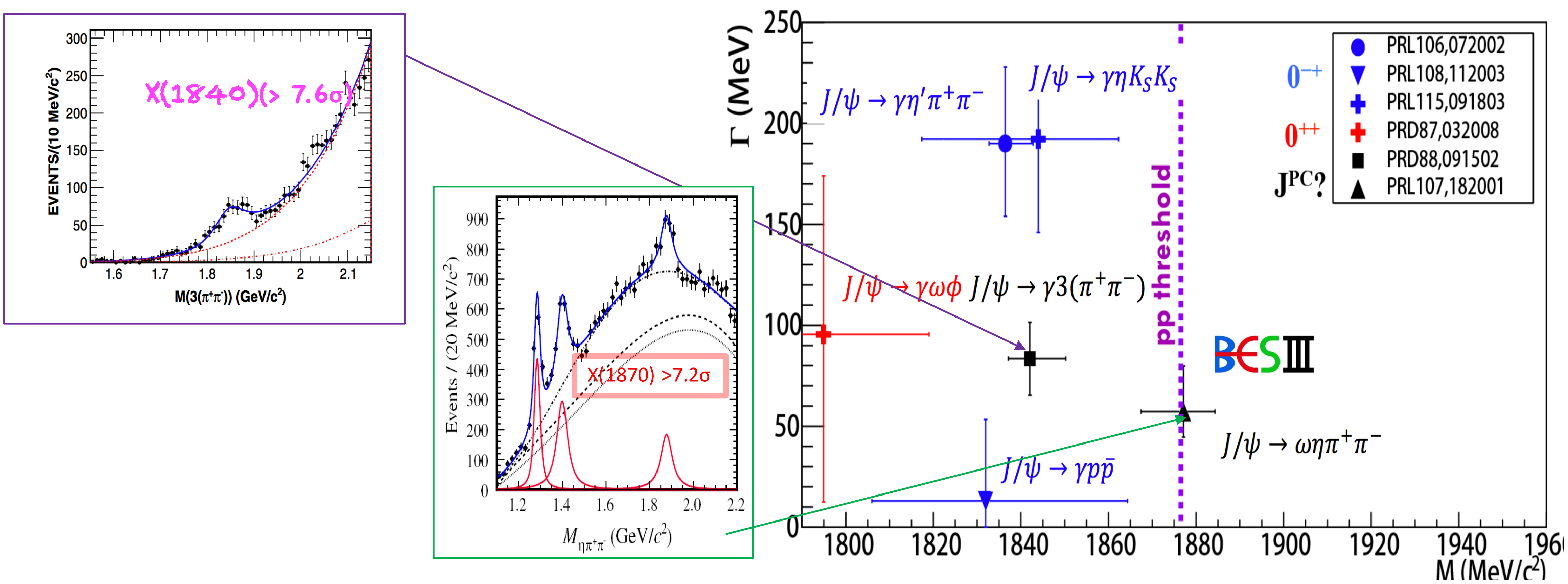
PRL 115, 091803 (2015)



+ a non-resonant $f_0(1500)\eta$ component

More statistics and other channels analysis needed to understand, like $\gamma K_S K_S \pi^0$

Comparison between BESIII results



X states near proton-antiproton threshold , what's the role of that threshold?

- X($p\bar{p}$) in agreement with X(1835), while its width is significantly different

$p\bar{p}$ bound state?
η′ radial excitation?
glueball?

Are X(1835) and X($p\bar{p}$) them SAME state?

- More studies are needed to answer this question, but connections are emerging! Larger statistics will help!

PWA in charmonia decays

- Model Independent PWA of $J/\psi \to \gamma\pi^0\pi^0$
- PWA of $J/\psi \to \gamma\phi\phi$
- Amplitude analysis of the $\chi_{c1} \to \eta\pi^+\pi^-$ decays

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

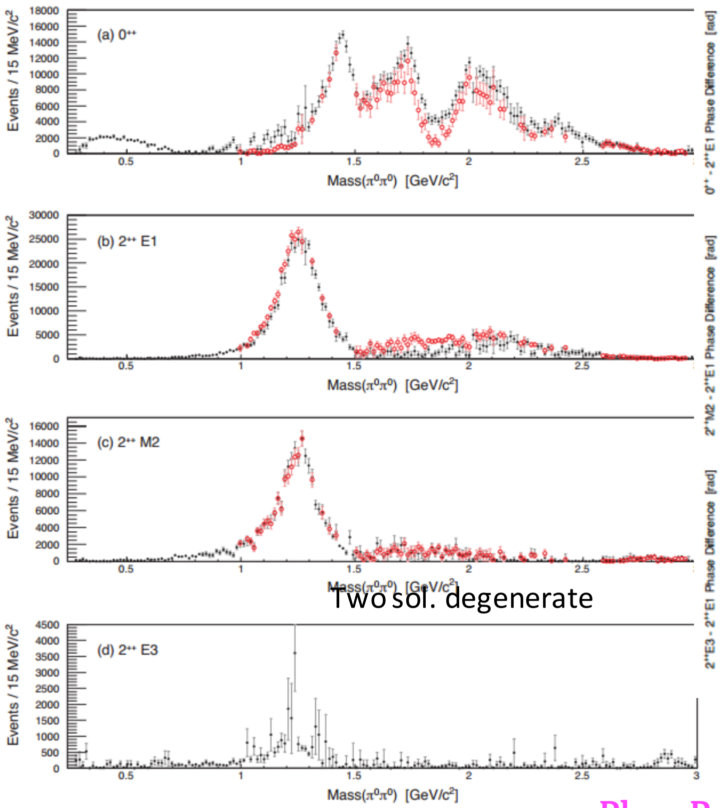
1.3×10^9 J/ψ events (2009 and 2012)

$\pi^0\pi^0$ is a very clean system with large statistics

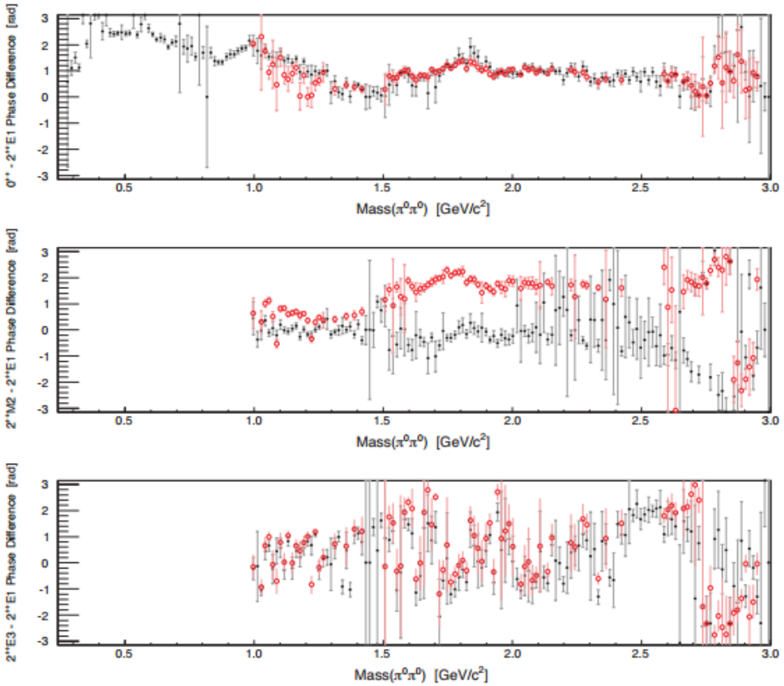
- Many broad and overlapping resonances (parameterization challenging)
- Model independent PWA (MIPWA): a piecewice complex function is built to describe the s dependence of $\pi\pi$ dynamics

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

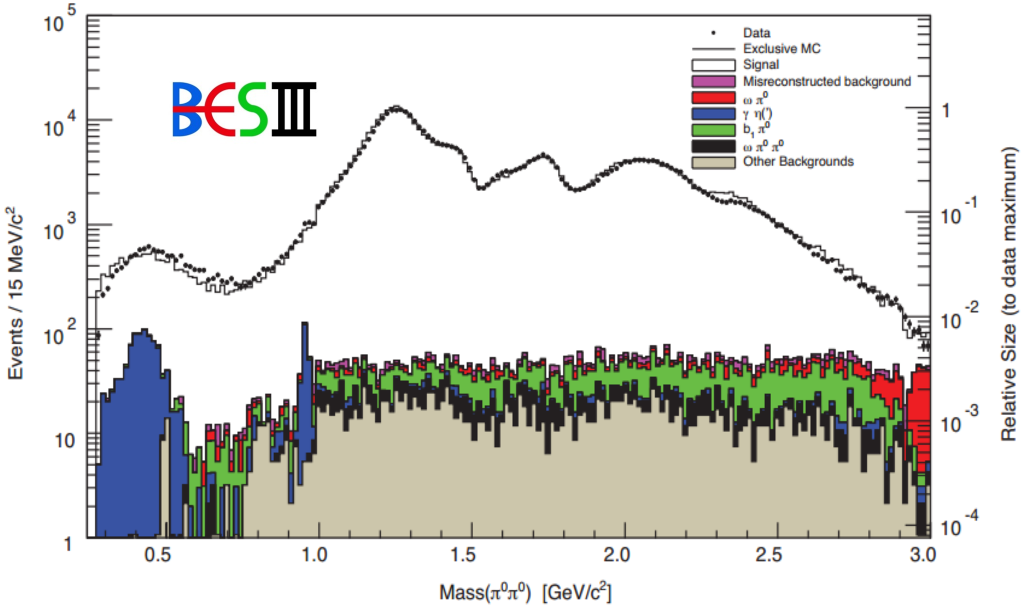
Extracted Intensity



Relative Phase



- Solution 1-nominal
- Solution 2-ambiguous



✓ Extract amplitudes in each $M(\pi^0\pi^0)$ mass bin

Scalar spectrum -> significant structures near 1.5, 1.7 and 2.0 GeV/c^2

2^{++} spectrum -> dominated by $f_2(1270)$ (tensor glueball candidate $f_J(2230)$ don't show up)

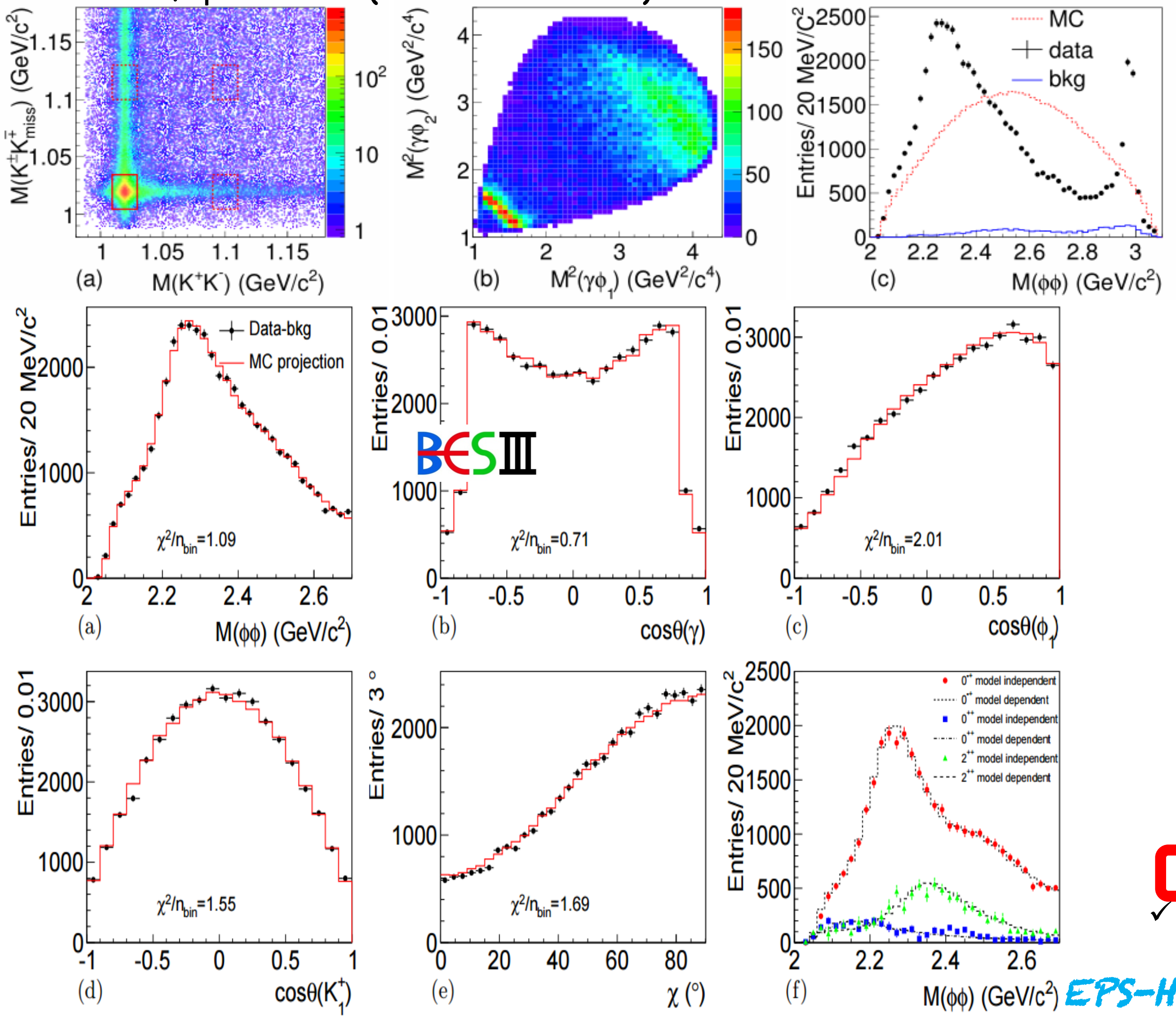
✓ Multiple solutions in MIPWA are usually unavoidable.

✓ Provides the scattering amplitude minimizing systematic bias due to assumptions about $\pi\pi$ dynamics and in a experiment-independent way

Phys. Rev. D 92, 052003 (2015)

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

1.3×10^9 J/ψ events (2009 and 2012)



BASELINE SOLUTION

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	B.F.$(\times10^{-4})$	Sig.
$\eta(2225)$	2216^{+4+18}_{-5-11}	185^{+12+44}_{-14-17}	$(2.40\pm0.10^{+2.47}_{-0.18})$	28.1σ
$\eta(2100)$	2050^{+30+77}_{-24-26}	$250^{+36+187}_{-30-164}$	$(3.30\pm0.09^{+0.18}_{-3.04})$	21.5σ
$X(2500)$	2470^{+15+63}_{-19-23}	230^{+64+53}_{-35-33}	$(0.17\pm0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2102	211	$(0.43\pm0.04^{+0.24}_{-0.03})$	24.2σ
$f_2(2010)$	2011	202	$(0.35\pm0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44\pm0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91\pm0.07^{+0.72}_{-0.69})$	10.7σ
0^{-+} PHSP	To model direct decay		$(2.74\pm0.15^{+0.16}_{-1.48})$	6.8σ

PDG fixed

Compatible with LQCD pred. for Tensor glueball

Phys. Rev. D 93, 112011 (2016)

Scalar state:
$f_0(2100)$

Tensor states:
$f_2(2010)$, $f_2(2300)$, $f_2(2340)$, obs. in $\pi^- N$ and $p\bar{p}$.
strong $f_2(2340)$ production. Tensor glueball?

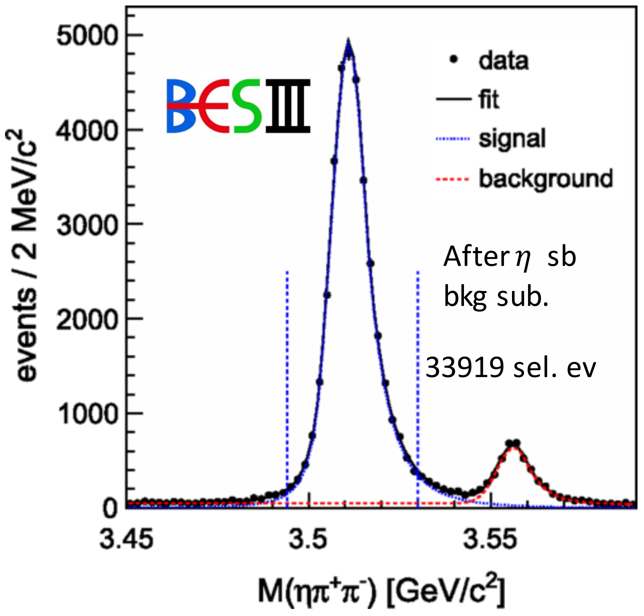
Help to map pseudoscalar excitations

Pseudoscalar states (DOMINANT):
$\eta(2225)$ confirmed (DM2, MARKIII, BESII)
$\eta(2100)$ and $X(2500)$ observed.

✓ Well consistent with the results from Model-independent PWA

Amplitude analysis of the $\chi_{c1} \to \eta\pi^+\pi^-$ decay

448.0 10^6 ψ(3686) events (>15 x CLEO-c sample), ≃ 34kχ_{c1}(World largest sample!)



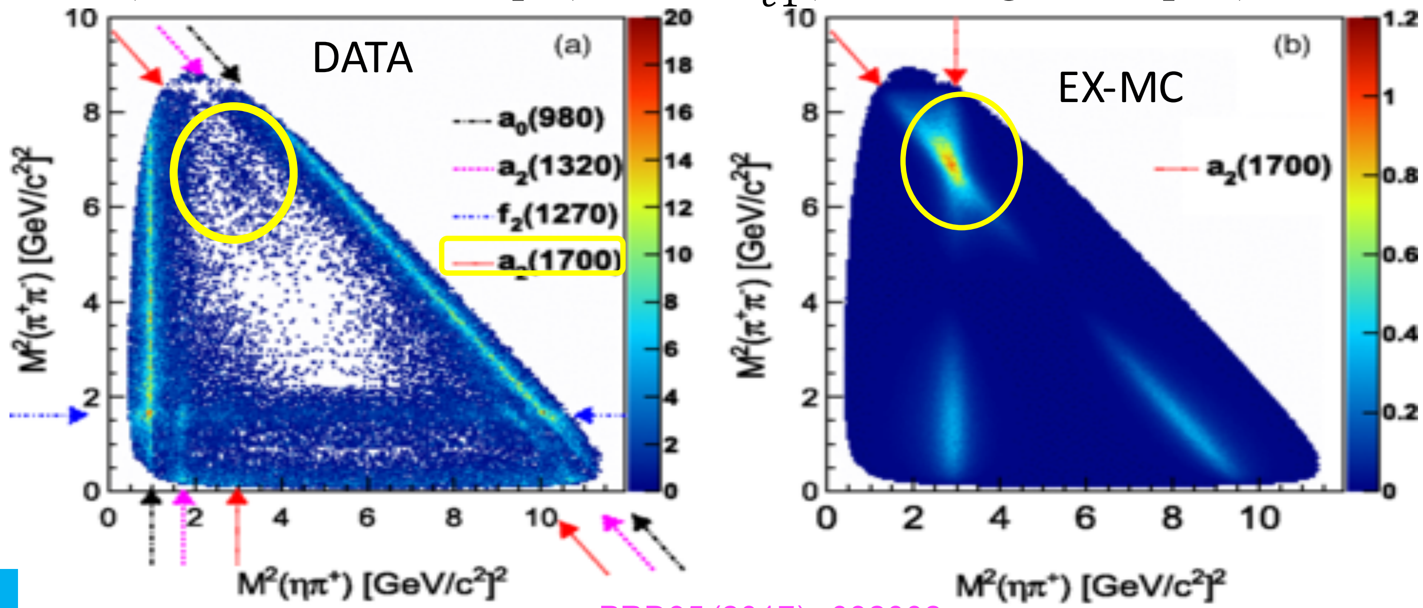
$\psi(3686) \to \gamma\chi_{c1}$

and

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

95% of η decays

η →3π, η→γγ

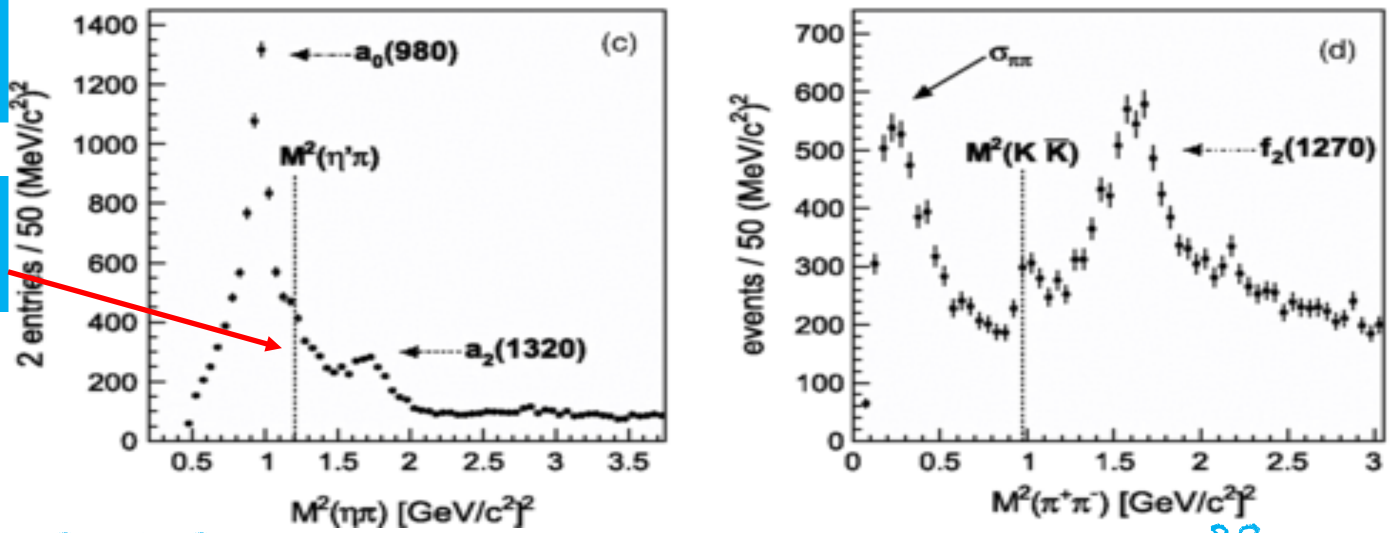


PRD95 (2017) , 032002

Search for exotic mesons with 1^{-+}in (1.3-2.0) GeV/c^2 mass region decaying $\eta\pi$ ($\pi_1$states, only π_1(1400) decaying $\eta\pi$ by CLEO-C, e.g)

Test sensitivity to $a_0(980) \to \eta'\pi$ production of $a_0(980)$ lineshape

Search for $\chi_{c1} \to a_2(1700)\pi$ with $a_2(1700) \to \eta\pi$



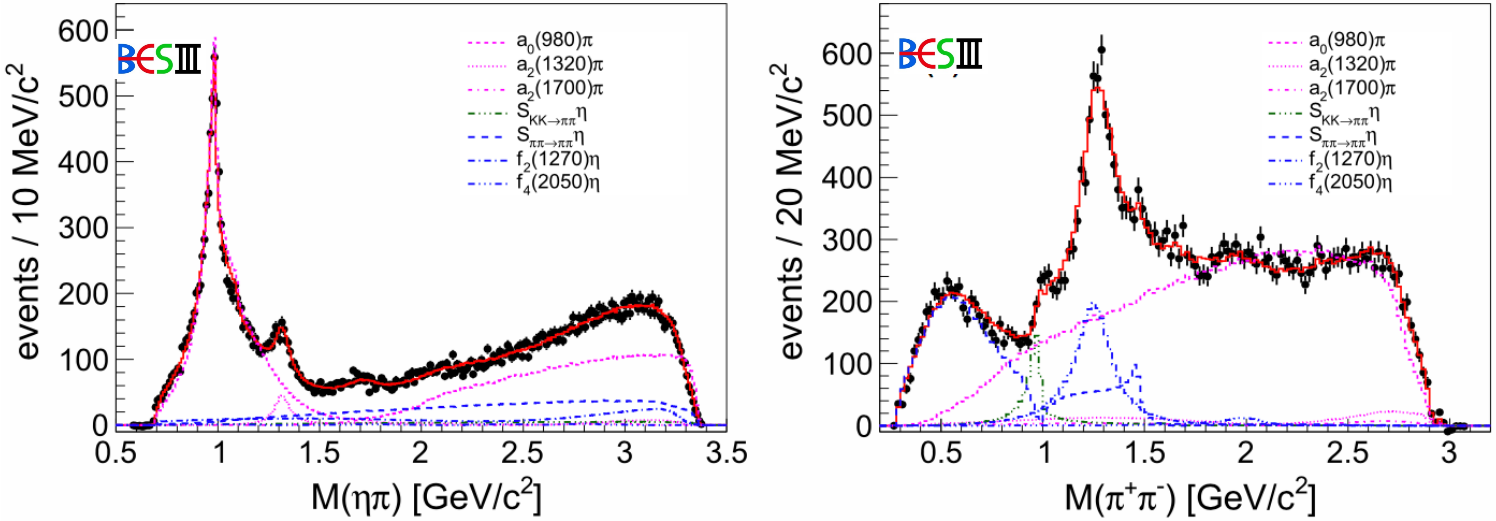
Isobar model ($\eta\pi$, $\pi\,\pi$)

Helicity formalism for Amplitudes

BW+ Blatt-Weisskopf factors for most of the resonances, $a_0(980)$ and $a_2(1700)$ free parameters, PDG for the others

Dispersion integrals for $a_0(980)$ considering $\eta\pi$, $\eta'\pi$, $K\bar{K}$ decay channels

OPTIMAL SOLUTION using amplitude with >0.5% contribution and significance >5σ



PRD95 (2017) , 032002

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	Weak	<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

Summary and conclusions

- BESIII is successfully operating since 2008, and continues to take data until 2022 at least

- Excellent laboratory to study light hadron spectroscopy (and many other items):
  - High statistics
  - Low backgrounds

- Many interesting results have been obtained, and only a few have been reported in this talk

- In the next three years new DATA for J/ψ are awaited towards 8 Billions J/ψ

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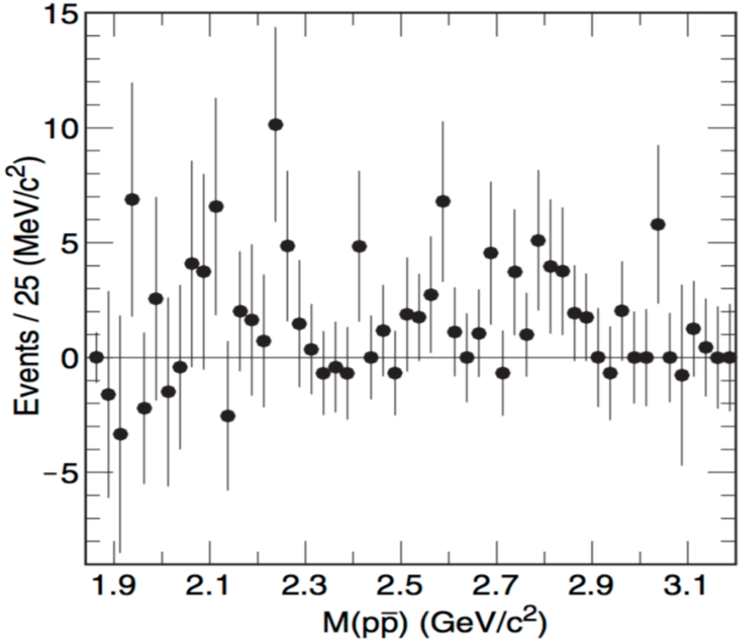
Thank you for your attention!

No $p\bar{p}$ threshold enhancement

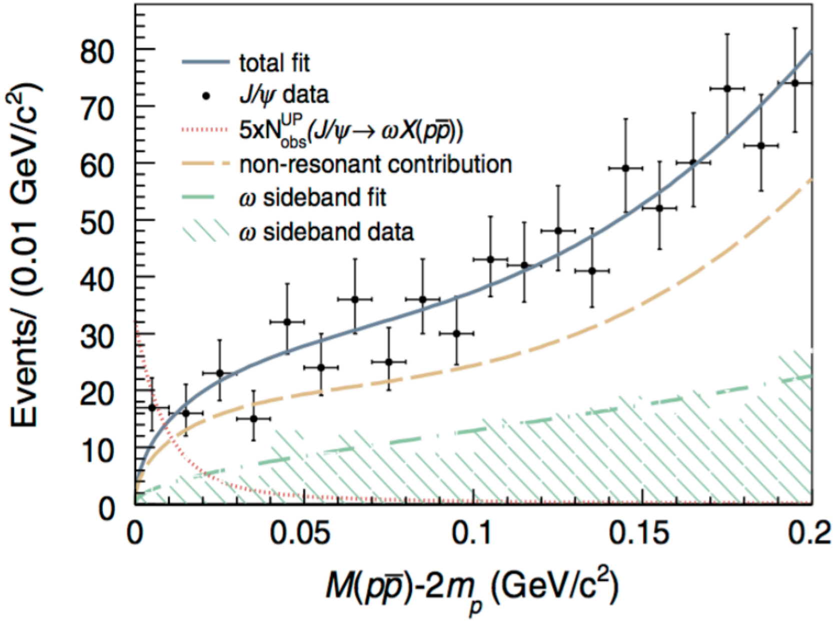
CLEO, $\Upsilon(1S) \to \gamma p\bar{p}$

PRD 73, 032001



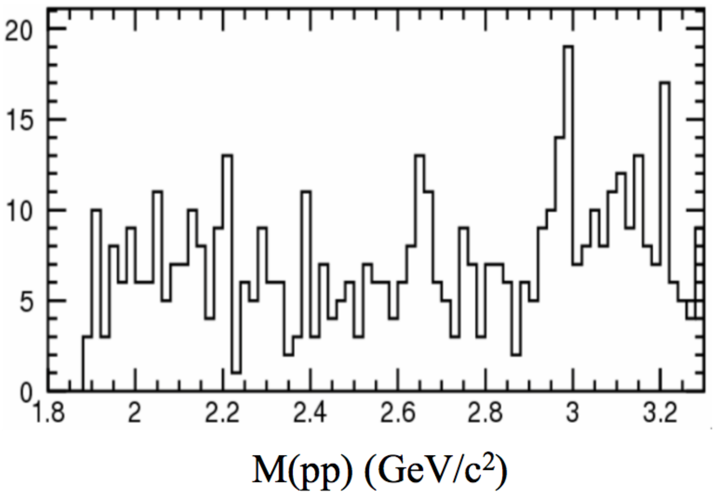
BESIII, $J/\psi \to \omega p\bar{p}$

PRD 87, 112004



BES, $\psi' \to \gamma p\bar{p}$

PRL 99, 011802



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

Threshold structure caused by the opening of additional $p\bar{p}$ decay mode

Fitting results	
$\mathcal{M}$ (MeV/c^2)	$1638.0^{+121.9\,+127.8}_{-121.9\,-254.3}$
g_0^2 ((GeV/c^2)^2)	$93.7^{+35.4\,+47.6}_{-35.4\,-43.9}$
$g^2_{p\bar{p}}/g^2_0$	$2.31^{+0.37\,+0.83}_{-0.37\,-0.60}$
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	$(3.93^{+0.38\,+0.31}_{-0.38\,-0.84})\times 10^{-4}$

BESIII

$$T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i\sum_k g_k^2 \rho_k}$$

S.M. Flatté PLB 63, 224 (1976)

$$\sum_k g_k^2 \rho_k \simeq g_0^2 \left(\rho_0 + \frac{g^2_{p\bar{p}}}{g_0^2}\rho_{p\bar{p}}\right)$$

coupling to $p\bar{p}$ channel

coupling to everything else

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

An additional resonance, X(1920), is needed with 5.7σ

Significance of $g^2_{p\bar{p}}/g^2_0$ being non-zero is larger than 7σ

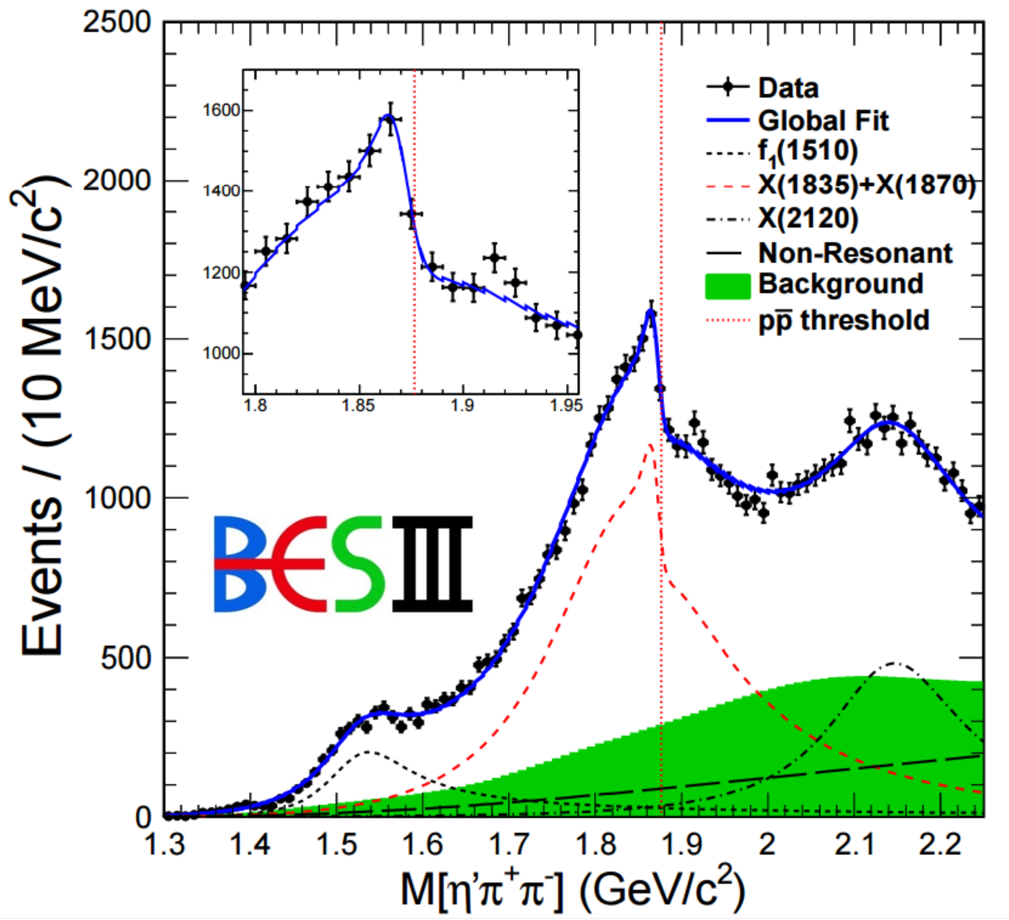
A $p\bar{p}$ molecule-like state?

PRL 117, 042002 (2016)

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

Interference between two resonances with one very narrow close to threshold:

Coherent sum of two Breit-Wigner amplitudes for the line shape:



PRL 117, 042002 (2016)

$$T = \frac{\sqrt{\rho_{out}}}{M_1^2 - s - iM_1\Gamma_1} + \frac{\beta \cdot e^{i\theta} \cdot \sqrt{\rho_{out}}}{M_2^2 - s - iM_2\Gamma_2}$$

FIRST RESONANCE: X(1835)	
M (MeV/c²)	$1825.3\,^{+2.4}_{-2.4}\,^{+17.3}_{-2.4}$
Γ (MeV/c²)	$245.2\,^{+14.2}_{-12.6}\,^{+4.6}_{-9.6}$
B.R. (constructive interference)	$(3.01\,^{+0.17}_{-0.17}\,^{+0.26}_{-0.28})\times10^{-4}$
B.R. (destructive interference)	$(3.72\,^{+0.21}_{-0.21}\,^{+0.18}_{-0.35})\times10^{-4}$

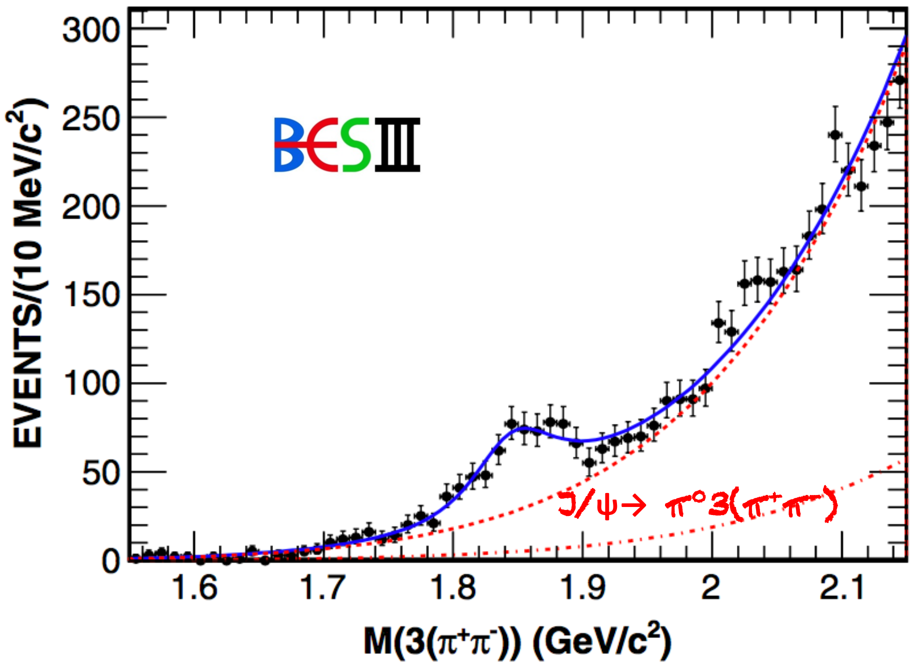
SECOND RESONANCE: X(1870)	
M (MeV/c²)	$1870.2\,^{+2.2}_{-2.3}\,^{+2.3}_{-0.7}$
Γ (MeV/c²)	$13.0\,^{+7.1}_{-5.5}\,^{+2.1}_{-3.8}$
B.R. (constructive interference)	$(2.03\,^{+0.12}_{-0.12}\,^{+0.43}_{-0.70})\times10^{-7}$
B.R. (destructive interference)	$(1.57\,^{+0.09}_{-0.09}\,^{+0.49}_{-0.86})\times10^{-5}$

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

X(1920) is not significant

Is it a pp̄ bound state?

X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$



PRD 88,091502(R) (2013)

230M J/ψ data sample

X(1840)(> 7.6σ)

$$M = 1842.2 \pm 4.2^{+7.1}_{-2.6}\ \frac{\text{MeV}}{c^2}$$

$$\Gamma = 83 \pm 14 \pm 11 \quad \text{MeV}/c^2$$

NO PWA

Mass consistent with the other X(1835), but width is much smaller

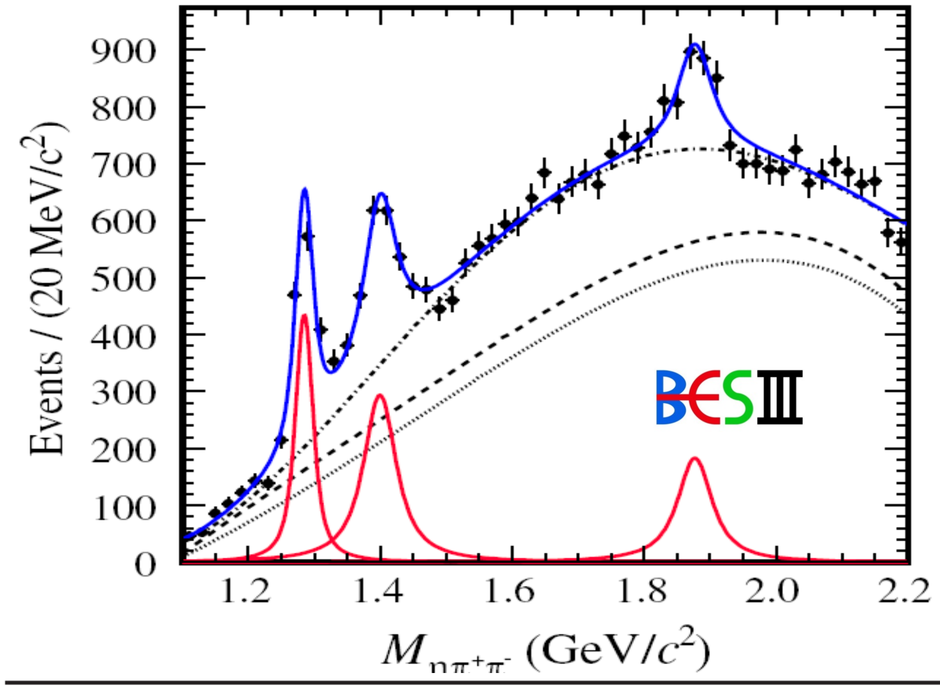
Results with higher statistics in progress.

X(1870) in $J/\psi \to \omega\eta\pi^+\pi^-$

230M J/ψ data sample

$J/\psi \to \omega\eta\pi^+\pi^-$

$a_0(980)$ in $\eta\pi^\pm$



X(1870) : 7.2σ
0^{-+} (?)
Is it X(1835) ?
NO PWA

PRL 107, 182001 (2011)

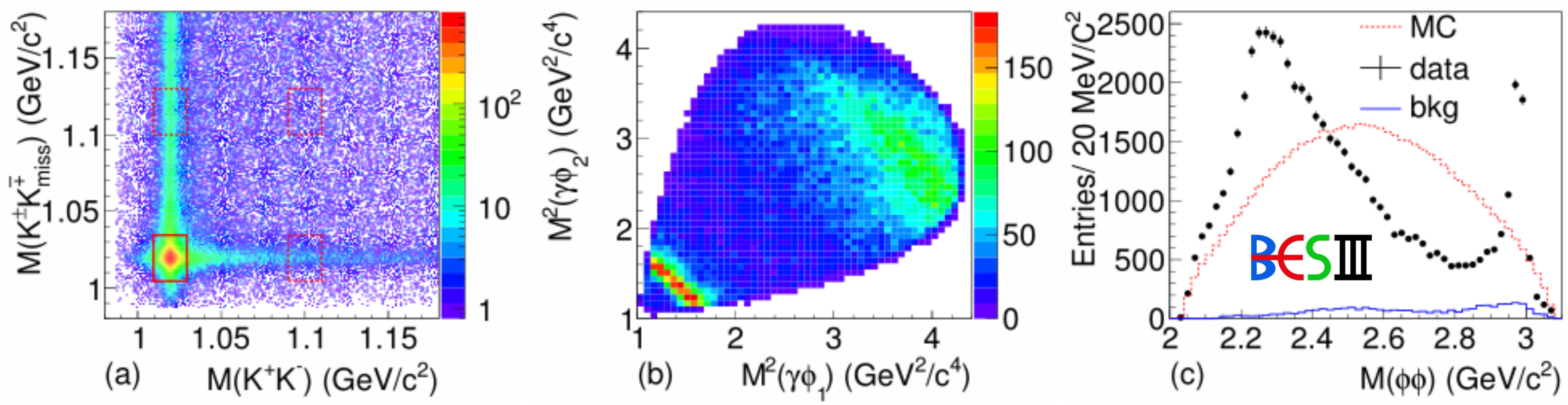
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(10^{-4})$
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$

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

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

- 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

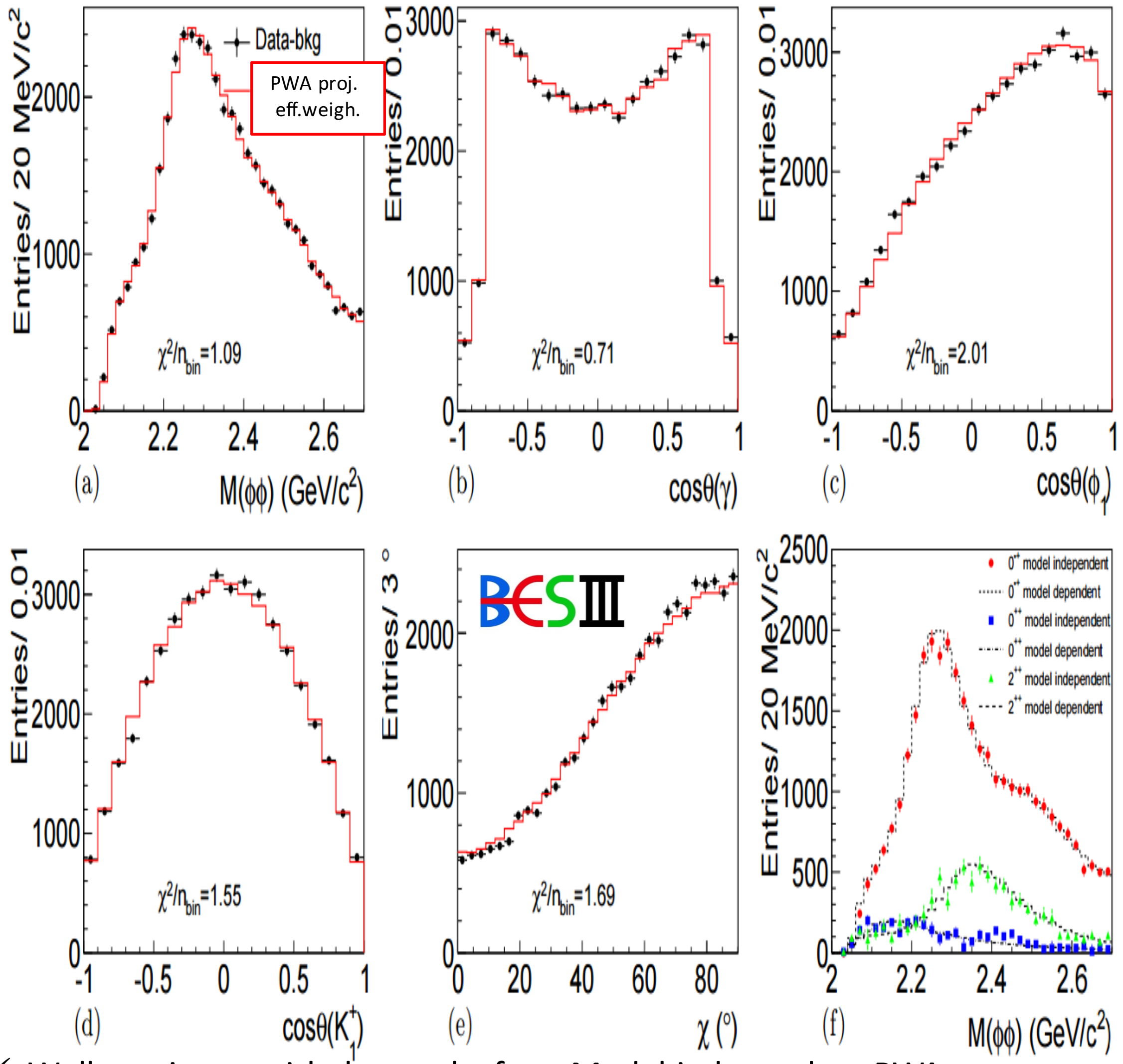
PWA procedure



Phys. Rev. D 93, 112011 (2016)

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

Both MIPWA and model dependent PWA performed on data



✓ Well consistent with the results from Model-independent PWA

BASELINE SOLUTION

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	To model direct decay		$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

Scalar state:
$f_0(2100)$

Tensor states:
$f_2(2010)$, $f_2(2300)$, $f_2(2340)$, obs. in $\pi^- p$ reac. strong $f_2(2340)$ production
Is it tensor glueball candidate(consistent with LQCD predictions)?

Pseudoscalar states (DOMINANT):
$\eta(2225)$ confirmed
$\eta(2100)$ and $X(2500)$ observed.

Phys. Rev. D 93, 112011 (2016)

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

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}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2 σ
$f_0(1710)$	$1759\pm6^{+14}_{-25}$	$172\pm10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0 σ
$f_0(2100)$	$2081\pm13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9 σ
$f_2'(1525)$	$1513\pm5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0 σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4 σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6 σ

Phys. Rev. D 87, 092009