Radiative J/ψ Decays at BESIII

Tianjue Min
mintj@mail.ihep.ac.cn
Institute of High Energy Physics

For BESIII Collaboration

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Outline

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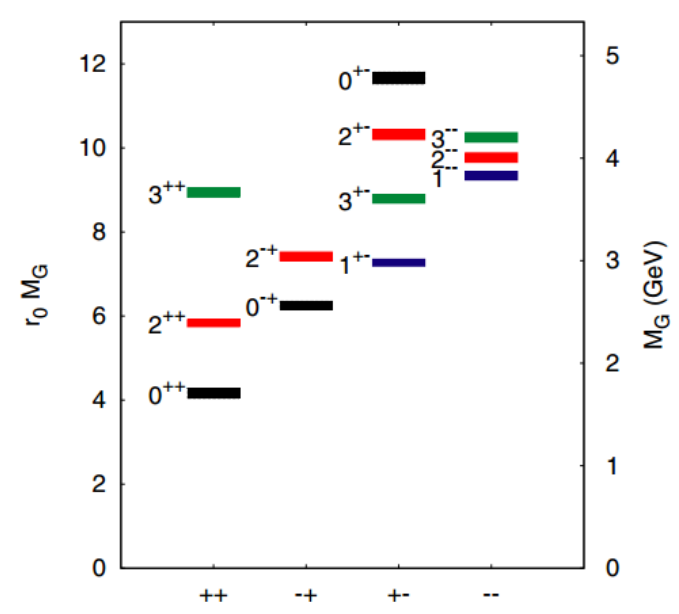
- Study of $J/\psi \to \gamma 3\pi$
- Partial Wave Analysis of $J/\psi \to \gamma\eta\eta$
- $\omega\phi$ threshold enhancement in $J/\psi \to \gamma\omega\phi$
- Summary & Perspective

Introduction

- Constituent Quark Model(CQM) has two types of hadrons:
  - Mesons: $q\bar{q}$
  - Baryons: qqq
- QCD allows hadrons of other types:
  - Multi-quark states: (more than 3 quarks)
  - Hybrids: $q\bar{q}g$
  - Glueballs: gg, ggg, …
  - …
- Up to now, none of the non-$q\bar{q}$ or non-qqq states is established experimentally.

Introduction

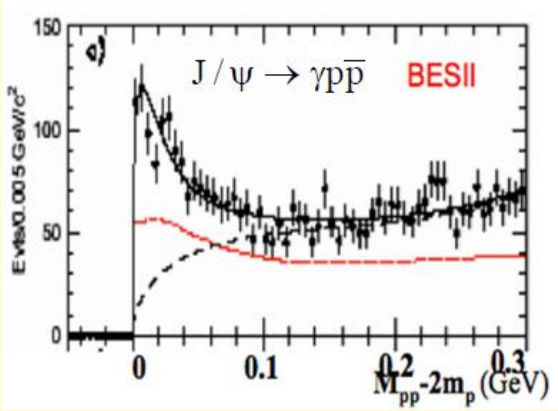
- Radiative J/ψ decays provide ideal lab for search of new hadrons.
  - Relative large radiative decays width compared to hadron decays width.
  - Large production of new hadrons.
  - Continuum mass spectrum.
- Perturbative QCD is not suitable in low energy region.
- Lattice QCD predicts glueballs in low energy region.
- BESIII has collected the largest J/ψ data sample in the world.
  - 225 million J/ψ events at 2009.
  - Another J/ψ sample with ~1 billion events is collected at 2012.
- Over the past few years, many new particles have been found or confirmed at BESIII.
  - X($p\bar{p}$), X(1810), X(1835), X(1840), X(1870), X(2120), X(2370), …



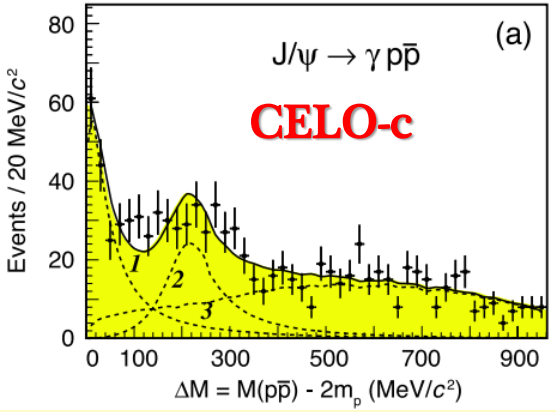
Phys. Rev. D 73, 014516 (2006)

$p\bar{p}$ threshold enhancement in $J/\psi \to \gamma p\bar{p}$

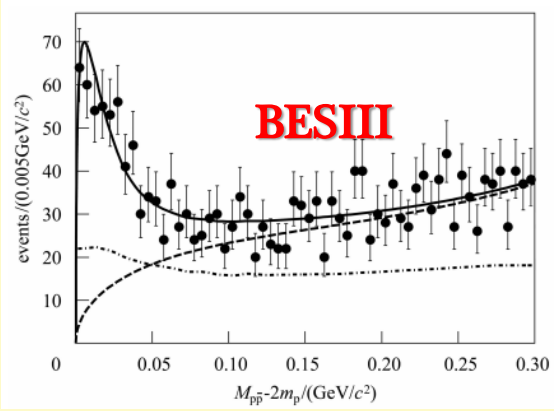
- A $p\bar{p}$ threshold enhancement structure was first observed at BESII.
  - $M=1859^{+3}_{-10}{}^{+5}_{-25}$ MeV/c^2.
  - $\Gamma<30$ MeV/c^2 (90% C.L.).
  - Spin 0?
- Confirmed at CLEO-c and BESIII in $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma p\bar{p}$.
  - CLEO-c: $M=1861^{+16}_{-6}$ MeV/c^2, $\Gamma=0^{+32}_{-0}$ MeV/c^2.
  - BESIII: $M=1861^{+6}_{-13}{}^{+7}_{-26}$ MeV/c^2, $\Gamma<38$ MeV/c^2(90% C.L.).
- Interpretations.
  - ~~Pure FSI effect?~~
    - Enhancement not seen in $J/\psi \to \omega/\pi^0 p\bar{p}$.
  - Normal meson?
  - $p\bar{p}$ bound state?
  - Multi-quark state?
  - Glueball?



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



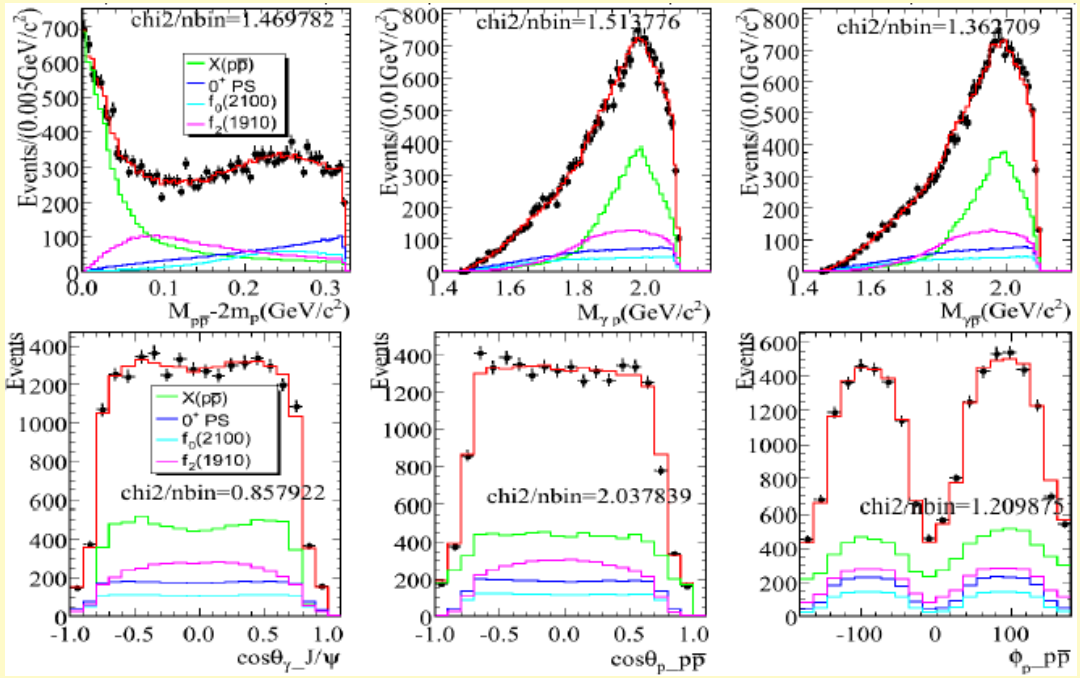
Phys. Rev. D 82, 092002 (2010)



Chinese Phys. C 34 421(2010)

$p\bar{p}$ threshold enhancement in $J/\psi \to \gamma p\bar{p}$

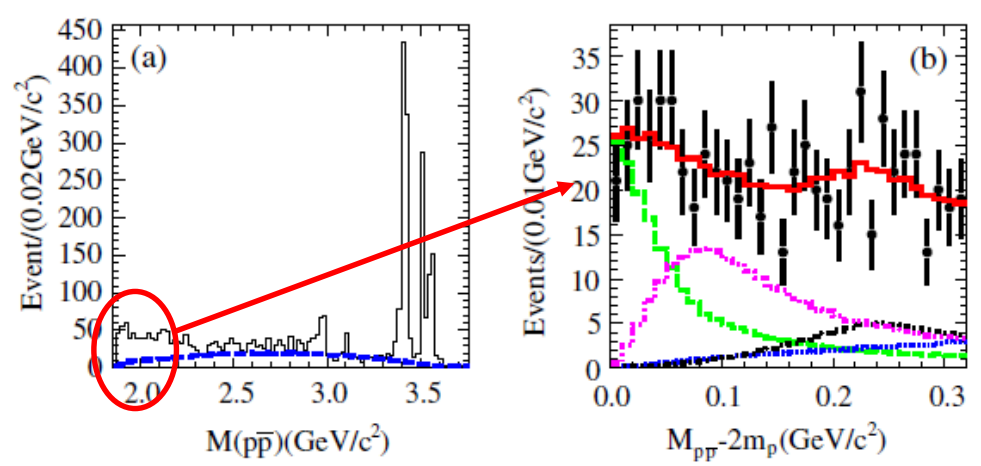
- PWA of $J/\psi \to \gamma p\bar{p}$
  - Solution includes $X(p\bar{p})$, $f_2(1910)$, $f_0(2100)$ and a 0^{-+} PHSP.
  - Fit using a BW resonance together with S-wave FSI(I=0) factor describes the structure above threshold well.
  - And it's much better than fit without FSI included.
    - $\Delta \ln L = 51 \to 7.1\sigma$
  - J^{PC} of $X(p\bar{p})$: 0^{-+}.
  - Significance of $X(p\bar{p})$ is much larger than 30σ.
  - $M = 1832^{+10}_{-5}{}^{+18}_{-17}{}^{+19}_{-19}$ MeV/c^2.
  - $\Gamma = 13^{+39}_{-39}{}^{+10}_{-13}{}^{+4}_{-4}$ MeV/c^2; $\Gamma < 76$MeV/c^2(@90%C.L.)
  - $Br(J/\psi \to \gamma X) \cdot Br(X \to p\bar{p}) = (9.0^{+0.4}_{-1.1}{}^{+1.5}_{-5.0}{}^{+2.3}_{-2.3}) \times 10^{-5}$.



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

$p\bar{p}$ threshold enhancement in $J/\psi \to \gamma p\bar{p}$

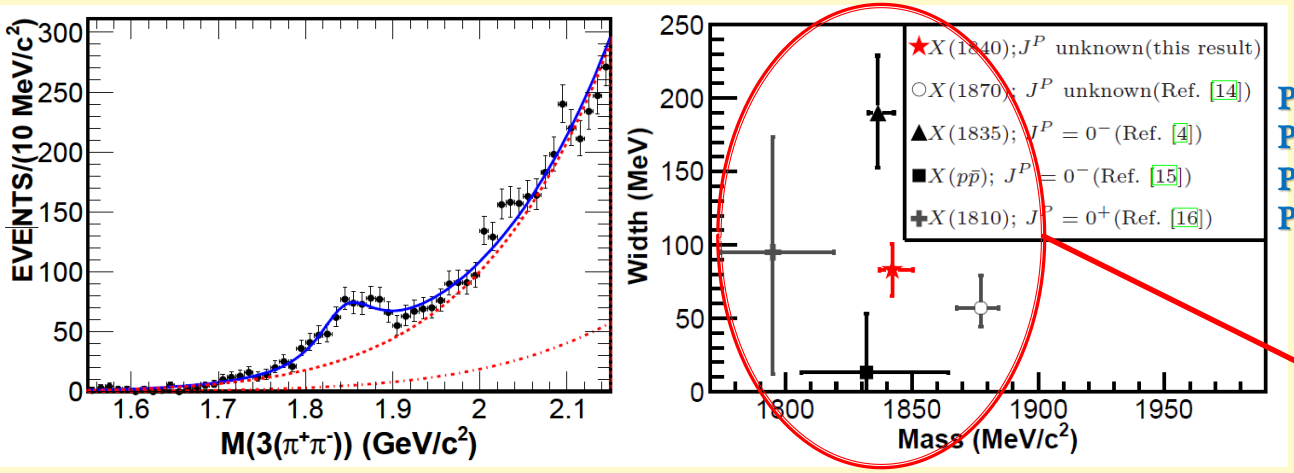
- PWA of $\psi' \to \gamma p\bar{p}$(based on 106 million ψ' data collected at BESIII)
  - Parameters of $X(p\bar{p})$ are fixed to results of $J/\psi \to \gamma p\bar{p}$.
  - Significance of $X(p\bar{p})$ is 6.9σ.
  - $Br(\psi' \to \gamma X) \cdot Br(X \to p\bar{p}) = (4.57^{+0.36}_{-0.36}{}^{+1.23}_{-4.07}{}^{+1.28}_{-1.28}) \times 10^{-6}$.
  - $R = \frac{Br(\psi' \to \gamma X(p\bar{p}))}{Br(J/\psi \to \gamma X(p\bar{p}))} = (5.08^{+0.71}_{-0.45}{}^{+0.67}_{-3.58}{}^{+0.12}_{-0.12})\%$.
  - Suppressed compare with the well known 12% rule.



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

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

- X(1835) is likely to have similar properties as η_c.
  - $3(\pi^+\pi^-)$ is a relatively large decay mode of η_c, also for X(1835)?
- A distinct enhancement can be clearly seen on mass spectrum of $3(\pi^+\pi^-)$ around 1.84 GeV/c^2.
  - Not from background process such as $J/\psi \to \pi^0 3(\pi^+\pi^-)$.
  - $M=1842^{+4.2}_{-4.2}{}^{+7.1}_{-2.6}$ MeV/c^2, $\Gamma=83^{+14}_{-14}{}^{+11}_{-11}$ MeV/c^2.
  - $Br(J/\psi \to \gamma X(1840)) \cdot Br(X(1840) \to 3(\pi^+\pi^-)) = (2.44^{+0.36}_{-0.36}{}^{+0.60}_{-0.74}) \times 10^{-5}$.



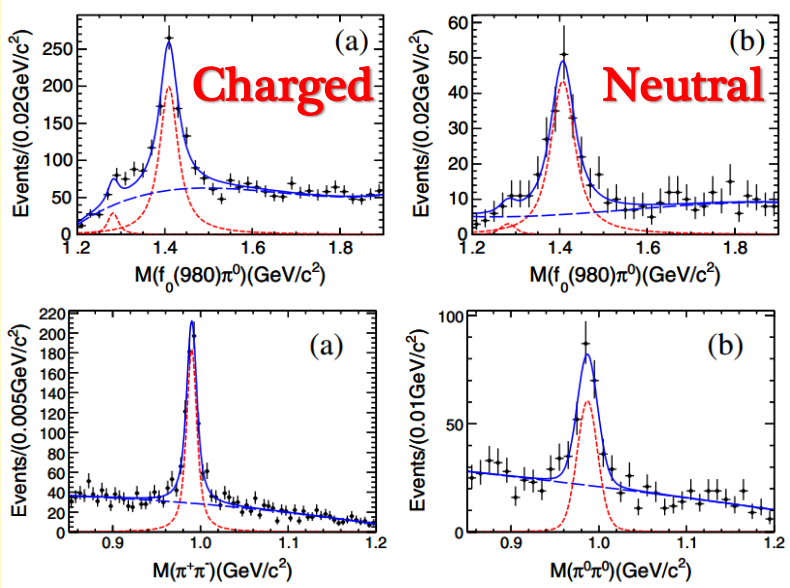
arXiv:1305.5333

Phys. Rev. Lett. 107, 182001 (2011)
Phys. Rev. Lett. 106, 072002 (2011)
Phys. Rev. Lett. 108, 112003 (2012)
Phys. Rev. D 87, 032008 (2013)

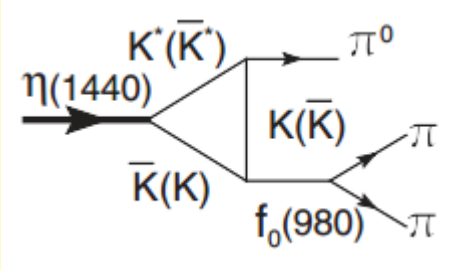
Need more study: more data, PWA, …

Study of $J/\psi \to \gamma 3\pi$

- First observation of an isospin-violate process: $\eta(1405) \to f_0(980)\pi^0$.
  - $Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0) = (1.50^{+0.11}_{-0.11}{}^{+0.11}_{-0.11}) \times 10^{-5}$.
  - $Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^0\pi^0\pi^0) = (7.10^{+0.82}_{-0.82}{}^{+0.72}_{-0.72}) \times 10^{-6}$.
  - $\frac{Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\eta(1405) \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} = (17.9^{+4.2}_{-4.2})\%$.
  - Much bigger than a_0-f_0 mixing rate(<1%)!
    - Phys. Rev. D 83, 032003 (2011)
- Narrow $f_0(980)$.
  - Charged channel: $\Gamma = 9.5^{+1.1}_{-1.1}$ MeV/c^2.
  - Neutral channel: $\Gamma = 4.6^{+5.1}_{-5.1}$ MeV/c^2.
  - Much smaller than PDG value: 40~100MeV/c^2!
- Theoretical explanation: Triangle Singularity?
  - Phys. Rev. Lett. 108, 081803 (2012)

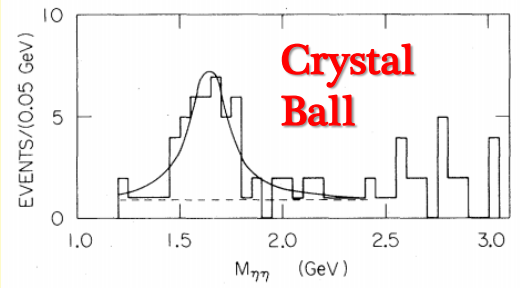


Phys. Rev. Lett. 108, 182001 (2012)

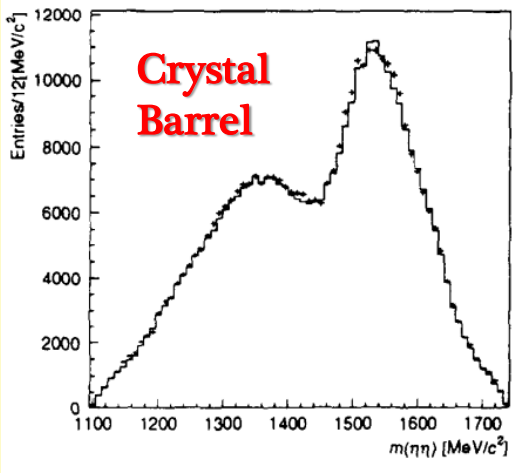


Partial Wave Analysis of $J/\psi \to \gamma\eta\eta$

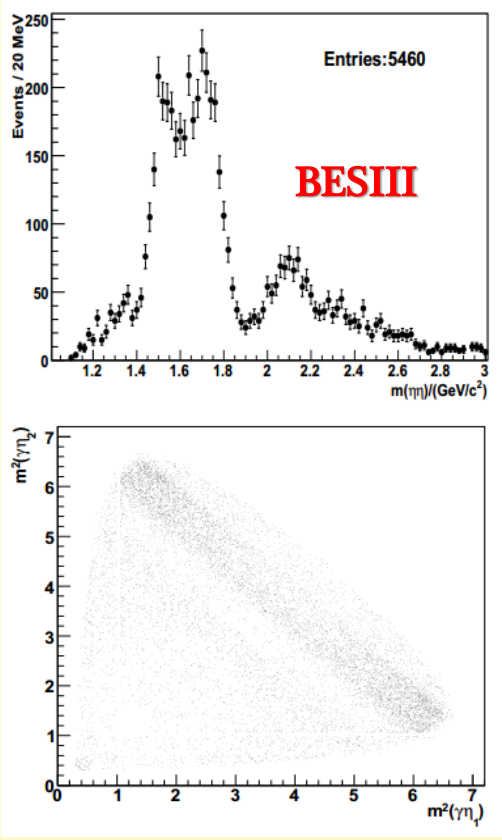
- Lattice QCD predicts the lowest lying 0^{++} glueball occurs in 1.5 to 1.7 GeV/c^2, and the lightest 2^{++} glueball has mass around 2.2GeV/c^2.
- $\eta\eta$ system:
  - Even^{++} states(mainly 0^{++} and 2^{++}): ideal place for search of scalar and tensor glueballs.
    - Crystal Ball observed $f_0(1710)$ in $J/\psi \to \gamma\eta\eta$.
    - Crystal Barrel observed $f_0(1500)$ in $p\bar{p} \to \pi^0\eta\eta$.
  - Avail comparison to $\pi\pi$, $K\bar{K}$, $\eta\eta'$ system.
- $J/\psi \to \gamma\eta\eta$ at BESIII.
  - High statistics.
  - EMC: CsI(T1) crystals, high performance.
  - Low background.



Phys. Rev. Lett. 48, 458 (1982)



Phys. Lett. B 353, 571 (1995)

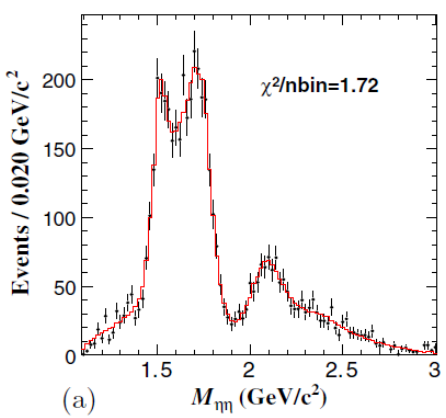


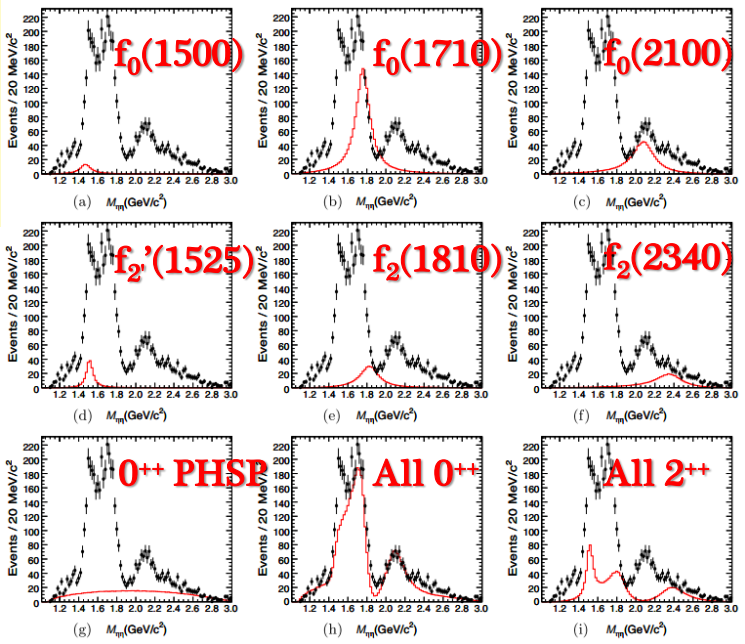
Phys. Rev. D 87, 092009 (2013)

Partial Wave Analysis of J/ψ→γηη

- **Scalar contributions**
  - $f_0(1500)$, $f_0(1710)$, $f_0(2100)$; ~~$f_0(1370)$, $f_0(1790)$~~.
  - Production rate of $f_0(1500)$ is approximately one order smaller than that of $f_0(1710)$ and $f_0(2100)$.
  - Production rate of $f_0(1710)$ in radiative J/ψ decays is compatible with LQCD's prediction on that of a pure gauge scalar glueball. Large overlap between $f_0(1710)$ and a glueball?
- **Tensor contributions**
  - $f_2'(1525)$, $f_2(1810)$, $f_2(2340)$; ~~$f_J(2220)$~~.

Resonance	$B(J/\psi\to\gamma X\to\gamma\eta\eta)$	Significance
$f_0(1500)$	$(1.65^{+0.36}_{-0.31}{}^{+0.51}_{-1.40})\times10^{-5}$	8.2σ
$f_0(1710)$	$(2.35^{+0.13}_{-0.11}{}^{+1.24}_{-0.74})\times10^{-4}$	25.0σ
$f_0(2100)$	$(1.13^{+0.09}_{-0.10}{}^{+0.64}_{-0.28})\times10^{-4}$	13.9σ
$f_2'(1525)$	$(3.42^{+0.43}_{-0.51}{}^{+1.37}_{-1.30})\times10^{-5}$	11.0σ
$f_2(1810)$	$(5.40^{+0.60}_{-0.67}{}^{+3.42}_{-2.35})\times10^{-5}$	6.4σ
$f_2(2340)$	$(5.60^{+0.62}_{-0.65}{}^{+2.37}_{-2.07})\times10^{-5}$	7.6σ
0^{++} PHSP	$(1.47^{+0.01}_{-0.02})\times10^{-4}$	12.4σ

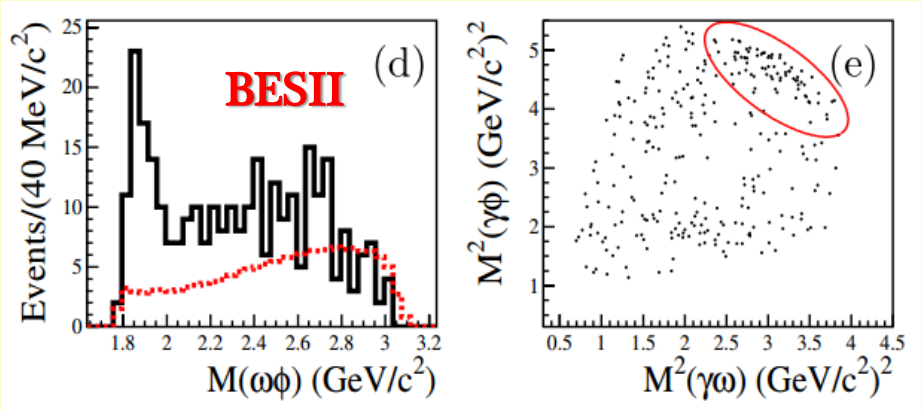




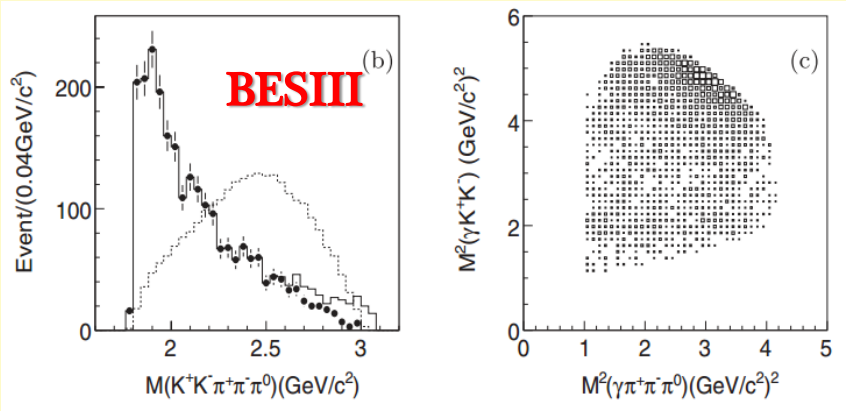
Phys. Rev. D 87, 092009 (2013)

ωϕ threshold enhancement in J/ψ→γωϕ

- An enhancement on ωϕ threshold in J/ψ→γωϕ was first observed at BESII and named X(1810):
  - J^{PC} favors 0^{++}.
  - $M=1812^{+19}_{-26}{}^{+18}_{-18}$ MeV/c^2, $\Gamma=105^{+20}_{-20}{}^{+28}_{-28}$ MeV/c^2.
  - $Br(J/\psi\to\gamma X(1810))\cdot Br(X(1810)\to\omega\phi)=(2.61^{+0.27}_{-0.27}{}^{+0.65}_{-0.65})\times10^{-4}$.
- BESIII confirmed X(1810) with much higher statistics.



Phys. Rev. Lett. 96, 162002 (2006)

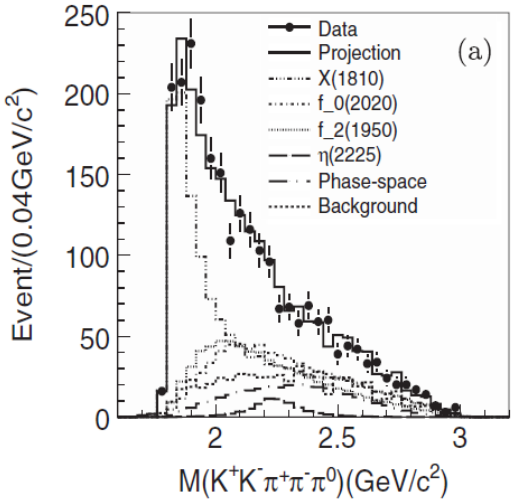


Phys. Rev. D 87, 032008 (2013)

ωϕ threshold enhancement in J/ψ→γωϕ

- Partial Wave Analysis(PWA) of J/ψ→γωϕ
  - Solution; X(1810), f_2(1950), f_0(2020), η(2025) and a 0^{-+} PHSP.
  - J^{PC} of X(1810): 0^{++}.
  - $M=1795^{+7}_{-7}{}^{+13}_{-15}{}^{+19}_{-19}$ MeV/c^2, $\Gamma=95^{+10}_{-10}{}^{+21}_{-34}{}^{+75}_{-75}$ MeV/c^2.
  - $Br(J/\psi\to\gamma X(1810))\cdot Br(X(1810)\to\omega\phi)=(2.00^{+0.08}_{-0.08}{}^{+0.45}_{-1.00}{}^{+1.3}_{-1.3})\times10^{-4}$.
- J/ψ→γωϕ is a DOZI process, but has a similar branch ratio compared to that of J/ψ→γϕϕ, an OZI process.
  - Dynamical effect arising from intermediate meson re-scattering.
  - A manifestation of f_0(1710).
  - Hadrons of new types: tetraquark, hybrid, glueball, …

Res.	J^{PC}	Sig.
X(1810)	0^{++}	>30σ
f_2(1950)	2^{++}	20.4σ
f_0(2020)	0^{++}	13.9σ
η(2225)	0^{-+}	6.4σ
PHSP	0^{-+}	9.1σ



Phys. Rev. D 87, 032008 (2013)

Summary & Perspective

- Over the past few years, BESIII has got many interesting physics results from radiative J/ψ decays:
  - $X(p\bar{p})$ is confirmed as a pseudoscalar particle, with mass and width measured.
  - X(1840) is observed.
  - First observation of $\eta(1405)\rightarrow f_0(980)\pi^0$.
  - Study of ηη system.
  - X(1810) is confirmed.
- Last year in a new run period, BESIII has collected more than 1 billion J/ψ events, which is approximately 5 times as large as previous sample. With such high statistics, it's excited to expect more and more interesting discoveries from radiative J/ψ decays at BESIII in the future.

THANK YOU!