Light Meson Spectroscopy at BESIII

Shuangshi FANG

(for the BESIII Collaboration)

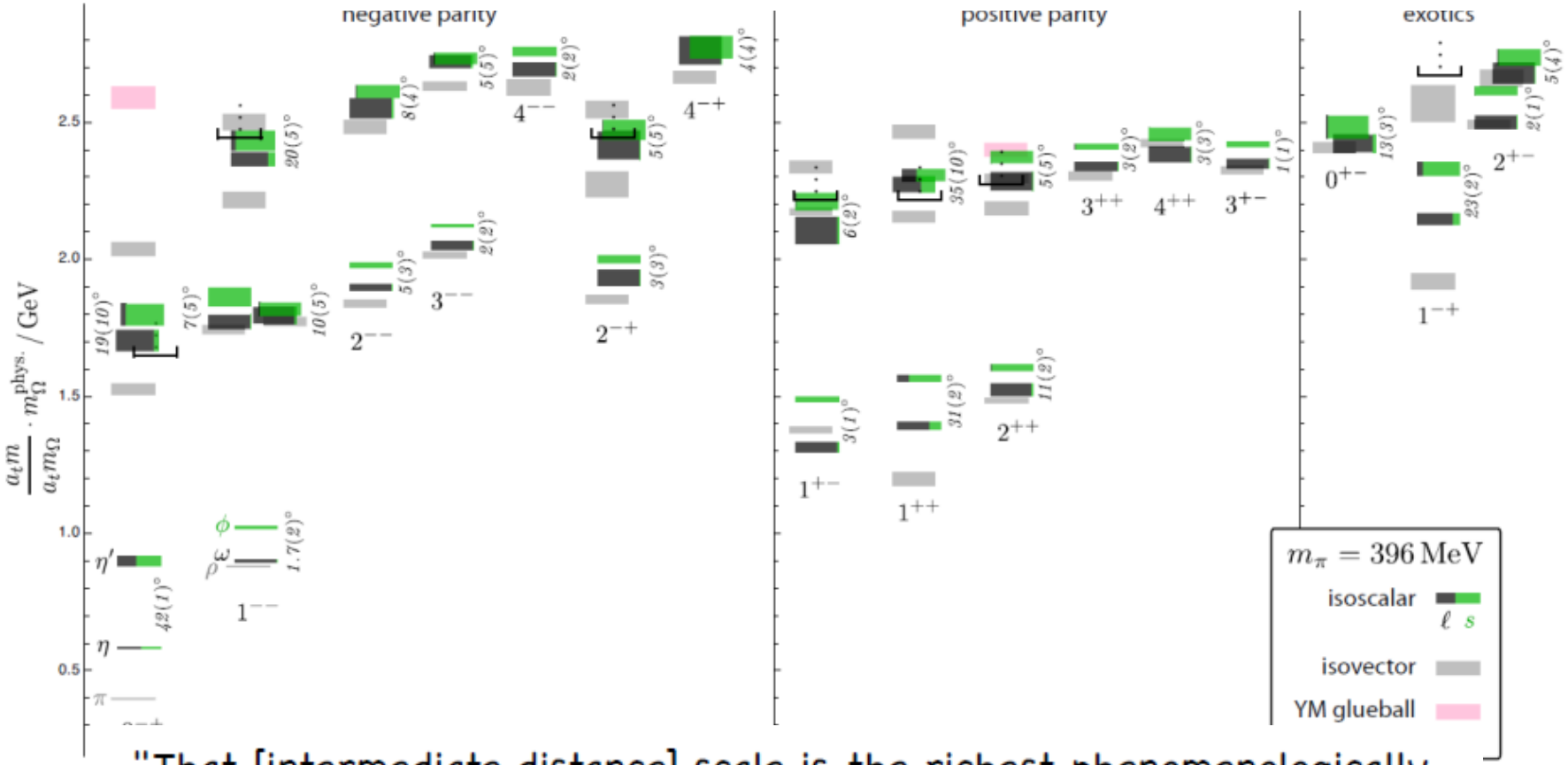
Institute of High Energy Physics

MENU2016 , 25-30 July, Kyoto , Japan

OUTLINE

- Introduction
- Progresses on Light Meson Spectroscopy
  - Structures around 1.85 GeV/c^2
  - Scalar/tensor mesons in J/ψ radiative decays
  - Search for exotics in $\chi_{c1} \to \eta\pi^+\pi^-$
  - Kaonia and strangeonia spectrum
  - Light meson decays
- Summary

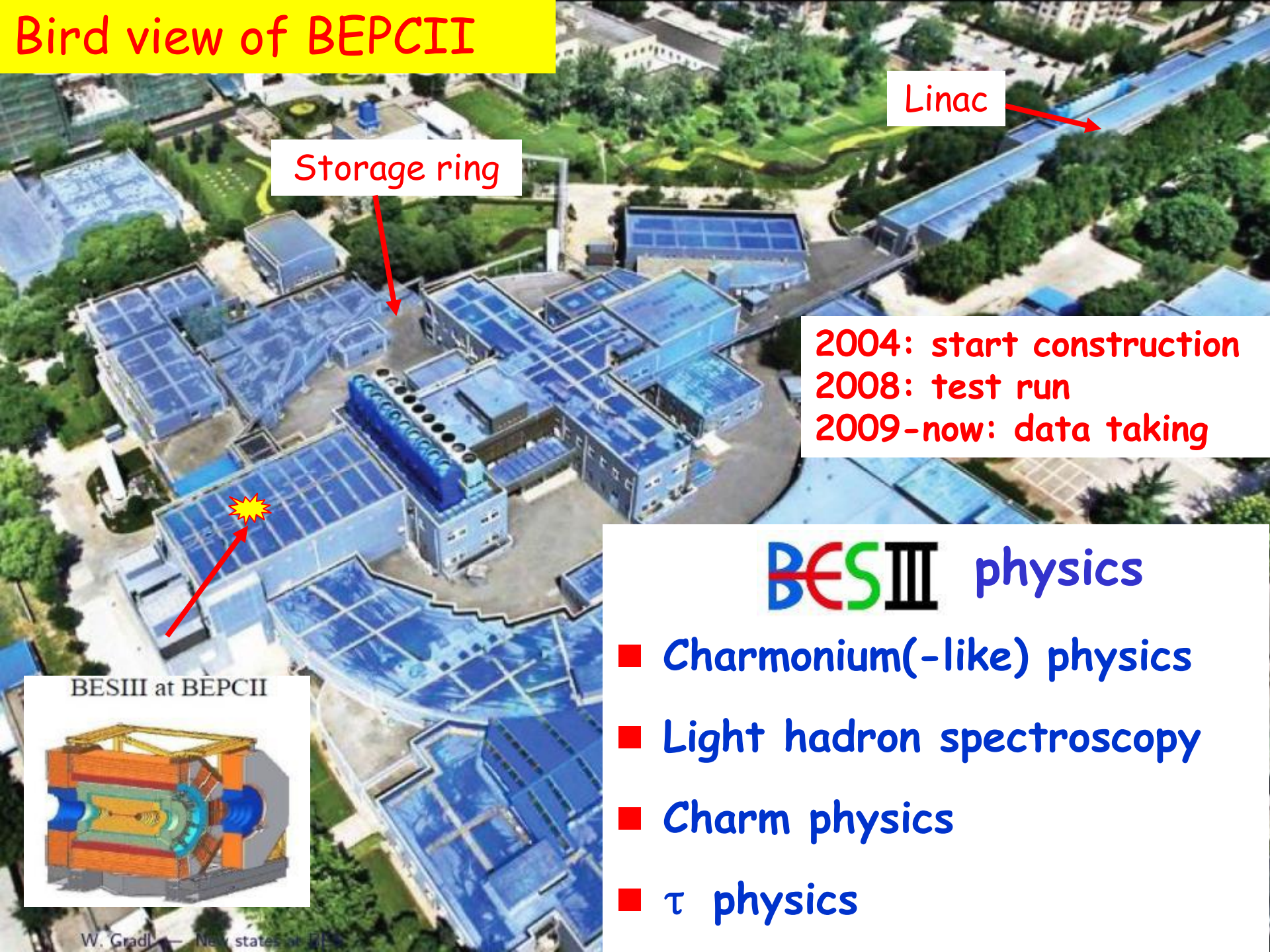
Meson spectroscopy in LQCD



"That [intermediate distance] scale is the richest phenomenologically, and is certainly the crux region to understand...what QCD is really about. And at the heart of the subject is the hadron spectrum, in particular the spectrum built from light quarks. (...) **Without question, there is a great need... for a new round of experiments,...**"

James D. Bjorken (2000)

Bird view of BEPCII

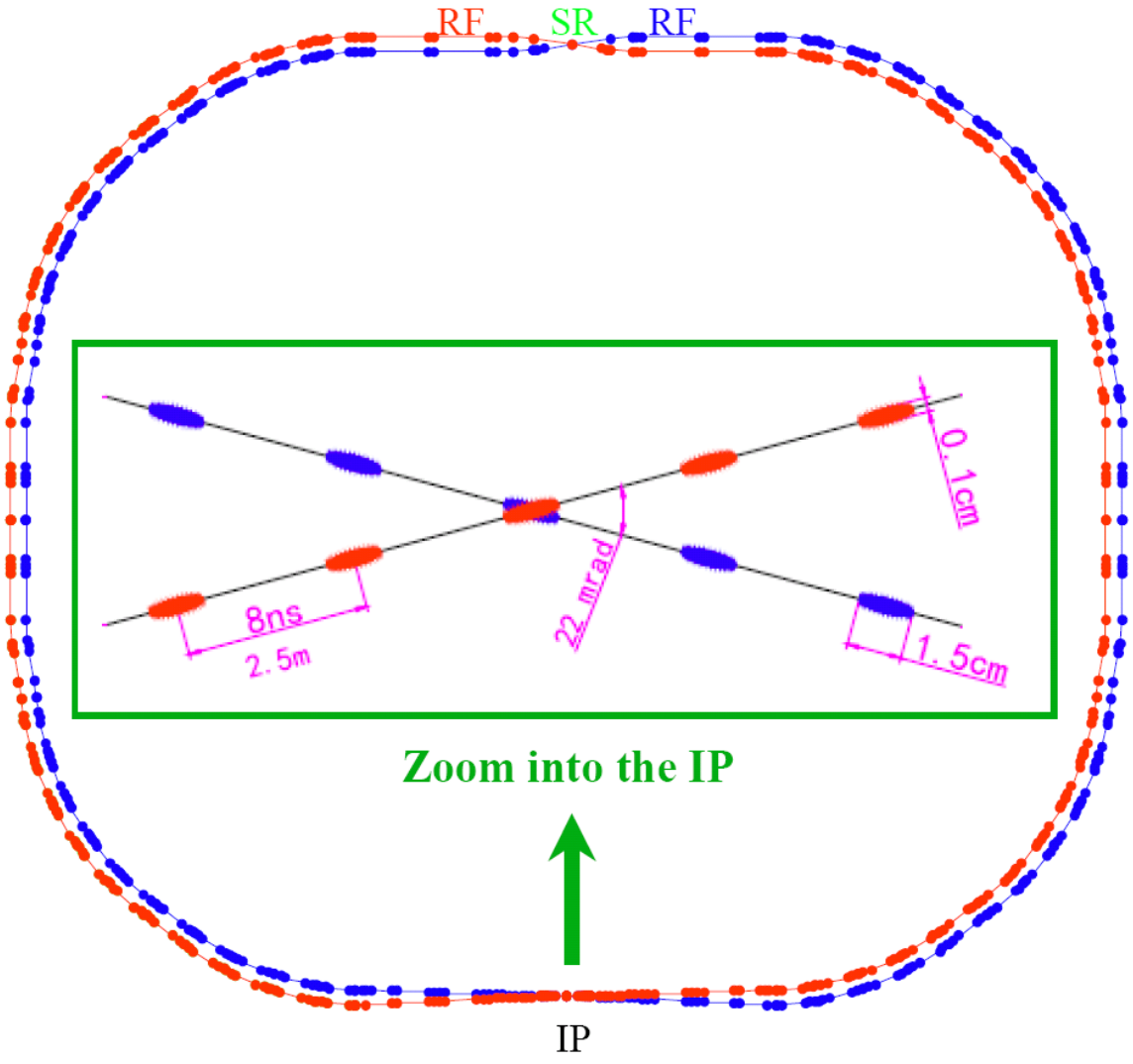


2004: start construction
2008: test run
2009-now: data taking

BESIII physics

- Charmonium(-like) physics
- Light hadron spectroscopy
- Charm physics
- τ physics

BEPCII storage rings



Beam energy:
1.0-2.3 GeV
Design Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
(achieved on 5th April,2016)
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
Circumference :
237m

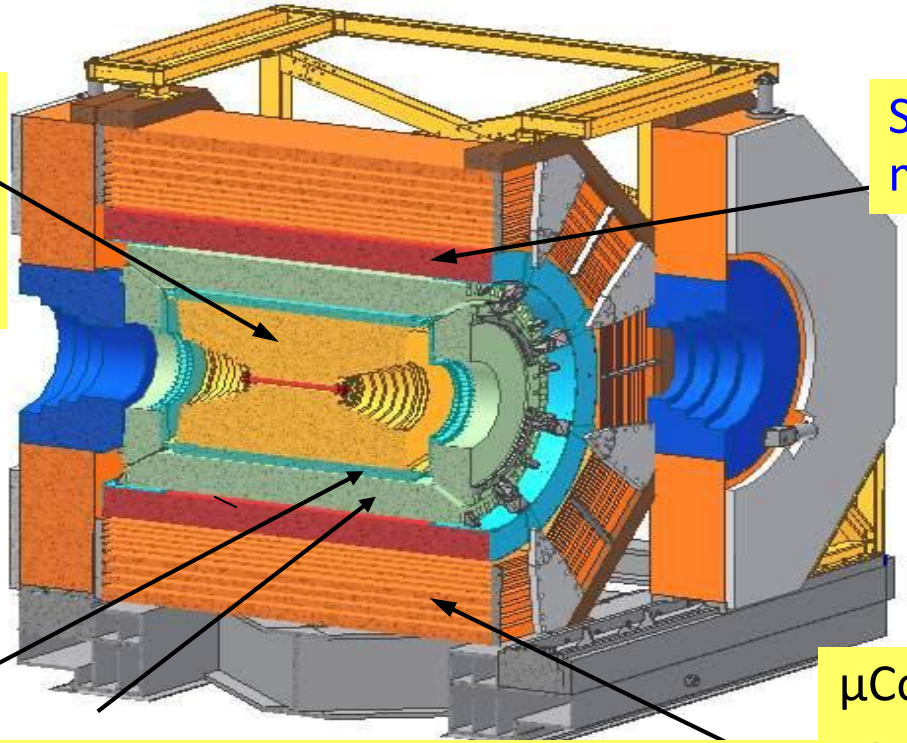
NIM A614, 345 (2010)

The BESIII Detector

Drift Chamber (MDC)

$\sigma P/P\ (^0/_0) = 0.5\%(1GeV)$

$\sigma_{dE/dx}\ (^0/_0) = 6\%$



Super-conducting magnet (1.0 tesla)

Time Of Flight (TOF)

σ_T: 90 ps Barrel

110 ps endcap

EMC: $\sigma E/\sqrt{E}(^0/_0) = 2.5\ \%$ (1 GeV)

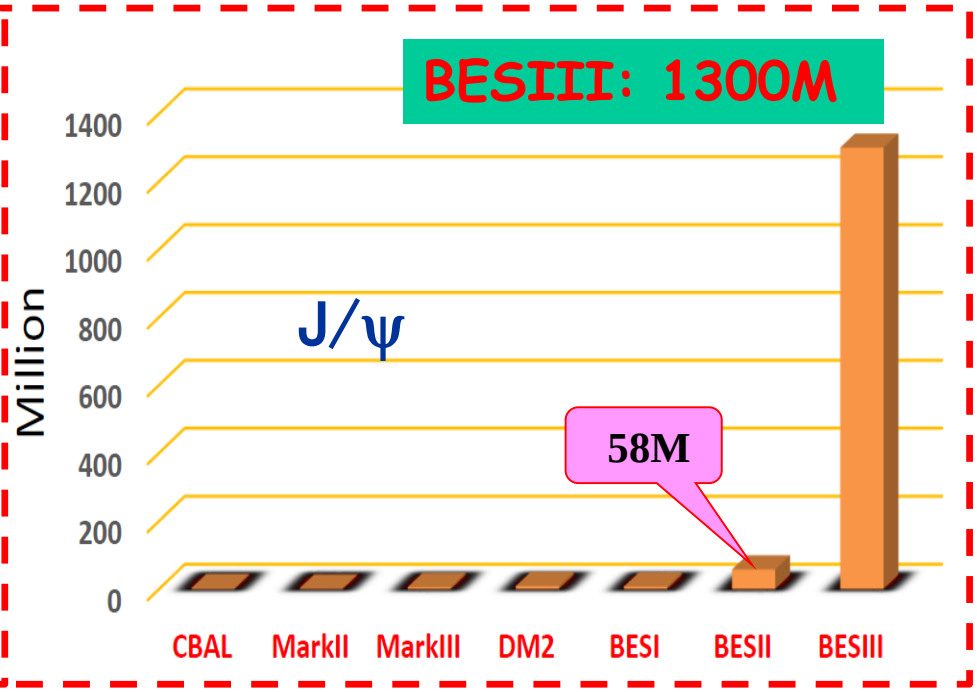
(CsI) $\sigma_{z,\phi}(cm) = 0.5 - 0.7\ cm/\sqrt{E}$

μCounter

8- 9 layers RPC

$\delta R\Phi$=1.4 cm~1.7 cm

J/ψ and ψ(3686)events at BESIII (2009+2012)



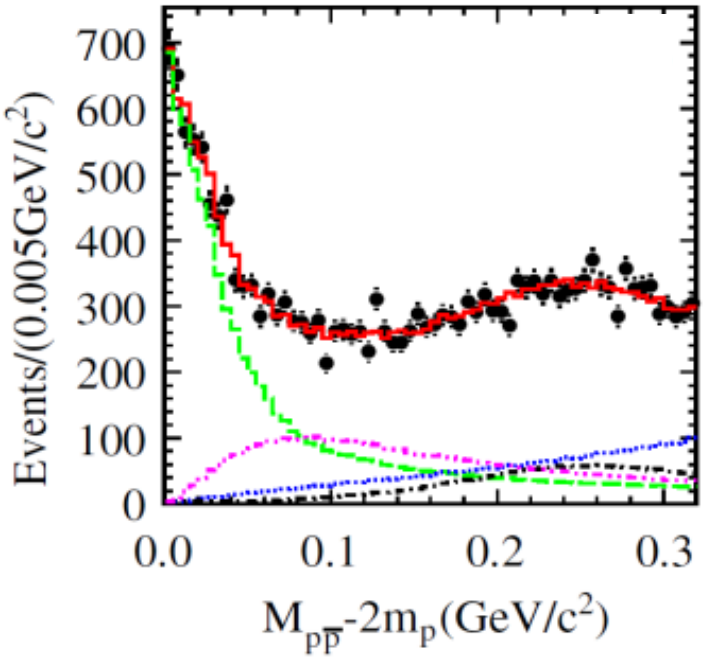
Structures around 1.85 GeV/c^2

X(p $\bar{p}$) in J/ψ→γp $\bar{p}$

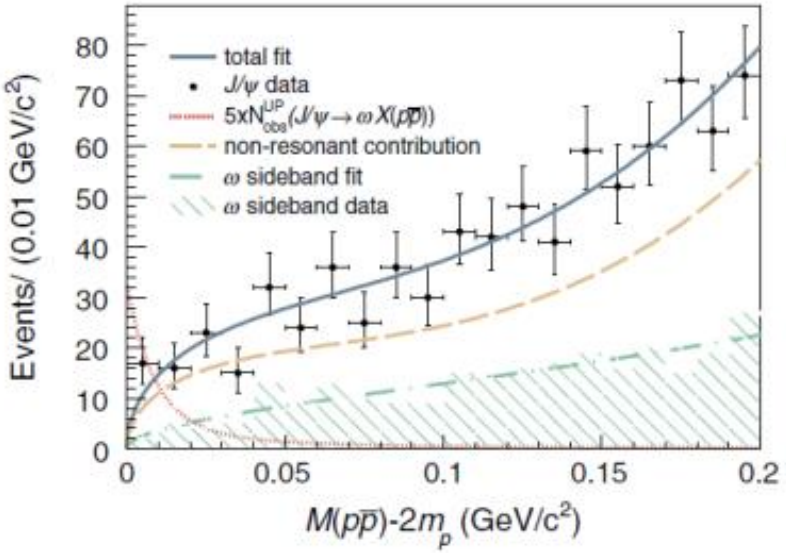
225M J/ψ

- PWA of J/ψ→γp $\bar{p}$ was first performed
- The fit with a BW and S-wave FSI(I=0) factor can well describe p $\bar{p}$ mass threshold structure.
- It is much better than that without FSI effect, and Δ2lnL=51 (7.1σ)

- Spin-parity of X(ppbar): $J^{PC}=0^{-+}$



PRL 108,112003(2012)

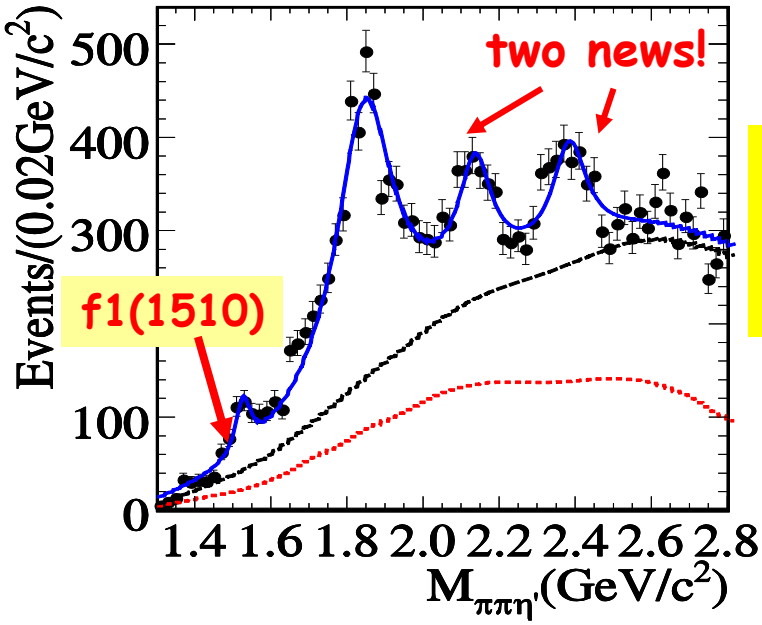


No similar structure was observed in J/ψ→ωp $\bar{p}$ and J/ψ→ϕp $\bar{p}$

PRD 87, 112004(2013)
PRD 93, 052010(2016)

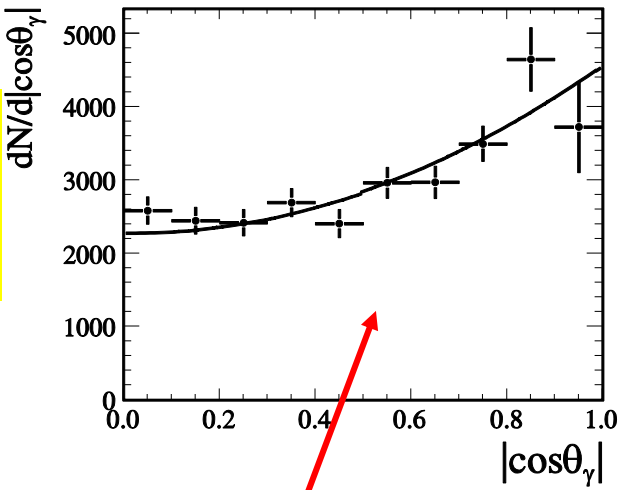
Confirmation of X(1835) and two new structures

PRL 106, 072002(2011)



225M J/ψ

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



X(1835) consistent with 0^-

BESIII fit results:

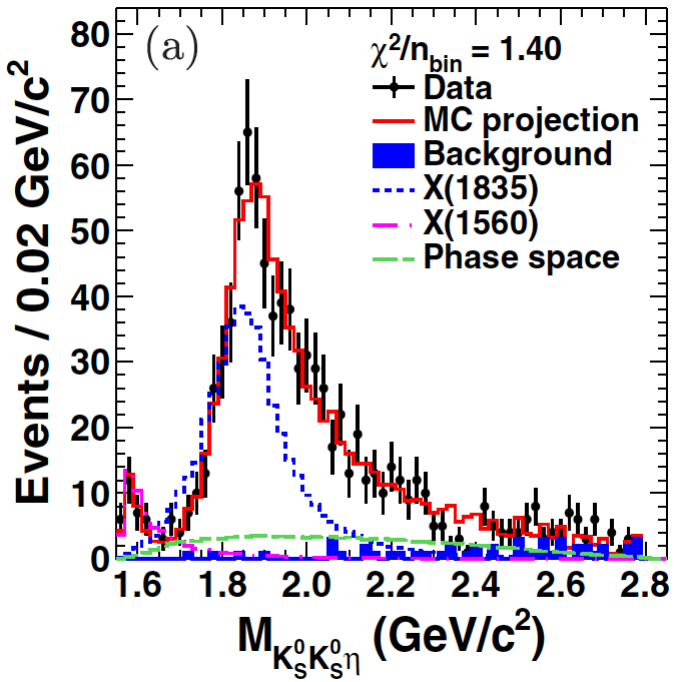
Resonance	M(MeV/c^2)	Γ(MeV/c^2)	Stat.Sig.
X(1835)	$1836.5 \pm 3.0^{+5.6}_{-2.1}$	$190.1 \pm 9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4 \pm 6.7^{+4.7}_{-2.7}$	$83 \pm 16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3 \pm 8.7^{+3.2}_{-4.3}$	$83 \pm 17^{+44}_{-6}$	6.4σ

✓Nature of X(2120)/X(2370): pseudoscalar glueball ? η/η′ excited states?

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

1. 3B J/ψ

Phys.Rev.Lett. 115 091803(2015)



PWA for $M(K_SK_S)$<1.1 GeV/c²

- **X(1835)→$K_SK_S\eta$**

M=1844$\pm$9(stat)$^{+16}_{-25}$(syst) MeV/c²

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

$J^{PC}=0^{-+}$

- **X(1560) → $f_0(980)\eta$: $J^{PC}=0^{-+}$**

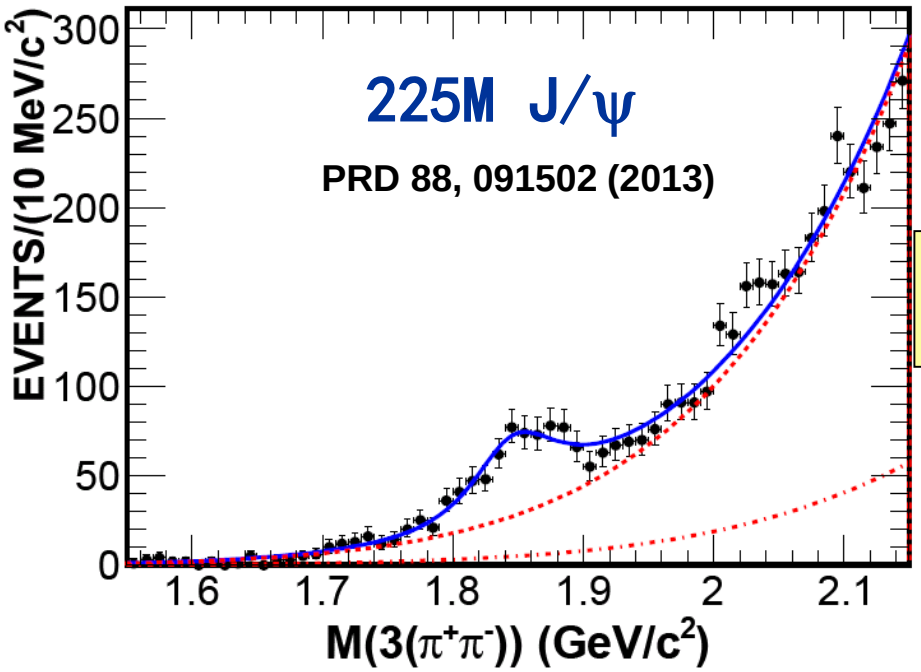
M=1565$\pm 8^{+0}_{-63}$ MeV/c²

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

$\eta(1405)$ / $\eta(1475)$ within 2.0 σ

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

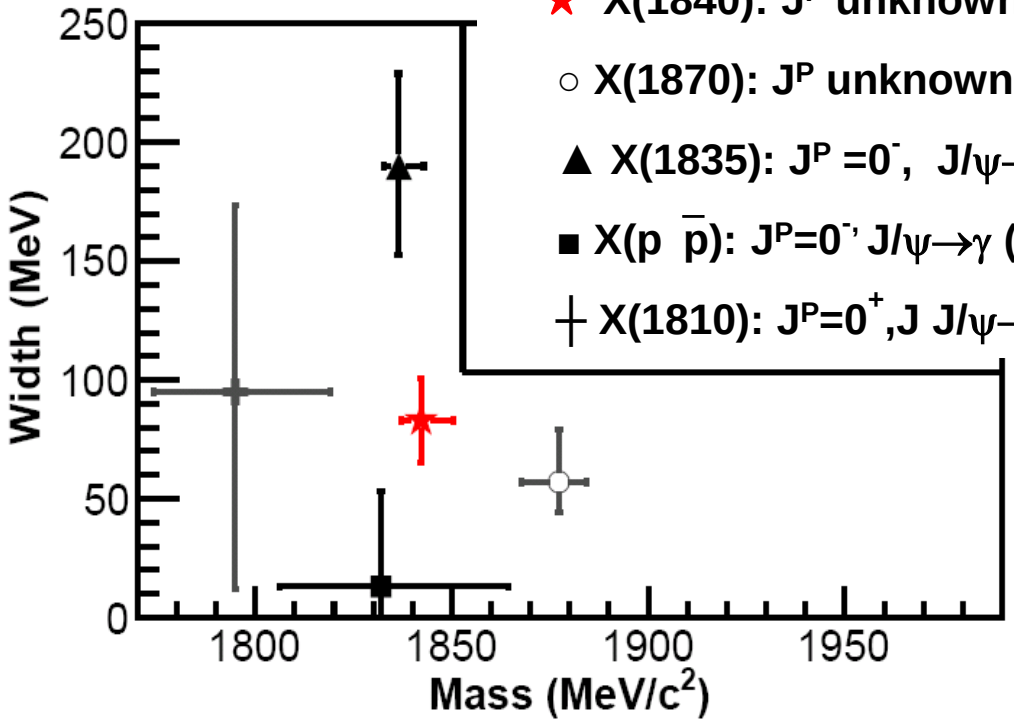
Observation of X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$



$M=1842.2\pm4.2\ ^{+7.1}_{-2.6}\ MeV/c^2$
$\Gamma = 83\pm14\pm11 MeV$

- Mass is consistent with that of X(1835), but the width is much smaller than $\Gamma_{x(1835)} = 190.1\pm9.0^{+38}_{-36}$ MeV
- A new decay mode of X(1835)?

Comparisons of the observations at BES



★ X(1840): J^P unknown,J/ψ→γ 3(π+ π-) PRD88,091502

○ X(1870): J^P unknown, J/ψ→ ω (ηππ) PRL107, 182001

▲ X(1835): $J^P = 0^-$, J/ψ→γ (η'ππ) PRL106, 072002

■ X(p $\bar{p}$): $J^P=0^-$, J/ψ→γ (p $\bar{p}$) PRL108,112003

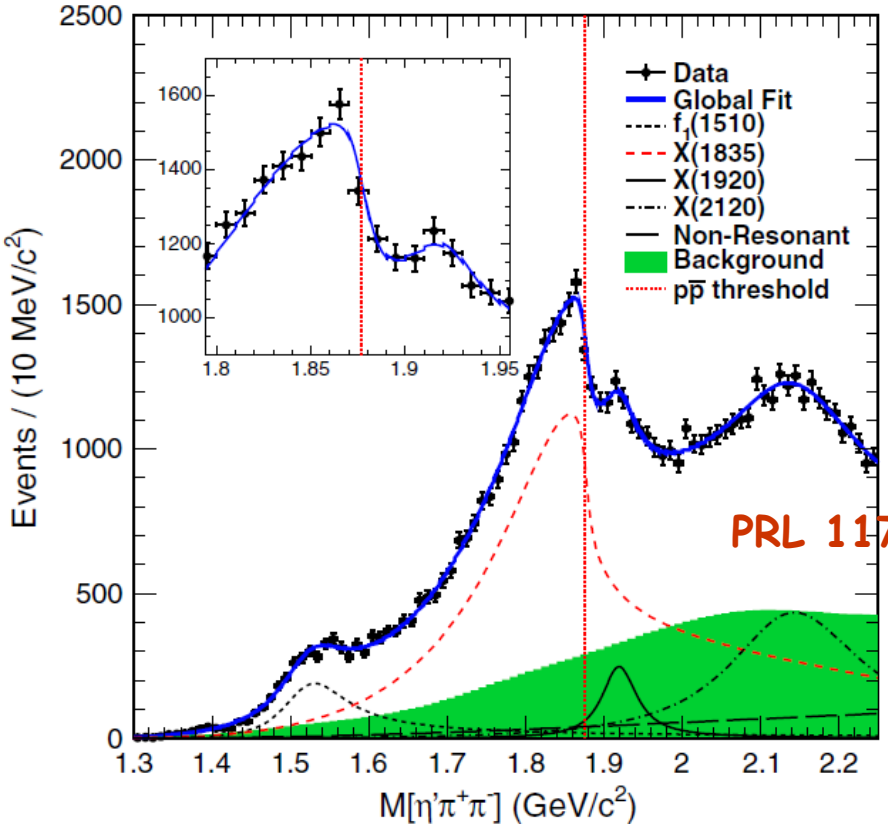
┼ X(1810): $J^P=0^+$,J J/ψ→γ (ωϕ) PRD 87, 032008

X(18??) near the threshold position of proton-antiproton

Are they the same particle? It is crucial to identify these observations.

Latest result on X(1835) from $J/\psi\to\gamma\eta'\pi^+\pi^-$ 1.3B J/ψ

Faltte formula

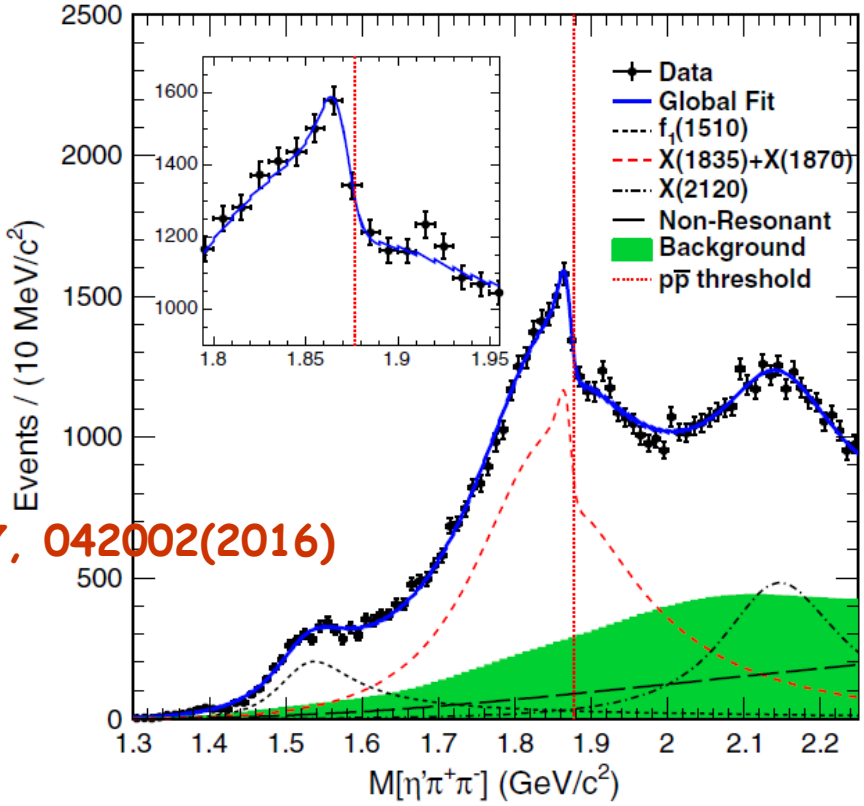


$M=1638.2\pm121.9\ ^{+127.8}_{-254.3}$ MeV/c^2

$g^2_0 = 93.7\pm35.4\ ^{+47.6}_{-43.9}$ GeV/c^2

$g^2_{p\bar{p}}/g^2_0 = 2.31\pm0.37\ ^{+0.83}_{-0.60}$

Two BWs



PRL 117, 042002(2016)

$M_1=1825.3\pm2.4\ ^{+17.2}_{-2.4}$ MeV/c^2

$\Gamma_1 = 245.2\pm13.1\ ^{+4.6}_{-9.6}$ MeV

$M_2=1870.2\pm2.2\ ^{+2.3}_{-0.7}$ MeV/c^2

$\Gamma_2 = 13.0\pm6.1\ ^{+2.1}_{-3.8}$ MeV

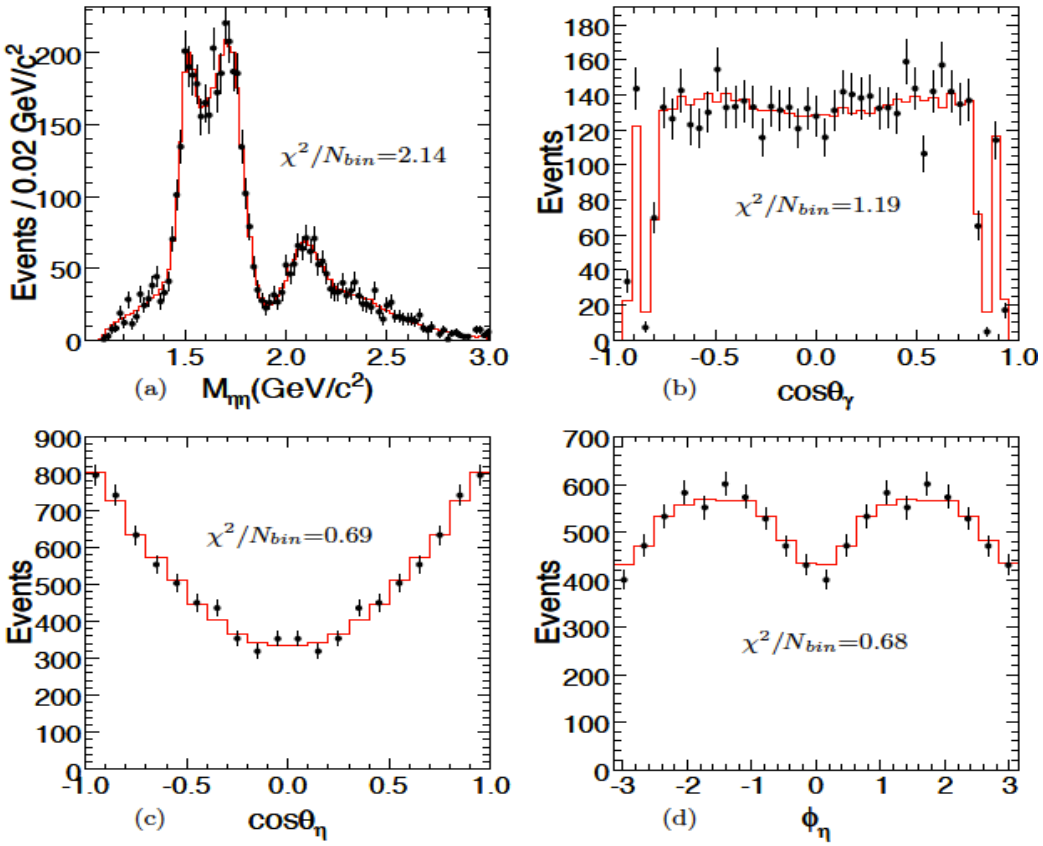
existence of a structure strongly coupling to $p\bar{p}$!

Scalar/tensor mesons in J/ψ radiative decays

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

225M J/ψ

Phys. Rev. D. 87, 092009 (2013)

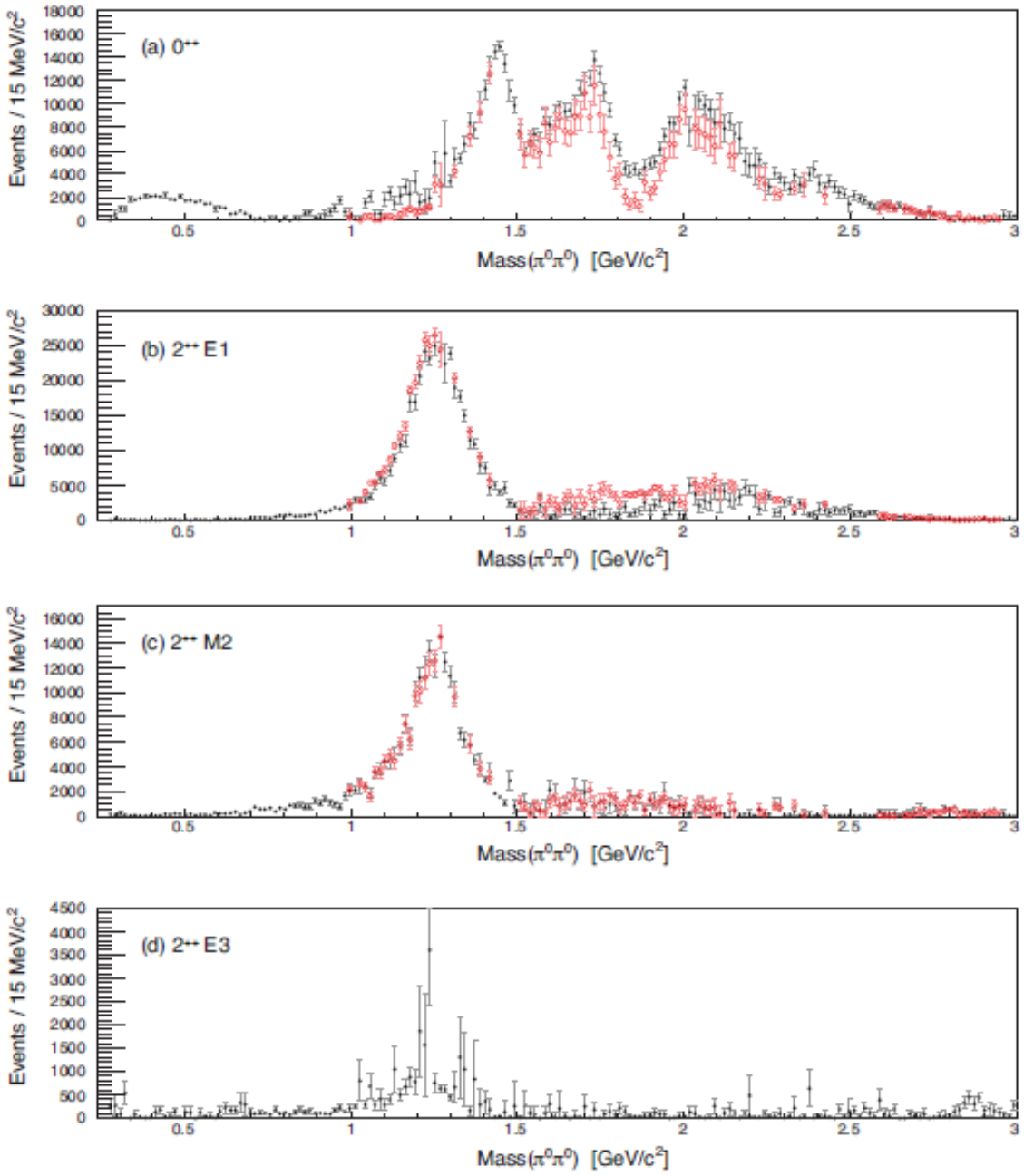


- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4 and 7.6σ)
- No evidence for $f_J(2220)$

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}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ

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

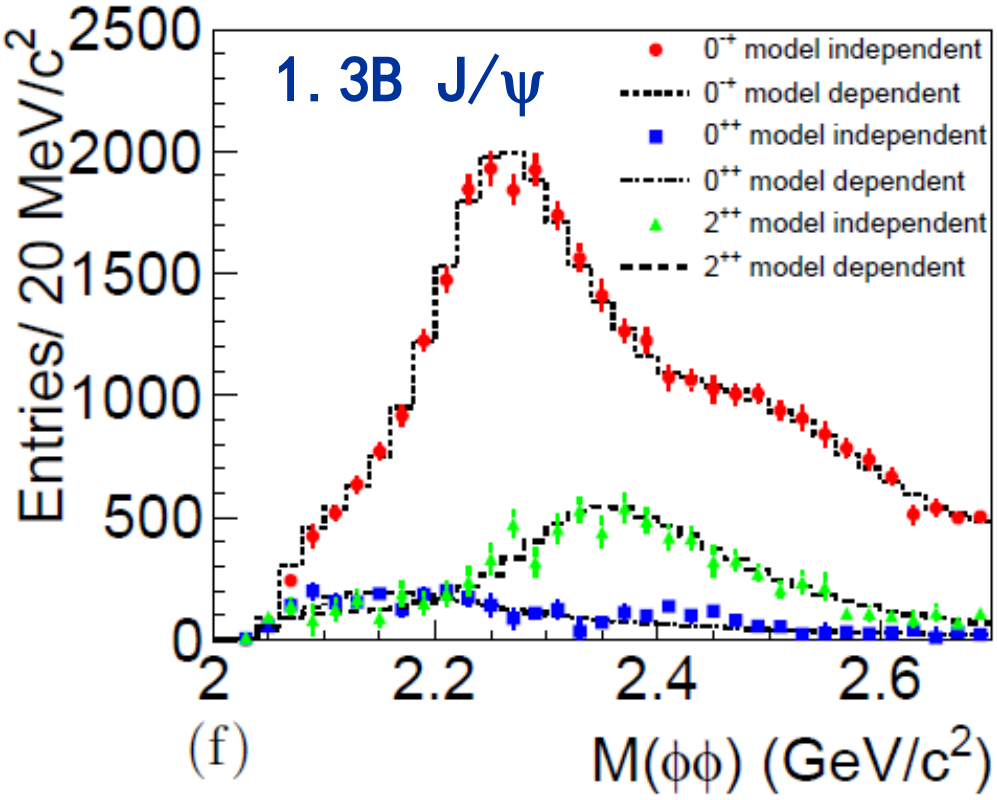
Phys. Rev. D 92, 052003 (2015



- **Model independent**
- **0^{++}: σ, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ and $f_0(2020)$**
- **2++: dominated by $f_2(1270)$**

PWA of J/ψ→γϕϕ

Phys. Rev. D. 93, 112011 (2016)



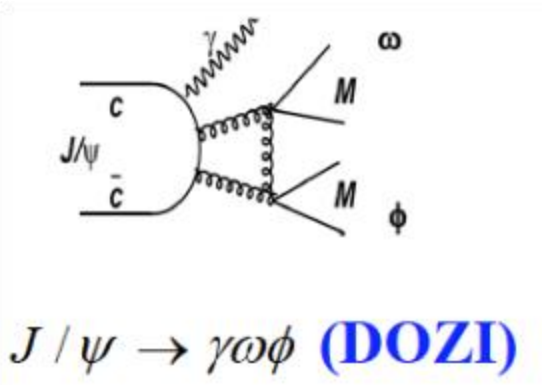
Resonance	M(MeV/c^2)	Γ(MeV/c^2)
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}
$f_0(2100)$	2101	224
$f_2(2010)$	2011	202
$f_2(2300)$	2297	149
$f_2(2340)$	2339	319
0^{-+} PHSP		

- Dominant contribution from pseudoscalars
  - η(2225) is confirmed;
  - η(2100) and X(2500) are observed

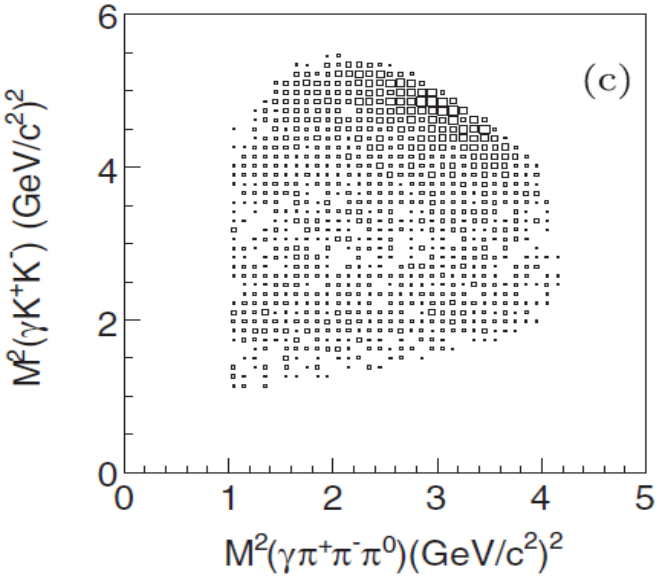
- The three tensors $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in p^-p reactions are also observed

PWA of J/ψ→γωϕ

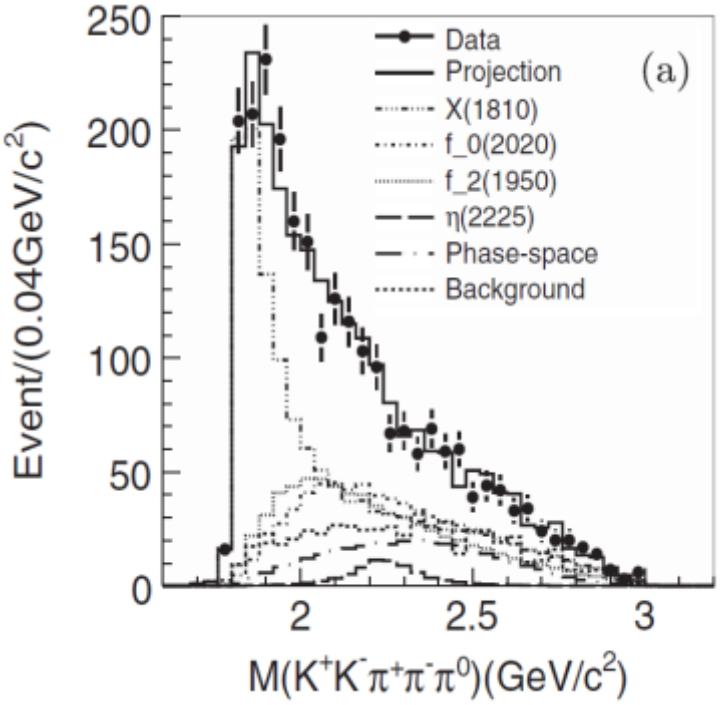
225M J/ψ



$J/\psi \to \gamma\omega\phi$ (DOZI)

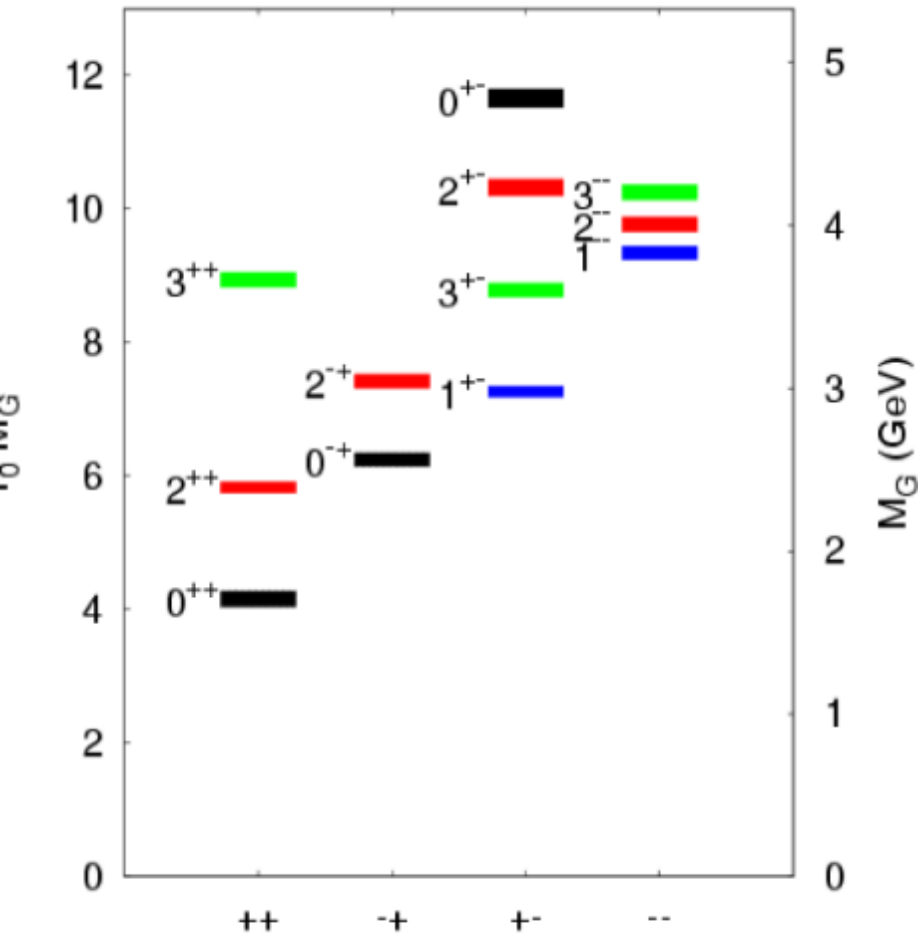


PRD 87, 032008(2013)



- Confirmed the enhancement observed at BESII
- M= $1795 \pm 7^{+13}_{-5} \pm 19$(model) MeV/c2,
  Γ =$95 \pm 10^{+21}_{-34} \pm 75$(model) MeV
- Spin-parity is determined to be 0^+
- the same as $f_0(1710)/f_0(1790)$, or a new state ?

Where is the glueball?



Phys. Rev. D 73, 014516

At BESIII

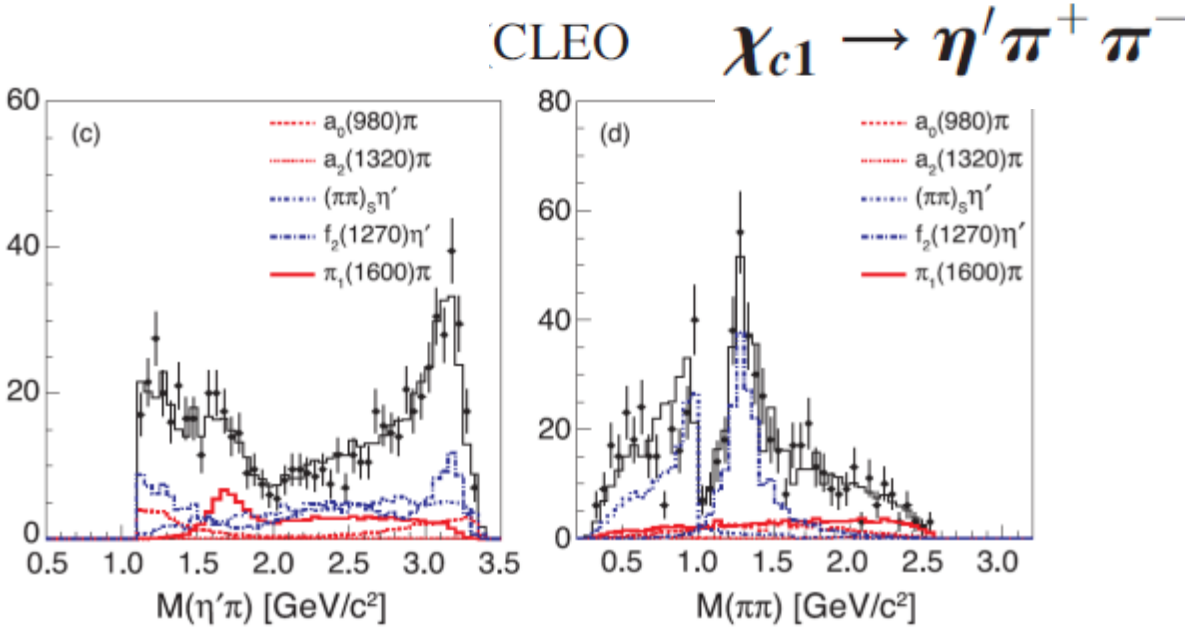
- **$f_0(1710)$ and $f_0(2100)$ are observed in $J/\psi \to \gamma\,\eta\eta, \gamma\pi^0\pi^0$**
- **$f_2(2340)$ is observed in $J/\psi \to \gamma\eta\eta/\phi\phi$ /$\pi^0\pi^0$**
- **X(2120) and X(2370) in of $J/\psi \to \gamma\pi^+\pi^-\eta'$**
- **Systematic studies needed**
  - $J/\psi \to \gamma\eta\eta'$
  - $J/\psi \to \gamma\eta'\eta'$
  - $J/\psi \to \gamma K_S K_S$
  - $J/\psi \to \phi X, \omega X$

Low lying glueballs have ordinary quantum number→mixing with $q\,\bar{q}$ mesons

Exotics ($J^{PC}=0^{--},0^{+-},1^{-+},2^{+-},3^{-+},\ldots$)

- J^{PC} exotic particles: beyond the naive quark model
- easily to distinguish from others due to the exotic J^{PC}
- production rate and dynamics are not well understood

- candidates?
  - $\pi_1(1400)$
  - $\pi_1(1600)$

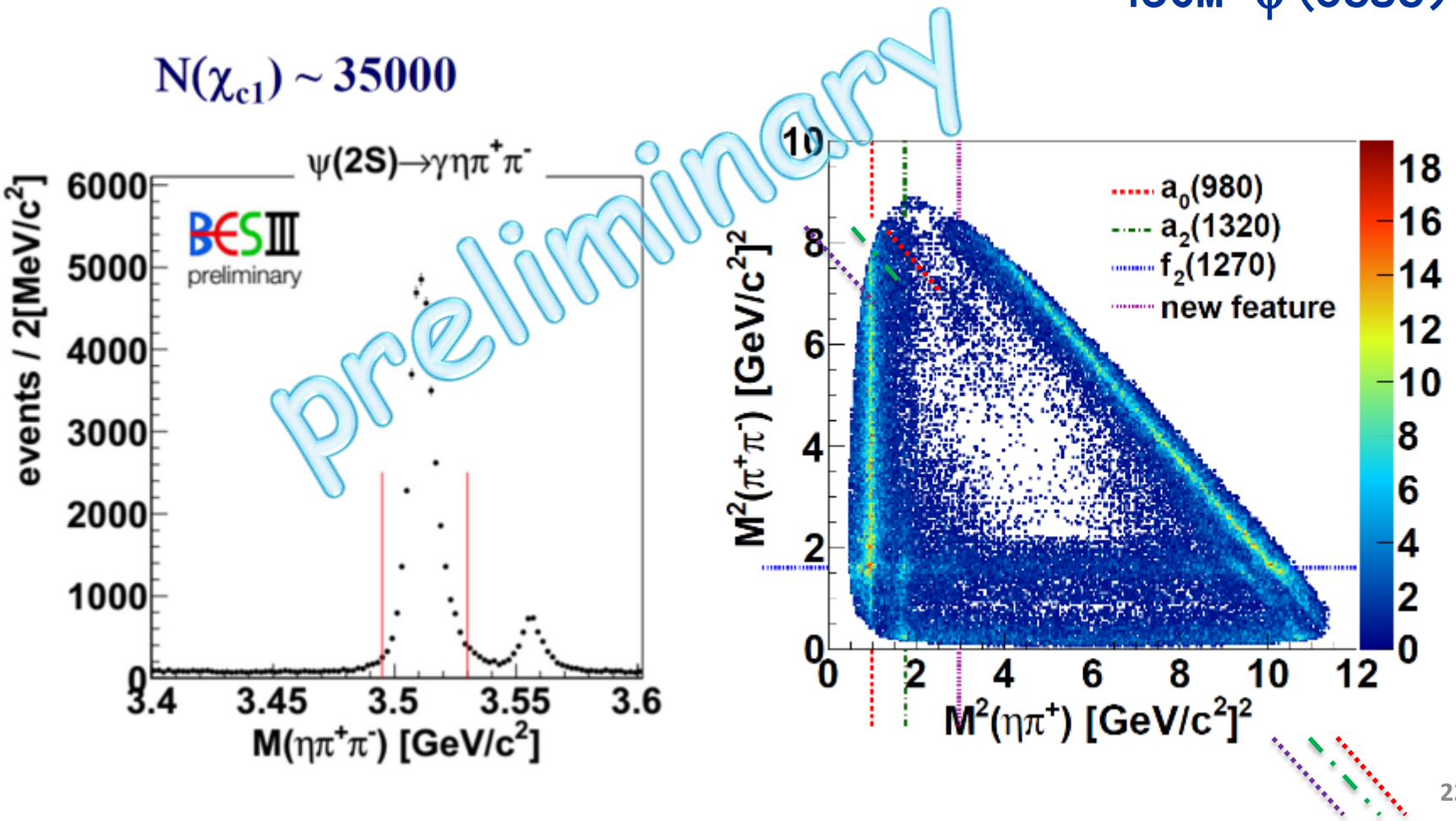


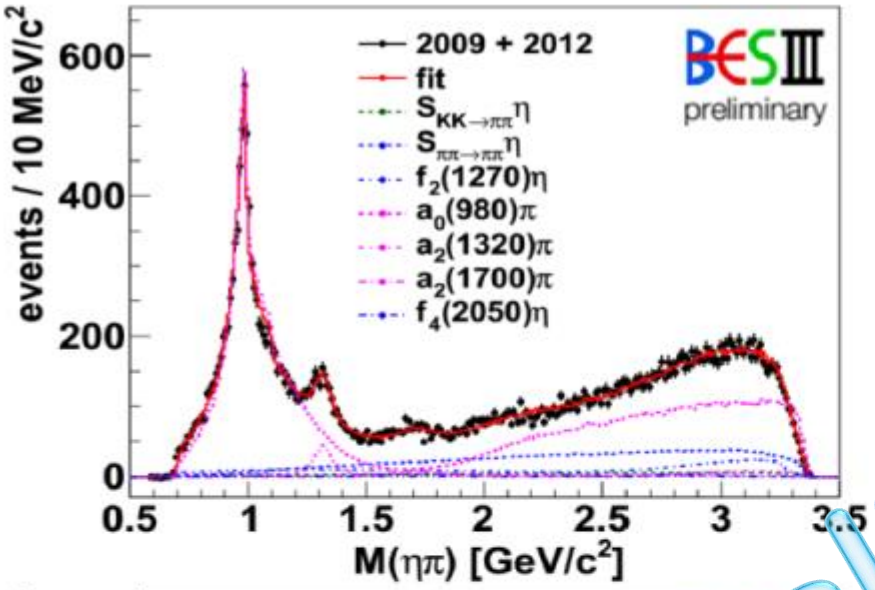
PRD84 (2011) 112009

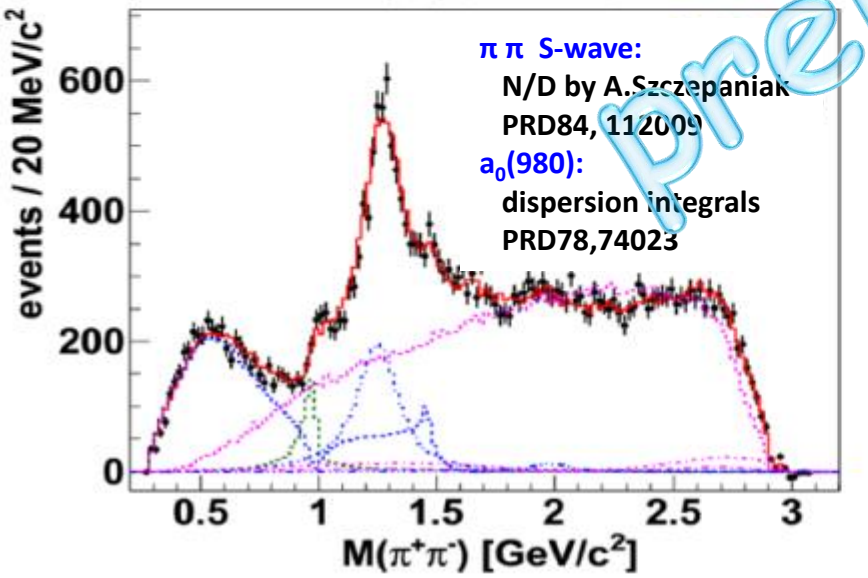
Evidence of an exotic η′π amplitude [$\pi_1(1600)$?] was seen

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

450M ψ(3686)







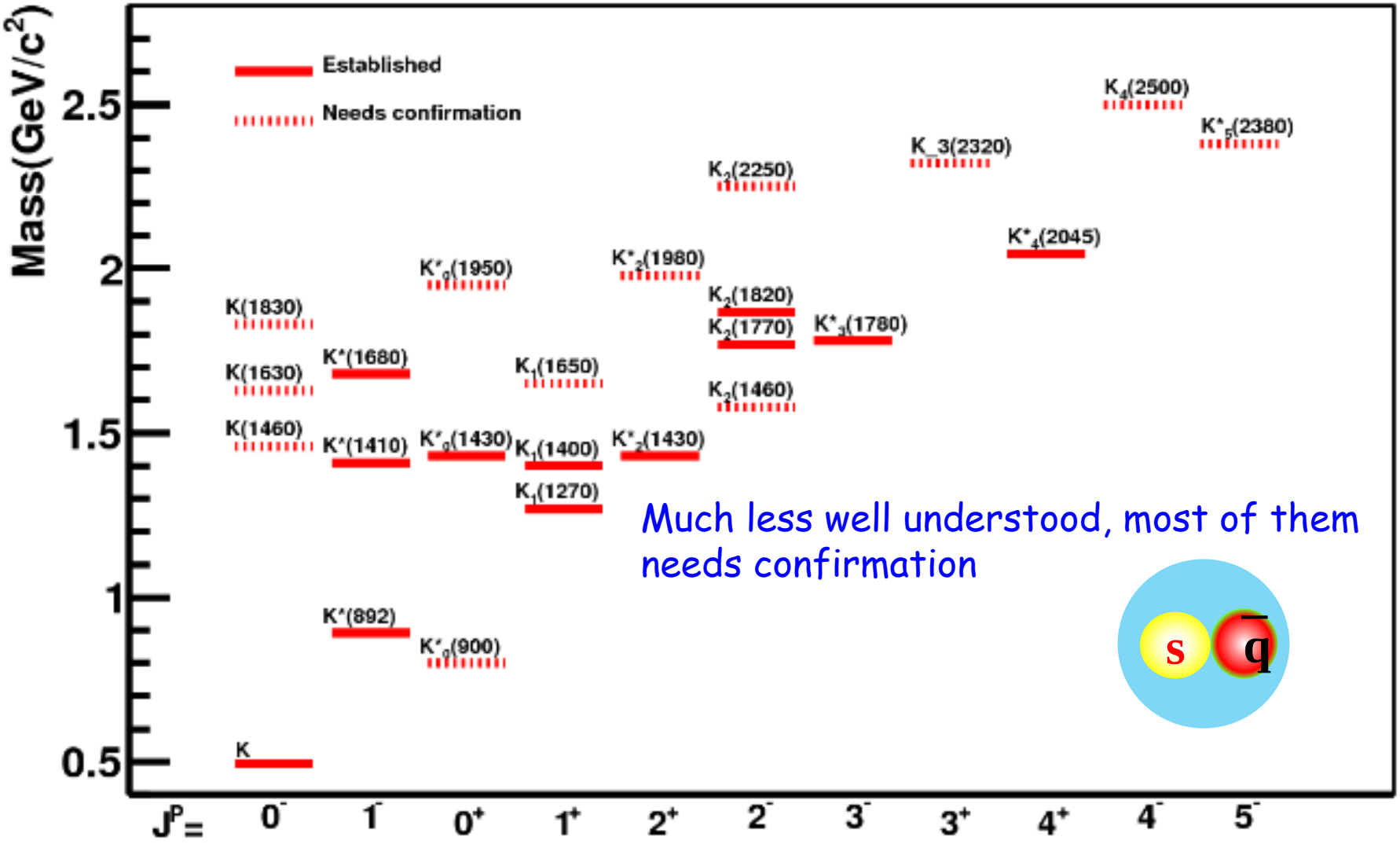
Decay mode	$\mathcal{B}(\chi_{c1} \to \eta\pi^+\pi^-) \times 10^{-3}$
$\eta\pi^+\pi^-$	$4.819 \pm 0.031 \pm 0.088 \pm 0.210$
$a_0(980)^\pm\pi^\mp$	$3.506 \pm 0.034 \pm 0.182 \pm 0.153$
$a_2(1320)^\pm\pi^\mp$	$0.185 \pm 0.009 \pm 0.038 \pm 0.008$
$a_2(1700)^\pm\pi^\mp$	$0.048 \pm 0.005 \pm 0.014 \pm 0.002$
$S_{kk}\eta$	$0.123 \pm 0.007 \pm 0.018 \pm 0.005$
$S_{\pi\pi}\eta$	$0.791 \pm 0.019 \pm 0.037 \pm 0.035$
$\pi\pi_S\eta$	$0.859 \pm 0.021 \pm 0.031 \pm 0.037$
$f_2(1270)\eta$	$0.371 \pm 0.012 \pm 0.054 \pm 0.016$
$f_4(2050)\eta$	$0.027 \pm 0.004 \pm 0.009 \pm 0.001$
BESIII Preliminary	U.L. [90% c.l.]
$\pi_1(1400)^\pm\pi^\mp$	0.028 ± 0.010 < 0.048
$\pi_1(1600)^\pm\pi^\mp$	0.005 ± 0.005 < 0.016
$\pi_1(2015)^\pm\pi^\mp$	0.003 ± 0.002 < 0.008

Errors: stat. ± syst. ± extern.

- Clear evidence for $a_2(1700)$ in χ_{c1} decays.
- First measurement of $g'_{\eta'\pi} \neq 0$ using $a_0(980) \to \eta\pi$ line shape.
- Upper limits for $\pi_1(1^{-+})$ in 1.4 - 2.0 GeV/c² region.

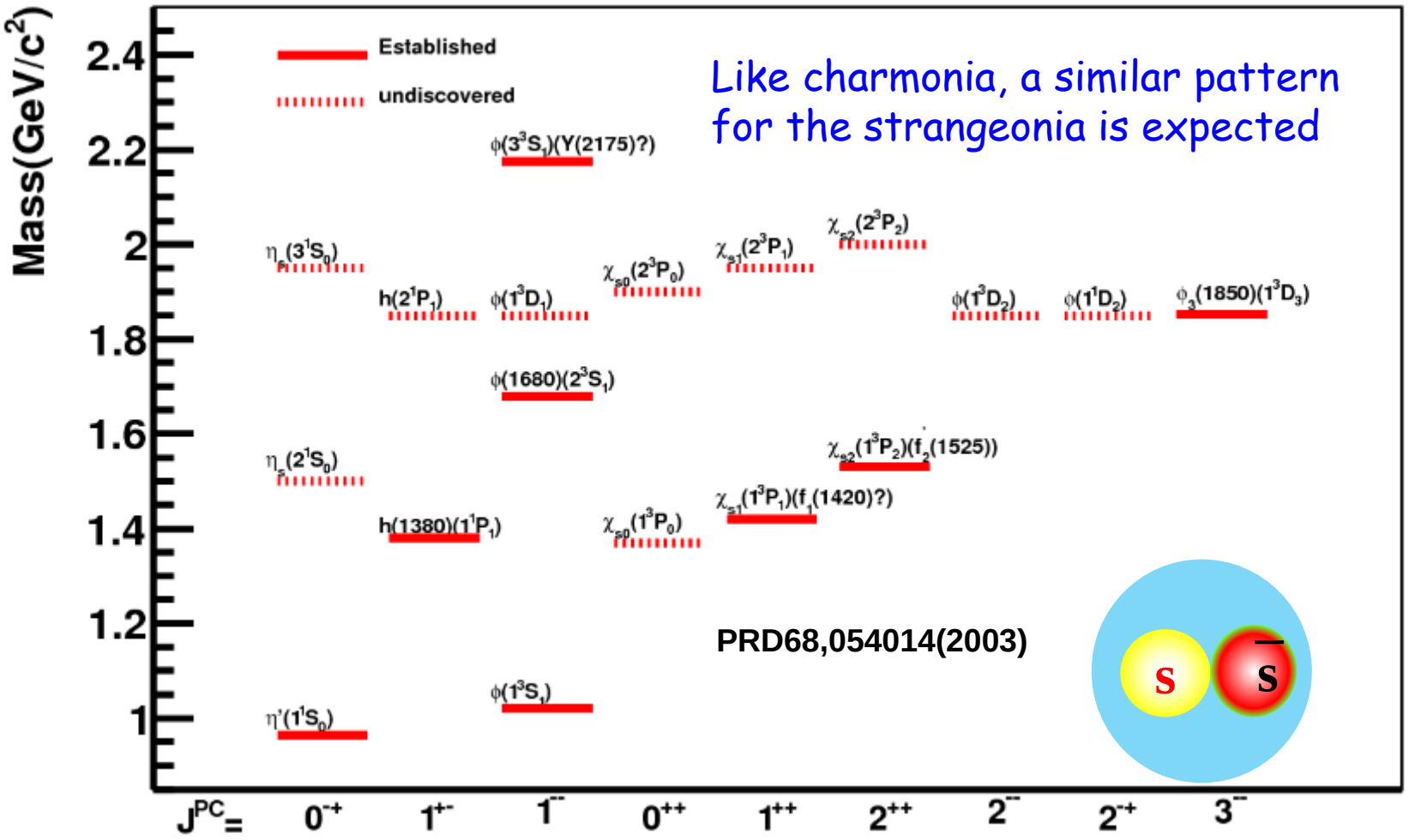
Kaonia/strangeonia spectrum

Kaonia spectrum



Much less well understood, most of them needs confirmation

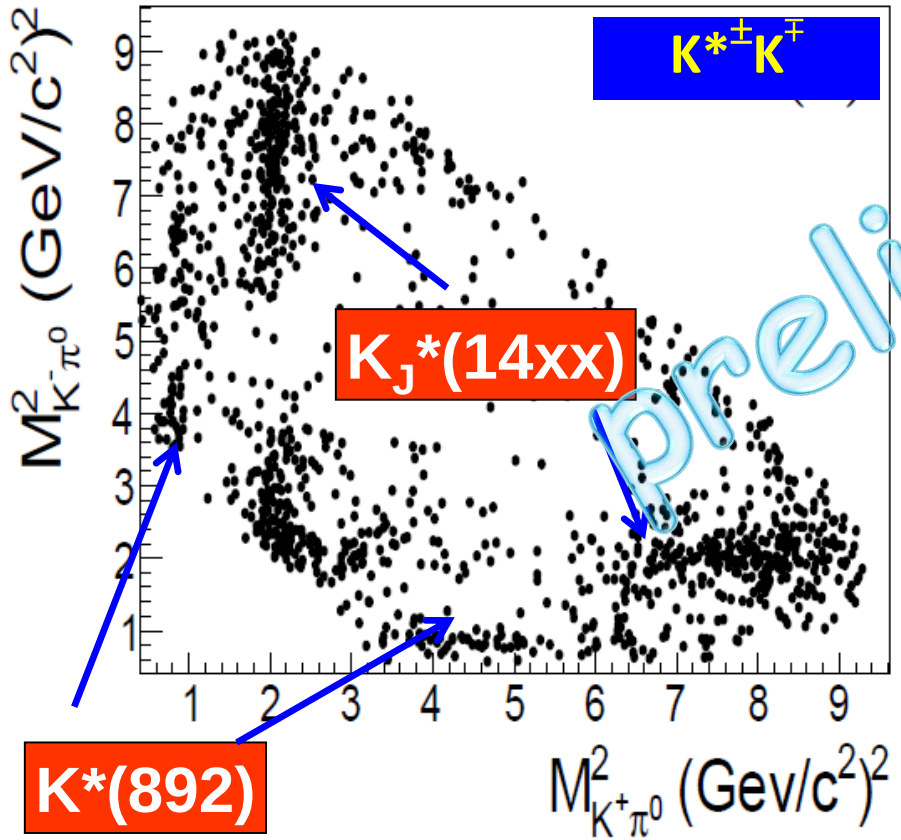
Strangeonia spectrum

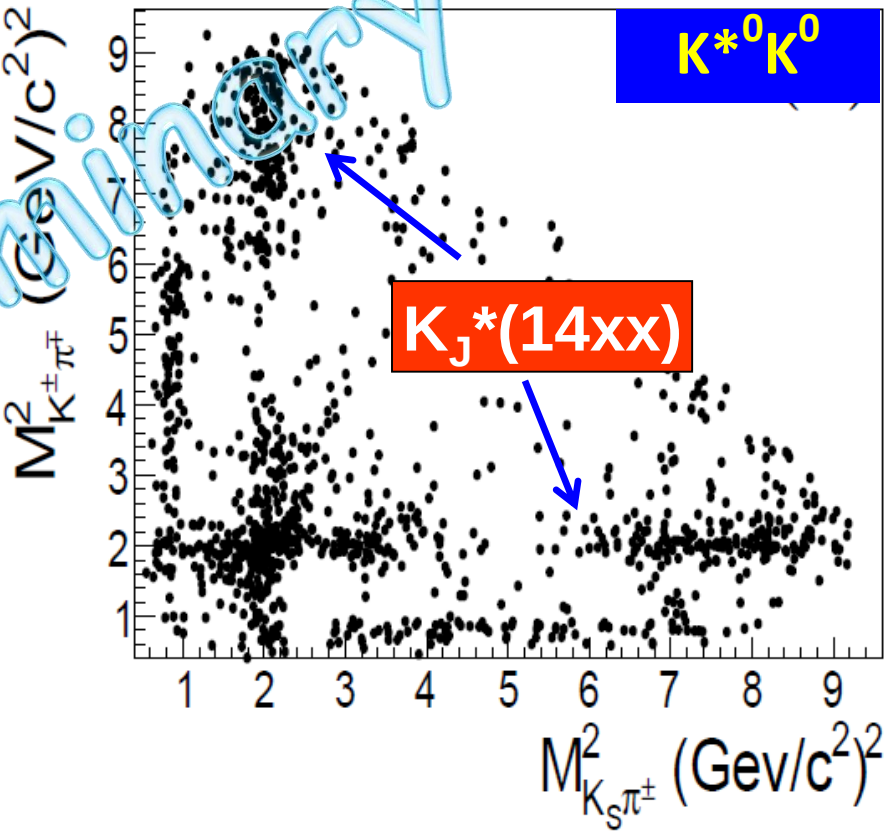


Like charmonia, a similar pattern for the strangeonia is expected

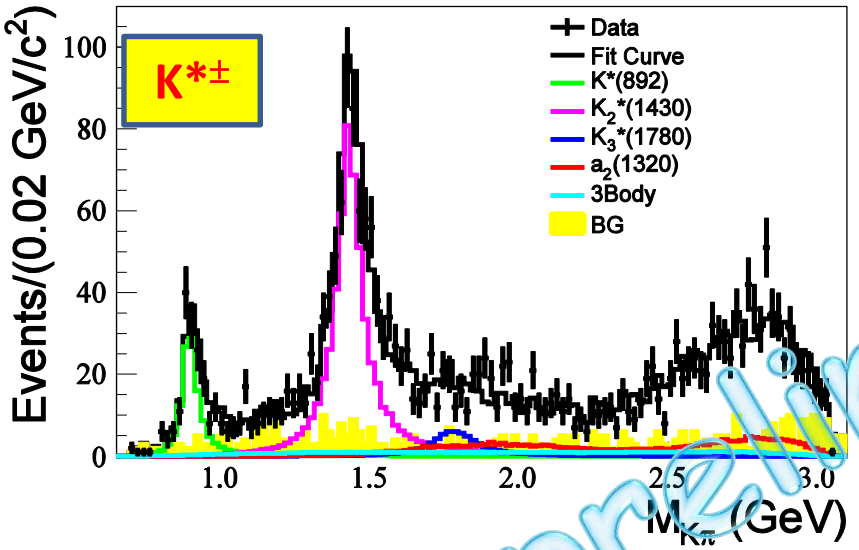
Much less well understood, most of them have not been observed yet

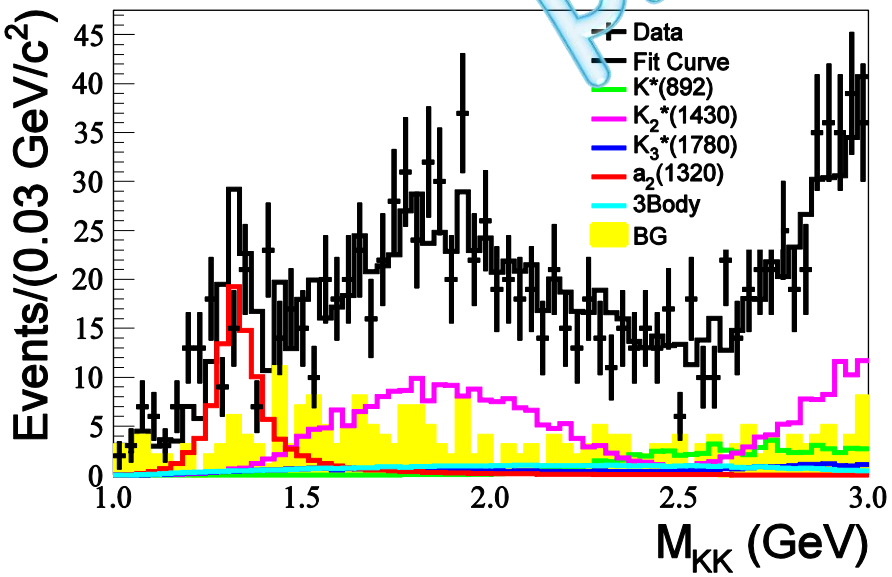
$\chi_{c1} \to K\ \bar{K}\pi$



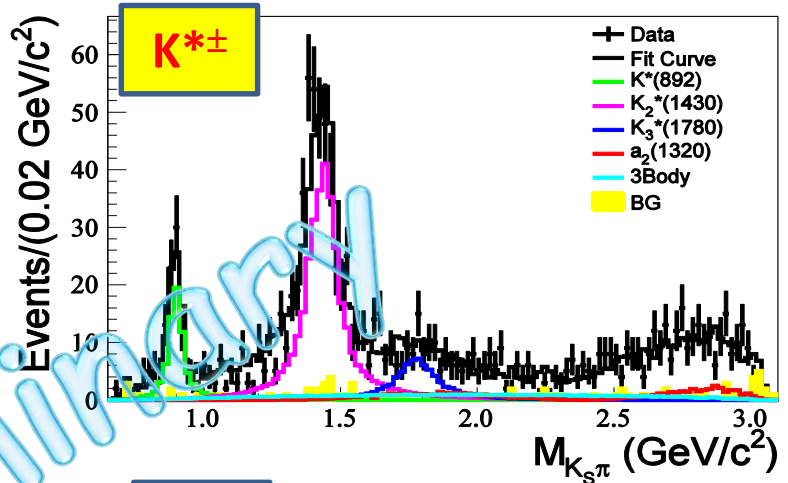


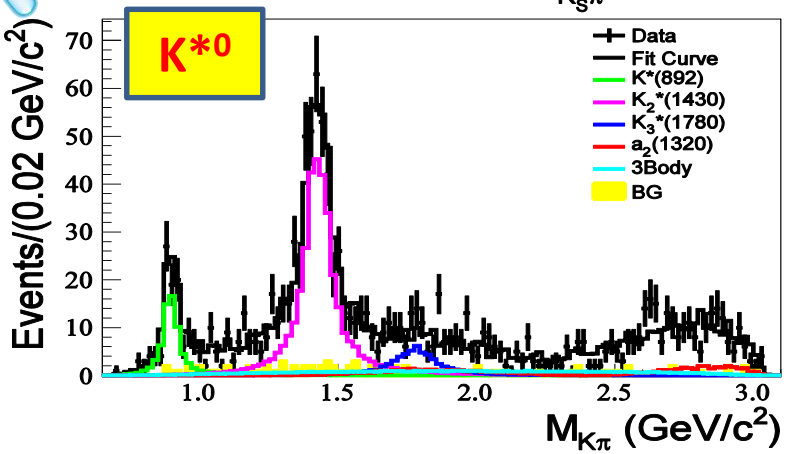
$\chi_{c2} \to K^+K^-\pi^0$

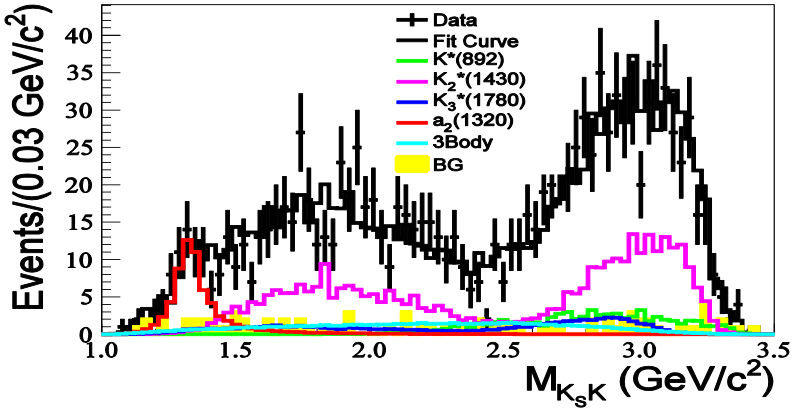




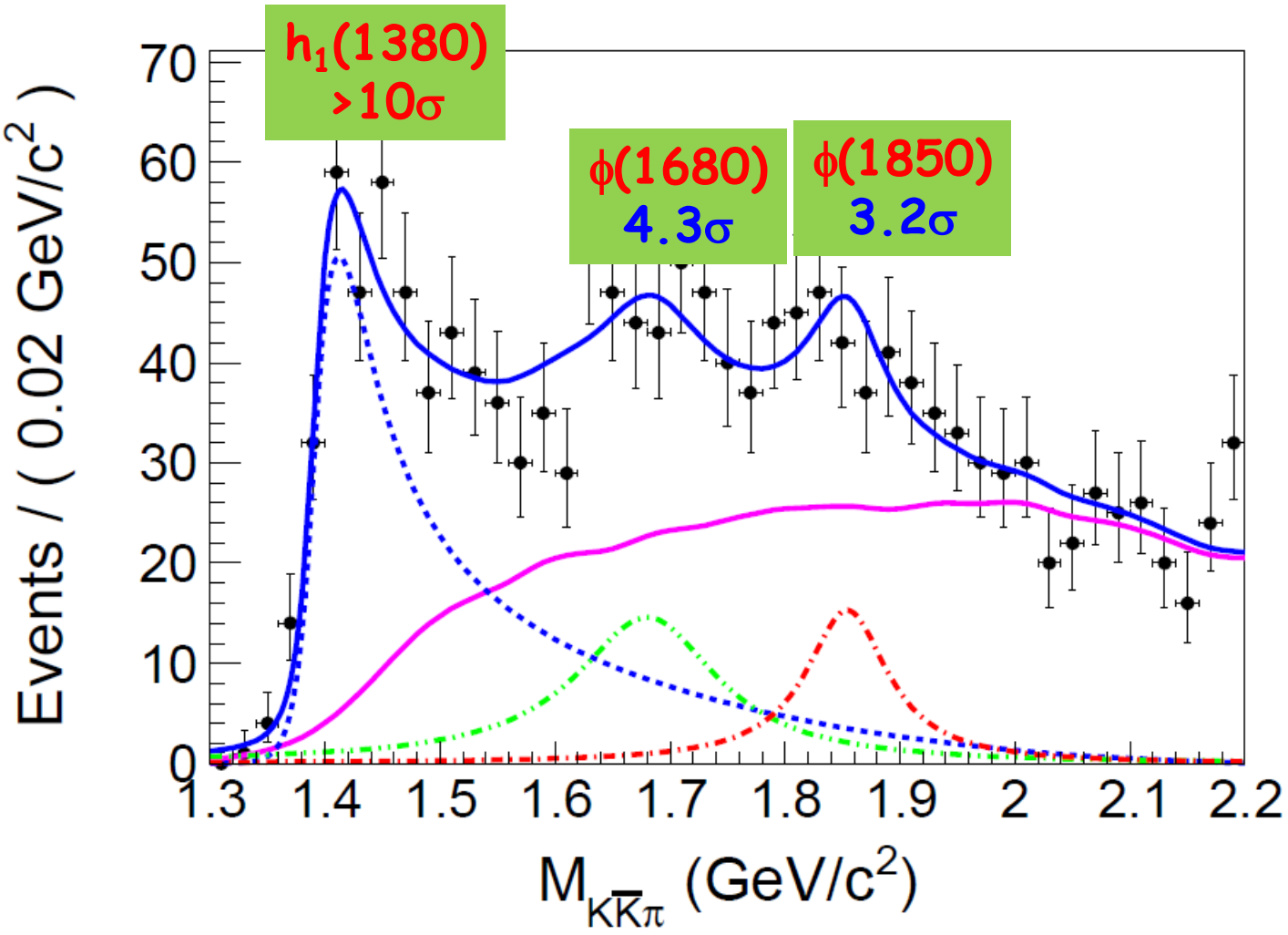
$\chi_{c2} \to K_S K^{\pm}\pi^{\mp}$







$\chi_{c1} \to \phi K \bar{K}\pi$ 106M $\psi(3686)$



M=1412±4±8 MeV/c²
Γ = 84±12±40MeV

PRD 91, 112008(20155)

Y(2175)/φ(2170) in J/ψ→ηφπ⁺π⁻

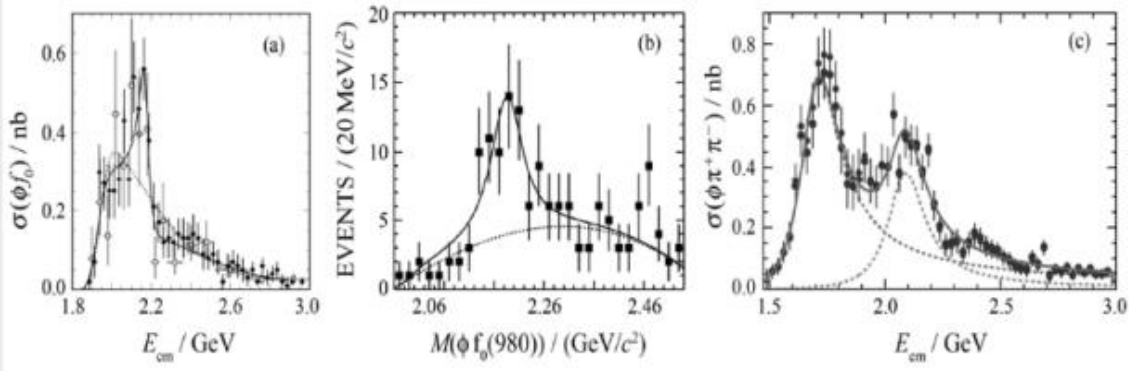
BESIII, PRD91,052017(2015)

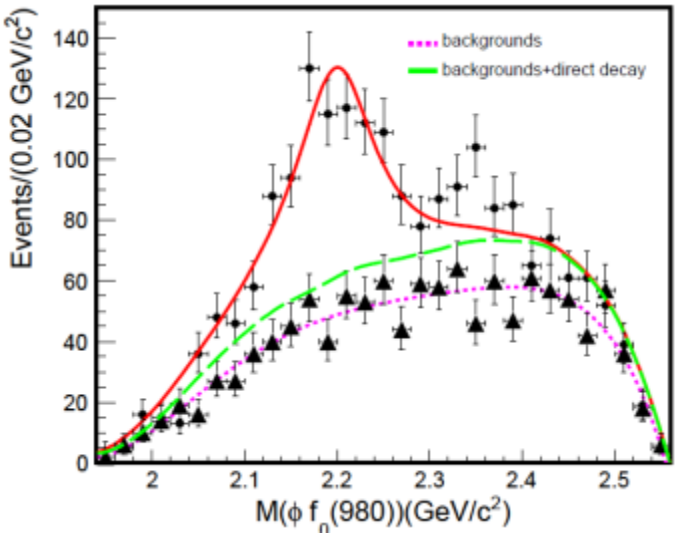
- a new φ-like state: Y(2175)
  first observed by Babar
  confirmed by Belle and BESII

Phys Rev, D74 : 091103(2006)

Phys Rev, 2009, D80 : 031101.

Phys. Rev Let t ,100:102003(2008)





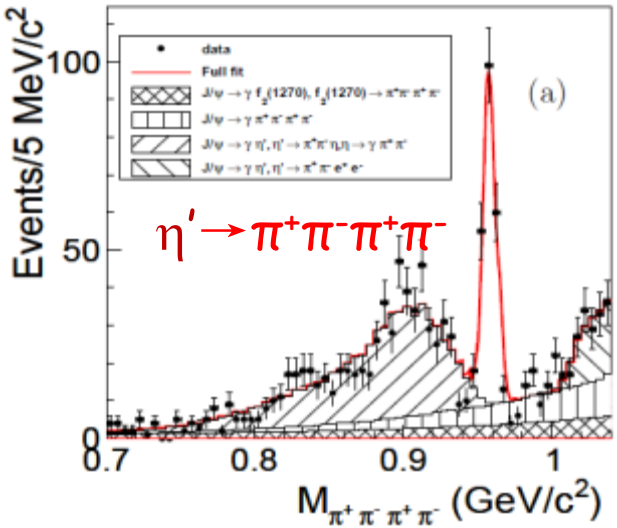
Collaboration	Process	M (MeV/c^2)	Γ (MeV)
BABAR	$e^+e^- \to \phi f_0 \quad (ISR)$	$2175 \pm 10 \pm 15$	$58 \pm 16 \pm 20$
BESII	$J/\psi \to \eta\phi f_0(980)$	$2186 \pm 10 \pm 6$	$65 \pm 23 \pm 17$
BELLE	$e^+e^- \to \phi f_0 \quad (ISR)$	$2079 \pm 13^{+79}_{-28}$	$192 \pm 23^{+25}_{-61}$
BABAR(updated)	$e^+e^- \to \phi f_0 \quad (ISR)$	$2172 \pm 10 \pm 8$	$96 \pm 19 \pm 12$
BESIII	$J/\psi \to \eta\phi f_0(980)$	$2200 \pm 6 \pm 5$	$104 \pm 15 \pm 15$

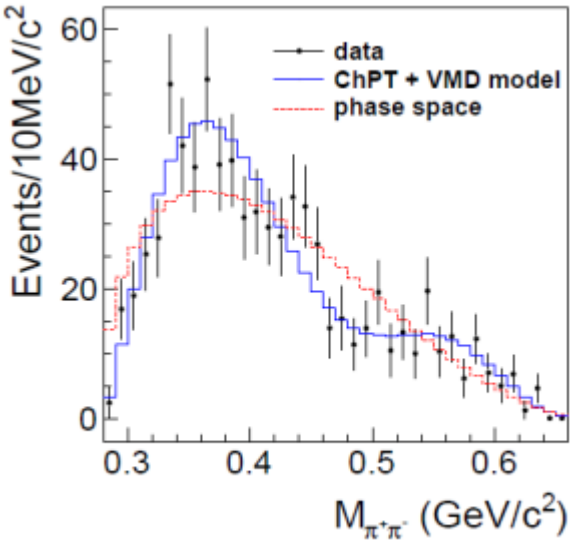
- hybrids or strangeonium ?

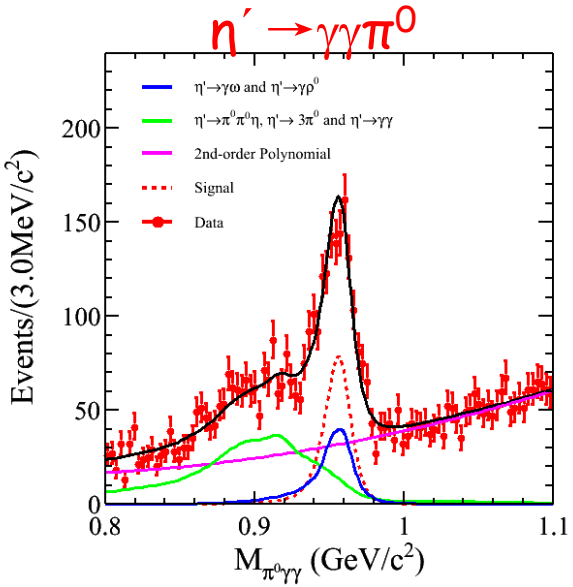
Light meson decays

η′ physics

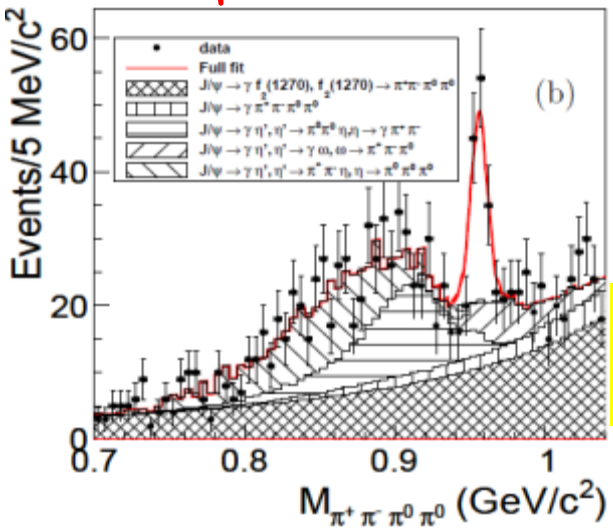
PRL112,251801(2014)







η′→π⁺π⁻π⁰π⁰



$B(\eta'\to\pi^+\pi^-\pi^+\pi^-)=(8.63\pm0.69\pm0.64)\times10^{-5}$
$B(\eta'\to\pi^+\pi^-\pi^0\pi^0)=(1.82\pm0.35\pm0.18)\times10^{-4}$

$B(\eta'\to\pi^+\pi^-\pi^+\pi^-)=(1.0\pm0.3)\times10^{-4}$
$B(\eta'\to\pi^+\pi^-\pi^0\pi^0)=(2.4\pm0.7)\times10^{-4}$

ChPT+VMD

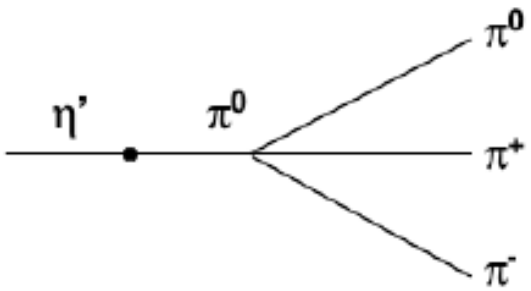
Phys. Rev. D 85,014014 (2012)

$B(\eta'\to\gamma\gamma\pi^0)=[6.91\pm0.51\pm0.54\pm0.20(PDG)]\times10^{-4}$
(preliminary)

$B(\eta'\to\gamma\gamma\pi^0)$: ~$6\times10^{-4}$

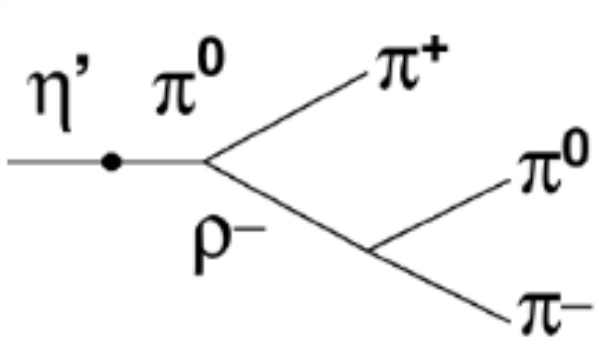
Nucl. Phys. Proc. Suppl. 207-208, 224 (2010)
R. Escribano, PoS QNP 2012, 079 (2012)

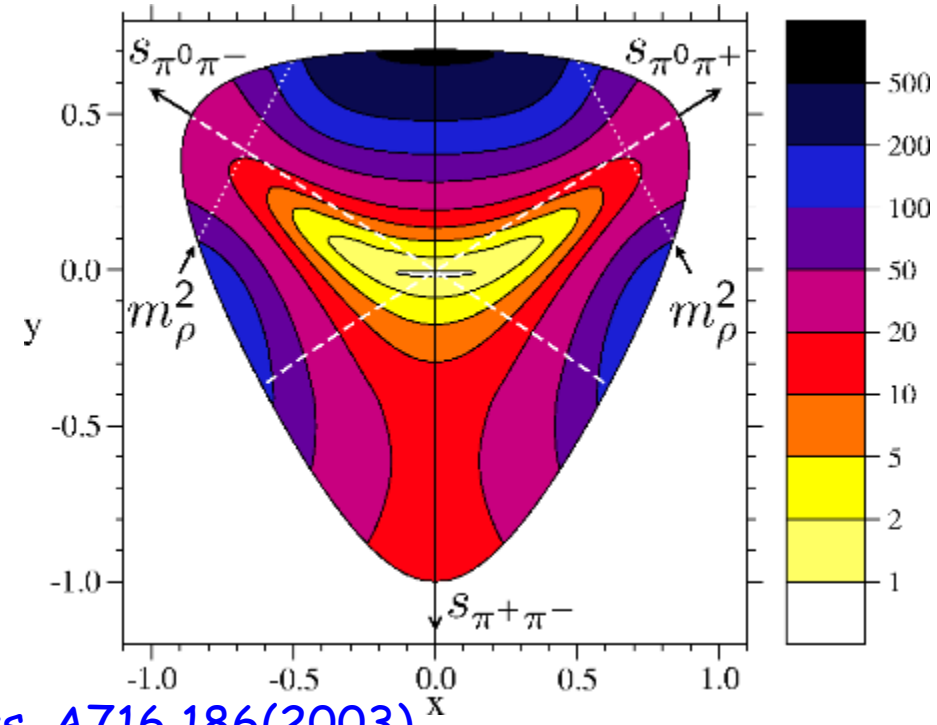
Observation of $\eta' \to \rho^+\pi^- + c.c.$



D. Gross et al., PRD19,2188(1979)

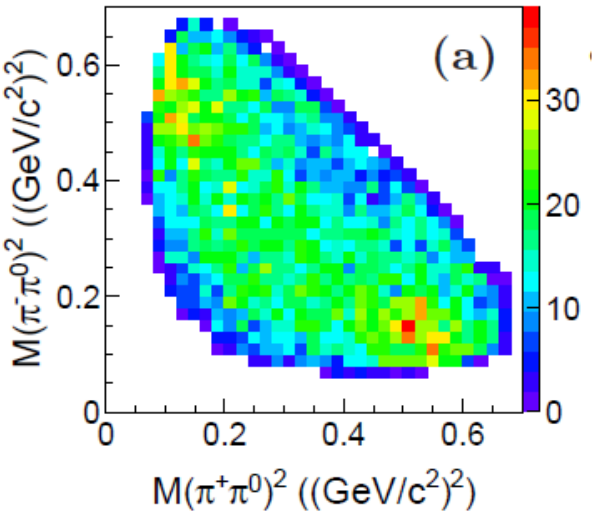
$$r = \frac{\Gamma_{\eta' \to \pi^+\pi^-\pi^0}}{\Gamma_{\eta' \to \eta\pi^+\pi^-}} \approx (16.8)\frac{3}{16}\left(\frac{m_d - m_u}{m_s}\right)^2$$

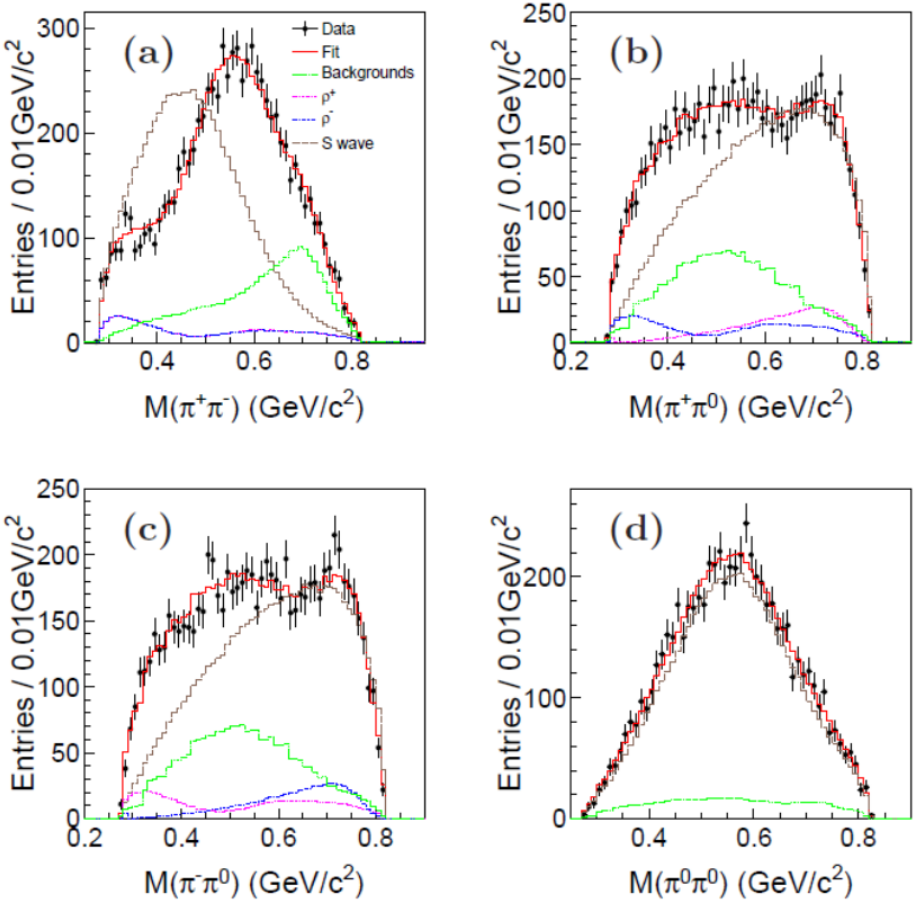




N. Beisert, B. Borasoy, Nucl. Phys. A716,186(2003)

Observation of $\eta' \to \rho^+\pi^- + c.c.$

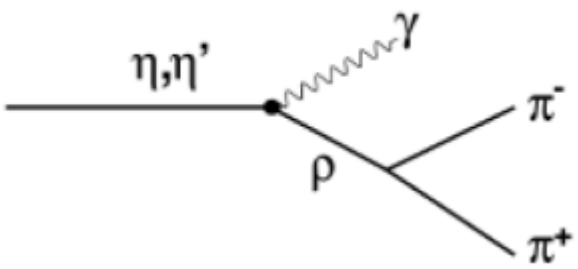


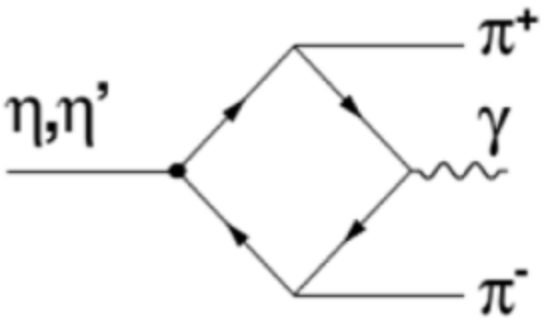


Decay Mode	$\mathcal{B}$ $(\times 10^{-4})$
$\pi^+\pi^-\pi^0$	$35.91 \pm 0.54 \pm 1.74$
$\pi^0\pi^0\pi^0$	$35.22 \pm 0.82 \pm 2.60$
$\rho^+\pi^-$	$3.72 \pm 0.30 \pm 0.63 \pm 0.92$
$\rho^-\pi^+$	$3.72 \pm 0.30 \pm 0.63 \pm 0.92$
$(\pi^+\pi^-\pi^0)_S$	$37.63 \pm 0.77 \pm 2.22 \pm 4.48$

$\eta' \to \gamma\pi^+\pi^-$ decay dynamics

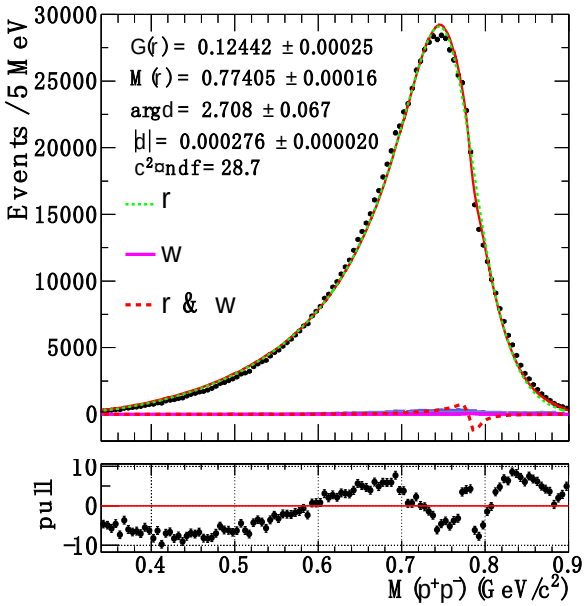
- high term of WZW ChPT$\to$ box anomaly
- studied by many experiments (CB, L3 …)
- no consistent picture due to limited statistics
  - ρ mass shift or not ?
  - box anomaly or not ?



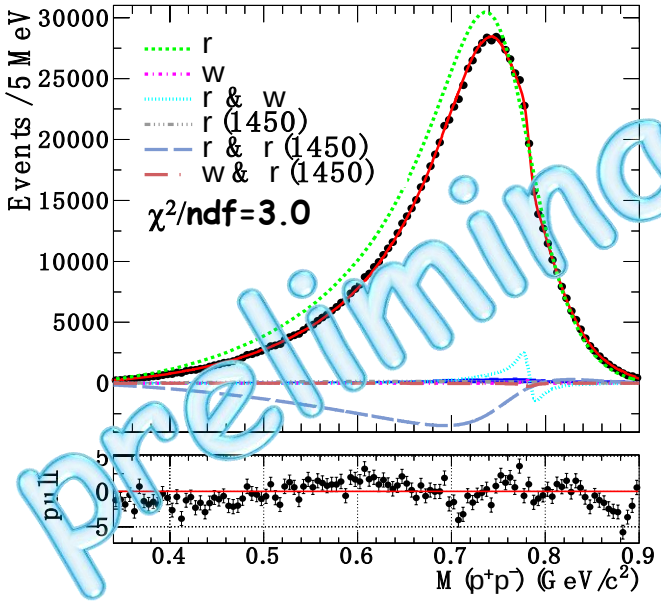


η′→γπ+π- decay dynamics

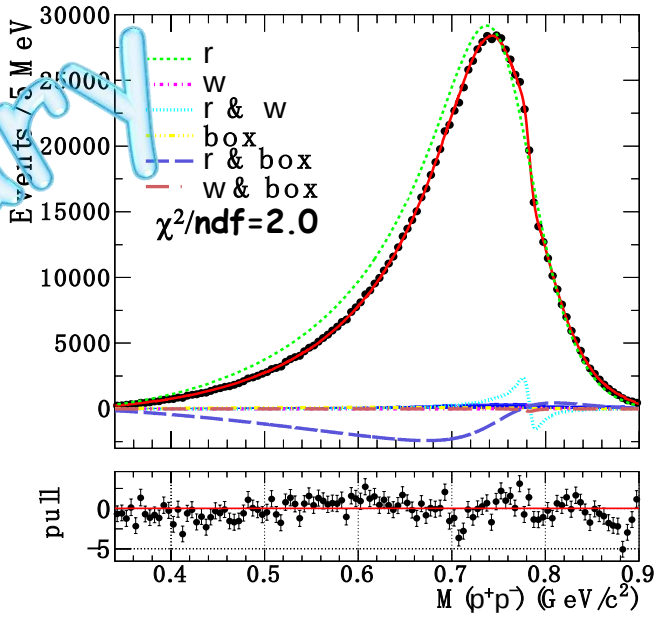
1). fit with ρ(770)-ω



2). fit with ρ(770)-ω-ρ(1450)



3). fit with ρ(770)-ω-box anomaly

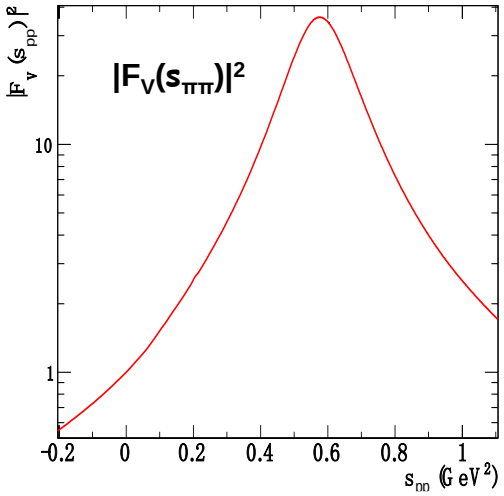


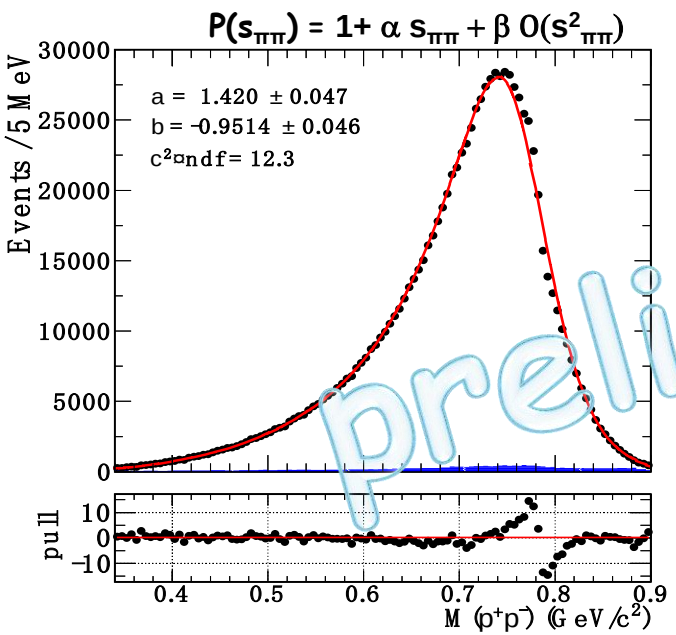
Model-dependent fit

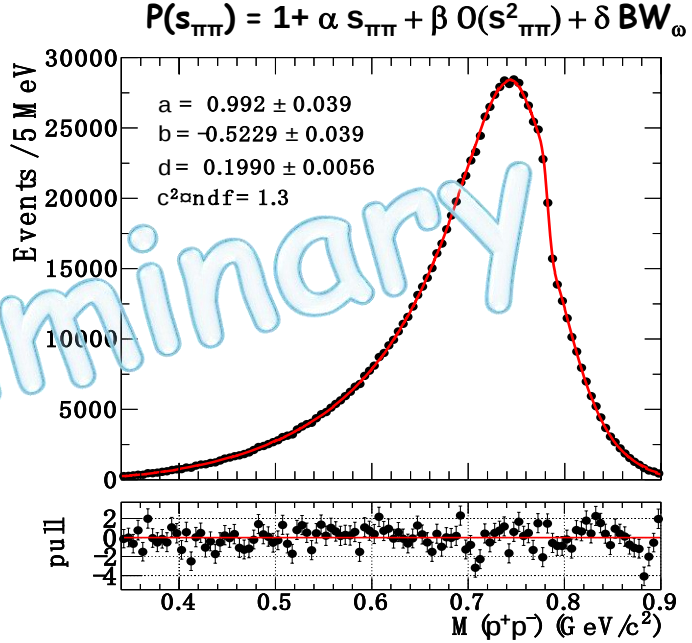
- ✓ Besides ρ(770), the ω is needed
- ✓ ρ(770)-ω cannot describe data well
- ✓ Extra contribution (maybe ρ(1450) or box-anomaly, maybe both of them) is also necessary to provide a good description of data

Model-independent fit

$$\frac{d\Gamma}{ds_{\pi\pi}} = \left|AP(s_{\pi\pi})F_V(s_{\pi\pi})\right|^2 \Gamma_0(s_{\pi\pi})$$







Crystal barrel: $\alpha = (1.80 \pm 0.49 \pm 0.04)\text{GeV}^{-2}$
$\beta = (0.04 \pm 0.36 \pm 0.03)\text{GeV}^{-4}$

GAMS-2000: $\alpha = (2.7 \pm 1.0)\text{GeV}^{-2}$

- ω is necessary
- Linear polynomial is insufficient

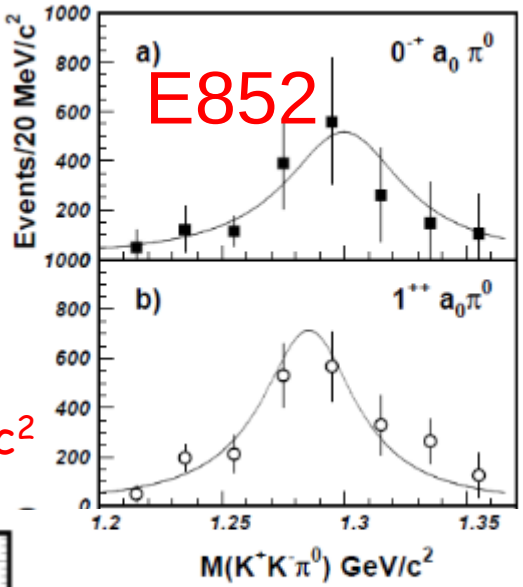
* Physics Letters B 707 (2012) 184-190

η(1295) & $f_1(1285)$

E852, PLB516,264(2001)

- η(1295)
  - only observed in πp interactions
  - Due to interference between $f_1(1285)$ and $\eta(\pi\pi)_{S\text{-wave}}$ E. Klempt Phys. Reports 454,1(2007)

Resonance	M (MeV/c^2)	Γ (MeV/c^2)
$f_1(1285)$	$1288 \pm 4 \pm 5$	$45 \pm 9 \pm 7$
$\eta(1295)$	$1302 \pm 9 \pm 8$	$57 \pm 23 \pm 21$

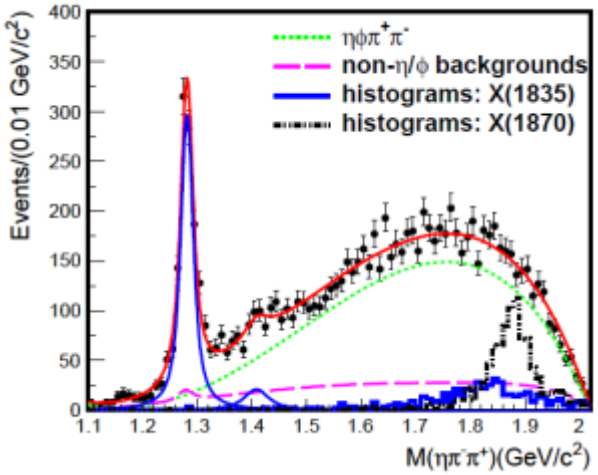


- More decays, e.g.,

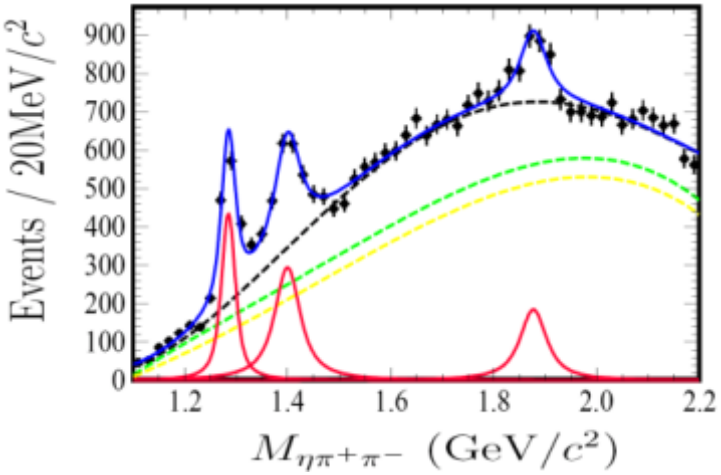
J/ψ→{ρ, γ}X, may shed light on η(1295)

Γ =21.0±1.7 MeV
M=1281.7±0.6 MeV/c²

Γ =22.0±3.1$^{+2.0}_{-1.5}$ MeV
M=1285.1±1.0$^{+1.6}_{-0.3}$ MeV/c²



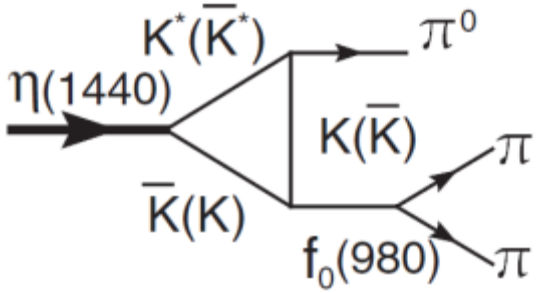
BESIII, PRD91,052017(2015)



BESIII, PRL107,182001(2011)

η(1405) & η(1475)

- η(1440)
  - η(1405)→$a_0\pi$
  - η(1475)→K* $\bar{K}$
- one or two resonances?



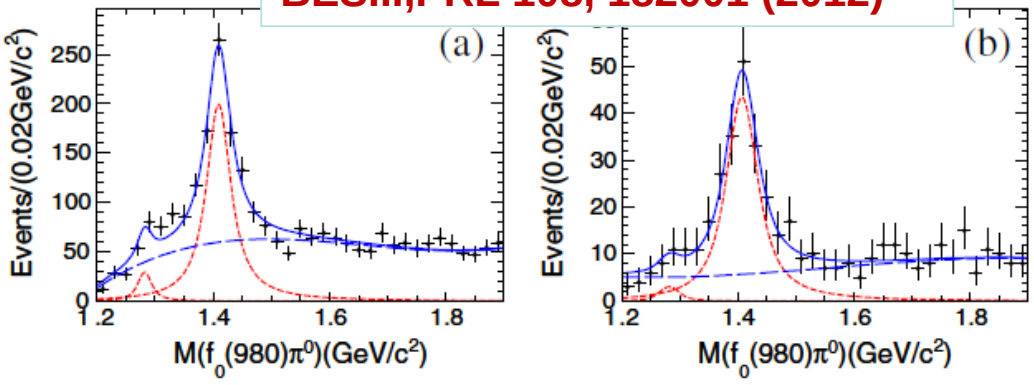
Triangle Singularity (TS)

one η(1440) is enough to describe the experimental data !

J.J.Wu et al, PRL 108, 081803(2012)

First observed: $\eta(1405)\to f_0(980)\pi^0$

BESIII,PRL 108, 182001 (2012)



Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$
$\eta(1405)(\pi^+\pi^-\pi^0)$	1409.0 ± 1.7	48.3 ± 5.2
$\eta(1405)(\pi^0\pi^0\pi^0)$	1407.0 ± 3.5	55.0 ± 11.0

$$\frac{BR(\eta(1405)\to f_0(980)\pi^0)}{BR(\eta(1405)\to a_0(980)\pi)} \approx 25\%$$

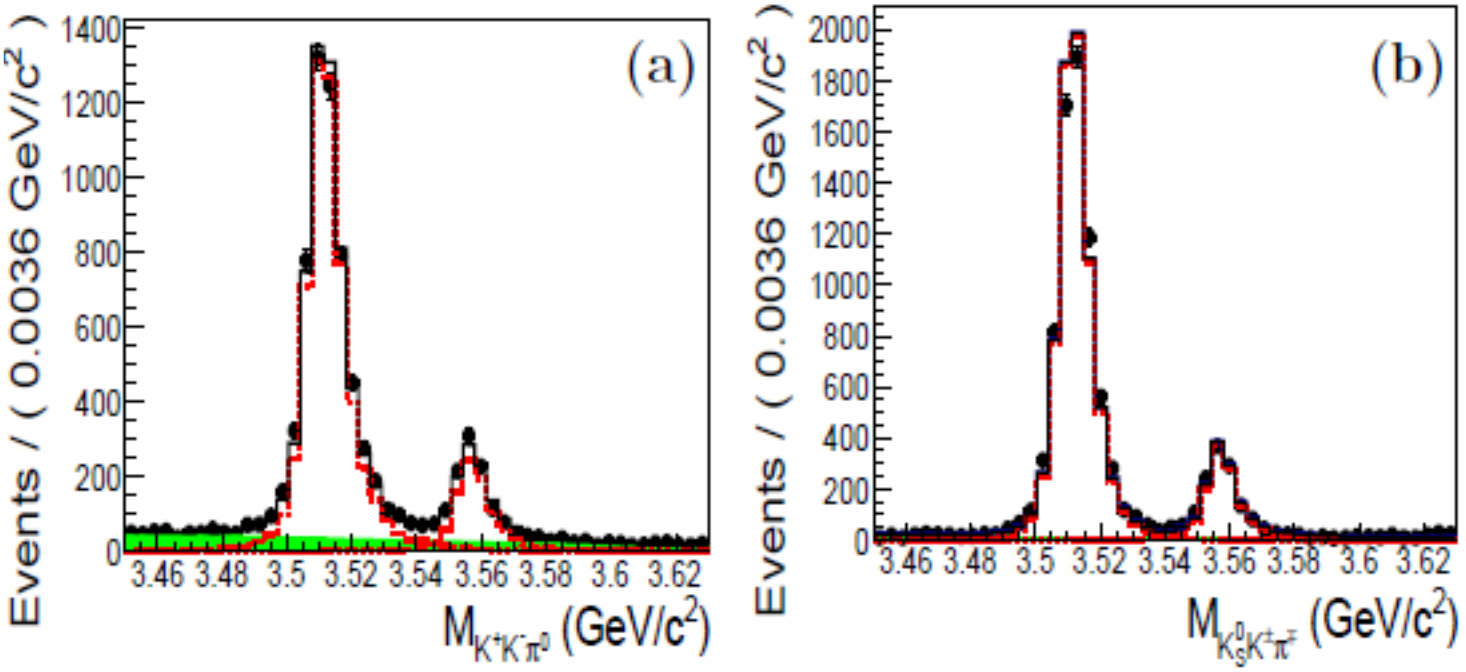
Large isospin breaking!

Summary

- Rich physics in light hadrons
  - meson spectroscopy→ QCD
  - Exotics search→ QCD, Quark model
  - Kaonia/strangeonia spectrum→ QCD, Quark model
  - light meson decays → test of ChPT

  ……
- Mapping out the light hadron spectroscopy is crucial
- 1.3 billion J/Ψ and 0.45 billion Ψ(3686) @ BESIII
- BESIII plays an important role in light hadron physics
- More results are expected to come soon !

Many thanks for your attention !


(a)
Events / (0.0036 GeV/c^2)
1400
1200
1000
800
600
400
200
0
3.46 3.48 3.5 3.52 3.54 3.56 3.58 3.6 3.62
$M_{K^+K^-\pi^0}$ (GeV/c^2)
(b)
Events / (0.0036 GeV/c^2)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
3.46 3.48 3.5 3.52 3.54 3.56 3.58 3.6 3.62
$M_{K^0_S K^\pm \pi^\mp}$ (GeV/c^2)