Light Meson Spectroscopy at BESIII

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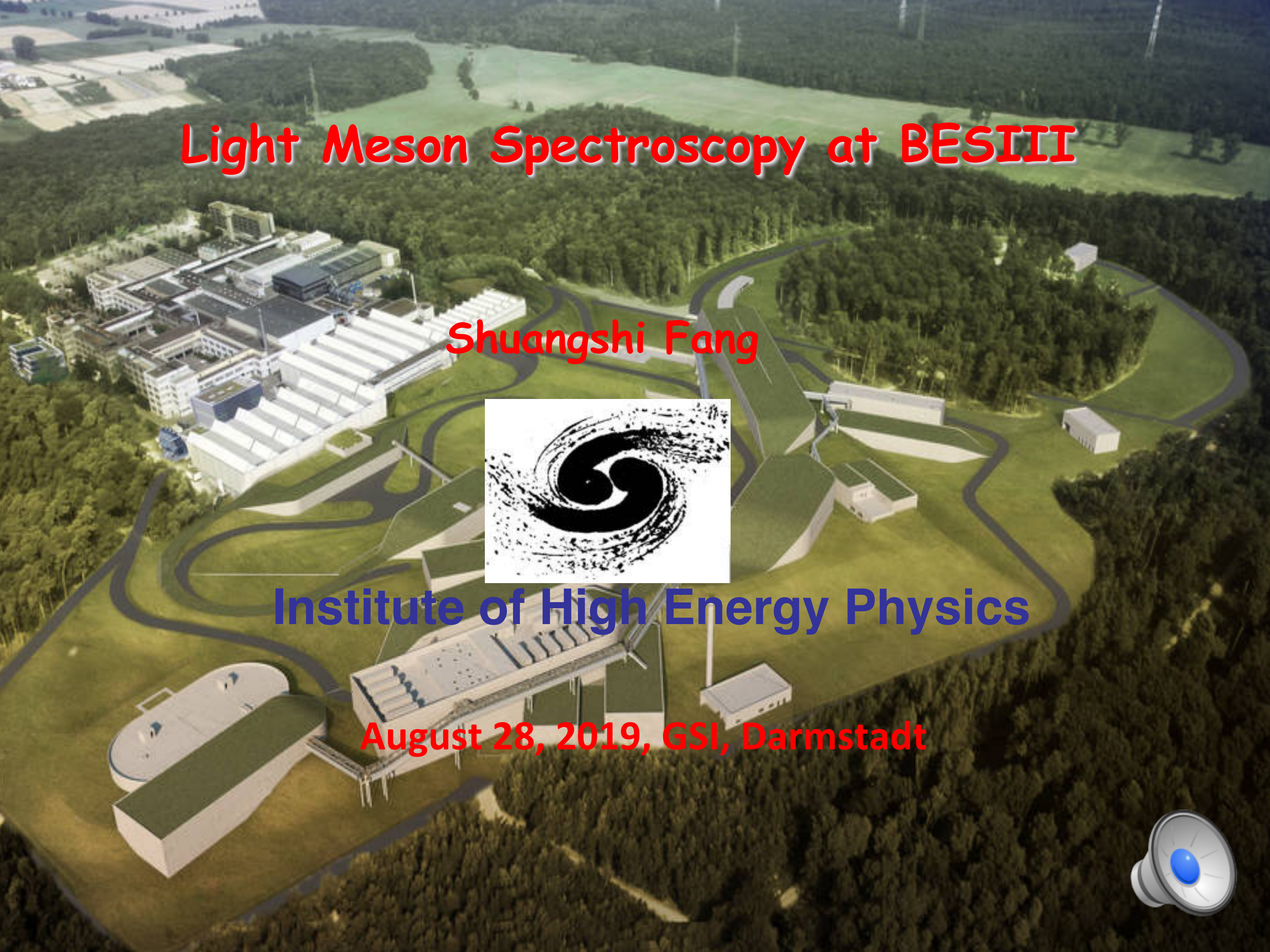
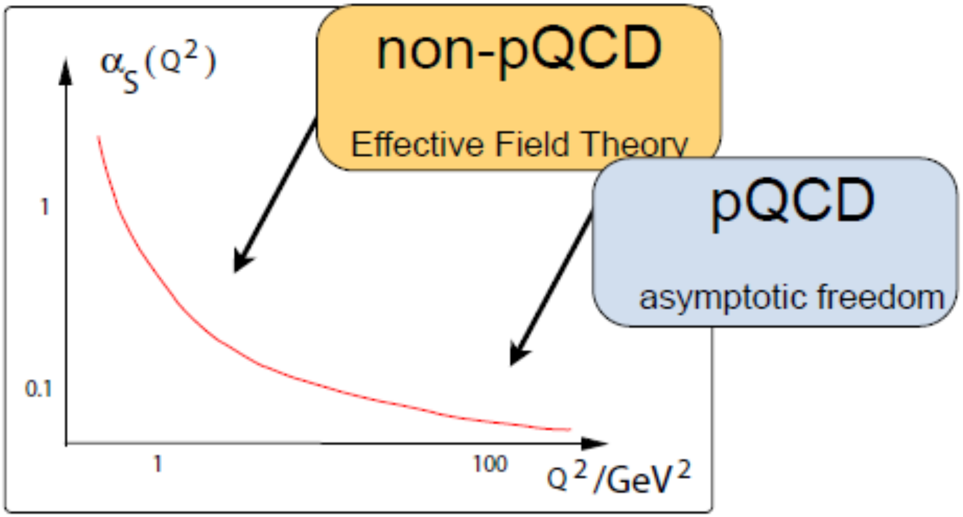


OUTLINE

- Why light hadron physics
- Current status and forefront issues
  - Meson spectroscopy
  - Exotics
  - Light meson decays
- Upgrades on BEPCII
- Summary

Why light hadron physics ?

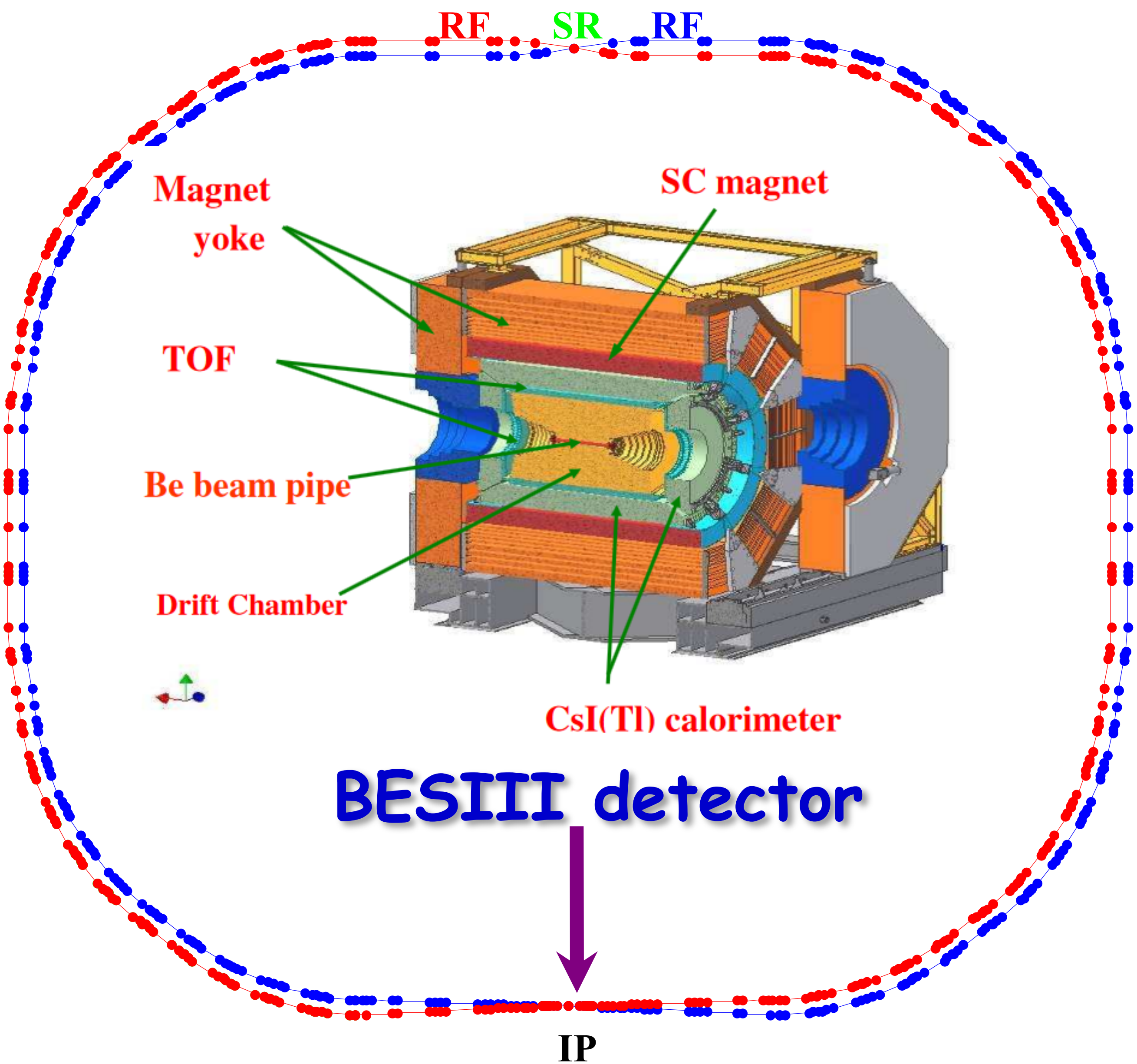


"That [intermediate distance] scale is the richest phenomenologically, and is certainly the crux region to understand...what QCD is really about. And at the heart of the subject is the hadron spectrum, in particular the spectrum built from light quarks. (...) **Without question, there is a great need...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

James D. Bjorken (2000)

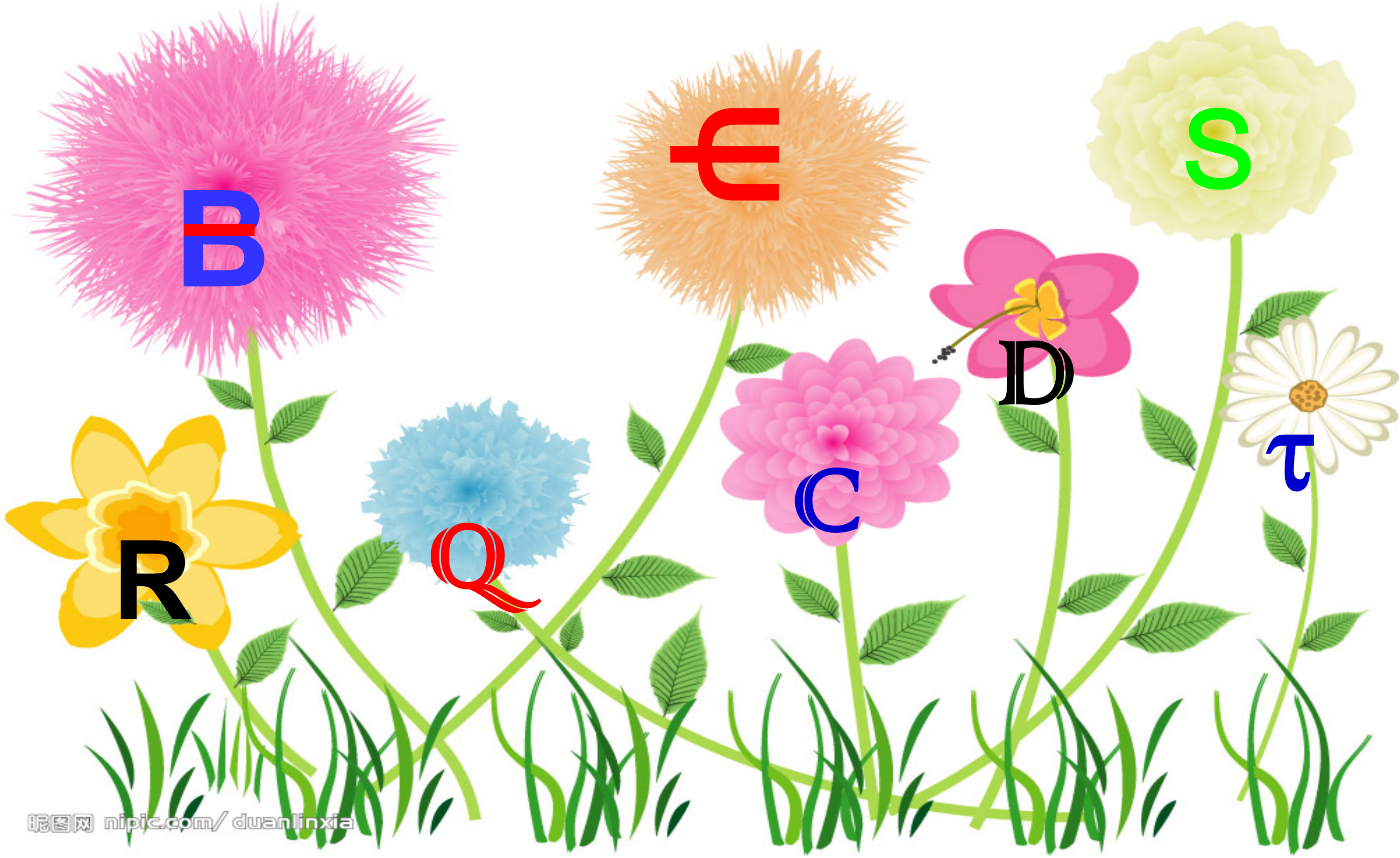
- ✓ QCD degrees of freedom at low energy
- ✓ Understanding of the quark and gluon confinement
- ✓ Particles beyond the QM

BEPC II/BESIII: τ –charm factory

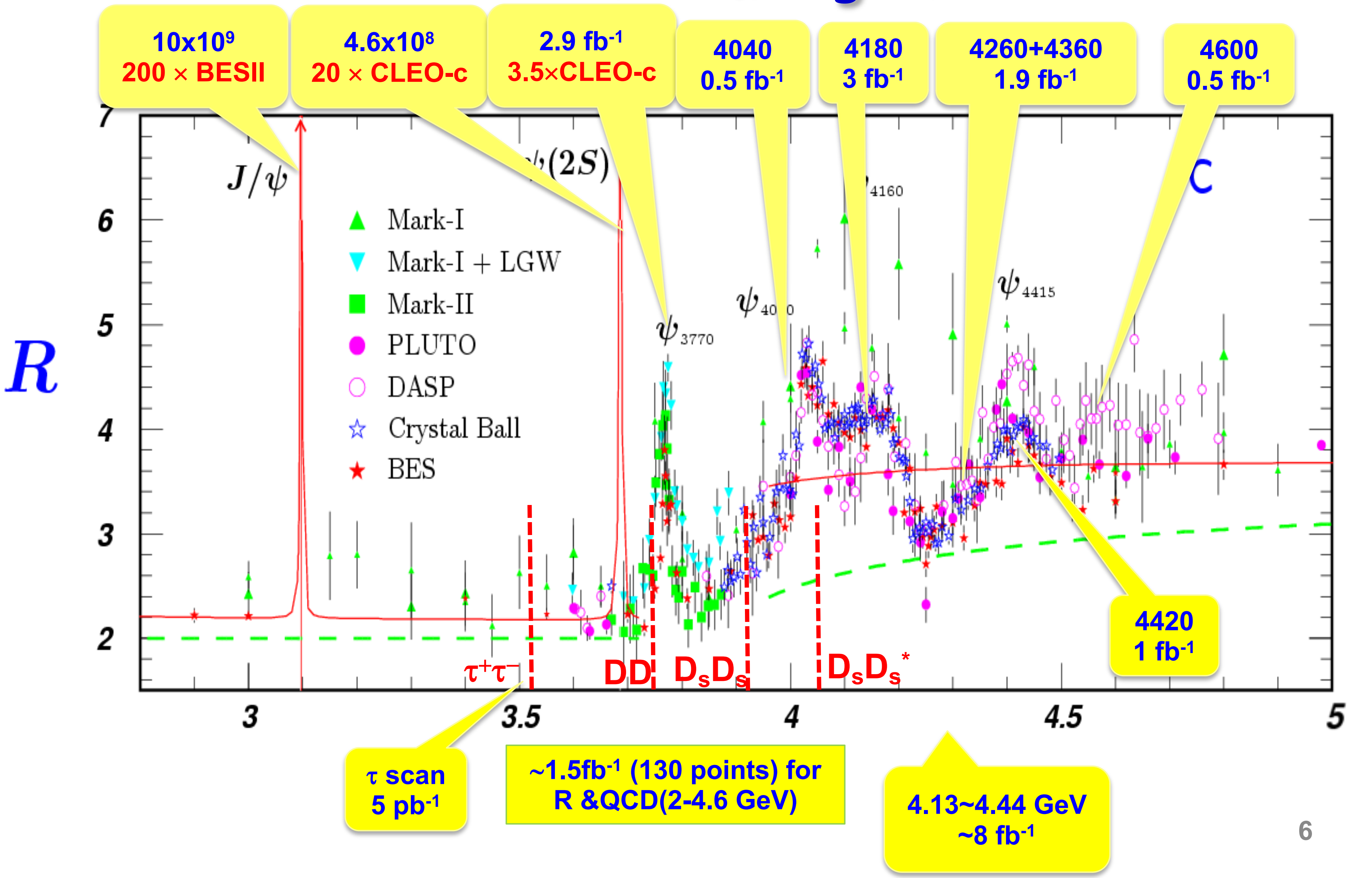


Beam energy:
1-2 GeV
Luminosity:
1×10^{33} cm^{-2}s^{-1}
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
SR mode:
0.25A @ 2.5 GeV

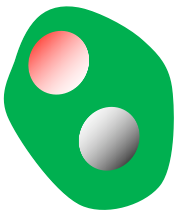
BESIII Physics

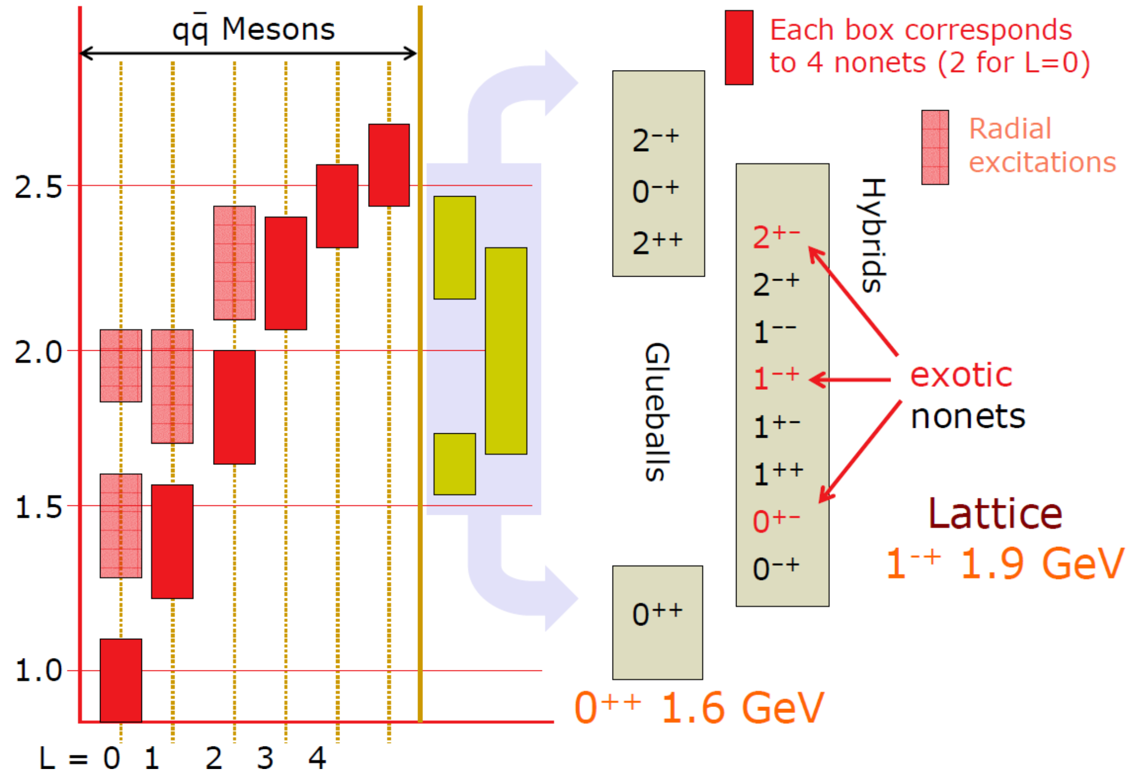


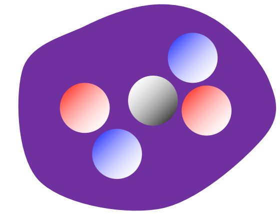
World largest data sample directly collected in the τ-charm region



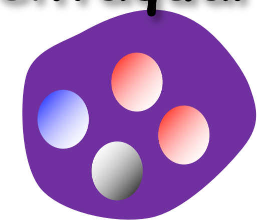
Light meson spectroscopy





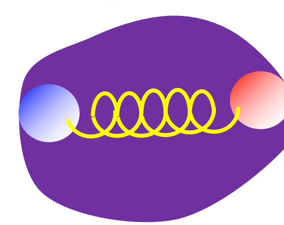


Pentaquark



tetraquark

Hybrid



glueball

QCD allows for hadrons beyond Quark Model

Scalar and Tensor mesons

Light scalar meson

- Why light scalar mesons are interesting?
  - There have been hot debates on **the existence of** **σ and κ**
  - **σ, κ and $f_0(980)$ are also possible mutiquark states. They are all near threshold.**
  - Lattice QCD predicts the **0^{++} scalar glueball mass ~ 1.6 GeV.** **$f_0(1500)$** and **$f_0(1710)$** are good candidates.

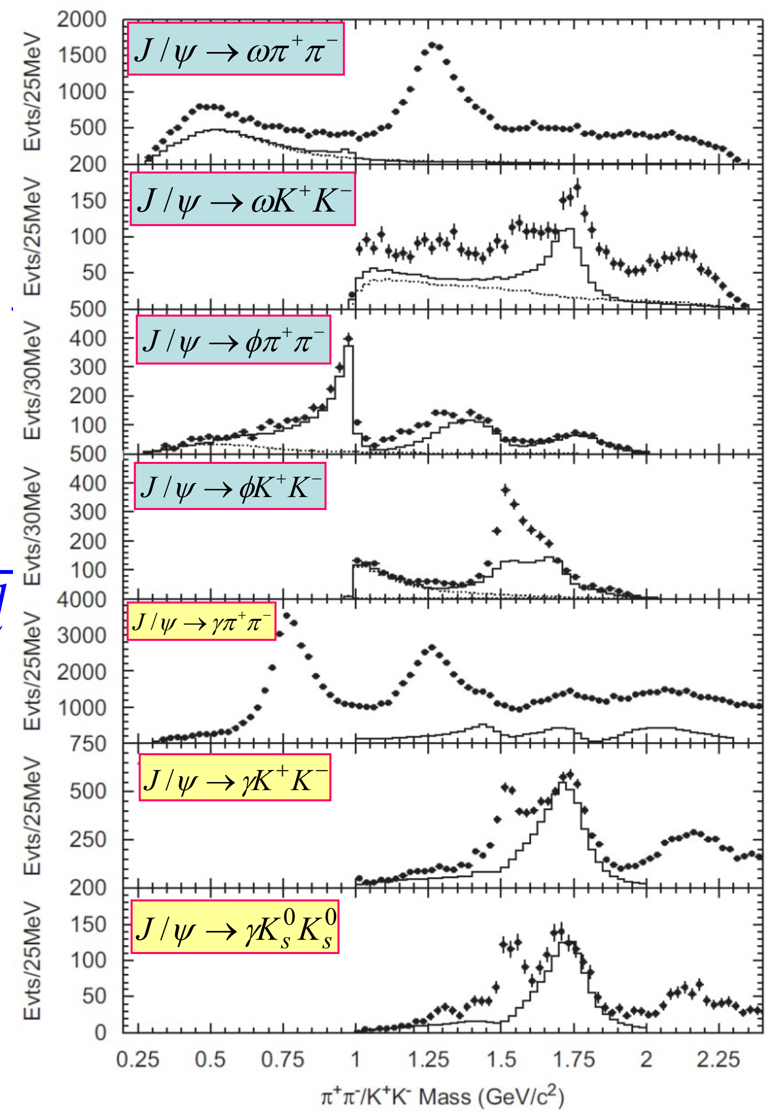
Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$f_0(600)$ *	$400-1200$	$600-1000$	$\pi\pi$, $\gamma\gamma$
$f_0(980)$ *	980 ± 10	$40-100$	$\pi\pi$, $K\bar{K}$, $\gamma\gamma$
$f_0(1370)$ *	$1200-1500$	$200-500$	$\pi\pi$, $\rho\rho$, $\sigma\sigma$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $K\bar{K}$
$f_0(1500)$ *	1507 ± 5	109 ± 7	$\pi\pi$, $\sigma\sigma$, $\rho\rho$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $\eta\eta'$ $K\bar{K}$, $\gamma\gamma$
$f_0(1710)$ *	1718 ± 6	137 ± 8	$\pi\pi$, $K\bar{K}$, $\eta\eta$, $\omega\omega$, $\gamma\gamma$
$f_0(1790)$			
$f_0(2020)$	1992 ± 16	442 ± 60	$\rho\pi\pi$, $\pi\pi$, $\rho\rho$, $\omega\omega$, $\eta\eta$
$f_0(2100)$	2103 ± 7	206 ± 15	$\eta\pi\pi$, $\pi\pi$, $\pi\pi\pi\pi$, $\eta\eta$, $\eta\eta'$
$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi$, $K\bar{K}$, $\eta\eta$

Unusual properties of $f_0(1370)$, $f_0(1710)$ and $f_0(1790)$

- **$f_0(1710)$:**
  - dominantly decays to KK (not to ππ) → $s\bar{s}$
  - I mainly produced together with ω (not φ) → $u\bar{u}$
  - What is it ?

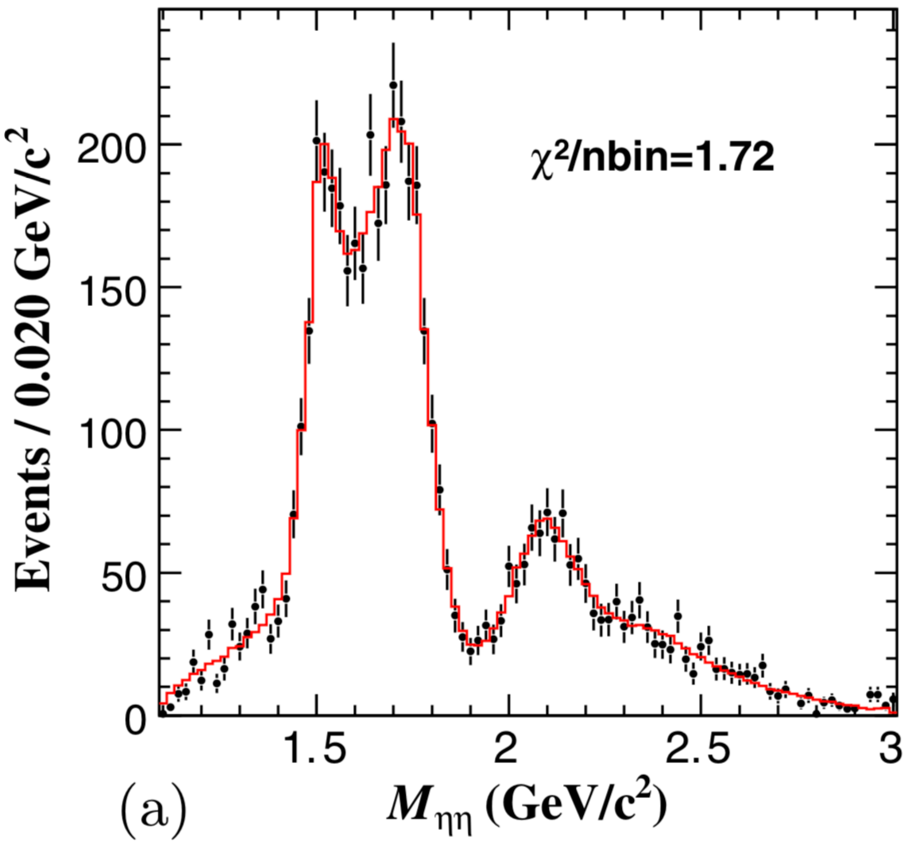
- **$f_0(1370)$ and $f_0(1790)$**
  - dominantly decays to ππ (not to KK) → $u\bar{u} + d\bar{d}$
  - mainly produced together with φ (not ω) → $s\bar{s}$
  - What are they ?

→ **Scalar Puzzle**



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

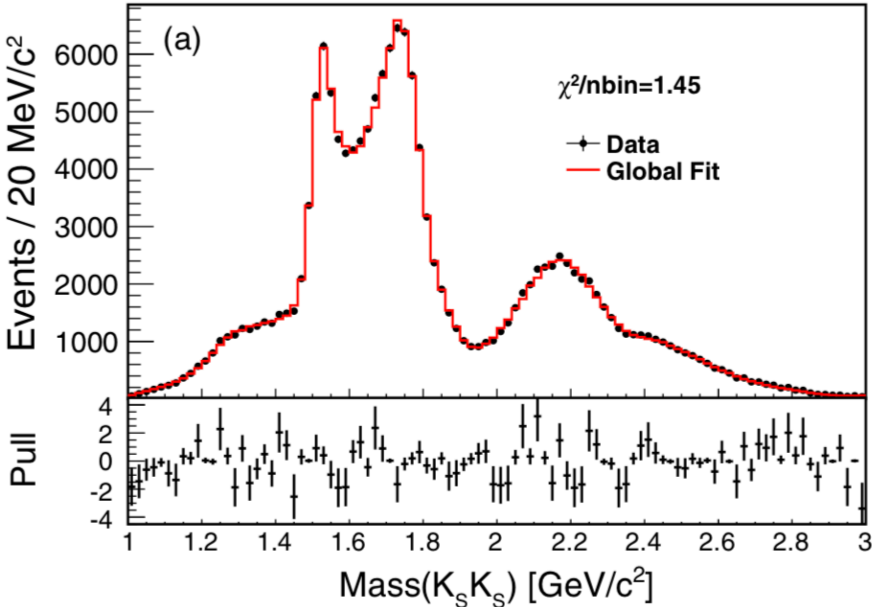
Phys. Rev. D. 87, 092009 (2013)



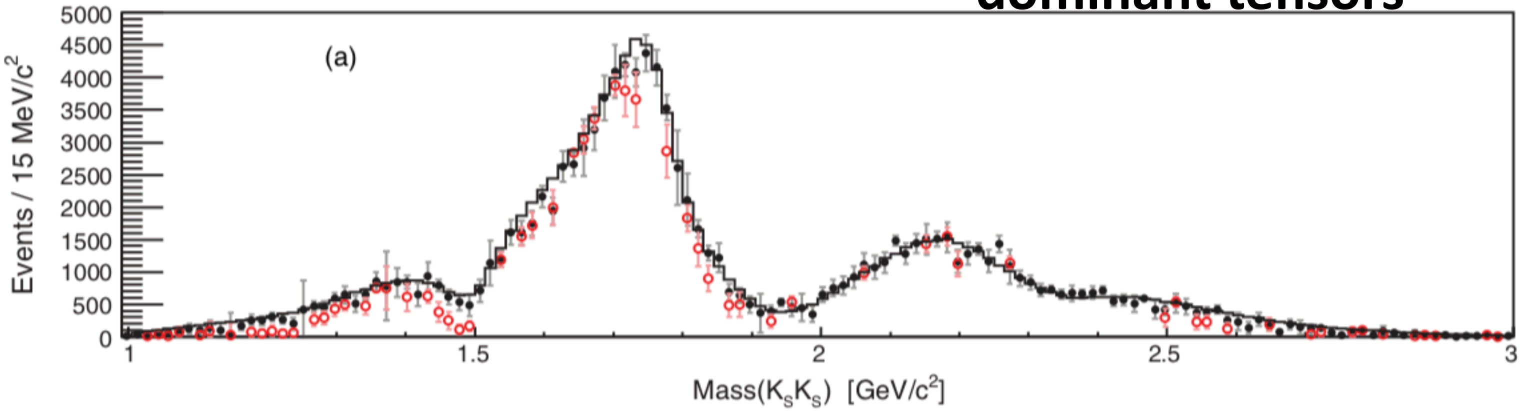
- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4 and 7.6σ)
- No evidence for $f_J(2220)$

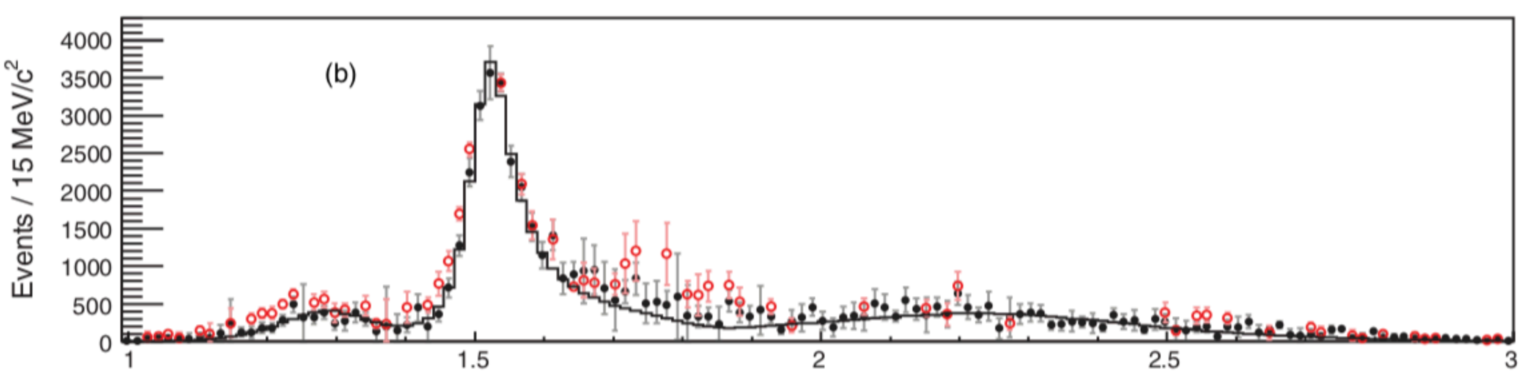
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	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 $J/\psi \to \gamma K_s K_s$



- $f_0(1710)$ and $f_0(2200)$ are dominant scalars
- low production for $f_0(1500)$
- $f_2'(1525)$ and f2(2340) are the dominant tensors

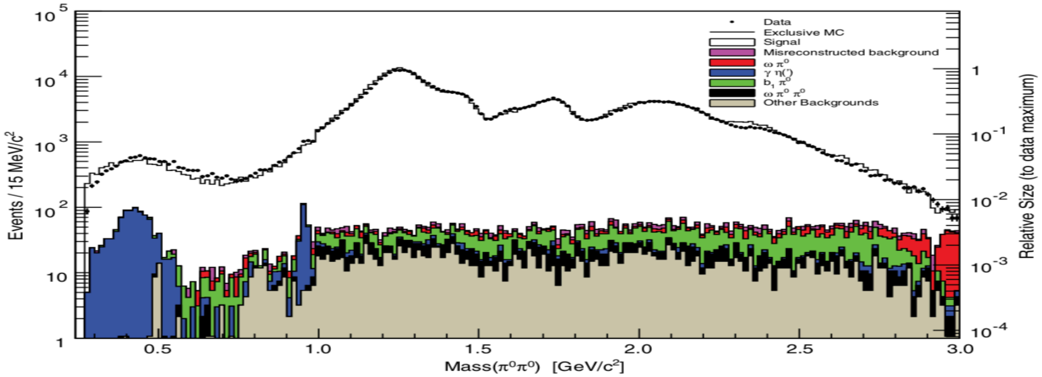


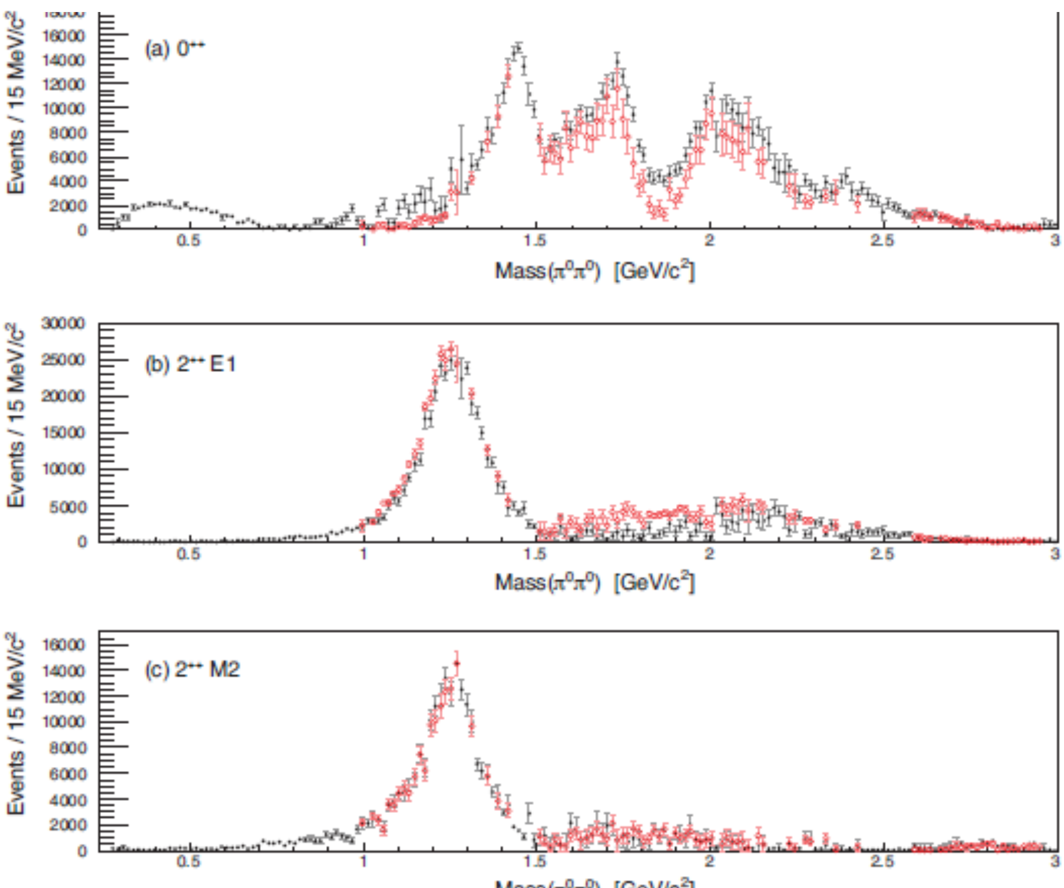


PWA of $J/\psi \rightarrow \gamma\pi^0\pi^0$

1. 3B J/ψ

Phys. Rev. D 92, 052003 (2015)

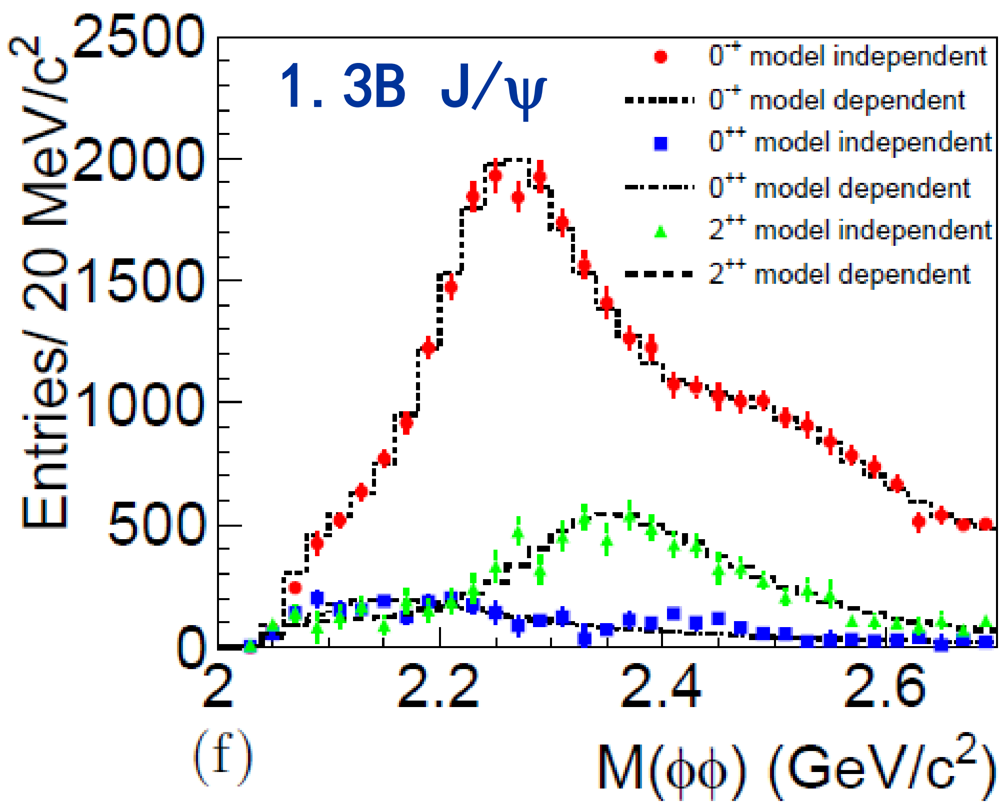




- **Model independent**
- **0^{++}: σ, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ and $f_0(2020)$**
- **2++: dominated by $f_2(1270)$**

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

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



(f)

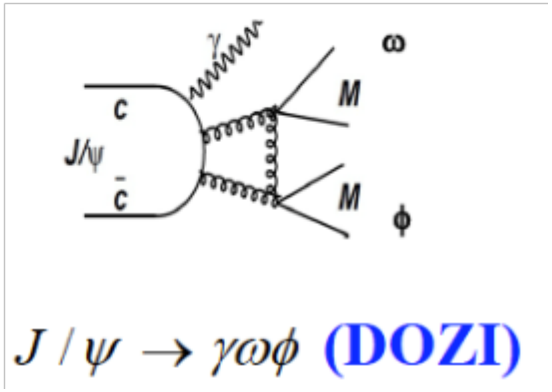
Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$
$\eta(2225)$	$2216^{+4}_{-5}{}^{+21}_{-11}$	$185^{+12}_{-14}{}^{+43}_{-17}$
$\eta(2100)$	$2050^{+30}_{-24}{}^{+75}_{-26}$	$250^{+36}_{-30}{}^{+181}_{-164}$
$X(2500)$	$2470^{+15}_{-19}{}^{+101}_{-23}$	$230^{+64}_{-35}{}^{+56}_{-33}$
$f_0(2100)$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

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

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

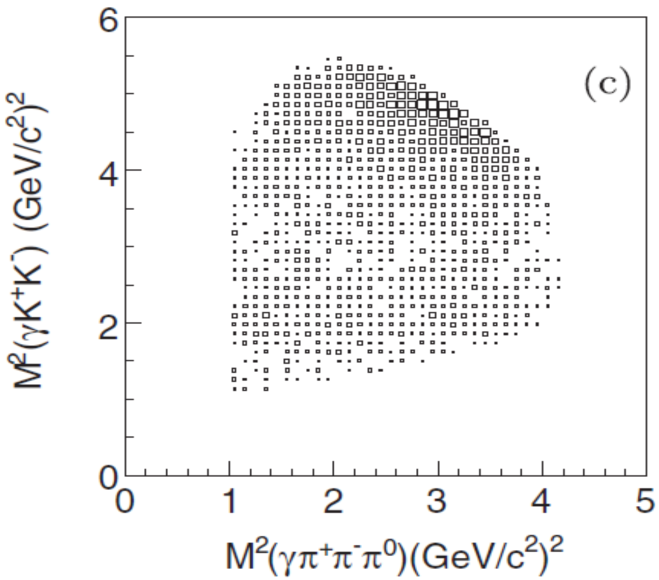
PWA of J/ψ→γωφ

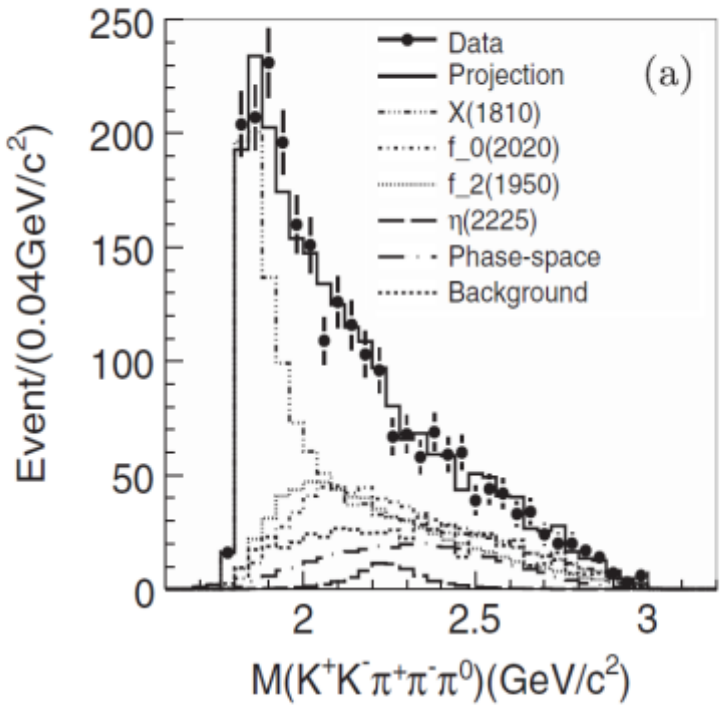
225M J/ψ



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

PRD 87, 032008(2013)

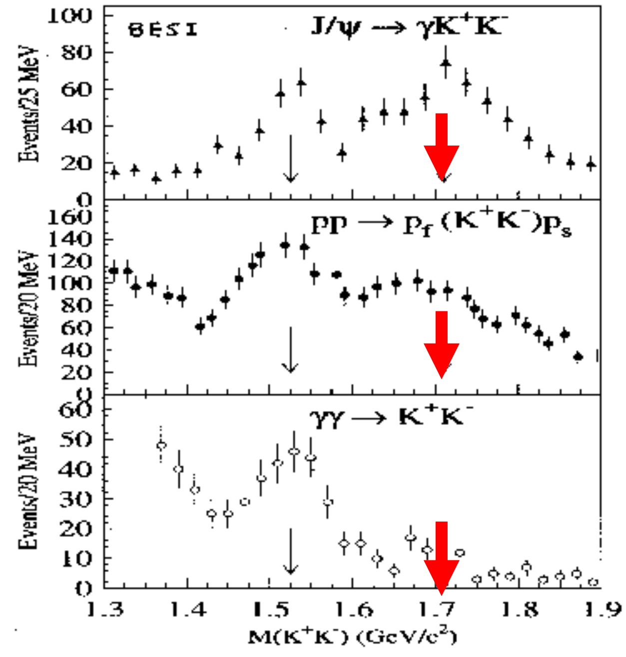




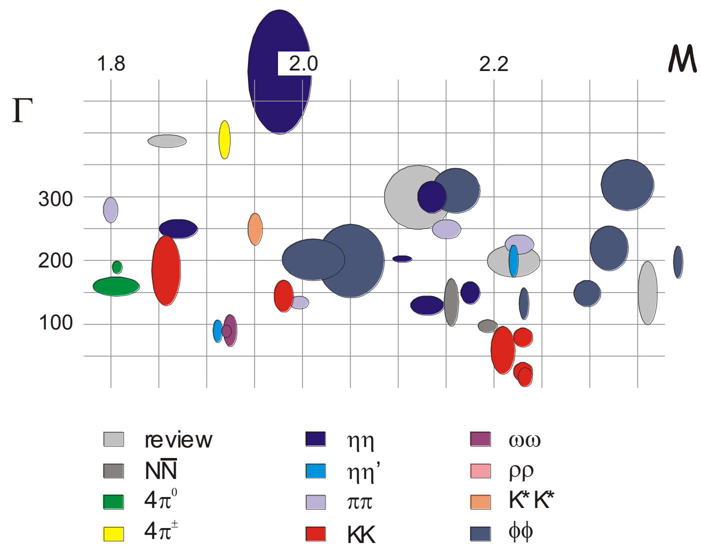
- Confirmed the enhancement observed at BESII
- $M= 1795\pm7^{+13}_{-5}\pm19$(model) MeV/c2,
  $\Gamma=95\pm10^{+21}_{-34}\pm75$(model) MeV
- Spin-parity is determined to be 0^+
- the same as $f_0(1710)/f_0(1790)$, or a new state ?

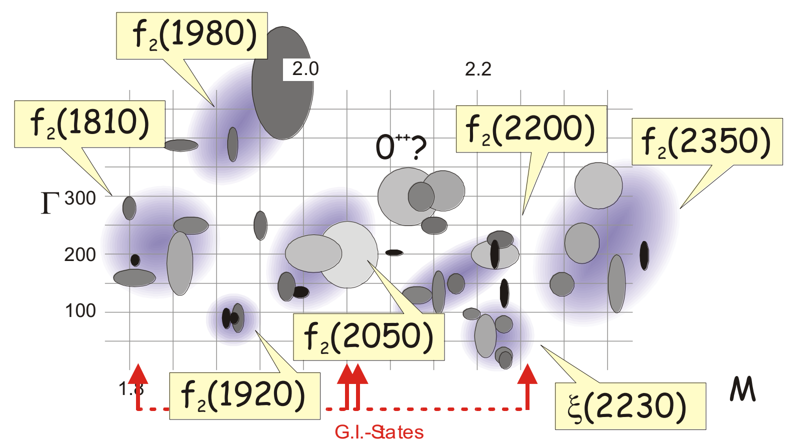
0^+ : experimental results saturated

- f_0 (1710) /f_0(1790) , one or two
- Large production rate of f_0(2100) in gluon rich environment ppbar annihilations and J/psi radiative decays



2^+: complicated situation around 2 GeV





About $f_0(1710)$: "Still controversial"?

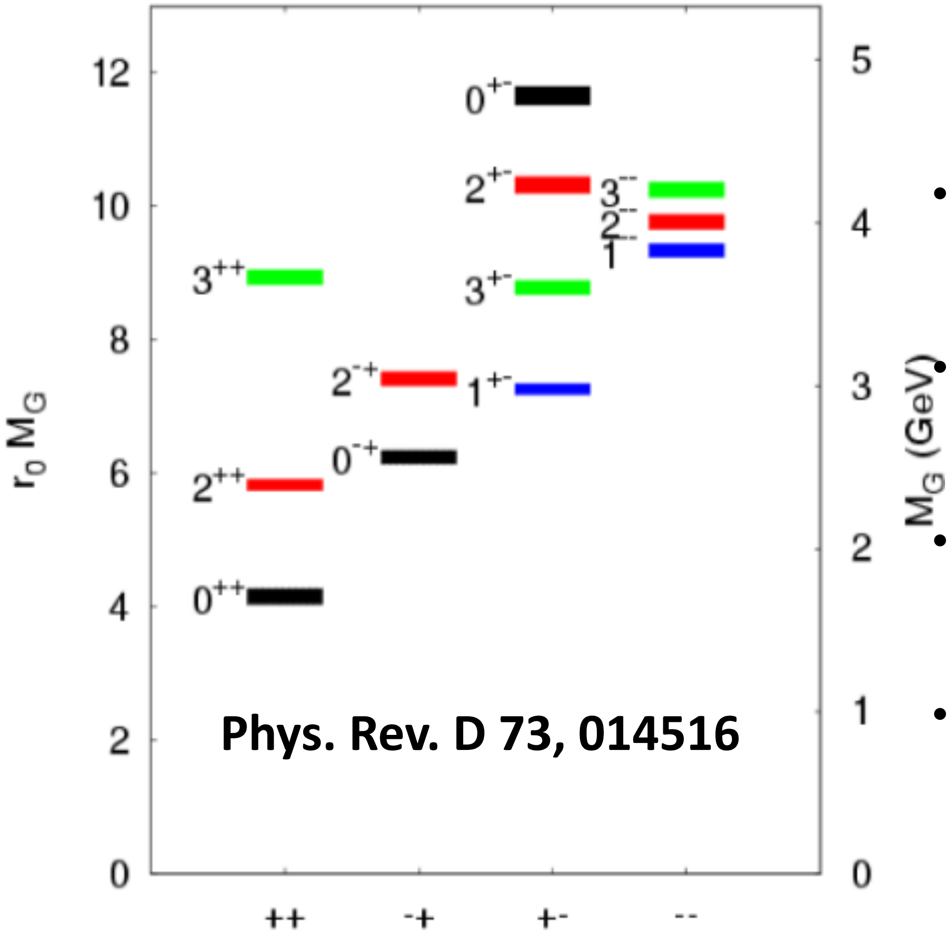
Phys.Rev. D92 (2015) no.9, 094006

TABLE V: Comparison of two different types of models for the mixing matrices of the isosinglet scalar mesons $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. Experimental results are taken from Sec. III.

Experiment	Model I [28]	Model II [23]
$\begin{pmatrix} \lvert f_0(1370)\rangle \\ \lvert f_0(1500)\rangle \\ \lvert f_0(1710)\rangle \end{pmatrix} = (\dots) \begin{pmatrix} \lvert N\rangle \\ \lvert S\rangle \\ \lvert G\rangle \end{pmatrix}$	$\begin{pmatrix} -0.91 & -0.07 & 0.40 \\ -0.41 & 0.35 & -0.84 \\ 0.09 & 0.93 & 0.36 \end{pmatrix}$	$\begin{pmatrix} 0.78(2) & 0.52(3) & -0.36(1) \\ -0.55(3) & 0.84(2) & 0.03(2) \\ 0.31(1) & 0.17(1) & 0.934(4) \end{pmatrix}$
Mass of the lightest scalar G in LQCD $\sim \mathcal{O}(1700)$MeV	$M_G \sim 1464 - 1519$ MeV	$M_G \sim 1665$ MeV
$\frac{\Gamma(J/\psi\to f_0(1710)\gamma)}{\Gamma(J/\psi\to f_0(1500)\gamma)} \sim \mathcal{O}(10)$	If $f_0(1500)$ is primarily a glueball, this ratio will be less than 1.	Yes, as $\lvert f_0(1710)\rangle \sim \lvert G\rangle$
$\frac{\Gamma(f_0(1710)\to\pi\pi)}{\Gamma(f_0(1710)\to K\bar{K})} = 0.31 \pm 0.05$	$f_0(1710)$ dominated by $s\bar{s}$	Chiral suppression
$\frac{\Gamma(f_0(1500)\to\pi\pi)}{\Gamma(f_0(1500)\to K\bar{K})} = 4.1 \pm 0.5$	If $f_0(1500)$ is primarily a glueball, this ratio will be of order unity. Needs a large mixing with $q\bar{q}$.	Well explained with the flavor octet structure of $f_0(1500)$.
$\frac{\Gamma(f_0(1710)\to\eta\eta)}{\Gamma(f_0(1710)\to K\bar{K})} = 0.48 \pm 0.15$	0.24	$0.52^{+0.33}_{-0.34}$
$\frac{\Gamma(f_0(1500)\to\eta\eta)}{\Gamma(f_0(1500)\to\pi\pi)} = \begin{cases} 0.230 \pm 0.097 \\ 0.18 \pm 0.03 \\ 0.080 \pm 0.033 \end{cases}$	0.19	$0.078^{+0.025}_{-0.027}$
$\frac{\Gamma(J/\psi\to f_0(1710)\omega)}{\Gamma(J/\psi\to f_0(1710)\phi)} = \begin{cases} 3.3 \pm 1.3 \\ 1.3 \pm 0.4 \end{cases}$	The ratio is naively less than 1. Needs large OZI-violating effects.	Yes, as $\lvert S\rangle$ is small in $f_0(1710)$
Non-observation of $f_0(1710)$ and observation of $f_0(1500)$ in $B_s \to J/\psi\pi^+\pi^-$ by LHCb	Dominant $f_0(1710)$ production followed by $f_0(1500)$	Dominant $f_0(1500)$ production, while $f_0(1710)$ is negligible
Near mass degeneracy of $a_0(1450)$ and $K_0^*(1430)$	No, it cannot be explained as $M_S - M_N \approx$ 200-300 MeV	Yes, as $M_S - M_N \approx 25$ MeV
$f_0(1500)$ not seen in $\gamma\gamma$ reactions except probably in $\gamma\gamma \to \pi^0\pi^0$	See Eq. (30)	See Eq. (30)

- **Clarify $f_0(1710)$ / $f_0(1790)$ / $f_0(1810)$**
  - **Pure glueball "cannot" decay to $\omega\phi$**
- **Establish $f_0(2100)$**
  - **First excitation of scalar glueball?**
- **Search for $f_0(1710)$ and $f_0(2100)$ in $J/\psi \to \gamma\eta'\eta^{(\prime)}$**
  - **Complete information on flavor**
  - **Pure glueball "cannot" decay to $\eta\eta'$**
- **Couple channel analysis**

Where is the glueball?



At BESIII

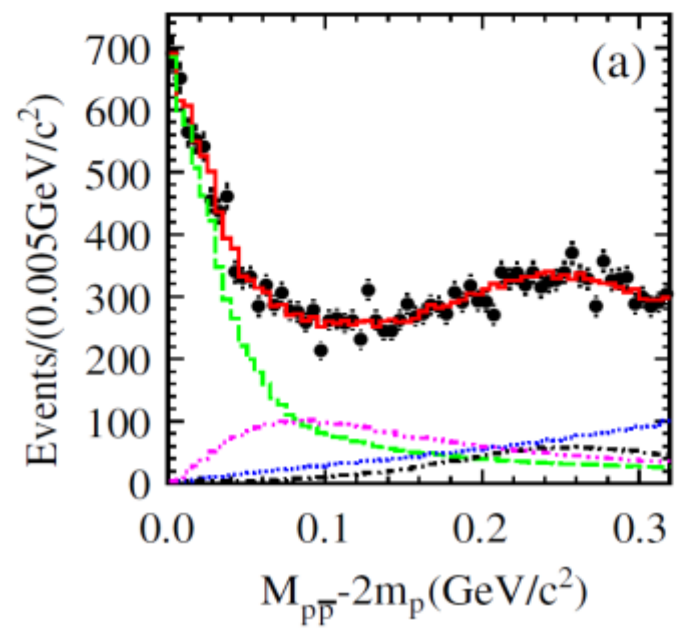
- **$f_0(1710)$ and $f_0(2100)$ are observed in $J/\psi \to \gamma\, \eta\eta, \gamma\pi^0\pi^0$**
- **$f_2(2340)$ is observed in $J/\psi \to \gamma\eta\eta/\phi\phi/\pi^0\pi^0$**
- **X(2120) and X(2370) in of $J/\psi \to \gamma\pi^+\pi^-\eta$'**
- **Systematic studies needed**
  - $J/\psi \to \gamma\eta\eta'$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

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

Exotic mesons

PWA of $J/\psi \to \gamma p\bar{p}$

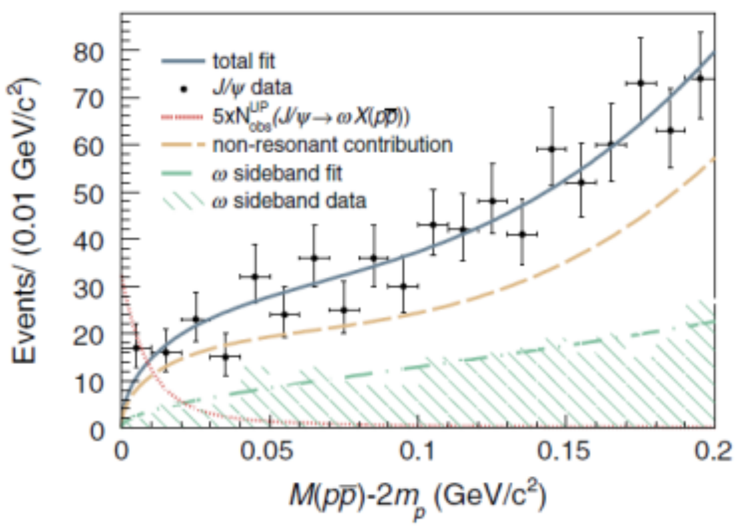
- PWA of $J/\psi \to \gamma p\bar{p}$ was first performed
- The fit with a BW and S-wave FSI(I=0) factor can well describe $p\bar{p}$ mass threshold structure.
- It is much better than that without FSI effect, and Δ2lnL=51 (7.1σ)



PRL 108,112003(2012)

■ **Spin-parity of $X(p\bar{p})$:** $J^{PC}=0^{-+}$

>6.8σ better than other J^{pc} assignments

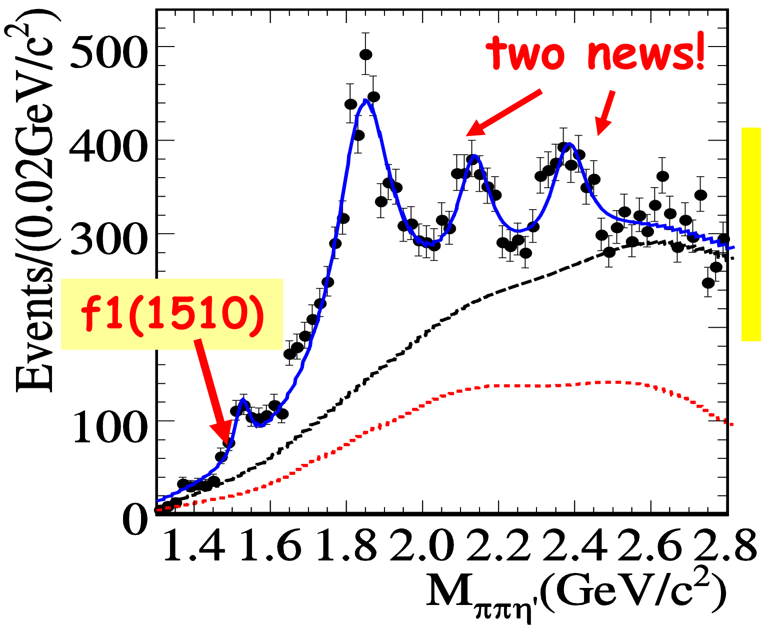


No similar structure was observed in $J/\psi \to \omega p\bar{p}$, $J/\psi \to \phi p\bar{p}$

PRD 87, 112004(2013)

Confirmation of X(1835) and two new structures

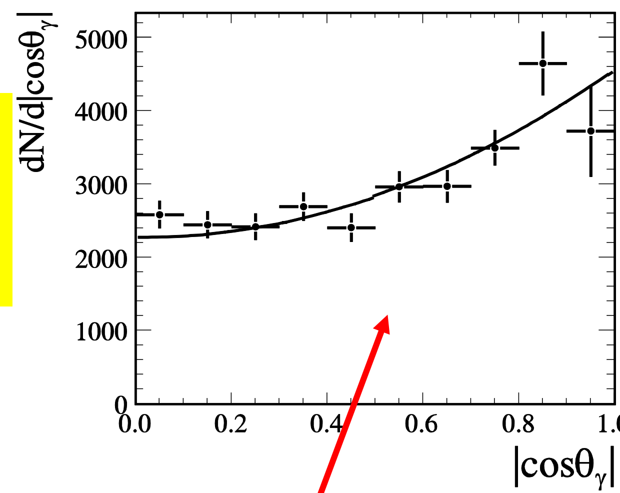
PRL 106, 072002(2011)



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

$\eta' \to \eta\pi^+\pi^-$

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



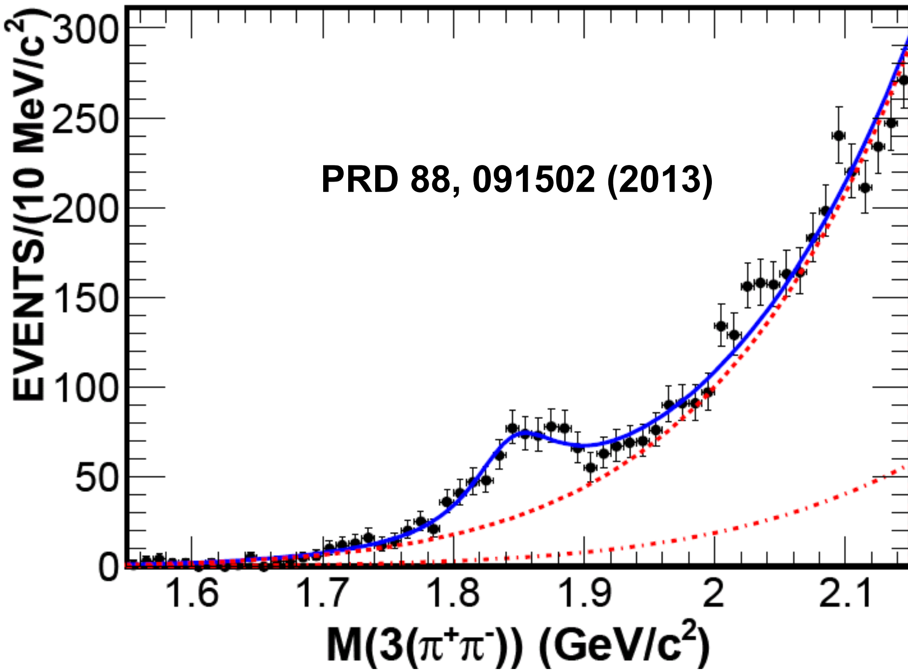
X(1835) consistent with 0^-

BESIII fit results:

Resonance	M(MeV/c²)	Γ(MeV/c²)	Stat.Sig.
X(1835)	$1836.5\pm3.0^{+5.6}_{-2.1}$	$190.1\pm9.0^{+38}_{-36}$	$>20\sigma$
X(2120)	$2122.4\pm6.7^{+4.7}_{-2.7}$	$83\pm16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3\pm8.7^{+3.2}_{-4.3}$	$83\pm17^{+44}_{-6}$	6.4σ

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

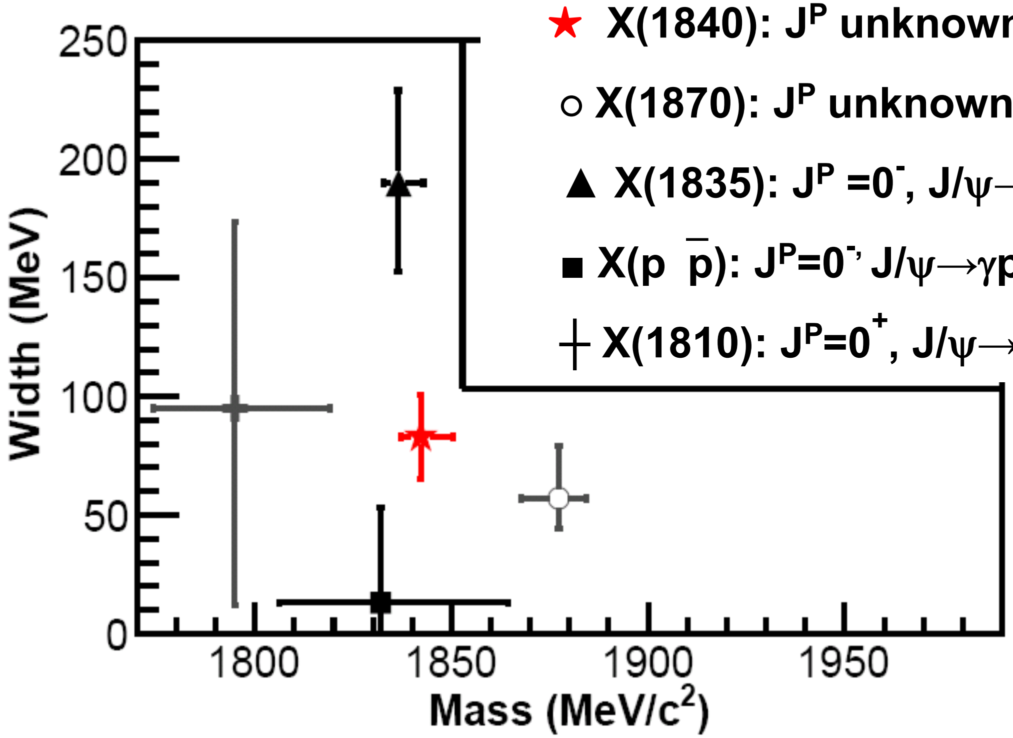
Observation of X(1840) in $J/\psi\to\gamma 3(\pi^+\pi^-)$



$M = 1842.2 \pm 4.2\ ^{+7.1}_{-2.6}$ MeV/c^2
$\Gamma = 83 \pm 14 \pm 11$ MeV

- **Mass is consistent with that of X(1835), but the width is much smaller than $\Gamma_{X(1835)} = 190.1 \pm 9.0^{+38}_{-36}$ MeV**
- **A new decay modes of X(1835)?**

Comparisons of the observations at BES



★ X(1840): J^P unknown, $J/\psi \to \gamma 3(\pi^+\pi^-)$ PRD88,091502

○ X(1870): J^P unknown, $J/\psi \to \omega\pi^+\pi^-\eta$ PRL107, 182001

▲ X(1835): $J^P = 0^-$, $J/\psi \to \gamma\pi^+\pi^-\eta'$ PRL106, 072002

■ X($p\bar{p}$): $J^P=0^-$, $J/\psi \to \gamma p\bar{p}$ PRL108,112003

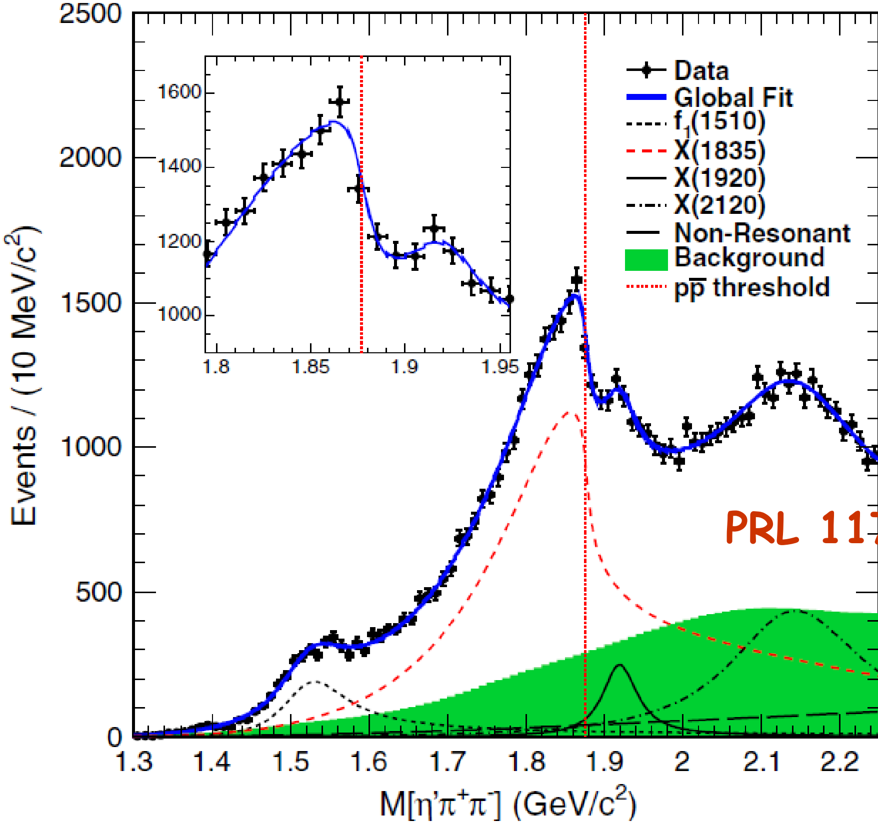
┼ X(1810): $J^P=0^+$, $J/\psi \to \gamma\omega\phi$ PRD 87, 032008

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

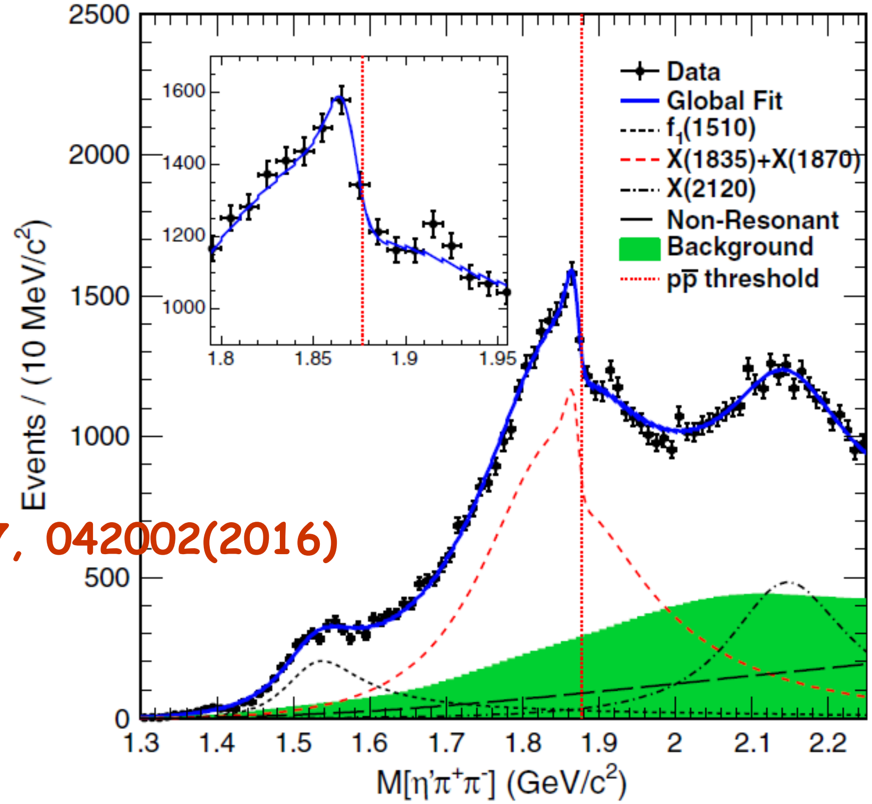
Are they the same particle? It is crucial to identify these observations.

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

Faltte formula



Two BWs



PRL 117, 042002(2016)

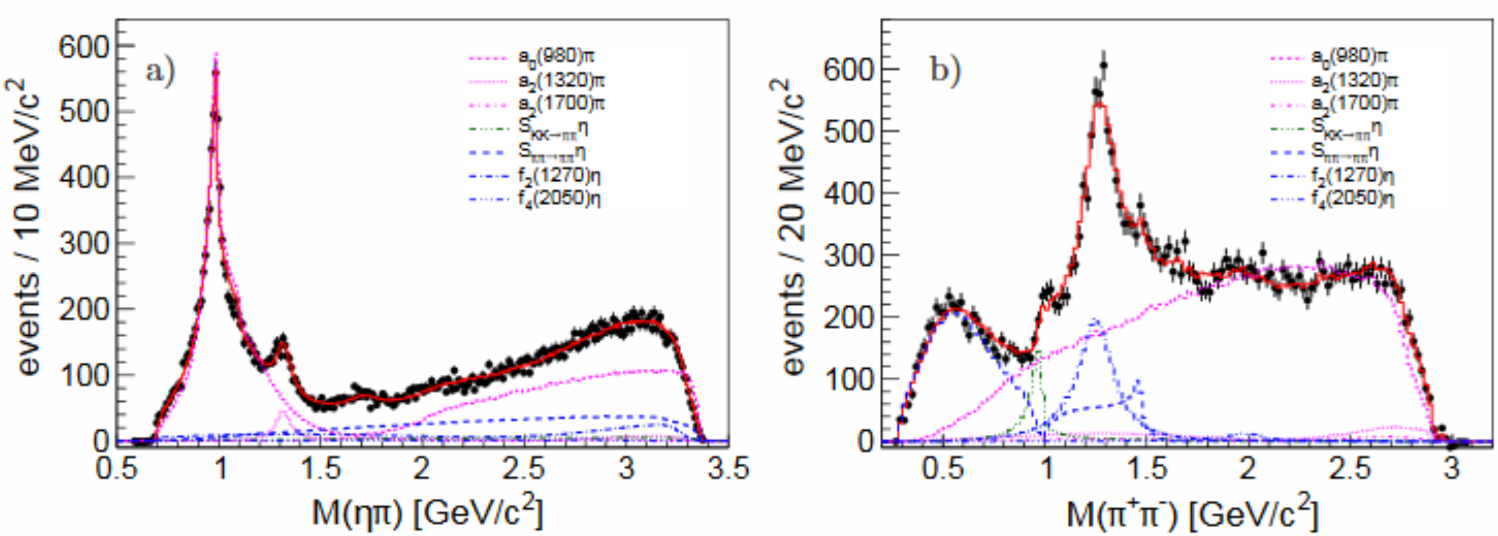
$M = 1638.2 \pm 121.9\ ^{+127.8}_{-254.3}$ MeV/c^2
$g^2_0 = 93.7 \pm 35.4\ ^{+47.6}_{-43.9}$ GeV/c^2
$g^2_{p\bar{p}} / g^2_0 = 2.31 \pm 0.37\ ^{+0.83}_{-0.60}$

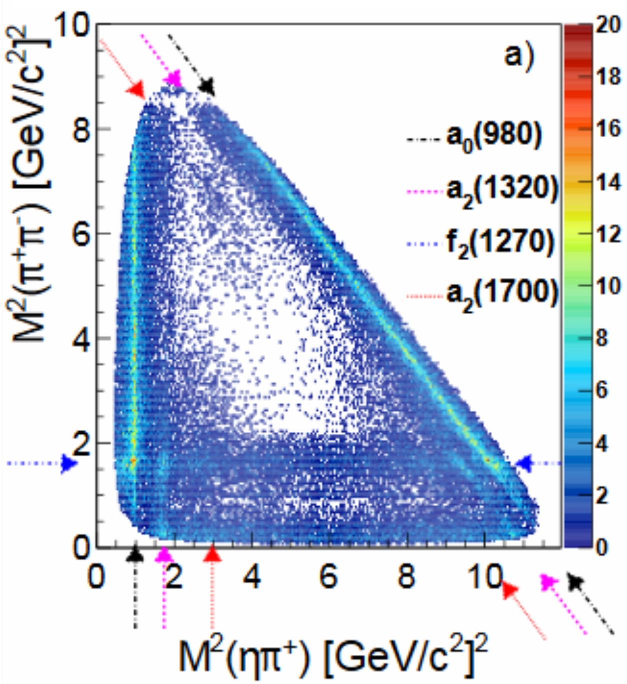
$M_1 = 1825.3 \pm 2.4\ ^{+17.2}_{-2.4}$ MeV/c^2
$\Gamma_1 = 245.2 \pm 13.1\ ^{+4.6}_{-9.6}$ MeV

$M_2 = 1870.2 \pm 2.2\ ^{+2.3}_{-0.7}$ MeV/c^2
$\Gamma_2 = 13.0 \pm 6.1\ ^{+2.1}_{-3.8}$ MeV

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

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

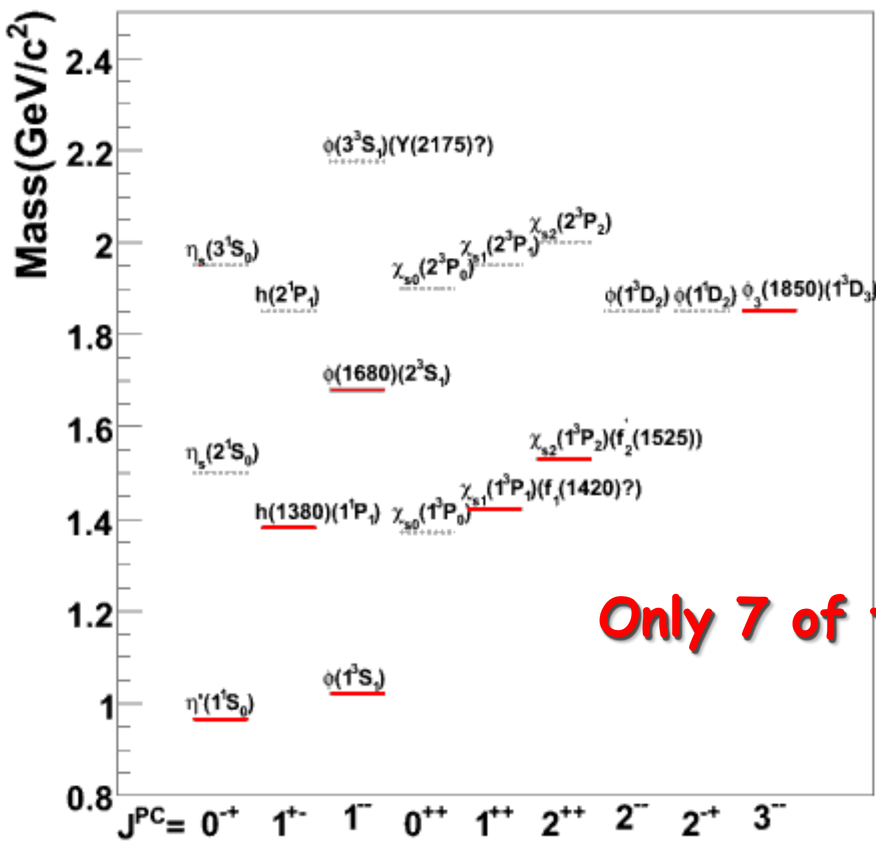




- Clear evidence for $a_2(1700)$ in χ_{c1} decays.
- First measurement of $g'_{\eta'\pi} \neq 0$ using $a_0(980) \to \eta\pi$ line shape.
- Upper limits for $\pi_1(1^{-+})$ in 1.4 - 2.0 GeV/c^2

Strangeonia spectrum

- Like charmonia, a similar pattern for the strangeonia is expected
- Much less well understood, most of them have not been observed yet
- Strangeonia serve as a bridge between short and large distance behavior of QCD confinement potential



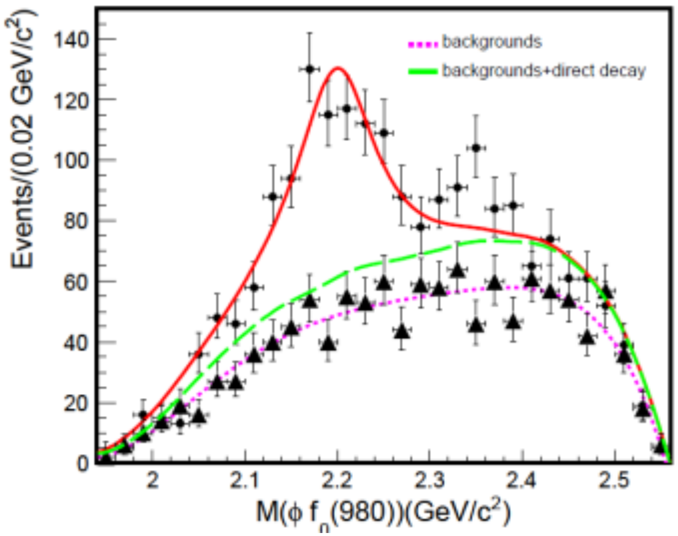
$S\bar{S}$ System – what do we know?

Only 7 of them have been identified !

Also listed in JLAB physics program

Y(2175)/ϕ(2170)

PRD **91**, 052017

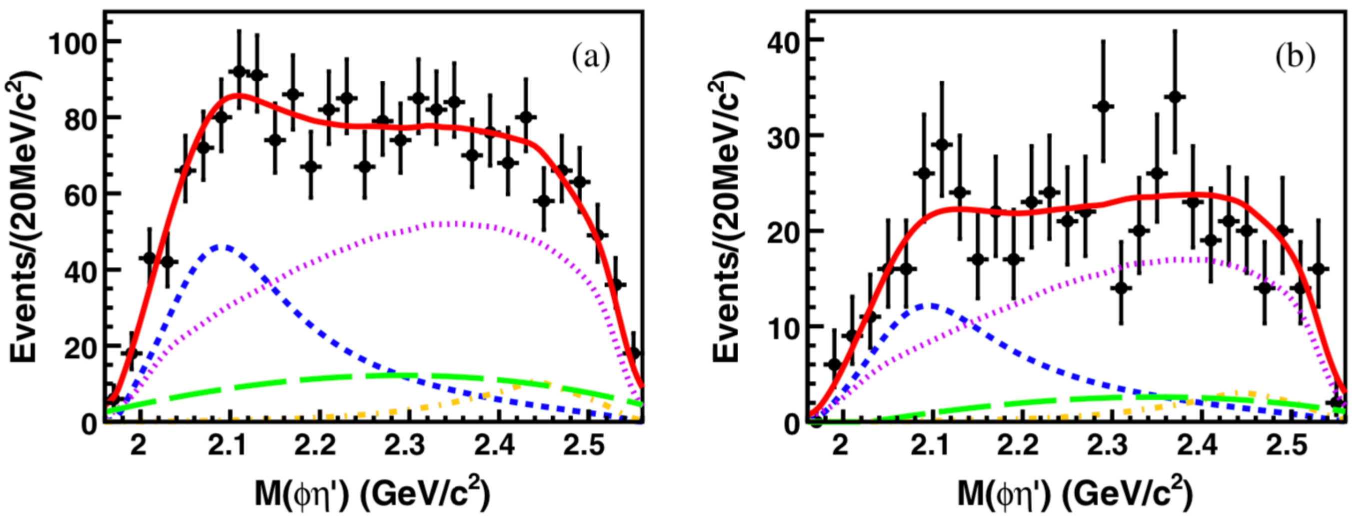


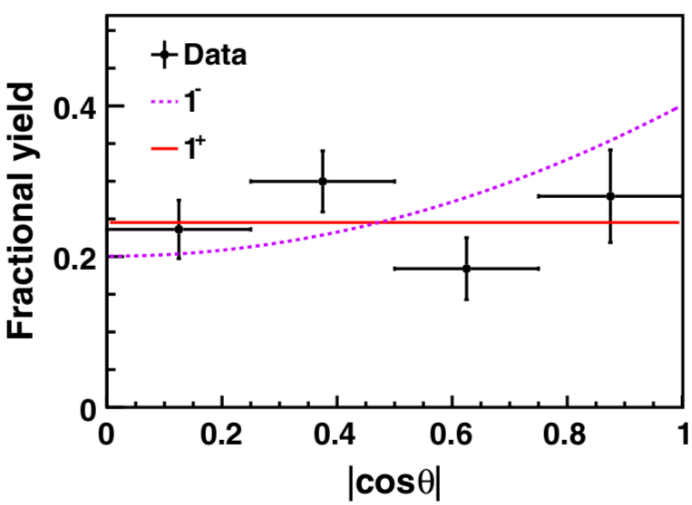
Collaboration	Process	M (MeV/c^2)	Γ (MeV)
BABAR [2]	$e^+e^- \to \phi f_0$ (ISR)	$2175 \pm 10 \pm 15$	$58 \pm 16 \pm 20$
BESII [3]	$J/\psi \to \eta\phi f_0(980)$	$2186 \pm 10 \pm 6$	$65 \pm 23 \pm 17$
BELLE [4]	$e^+e^- \to \phi f_0$ (ISR)	$2079 \pm 13^{+79}_{-28}$	$192 \pm 23^{+25}_{-61}$
BABAR(updated) [5]	$e^+e^- \to \phi f_0$ (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 ?

$J/\psi \to \phi\eta\eta'$

PRD99,112008(2019)





- **JP=1⁺**

$(2062.8 \pm 13.1 \pm 7.2)\ \mathrm{MeV}/c^2$

$(177 \pm 36 \pm 35)\ \mathrm{MeV}$

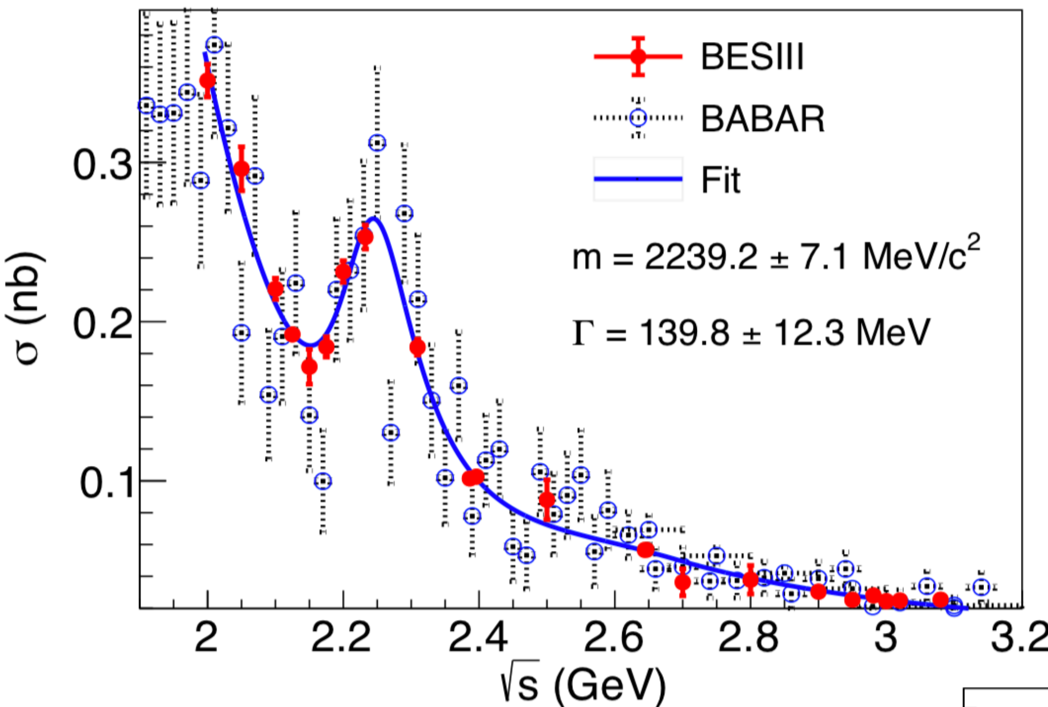
- **JP=1⁻**

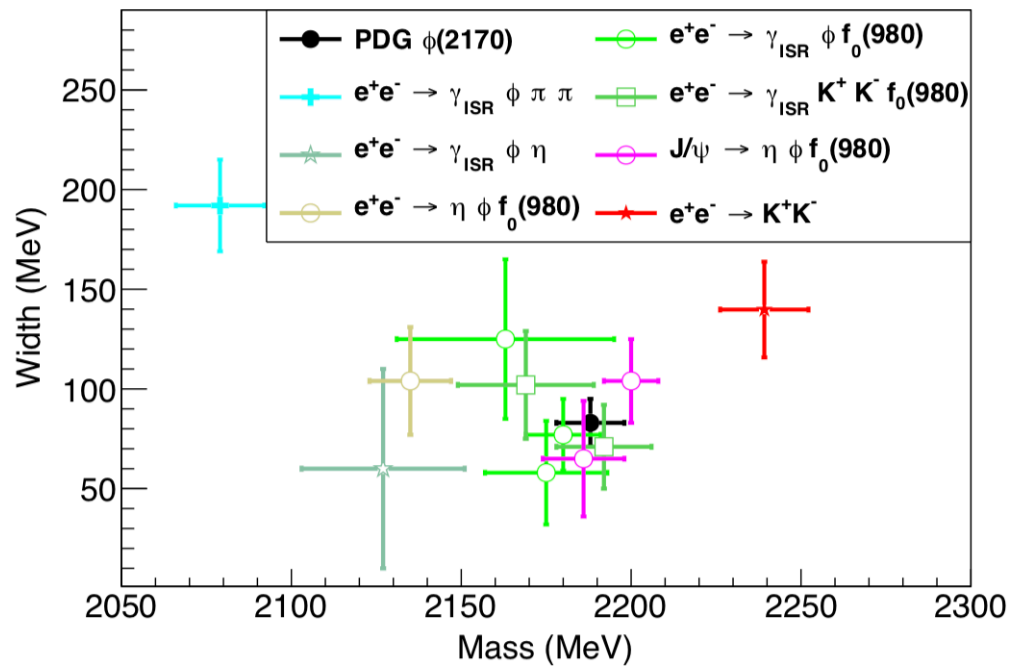
$(2002.1 \pm 27.5 \pm 21.4)\ \mathrm{MeV}/c^2$

$(129 \pm 17 \pm 9)\ \mathrm{MeV}$

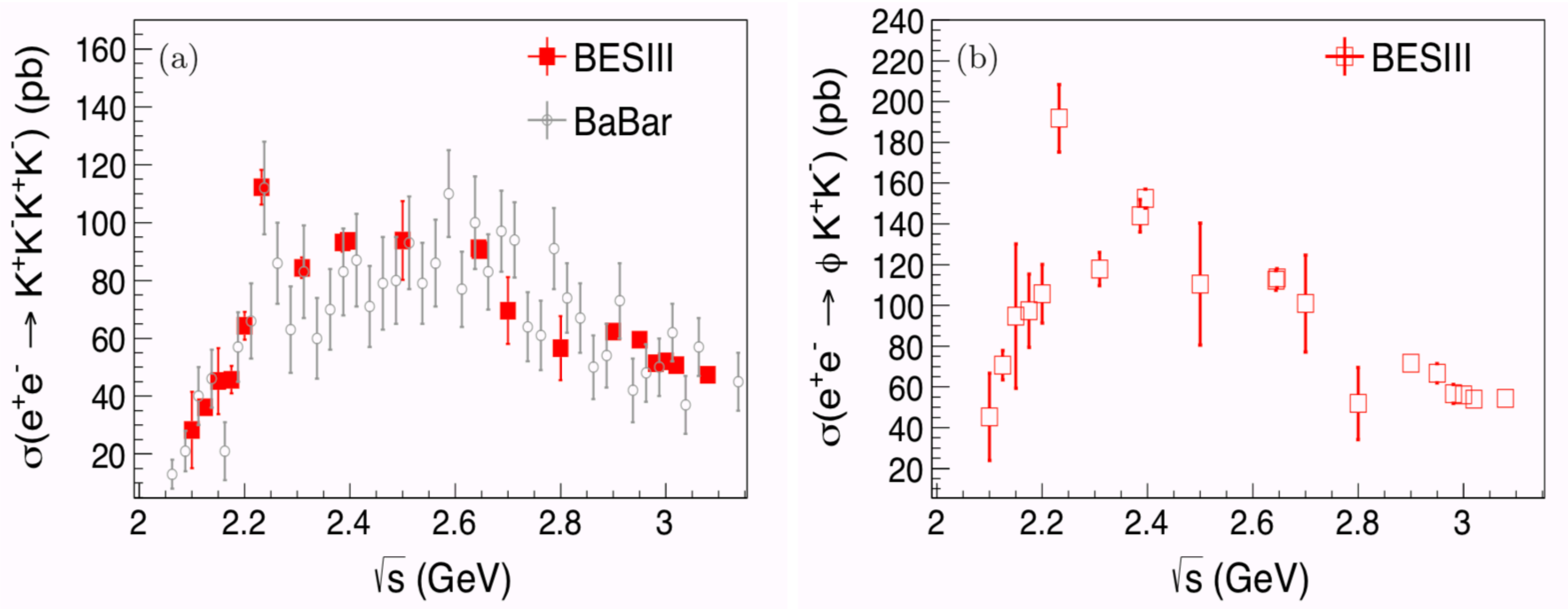
$e^+e^- \to K^+K^-$

PRD99,032001(2019)



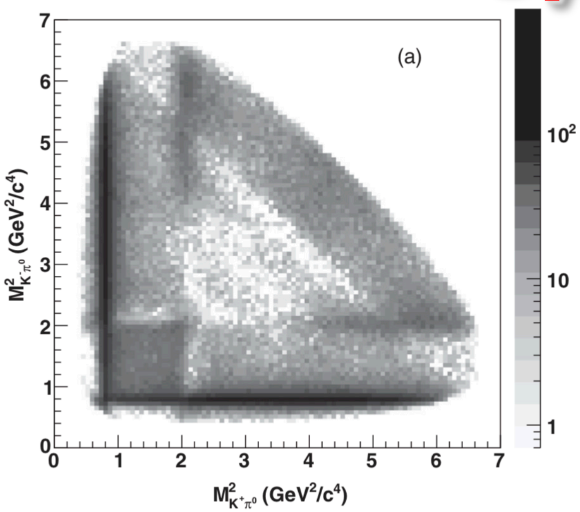


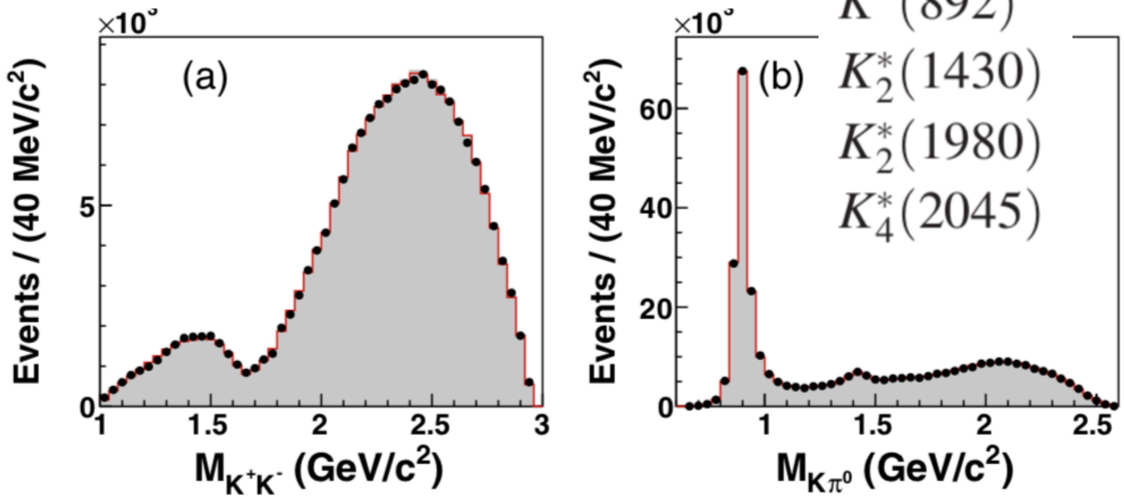
$e^+e^- \to K^+K^-K^+K^-$ arXiv:1907.06015



- **Too narrow for $\phi(2170)$?**
- **New strangeonium state?**
- **$\Lambda\Lambda$bar mass threshold enhancement?**

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

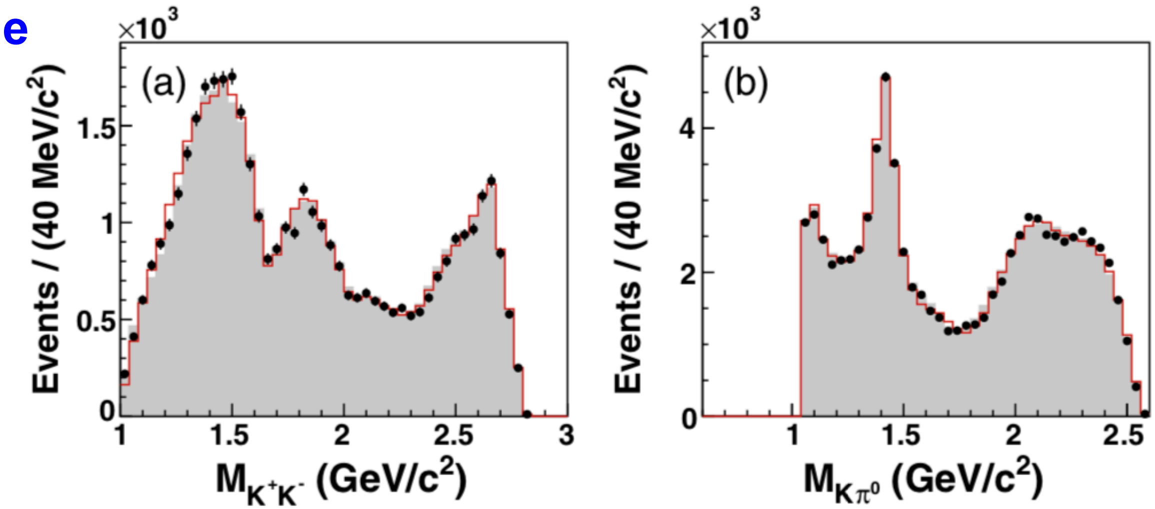




$K^*(892)$
$K_2^*(1430)$
$K_2^*(1980)$
$K_4^*(2045)$

$1^{--}(1650\ \mathrm{MeV}/c^2)$
$1^{--}(2050\ \mathrm{MeV}/c^2)$

- Clear structures were observed
- Further study needed for the structures observed in K+K- mass spectrum



Mkπ>1.05 GeV

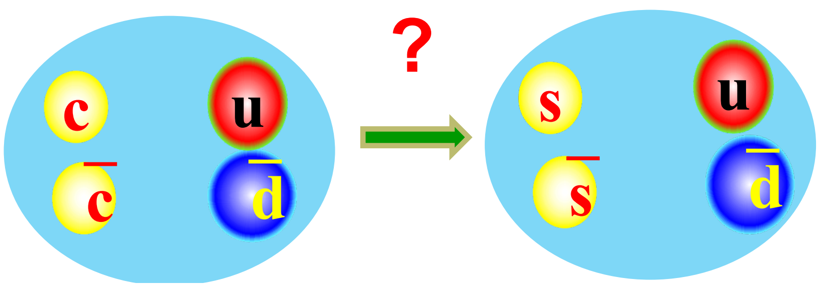
Search for Zs in e+e-→ $\phi\pi\ \pi$

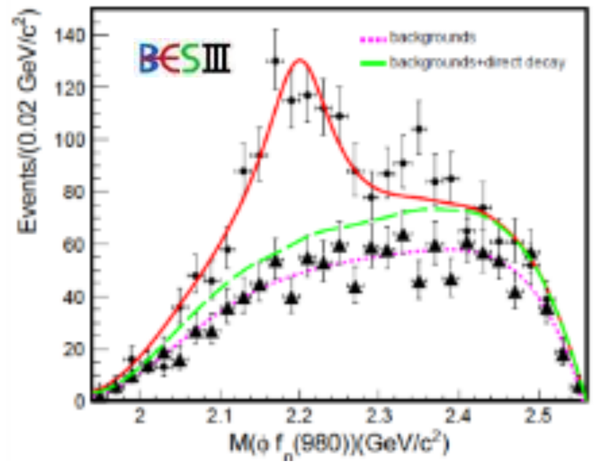
PRD99，011101

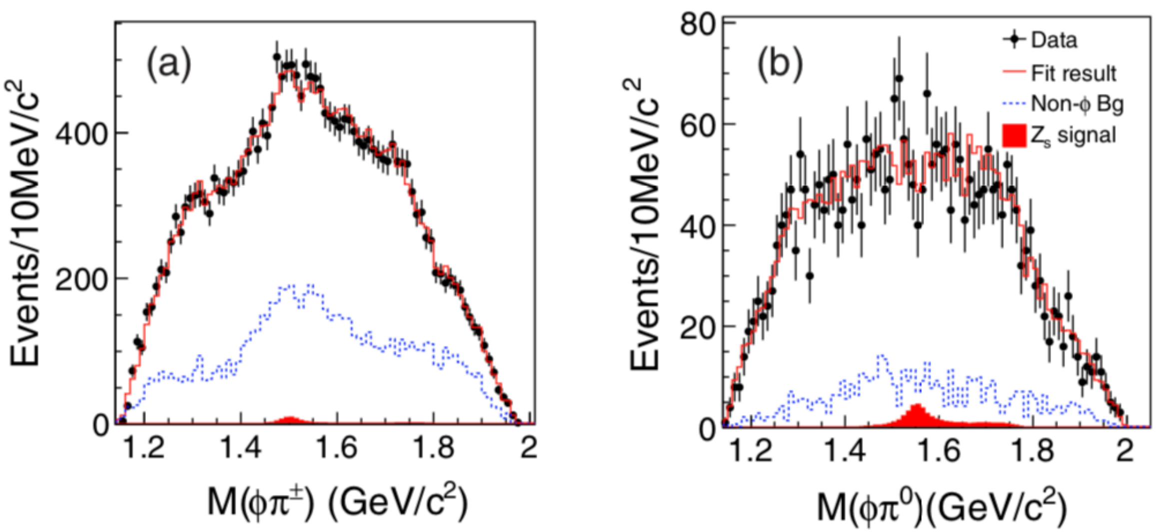
$Y(4260) \to J/\psi\pi^+\pi^-$ charm, → Z_c

$Y(2175) \to \phi(1020)\pi^+\pi^-$ strange, → Z_s ?

Z_c







Upgrades on BEPCII/BESIII

- Beam energy
  - Ebeam = 2.3→2.35 GeV in 2019
  - Ebeam = 2.35→2.45 GeV in 2020-21
- Top-up injection
  - Data taking efficiency increases by 20-30%
- Inner tracker →CGEM inner tracker
  - Construction by Italian group
  - Will be shipped to IHEP this summer, installation in summer 2020
- Super conducting magnet
  - New valve box of SC magnet

Summary

- BESIII plays an important role in light hadron physics
- Rich physics in light hadrons
  - search for exotics → QCD
  - study of strangeonia → Quark model

  ……
- Couple channel analysis may help map the spectroscopy
- 10 billion J/ψ events available !
- More surprises @ BESIII

Thank you !