Progresses on light hadron physics from BESIII

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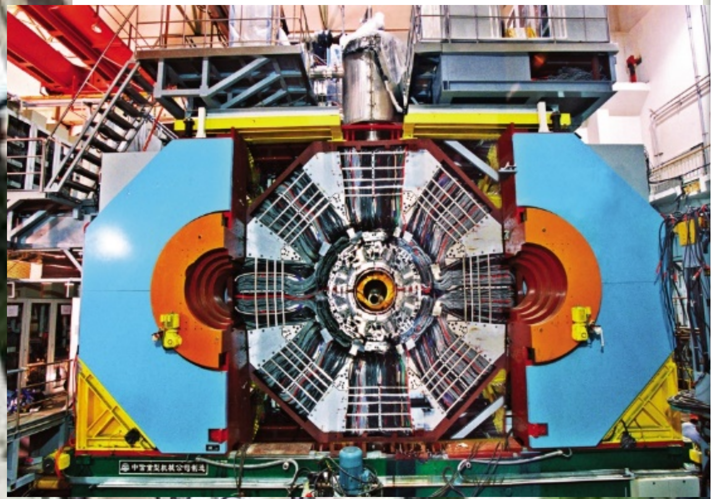
BEPCII / BESIII

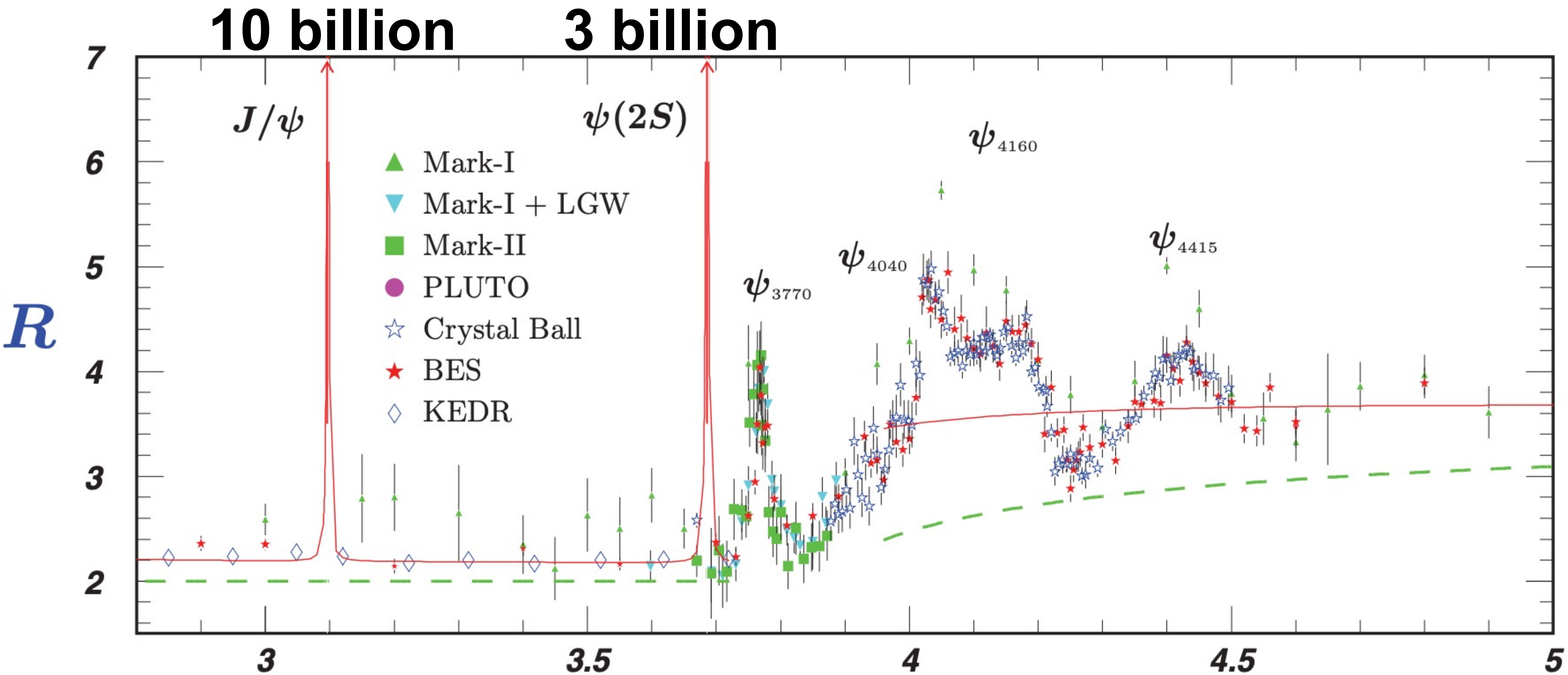


MDC: σ_p/p ~0.5% @ 1GeV
$\sigma_{dE/dx}$ ~ 6%
TOF: σ_T ~90 ps (barrel)
110 ps (endcap)
SCS: 1.0T (2009)
0.9T (2012)
EMC: $\sigma_E/\sqrt{E}$ ~ 2.5%@1GeV

2004: started BEPCII/BESIII construction
- ✓ Double rings
- ✓ Beam energy: 1-2.3 GeV
- ✓ Designed luminosity: 1×10^{33} cm^{-2}s^{-1}

2008: test run
2009 – today: BESIII physics runs

BESIII Data sets



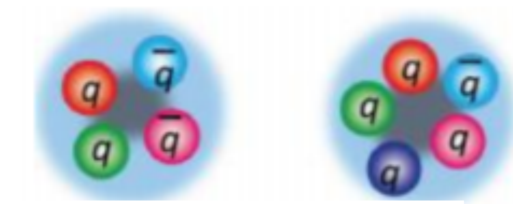
PRD 98 (2018) 030001

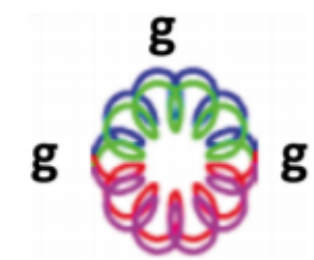
World largest J/ψ, ψ(3686), ψ(3770)

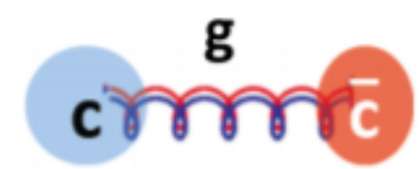
New forms of hardons

- ◈ **In quark model:**

- ◈ **New forms of hardrons in QCD prediction：**
  - **Multi-quark:** quark number >= 4
  - **Hybrid state:** the mixture of quark and gluon
  - **Glueball:** composed of gluons



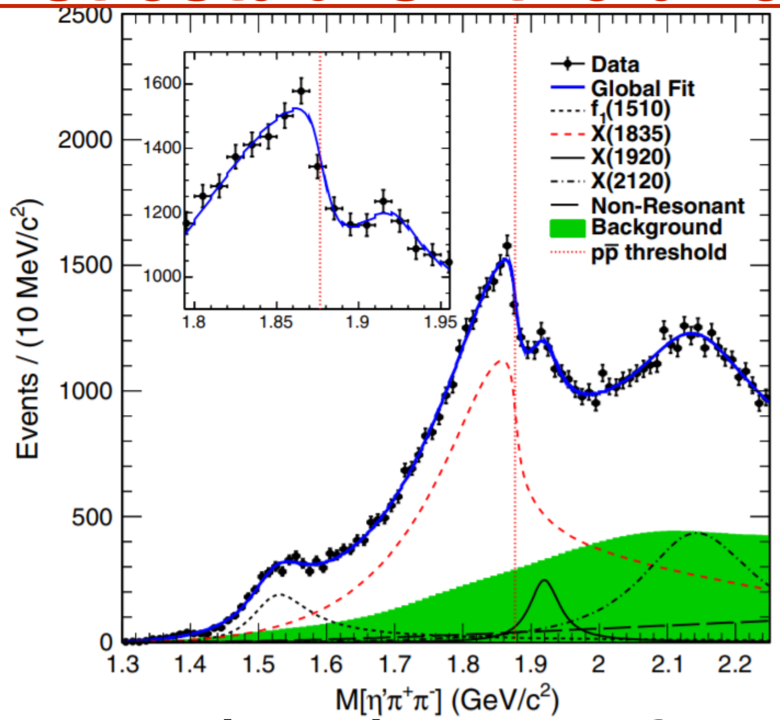


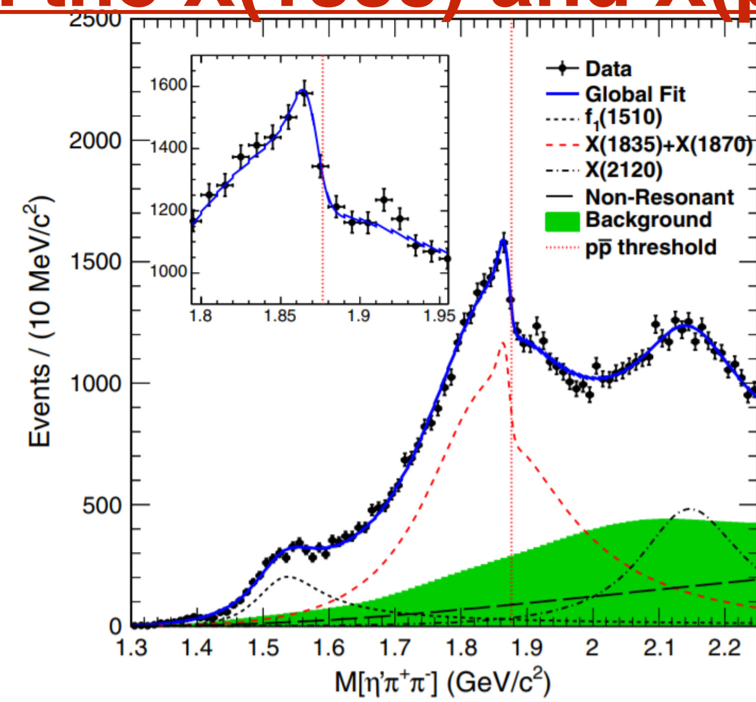


- ◈ **Light hadron spectroscopy is a key tool to test and develop theory. Highlights from BESIII:**
  - **X(1835) / X(ppb) studies**
  - **Search for the glueball**
  - **$a_0(980)$-$f_0(980)$ mixing**
  - **PWA in $\psi(3686)\rightarrow K^+K^-\eta$**

Anomalous $\pi\pi\eta'$ line shape near M_{ppb} threshold

First establish the direct link between the X(1835) and X(ppb)





Model I (9.6σ): Flatte formula

The state around 1.85 GeV/c^2	
$\mathcal{M}$ (MeV/c^2)	$1638.0 \pm 121.9^{+127.8}_{-254.3}$
g_0^2 [(GeV/c^2)^2]	$93.7 \pm 35.4^{+47.6}_{-43.9}$
$g^2_{p\bar{p}}/g_0^2$	$2.31 \pm 0.37^{+0.83}_{-0.60}$
$M_{\rm pole}$ (MeV/c^2)	$1909.5 \pm 15.9^{+9.4}_{-27.5}$
$\Gamma_{\rm pole}$ (MeV/c^2)	$273.5 \pm 21.4^{+6.1}_{-64.0}$
Branching ratio	$(3.93 \pm 0.38^{+0.31}_{-0.84}) \times 10^{-4}$

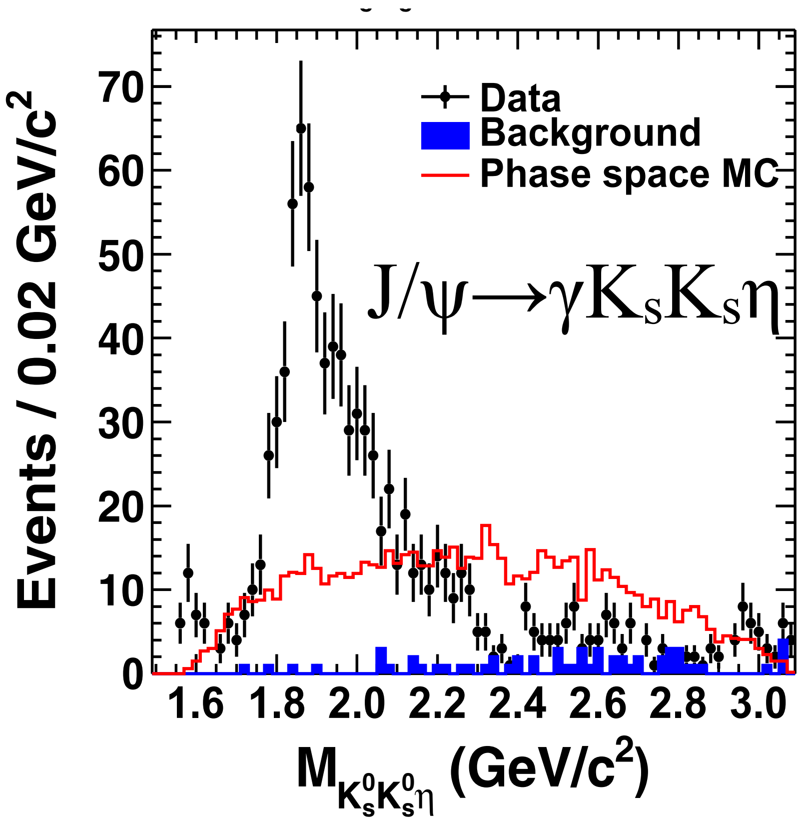
PRL 117, 042002

Model II: 2 resonances

$X(1835)$	
Mass (MeV/c^2)	$1825.3 \pm 2.4^{+17.3}_{-2.4}$
Width (MeV/c^2)	$245.2 \pm 13.1^{+4.6}_{-9.6}$
B.R. (constructive interference)	$(3.01 \pm 0.17^{+0.26}_{-0.28}) \times 10^{-4}$
B.R. (destructive interference)	$(3.72 \pm 0.21^{+0.18}_{-0.35}) \times 10^{-4}$
$X(1870)$	
Mass (MeV/c^2)	$1870.2 \pm 2.2^{+2.3}_{-0.7}$
Width (MeV/c^2)	$13.0 \pm 6.1^{+2.1}_{-3.8}$
B.R. (constructive interference)	$(2.03 \pm 0.12^{+0.43}_{-0.70}) \times 10^{-7}$
B.R. (destructive interference)	$(1.57 \pm 0.09^{+0.49}_{-0.86}) \times 10^{-5}$

- Both models describe data with almost equally good fit quality
- **The ppb threshold structure is a molecule state or a bound state?**

Search for the X(1835) in different decay modes



PRL 115, 091803

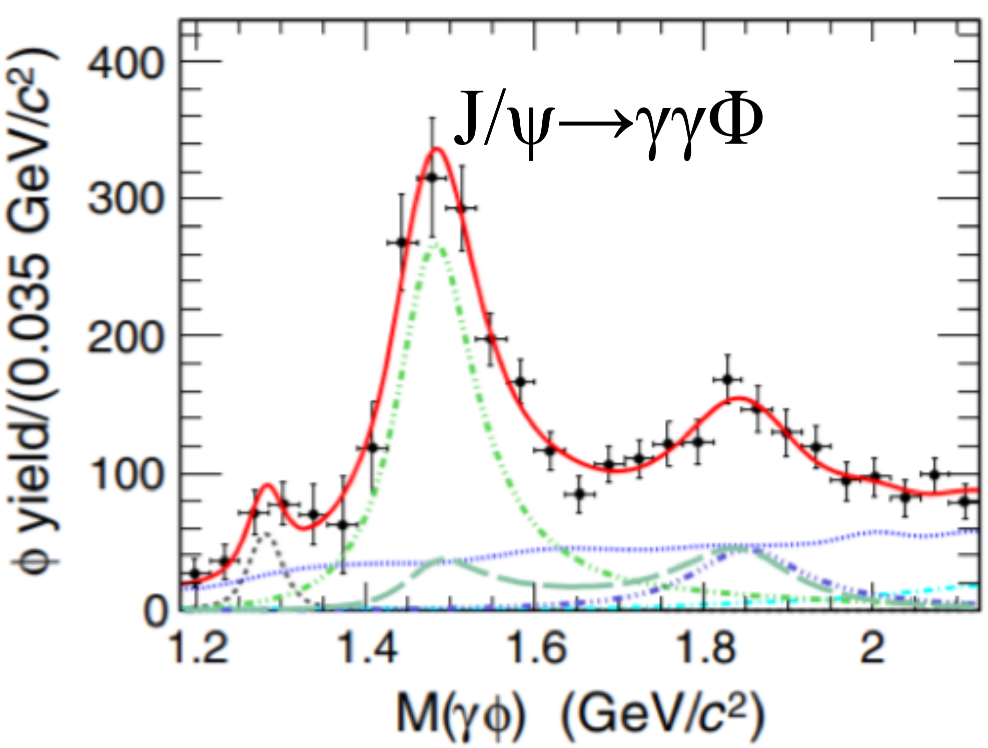
Dominant decays: $X(1835)\to f_0(980)\eta$

M = 1844±9$^{+16}_{-25}$ MeV

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

$B(J/\psi\to\gamma X(1835))B(X(1835)\to f_0(980)\eta)$

$= 3.31^{+0.33}_{-0.30}{}^{+1.96}_{-1.29}\times10^{-5}$



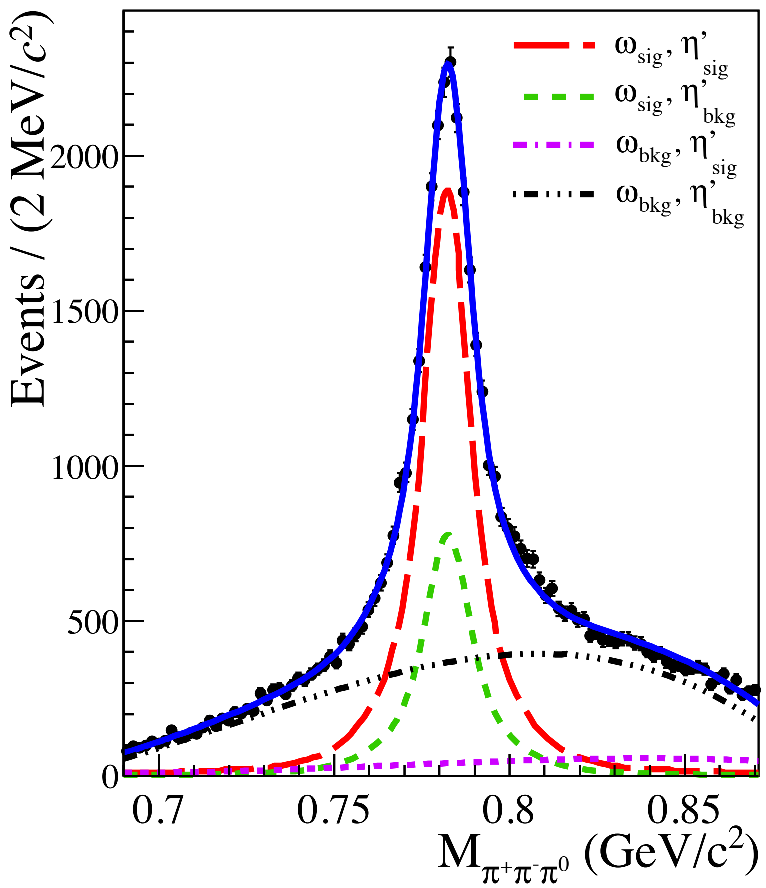
PRD 97, 051101

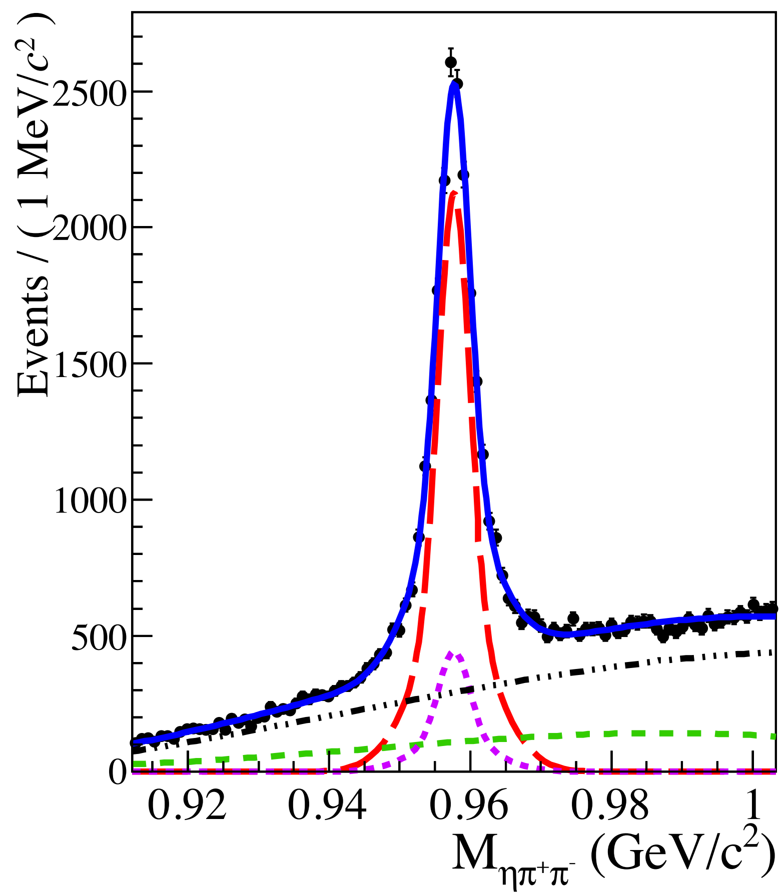
Resonance	m_R (MeV/c^2)	Γ (MeV)	B (10^{-6})
$\eta(1475)$	$1477\pm7\pm13$	$118\pm22\pm17$	$7.03\pm0.92\pm0.91$
$X(1835)$	$1839\pm26\pm26$	$175\pm57\pm25$	$1.77\pm0.35\pm0.25$
$\eta(1475)$	$1477\pm7\pm13$	$118\pm22\pm17$	$10.36\pm1.51\pm1.54$
$X(1835)$	$1839\pm26\pm26$	$175\pm57\pm25$	$8.09\pm1.99\pm1.36$

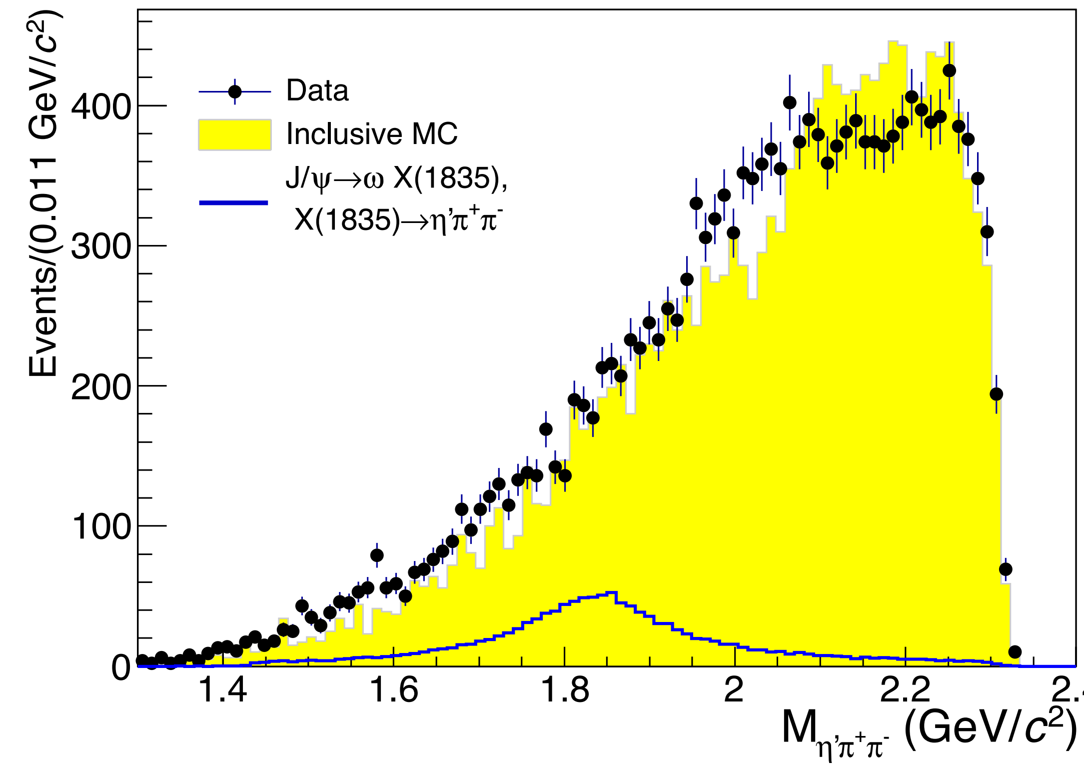
Two solutions with different interference options

The X(1835) may contain a sizable ss component

Search for the X(1835) in J/ψ→ωππη’



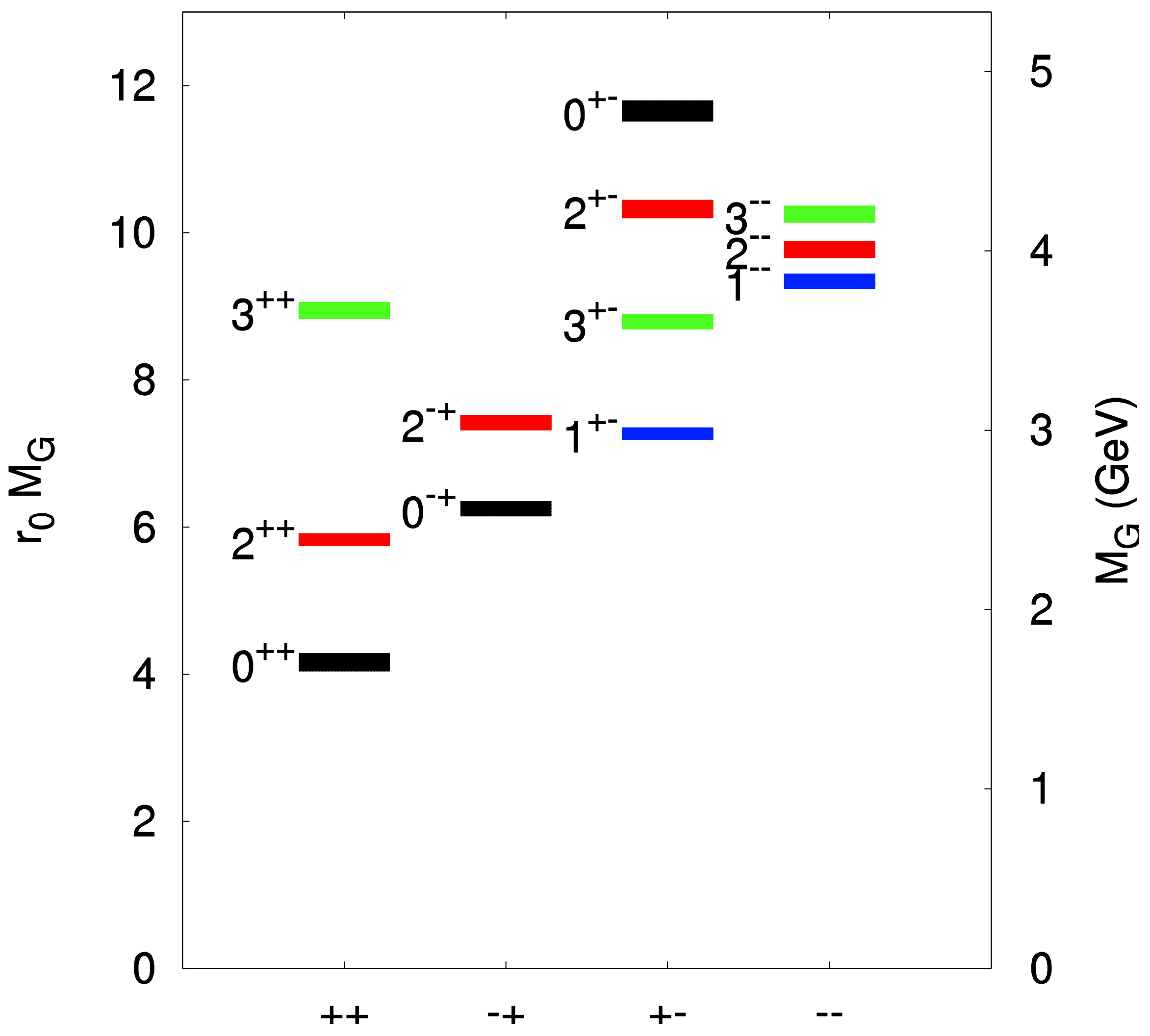




PRD 99 (2019) 071101

- 2-dimension fit is used for the signal extraction.
- No obvious signal of the X(1835), the corresponding B.R. rate is measured: $<6.2\times10^{-5}$ @ 90% CL

Search for glueball



◈ **Possible potential glueball candidates:**

◈ **0^{++}: $f_0(1700)$ $f_0(1500)$**

- $J/\psi \to \gamma\eta\eta$, $\gamma K_S K_S$, $\gamma\pi^0\pi^0$

◈ **0^{-+}: X(2370)**

- $J/\psi \to \gamma\pi\pi\eta'$, $\gamma KK\eta$

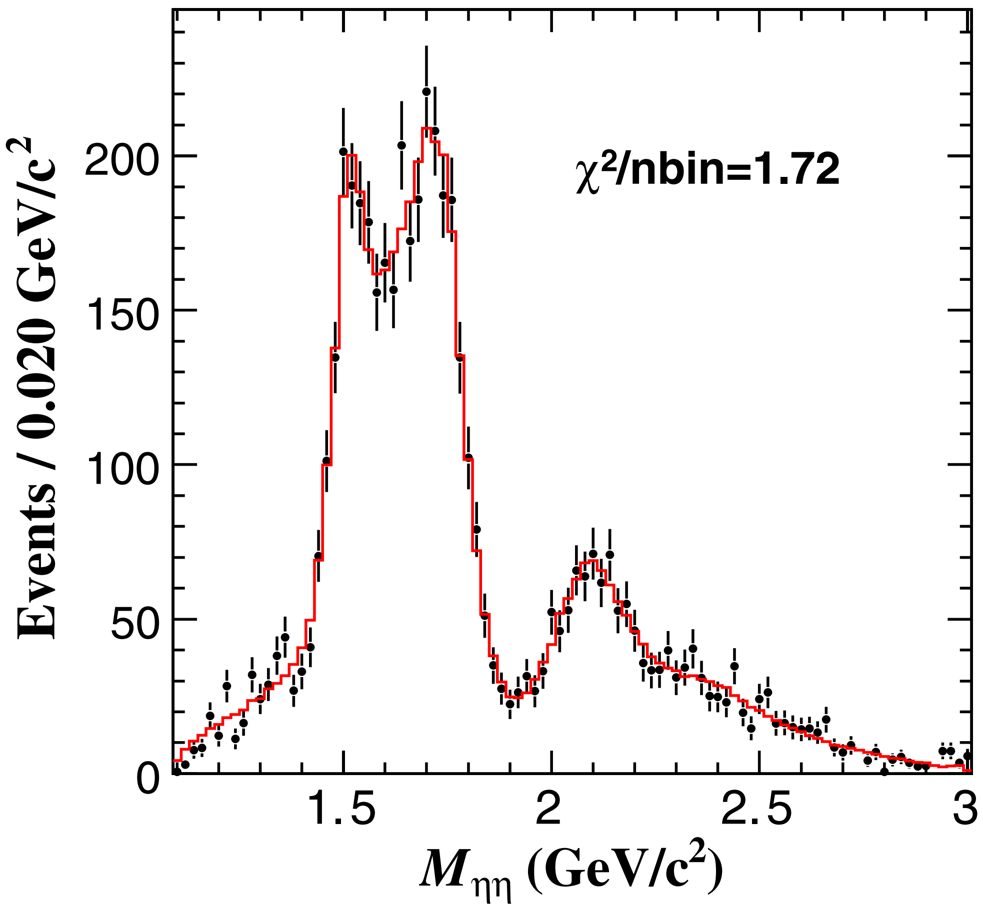
◈ **2^{++}: $f_2(2340)$**

- $J/\psi \to \gamma\eta\eta$, $\gamma K_S K_S$, $\gamma\Phi\Phi$

Radiative J/ψ decays are ideal for searching for glueballs — one of the BESIII advantages with the world largest J/ψ data sample.

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

A good channel for the 0^{++} and 2^{++} state search



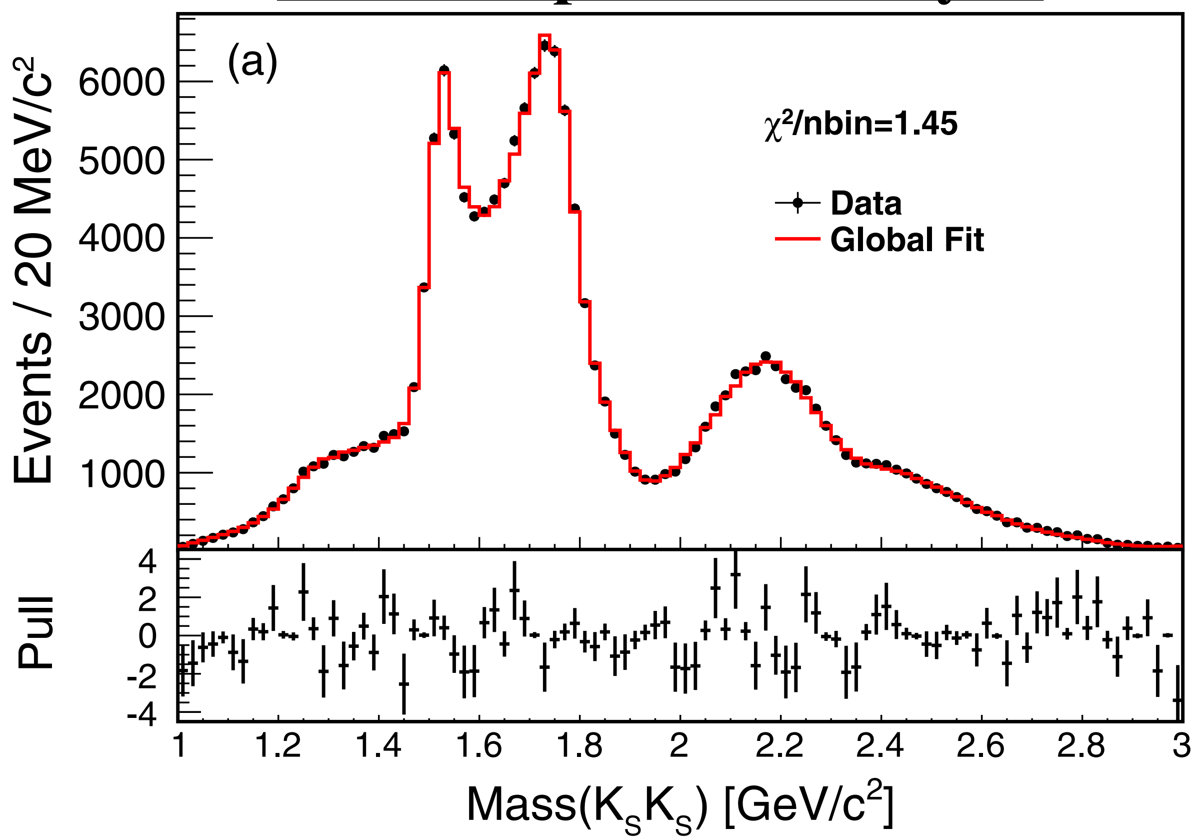
PRD 87 (2013) 092009

- **Large production rate of $f_0(1710)$**
  - Comparable with the LQCD prediction
  - Large overlap with other scale glueball candidates [e.g. $f_0(1500)$]
- **A strong contribution from $f_2(2340)$**: candidate for the lowest lying tensor glueball

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 $J/\psi \to \gamma K_s K_s$

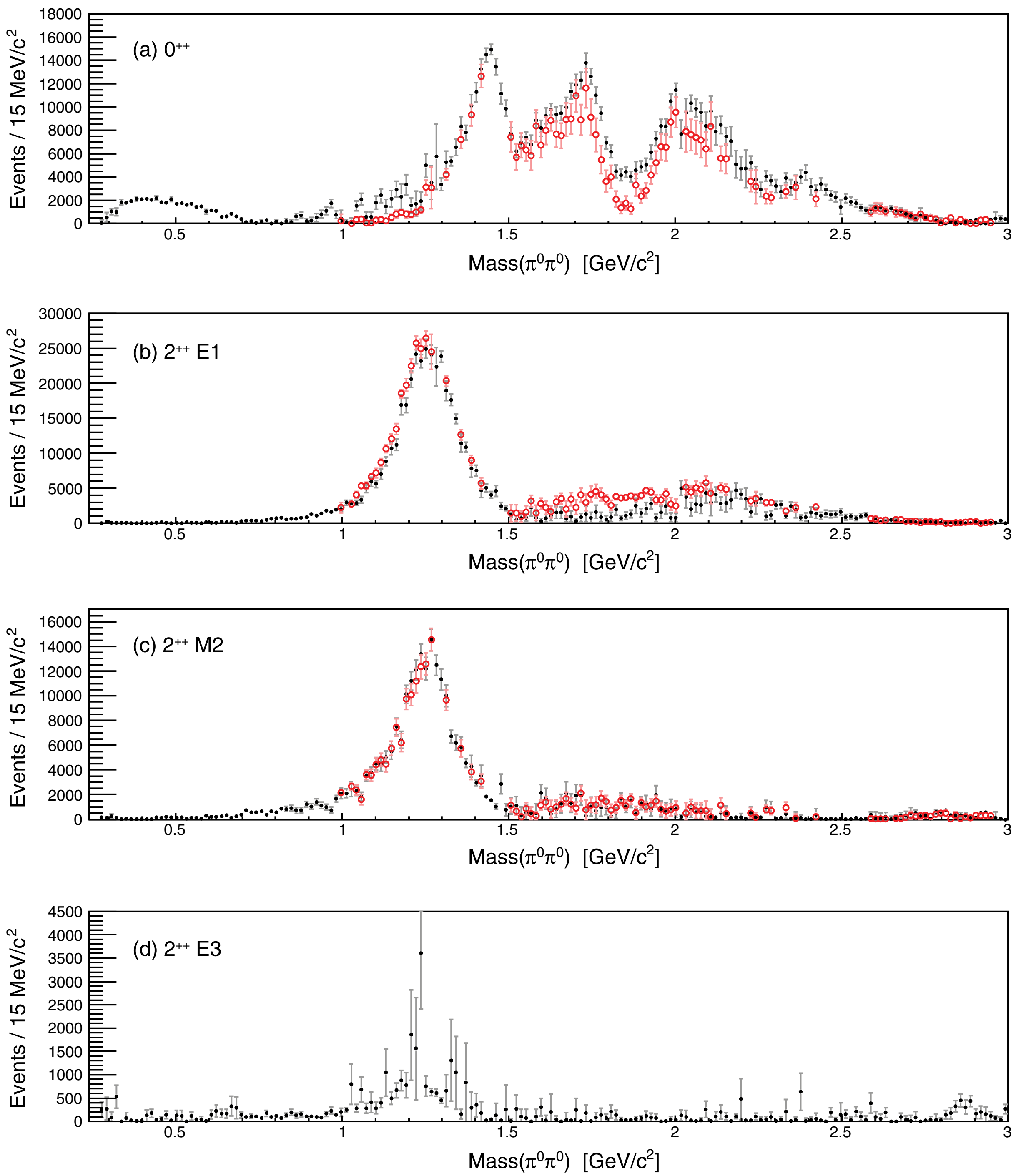
Model dependent analysis



PRD 98 (2018) 072003

Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significanc
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	1200 to 1500	$231 \pm 21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$	25σ
$f_0(1500)$	1505	1504 ± 6	109	109 ± 7	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$	23σ
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	1723^{+6}_{-5}	$146 \pm 3^{+7}_{-1}$	139 ± 8	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$\cdots$	$146 \pm 14^{+7}_{-15}$	$\cdots$	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	$\cdots$	$349 \pm 18^{+23}_{-1}$	$\cdots$	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	35σ
$f_2(1270)$	1275	1275.5 ± 0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$	33σ
$f_2'(1525)$	1516 ± 1	1525 ± 5	$75 \pm 1 \pm 1$	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$	$\gg 35\sigma$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	2345^{+50}_{-40}	$507 \pm 37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$	26σ
0^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

Amplitude analysis of $J/\psi \to \gamma\pi^0\pi^0$

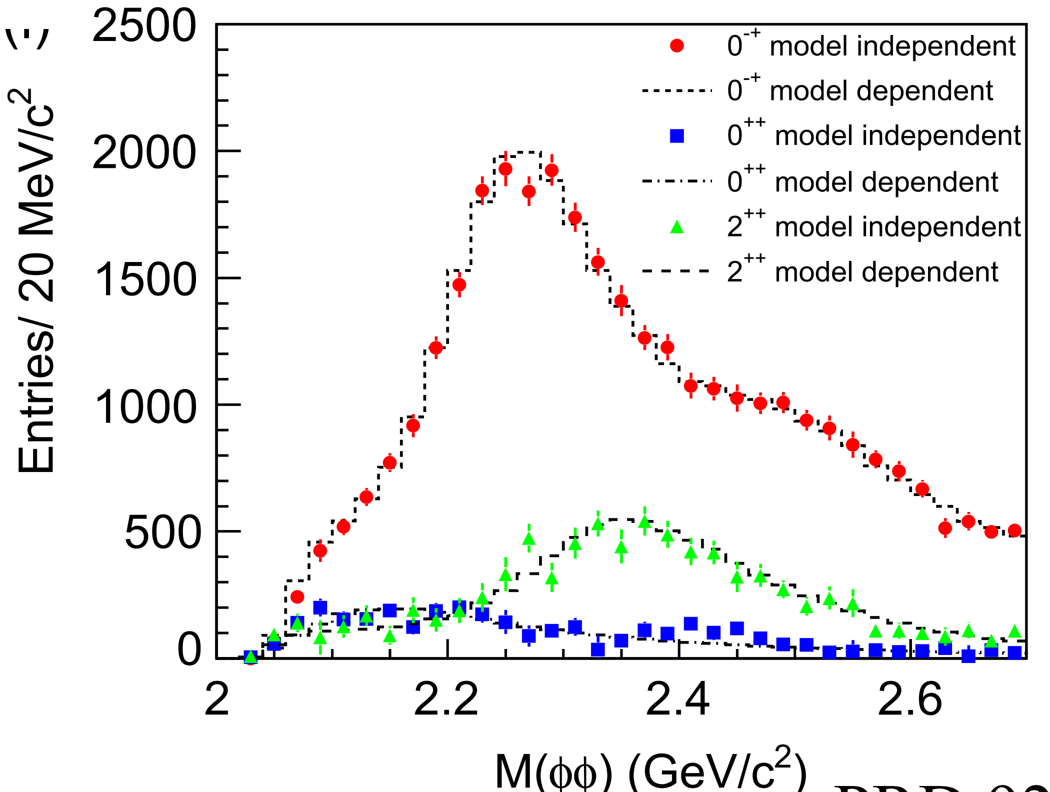


PRD 92 (2015) 052003

- **Model independent analysis**: two distinct sets of solutions above KK threshold.
- Significance structures in the scalar spectrum near **1.5GeV, 1.7GeV (f_0(1500), f_0(1710))**.

PWA of J/ψ→γΦΦ

A good channel for 0^{-+} and 2^{++} state search above 2GeV



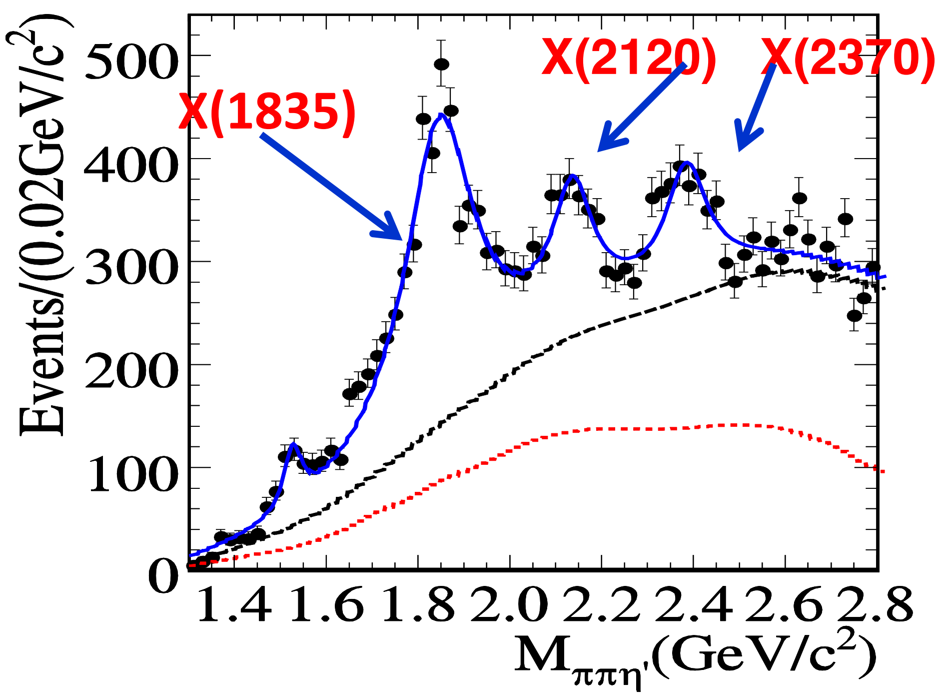
Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}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

PRD 92, (2018) 112011

- 0^{-+} states are dominant
- For $f_2(2340)$, the large production rate is compatible with the LQCD prediction for tensor glueball, similar to that in the J/ψ→γηη, $\gamma K_S K_S$
- X(2500) is observed with 8.8σ

The X(2370)

$J/\psi \to \gamma\pi\pi\eta'$

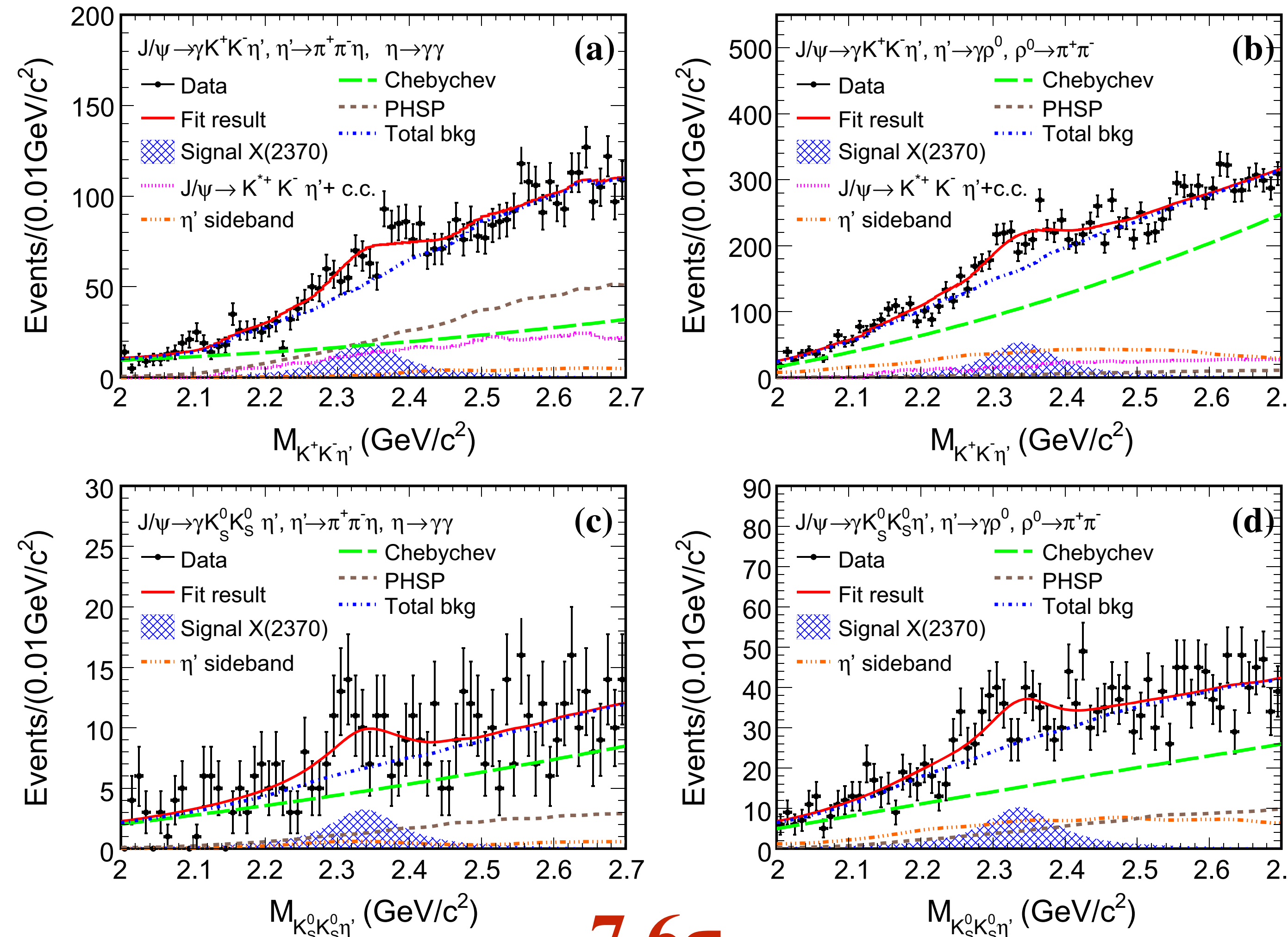


X(2370)	$2376.3 \pm 8.7^{+3.2}_{-4.3}$	$83 \pm 17^{+44}_{-6}$

◈ First observation of the X(2370) in $J/\psi \to \gamma\pi\pi\eta'$

PRL 106, 072002

$J/\psi \to \gamma KK\eta'$



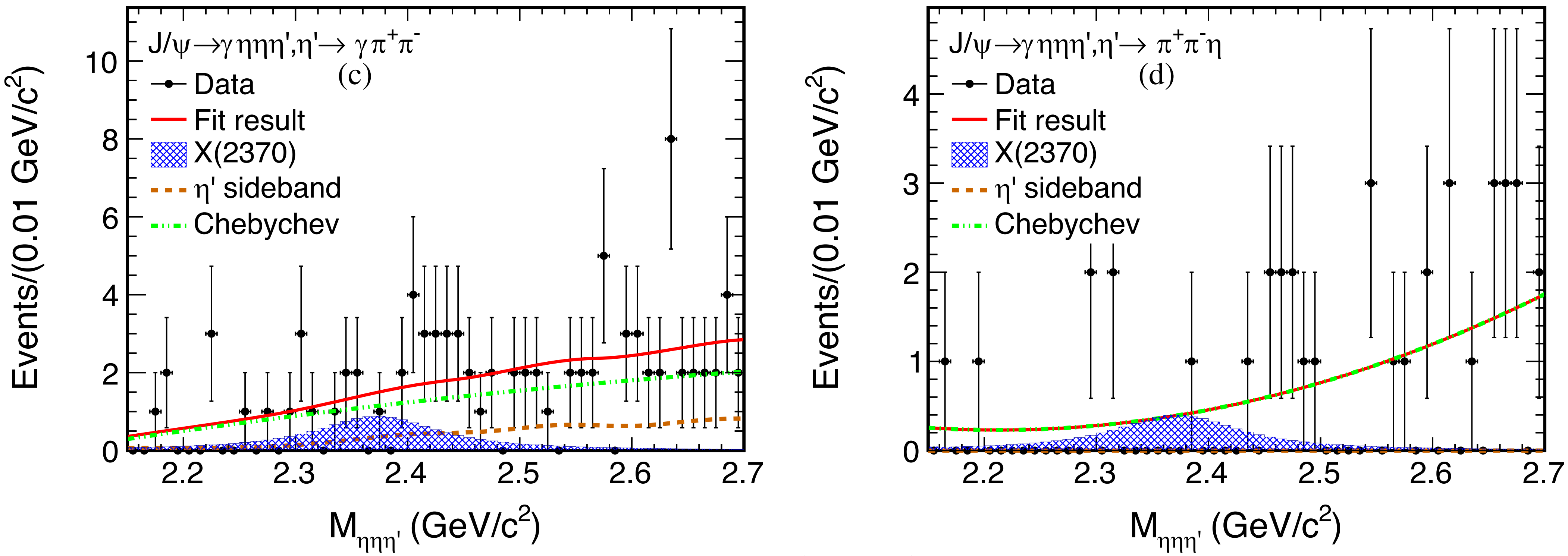
7.6σ

	combined results
M (MeV/c^2)	$2343.91 \pm 6.88(stat.) \pm 1.23(sys.)$
Γ (MeV)	$117.73 \pm 12.75(stat.) \pm 4.14(sys.)$
$B(J/\psi \to \gamma X(2370) \to \gamma K^+K^-\eta')$	$(1.86 \pm 0.39\ (stat.) \pm 0.29\ (sys.)) \times 10^{-5}$
$B(J/\psi \to \gamma X(2370) \to \gamma K_S^0 K_S^0 \eta')$	$(1.19 \pm 0.37\ (stat.) \pm 0.18\ (sys.)) \times 10^{-5}$

EPJC 80 (2020) 746

Explanation from the comparison with LQCD prediction: 0^{-+} glueball candidate

Search for the X(2370) in J/ψ→γηηη'



PRD 103, (2021) 012009

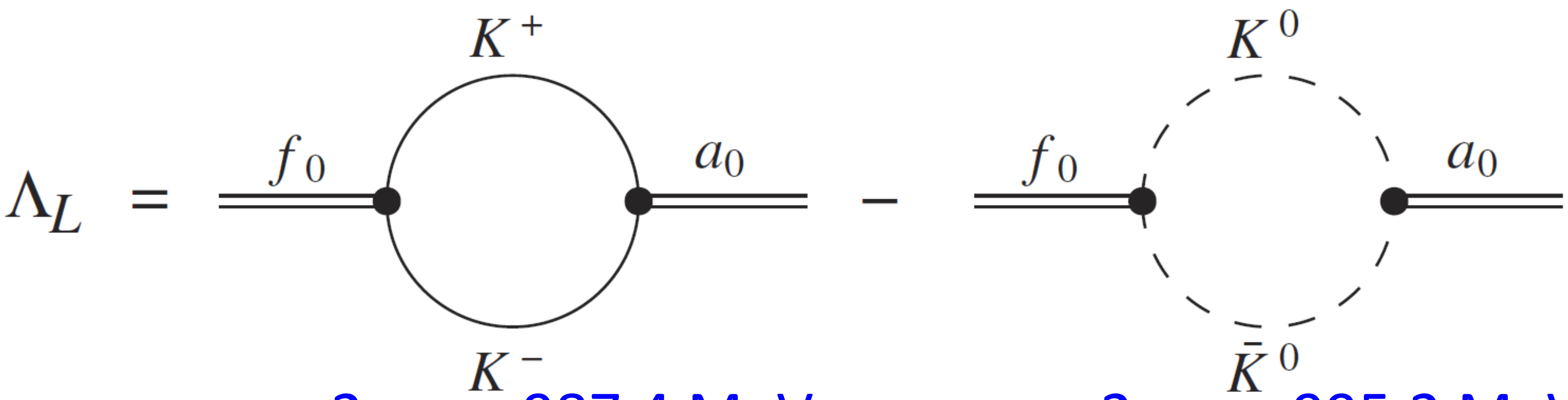
$Br(J/\psi \to \gamma X(2370)) \times Br(X(2370) \to \eta\eta\eta') < 9.2 \times 10^{-6}$ @ 96% CL

- No evident of the X(2370) in the ηηη' mass spectrum
- The upper limit is consistent in the 0^{-+} global assumption of the X(2370)

$a_0(980)$-$f_0(980)$ mixing

N.N. Achasov, S.A. Devanin & G.N. Shestakov, Phys. Lett. B88, 367 (1979)

isospin violation enhanced by $K^0 - K^+$ mass difference

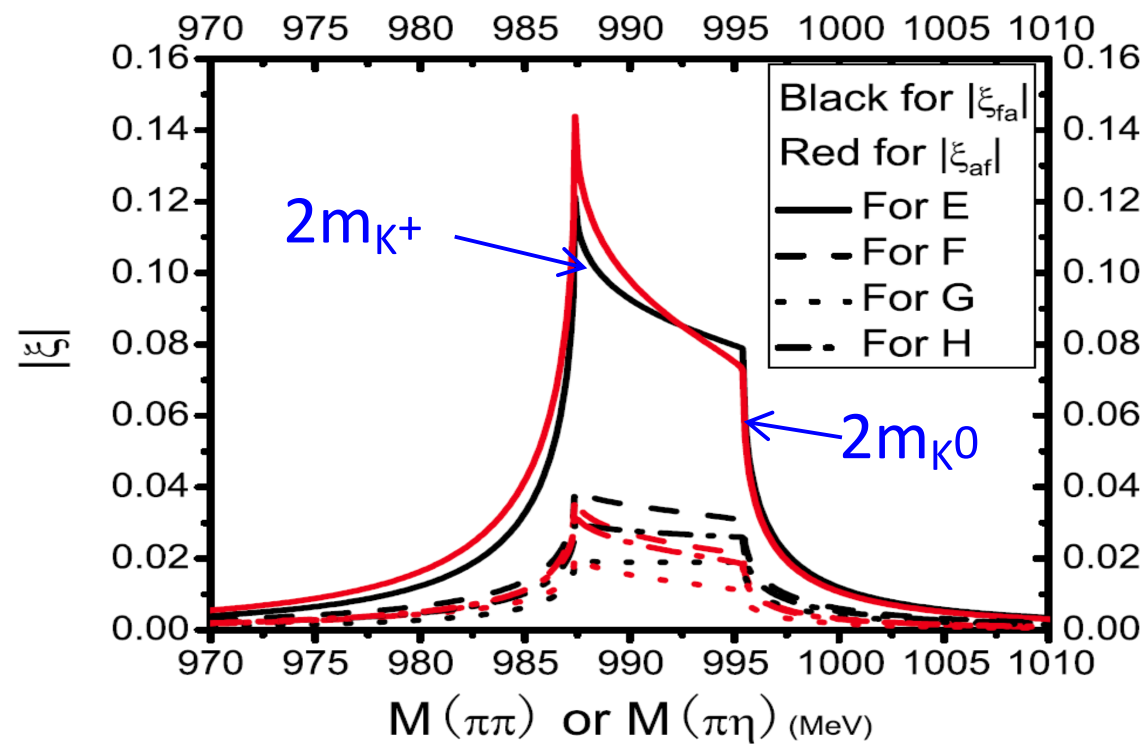


$2m_{K^+}$ = 987.4 MeV

$2m_{K^0}$ = 995.2 MeV

expect a narrow line shape:

$\Gamma \approx 2(m_{K^0} - m_{K^+}) = 7.8$ MeV



PDG2010:

M_{f_0} = 980 ± 10 MeV

Γ_{f_0} = 40 ~ 100 MeV

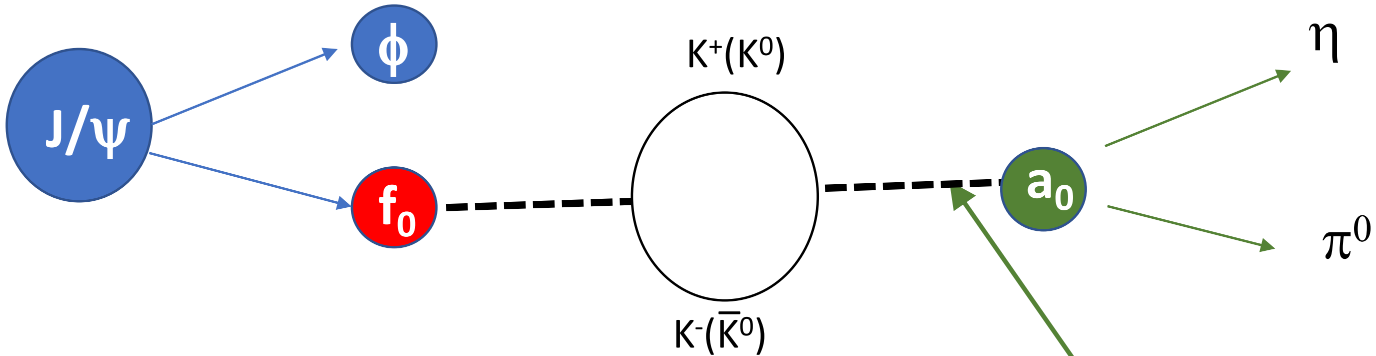
M_{a_0} = 980 ± 20 MeV

Γ_{a_0} = 50 ~ 100 MeV

C. Hanhart, B. Kubis, and J.R. Pelaez, Phys. Rev. D **76**, 074028 (2007)

J.J. Wu and B.S. Zou, Phys. Rev. D **78**, 074017 (2007)

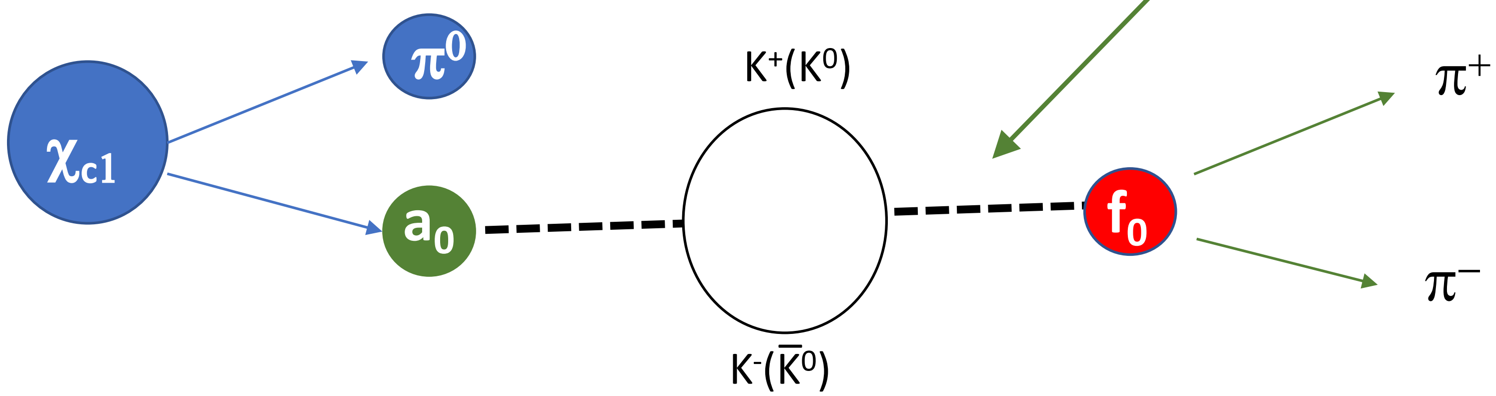
$a_0(980)$-$f_0(980)$ mixing



$$\xi_{fa} = \frac{\mathcal{B}[J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi\eta\pi^0]}{\mathcal{B}[J/\psi \to \phi f_0(980) \to \phi\pi\pi]}$$

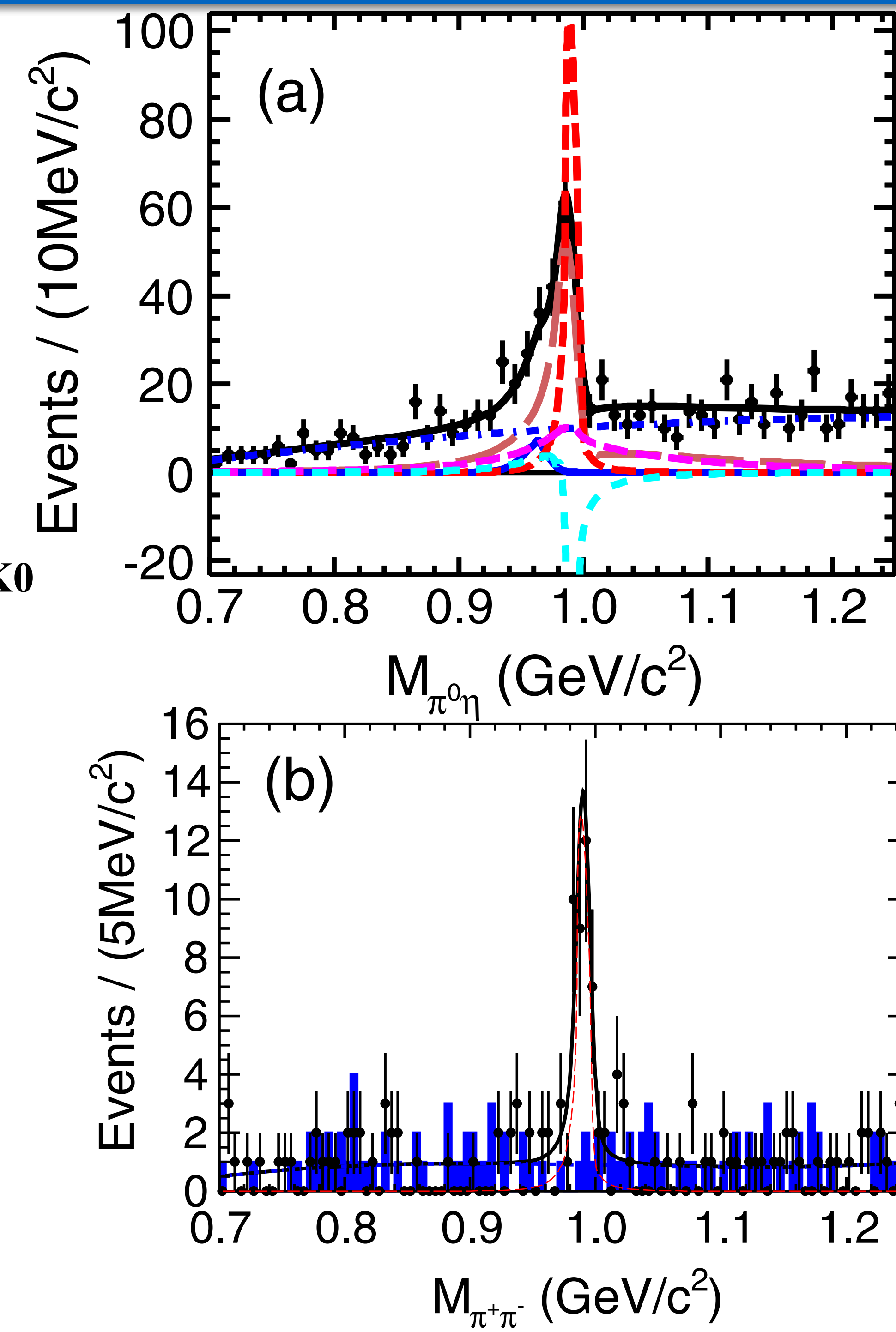
Solution I: 0.99±0.16±0.30+0.09
Solution II: 0.41±0.13±0.17±0.13

$2m_{K^+}<M<2m_{K^0}$



$$\xi_{af} = \frac{\mathcal{B}[\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-]}{\mathcal{B}[\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0\pi^0\eta]}$$

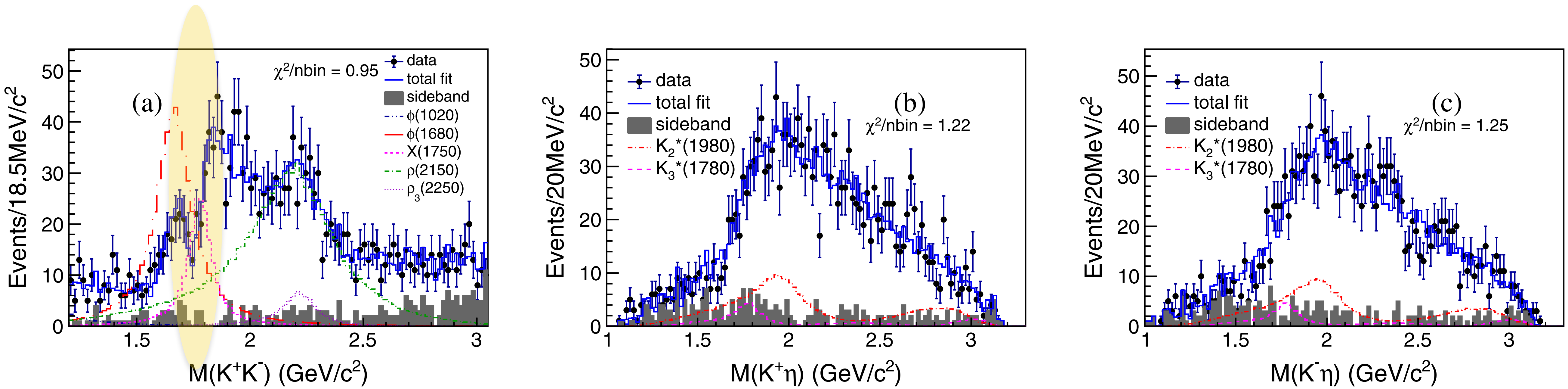
0.40±0.07±0.14±0.07



PRL 121 (2018) 022001

- Include the **interference** between the mixing signal and EM process in the mass fitting.
- **First observation of the $a_0(980)$-$f_0(980)$ mixing** with **7.4σ for $f_0(980)\to a_0(980)$** and **5.5σ for $a_0(980)\to f_0(980)$**

PWA in ψ(3686)→K⁺K⁻η



Resonance	M (MeV/c^2)	Γ (MeV)	Significance
$\phi(1680)$	1680^{+12+21}_{-13-21}	185^{+30+25}_{-26-47}	14.3σ
$X(1750)$	1784^{+12+0}_{-12-27}	106^{+22+8}_{-19-36}	10.0σ
$\rho(2150)$	2255^{+17+50}_{-18-41}	$460^{+54+160}_{-48-90}$	23.5σ
$\rho_3(2250)$	2248^{+17+59}_{-17-5}	$185^{+31+17}_{-26-103}$	8.5σ
$K_2^*(1980)$	2046^{+17+67}_{-16-15}	408^{+38+72}_{-34-44}	19.9σ
$K_3^*(1780)$	1813^{+15+65}_{-15-16}	191^{+43+3}_{-37-81}	11.2σ

PRD 101 (2020) 032008

- The dip ~1.7GeV in the K^+K^- mass spectrum can be well described with the ϕ(1680) and the X(1750)
- The X(1750) is determined to be $J^{PC}= 1^{--}$

Summary

- BESIII detector has successfully collected data samples, including 10billion J/ψ events.

- A set of interesting and important results from the light hadron spectrum achieved:

  - Strong correlation between the X(1835) and mppb threshold enhancement. A molecule state or a bound state?

  - Wide search for the glueball and current glueball candidates (component): $f_0(1710)$, $f_2(2340)$, X(2370)

  - First observation of $a_0(980)$-$f_0(980)$ mixing.

  - The X(1750) was observed with the $J^{PC}=1^{--}$

- With the highest J/ψ dataset, the more extensive and intensive investigation is ongoing, looking forward to new results in the near future.