IFAE 2023
Incontri di Fisica delle Alte Energie

La Fisica di BESIII: risultati recenti e prospettive future

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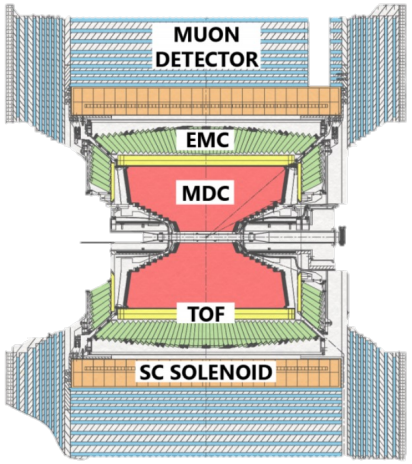
On behalf of the BESIII Collaboration

Catania,
Monastero dei Benedettini
April 12-14, 2023

Università degli Studi di Ferrara

INFN
Istituto Nazionale di Fisica Nucleare

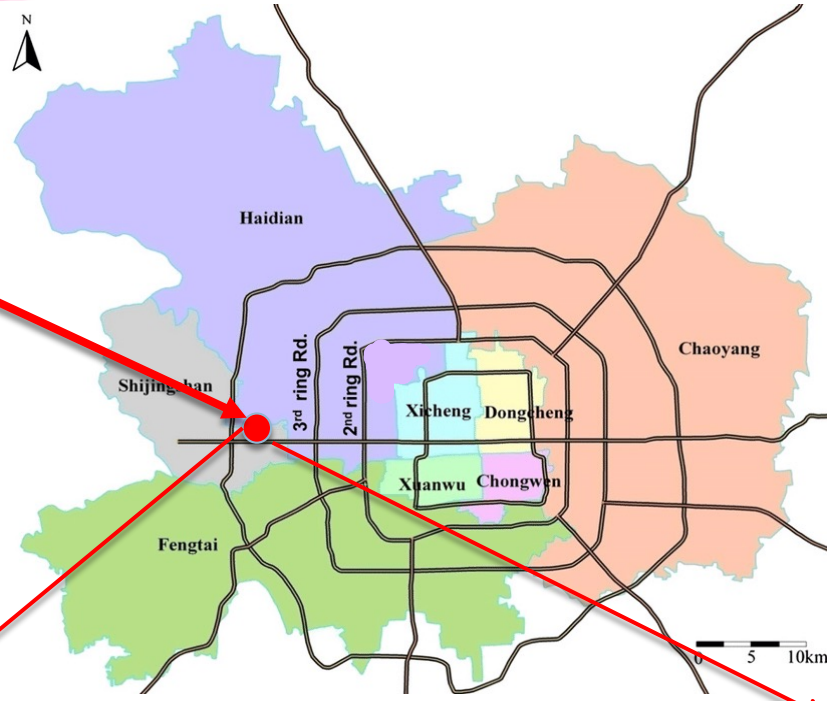
The BESIII experiment @ BEPCII



中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

BESIII

Nucl. Instr. Meth. A614, 345 (2010)



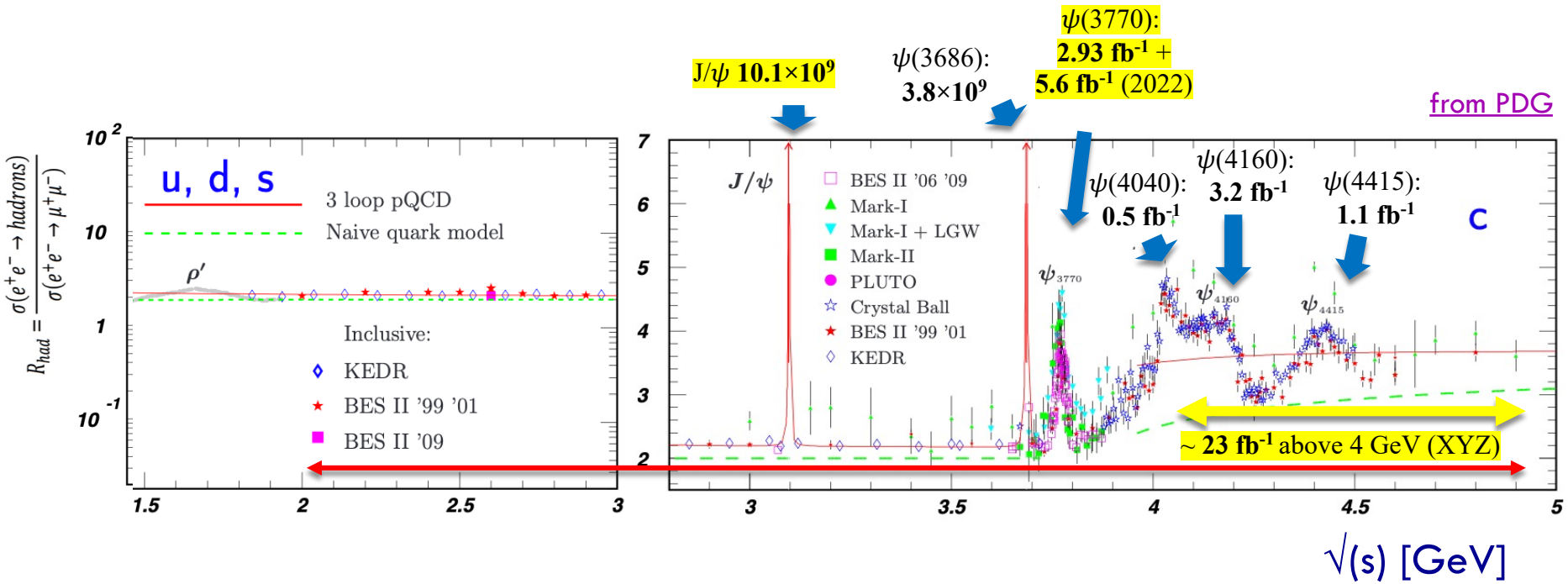
2004: started Beijing Electron Positron Collider II/BESIII construction

- ✓ Double rings
- ✓ Beam energy: 1 - 2.45 GeV
- ✓ Peak luminosity: 1.05×10^{33} cm^{-2}s^{-1} @ $\psi(3770)$ (January 7th, 2023)

2009 – today: BESIII physics runs

BESIII dataset and physics program

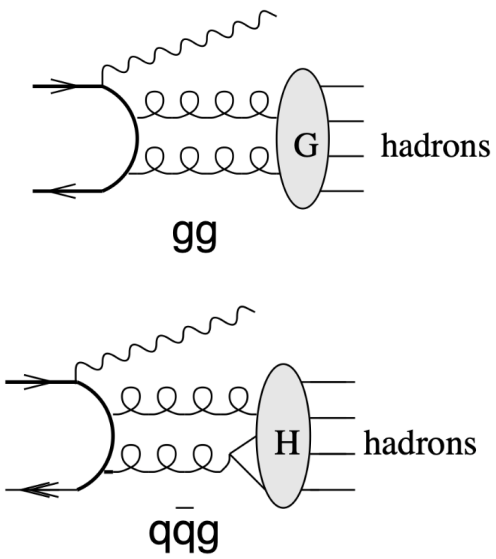
Optimised for flavour physics in the τ-charm region



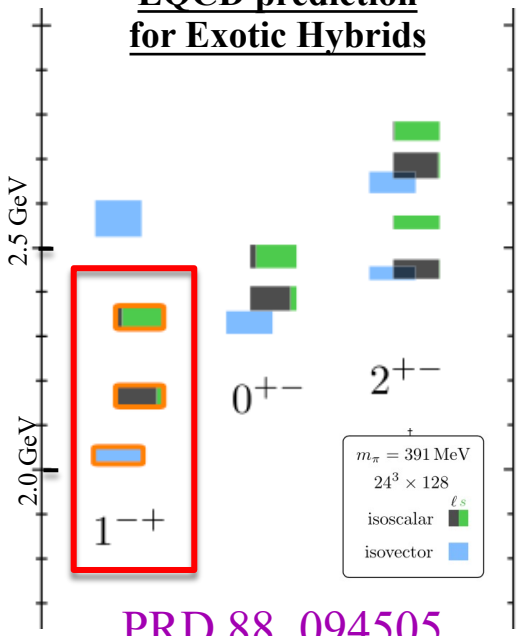
- 130 points between 2 and 4.6 GeV (~715 pb^{-1} up to 3.08 GeV for ρ*, ω*, ϕ*,… studies)
- Light hadron spectroscopy
- η/η' decays
- Hyperon physics
- Charmonium transitions
- D^0D^0pairs
- $D_{(S)}$ meson decays
- $D^*_{(s)}$
- …
- XYZ decays and spectroscopy
- Open charm production
- Charmed baryons
- ...

Hunting for glueballs and new forms of hadrons

- Charmonium radiative decays is the ideal laboratory for light glueballs and hybrids hadron studies (clean, high statistics and gluon-rich process)

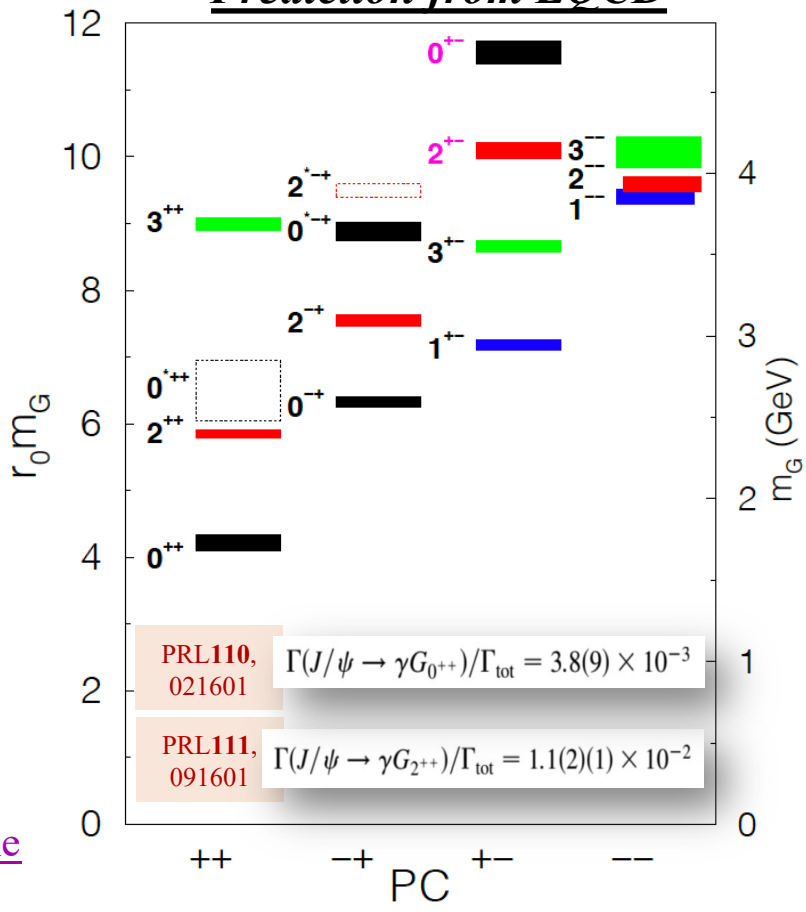


LQCD prediction for Exotic Hybrids



PRD 88, 094505

Prediction from LQCD



https://doi.org/10.1142/S0218301309012124

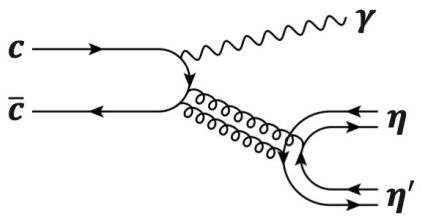
- **Establish the hybrid nonet**:
  - Isovector candidate observed: $\pi_1(1400)$, $\pi_1(1600)$ [the most extensively studied], $\pi_1(2015)$
  - Isoscalar 1^{-+} hybrids can decay to ηη' in P-wave (PRD 83,014021, PRD 83, 014006, Eur.Phys.J.Plus 135, 945)

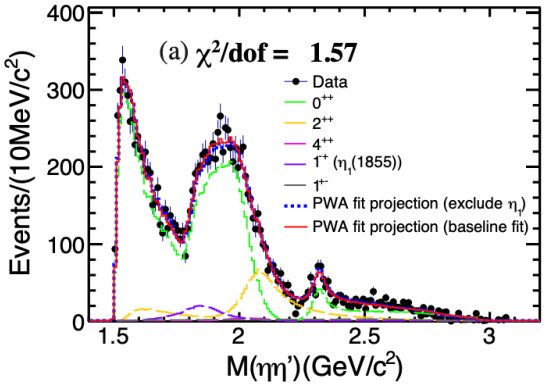
Observation of Exotic Isoscalar State $\eta_1(1855)$ in $J/\psi\to\gamma\eta\eta'$

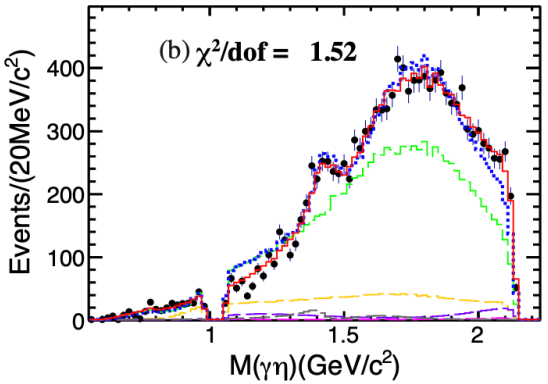
PRL 129, 192002 (2022)
PRD 106,072012 (2022)

PWA of **$J/\psi\to\gamma\eta\eta'$** using 10 Billion of J/ψ data @ BESIII

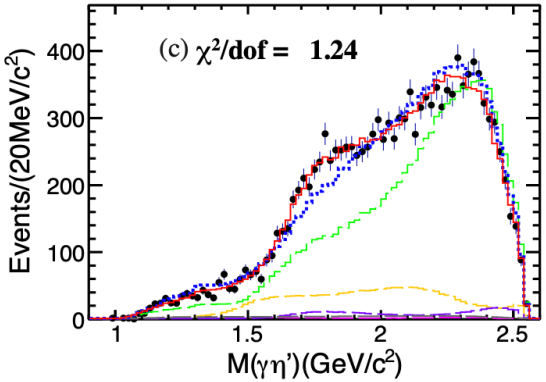
- $\eta\to\gamma\gamma$ and $\eta'\to\gamma\pi^+\pi^-$/ $\eta\pi^+\pi^-$

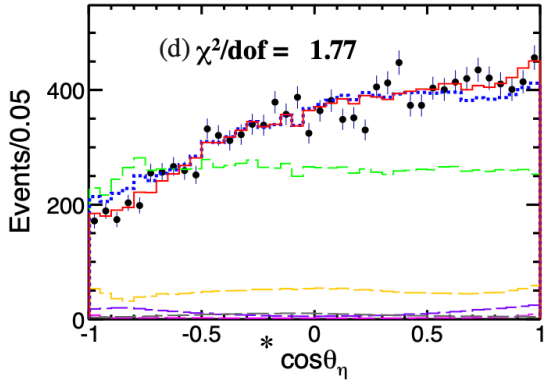






- An isoscalar 1^{-+} state, $\eta_1(1855)$, has been observed with statistical significance larger than 19σ
- Mass is consistent with LQCD calculation for the 1^{-+} hybrid (1.7 – 2.1 GeV/c^2)





*spin information

$$M = (1855 \pm 9^{+6}_{-1})\,\mathrm{MeV}/c^2; \quad \Gamma = (188 \pm 18^{+3}_{-8})\,\mathrm{MeV}$$

$$\mathcal{B}(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$$

Further Checks on the $\eta_1(1855)$

PRL 129, 192002 (2022)
PRD 106,072012 (2022)

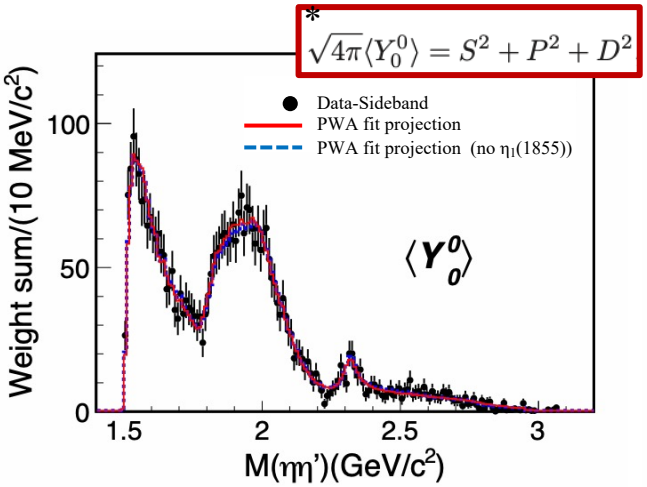
The $\cos(\theta_\eta)$ distribution can be expressed as an expansion in terms of Legendre polynomials; the coefficients (unnormalized moments of expansion) characterize the spin of the ηη' resonances

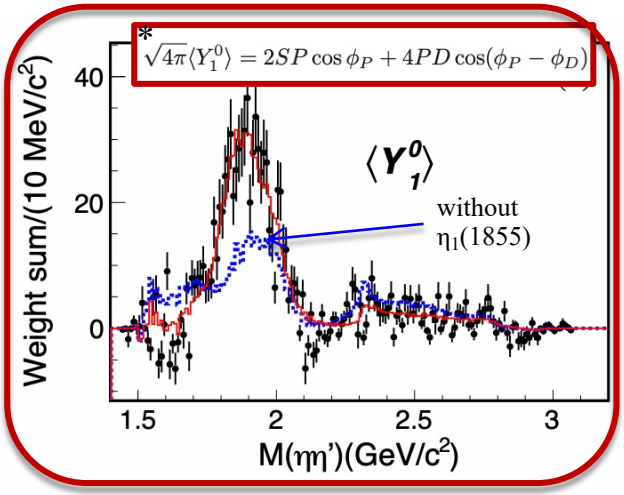
$$\langle Y_l^0 \rangle \equiv \sum_{i=1}^{N_k} W_i Y_l^0(\cos\theta_\eta^i).$$

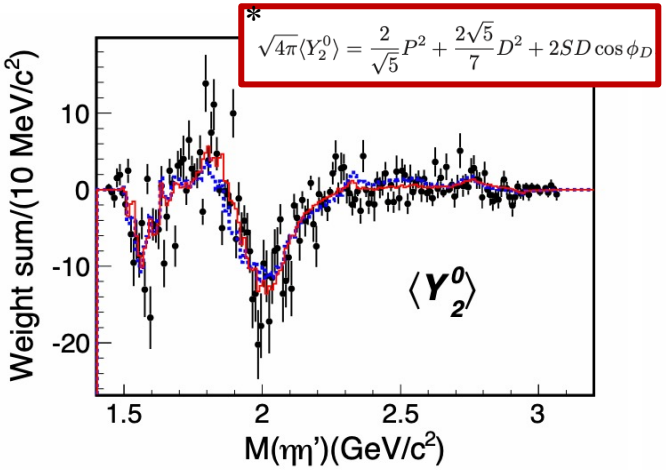
- Neglecting resonance contributions in the $\gamma\eta^{(')}$ subsystem and amplitude with spin greater than 2, the moments are related to the spin-0 (S), spin-1 (P) and spin-2 (D) amplitudes

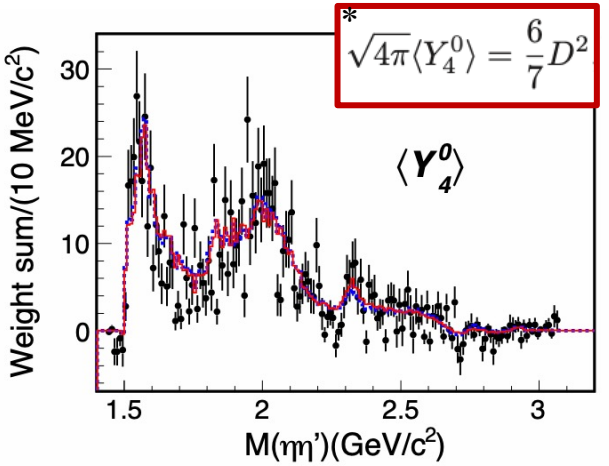
- Good data/PWA consistency
- Narrow structure in $\langle Y^0_1 \rangle$: $\eta_1(1855)$ P-wave component is needed

*Assuming ηη' system has zero helicity









Discussion about $f_0(1500)$ and $f_0(1710)$

The dominant contributions in the baseline PWA are from scalar resonance:

PRL 129, 192002 (2022)
PRD 106,072012 (2022)

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	-	-	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	2011	202	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

$$\frac{\mathcal{B}(f_0(1500)\to\eta\eta')}{\mathcal{B}(f_0(1500)\to\pi\pi)} = \frac{\cancel{(8.96^{+2.95}_{-2.87}\times10^{-2})}}{(1.66^{+0.42}_{-0.40}\times10^{-1})}\ *$$

Consistent with PDG

$$\frac{\mathcal{B}(f_0(1710)\to\eta\eta')}{\mathcal{B}(f_0(1710)\to\pi\pi)} < \frac{\cancel{1.61\times10^{-3}}}{2.87\times10^{-3}}\ *$$

@90% C.L.

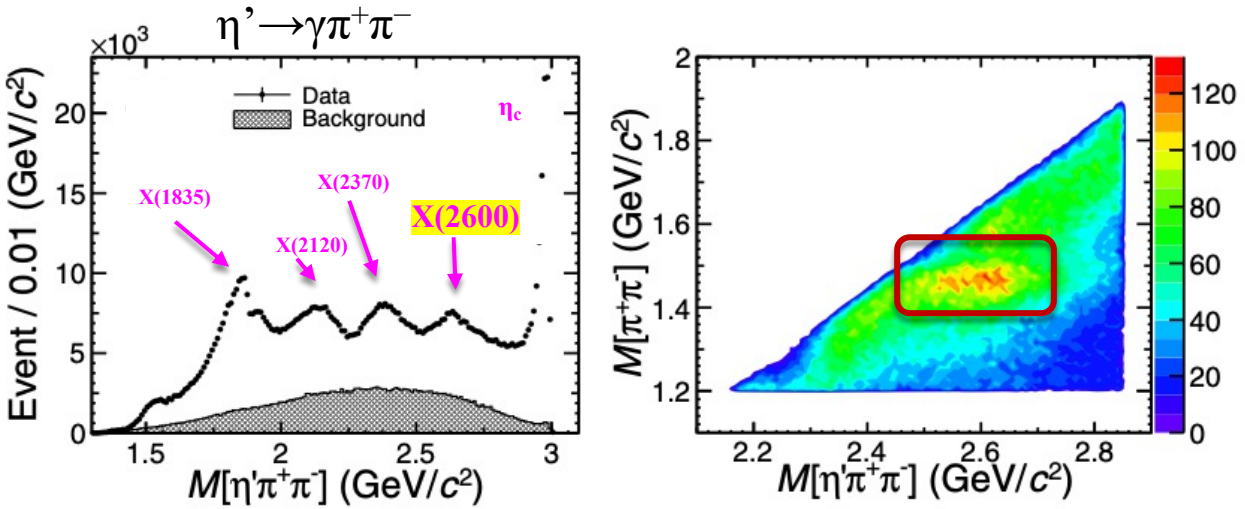
This suppressed decay rate supports the hypothesis that the $f_0(1710)$ has a large overlap with the ground state scalar glueball (PRD 92,121902)

*Erratum ready soon

X(2600): A New State Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

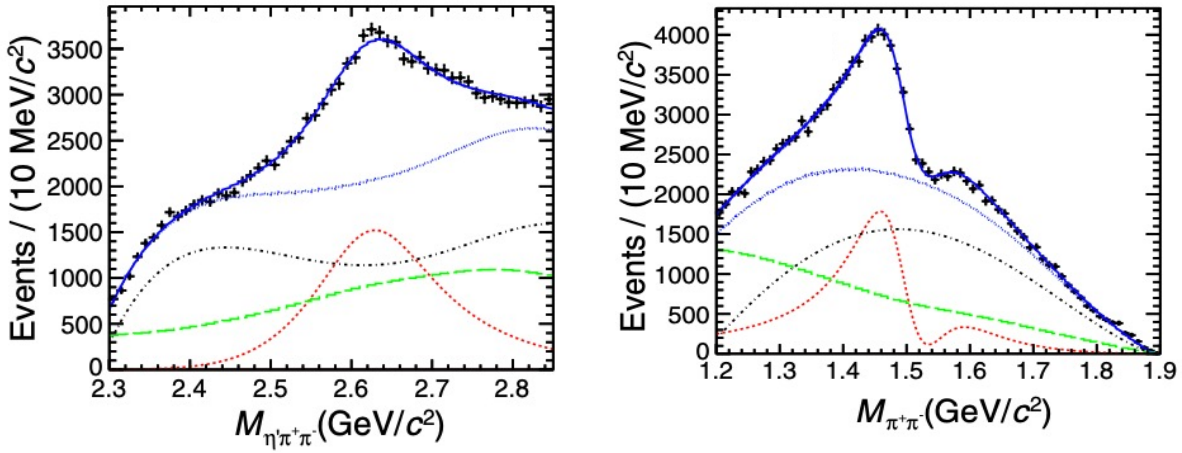
10 Billion of J/ψ data @ BESIII ($\eta' \to \gamma\pi^+\pi^-/\eta\pi^+\pi^-$)

PRL 129, 042001 (2022)



A new state in $M(\eta'\pi^+\pi^-)$ invariant mass is observed around 2.6 GeV/c^2, which is correlated to a structure in $M(\pi^+\pi^-)$ @ 1.5 GeV/c^2

- Simultaneous fit to $\eta'\pi^+\pi^-$ and $\pi^+\pi^-$ mass spectra:

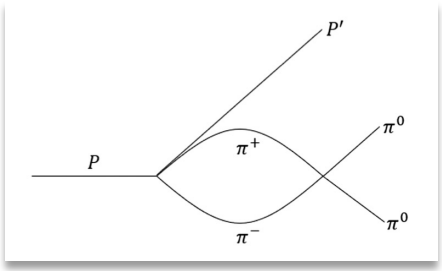


- X(2600): observed for the first time with a statistical significance greater than 20σ
- The structure in $M(\pi^+\pi^-)$ around 1.5 GeV/c^2 well described with the interference between $f_0(1500)$ and the X(1540) resonances

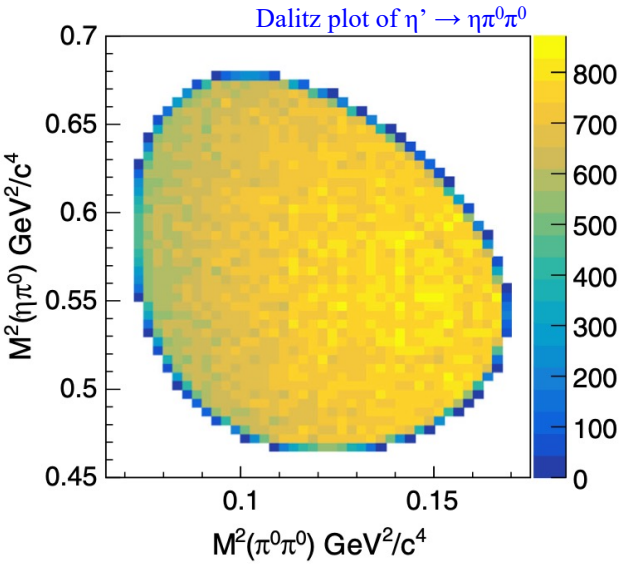
Cusp Effect in $\eta' \to \eta\pi^0\pi^0$

The S-wave charge-exchange rescattering $\pi^+\pi^- \to \pi^0\pi^0$ causes a prominent cusp at the center of mass energy corresponding to the summed mass of two charged pions

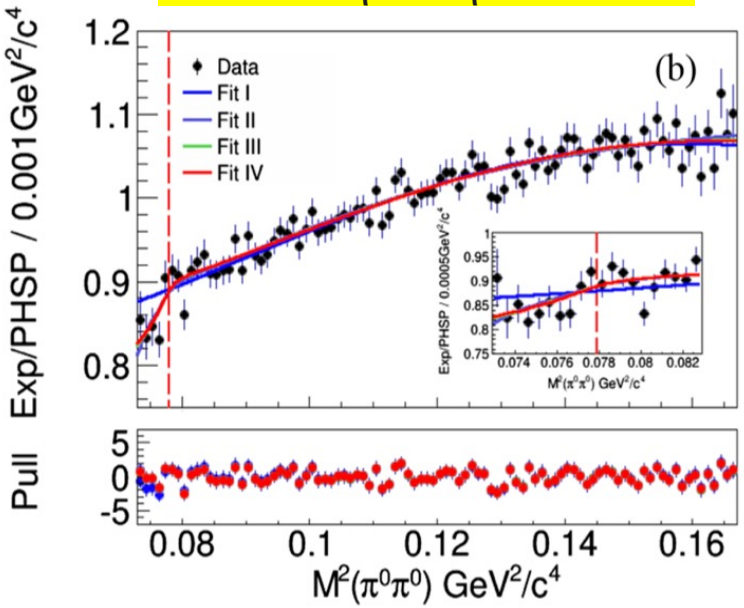
The cusp effect can shed light on the fundamental properties of QCD at low energies, by determining the strength of the S-wave $\pi\pi$ interaction



PRL 130, 081901 (2023)



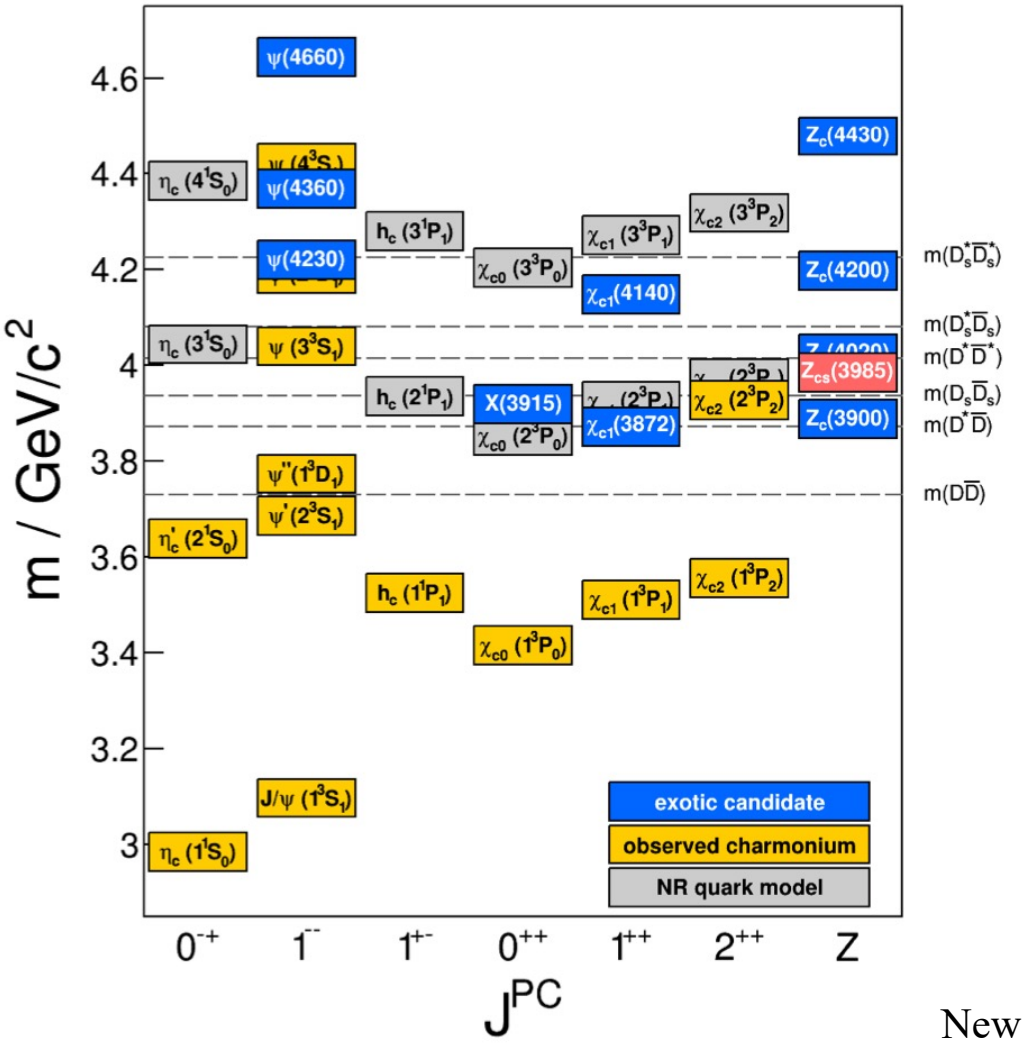
4.3×10^5 $\eta' \to \eta\pi^0\pi^0$ events



Fit to the Dalitz plot within the framework of NREFT

- one-loop and two-loop contributions needed to describe the data
- Statistical significance of about 3.5σ
- Excellent potential to investigate the underlying dynamics of light mesons

The Charmonium System



Conventional charmonia fit well with potential model calculations

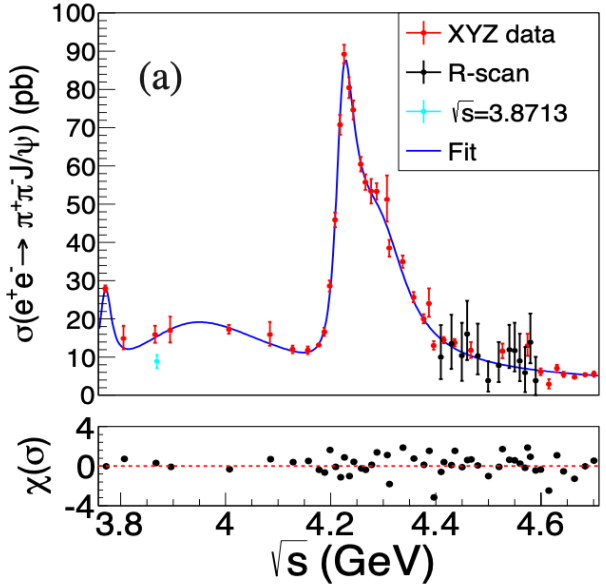
$$V_{c\bar{c}} = -\frac{4}{3}\cdot\frac{\alpha_s(r)}{r} + k\cdot r$$

+ spin-dependent terms

Several unexpected states observed

New naming scheme proposed from PDG and LHCb

Vector states

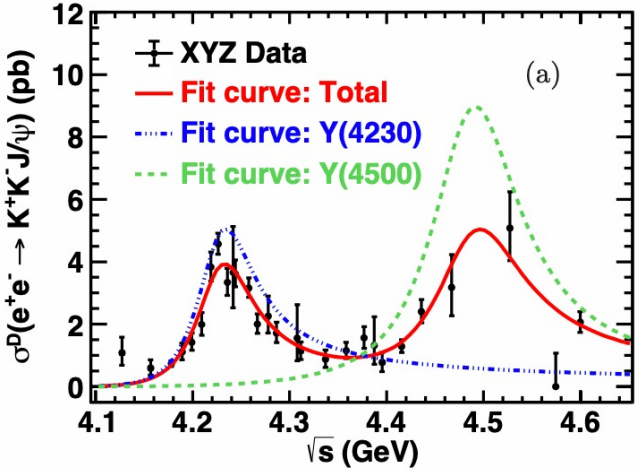


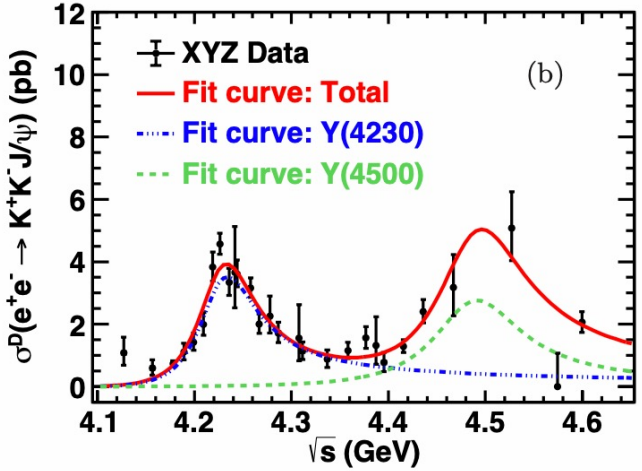
Y(4260) first seen by BaBar (PRL95, 142001); split into to states Y(4230) and Y(4360) by BESIII

PRD106, 072001 (2022) $e^+e^- \to \pi^+\pi^- J/\psi$

- **Improved** precision w.r.t previous results PRL118, 092001
- Y(4220) and Y(4320) resonances are observed with > 10σ
- Structure around 4.0 GeV is better described using a BW
- Evidence of additional structure around 4.5 GeV, identified with the $\psi(4415)$
  - it influences the evaluation of the Y(4230) parameters

Chin.Phys.C46, 111002 (2022) $e^+e^- \to K^+K^- J/\psi$



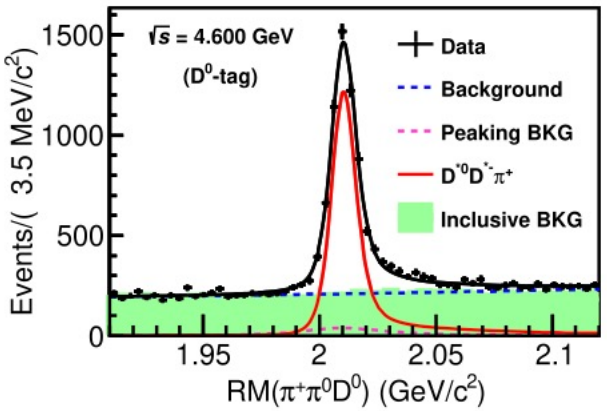


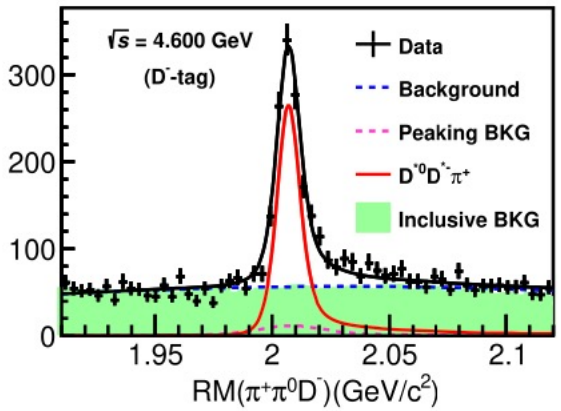
- Observation of the **Y(4230)** with >5σ and **new structure Y(4500)** with >8σ
- related analysis: $e^+e^- \to K_S^0 K_S^0 J/\psi$ (arXiv:2211.08561)

Vector states: $e^+e^- \to D^{*0}D^{*-}\pi^+$

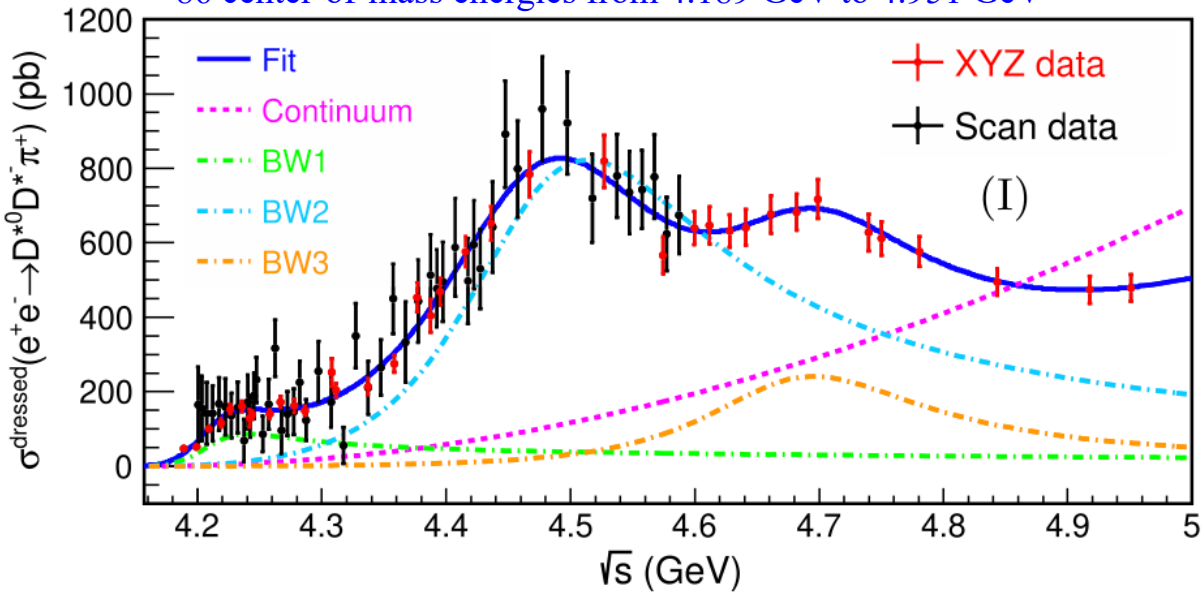
PRL130, 121901(2023)

- Three charmonium-like structures found in open-charm final state
- Fit to the dressed cross section line shape: coherent sum of a continuum and three resonance amplitudes



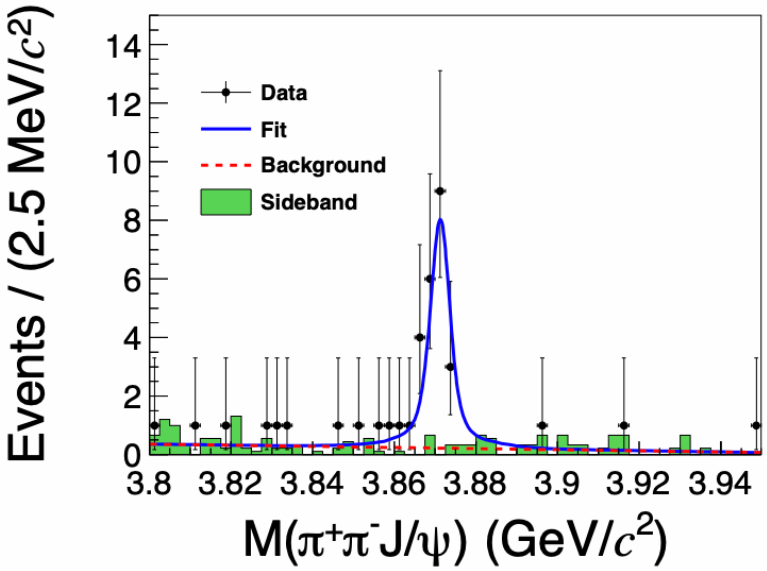


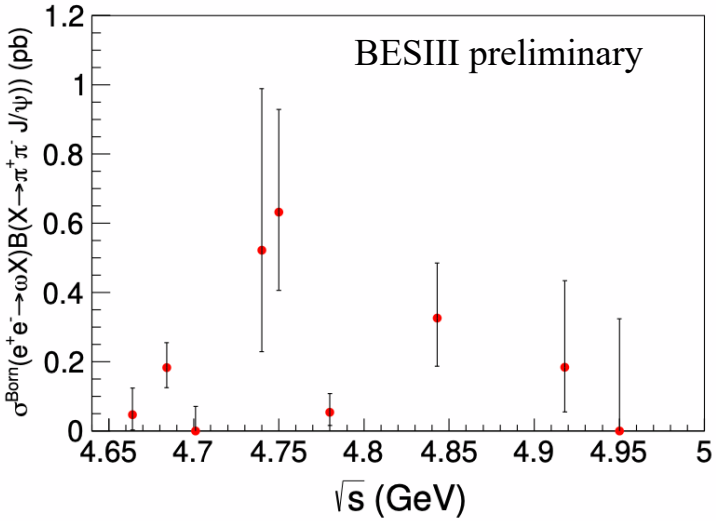
86 center-of-mass energies from 4.189 GeV to 4.951 GeV



- Left and right structures consistent with Y(4230) and Y(4660)
- Would disfavor hybrid interpretation of Y(4230)
- First observation of Y(4660) in open charm final states
- Center structure compatible with Y(4500) → inconsistent with hidden strangeness tetraquark nature

New X(3872) production process $e^+e^- \to \omega X(3872)$





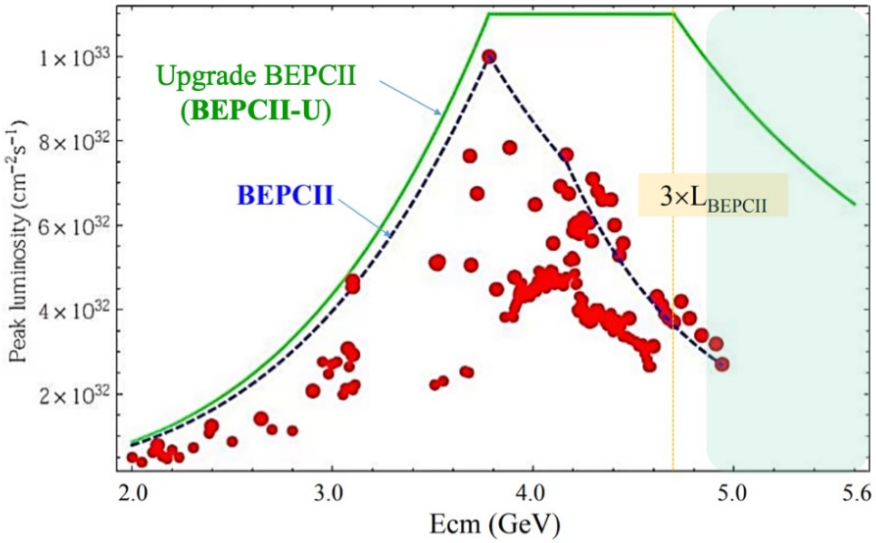
arXiv:2212.07291 (accepted by PRL)

- 4.7 fb^{-1} with $\sqrt{s}$ between 4.661 GeV and 4.951 GeV
- First observation of new production mechanism for X(3872) at 7.5σ
- Suggests X(3872) has some $\chi_{c1}(2P)$ component
- Born cross section and corresponding UL extracted: enhancement around 4.75 GeV indicating that the ωX(3872) signals may be from decays of some non-trivial structure
  - further study required

Conclusions

BESIII experiment is an excellent laboratory to study light hadron physics, charmonium and charm physics, QCD and τ studies, XYZ meson searches and studies, ….

- BESIII is taking data since 2008. It will continue to run ~2030
- Selection of latest physics results (based mainly on spectroscopy) are presented
  - $\eta_1(1855)$, X(2600) in J/ψ radiative decays, cusp effect in $\eta' \to \eta\pi^0\pi^0$
  - Y states and new X(3872) production process
  - …. Many others not covered in this talk
  - Many analysis in progress!!!



- Further upgrade in energy (5.6 GeV) and luminosity (BEPCII-U, 3x) planned for the next year
- Inner MDC ➔ CGEM-IT

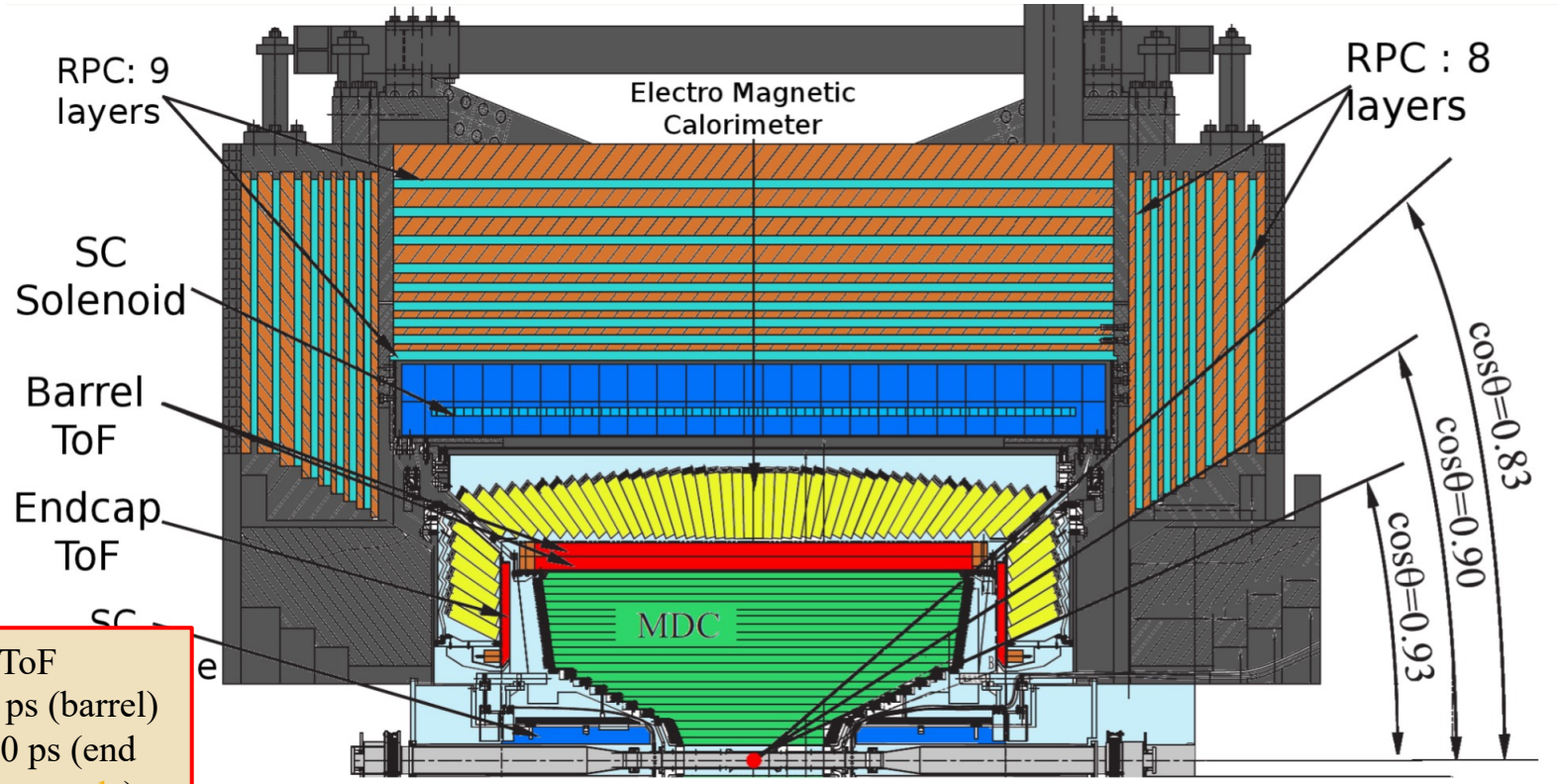
More interesting results are expected

Thank you for your attention

Back-up slides

The BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)



ToF
σ_t ~ 68 ps (barrel)
σ_t ~ 60 ps (end caps, upgrade)

Drift Chamber
$\sigma_{r\phi}$ ~ 130 μm (single wire)
σ_{pt}/p_t ~ 0.5 % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
σ_{xy} ~ (6 mm)/$E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi$=93%

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

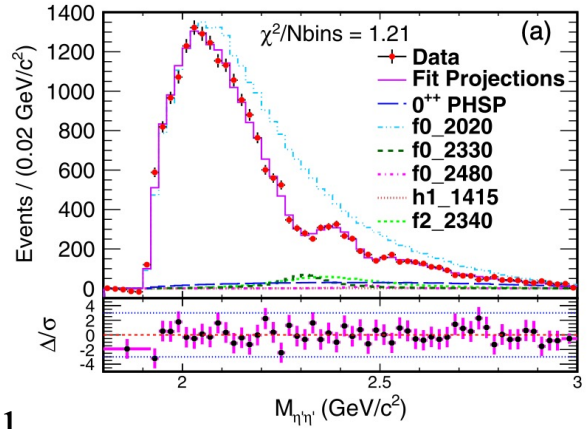
PRD 105, 072002(2022)

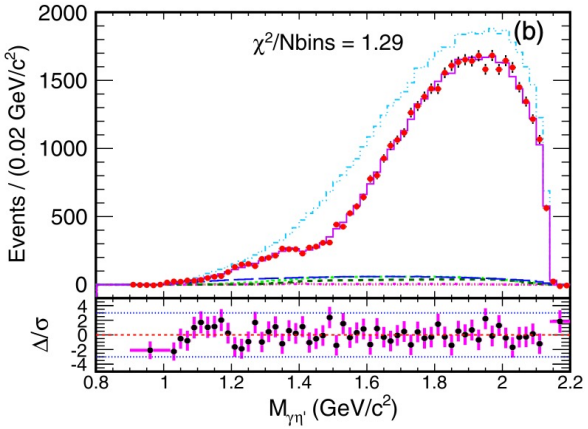
PWA of $J/\psi\to\gamma\eta'\eta'$ using 10 Billion of J/ψ data @ BESIII

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

Resonance	M(MeV/c^2)	Γ(MeV)	B.F.	Significance (σ)	
$f_0(2020)$	$1982\pm3^{+54}_{-0}$	$436\pm4^{+46}_{-49}$	$(2.63\pm0.06^{+0.31}_{-0.46})\times10^{-4}$	$\gg25$	Dominant contributions
$f_0(2330)$	$2312\pm2^{+10}_{-0}$	$134\pm5^{+30}_{-9}$	$(6.09\pm0.64^{+4.00}_{-1.68})\times10^{-6}$	16.3	
$f_0(2480)$	$2470\pm4^{+4}_{-6}$	$75\pm9^{+11}_{-8}$	$(8.18\pm1.77^{+3.73}_{-2.23})\times10^{-7}$	5.2	new 0^{++} state
$h_1(1415)$	$1384\pm6^{+9}_{-0}$	$66\pm10^{+12}_{-10}$	$(4.69\pm0.80^{+0.74}_{-1.82})\times10^{-7}$	5.3	
$f_2(2340)$	$2346\pm8^{+22}_{-6}$	$332\pm14^{+26}_{-12}$	$(8.67\pm0.70^{+0.61}_{-1.67})\times10^{-6}$	16.1	
0^{++} PHSP	...	...	$(1.17\pm0.23^{+4.09}_{-0.70})\times10^{-5}$	15.7	

- $f_0(2020)$, $f_0(2330)$ and $f_2(2340)$ observed in $\eta'\eta'$ decay mode for the first time





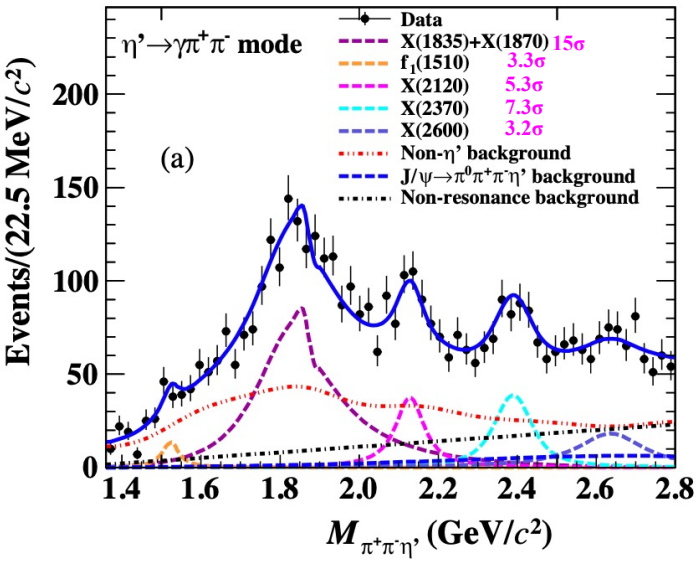
$f_0(2020)$:

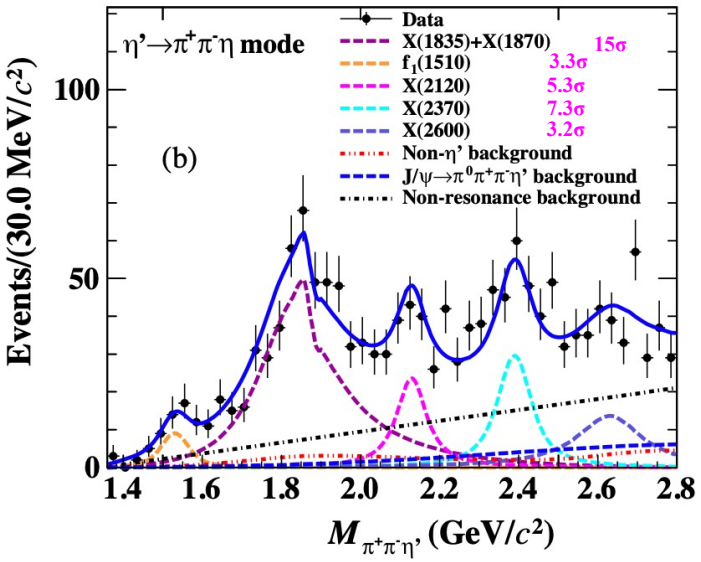
- Its large production rate in radiative J/ψ decay suggest a large overlap with scalar glueball
- Consistent with previous analysis results, but its mass is lower than the mass of the first excitation of scalar glueball from the LQCD prediction (Phys. Lett. B 309, 378, Phys. Rev. D 60, 034509)

Observation of X(1835), X(2120), X(2370) in J/ψ EM Dalitz Decays

10 Billion of J/ψ data @ BESIII

PRL 129, 022002





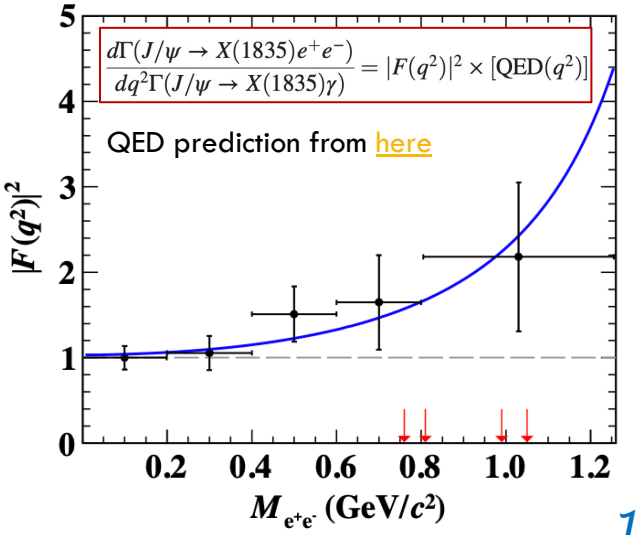
$J/\psi \to e^+e^-\eta'\pi^+\pi^-$
Confirmation of X(1835), X(2120) and X(2370) observed in J/ ψ radiative decays

Access to the EM transition form factor between J/ ψ and X(1835) states

- Additional information on the internal structure of X(1835)

$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$

$$\Lambda = 1.75 \pm 0.29 \pm 0.05\ GeV/c^2$$



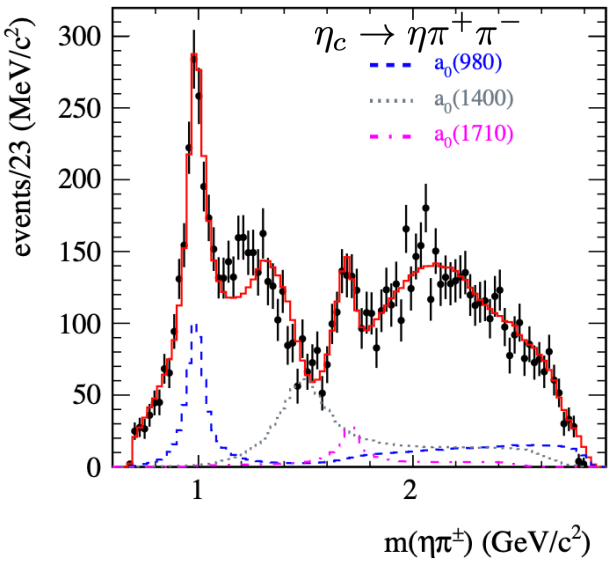
Light hadrons in open-charm decays

Ground state
- $f_0(500)$, $f_0(980)$:0++, I = 0
- $a_0(980)$: 0++, I = 1

Radially excited states
- $f_0(1370)$, $f_0(1500)$
- $a_0(1450)$

Higher set of excitations
- $f_0(1710)$, $f_0(1770)$
- $a_0(1710)$???

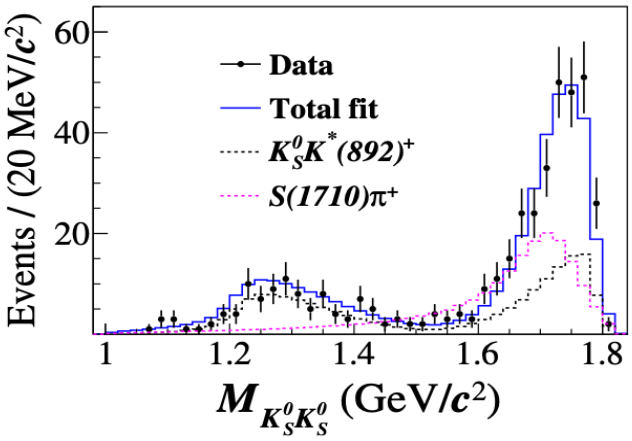
BABAR PRD104, 072002 (2021)



$m(a_0(1700)) = 1704 \pm 5_{\rm stat} \pm 2_{\rm sys}$ MeV/c^2,

$\Gamma(a_0(1700)) = 110 \pm 15_{\rm stat} \pm 11_{\rm sys}$ MeV/c^2.

$D_s^+ \to K_S^0 K_S^0 \pi^+$



BESIII PRD105, L051103 (2022)

$\mathcal{B}(D_s^+ \to S(980)\pi^+) < 1.8 \times 10^{-4}$ @ 90% CL

suppression attributed to the destructive int. between $a_0(980)$ and $f_0(980)$

$\mathcal{B}(D_s^+ \to S(1710)\pi^+) = (0.31 \pm 0.03 \pm 0.01)\%$

One order of magnitude larger than the expectation ➔ existence of isospin partner of $f_0(1710)$ ➔ constructive int.

Light hadrons in open-charm decays

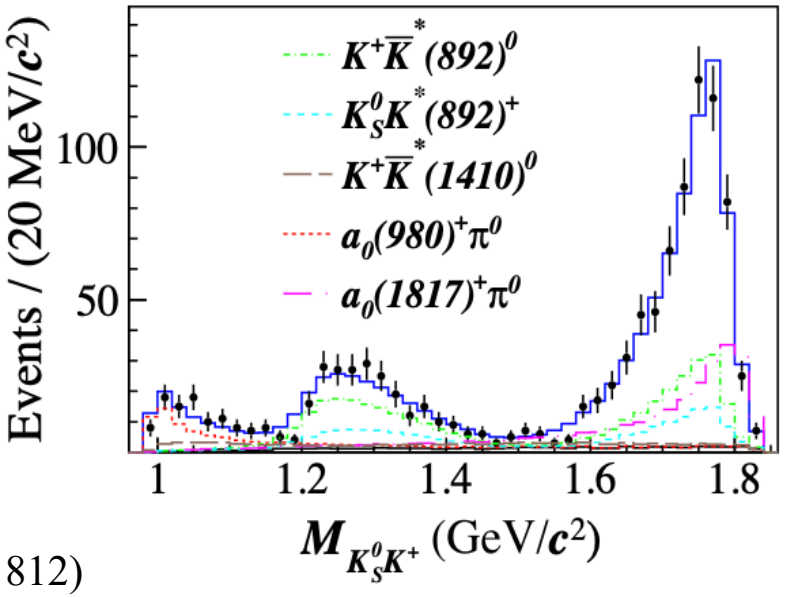
6.32 fb^{-1} between 4.178 and 4.226 GeV

PRL129, 182001 (2022)

- Amplitude analysis of Cabibbo-favored $D_s^+ \to K^0_S K^+ \pi^0$

- Together with $D_s^+ \to K^0_S K^0_S \pi^+$ BESIII analysis, this result support the existence of a new a_0 triplet
- BF of $D_s^+ \to a_0(1817)^+ \pi^0$ with $a_0(1817)^+ \to K^0_S K^+ \pi^0$ is roughly consistent with the prediction EPJC **82**, 225(2022)
- $m(a_0)$ about 100 MeV/c^2 greater than the expectation

$$m(a_0) = (1.817 \pm 0.008 \pm 0.020)\ \text{GeV}/c^2$$
$$\Gamma(a_0) = (0.097 \pm 0.022 \pm 0.015)\ \text{GeV}/c^2$$

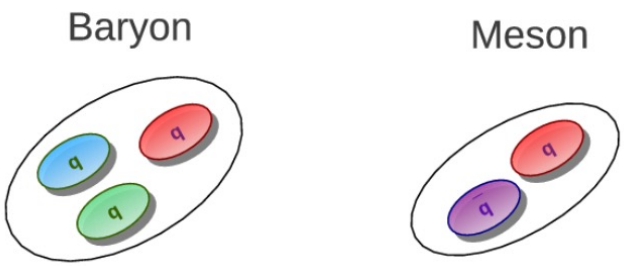


- $a_0(1817)$ could be the isospin one partner of the X(1812) PRD105, 114014(2022)

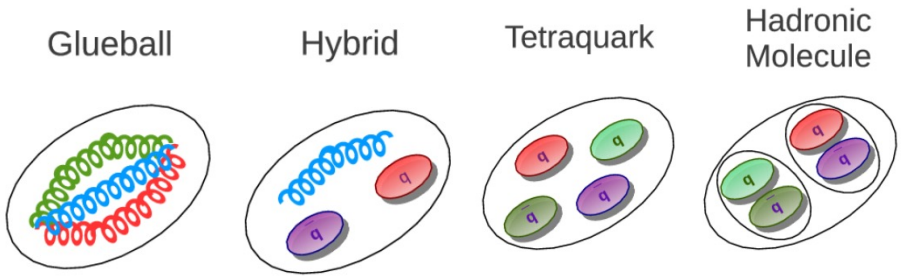
Amplitude	Phase (rad)	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	0.0 (fixed)	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K^0_S$	$-0.16 \pm 0.12 \pm 0.11$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$-0.97 \pm 0.27 \pm 0.25$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	6.7
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$0.17 \pm 0.15 \pm 0.08$	$6.0 \pm 1.4 \pm 1.3$	$0.88 \pm 0.21 \pm 0.19$	7.6
$D_s^+ \to a_0(1817)^+ \pi^0$	$-2.55 \pm 0.21 \pm 0.07$	$23.6 \pm 3.4 \pm 2.0$	$3.44 \pm 0.52 \pm 0.32$	> 10

Hadron Spectrum

Hadron spectroscopy: establish the spectrum and study the exotic hadrons properties



Naïve Quark Model:
conventional hadrons
contain two or three quarks



… ***but*** QCD allows also different combinations of quarks and gluons:
EXOTIC hadrons

A lot of exotic states observed experimentally, but their nature is still far from being understood!!!

@ BESIII J/ψ **10.1×10^9**

Light hadron physics
- Meson and baryon spectroscopy
- Glueballs and hybrids
- ….

BESIII physics programme

Light hadron physics

- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- two-photon physics
- Form factors

XYZ meson physics

- Y(4260), Y(4360) properties
- $Z_c(3900)^+$, …

QCD and τ

- Precision R measurement
- τ decay

Charm physics

- Semi-leptonic form factors
- Decay constants f_D and f_{Ds}
- CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
- D^0-$\overline{D}^0$ mixing, CPV
- Strong phases

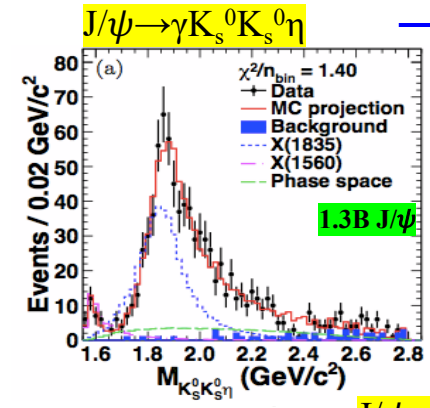
Charmonium physics

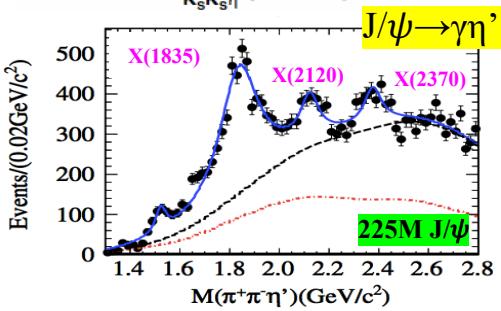
- Precision spectroscopy
- Transitions and decays

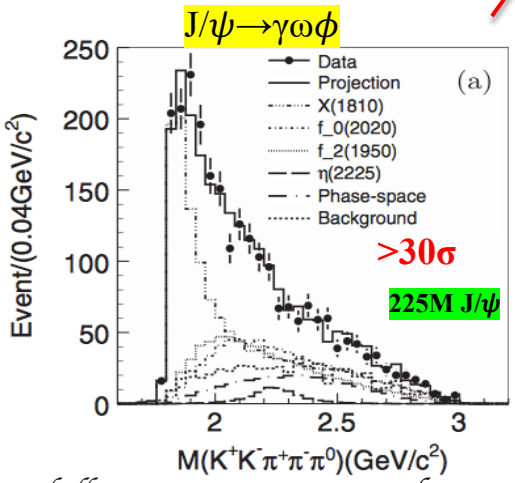
Precision mass measurements

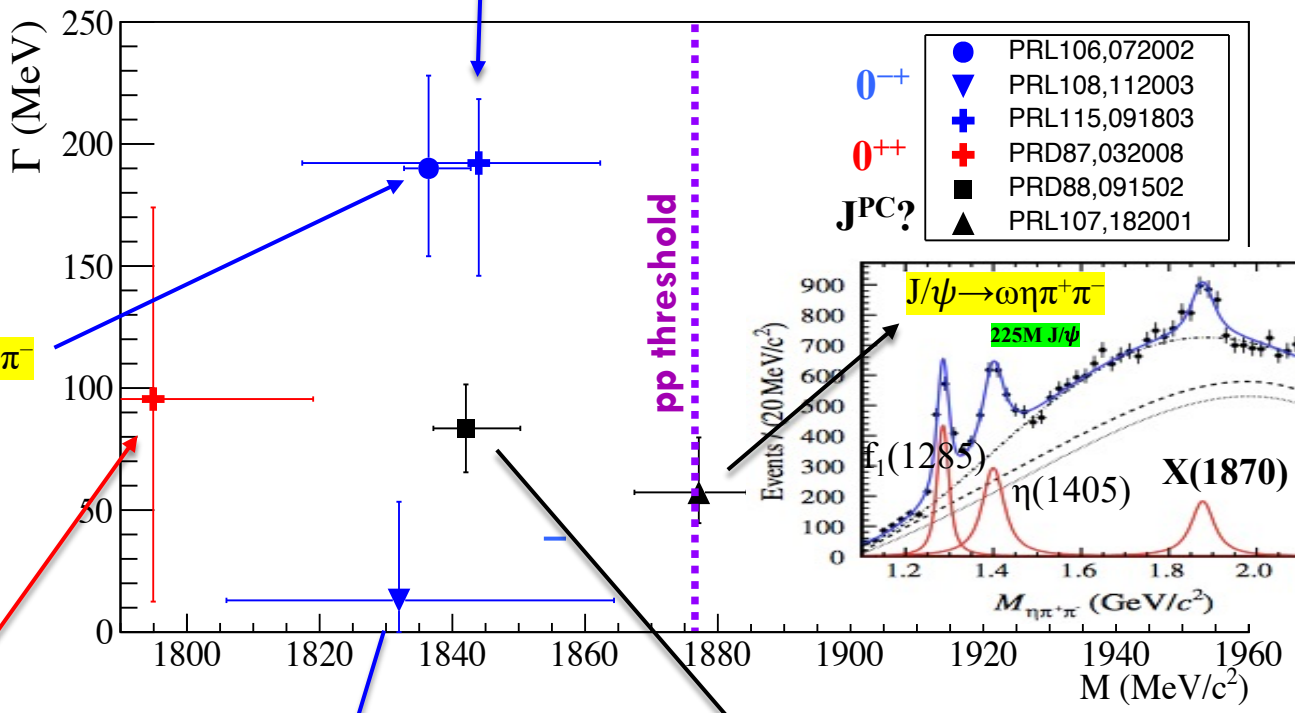
- τ mass
- D, D^* mass

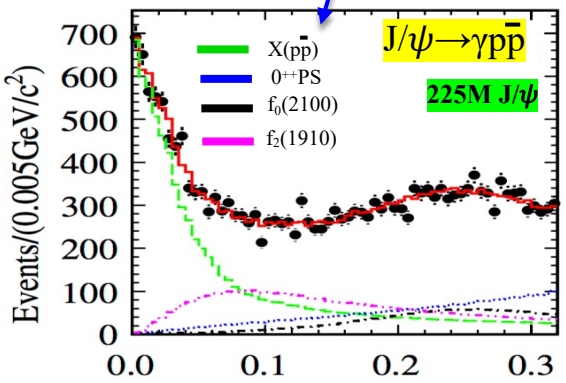
X(18xx) between 1.8 -1.9 GeV

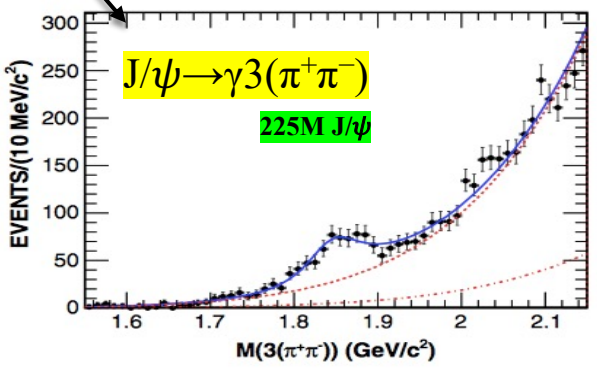






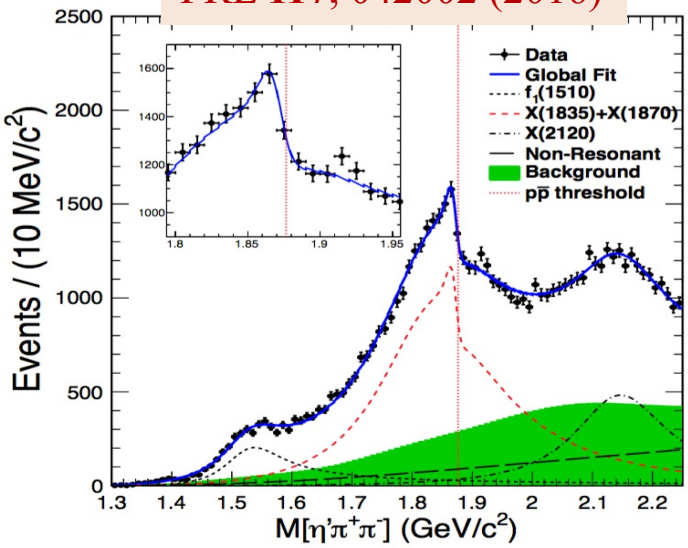






Other Results on X(1835)

PRL **117**, 042002 (2016)



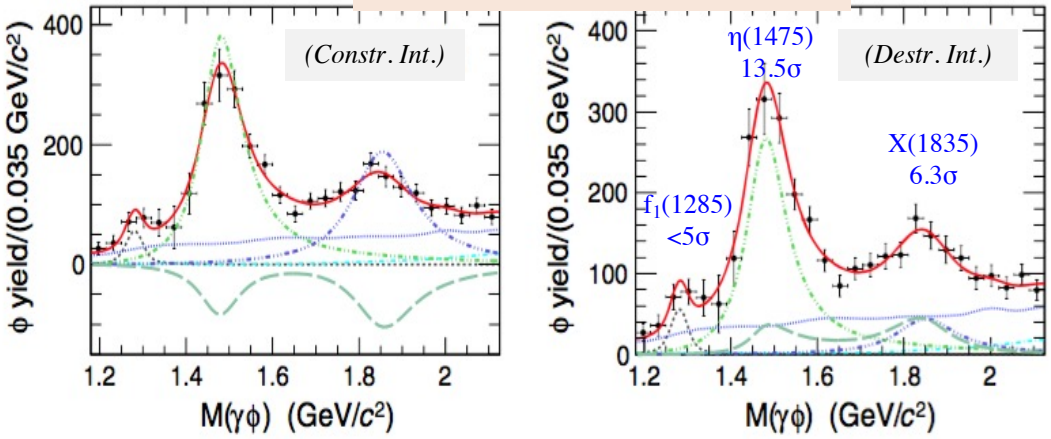
1.09×10⁹ J/ψ @ BESIII

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

Significant distortion of the $\eta'\pi^-\pi^+$ line shape near the ppbar mass threshold

Two fit models are taken into account and both support the existence of a $p\bar{p}$ moleculelike or bound state

PRD **97**,051101(R) (2018)



1.3×10⁹ J/ψ @ BESIII

$J/\psi \to \gamma\gamma\phi$: two structures corresponding to η(1475) and X(1835) are observed

- X(1835) and η(1475): $J^{PC} = 0^{-+}$ assignment favored
- Sizable $s\bar{s}$ component in X(1835)
  - more complicated than a pure $N\bar{N}$ state

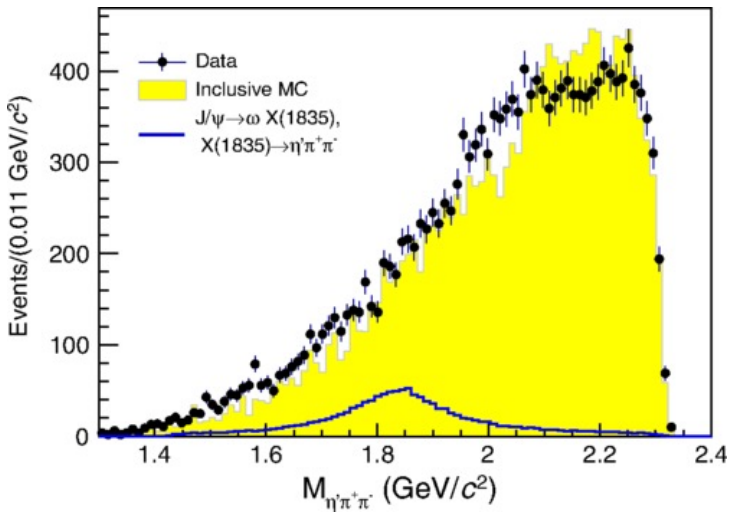
Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)
I *(Destr. Int.)*	η(1475)	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$
	X(1835)	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$
II *(Constr. Int.)*	η(1475)	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$
	X(1835)	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$

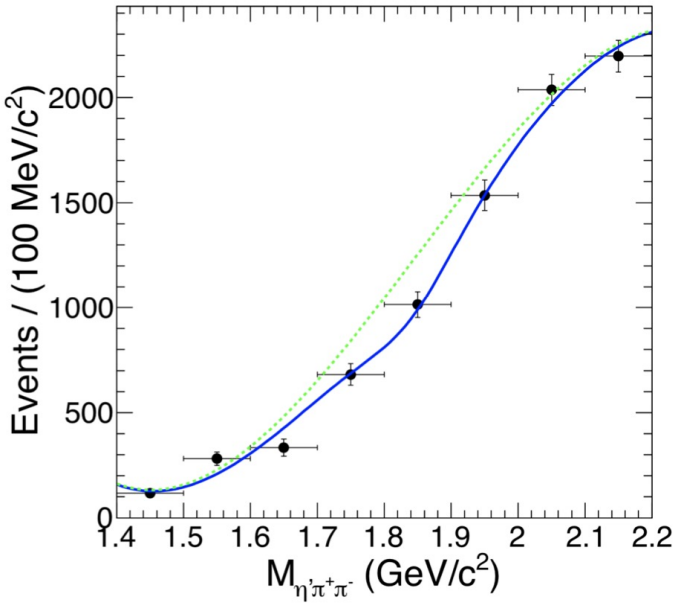
Search for X(1835) in other decay modes

- $J/\psi \to \omega\eta'\pi^+\pi^-$ hadronic decay and search for $X(1835) \to \eta'\pi^+\pi^-$

PRD **99**, 071101 (R) (2019)

1.3×10^9 J/ψ @ BESIII





- No obvious sign of X(1835)'s existence
- Large gluon component? [PRD74,034019]

$$\mathcal{B}(J/\psi \to \omega\eta'\pi^+\pi^-) = (1.12 \pm 0.02 \pm 0.13) \times 10^{-3}$$
$$\mathcal{B}(J/\psi \to \omega X(1835),\ X(1835) \to \eta'\pi^+\pi^-) < 6.2 \times 10^{-5}$$

@ 90% C.L.

The puzzle is still not complete ….

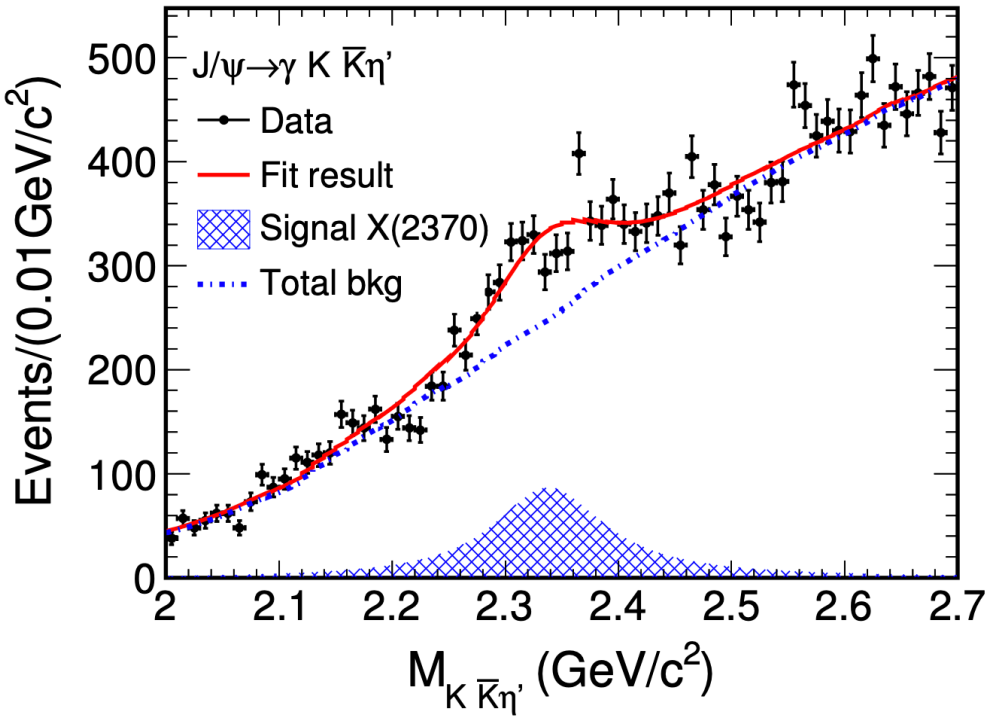
First Observation of X(2370) in $J/\psi \to \gamma K\bar{K}\eta'$

- X(2120) and X(2370) states observed in the $\pi^-\pi^+\eta'$ invariant mass spectra (PRL**106**,072002)
- The **X(2370)** measured mass is consistent with the pseudoscalar glueball candidate predicted by LQCD calculation (PRD**73**,014516)

➢ Simulataneus fit performed for two decay η' modes

1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)



➢ **No evidence of X(2120) is found**

$$\mathcal{B}(J/\psi \to \gamma X(2120) \to \gamma K^+K^-\eta') < 1.49 \times 10^{-5}$$
$$\mathcal{B}(J/\psi \to \gamma X(2120) \to \gamma K^0_S K^0_S \eta') < 6.38 \times 10^{-6}$$

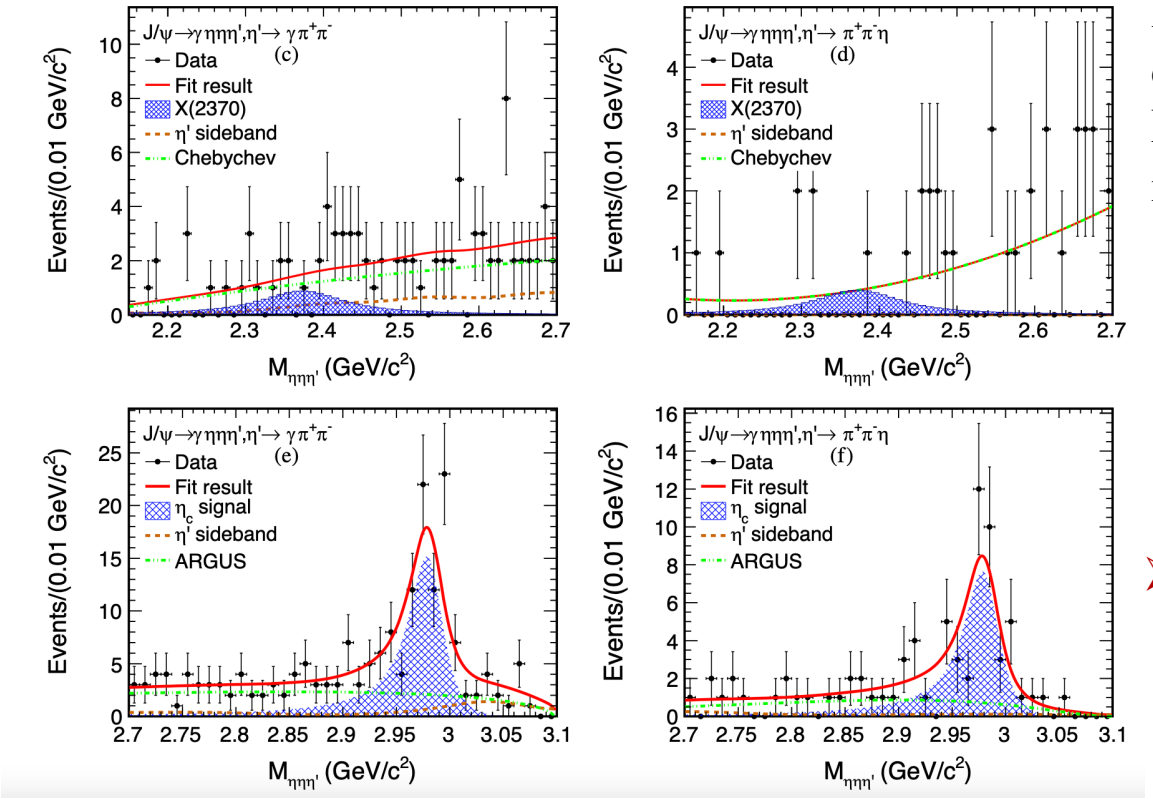
➢ **Clear X(2370) signal observed with significance of about 8.3σ**

$$M_{X(2370)} = 2341.6 \pm 6.5 \pm 5.7\ \mathrm{MeV}/c^2 \quad \Gamma_{X(2370)} = 117 \pm 10 \pm 8\ \mathrm{MeV}$$
$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^+K^-\eta') = (1.79 \pm 0.23 \pm 0.65) \times 10^{-5}$$
$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^0_S K^0_S \eta') = (1.18 \pm 0.32 \pm 0.39) \times 10^{-5}$$

Search for X(2370) in $J/\psi \to \gamma\eta\eta\eta'$

PRD **103**, 012009 (2021)

1.3×10^9 J/ψ @ BESIII



Branching ratios prediction for the decay of pseudoscalar glueball with M~2.37 GeV into three pseudoscalar mesons (PRD **87**,054036 (2013))

$$\Gamma_{G\to\eta\eta\eta'}/\Gamma_G^{tot} = 0.00082$$
$$\Gamma_{G\to KK\eta'}/\Gamma_G^{tot} = 0.011$$
$$\Gamma_{G\to\pi\pi\eta'}/\Gamma_G^{tot} = 0.090$$

➢ **No obvious signal of X(2370)**

Simultaneous unbinned maximum likelihood fit to the ηηη' is performed and the 90% C.L. upper limit is calculated

$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma\eta\eta\eta') < 9.2\times10^{-6}$$

(it does not contradict PRD **87**,054036)

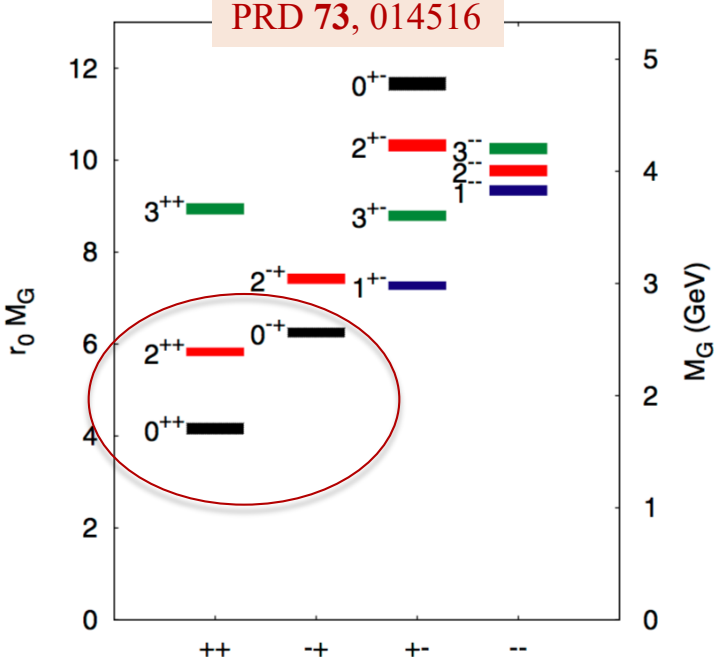
$$\mathcal{B}(J/\psi \to \gamma\eta_c)\cdot\mathcal{B}(\eta_c \to \eta\eta\eta') = (4.86\pm0.62\pm0.45)\times10^{-5}$$

FIRST OBSERVATION in the ηηη' invariant mass spectra

Amplitude Analyses in BESIII

- J/ψ radiative decays are ideal for searching glueballs
  - **J/ψ → γPP: 0^{++}, 2^{++}, …**
  - **J/ψ → γPPP, γVV: 0^{-+}**
- Neutral channel is much cleaner than the charged ones
- Very complicated mass spectrum in the low mass region: many broad, overlapping states complicate the study of the spectra

PRD **73**, 014516

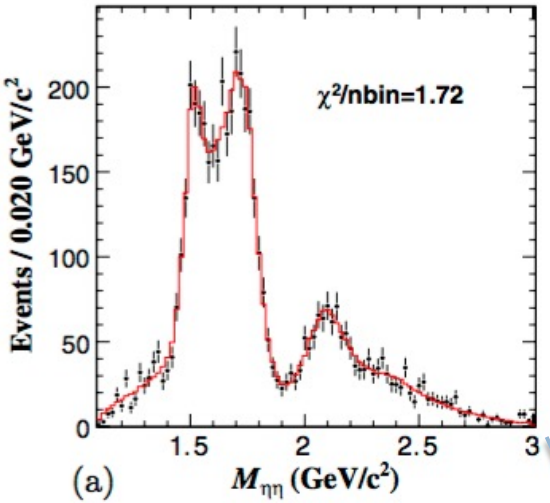


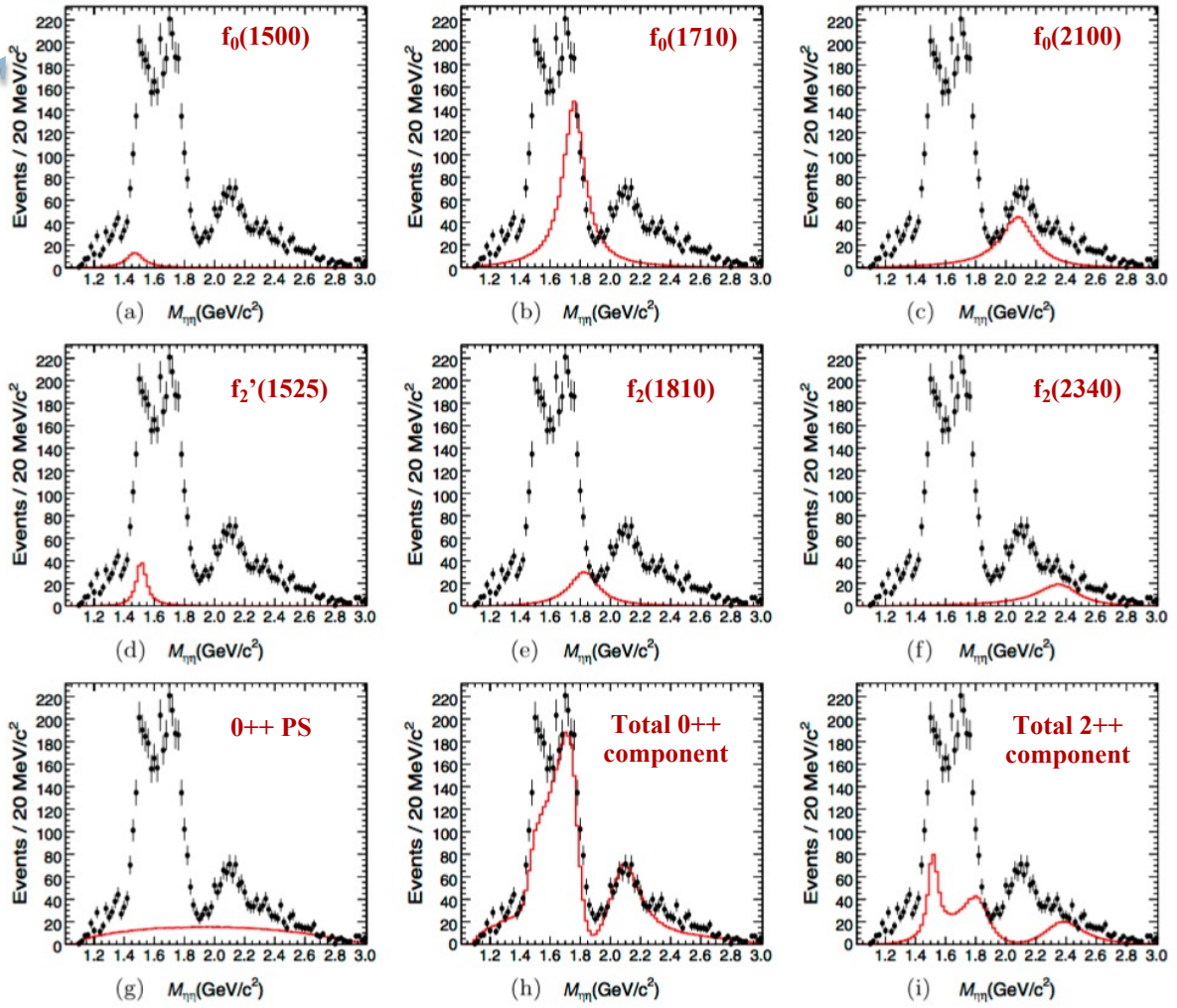
- **Amplitude analysis: toll to extract the complex amplitudes from experimental data**
  - Models with free parameters
  - Consider the kinematic of final states particles
  - Vary the parameters to maximize the likelihood
  - **Mass Dependent (MD) PWA**: model the dynamics of particle interactions as coherent sum of resonances
  - **Mass Independent (MI) PWA**: make minimal model assumptions and measure the dynamical amplitudes independently in small regions of two-meson invariant mass (PRD92, 052003 (2015))

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

PRD **87**, 092009 (2013)

- $J/\psi \to \gamma\eta\eta$: clean laboratory to search for 0++ and 2++ states
- PWA based on 2.25×10^8 J/ψ events

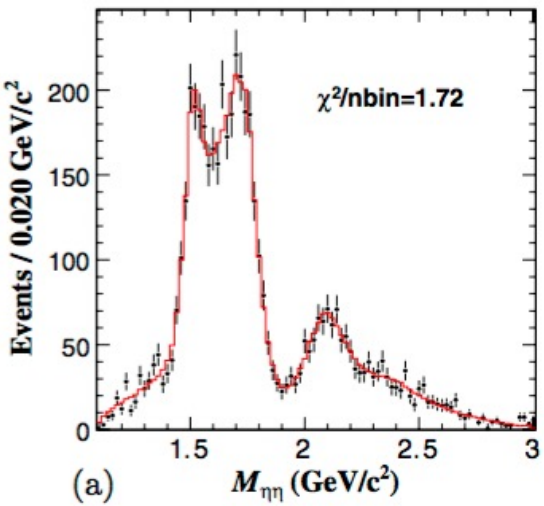




PWA of $J/\psi \to \gamma\eta\eta$

PRD **87**, 092009 (2013)

- $J/\psi \to \gamma\eta\eta$: clean laboratory to search for 0++ and 2++ states
- PWA based on 2.25×10^8 J/ψ events



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

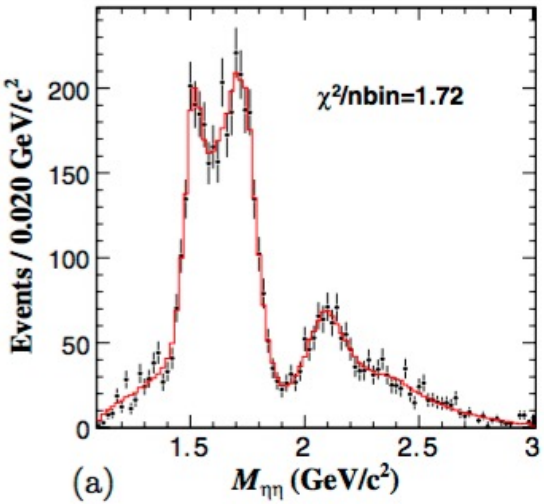
- $f_0(1500)$ dominant decays are 4π and $\pi\pi$
- The production rate of $f_0(1710)$ is compatible with LQCD (PRL110,021601) prediction for a pure scalar glueball
  - Suggest a large overlap with 0++ gluball

- PWA requires a strong contribution from **$f_2(2340)$** with fairly large production rate ⇒ it ***could be a good candidate for the lowest lying tensor glueball***

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

PRD **87**, 092009 (2013)

- $J/\psi \to \gamma\eta\eta$: clean laboratory to search for 0++ and 2++ states
- PWA based on 2.25×10^8 J/ψ events



	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	
$f_0(1500)$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	**8.2σ**
$f_0(1710)$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	**25.0σ**
$f_0(2100)$	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	**13.9σ**
$f_2'(1525)$	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	**6.4σ**
$f_2(1810)$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	**7.6σ**
$f_2(2340)$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	

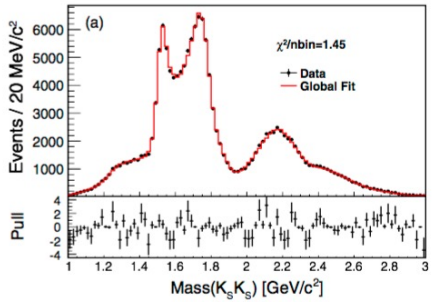
- $f_0(1500)$ dominant decays are 4π and $\pi\pi$
- The production rate of $f_0(1710)$ is compatible with LQCD (PRL110,021601) prediction for a pure scalar glueball
  - Suggest a large overlap with 0++ glueball

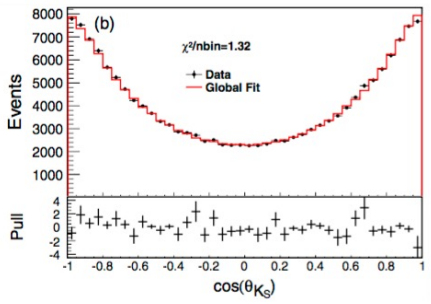
- PWA requires a strong contribution from **$f_2(2340)$** with fairly large production rate ⇒ it ***could be a good candidate for the lowest lying tensor glueball***

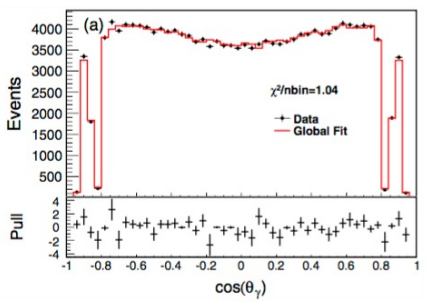
PWA of $J/\psi \to \gamma K^0_S K^0_S$

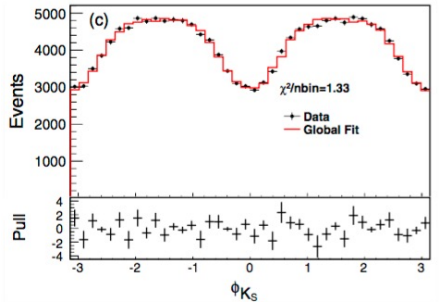
PRD **98**, 072003 (2018)

- $J/\psi \to \gamma K_S K_S$: clean laboratory to search for even++ states
- PWA based on 1311M of J/ψ events









Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	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	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	...	$146 \pm 14^{+7}_{-15}$	...	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	...	$349 \pm 18^{+23}_{-1}$	...	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	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	...	...	...	...	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	...	...	...	...	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

- $f_0(1710)$ and $f_0(2200)$ dominate the scalar spectrum, but we need also to include $f_0(2330)$
- BR of $f_0(1710)$ is one order of magnitude larger than BR of $f_0(1500)$: $f_0(1710)$ overlap with glueball state
- Structure near 1.5 GeV dominated by tensor contribution $f_2'(1525)$, while above 2 GeV is dominantly $f_2(2340)$

First Observation of X(2370) in $J/\psi\to\gamma K\bar{K}\eta'$

1.3×10^9 J/ψ @ BESIII

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