Light Meson Spectroscopy at BESIII

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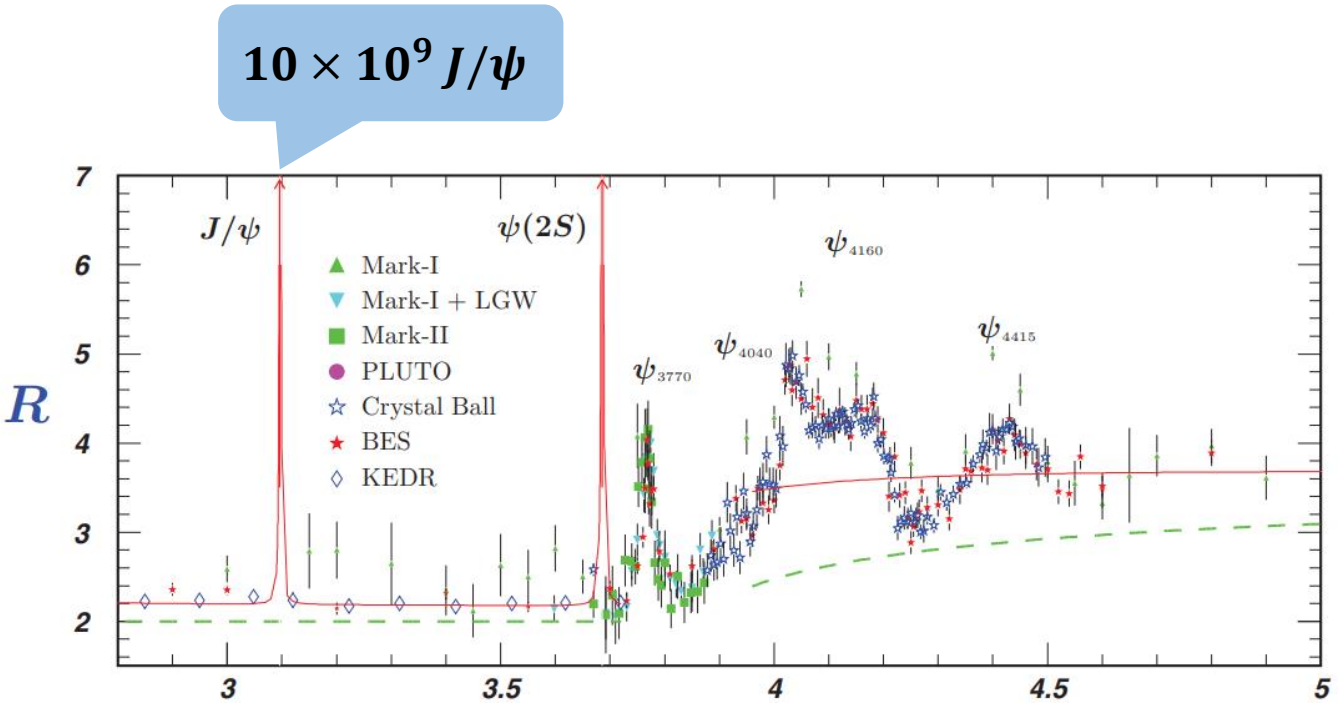
World's Largest τ-$charm$ Data Sets in e^+e^- Annihilation

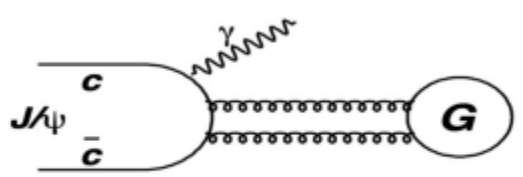
- τ-$charm$ factory $2.0 \leq \sqrt{s} \leq 4.9$ GeV
- Design luminosity: $L_{\psi(3770)} = 10^{33}\ \mathrm{cm^{-2}s^{-1}}$



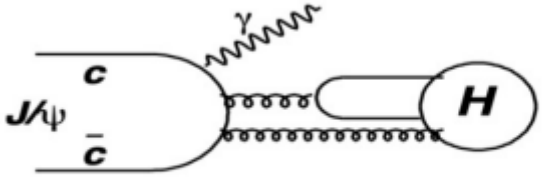
Ideal lab for light hadron physics

- Clean **high statistics** data samples
- Well defined initial and final states
  - Kinematic constraints
  - $I(J^{PC})$ filter
- "**Gluon-rich**" processes

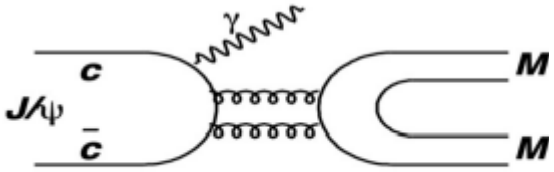
$$\Gamma(J/\psi \to \gamma G) > \Gamma(J/\psi \to \gamma H) > \Gamma(J/\psi \to \gamma M) > \Gamma(J/\psi \to \gamma F)$$



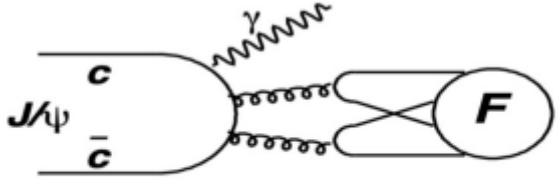
$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2)$



$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$



$\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4)$



$\Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$

Glueballs

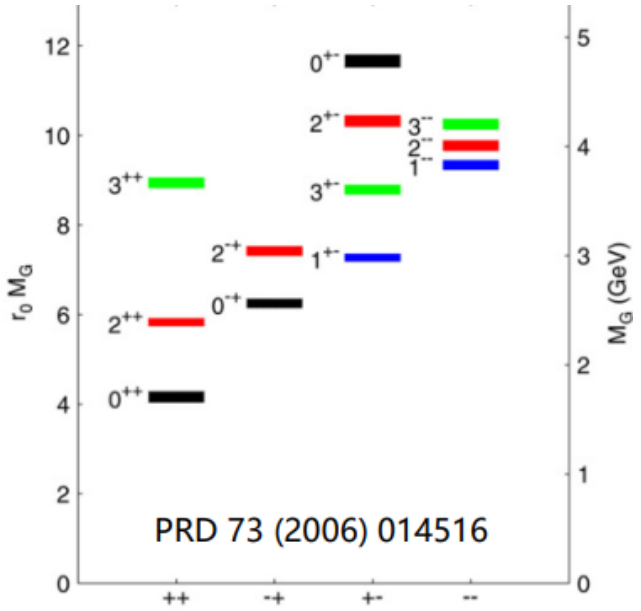
- **Low-lying glueballs** with ordinary J^{PC} → **mixing** with $q\bar{q}$ mesons
  - ➢ **Systematic studies required**
  - ➢ **out-numbering** of quark model (e.g. $f_0(1370)$& $f_0(1500)$& $f_0(1710)$)
  - ➢ study the **production & decay properties**

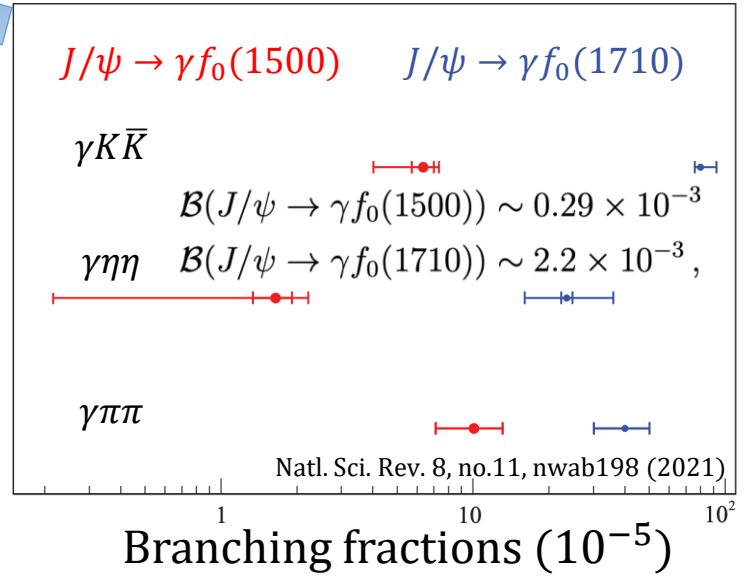
- **Scalar glueball** expected to have a **large production** in J/ψ radiative decay: $B(J/\psi \to \gamma G_{0^+}) = 3.8(9) \times 10^{-3}$ [1]LQCD
  - Observed $B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$
  - ➢ $f_0(1710)$ largely overlapped with scalar glueball

- **G → $\eta\eta'$ decay** is expected to be **suppressed**
  - SU(3) F symmetry for a pure glueball
    $\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3 : 4 : 1 : 0 : 1$
  - $B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$, predicted by Ref. [1]

➢ $J/\psi \to \gamma\eta\eta'$ provides important information

LQCD prediction of glueball spectrum





[1] PRD 92, 121902 (2015)

Hybrids

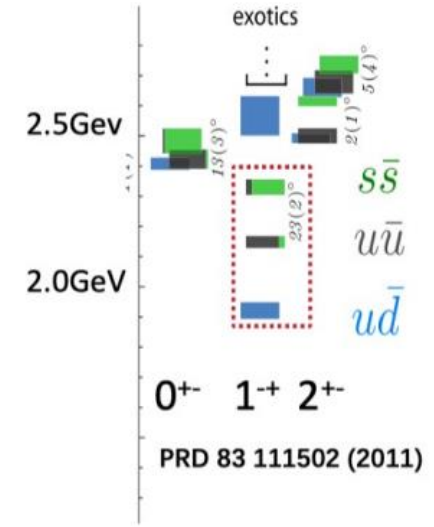
- Low-lying hybrids can have **exotic quantum numbers** $0^{+-}, 1^{-+}, 2^{+-}$, which is **forbidden by $q\bar{q}$** configuration

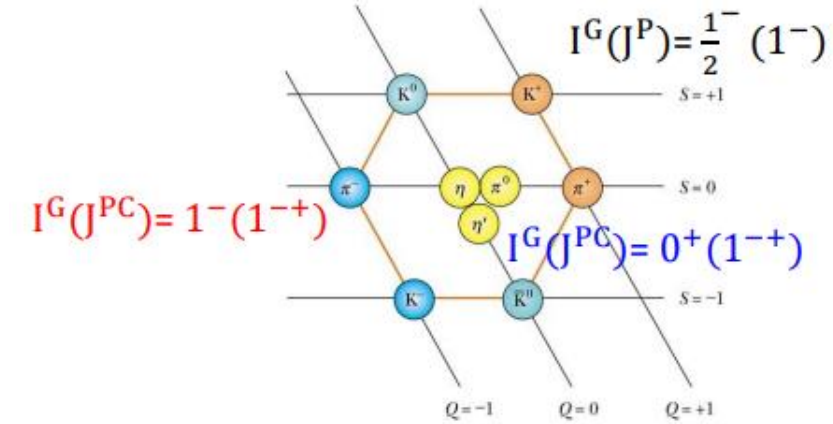
- The exotic $J^{PC} = \mathbf{1^{-+}}$ **nonet of hybrids** is predicted to be the **lightest** ($1.7\sim2.1$ GeV/c^2)
  - **Only isovector candidate** $\pi_1(1400), \pi_1(1600), \pi_1(2015)$ observed yet

- **Isoscalar $\mathbf{1^{-+}}$** is critical to establish the **hybrid nonet**
  - Can be produced in the gluon-rich charmonium decays
  - Can decay to $\eta\eta'$ in P-wave [2][3][4]

➢ Search for Isoscalar 1^{-+} in $J/\psi \to \gamma\eta\eta'$

Lattice QCD Predictions:





[2] PRD 83,014021 (2011)
[3] PRD 83,014006 (2011)
[4] Eur.Phys.J.Plus 135, 945(2020)

Observation of An Exotic Isoscalar State $\eta_1(1855)$ (1^{-+}) in $J/\psi \to \gamma\eta\eta'$

10 billion J/ψ

arXiv:2202.00621

arXiv:2202.00623

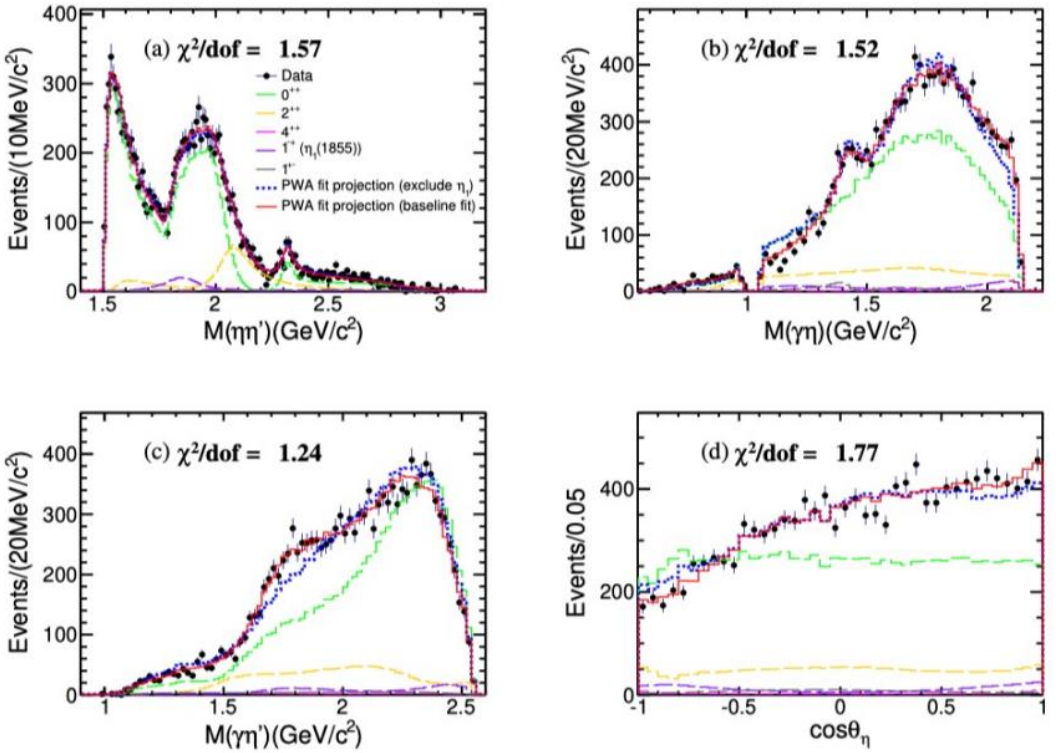
- The η' is reconstructed from $\gamma\pi^+\pi^-$ & $\eta\pi^+\pi^-$, η from $\gamma\gamma$
- Partial wave analysis of $J/\psi \to \gamma\eta\eta'$

  Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta X, X \to \gamma\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$ are constructed using the **covariant tensor formalism**[5]

- **All kinematically allowed known resonances** with 0^{++}, 2^{++}, 4^{++} $(\eta\eta')$ and 1^{+-}, $1^{-+}(\gamma\eta^{(\prime)})$ are considered

  1^{-+} in $\eta\eta'$ is also considered (η/η' not identical particle)

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



- An **isoscalar** resonance with **exotic** $J^{PC} = 1^{-+}$

➢ **consistent** with **LQCD calculation** for the 1^{-+} hybrid (1.7~2.1 GeV/c^2)

[5] Eur. Phys. J. A 16, 537 (2003)

Further Checks on the 1^{-+} State $\eta_1(1855)$

Angular distribution as a function of $M(\eta\eta')$ can be expressed **model-independently** in terms of Legendre polynomial moments

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

- **Neglecting** resonance contributions in the **$\gamma\eta$ and $\gamma\eta'$** subsystems, the moments are related to the spin-0(S), spin-1(P), spin-2(D) amplitudes in $\eta\eta'$ by:

$$\sqrt{4\pi}\langle Y_0^0 \rangle = S^2 + P^2 + D^2$$

$$\sqrt{4\pi}\langle Y_1^0 \rangle = 2SP\cos\phi_P + 4PD\cos(\phi_P - \phi_D)$$

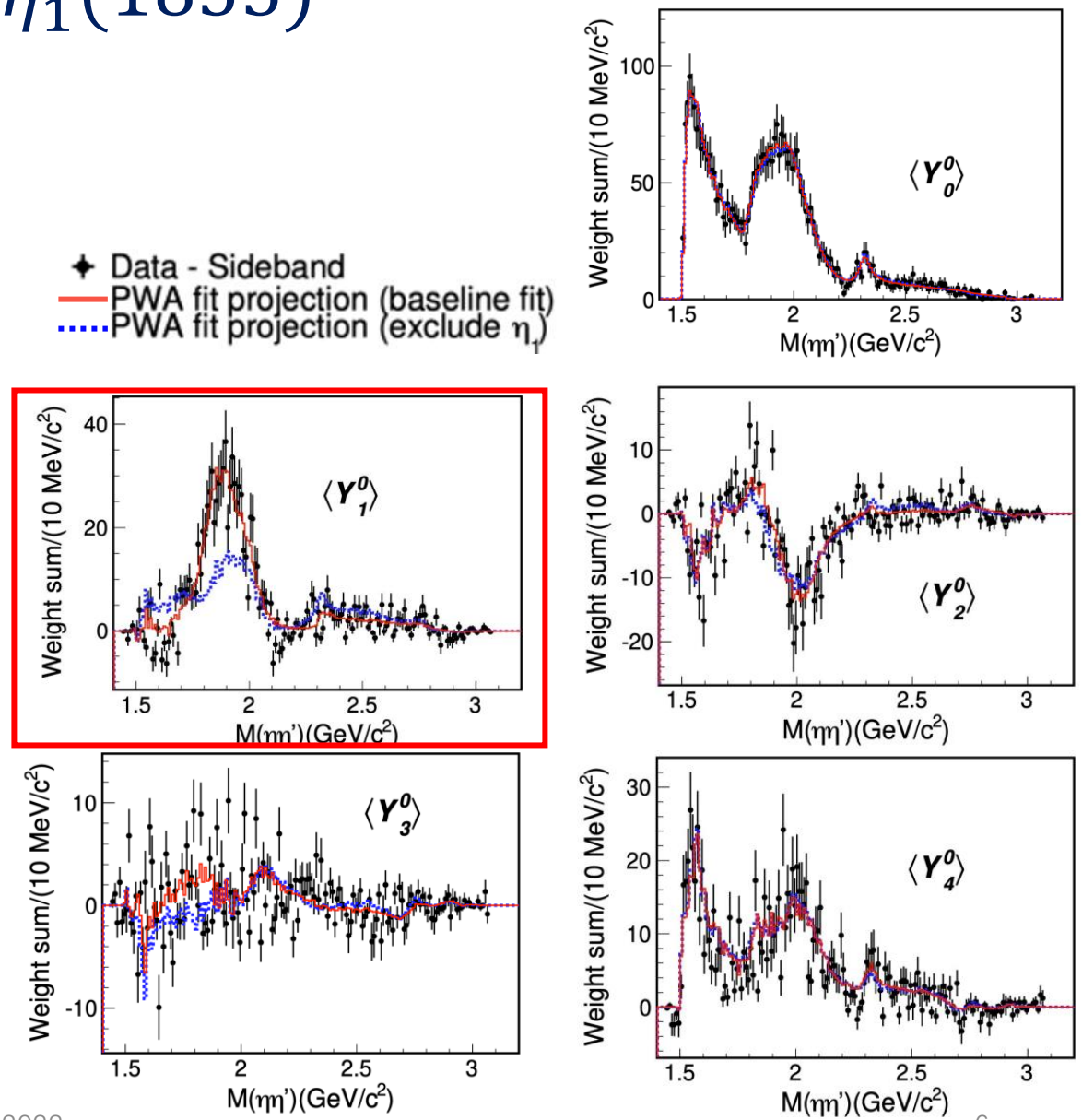
$\langle Y_1^0 \rangle = 0$ without P-wave contribution

$$\sqrt{4\pi}\langle Y_2^0 \rangle = \frac{2}{\sqrt{5}}P^2 + \frac{2\sqrt{5}}{7}D^2 + 2SD\cos\phi_D$$

$$\sqrt{4\pi}\langle Y_3^0 \rangle = \frac{6}{5}\sqrt{\frac{15}{7}}PD\cos(\phi_P - \phi_D)$$

$$\sqrt{4\pi}\langle Y_4^0 \rangle = \frac{6}{7}D^2$$

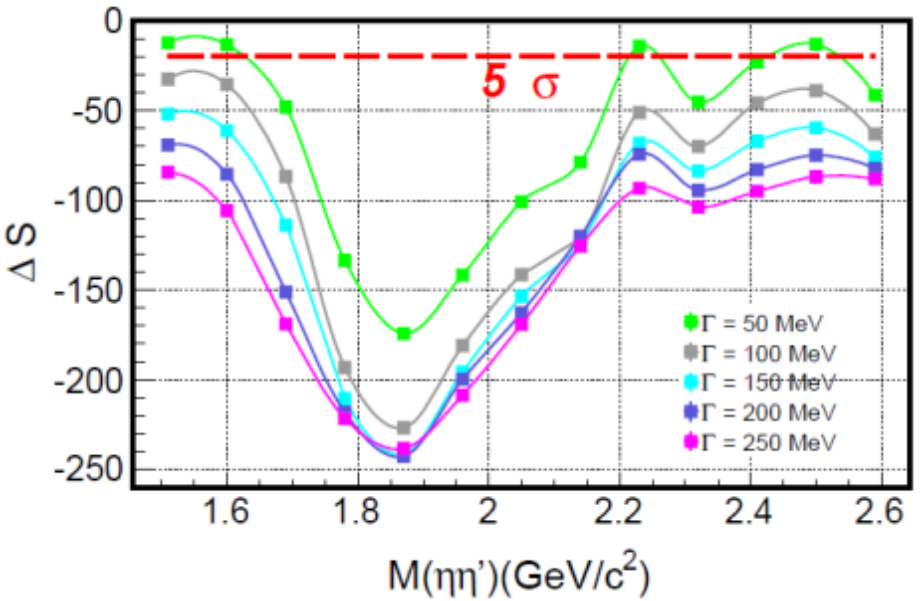
- Narrow structure in $\langle Y_1^0 \rangle$
  - ➢ Cannot be described by resonances in $\gamma\eta(\eta')$
  - $\eta_1(1855) \rightarrow \eta\eta'$ needed



Further Checks on the 1^{-+} State $\eta_1(1855)$

- Change J^{PC} of $\eta_1(1855)$: log-likelihood ↓235
  - J^{PC} **prefer** 1^{-+}
- Remove **BW phase motion** of $\eta_1(1855)$: log-likelihood ↓43
  - **Resonance structure** needed
- **Assuming $\eta_1(1855)$ as additional resonance**, evaluate its significance with various **masses and widths**
  - Significant 1^{-+} contribution around **$1.8\ \mathrm{GeV/c^2}$** needed
- Systematic uncertainties are studied, and **significance of $\eta_1(1855)$ remains larger than 19σ** in all cases

significance of $\eta_1(1855)$ with various masses and widths



Discussions about $f_0(1500)$ & $f_0(1710)$

- **Significant $f_0(1500)$**

$$\frac{B(f_0(1500) \to \eta\eta')}{B(f_0(1500) \to \pi\pi)} = \left(8.96^{+2.95}_{-2.87}\right) \times 10^{-2}$$

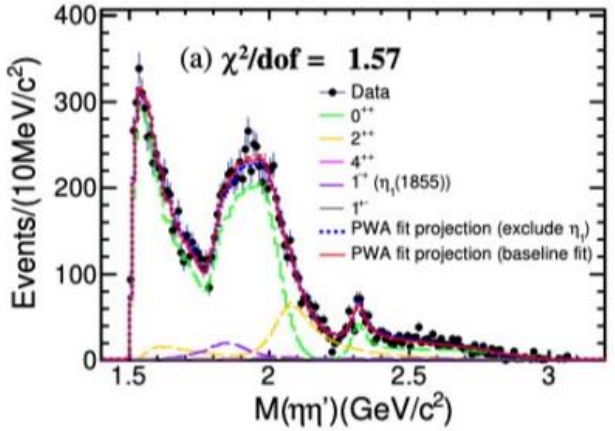
consistent with PDG

- **Absence of $f_0(1710)$**

$$\frac{B(f_0(1500) \to \eta\eta')}{B(f_0(1500) \to \pi\pi)} < 1.61 \times 10^{-3} \ @90\%\ C.L.$$

➢ **Supports** to the hypothesis that **$f_0(1710)$ overlaps** with the ground state scalar **(0^{++}) glueball**

- Scalar glueball expected to be **suppressed in $\eta\eta'$**:
  $B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$



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

- Observation of the $f_0(2480)$, $f_0(2020)$, $f_0(2330)$ and $f_2(2340)$ decays to $\eta'\eta'$
  - **A new 0^{++} state $f_0(2480)$**

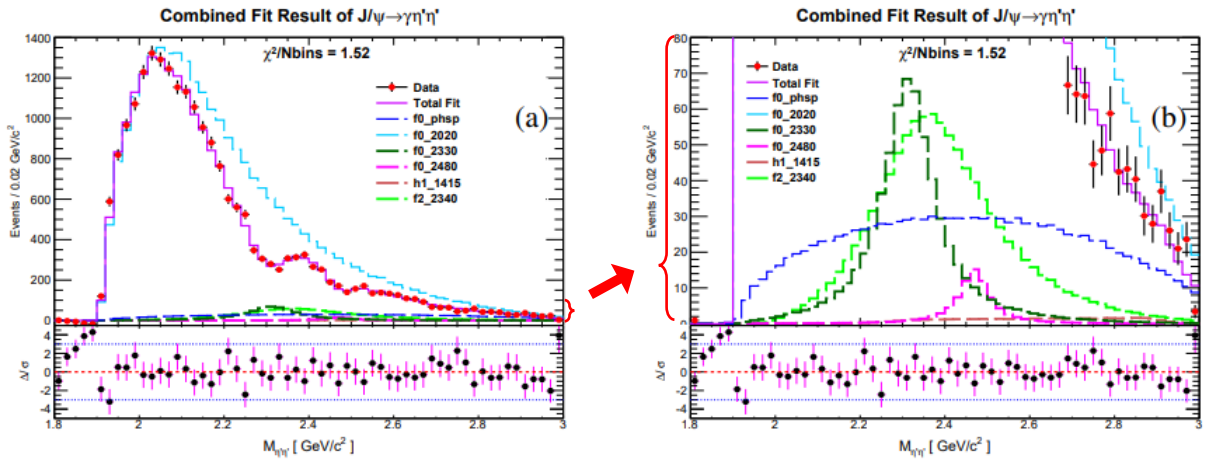
- after considering the phase-space factor :

$$\frac{\Gamma(f_0(2020) \to \eta\eta')}{\Gamma(f_0(2020) \to \eta'\eta')} = 0.0148$$

➢ Indicates that $f_0(2020)$ is a **flavor singlet**[5]

10 billion J/ψ
Phys. Rev. D **105**,072002 (2022)

Resonance	M(MeV/c^2)	Γ(MeV)	B.F.	Significance (σ)
$f_0(2020)$	$1982 \pm 3^{+54}_{-0}$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$	$\gg 25$
$f_0(2330)$	$2312 \pm 2^{+10}_{-0}$	$134 \pm 5^{+30}_{-9}$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$	16.3
$f_0(2480)$	$2470 \pm 4^{+4}_{-6}$	$75 \pm 9^{+11}_{-8}$	$(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$	5.2
$h_1(1415)$	$1384 \pm 6^{+9}_{-0}$	$66 \pm 10^{+12}_{-10}$	$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$	5.3
$f_2(2340)$	$2346 \pm 8^{+22}_{-6}$	$332 \pm 14^{+26}_{-12}$	$(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$	16.1
0^{++} PHSP	...	...	$(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$	15.7



[5] Phys. Lett. B 826, 136906 (2022)

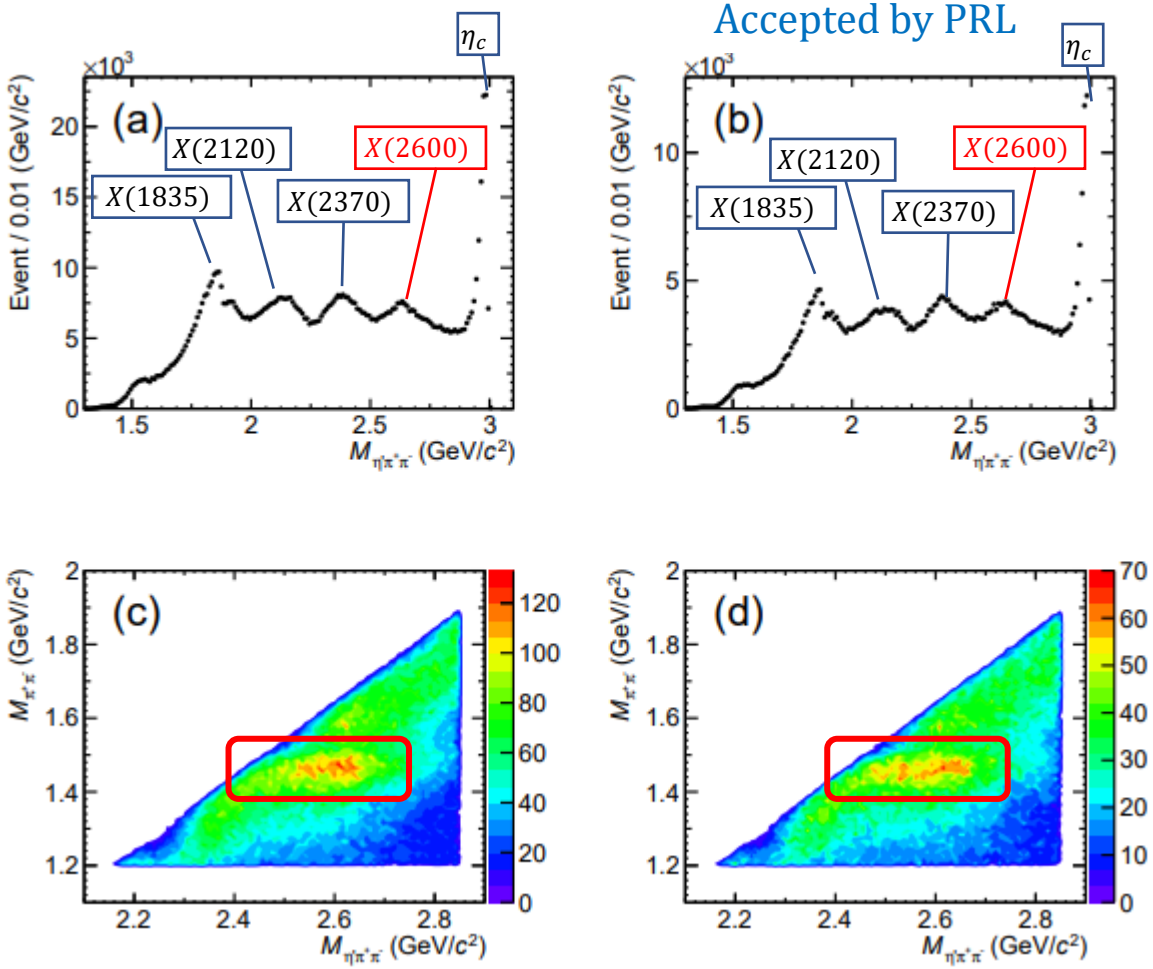
A New State $X(2600)$ Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

- $X(1835)$ was first observed and confirmed in $J/\psi \to \gamma\pi^+\pi^-\eta'$[6][7], with $J^{PC} = 0^{-+}$[8], and an anomalous line shape at $p\bar{p}$ threshold[9]

- $X(2120)$, $X(2370)$ also observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$[7]

- With the 10 billon J/ψ events, a **new state $X(2600)$** in $M(\eta'\pi^+\pi^-)$ is observed, which is correlated to a **structure @$1.5\ \mathrm{GeV/c^2}$ in $M(\pi^+\pi^-)$**

arXiv:2201.10796
Accepted by PRL



reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\to\gamma\gamma)\pi^+\pi^-$ (right)

[6] PRL 95, 262001 (2005)
[7] PRL 106, 072002 (2011)
[8] PRL 115, 091803 (2015)
[9] PRL 117, 042002 (2016)

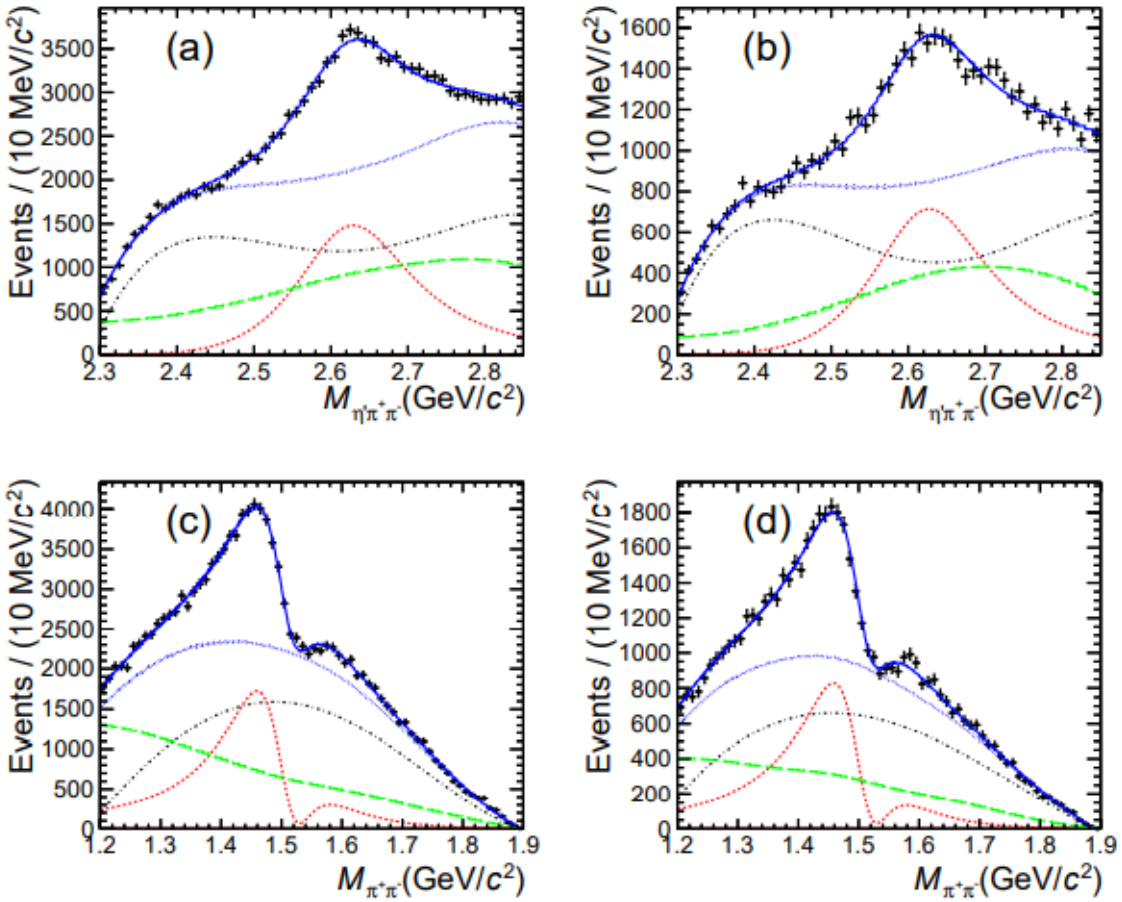
A New State $X(2600)$ Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

- To study **$X(2600)$ parameters**, a simultaneous fit to $\eta'\pi^+\pi^-$ and $\pi^+\pi^-$ is performed
- The **structure in $M(\pi^+\pi^-)$** well described with the interference between $f_0(1500)$ and $X(1540)$

@ > 20σ	Mass (MeV/c^2)	Width (MeV)
$f_0(1500)$	$1492.5 \pm 3.6^{+2.4}_{-20.5}$	$107 \pm 9^{+21}_{-7}$
$X(1540)$	$1540.2 \pm 7.0^{+36.3}_{-6.1}$	$157 \pm 19^{+11}_{-77}$
$X(2600)$	$2618.3 \pm 2.0^{+16.3}_{-1.4}$	$195 \pm 5^{+26}_{-17}$

Case	$f_0(1500)$	$X(1540)$
Events	24585 ± 1689	21203 ± 1456
BF ($\times 10^{-5}$)	$3.09 \pm 0.21^{+1.14}_{-0.77}$	$2.69 \pm 0.19^{+0.38}_{-1.21}$

$$X(2600)$$
$$J^{PC} = 0^{-+} or\ 2^{-+}$$



reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\to \gamma\gamma)\pi^+\pi^-$ (right)

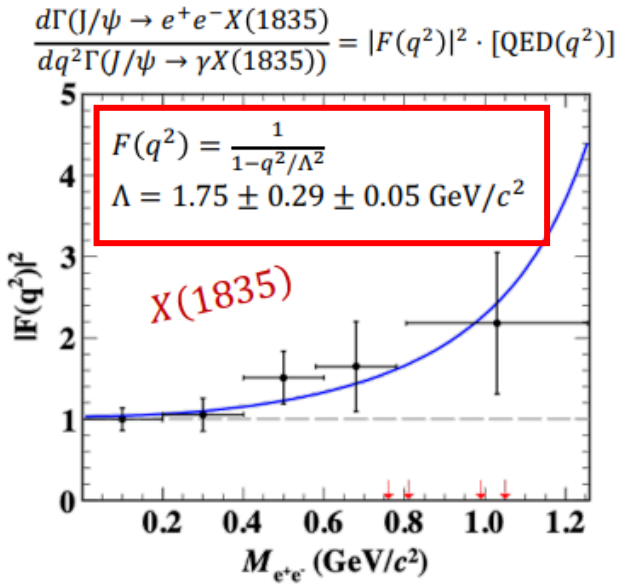
Observation of X(1835), X(2120) and X(2370) in J/ψ EM Dalitz Decays

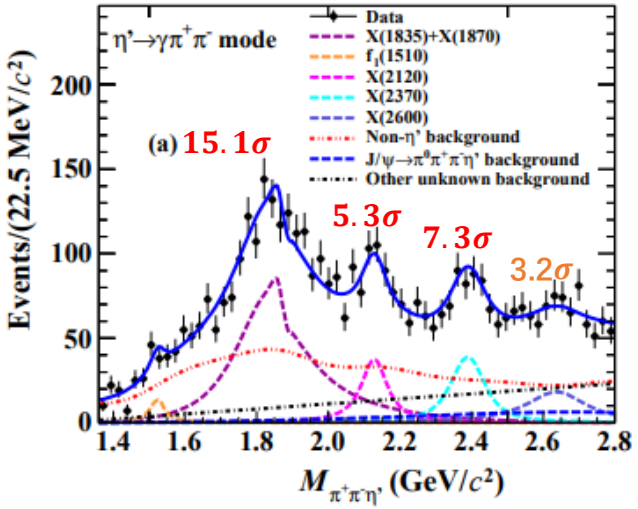
$$J/\psi \to e^+e^-\pi^+\pi^-\eta'$$

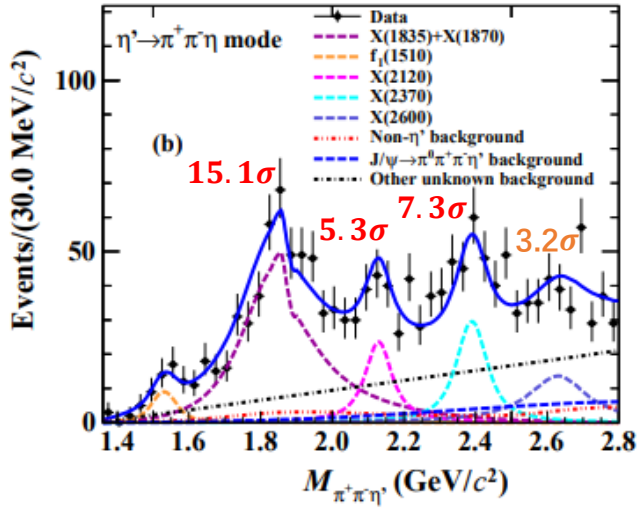
- **Confirmation** of $\boldsymbol{X(1835), X(2120), X(2370)}$ previously observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

- Measurement of the **Transition Form Factor** of $J/\psi \to e^+e^-X(1835)$
  - ➢ Gives additional information of the **internal structure of $\boldsymbol{X(1835)}$**

10 billion J/ψ
arXiv:2112.14369
Accepted by PRL





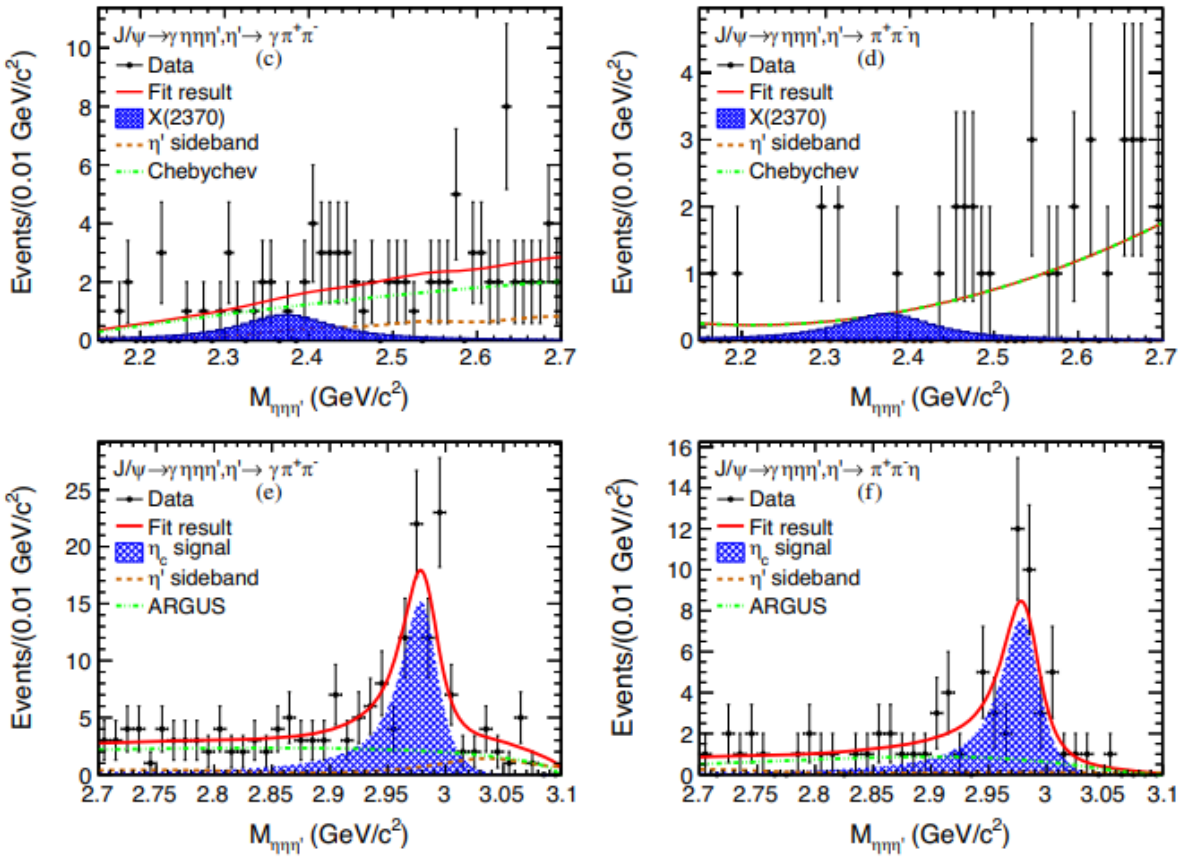


reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\to \gamma\gamma)\pi^+\pi^-$ (right)

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

1.3 billion J/ψ

Phys. Rev. D 103, 012009(2021)



reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\to \gamma\gamma)\pi^+\pi^-$(right)

$X(2370)$ previously observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$ [10] and $J/\psi \to \gamma K\bar{K}\eta'$ [11], and possibly a **pseudoscalar glueball candidate**

- **No evident signal of $X(2370)$** in $J/\psi \to \gamma\eta\eta\eta'$

  $B(J/\psi \to \gamma X(2370) \to \gamma\eta\eta\eta') < 9.2 \times 10^{-6}$ (@ 90% $C.L.$)

➢ No contradiction with prediction of the branching ratio for pseudoscalar glueball [12]

- Observation of **$\eta_c \to \eta\eta\eta'$**

  $B(J/\psi \to \gamma\eta_c \to \gamma\eta\eta\eta') = 4.86 \pm 0.62(stat.) \pm 0.45(sys.)$

[10] PRL 106, 072002 (2011)
[11] Eur. Phys.J.C 80,746 (2020)
[12] PRD 87, 054036 (2013)

Summary

- $J/\psi \to \gamma\eta\eta'$
  - Observation of **exotic isoscalar 1^{-+} $\eta_1(1855)$**
    - ➢ Hybrid? Molecule? Tetraquark? … needs **further study**
  - Support $f_0(1710)$ overlap with **scalar glueball**
- $J/\psi \to \gamma\eta'\eta'$
  - $f_0(2020), f_0(2330), f_2(2340)$ and a **new state $f_0(2480)$** observed
  - $f_0(2020)$ observed to be a **flavor singlet**

- **Other partners** in hybrid nonet:
  $\pi_1(b_1\pi, f_1\pi, \dots)$ and $K_1(K_1(1270)\pi, \dots)$
- **Production & decay** of $\eta_1(1855)$
  - $J/\psi(\psi') \to VX, \dots$
  - $X \to a_1\pi, K_1K, f_1\eta, \dots$

- **New $X(2600)$** observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$ in addition to $X(1835), X(2120), X(2370)$
- **Confirmation of $X(1835), X(2120), X(2370)$** in $J/\psi \to e^+e^-\pi^+\pi^-\eta'$ and measurement of **Transition form factor** of $J/\psi \to e^+e^-X(1835)$
- **Upper limit for $X(2370)$ in $J/\psi \to \gamma\eta\eta\eta'$** and observation of $\eta_c \to \eta\eta\eta'$

➢ With the world's largest charmonium data sets, BESIII provides great opportunities to map out light meson spectroscopy and study QCD exotics.

Thank you for your attention!

Backup slide

Amplitude analysis of $J/\psi \to \gamma K_S K_S$

1.3 billion J/ψ

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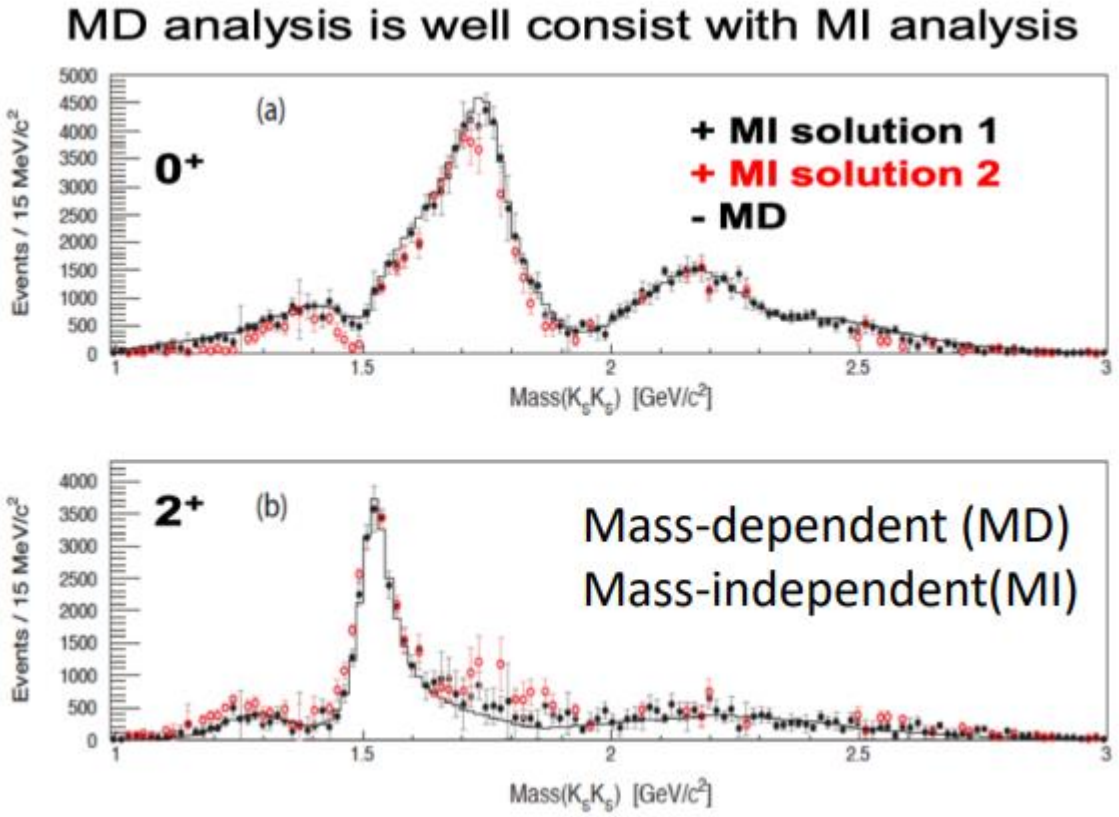

Resonance	M (MeV/c^2)	$M_{\rm PDG}$ (MeV/c^2)	Γ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81±0.19	48	47.4±0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52})\times10^{-6}$	35σ
$K_1(1270)$	1272	1272±7	90	90±20	$(8.54^{+1.07+2.35}_{-1.20-2.13})\times10^{-7}$	16σ
$f_0(1370)$	$1350\pm9^{+12}_{-2}$	1200 to 1500	$231\pm21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34})\times10^{-5}$	25σ
$f_0(1500)$	1505	1504±6	109	109±7	$(1.59^{+0.16+0.18}_{-0.16-0.56})\times10^{-5}$	23σ
$f_0(1710)$	$1765\pm2^{+1}_{-1}$	1723^{+6}_{-5}	$146\pm3^{+7}_{-1}$	139±8	$(2.00^{+0.03+0.31}_{-0.02-0.10})\times10^{-4}$	$\gg35\sigma$
$f_0(1790)$	$1870\pm7^{+2}_{-3}$	-	$146\pm14^{+7}_{-15}$	-	$(1.11^{+0.06+0.19}_{-0.06-0.32})\times10^{-5}$	24σ
$f_0(2200)$	$2184\pm5^{+4}_{-2}$	2189±13	$364\pm9^{+4}_{-7}$	238±50	$(2.72^{+0.08+0.17}_{-0.06-0.47})\times10^{-4}$	$\gg35\sigma$
$f_0(2330)$	2411±10±7	-	$349\pm18^{+23}_{-1}$	-	$(4.95^{+0.21+0.66}_{-0.21-0.72})\times10^{-5}$	35σ
$f_2(1270)$	1275	1275.5±0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20})\times10^{-5}$	33σ
$f_2'(1525)$	1516±1	1525±5	75±1±1	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50})\times10^{-5}$	$\gg35\sigma$
$f_2(2340)$	$2233\pm34^{+9}_{-25}$	2345^{+50}_{-40}	$507\pm37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49})\times10^{-5}$	26σ
0^{++} PHSP	-	-	-	-	$(1.85^{+0.05+0.68}_{-0.05-0.26})\times10^{-5}$	26σ
2^{++} PHSP	-	-	-	-	$(5.73^{+0.99+4.18}_{-1.00-3.74})\times10^{-5}$	13σ