J/ψ radiative decays and the glueball candidates

Hadron 2021

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CHARTERED 1693

Jefferson Lab
Exploring the Nature of Matter

JPAC

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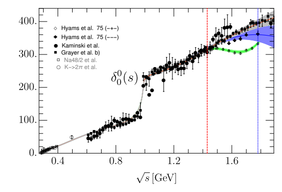
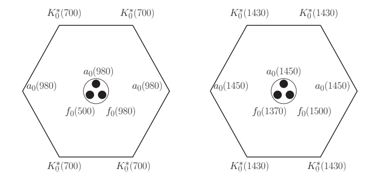
The scalar sector

- Many of them are not ordinary $q\bar{q}$





- The isoscalars-scalars → vacuum quantum numbers

1909.07306

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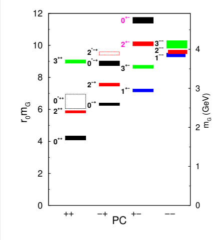
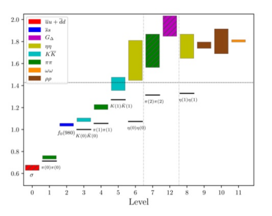




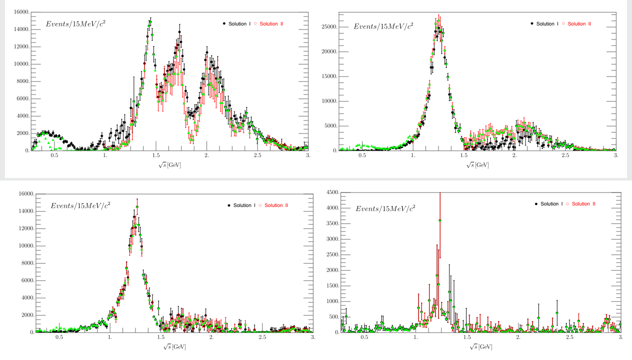
- $f_0(1710)$ → supernumerous state?
- Lightest glueball (0^{++}) candidate is expected below 2 GeV

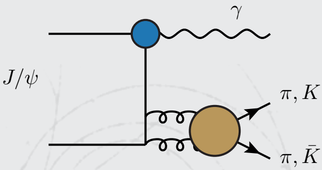
- Many of these are poorly determined
- Heavier $\rightarrow$ even worse

	Mass (MeV)	Width (MeV)	$\mathscr{B}(f \to \pi\pi)$	$\mathscr{B}(f \to K\bar{K})$	$\mathscr{B}(f \to 4\pi)$	Summary Table
$f_0(1370)$	$1200-1500$	$300-500$	<0.1	0.35 ± 0.13	>0.72	Yes
$f_0(1500)$	1506 ± 6	112 ± 9	0.345 ± 0.022	0.085 ± 0.010	0.489 ± 0.033	Yes
$f_0(1710)$	1704 ± 12	123 ± 18	$0.039^{+0.03}_{-0.024}$	0.36 ± 0.12	–	Yes
$f_0(2020)$	1992 ± 16	442 ± 60	–	–	–	No
$f_0(2200)$	2187 ± 14	207 ± 40	–	–	–	No
$f_2(1270)$	1275.5 ± 0.8	$186.7^{+2.2}_{-2.5}$	$0.842^{+0.029}_{-0.009}$	$0.046^{+0.5}_{-0.4}$	$0.104^{+0.016}_{-0.037}$	Yes
$f_2(1430)$	≈ 1430	–	–	–	–	No
$f_2'(1525)$	1517.4 ± 2.5	86 ± 5	$(8.3\pm1.6)\times10^{-3}$	0.876 ± 0.022	–	Yes
$f_2(1565)$	1542 ± 19	122 ± 13	–	–	–	No
$f_2(1640)$	1639 ± 6	99^{+60}_{-40}	–	–	–	No
$f_2(1810)$	1815 ± 12	197 ± 22	$0.21^{+0.02}_{-0.03}$	$0.003^{+0.019}_{-0.002}$	–	No
$f_2(1910)$	1900 ± 9	167 ± 21	–	–	–	No
$f_2(1950)$	1936 ± 12	464 ± 24	–	–	–	Yes
$f_2(2010)$	2011^{+62}_{-76}	202^{+67}_{-62}	–	–	–	Yes
$f_2(2150)$	2157 ± 12	152 ± 30	–	–	–	No
$f_2(2300)$	2297 ± 28	149 ± 41	–	–	–	Yes

Data: BESIII

- Data from BESIII $J/\psi \to \gamma(\pi_0\pi_0)(K_sK_s)$ BESIII (1506.00546, 1808.06946)
- Data on both S and D-wave 3 multipoles





- Glueball production

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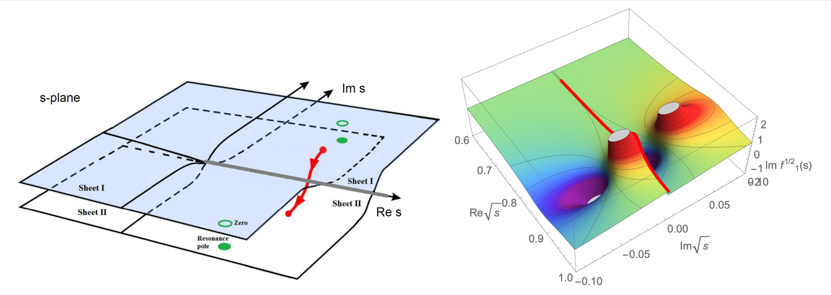
S-matrix principles: Unitarity

- UNITARITY $\Leftrightarrow$ probability $\sum |\langle f|S|i\rangle|^2 = 1$
- Both right and left branch cuts $SS^\dagger = I \Rightarrow F - F^\dagger = \mathrm{i}FF^\dagger$.
- Elastic unitarity $\rightarrow S^{II}(z) = \frac{1}{S^I(z)}$
- Zero of $S^I(z) \rightarrow$ pole of $S^{II}(z)$

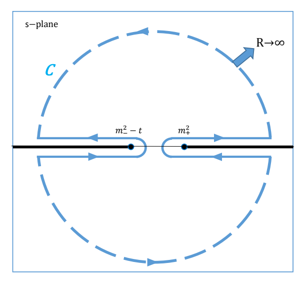


S-matrix principles: Analiticity and Crossing

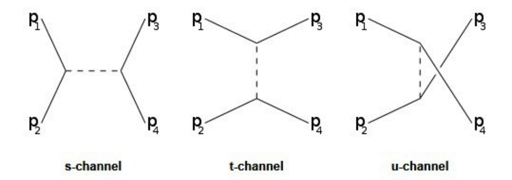
- CAUSALITY⇔ANALITICITY
- No poles in the first sheet

$$F(s,t) = \frac{1}{\pi}\int_{s_{th}}^{\infty} ds' \frac{\operatorname{Im} F(s',t)}{s'-s} + LHC$$

- Structures → unitarity, bound states,cusp

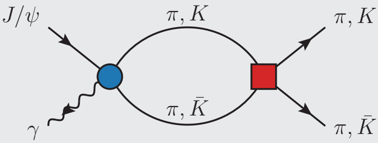


- Together with CROSSING → Mandelstam analyticity



- Production ⇒ factorization of the photon ⇒ $Ima(s) = \rho(s)t^*(s)a(s)$.

- Amplitude $t(s) = \frac{N(s)}{D(s)}$ ⇒ $a(s) = E_\gamma p^J \frac{n(s)}{D(s)}$.
- Numerators are smooth polynomials
  $n(s) = \sum_j a_j T_j(\omega(s))$
  1. $\omega(s)_1 = \frac{s}{s+s_0}$.
  2. $\omega(s)_2 = 2\frac{s-s_{\text{min}}}{s_{\text{max}}-s_{\text{min}}} - 1$
  3. $\omega(s)_3 = 2\frac{\omega(s)_1-\omega(s_{\text{min}})_1}{\omega(s_{\text{min}})_1-\omega(s_{\text{max}})_1} - 1$



- K-matrix approach with dispersive phase space.

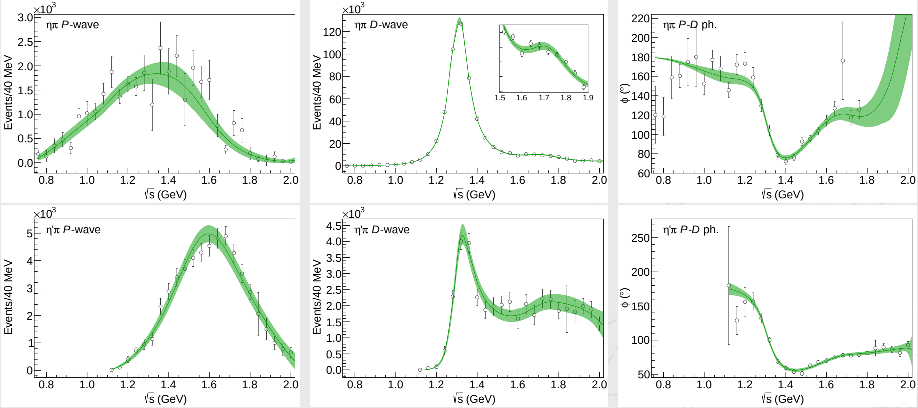
$$D^J(s)_{ki} = (K^J(s)^{-1})_{ki} - \frac{s}{\pi}\int_{s_k}^{\infty} ds' \frac{\rho(s')N^J_{ki}(s')}{s'(s'-s-i\varepsilon)}.$$

$$\rho N^J_{ki}(s')_{\text{nominal}} = \delta_{ki}\frac{(2p_i)^{2J+1}}{(s'+s_L)^{2J+\alpha}}, \qquad \rho N^J_{ki}(s')_{Q\text{-model}} = \delta_{ki}\frac{Q_J(z_{s'})}{2p_i^2}$$

Hunting the $\pi_1(1600)$

Phys.Rev.Lett. 122 042002

- We use an average of 6 parameters for each figure.
- $\chi^2 \approx 1.3$, no significant deviation for any partial wave.
- 1 T-matrix pole produces 2 different peaks for the P-wave → 300 MeV distance.

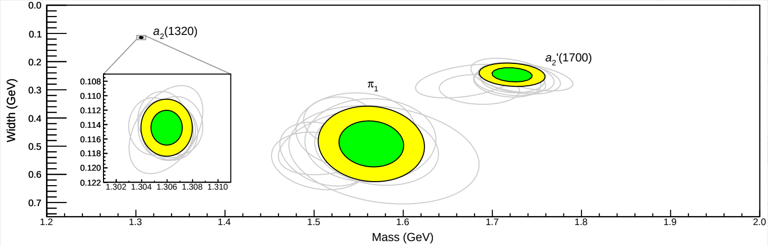


Hunting the $\pi_1(1600)$ Phys.Rev.Lett. 122 042002

- Most robust extraction of this hybrid candidate.
- Theoretical predictions and experiment reconciled.
- Statistical uncertainties $\rightarrow$ 100k sample bootstrap.

Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
$\pi_1(1600)$	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

- Systematics (diferent LHC, numerators, subtractions ...) included.



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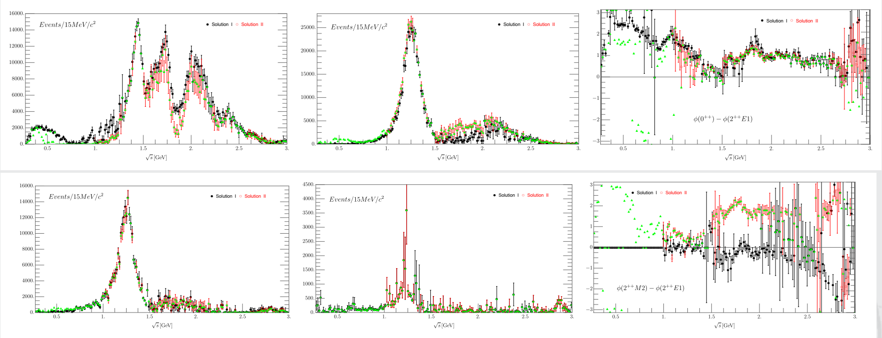
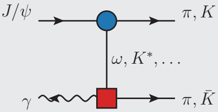
Data problems

- Data on both S and D-wave 3 multipoles

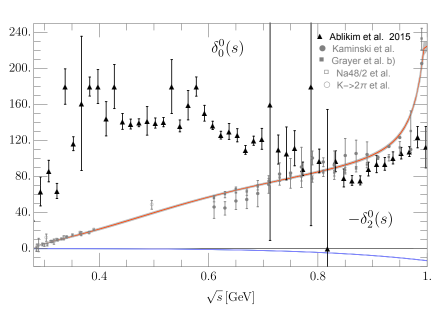


- 2 ambiguous solutions

Data Problems



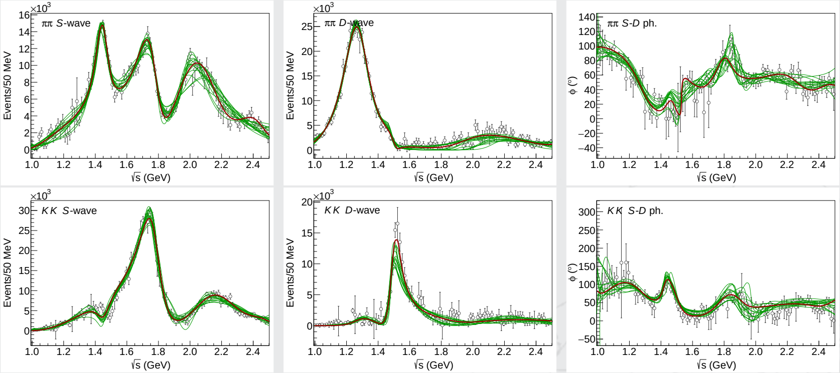
- BESIII and $\pi\pi$ scattering disagree $\to \chi^2 \sim 7\sigma$



- Multiple resonances $\to$ more than 10 different decay channels
- Only control $\to$ two body
- One of the solutions seems disfavored
- We fit solution I > 1 GeV

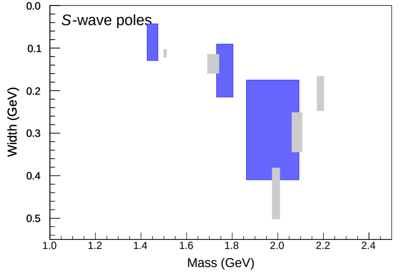
2-channel fits

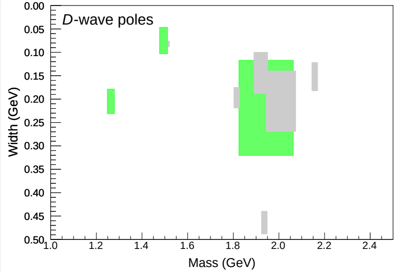
- Not terrible → room for improvement
- Not quite the same within systematics
- $\chi^2_{2-channel} \sim 2$ vs $\chi^2_{3-channel} \sim 1.2$



2-channel fits

- Not terrible $\rightarrow$ room for improvement
- Possible contribution from other channels $\rightarrow 4\pi$?

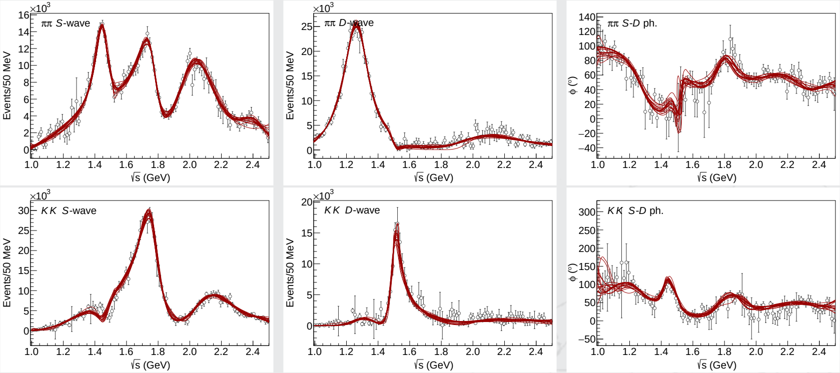




- $\rho\rho \rightarrow$ 3rd channel

3-channel fits

- Starting from best 2-channel
- Up ~ 30 different systematics, thousands of trials
- Better description an consistency $\chi^2_{3-channel} \sim 1.2$



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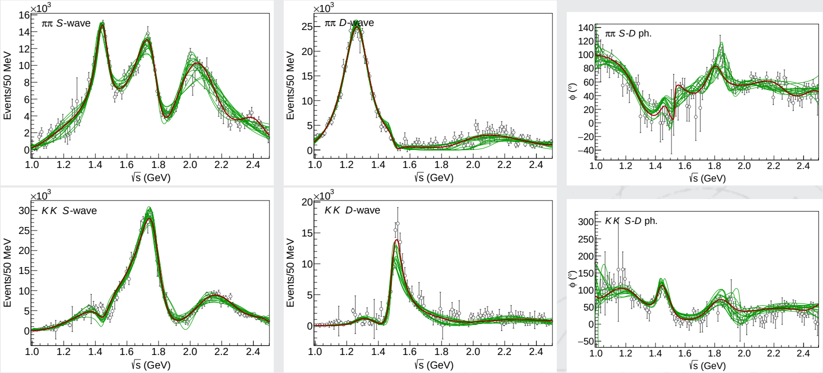

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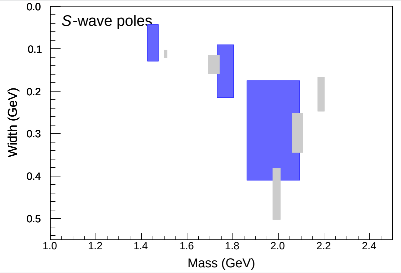

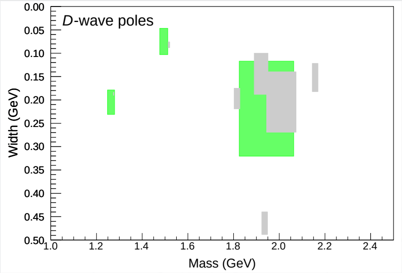

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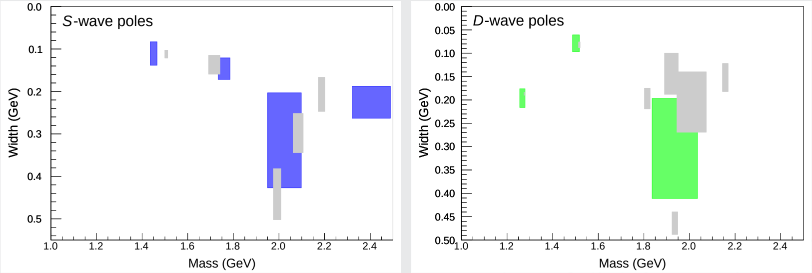
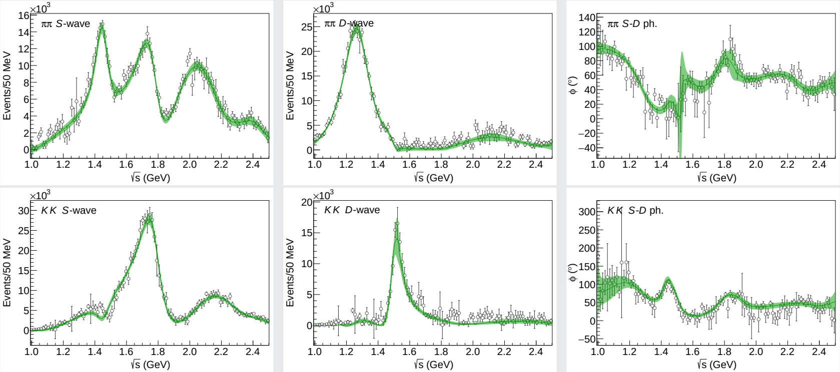


- $\rho\rho \rightarrow$ 3rd channel

3-channel fits

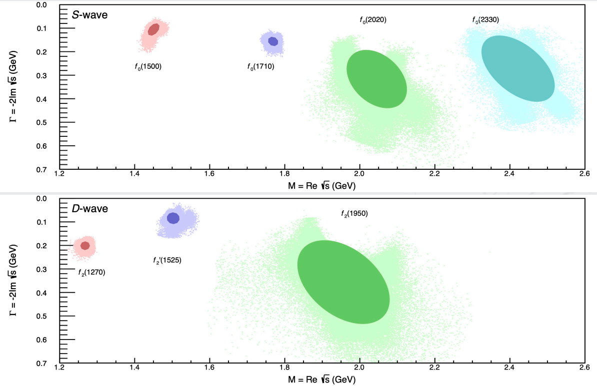
- 16 selected fits with different parameterizations $\chi^2 \sim 1.1 - 1.2$



- Statistics → Bootstrapping ∼ 10k samples
- Negative intensities? $\to \Gamma$ distribution

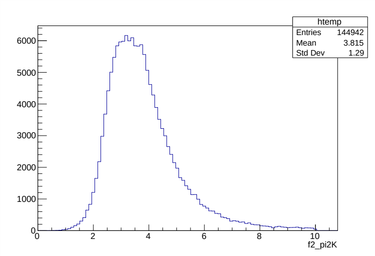
- "Only" 7 resonances
- No evidence for $\rightarrow f_0(1370)$

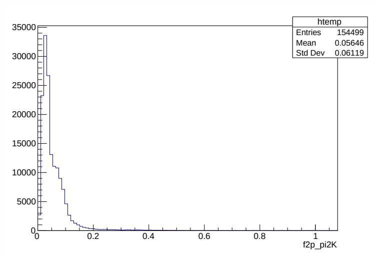
	$\sqrt{s_p}$ (S-wave)		$\sqrt{s_p}$ (D-wave)
$f_0(1500)$	(1.450 ± 0.010) - $i\,(0.106\pm0.016)/2$	$f_2(1270)$	(1.268 ± 0.008) - $i\,(0.201\pm0.011)/2$
$f_0(1710)$	(1.769 ± 0.008) - $i\,(0.156\pm0.012)/2$	$f_2(1525)$	(1.502 ± 0.011) - $i\,(0.084\pm0.015)/2$
$f_0(2020)$	(2.045 ± 0.052) - $i\,(0.316\pm0.081)/2$	$f_2(1950)$	(1.956 ± 0.081) - $i\,(0.356\pm0.116)/2$
$f_0(2330)$	(2.422 ± 0.064) - $i\,(0.272\pm0.092)/2$		



Couplings: D-wave

- Ordinary resonances
- f_2, f_2' decay almost elastic to $\pi\pi, K\bar{K}$
- $\mathscr{B}_{f_2(1270)\to\pi\pi} = 80 \pm 5\%$ $\mathscr{B}_{f_2(1270)\to K\bar{K}} \sim 20\%$
- $\mathscr{B}_{f_2'(1525)\to\pi\pi} \sim 6 \pm 6\%$ $\mathscr{B}_{f_2'(1525)\to K\bar{K}} \sim 94 \pm 6\%$

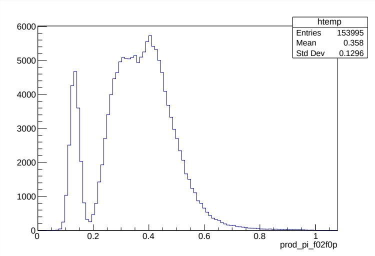


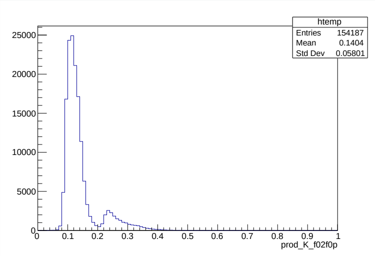


- Production residues do not offer new information

Couplings: S-wave

- Much richer decay modes $\rightarrow$ scattering couplings not well constrained
- 4π non negligible for several fits $\rightarrow$ systematic spread





- $\frac{\mathscr{P}_{f_0(1500)\to\pi\pi}}{\mathscr{P}_{f_0(1710)\to\pi\pi}} \sim 0.36 \pm 0.13$
- $\frac{\mathscr{P}_{f_0(1500)\to K\bar{K}}}{\mathscr{P}_{f_0(1710)\to K\bar{K}}} \sim 0.14 \pm 0.06$

☐ Study the bimodal distribution

Summary

- J/ψ radiative decay analysis with BESIII data
- Both S and D wave required
- Up to 7 resonances
  1. 4 scalars
  2. 3 tensors
- Tensors $\rightarrow$ ordinary behavior
- $f_0(1710)$ couples more than $f_0(1500)$

Spare slides!

Branching ratios

$\mathscr{B}\left(J/\psi \to \gamma\pi^0\pi^0\right)$	$(11.5 \pm 0.5) \times 10^{-4}$
$\mathscr{B}\left(J/\psi \to \omega\pi^0 \to \gamma\pi^0\pi^0\right)$	$(3.8 \pm 0.4) \times 10^{-5}$
$\mathscr{B}\left(J/\psi \to \rho\pi^0 \to \gamma\pi^0\pi^0\right)$	$(2.6 \pm 0.5) \times 10^{-6}$
$\mathscr{B}\left(J/\psi \to b_1(1232)\pi^0 \to \gamma\pi^0\pi^0\right)$	$(3.6 \pm 1.3) \times 10^{-6}$
$\mathscr{B}\left(J/\psi \to \gamma K_S^0 K_S^0\right)$	$(8.1 \pm 0.4) \times 10^{-4}$
$\mathscr{B}\left(J/\psi \to K^*(892)^0 K_S^0 \to \gamma K_S^0 K_S^0\right)$	$(6.3 \pm 0.6) \times 10^{-6}$
$\mathscr{B}\left(J/\psi \to K_1(1270)^0 K_S^0 \to \gamma K_S^0 K_S^0\right)$	$(8.5 \pm 2.5) \times 10^{-7}$