RUHR-UNIVERSITÄT BOCHUM

Light Meson Spectroscopy At BESIII

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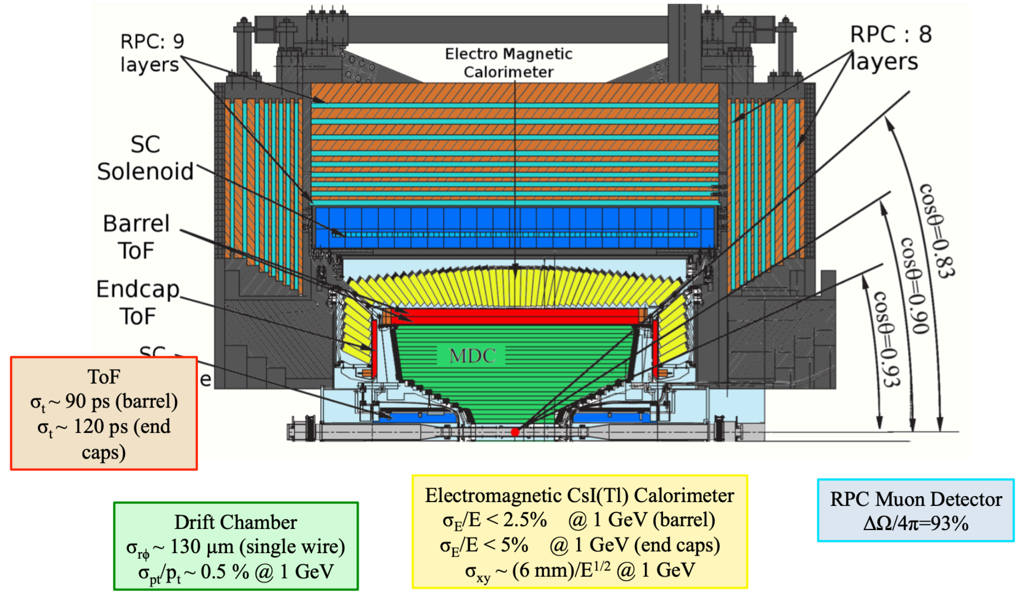
Ruhr-Universität Bochum
(on behalf of the BESIII Collaboration)

PWA 12 / ATHOS 7
September 6-10, 2021

BESIII at BEPC II



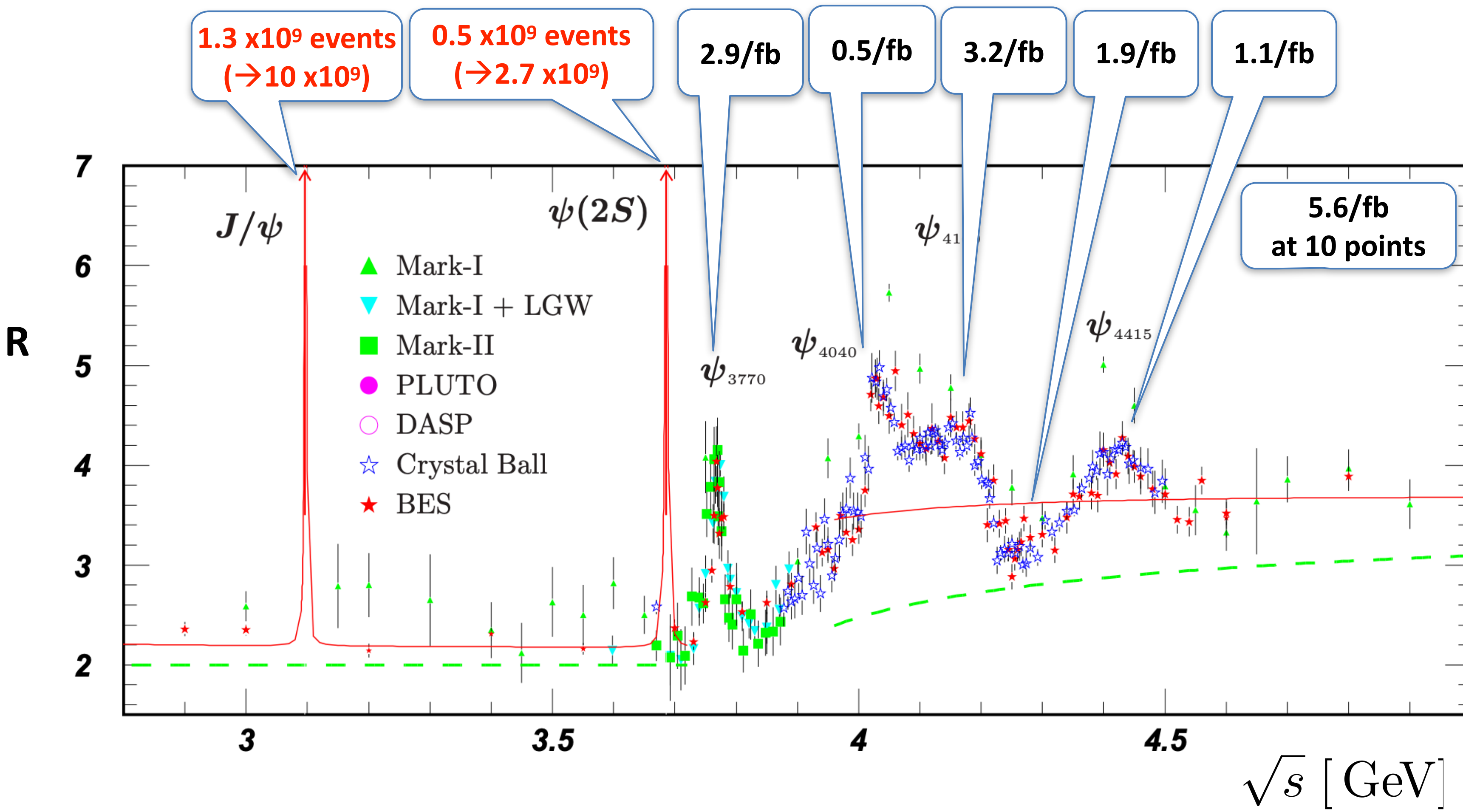
Symmetric electron-positron collider BEPC II

- Energy range: $\sqrt{s}$ = 2.0 - 4.6 GeV (~5 GeV since summer 2019)
- Design luminosity achieved: $1\text{x}10^{33}$ $cm^{-2}s^{-1}$ (at $\psi(3770)$)
- Energy spread: ~$5\text{x}10^{-4}$
- Operating since March 2008

also see Chun Hua Li's talk on X(3872) at BESIII

Data Samples

World's largest τ-charm data samples in direct e^+e^- annihilations

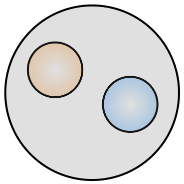


Clean environment, complementary to hadron machines

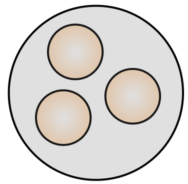
QCD Bound States

Conventional hadrons

mesons: $q\bar{q}$

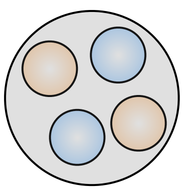


baryons: qqq

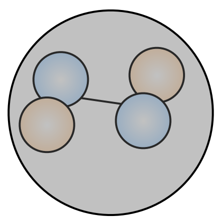


Exotic hadrons (other color-neutral configurations)

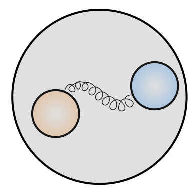
tetraquarks: $qq\bar{q}\bar{q}$



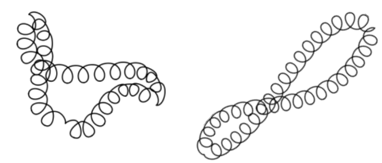
molecules: $[q\bar{q}][q\bar{q}]$



hybrids: $q\bar{q}g$



glueballs: gg, ggg



Candidates for exotic hadrons exist
Nature of these states is far from being understood

Glueballs

- Lattice predictions
  - 0^{++}: m ~ 1710 MeV
  - 2^{++}: m ~ 2390 MeV
  - 0^{-+}: m ~ 2560 MeV

- Production in (gluon-rich) radiative J/ψ decays

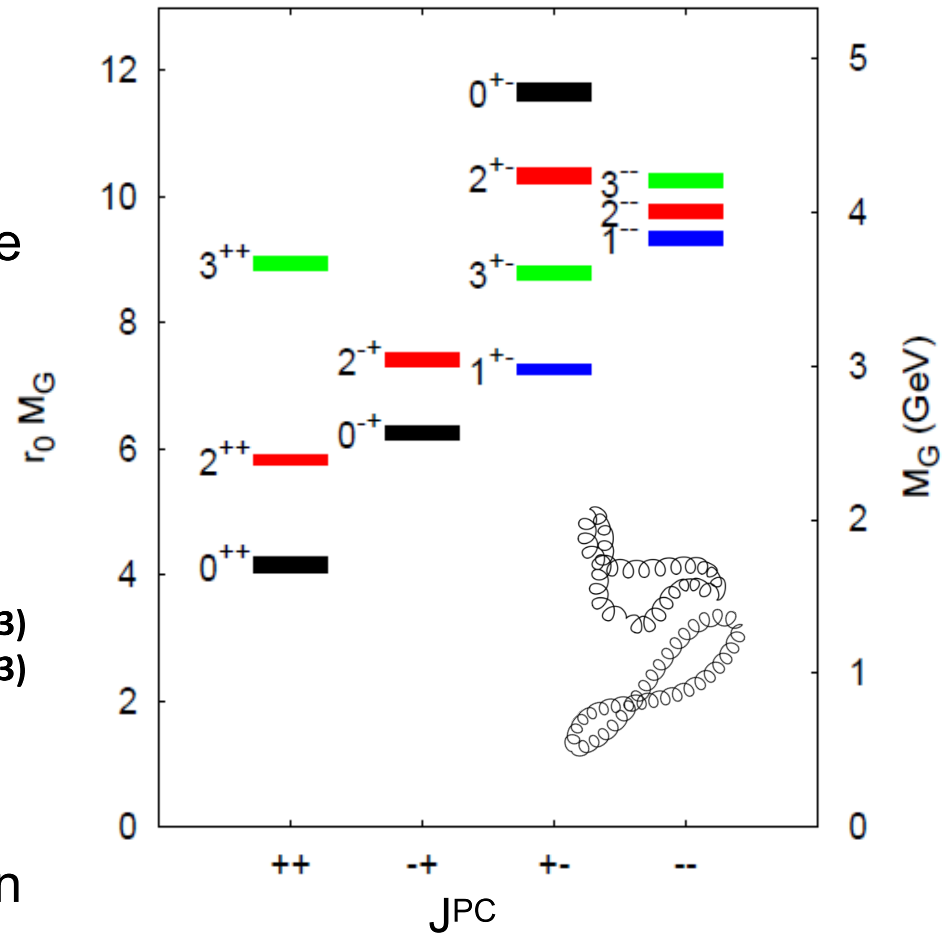
  large branching fractions predicted

$$\mathcal{B}(J/\psi \to \gamma G_{0^{++}}) = 3.8(9) \cdot 10^{-3}$$
$$\mathcal{B}(J/\psi \to \gamma G_{2^{++}}) = 1.1(2)(1) \cdot 10^{-2}$$

CLQCD, Phys. Rev. Lett. 110, 021601 (2013)
CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

- Mixing with nearby q$\bar{q}$ states complicates the clear identification

Glueball Spectrum
(Lattice QCD)

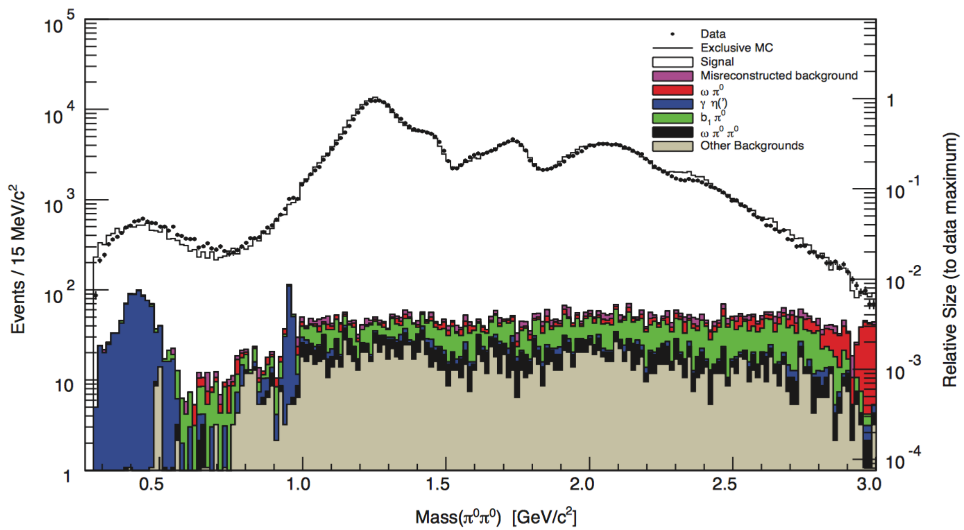


Y. Chen et al., Phys. Rev. D73, 014516 (2006)

Partial Wave Analyses

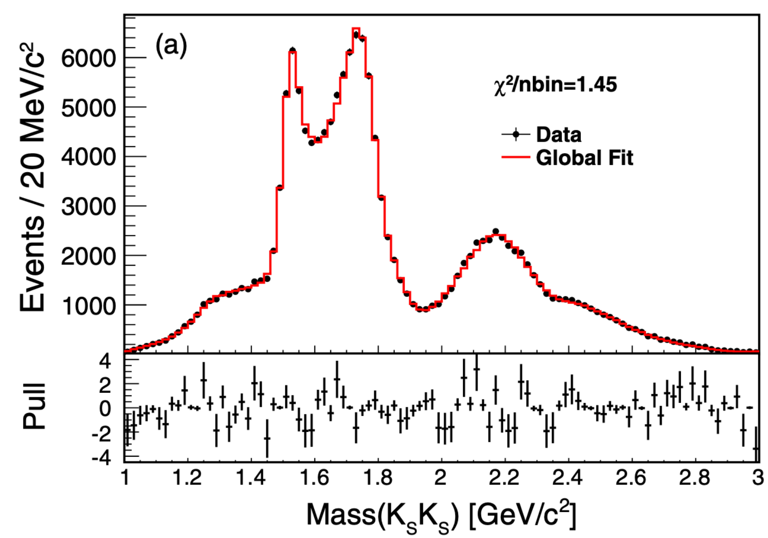
- Partial Wave Analyses of $J/\psi \to \gamma\pi^0\pi^0, \eta\eta, K_S^0 K_S^0$
  - many broad and overlapping resonances, many open channels
  - complex structure, parameterization challenging
- Approach: Model Independent Partial Wave Analysis
  - do not parameterize mass-dependent kinematics of the amplitudes

$$J/\psi \to \gamma\pi^0\pi^0$$



Phys.Rev. D92 052003 (2015)

$$J/\psi \to \gamma K_S^0 K_S^0$$

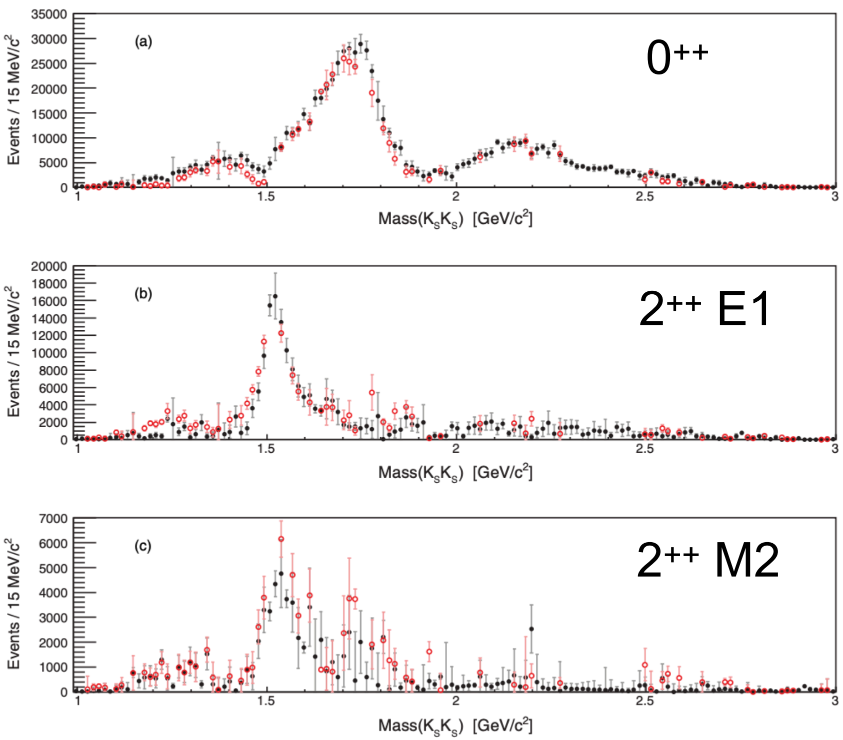


Phys. Rev. D 98, 072003 (2018)

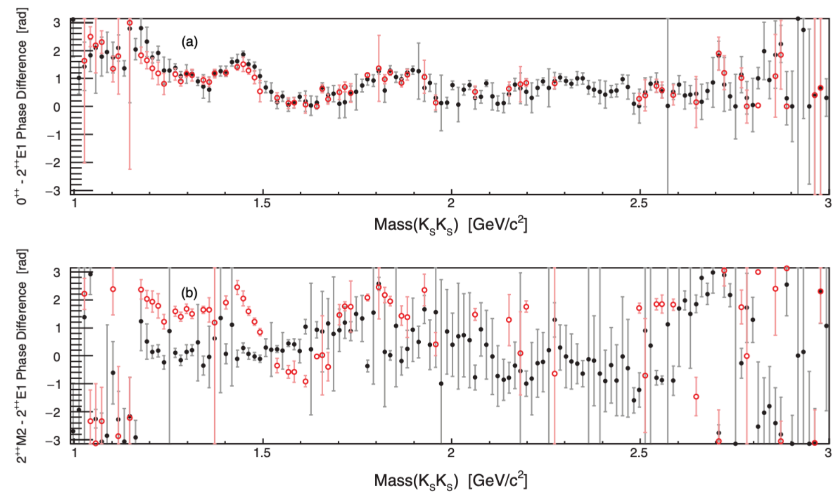
Partial Wave Analysis of $J/\psi \to \gamma K_S^0 K_S^0$

Phys. Rev. D 98, 072003 (2018)

Extracted Intensity



Relative Phase wrt/ 2^{++} E1 amplitude



model independent solution

Only 0^{++} and 2^{++} amplitudes contribute significantly

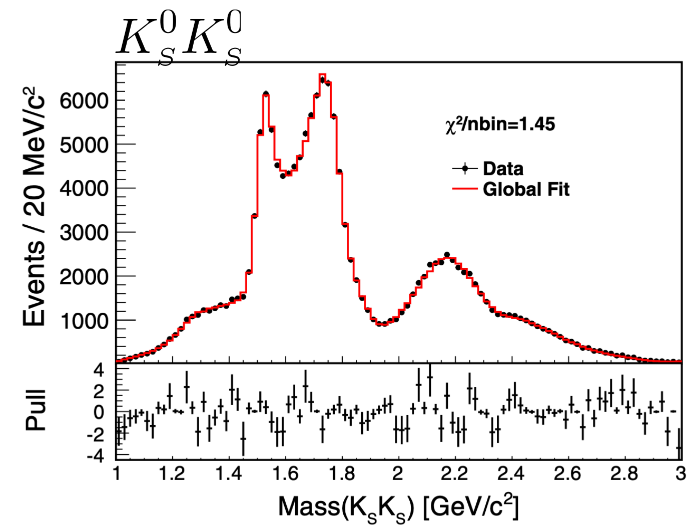
Partial Wave Analysis of $J/\psi \to \gamma K_S^0 K_S^0$

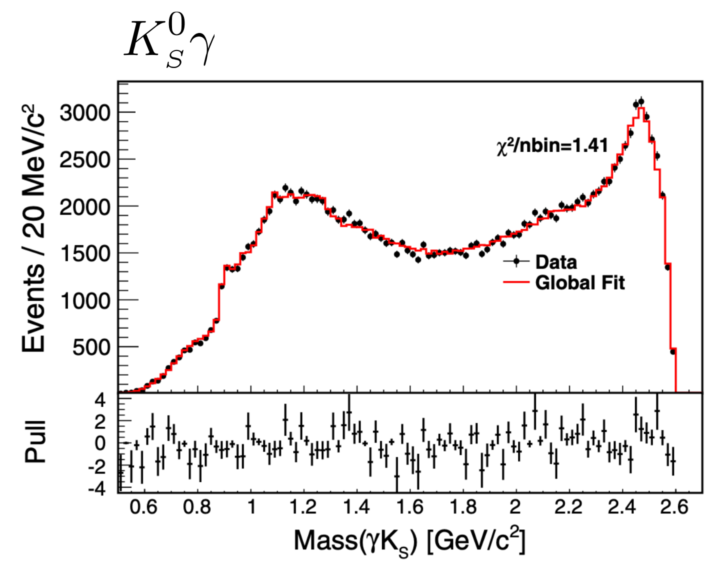
Phys. Rev. D 98, 072003 (2018)

Parameterization:

- 7 contributions 0^{++} $K_S^0 K_S^0$
- 4 contributions 2^{++} $K_S^0 K_S^0$
- K*(892) and K_1(1270) in $K_S^0 \gamma$

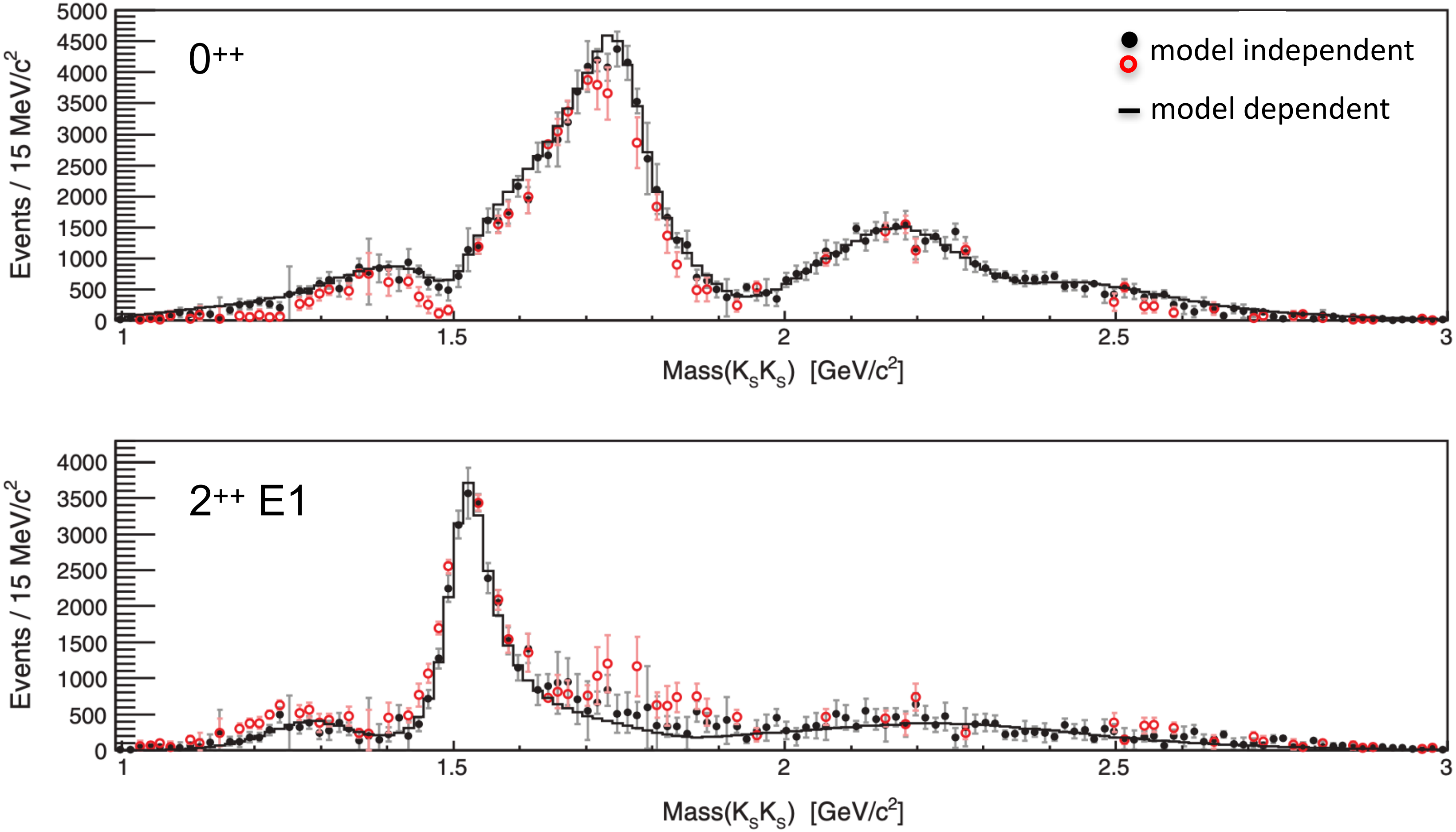
Resonance	M (MeV/c^2)	Γ (MeV/c^2)	Branching fraction
$K^*(892)$	896	48	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$
$K_1(1270)$	1272	90	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	$231 \pm 21^{+28}_{-48}$	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$
$f_0(1500)$	1505	109	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	$146 \pm 3^{+7}_{-1}$	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$146 \pm 14^{+7}_{-15}$	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	$364 \pm 9^{+4}_{-7}$	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$
$f_0(2330)$	$2411 \pm 10 \pm 7$	$349 \pm 18^{+23}_{-1}$	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$
$f_2(1270)$	1275	185	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$
$f_2'(1525)$	1516 ± 1	$75 \pm 1 \pm 1$	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	$507 \pm 37^{+18}_{-21}$	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$
0^{++} PHSP	...	...	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$
2^{++} PHSP	...	...	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$





Partial Wave Analysis of $J/\psi \to \gamma K_S^0 K_S^0$

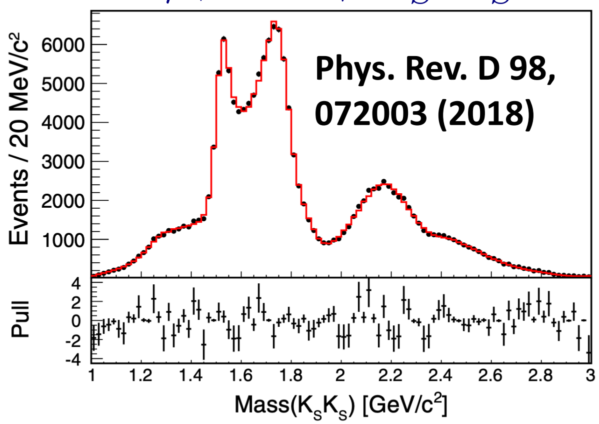
Phys. Rev. D 98, 072003 (2018)



Good agreement of extracted intensities by model dependent and independent PWA

Partial Wave Analysis of $J/\psi \to \gamma K_S^0 K_S^0 / \eta\eta$

$J/\psi \to \gamma K_S^0 K_S^0$



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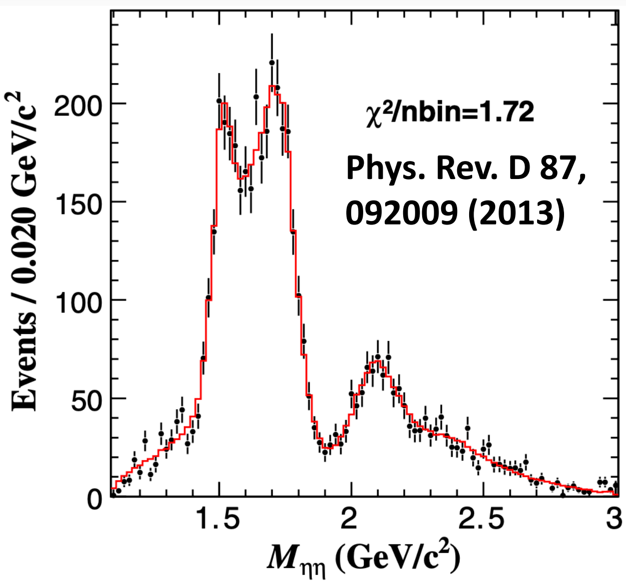
$J/\psi \to \gamma\eta\eta$



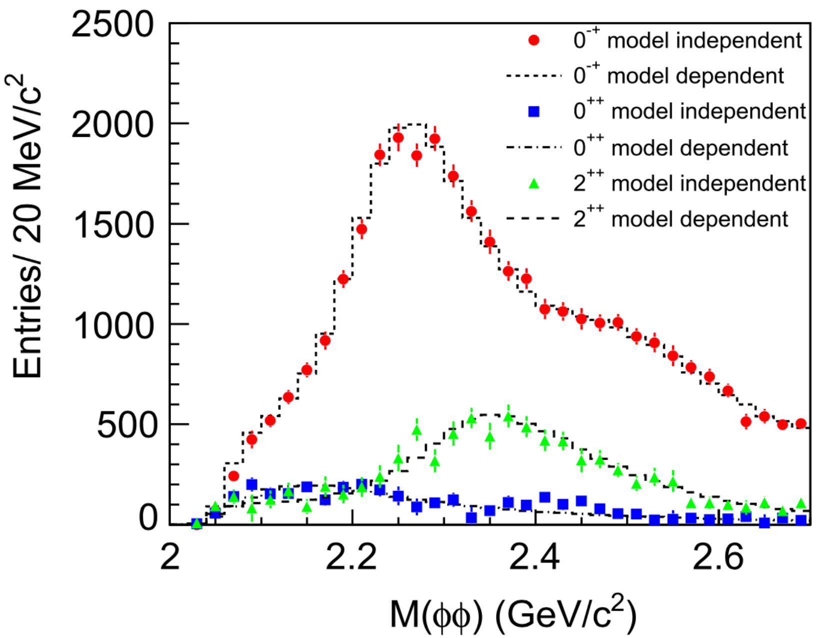
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$

10x larger BF for $f_0(1710)$ compared to $f_0(1500)$ observed in both channels

Also see a recent coupled channel analysis of BESIII and other data:
A. V. Sarantsev, I. Denisenko, U. Thoma and E. Klempt,
Phys. Lett. B 816, 136227 (2021)

Partial Wave Analysis of $J/\psi \to \gamma\phi\phi$

Phys. Rev. D 93, 112011 (2016)



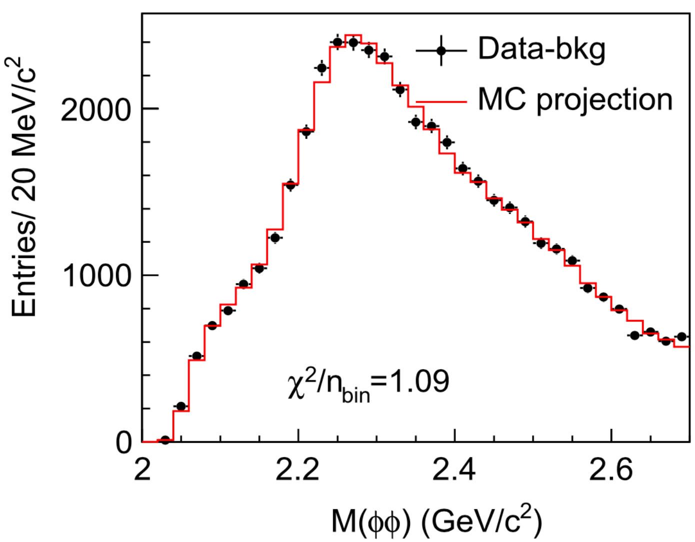
dominant 0^{-+} component

broad 2^{++} component at ~2.3 GeV

$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$

previously observed in πN scattering

Phys. Lett. B 201, 568 (1988)

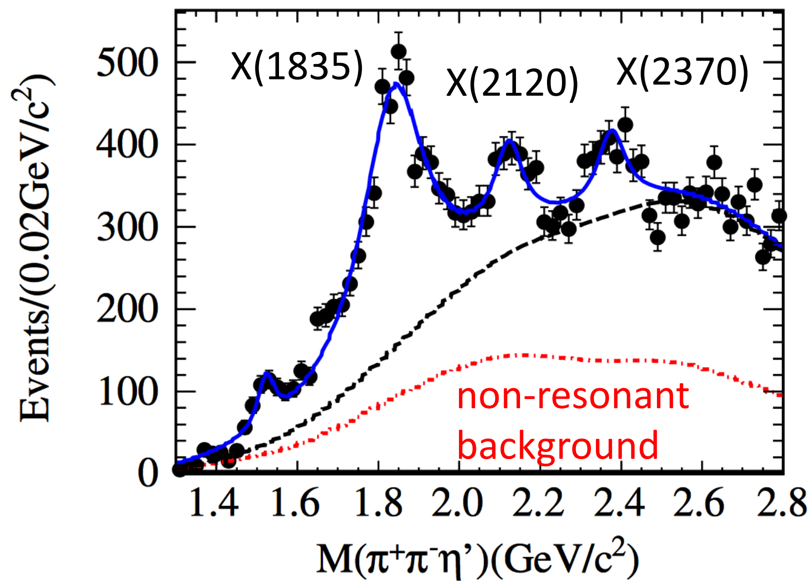


Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$

X(1835)

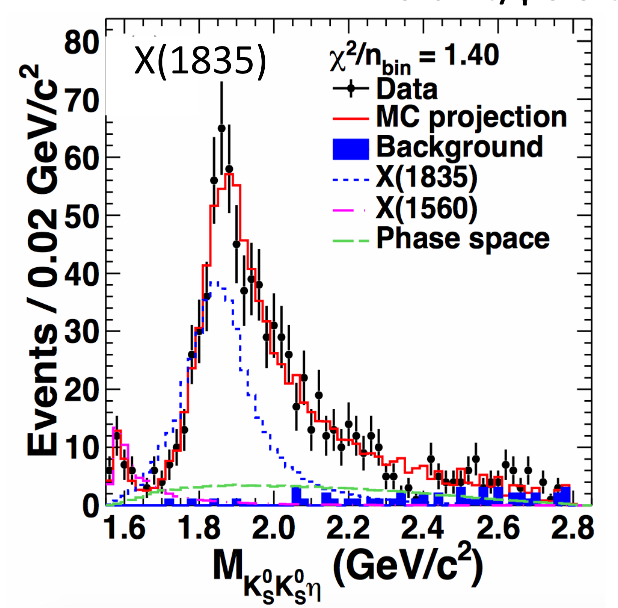
- Systematic study of X(1835) at BESIII with large statistics
  - previously observed at BES and BESII
- J^{PC} consistent with 0^{-+}
- observed in $J/\psi \to \gamma\pi^+\pi^-\eta', \gamma K_S^0 K_S^0 \eta$

225 M J/ψ events



Resonance	M(MeV/c^2)	Γ(MeV/c^2)
$f_1(1510)$	1522.7 ± 5.0	48 ± 11
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0
$X(2120)$	2122.4 ± 6.7	83 ± 16
$X(2370)$	2376.3 ± 8.7	83 ± 17

1310 M J/ψ events



Nature of X(1835) unclear, interpretations include glueball, $p\bar{p}$ bound state, excited η meson

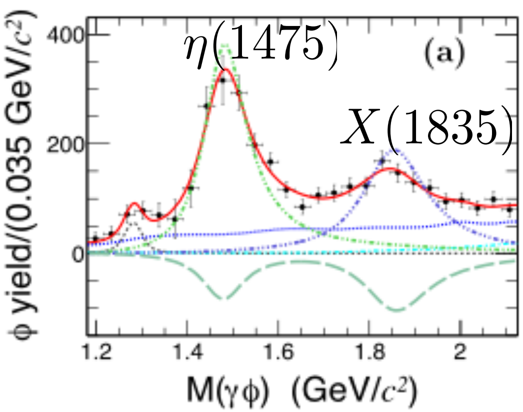
Phys. Rev. Lett. 106, 072002 (2011)
Phys. Rev. Lett. 115, 091803 (2015)

Studies of X(1835)

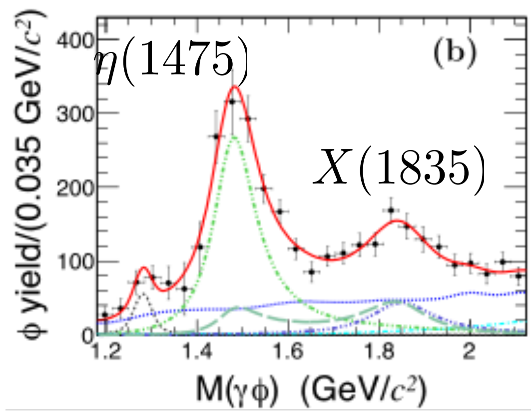
Search for X(1835) in $J/\psi \to \gamma X(1835) \to \gamma\gamma\phi$

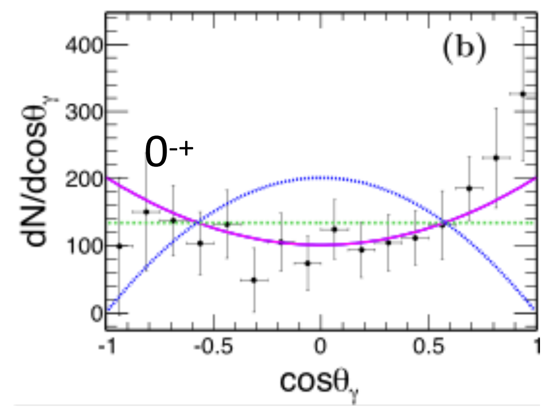
Phys. Rev. D 97, 051101 (2018)

Constructive interference



Destructive interference





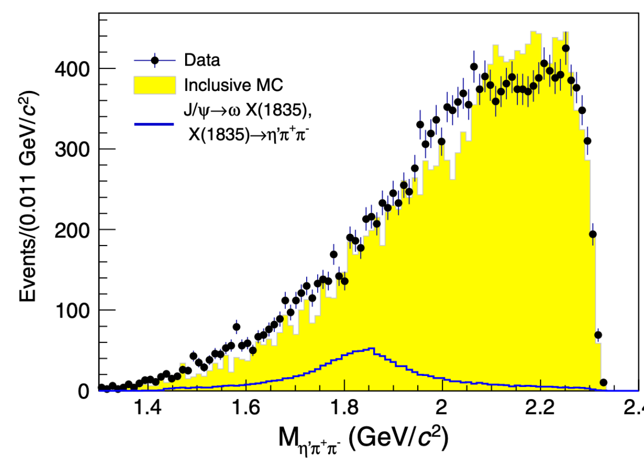
First observation of $J/\psi \to \omega\pi^+\pi^-\eta'$

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

$$\mathcal{B}(J/\psi \to \omega X(1835)\mathcal{B}(X(1835) \to \eta'\pi^+\pi^-)$$

$$< 6.2 \times 10^{-5}$$ (at 90% CL)

Phys. Rev. D 99, 071101 (R) (2019)



Study of X(2120) and X(2370)

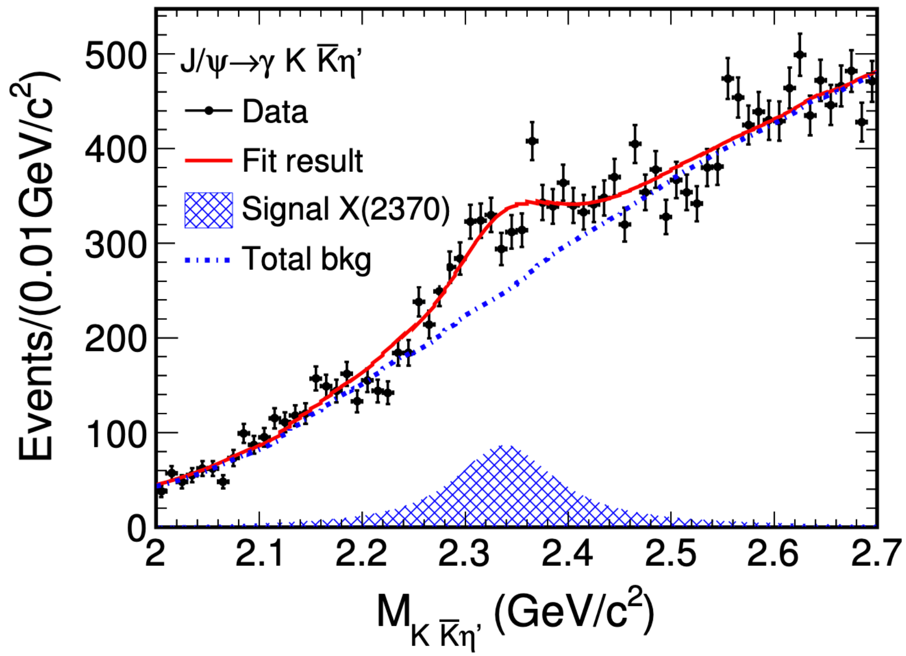
Study of

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

$J/\psi \to \gamma K^0_S K^0_S \eta'$

with both $\eta' \to \gamma\pi^+\pi^-, \eta\pi^+\pi^-$

Eur. Phys. J. C 80:746 (2020)



No significant X(2120) observed

First observation (8.3σ) of $X(2370) \to K\bar{K}\eta'$

m(X(2370))=

$2341.6 \pm 6.5 \pm 5.7\,\mathrm{MeV}/c^2$

$\Gamma = 117 \pm 10 \pm 8\,\mathrm{MeV}$

X(2370): Candidate for the pseudo-scalar glueball? predicted by LQCD at 2.56 (0.035) (0.12) GeV

predicted decay pattern (effective chiral Lagrangian):

$$\Gamma_{G\to\eta\eta\eta'}/\Gamma_G^{tot} = 0.00082$$

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

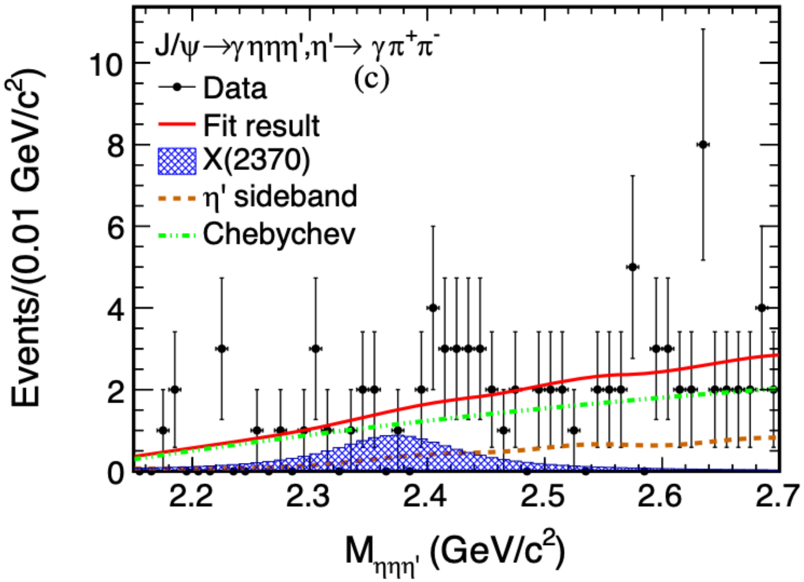
$$\Gamma_{G\to\pi\pi\eta'}/\Gamma_G^{tot} = 0.090$$

W. I. Eshraim, S. Janowski, F. Giacosa, and D. H. Rischke, Phys. Rev. D 87, 054036 (2013)

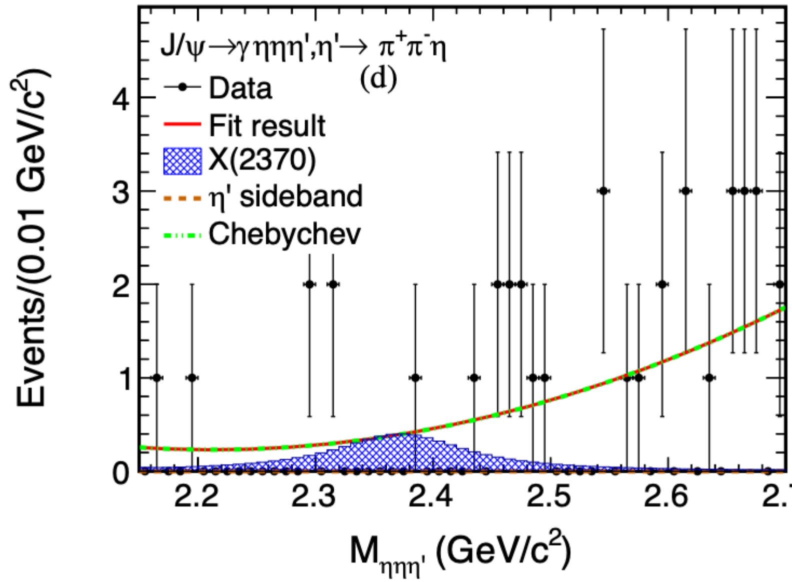
Study of X(2370)

Search for X(2370) in $J/\psi \rightarrow \gamma X(2370) \rightarrow \gamma\eta\eta\eta'$ **Phys. Rev. D 103, 012009 (2021)**

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



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



$\mathcal{B}(J/\psi \rightarrow \gamma X)\mathcal{B}(X \rightarrow \eta\eta\eta') < 9.2 \cdot 10^{-6}$ (at 90% CL)

does not contradict calculation for pseudo-scalar glueball:

$\mathcal{B}_{\eta\eta\eta'}/\mathcal{B}_{K\bar{K}\eta'} \approx 0.075$ **W. I. Eshraim, S. Janowski, F. Giacosa, and D. H. Rischke, Phys. Rev. D 87, 054036 (2013)**

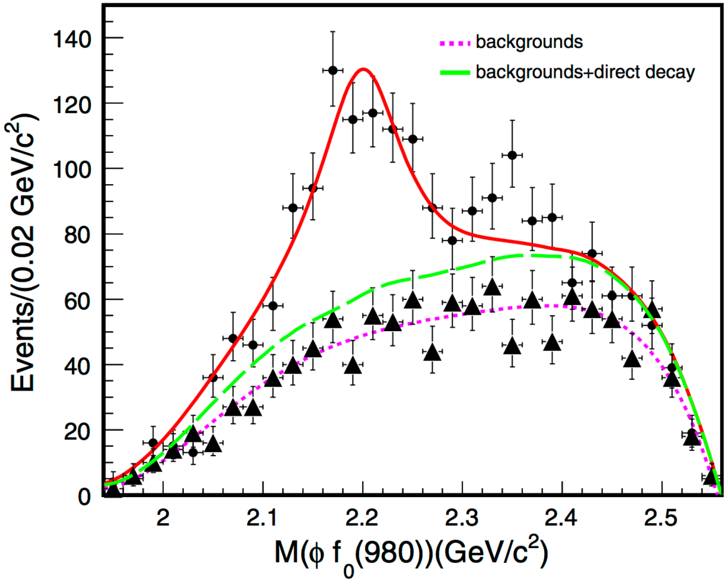
Strangeonium Spectroscopy

- Strangeonium $s\bar{s}$ system bridges between light and heavy quark domain
- Only a few states have been established
  - comparable small cross sections and large widths
- Search for exotic states (counterparts of Y's)

- $\phi(2170) \to \phi f_0(980)$ observed in e^+e^- annihilation by BaBar, Belle and BESII
- Also seen in $J/\psi \to \eta\phi f_0(980)$ by BESII and BESIII

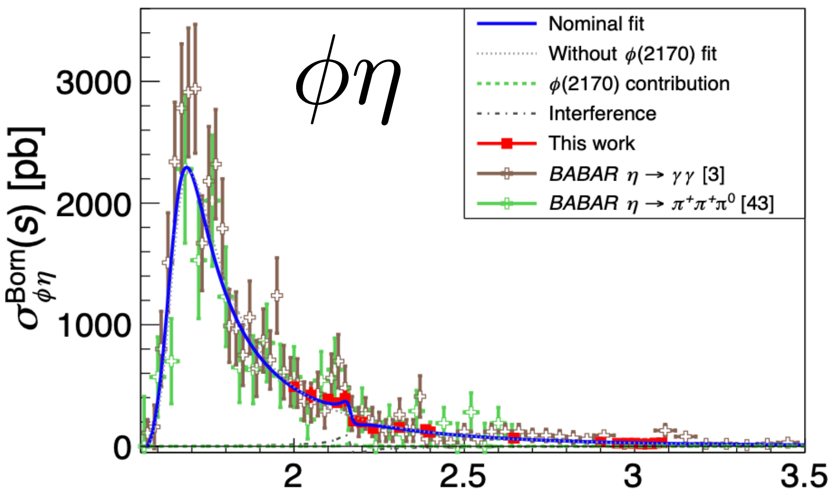
- Many theoretical interpretations exist, including $s\bar{s}$ hybrid, excited Φ state, tetraquark, $\Lambda\Lambda$ bound state, FSI effect

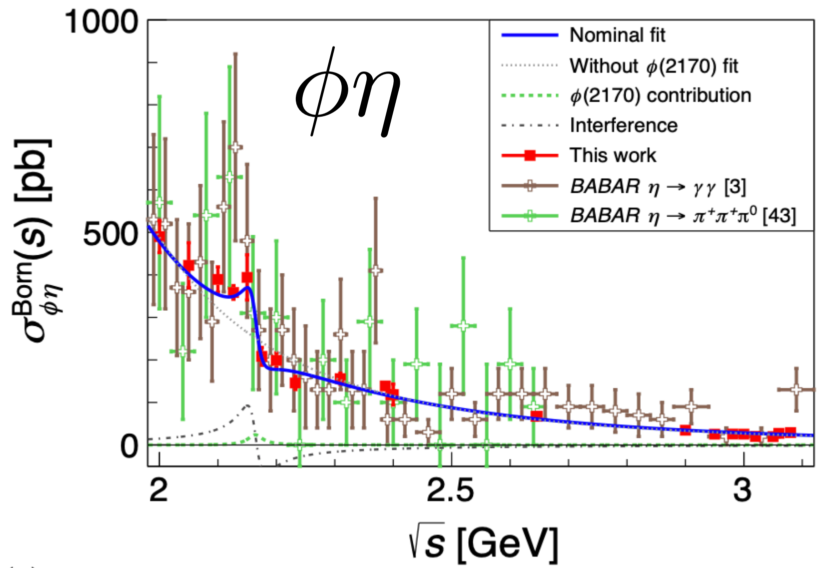
BESIII, Phys. Rev. D 91, 052017 (2015)
225M J/ψ



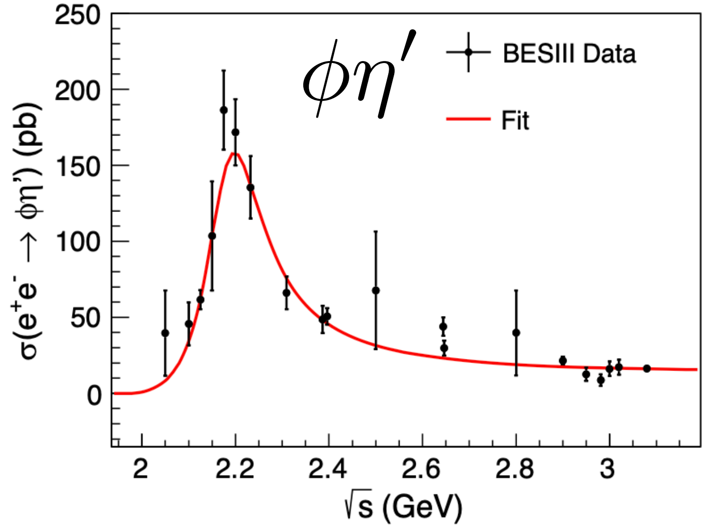
$e^+e^- \to \phi\eta^{(\prime)}$

arXiv:2104.05549





PRD 102,012008(2020)



Two possible solutions for $B(\phi(2170) \to \phi\eta)$ depending on phase wrt/ non-resonant component

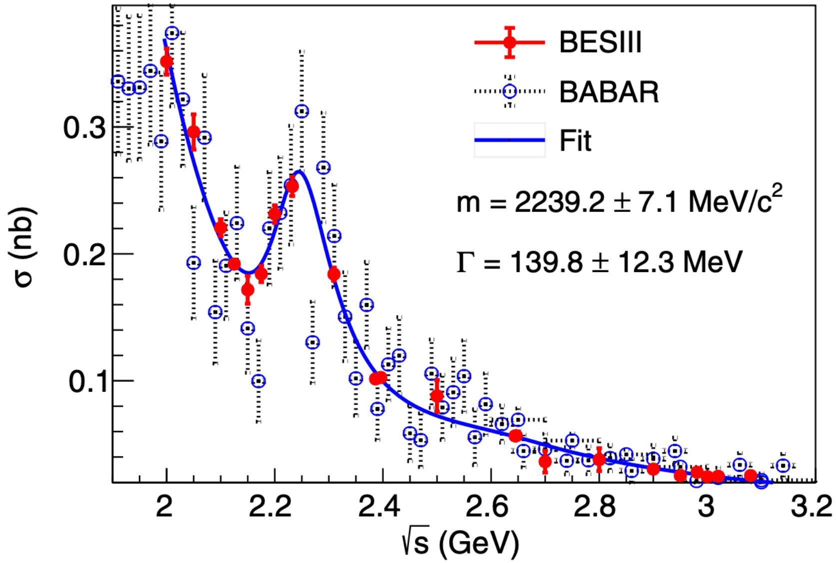
$$\frac{Br\,[\phi(2170)\to\phi\eta]\Gamma_{ee}}{Br\,[\phi(2170)\to\phi\eta']\Gamma_{ee}} = \begin{cases} 0.03^{+0.02}_{-0.01} \\ 1.42^{+0.56}_{-0.46} \end{cases}$$

Predictions for $s\bar{s}$ hybrids range from 3 and 200

P. R. Page, E. S. Swanson, and
A. P. Szczepaniak, Phys. Rev. D 59, 034016 (1999)
G. J. Ding and M. L. Yan, Phys. Lett. B 650, 390 (2007).

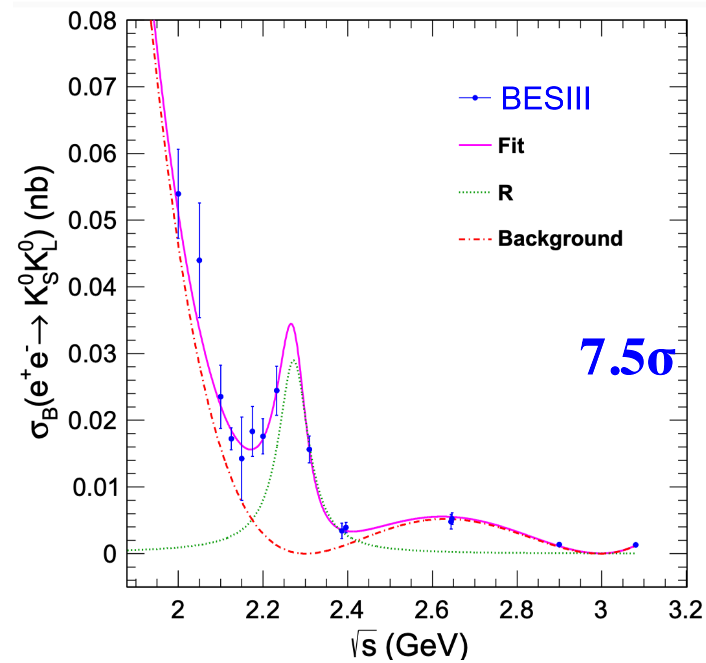
$e^+e^- \to K\bar{K}$

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



Phys. Rev. D 99, 032001 (2019)

$e^+e^- \to K_S^0 K_L^0$



arXiv:2105.13597 (2021)

$$M = 2239.2 \pm 7.1 \pm 11.3 \text{ MeV}/c^2$$
$$\Gamma = 139.8 \pm 12.3 \pm 20.6 \text{ MeV}$$

Consistent with BaBar
Phys. Rev. D88, 032012 (2018)
Phys. Rev. D92, 072008 (2015)

$$M = 2273.7 \pm 5.7 \pm 19.3 \text{ MeV}/c^2,$$
$$\Gamma = 86 \pm 44 \pm 51 \text{ MeV},$$

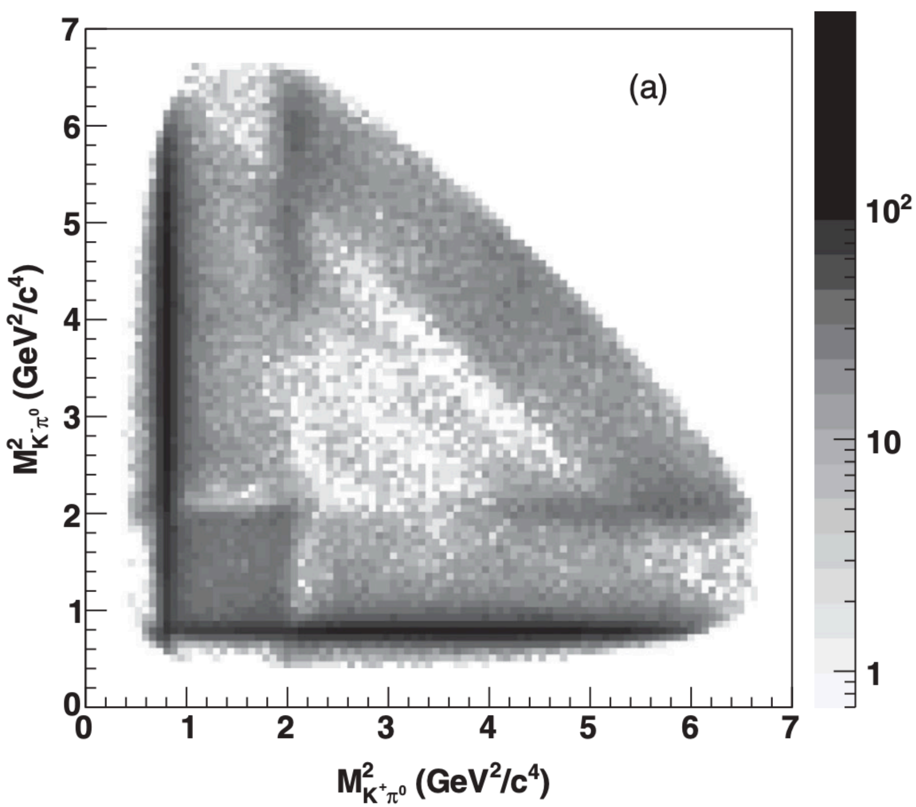
Consistent with BaBar
Phys. Rev. D101, 012011(2020)

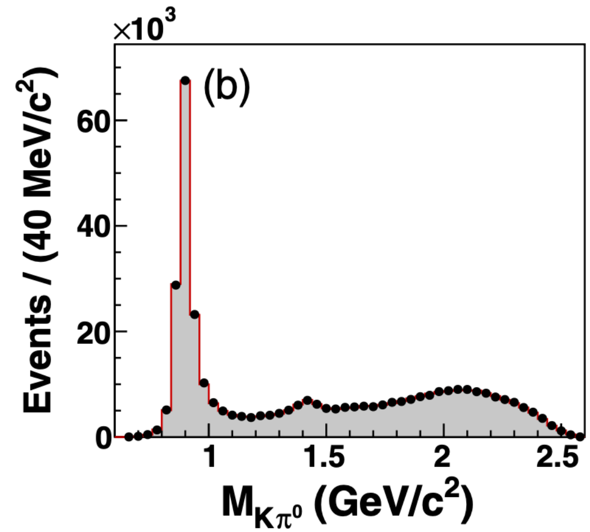
Mass and/or width deviate from averaged values of $\phi(2170)$ in both channels

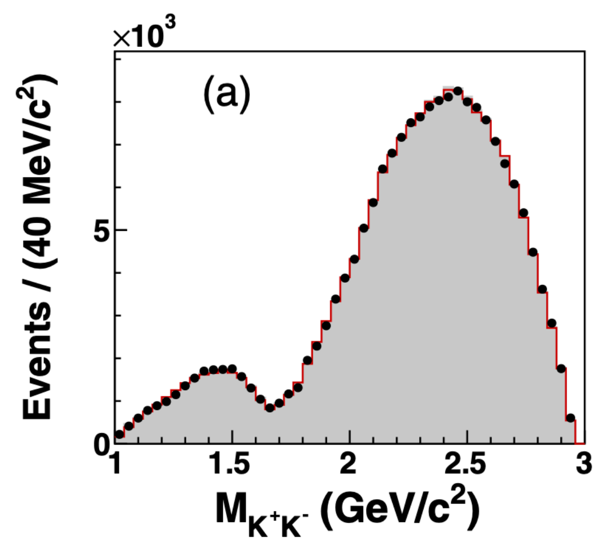
Partial Wave Analysis of $J/\psi \to K^+K^-\pi^0$

- Sample of ~183k reconstructed events
- Parameterization (Breit-Wigner)
  - 7 contributions in $K\pi$
  - 2 contributions in K^+K^-

Phys. Rev. D 100,032004(2019)







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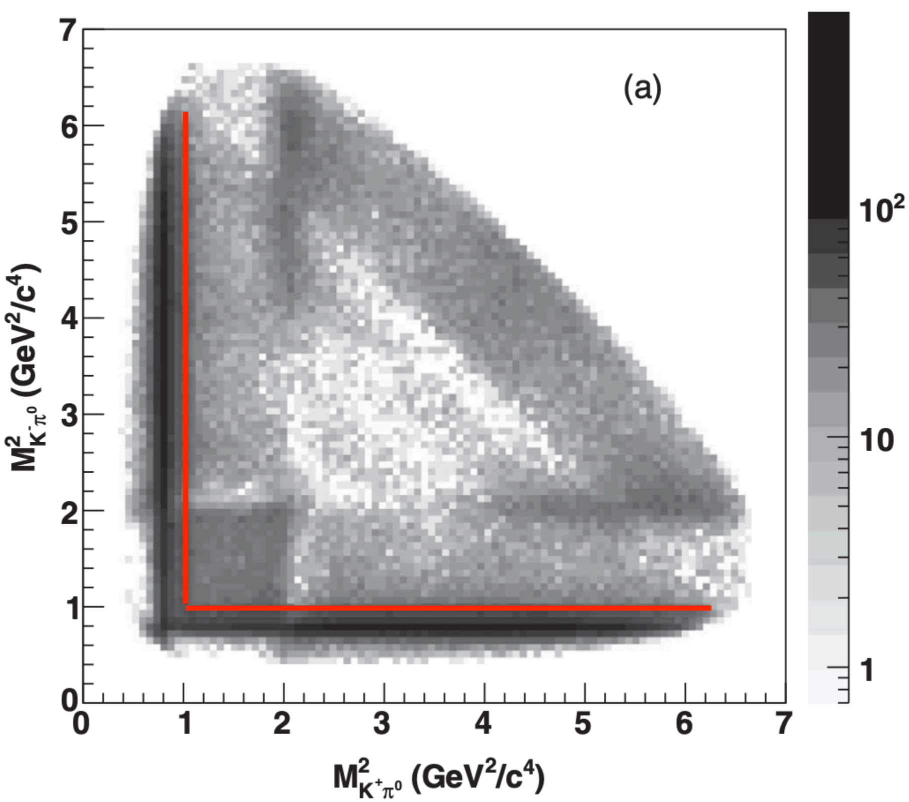
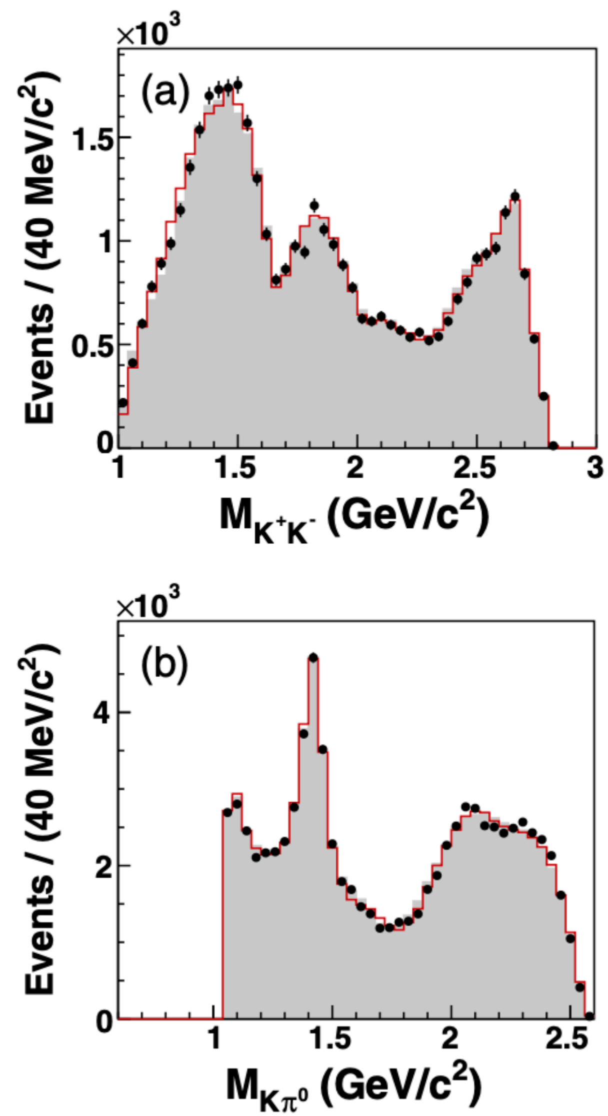
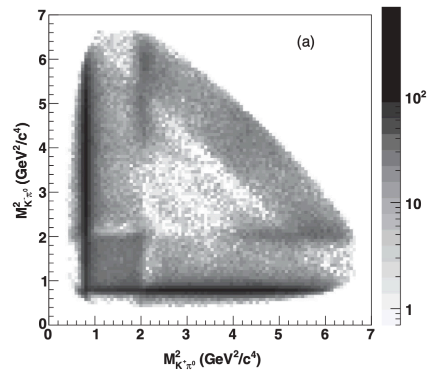


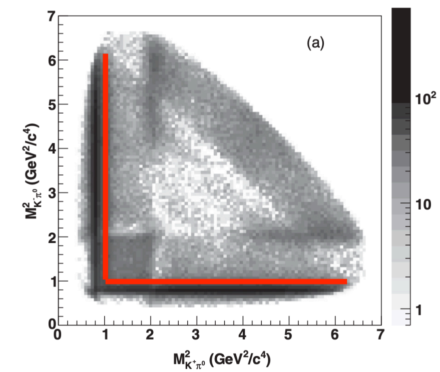
Phys. Rev. D 100,032004(2019)

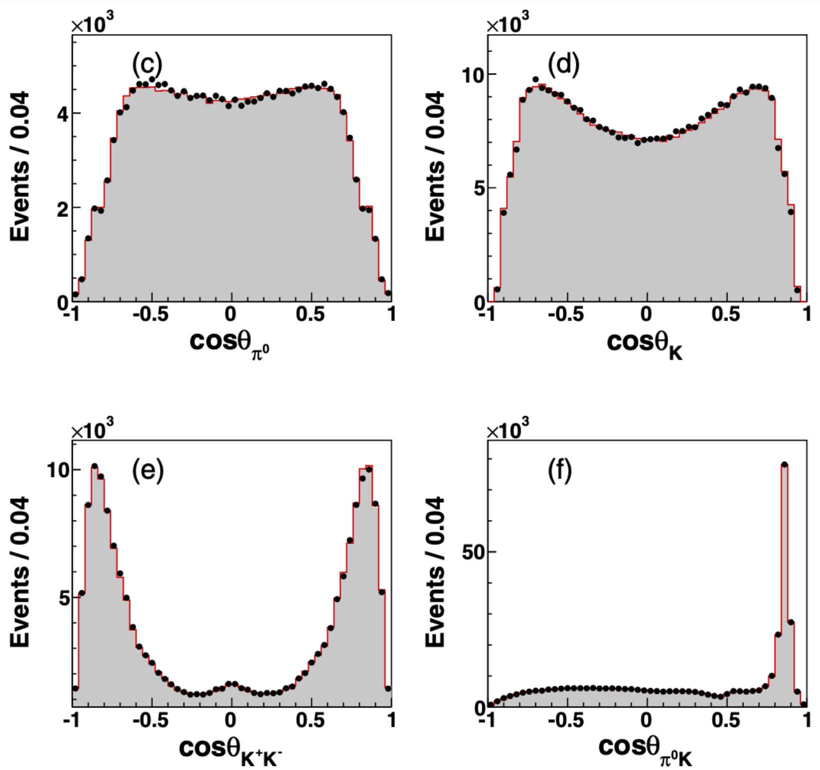


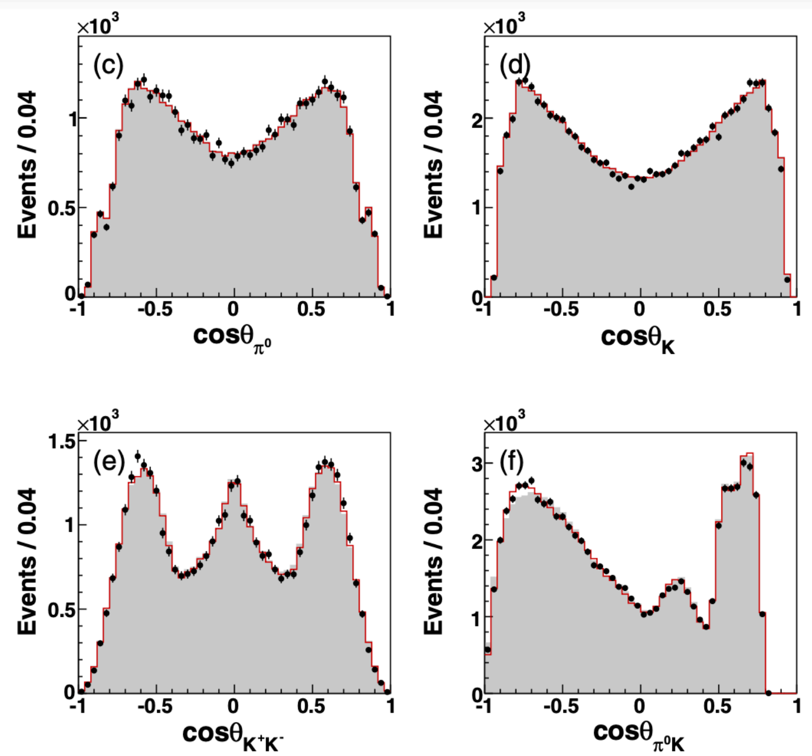
Partial Wave Analysis of $J/\psi \to K^+K^-\pi^0$

Phys. Rev. D 100,032004(2019)









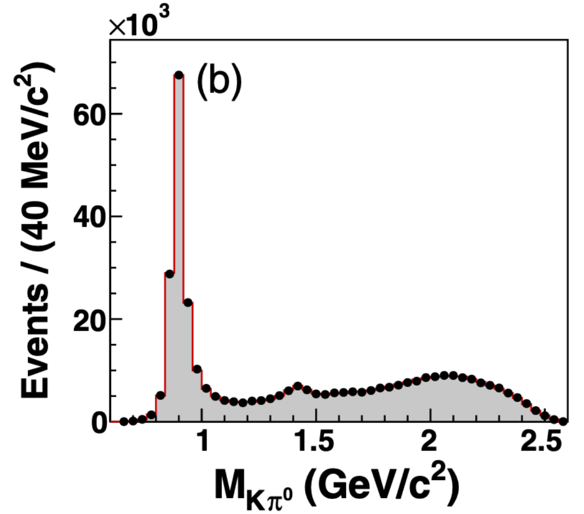
Partial Wave Analysis of $J/\psi \to K^+K^-\pi^0$

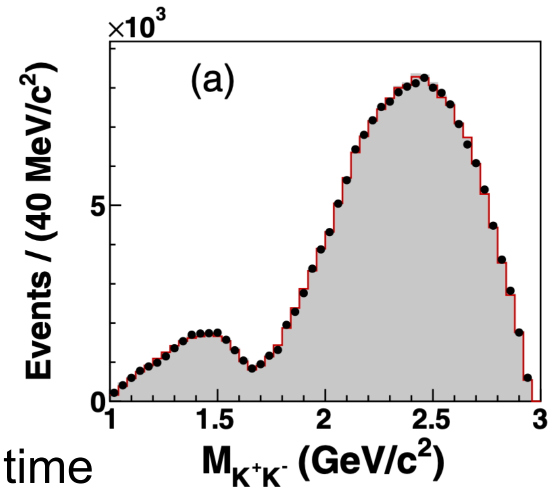
- Robust contributions tested against alternative parameterization for remaining intensities

J^{PC}	PDG	M (MeV/c^2)	Γ (MeV/c^2)
1^-	$K^*(892)^\pm$	$893.6 \pm 0.1^{+0.2}_{-0.3}$	$46.7 \pm 0.2^{+0.1}_{-0.2}$
1^-	$K^*(1410)^\pm$	$1380^\star$	$176^\star$
1^-	$K^*(1680)^\pm$	$1677^\star$	$205^\star$
2^+	$K_2^*(1430)^\pm$	$1432.7 \pm 0.7^{+2.2}_{-2.3}$	$102.5 \pm 1.6^{+3.1}_{-2.8}$
2^+	$K_2^*(1980)^\pm$	$1868 \pm 8^{+40}_{-57}$	$272 \pm 24^{+50}_{-15}$
3^-	$K_3^*(1780)^\pm$	$1781^\star$	$203^\star$
4^+	$K_4^*(2045)^\pm$	$2090 \pm 9^{+11}_{-29}$	$201 \pm 19^{+57}_{-17}$
3^-	Nonresonant	...	...

J^{PC}	PDG	M (MeV/c^2)	Γ (MeV/c^2)
1^{--}		$1651 \pm 3^{+16}_{-6}$	$194 \pm 8^{+15}_{-7}$
1^{--}		$2039 \pm 8^{+36}_{-18}$	$196 \pm 23^{+25}_{-27}$

Phys. Rev. D 100,032004 (2019)



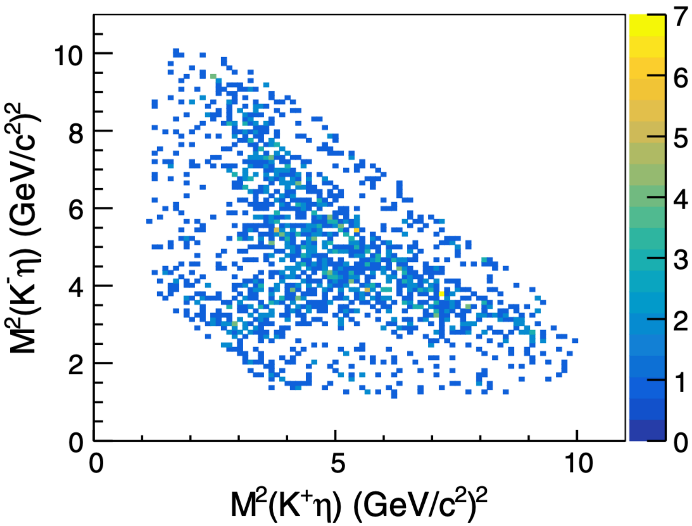


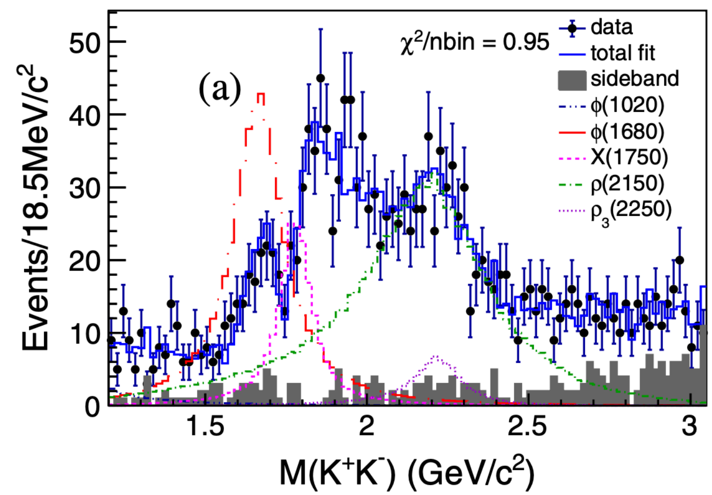
- Dominant $K^*(892)$ contribution
- $K_2^*(1980)$ and $K_4^*(2045)$ observed in J/ψ decays first time
- Two broad 1^{--} K^+K^- contributions ($\omega(1650)$ and $\rho(2150)$?)

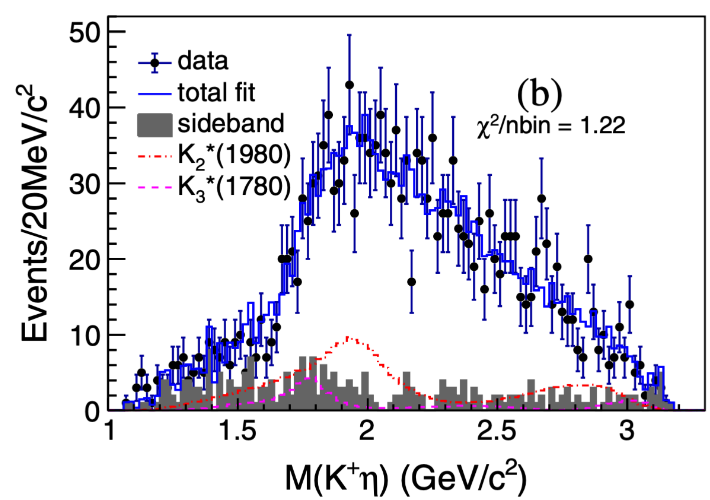
Partial Wave Analysis of $\psi(2S) \to K^+K^-\eta$

Phys. Rev. D 101, 032008 (2020)

- Sample of 1787 reconstructed events
- after veto on ϕ, $J/\psi \to K^+K^-$ and $\chi_{c2} \to \gamma K^+K^-$



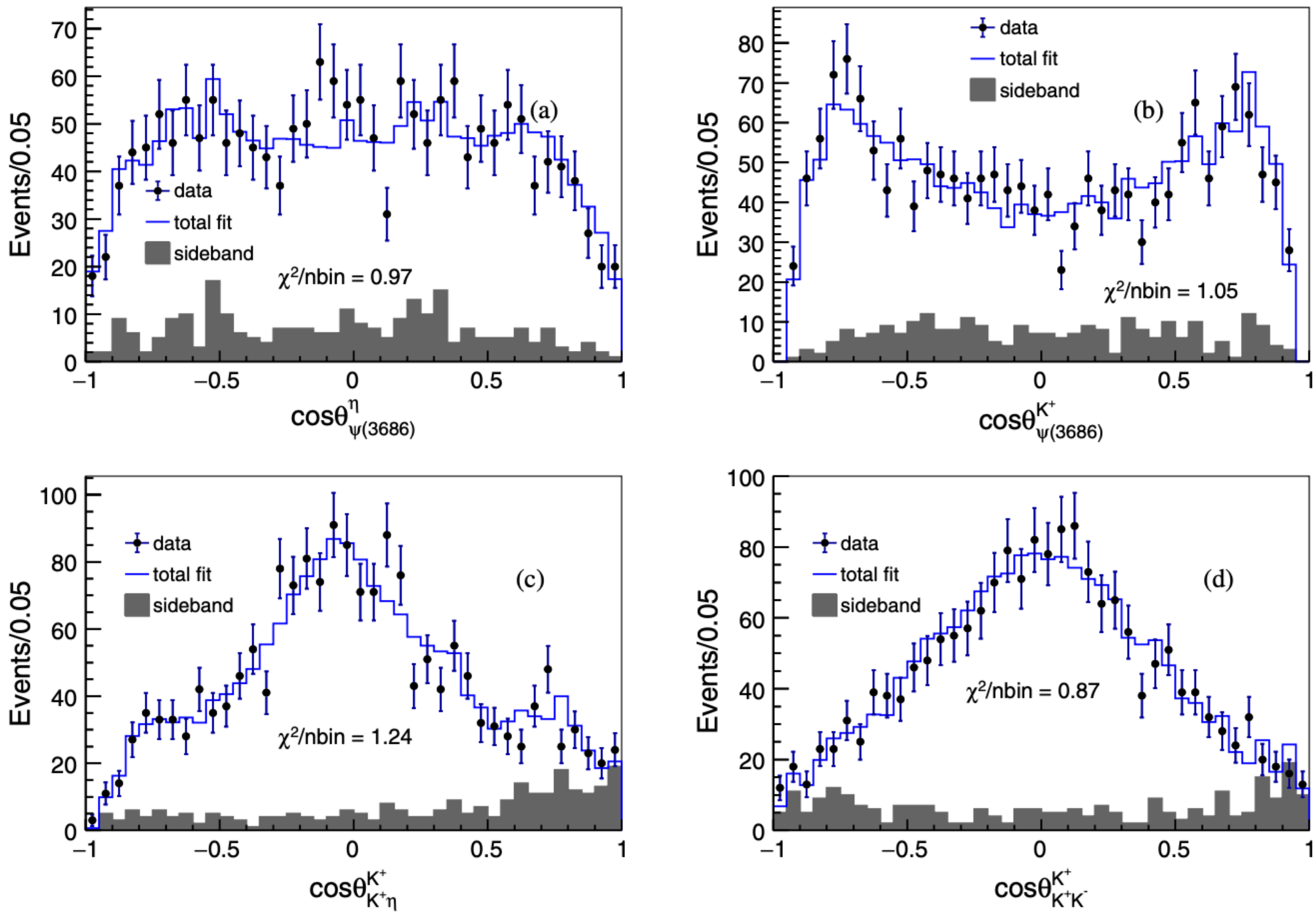




Parameterization (Breit-Wigner):
3 contributions 1^{--} K^+K^-
1 contribution 3^{--} K^+K^-
1 contribution 2^{-} $K\eta$
1 contribution 3^{+} $K\eta$

Partial Wave Analysis of $\psi(2S) \rightarrow K^+K^-\eta$

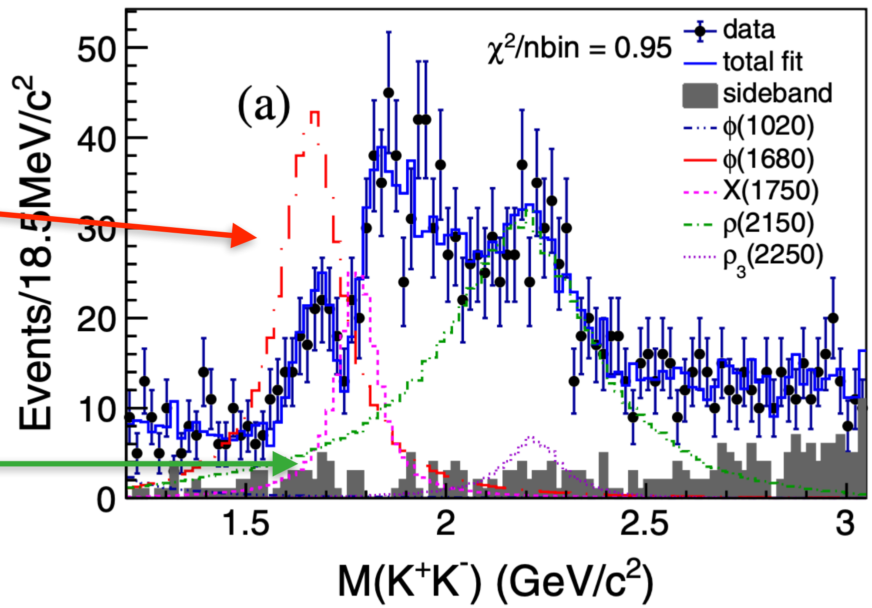
Phys. Rev. D 101, 032008 (2020)



Partial Wave Analysis of $\psi(2S) \to K^+K^-\eta$

- Besides established $\phi(1680)$ another vector included in the fit to describe dip at ~1.7 GeV
  - $X(1750)$ $[1^{--}]$ or $\rho(1700)$?
  - $X(1750)$ first seen by FOCUS in photo-production
- Structure at ~2.2 GeV
  - $\phi(2170)$ or $\rho(2150)$?

Phys. Rev. D 101, 032008 (2020)



	This work		PDG [23]	
Resonance	M (MeV/c^2)	Γ (MeV)	M (MeV/c^2)	Γ (MeV)
$\phi(1680)$	1680^{+12+21}_{-13-21}	185^{+30+25}_{-26-47}	1680 ± 20	150 ± 50
$X(1750)$	1784^{+12+0}_{-12-27}	106^{+22+8}_{-19-36}	$(1720 \pm 20)_{\rho(1700)}$ $(1753.5 \pm 1.5 \pm 2.3)_{X(1750)}$ [15]	$(250 \pm 100)_{\rho(1700)}$ $(122.2 \pm 6.2 \pm 8.0)_{X(1750)}$ [15]
$\rho(2150)$	2255^{+17+50}_{-18-41}	$460^{+54+160}_{-48-90}$	$(2153 \pm 27)_{\rho(2150)}$ [31] $(2175 \pm 15)_{\phi(2170)}$	$(389 \pm 79)_{\rho(2150)}$ [31] $(61 \pm 18)_{\phi(2170)}$
$\rho_3(2250)$	2248^{+17+59}_{-17-5}	$185^{+31+17}_{-26-103}$	2232 [32]	220 [32]
$K_2^*(1980)$	2046^{+17+67}_{-16-15}	408^{+38+72}_{-34-44}	$1973 \pm 8 \pm 25$	$373 \pm 33 \pm 60$
$K_3^*(1780)$	1813^{+15+65}_{-15-16}	191^{+43+3}_{-37-81}	1776 ± 6	159 ± 21

Summary

- BESIII is successfully operating since 2008
  - world's largest data sample at the J/ψ and ψ' resonance recorded
  - clean and rich source for light meson production

- Excellent opportunities to
  - map out the spectrum of light and strange quark states
  - search for glueballs and other light exotics

- Further studies including new data recorded at the ψ' are under way