ϕ(2170): a strangeonium or exotic state ?

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PDG2018 $\phi(2170)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	seen
Γ_2	$\phi\eta$	
Γ_3	$\phi\pi\pi$	
Γ_4	$\phi f_0(980)$	seen
Γ_5	$K^+K^-\pi^+\pi^-$	
Γ_6	$K^+K^-f_0(980) \rightarrow K^+K^-\pi^+\pi^-$	seen
Γ_7	$K^+K^-\pi^0\pi^0$	
Γ_8	$K^+K^-f_0(980) \rightarrow K^+K^-\pi^0\pi^0$	seen
Γ_9	$K^{*0}K^{\pm}\pi^{\mp}$	not seen
Γ_{10}	$K^*(892)^0\overline{K}^*(892)^0$	not seen

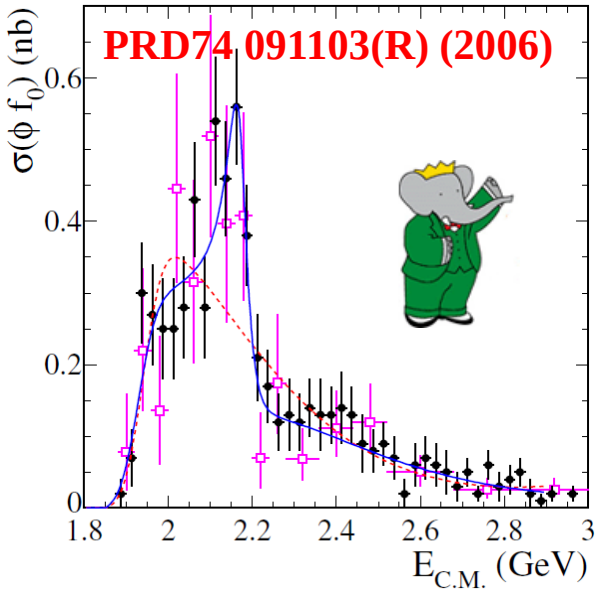
PDG2024 $\phi(2170)$ $I^G(J^{PC}) = 0^-(1^{--})$

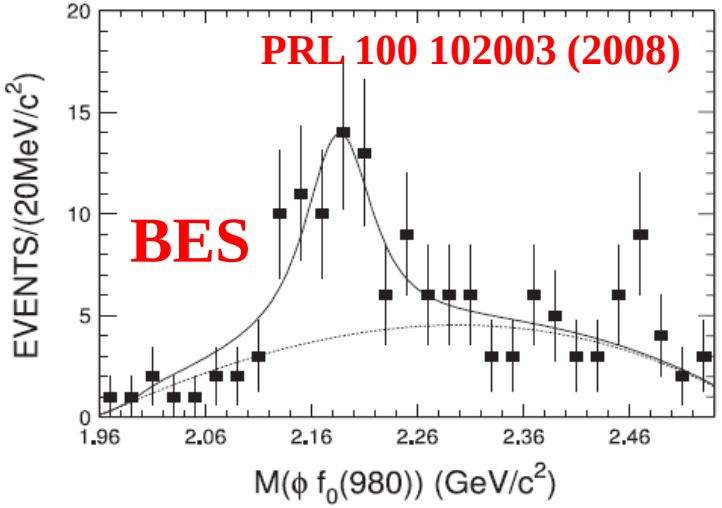
See the review on "Spectroscopy of Light Meson Resonances."

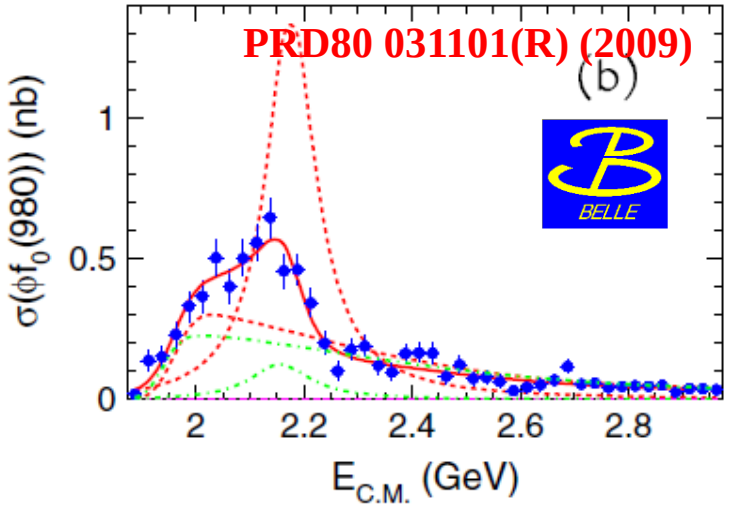
$\phi(2170)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2164 ± 6 OUR AVERAGE					
2178 ±20 ± 5		[1] ABLIKIM	23AX	BES3	$e^+e^- \rightarrow \phi\pi^+\pi^-$
2190 ±19 ±37		[2] ABLIKIM	22L	BES3	2.0–3.08 $e^+e^- \rightarrow K^+K^-\pi^0$
2176 ±24 ± 3		[3] ABLIKIM	21A	BES3	$e^+e^- \rightarrow \omega\eta$
2163.5± 6.2± 3.0		[4] ABLIKIM	21T	BES3	$e^+e^- \rightarrow \phi\eta$
2177.5± 4.8±19.5		[5] ABLIKIM	20M	BES3	$e^+e^- \rightarrow \eta'\phi$
2126.5±16.8±12.4		[6] ABLIKIM	20S	BES3	$e^+e^- \rightarrow K^+K^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2215.7± 8.3		[7] LICHARD	23	RVUE	$e^+e^- \rightarrow \Upsilon(nS) \rightarrow \phi\eta\gamma$
2273.7± 5.7±19.3		[9] ABLIKIM	21AP	BES3	$e^+e^- \rightarrow K^0_S K^0_L$
2239.2± 7.1±11.3		[10] ABLIKIM	19L	BES3	$e^+e^- \rightarrow K^+K^-$
2180 ± 8 ± 8		[11,12] LEES	12F	BABR	10.6 $e^+e^- \rightarrow \phi\pi^+\pi^-\gamma$
2079 ±13 $^{+79}_{-28}$	4.8k	[13] SHEN	09	BELL	10.6 $e^+e^- \rightarrow K^+K^-\pi^+\pi^-\gamma$
2186 ±10 ± 6	52	ABLIKIM	08F	BES	$J/\psi \rightarrow \eta\phi f_0(980)$
2125 ±22 ±10	483	AUBERT	08S	BABR	10.6 $e^+e^- \rightarrow \phi\eta\gamma$
2192 ±14	116	[14] AUBERT	07AK	BABR	10.6 $e^+e^- \rightarrow K^+K^-\pi^+\pi^-\gamma$
2169 ±20	149	[14] AUBERT	07AK	BABR	10.6 $e^+e^- \rightarrow K^+K^-\pi^0\pi^0\gamma$
2175 ±10 ±15	201	[12,15] AUBERT,BE	06D	BABR	10.6 $e^+e^- \rightarrow K^+K^-\pi\pi\gamma$

ϕ(2170)/Y(2175)

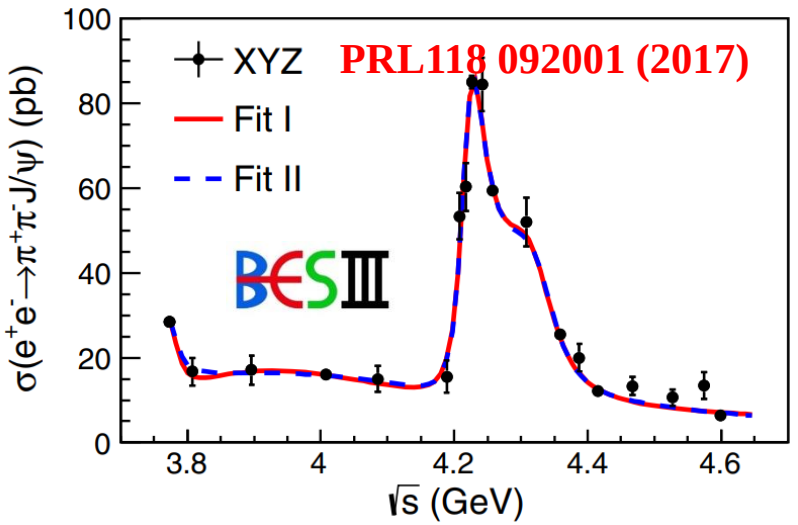






Eur. Phys. J. C72 2008 (2012)

$$e^+e^- \Rightarrow \begin{cases} Y(2175) \to \phi(1020)\pi^+\pi^- & \text{strange,} \\ Y(4260) \to J/\psi\pi^+\pi^- & \text{charm,} \\ \Upsilon(10860) \to \Upsilon(1S,2S)\pi^+\pi^- & \text{bottom,} \end{cases}$$

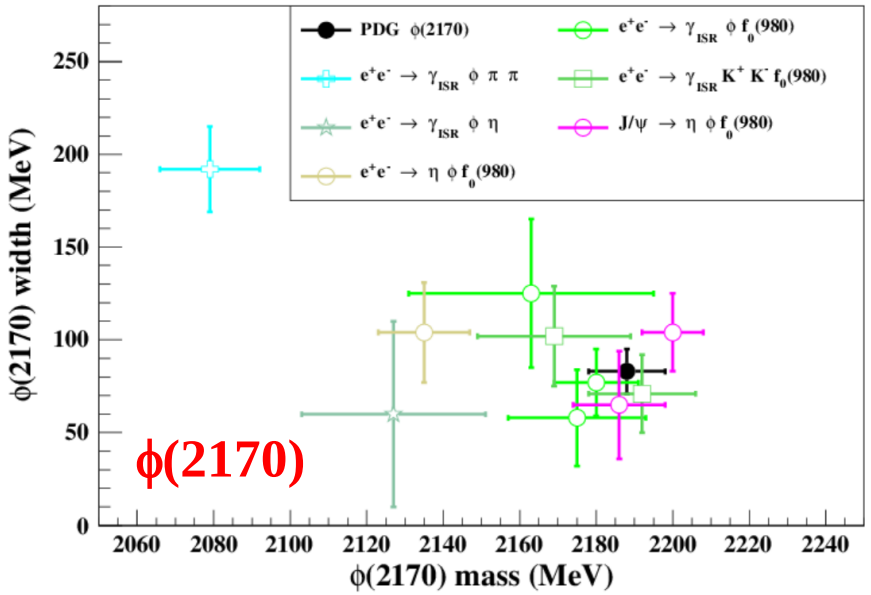


ϕ(2170) as strange analogue of Y(4230)

$\phi(2170)$

PDG2018 $\phi(2170)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$e^+ e^-$	seen
Γ_2	$\phi\eta$	
Γ_3	$\phi\pi\pi$	
Γ_4	$\phi f_0(980)$	seen
Γ_5	$K^+K^-\pi^+\pi^-$	
Γ_6	$K^+K^- f_0(980) \rightarrow K^+K^-\pi^+\pi^-$	seen
Γ_7	$K^+K^-\pi^0\pi^0$	
Γ_8	$K^+K^- f_0(980) \rightarrow K^+K^-\pi^0\pi^0$	seen
Γ_9	$K^{*0}K^{\pm}\pi^{\mp}$	not seen
Γ_{10}	$K^*(892)^0\overline{K}^*(892)^0$	not seen

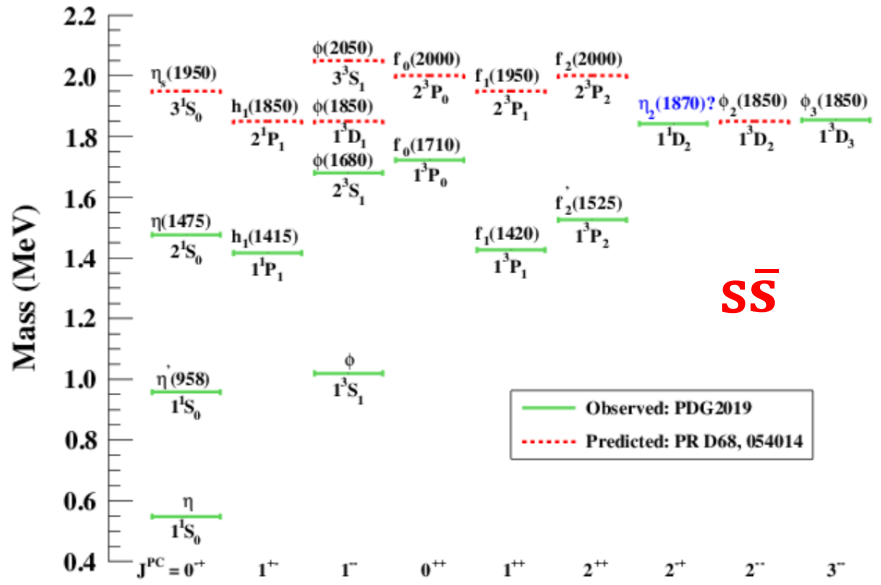


- **Published experimental information**
  - ✓ **limited decay modes**
  - ✓ **inconsistence on mass & width**

- **@ 2018: Theorists explain $\phi(2170)$ as**
  - ✓ **2^3D_1 or 3^3S_1 $s\bar{s}$**
  - ✓ **$s\bar{s}g$ hybrid**
  - ✓ **tetraquark**
  - ✓ **molecular state $\Lambda\bar{\Lambda}$**
  - ✓ **$\phi f_0(980)$ resonance with FSI**
  - ✓ **three body system ϕKK**
  - ✓ **estimated or ruled out: not yet**

- **Nature of $\phi(2170)$: open question ?**

Difficulty @ ϕ(2170)



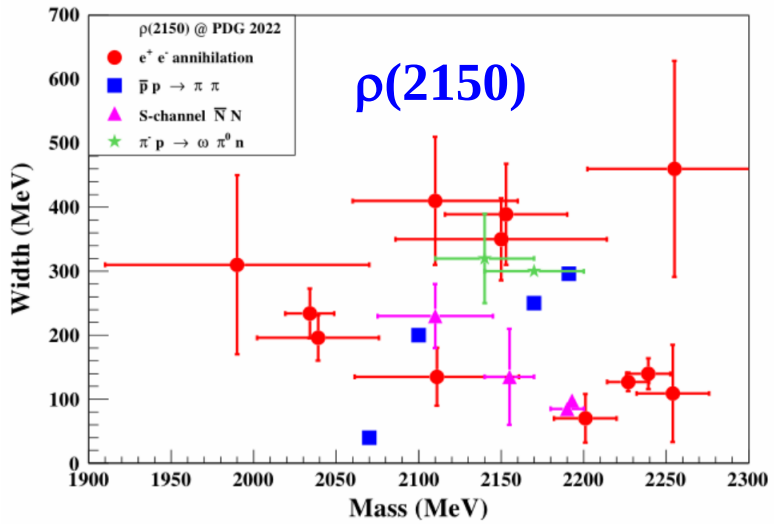
ss̄

TABLE XII. Decay amplitudes squared (excluding the decay strength constants).

Decay	Products	Squared amplitude
$\rho^* \to PP$	$K\bar{K}$	4
	$\pi\pi$	2
$\rho^* \to VP$	$\bar{K}^*K$	2
	$\rho\eta$	$2\cos^2\phi_P$
	$\rho\eta'$	$2\sin^2\phi_P$
	$\omega\pi$	$2\sin^2\phi_V$
	$\phi\pi$	$2\cos^2\phi_V$
$\omega^* \to PP$	$K\bar{K}$	$12\sin^2\theta_V^*$
$\omega^* \to VP$	$\phi\eta$	$2(\sqrt{2}\cos\phi_V^*\sin\phi_V\sin\phi_P + \sin\phi_V^*\cos\phi_V\cos\phi_P)^2$
	$\phi\eta'$	$2(\sqrt{2}\cos\phi_V^*\sin\phi_V\cos\phi_P - \sin\phi_V^*\cos\phi_V\sin\phi_P)^2$
	$\omega\eta$	$2(\sqrt{2}\cos\phi_V^*\cos\phi_V\sin\phi_P - \sin\phi_V^*\sin\phi_V\cos\phi_P)^2$
	$\omega\eta'$	$2(\sqrt{2}\cos\phi_V^*\cos\phi_V\cos\phi_P + \sin\phi_V^*\sin\phi_V\sin\phi_P)^2$
	$\rho\pi$	$6\sin^2\phi_V^*$
	$K^*\bar{K}$	$2(\sin\phi_V^* + \sqrt{2}\cos\phi_V^*)^2$
$\phi^* \to PP$	$K\bar{K}$	$12\cos^2\theta_V^*$
$\phi^* \to VP$	$\phi\eta$	$2(-\sqrt{2}\sin\phi_V^*\sin\phi_V\sin\phi_P + \cos\phi_V^*\cos\phi_V\cos\phi_P)^2$
	$\phi\eta'$	$2(\sqrt{2}\sin\phi_V^*\sin\phi_V\cos\phi_P + \cos\phi_V^*\cos\phi_V\sin\phi_P)^2$
	$\omega\eta$	$2(\sqrt{2}\sin\phi_V^*\cos\phi_V\sin\phi_P + \cos\phi_V^*\sin\phi_V\cos\phi_P)^2$
	$\omega\eta^*$	$2(-\sqrt{2}\sin\phi_V^*\cos\phi_V\cos\phi_P + \cos\phi_V^*\sin\phi_V\sin\phi_P)^2$
	$\rho\pi$	$6\cos^2\phi_V^*$
	$K^*\bar{K}$	$2(\cos\phi_V^* - \sqrt{2}\sin\phi_V^*)^2$

PRD79 014036 (2009)

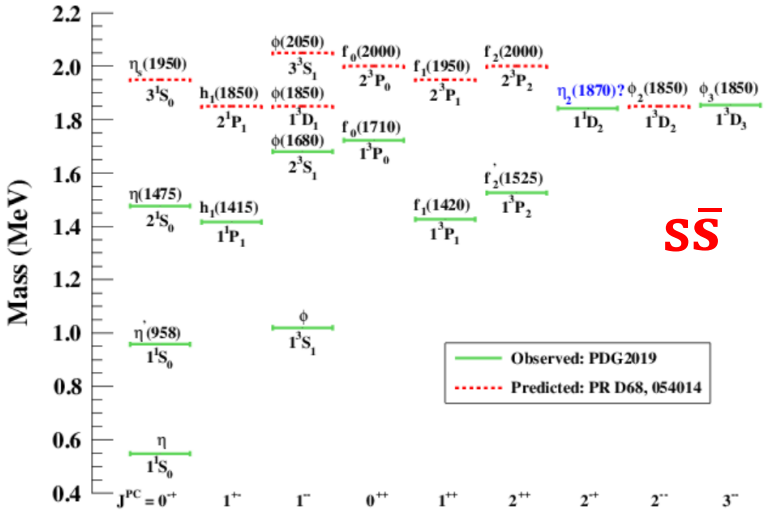
- Better understanding ss̄ spectrum ?
  - ✓ unobserved 1^{--} ss̄ mesons
- OZI rule and isospin
  - ✓ contribution of ρ*/ω*/ϕ*
- ρ*/ω* @ [2-3] GeV: "omitted from summary table" or "further states"

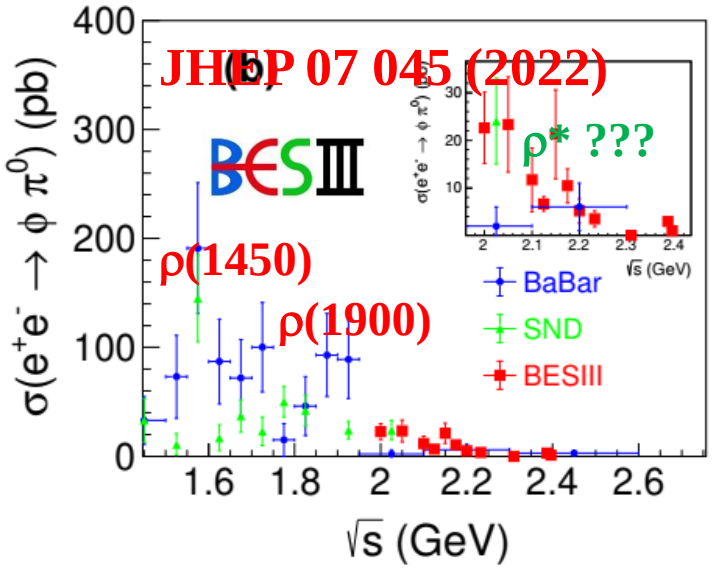


$s\bar{s}$ vector states @ $J/\psi \to \phi\,\pi^0\,\eta$

$\phi + R(\pi^0\eta)$	$R(\phi\eta) + \pi^0$	$R(\phi\pi^0) + \eta$	Three-body PHSP
$\phi a_0(980)$	$\phi(1680)\pi^0$	$\rho(1450)\eta$	$\phi + \pi^0\eta(0^{++})$
$\phi a_0(980)$ mixing	$X(2000)\pi^0$	$\rho(1570)\eta$	–
$\phi a_0(1450)$	$\phi(2170)\pi^0$	$\rho(1700)\eta$	–
$\phi a_2(1320)$	$h_1(1900)\pi^0$	$\rho(1900)\eta$	–
$\phi a_2(1700)$	$\phi_3(1850)\pi^0$	$X(2000)/\rho(2150)\eta$	–
$\phi a_0(1950)$	$X(1750)\pi^0$	$\rho_3(1690)\eta$	–

arXiv:2311.07043





$h_1(1415)$

was $h_1(1380)$

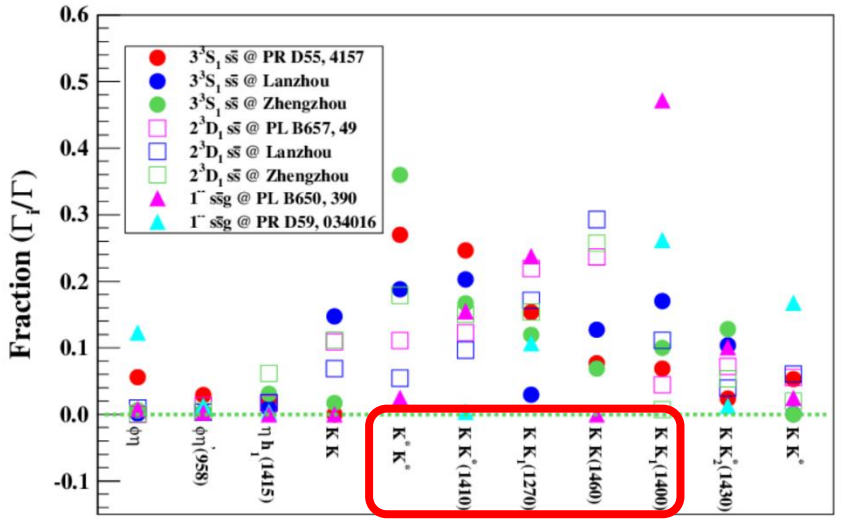
$I^G(J^{PC}) = 0^-(1^{+-})$

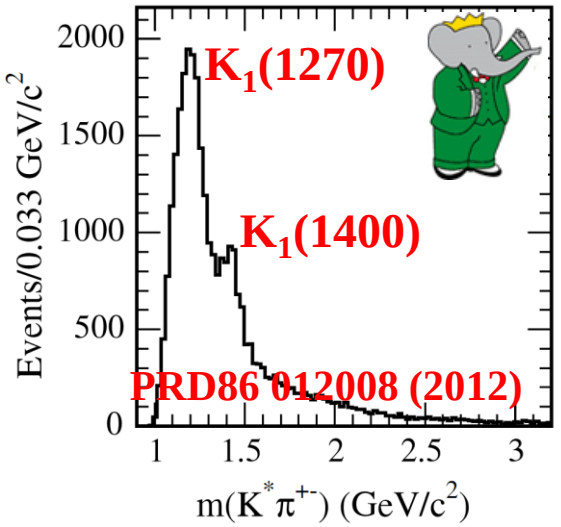
$h_1(1415)$ MASS

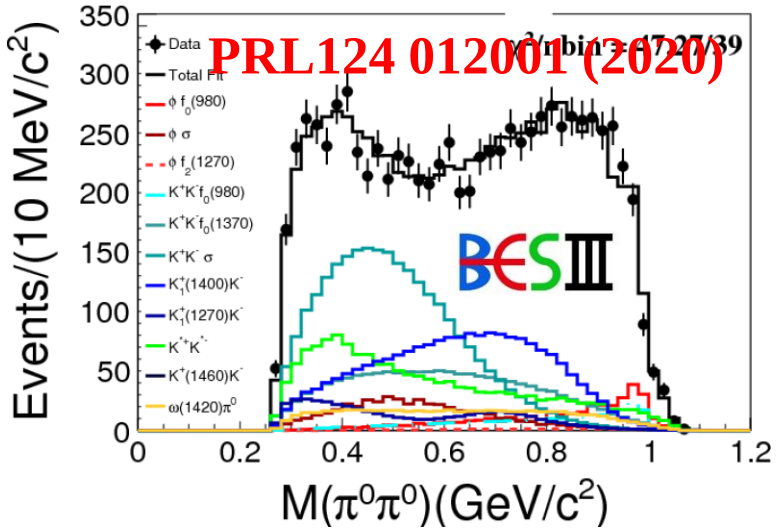
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1416± 8 OUR AVERAGE		Error includes scale factor of 1.5. See the ideogram below.		
1423± 2.1±7.3	2.2k	[1] ABLIKIM	18AB BES3	$J/\psi \to \eta' h_1 \to \eta' K^* \overline{K}$
1412± 4 ±8		[1] ABLIKIM	15M BES3	$\psi(2S) \to \gamma\chi_{c1,2} \to \gamma\phi(h_1 \to K^*\overline{K})$
1440±60		ABELE	97H CBAR	$\overline{p}p \to K^0_L K^0_S \pi^0\pi^0$
1380±20		ASTON	88C LASS	11 $K^- p \to K^0_S K^\pm \pi^\mp \Lambda$

- $J^{PC} = 1^-$ $s\bar{s}$ vector states
  - ✓ a_0 & a_2 states
  - ✓ $J^{PC} = 1^{--}$ states
  - ✓ $J^{PC} = 1^{+-}$ states
- energy scan method
  - ✓ 1^{+-}, a_0 and a_2 states: ×

$\phi(2170)$ decay ⇐ PWA for multi $\sqrt{s}$



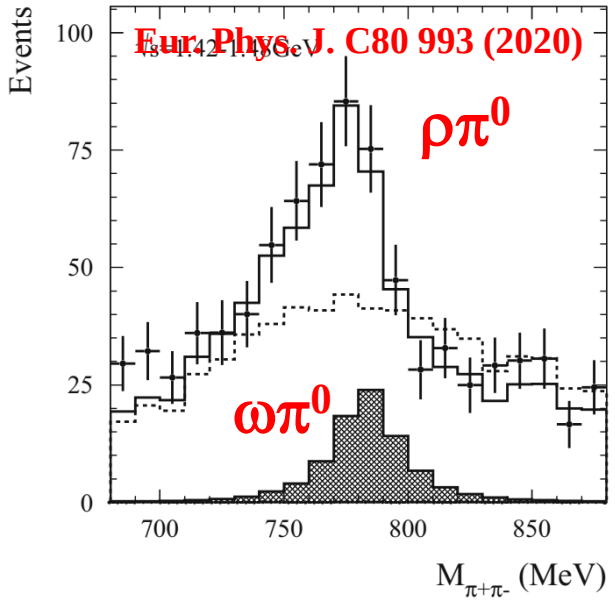




- $e^+e^- \rightarrow K\,K\,\pi\,\pi$: important to distinguish $\phi(2170)$ theory models
  - ✓ K^*K^*: s$\bar{s}$g (unfavored), 3^3S_1 (favored)
  - ✓ $KK_1(1400)$: s$\bar{s}$g (favored)
  - ✓ $KK(1460)$: s$\bar{s}$g (unfavored), 2^3D_1 (favored)
- PWA for multi $\sqrt{s}$ points
  - ✓ (only) focus on dominant components
  - ✓ fraction and phase angle: smoothness and continuity

Why PWA ? a lesson @ $e^+ e^- \to \pi^+ \pi^- \pi^0$

- **Isospin & G-parity: ω*/ϕ***
  - ✓ **ϕ*: OZI-suppressed**
  - ✓ **ρ*: ignored**
- **$\omega\pi^0$ with $\omega \to \pi^+ \pi^-$ events: 16% @ 1.45 GeV**
- **ρ* @ $\omega\pi^0$ ⇐ ρ(1450) & ρ(1700) contribution**
- **SND: ω, ϕ, ω(1420) and ω(1650), without ρ***



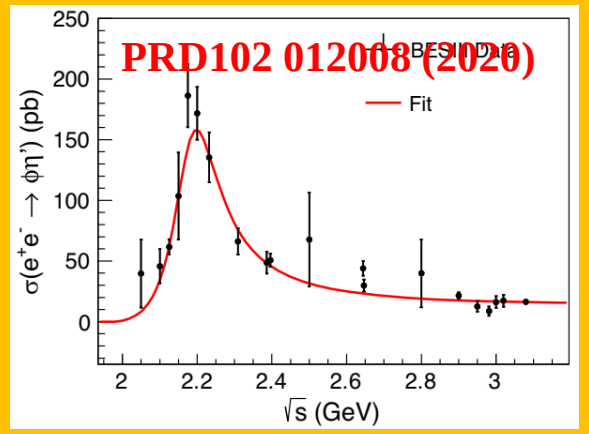
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
290 ± 190	OUR ESTIMATE				
	• • We do not use the following data for averages, fits, limits, etc. • •				
440 ±125	267	[1] ACHASOV	2020B	SND	$e^+ e^- \to \omega\eta \to \eta\pi^0\gamma$
104 ±35 ±10	824	[2] AKHMETSHIN	2017A	CMD3	$1.4 - 2.0\ e^+ e^- \to \omega\eta$
880 ±170	13.1k	[3] AULCHENKO	2015A	SND	$1.05 - 1.80\ e^+ e^- \to \pi^+\pi^-\pi^0$
480 ±180		[4] ACHASOV	2010D	SND	$1.075 - 2.0\ e^+ e^- \to \pi^0\gamma$
130 ±50 ±100		AUBERT	2007AU	BABR	$10.6\ e^+ e^- \to \omega\pi^+\pi^-\gamma$
450 ±70 ±70		AUBERT,B	2004N	BABR	$10.6\ e^+ e^- \to \pi^+\pi^-\pi^0\gamma$
870 $^{+500}_{-300}$ ±450	1.2M	[5] ACHASOV	2003D	RVUE	$0.44 - 2.00\ e^+ e^- \to \pi^+\pi^-\pi^0$
199 ±15		[6] HENNER	2002	RVUE	$1.2 - 2.0\ e^+ e^- \to \rho\pi\ ,\ \omega\pi\pi$
188 ±45	177	[7] AKHMETSHIN	2000D	CMD2	$1.2 - 1.38\ e^+ e^- \to \omega\pi^+\pi^-$
360 $^{+100}_{-60}$	5095	ANISOVICH	2000H	SPEC	$0.0\ p\bar{p} \to \omega\pi^0\pi^0\pi^0$
240 ±70		[8] CLEGG	1994	RVUE	
174 ±59	315	[9] ANTONELLI	1992	DM2	$1.34-2.4\ e^+ e^- \to \rho\pi$

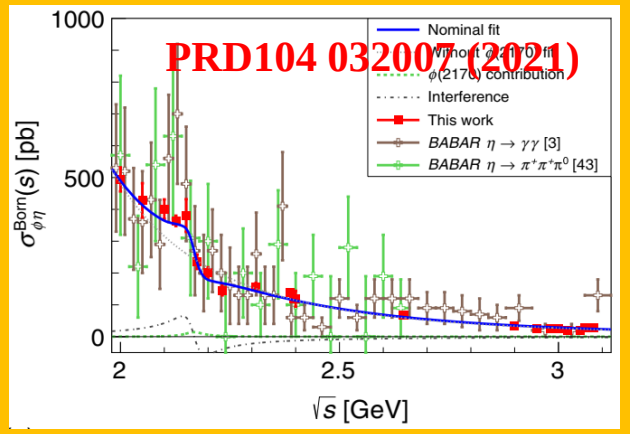
ω(1420) @ PDG2022

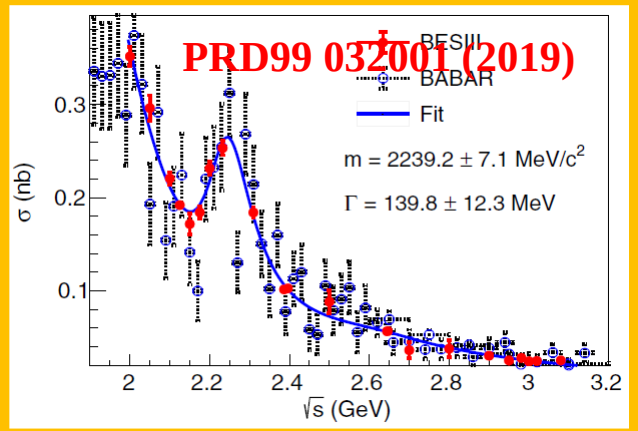
	SND 2003	BABAR	This work
$m_{\omega'}$, MeV	$1400 \pm 50 \pm 130$	$1350 \pm 20 \pm 20$	1470 ± 50
$\Gamma_{\omega'}$, MeV	$870 \pm {}^{500}_{300} \pm 450$	$450 \pm 70 \pm 70$	880 ± 170
$B(\omega' \to e^+e^-)B(\omega' \to \pi^+\pi^-\pi^0) \times 10^6$	$0.65 \pm 0.13 \pm 0.21$	$0.82 \pm 0.05 \pm 0.06$	0.73 ± 0.08
$m_{\omega''}$, MeV	$1770 \pm 50 \pm 60$	$1660 \pm 10 \pm 2$	1680 ± 10
$\Gamma_{\omega''}$, MeV	$490 \pm {}^{200}_{150} \pm 130$	$230 \pm 30 \pm 20$	310 ± 30
$B(\omega'' \to e^+e^-)B(\omega'' \to \pi^+\pi^-\pi^0) \times 10^6$	$1.15 \pm {}^{0.44}_{0.09} \pm 0.83$	$1.3 \pm 0.1 \pm 0.1$	1.56 ± 0.23

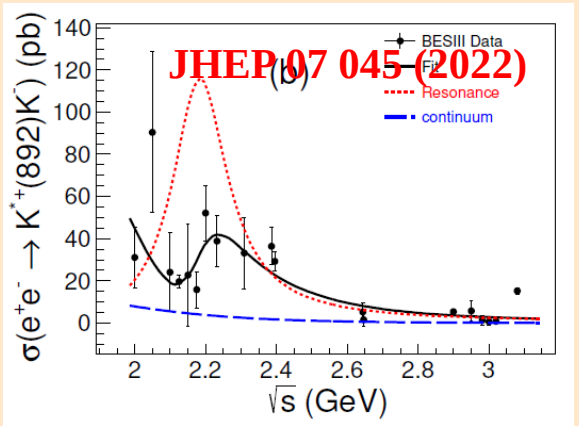
JETP 121 27 (2015)

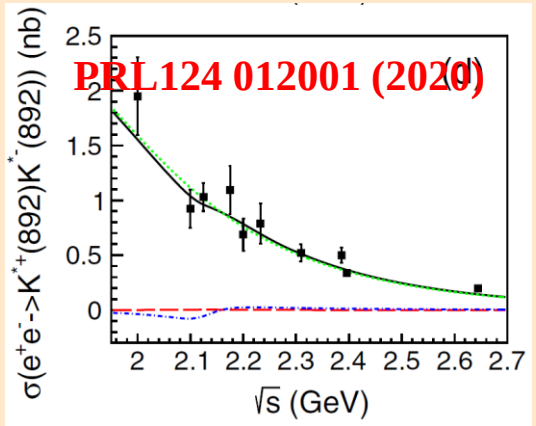
Roadmap for $\phi(2170)$: two body decay

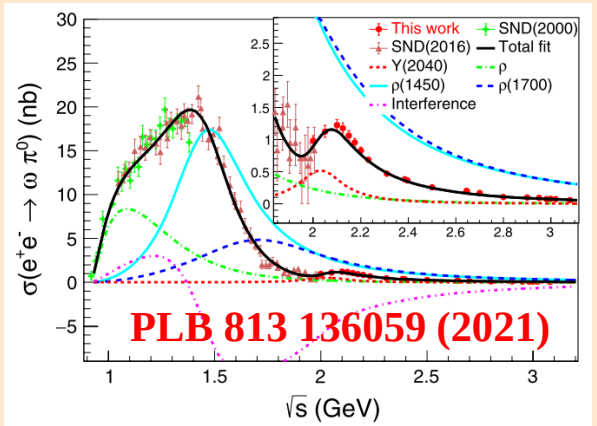






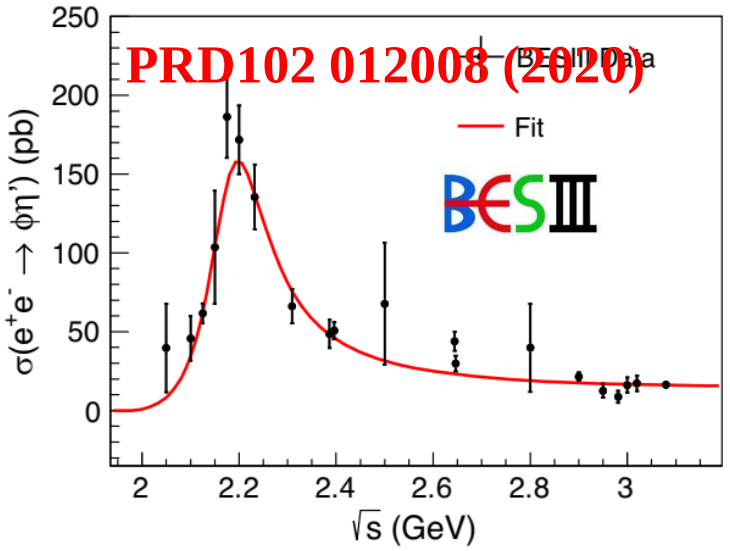


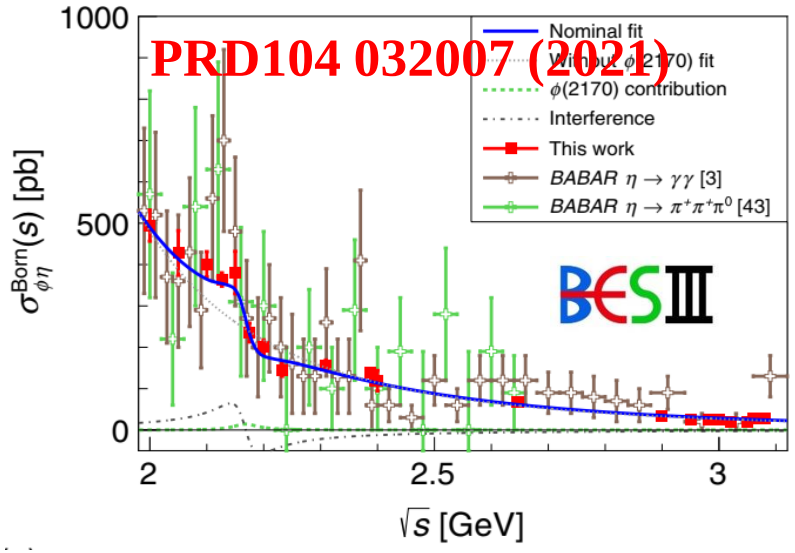


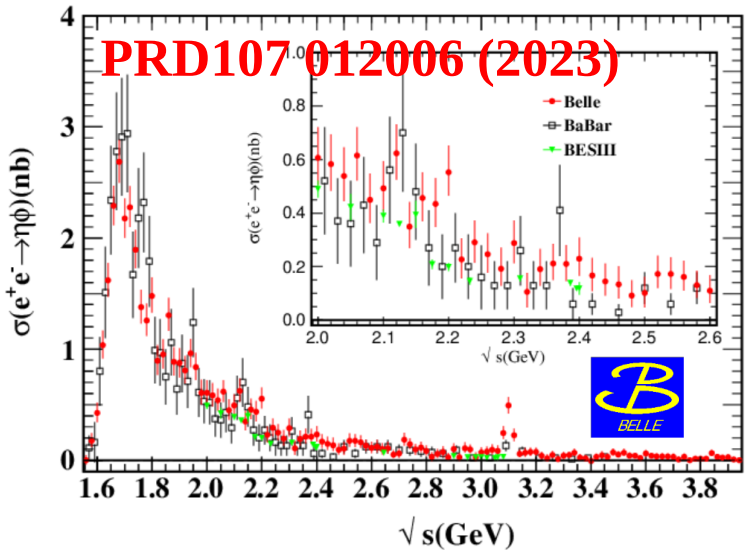


- OZI & isospin favoured: $\phi\eta$, $\phi\eta'$, $\phi f_0(980)$ and so on
- KK, K*K and K*K* $\Leftarrow \rho^*/\omega^*$ contribution
- OZI & isospin un-favoured: $\rho\pi^0$, $\omega\pi^0$ and so on

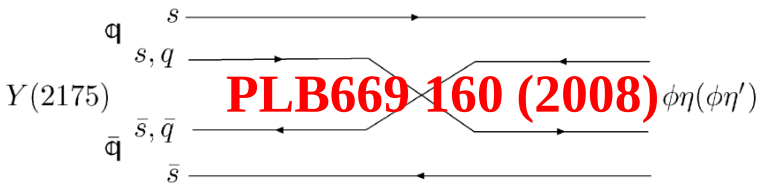
$e^+ e^- \to \phi\eta'$ and $\phi\eta$







- $\phi\eta$ and $\phi\eta'$ modes: isoscalar
  - ✓ ϕ^* and ω^* (OZI suppressed)
  - ✓ useful to measure parameters
- tetraquark favorites $\phi\eta$ and $\phi\eta'$
- 1^{--} $s\bar{s}g$ hybrid has large $\Gamma_{\phi\eta}$ and smaller $\Gamma_{\phi\eta'}$
- BESIII data vs. Belle data
  - ✓ Belle II data ?

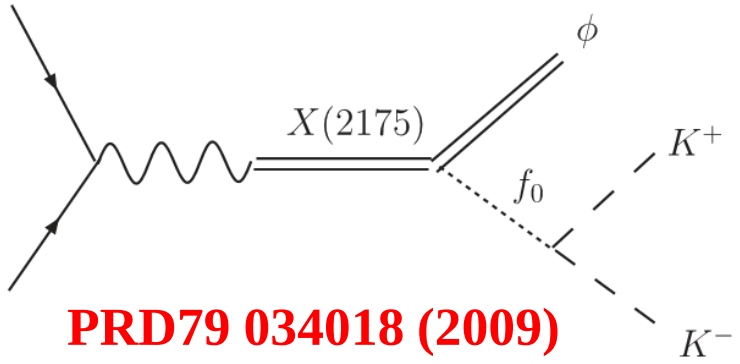


PLB669 160 (2008)

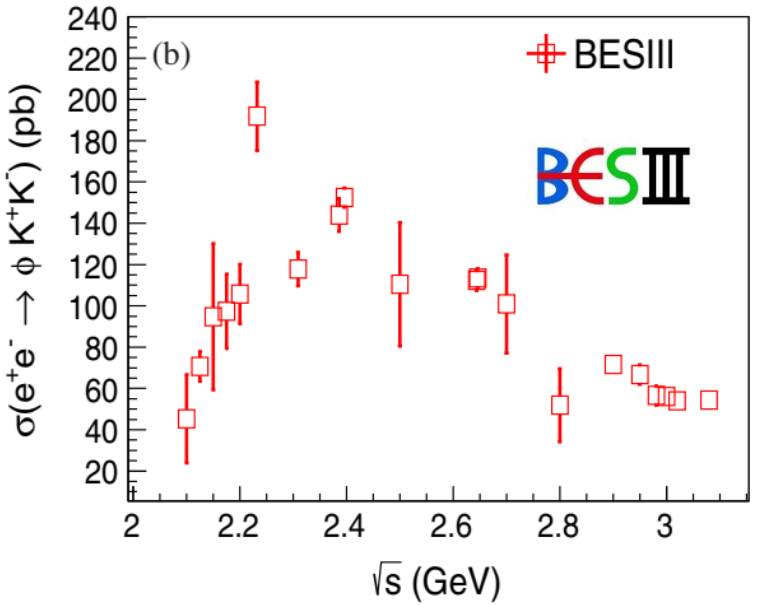
1^{--} $s\bar{s}g$	PRD59 034016				PLB650 390
$\phi\eta$	2	19	11	3	1.2
$\phi\eta'$	0.01	2	0.1	0.02	0.4
Ratio	200	9.5	110	150	3

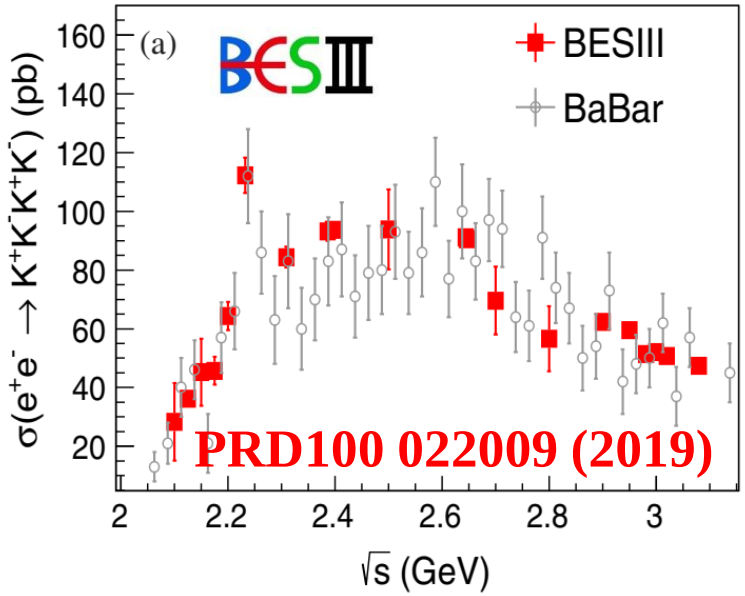
$e^+ e^- \to \phi K^+ K^-$ and $2(K^+ K^-)$

- $\phi(2170)$: resonant of ϕKK



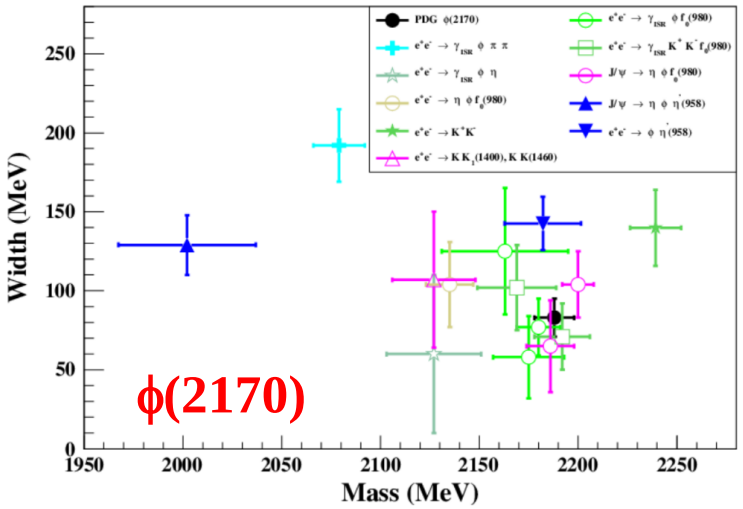
PRD79 034018 (2009)





PRD100 022009 (2019)

- ϕK^+K^- & $2(K^+K^-)$: similar enhancement around 2.2324 GeV
- hint for a narrow resonance around $\Lambda\bar{\Lambda}$ threshold
  - ✓ Width < 20 MeV
- three body system ϕKK ???

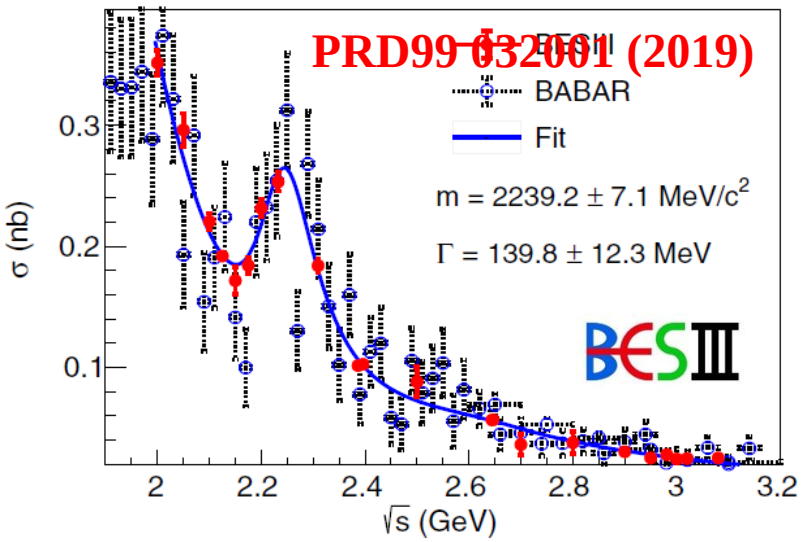


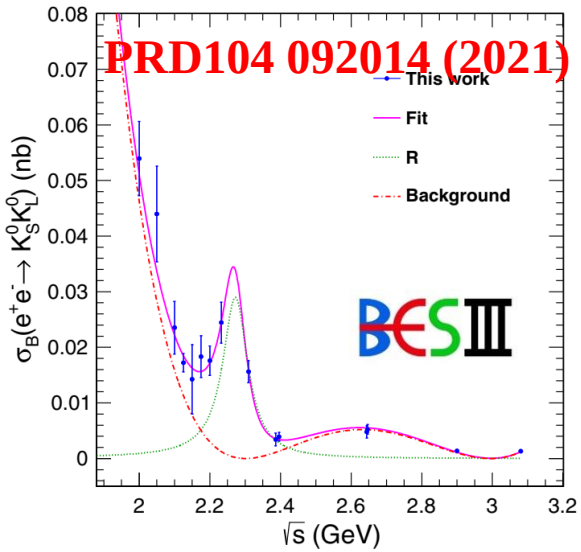
$e^+ e^- \to K^+ K^-$ & $K_S K_L$

- $\phi(2170)$: molecular state $\Lambda\bar{\Lambda}$

$\phi(2170)$ decay	This work	$^3P_0$ model within $s\bar{s}$ [10]	Data [5]
	$^3S_1\Lambda\bar{\Lambda}$		
KK	73.8–87.7	...	...
$\phi f_0(980)$	0.25–0.3	<10	Seen
$\omega\sigma$	4.2–4.9	...	...
$K^*K_0^*(800)$	1.8–2.1	...	...
Total	80.1–95		83 ± 12

PRD96 074027 (2017)

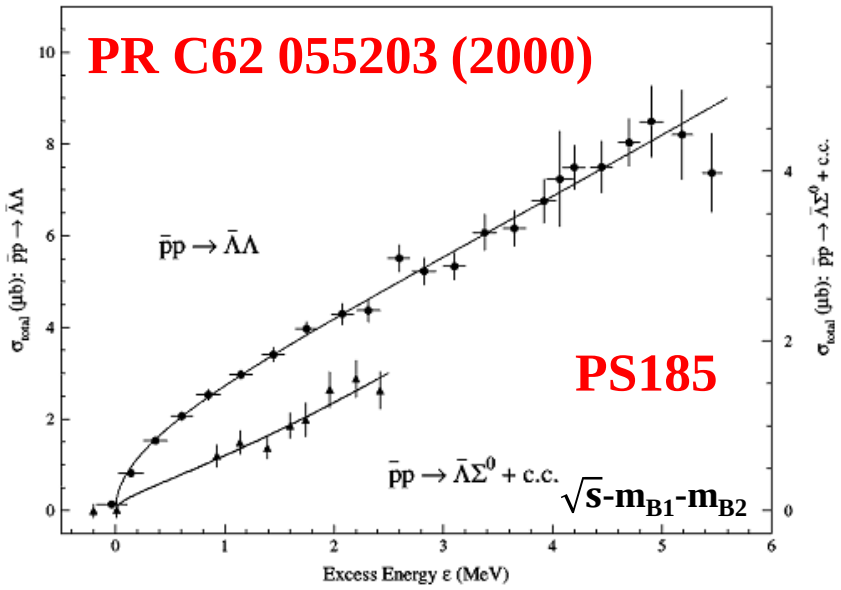


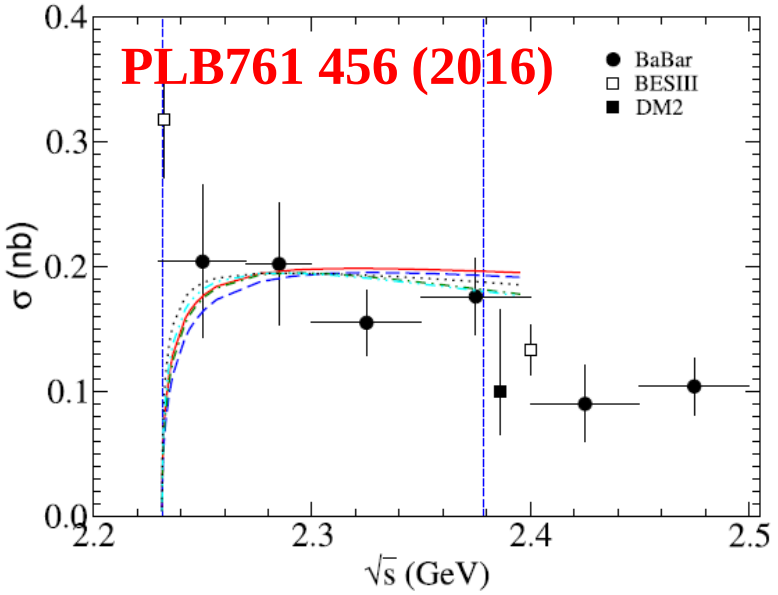


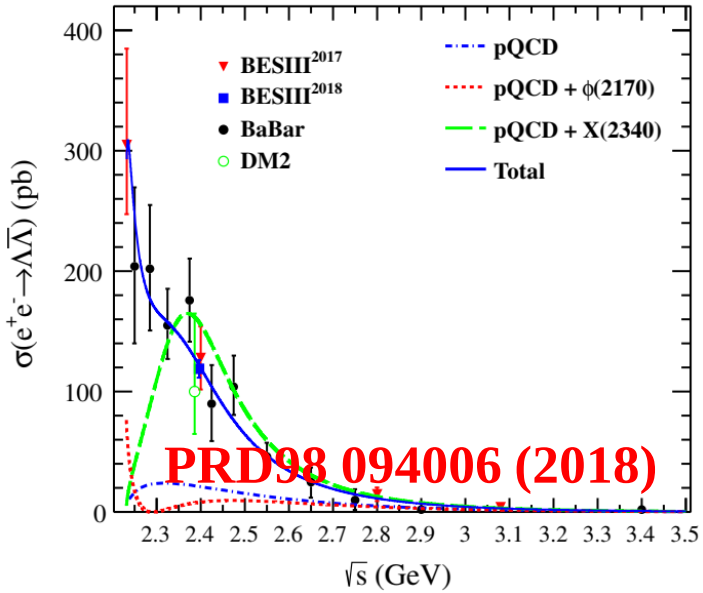
- dominant KK mode @ $\phi(2170)$?
  - ✓ iso-scalar: ω^*/ϕ^*; iso-vector: ρ^*
  - ✓ extract isospin component
- one resonance @ K^+K^- & K_SK_L
- $\Gamma(K^+K^-) \approx 10\,\Gamma(K_SK_L)$
  - ✓ PRC 102 015201: valence quark charge

	K^+K^-	K_SK_L
Mass (MeV/c^2)	2239.2±7.1±11.3	2273.7±5.7±19.3
Width (MeV)	139.8±12.3±20.6	86±44±51
$\Gamma_{ee}Br$ (eV)		0.9±0.6±0.7

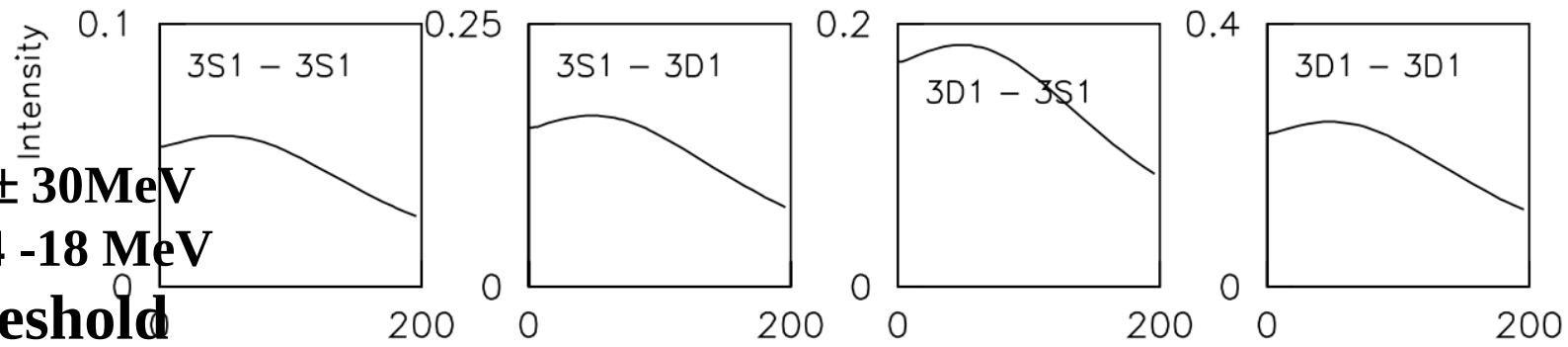
$e^+e^- \to \Lambda\bar{\Lambda}$







- ϕ(2170): molecular state $\Lambda\bar{\Lambda}$
- Fitting @ EPJ C36 161 (2004)
  - ✓ 1^- M = 2290 ± 20MeV; Γ = 275 ± 30MeV
  - ✓ ϕ(2170): 2164 ± 6 MeV; 106 +24 -18 MeV
- non-zero behavior around threshold
- A resonance @ $\Lambda\bar{\Lambda}$?



$e^+ e^- \to K^+ K^- \pi^0 \pi^0$

- $e^+e^- \to K\,K\,\pi\,\pi$: important to distinguish $\phi(2170)$ theory models
  - ✓ K^*K^*: $s\bar{s}g$ (unfavored), 3^3S_1 (favored)
  - ✓ $KK_1(1400)$: $s\bar{s}g$ (favored)
  - ✓ $KK(1460)$: $s\bar{s}g$ (unfavored), 2^3D_1 (favored)

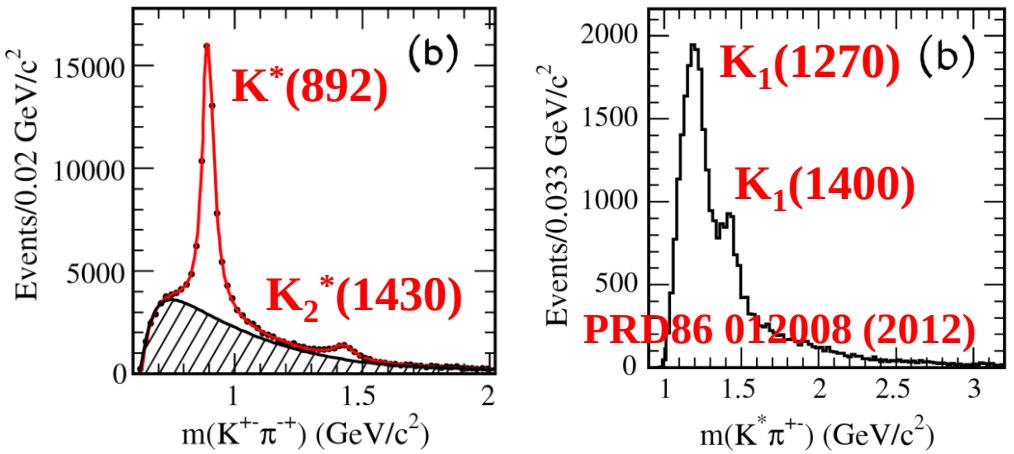
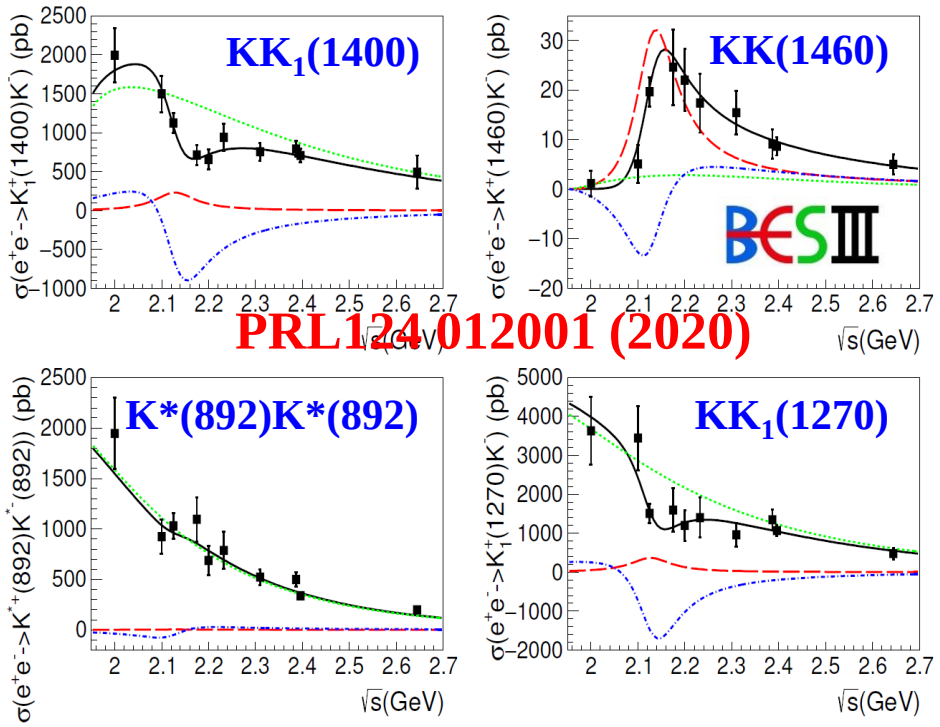


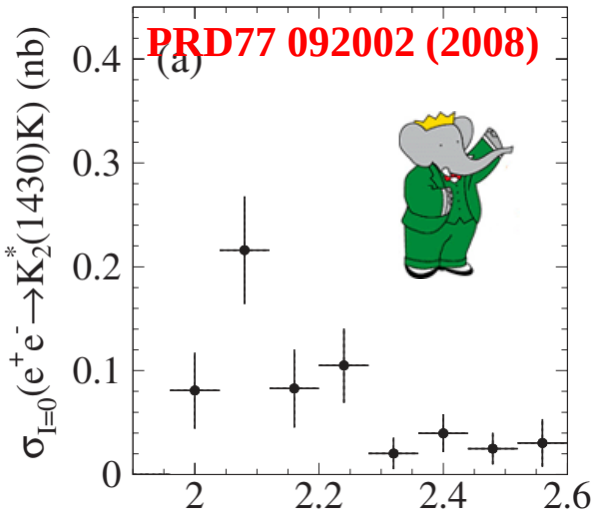
Table 22: Fitting parameters.

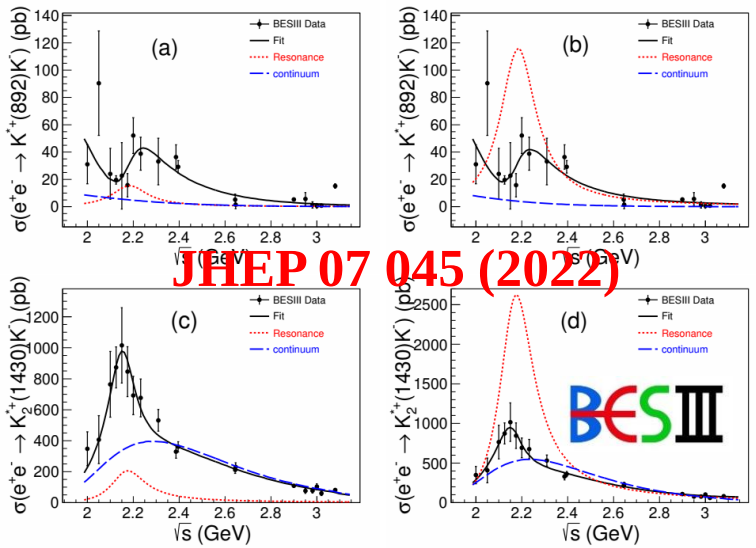
channel	$e^+e^- \to K_1^+(1400)K^-$		$e^+e^- \to K^+(1460)K^-$	$e^+e^- \to K_1^+(1270)K^-$		$e^+e^- \to K^{*+}K^{*-}$
Mass (MeV/c^2)	2126.5 ± 16.8					
Width (MeV)	106.9 ± 32.1					
	Solution1	Solution2		Solution1	Solution2	
$\mathcal{B}_R\Gamma^{e^+e^-}$ (eV)	7.6 ± 3.7	152.6 ± 14.2	1.0 ± 1.3	4.7 ± 3.3	98.8 ± 7.8	0.04 ± 0.2
ϕ (rad)	3.7 ± 0.4	4.5 ± 0.3	5.6 ± 1.5	4.0 ± 0.2	4.5 ± 0.1	5.8 ± 1.9
Significance(σ)	4.8		4.5	1.4		1.2



- ✓ dots: BESIII data
- ✓ black curves: fit results
- ✓ red long-dashed: $\phi(2170)$
- ✓ green shot-dashed: $1/s^n$
- ✓ blue dash-dotted: interference

$e^+ e^- \to K^+ K^- \pi^0$ & $e^+ e^- \to K_S^0 K_L^0 \pi^0$

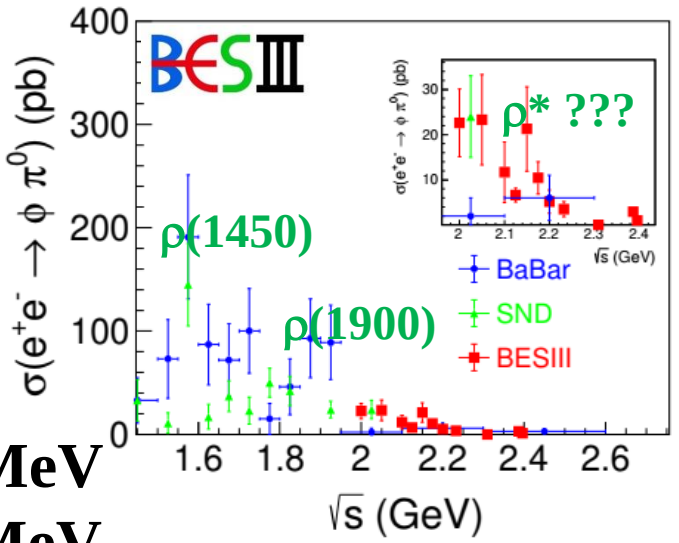


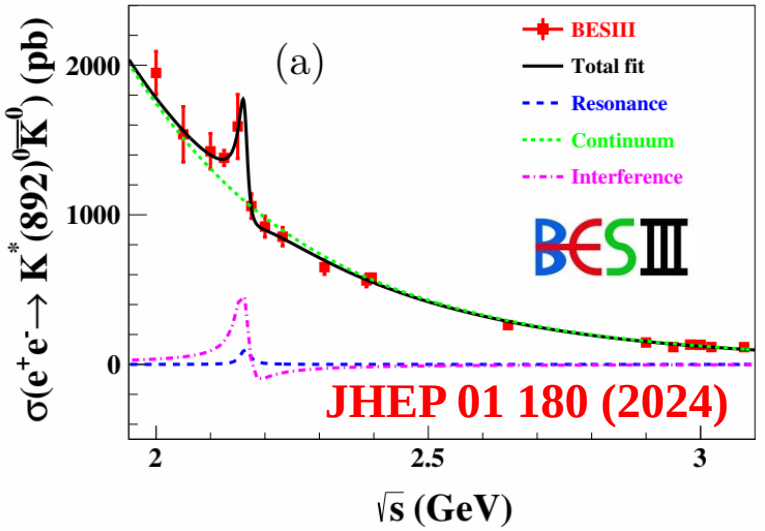


	$K_2^*(1430)K$	$K^*(892)K$
Mass	$2190\pm19\pm37$ MeV/c^2	
Width	$191\pm28\pm60$ MeV	
$\Gamma_{ee}Br$	12.6 ± 2.4 eV	1.0 ± 0.3 eV
	161.1 ± 20.6 eV	7.1 ± 0.9 eV

$$\frac{\mathcal{B}(\phi(2170)\to K^{*+}(1430)K^-)}{\mathcal{B}(\phi(2170)\to K^{*+}(892)K^-)} = \frac{12.6\pm4.5}{(22.7\pm4.1)}$$

- $K_2^*(1430)K$ @ $\phi(2170)$?
  - ✓ BaBar: hint @ 2.1 GeV
- Vector state @ $\phi\pi^0$
  - ✓ ρ*: OZI-suppressed
  - ✓ ω/ϕ*: isospin-violated
- Vector state @ $K_S^0 K_L^0 \pi^0$
  - ✓ Mass: 2164.7 ± 9.1 ± 3.1 MeV
  - ✓ Width: 32.4 ± 21.0 ± 1.8 MeV





$e^+ e^- \to K^+ K^- \pi^0$ vs. $e^+ e^- \to K^0_S K^0_L \pi^0$

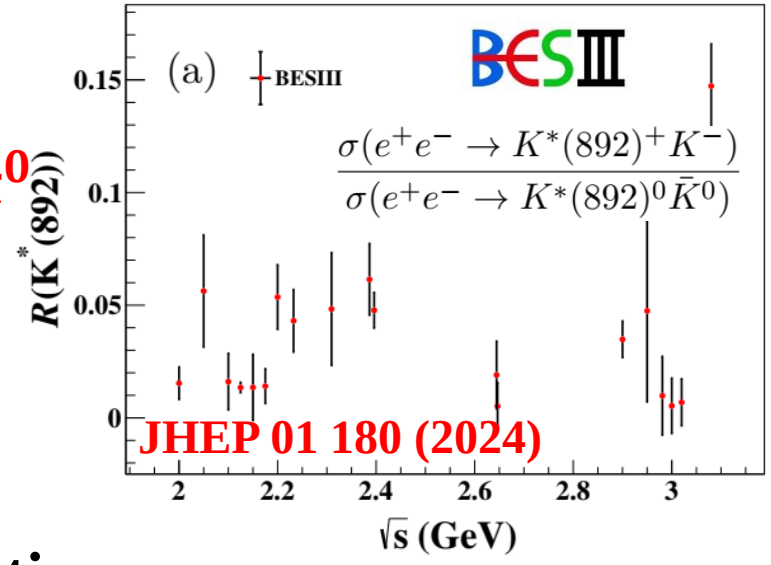
Process	Fraction (%) (2.125 GeV)	Fraction (%) (2.396 GeV)
$\phi\pi^0$	1.8 ± 0.4	0.7 ± 0.3
$\rho(1450)\pi^0$	3.8 ± 0.7	0.2 ± 0.2
$\phi(1680)\pi^0$	14.6 ± 2.3	13.6 ± 2.9
$\rho(1900)\pi^0$	2.1 ± 0.3	3.0 ± 1.0
$\rho_3(2250)$	0.9 ± 0.5	0.9 ± 0.6
$K^*(892)K$	2.8 ± 0.3	9.3 ± 1.2
$K^*(1410)K$	1.1 ± 0.8	3.6 ± 1.4
$K_2^*(1430)K$	73.0 ± 3.7	64.6 ± 3.2
$K_3^*(1780)K$	1.3 ± 0.5	2.1 ± 1.4

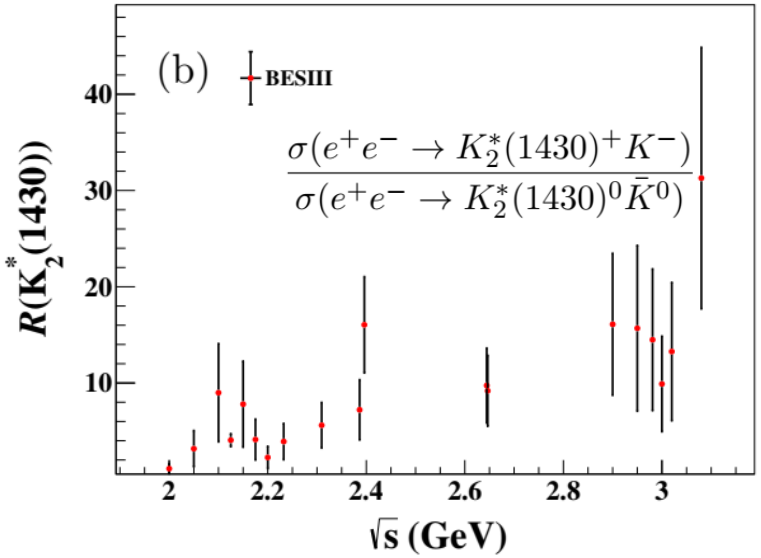
JHEP 07 045 (2022)

Process	Fraction (%)		
	2.125 GeV	2.396 GeV	2.900 GeV
$\phi\pi^0$	0.78±0.56	0.87±0.01	1.82±1.11
$\phi(1680)\pi^0$	2.39±1.23	5.96±2.10	5.22±1.50
$K^*(892)^0\bar{K}^0$	79.89±1.12	86.01±1.38	72.65±2.11
$K_2^*(1430)^0\bar{K}^0$	7.42±0.83	1.93±0.57	1.85±0.82
$K(1680)^0\bar{K}^0$	3.00±1.11	6.73±1.91	5.82±1.96

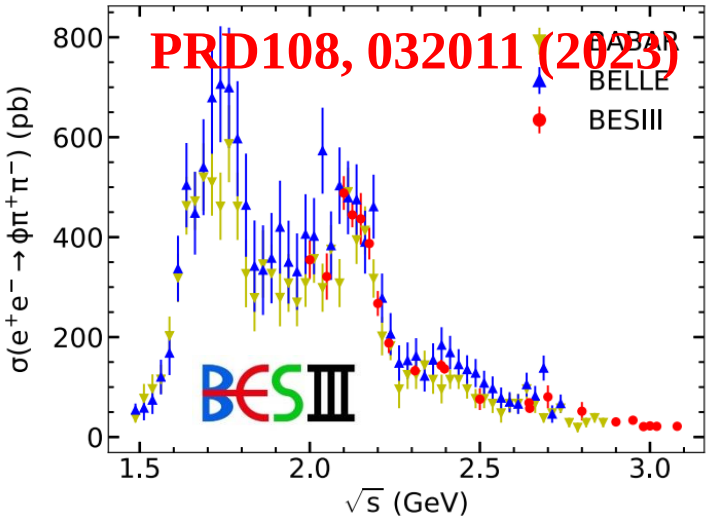
JHEP 01 180 (2024)

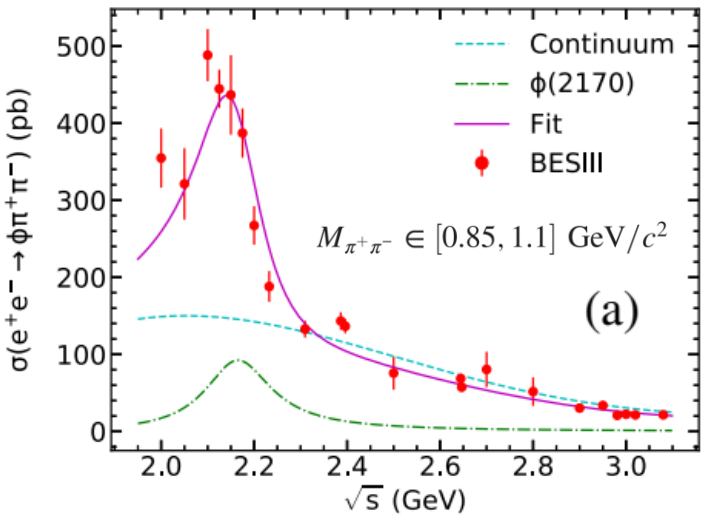
- **KKπ system**
  - ✓ $K_2^*(1430)K$ @ $K^+K^-\pi^0$
  - ✓ $K^*(892)^0\bar{K}^0$ @ $K^0_S K^0_L \pi^0$
  - ✓ Missing $K^0_S K^\pm \pi^\mp$
- **$\Gamma(K^+K^-) \approx 10\,\Gamma(K_S K_L)$**
  - ✓ valence quark charge
- **K*K: isospin → one**
  - ✓ electromagnetic interaction





$e^+ e^- \to \phi \pi^+ \pi^-$



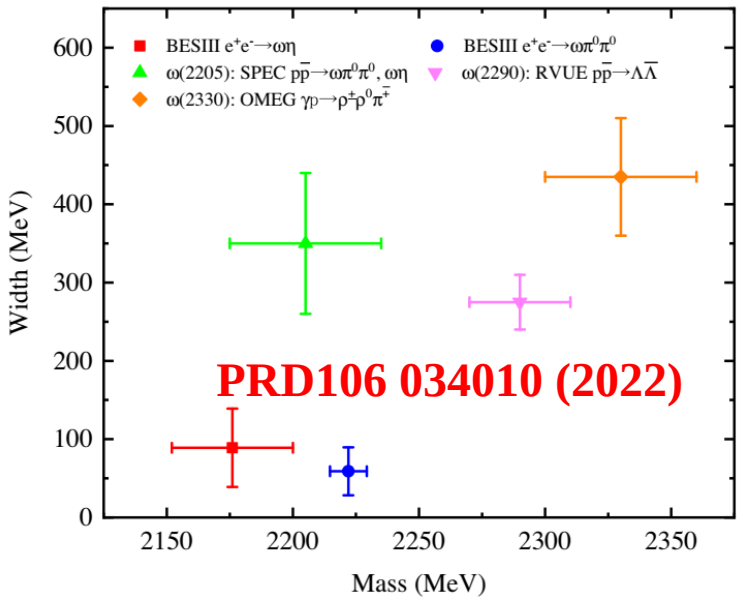


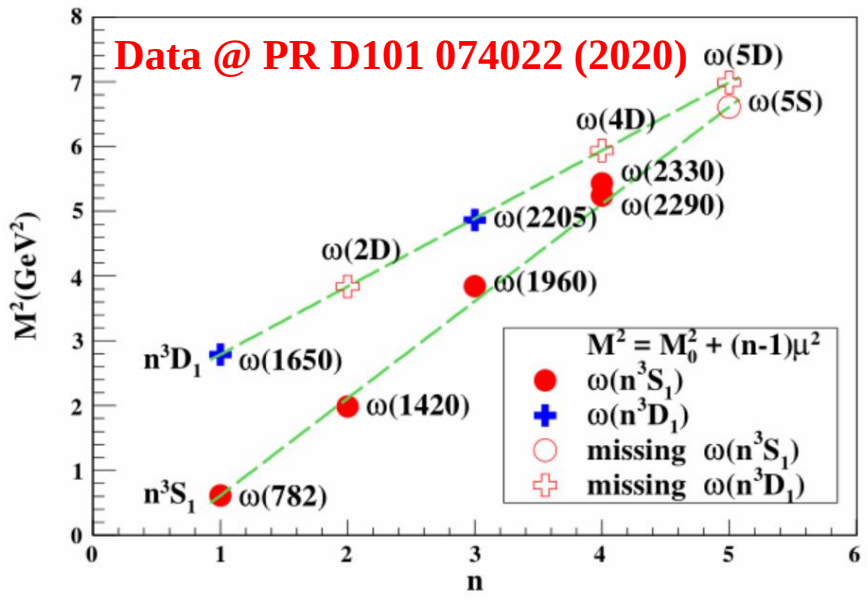
ϕ $f_0(980)$	Mass (MeV)	Width (MeV)
BaBar (2006)	2175±10±15	58±16±20
BES (2008)	2186±10±6	65±23±17
Belle (2009)	2163±32	125±40
BaBar (2012)	2172±10±8	96±19±12
BESIII (2015)	2200±6±5	104±15±15
BESIII (2019)	2135±8±9	104±24±12
PDG2024	2163±7	103+28-21

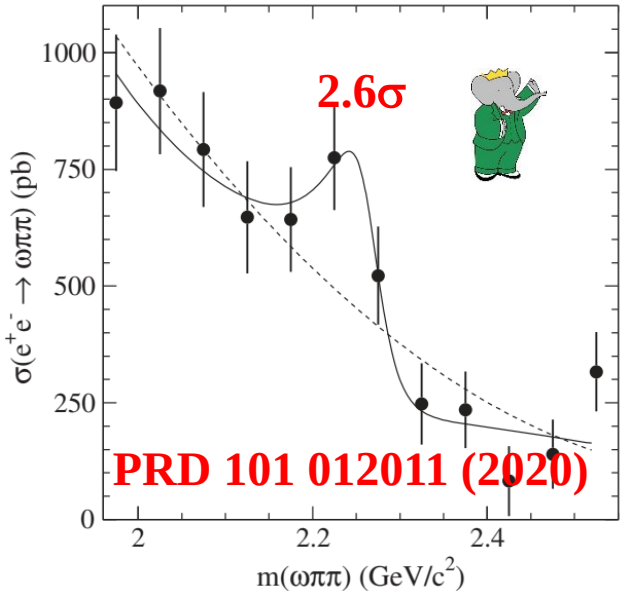
- **Belle & Babar results: general consistency, small systematic difference around 2.4GeV.**
  - ✓ **Belle data: structure @ 2.4GeV with 1.5σ**
- **$\phi\pi^+\pi^-$ @ $M_{\pi\pi}$ [0.85, 1.1] GeV/c^2**
  - ✓ **Really $\phi f_0(980)$? ×**
  - ✓ **$\phi(2170)$?**

Parameter	σ	σ^*
$M_r(\phi(2170))$	2171 ± 12	2178 ± 20
$\Gamma_r(\phi(2170))$	115 ± 28	140 ± 36
ϕ_P^D	1.01 ± 0.14	1.13 ± 0.06
ϕ_P^C	-1.87 ± 0.16	-1.71 ± 0.12
χ^2/ndf	28/15	23/15

ω* spectrum





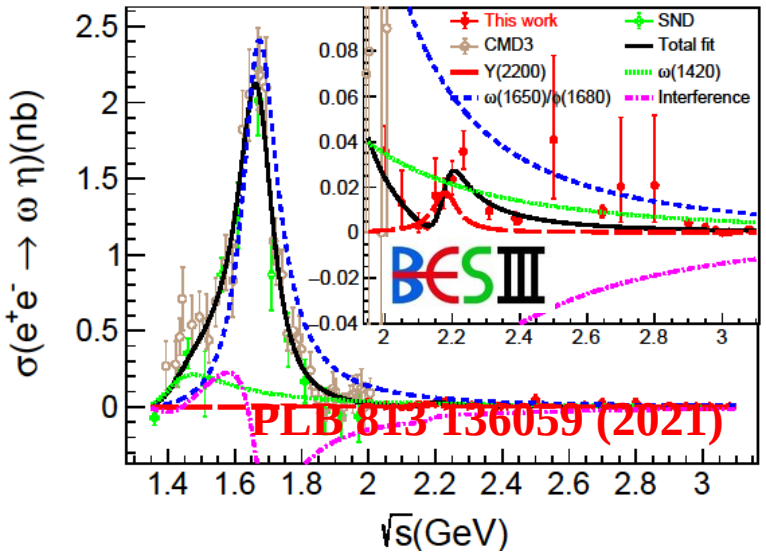


- ω* vector states
  - ✓ ω(2205): possible 3D/4S, further states
  - ✓ ω(2290): possible 4S, further states
  - ✓ ω(2330): possible 4S, further states
- ω* @ e^+ e^- collision ?

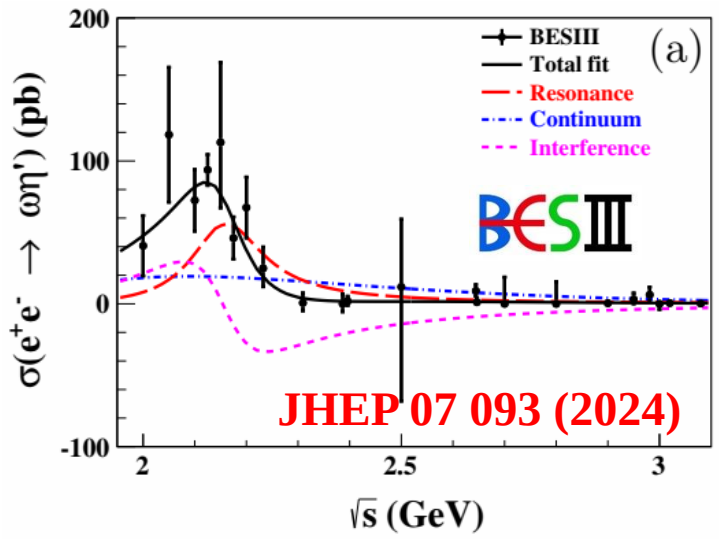
PRD 104 054027 (2020)

Mode	ω(2205) Width (MeV)	ω(2290) Width (MeV)
$b_1(1235)\pi$	24	35
$\rho(1450)\pi$	30	26
$\rho\pi$	4	16
$\omega\eta'$	0.4	0.4
$\omega\eta$	0	0.1
Total	141	138
Experiment	350±90 (SPEC 02)	275±35

$e^+ e^- \to \omega\eta$ & $\omega\eta'$



Parameters	Solution I	Solution II
$m_{Y(2180)}$ (MeV/c^2)	2176 ± 24	
$\Gamma_{Y(2180)}$ (MeV)	89 ± 50	
$\Gamma^{ee} \cdot B^{\omega\eta}$ (eV)	0.43 ± 0.15	1.25 ± 0.48
φ	2.6 ± 0.3	1.9 ± 0.2
significance	6.2σ	



Parameter	Solution 1	Solution 2
M_R (MeV/c^2)	$2153 \pm 30(\text{stat.}) \pm 31(\text{syst.})$	
Γ_R (MeV)	$167 \pm 77(\text{stat.}) \pm 7(\text{syst.})$	
ϕ (rad)	$3.78 \pm 0.24(\text{stat.}) \pm 0.12(\text{syst.})$	$3.16 \pm 0.4(\text{stat.}) \pm 0.2(\text{syst.})$
$\Gamma_R^{e^+e^-}\mathcal{B}_R^{\omega\eta'}$ (eV)	$5.72 \pm 1.68(\text{stat.}) \pm 1.5(\text{syst.})$	$2.99 \pm 1.68(\text{stat.}) \pm 1.2(\text{syst.})$
Significance	9.6σ	

PDG	Mass	Width
ω(2205)	2205±30	350±90
ω(2290)	2290±20	375±35
ω(2330)	2330±30	435±75

PDG2024 ω(2220) WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
93±53±20	[5] ABLIKIM	23G	BES3	2.0–3.1 $e^+e^- \to \omega\pi\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
125±43±15	[6] ABLIKIM	23G	BES3	2.0–3.1 $e^+e^- \to \omega\pi^+\pi^-$
59±30± 6	[7] ABLIKIM	22I	BES3	2.0–3.8 $e^+e^- \to \omega\pi^0\pi^0$
350±90	[8] ANISOVICH	02B	SPEC	0.6–1.9 $p\bar{p} \to \omega\eta, \omega\pi^0\pi^0$

- **Isospin zero: ω* and ϕ* ?**
- **ω(2220) width**
  - ✓ **~ 100 MeV @ BESIII**
  - ✓ **~ 350 MeV @ SPEC**

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix}$$

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PHYSICS LETTERS B

Physics Letters B 542 (2002) 19–28

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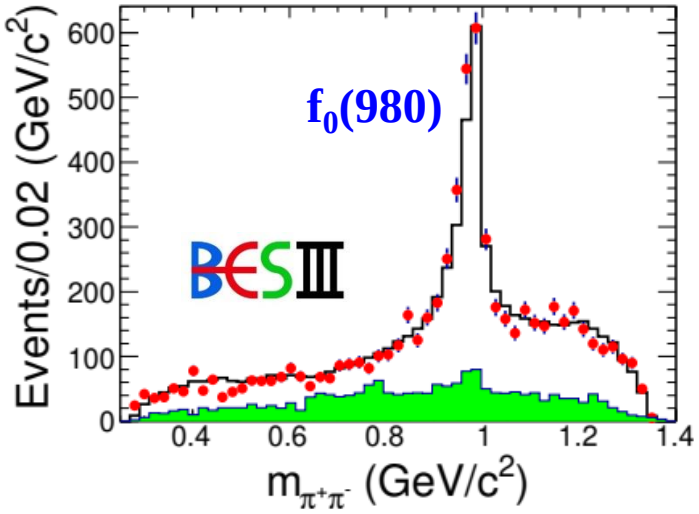
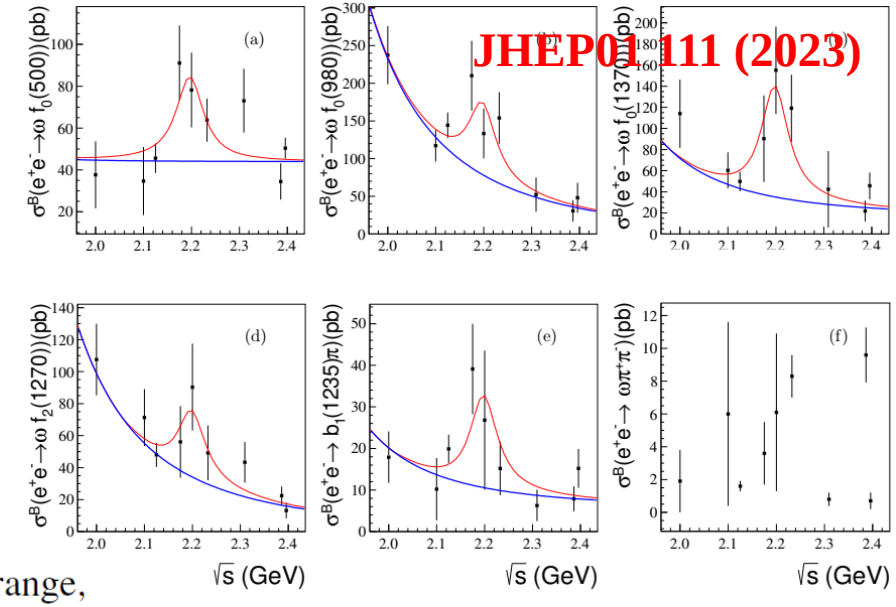
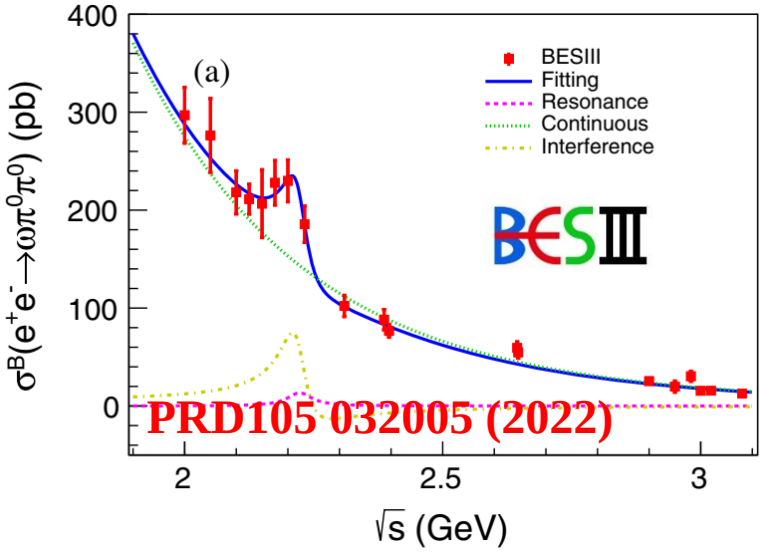
$I = 0, C = -1$ mesons from 1940 to 2410 MeV

A.V. Anisovich [d], C.A. Baker [a], C.J. Batty [a], D.V. Bugg [c], L. Montanet [b], V.A. Nikonov [d], A.V. Sarantsev [d], V.V. Sarantsev [d], B.S. Zou [c,1]

$e^+ e^- \to \omega \pi^+ \pi^-$ & $\omega \pi^0 \pi^0$

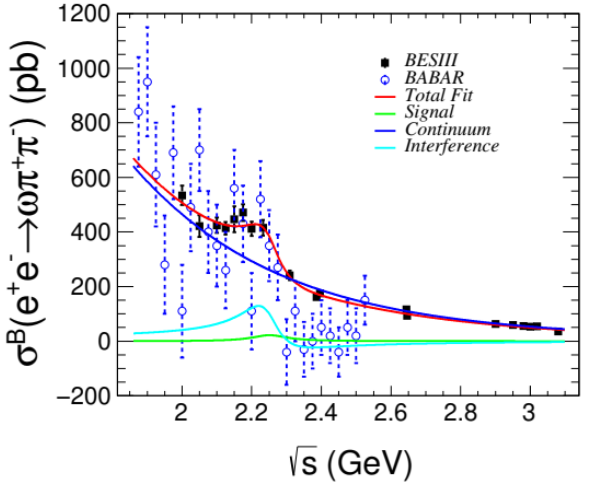






$$e^+e^- \Rightarrow \begin{cases} Y(2175) \to \phi(1020)\pi^+\pi^- & \text{strange,} \\ Y(4260) \to J/\psi\pi^+\pi^- & \text{charm,} \\ \Upsilon(10860) \to \Upsilon(1S,2S)\pi^+\pi^- & \text{bottom,} \end{cases}$$

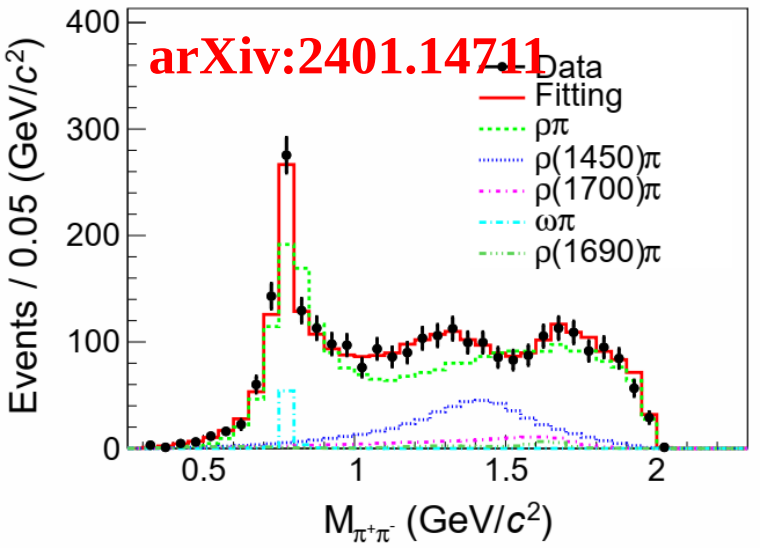
Eur. Phys. J. C72, 2008 (2012)

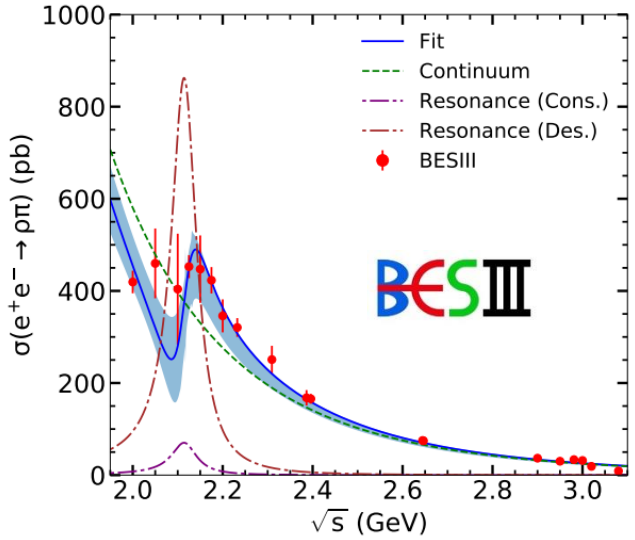


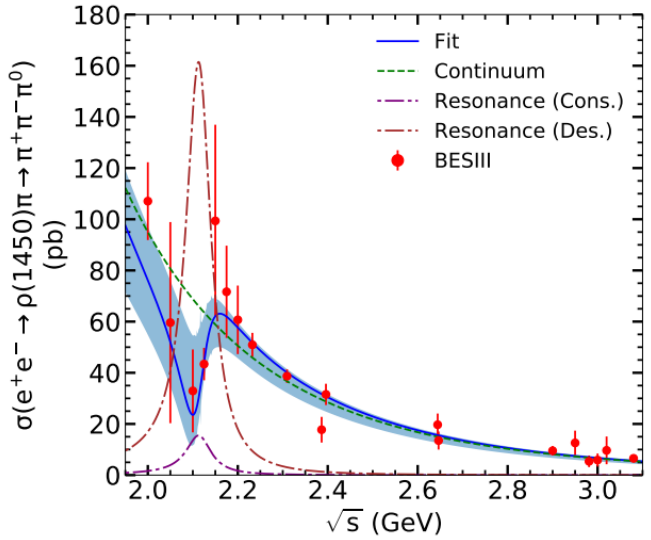
- $e^+ e^- \to \omega/\rho \pi^+ \pi^-$?
- $\pi^+\pi^-$: $f_0(980)$ signal
- G parity = -, ω^* state ?

Parameter	Solution I	Solution II
m_r (MeV/c^2)	2250 ± 25	
Γ_r (MeV)	125 ± 23	
$\Gamma_r^{ee} \cdot Br$(eV)	0.9 ± 0.4	52.9 ± 17.0
ϕ (rad.)	2.4 ± 0.3	-1.8 ± 0.1
$a(10^3)(\text{pb}^{1/2})$	1.1 ± 0.2	
b	4.4 ± 0.1	
Significance	10.3σ	

$e^+ e^- \to \pi^+ \pi^- \pi^0$

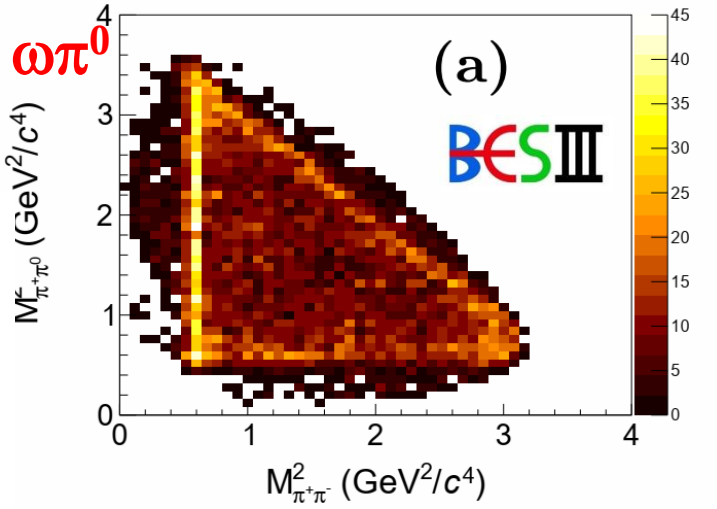


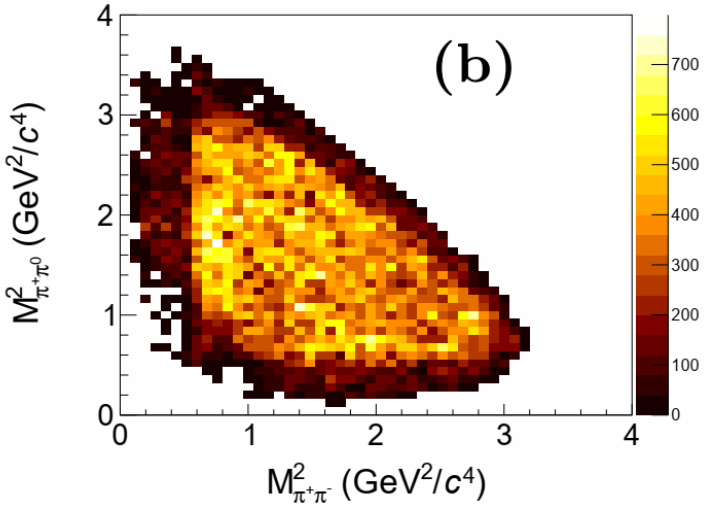




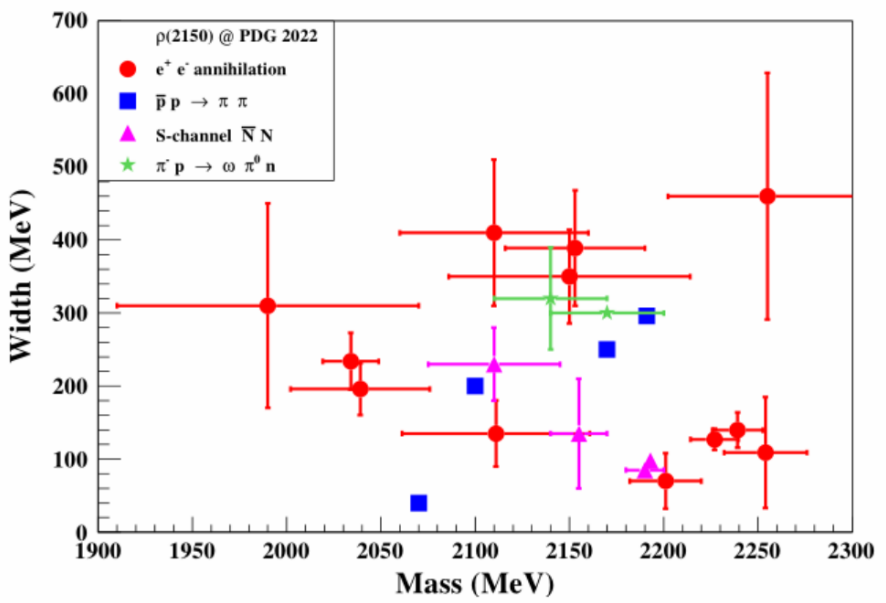
- $\rho^0\pi^0$: G parity -, OZI, ω^* state
- Dominant $\rho^0\pi^0$, visible $\rho(1450)\pi^0$ & $\omega\pi^0$
- PHOKHARA MC fails @ BESIII

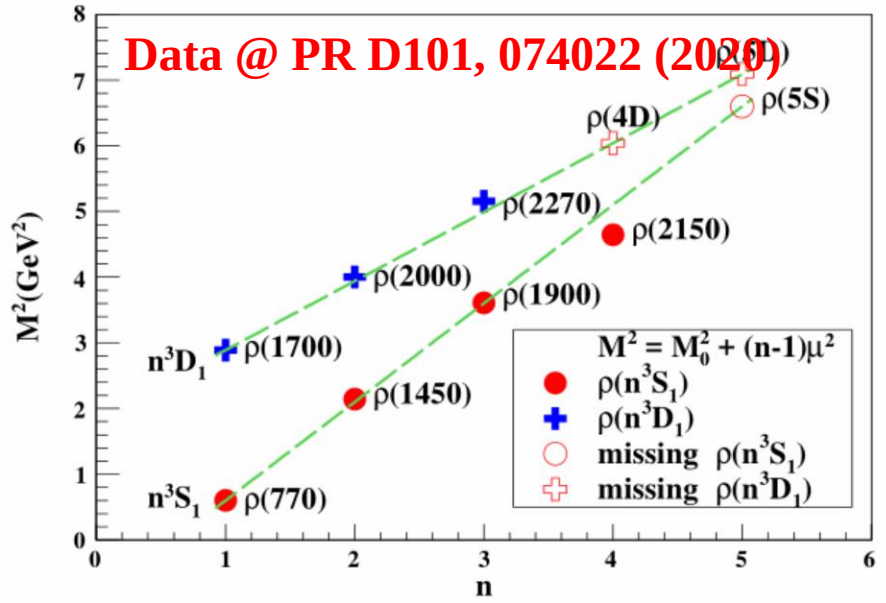
	Nominal fit	Alternative fit
Mass	2119 ± 11 MeV/c^2	2134 ± 14 MeV/c^2
Width	69 ± 30 MeV	74 ± 31 MeV
χ^2	41.9	73.3
Number of free parameters	10	18
Degrees of freedom (ndf)	28	48
χ^2/ndf	1.50	1.53
Significance	5.9σ	5.2σ





ρ* spectrum





- ρ(2000): possible 2D, further states
- ρ(2150): possible 2D or 4S
  - ✓ ρ(2150): inconsistent results between e^+e^-, $\bar{p}p$, s-channel $\bar{N}N$ and π^-p
- ρ(2270): possible 3D, further states
- ρ(2000) & ρ(2270) @ e^+ e^- collision ?

PDG2022

ρ(2000) $I^G(J^{PC}) = 1^+(1^{--})$

MASS (MeV)	WIDTH (MeV)	DOCUMENT ID		TECN	COMMENT
2000±30	260 ± 45	[23] BUGG	04C	RVUE	Compilation
~ 1988	~ 244	HASAN	94	RVUE	$\bar{p}p \to \pi\pi$

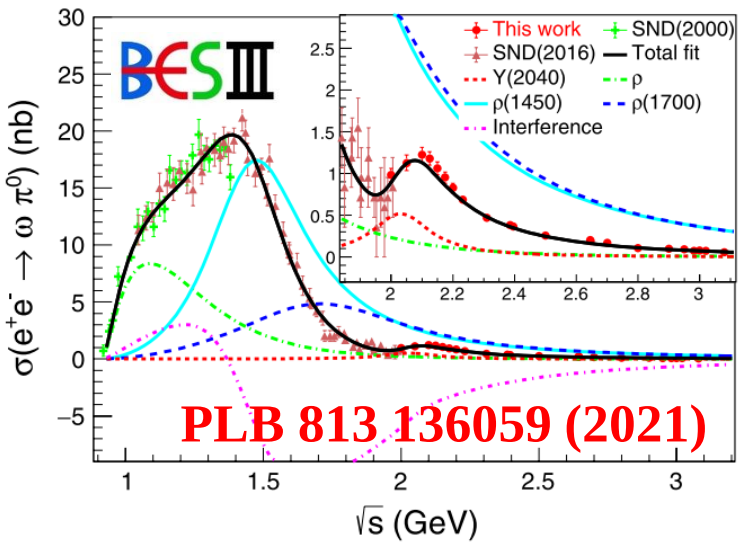
[23] From the combined analysis of ANISOVICH 00J, ANISOVICH 01D, ANISOVICH 01E, and ANISOVICH 02.

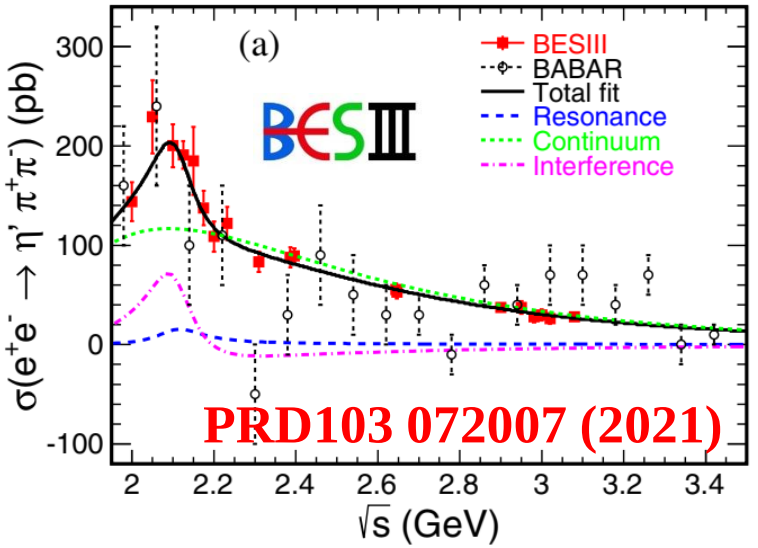
ρ(2270) $I^G(J^{PC}) = 1^+(1^{--})$

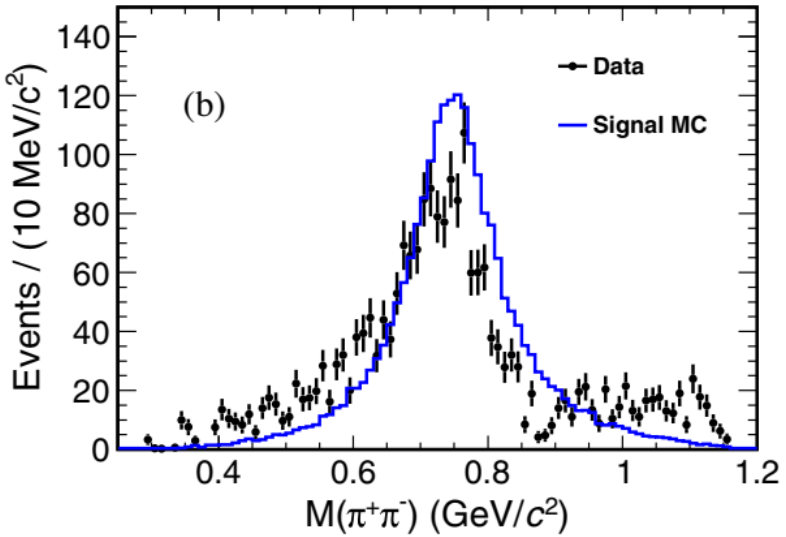
MASS (MeV)	WIDTH (MeV)	DOCUMENT ID		TECN	COMMENT
2265±40	325 ± 80	[50] ANISOVICH	02	SPEC	0.6–1.9 $p\bar{p} \to \omega\pi^0$, $\omega\eta\pi^0$, $\pi^+\pi^-$
2280±50	440 ± 110	ATKINSON	85	OMEG	20–70 $\gamma p \to p\omega\pi^+\pi^-\pi^0$

[50] From the combined analysis of ANISOVICH 00J, ANISOVICH 01D, ANISOVICH 01E, and ANISOVICH 02.

$e^+ e^- \to \omega \pi^0$ & $\eta' \pi^+ \pi^-$

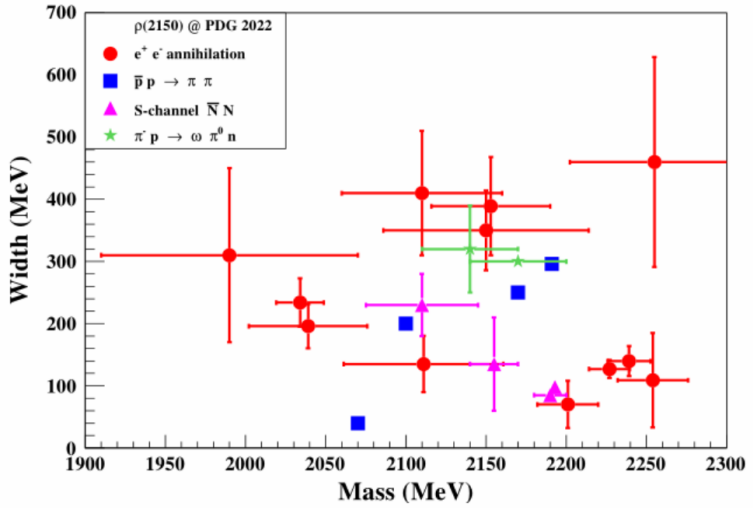






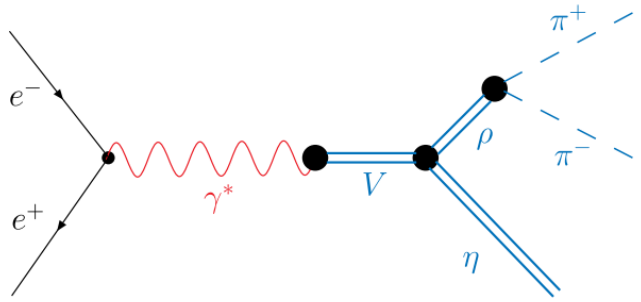
Parameters	Solution I	Solution II
$m_{Y(2180)}$ (MeV/c^2)	2176 ± 24	
$\Gamma_{Y(2180)}$ (MeV)	89 ± 50	
$\Gamma^{ee} \cdot B^{\omega\eta}$ (eV)	0.43 ± 0.15	1.25 ± 0.48
φ	2.6 ± 0.3	1.9 ± 0.2
significance	6.2σ	

Parameter	Solution 1	Solution 2
M_R (MeV/c^2)	$2111 \pm 43 \pm 25$	
$\Gamma_R^{\rm tot}$ (MeV)	$135 \pm 34 \pm 30$	
$\mathcal{B}_R\Gamma_R^{ee}$ (eV)	$0.64 \pm 0.49 \pm 0.42$	$23.3 \pm 5.3 \pm 3.3$
ϕ (rad)	$2.24 \pm 0.73 \pm 0.48$	$4.46 \pm 0.06 \pm 0.10$
$n(n')$	$4.42 \pm 0.22 \pm 0.20$	$(1.66 \pm 0.12 \pm 0.07)$
$C_0(C_0')$	$921 \pm 240 \pm 114$	$(53.0 \pm 13.2 \pm 0.1)$



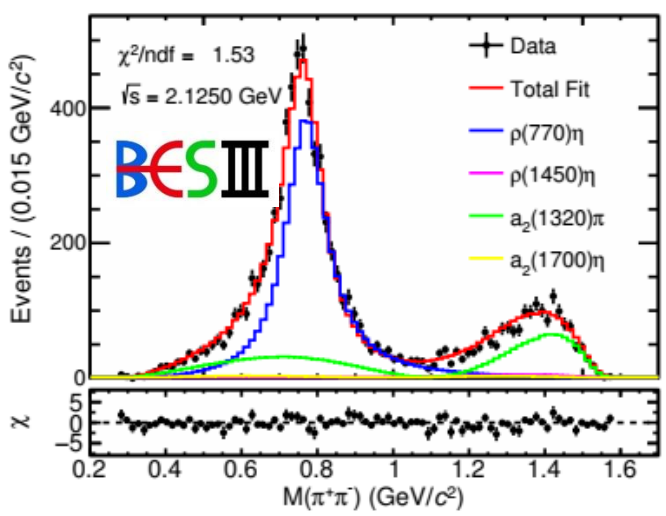
- $\omega\pi^0$ & $\rho\eta'$: G parity = +, ρ^* state $\rho(2000)$ or $\rho(2150)$?
- dominant component $\rho\eta'$, non-ρ contribution < 10%.

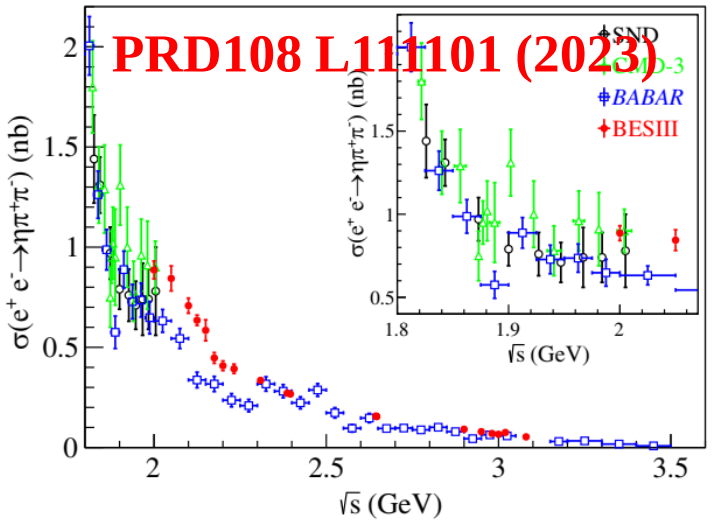
$e^+ e^- \to \pi^+ \pi^- \eta$

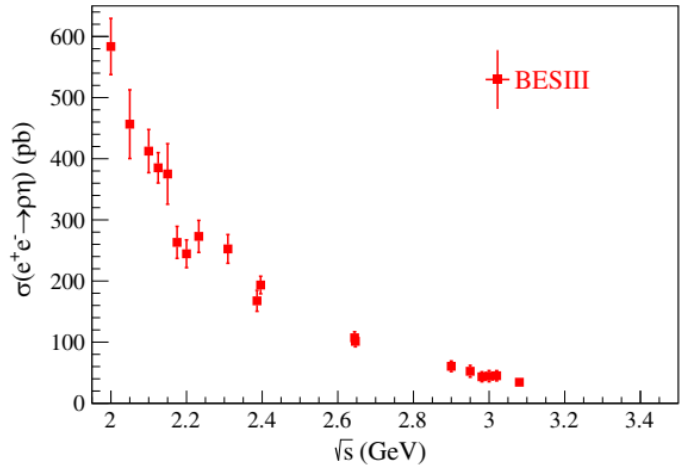


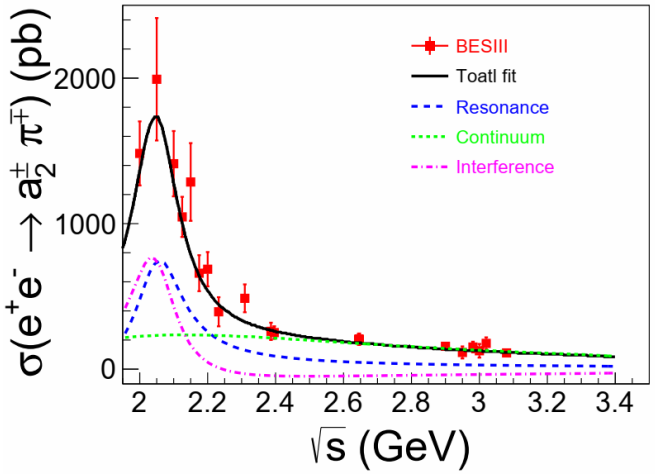
- $\rho\,\eta$ mode: G parity = +, ρ^* state
- Default MC $e^+ e^- \to \rho\,\eta$ for $\eta\,\pi^+\pi^-$
- BESIII results vs. BABAR results
  - ✓ Systematically 30% higher
- Dominant component $\rho\eta$ @ $\pi^+\pi^-\eta$
  - ✓ A dip around 2.18 GeV, hint ?
- A resonance @ $a_2(1320)\pi$

Parameter	Solution 1	Solution 2
M_R (MeV/c^2)	$2044 \pm 31 \pm 4$	
$\Gamma^R_{\rm tot}$ (MeV)	$163 \pm 69 \pm 24$	
$\mathcal{B}_R\Gamma^R_{e^+e^-}$ (eV)	$34.6 \pm 17.1 \pm 6.0$	$137.1 \pm 73.3 \pm 2.1$
ϕ (rad)	$1.95 \pm 0.97 \pm 0.06$	$4.35 \pm 0.48 \pm 0.43$

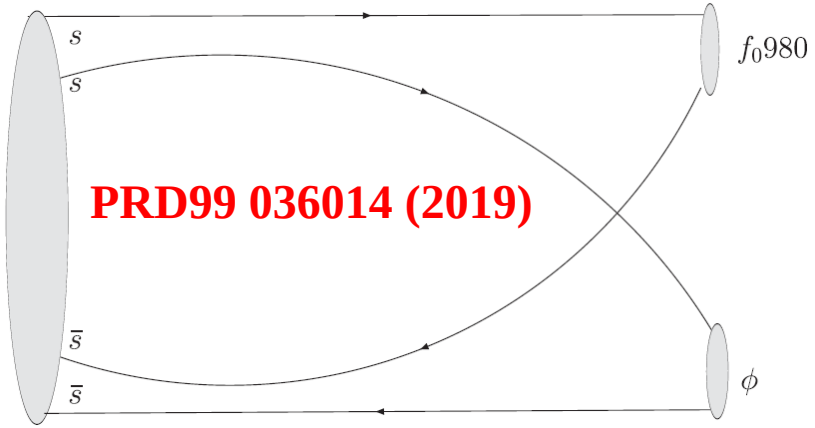






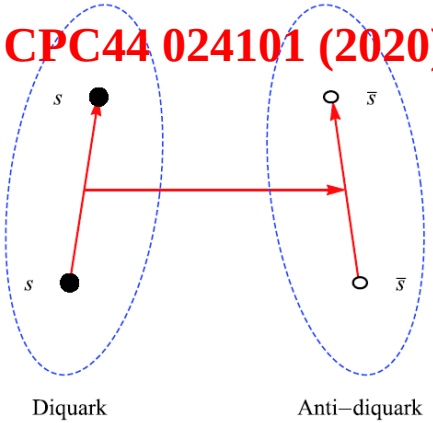


Nature of ϕ(2170)



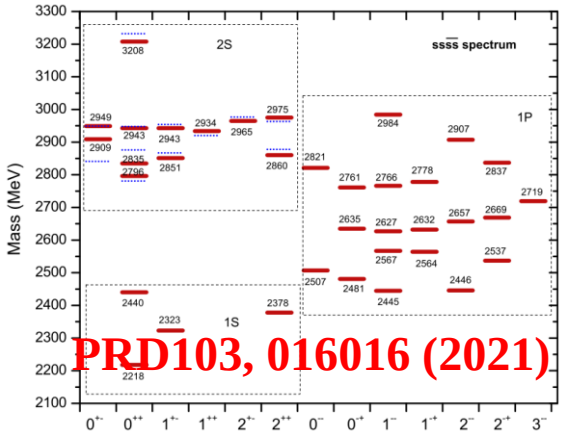
PRD99 036014 (2019)

CPC44 024101 (2020)



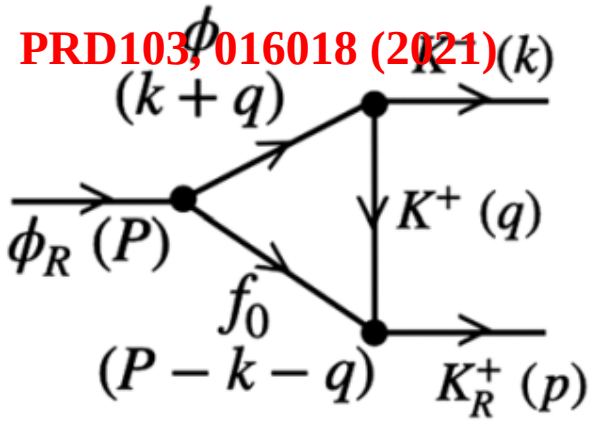
	$\phi(3S)$		$s\bar{s}$ hybrid	$\phi(4S)$	
Mass	2188	2002	2000 [29]	2498	
Channel	Value	Value	Value [29]	Channel	Value
Total	217	133	120	Total	942
$KK^*(1410)$	48.4	45.2	9	$KK_3^*(1780)$	178
KK^*	60	26.9	16	$K^*K_2^*(1430)$	160
KK_1'	4.36	21.4	64	KK_1'	123
KK_1	23.6	19.3	26	K^*K^*	94.9
KK	11.9	10.8	···	$KK_2^*(1430)$	84.6
$KK_2^*(1430)$	39.8	4.48	2	$KK^*(1410)$	80.9
K^*K^*	22.7	4.40	···	KK^*	67.5
$\eta\phi$	6.66	0.363	3	KK_1	54.2
$\eta'\phi$	0.0862	0.0729	0.02	$KK_4^*(2045)$	54.8
				[illegible]	29.0
				$KK^*(1680)$	14.9

PRD99 074015 (2019)



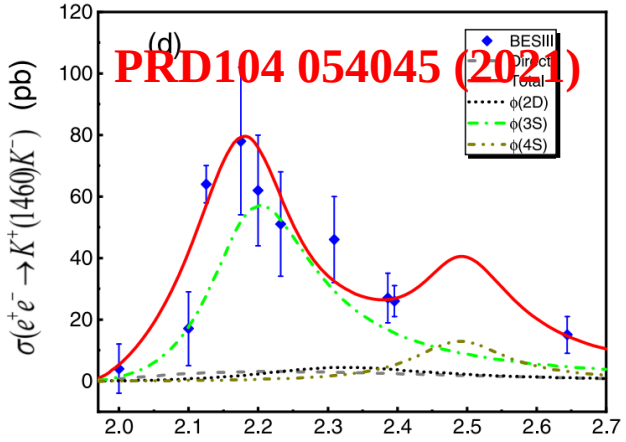
PRD103, 016016 (2021)

PRD103, 016018 (2021)



Mode	$\phi(2170)$ Width (MeV)	$\phi(2050)$ Width (MeV)
$K_1(1400)K$	120	64
$K_1(1270)K$	111	71
KK	77	51
K^*K	35	11
K^*K^*	20	25
$h_1(1415)\eta$	15	8
$\phi\eta$	4	0.4
$K_2^*(1430)K$	3	0
$K^*(1410)K$	3	37
$K(1460)K$	2	6
$\phi\eta'$	0.6	0.4
Total	410	277
Experiment	125 ± 65	

PRD104, 054027 (2021)



PRD104 054045 (2021)

tetraquark ? sȳ state ? ϕf$_0$(980) molecular state ? mixing state ?

Nature of $\phi(2170)$

PHYSICAL REVIEW D **101,** 074012 (2020)

Nature of the vector resonance $Y(2175)$

S. S. Agaev,[1] K. Azizi,[2,3] and H. Sundu[4]

PHYSICAL REVIEW D **101,** 074045 (2020)

Reconciling the $X(2240)$ with the $Y(2175)$

Dian-Yong Chen,[1,*] Jing Liu,[1] and Jun He[2]

[1]Sch... China
[2]Depa... versity,

PHYSICAL REVIEW D **100,** 034012 (2019)

Is the $Y(2175)$ a strangeonium hybrid meson?

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Department of Physics and Engineering Physics University of Saskatchewan Saskatoon, Saskatchewan, S7N 5E2, Canada

W. Chen
School of Physics Sun Yat-Sen University Guangzhou 510275, China

D. Harnett
Department of Physics University of the Fraser Valley Abbotsford, British Columbia, V2S 7M8, Canada

Chinese Physics C Vol. 45, No. 1 (2021) 013112

Strangeonium-like hybrids on the lattice*

Yunheng Ma(马运恒)[1,2] Ying Chen(陈莹)[1,2†] Ming Gong(宫明)[1,2] Zhaofeng Liu(刘朝峰)[1,2]
[1]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[2]School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China

Chinese Physics C Vol. 45, No. 2 (2021) 023116

Mass spectrum and strong decays of strangeonium in a constituent quark model*

Qi Li(李琦) Long-Cheng Gui(桂龙成)[1,2,3†] Ming-Sheng Liu(刘名声)[1,2,3]
Qi-Fang Lü(吕齐放)[1,2,3] Xian-Hui Zhong(钟显辉)[1,2,3‡]
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Chinese Physics C Vol. 43, No. 11 (2019) 113105

A possible explanation of the threshold enhancement in the process $e^+e^- \to \Lambda\bar{\Lambda}^*$

Li-Ye Xiao(肖立叶)[1,2;1)] Xin-Zhen Weng(翁新震)[1;2)] Xian-Hui Zhong(钟显辉)[3,4;3)] Shi-Lin Zhu(朱世琳)[1,2,5;4)]
[1]School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
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[3]Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China
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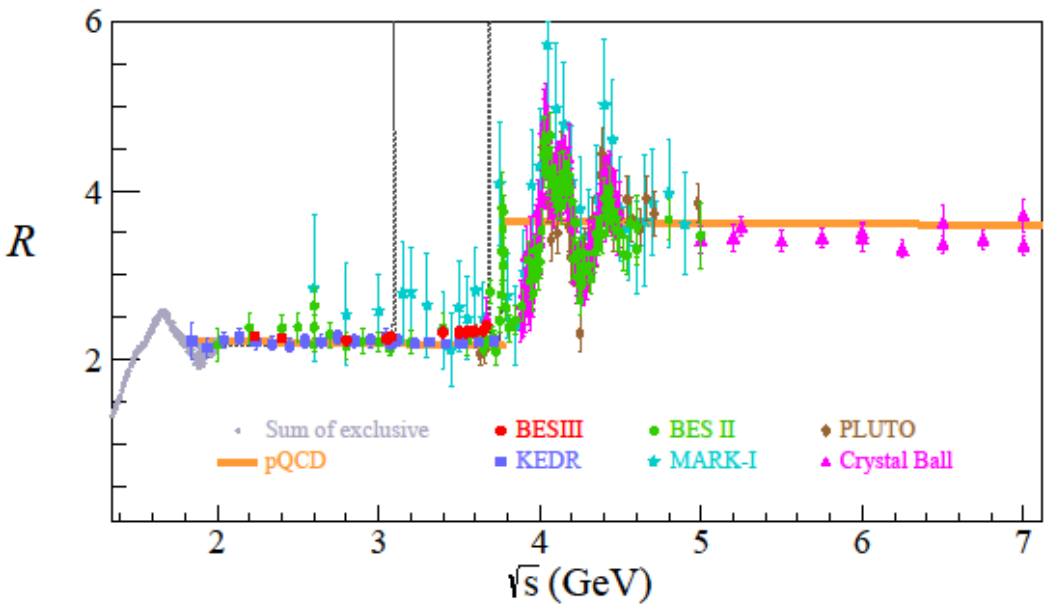
[5]Collaborative Innovation Center of Quantum Matter, Beijing 100871, China

need more experimental data ? ⇒ Belle II

ϕ(2170) @ 2015 R scan data

16 published paper + 1 draft

① e^+e^- -> $K^+ K^-$: PRD 99, 032001 (2019)
② e^+e^- -> ϕ $K^+ K^-$: PRD 100, 032009 (2019)
③ e^+e^- -> $K^+ K^- \pi^0 \pi^0$: PRL 124, 112001 (2020)
④ e^+e^- -> ϕ η': PRD 102, 012008 (2020)
⑤ e^+e^- -> ω η & ω π^0 : PLB 813, 136059 (2021)
⑥ e^+e^- -> η' $\pi^+ \pi^-$: PRD 103, 072007 (2021)
⑦ e^+e^- -> ϕ η: PRD 104, 032007 (2021)
⑧ e^+e^- -> $K_S K_L$: PRD 104, 092014 (2021)
⑨ e^+e^- -> ω $\pi^0 \pi^0$: PRD 105, 032005 (2022)
⑩ e^+e^- -> $K^+ K^- \pi^0$: JHEP 07, 045 (2022)
⑪ e^+e^- -> ϕ $\pi^+ \pi^-$: PRD 108, 032011 (2023)
⑫ e^+e^- -> η $\pi^+ \pi^-$: PRD 108, L111101 (2023)
⑬ e^+e^- -> ω $\pi^+ \pi^-$: JHEP 01, 111 (2023)
⑭ e^+e^- -> $K_S K_L \pi^0$: JHEP 01, 180 (2024)
⑮ e^+e^- -> ω η': JHEP 07, 093 (2024)
⑯ e^+e^- -> $\pi^+ \pi^- \pi^0$: arXiv:2401.14711, PRD
⑰ e^+e^- -> ω η π^0: draft @ Wenbiao



BESIII

$e^+ e^-$ -> ω η π^0

Memo version 2.3

BESIII Analysis Memo

November 15, 2022

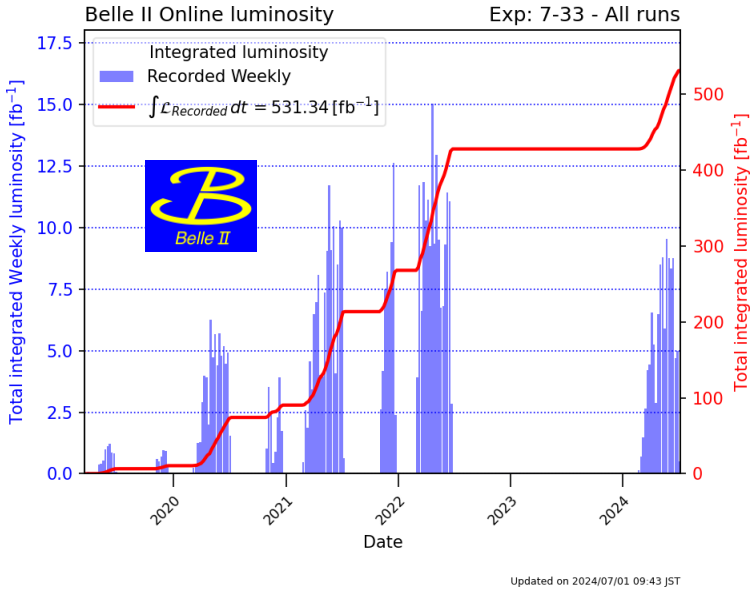
Measurement of the Born cross sections for $e^+e^- \to \omega\eta\pi^0$ at center-of-mass energies between 2.00 and 3.08 GeV

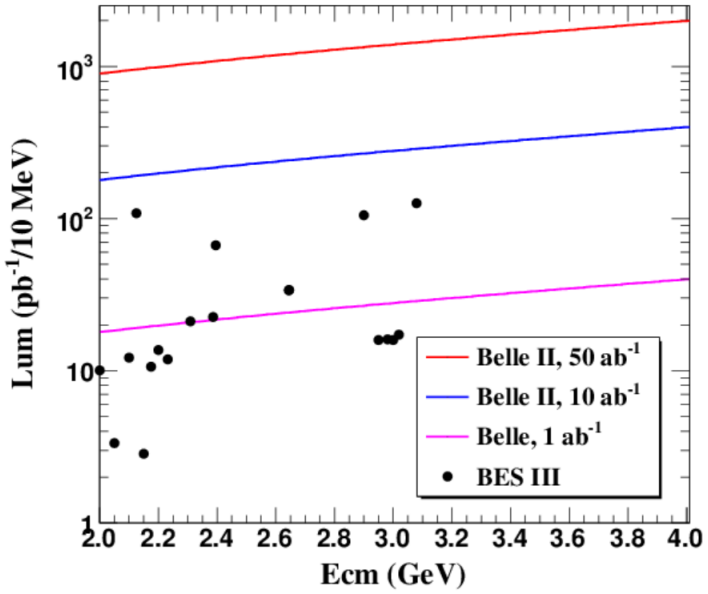
Linqin Huang[a], Yateng Zhang[b], and Wenbiao Yan[c], and Yuxiang Zhao[a]

[a]*Institute of Modern Physics, CAS*
[b]*Zhengzhou University*
[c]*University of Science and Technology of China*

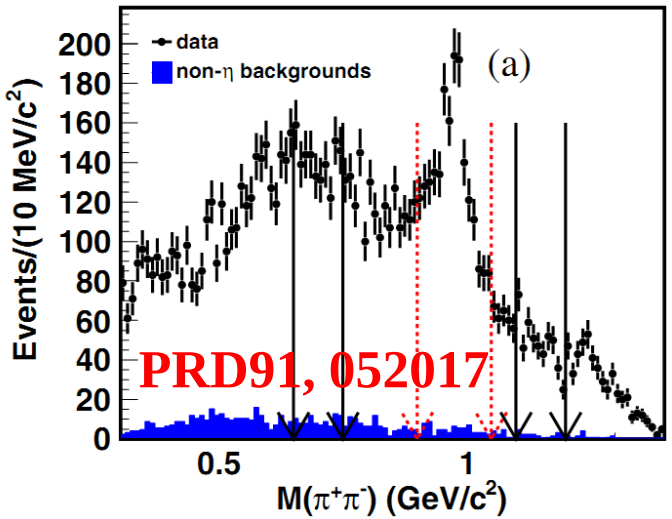
Summary and outlook

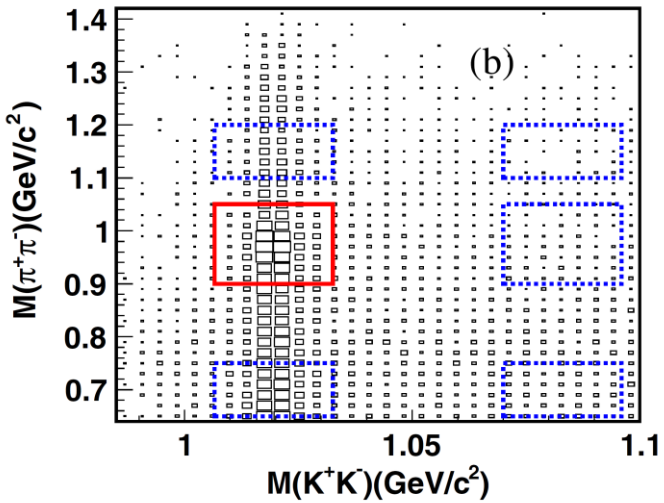
- Using BESIII R scan data, we are extensively studying $\phi(2170)$
  - ✓ $\phi(2170)$ as pure 3^3S_1 $s\bar{s}$? 2^3D_1 $s\bar{s}$?
  - ✓ $\phi(2170)$ as 1^{--} $s\bar{s}g$ hybrid ? molecular state $\Lambda\bar{\Lambda}$? three body system ϕKK ?
  - ✓ $\phi(2170)$ as tetraquark: ? mixing state: ? $\phi f_0(980)$ molecular state: ?
- Need ρ^* and ω^* spectrum to understand $\phi(2170)$.
- Belle II: 50 ab^{-1} data, study $\phi(2170)$ with ISR method.

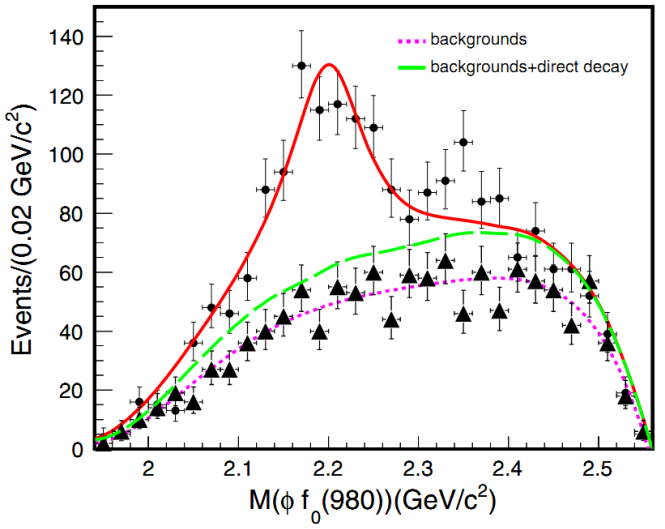




$\phi(2170)$ @ $J/\psi \to \eta\,\phi\,\pi^+\,\pi^-$



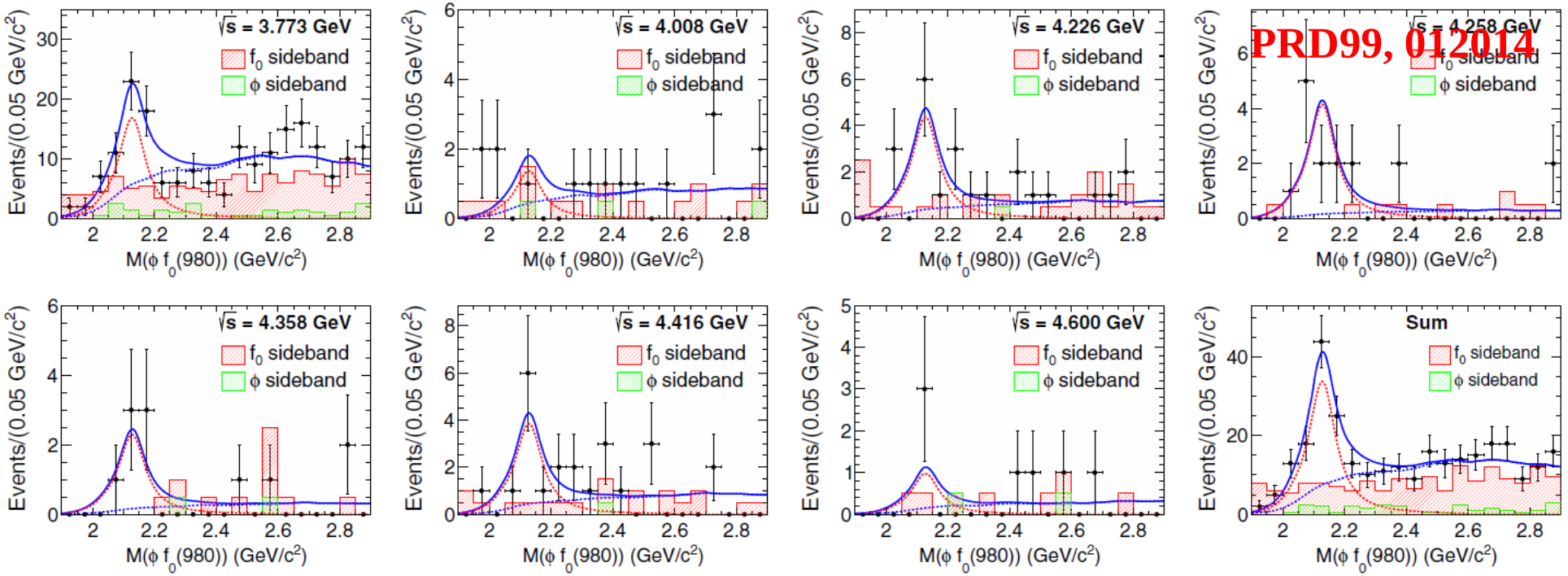




- **Fit: $\phi(2170)$ + direct decay of $/\psi \to \eta\phi f_0(980)$ + background**
- **No interference between $\phi(2170)$ and direct decay**

Decay mode	Branching fraction $\mathcal{B}$
$J/\psi \to \eta Y(2175)$, $Y(2175) \to \phi f_0(980)$, $f_0(980) \to \pi^+\pi^-$	$(1.20 \pm 0.14 \pm 0.37) \times 10^{-4}$

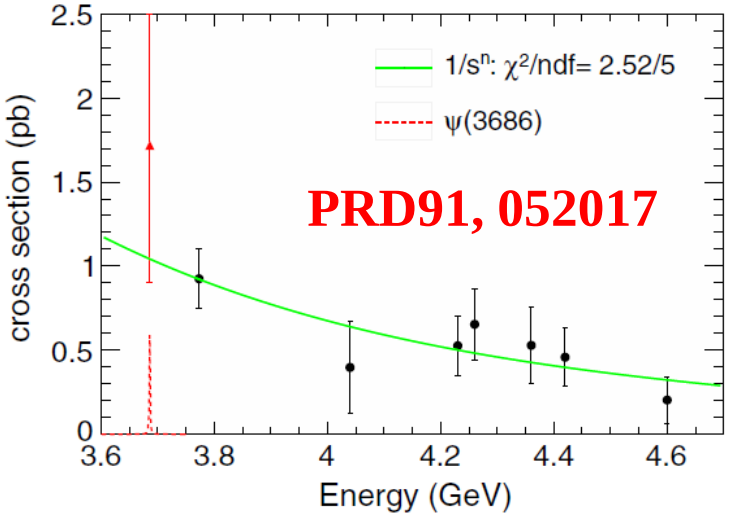
$\phi(2170)$ @ $e^+ e^- \to \eta \phi \pi^+ \pi^-$



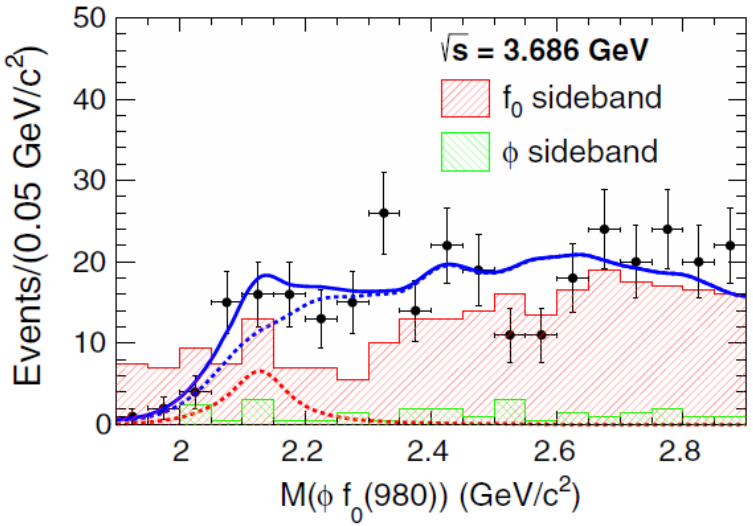
PRD99, 012014

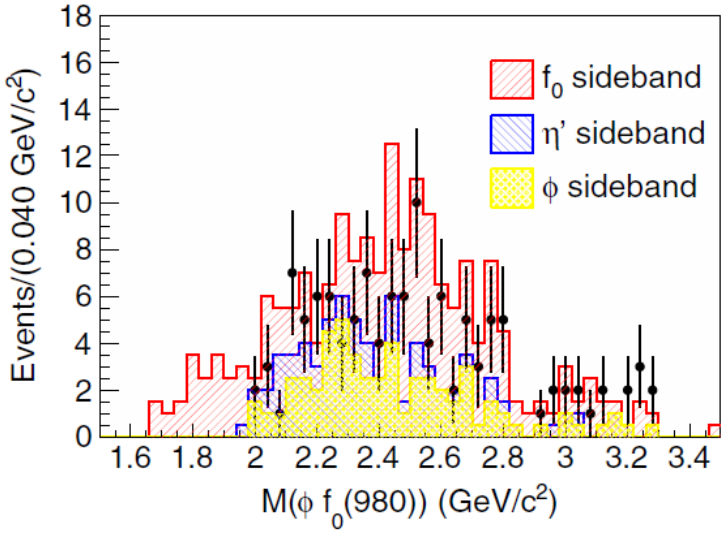
- $\phi(2170)$ @ ϕ $f_0(980)$ with $\sqrt{s}$ = [3.773, 4.600]GeV date
- Limited samples for $\phi(2170)$

$e^+ e^- \to \eta \phi(2170)$

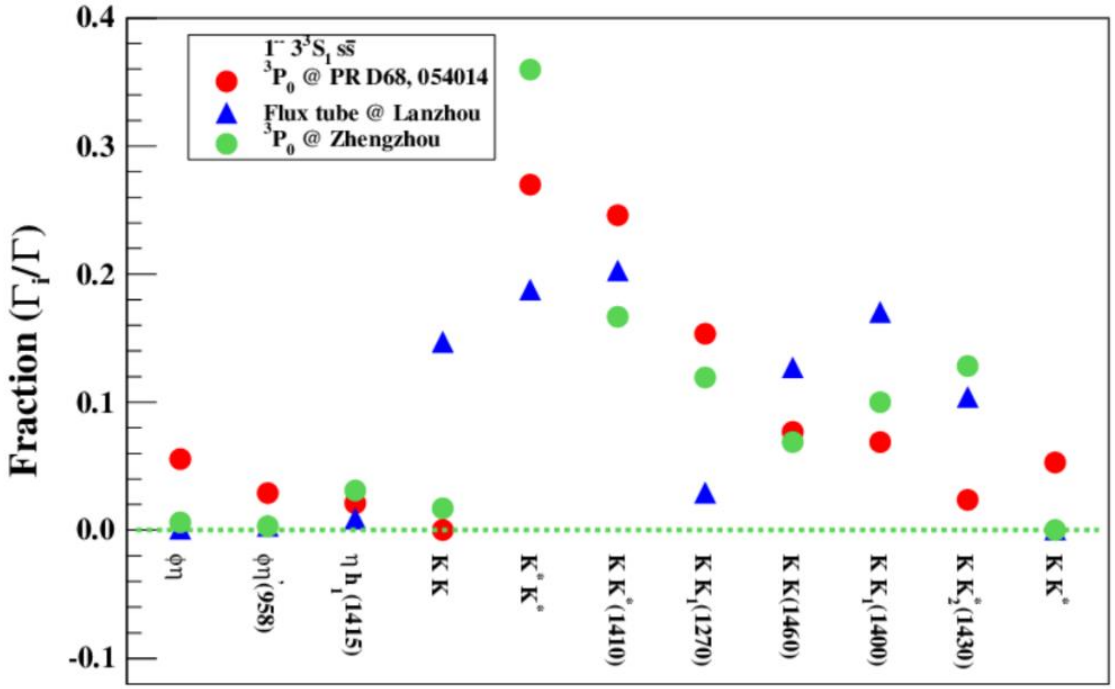


- The Born cross section varies as $1/s^n$ with $n=2.65\pm0.86$.
- $Br[\psi(3686) \to \eta\phi(2170)] < 2.2*10^{-6}$ @ 90% U.L., suppression for "12% rule"
- No significant signal $e^+e^- \to \eta'\phi(2170)$
- $\frac{\sigma[e^+e^- \to \eta'\phi(2170)]}{\sigma[e^+e^- \to \eta\phi(2170)]} < 0.43$ @ 90% U.L.





How ? $\phi(2170)$ as pure 3^3S_1 $s\bar{s}$



- reduction to Absurdity
  - ✓ 3^3S_1 $s\bar{s}$: $\Gamma_{K^*K^*} > \Gamma_{KK1(1400)}$
  - ✓ Exp. $\phi(2170)$ @ $KK_1(1400)$
  - ✓ Exp. no $\phi(2170)$ @ K^*K^*
  - ✓ Exp. similar ε_{eff}
  - ✓ $\phi(2170)$ as pure 3^3S_1 $s\bar{s}$?
- similar check for several modes
  - ✓ $KK^*(1410)$: No $\phi(2170)$
  - ✓ KK(1460): Yes $\phi(2170)$
- $\phi(2170)$ as pure 3^3S_1 $s\bar{s}$: No ?

- fraction Γ_i/Γ: weakly model & input parameters dependent
- dominant decay modes:
  - ✓ $KK^*(1410)$ & K^*K^*

pure 3^3S_1 $s\bar{s}$?
pure 2^3D_1 $s\bar{s}$?
molecular state $\Lambda\bar{\Lambda}$?
three body system ϕKK ?
1^{--} $s\bar{s}g$ hybrid ?