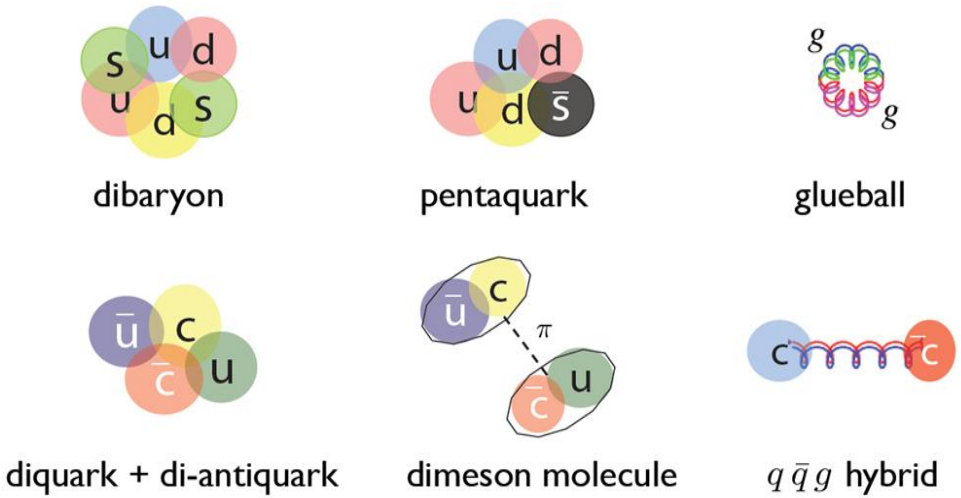
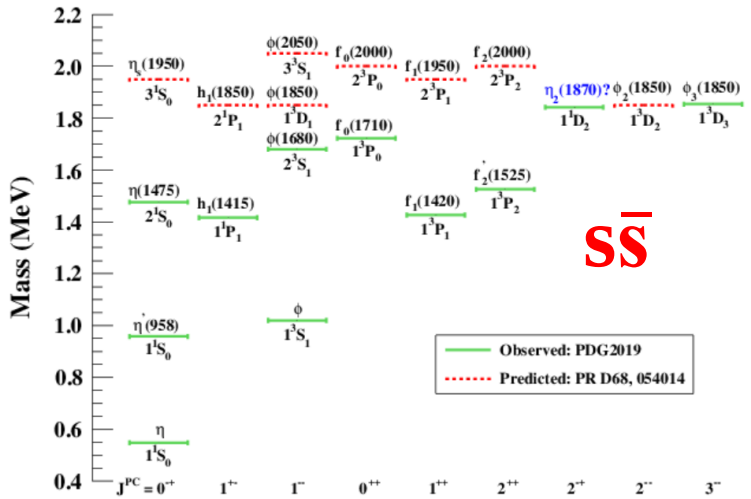
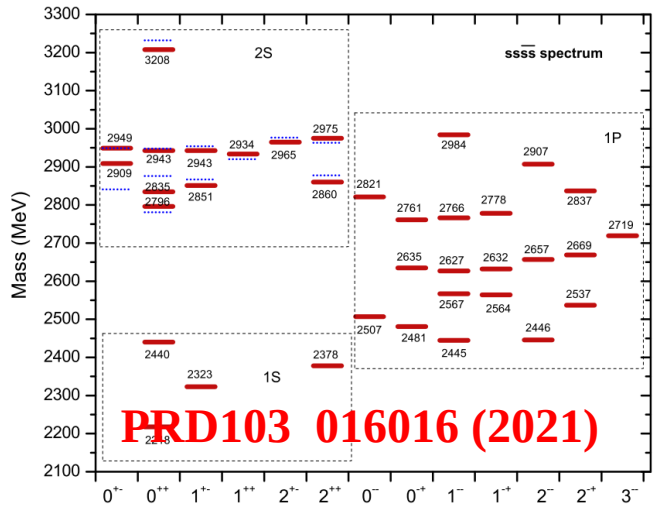
Strangeonium & strangeonium-like states @ BESIII

鄢文标 (中国科学技术大学)

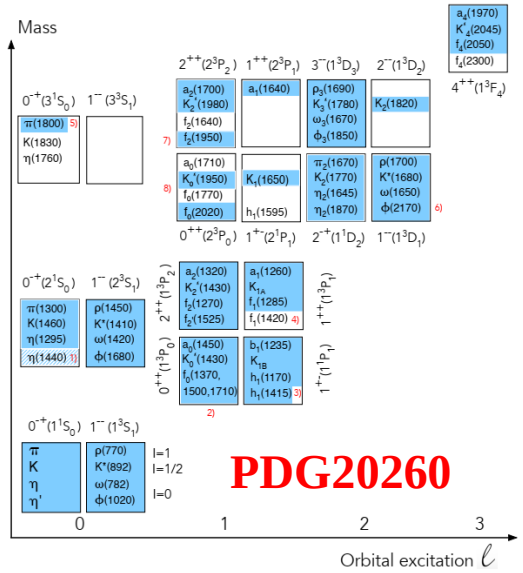


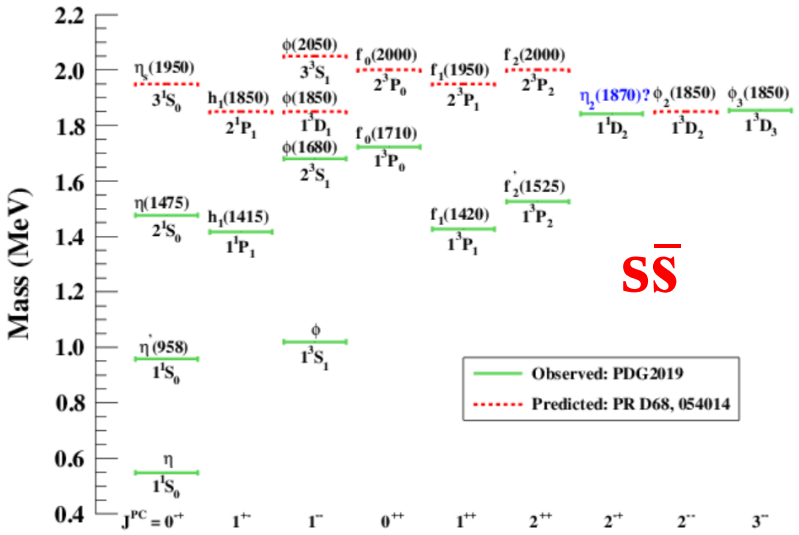


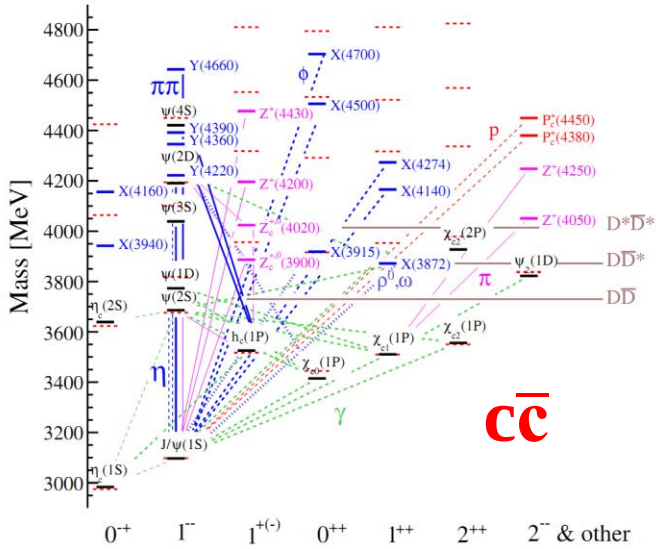


第九届强子谱和强子结构研讨会，2026.8.18，新乡

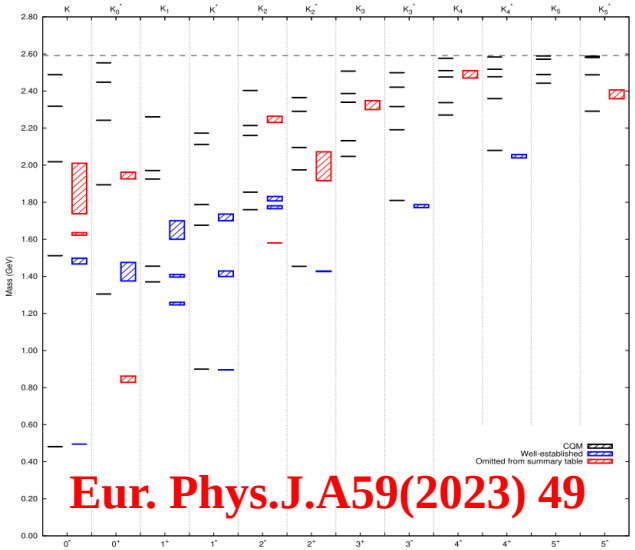
Strange quark



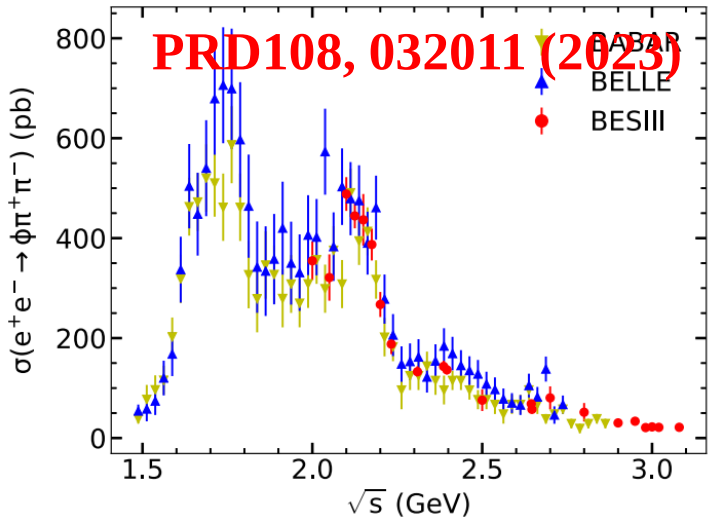




- **Light meson: u/d/s quark ⇨ $SU(3)_{flavor}$ nonets**
  - ✓ **$s\bar{s}$ is a terra incognita**
- **Exotics states with c & b quark**
  - ✓ **(light) particles with s quark ?**
- **s quark: bridge between light and heavy quark.**
- **Strangeonium & strangeonium-like: 1^{--} & 1^{+-} states**
- **Strange meson: AMBER @ CERN**



How to study $J^{PC} = 1^{--}/1^{+-}$ $s\bar{s}$ states ?

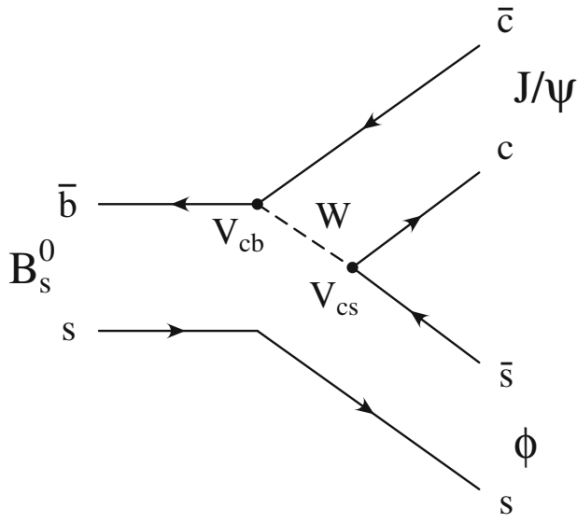


SLAC – PUB – 5081
August 1989
(N)

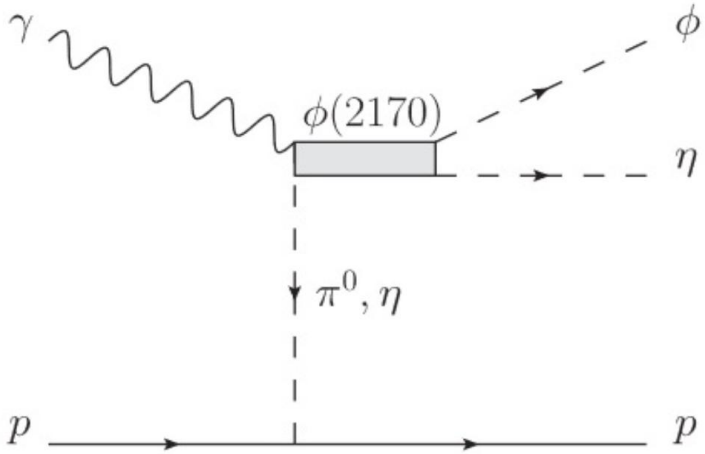
Strangeonium Spectroscopy at the J/ψ:
A Comparison with Kaon Hadroproduction*

B. N. RATCLIFF

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

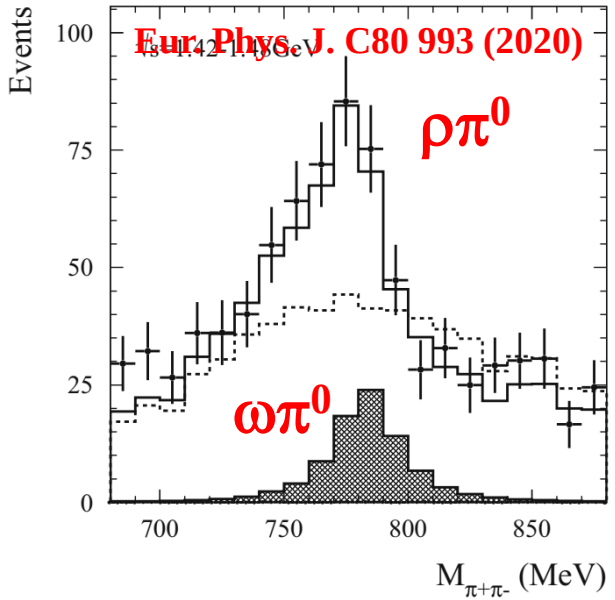


- Cross section of hadron final states @ e^+e^-
  - ✓ energy scan & ISR methods
  - ✓ only for $J^{PC} = 1^{--}$ states
- $s\bar{s}$ spectrum @ charmonium decay
  - ✓ 10B J/ψ, 3.7B ψ(3686) & 20 fb^{-1} ψ(3770)
  - ✓ J^{PC} conversion ⇨ J^{PC} filter, χ_{cJ} decay
- $s\bar{s}$ spectrum @ B decay
- $s\bar{s}$ spectrum @ γ p, K p & p $\bar{p}$ collisions



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***



ω(1420) WIDTH

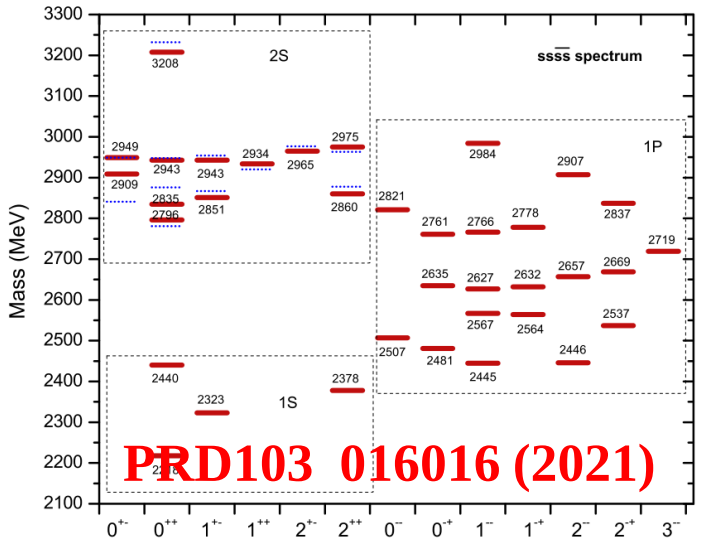
ω(1420) @ PDG2026

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
290±190 OUR ESTIMATE					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
590± 90		[1] DIMOVA	25	SND	$e^+e^- \to \pi^+\pi^-\pi^0$
590± 90		[2] ACHASOV	24A	SND	$e^+e^- \to \pi^+\pi^-\pi^0$
440±125	267	[3] ACHASOV	20B	SND	$e^+e^- \to \omega\eta \to \eta\pi^0\gamma$
104± 35± 10	824	[4] AKHMETSHIN	17A	CMD3	1.4–2.0 $e^+e^- \to \omega\eta$
880±170	13.1k	[5] AULCHENKO	15A	SND	1.05–1.80 $e^+e^- \to \pi^+\pi^-\pi^0$
480±180		[6] ACHASOV	10D	SND	1.075–2.0 $e^+e^- \to \pi^0\gamma$
130± 50±100		AUBERT	07AU	BABR	10.6 $e^+e^- \to \omega\pi^+\pi^-\gamma$
450± 70± 70		AUBERT,B	04N	BABR	10.6 $e^+e^- \to \pi^+\pi^-\pi^0\gamma$
870^{+500}_{-300} ±450	1.2M	[7] ACHASOV	03D	RVUE	0.44–2.00 $e^+e^- \to \pi^+\pi^-\pi^0$
199± 15		[8] HENNER	02	RVUE	1.2–2.0 $e^+e^- \to \rho\pi, \omega\pi\pi$
188± 45	177	[9] AKHMETSHIN	00D	CMD2	1.2–1.38 $e^+e^- \to \omega\pi^+\pi^-$
360^{+100}_{-60}	5095	ANISOVICH	00H	SPEC	0.0 $p\overline{p} \to \omega\pi^0\pi^0\pi^0$
240± 70		[10] CLEGG	94	RVUE	
174± 59	315	[11] ANTONELLI	92	DM2	1.34–2.4 $e^+e^- \to \rho\pi$

JETP 121 27 (2015)

	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

Key points for 1^{--} strangeonium-like states



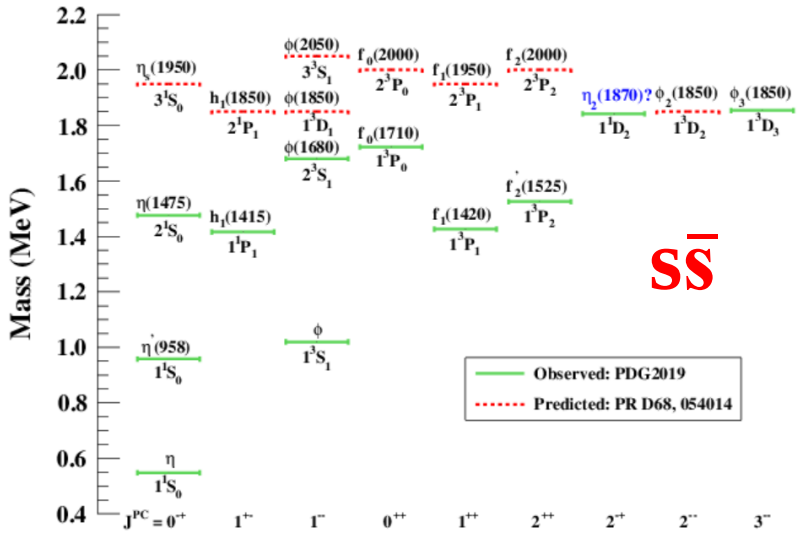
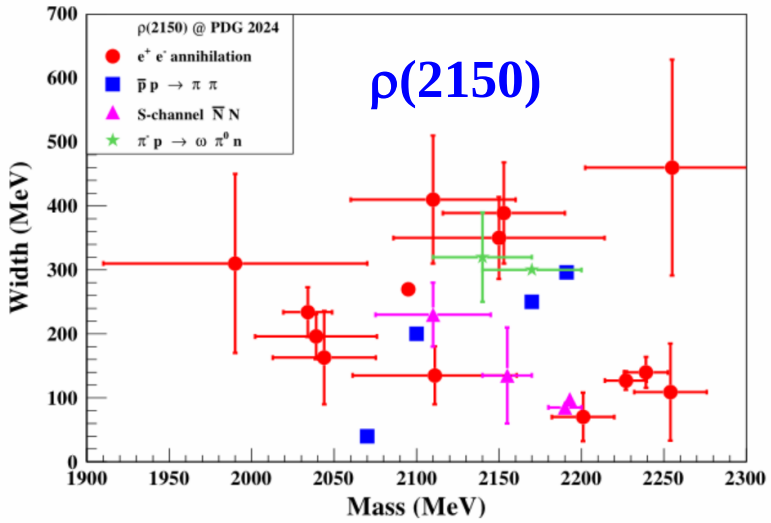


TABLE XII. Decay amplitudes squared (excluding the decay strength constants).

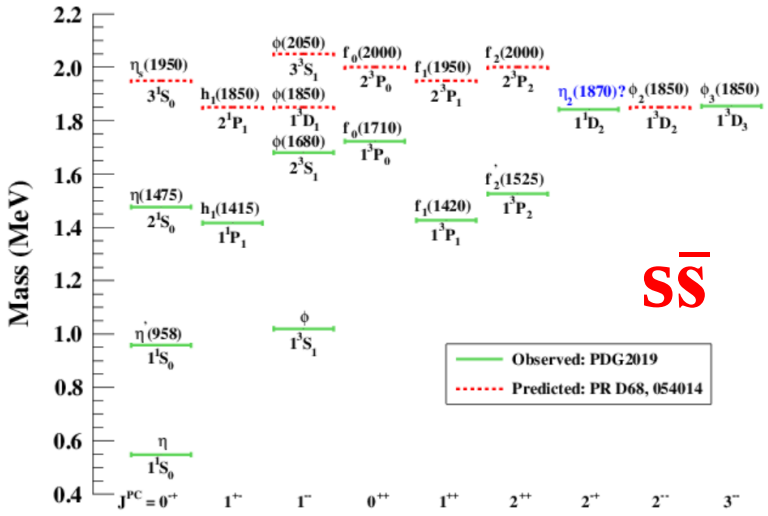
Decay	Products	Squared amplitude
$\rho^* \to PP$	$K\bar{K}$	4
	$\pi\pi$	8
$\rho^* \to VP$	$K^*\bar{K}$	2
	$\rho\eta$	$2\cos^2\phi_P$
	$\rho\eta'$	$2\sin^2\phi_P$
	$\omega\pi$	$2\sin^2\phi_V$
	$\phi\pi$	$2\cos^2\phi_V$
$\omega^* \to PP$	$K\bar{K}$	$12\sin^2\theta_V^*$
$\omega^* \to VP$	$\phi\eta$	$2(\sqrt{2}\cos\phi_V^*\sin\phi_V\sin\phi_P + \sin\phi_V^*\cos\phi_V\cos\phi_P)^2$
	$\phi\eta'$	$2(\sqrt{2}\cos\phi_V^*\sin\phi_V\cos\phi_P - \sin\phi_V^*\cos\phi_V\sin\phi_P)^2$
	$\omega\eta$	$2(\sqrt{2}\cos\phi_V^*\cos\phi_V\sin\phi_P - \sin\phi_V^*\sin\phi_V\cos\phi_P)^2$
	$\omega\eta'$	$2(\sqrt{2}\cos\phi_V^*\cos\phi_V\cos\phi_P + \sin\phi_V^*\sin\phi_V\sin\phi_P)^2$
	$\rho\pi$	$6\sin^2\phi_V^*$
	$K^*\bar{K}$	$2(\sin\phi_V^* + \sqrt{2}\cos\phi_V^*)^2$
$\phi^* \to PP$	$K\bar{K}$	$12\cos^2\theta_V^*$
$\phi^* \to VP$	$\phi\eta$	$2(-\sqrt{2}\sin\phi_V^*\sin\phi_V\sin\phi_P + \cos\phi_V^*\cos\phi_V\cos\phi_P)^2$
	$\phi\eta'$	$2(\sqrt{2}\sin\phi_V^*\sin\phi_V\cos\phi_P + \cos\phi_V^*\cos\phi_V\sin\phi_P)^2$
	$\omega\eta$	$2(\sqrt{2}\sin\phi_V^*\cos\phi_V\sin\phi_P + \cos\phi_V^*\sin\phi_V\cos\phi_P)^2$
	$\omega\eta^*$	$2(-\sqrt{2}\sin\phi_V^*\cos\phi_V\cos\phi_P + \cos\phi_V^*\sin\phi_V\sin\phi_P)^2$
	$\rho\pi$	$6\cos^2\phi_V^*$
	$K^*\bar{K}$	$2(\cos\phi_V^* - \sqrt{2}\sin\phi_V^*)^2$

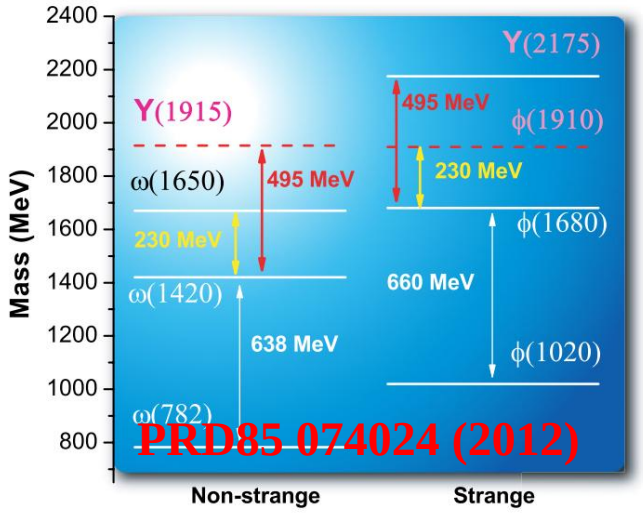
PRD79 014036 (2009)

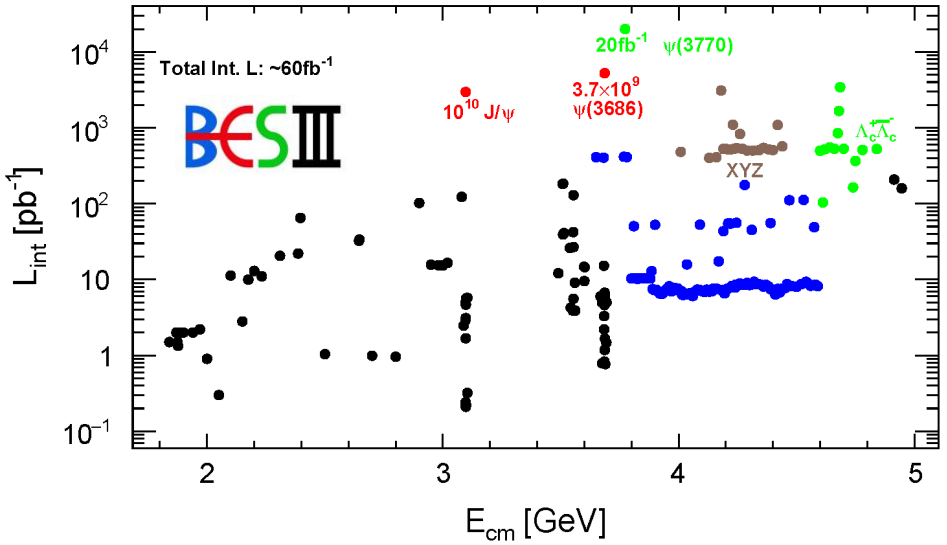
- **Theory prediction on exotic states with strange quark**
- **Better understanding $s\bar{s}$ spectrum ?**
  - ✓ **unobserved 1^{--} $s\bar{s}$ mesons**
- **OZI rule and isospin**
  - ✓ **contribution of $\rho^*/\omega^*/\phi^*$**
- **ρ^*/ω^* @ [2-3] GeV: "omitted from summary table" or "further states"**



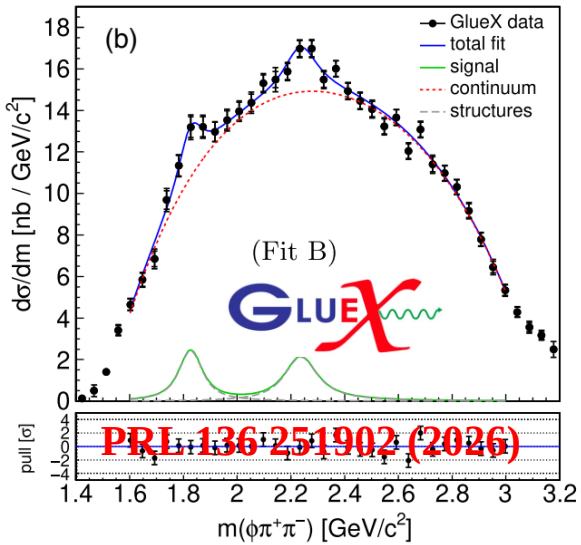
Vector states



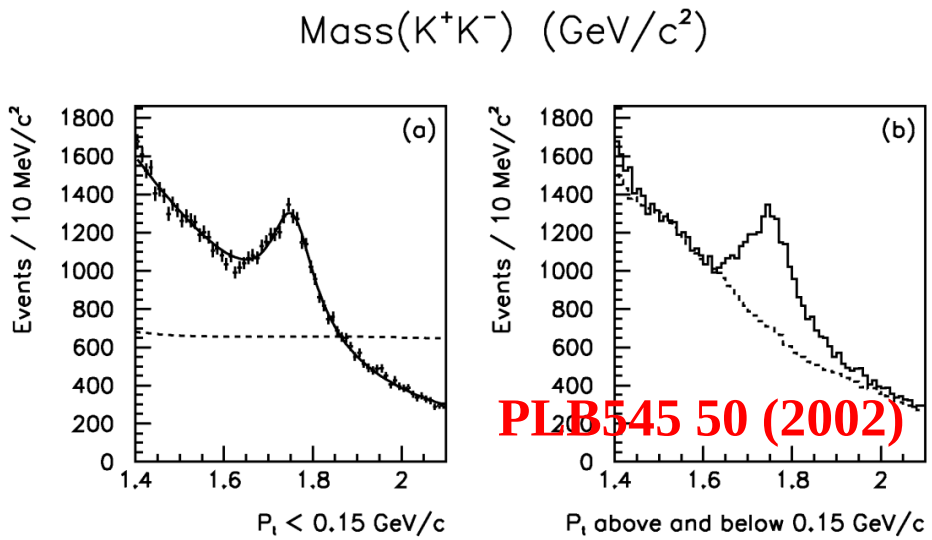




- 2^3S_1 **φ(1680) vs. X(1750): e^+e^- & photoproduction**
- **$J^{PC} = 1^-$ states: missing 1D, 2D, 3S & 3D**
  - ✓ **φ(2170)/Y(2175) @ experiment**
- **BESIII data samples**
  - ✓ **J/ψ, ψ(3686) and ψ(3770) data: strong decay & ISR**
  - ✓ **2015 R scan data @ [2.00, 3.08] GeV: energy scan**
  - ✓ **scan data @ [1.84, 2.00] GeV: energy scan**



2^3S_1 $\phi(1680)$ vs. X(1750)



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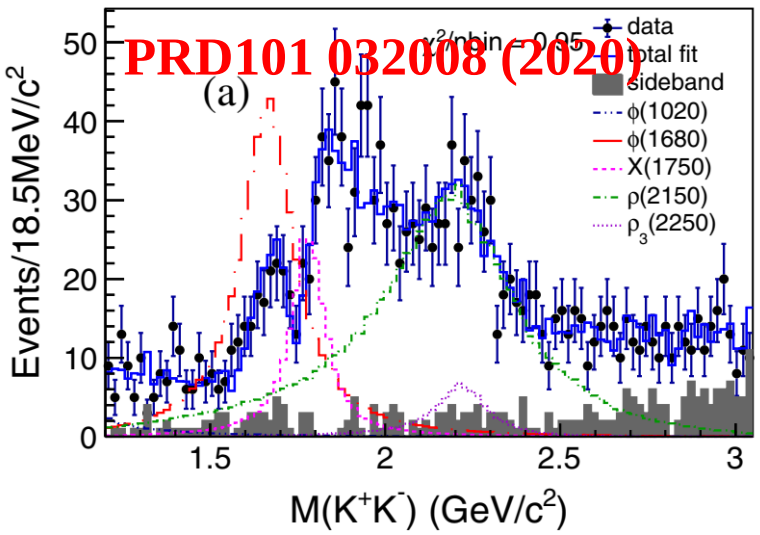
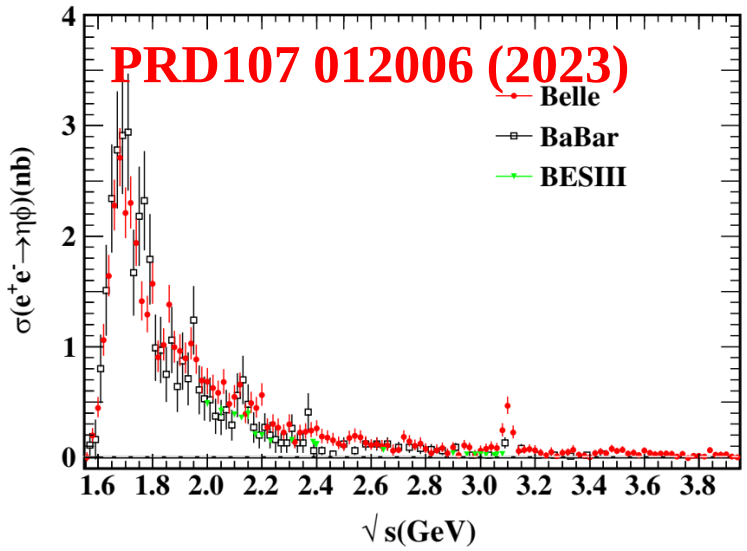
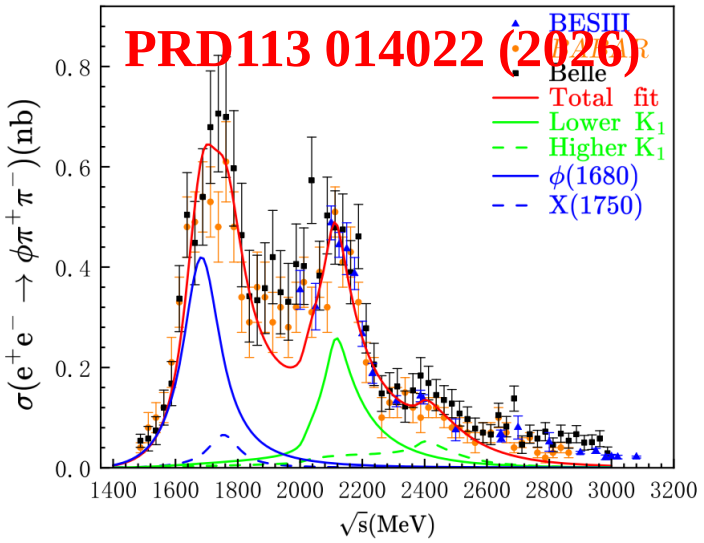
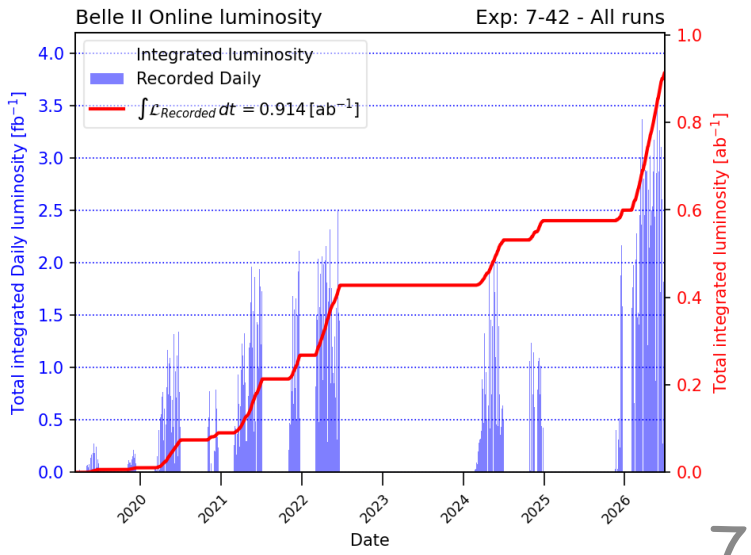


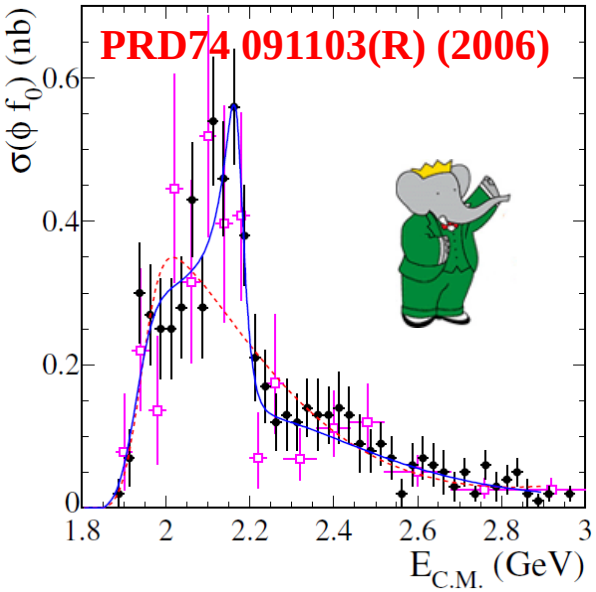


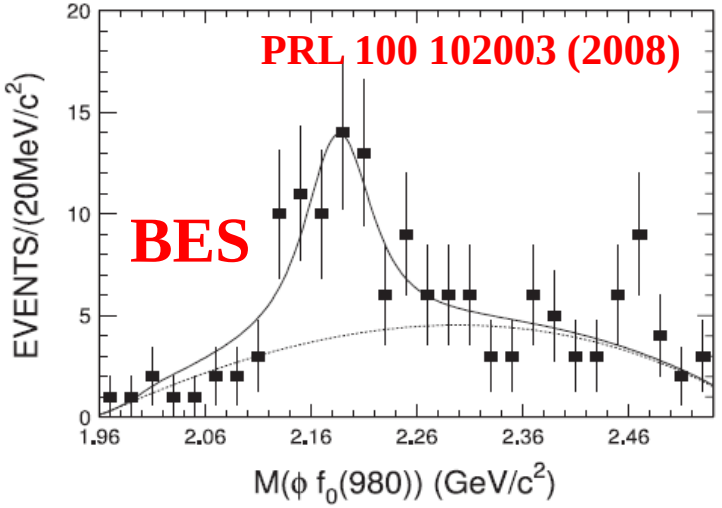
- $\phi(1680)$ vs. X(1750):
  - ✓ e^+e^- & photoproduction
- BESIII: $\psi(3686) \rightarrow K^+ K^- \eta$
- Two particles since PDG2022
  - ✓ nature of X(1750) ?
- K^+K^-: iso-scalar & iso-vector
- How about $\phi\eta/\phi\pi^+\pi^-$ mode ?

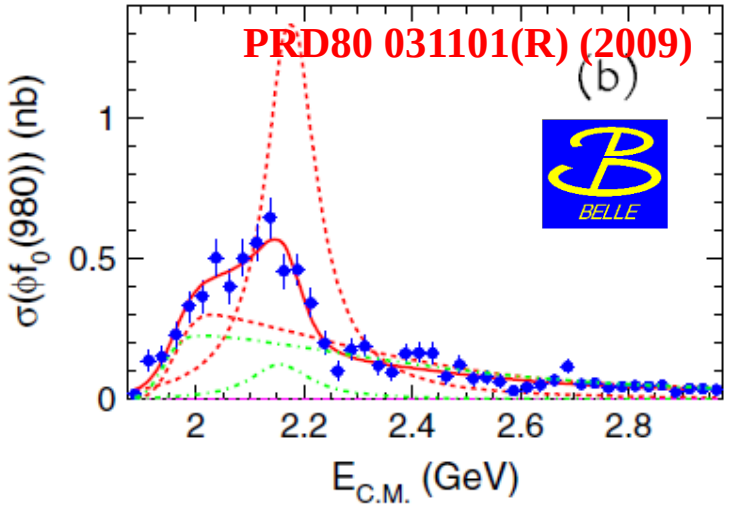




$J^{PC} = 1^{--}$ $\phi(2170)$/Y(2175)

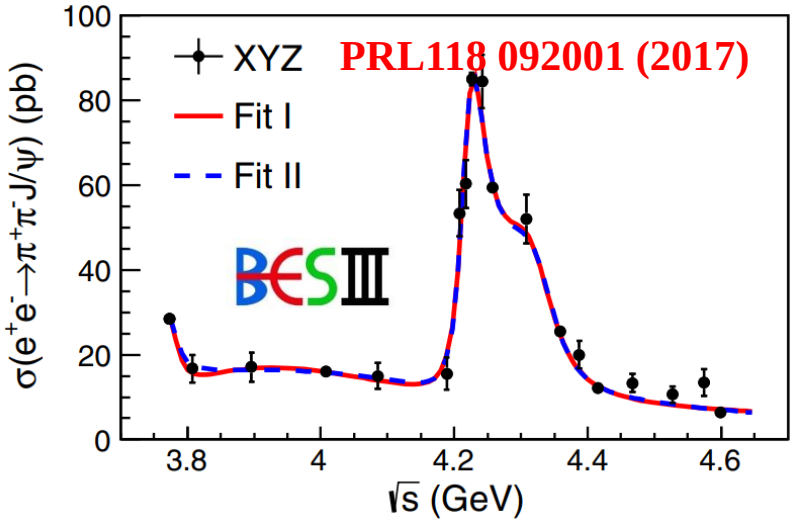






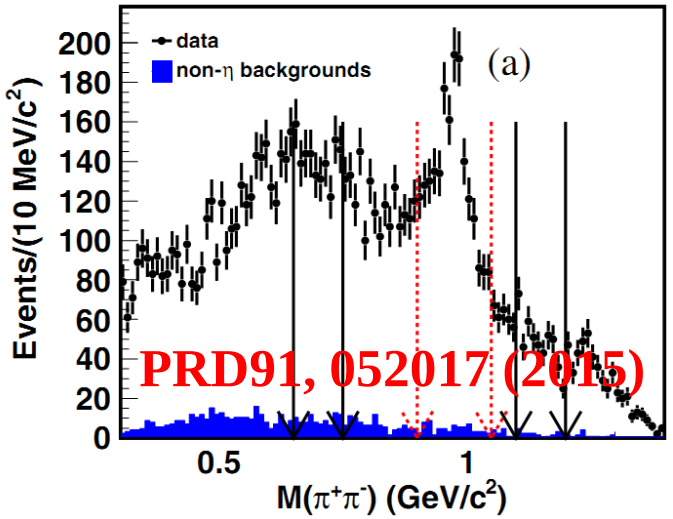
Eur. Phys. J. C72 2008 (2012)

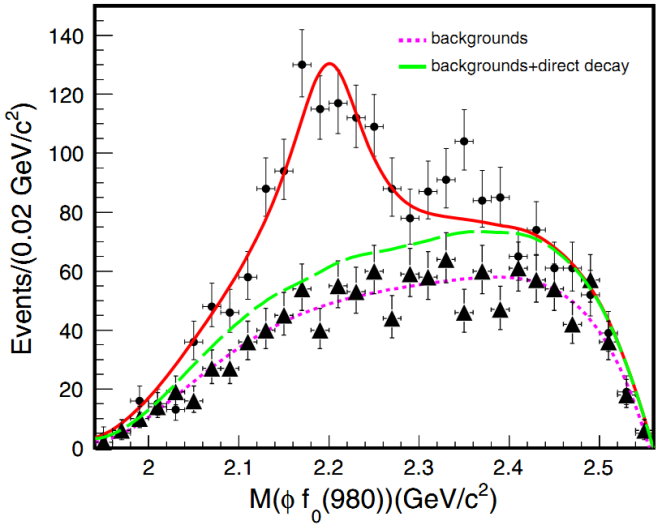
$$e^+e^- \Rightarrow \begin{cases} Y(2175) \to \phi(1020)\pi^+\pi^- & \text{strange,} \\ Y(4260) \to J/\psi\pi^+\pi^- & \text{charm,} \\ \Upsilon(10860) \to \Upsilon(1S,2S)\pi^+\pi^- & \text{bottom,} \end{cases}$$

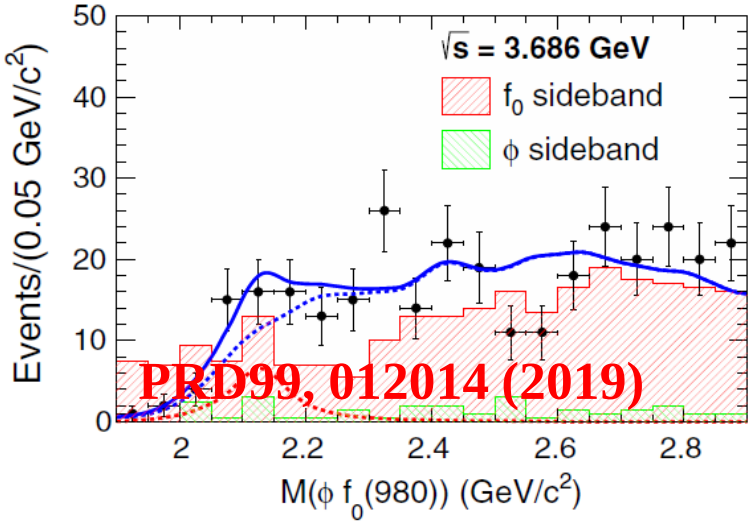


$\phi(2170)$ as strange analogue of Y(4230)

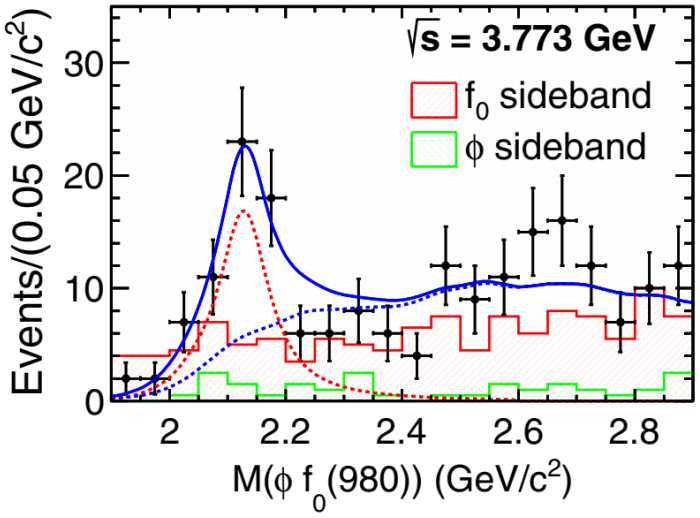
ϕ(2170) @ charmonium decay



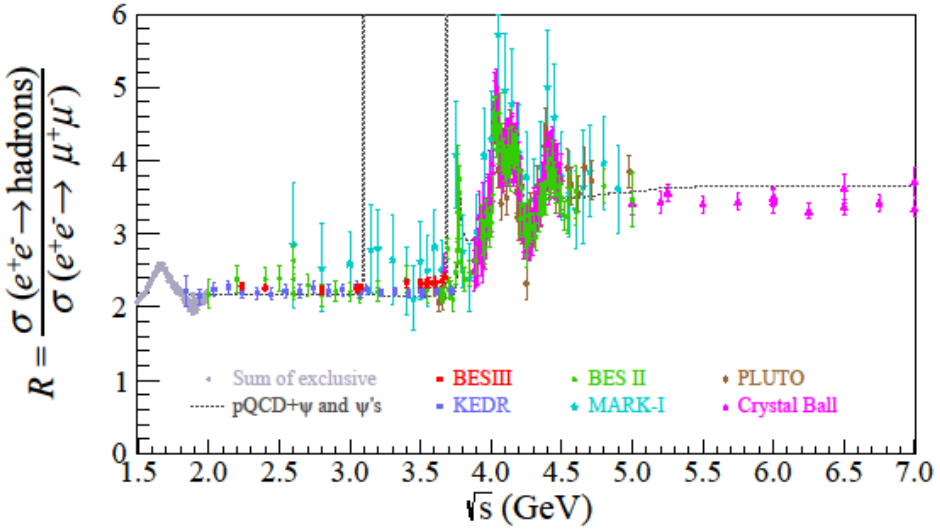




- J/ψ, ψ(3686), ψ(3770) → η ϕ π^+ π^-
- ϕ(2170) @ invariant mass of ϕ $f_0(980)$
- Br of e^+ e^- → η ϕ(2170) $f_0(980)$ → η ϕ π^+ π^-
- Br[ψ(3686)→ ηϕ(2170)] < $2.2*10^{-6}$ @ 90% U.L.
  - ✓ suppression for "12% rule"
- No significant signal e^+e^- → η'ϕ(2170)
  - ✓ $\frac{\sigma[e^+e^- \to \eta'\phi(2170)]}{\sigma[e^+e^- \to \eta\phi(2170)]}$ < 0.43 @ 90% U.L.



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



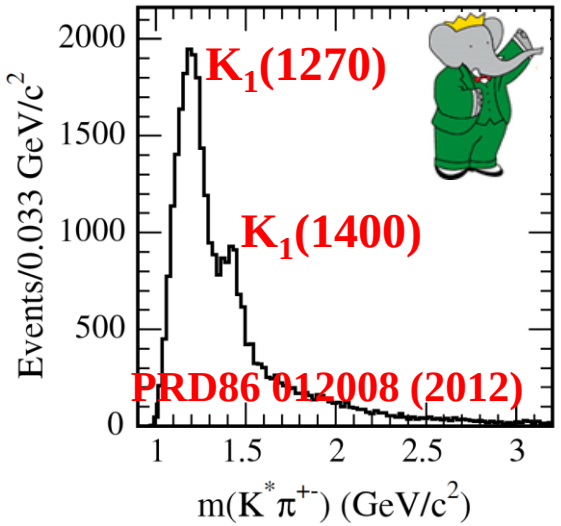


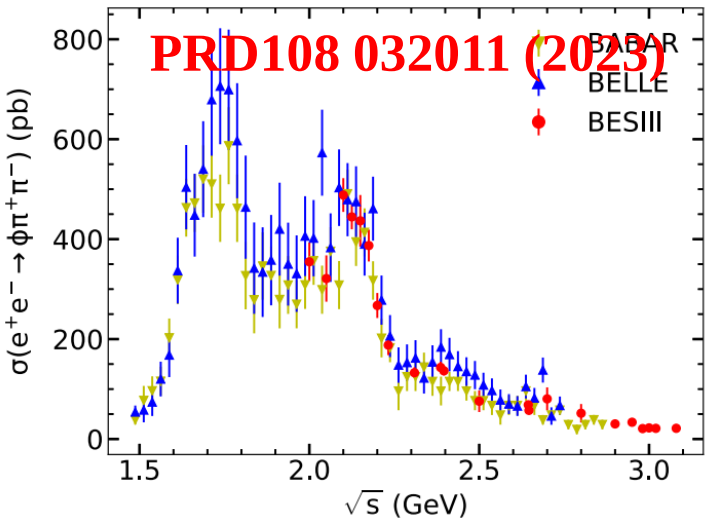
TABLE IV. $3S\ s\bar{s}$.

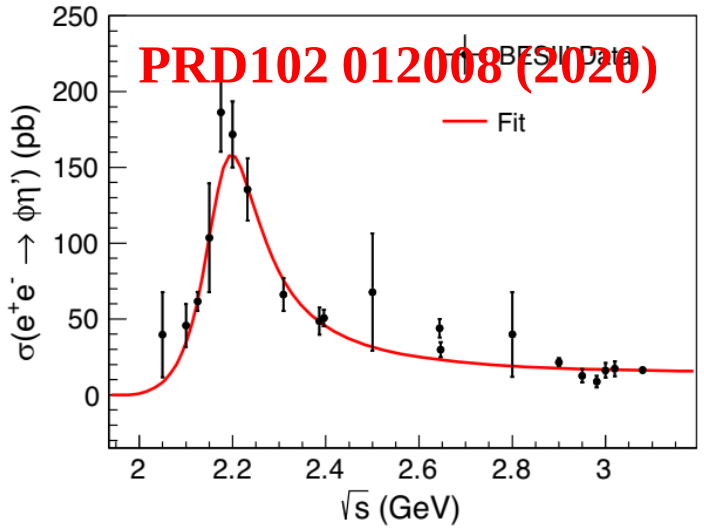
Mode	$\phi(2050)$ Γ_i (MeV)	$\phi(2050)$ Amps.	$\eta_s(1950)$ Γ_i (MeV)	$\eta_s(1950)$ Amps.
KK	0	$^1P_1 = +0.0029$		
KK^*	20	$^3P_1 = -0.047$	53	$^3P_0 = +0.081$
K^*K^*	102	$^1P_1 = -0.039$ $^5P_1 = +0.17$	67	$^3P_0 = -0.17$
$KK_1(1273)$	58	$^3S_1 \equiv 0$ $^3D_1 = -0.10$		
$KK_1(1402)$	26	$^3S_1 = +0.083$ $^3D_1 \equiv 0$		
$KK_0^*(1412)$			30	$^1S_0 = -0.13$
$KK_2^*(1429)$	9	$^5D_1 = +0.053$	0	$^5D_0 = -0.016$
$KK^*(1414)$	93	$^3P_1 = -0.16$	25	$^3P_0 = +0.12$
$KK(1460)$	29	$^1P_1 = -0.10$		
$\eta\phi$	21	$^3P_1 = +0.10$		
$\eta'\phi$	11	$^3P_1 = -0.11$		
$\eta h_1(1386)$	8	$^3S_1 = -0.078$ $^3D_1 = -0.060$		
	$\Gamma_{thy} = 378$ MeV		$\Gamma_{thy} = 175$ MeV	

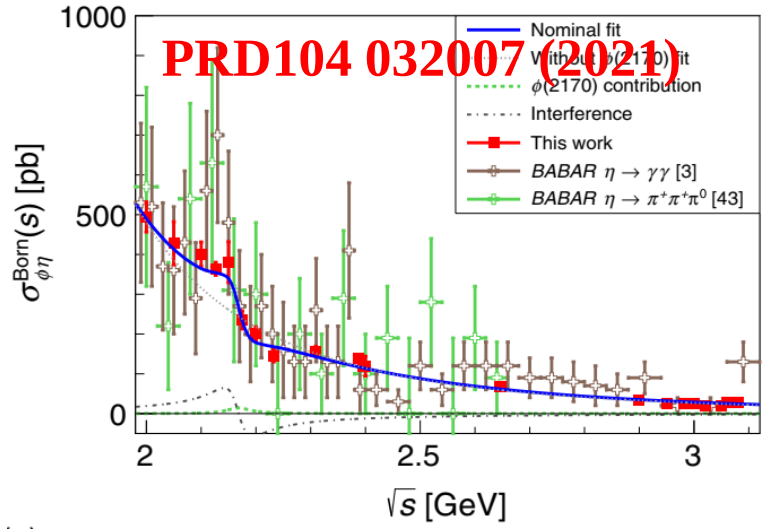
PRD68 054014 (2003)

- Energy scan: BESIII R scan @ [2.00, 3.08] GeV
- Two-body decay @ theory prediction
  - ✓ PWA @ multi-body decay
- OZI & isospin favored: $\phi\eta$, $\phi\eta'$, $\phi f_0(980)$ and so on
- KK, K*K and K*K* ⇐ ρ^*/ω^* contribution
- OZI & isospin un-favored: $\rho\pi^0$, $\omega\pi^0$ and so on

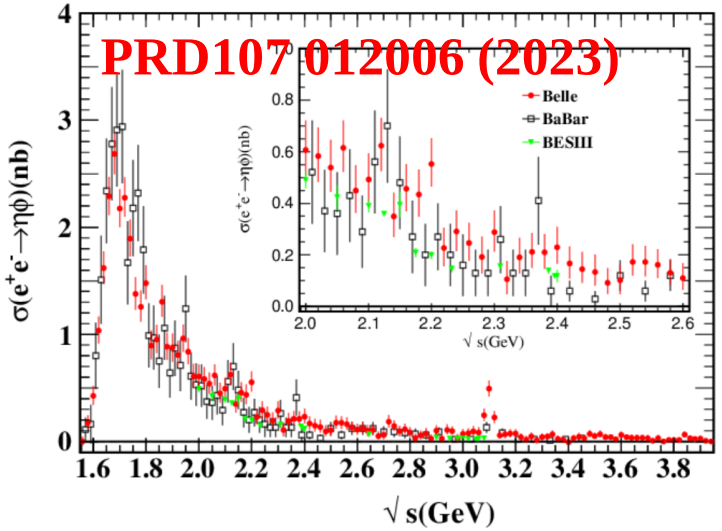
$e^+ e^- \to \phi\eta'$, $\phi\eta$ and $\phi \pi^+ \pi^-$

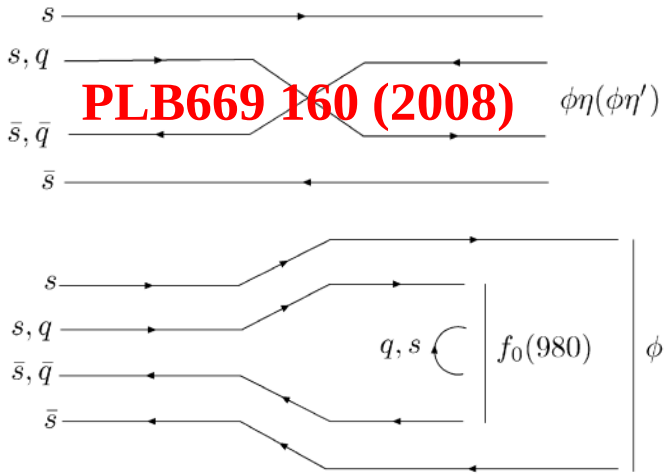




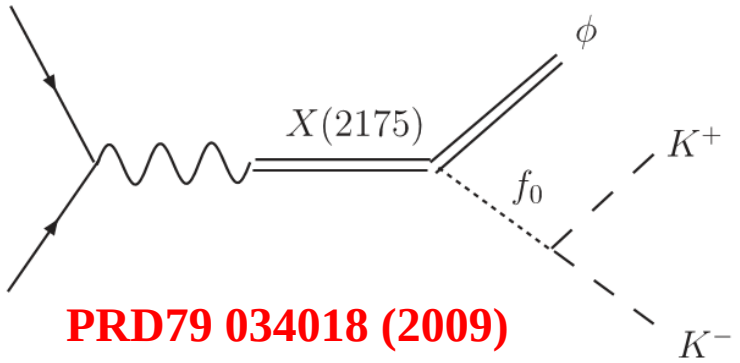


- visible $\phi(2170)$ @ $\phi\pi^+\pi^-$ mode
- $\phi\eta$ and $\phi\eta'$ modes: isoscalar
  - ✓ ϕ^* and ω^* (OZI suppressed)
- $\phi(2170)$ @ $\phi\eta$: tail from $\phi(1680)$
  - ✓ reliable $\phi(1680)$ information ?
  - ✓ BESIII vs. Belle @ 2.15 GeV
- tetraquark favorites $\phi\eta$ and $\phi\eta'$

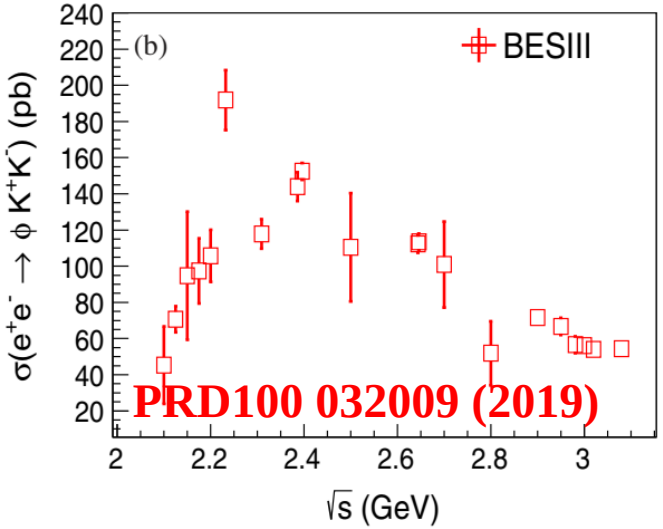




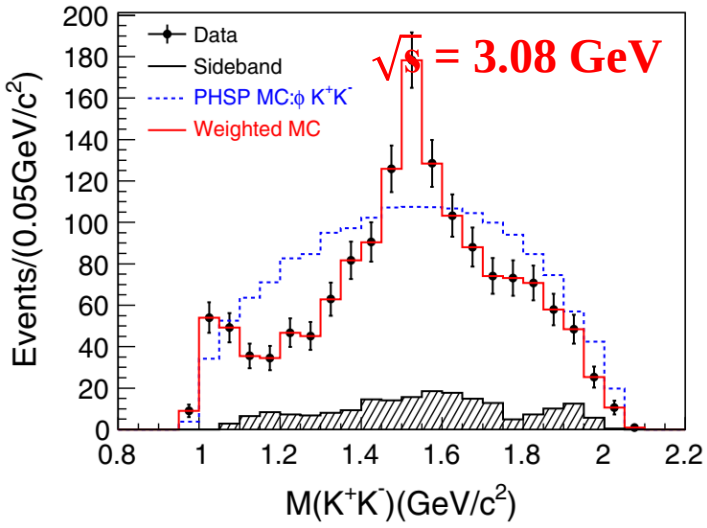
$e^+ e^- \to \phi K^+ K^-$, $K^+ K^-$ and $K_S K_L$



PRD79 034018 (2009)



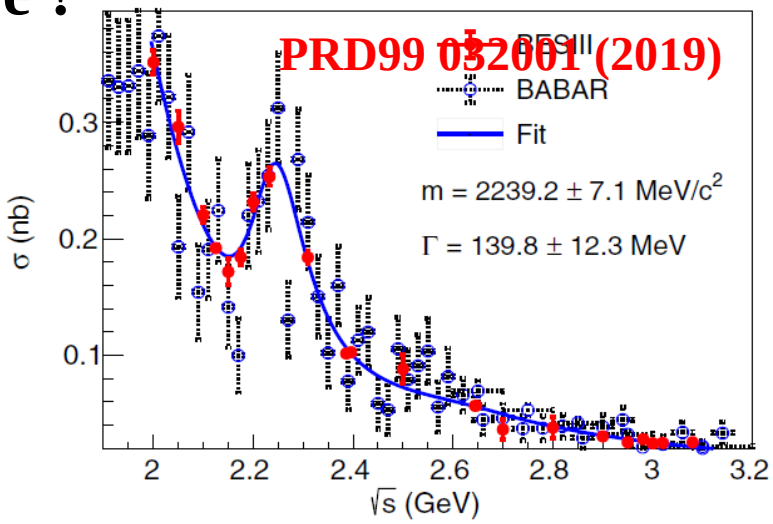
PRD100 032009 (2019)



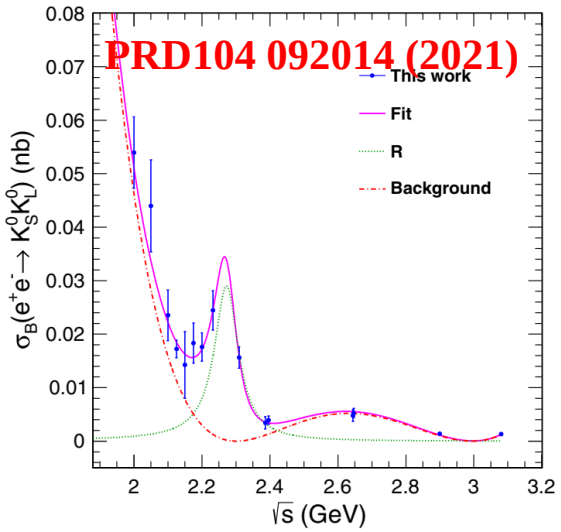
- $\phi(2170)$: resonant of ϕKK
- ϕK^+K^- @ BESIII: a narrow structure ?
  - ✓ dominant $f_2'(1525)$ @ 3.08 GeV
- $\phi(2170)$: molecular state $\Lambda\bar{\Lambda}$
  - ✓ KK: iso-vector & iso-scalar

$\phi(2170)$ 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)

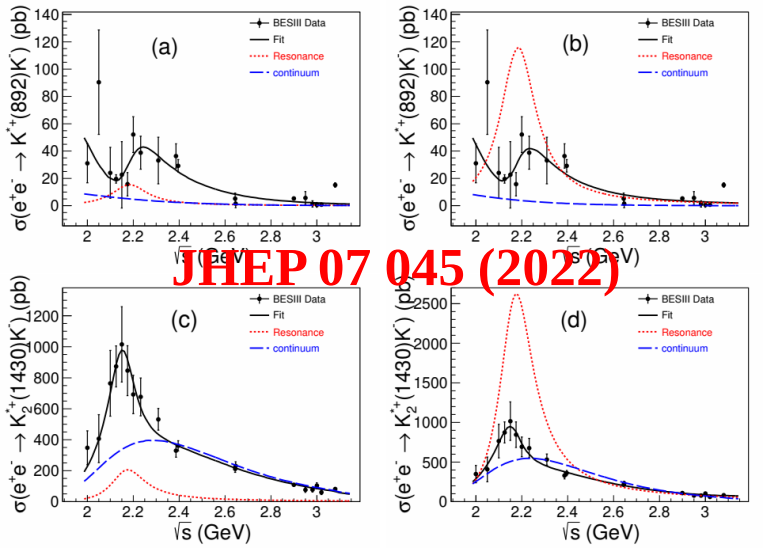


PRD99 032001 (2019)

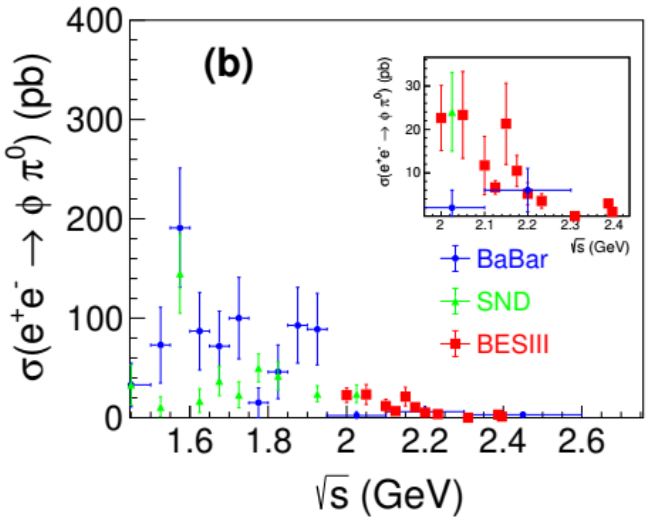


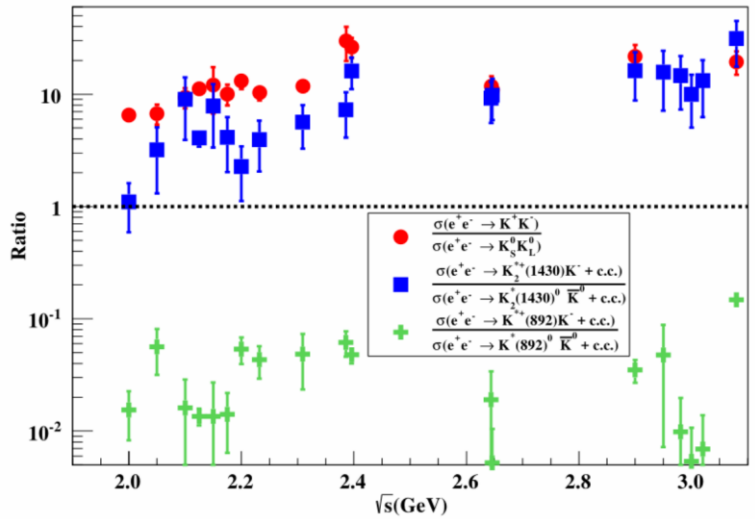
PRD104 092014 (2021)

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

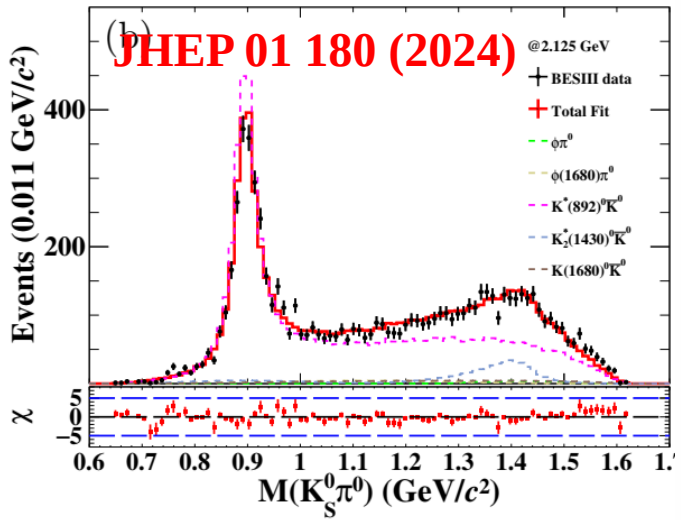


JHEP 07 045 (2022)

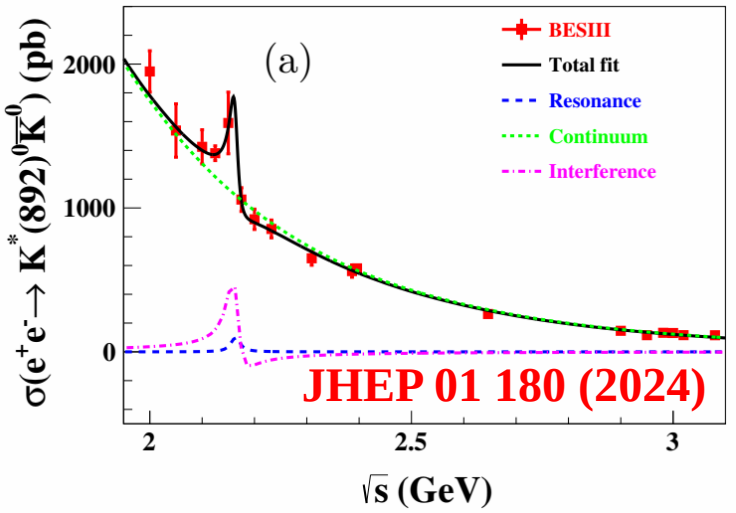




- $K^+K^-\pi^0$ mode
  - ✓ Dominant charged $K_2^*(1430)K$
  - ✓ $\phi\pi^0$: OZI-suppressed ρ^* & isospin-violated ω/ϕ^*
- $K_S^0 K_L^0 \pi^0$ mode
  - ✓ Dominant neutral $K^*(892)^0\bar{K}^0$
- charged vs. neutral K*K mode
  - ✓ isospin symmetry violation



JHEP 01 180 (2024)



JHEP 01 180 (2024)

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

- $e^+e^- \to K\,K\,\pi\,\pi$: 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)

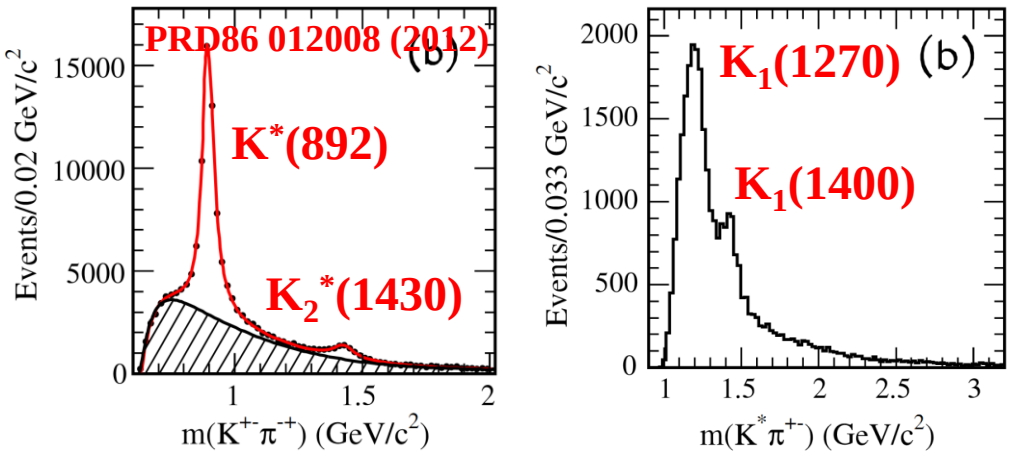
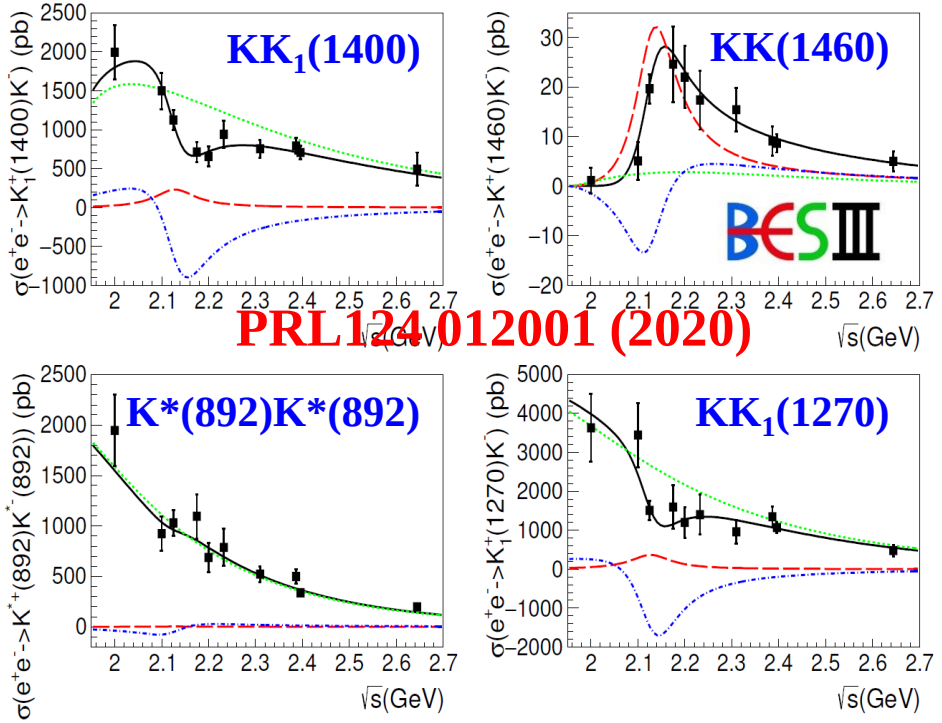


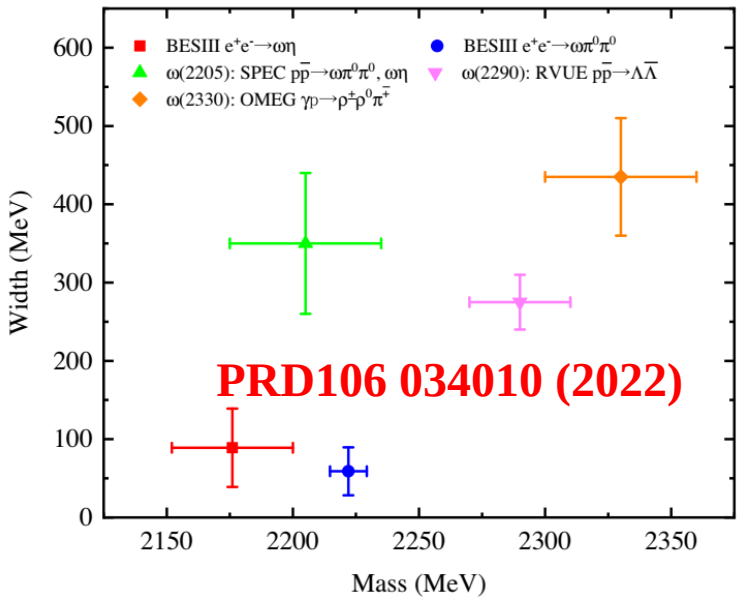
Table 22: Fitting parameters.

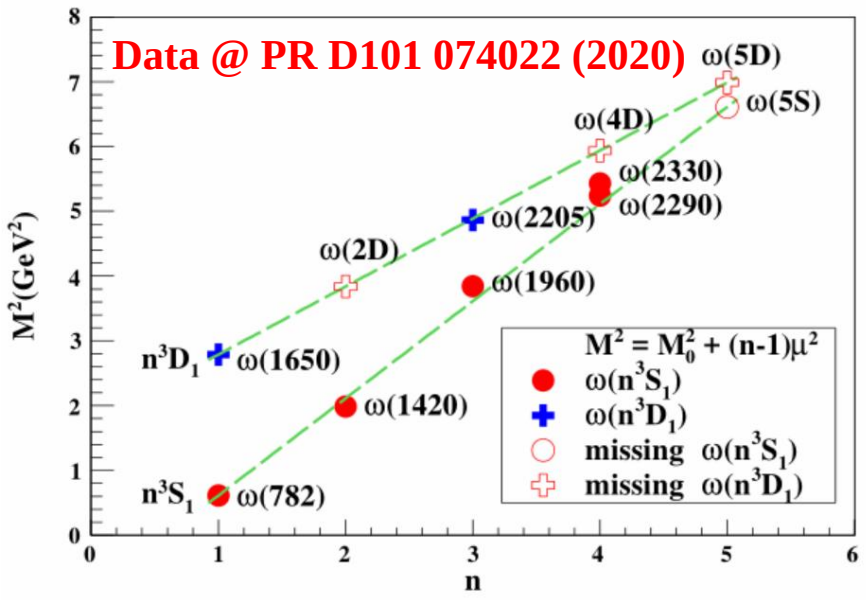
channel	$e^+e^- \to K_1^+(1400)K^-$		$e^+e^- \to K^+(1460)K^-$	$e^+e^- \to K_1^+(1270)K^-$		$e^+e^- \to K^{*+}K^{*-}$
Mass (MeV/c^2)	2126.5 ± 16.8					
Width (MeV)	106.9 ± 32.1					
	Solution1	Solution2		Solution1	Solution2	
$\mathcal{B}_R\Gamma^{e^+e^-}$ (eV)	7.6 ± 3.7	152.6 ± 14.2	1.0 ± 1.3	4.7 ± 3.3	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

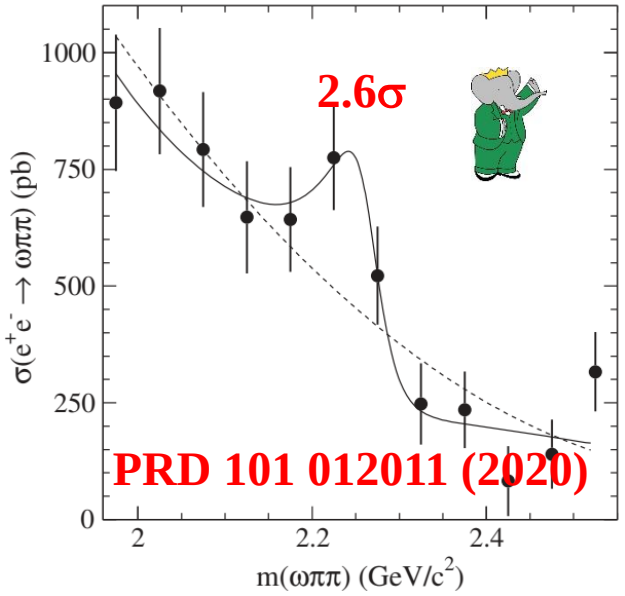


- reduction to Absurdity
  - ✓ 3^3S_1 $s\bar{s}$: $\Gamma_{K^*K^*} > \Gamma_{KK1(1400)}$
  - ✓ Exp. $\phi(2170)$ @ $KK_1(1400)$
  - ✓ Exp. no $\phi(2170)$ @ K^*K^*
  - ✓ Exp. similar ε_{eff}
  - ✓ $\phi(2170)$ as pure 3^3S_1 $s\bar{s}$?

ω* spectrum





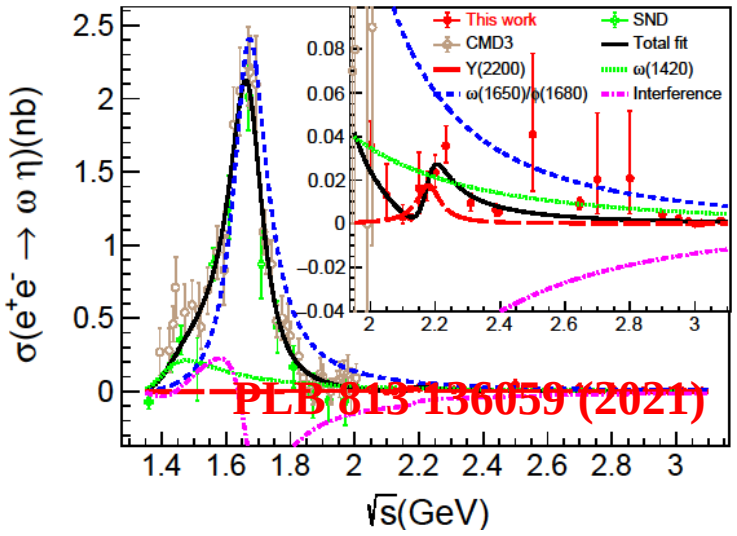


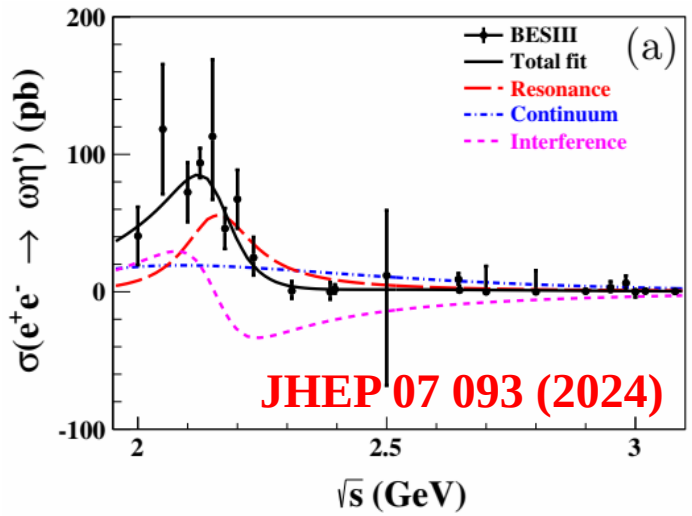
- ω* vector states
  - ✓ ω(2205): possible 3D/4S, further states
  - ✓ ω(2290): possible 4S, further states
  - ✓ ω(2330): possible 4S, further states
- ω* @ e^+ e^- collision ?
- ω*: theory vs. experiment

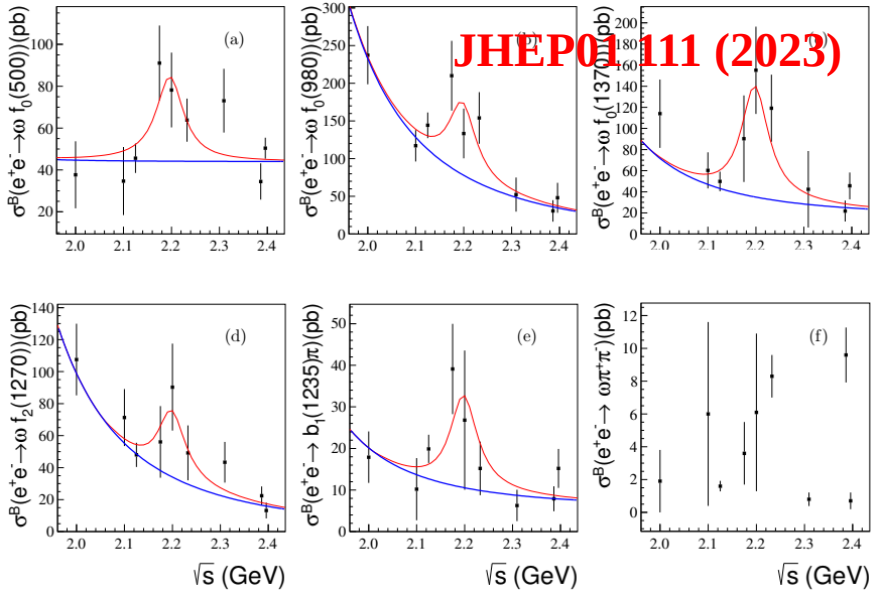
PRD 104 054027 (2020)

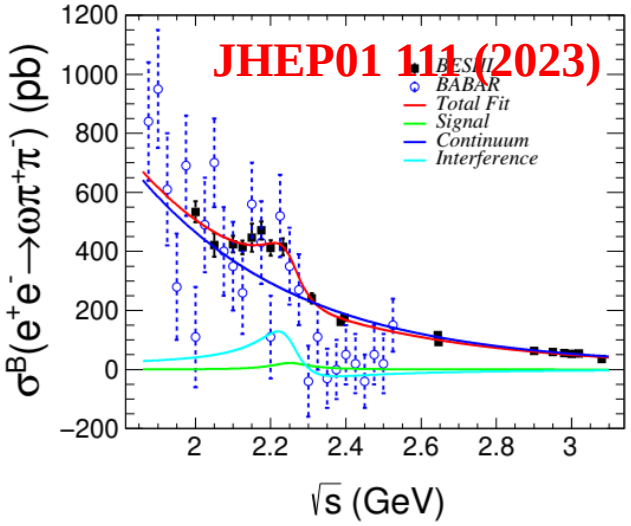
Mode	ω(2205) Width (MeV)	ω(2290) Width (MeV)
$b_1(1235)\pi$	24	35
$\rho(1450)\pi$	30	26
$\rho\pi$	4	16
$\omega\eta'$	0.4	0.4
$\omega\eta$	0	0.1
Total	141	138
Experiment	350±90 (SPEC 02)	275±35

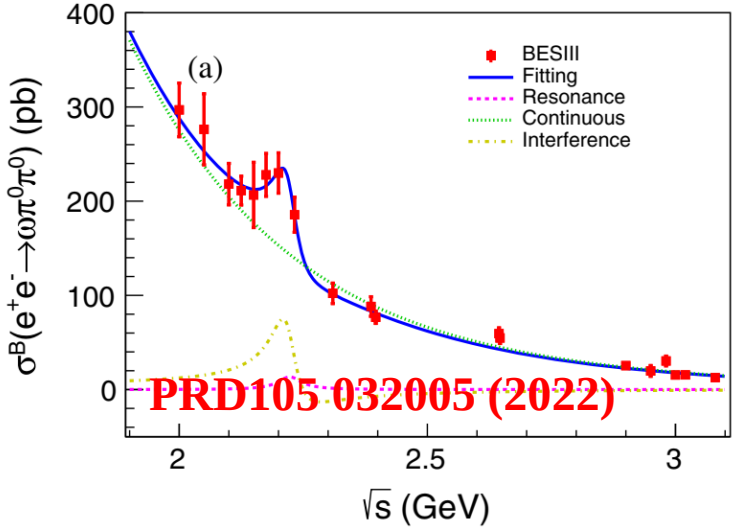
$e^+ e^- \to \omega\eta, \omega\eta', \omega\pi^+\pi^-$ & $\omega\pi^0\pi^0$









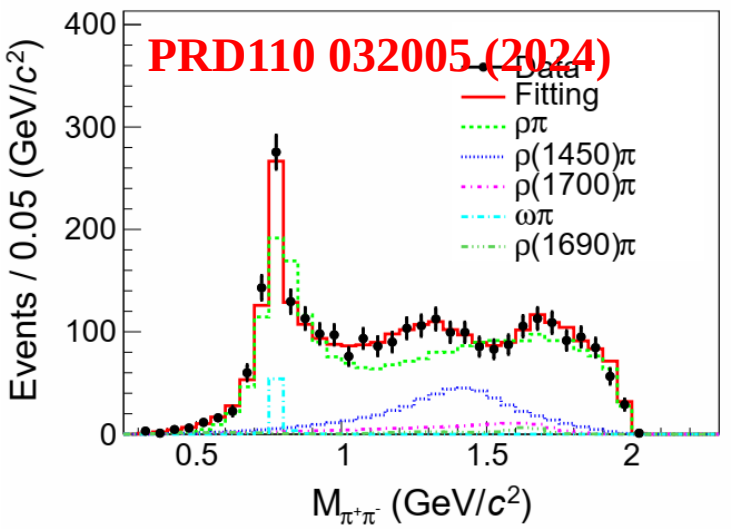


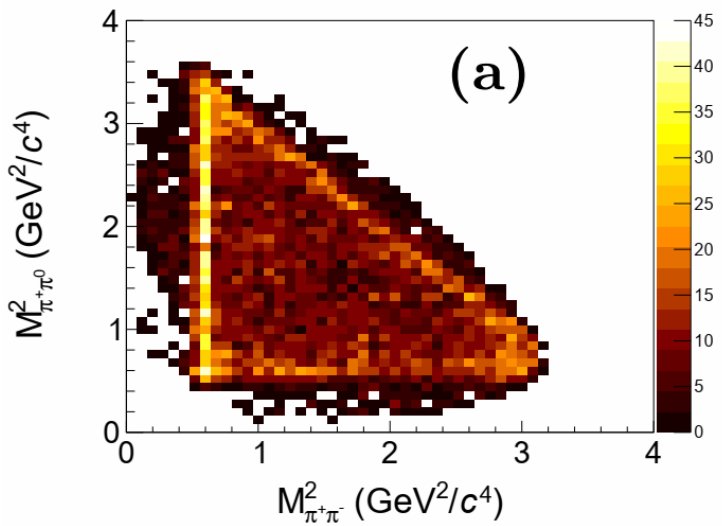
PDG2026 **ω(2220) WIDTH**

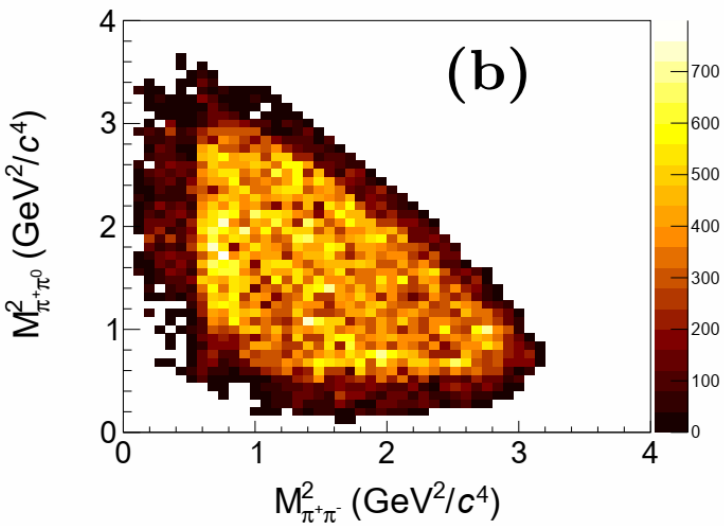
VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
105±34 OUR AVERAGE				
167±77± 7	[1] ABLIKIM	24AJ	BES3	$e^+e^- \to \omega\eta'$
93±53±20	[2] ABLIKIM	23G	BES3	2.0–3.1 $e^+e^- \to \omega\pi\pi$
89±50± 5	[3] ABLIKIM	21A	BES3	$e^+e^- \to \omega\eta$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
125±43±15	[4] ABLIKIM	23G	BES3	2.0–3.1 $e^+e^- \to \omega\pi^+\pi^-$
59±30± 6	[5] ABLIKIM	22I	BES3	2.0–3.8 $e^+e^- \to \omega\pi^0\pi^0$
350±90	[6] ANISOVICH	02B	SPEC	0.6–1.9 $p\bar{p} \to \omega\eta, \omega\pi^0\pi^0$

- **ω(2220) width: ~100 MeV**

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

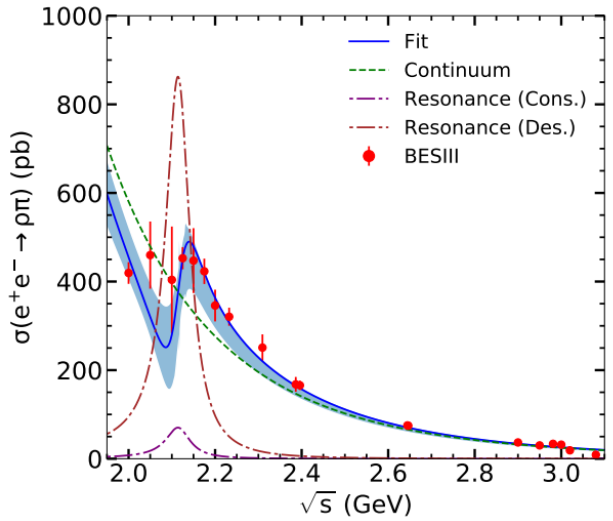


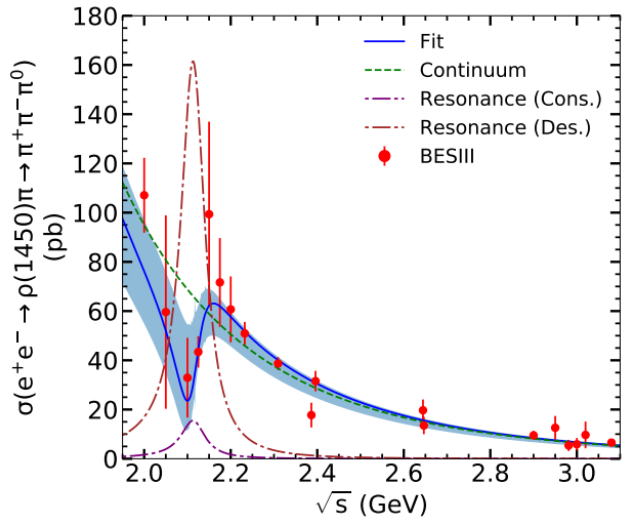




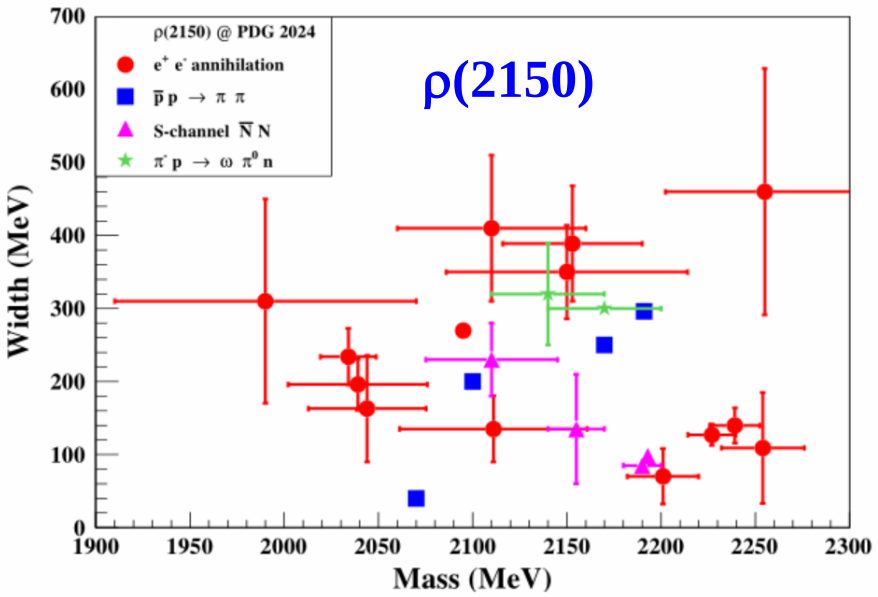
- **Dominant $\rho^0\pi^0$, visible $\rho(1450)\pi^0$ & $\omega\pi^0$**
- **PHOKHARA MC fails @ $\sqrt{s} \geq 2.0$ GeV**

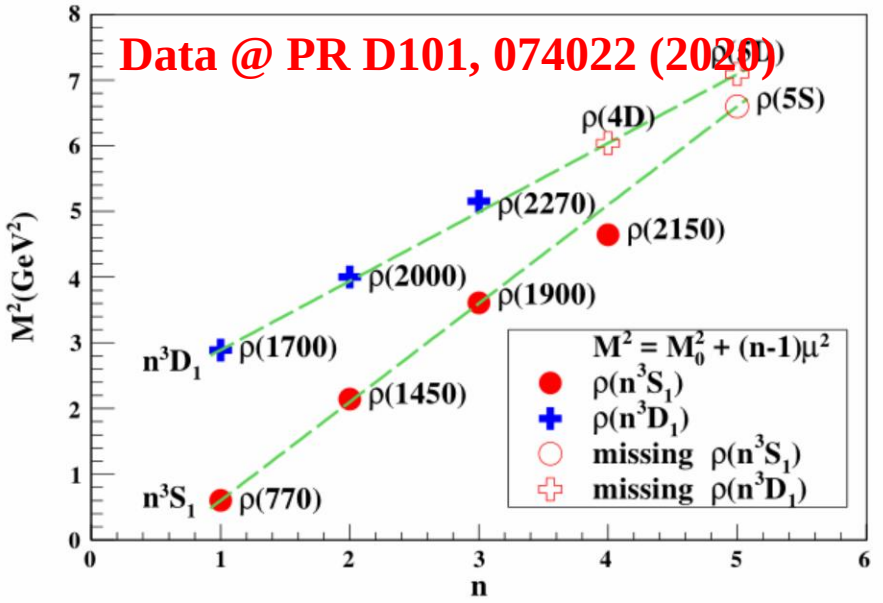
	Nominal fit	Alternative fit
Mass	2119 ± 11 MeV/c^2	2134 ± 14 MeV/c^2
Width	69 ± 30 MeV	74 ± 31 MeV
χ^2	41.9	73.3
Number of free parameters	10	18
Degrees of freedom (ndf)	28	48
χ^2/ndf	1.50	1.53
Significance	5.9σ	5.2σ





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 ?

PDG2024

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	$\bar{p}p \to \pi\pi$

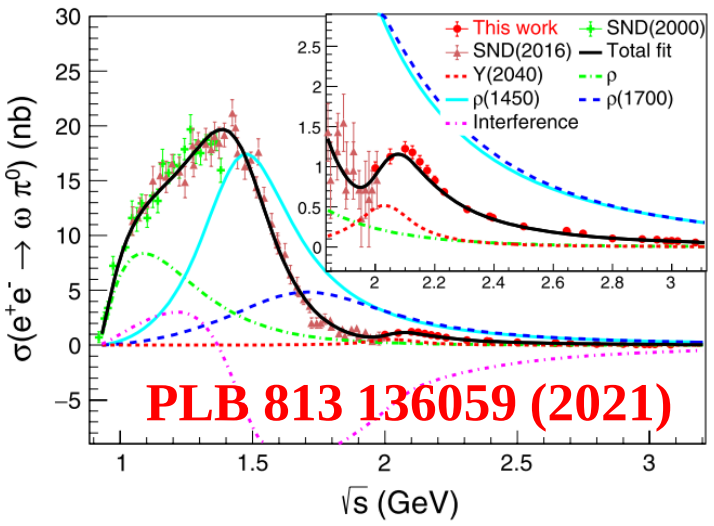
[23] From the combined analysis of ANISOVICH 00J, ANISOVICH 01D, ANISOVICH 01E, and ANISOVICH 02.

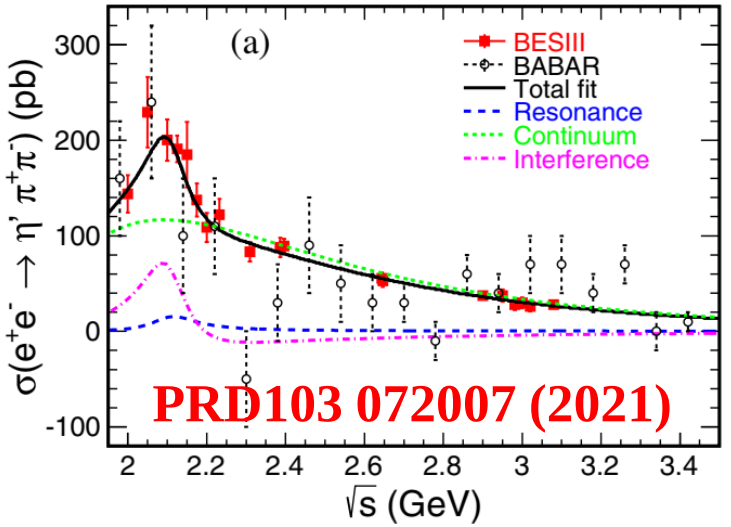
ρ(2270) $I^G(J^{PC}) = 1^+(1^{--})$

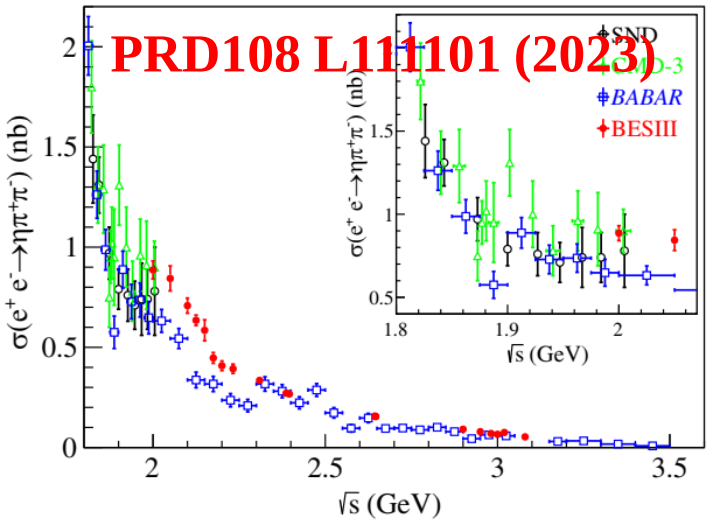
MASS (MeV)	WIDTH (MeV)	DOCUMENT ID		TECN	COMMENT
2265±40	325 ± 80	[50] ANISOVICH	02	SPEC	0.6–1.9 $p\bar{p} \to \omega\pi^0$, $\omega\eta\pi^0$, $\pi^+\pi^-$
2280±50	440 ± 110	ATKINSON	85	OMEG	20–70 $\gamma p \to p\omega\pi^+\pi^-\pi^0$

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

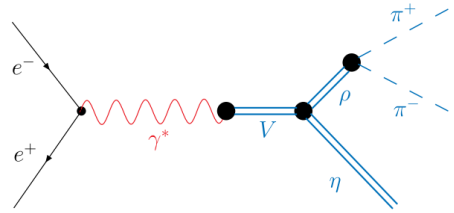
$e^+ e^- \to \omega \pi^0$, $\eta' \pi^+ \pi^-$ & $\eta \pi^+ \pi^-$

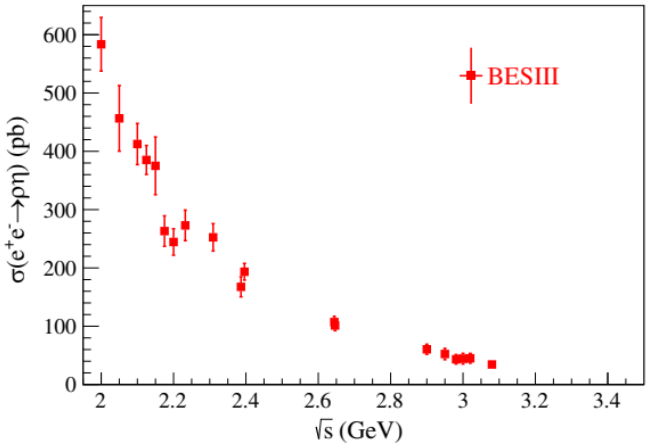


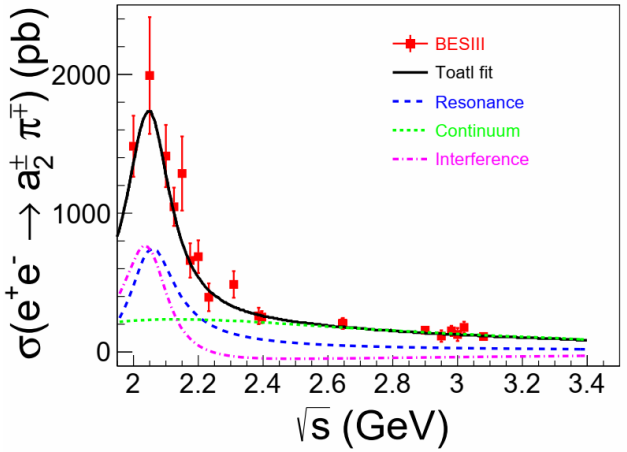




- States ρ(2000) or ρ(2150)
- $e^+ e^- \to \pi^+ \pi^- \eta$
  - ✓ default MC $e^+ e^- \to \rho \eta$
  - ✓ BESIII vs. BABAR: 30% higher
  - ✓ A dip around 2.18 GeV @ ρ η







$\phi(2170)$ @ R scan data

① e^+e^- -> $K^+ K^-$: PRD 99, 032001 (2019)
② e^+e^- -> $\phi K^+ K^-$: PRD 100, 032009 (2019)
③ e^+e^- -> $K^+ K^- \pi^0 \pi^0$: PRL 124, 112001 (2020)
④ e^+e^- -> $\phi \eta'$: PRD 102, 012008 (2020)
⑤ e^+e^- -> $\omega \eta$ & $\omega \pi^0$: PLB 813, 136059 (2021)
⑥ e^+e^- -> $\eta' \pi^+ \pi^-$: PRD 103, 072007 (2021)
⑦ e^+e^- -> $\phi \eta$: PRD 104, 032007 (2021)
⑧ e^+e^- -> $K_S K_L$: PRD 104, 092014 (2021)
⑨ e^+e^- -> $\omega \pi^0 \pi^0$: PRD 105, 032005 (2022)
⑩ e^+e^- -> $K^+ K^- \pi^0$: JHEP 07, 045 (2022)
⑪ e^+e^- -> $\phi \pi^+ \pi^-$: PRD 108, 032011 (2023)
⑫ e^+e^- -> $\eta \pi^+ \pi^-$: PRD 108, L111101 (2023)
⑬ e^+e^- -> $\omega \pi^+ \pi^-$: JHEP 01, 111 (2023)
⑭ e^+e^- -> $K_S K_L \pi^0$: JHEP 01, 180 (2024)
⑮ e^+e^- -> $\omega \eta'$: JHEP 07, 093 (2024)
⑯ e^+e^- -> $\pi^+ \pi^- \pi^0$: PRD 110, 032005 (2024)
⑰ e^+e^- -> $\omega \eta \pi^0$: draft ???
⑱ e+e- -> $\omega K^+K^-/K^+K^-\pi^+\pi^-/K_SK^\pm\pi^\mp/2(\pi^+\pi^-)/\pi^+\pi^-\pi^0\pi^0$

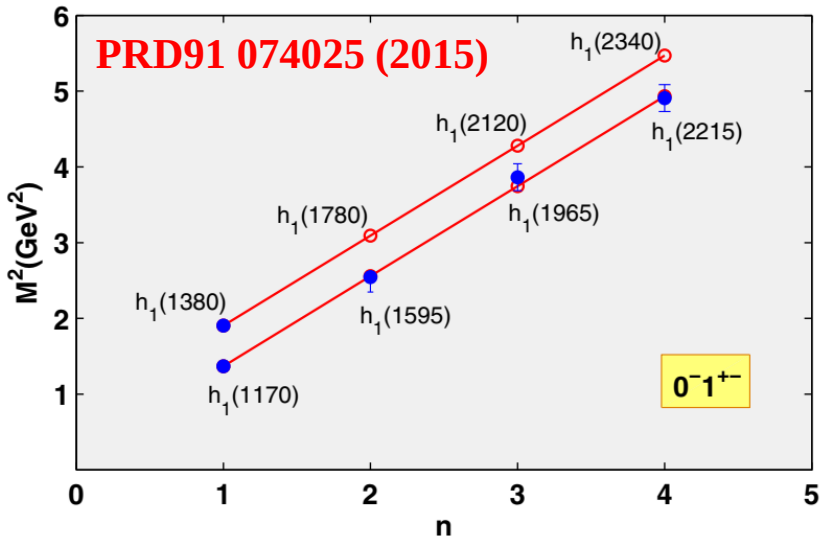
$\phi(2170)$ **PDG2026** $I^G(J^{PC}) = 0^-(1^{--})$

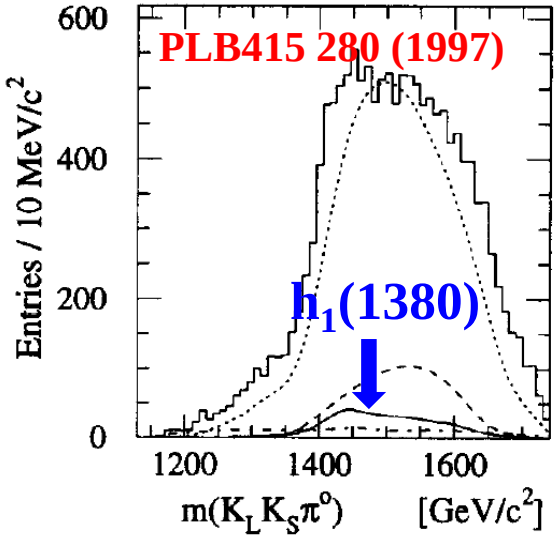
See the review on "Spectroscopy of Light Meson Resonances."

$\phi(2170)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2164 ± 5 OUR AVERAGE					
2164.7± 9.1± 3.1		[1] ABLIKIM	24AN	BES3	$e^+e^- \to K^0_S K^0_L \pi^0$
2178 ±20 ± 5		[2] ABLIKIM	23AX	BES3	$e^+e^- \to \phi\pi^+\pi^-$
2190 ±19 ±37		[3] ABLIKIM	22L	BES3	2.0–3.08 $e^+e^- \to K^+K^-\pi^0$
2163.5± 6.2± 3.0		[4] ABLIKIM	21T	BES3	$e^+e^- \to \phi\eta$
2177.5± 4.8±19.5		[5] ABLIKIM	20M	BES3	$e^+e^- \to \eta'\phi$
2126.5±16.8±12.4		[6] ABLIKIM	20S	BES3	$e^+e^- \to K^+K^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2191.6± 5.0		[7] CHEN	25D	RVUE	$e^+e^- \to K^+K^-,\ K^0_S K^0_L$
2215.7± 8.3		[8] LICHARD	23	RVUE	$e^+e^- \to \Upsilon(nS) \to \phi\eta\gamma$
2169 ± 5 ± 6		[9] ZHU	23A	RVUE	$e^+e^- \to \eta\phi$
2273.7± 5.7±19.3		[10] ABLIKIM	21AP	BES3	$e^+e^- \to K^0_S K^0_L$
2135 ± 8 ± 9	9k	ABLIKIM	19L	BES3	$e^+e^- \to \eta\phi f_0(980)$
2239.2± 7.1±11.3		[11] ABLIKIM	19L	BES3	$e^+e^- \to K^+K^-$
2200 ± 6 ± 5	471	ABLIKIM	15H	BES3	$J/\psi \to \eta\phi\pi^+\pi^-$
2180 ± 8 ± 8		[12,13] LEES	12F	BABR	10.6 $e^+e^- \to \phi\pi^+\pi^-\gamma$
2079 ±13 $^{+79}_{-28}$	4.8k	[14] SHEN	09	BELL	10.6 $e^+e^- \to K^+K^-\pi^+\pi^-\gamma$
2186 ±10 ± 6	52	ABLIKIM	08F	BES	$J/\psi \to \eta\phi f_0(980)$
2125 ±22 ±10	483	AUBERT	08S	BABR	10.6 $e^+e^- \to \phi\eta\gamma$
2192 ±14	116	[15] AUBERT	07AK	BABR	10.6 $e^+e^- \to K^+K^-\pi^+\pi^-\gamma$
2169 ±20	149	[15] AUBERT	07AK	BABR	10.6 $e^+e^- \to K^+K^-\pi^0\pi^0\gamma$
2175 ±10 ±15	201	[13,16] AUBERT,BE	06D	BABR	10.6 $e^+e^- \to K^+K^-\pi\pi\gamma$

Axial vector states





PDG2018

$h_1(1380)$ $I^G(J^{PC}) = ?^-(1^{+-})$

OMITTED FROM SUMMARY TABLE

Seen in partial-wave analysis of the $K\overline{K}\pi$ system. Needs confirmation.

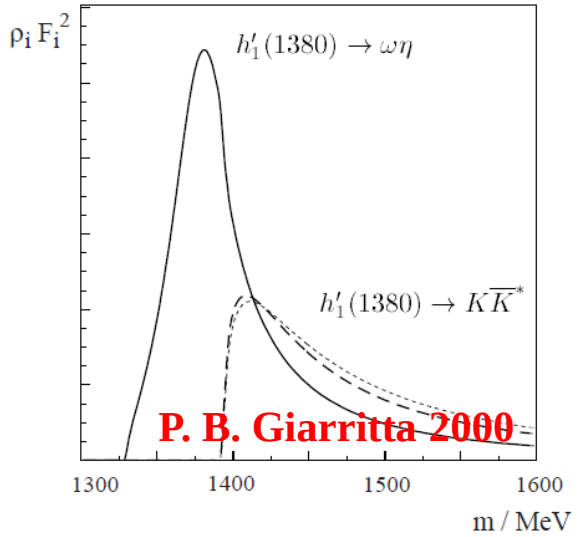
$h_1(1380)$ MASS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1407±12 OUR AVERAGE	Error includes scale factor of 1.5.		
1412± 4±8	ABLIKIM	15M BES3	$\psi(2S) \to \gamma\chi_{c1,2} \to \gamma K^*\overline{K}$
1440±60	ABELE	97H CBAR	$\overline{p}p \to K_L^0 K_S^0 \pi^0 \pi^0$
1380±20	ASTON	88C LASS	11 $K^- p \to K_S^0 K^{\pm}\pi^{\mp}\Lambda$

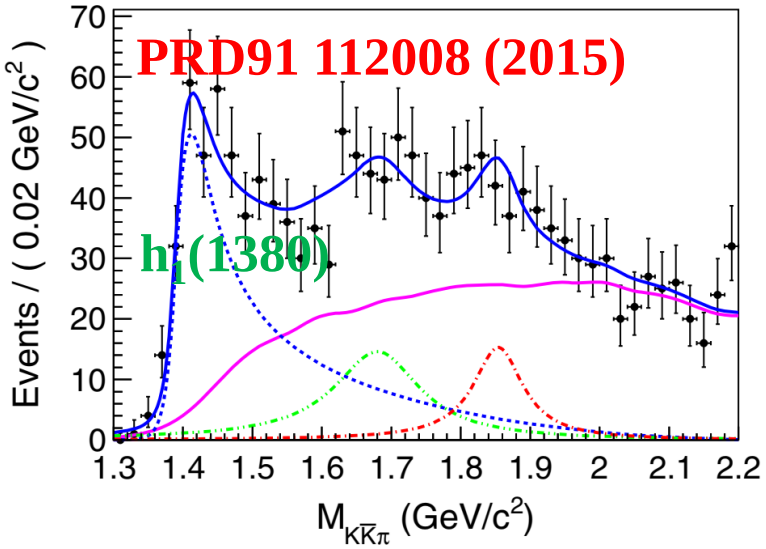
- 1^1P_1 $s\bar{s}$: ground state $h_1(1380)$?
  - ✓ consistent with large uncertainty
  - ✓ favor Crystal Barrel's result
  - ✓ disfavor LASS's results
- Missing excited h_1 states
- Only K*(892)K mode
  - ✓ ωη mode @ Crystal Barrel thesis

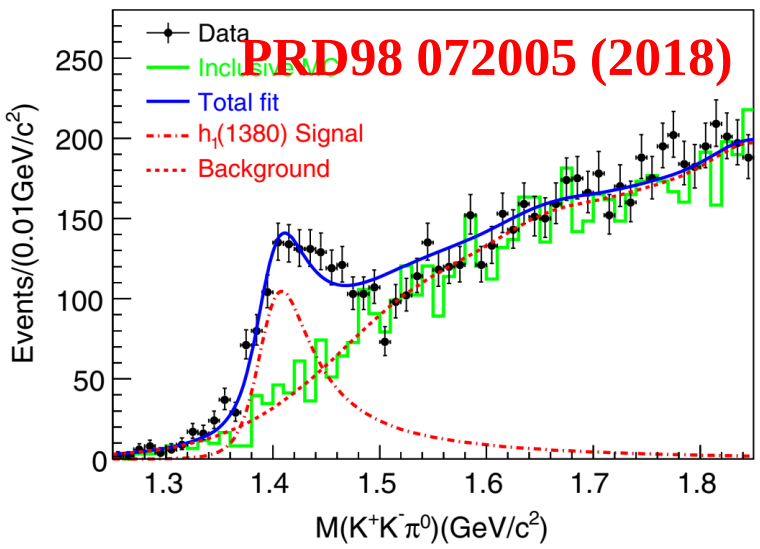
mass (MeV/c^2)	*model*
1495.18 ± 8.82 *or* 1468	$h_1(1170) - h_1(1380)$ *mixing*
1457 ± 11 *or* 1490 ± 5	*non-relativistic quark*
1470	*relativistic quark*
1511	*constituent quark*

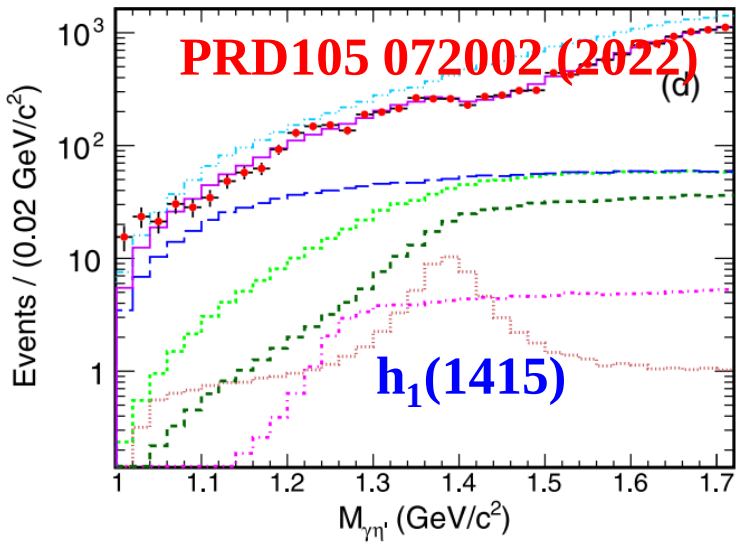
$$\frac{Br(h_1(1380) \to K\bar{K}^*)}{Br(h_1(1380) \to \omega\eta)} = 0.17 \pm 0.06$$



$h_1(1380) \Rightarrow h_1(1415)$







- $h_1(1380)$, $\phi(1680)$ and $\phi(1850)$ @ χ_{c1} & χ_{c2}
  - ✓ χ_{c1} & χ_{c2} -> ϕ K*(892) K modes
  - ✓ 106M $\psi(3686) \Rightarrow$ 3.7B $\psi(3686)$
- $h_1(1380)$ @ J/ψ -> η' K*(892) K
  - ✓ 1.31B J/$\psi \Rightarrow$ 10B J/ψ
- PDG2019: "omitted from summary table" ✘
- $h_1(1380)$ @ J/ψ -> $\gamma\,\eta$' η'

$h_1(1415)$ PDG2026 $I^G(J^{PC}) = 0^-(1^{+-})$

$h_1(1415)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$1409^{+\ 9}_{-\ 8}$ OUR AVERAGE		Error includes scale factor of 1.9. See the ideogram below.			
$1384 \pm 6\ ^{+9}_{-0}$		[1] ABLIKIM	22C	BES3	$J/\psi \to \gamma\eta'\eta' \to 4/5\gamma 2(\pi^+\pi^-)$
$1423 \pm 2.1 \pm 7.3$	2.2k	[2] ABLIKIM	18AB	BES3	$J/\psi \to \eta' h_1 \to \eta' K^* \overline{K}$
$1412 \pm 4 \pm 8$		[2] 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 $K^- p \to K^0_S K^\pm \pi^\mp \Lambda$

$h_1(1900)$ @ $J/\psi \to \phi\,\eta\,\pi^0$

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

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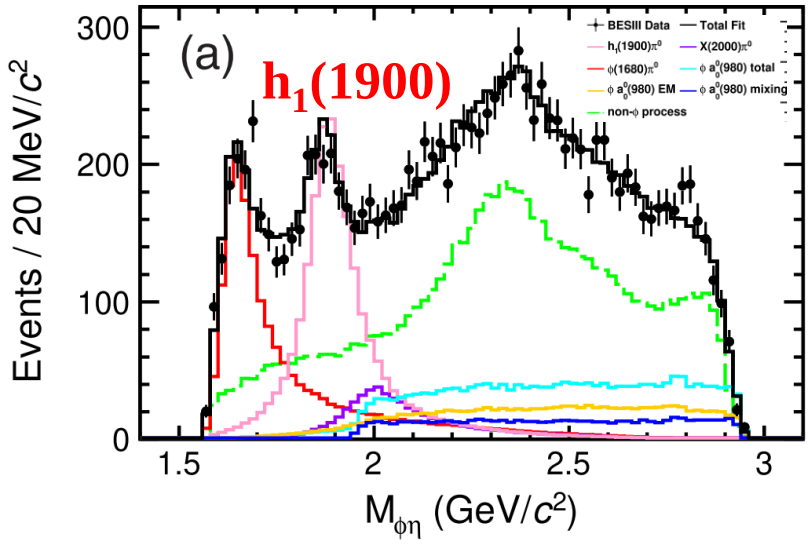
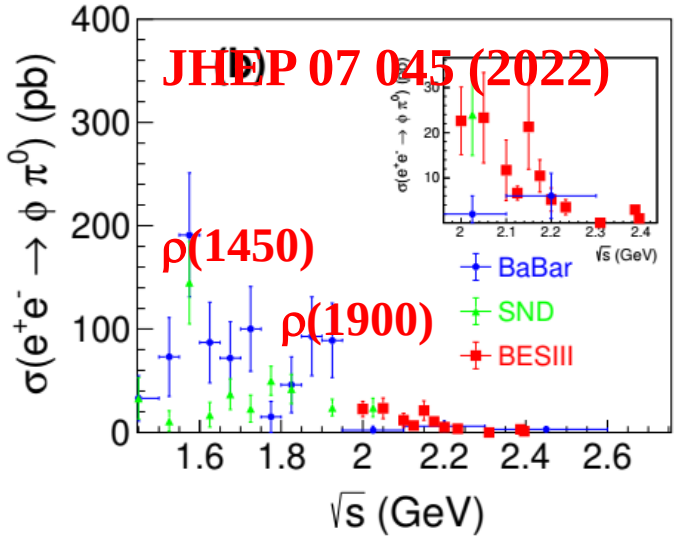


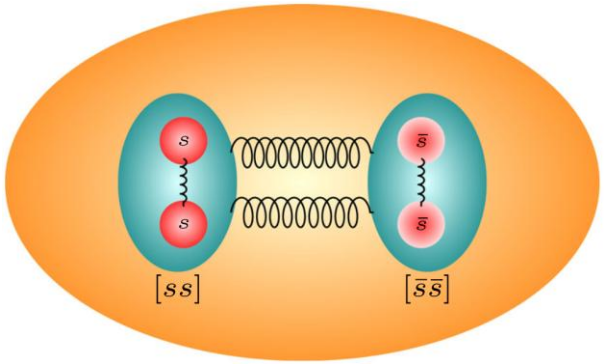
- **Possible resonances**
  - ✓ a_0 & a_2 states @ $\pi^0\,\eta$
  - ✓ $J^{PC} = 1^{--}/1^{+-}$ states @ $\phi\,\eta$
  - ✓ $J^{PC} = 1^{--}$ states @ $\phi\,\pi^0$
- **1^{+-} $h_1(1900)$, 1^{--} $X(2000)$ @ $\phi\,\eta$**
- **$h_1(1900)$ as 2^1P_1 $s\bar{s}$ candidate ?**
  - ✓ need more decay modes

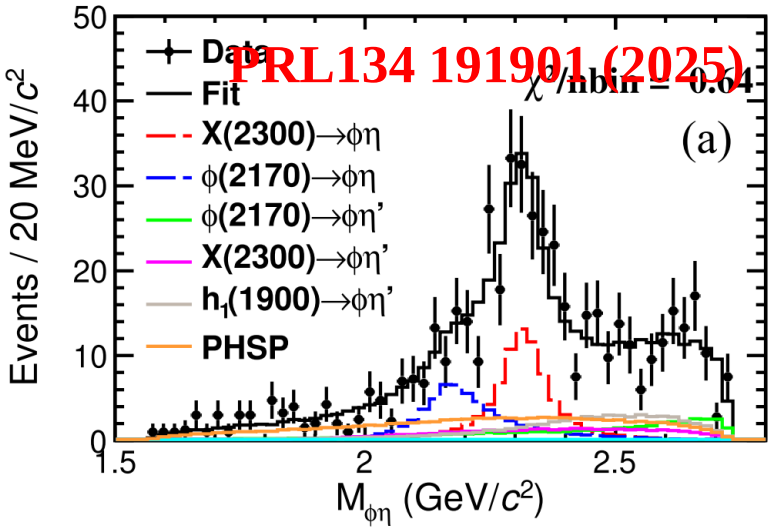


Process	M (MeV/c^2)	Γ (MeV)	Sig. (σ)
$\phi(1680)\pi^0$	$1663 \pm 5^{+16}_{-4}$	$159 \pm 15^{+11}_{-11}$	32.3
$X(2000)\pi^0$	$1992 \pm 12^{+15}_{-6}$	$132 \pm 22^{+17}_{-4}$	13.2
$h_1(1900)\pi^0$	$1908 \pm 6^{+8}_{-4}$	$175 \pm 13^{+7}_{-16}$	30.1
$\phi a_0(980)_{\rm EM}$	–	–	19.9
$\phi a_0(980)_{\rm mix}$	–	–	31.6

$h_1(2300)$ @ $\psi(3686)$ -> $\phi\eta\eta'$

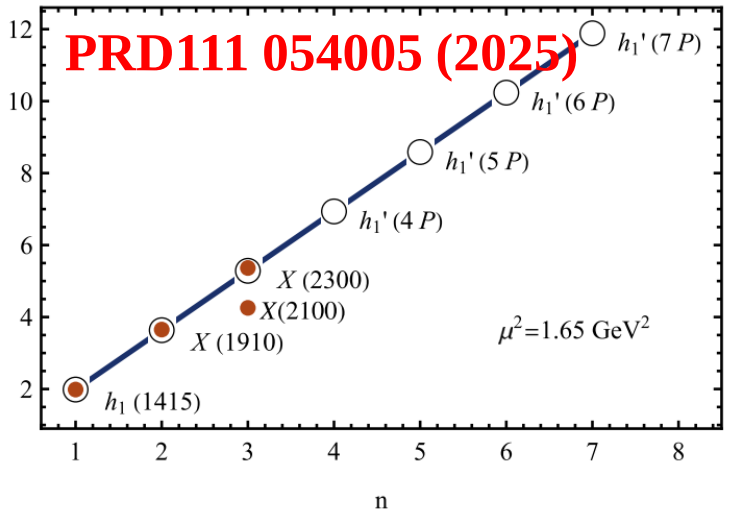
- **Possible resonances**
  - ✓ $f_0/f_2/f_4/\eta_1(1855)$ states @ $\eta\eta'$
  - ✓ $1^{--}/1^{+-}$ states @ $\phi\eta$ & $\phi\eta'$
  - ✓ $2^{--}/3^{--}$ states @ $\phi\eta$ & $\phi\eta'$
- **1^{+-} $h_1(2300)$ @ $\phi\eta$ & $\phi\eta'$**
  - ✓ **mass: $2316 \pm 9 \pm 30$ MeV/c^2**
  - ✓ **width: $89 \pm 15 \pm 26$ MeV/c^2**
- **Nature of $h_1(2300)$**
  - ✓ **n^1P_1 $s\bar{s}$ or $ss\bar{s}\bar{s}$ candidate**





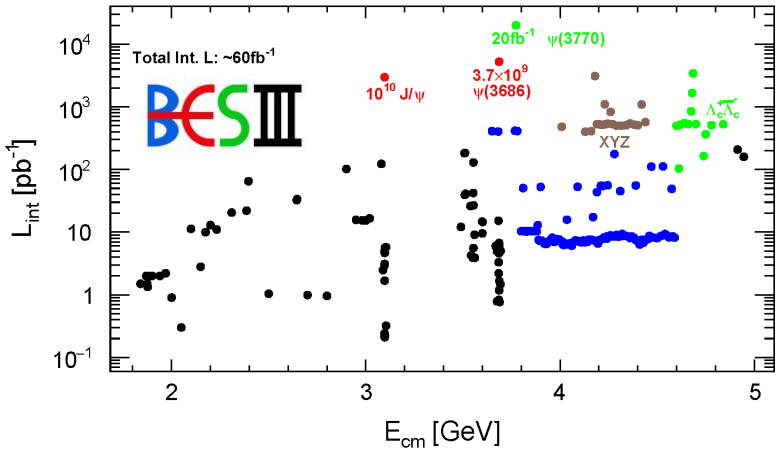
Process	$\mathcal{B}$ (10^{-6})	Sig.
$h_1(1900)\eta$	$3.8 \pm 1.4 \pm 1.5$	5.3σ
$\phi(2170)\eta$	$3.3 \pm 1.4 \pm 1.2$	5.1σ
$\phi(2170)\eta'$	$3.8 \pm 0.9 \pm 0.5$	6.0σ
$X(2300)\eta$	$2.2 \pm 0.7 \pm 0.7$	5.6σ
$X(2300)\eta'$	$4.8 \pm 1.3 \pm 0.7$	9.6σ
PHSP	$6.1 \pm 2.3 \pm 1.8$	5.2σ

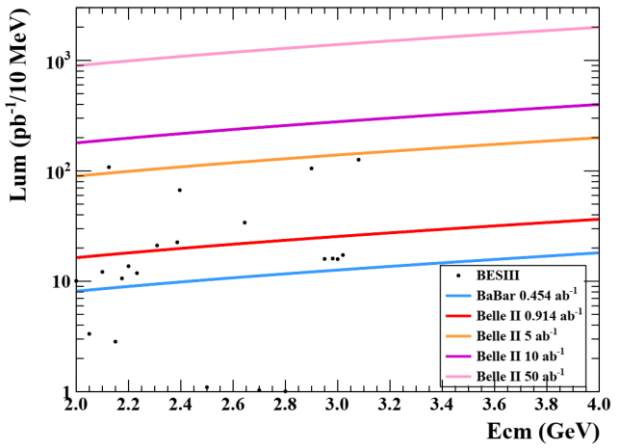
Resonance	M (MeV/c^2)	Γ (MeV)
$h_1(3P)$	2435 [4]	269 [4]
$h_1(3P)$	2449 [8]	N/A
$h_1(3P)$	2100 [12,15]	N/A
$h_1(3P)$	2490 [9]	N/A
$h_1(3P)$	2398 [10]	N/A
$h_1(3P)$	2495.51 ± 1.46 [11]	N/A
$h_1(4P)$	2340 [12,15]	N/A
$T_{(ss\bar{s}\bar{s})1^{+-}}$	2323 [26]	N/A
$T_{(ss\bar{s}\bar{s})1^{+-}}$	1960 [27]	N/A
$T_{(ss\bar{s}\bar{s})1^{+-}}$	2000^{+100}_{-90} [28]	N/A
This Letter	$2316 \pm 9 \pm 30$	$89 \pm 15 \pm 26$

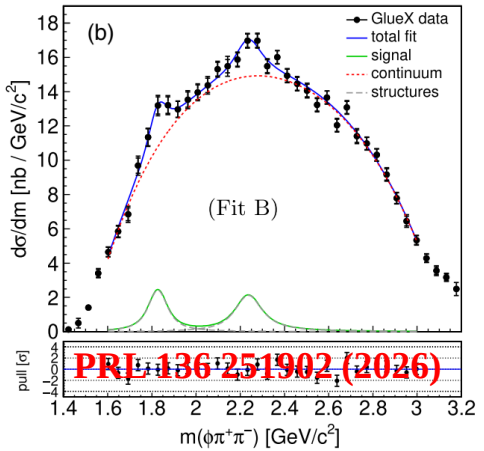


Summary and outlook

- Strangeonium and strangeonium-like states are a terra incognita
- 3^3S_1 $s\bar{s}$: $\phi(1680)$ vs. X(1750), more decay modes
- Using BESIII data, we are extensively studying $\phi(2170)$
  - ✓ Need ρ^* and ω^* spectrum to understand $\phi(2170)$.
  - ✓ $\phi(2170)$ 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 ?
- $\phi(2170)$ with ISR @ Belle II; $\phi(2170)$ with photoproduction @ GlueX
- Three $h_1(1415)$, $h_1(1900)$ & $h_1(2300)$, their nature ? more decay modes







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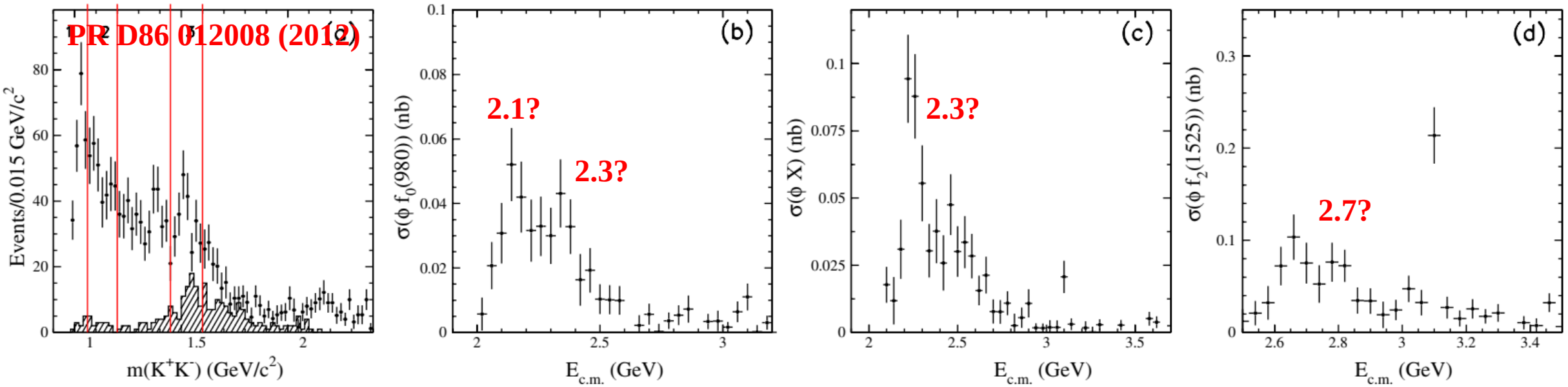
Structures @ $e^+ e^- \to \phi K^+ K^-$



- m_{KK} @ $\phi K^+ K^-$
  - ✓ m_{KK} < 1.06 GeV: $\phi f_0(980)$
  - ✓ 1.06 < m_{KK} < 1.45 GeV
  - ✓ 1.45 < m_{KK} < 1.6 GeV: $\phi f_2'(1525)$
- m_{KK} @ 3.08 GeV: $f_0(980)$ & $f_2'(1525)$
- Belle II 914 fb^{-1} vs. BaBar 454 fb^{-1}