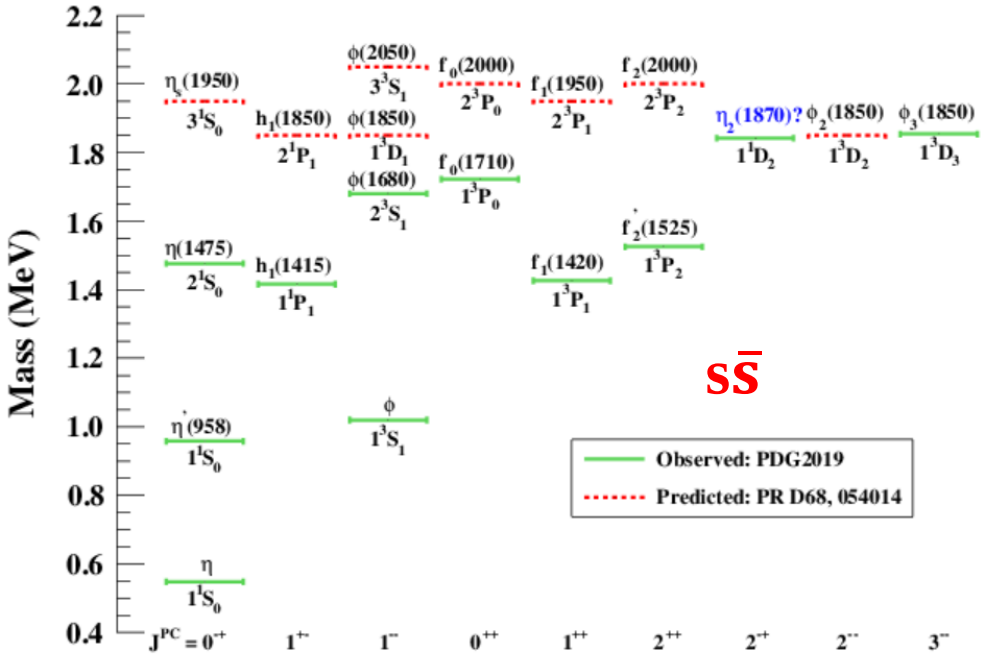
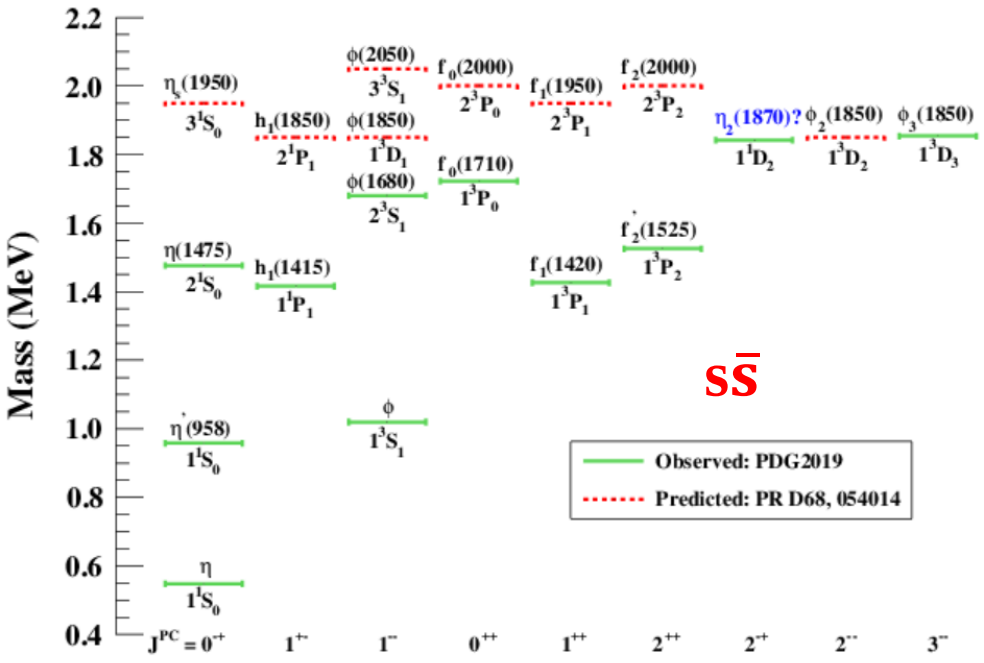
Recent results on ϕ(2170) at BESIII

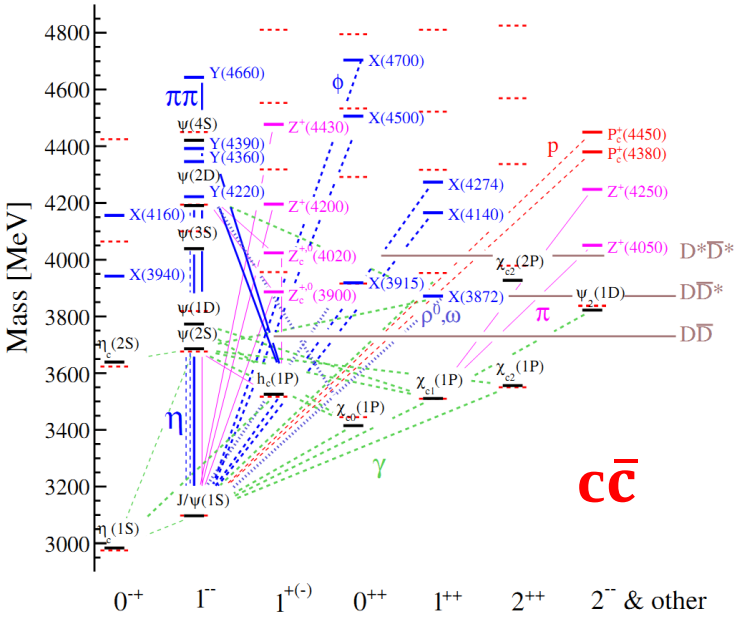
鄢文标 (中国科学技术大学)



“6th workshop on the XYZ particles”，2020.01.20，上海

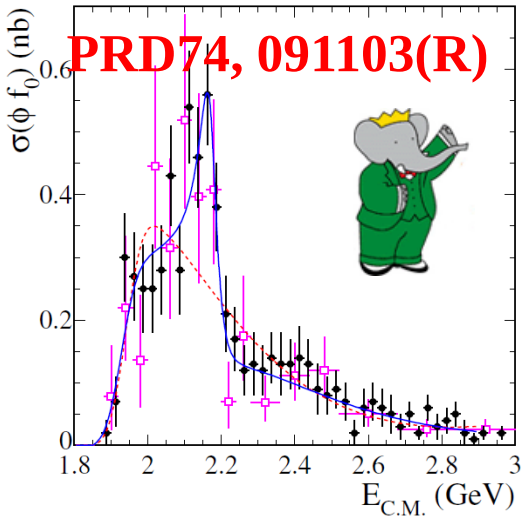
Strange quarkonium

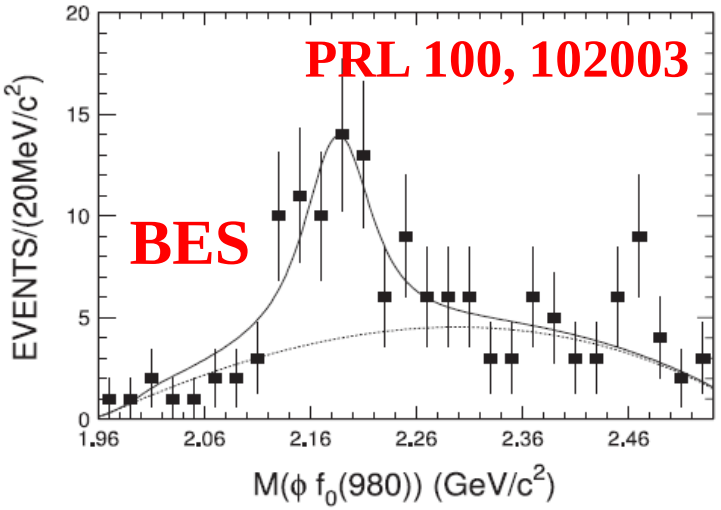


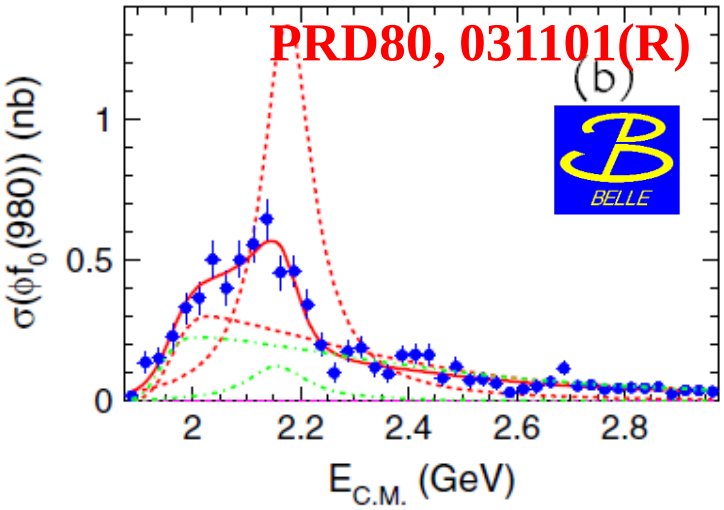


- Compared with $c\bar{c}$ and $b\bar{b}$, $s\bar{s}$ is a terra incognita.
- There are XYZ particles with charm & bottom quark, how about strange quark ?
- The strange quark has intermediate mass, $s\bar{s}$ serves as bridge between light and heavy quark.

ϕ(2170)/Y(2175)





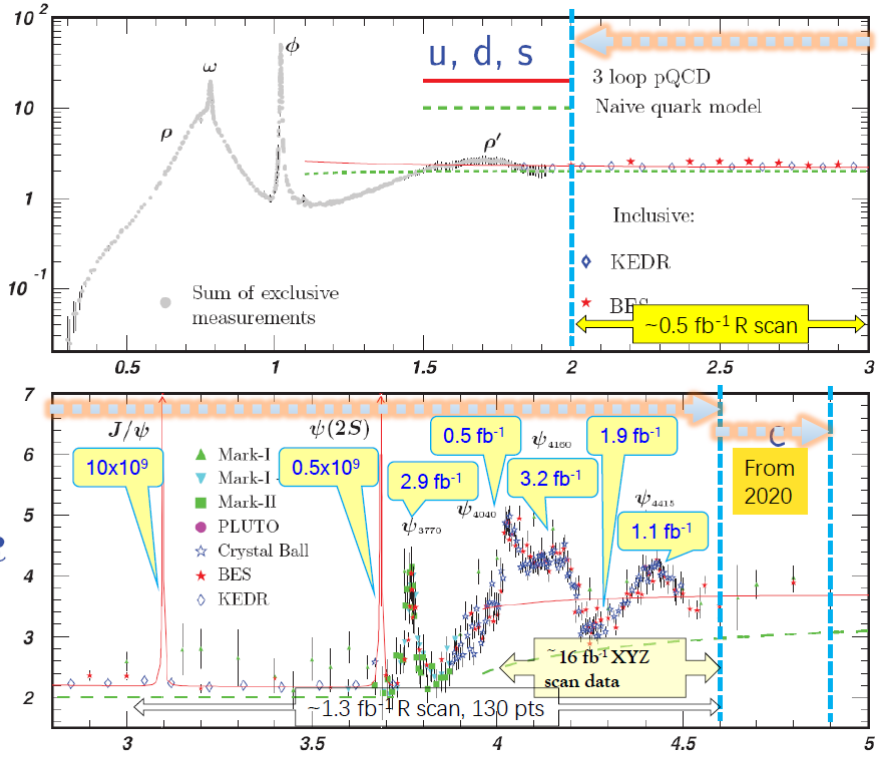


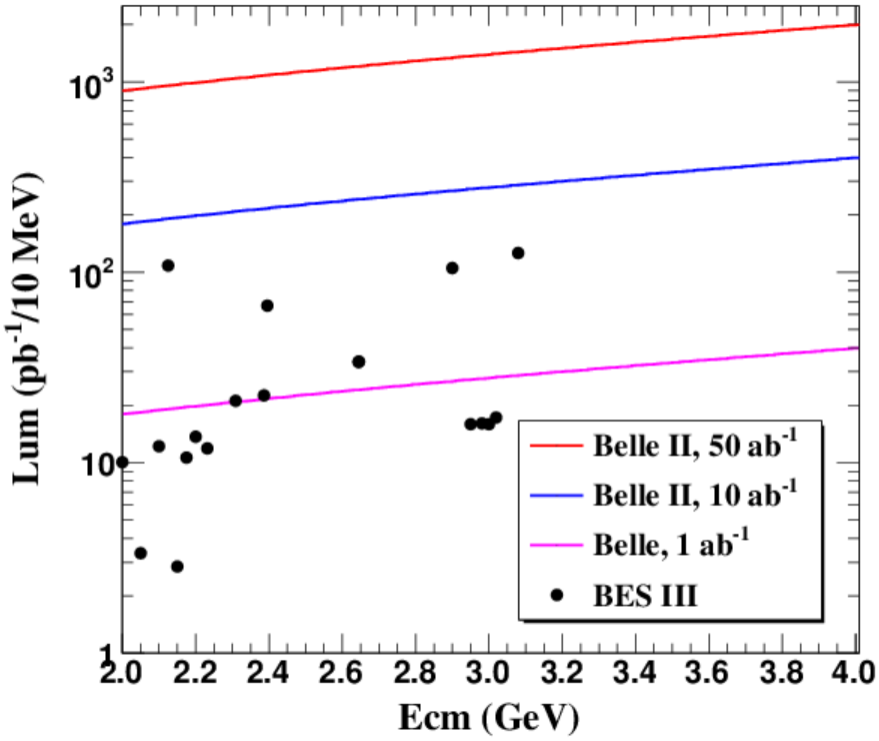
Eur. Phys. J. C72, 2008

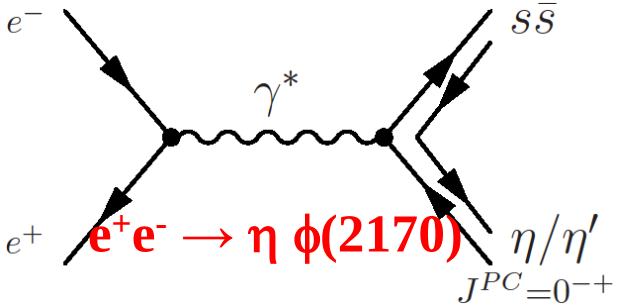
$$e^+e^- \Rightarrow \begin{cases} Y(2175) \to \phi(1020)\pi^+\pi^- & \text{strange,} \\ Y(4260) \to J/\psi\pi^+\pi^- & \text{charm,} \\ \Upsilon(10860) \to \Upsilon(1S,2S)\pi^+\pi^- & \text{bottom,} \end{cases}$$

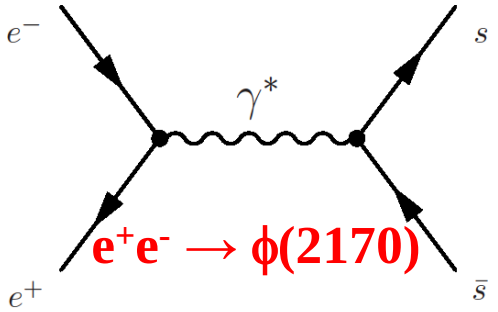
ϕ(2170) as strange analogue of Y(4220)

$J^{PC} = 1^{--}$ $\phi(2170)$ @ BESIII





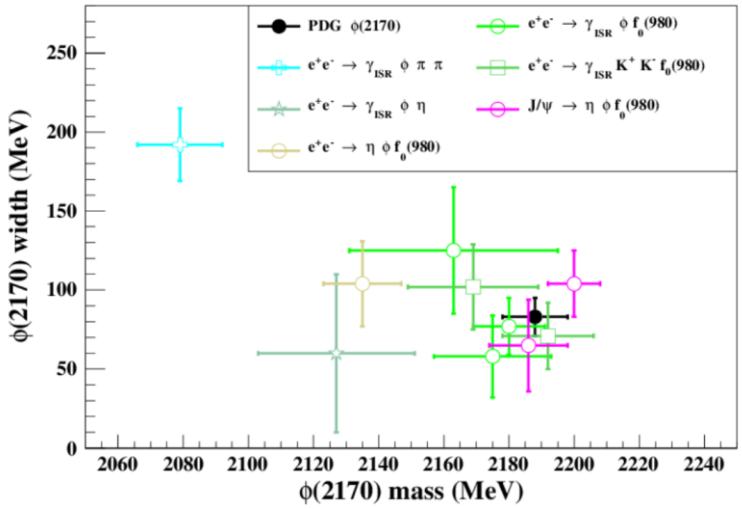




$\phi(2170)$

PDG $\phi(2170)$ DECAY MODES

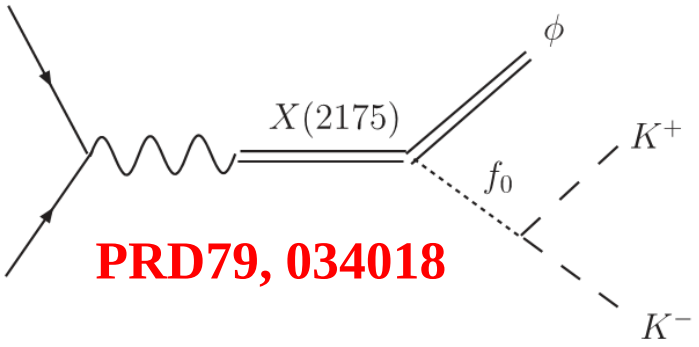
	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	seen
Γ_2	$\phi\eta$	
Γ_3	$\phi\pi\pi$	
Γ_4	$\phi f_0(980)$	seen
Γ_5	$K^+K^-\pi^+\pi^-$	
Γ_6	$K^+K^-f_0(980) \rightarrow K^+K^-\pi^+\pi^-$	seen
Γ_7	$K^+K^-\pi^0\pi^0$	
Γ_8	$K^+K^-f_0(980) \rightarrow K^+K^-\pi^0\pi^0$	seen
Γ_9	$K^{*0}K^{\pm}\pi^{\mp}$	not seen
Γ_{10}	$K^*(892)^0\overline{K}^*(892)^0$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



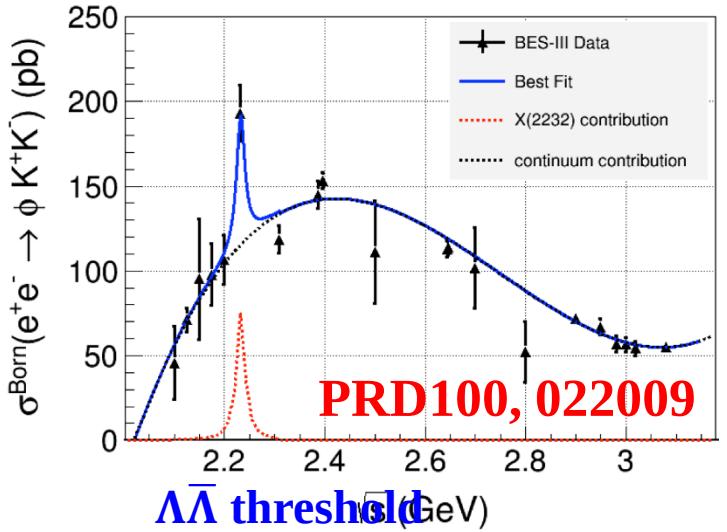
- **Published experimental information**
  - ✓ **Limited decay modes**
  - ✓ **Inconsistence on mass & width**
- **Theorists explain $\phi(2170)$ as**
  - ✓ **$s\bar{s}g$ hybrid**
  - ✓ **2^3D_1 or 3^3S_1 $s\bar{s}$**
  - ✓ **tetraquark**
  - ✓ **Molecular state $\Lambda\bar{\Lambda}$**
  - ✓ **$\phi f_0(980)$ resonance with FSI**
  - ✓ **Three body system ϕKK**
  - ✓ **Estimated or ruled out: not yet**
- **aspects of $\phi(2170)$ are still not fully understood.**

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

- **ϕ(2170): resonant of ϕKK**

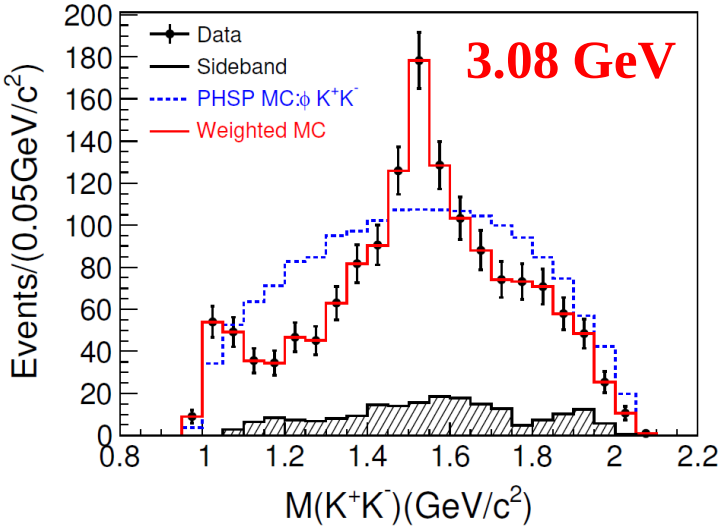


PRD79, 034018



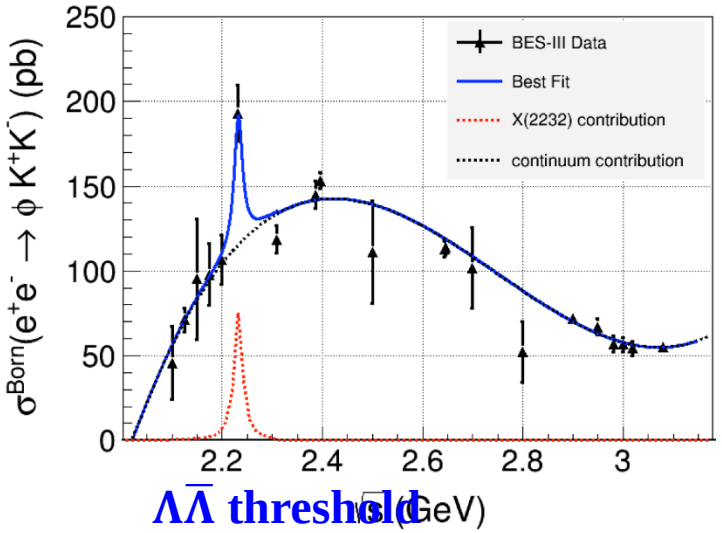
PRD100, 022009

$\Lambda\bar{\Lambda}$ threshold

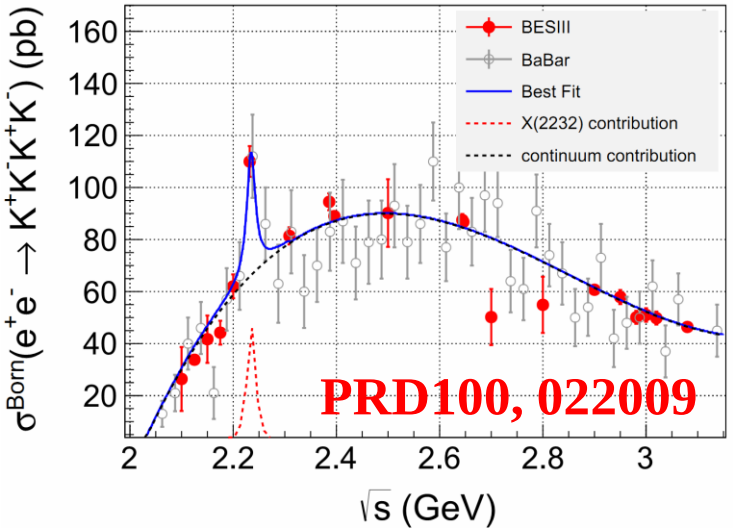


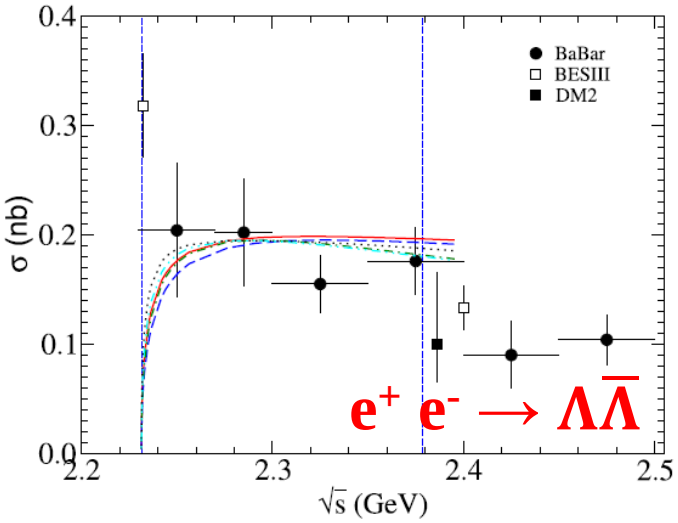
- **A hint for a resonance around $\Lambda\bar{\Lambda}$ threshold**
  - ✓ **Mass = 2232±3.5MeV;**
  - ✓ **Width < 20 MeV**
- **Three body system ϕKK: ?**

$e^+ e^- \rightarrow 2(K^+ K^-)$



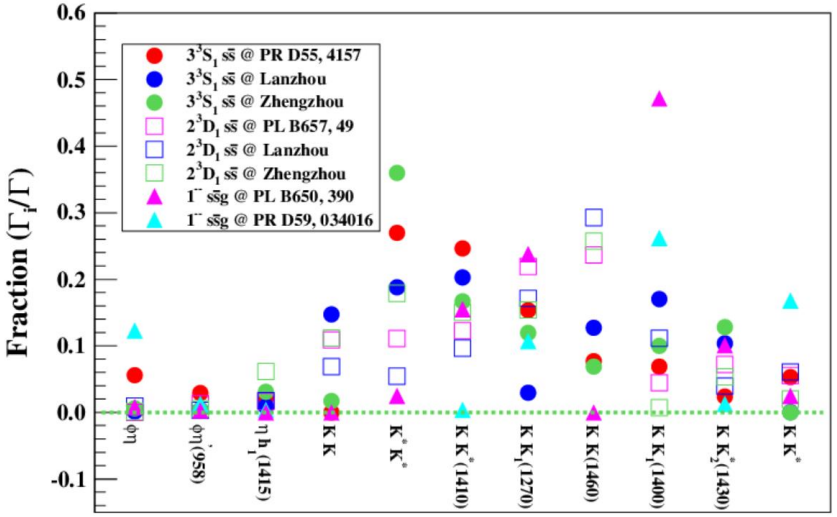
$\Lambda\bar{\Lambda}$ threshold





- ϕK^+K^- and $2(K^+K^-)$ have similar enhancement around 2.2324 GeV
- $\Lambda\bar{\Lambda}$ threshold ?
- More ideas ?

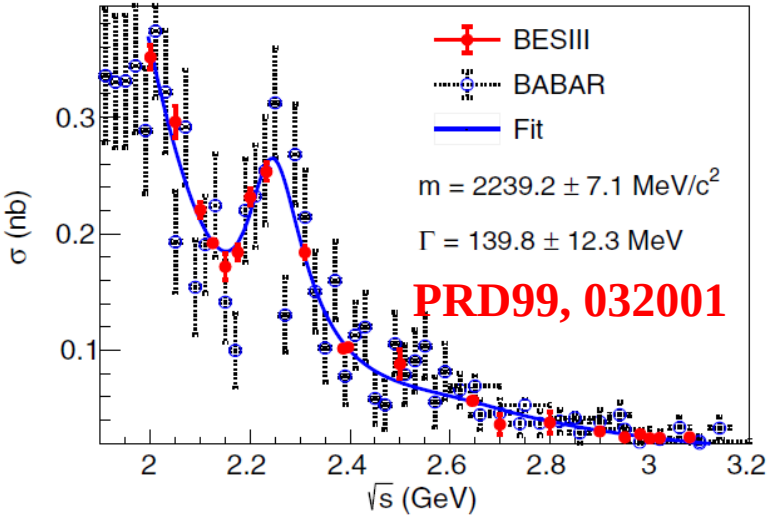
$e^+ e^- \rightarrow K^+ K^-$



- K^+K^- @ $\phi(2170)$
  - ✓ Obvious discrepancy between different theory models
  - ✓ isoscalar: ω^*/ϕ^*; isovector: ρ^*
- $\sigma(e^+e^- \rightarrow K^+K^-)$ @ [2.0-3.08]GeV

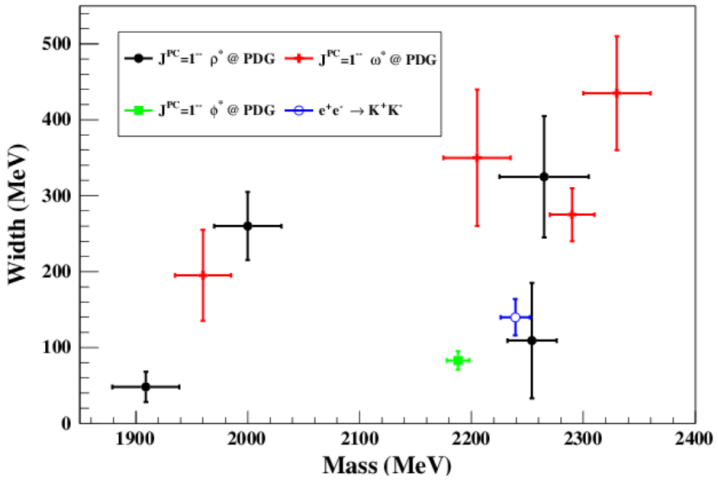
$\phi(2170)$ decay	This work $^3S_1\Lambda\bar{\Lambda}$	$^3P_0$ model within $s\bar{s}$ [10]	Data [5]
KK	73.8–87.7	...	...
$\phi f_0(980)$	0.25–0.3	<10	Seen
$\omega\sigma$	4.2–4.9	...	...
$K^*K_0^*(800)$	1.8–2.1	...	...
Total	80.1–95	...	83 ± 12

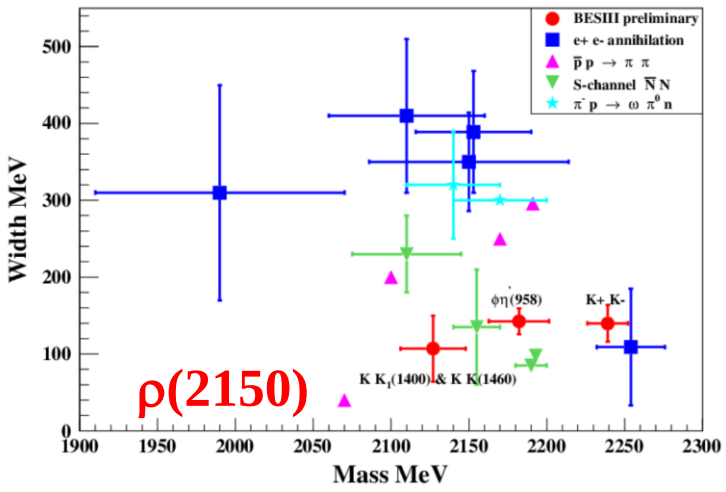
PRD96, 074027



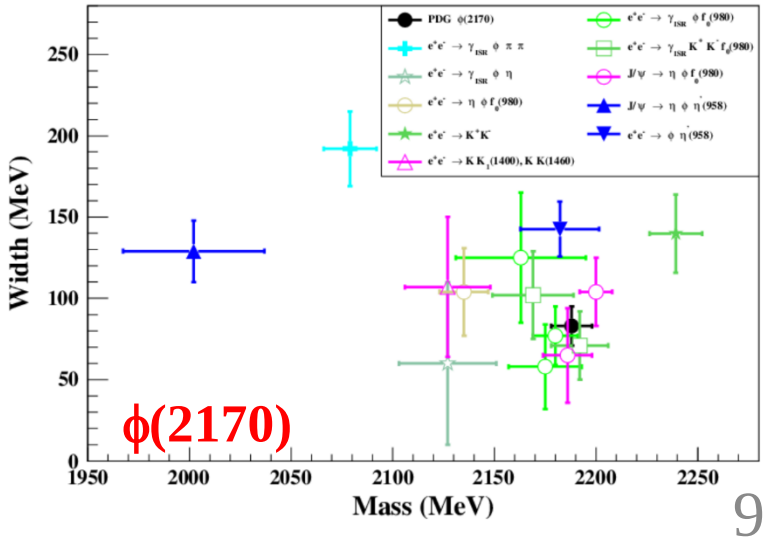
PRD99, 032001

$e^+ e^- \rightarrow K^+ K^-$



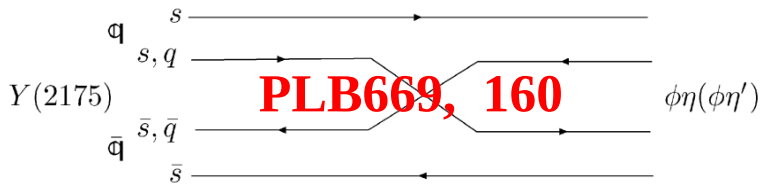


- **Compare K^+K^- resonance**
  - ✓ **$J^{PC}=1^{--}$ vector: ω*/ϕ*/ρ***
  - ✓ **ρ(2150) @ PDG**
  - ✓ **ϕ(2150) experimental results**
- **K^+K^- resonance: ρ(2150) ?**

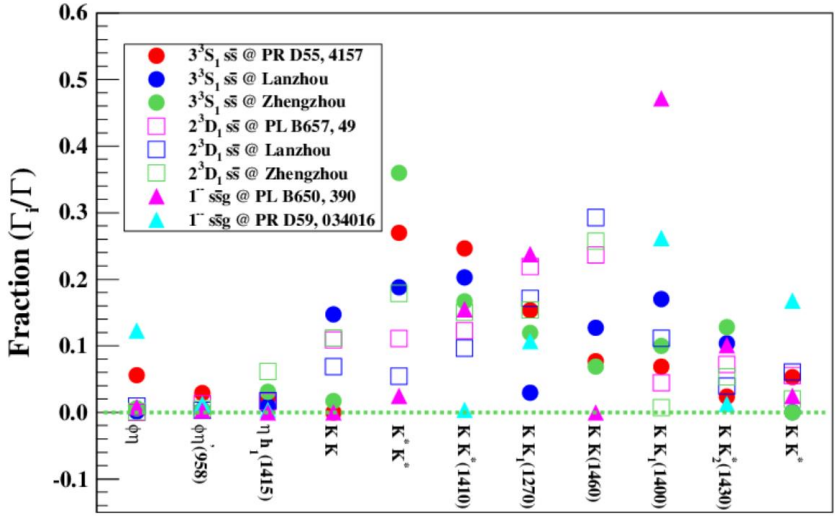


$e^+ e^- \to \phi\eta$ and $\phi\eta'$

- $\phi\eta$ and $\phi\eta'$ modes: isoscalar
  - ✓ ϕ^* and ω^* (OZI suppressed)
  - ✓ useful to measure parameters
- Tetraquark favorites $\phi\eta$ and $\phi\eta'$



PLB669, 160

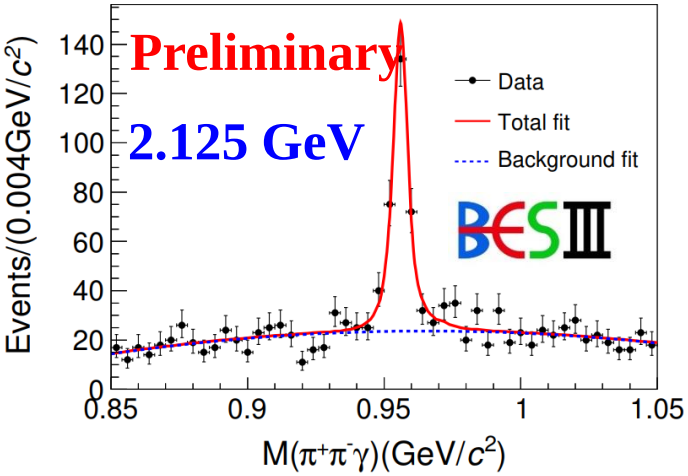


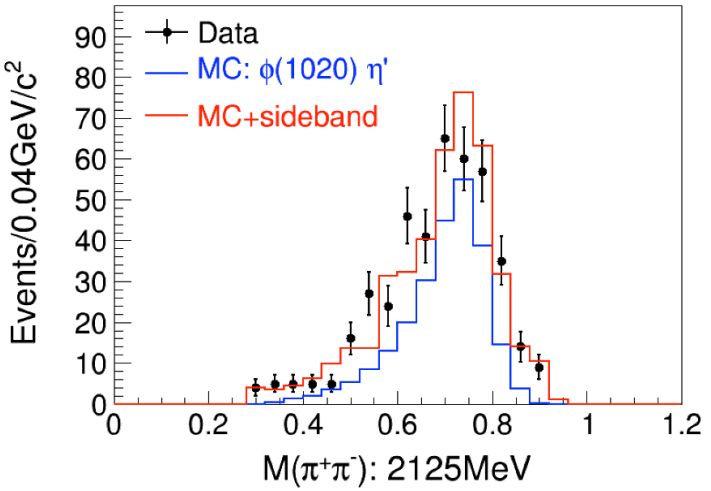
- 1^{--} s$\bar{s}$g hybrid has large $\Gamma_{\phi\eta}$ and smaller $\Gamma_{\phi\eta'}$

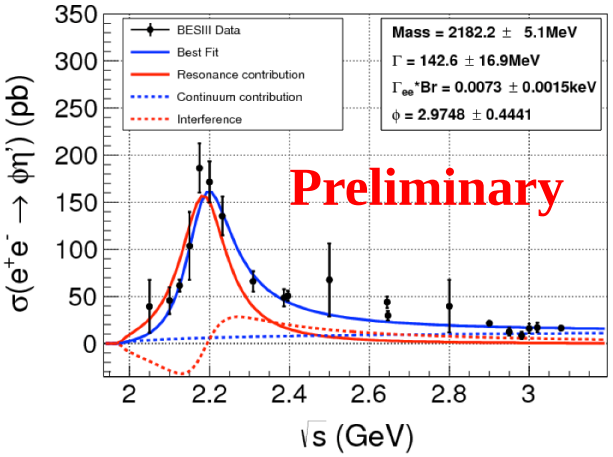
1^{--} s$\bar{s}$g	alt	2.2GeV	standard	IKP	Ding
	PRD59, 034016				PLB650,390
$\phi\eta$	2	19	11	3	1.2
$\phi\eta'$	0.01	2	0.1	0.02	0.4
Br($\phi\eta$)/Br($\phi\eta'$)	200	9.5	110	150	3

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

- **BESIII: $e^+ e^- \to \phi\eta'$ with $\eta' \to \gamma \pi^+ \pi^-$**

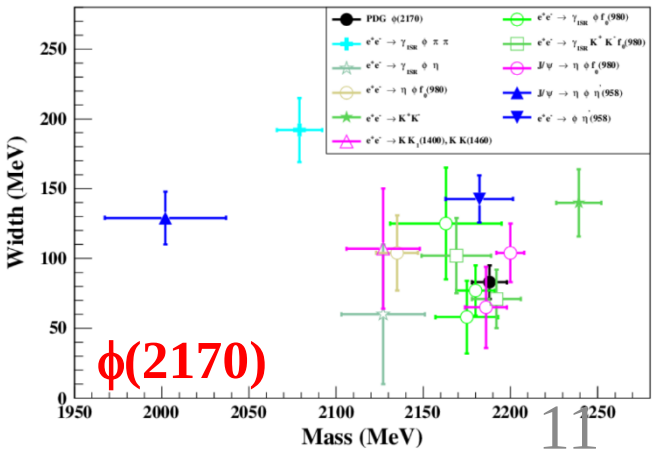






$$\frac{M_R}{\sqrt{s}} \frac{\sqrt{12\pi\Gamma^R_{e^+e^-}\mathcal{B}_{\mathcal{R}}(\phi\,\eta')\Gamma^R_{tot}}}{s - M_R^2 + iM_R\Gamma^R_{tot}} \cdot \sqrt{\frac{\Phi(\sqrt{s})}{\Phi(M_R)}}$$

- **$\phi(2170)$ @ $\phi\eta'$?**



$\phi\eta$ and $\phi\eta'$

- $e^+ e^- \rightarrow \phi\eta$ and $\phi\eta'$
  - ✓ BarBar $\phi\eta$: 1.7±0.7±1.3eV

$$\frac{Br\,[\phi(2170)\rightarrow\phi\eta]\Gamma_{ee}}{Br\,[\phi(2170)\rightarrow\phi\eta\prime]\Gamma_{ee}}=0.23\pm0.11$$

- If we observed $\phi(2150)$ in $e^+ e^- \rightarrow \phi\eta'$, $\phi(2150)$ as an 1^{--} $s\bar{s}g$?

1^{--} $s\bar{s}g$	alt	2.2GeV	standard	IKP	Ding
	PRD59, 034016				PLB650,390
$\phi\eta$	2	19	11	3	1.2
$\phi\eta'$	0.01	2	0.1	0.02	0.4
Br($\phi\eta$)/Br($\phi\eta'$)	200	9.5	110	150	3

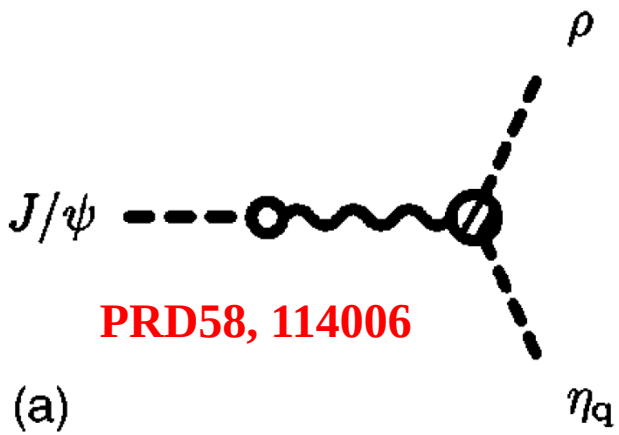
η–η' mixing

- **SU(3) quark model, SU(3) singlet state η_0 and octet state η_8, $\eta_q = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ and aa $\eta_s = s\bar{s}$. θ = -11.7°.**

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix} \qquad \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{1}{3}} & -\sqrt{\frac{2}{3}} \\ \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} \end{pmatrix} \begin{pmatrix} \eta_q \\ \eta_s \end{pmatrix}$$

- **Resonances decay**

$$\frac{\Gamma[J/\psi \to \eta'\rho]}{\Gamma[J/\psi \to \eta\rho]} = \tan^2\phi \left(\frac{k_{\eta'\rho}}{k_{\eta\rho}}\right)^3$$



PRD58, 114006

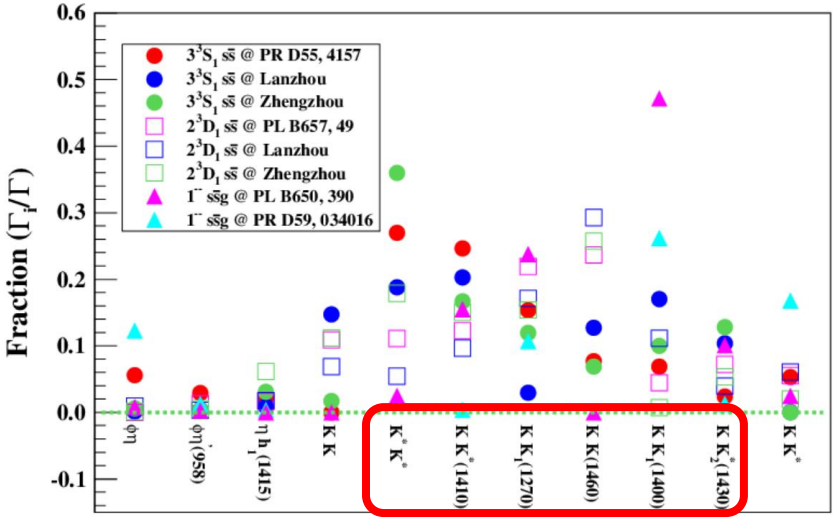
ρη': (0.81±0.08) < ρη: (1.93±0.23)*10^{-4}

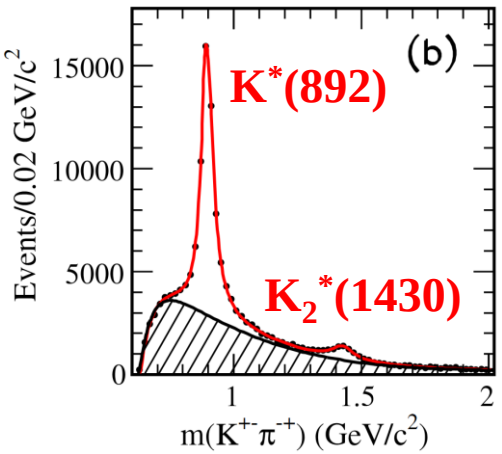
- **φ(2170) → φη and φη': normal ?**

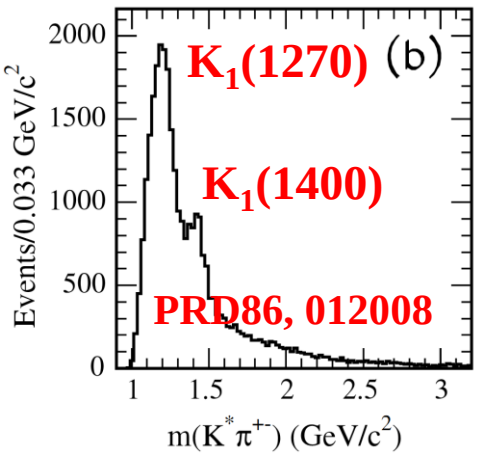
$$\frac{Br\,[\phi(2170)\to\phi\eta]\Gamma_{ee}}{Br\,[\phi(2170)\to\phi\eta\prime]\Gamma_{ee}} = \mathbf{0.23\pm0.11}$$

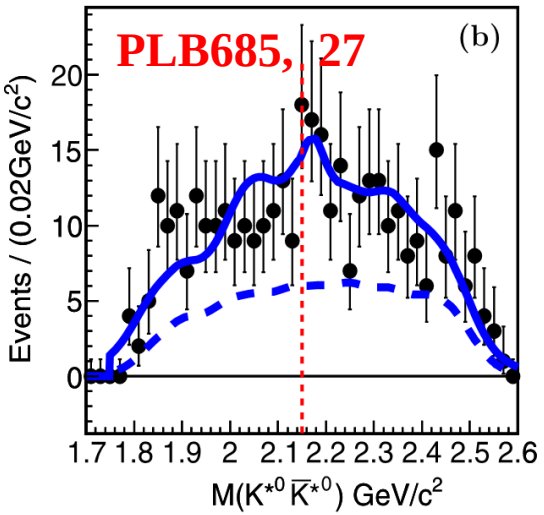
$e^+ e^- \to K K \pi \pi$

- $e^+e^- \to KK\pi\pi$: 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)
- BaBar: $K^*(892)$, $K_2^*(1430)$, $K_1(1270)$ and $K_1(1400)$
- $J/\psi \to \eta\phi(2170) \to \eta K^*K^*$
  - ✓ BES: 58M J/ψ, a upper limit

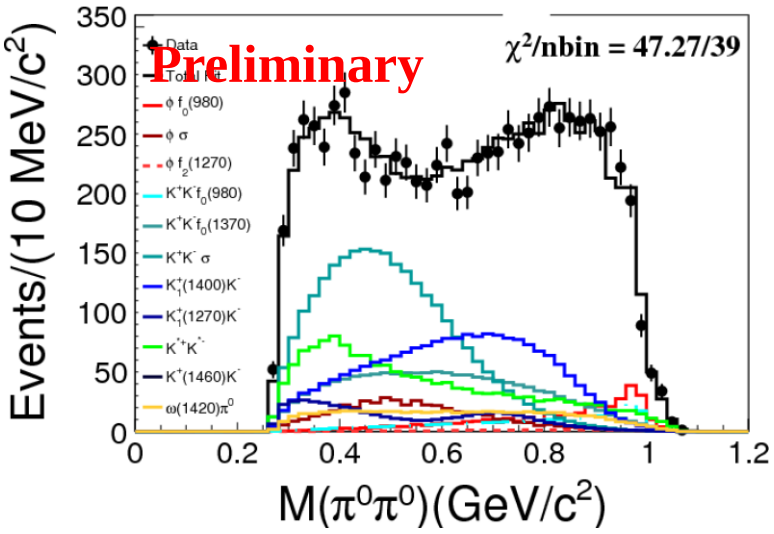


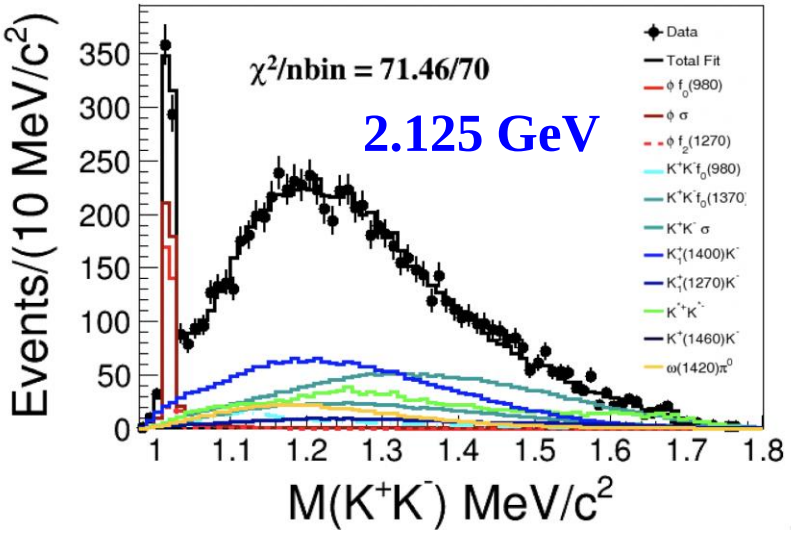






$e^+ e^- \to K^+ K^- \pi^0 \pi^0$

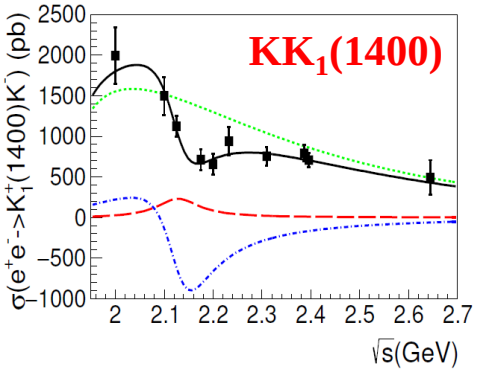


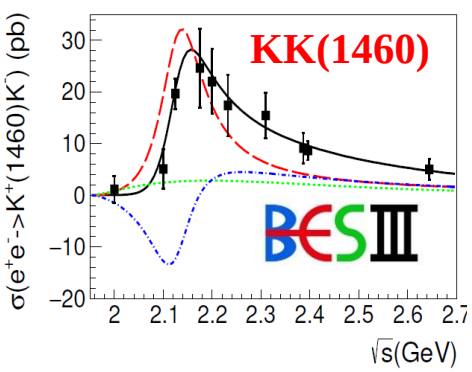


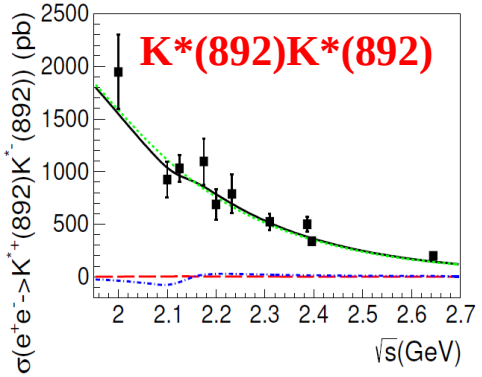
process	Significance (2.1250 GeV)	Significance (2.3960 GeV)
$\phi f_0(980)$	>8.0 σ	>8.0 σ
$\phi\sigma$	>8.0 σ	–
$\phi f_2(1270)$	5.0 σ	–
$\phi f_0(1370)$	–	6.9 σ
$K^{*+}(892)K^{*-}(892)$	>8.0 σ	>8.0 σ
$K^+(1460)K^-$	>8.0 σ	6.4 σ
$K_0^{*+}(1430)K^{*-}(892)$	>8.0 σ	7.5 σ
$K_2^{*+}(1430)K^{*-}(892)$	–	6.4 σ
$K_1^+(1400)K^-$	>8.0 σ	>8.0 σ
$K_1^+(1270)K^-$	>8.0 σ	>8.0 σ
$K^{*+}(892)K^-\pi^0$	–	5.4 σ
$K^+K^- f_0(980)$	6.2 σ	>8.0 σ
$K^+K^-\sigma$	>8.0 σ	>8.0 σ
$K^+K^- f_0(1370)$	>8.0 σ	7.4 σ
$\omega(1420)\pi^0$	>8.0 σ	5.2 σ

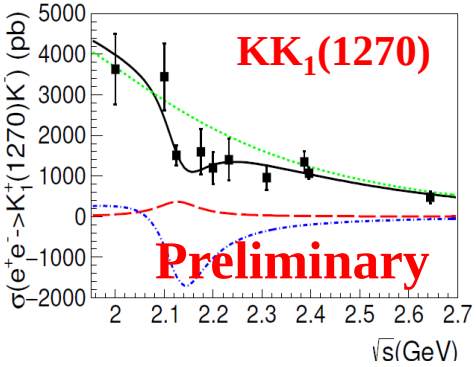
- **A PWA for multi-energy points @ [2.0, 2.644]GeV**
- **There is no significant signal of $e^+e^- \to KK^*(1410)$.**
- **Extract Born cross section of intermediate states.**

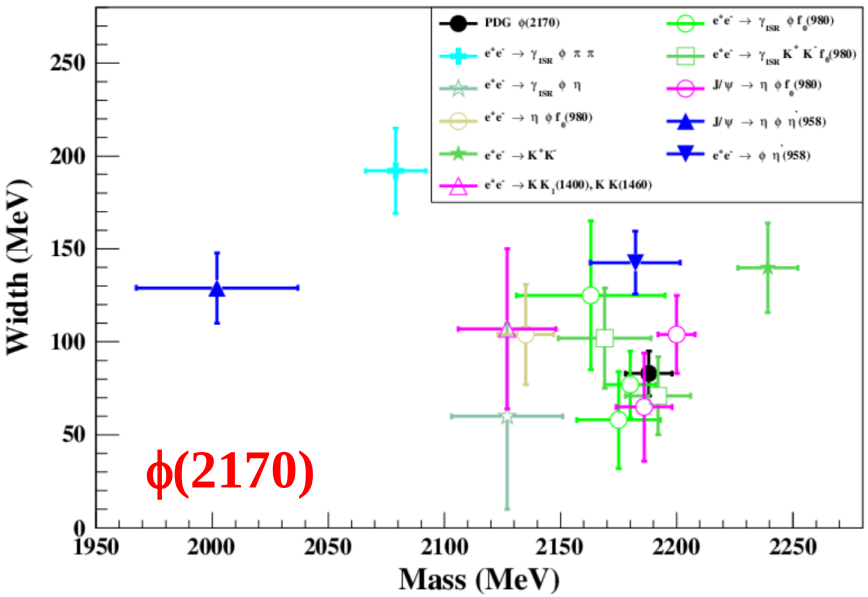
$e^+ e^- \to K^+ K^- \pi^0 \pi^0$











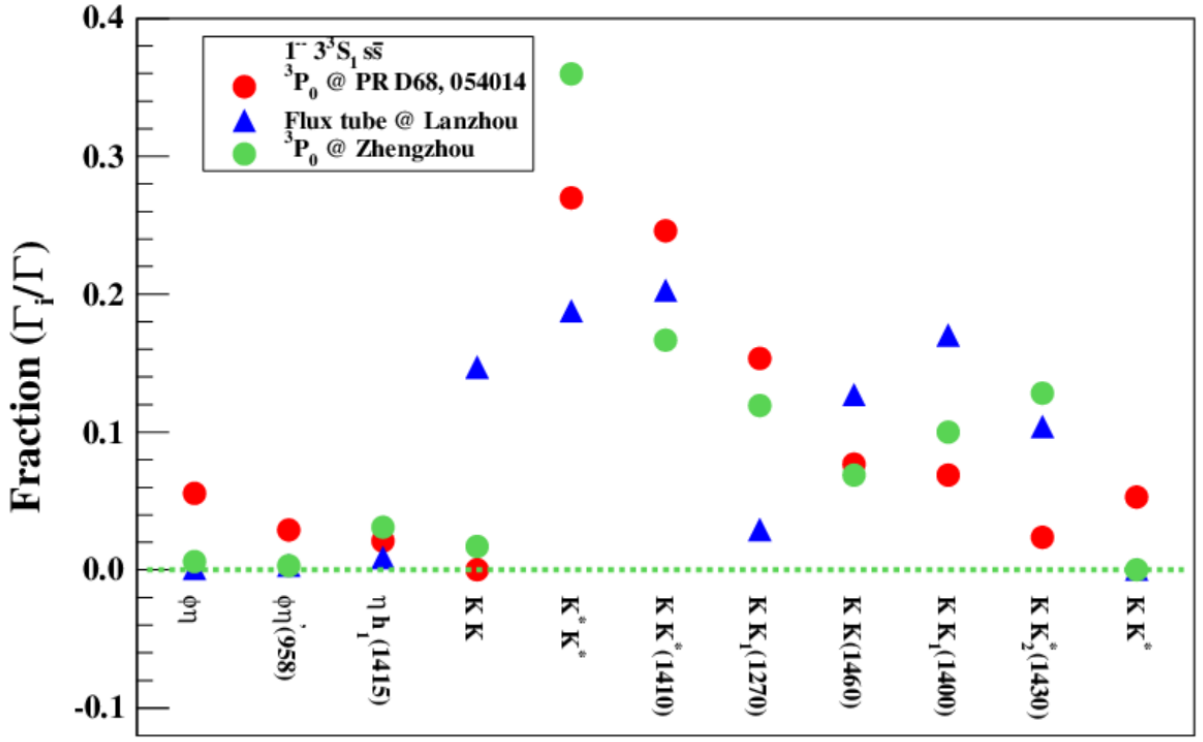
- ✓ **Dots: BESIII data**
- ✓ **Black curves: fit results**
- ✓ **Red long-dashed: ϕ(2170)**
- ✓ **Green shot-dashed: 1/s^n**
- ✓ **Blue dash-dotted: interference**

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

- ● **ϕ(2170) -> K K$_1$(1400) and K K(1460): Yes ?**

$1^{--}\ 3^3S_1\ s\bar{s}$



- Fraction Γ_i/Γ: weakly model & input parameters dependent
- Dominant decay modes: $KK^*(1410)$ & K^*K^*
- KK: sharp distinction ?

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

Decay modes	3^3S_1 $s\bar{s}$	
	$^3P_0$ model	Lanzhou
KK	0	35.8
K^*K^*	102	45.7
KK(1460)	29	30.9
$KK^*(1410)$	93	49.3
$KK_1(1270)$	58	7.1
$KK_1(1400)$	26	41.4
$KK_2^*(1430)$	9.0	25.2
$\phi\eta$	21	0.3
$\phi\eta'$	11	0.8

- 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 $s\bar{s}$: ???

1^{--} $s\bar{s}g$

Decay modes	1^{--} $s\bar{s}g$				$\phi(2170)$
	Ding	IKP	standard	2.2GeV	BESIII
KK	0				NO
K^*K^*	0				NO
KK(1460)	0				Yes
$KK^*(1410)$	23	9	11	55	NO
$KK_1(1270)$	35.3	26	18.1	16.6	?
$KK_1(1400)$	70.1	63.7	32.04	40.6	Yes
$KK_2^*(1430)$	15.0	2	0.07	2	Not yet
$\phi\eta$	1.2	3	11	19	Not yet
$\phi\eta'$	0.4	0.02	0.1	2	Yes

- No $\phi(2170)$ at $K^*(1410)$
- Yes $\phi(2170)$ at KK(1460) line-shape
- Small $\Gamma(\phi\eta)/\Gamma(\phi\eta')$ at BESIII

Summary and outlook

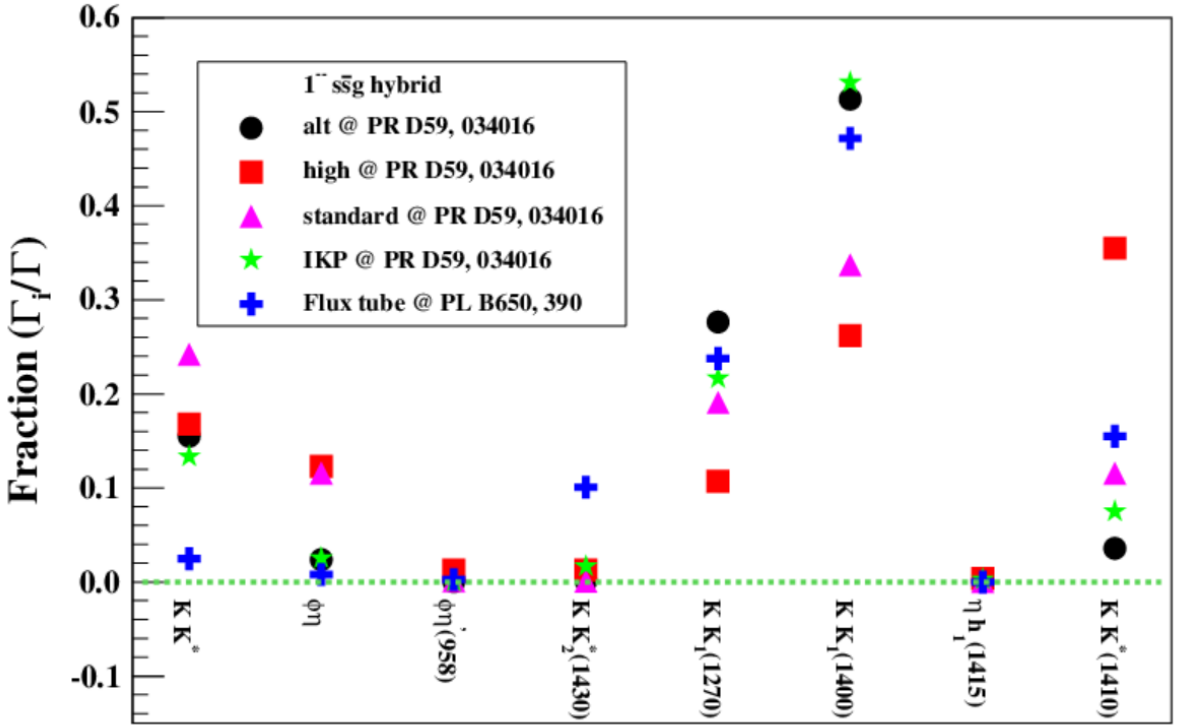
- Compared with $c\bar{c}$ and $b\bar{b}$, $s\bar{s}$ is a terra incognita
- Aspects of $\phi(2170)$ are still not fully understood
- Using BESIII R scan data, we are extensively studying $\phi(2170)$
  - ✓ $\phi(2170)$ as pure 3^3S_1 $s\bar{s}$: ???
  - ✓ $\phi(2170)$ as pure 2^3D_1 $s\bar{s}$: ???
  - ✓ $\phi(2170)$ as molecular state $\Lambda\bar{\Lambda}$: ???
  - ✓ $\phi(2170)$ as three body system ϕKK: ???
  - ✓ $\phi(2170)$ as 1^{--} $s\bar{s}g$ hybrid: ???
  - ✓ $\phi(2170)$ as tetraquark: ???
  - ✓ $\phi(2170)$ as mixing state: ???
- Theorists revisited $\phi(2170)$ decay again, please.

1^{--} $s\bar{s}g$ hybrid

1^{--} $s\bar{s}g$	alt	2.2GeV	standard	IKP	Ding
	PRD59, 034016				PLB650,390
K^*K	13	26	23	16	3.7
$\phi\eta$	2	19	11	3	1.2
$\phi\eta'$	0.01	2	0.1	0.02	0.4
$KK_2^*(1430)$	0.1	2	0.07	2	15
$KK_1(1270)$	23.2	16.6	18.1	26	35.3
$KK_1(1400)$	43.1	40.6	32.04	63.7	70.1
$h_1(1415)\eta$	0.07	0.6	0.04	0.3	0
$KK^*(1410)$	3	55	11	9	23
Width(MeV)	84	155	95	120	148.7

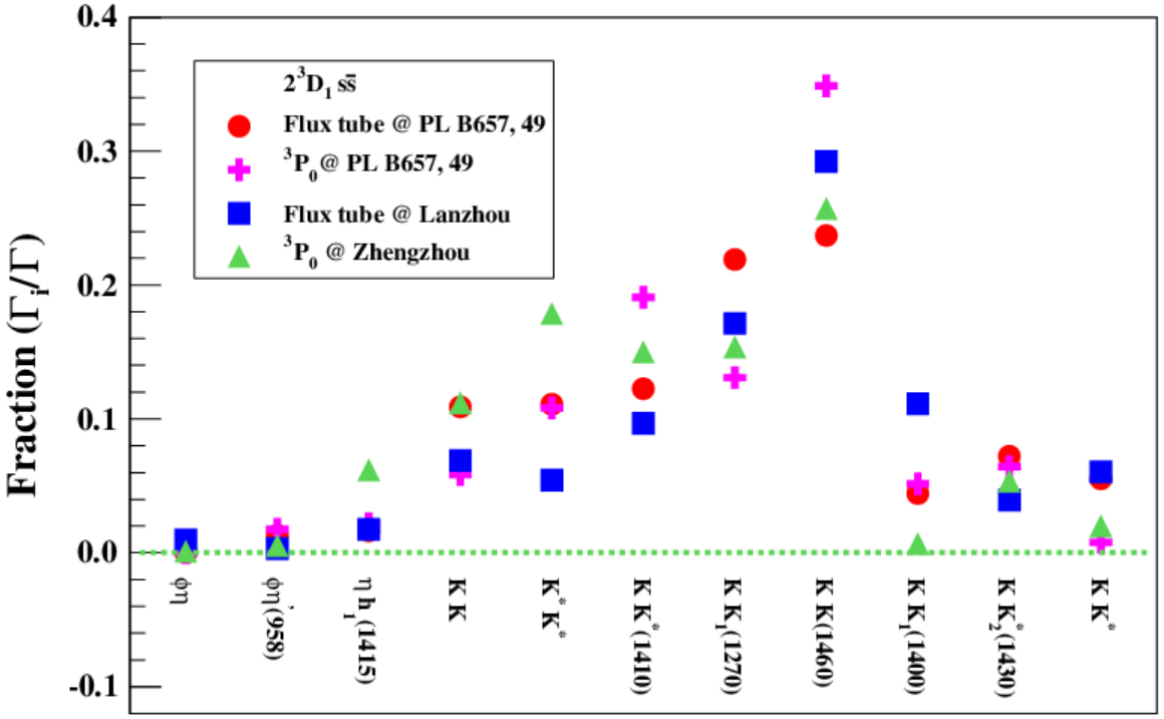
- **Theory prediction: model & input parameters dependent**

1^{--} $s\bar{s}g$ hybrid



- Fraction Γ_i/Γ: weakly model & input parameters dependent
- Dominant decay modes: $KK_1(1400)$ & $KK_1(1270)$

$1^- 2^3D_1\ s\bar{s}$



- Fraction Γ_i/Γ: weakly model & input parameters dependent
- Dominant decay modes: KK(1460) & $KK_1(1270)$

$\phi(2170)$: $2^3D_1\ s\bar{s}$

Decay modes	$2^3D_1\ s\bar{s}$			$\phi(2170)$
	$^3P_0$ model	Flux tube	Lanzhou	BESIII
KK	9.8	23.1	40.8	NO
K^*K^*	18.11	23.5	32.2	NO
KK(1460)	58.3	50.2	173.5	YES
$KK^*(1410)$	31.9	26.0	57.3	NO
$KK_1(1270)$	21.9	46.4	101.5	?
$KK_1(1400)$	8.6	9.4	65.9	Yes
$KK_2^*(1430)$	10.8	15.3	23.3	Not yet
$\phi\eta$	0	0	5.7	Not yet
$\phi\eta'$	2.9	2.8	1.8	Yes

- No $\phi(2170)$ at KK, K*K* and $KK_1(1270)$ line-shape
- Yes $\phi(2170)$ at $KK_1(1400)$

$\phi(2170)$ @ $\phi f_0(980)$

$\phi f_0(980)$	Mass (MeV)	Width (MeV)	Events
BaBar (2006)	2175±10±15	58±16±20	271
BES (2008)	2186±10±6	65±23±17	52
Belle (2009)	2163±32	125±40	4.8K
BaBar (2012)	2172±10±8	96±19±12	
BESIII (2015)	2200±6±5	104±15±15	471
BESIII (2019)	2135±8±9	104±24±12	95
PDG2018	2188±10	83±12	

- $\phi(2170)$ @ PDG2019: NO PDG estimated value