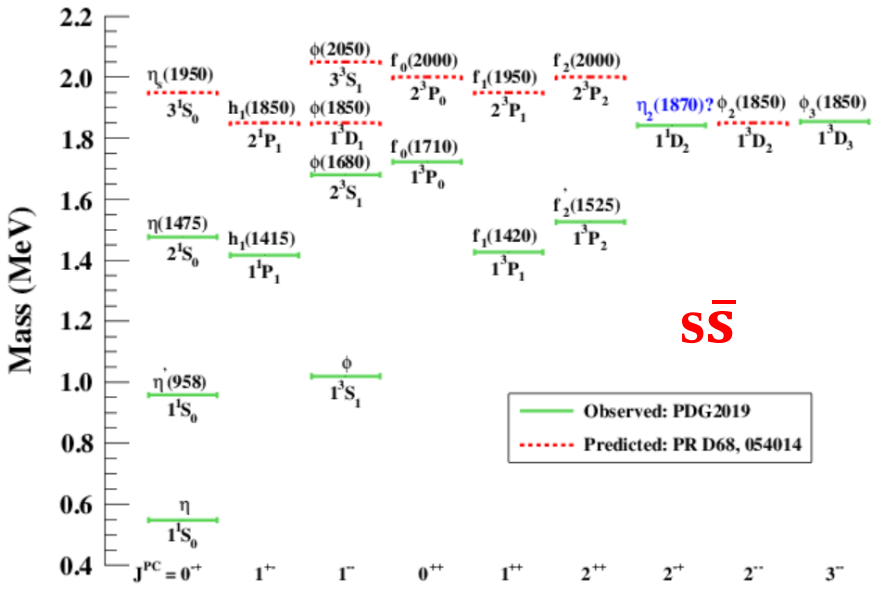
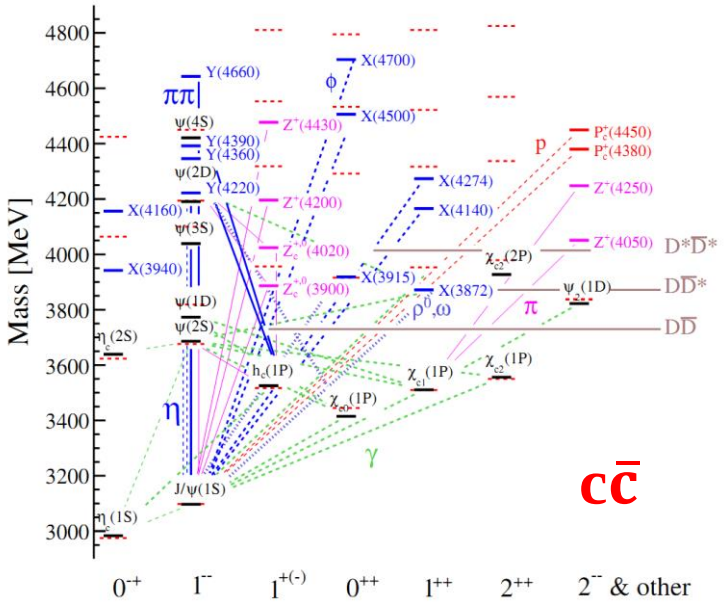
Study of $\phi(2170)$ at BESIII

Wenbiao Yan (USTC)

On behalf of BESIII Collaboration

Strange quarkonium





- **Compared with $c\bar{c}$ and $b\bar{b}$, $s\bar{s}$ is a terra incognita.**
- **There are XYZ particles with c & b quark, how about XYZ particles with strange quark ?**

Eur. Phys. J. C72, 2008

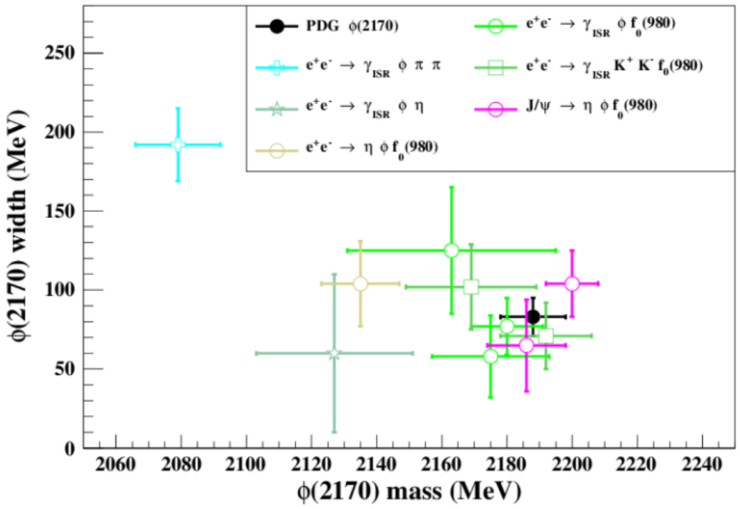
$$e^+e^- \Rightarrow \begin{cases} Y(2175) \to \phi(1020)\pi^+\pi^- & \text{strange,} \\ Y(4260) \to J/\psi\pi^+\pi^- & \text{charm,} \\ \Upsilon(10860) \to \Upsilon(1S,2S)\pi^+\pi^- & \text{bottom,} \end{cases}$$

$\phi(2170)$ as strange analogue of Y(4220)

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

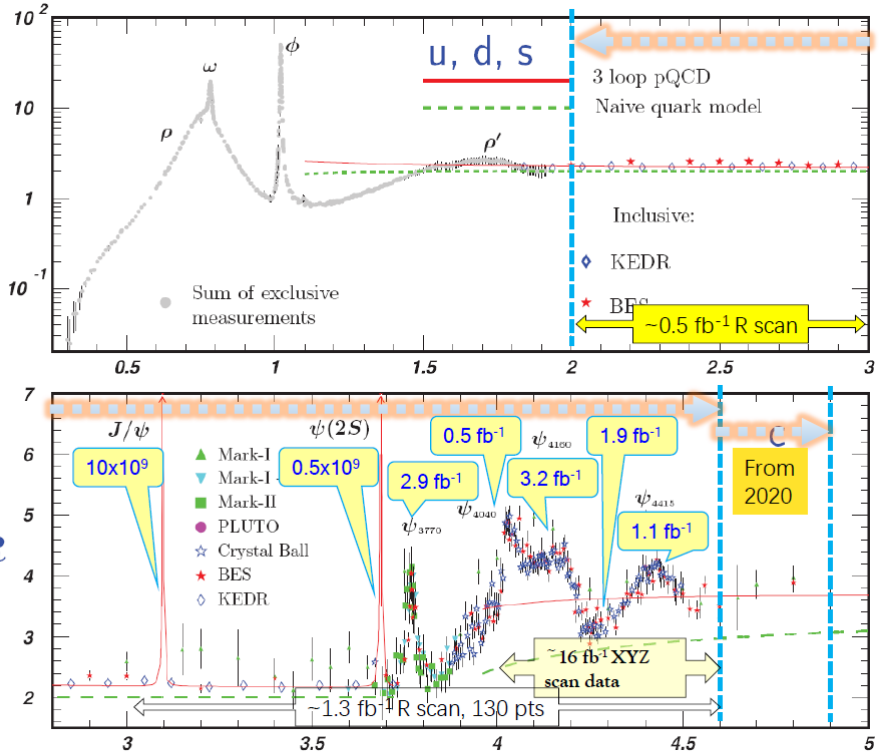
PDG $\phi(2170)$ DECAY MODES

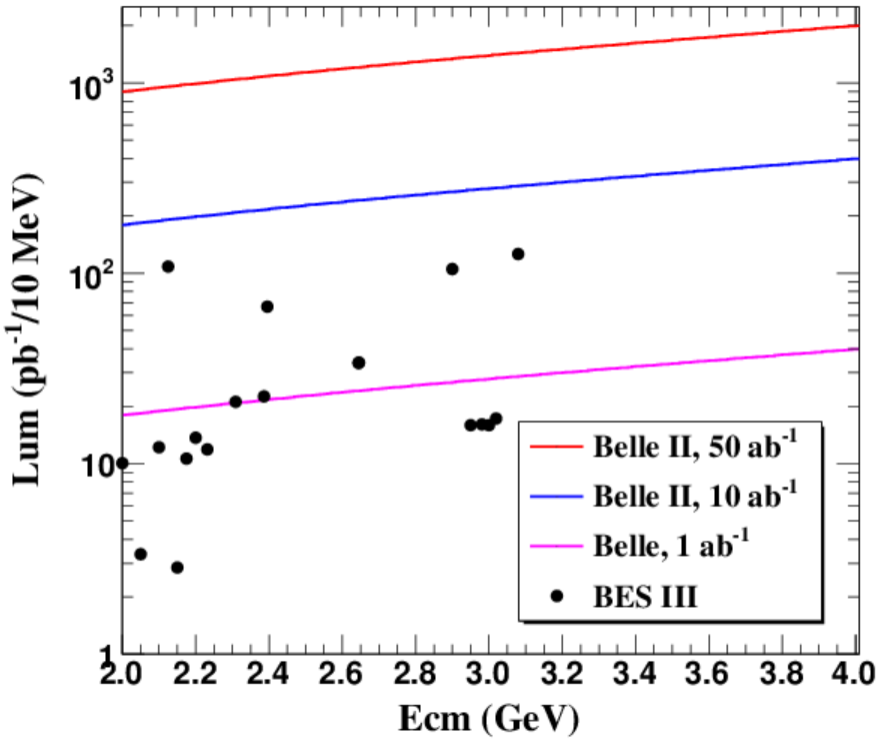
	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	seen
Γ_2	$\phi\eta$	
Γ_3	$\phi\pi\pi$	
Γ_4	$\phi f_0(980)$	seen
Γ_5	$K^+K^-\pi^+\pi^-$	
Γ_6	$K^+K^-f_0(980) \rightarrow K^+K^-\pi^+\pi^-$	seen
Γ_7	$K^+K^-\pi^0\pi^0$	
Γ_8	$K^+K^-f_0(980) \rightarrow K^+K^-\pi^0\pi^0$	seen
Γ_9	$K^{*0}K^{\pm}\pi^{\mp}$	not seen
Γ_{10}	$K^*(892)^0\overline{K}^*(892)^0$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

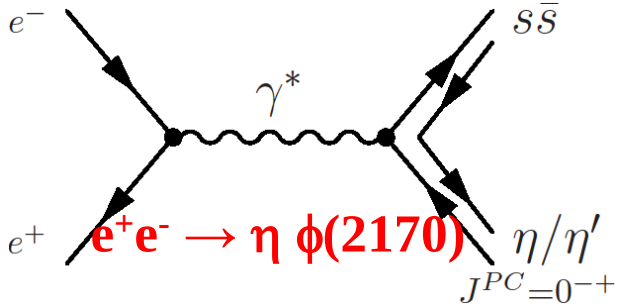


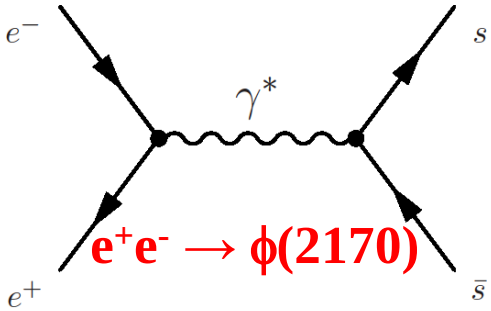
- **Published experimental information**
  - ✓ **Limited decay modes**
  - ✓ **Inconsistence on mass & width**
- **Theorists explain $\phi(2170)$ as**
  - ✓ **$s\bar{s}g$ hybrid**
  - ✓ **2^3D_1 or 3^3S_1 $s\bar{s}$**
  - ✓ **tetraquark**
  - ✓ **Molecular state $\Lambda\bar{\Lambda}$**
  - ✓ **$\phi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

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



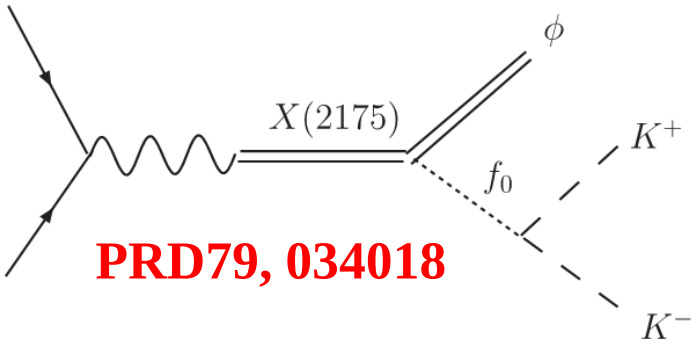




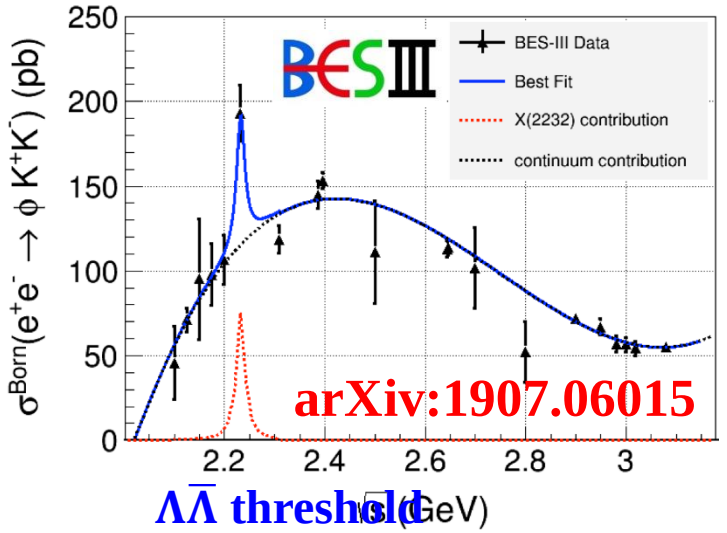


$e^+ e^- \to \phi K^+ K^-$

- **ϕ(2170): resonant of ϕKK**

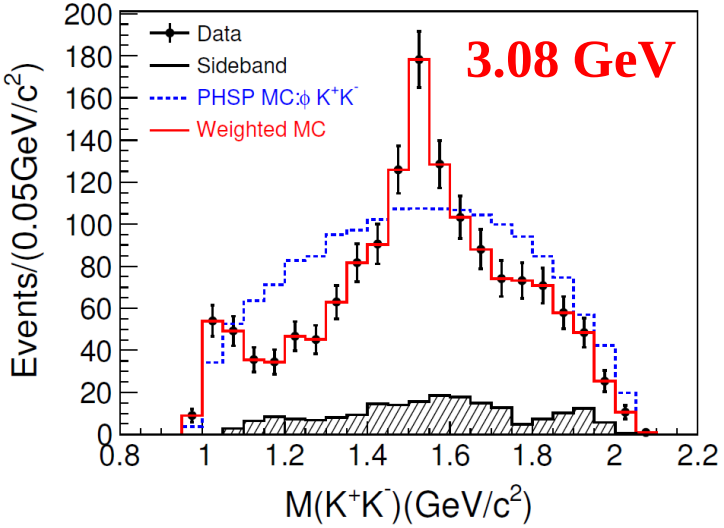


PRD79, 034018



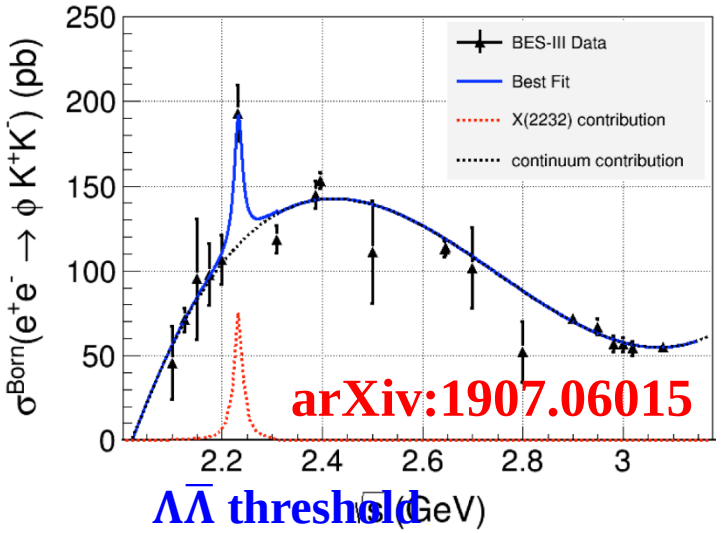
arXiv:1907.06015

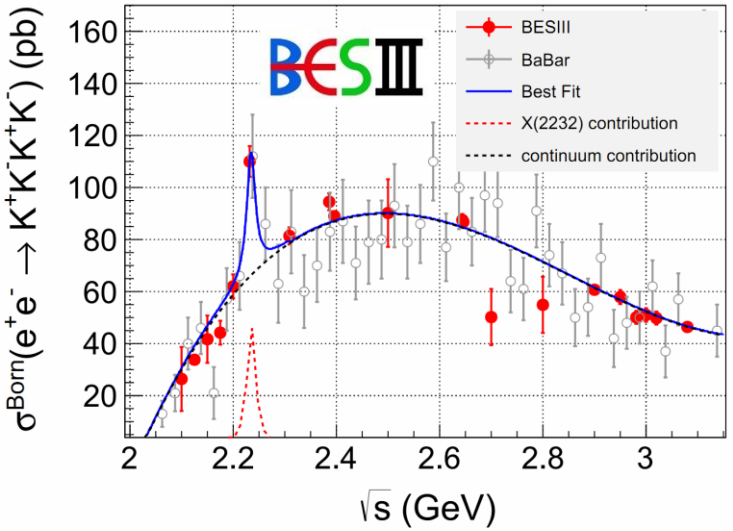
$\Lambda\bar{\Lambda}$ threshold

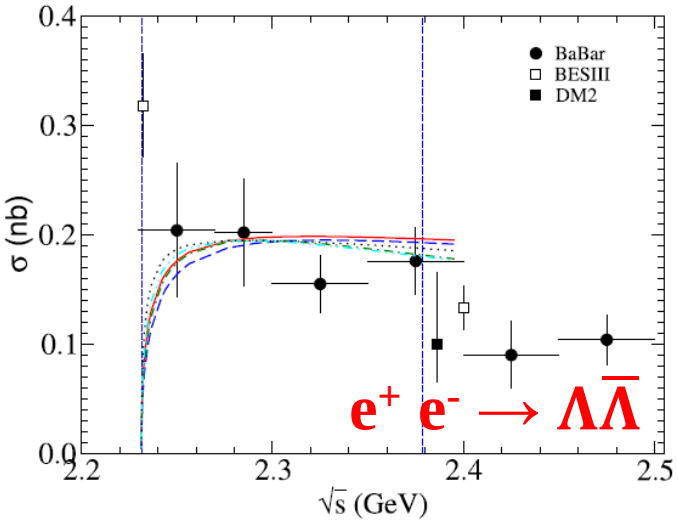


- **A hint for a resonance around $\Lambda\bar{\Lambda}$ threshold**
  - ✓ **Mass = 2232±3.5MeV;**
  - ✓ **Width < 20 MeV**
- **(no-ϕ) $K^+ K^-$: $f_0(980)$, $f_2'(1525)$**

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







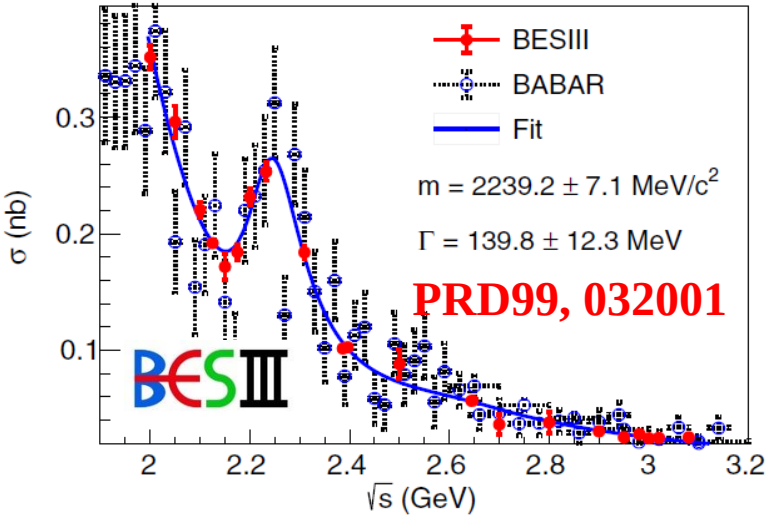
- ϕK^+K^- and $2(K^+K^-)$ have similar enhancement around 2.2324 GeV
- Due to $\Lambda\bar{\Lambda}$ threshold ?

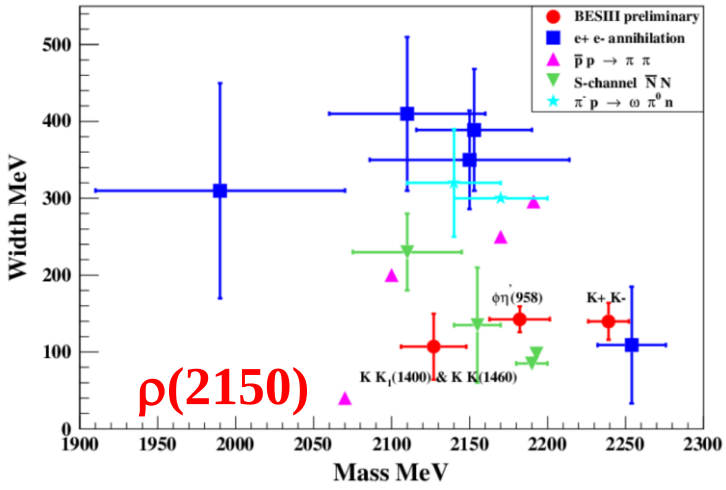
$e^+ e^- \to K^+ K^-$

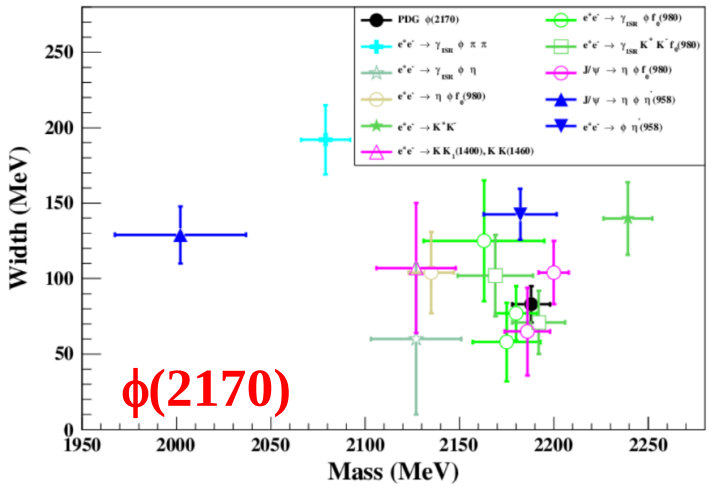
- **$\phi(2170)$ as $^3S_1\Lambda\bar{\Lambda}$ molecular**
- **Isoscalar: ω^*/ϕ^*; isovector: ρ^***
  - ✓ **K^+K^- resonance: $\rho(2150)$?**

$\phi(2170)$ 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

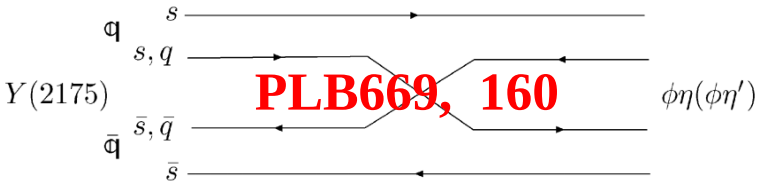




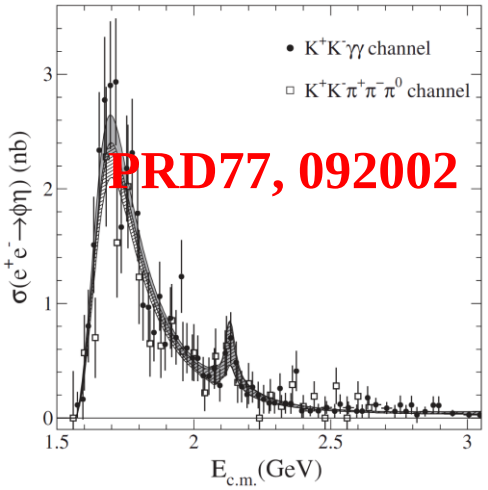


$e^+ e^- \rightarrow \phi\eta$ and $\phi\eta'$

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



PLB669, 160



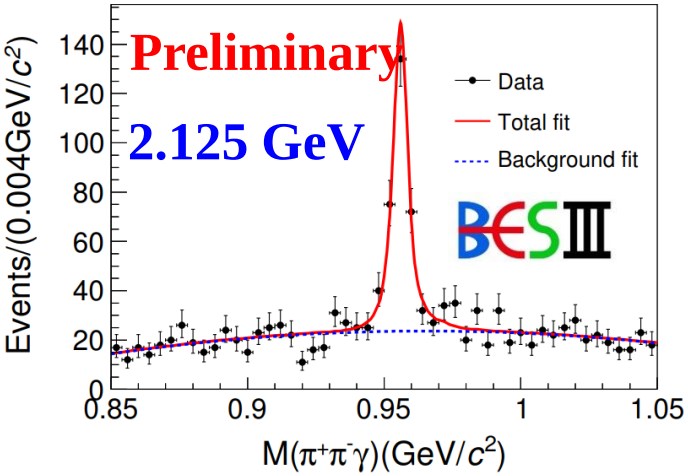
PRD77, 092002

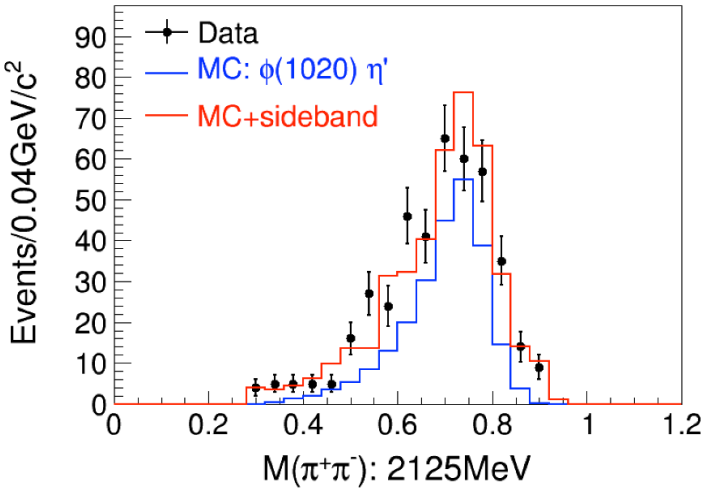
- 1^{--} $s\bar{s}g$ has large $\Gamma_{\phi\eta}$ and smaller $\Gamma_{\phi\eta'}$

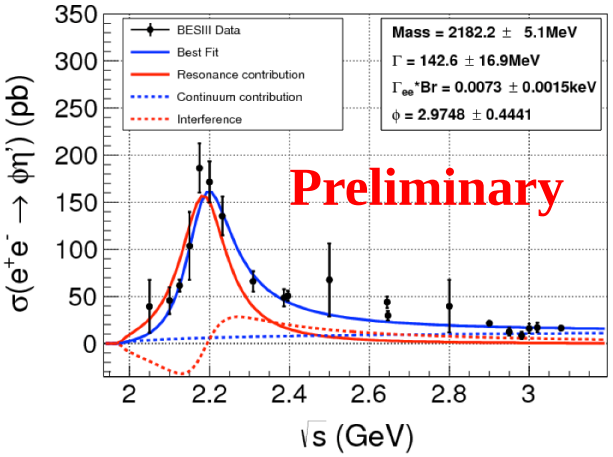
1^{--} $s\bar{s}g$	alt	2.2GeV	standard	IKP	Ding
	PRD59, 034016				PLB650,390
$\phi\eta$	2	19	11	3	1.2
$\phi\eta'$	0.01	2	0.1	0.02	0.4
$\Gamma(\phi\eta')/\Gamma(\phi\eta)$	200	9.5	110	150	3

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

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

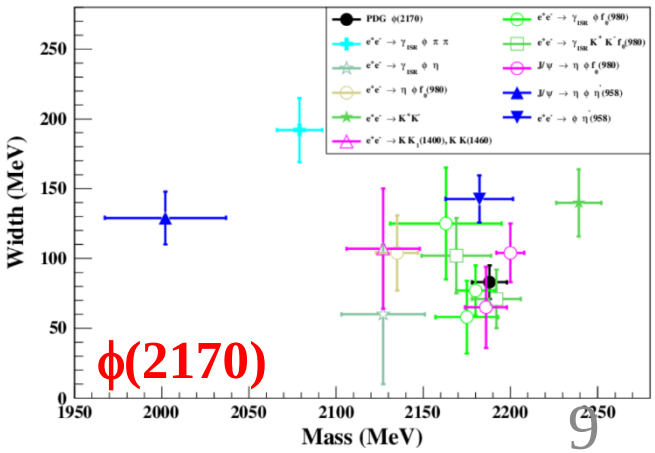






$$\frac{M_R}{\sqrt{s}} \frac{\sqrt{12\pi\Gamma^R_{e^+e^-}\mathcal{B}_{\mathcal{R}}(\phi\,\eta')\Gamma^R_{tot}}}{s - M_R^2 + iM_R\Gamma^R_{tot}} \cdot \sqrt{\frac{\Phi(\sqrt{s})}{\Phi(M_R)}}$$

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



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

- **$e^+ e^- \to \phi\eta$ and $\phi\eta'$**
  - ✓ **$\phi\eta$ @ BaBar: 1.7±0.7±1.3eV**

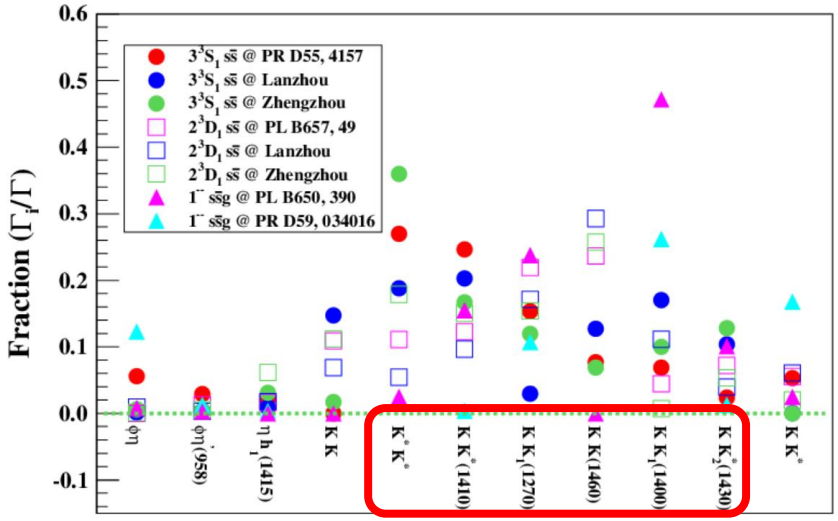
$$\frac{\text{BaBar: Br}[\phi(2170)\to\phi\eta]\Gamma_{ee}}{\text{BESIII: Br}[\phi(2170)\to\phi\eta']\Gamma_{ee}} = \mathbf{0.23\pm0.11}$$

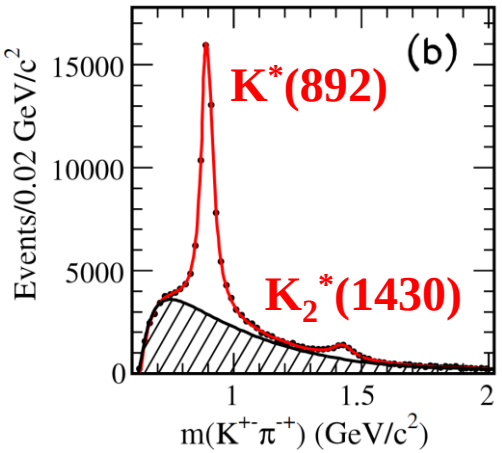
- **If we observed $\phi(2170)$ in $e^+ e^- \to \phi\eta'$, $\phi(2170)$ as an 1^{--} $s\bar{s}g$?**

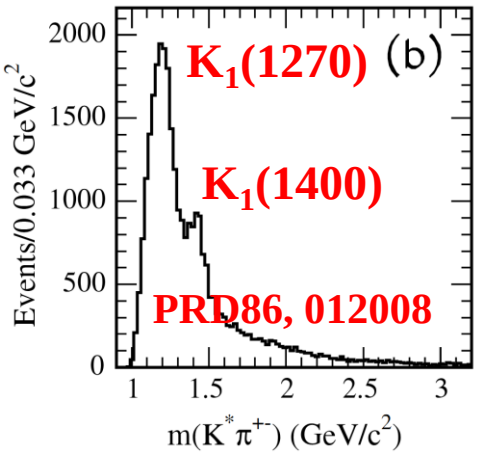
1^{--} $s\bar{s}g$	alt	2.2GeV	standard	IKP	Ding
	PRD59, 034016				PLB650,390
$\phi\eta$	2	19	11	3	1.2
$\phi\eta'$	0.01	2	0.1	0.02	0.4
$\Gamma(\phi\eta')/\Gamma(\phi\eta)$	200	9.5	110	150	3

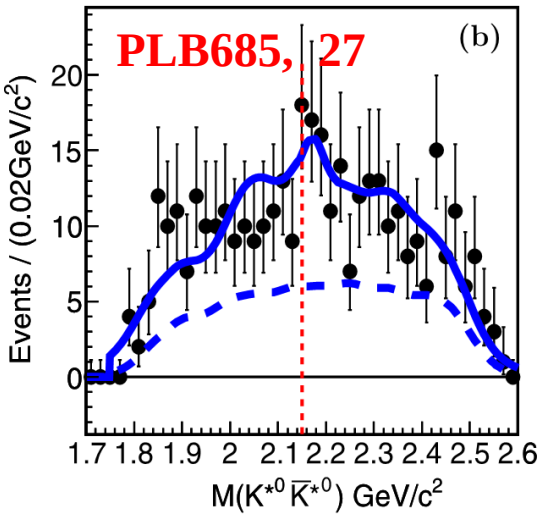
$e^+ e^- \to K K \pi \pi$

- The KKππ mode is important to distinguish ϕ(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)
- $K^+K^-\pi^+\pi^-$ & $K^+K^-\pi^0\pi^0$ @ BaBar
- $J/\psi \to \eta\phi(2170) \to \eta K^*K^*$ @ BES

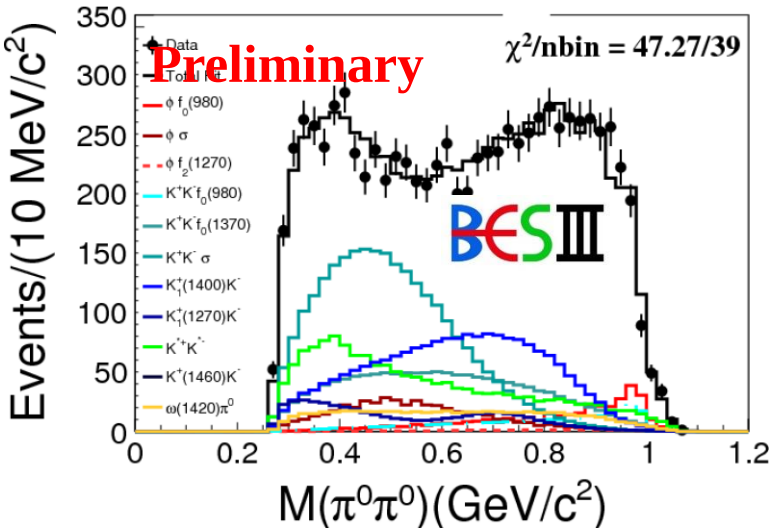




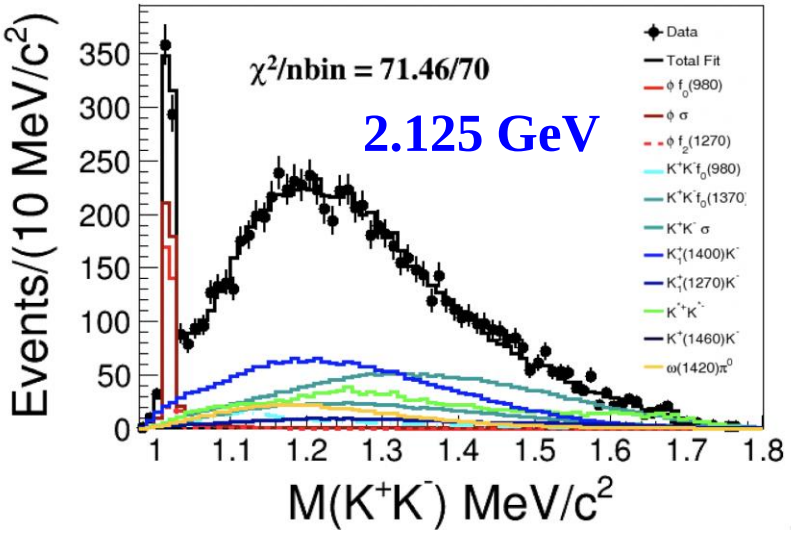




$e^+ e^- \to K^+ K^- \pi^0 \pi^0$

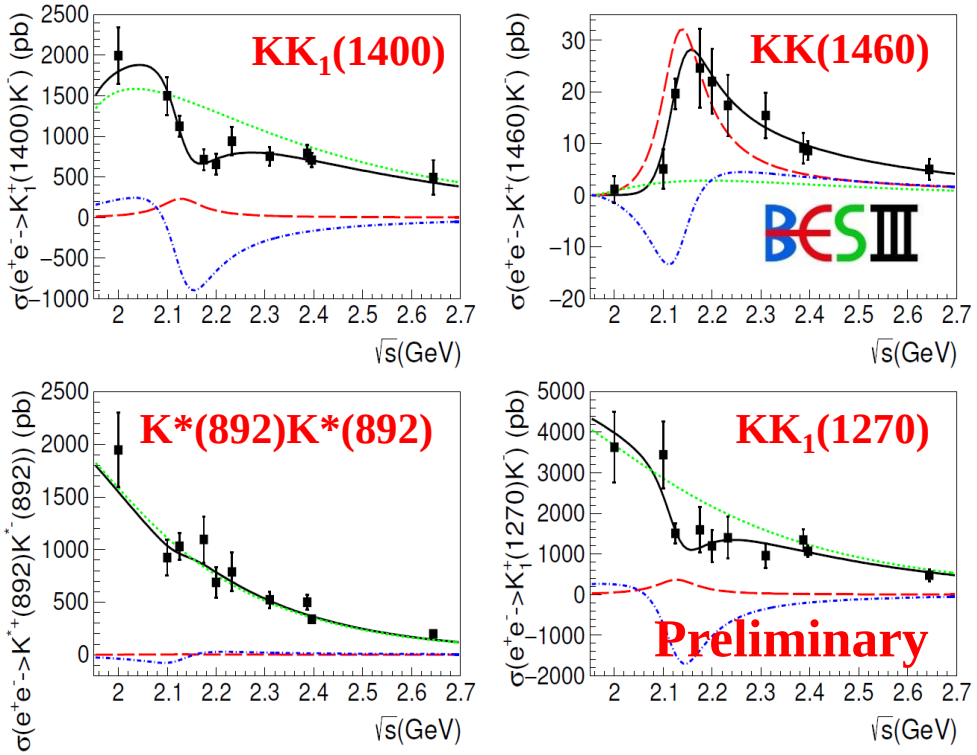


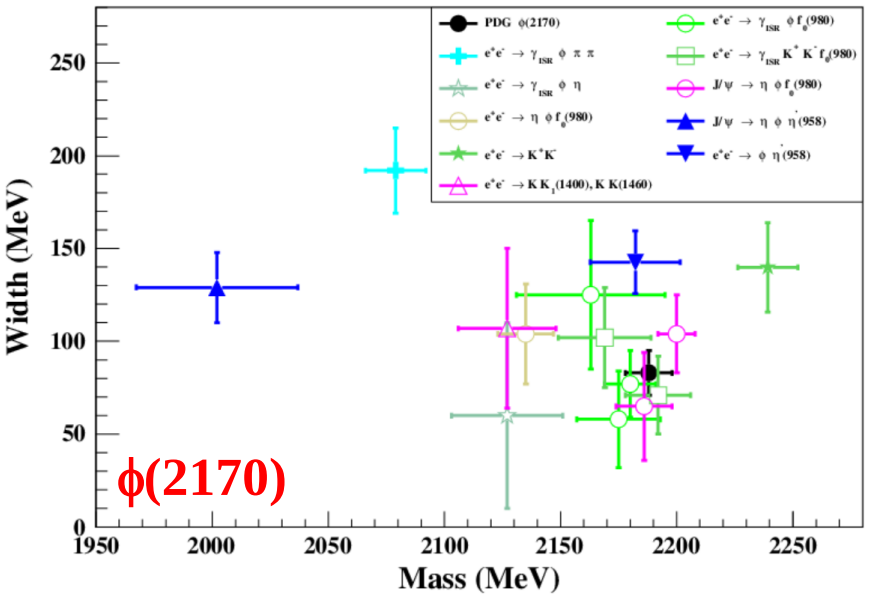
process	Significance (2.1250 GeV)	Significance (2.3960 GeV)
$\phi f_0(980)$	$>8.0\ \sigma$	$>8.0\ \sigma$
$\phi\sigma$	$>8.0\ \sigma$	**2776 event**
$\phi f_2(1270)$	$5.0\ \sigma$	–
$\phi f_0(1370)$	**8544 event**	$6.9\ \sigma$
$K^{*+}(892)K^{*-}(892)$	$>8.0\ \sigma$	$>8.0\ \sigma$
$K^+(1460)K^-$	$>8.0\ \sigma$	$6.4\ \sigma$
$K_0^{*+}(1430)K^{*-}(892)$	$>8.0\ \sigma$	$7.5\ \sigma$
$K_2^{*+}(1430)K^{*-}(892)$	–	$6.4\ \sigma$
$K_1^+(1400)K^-$	$>8.0\ \sigma$	$>8.0\ \sigma$
$K_1^+(1270)K^-$	$>8.0\ \sigma$	$>8.0\ \sigma$
$K^{*+}(892)K^-\pi^0$	–	$5.4\ \sigma$
$K^+K^- f_0(980)$	$6.2\ \sigma$	$>8.0\ \sigma$
$K^+K^-\sigma$	$>8.0\ \sigma$	$>8.0\ \sigma$
$K^+K^- f_0(1370)$	$>8.0\ \sigma$	$7.4\ \sigma$
$\omega(1420)\pi^0$	$>8.0\ \sigma$	$5.2\ \sigma$



- **A PWA for multi-energy points @ [2.0, 2.644]GeV**
- **There is no significant signal of $e^+e^- \to KK^*(1410)$.**
- **Only dominant processes, $KK_1(1270)$, $KK_1(1400)$, $KK(1460)$ and K*+(892)K*-(892)**

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





- ✓ 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 ?

$\phi(2170)$ 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 $s\bar{s}$ No
- Similar check for modes
  - ✓ $KK^*(1410)$: No $\phi(2170)$
  - ✓ KK(1460): Yes $\phi(2170)$
- $\phi(2170)$ as pure 3^3S_1 $s\bar{s}$: No

- No $\phi(2170)$ at K^*K^* and $KK^*(1410)$
- Yes $\phi(2170)$ at KK(1460) and $KK_1(1400)$

$\phi(2170)$ as pure $2^3D_1\ s\bar{s}$?

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 $KK_1(1270)$
- Yes $\phi(2170)$ at $KK_1(1400)$

$\phi(2170)$ as pure 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)
- Small $\Gamma(\phi\eta)/\Gamma(\phi\eta')$

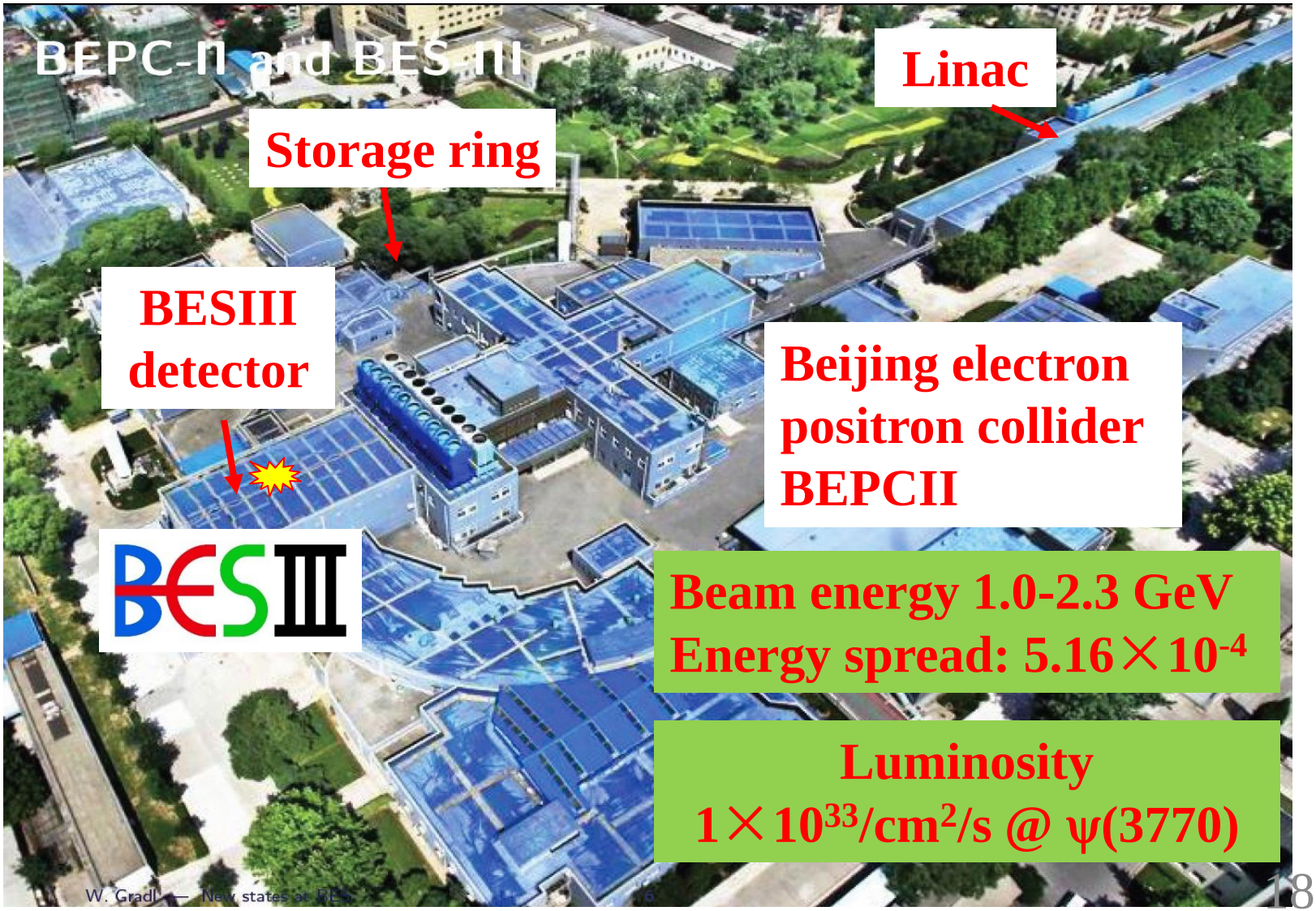
Summary and outlook

- 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 studying $\phi(2170)$
  - ✓ $e^+ e^- \to \phi K^+ K^-$: narrow enhancement around 2.2324 GeV
  - ✓ $e^+ e^- \to K^+ K^-$: (possible) $\rho(2150)$, (unlikely) $\phi(2170)$
  - ✓ $e^+ e^- \to \phi \eta'$: $\phi(2170)$ with

$$\frac{\text{BaBar: Br}[\phi(2170)\to\phi\eta]\Gamma_{ee}}{\text{BESIII: Br}[\phi(2170)\to\phi\eta\prime]\Gamma_{ee}} = 0.23\pm0.11$$

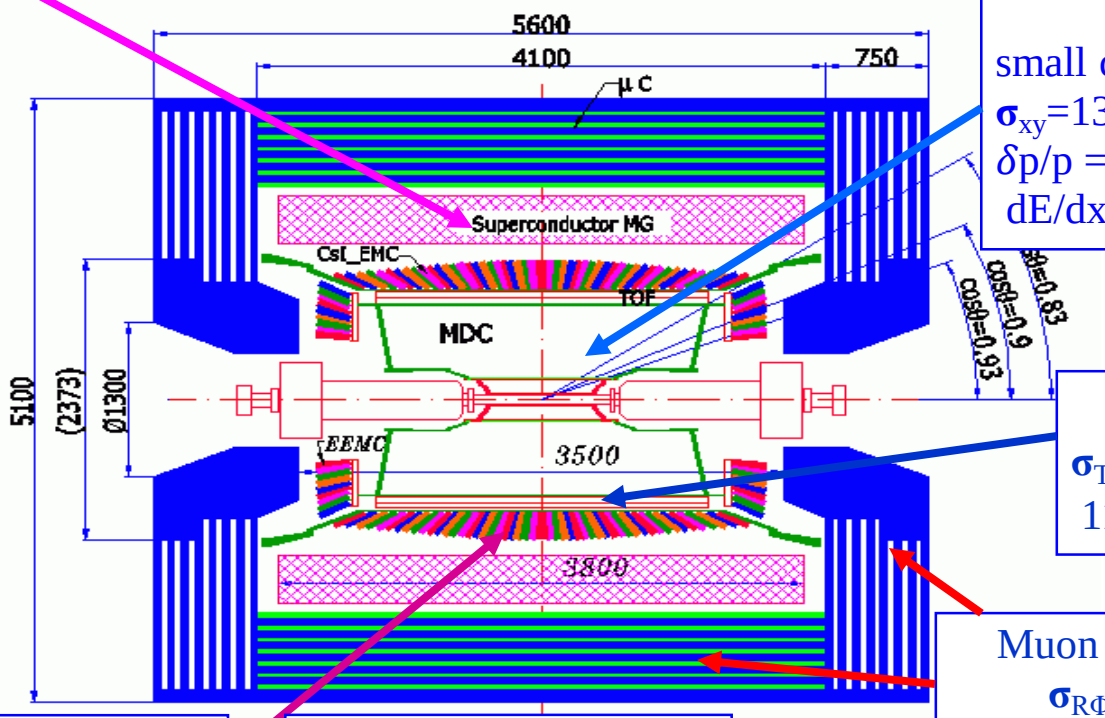
  - ✓ $e^+ e^- \to K^+ K^- \pi^0 \pi^0$: observe $\phi(2170)$ with $KK(1460)$ and $KK_1(1400)$, modes, without K^*K^* and $KK^*(1410)$ modes
- Apply reduction to absurdity, $\phi(2170)$ is not a pure 3^3S_1, 2^3D_1 $s\bar{s}$ and 1^{--} $s\bar{s}g$?
- Theorists revisit $\phi(2170)$ decay again, please.

Bird's View of BEPCII & BESIII



BESIII Detector

Solenoid Magnet: 1 T Super conducting



NIM A614 345 (2010)

MDC
small cell & He gas
σ_{xy}=130 μm
δp/p = 0.5%@1GeV
dE/dx=6%

TOF
σ_T = 90 ps Barrel
110->80ps Endcap

Muon ID: 8~9 layer RPC
$\sigma_{R\Phi}$=1.4 cm~1.7 cm

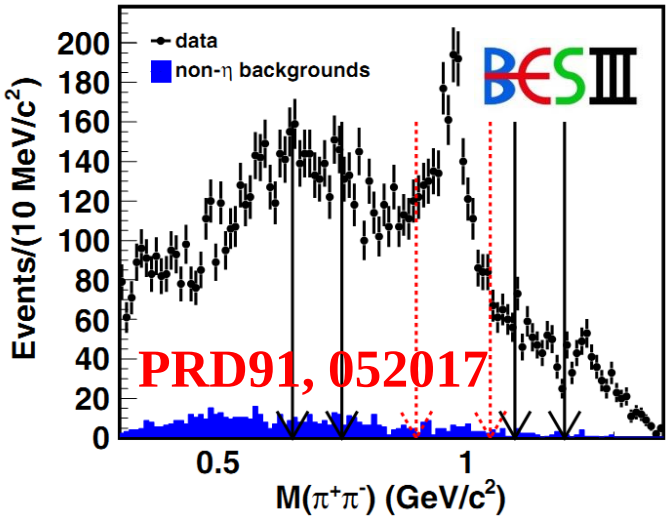
EMCAL: CsI crystal
ΔE/E = 2.5% @1 GeV
$\sigma_{\varphi,z}$ = 0.5~0.7 cm/√E

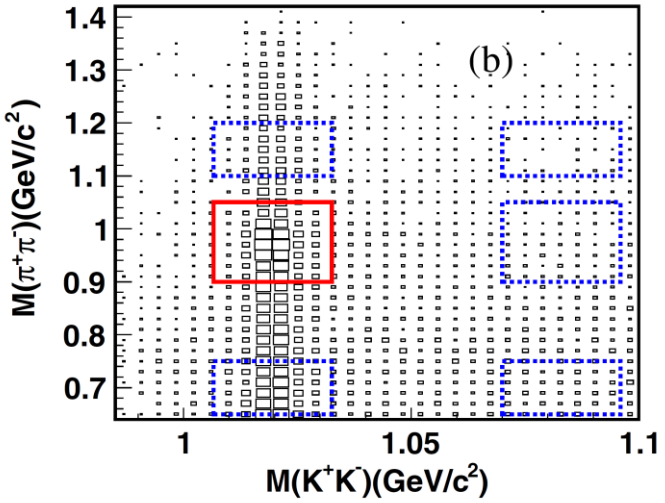
Data Acquisition:
Event rate = 3 kHz
Throughput ~ 50 MB/s

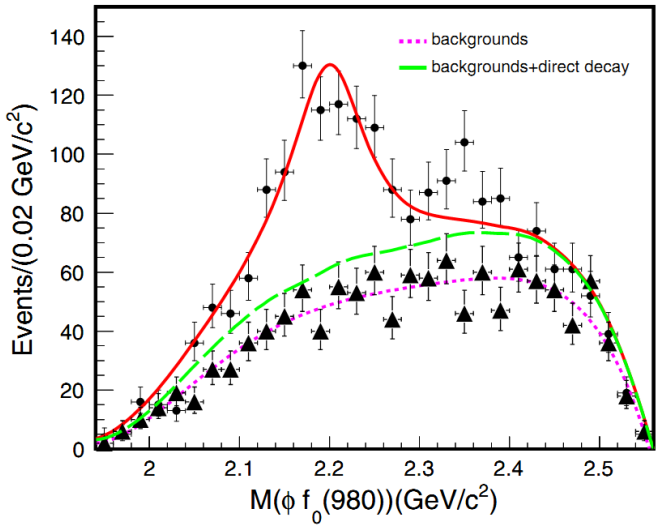
Trigger: Tracks & Showers
Pipelined; Latency = 6.4 μs

Hermetic spectrometer for neutral and charged particle with excellent resolution, PID, and large coverage

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



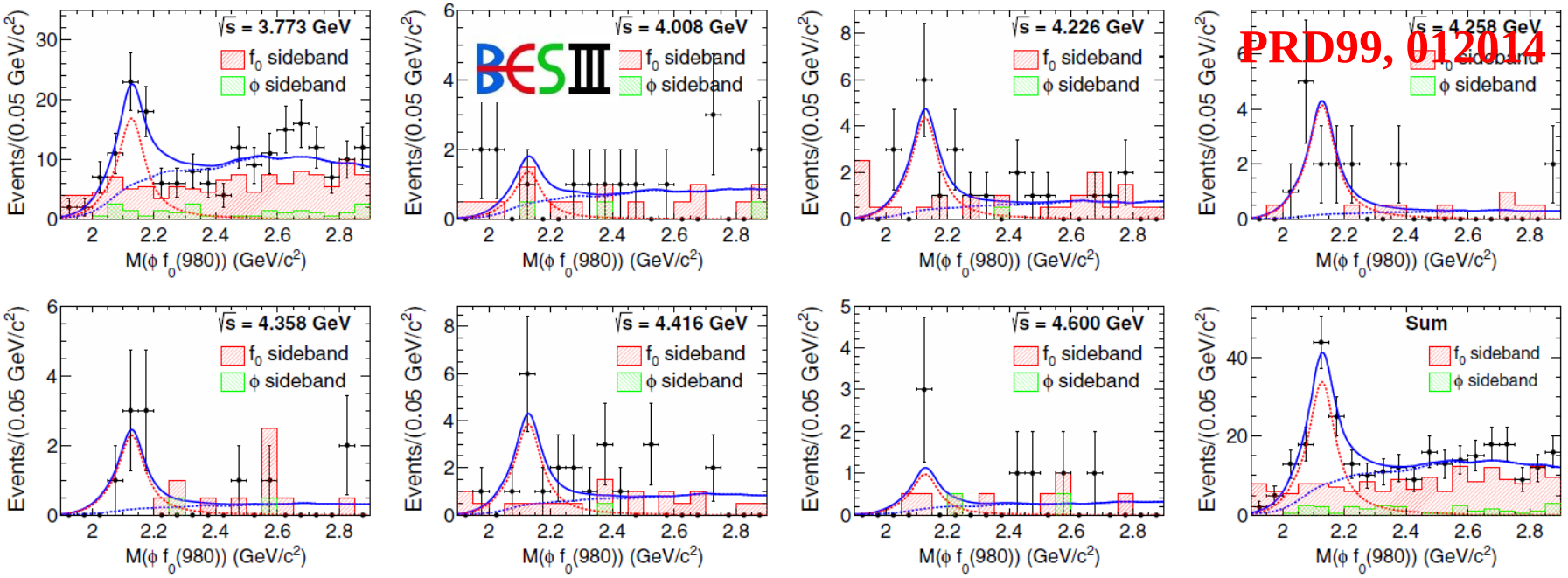




- **Fit: $\phi(2170)$ + direct decay of $/\psi \rightarrow \eta\phi f_0(980)$ + background**
- **No interference between $\phi(2170)$ and direct decay**

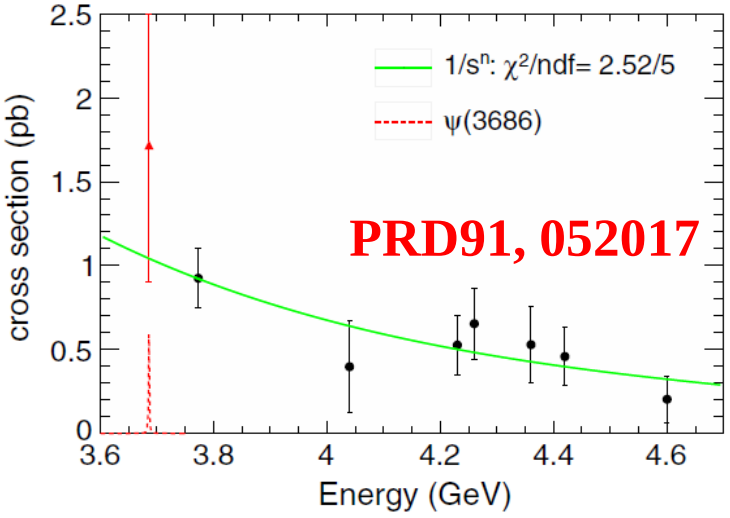
Decay mode	Branching fraction $\mathcal{B}$
$J/\psi \rightarrow \eta Y(2175)$, $Y(2175) \rightarrow \phi f_0(980)$, $f_0(980) \rightarrow \pi^+\pi^-$	$(1.20 \pm 0.14 \pm 0.37) \times 10^{-4}$

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

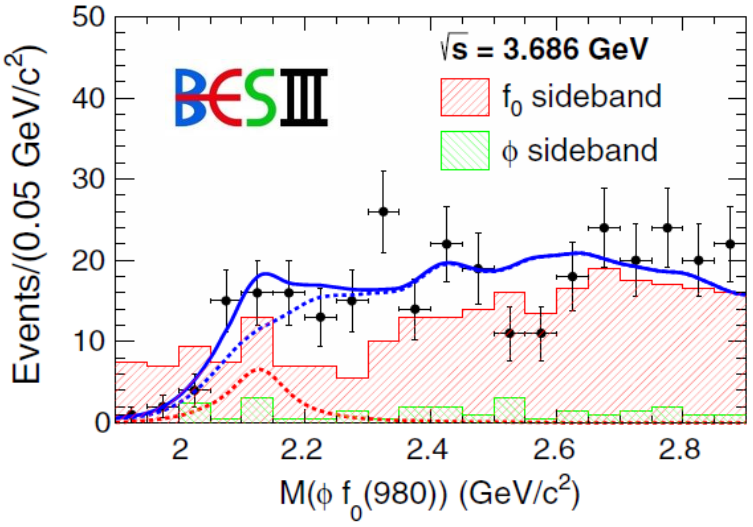


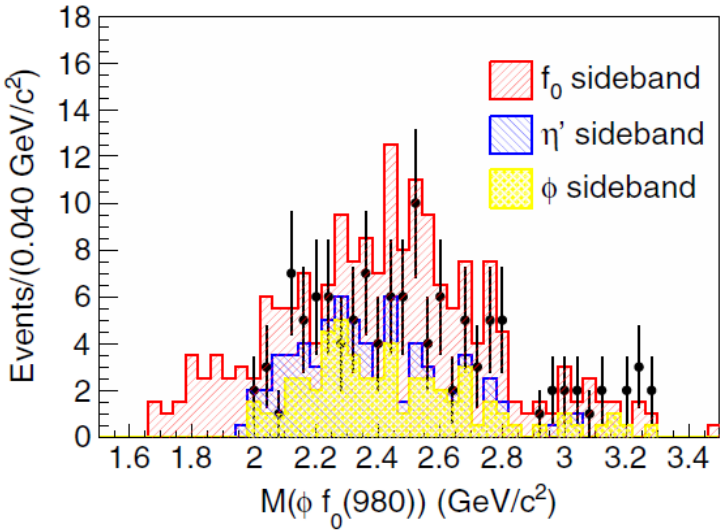
- $\phi(2170)$ @ ϕ $f_0(980)$ with $\sqrt{s}$ = [3.773, 4.600]GeV date
- Limited samples for $\phi(2170)$

$e^+ e^- \rightarrow \eta\, \phi(2170)$



- The Born cross section varies as $1/s^n$ with n=2.65±0.86.
- $Br[\psi(3686) \rightarrow \eta\phi(2170)] < 2.2*10^{-6}$ @ 90% U.L., suppression for "12% rule"
- No significant signal $e^+e^- \rightarrow \eta'\phi(2170)$
- $\dfrac{\sigma[e^+e^- \rightarrow \eta'\phi(2170)]}{\sigma[e^+e^- \rightarrow \eta\phi(2170)]} < 0.43$ @ 90% U.L.





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

$\phi f_0(980)$	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

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

Modes	$2^3D_1\ s\bar{s}$	$1^{--}\ s\bar{s}g$	$3^3S_1\ s\bar{s}$	$K^+K^-\pi^+\pi^-$	$K^+K^-\pi^0\pi^0$	$K^+K^-\pi^0$
	Flux tube	Flux tube	$^3P_0$			
K^*K^*	23.5	0	102	14.8%	7.4%	
KK(1460)	50.2	0	29	25.7%	6.4%	
$KK^*(1410)$	26.0	23	93	27.0%	6.4%	1.6%
$KK_1(1270)$	46.4	35.3	58	23.7%	4.0%	
$KK_1(1400)$	9.4	70.1	26	29.5%	7.4%	
$KK_2^*(1430)$	15.3	15.0	9.0	9.5%	1.9%	11.1%
$\phi\eta$	0	1.2	21			
$\phi\eta'$	2.8	0.4	11			

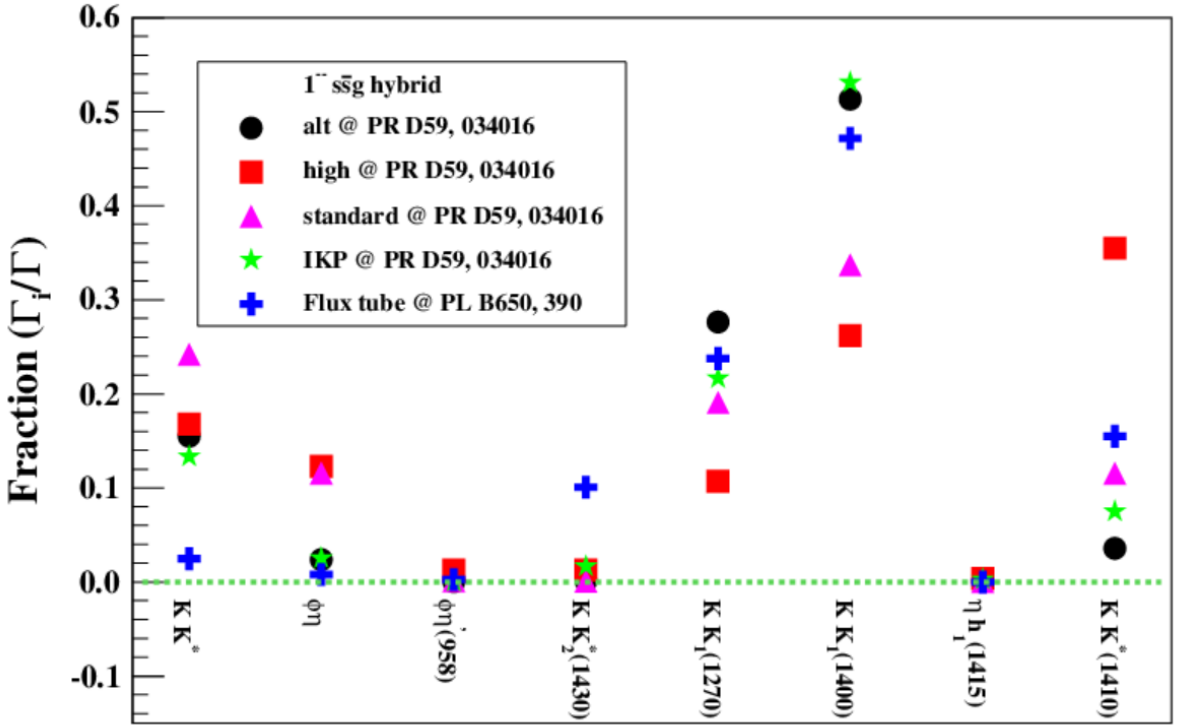
- Mode $K^+K^-\pi^+\pi^-$ is better than $K^+K^-\pi^0\pi^0$
- $KK_2^*(1430)$: (favored) $K^+K^-\pi^0$
- Notice: charged & neutral K meson; Brs

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

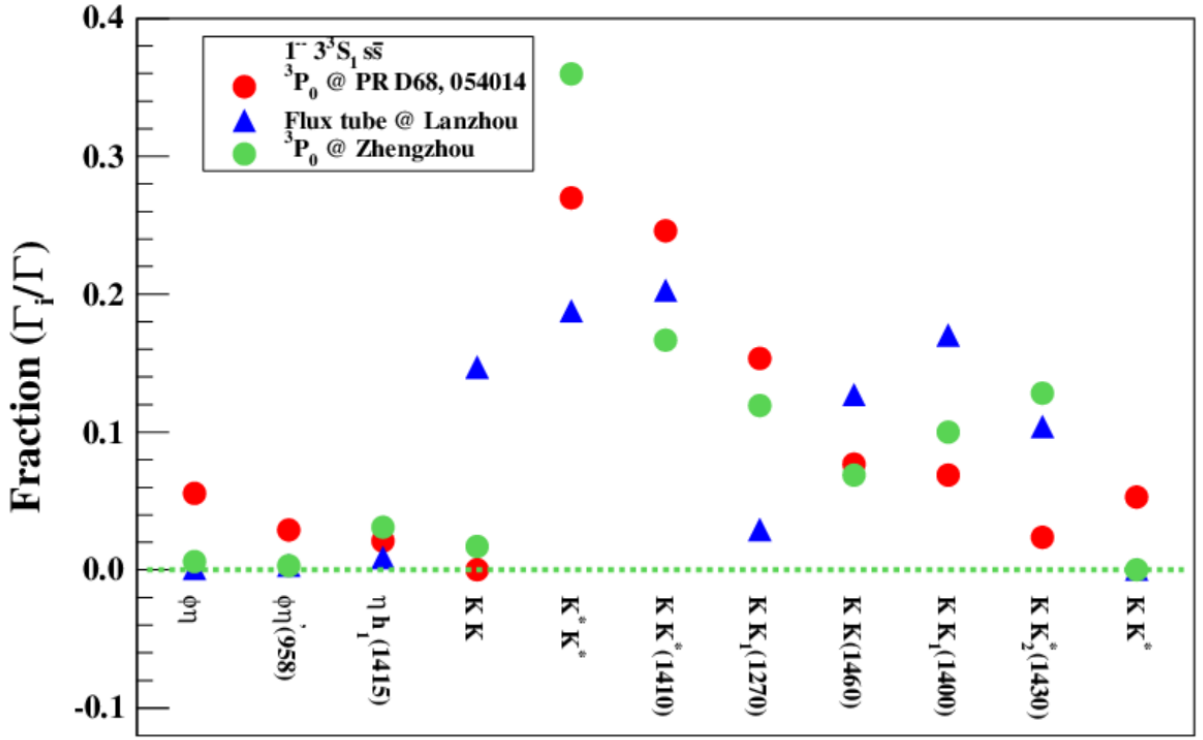
- Theory prediction: model & input parameters dependent

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



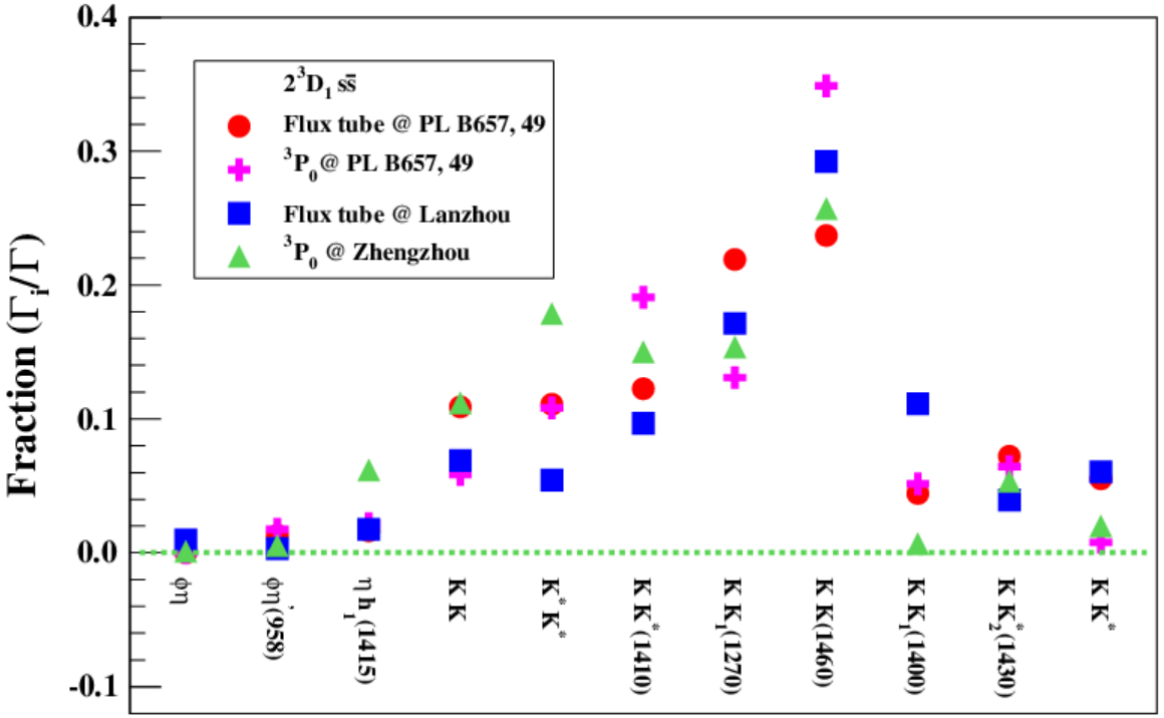
- Fraction Γ_i/Γ: weakly model & input parameters dependent
- Dominant decay modes: $KK_1(1400)$ & $KK_1(1270)$

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



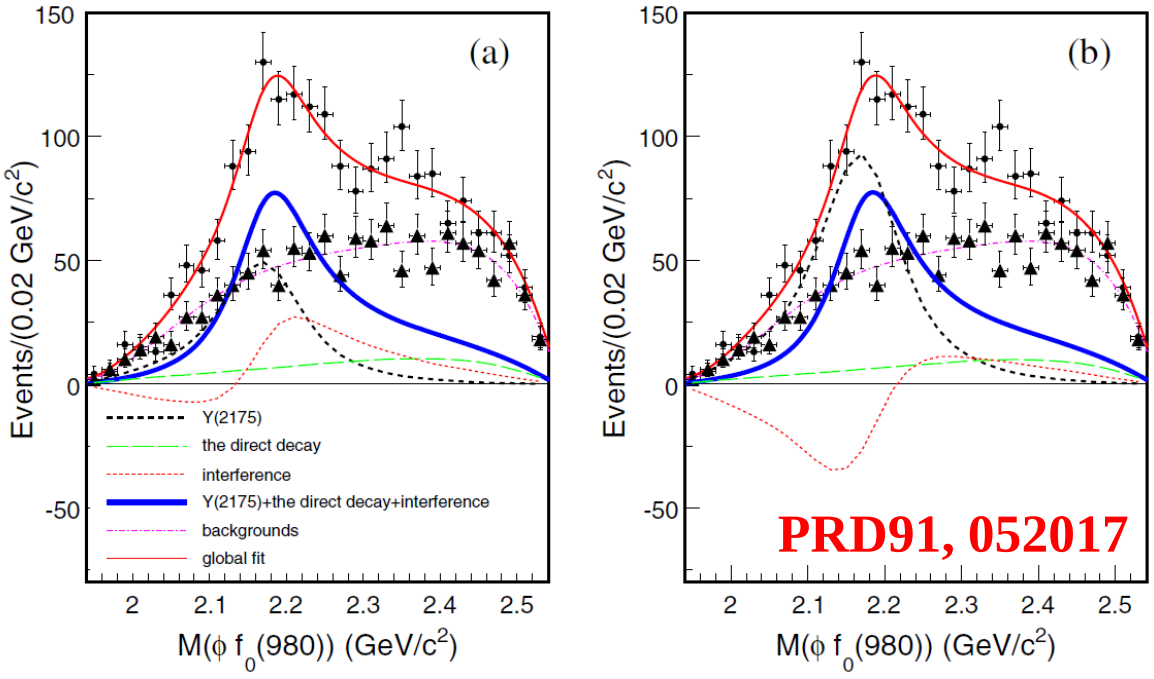
- Fraction Γ_i/Γ: weakly model & input parameters dependent
- Dominant decay modes: $KK^*(1410)$ & K^*K^*
- KK: sharp distinction ?

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



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

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



- Fit: $\phi(2170)$ + direct decay of $J/\psi \to \eta\phi f_0(980)$ + background
- Interference between $\phi(2170)$ and direct decay
- A Partial Wave analysis ?

Parameters	Constructive	Destructive
M (MeV/c^2)	2171 ± 10	2170 ± 9
Γ (MeV)	128 ± 26	126 ± 25
Signal yields	400 ± 167	744 ± 40
relative angle Φ(rad)	-0.51 ± 0.78	0.60 ± 0.64