Study of $\phi(2170)$ at BESIII

Guangshun Huang

(on behalf of the BESIII Collaboration)

University of Science and Technology of China (USTC)

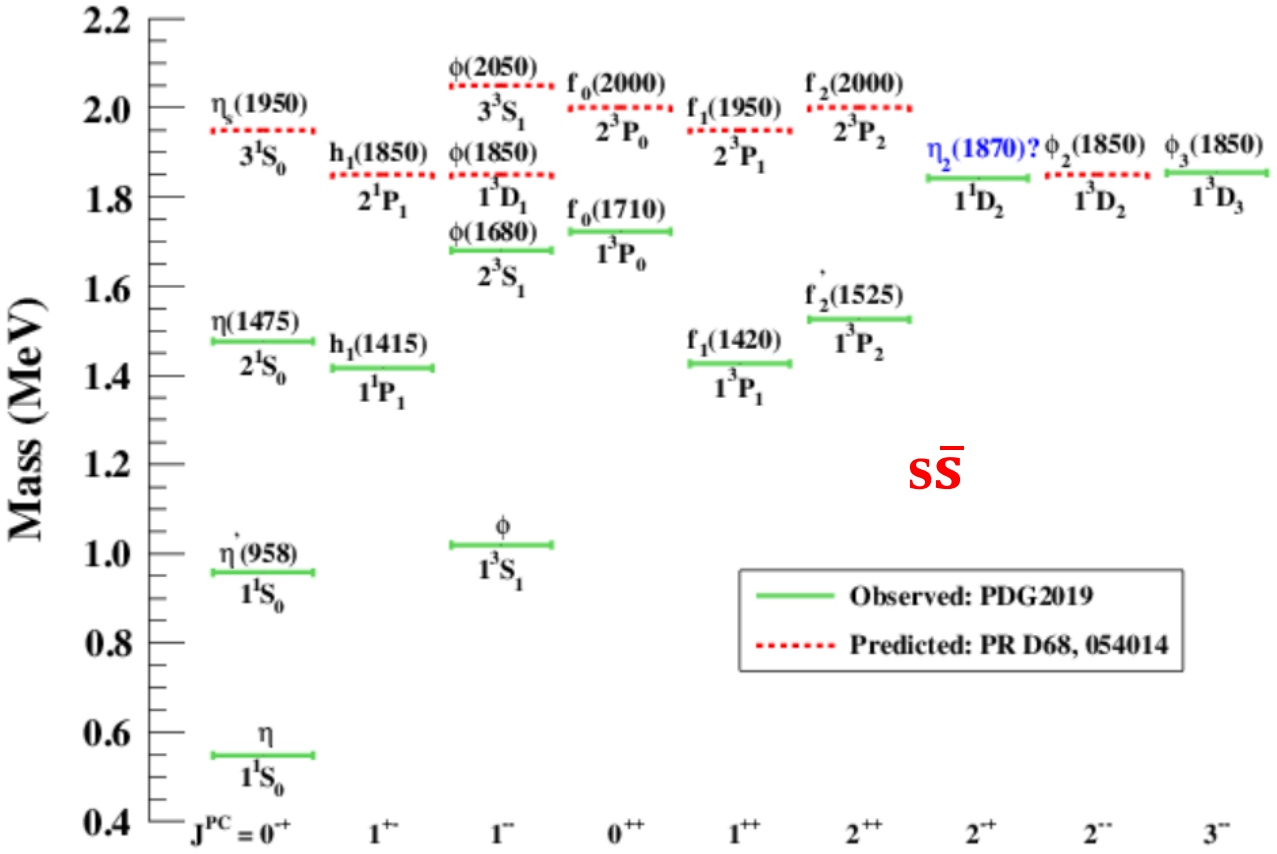
40th International Conference on High Energy Physics

Jul. 28-Aug.6, 2020, Prague, Czech (virtual ICHEP2020)

Outline

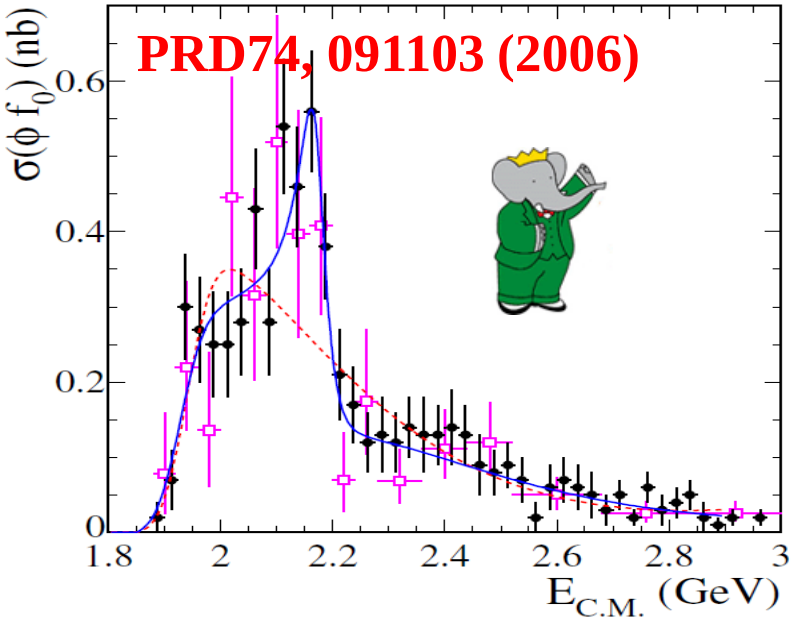
- Strangenium states
- BEPCII/BESIII
- $\phi(2170)$ studies at BESIII
  - $e^+e^- \to K^+K^-$
  - $e^+e^- \to \phi K^+K^- / K^+K^-K^+K^-$
  - $e^+e^- \to \phi\eta / \phi\eta'$
  - $e^+e^- \to K^+K^-\pi^0\pi^0$
- Summary

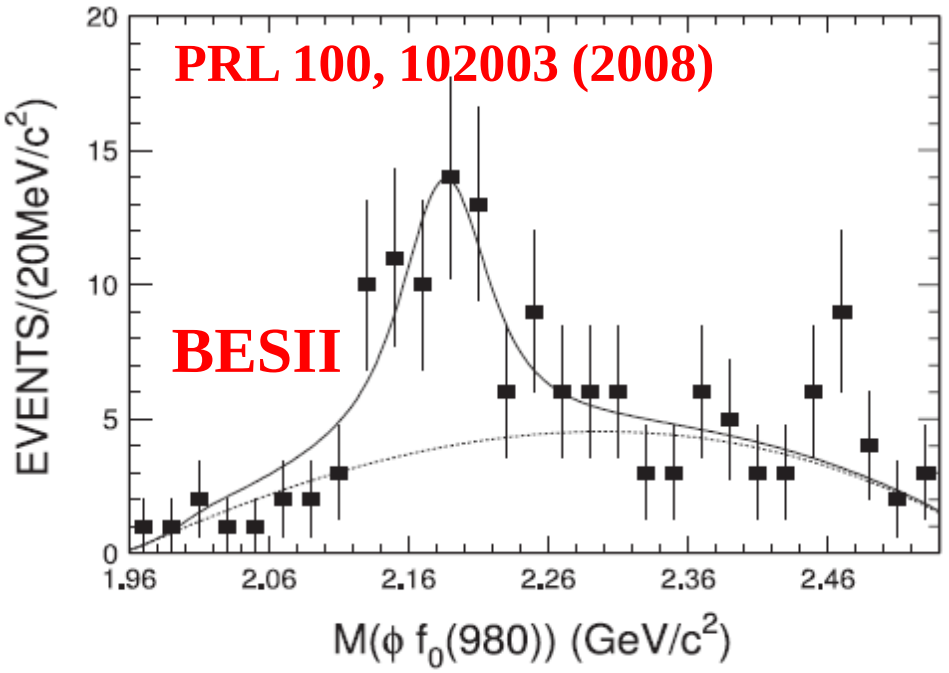
The strange quarkonium

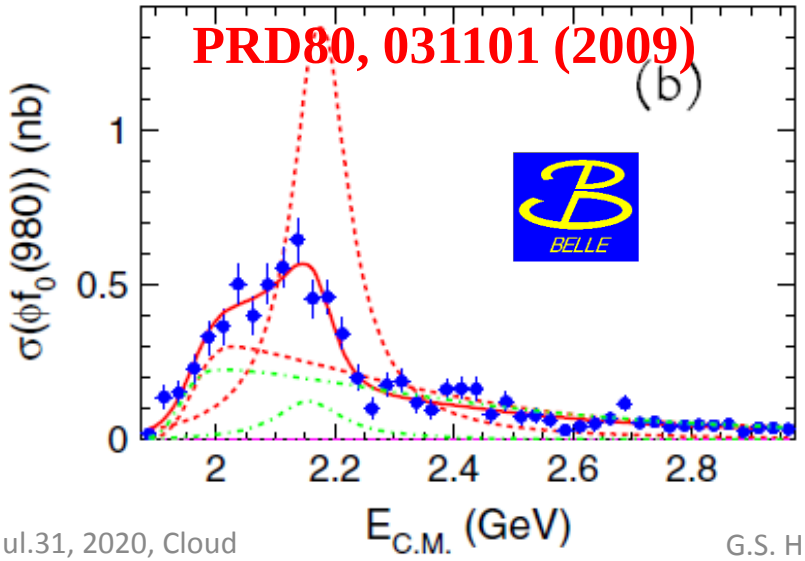


- $s\bar{s}$ analogue of $c\bar{c}$ and $b\bar{b}$, poorly known;
- XYZ particles with strange quark as well?
- a bridge between light and heavy quark.

ϕ(2170)/Y(2175)







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

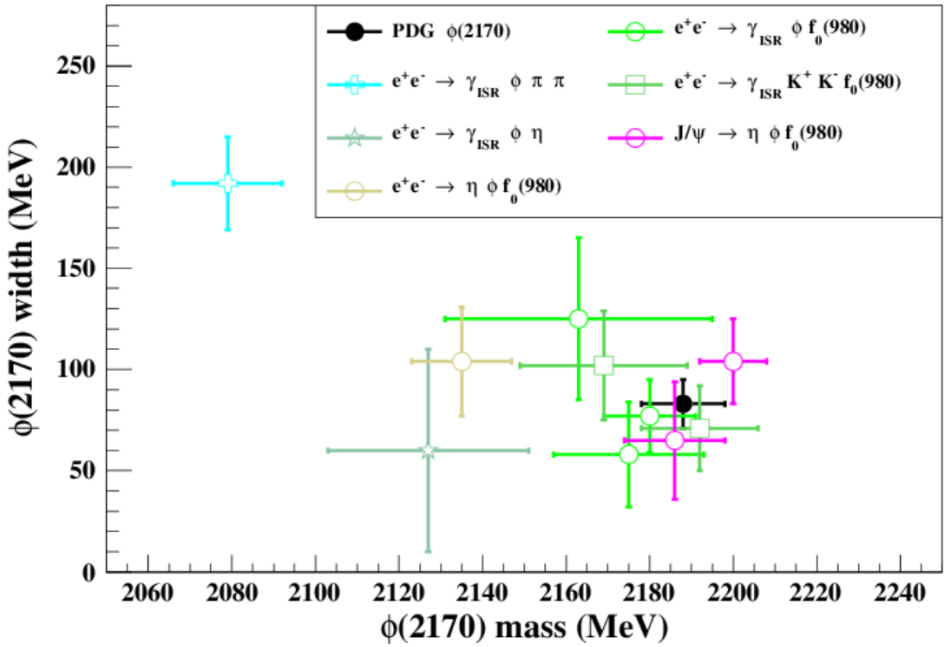
$$e^+e^- \Rightarrow \begin{cases} Y(2175) \to \phi(1020)\pi^+\pi^- & \text{strange,} \\ Y(4260) \to J/\psi\pi^+\pi^- & \text{charm,} \\ \Upsilon(10860) \to \Upsilon(1S,2S)\pi^+\pi^- & \text{bottom,} \end{cases}$$

Y(2175), strange partner as Y(4260)

The nature of $\phi(2170)$

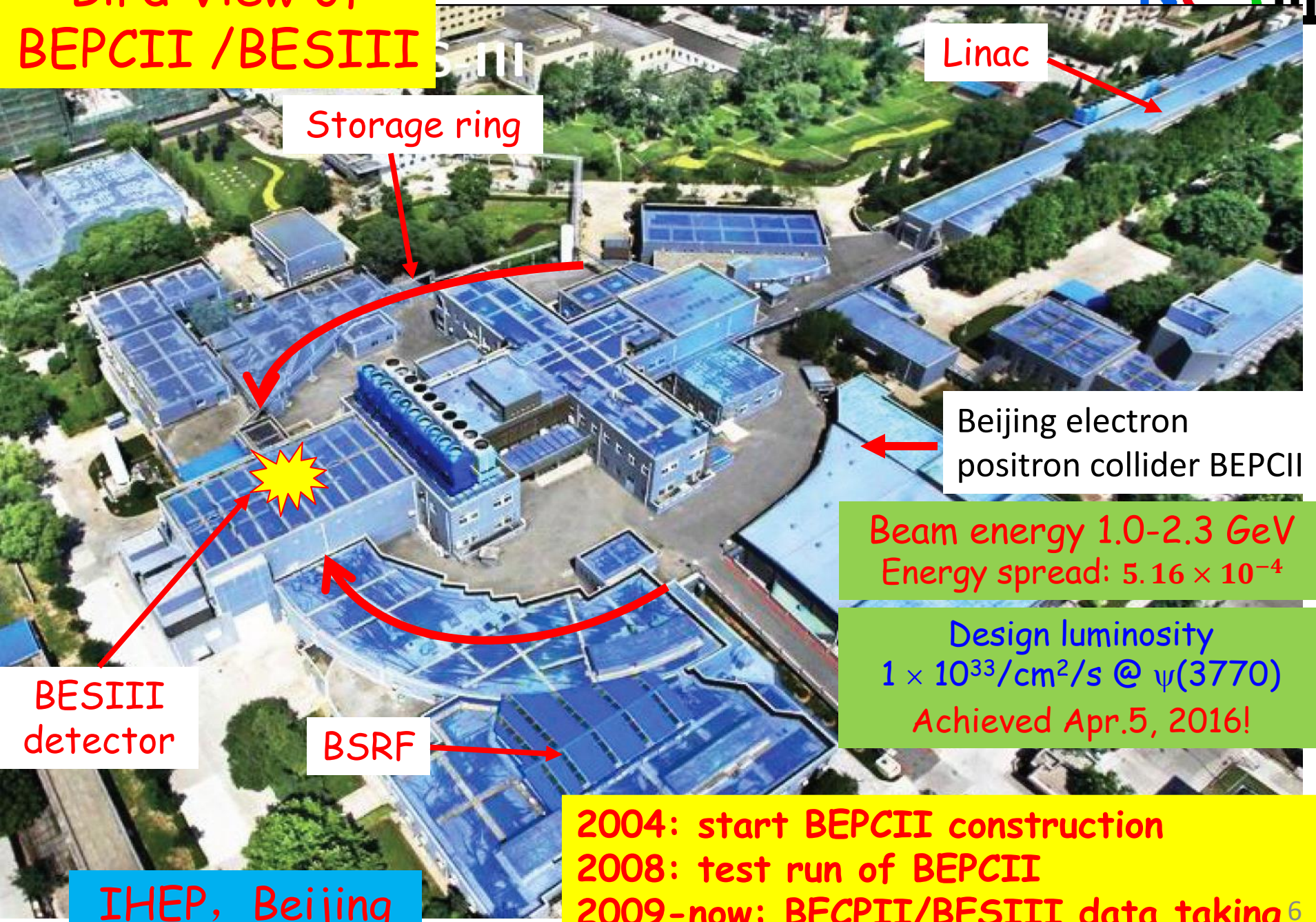
PDG2018 $\phi(2170)$ DECAY MODES

	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



- **From experiments:**
  - ✓ **Limited decay modes**
  - ✓ **Diverged mass & width**
- **On theory side:**
  - ✓ **$s\bar{s}g$ hybrid**
  - ✓ **2^3D_1 or 3^3S_1 $s\bar{s}$**
  - ✓ **Tetraquark**
  - ✓ **Molecular state $\Lambda\bar{\Lambda}$**
  - ✓ **$\phi f_0(980)$ resonance w/ FSI**
  - ✓ **Three-body system ϕKK**
  - ✓ **Conclusion? Not yet.**
- **Not fully understood.**

Bird View of BEPCII /BESIII

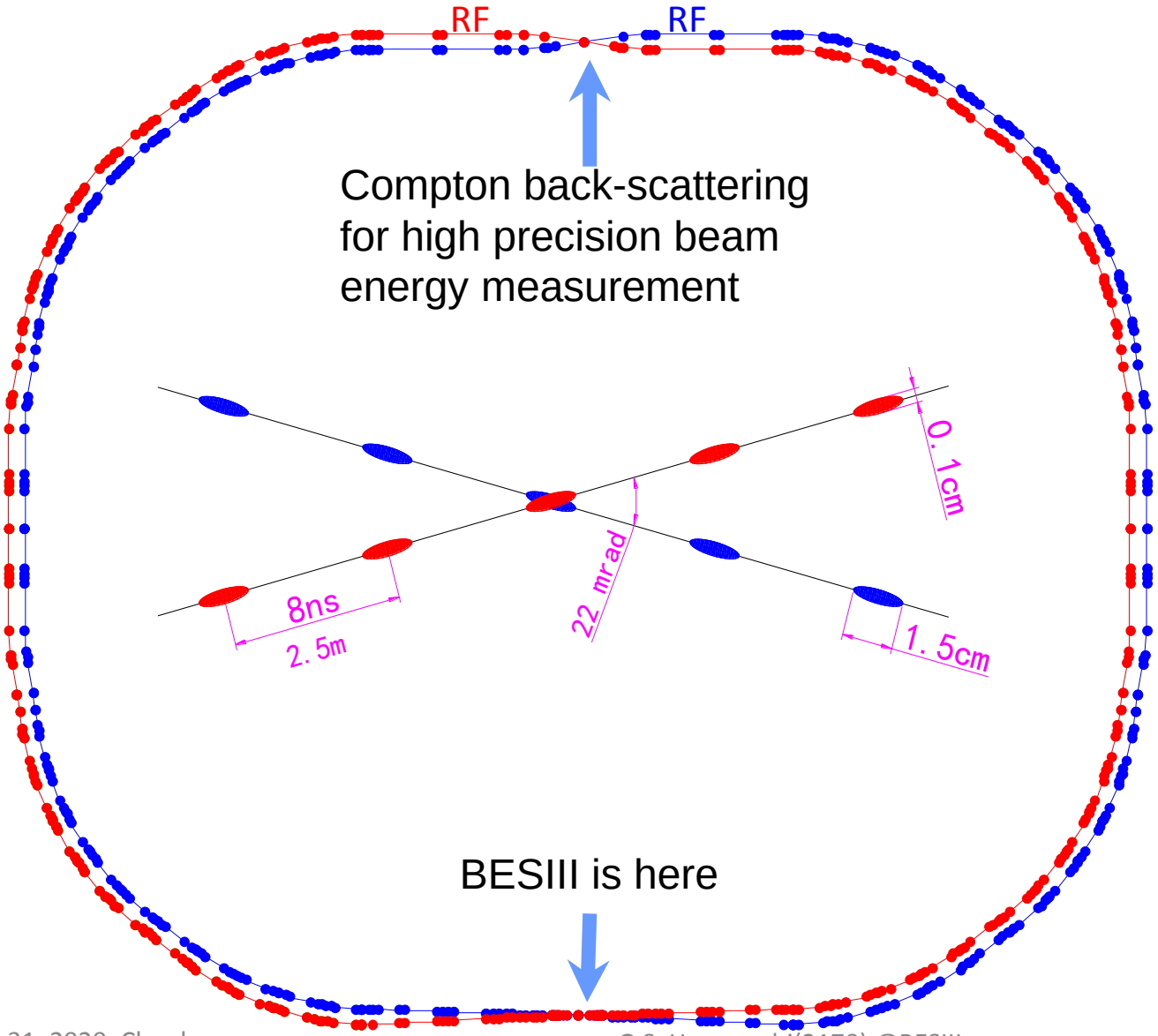


Beam energy 1.0-2.3 GeV
Energy spread: 5.16×10^{-4}

Design luminosity
$1 \times 10^{33}/cm^2/s$ @ $\psi(3770)$
Achieved Apr.5, 2016!

2004: start BEPCII construction
2008: test run of BEPCII
2009-now: BECPII/BESIII data taking

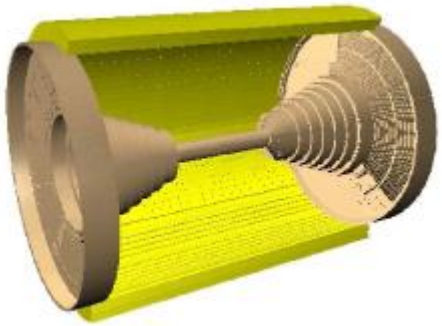
BEPC II: Large Crossing Angle, Double-ring



Beam energy:
1-2.3 GeV
Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
SR mode:
0.25A@2.5GeV

BESIII Detector

MDC

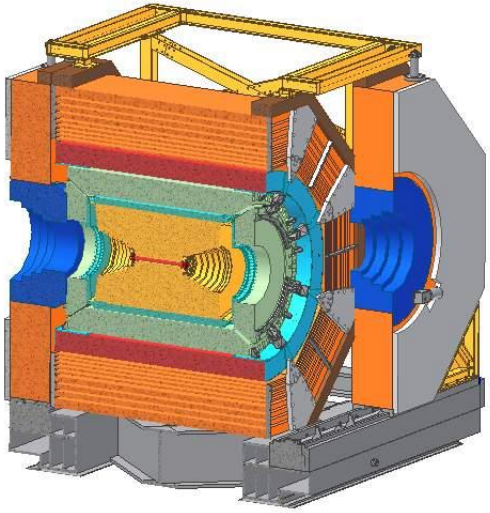


R inner: 63mm ;

R outer: 810mm

Length: 2582 mm

Layers: 43

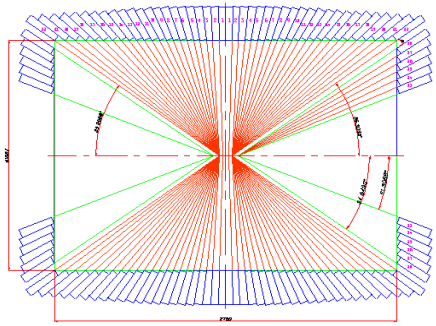


TOF

BTOF: two layers

ETOF: 48 for each

CsI(Tl) EMC



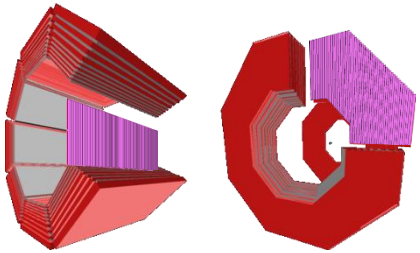
Crystals: 28 cm(15 X_0)

Barrel: $|\cos\theta|<0.83$

Endcap:

$0.85 < |\cos\theta| < 0.93$

RPC MUC

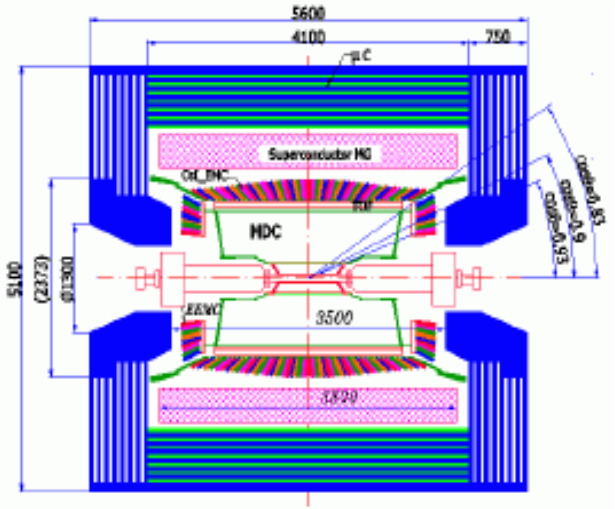


BMUC: 9 layers – 72 modules

EMUC: 8 layers – 64 modules

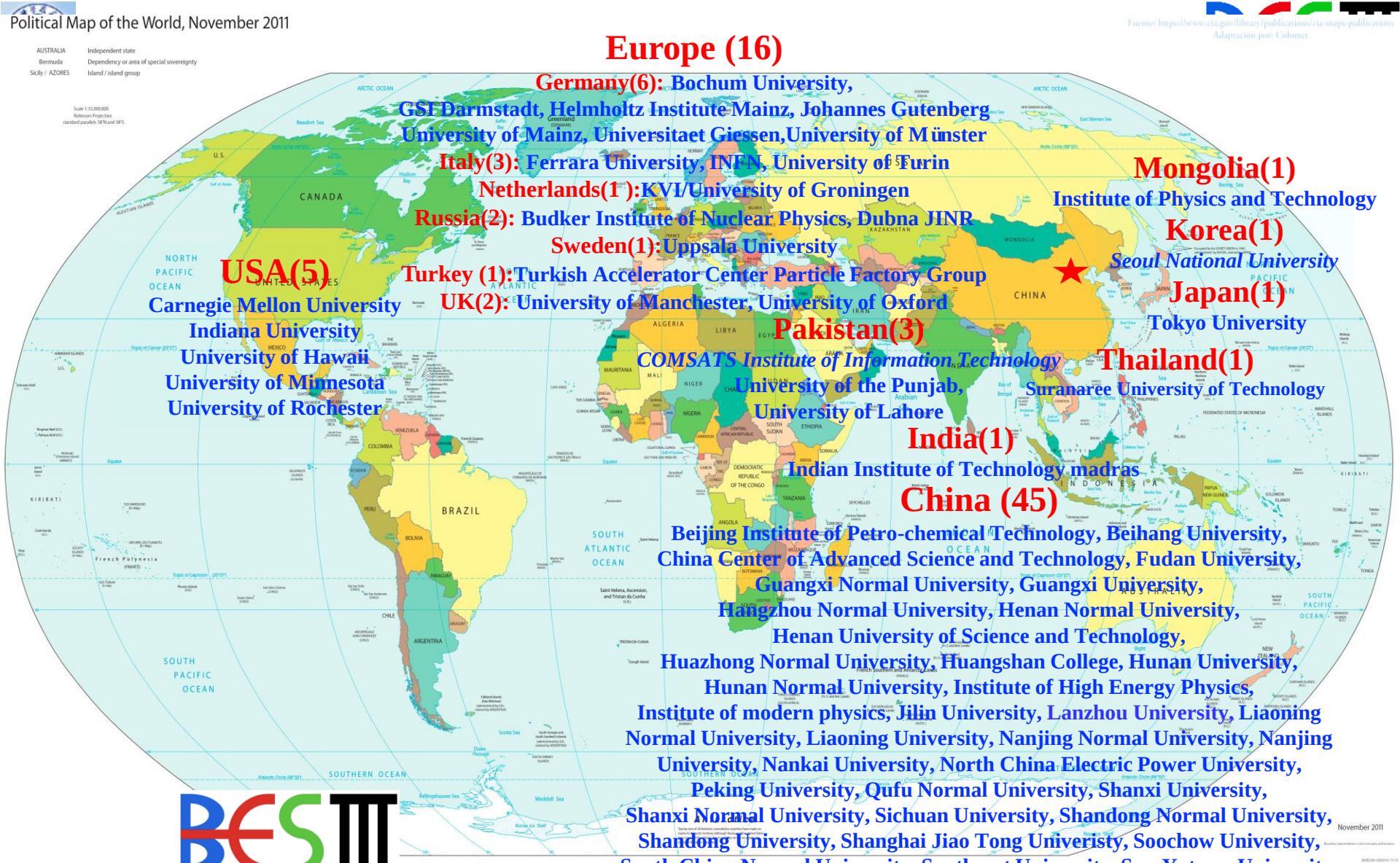
BESIII Detector

Exps.	MDC Wire resolution	MDC dE/dx resolution	EMC Energy resolution
CLEO	110 μm	5%	2.2-2.4 %
Babar	125 μm	7%	2.67 %
Belle	130 μm	5.6%	2.2 %
BESIII（XYZ data）	115 μm	<5% (Bhabha)	2.3%



Exps.	TOF time resolution
CDFII	100 ps
Belle	90 ps
BESIII (XYZ data)	68 ps (BTOF) 100 → 65 ps (ETOF)

- New ETOF (MRPC)
- Cylindrical GEM/New Inner MDC



Europe (16)

Germany(6): Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster

Italy(3): Ferrara University, INFN, University of Turin

Netherlands(1): KVI/University of Groningen

Russia(2): Budker Institute of Nuclear Physics, Dubna JINR

Sweden(1): Uppsala University

Turkey (1): Turkish Accelerator Center Particle Factory Group

UK(2): University of Manchester, University of Oxford

USA(5)

Carnegie Mellon University
Indiana University
University of Hawaii
University of Minnesota
University of Rochester

Mongolia(1)

Institute of Physics and Technology

Korea(1)

Seoul National University

Japan(1)

Tokyo University

Pakistan(3)

COMSATS Institute of Information Technology
University of the Punjab,
University of Lahore

Thailand(1)

Suranaree University of Technology

India(1)

Indian Institute of Technology madras

China (45)

Beijing Institute of Petro-chemical Technology, Beihang University, China Center of Advanced Science and Technology, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Hunan Normal University, Institute of High Energy Physics, Institute of modern physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu Normal University, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shanghai Jiao Tong University, Soochow University, South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Zhejiang University, Zhengzhou University

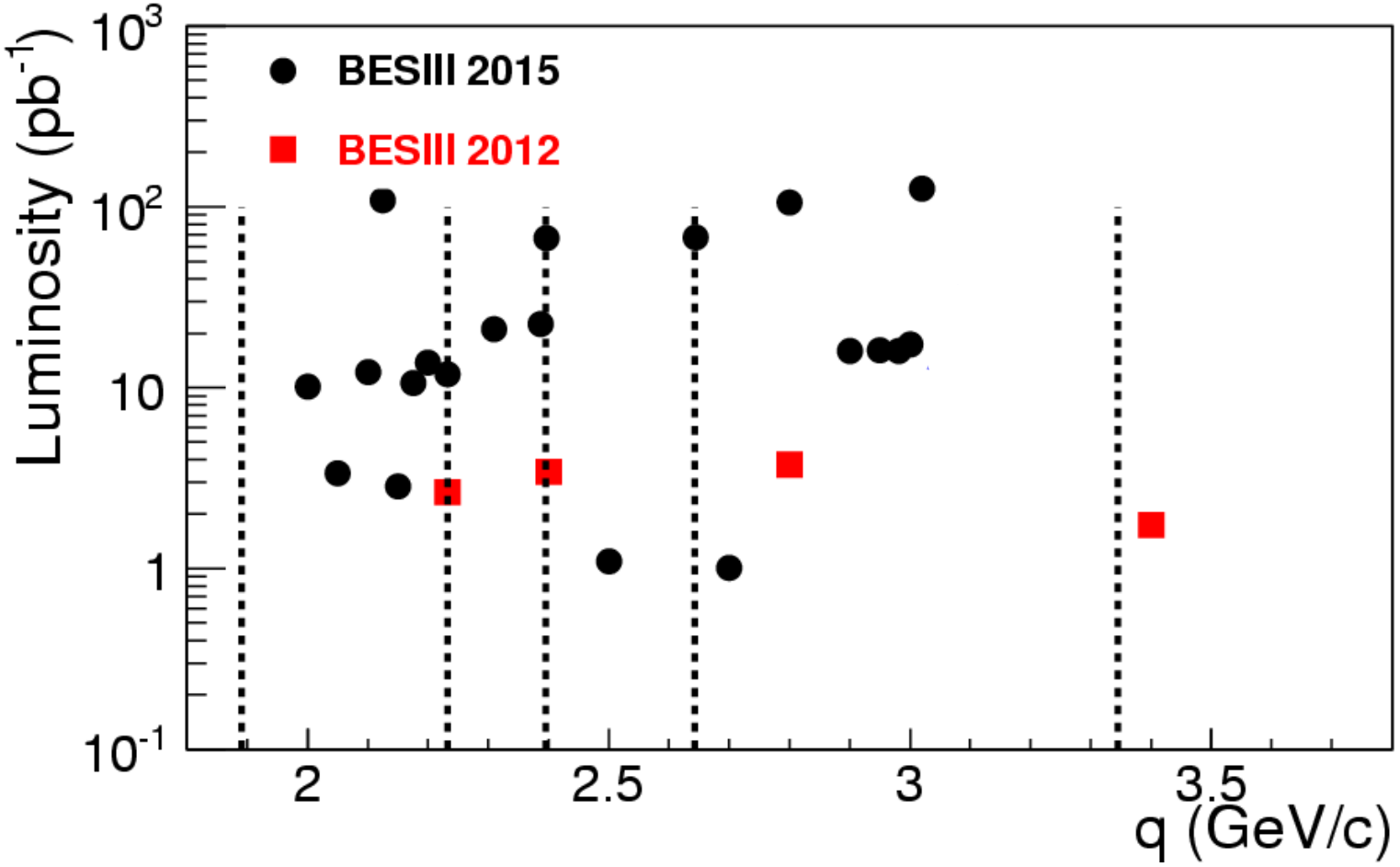
BESIII

http://bes3.ihep.ac.cn

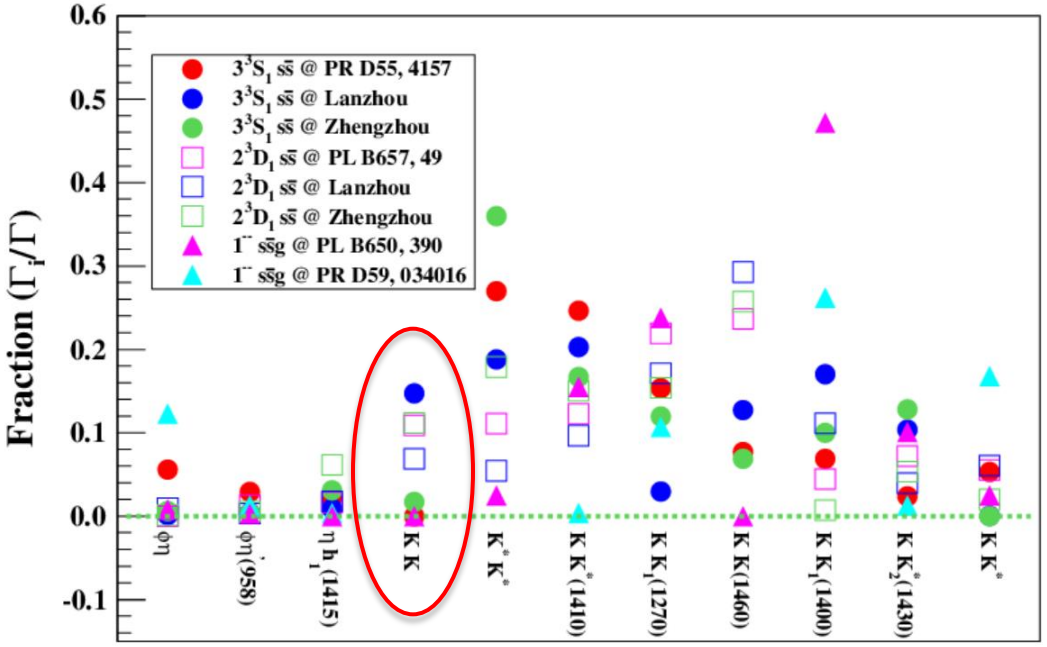
The Collaboration has ~500 members from 74 institutions in 15 countries.

Data used in this talk

- ~650 pb^{-1} in 2.0 – 3.08 GeV collected in 2015.

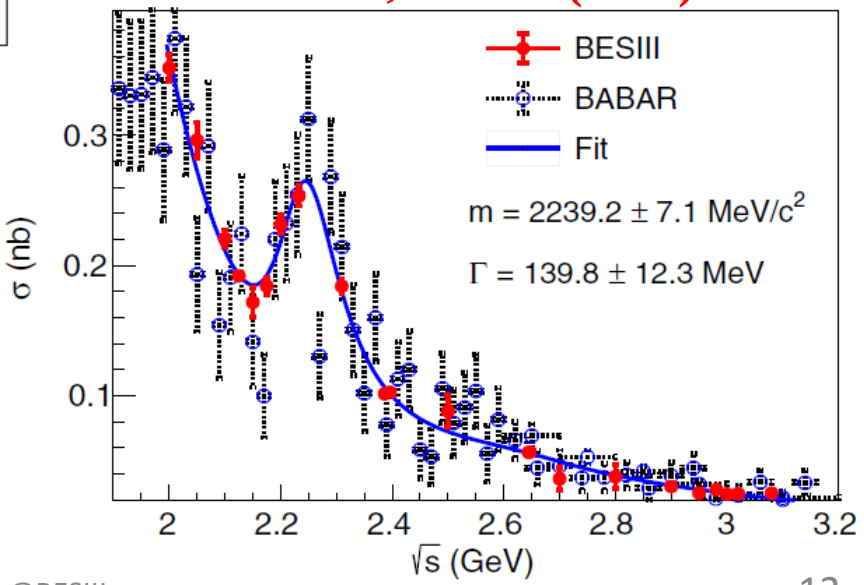


$e^+ e^- \to K^+ K^-$



- K^+K^- @ $\phi(2170)$
  - ✓ Controversial in theory;
  - ✓ isoscalar: ω^*/ϕ^*;
  - ✓ isovector: ρ^*.
- $\sigma(e^+e^- \to K^+K^-)$ measured in [2.0-3.08] GeV:

PRD99, 032001 (2019)

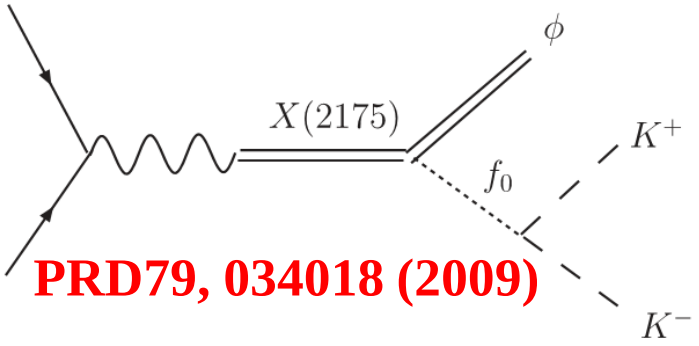


$\phi(2170)$ decay	This work $^3S_1\Lambda\bar{\Lambda}$	$^3P_0$ model within $s\bar{s}$ [10]	Data [5]
KK	73.8–87.7	...	...
$\phi f_0(980)$	0.25–0.3	<10	Seen
$\omega\sigma$	4.2–4.9	...	...
$K^*K_0^*(800)$	1.8–2.1	...	...
Total	80.1–95		83 ± 12

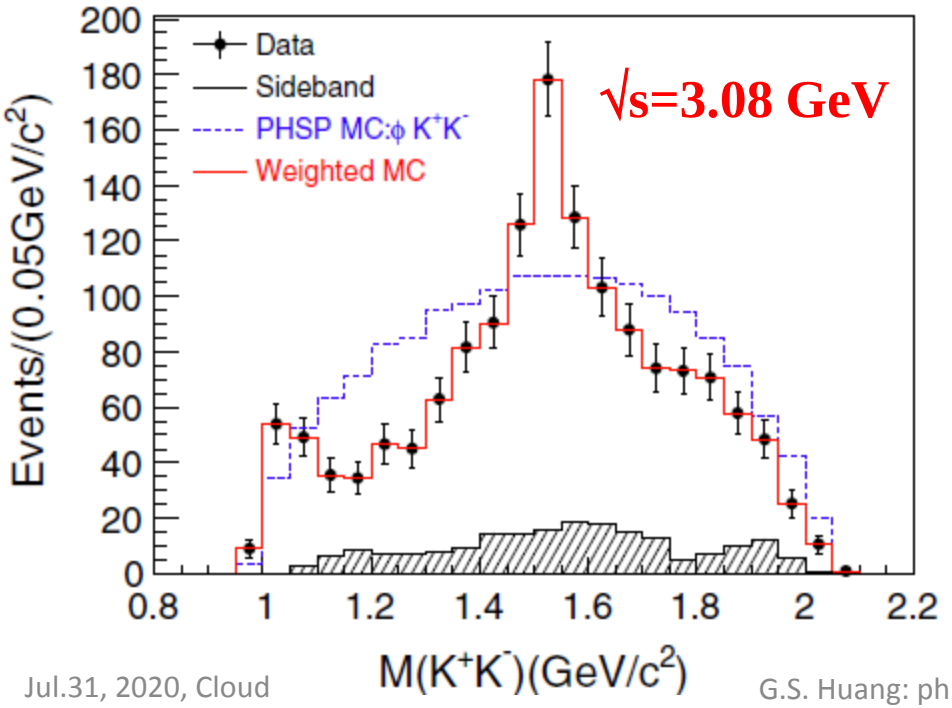
PRD96, 074027 (2017)

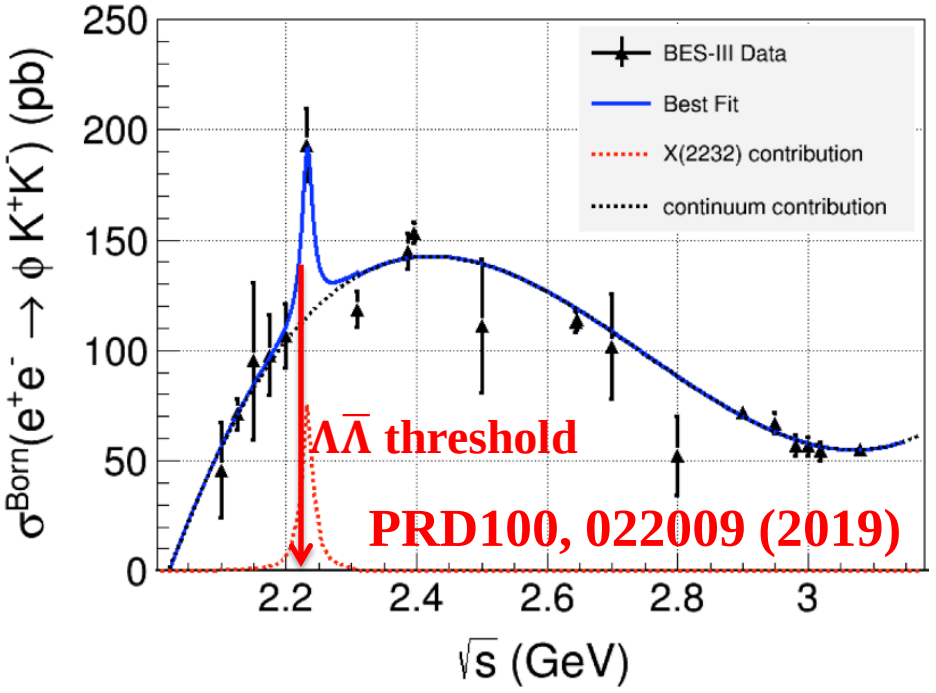
$e^+ e^- \to \phi K^+ K^-$

- **ϕ(2170): resonance of ϕKK**



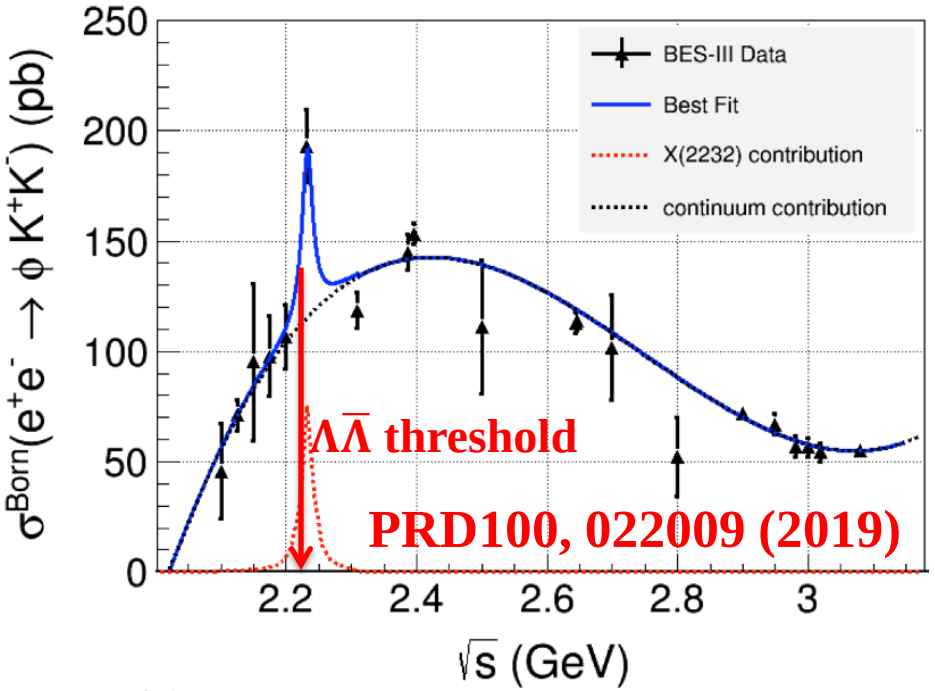
PRD79, 034018 (2009)

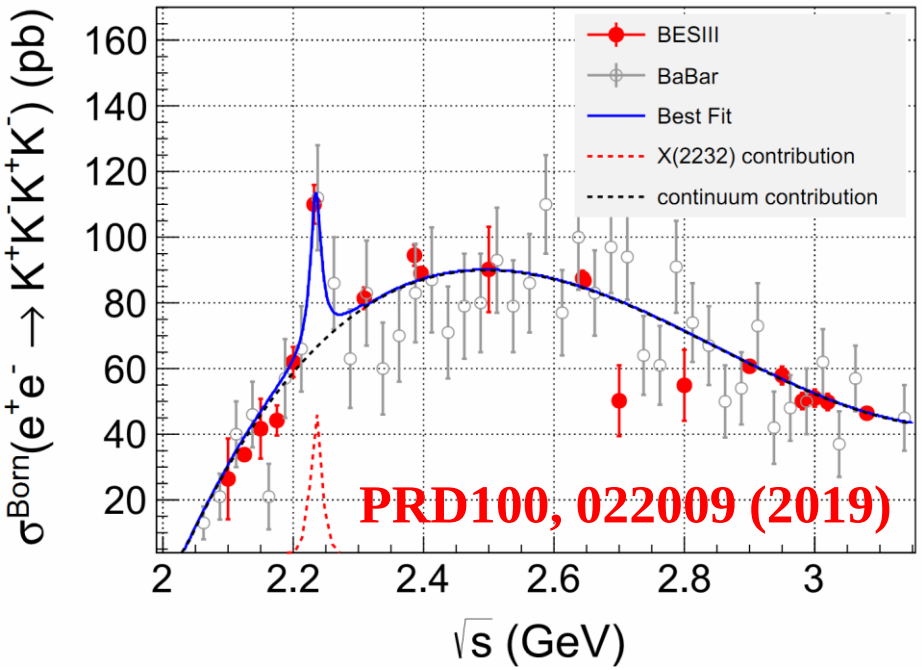


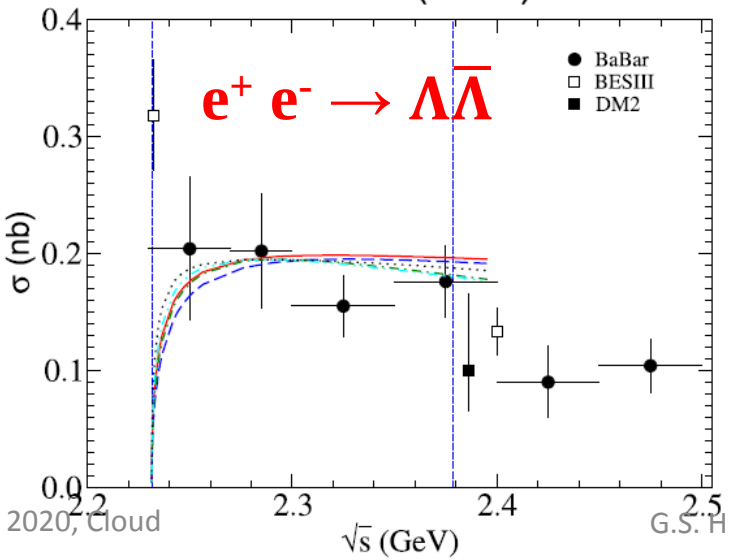


- **A hint for a resonance around $\Lambda\bar{\Lambda}$ threshold:**
  - ✓ **Mass = 2232±3.5MeV;**
  - ✓ **Width < 20 MeV**
- **Three-body system ϕKK: ?**

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



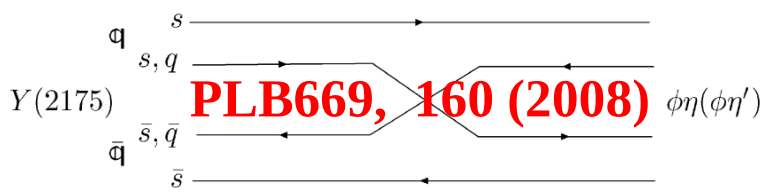


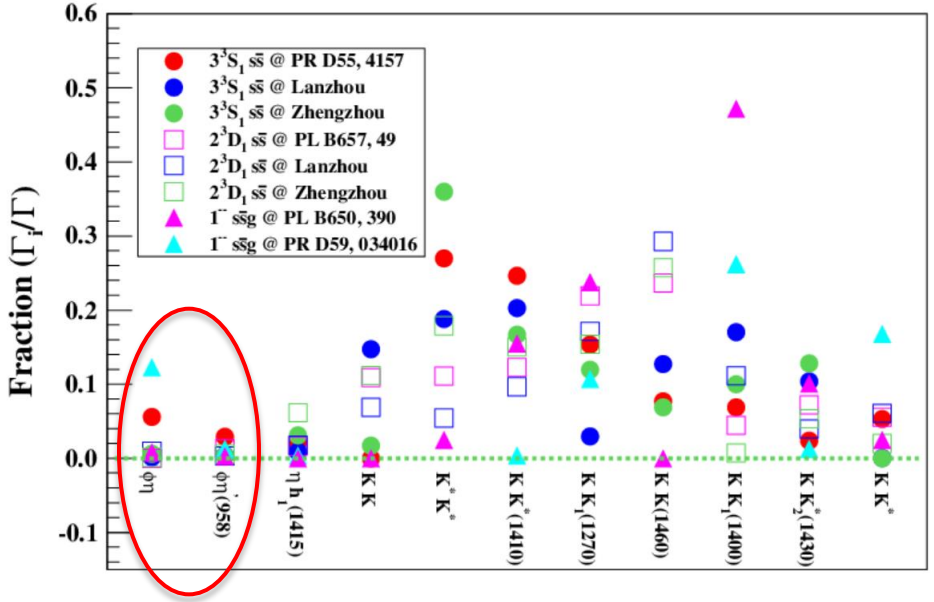


- **Both ϕK^+K^- and $2(K^+K^-)$ show similar enhancement around 2.2324 GeV;**
- **$\Lambda\bar{\Lambda}$ threshold effect?**
- **Any other explanations?**

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

- $\phi\eta$ / $\phi\eta'$ modes: isoscalar
  - ✓ ϕ* or ω* (OZI suppressed)
  - ✓ Parameter info helpful
- Tetraquark favors $\phi\eta$ and $\phi\eta'$



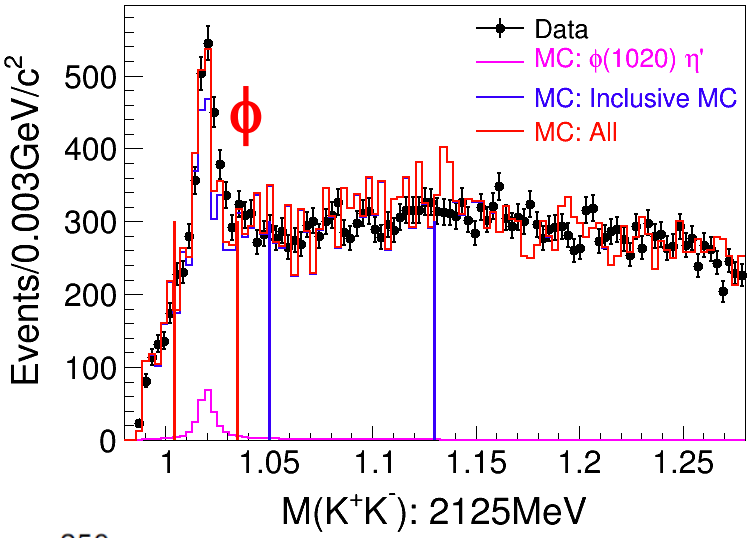


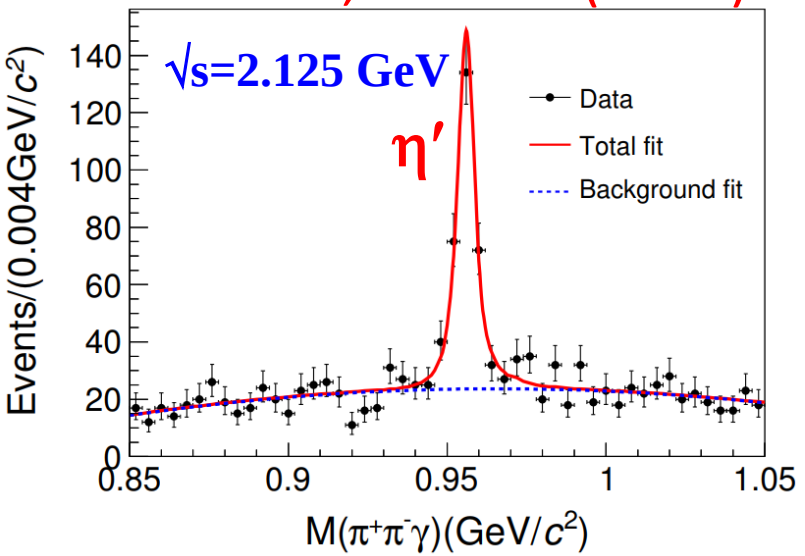
- 1^{--} $s\bar{s}g$ hybrid has larger $\Gamma_{\phi\eta}$ and smaller $\Gamma_{\phi\eta'}$

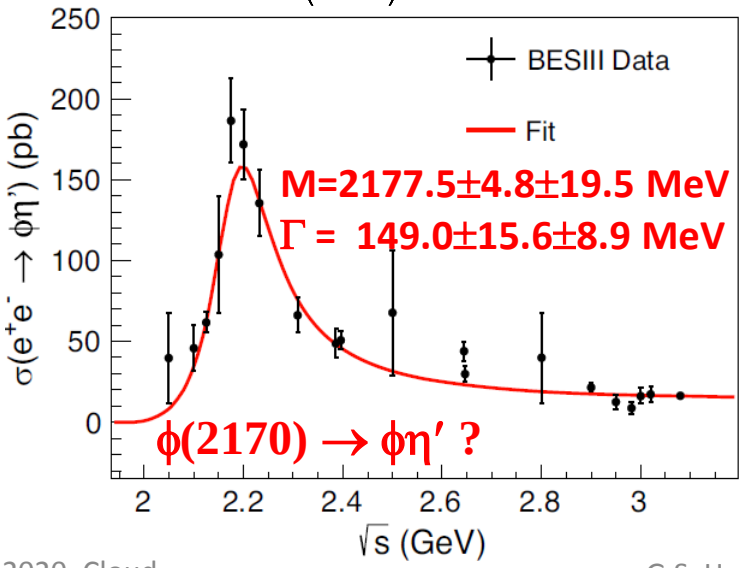
1^{--} $s\bar{s}g$	alt	2.2 GeV	Standard	IKP	Ding
	PRD59, 034016 (1999)				PLB650,390(2007)
$\phi\eta$	2	19	11	3	1.2
$\phi\eta'$	0.01	2	0.1	0.02	0.4
Br($\phi\eta$)/Br($\phi\eta'$)	200	9.5	110	150	3

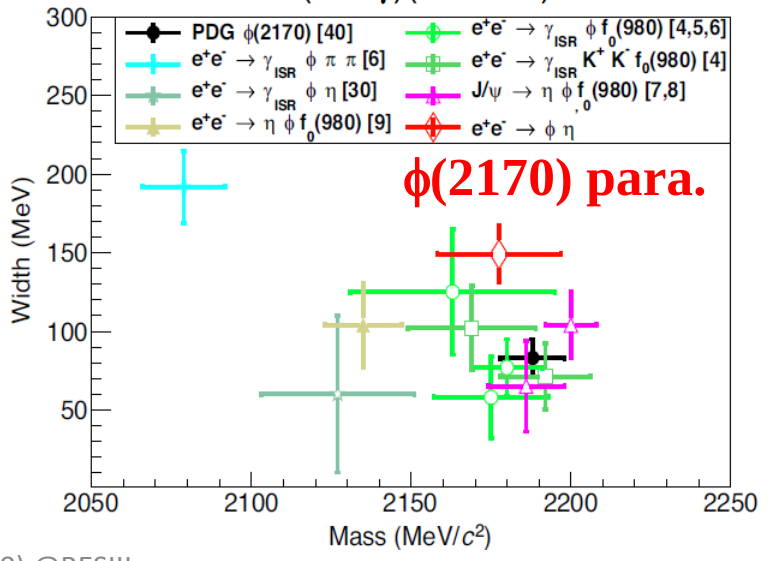
$e^+ e^- \to \phi\eta'$

- $e^+ e^- \to \phi\eta'$ with $\phi \to K^+K^-$, $\eta' \to \gamma\, \pi^+\pi^-$ PRD102, 012008 (2020)









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

- $e^+e^- \rightarrow \phi\eta$ and $\phi\eta'$
  - ✓ **BaBar $\phi\eta$: 1.7±0.7±1.3 eV, [PRD77, 092002(2008)]**
  - ✓ **BESIII $\phi\eta'$: 7.1±0.7±0.7 eV, [PRD102,012008(2020)]**

$$\frac{Br\,[\phi(2170)\rightarrow\phi\eta]\Gamma_{ee}}{Br\,[\phi(2170)\rightarrow\phi\eta\prime]\Gamma_{ee}} = 0.24\pm0.21$$

- **With $e^+e^- \rightarrow \phi\eta'$ prevailing, can $\phi(2170)$ still be an 1^{--} $s\bar{s}g$?**

1^{--} $s\bar{s}g$	alt	2.2GeV	standard	IKP	Ding
	PRD59, 034016 (1999)				PLB650,390(2007)
$\phi\eta$	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

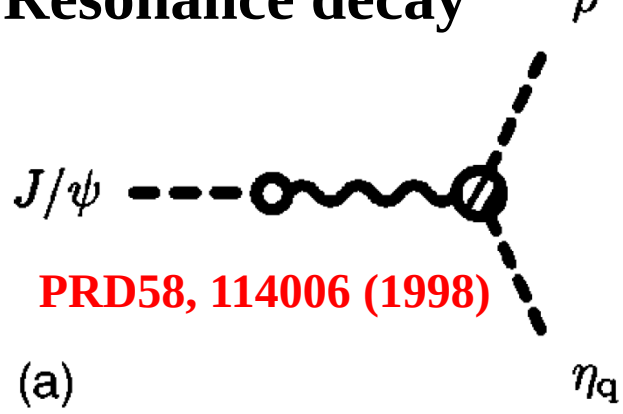
η–η' mixing

- **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 $\eta_s = s\bar{s}$. θ = -11.7°.

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

- **Resonance decay**



PRD58, 114006 (1998)

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

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

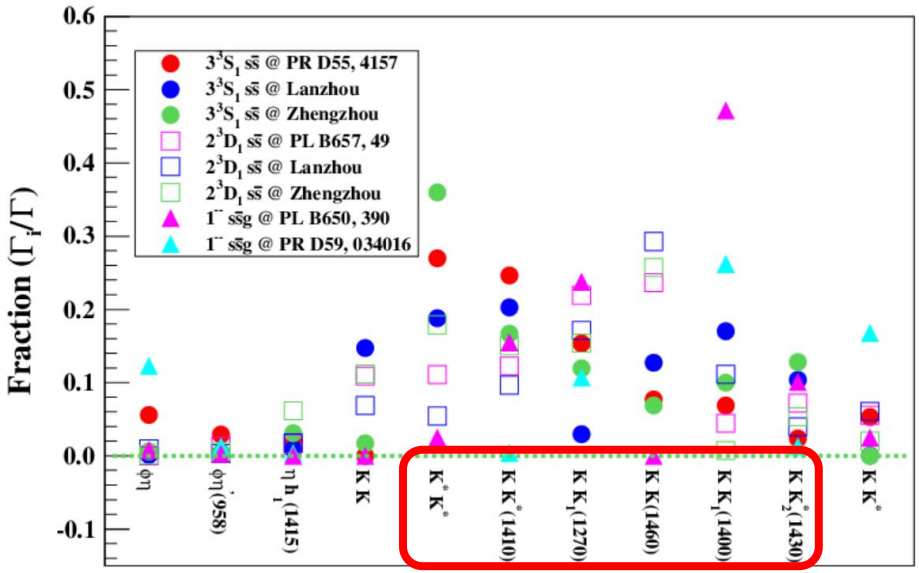
- **ϕ(2170) → ϕη / ϕη′, arXiv:2007.14893[hep-lat] Jul.29, 2020,**

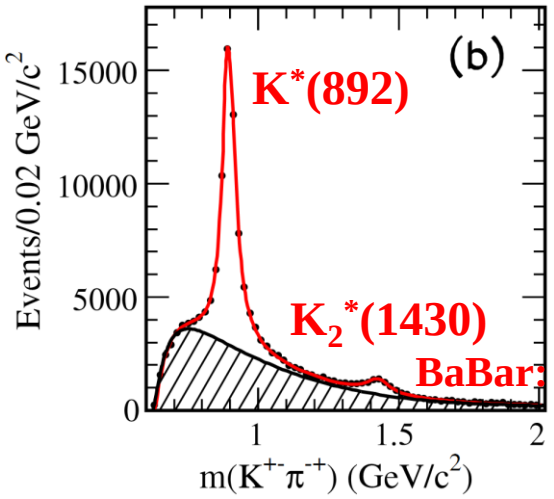
$$\frac{Br\,[\phi(2170)\to\phi\eta]\Gamma_{ee}}{Br\,[\phi(2170)\to\phi\eta\prime]\Gamma_{ee}} = \mathbf{0.23\pm0.10\pm0.18}$$

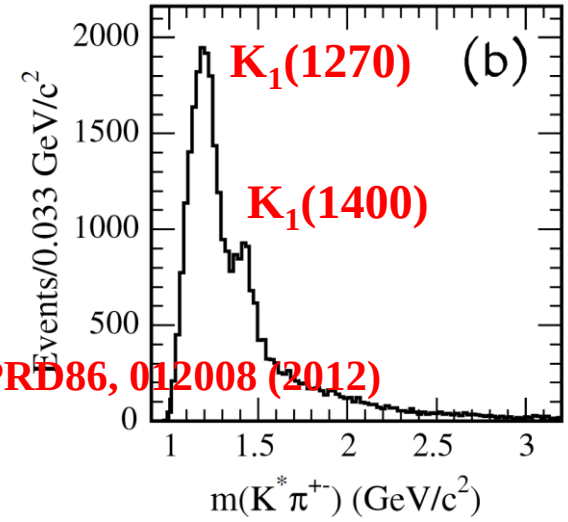
Can be understood as either 3S $s\bar{s}$ or 1^{--} $s\bar{s}g$ along with mixing.

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

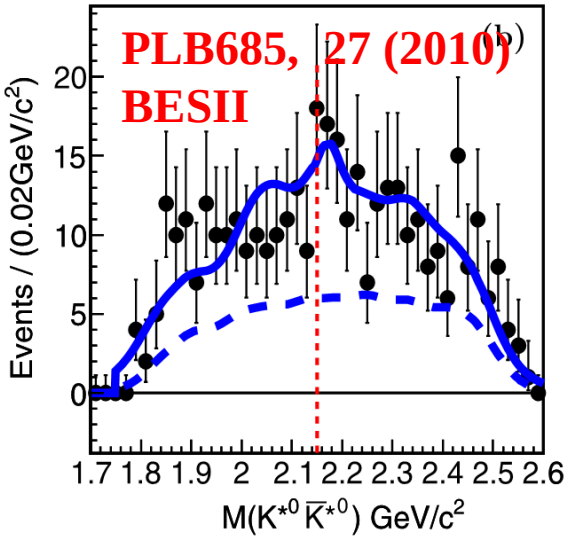
- $e^+e^- \to KK\pi\pi$: important to distinguish $\phi(2170)$ theory models
  - ✓ K^*K^*: $s\bar{s}g$ (unfavored), 3^3S_1 (favored)
  - ✓ $KK_1(1400)$: $s\bar{s}g$ (favored)
  - ✓ $KK(1460)$: $s\bar{s}g$ (unfavored), 2^3D_1 (favored)
- BaBar: $K^*(892)$, $K_2^*(1430)$, $K_1(1270)$ and $K_1(1400)$
- $J/\psi \to \eta\phi(2170) \to \eta K^*K^*$
  - ✓ BESII: 58M J/ψ, an upper limit



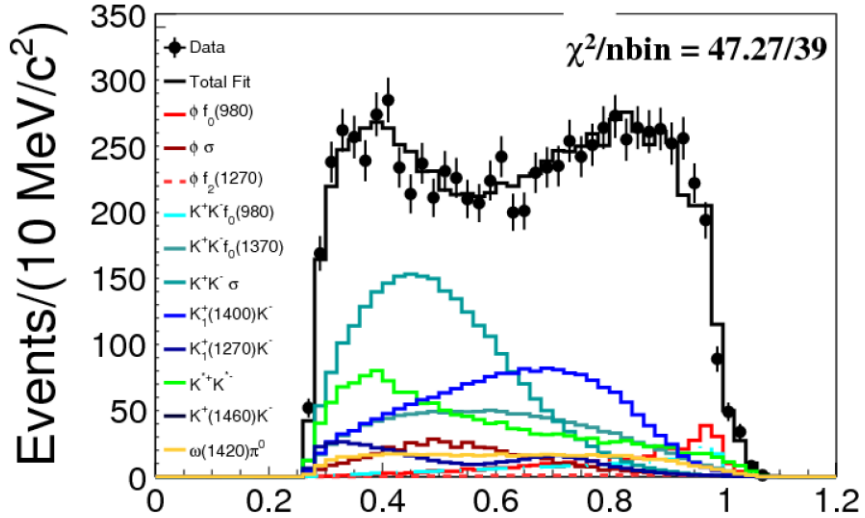


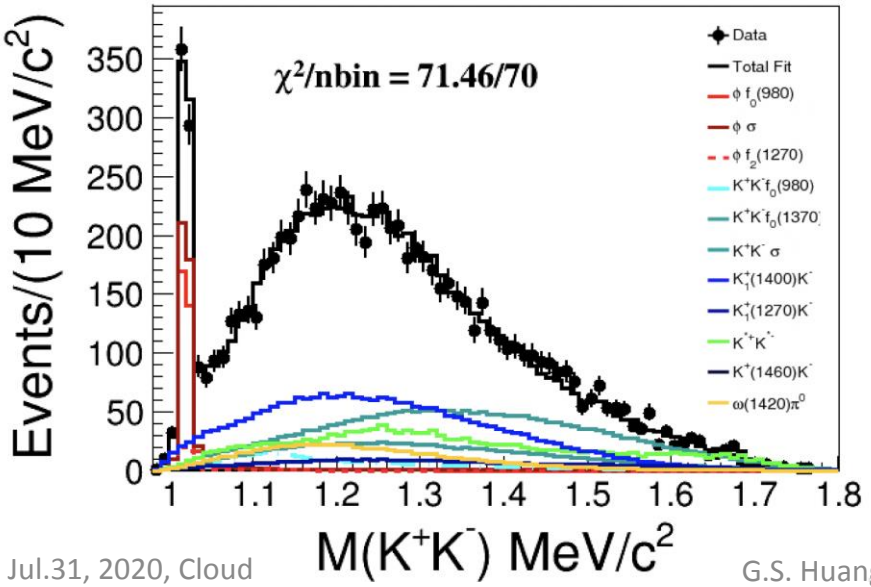


BaBar: PRD86, 012008 (2012)



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



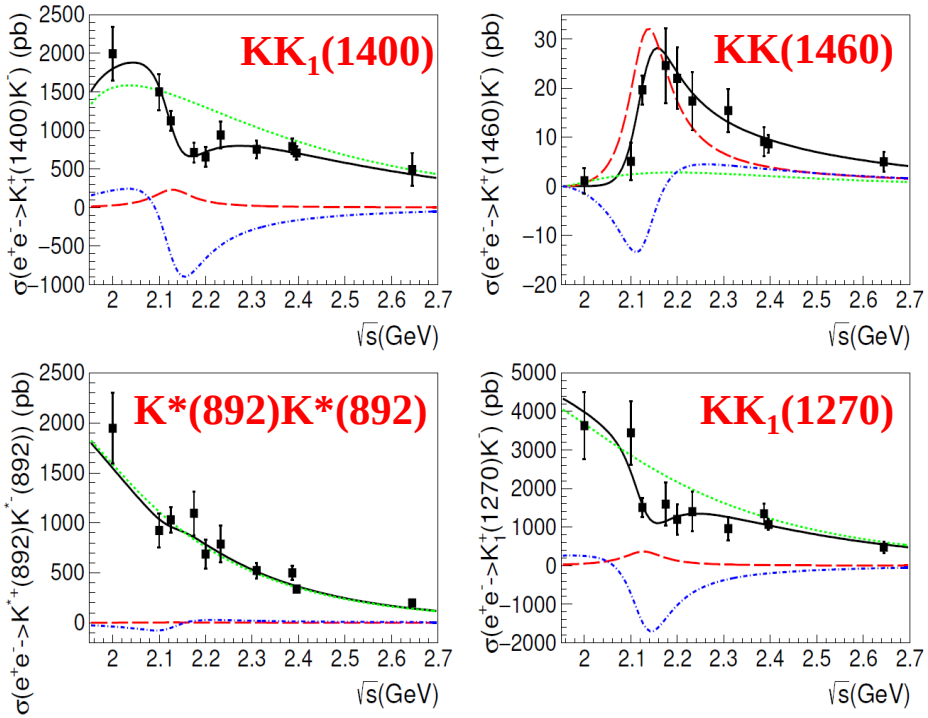


process	Significance (2.1250 GeV)	Significance (2.3960 GeV)
$\phi f_0(980)$	>8.0 σ	>8.0 σ
$\phi\sigma$	>8.0 σ	–
$\phi f_2(1270)$	5.0 σ	–
$\phi f_0(1370)$	–	6.9 σ
$K^{*+}(892)K^{*-}(892)$	>8.0 σ	>8.0 σ
$K^+(1460)K^-$	>8.0 σ	6.4 σ
$K_0^{*+}(1430)K^{*-}(892)$	>8.0 σ	7.5 σ
$K_2^{*+}(1430)K^{*-}(892)$	–	6.4 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

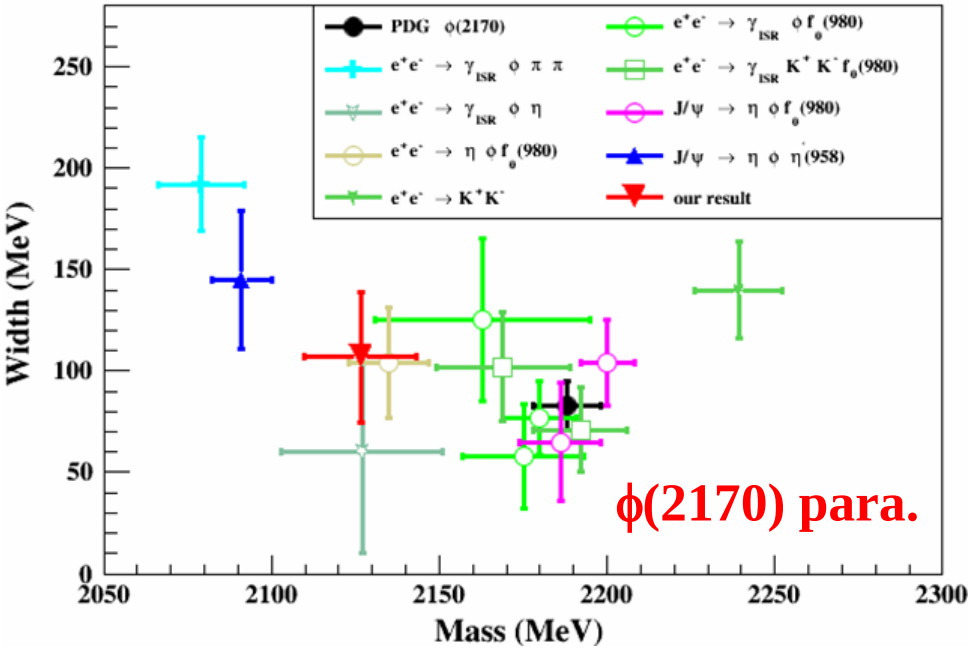
PhysRevLett.124, 112001 (2020)

- **PWA at multiple energies in [2.0, 2.644] GeV**
- **No significant signal observed for $e^+e^- \to KK^*(1410)$.**
- **Born cross section measured for intermediate states as well.**

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



PhysRevLett.124, 112001 (2020)



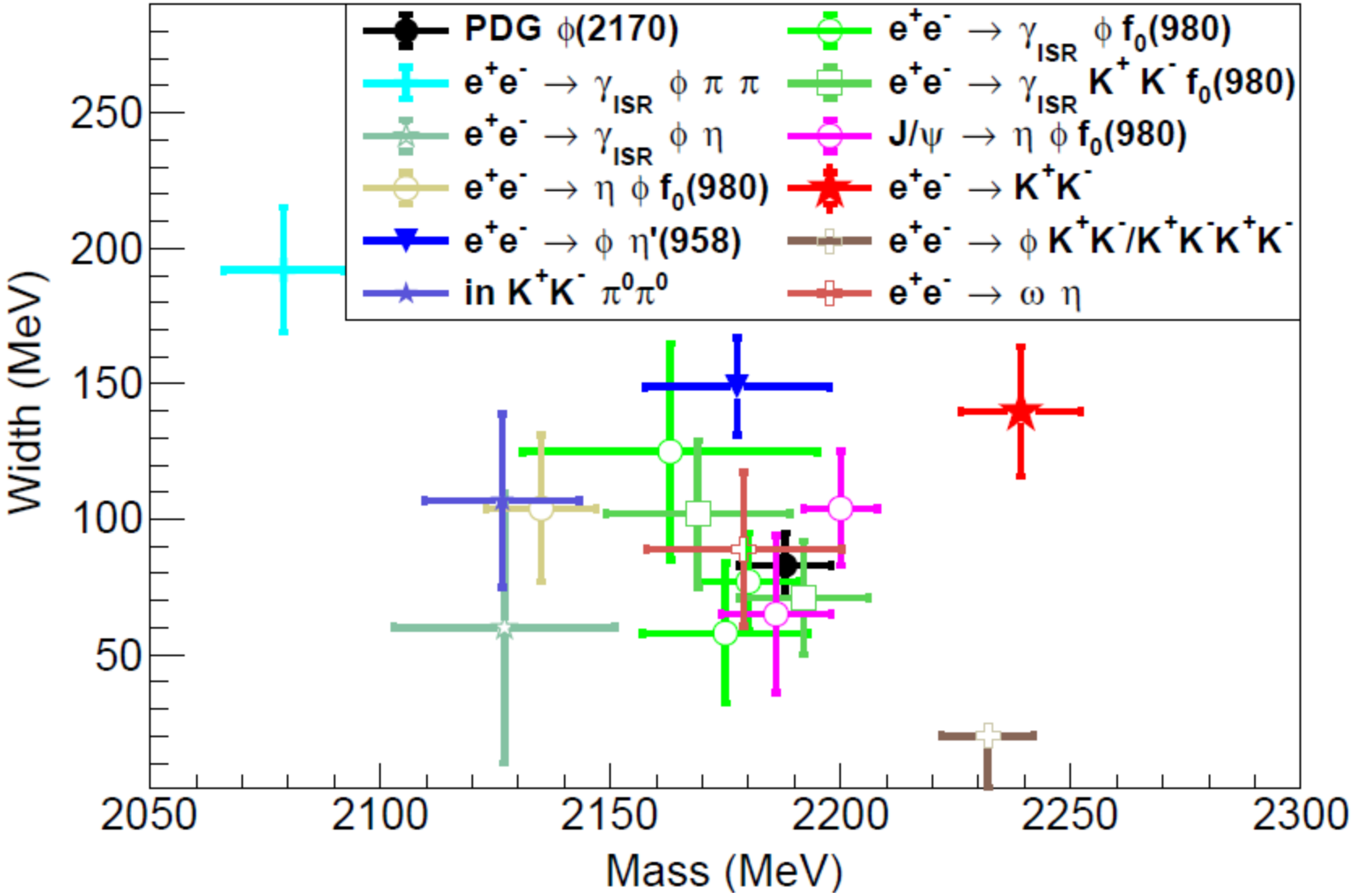
- ✓ **Dots: BESIII data**
- ✓ **Black curves: fit results**
- ✓ **Red long-dashed: ϕ(2170)**
- ✓ **Green shot-dashed: 1/s^n**
- ✓ **Blue dash-dotted: interference**

Fitting results

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	3.0 ± 3.8	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) / K K(1460)? Likely!

Results in a glance

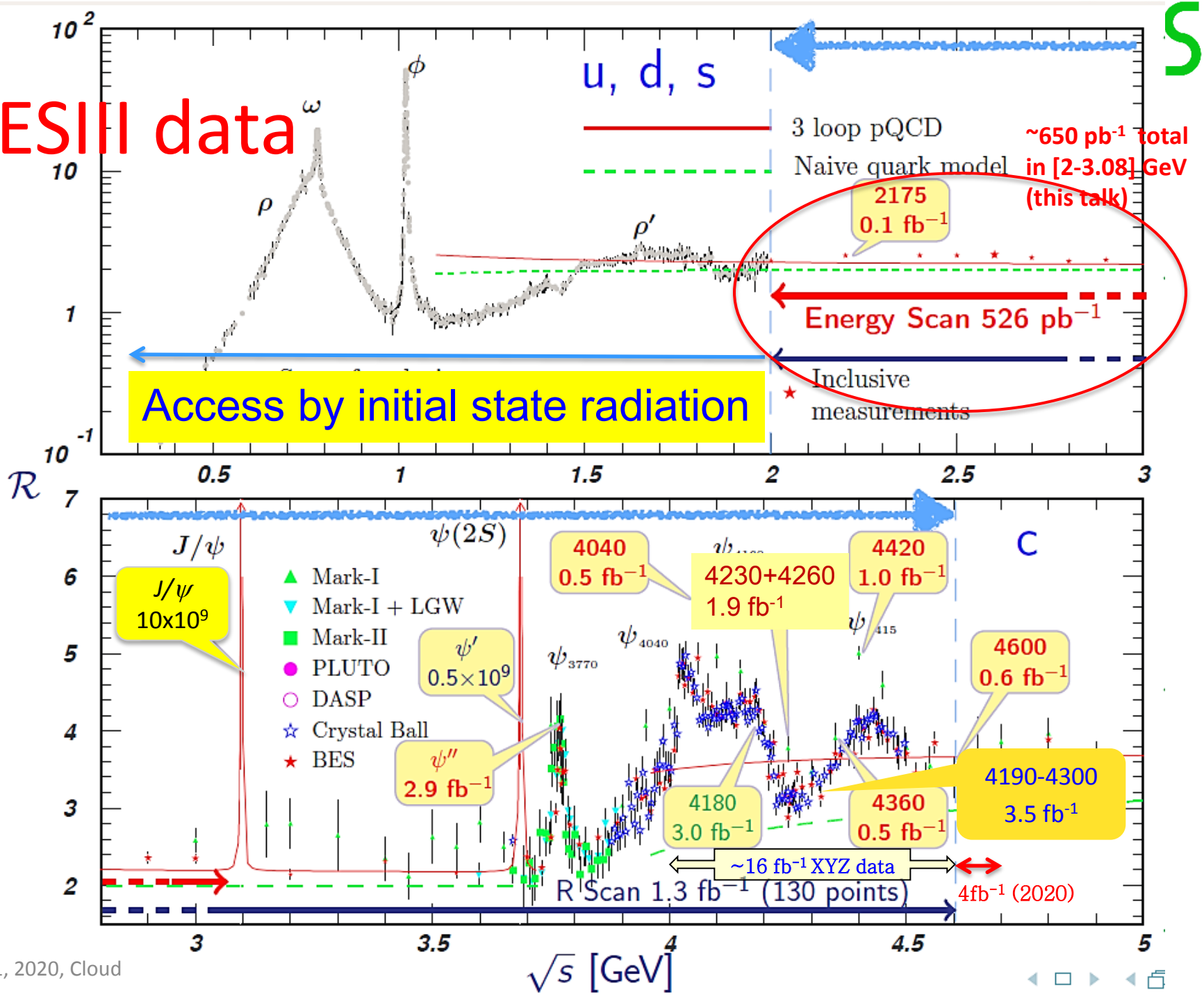


- Hopefully help to know the $\phi(2170)$ better?

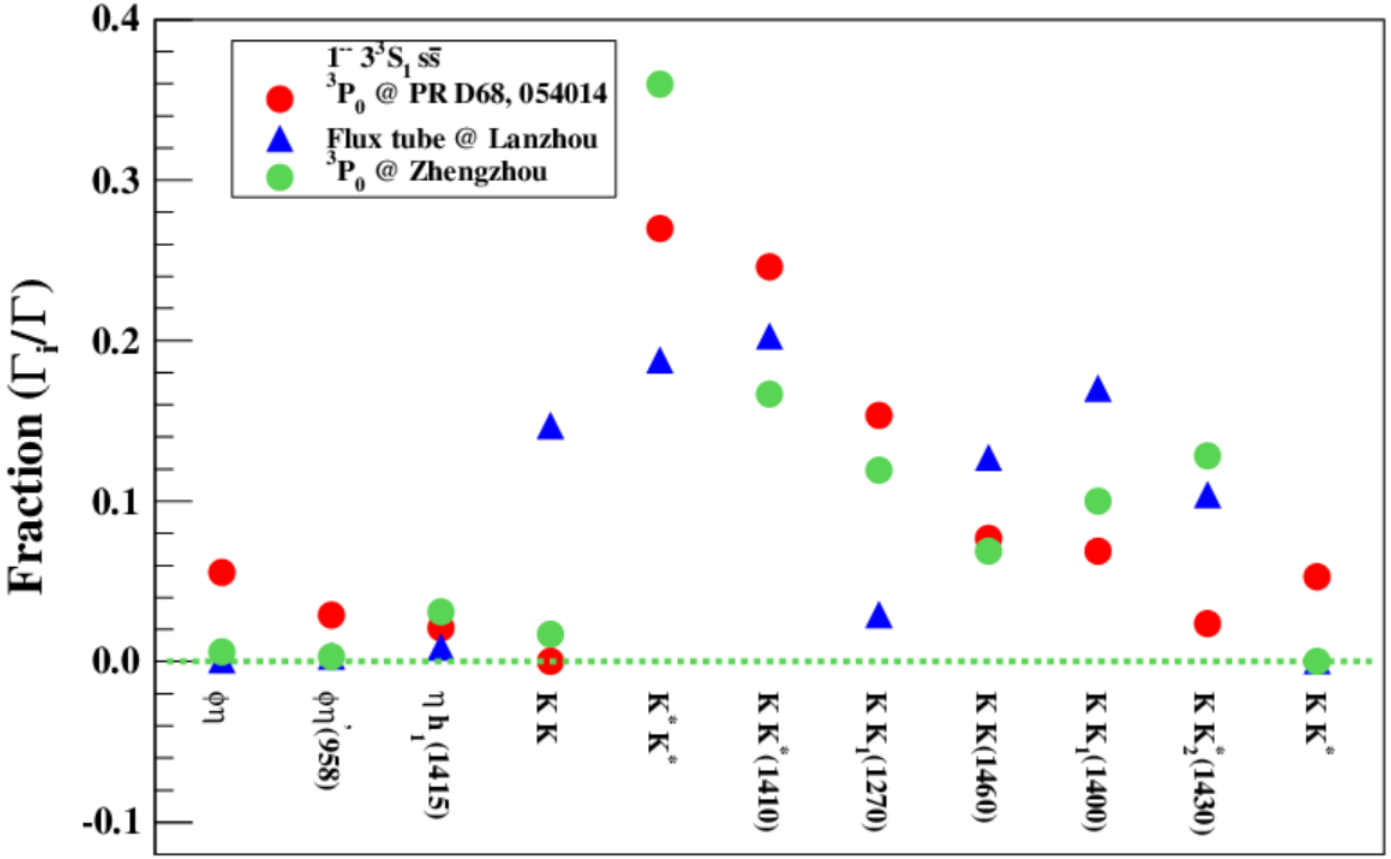
Summary

- Strangenium $s\bar{s}$ is a terra incognita to be explored;
- BESIII provides experimental data on $\phi(2170)$;
- May help to resolve the property of $\phi(2170)$:
  - ✓ 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 ?
  - ✓ Tetraquark ?
  - ✓ Mixing state ?
- More studies needed; some ongoing at BESIII;
- Revisits/Inputs from theory are highly desired!

BESIII data


u, d, s
3 loop pQCD
Naive quark model
~650 pb-1 total
in [2-3.08] GeV
(this talk)
2175
0.1 fb−1
Energy Scan 526 pb−1
Inclusive
measurements
Access by initial state radiation
R
J/ψ
ψ(2S)
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
J/ψ
10x10^9
ψ′
0.5×10^9
ψ″
2.9 fb−1
4040
0.5 fb−1
4230+4260
1.9 fb−1
4420
1.0 fb−1
4600
0.6 fb−1
4190-4300
3.5 fb−1
4180
3.0 fb−1
4360
0.5 fb−1
~16 fb−1 XYZ data
R Scan 1.3 fb−1 (130 points)
4fb−1 (2020)
√s [GeV]

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



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