Studies of $\gamma\gamma \to \gamma\psi(2S)$ and $e^+e^- \to \eta\phi$ via ISR at Belle

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中国物理学会高能物理分会
第十一届全国会员代表大会暨学术年会
2022.08.10, 大连

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Study of $\gamma\gamma \to \gamma\psi(2S)$

Phys. Rev. D 105, 112011 (2022)

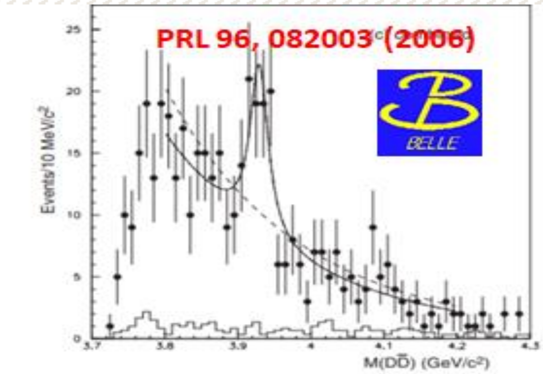
Motivation

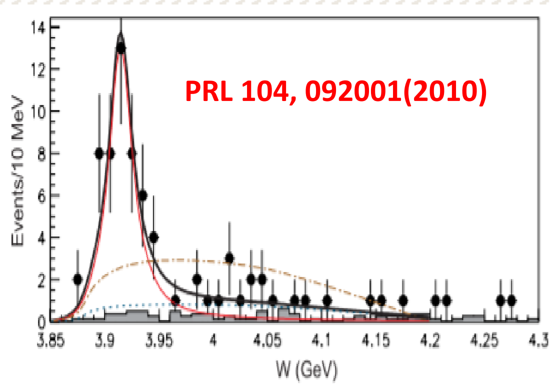
- More than two dozen new resonances that are dubbed as X, Y or Z states have been found above the $D\overline{D}$ threshold since Belle observed the $X(3872)$ in $B \to K\pi^+\pi^- J/\psi$ [Phys. Rev. Lett. 91, 262001(2003)].

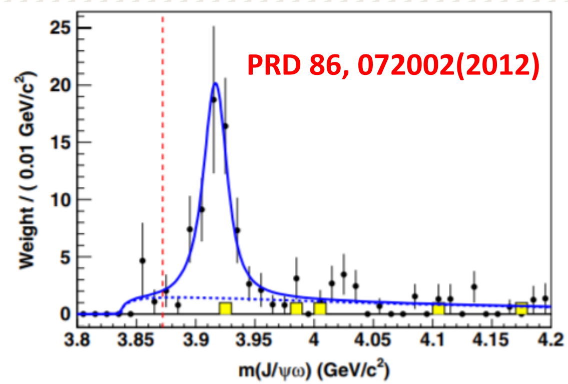
- Many puzzles arise from these XYZ states, and one of them concerns the candidates for P-wave triplet states near 3.9 GeV/c^2.

- The $Z(3930)$ was discovered by Belle in the process $\gamma\gamma \to D\overline{D}$, and the angular distribution was used to identify it as the $\chi_{c2}(2P)$ state. [PRL 96, 082003 (2006)] The $X(3915)$ was discovered by both Belle and BABAR favored the $J^{PC} = 0^{++}$.[PRL 104, 092001 (2010)]

- Both 0^{++} and 2^{++} states can be produced in two-photon collisions and can decay to $\gamma\psi(2S)$ via E_1 transition. The partial widths are expected to be $\Gamma(\chi_{c0}(2P) \to \gamma\psi(2S)) \approx$ 135 keV and $\Gamma(\chi_{c2} \to \gamma\psi(2S)) \approx 207$keV.
  [PRD 72, 054026 (2005)]



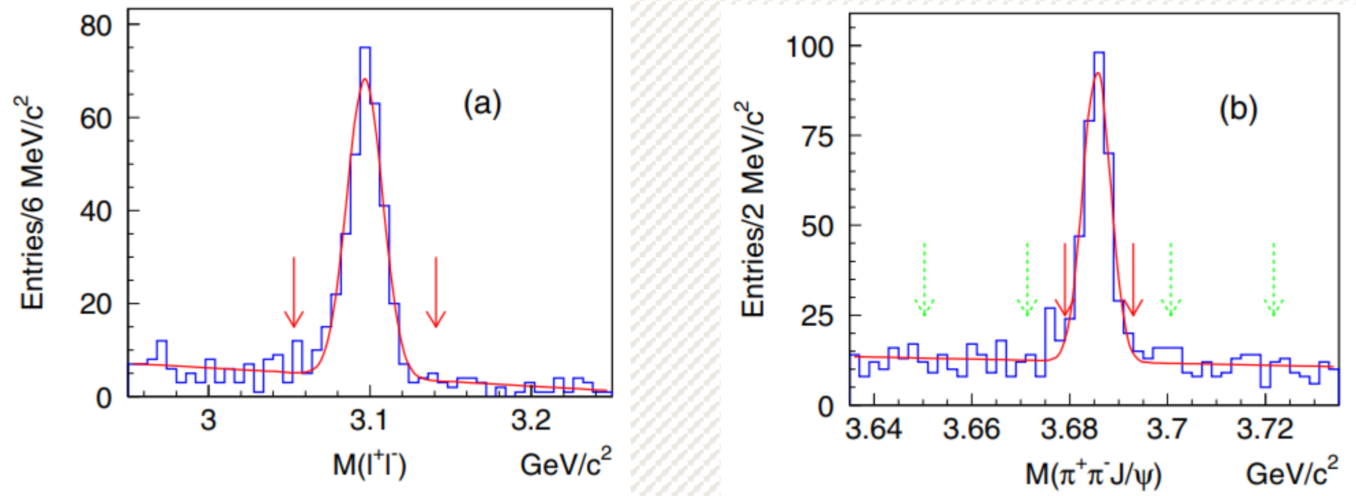




J/ψ and $\psi(2S)$ reconstructions

- Fitting functions: A Gaussian function for $J/\psi(\psi(2S))$ signals, 1st-order polynominal for background

- Mass resolution: $\sigma_{J/\psi} = 11.0 \pm 0.6$ MeV/c^2, $\sigma_{\psi(2S)} = 2.80 \pm 0.21$MeV/$c^2$
  M($\pi^+\pi^-J/\psi$) = M($\pi^+\pi^-l^+l^-$)-M(l^+l^-)+$m_{J/\psi}$ to improve $\psi(2S)$ mass resolution

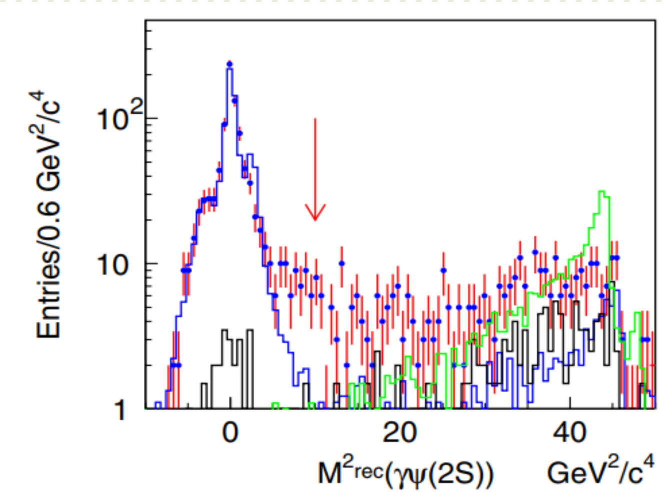


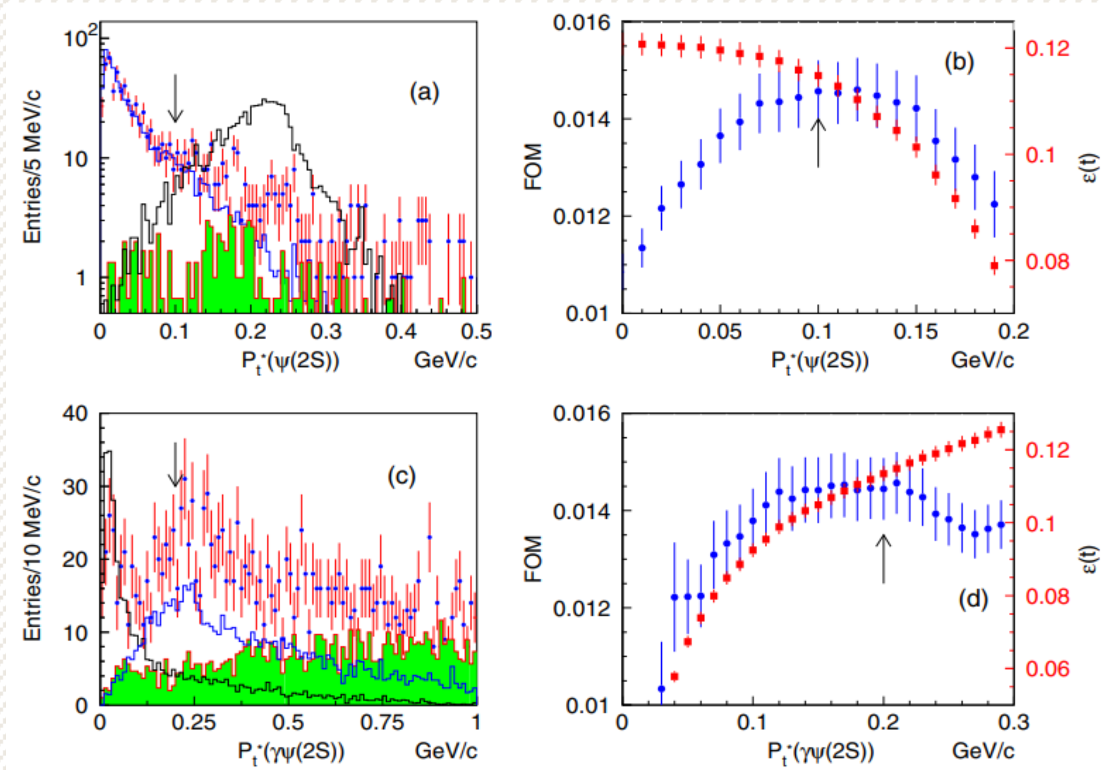
- ☐ Signal regions : $|M_{l^+l^-} - m_{J/\psi}| < 4\sigma_{J/\psi}(\sigma_{J/\psi} \equiv 11.0$ MeV/$c^2)$

  $|M_{\pi^+\pi^-J/\psi} - m_{\psi(2S)}| < 2.5\sigma_{\psi(2S)}(\sigma_{\psi(2S)} \equiv 2.8$MeV/$c^2)$
- ☐ Sideband region : $|M_{\pi^+\pi^-J/\psi} - m_{\psi(2S)} \pm 9\sigma_{\psi(2S)}| < 3.75\sigma_{\psi(2S)}$

Optimization of selection criteria

◆ The background is dominated by $e^+e^- \to \psi(2S)$ via ISR



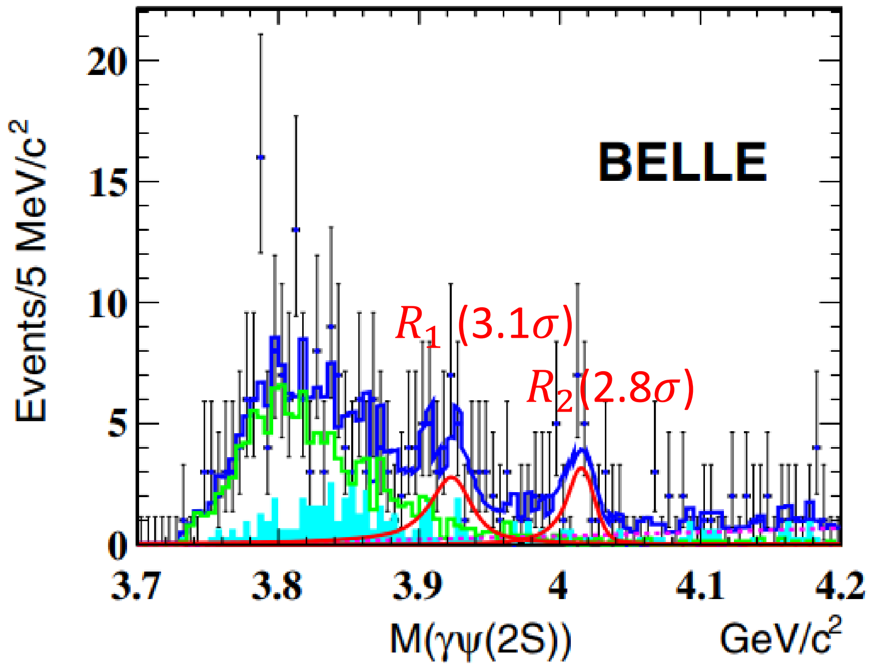


- For two-photon collision events, $M^2{}_{rec}(\gamma\psi(2S))$ would be large.
- For ISR events, $M^2{}_{rec}(\gamma\psi(2S))$ is around zero.
- $M^2{}_{rec}(\gamma\psi(2S))$ > 10 $(GeV/c^2)^2$ to remove most ISR events

□ Optimize the selections of $P_t{}^*(\psi(2S))$ and $P_t{}^*(\gamma\psi(2S))$ based on the Punzi figure of merit(FOM), defined as FOM $\equiv \frac{\varepsilon(t)}{\frac{a}{2}+\sqrt{N_{bkg(t)}}}$

$P_t{}^*(\psi(2S))$>0.1GeV/c, $P_t{}^*(\gamma\psi(2S))$ <0.2 GeV/c

Mass distribution of $\gamma\psi(2S)$ and two structures



- Two excesses around 3.92 and 4.02 GeV/c^2
- Fit function: $f_{sum} = f_{R1} + f_{R2} + f_{ISR} + f_{bkg} + f_{SB}$

f_{R1}、f_{R2}: Breit-Wigner ⊗ Crystall Ball function (solid red line)

f_{ISR}: for ISR events (green blank histogram)

f_{bkg}: possible addition backgrounds(pink dashed line)

f_{SB} : the background in $\psi(2S)$ reconstruction (blue shaded histogram)

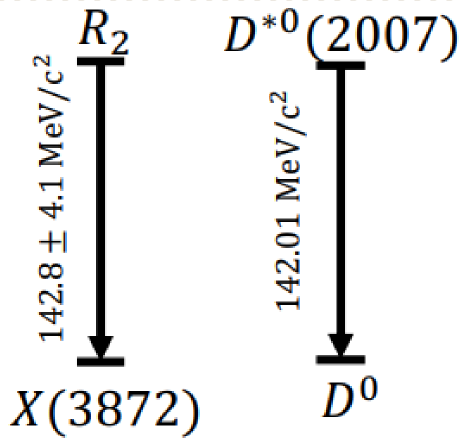
Resonant parameters	$J=0$	$J=2$
M_{R_1}	$3922.4 \pm 6.5 \pm 2.0$	
Γ_{R_1}	$22 \pm 17 \pm 4$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$9.8 \pm 3.6 \pm 1.3$	$2.0 \pm 0.7 \pm 0.2$
M_{R_2}	$4014.3 \pm 4.0 \pm 1.5$	
Γ_{R_2}	$4 \pm 11 \pm 6$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$6.2 \pm 2.2 \pm 0.8$	$1.2 \pm 0.4 \pm 0.2$

- **R_1 near 3.92 GeV/c^2: 3.1σ including systematic uncertainties**
- **R_2 near 4.01 GeV/c^2: study on look-elsewhere effect show a global significance of 2.8σ.**

Discussion on the two structures

- R_1 may be $X(3915)$, χ_{c2}(3930), or mix of them. Assuming R_1 is the $\chi_{c2}(3930)$, a rough estimation shows $\Gamma(\chi_{c2}(3930) \to \gamma\psi(2S)) = 200\sim300\mathrm{keV}$. [207 keV calculated by GI model in PRD 72, 054026 (2005)]

- R_2 has the same mass and width with 2^{++} partner of $X(3872)$ predicted in PRD 88, 054007(2013), Eur. Phys. J. C 75, 547 (2015)



R_2 may be helped for the study of $X(3872)$

- The newly reported $X(4014)$ state still needs to be studied, and the study on the $D^*\overline{D}^*$ interaction is crucial to explore possible internal structure.

- The possibility of the $X(4014)$ as the $D^*\overline{D}^*$ molecular state and its favored quantum numbers.[arXiv:2207.03930]

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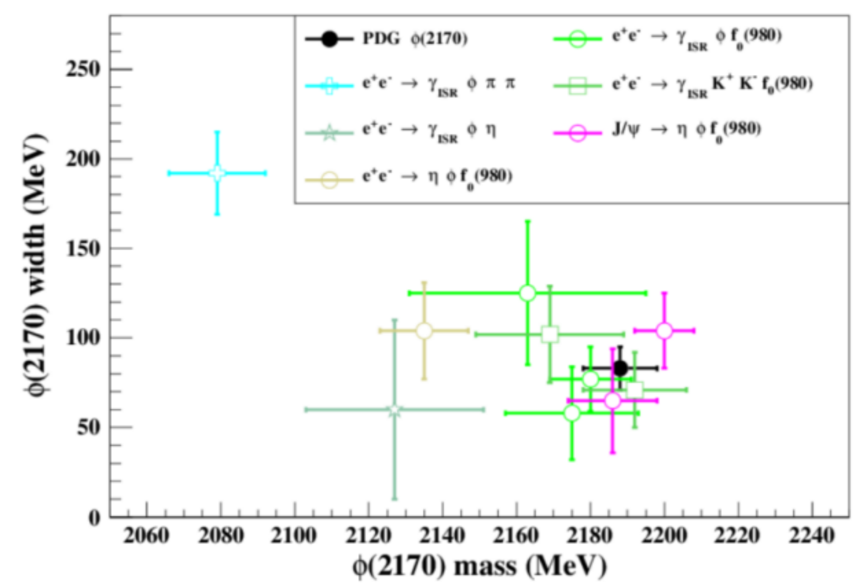
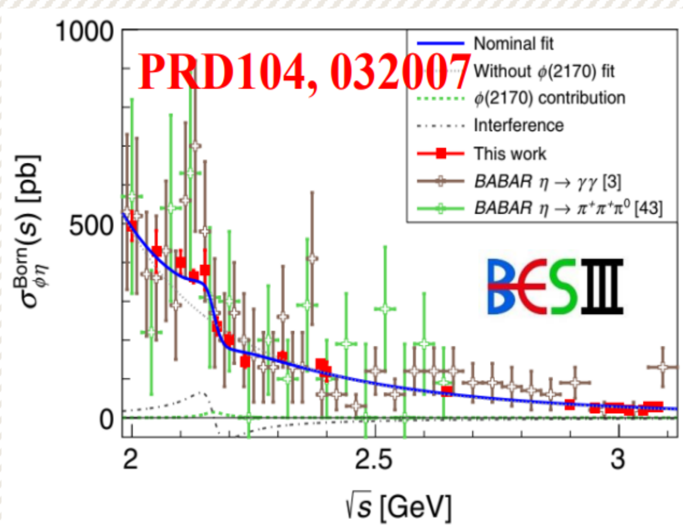
Study of $e^+e^- \to \eta\phi$ via ISR

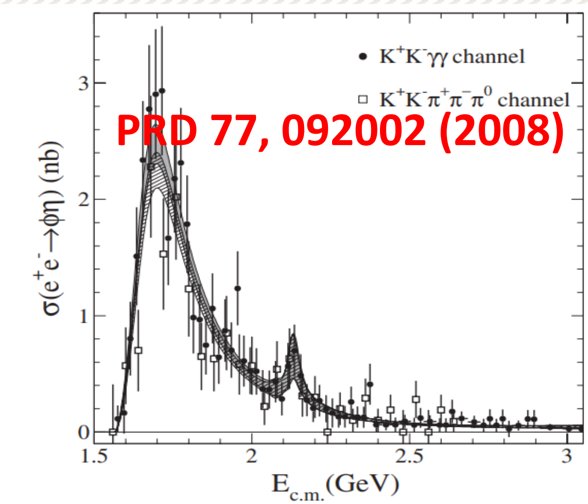
Motivation



- 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.

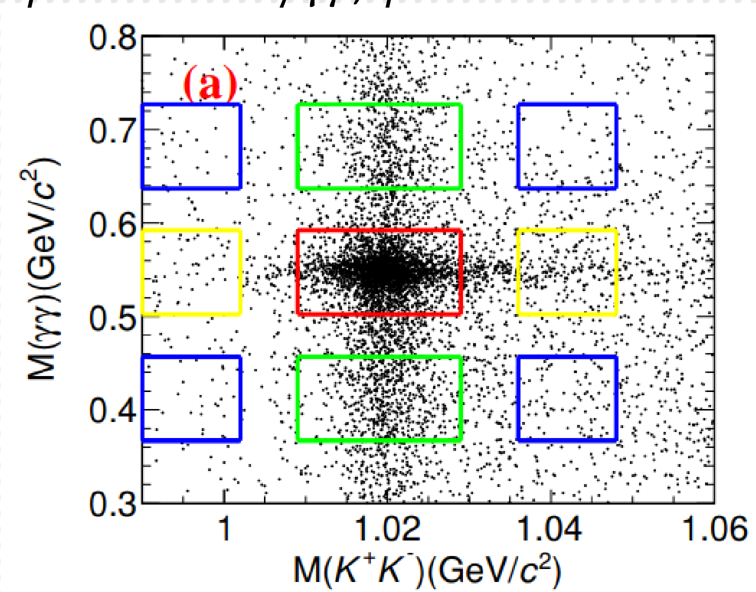


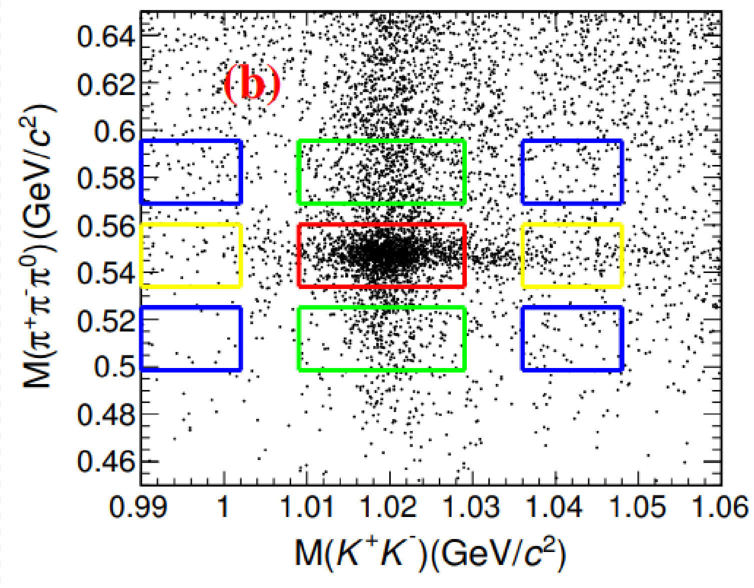


- $e^+e^- \to \eta\phi$:
  - ✓ BaBar: $(1.7 \pm 0.7 \pm 1.3)$ eV
  - ✓ BESIII: $0.24^{+0.12}_{-0.07}$ eV, $10.11^{+3.87}_{-3.13}$ eV
  - ✓ Need more data

ϕ and η signals and sidebands

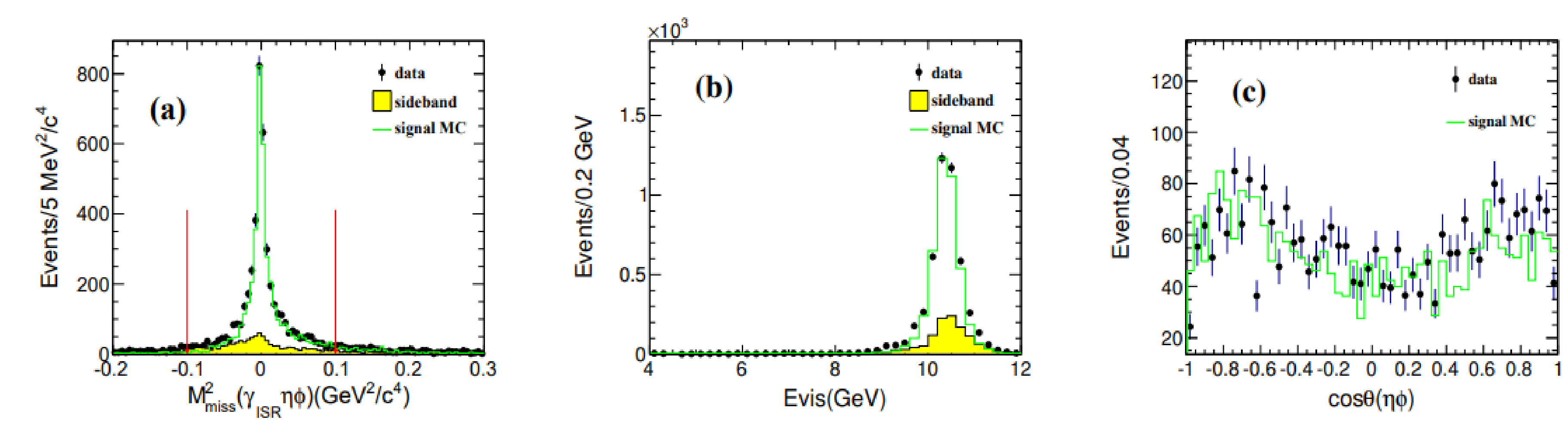
- $\eta \to \pi^+\pi^-\pi^0/\gamma\gamma, \phi \to K^+K^-$





- $|M_{K^+K^-} - m(\phi)| < 12\text{MeV}/c^2$ as signal region, 0.990< $M_{K^+K^-}$ <1.002GeV/c^2, 1.036< $M_{K^+K^-}$ <1.048 GeV/c^2 as sideband region.
- $\left|M_{\pi^+\pi^-\pi^0/\gamma\gamma} - m_\eta\right| < 3\sigma_{\pi^+\pi^-\pi^0/\gamma\gamma}$ as signal region, $\left|M_{\pi^+\pi^-\pi^0/\gamma\gamma} - m_\eta \pm 9\sigma_{\pi^+\pi^-\pi^0/\gamma\gamma}\right| < 3\sigma_{\pi^+\pi^-\pi^0/\gamma\gamma}$ as sideband region($\sigma_{\pi^+\pi^-\pi^0} = 4.2\text{MeV}/c^2$, $\sigma_{\gamma\gamma}$=11.3 MeV/c^2)
- S1, S2 and S3 represent the sum of the events in the horizontal two, vertical two nearest sideband boxes and the four diagonal sideband boxes to the signal box
- The normalized factor : S = a · S_1 + b · S_2 - ab · S_3

ISR characters of the final states



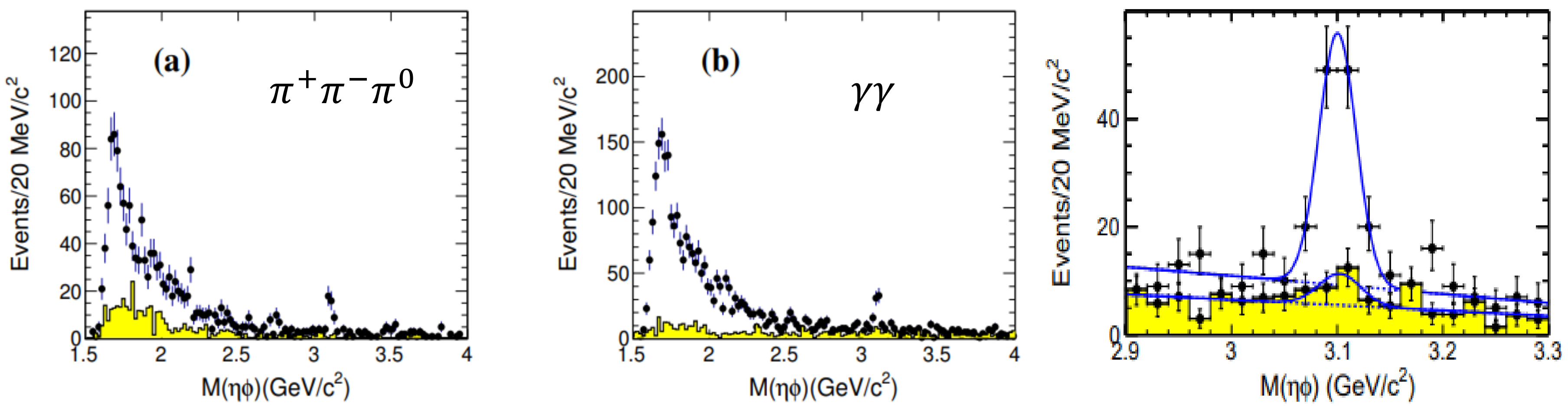
- The photon with the highest energy is identified to be γ_{ISR}.

- The missing component after η, ϕ and γ_{ISR} being reconstructed is nothing or another ISR photon with lower energy

- $\left|M_{miss}{}^{2}(\gamma_{ISR}\eta\phi)\right| < 0.1(GeV/c^{2})^{2}$, the efficiency is about 97~98%

- The good agreements between data and signal MC simulations on visible energy (E_{vis}) and the polar angle of the $\eta\phi$ system in the $e^{+}e^{-}$ CM frame ($\cos\theta(\eta\phi)$).

Invariant mass spectrum of $\eta\phi$



- Clear J/ψ signals in both $\pi^+\pi^-\pi^0$ and $\gamma\gamma$ mode

- The branching fraction of $J/\psi \to \eta\phi$

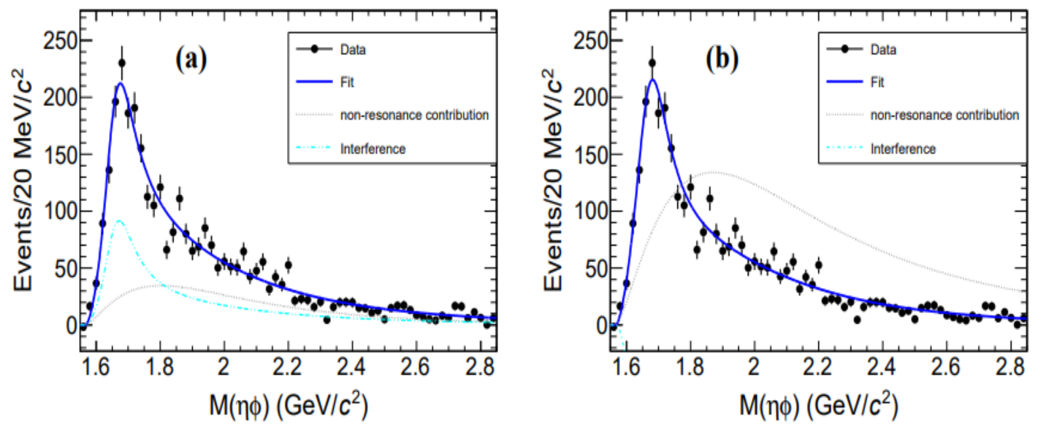
$$\mathcal{B}(J/\psi \to \eta\phi) = \frac{N_{sig}^{fit}}{\sigma_{ISR}^{prod} \times \mathcal{L} \times \varepsilon \times \mathcal{B}(\phi \to K^+K^-) \times \mathcal{B}(\eta \to \gamma\gamma/\pi^+\pi^-\pi^0)}$$

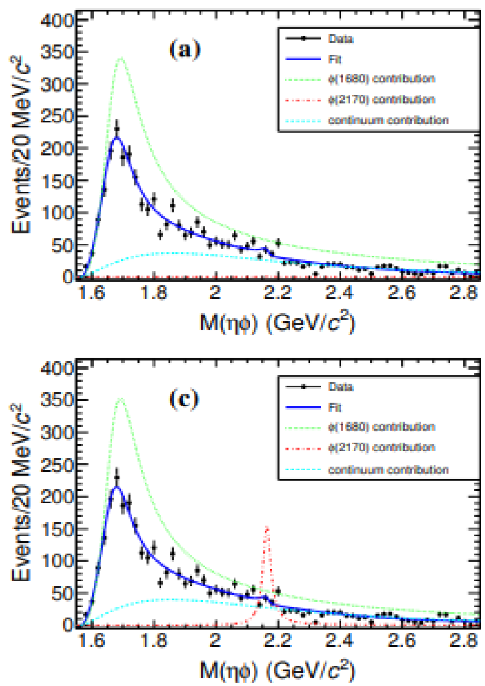
- $\mathcal{B}(J/\psi \to \eta\phi)$ = $(0.71 \pm 0.10 \pm 0.05) \times 10^{-3}$, which agrees well with the world average value, $(0.74 \pm 0.08) \times 10^{-3}$.

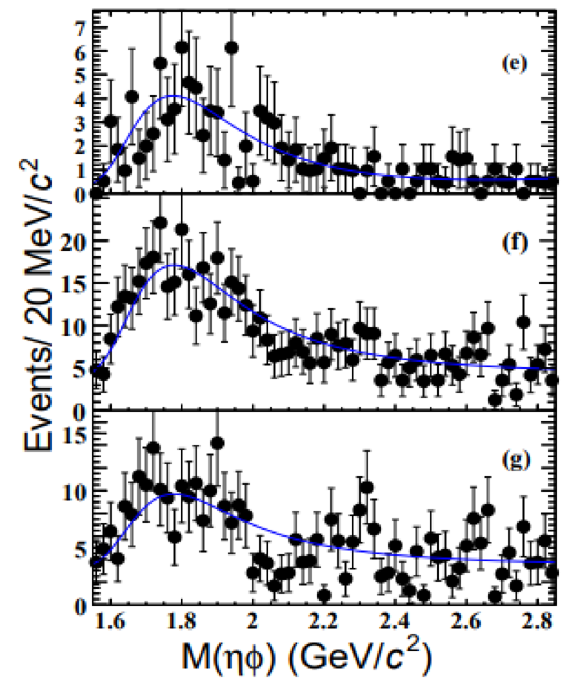
- There is no obvious signal of $\phi(2170)$, but the resonant parameters of $\phi(1680)$ could be measured more precisely.

Fitting the $M(\eta\phi)$

- An unbinned maximum likelihood fit is perform to the $M_{\eta\phi}$ mass spectra $\in[1.55, 2.85]$ GeV/c^2 using signal candidate events and 2D sideband events simultaneously.







Fitting the M($\eta\phi$)

- Fit results with $\phi(1680)$ and $\phi(2170)$ both included, and also excluding $\phi(2170)$. The mass and width of $\phi(2170)$ are fixed from prior BESIII measurement.

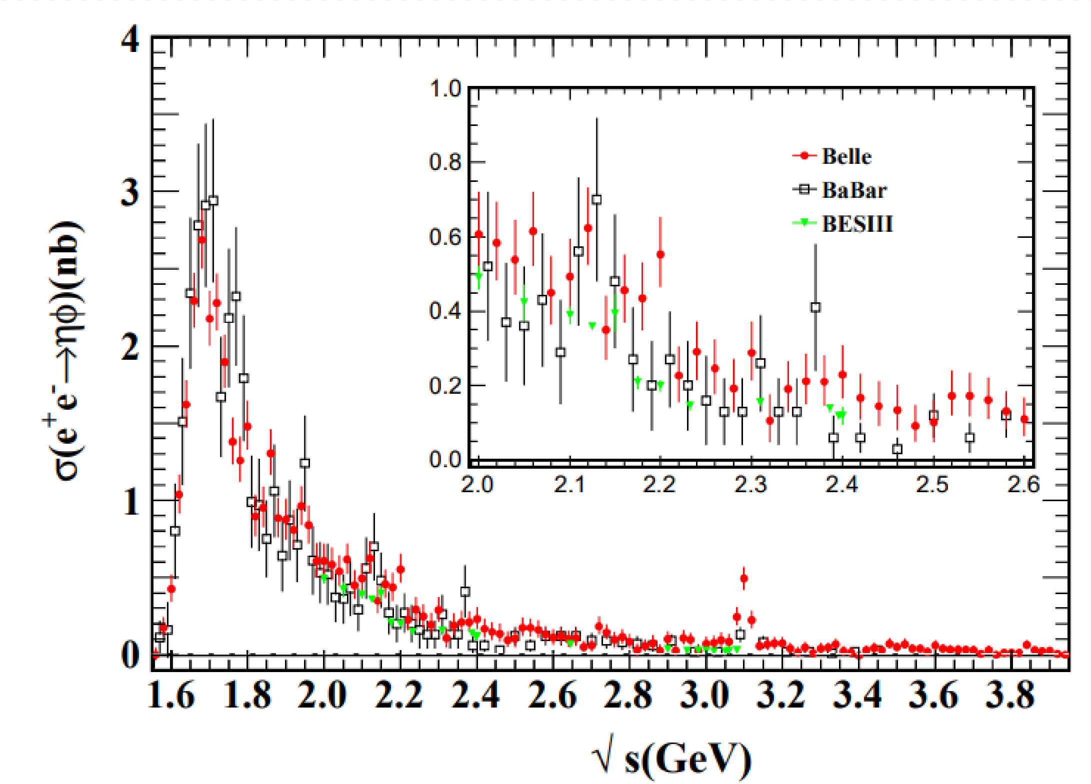
Parameters	with $\phi(2170)$				without $\phi(2170)$	
	Solution I	Solution II	Solution III	Solution IV	Solution I	Solution II
χ^2/ndf	77/56				85/60	
a_0	-4.1 ± 0.5	5.0 ± 0.7	-5.0 ± 0.5	-4.8 ± 0.2	-3.2 ± 0.7	5.0 ± 0.1
a_1	2.7 ± 0.1	2.6 ± 0.1	2.7 ± 0.1	2.6 ± 0.1	2.9 ± 0.1	2.6 ± 0.1
$\mathcal{B}^{\phi(1680)}_{\eta\phi}\Gamma^{\phi(1680)}_{e^+e^-}$(eV)	122 ± 6	219 ± 15	163 ± 11	203 ± 12	75 ± 10	207 ± 16
$M_{\phi(1680)}$(MeV/c^2)	1683 ± 7				1696 ± 8	
$\Gamma_{\phi(1680)}$(MeV)	149 ± 12				175 ± 13	
$\mathcal{B}^{\phi(1680)}_{\eta\phi}$	0.18 ± 0.02	0.19 ± 0.04	0.21 ± 0.02	0.17 ± 0.04	0.25 ± 0.12	0.23 ± 0.10
$\mathcal{B}^{\phi(2170)}_{\eta\phi}\Gamma^{\phi(2170)}_{e^+e^-}$(eV)	0.09 ± 0.05	0.06 ± 0.02	16.7 ± 1.2	17.0 ± 1.2	—	
$M_{\phi(2170)}$(MeV/c^2)	2163.5(*fixed*)				—	
$\Gamma_{\phi(2170)}$(MeV)	31.1(*fixed*)				—	
$\theta_{\phi(1680)}$(°)	-89 ± 2	96 ± 6	-92 ± 1	-86 ± 7	-87 ± 15	108 ± 22
$\theta_{\phi(2170)}$(°)	37 ± 14	-102 ± 11	-167 ± 6	-155 ± 5	—	

- The statistical significance of $\phi(2170)$ is 1.7σ, the upper limit of $\phi(2170)$ at 90% *C.L* is determined to be 0.17 eV or 18.6 eV.

Cross sections of $e^+e^- \to \eta\phi$

- The $M_{\eta\phi}$ distributions are combined and the cross section of $e^+e^- \to \eta\phi$ for each $M_{\eta\phi}$ bin is calculated according to

$$\sigma_i = \frac{n_i{}^{obs} - n_i{}^{bkg}}{\mathcal{L}_i \times \sum_j \varepsilon_{ij}\mathcal{B}_j}$$



Summary

- With the full data sample taken by Belle, the ISR process $e^+e^- \to \eta\phi$ has been scanned from threshold to 3.95 GeV/c^2.

- The branching fraction of $J/\psi \to \eta\phi$ is measured , which is in good agreement with the world average value from PDG.

- No significant $\phi(2170)$ in this work; the upper limit of ϕ(2170) at 90% *C.L* is calculated and $\phi(1680)$ resonant parameters are measured in this work.

Thank you for your attentions!

Back up

Systematic Uncertainties

Source	Relative error (%)		
…	$J=0$		$J=2$
Particle identification		2.8	
Tracking efficiency		1.4	
Photon reconstruction		2.0	
$\psi(2S)$ mass window		0.6	
$P_t^*(\psi(2S))$ and $P_t^*(\gamma\psi(2S))$		1.0	
$M_{\rm rec}^2(\gamma\psi(2S))$		0.5	
Integrated luminosity		1.4	
Helicity	…		4.3
Luminosity function		2.5	
Branching fractions		1.3	
Statistics of MC samples		0.7	
Sum in quadrature	5.1		6.6

Data and MC samples

- Data: HadronB(J) and tauskimB (980 fb^{-1}, exp7-73)
- MC:
  - $J/\psi \to \eta\phi, \eta \to \pi^+\pi^-\pi^0/\gamma\gamma, \phi \to K^+K^-$ (10^5 events)

    $Y(2175) \to \eta\phi, \eta \to \pi^+\pi^-\pi^0/\gamma\gamma, \phi \to K^+K^-$ (10^5 events)

    $\phi(1680) \to \eta\phi, \eta \to \pi^+\pi^-\pi^0/\gamma\gamma, \phi \to K^+K^-$ (3×10^5 events)
  - SVD2a(Exp.31-55):SVD2b(Exp.61-69):SVD1(Exp.7-27):5S(Exp71-73)=8:5:3:4, PHOKHARA

Selection Criteria

	$\pi^+\pi^-\pi^0$ mode	$\gamma\gamma$ mode
The number of charged tracks	3$\leq N_{trk} \leq 4$	$N_{trk} = 2$
PID	for $K^\pm, \frac{\mathcal{L}K}{\mathcal{L}K+\mathcal{L}\pi} > 0.6$ for $\pi^\pm, \frac{\mathcal{L}K}{\mathcal{L}K+\mathcal{L}\pi} < 0.4$	For $K^\pm, \frac{\mathcal{L}K}{\mathcal{L}K+\mathcal{L}\pi} > 0.6$
Photon energies	E(γ)>25MeV in the barrel E(γ)>50MeV in the endcap	$E_l(\gamma)$>120MeV $E_h(\gamma)$>350MeV
ϕ mass cut	$\lvert M(K^+K^-) - m(\phi)\rvert < 3\sigma(\sigma = 4MeV/c^2)$	
π^0mass cut	120MeV/c^2<M($\gamma\gamma$)<150MeV/c^2 $\chi^2(\pi^0) < 25$	–
η mass cut	$\lvert M(\pi^+\pi^-\pi^0) - m(\eta)\rvert < 3\sigma$ $(\sigma = 4.2MeV/c^2)$	$\lvert M(\gamma\gamma) - m(\eta)\rvert < 3\sigma$ $(\sigma = 11.3MeV/c^2)$
Recoil mass cut	$\left\lvert {M_{miss}}^2(\gamma_{ISR}\eta\phi)\right\rvert < 0.1(GeV/c^2)^2$	

Fitting the M($\eta\phi$)

- The parametrization for the cross section of $e^+e^- \to \eta\phi$

$$\sigma_{\eta\phi}(\sqrt{s}) = 12\pi\mathcal{P}_{\eta\phi}(\sqrt{s})\left|A_{\eta\phi}{}^{n.r.}(\sqrt{s}) + A_{\eta\phi}{}^{\phi(1680)}(\sqrt{s}) + A_{\eta\phi}{}^{\phi(2170)}(\sqrt{s})\right|^2$$

$A_{\eta\phi}{}^{n.r.}(\sqrt{s}) = a_0/s^{a_1}$ is used to describe the non-resonant contribution

$$A_{\eta\phi}^{\phi(1680)}(\sqrt{s}) = \sqrt{\mathcal{B}_{\phi(1680)}^{\eta\phi}\Gamma_{\phi(1680)}^{e^+e^-}}\frac{\sqrt{\Gamma_{\phi(1680)}/\mathcal{P}_{\eta\phi}(M_{\phi(1680)}^2)}e^{i\theta_{\phi(1680)}}}{M_{\phi(1680)}^2 - s - i\sqrt{s}\Gamma_{\phi(1680)}(\sqrt{s})}$$

$$\Gamma_{\phi(1680)}(\sqrt{s}) = \Gamma_{\phi(1680)}[\frac{\mathcal{P}_{KK^*(892)}(\sqrt{s})}{\mathcal{P}_{KK^*(892)}(M_{\phi(1680)})}\mathcal{B}_{\phi(1680)}^{KK^*(892)} + \frac{\mathcal{P}_{\eta\phi}(\sqrt{s})}{\mathcal{P}_{\eta\phi}(M_{\phi(1680)})}\mathcal{B}_{\phi(1680)}^{\eta\phi}$$
$$+(1 - \mathcal{B}_{\phi(1680)}^{\eta\phi} - \mathcal{B}_{\phi(1680)}^{KK^*(892)})].$$

$\mathcal{B}_{\phi(1680)}{}^{KK^*(892)} \approx 2 \times \mathcal{B}_{\phi(1680)}{}^{\eta\phi}$ from Ref. [1] directly

$$A_{\eta\phi}^{\phi(2170)}(s) = \sqrt{\mathcal{B}_{\phi(2170)}^{\eta\phi}\Gamma_{\phi(2170)}^{e^+e^-}}\frac{\sqrt{\Gamma_{\phi(2170)}/\mathcal{P}_{\eta\phi}(M_{\phi(2170)}^2)}e^{i\theta_{\phi(2170)}}}{M_{\phi(2170)}^2 - s - i\sqrt{s}\Gamma_{\phi(2170)}} \cdot \frac{B(p)}{B(p')}$$

[1] Phys. Rev. D 77, 092002 (2008)

Systematic Uncertainty

Source	$\gamma\gamma$ mode	$\pi^+\pi^-\pi^0$ mode	common
Particle identification	2.0	4.0	2.0
Tracking	0.7	1.4	0.7
Photon reconstruction	6.0	6.0	6.0
ϕ, η masses and $M^2_{\rm miss}(\eta\phi\gamma_{\rm ISR})$	1.7	1.4	1.4
Luminosity	1.4	1.4	1.4
Generator	0.5	0.5	0.5
$\sigma^{\rm prod}_{\rm ISR}(J/\psi)$	1.0	1.0	1.0
Trigger	1.5	1.0	...
Branching fractions	0.6	0.6	0.6
J/ψ signal fitting	1.8	1.5	...
MC statistics	0.1	0.1	0.1
Sum for $\sigma(e^+e^- \to \eta\phi)$	6.9	7.3	6.7
Sum for $\mathcal{B}(J/\psi \to \eta\phi)$	7.2	7.9	6.8

- The total irrelevant uncertainties (σ_{tot}) is calculated by $\sqrt{\sum_i(\Delta\varepsilon_i \times \mathcal{B}_i)^2} / \sum_i(\varepsilon_i \times \mathcal{B}_i)$, where $\Delta\varepsilon_i$ equal to $\sigma_i \times \varepsilon_i$, i is i-th mode of η decays.
- σ_{sys}=6.8% is calculated by $\sqrt{\sum_j \sigma_j^{\,2} + \sigma_{tot}^{\,2}}$ (σ_j is the each source of common uncertainties mentioned above)