Search for invisible decays of light mesons via $J/\psi \to VP(V = \omega/\phi, P = \eta/\eta')$ decays at STCF

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Outline

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2. Search for $\omega/\phi \to invisible$
3. Search for $\eta/\eta' \to invisible$
4. Summary

Motivation

Invisible particles

Particles like ν interact so weakly that they are not observable in the detector.

New physics

Quarkonium can decay to the neutrino-pair via virtual Z^0 boson rarely.

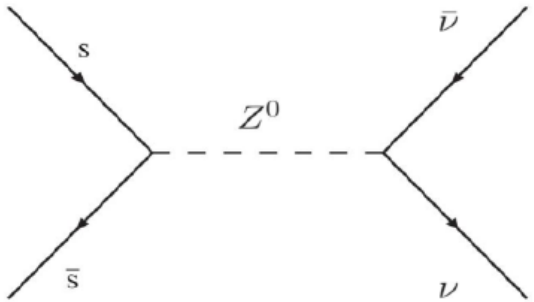
- $\mathcal{B}(\omega \to v\bar{v}) = 2.79 \times 10^{-13}$
- $\mathcal{B}(\phi \to v\bar{v}) = 1.67 \times 10^{-11}$

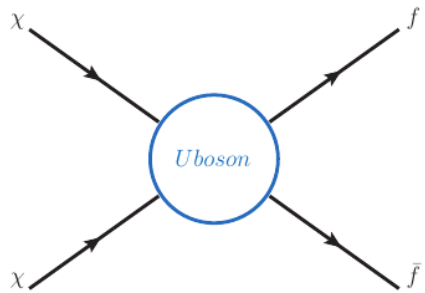
Branching fraction of the invisible decays might be enhanced in the presence of light dark matter(LDM) χ particles.

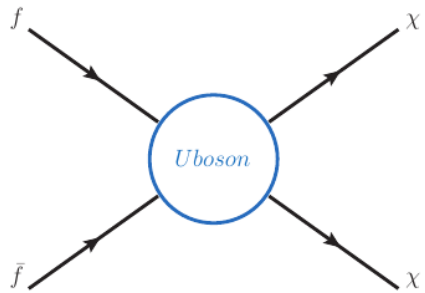
- $\mathcal{B}(\omega \to invisible) = 7.2 \times 10^{-8}$
- $\mathcal{B}(\phi \to invisible) = 1.9 \times 10^{-8}$
- $\mathcal{B}(\eta \to invisible) = 3.4 \times 10^{-5}$
- $\mathcal{B}(\eta' \to invisible) = 3.7 \times 10^{-7}$

Search for the invisible meson decays is one of the major ways to discover LDM.

Motivation



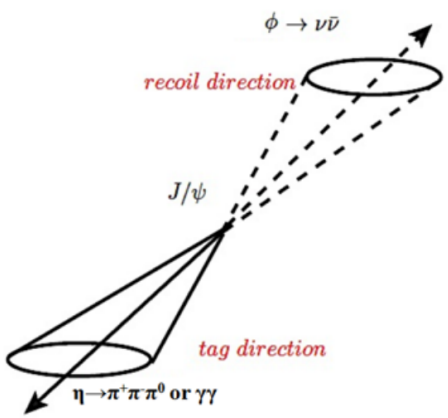


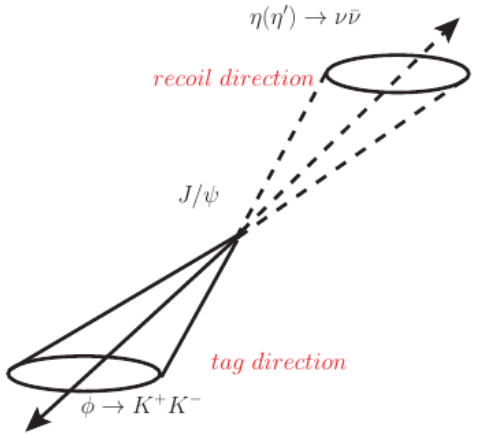


Future τ-charm facility

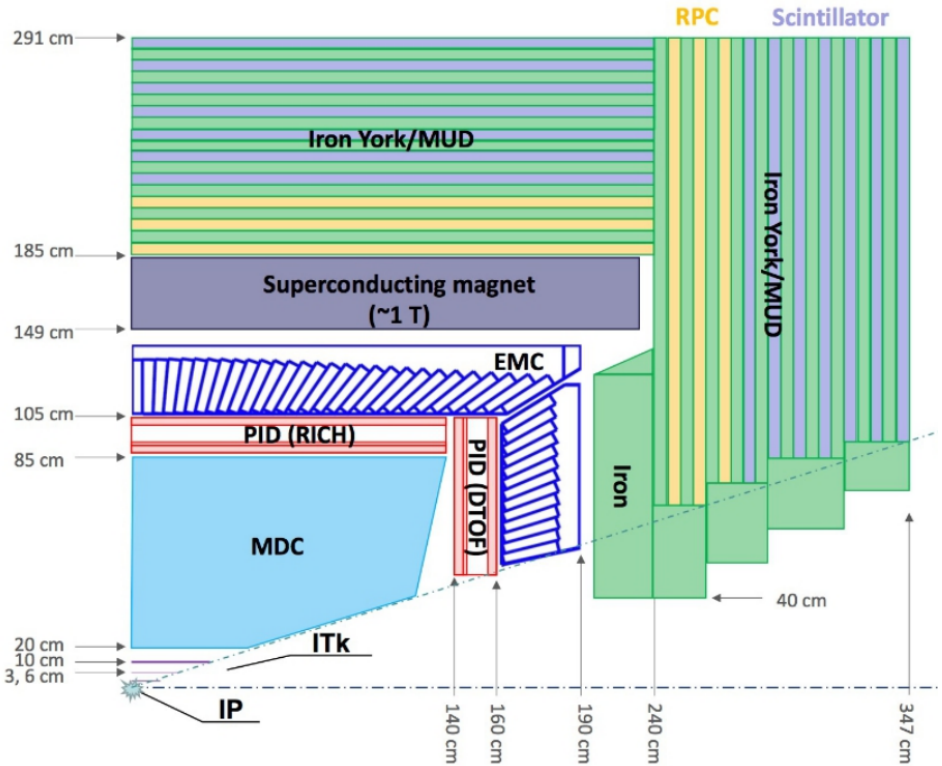
STCF experiment is the next generation of τ-charm facility with higher luminosity and wider energy range based in Hefei China.

It is expected to collect 3.4×10^{12} J/ψ events per year at STCF, which will offer great opportunity to search for invisible decays.





Data set



- OSCAR version: 2.6.2
- Inclusive MC:
  1.3×10^9 official J/ψ samples
- Signal MC:
  10k PHSP model for invisible

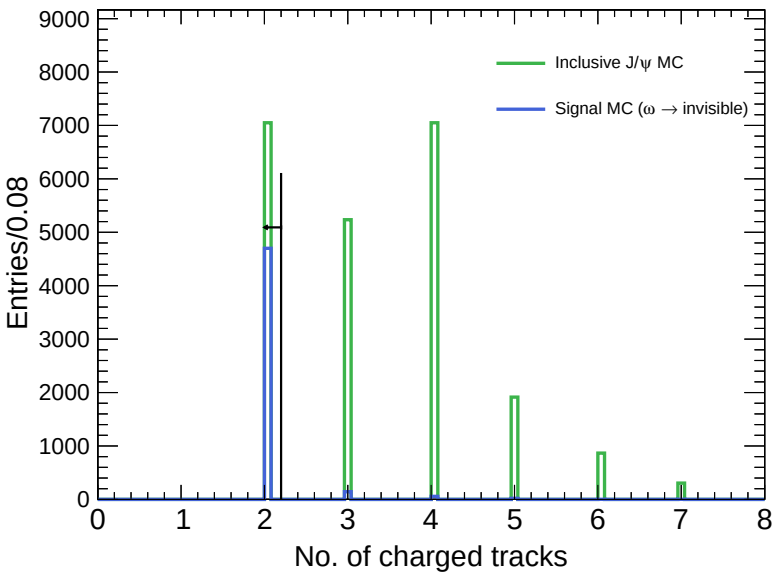
Analysis strategy

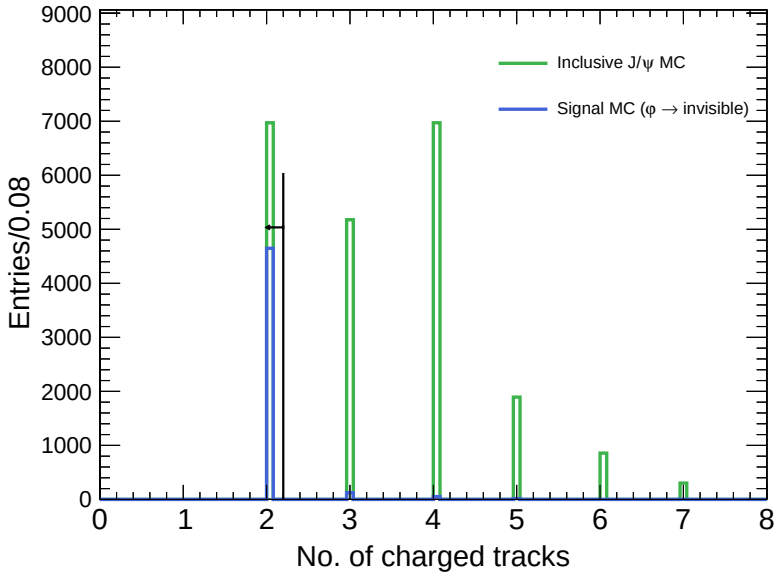
$$\frac{\mathcal{B}(V/P \to invisible)}{\mathcal{B}(V/P \to visible)} = \frac{N_{sig}^{invisible} \cdot \epsilon^{visible}}{N_{sig}^{visible} \cdot \epsilon^{invisible}}$$

Event selection: $\omega/\phi \to invisible$

- Good charged tracks:
  - $|V_r| < 1.0\text{cm}, |V_z| < 10\text{cm}$
  - $|\cos\theta| < 0.93$
- $\mathrm{N}_{tracks} = 2, \mathrm{N}_{charge} = 0, \mathrm{N}_{\gamma} \geq 2$

- Good photons:
  - Barrel($|\cos\theta_\gamma| < 0.8325$): $\mathrm{E}_\gamma > 25\text{MeV}$
  - End-cap ($0.8325 < |\cos\theta_\gamma| < 0.9445$): $\mathrm{E}_\gamma > 50\text{MeV}$
  - $\theta_{\gamma,x\pm} > 10$ degrees



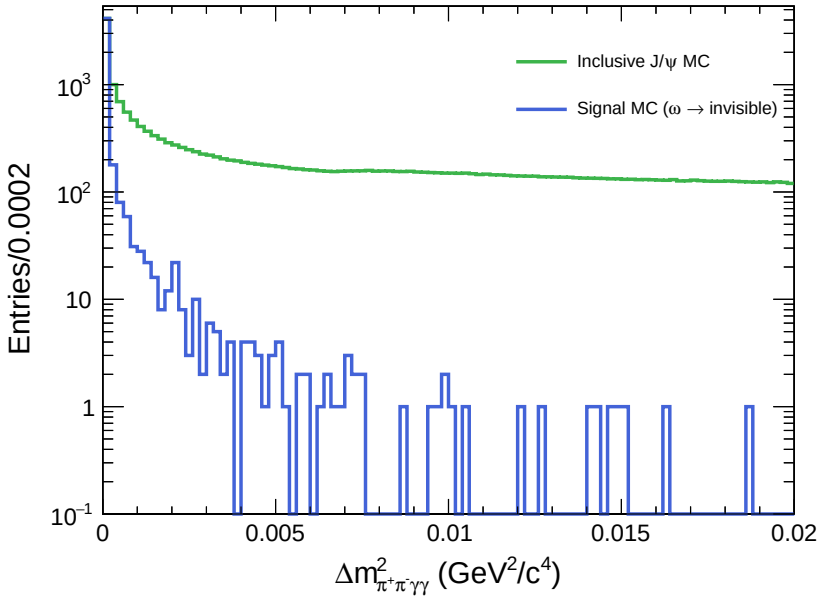


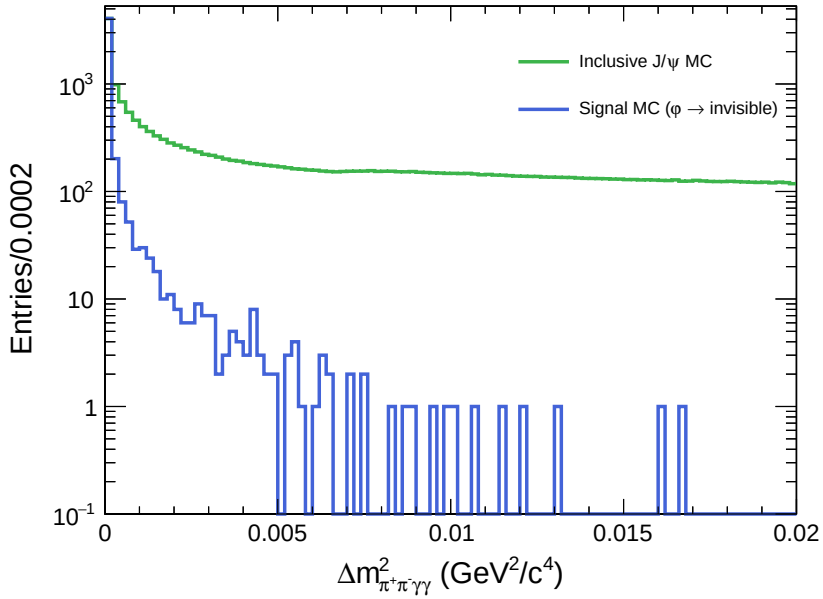
Event selection: $\omega/\phi \to invisible$

- Perform the vertex fit with 2 charged tracks.
- GlobalPID is used to identify pions:
  - Prob(π) > Prob(e)
  - Prob(π) > Prob(K)
- Perform 1 constrain kinematic fit for $\pi^0 \to \gamma\gamma$ reconstruction.
- Reconstruct the decay process of $\eta \to \pi^+\pi^-\pi^0$ for a minimum value of $\Delta m^2_{\pi^+\pi^-\gamma\gamma}$.

$$\Delta m^2_{\pi^+\pi^-\gamma\gamma} = (m_\eta^{PDG} - m_{\pi^+\pi^-\gamma\gamma})^2$$

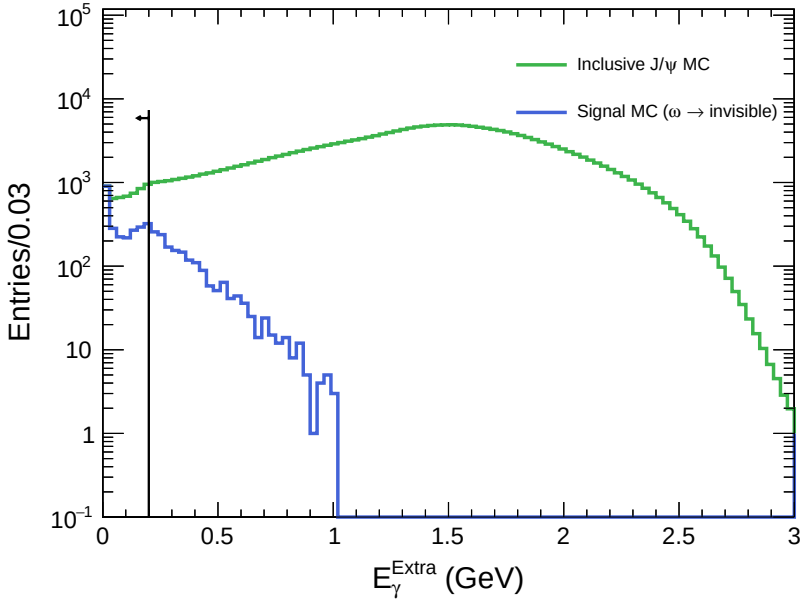
Event selection: $\omega/\phi \to invisible$

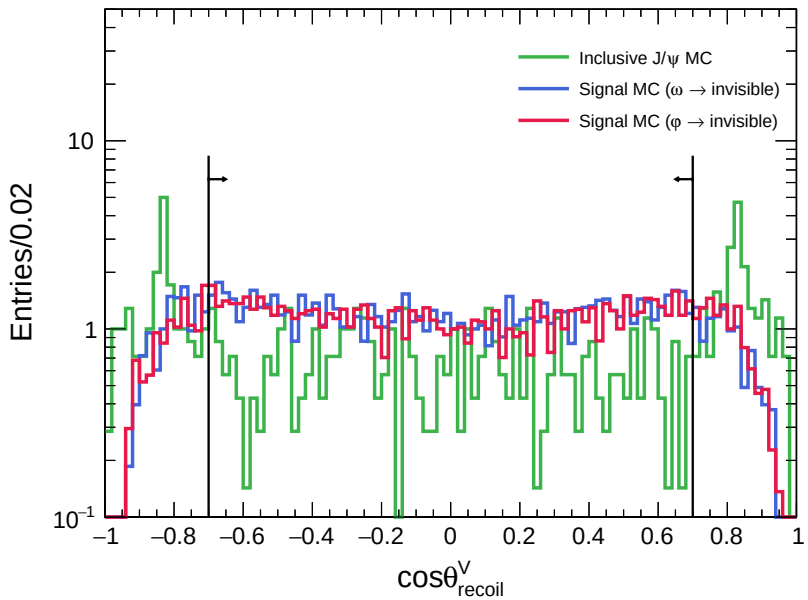


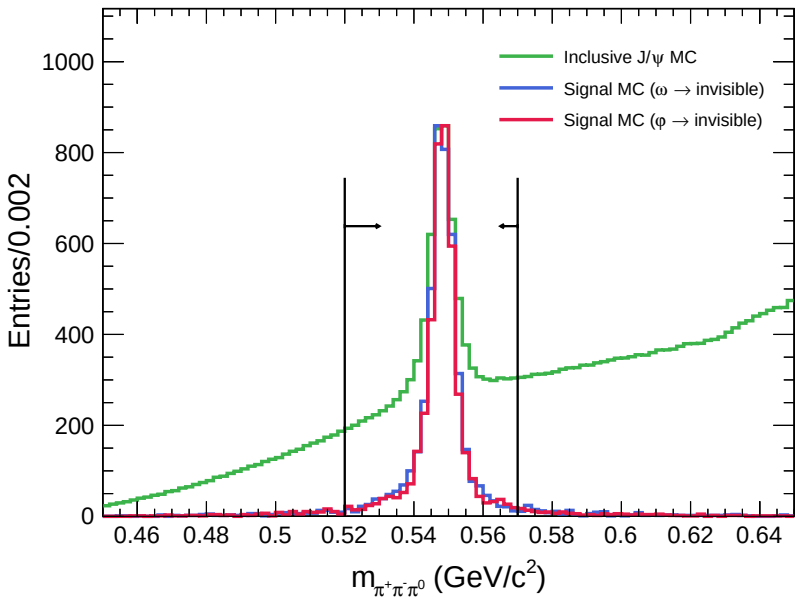


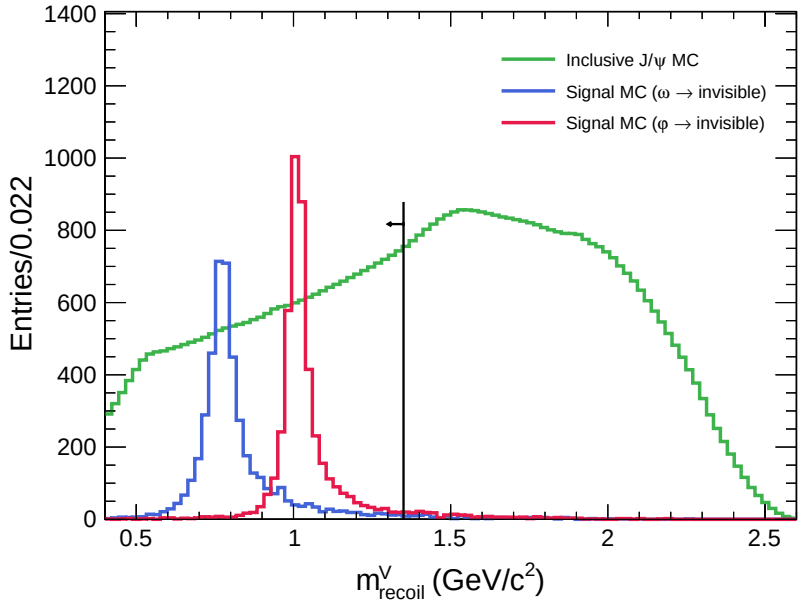
- Energy of extra γ not used for π^0 reconstruction(E_γ^{Extra}): $E_\gamma^{Extra} < 0.2\text{GeV}$
- Polar angle of the system recoiling against the η candidate(θ_{recoil}^V): $|\cos\theta_{recoil}^V| < 0.7$
- η candidate mass window: $m_{\pi^+\pi^-\pi^0} \in (0.52, 0.57)\text{GeV}/c^2$
- Mass of the system recoiling against the η candidate: $m_{recoil}^V \in (0.4, 1.35)\text{GeV}/c^2$

Event selection: $\omega/\phi \to invisible$









Cut flow: $\omega/\phi \to invisible$

Table: The cut flow comparison between BESIII and STCF.

	Signal MC for $\omega \to invisible$		Signal MC for $\phi \to invisible$		Inclusive MC
	BESIII	STCF	BESIII	STCF	
Total	1000000	10000	1000000	10000	1291048000
Pre-selection cut	285193	4700	291367	4648	104942595
$E_\gamma^{extra} < 0.2$ GeV	254882	2835	263141	2792	2878786
$0.52 < m_{\pi^+\pi^-\pi^0} < 0.57$ GeV/c^2	238988	2693	247552	2652	129434
$0.4 < m_{recoil}^V < 1.35$ GeV/c^2	235366	2664	243097	2616	403
$\lvert\cos\theta_{recoil}^V\rvert < 0.7$	199193	2122	206475	2085	151
Efficiency	19.92%	21.22%	20.65%	20.85%	

Cut flow: $\omega/\phi \to invisible$

Table: The cut flow comparison without extra gamma energy cut.

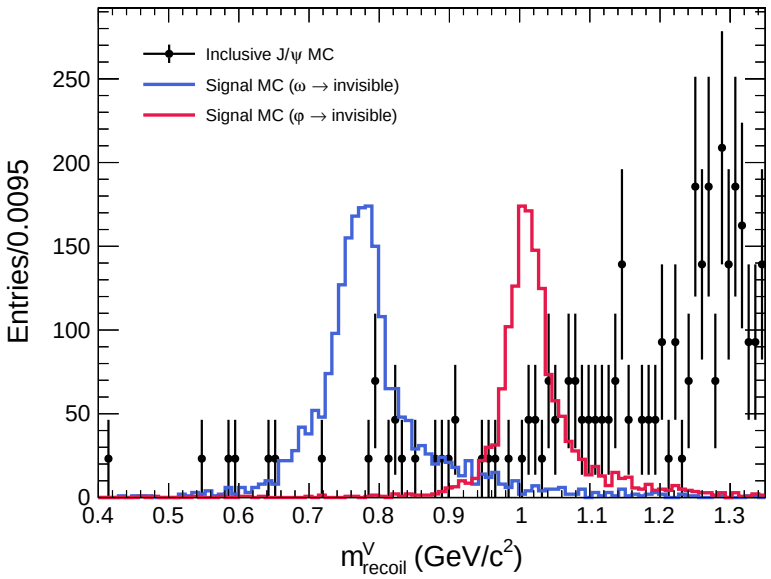
	$\omega \to invisible$ Signal MC			
	BESIII	Rel. Eff.	STCF	Rel. Eff.
Pre-selection cut	14341		4700	
$0.52 < m_{\pi^+\pi^-\pi^0} < 0.57$	13398	93.42%	4346	92.47%
$0.4 < m^V_{recoil} < 1.35$	13166	98.27%	4251	97.81%
$\lvert\cos\theta^V_{recoil}\rvert < 0.7$	11211	85.15%	3396	79.89%

	$\phi \to invisible$ Signal MC			
	BESIII	Rel. Eff.	STCF	Rel. Eff.
Pre-selection cut	14732		4648	
$0.52 < m_{\pi^+\pi^-\pi^0} < 0.57$	13861	94.09%	4310	92.73%
$0.4 < m^V_{recoil} < 1.35$	13596	98.09%	4195	97.33%
$\lvert\cos\theta^V_{recoil}\rvert < 0.7$	11579	85.16%	3323	79.21%

Signal yield: $\omega/\phi \to invisible$

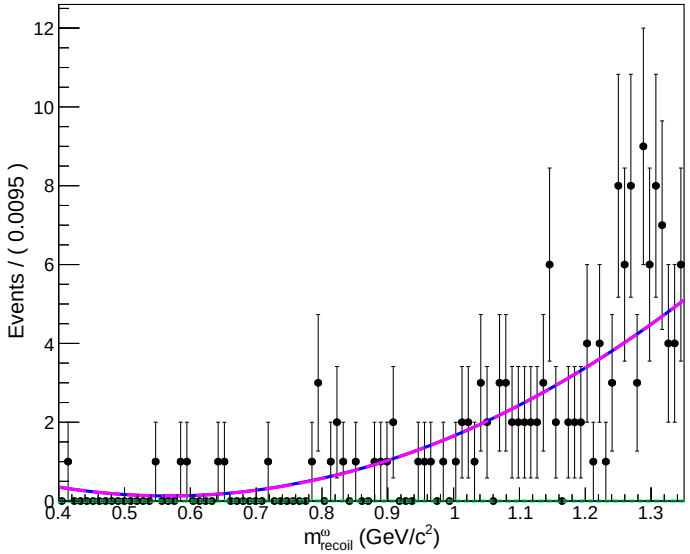
- $\omega \to invisible$: $N_{sig} = 0.05 \pm 4.57$.
- $\phi \to invisible$: $N_{sig} = -7.40 \pm 4.53$.
- The signal yields are consistent with 0.

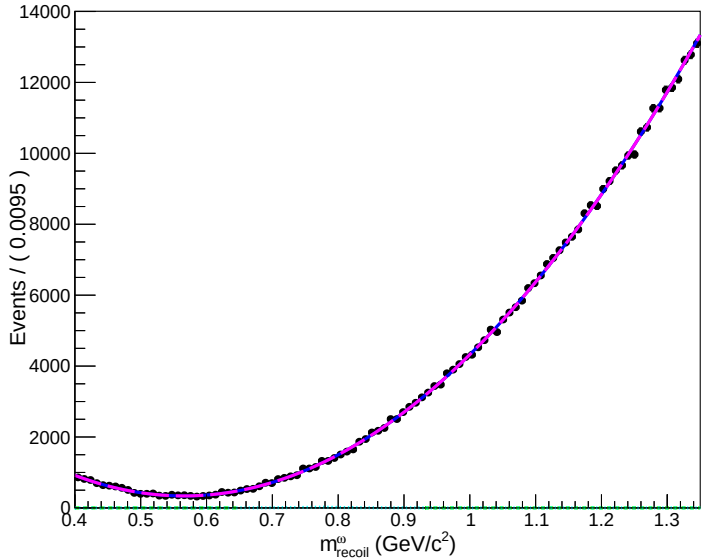
- Generate fake data to simulate the expected result at 3.4×10^{12} J/ψ events level.
  - $\omega \to invisible$: $N_{sig}^{fake} = -199.12 \pm 238$.
  - $\phi \to invisible$: $N_{sig}^{fake} = 17.56 \pm 305$.

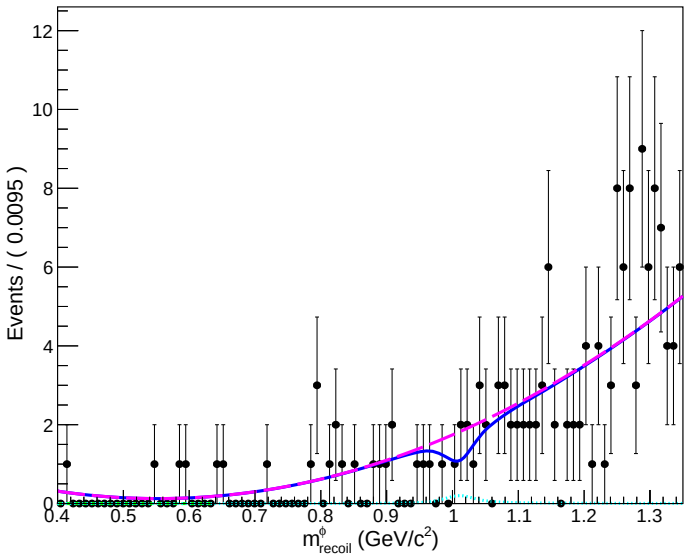


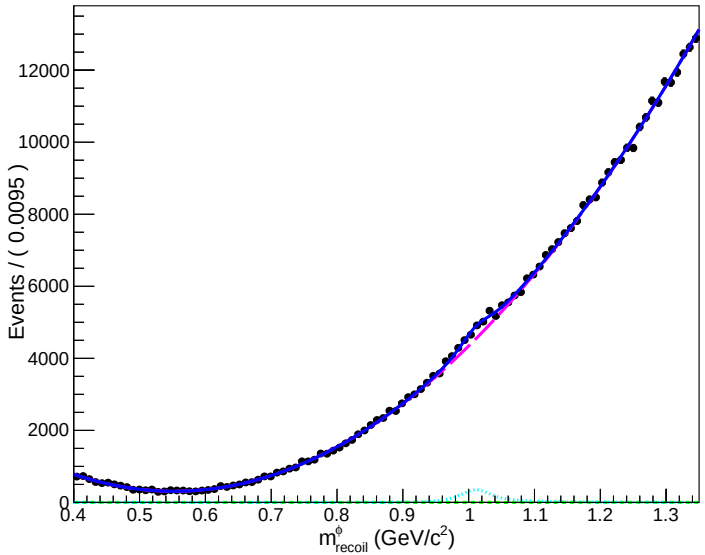
- Signal: signal MC derived shapes
- Background: 2^{nd} order polynomial.

Signal yield: $\omega/\phi \to invisible$









- $1.3 \times 10^9 J/\psi$ Inclusive MC.
- Generated fake data.

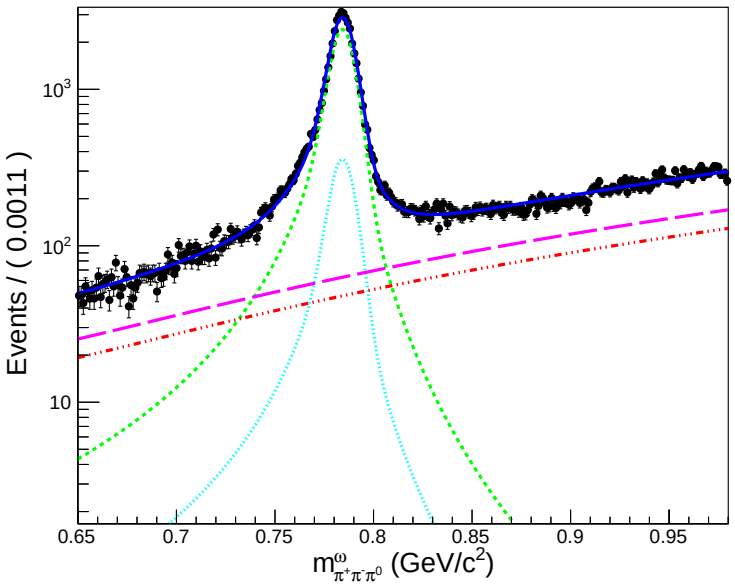
Event selection: $J/\psi \to \omega\eta, \omega \to \pi^+\pi^-\pi^0$

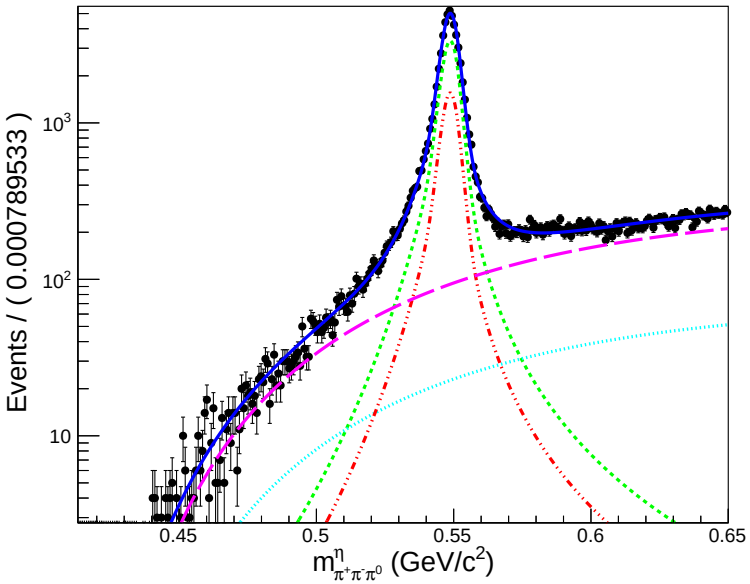
- Same selection for good tracks and photons.
- $2\pi^+$, $2\pi^-$, at least 4 γ
- Vertex fit for 4 tracks, 1C kinematic fit for $\pi^0 \to \gamma\gamma$ reconstruction.
- Loop all π^+, π^-, π^0 to get min $\chi^2_{\omega\eta}$

$$\chi^2_{\omega\eta} = \frac{(m_{\pi^+\pi^-\pi^0} - m_\omega^{PDG})^2}{\sigma_\omega^2} + \frac{(m_{\pi^+\pi^-\pi^0} - m_\eta^{PDG})^2}{\sigma_\eta^2}$$

- Total energy(E^{tot}) of the selected candidate: $E^{tot} > 2.95\text{GeV}$
- Polar angle of the system recoiling against the η candidate(θ_{recoil}): $|\cos\theta_{recoil}| < 0.7$

Signal yield: $J/\psi \to \omega\eta, \omega \to \pi^+\pi^-\pi^0$



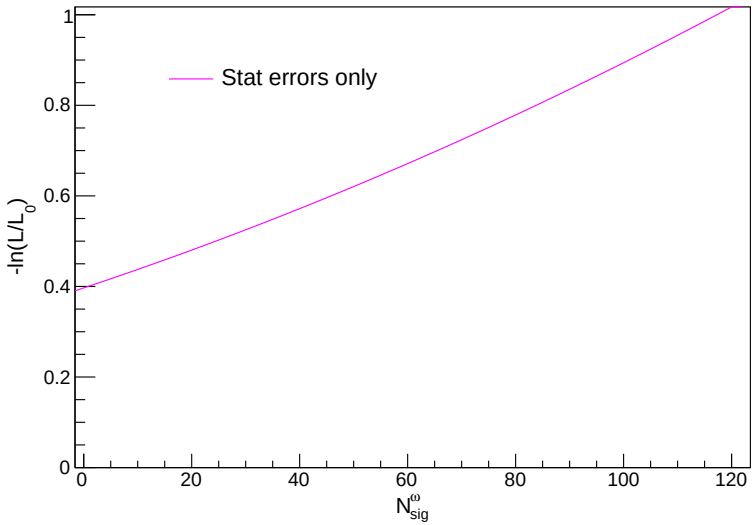


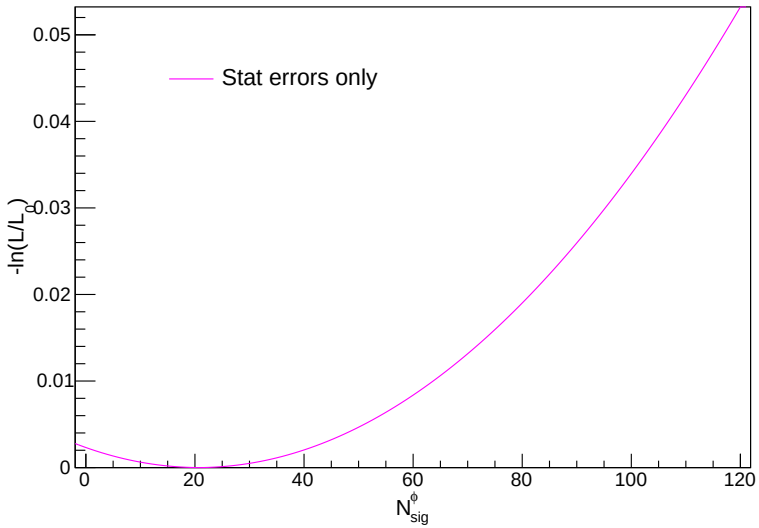
- Signal and peaking background PDF: sum of the 2 Crystal Ball functions
- Non-peaking background PDF for ω candidate: 2^{nd} order polynomial
- Non-peaking background PDF for η candidate: Reversed Argus function

- $N_{sig} = 40801 \pm 327$
- $\epsilon_{sig} = 9.1\%$

- $\mathcal{B}(J/\psi \to \omega\eta) = 1.72 \times 10^{-3}$
- Consistent with the input value 1.74×10^{-3}

Upper limit with fake data: $\omega/\phi \to invisible$





- $\omega \to invisible$: $N_{sig}^{up} = 104.48.$
- $\phi \to invisible$: $N_{sig}^{up} = 108.59.$
- $\omega \to \pi^+\pi^-\pi^0$: $N_{sig}^{fake} = 1.0659 \times 10^8$
- $\frac{\mathcal{B}(\omega \to invisible)}{\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)} < 4.2 \times 10^{-7}$

Upper limit with fake data: $\omega/\phi \to invisible$

- This time we set upper limit of $\mathcal{B}(\phi \to invisible)$ by following

$$\mathcal{B}(\phi \to invisible) < \frac{N_{sig}^{up}}{N_{J/\psi} \cdot \epsilon \cdot \mathcal{B}(J/\psi \to \phi\eta) \cdot \mathcal{B}(\eta \to \pi^+\pi^-\pi^0) \cdot \mathcal{B}(\pi^0 \to \gamma\gamma)}$$

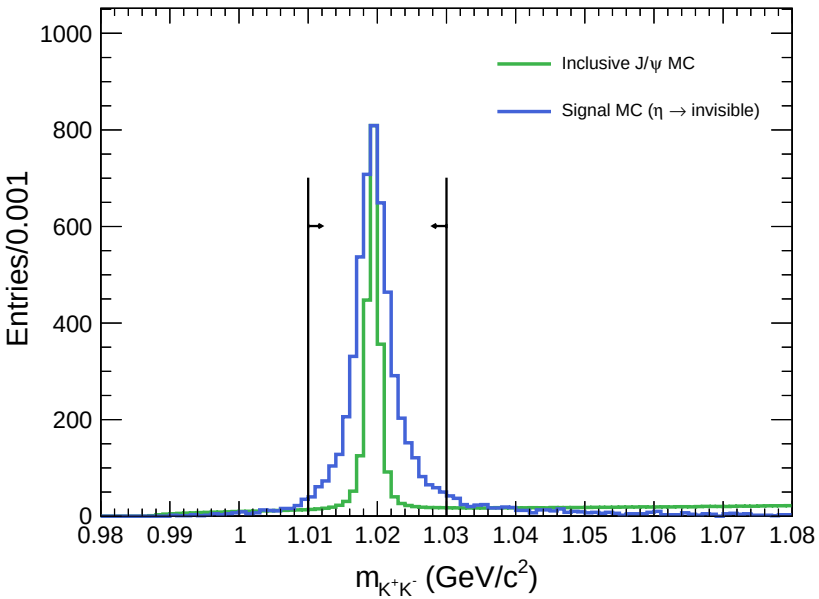
- STCF results:
  - $\mathcal{B}(\omega \to invisible) < 4.7 \times 10^{-7}$.
  - $\mathcal{B}(\phi \to invisible) < 9.1 \times 10^{-7}$.
- BESIII results:
  - $\mathcal{B}(\omega \to invisible) < 7.3 \times 10^{-5}$.
  - $\mathcal{B}(\phi \to invisible) < 1.7 \times 10^{-4}$.

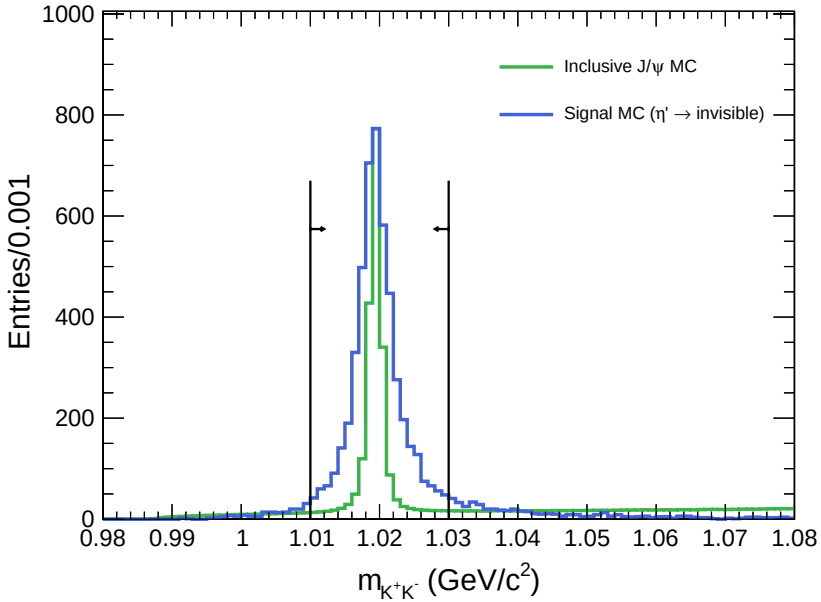
Event selection: $\eta/\eta' \to invisible$

- Good charged tracks:
  - $|V_r| < 1.0\text{cm}, |V_z| < 10\text{cm}$
  - $|\cos\theta| < 0.93$
- $\mathrm{N}_{tracks} = 2, \mathrm{N}_{charge} = 0$
- Good photons:
  - Barrel($|\cos\theta_\gamma| < 0.8325$): $\mathrm{E}_\gamma > 25\text{MeV}$
  - End-cap ($0.8325 < |\cos\theta_\gamma| < 0.9445$): $\mathrm{E}_\gamma > 50\text{MeV}$
  - $\theta_{\gamma,x^\pm} > 10$ degrees
- Perform the vertex fit with 2 charged tracks.
- GlobalPID is used to identify kaons:
  - $\text{Prob}(K) > \text{Prob}(e)$
  - $\text{Prob}(K) > \text{Prob}(\pi)$

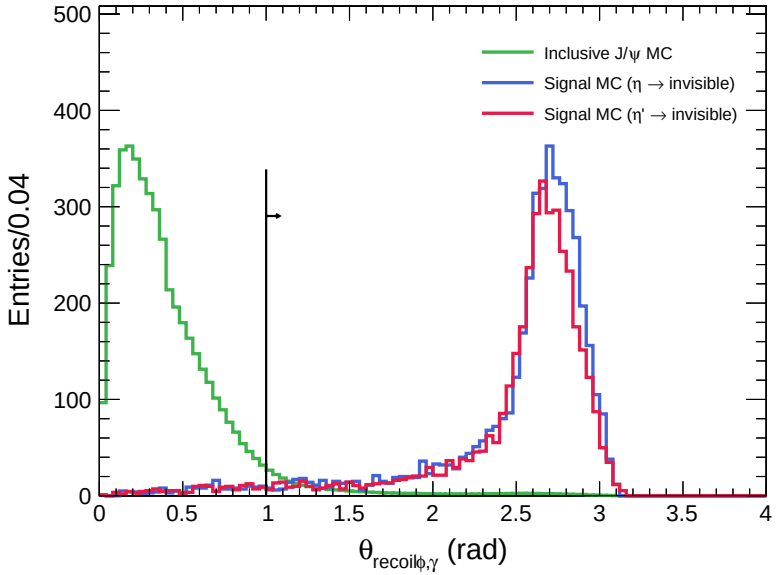
Event selection: $\eta/\eta' \to invisible$

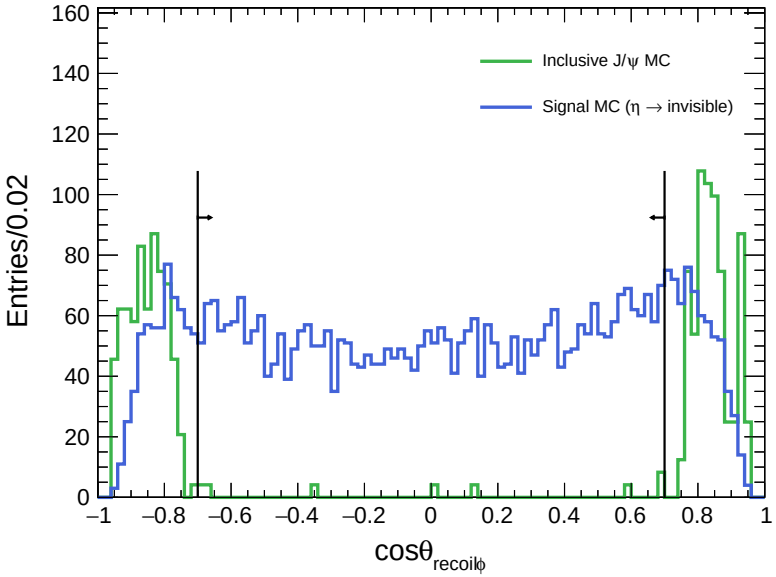
- ϕ candidate mass window: $m_{K^+K^-} \in (1.01, 1.03)\mathrm{GeV}/c^2$
- Angle between γ and the system recoiling against ϕ candidate: $\theta_{rocoil\phi,\gamma} > 1$
- Polar angle of the system recoiling against the ϕ candidate: $|\cos\theta_{recoil}| < 0.7$

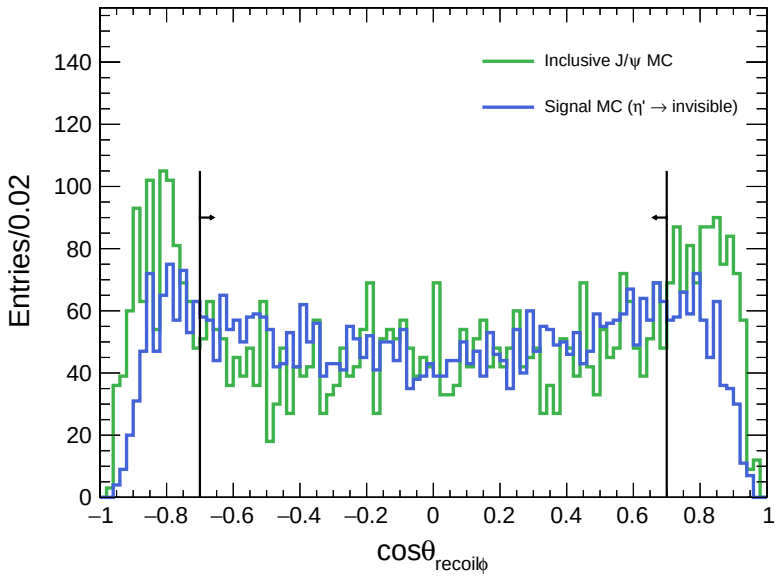




Event selection: $\eta/\eta' \to invisible$







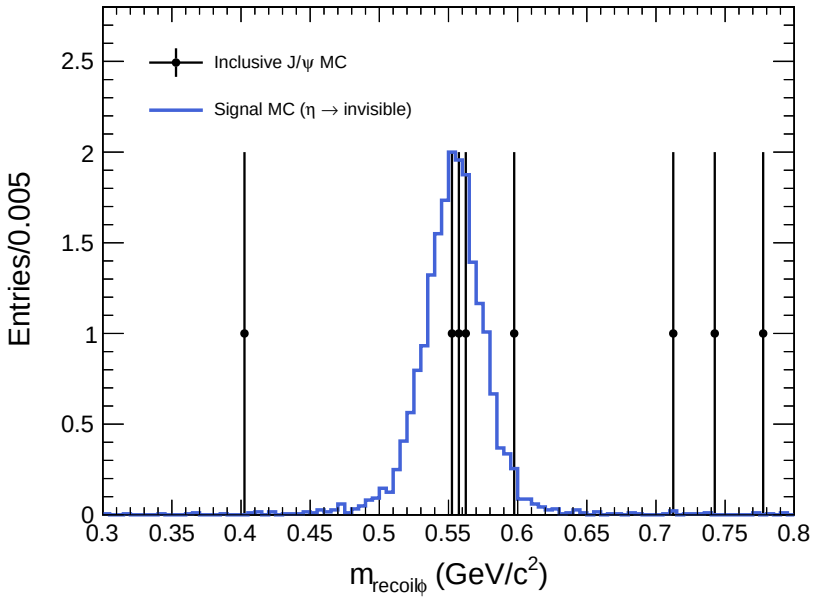
Cut flow: $\eta/\eta' \to invisible$

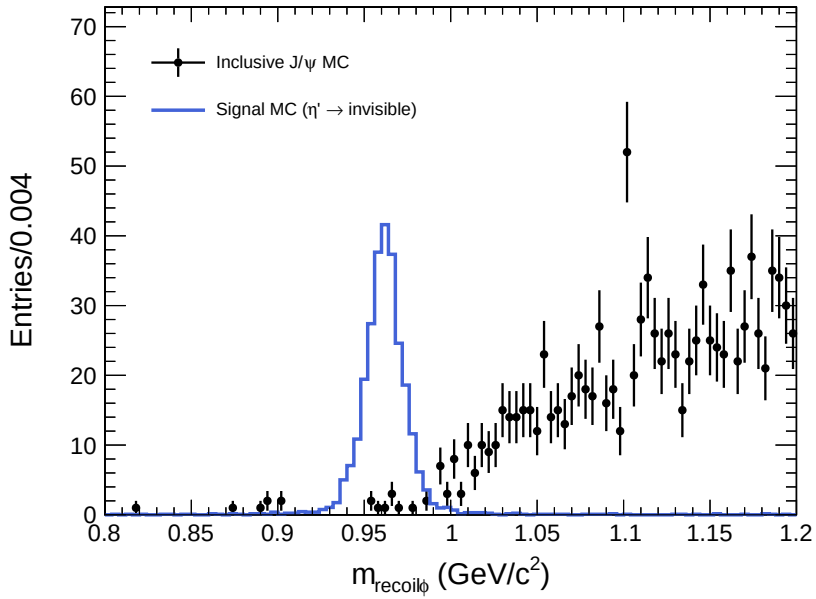
Table: The cut flow comparison between BESIII and STCF.

	Signal MC for $\eta \to invisible$			
	BESIII	Rel. Eff.	STCF	Rel. Eff.
Total	50000		10000	
$1.01 < m_{K^+K^-} < 1.03\ \mathrm{GeV}/c^2$	26010	52.02%	5437	54.37%
$\theta_{recoil\phi,\gamma} > 1$ rad	24429	93.92%	5273	96.98%
$\lvert\cos\theta_{recoil\phi}\rvert < 0.7$	18728	76.66%	3904	74.04%
$N_{track} = 2$	17989	96.05%	3697	94.70%
Efficiency	35.98%		36.97%	

	Signal MC for $\eta' \to invisible$			
	BESIII	Rel. Eff.	STCF	Rel. Eff.
Total	50000		10000	
$1.01 < m_{K^+K^-} < 1.03\ \mathrm{GeV}/c^2$	25515	51.03%	5291	52.91%
$\theta_{recoil\phi,\gamma} > 1$ rad	24228	95.19%	5105	96.48%
$\lvert\cos\theta_{recoil\phi}\rvert < 0.7$	18819	77.48%	3804	74.52%
$N_{track} = 2$	18056	95.95%	3522	92.59%
Efficiency	36.11%		35.22%	

Signal yield: $\eta/\eta' \to invisible$

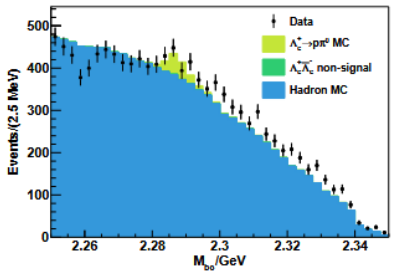




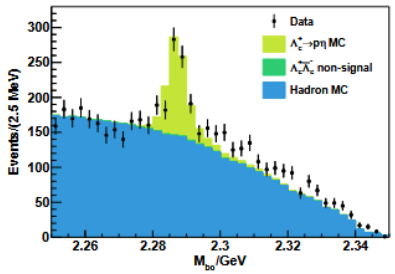
- This analysis is still ongoing, not completed.

Why considering Deep Learning

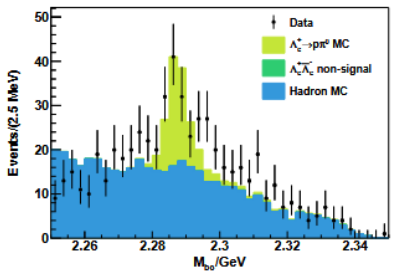
- For the BF of invisible decays of ω/ϕ, traditional methods is expected to reach $\sim 10^{-7}$ while theoretical prediction is around $\sim 10^{-8}$.
- For $\omega/\phi \to invisible$ we got up to 10^2 signal events while background reached 10^5 events level as expected.
- We can further improve the sensitivity by suppressing the backgrounds.
- On BESIII, Deep Learning helps the observation of $\Lambda_c^+ \to p\pi^0$ and becomes more and more popular.



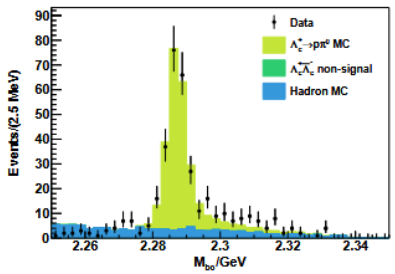
(a) $\Lambda_c^+ \to p\pi^0$, before score veto



(b) $\Lambda_c^+ \to p\eta$, before score veto



(c) $\Lambda_c^+ \to p\pi^0$, after score veto



(d) $\Lambda_c^+ \to p\eta$, after score veto

Summary and future plan

- Preliminary analysis of the invisible decays of $\omega/\phi/\eta/\eta'$ by following traditional methods.

- Future plan:
  - Complete and optimize the results.
  - Generate background MC samples for further study.
  - Try to apply Deep Learning to suppress backgrounds.

Thanks!