Study of $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$

Ying Yue

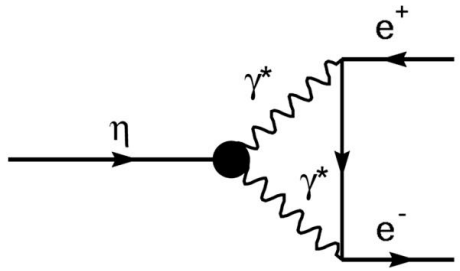
2024.3.19

OUTLINE

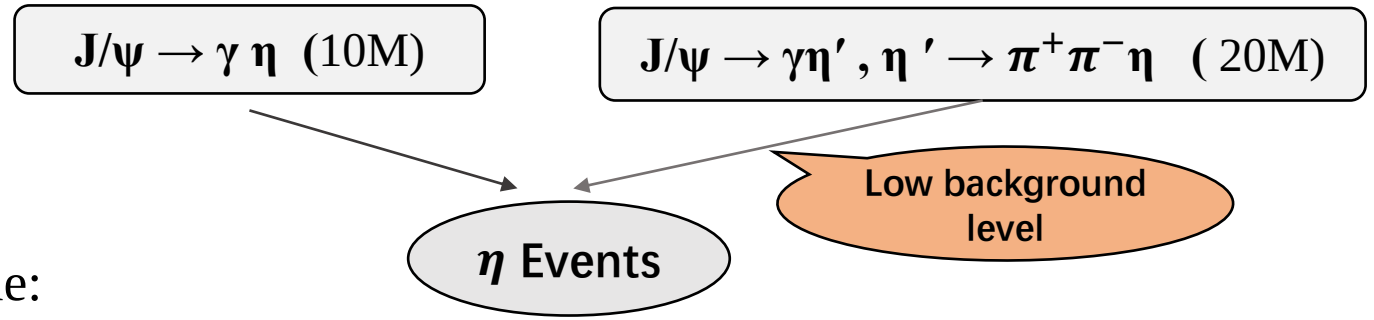
1. Motivation
2. Data Set
3. Initial Event selection
4. Study of $\eta \to \mu^+\mu^-$
5. Search for $\eta \to e^+e^-$
6. Systematic Uncertainty
7. Summary

Motivation

- η meson plays an important role in low-energy of QCD.
- Decays of pseudoscalar mesons to lepton pairs $\eta \to l^+l^-(l = e, \mu)$ are rare.



- In the standard model , the decay of $\eta \to l^+l^-$ proceed through the two-photon intermediate state.
- Using 10 billion J/ψ events collected from BESIII, there are two decay channels can provide abundant η samples.



- Theoretical result and PDG value:

$B(\eta \to l^+l^-)$	Theoretical result		PDG value
	Hidden gauge	VMD	
$B(\eta \to e^+e^-)$	$(4.68 \pm 0.01) \times 10^{-9}$	$(4.65 \pm 0.01) \times 10^{-9}$	$< 7 \times 10^{-7}(CL = 90\%)$
$B(\eta \to \mu^+\mu^-)$	$(4.87 \pm 0.02) \times 10^{-6}$	$(4.96 \pm 0.06) \times 10^{-6}$	$(5.8 \pm 0.8) \times 10^{-6}$

Data Set

- Boss version : 7.0.8
- Data :10 Billion J/ψ events
- MC Sample:

Decay mode		Generation
Signal	$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^- \eta, \eta \to \mu^+\mu^-$	HELAMP 1.0 0.0 1.0 0.0 , DIY , PHSP
	$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^- \eta, \eta \to e^+e^-$	HELAMP 1.0 0.0 1.0 0.0 , DIY , PHSP
Background	$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^- \mu^+\mu^-$	HELAMP 1.0 0.0 1.0 0.0 , DIY
	$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\pi^+\pi^-$	HELAMP 1.0 0.0 1.0 0.0 , DIY
	$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$	mPHSP
	$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^- e^+e^-$	HELAMP 1.0 0.0 1.0 0.0 , DIY
	$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^- \eta, \eta \to \gamma e^+e^-$	HELAMP 1.0 0.0 1.0 0.0 , DIY , DIY

Initial event selection

Good Charged Tracks

- ✓ $|R_Z| \leq 10\ cm$, $|R_{xy}| \leq 1\ cm$
- ✓ $|\cos\theta| \leq 0.93$
- ✓ $N_{good} = 4$, $N_P = 2, N_m = 2$

Good Photons

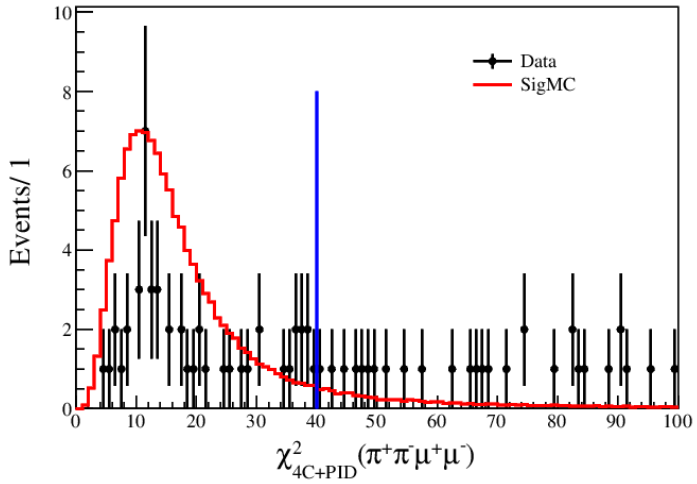
- ✓ $E_\gamma \geq 25MeV$, $|\cos\theta| < 0.8\ (Barrel)$
- ✓ $E_\gamma > 50MeV$, $0.86 < |\cos\theta| < 0.92\ (Endcap)$
- ✓ $0 \leq TDC_{EMC} \leq 14\ (\times 50ns)$
- ✓ $N_\gamma \geq 1$

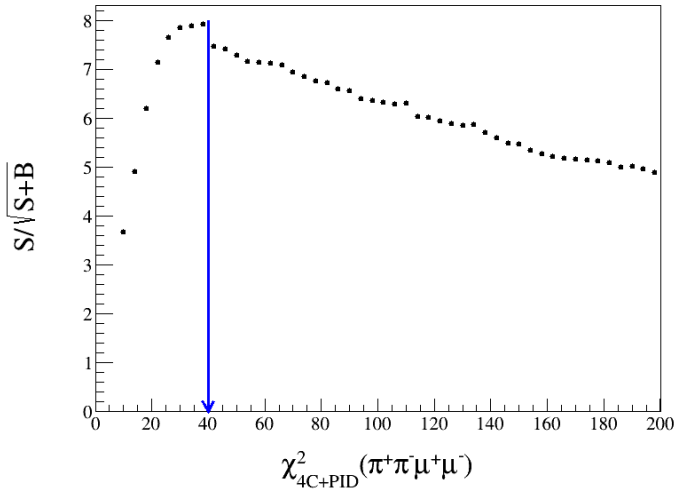
Particle identification (PID) && Kinematic Fit

- ✓ PID: TOF + dE/dx ;
- ✓ Obtain the χ^2_{PID} value for each assumed combination of $\pi^+, \pi^-, \mu^+, \mu^- or\ \pi^+, \pi^-, e^+, e^-$.
- ✓ 4C kinematic fit for π^+, π^-, l^+, l^-
- ✓ Select the best combination with the minimum value of $x^2_{4c+pid} = x^2_{4c} + \sum_{i=1}^{4} x^2_{pid}\ (i)$ from the combinations.

Study of $\eta \to \mu^+\mu^-$

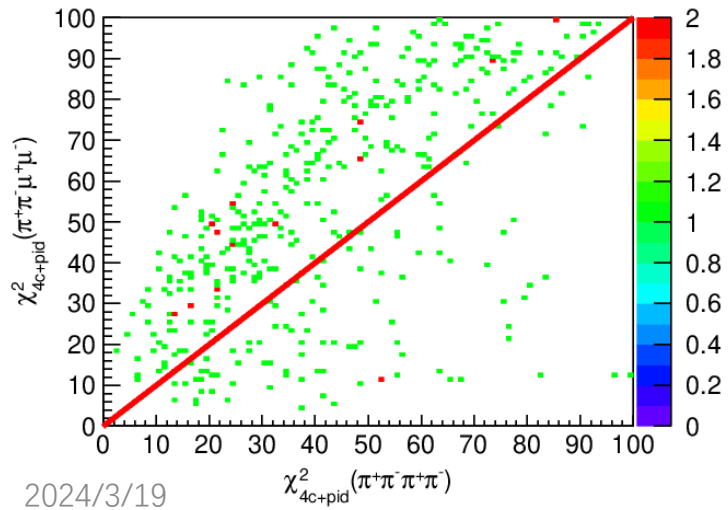
Further Events selection

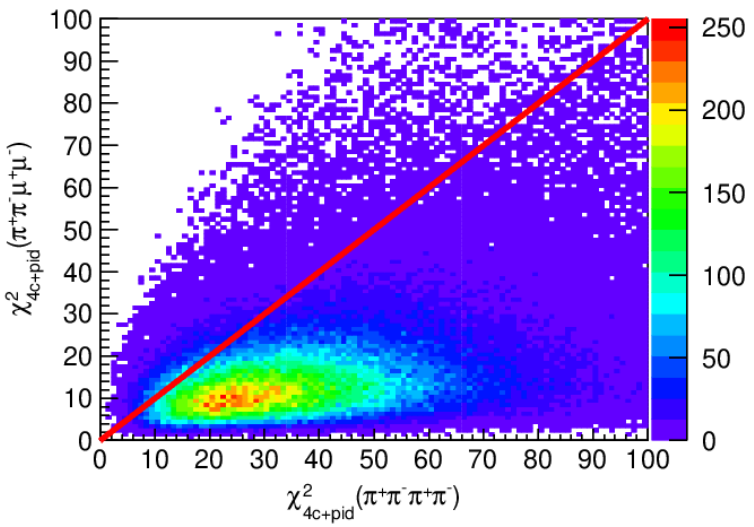




$$\chi^2_{4C+PID} < 40$$

$$x^2_{4c+pid}(\pi^+\pi^-\mu^+\mu^-) < x^2_{4c+pid}(\pi^+\pi^-\pi^+\pi^-)$$





Background Study

rowNo	decay tree	decay final state	iDcyTr	nEtr	nCEtr
1	$J/\psi \to \pi^+\pi^+\pi^-\pi^-\gamma^F$	$\pi^+\pi^+\pi^-\pi^-\gamma^F$	2	63	63
2	$J/\psi \to f_0'\gamma, f_0' \to \pi^+\pi^+\pi^-\pi^-$	$\pi^+\pi^+\pi^-\pi^-\gamma$	3	56	119
3	$J/\psi \to \pi^0\pi^+\pi^+\pi^-\pi^-$	$\pi^0\pi^+\pi^+\pi^-\pi^-$	0	28	147
4	$J/\psi \to K_S^0K_S^0\gamma, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^+\pi^-$	$\pi^+\pi^+\pi^-\pi^-\gamma$	8	18	165
5	$J/\psi \to \eta'\gamma, \eta' \to \pi^+\pi^-\eta, \eta \to \mu^+\mu^-\gamma^F$	$\mu^+\mu^-\pi^+\pi^-\gamma^F\gamma$	1	7	172
6	$J/\psi \to f_2(1270)\gamma, f_2(1270) \to \pi^+\pi^+\pi^-\pi^-$	$\pi^+\pi^+\pi^-\pi^-\gamma$	5	5	177
7	$J/\psi \to f_0'\gamma, f_0' \to \pi^+\pi^+\pi^-\pi^-\gamma^f$	$\pi^+\pi^+\pi^-\pi^-\gamma\gamma^f$	6	1	178
8	$J/\psi \to \eta'\gamma, \eta' \to \pi^+\pi^-\eta, \eta \to e^+e^-\gamma^F$	$e^+e^-\pi^+\pi^-\gamma^F\gamma$	7	1	179
9	$J/\psi \to \eta'\gamma, \eta' \to \pi^+\pi^-\eta, \eta \to \pi^+\pi^-\gamma^F$	$\pi^+\pi^+\pi^-\pi^-\gamma^F\gamma$	4	1	180
10	$J/\psi \to \pi^+\rho(3S)^-, \rho(3S)^- \to \pi^+\pi^-\rho^-, \rho^- \to \pi^0\pi^-$	$\pi^0\pi^+\pi^+\pi^-\pi^-$	9	1	181
11	$J/\psi \to K_S^0K_S^0\gamma, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^+\pi^-\gamma^f$	$\pi^+\pi^+\pi^-\pi^-\gamma\gamma^f$	10	1	182

- **Background and Normalized Event Number**

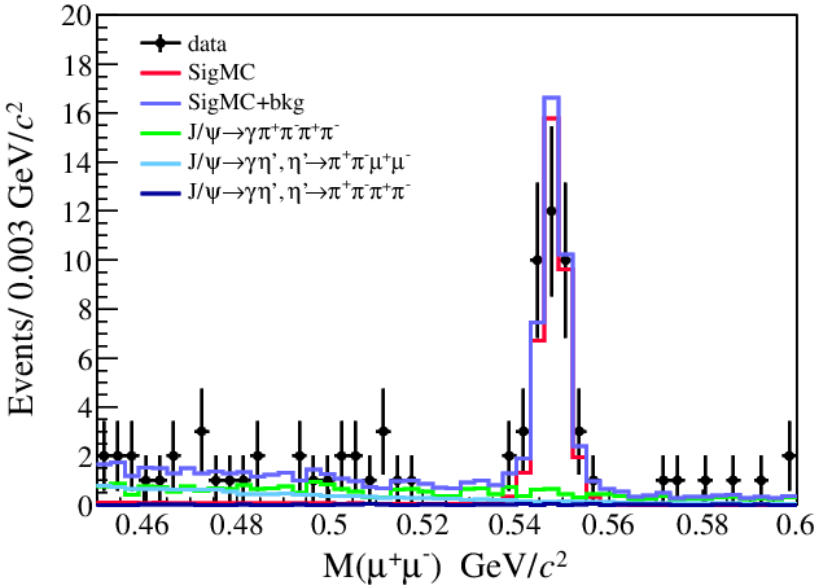
Decay mode	Normalized Event Number
$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\pi^+\pi^-$	0.774±0.08
$J/\psi \to \gamma\eta', \eta' \to \pi^+\pi^-\mu^+\mu^-$	15.0±3.01
$J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$	free

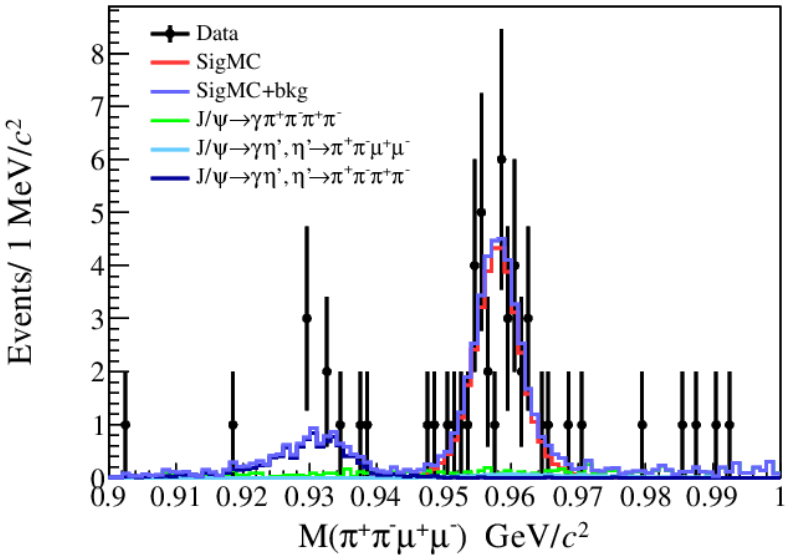
- **Cut Flow and Detection Efficiency**

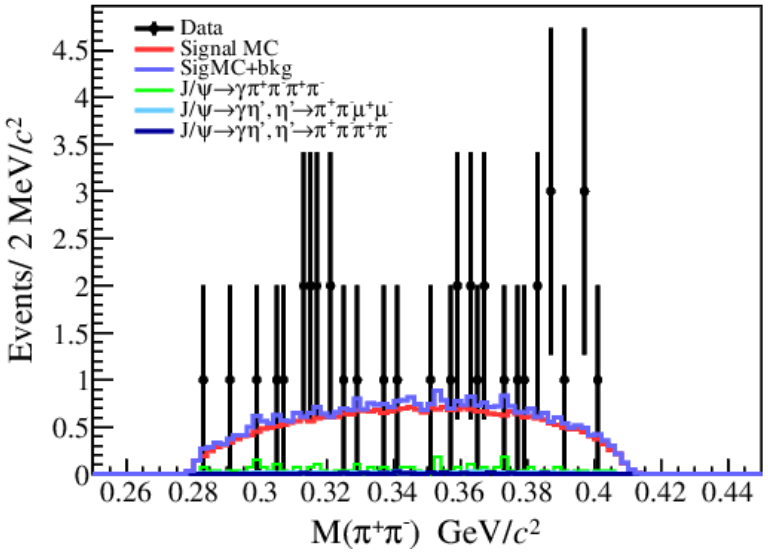
Cut	Efficiency
$x^2_{PID+4C}(\pi^+\pi^-\mu^+\mu^-) < 40$	39.21%
$x^2_{PID+4C}(\pi^+\pi^-\mu^+\mu^-)$ $< x^2_{PID+4C}(\pi^+\pi^-\pi^+\pi^-)$	36.65%
$0.945 < M_{\pi^+\pi^-\mu^+\mu^-} < 0.97$	34.18%
$0.45 < M_{\mu^+\mu^-} < 0.6$	29.19%

Data/MC Comparison

- The distribution of $M2_{\mu}, M_{2\pi 2\mu}, M_{2\pi}$

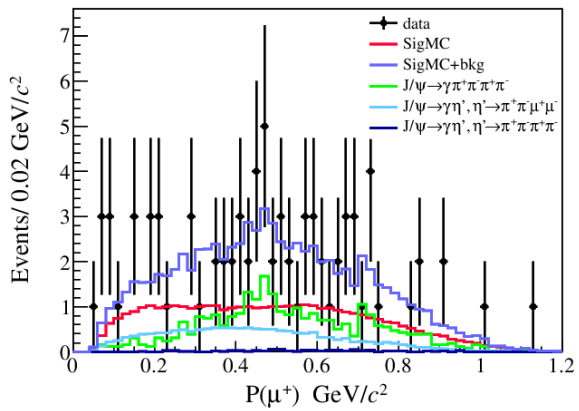


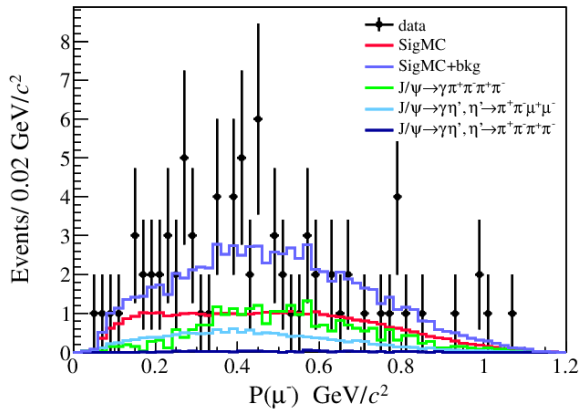


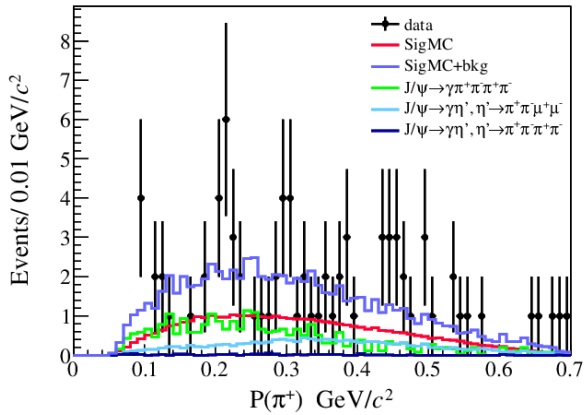


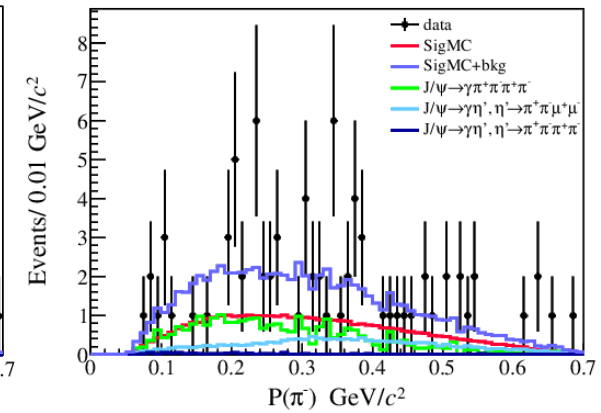
Data/MC Comparison

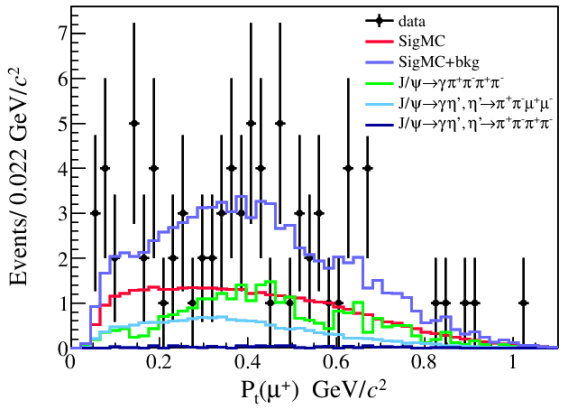
- **The distribution of** P and P_t for $\mu^+, \mu^-, \pi^+, \pi^-$:

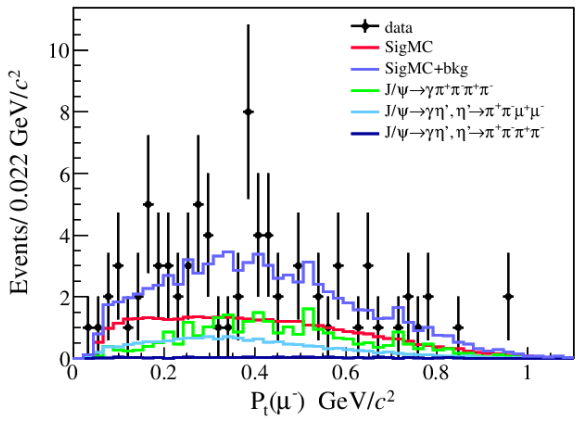


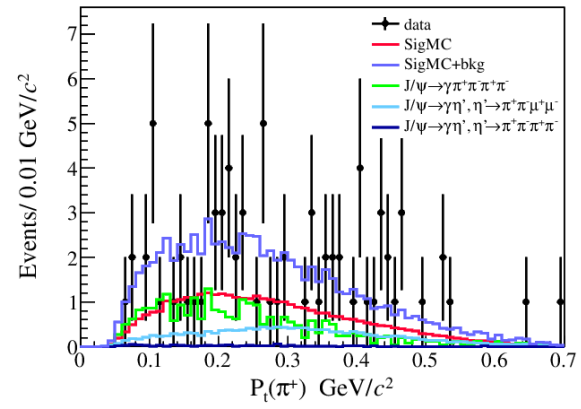


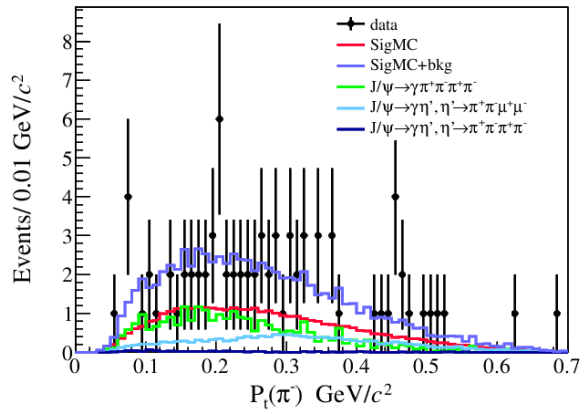




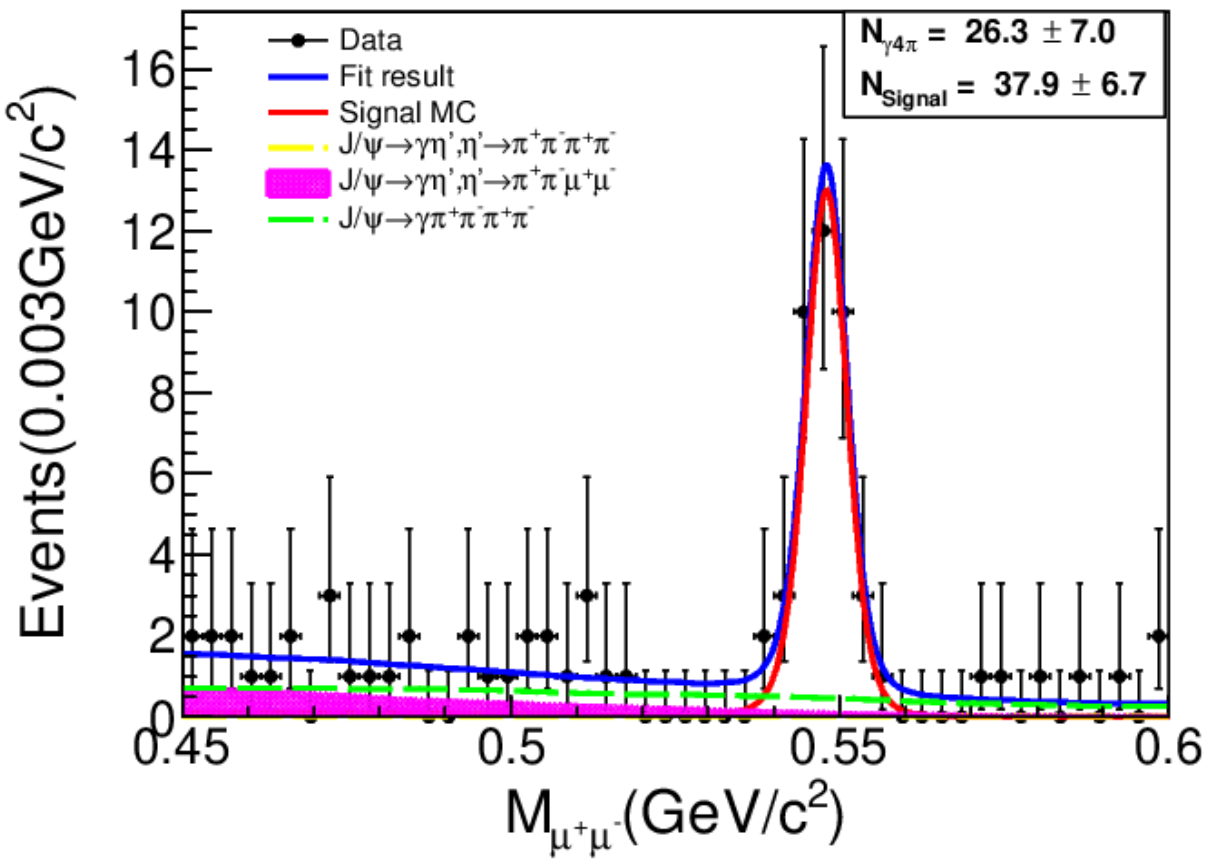








Fit to $\mu^+\mu^-$ mass spectrum



- PDF : Signal MC shape +Background MC shape
- $N_{sig} = 37.9 \pm 6.7$
- Detection Efficiency= (29.19+0.07)%
- Branching fraction:

$$\mathcal{B}(\eta \to \mu^+\mu^-) = \frac{N_{sig}}{N_{J/\psi}.\mathcal{B}(J/\Psi \to \gamma\eta').\mathcal{B}(\eta' \to \pi^+\pi^-\eta).\varepsilon}$$

$$= \frac{37.9 \pm 6.7}{10087 \times 10^6 \times 5.25 \times 10^{-3} \times 42.5 \times 10^{-2} \times 0.2919}$$

$$= (5.78 \pm 1.02) \times 10^{-6}$$

- Significance： 9.8δ

Search for $\eta \to e^+e^-$

Background Study

rowNo	decay tree	decay final state	iDcyTr	nEtr	nCEtr
1	$J/\psi \to \eta'\gamma, \eta' \to e^+e^-\pi^+\pi^-$	$e^+e^-\pi^+\pi^-\gamma$	0	2141	2141
2	$J/\psi \to \eta'\gamma, \eta' \to \pi^+\pi^-\eta, \eta \to e^+e^-\gamma^F$	$e^+e^-\pi^+\pi^-\gamma^F\gamma$	1	82	2223
3	$J/\psi \to \eta'\gamma, \eta' \to e^+e^-\pi^+\pi^-\gamma^f$	$e^+e^-\pi^+\pi^-\gamma\gamma^f$	2	70	2293
4	$J/\psi \to \eta'\gamma, \eta' \to \pi^+\pi^-\eta, \eta \to e^+e^-\gamma^F\gamma^f$	$e^+e^-\pi^+\pi^-\gamma^F\gamma\gamma^f$	3	4	2297
5	$J/\psi \to K_S^0K_S^0\gamma, K_S^0 \to \pi^+\pi^-, K_S^0 \to \pi^+\pi^-$	$\pi^+\pi^+\pi^-\pi^-\gamma$	4	1	2298
6	$J/\psi \to \pi^+\pi^+\pi^-\pi^-\gamma^F$	$\pi^+\pi^+\pi^-\pi^-\gamma^F$	5	1	2299
7	$J/\psi \to \pi^0\rho^0, \rho^0 \to \pi^+\pi^-\gamma^F$	$\pi^0\pi^+\pi^-\gamma^F$	6	1	2300
8	$J/\psi \to f_0'\gamma, f_0' \to \pi^+\pi^+\pi^-\pi^-$	$\pi^+\pi^+\pi^-\pi^-\gamma$	7	1	2301
9	$J/\psi \to \pi^0\pi^+\pi^+\pi^-\pi^-$	$\pi^0\pi^+\pi^+\pi^-\pi^-$	8	1	2302

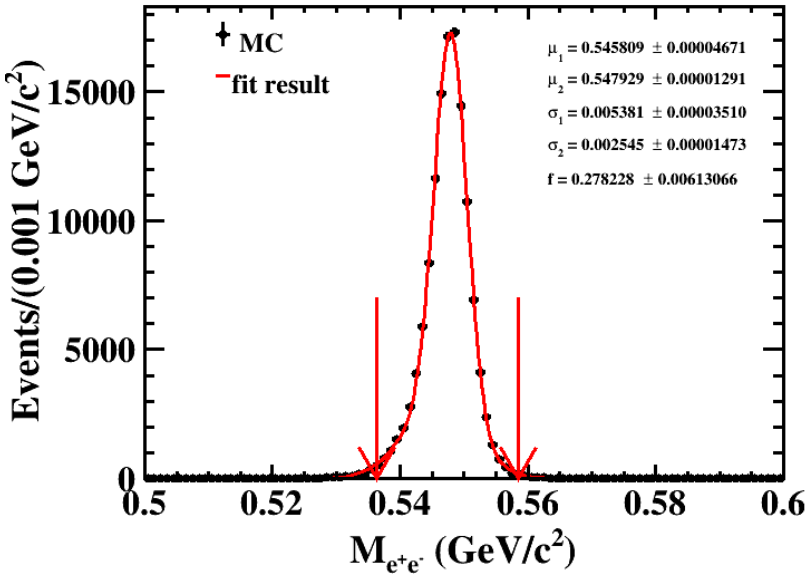
- **Background and Normalized Event Number**

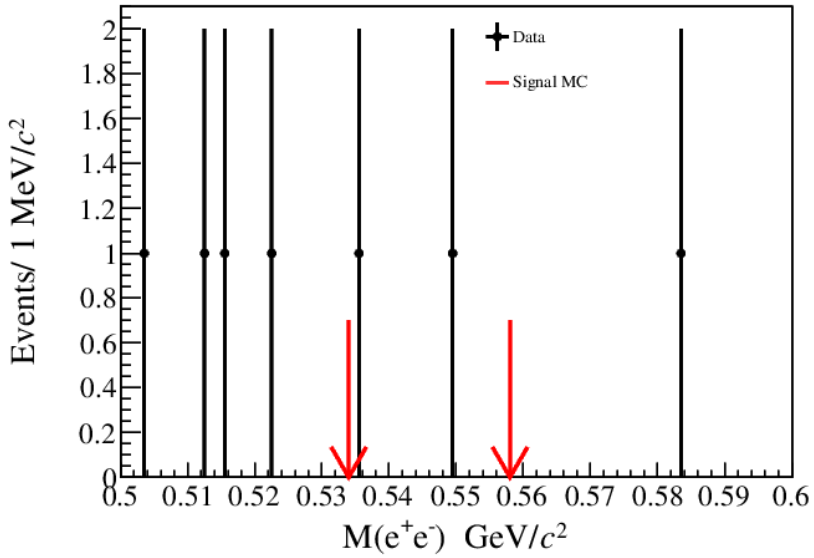
Decay mode	Normalized Event Number	
	$0.5 < M_{(e^+e^-)} < 0.6$	$0.536 < M_{(e^+e^-)} < 0.558$
$\eta \to \gamma e^+e^-$	0.932	0.776
$\eta' \to \pi^+\pi^-e^+e^-$	4.23	0.897

- **Cut Flow and Detection Efficiency**

Cut	Efficiency
$x^2_{PID+4C}(\pi^+\pi^-e^+e^-) < 50$	34.56%
$0.945 < M_{\pi^+\pi^-e^+e^-} < 0.97$	29.06%
$0.536 < M_{e^+e^-} < 0.558$	28.7%

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





- Double Gaussian Function

$$\mu = \mu_1 f + \mu_2(1-f)$$

$$\sigma^2 = \sigma_1^2 f + \sigma_2^2(1-f) + (\mu_1-\mu_2)^2 f(1-f)$$

- $N_{Data} = 2, N_{bkg} = 1.67$
- Detection Efficiency =(28.7+0.07)%

- The signal window is determined by $[\mu - 3\sigma, \mu + 3\sigma]$, which is **[0.536, 0.558]**.

Systematic Uncertainty

- **Number of J/Ψ events:** 0.44% is taken as uncertainty.
- **$\mathcal{B}(J/\Psi \to \gamma\eta')$:** 1.33% is taken as uncertainty, by PDG.
- **$\mathcal{B}(\eta' \to \pi^+\pi^-\eta)$:** 1.18% is taken as uncertainty, by PDG.
- **Photon detection:** The systematic uncertainty is studied using the control sample of $e^+e^- \to \gamma\mu^+\mu^-$ the result shows that the difference between data and MC is about 0.5%, then we take 0.5% as the systematic uncertainty for each photon.

☐ MDC Tracking

- Using the control sample of $J/\psi \to \pi^+\pi^-\pi^0$ to study the tracking of π. Since there is nonspecific samples to study μ at low momentum region, and μ mass is similar to π, so we consider μ with the factor similar to π. And using the mixed sample of $e^+e^- \to e^+e^-\gamma$ at the J/ψ meson mass and $J/\psi \to e^+e^-\gamma FSR$ to study the tracking of e.

	MDC Tracking	N_{total}	$N_{selected}$	Efficiency	Uncertainty
$\eta \to \mu^+\mu^-$	Before correction	450000	131340	29.19%	—
	After correction	450000	130387	28.97%	0.75%
$\eta \to e^+e^-$	Before correction	450000	129160	28.7%	—
	After correction	450000	126387	28.09%	2.1%

PID

- The control samples used are $J/\psi \to \pi^+\pi^-\pi^0$ for pion and $e^+e^- \to e^+e^-\gamma$ at the J/ψ meson mass and $J/\psi \to e^+e^-\gamma FSR$ for electrons. For the PID of μ, we take the same factor as π.

	PID	N_{total}	$N_{selected}$	Efficiency	Uncertainty
$\eta \to \mu^+\mu^-$	Before correction	450000	131340	29.19%	—
	After correction	450000	129974	28.88%	1.1%
$\eta \to e^+e^-$	Before correction	450000	129160	28.7%	—
	After correction	450000	126387	28.35%	1.2%

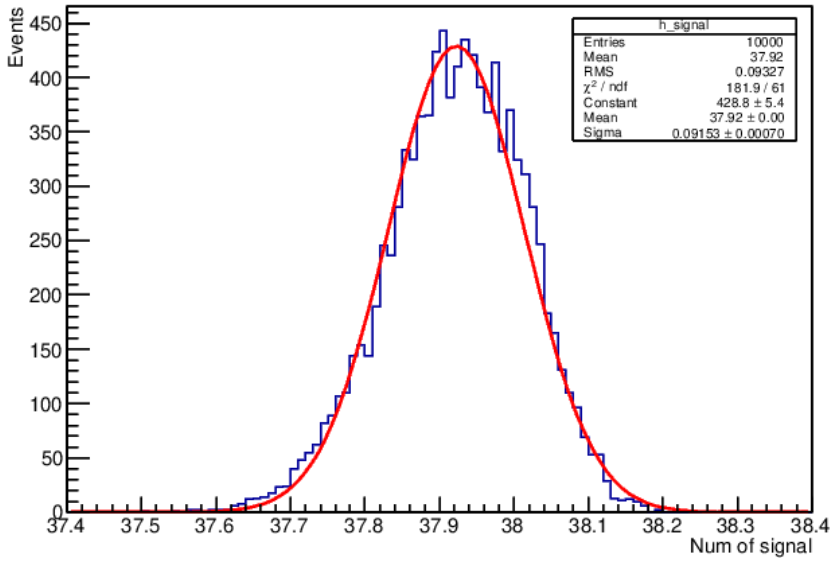
☐ Fit range for $\eta \to \mu^+\mu^-$

Change the lower and upper boundaries of the η range independently by 0.01 GeV/c^2 or 0.02 GeV/c^2 .

Fit range		N_{signal}	Efficiency(%)	$\mathcal{B}_r(\times 10^{-6})$	Uncertainty （%）
Original	[0.45,0.6]	37.8±6.7	29.19		
1	[0.45,0.61]	38.1±6.9	29.19	5.80±1.05	0.35
2	[0.45,0.59]	38.4±6.7	29.19	5.85±1.02	1.21
3	[0.44,0.6]	38.7±6.8	29.40	5.85±1.03	1.21
4	[0.46,0.6]	37.5±6.6	28.93	5.76±1.02	0.35
5	[0.44,0.61]	38.9±6.8	29.44	5.87±1.03	1.56
6	[0.46,0.59]	38.0±6.7	28.93	5.84±1.03	1.04

Background shape

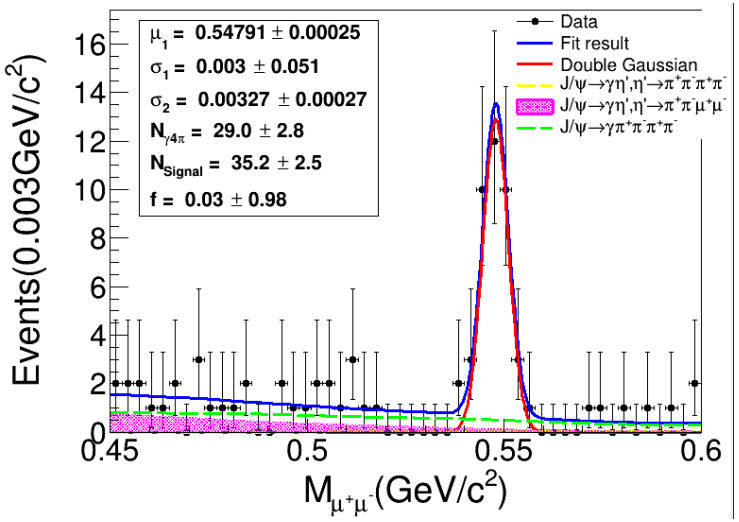
Fixed Backgrounds → 10000 groups scale factors → 10000 new fitting result → Gaussion distribution → $\delta = \frac{\sigma}{m}$



$$\delta = \frac{Sigma}{Mean} = \frac{0.09153}{37.92} = 0.24\%$$

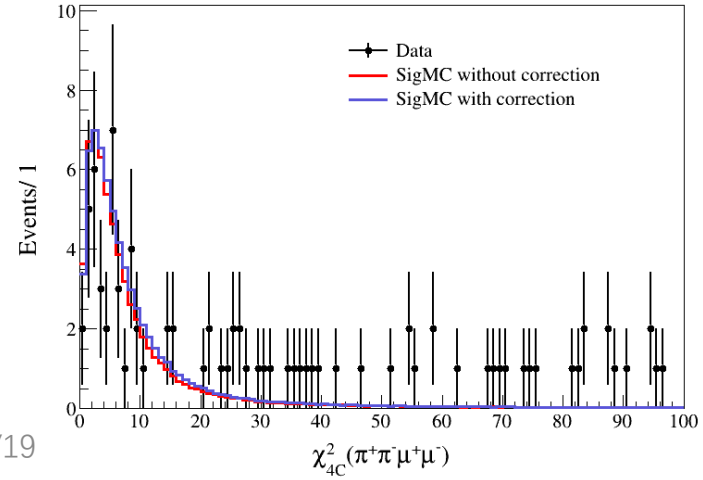
Signal shape

Use a double Gaussian function instead of the signal MC shape to fit $\mu^+\mu^-$ mass spectrum.



$$B_r' = 5.\mathbf{36}\times 10^{-6}\ ,\delta = \frac{5.78-5.\mathbf{36}}{5.78} = 1.04\%$$

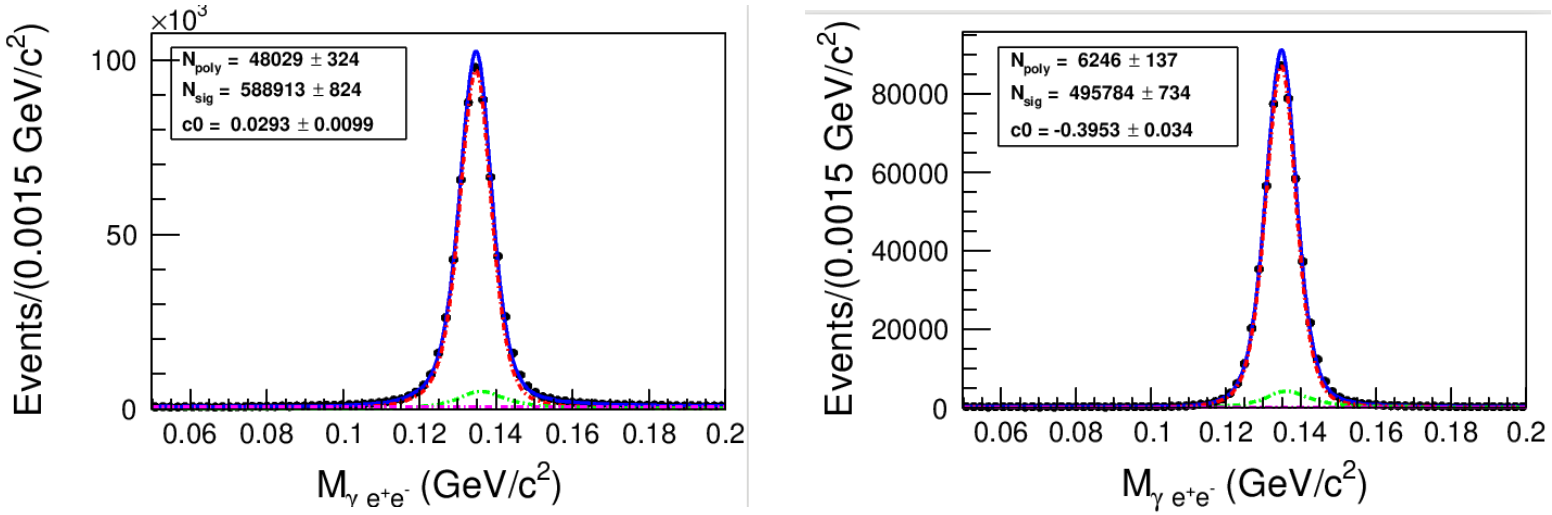
4C Kinematic Fit



$$\delta = \frac{\epsilon_1-\epsilon_2}{2\epsilon_1} = \frac{29.19\%-27.79\%}{2\times 29.19\%} = 2.4\%$$

Combine PID and Kinematic Fit for $\eta \to e^+e^-$

- $x^2_{PID+4C} < 50$ is imposed on $\eta \to e^+e^-$. Using the control sample of $J/\psi \to \pi^+\pi^-\pi^0, \pi^0 \to \gamma e^+e^-$ to study the systematic uncertainty from combine PID and kinematic fit.

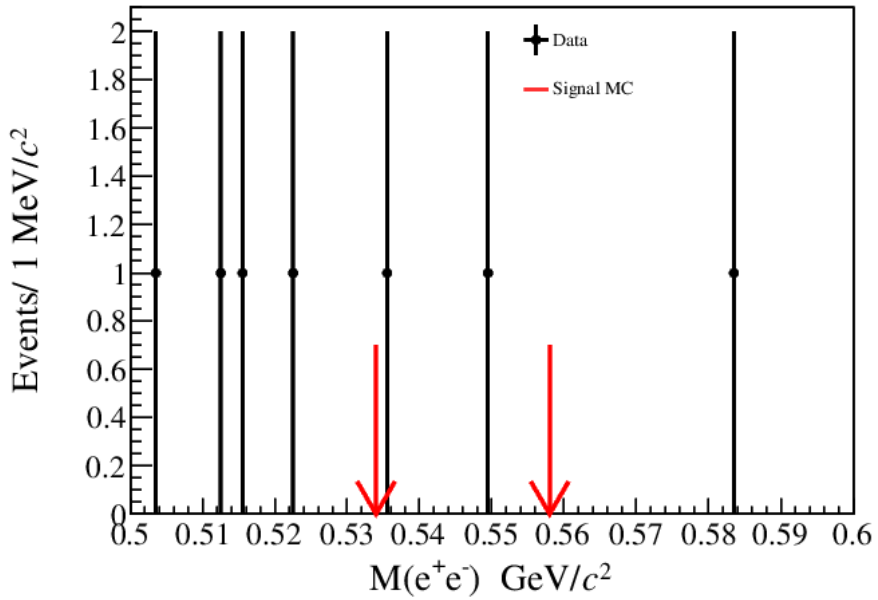


$$\delta = \frac{\varepsilon_{mc}}{\varepsilon_{data}} - 1 = \frac{169758/195428}{495784/588913} - 1 = 3.2\%$$

Summary of the Systematic Uncertainty Study

Source	Uncertainty(%)		
	$\eta \to \mu^+\mu^-$		$\eta \to e^+e^-$
$N(J/\psi)$	0.44		0.44
$\mathcal{B}_r(J/\Psi \to \gamma\eta')$	1.33		1.33
$\mathcal{B}_r(\eta' \to \pi^+\pi^-\eta)$	1.18		1.18
MDC Tracking	0.75		2.10
Photon detection	0.50		0.50
Signal shape	7.3		-
Background shape	0.24		-
PID and Kinematic fit	1.10	2.40	3.20
Fit range	1.56		-
Total	8.18		4.27

Upper limit for $\eta \to e^+e^-$



- $N_{Data} = 2, N_{bkg} = 1.67$
- Detection Efficiency=129160/450000=28.7%
- Using the TROLKE approach, N^{UL} =15.8, at 90% C.L.
- Upper limit:

$$\mathcal{B}(\eta \to e^+e^-)$$

$$= \frac{N_{sig}}{N_{J/\psi}.\mathcal{B}(J/\Psi \to \gamma\eta').\mathcal{B}(\eta' \to \pi^+\pi^-\eta)}$$

$$= \frac{15.8036}{1.0087 \times 10^{10} \times 5.25 \times 10^{-3} \times 0.425}$$

$$< 7.02 \times 10^{-7} (CL = 90\%).$$

Summary

- Using 10 Billion J/ψ events from BESIII, we studied the decay of η -> $\boldsymbol{\mu^+\mu^-}$ **and** $\eta \to \boldsymbol{e^+e^-}$.
- η is observed in the $\mu^+\mu^-$mass spectrum with 9.8 σ, but did not observed in the e^+e^- mass spectrum.
- The branching fraction：

Decay mode	N_{sig}	Efficiency (%)	Significance	δ	B_r	PDG value
$\boldsymbol{\eta}$ -> $\boldsymbol{\mu^+\mu^-}$	37.9	29.19	9.8δ	3.84%	$(\mathbf{5.78 \pm 1.02 \pm 0.47}) \times \mathbf{10^{-6}}$	$(5.8 \pm 0.8) \times 10^{-6}$
$\boldsymbol{\eta \to e^+e^-}$	N^{UL} =15.8	28.7	-	4.27%	$<7.02 \times \mathbf{10^{-7}}$ $(CL = 90\%)$	$< 7 \times 10^{-7} (CL = 90\%)$

- Memo is ready.