Study the Azimuthal Asymmetry with Two-photon Channels $e^+e^- \to e^+e^-\pi^+\pi^-, e^+e^-\mu^+\mu^-, e^+e^-\omega\omega$ by Untagged Method

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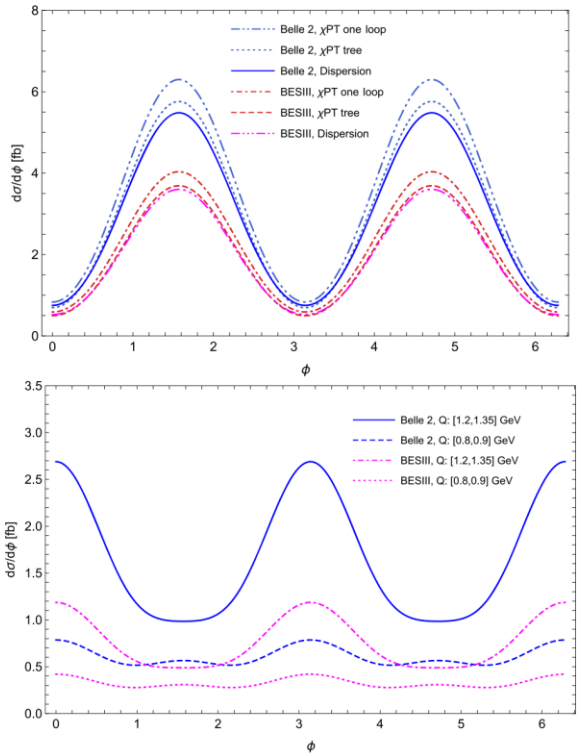
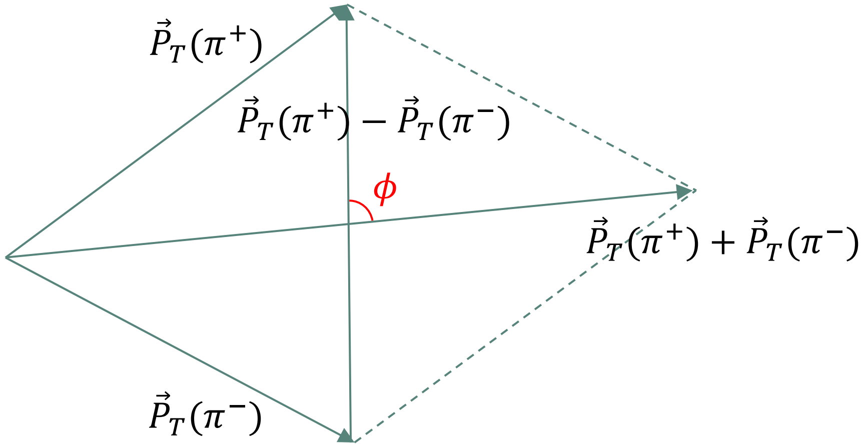
2025/10/29

Motivation

- An azimuthal asymmetry is predicted within the Tranverse-Momentum-Dependent factorization theory and chiral perturbation theory in the process $e^+e^- \to e^+e^-\pi^+\pi^-$ [1]. Using the dispersion relation as input, the $\cos 2\phi$ azimuthal modulation may reach 40% at Belle2 and BESIII.
  - Differential cross section of $e^+e^- \to e^+e^-\pi^+\pi^-$ with respect to azimuthal angle ϕ is predicted to show some oscillation structures.
  - ϕ is defined as the angle between $\vec{\boldsymbol{P}}_{\boldsymbol{T}}(\boldsymbol{\pi}^+) + \vec{\boldsymbol{P}}_{\boldsymbol{T}}(\boldsymbol{\pi}^-)$ and $\vec{\boldsymbol{P}}_{\boldsymbol{T}}(\boldsymbol{\pi}^+) - \vec{\boldsymbol{P}}_{\boldsymbol{T}}(\boldsymbol{\pi}^-)$.

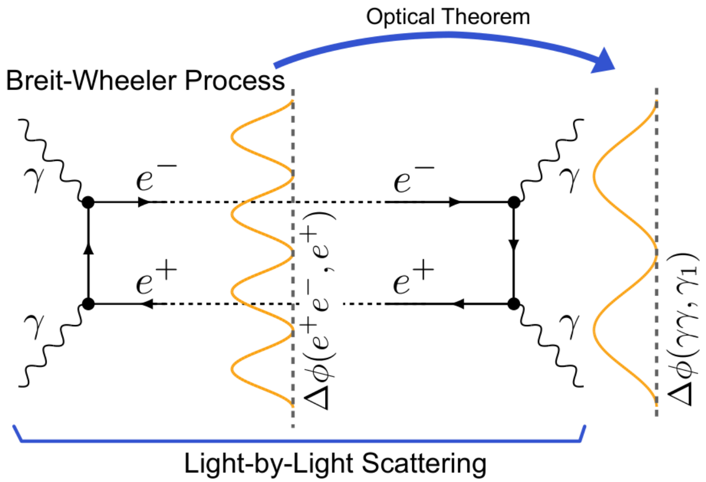


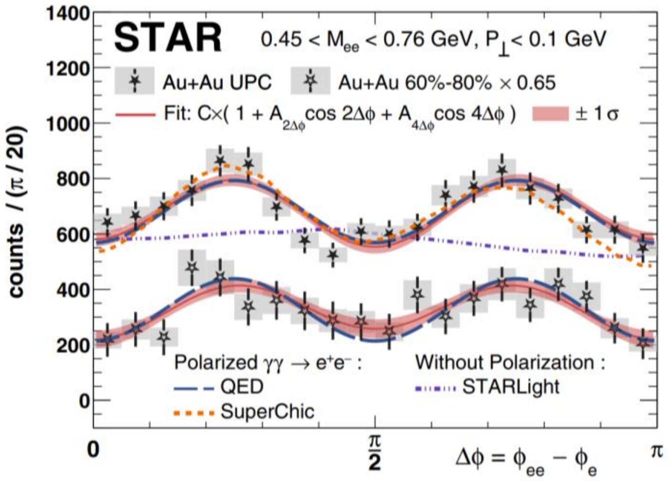


[1] PRL 134, 141901 (2025)

Motivation

- STAR experiment has measured the azimuthal asymmetry by $\gamma\gamma \to e^+e^-$ process [2].
  - The $\cos 4\phi$ modulation is observed with an amplitude of $(16.8 \pm 2.5)\%$.
  - The data are in good agreement with numerical lowest-order QED calculations, 16.5%.





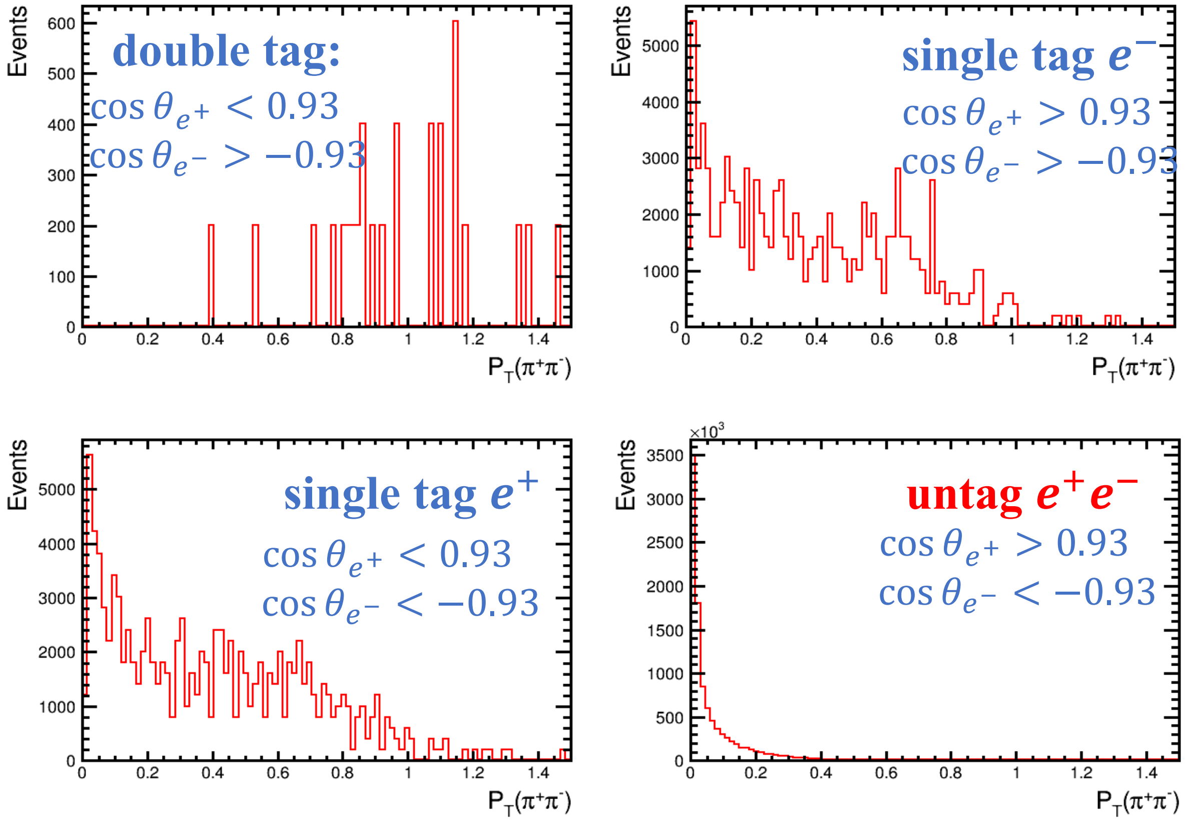
- With the large statistics collected at BESIII, the azimuthal asymmetry can be studied with a cleaner and superior playground than UPCs.
- The azimuthal asymmetry, originating from the photon linear polarization, should also exists in the $\gamma\gamma \to \pi^+\pi^-, \mu^+\mu^-, \omega\omega$ processes at BESIII. The results of $\gamma\gamma \to \omega\omega$ has been introduced in previous tau-QCD report.
- This report will concentrate on $\gamma\gamma \to \pi^+\pi^-, \mu^+\mu^-$ process.

[2]PRL 127, 052302 (2021)

Motivation

- The TMD factorization theory is based on the quasireal photons emitted off e^+ and e^-, which leads to a requirement of $P_T(\pi^+\pi^-) < 0.1\ \mathrm{GeV}/c$.

MC truth distributions (generated by Galuga generator)



method	statistic ratio	$P_T < 0.1$ ratio
double tag	0%	0%
single tag e^-	1%	18%
single tag e^+	1%	20%
untag e^+e^-	98%	80%

- ✓ **98%** of two-photon events comes from untag region!
- ✓ **80%** events from untag region satisfy $P_T(\pi^+\pi^-) < 0.1\ \mathrm{GeV}/c$.

⇒ untag method is best to study the azimuthal asymmetry.

Data sets and MC sample

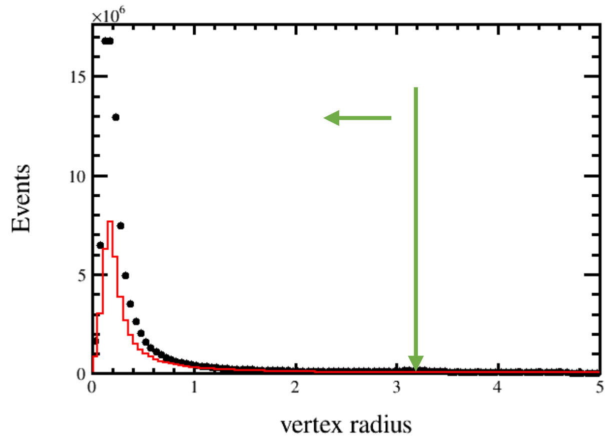
- **Data sets:**
  - $\mathbf{20.3\ fb^{-1}\ \psi(3770)}$
  - Round17 data for event selection study
- **Signal MC:**
  - $e^+e^- \to e^+e^-\pi^+\pi^-$, 10M, by Galuga generator.
  - $e^+e^- \to e^+e^-\mu^+\mu^-$, 130M, by Diag36 generator.
  - $e^+e^- \to e^+e^-\omega\omega$, 1M, by CppGamGam generator.[3]
- **Inclusive background:**
  - Hadrons background generated by R-QCD group by Weiping Wang.
  - /besfs5/offline/data/tauqcd/bes3gen/712/psipp/
- **Exculsive background MC:**
  - $e^+e^- \to e^+e^-\omega\pi^+\pi^-\pi^0$, 1M, by CppGamGam generator.

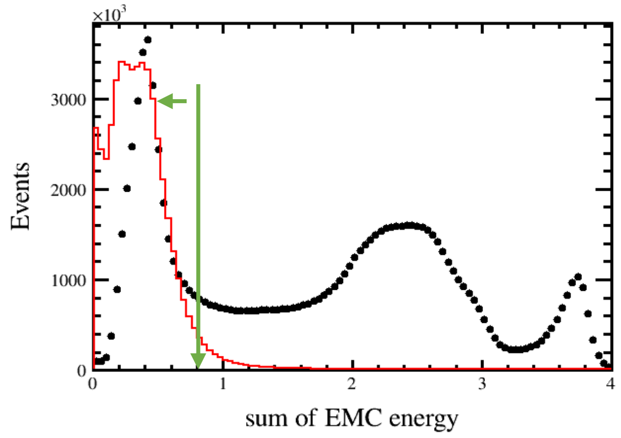
[3]BAM-636

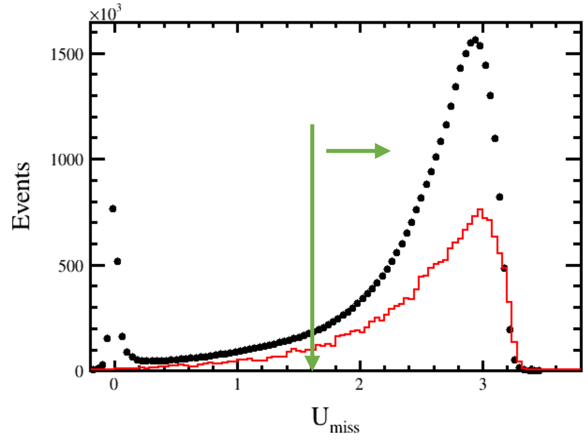
1. $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$

Event Selection (I)

- Good charged track
  - $V_r < 1$ cm, $|V_z| < 10$ cm, $|\cos\theta| < 0.93$
  - $N_{good} \geq 2$
- PID (dE/dx+TOF)
  - Prob(π)>Prob(p/K)
  - $N(\pi^+) = N(\pi^-) = 1$
- Vertex Fit:
  - SUCCESS
  - Vertex within beampipe
- Further selection:
  - $\cos\theta(\pi^+,\pi^-) \geq -0.9$
  - sum of EMC deposited energy $\leq$ 0.8 GeV
  - $U_{miss} \geq$ 1.6 GeV



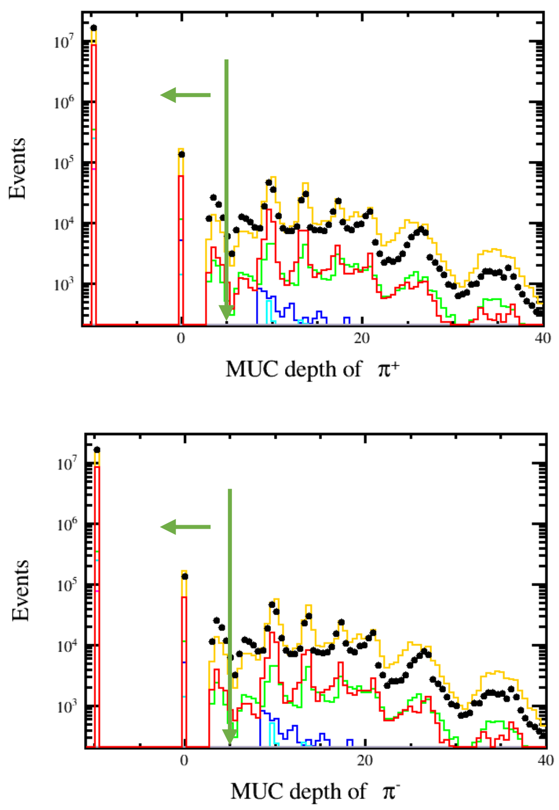




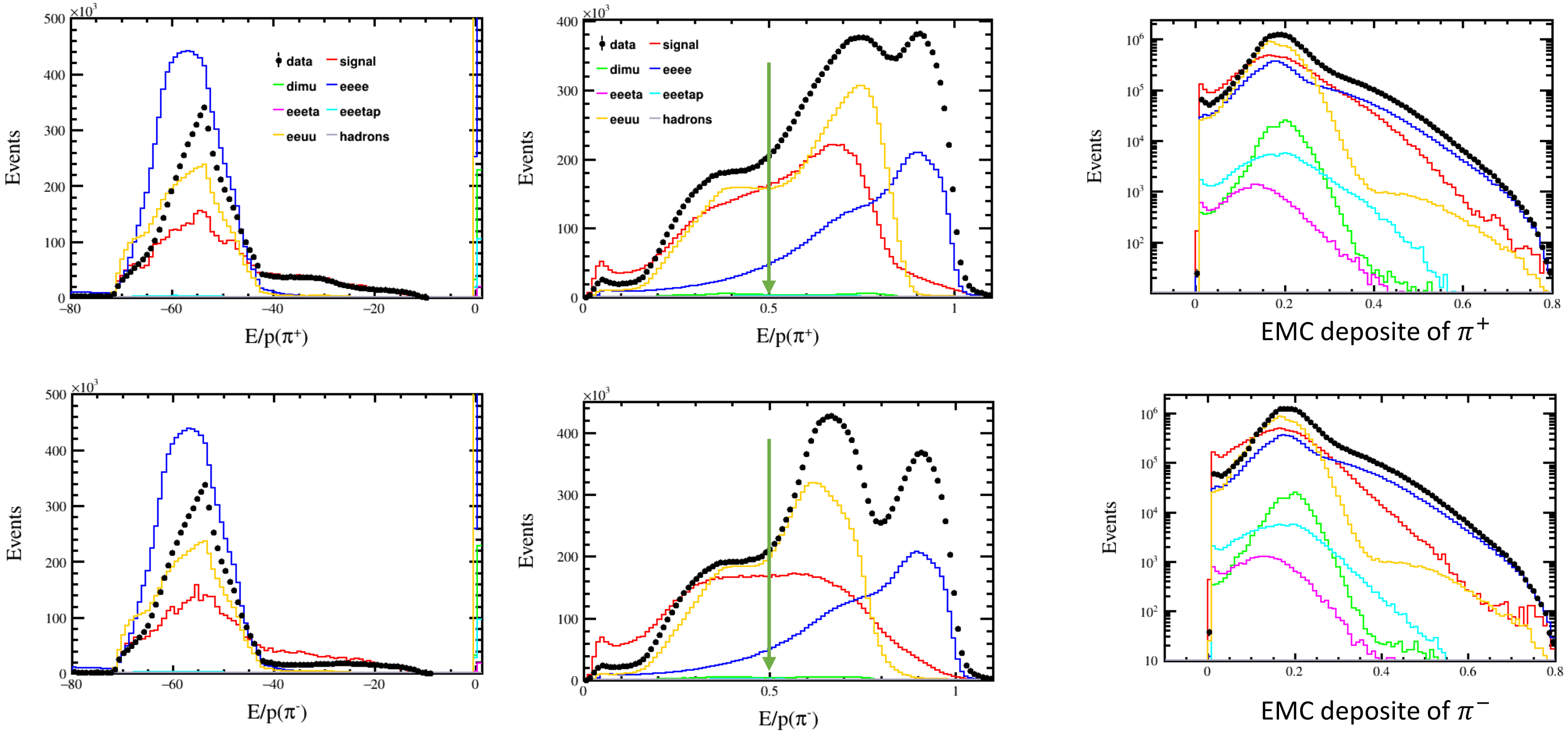
(Signal mc is scaled to 0.5x **data** by amount.)

Event Selection (II)

➢ MUC depth ≤ 5

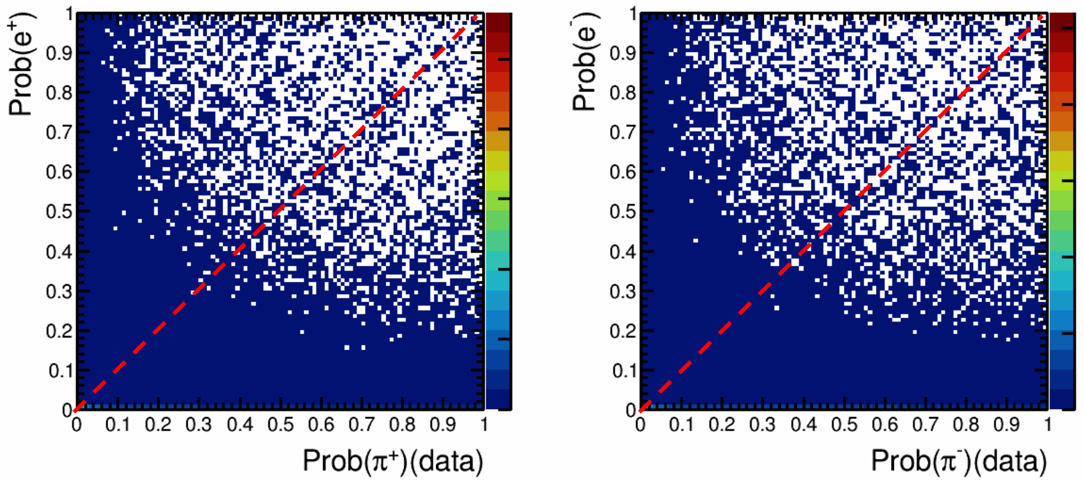


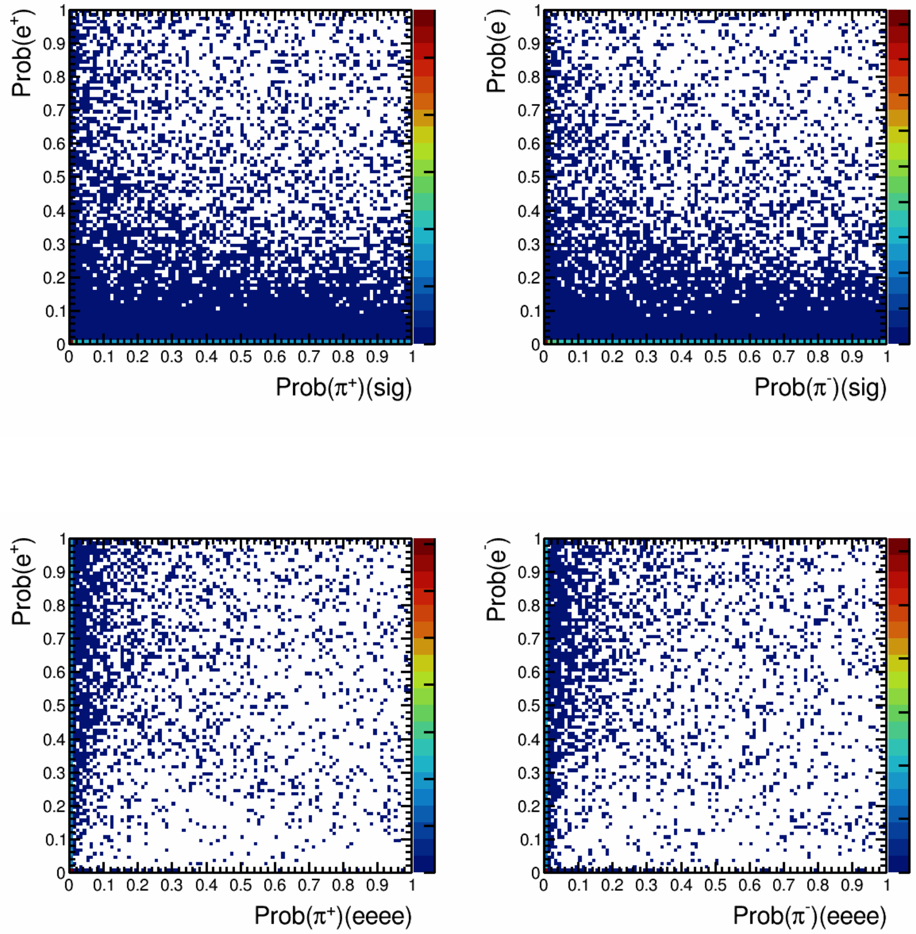
➢ $0 \leq E/p \leq 0.5$ (for particles those do not hit EMC, E is -9.9)



- Signal mc is scaled to 0.5x **data** by amount.
- Inclusive mc samples are scaled to data by luminosity.

Event Selection (III): Prob(π)>Prob(e)



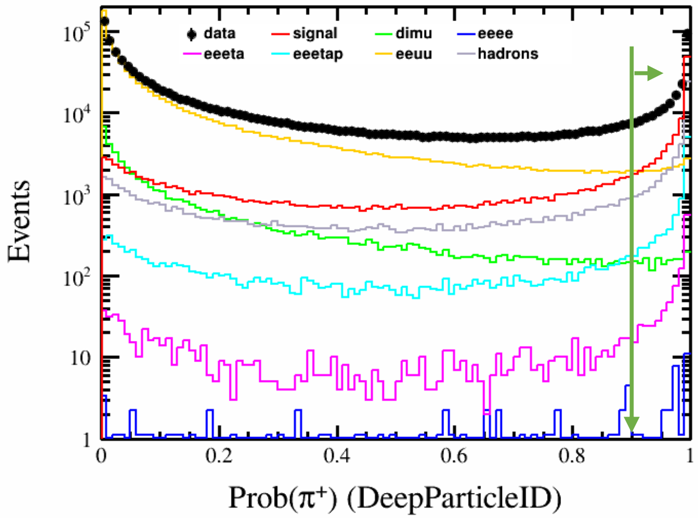


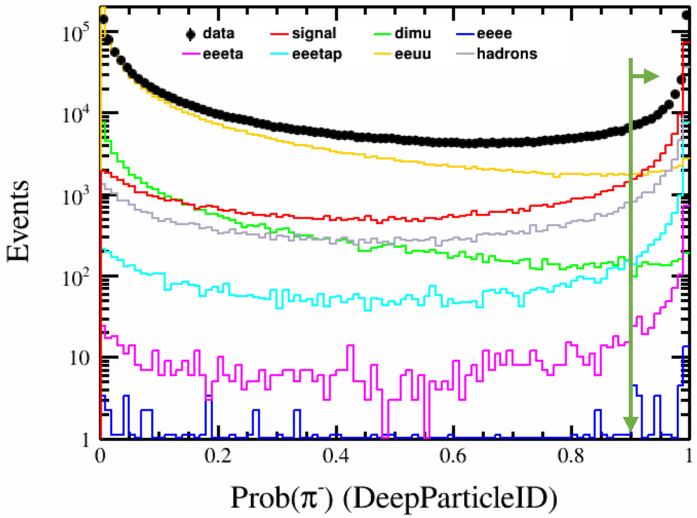
After requiring $Prob(\pi) > Prob(e)$, the number of eeee background is from 40,531 to 85, nearly absent.

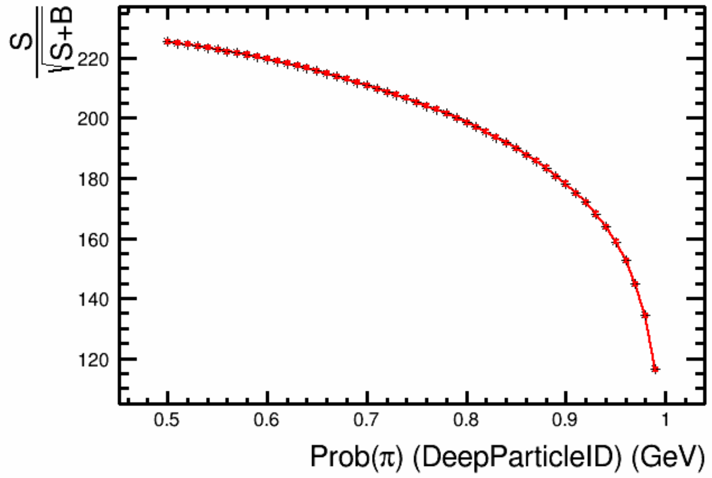
Event Selection (IV): Prob(π)>Prob(μ)

Using the **DeepParticleID**[4] algorithm, the probability of π can be calculated with respect to μ.

- $Prob(\pi) + Prob(\mu) = 1$
- Require $Prob(\pi) > 0.9$







[4] A machine learning algorithm developed by BESIII group from Shandong University, 2025(翟云聪 李腾 秦小帅 黄性涛)

Cutflow of Event Selection

	eepipi	bhabha	digam	dimu	eeee	eeeta	eeetap	eekk	eeuu	hadrons
Total	10,050,000	1,000,000	1,000,000	1.3E8	1.2E9	1,300,000	1,150,000	800,000	1.3E8	1.2E8
Ngood	2,961,154	410,647	22,841	8.7E7	5.6E7	110,550	515,285	364,006	2.8E7	1.1E8
PID	2,730,389	326,209	15,032	7.3E7	2.5E7	91,614	378,349	4,034	2.5E7	2.4E7
VertexFit	2,728,997	326,179	14,983	7.3E7	2.5E7	91,562	378,060	3,999	2.5E7	2.4E7
$\cos\theta_{\pi\pi} \geq 0.9$	2,247,822	8,039	14,962	2.3E7	1.9E7	85,841	344,333	3,401	2.0E7	2.2E7
VertexPosition	2,166,107	7,873	6,362	2.3E7	1.8E7	80,500	334,025	2,973	1.9E7	2.1E7
EMC sum	2,069,785	15	48	1.5E7	1.6E7	77,596	264,479	1,119	1.9E7	1.1E6
Umiss	1,902,541	13	47	440,462	1.6E7	77,502	251,553	851	1.8E7	681467
MUC depth	1,854,493	12	46	309,168	1.6E7	77,278	245,583	815	1.6E7	622027
E/P	181,153	0	0	56,713	40,531	2,123	18,693	22	933,842	94,134
Prob(π)>Prob(e)	171,265	-	-	52,161	85	1,834	17,577	17	839,875	89,148
Prob(π)>0.9	51,574	-	-	67	10	646	5,343	3	1,263	24,918
Rate	62%	-	-	-	-	1%	6%	-	2%	30%

After above selections, there are 93,364 events left for Round17-$\psi(3770)$ data.

Topology of Hadrons Background

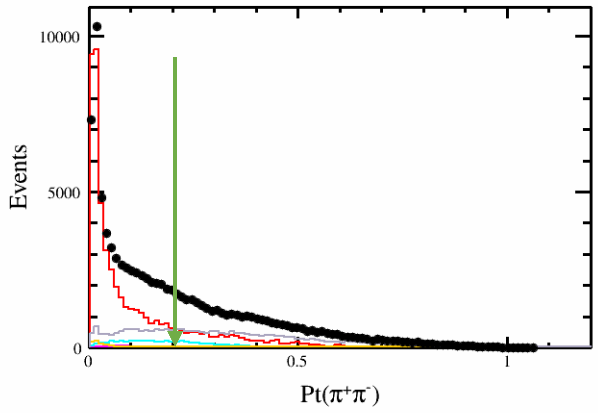
Table 1: Decay trees and their respective final states.

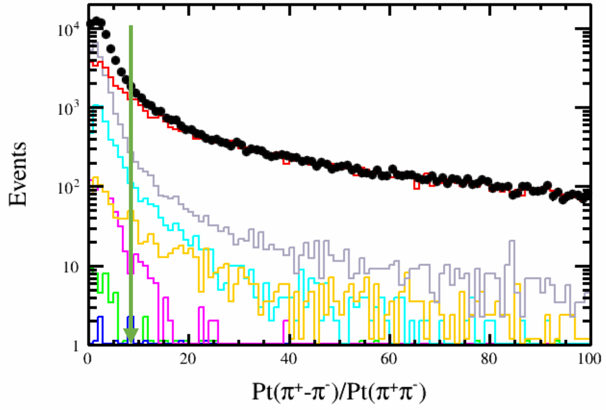
rowNo	decay tree	decay final state	iDcyTr	nEtr	nCEtr
1	$e^+e^- \to \pi^+\pi^-\gamma^I\gamma^I$	$\pi^+\pi^-\gamma^I\gamma^I$	4	3354	3354
2	$e^+e^- \to \pi^0\pi^+\pi^-\gamma^I\gamma^I$	$\pi^0\pi^+\pi^-\gamma^I\gamma^I$	10	1549	4903
3	$e^+e^- \to \pi^0\pi^0\pi^+\pi^-\gamma^I\gamma^I$	$\pi^0\pi^0\pi^+\pi^-\gamma^I\gamma^I$	13	1207	6110
4	$e^+e^- \to \pi^+\pi^+\pi^-\pi^-\gamma^I\gamma^I$	$\pi^+\pi^+\pi^-\pi^-\gamma^I\gamma^I$	15	1086	7196
5	$e^+e^- \to \pi^0\pi^+\pi^-\gamma^I$	$\pi^0\pi^+\pi^-\gamma^I$	12	1020	8216
6	$e^+e^- \to \pi^0\pi^0\pi^+\pi^-\gamma^I$	$\pi^0\pi^0\pi^+\pi^-\gamma^I$	2	961	9177
7	$e^+e^- \to \pi^+\pi^+\pi^-\pi^-\gamma^I$	$\pi^+\pi^+\pi^-\pi^-\gamma^I$	1	916	10093
8	$e^+e^- \to K_L^0K_S^0\gamma^I\gamma^I, K_S^0 \to \pi^+\pi^-$	$K_L^0\pi^+\pi^-\gamma^I\gamma^I$	3	536	10629
9	$e^+e^- \to vgam\gamma^I, vgam \to \pi^+\pi^-K^+K^-$	$\pi^+\pi^-K^+K^-\gamma^I$	17	536	11165
10	$e^+e^- \to vgam\gamma^I, vgam \to \pi^+K^*K^-, K^* \to \pi^-K^+$	$\pi^+\pi^-K^+K^-\gamma^I$	5	400	11565
11	$e^+e^- \to K_L^0K_S^0\gamma^I, K_S^0 \to \pi^+\pi^-$	$K_L^0\pi^+\pi^-\gamma^I$	49	343	11908
12	$e^+e^- \to vgam\gamma^I, vgam \to \pi^-\bar{K}^*K^+, \bar{K}^* \to \pi^+K^-$	$\pi^+\pi^-K^+K^-\gamma^I$	11	337	12245
13	$e^+e^- \to vgam\gamma^I, vgam \to \pi^0\pi^+\pi^-K^+K^-$	$\pi^0\pi^+\pi^-K^+K^-\gamma^I$	23	325	12570
14	$e^+e^- \to vgam\gamma^I, vgam \to \rho^0K^+K^-, \rho^0 \to \pi^+\pi^-$	$\pi^+\pi^-K^+K^-\gamma^I$	9	253	12823
15	$e^+e^- \to vgam\gamma^I, vgam \to \pi^0\pi^0\pi^+\pi^+\pi^-\pi^-$	$\pi^0\pi^0\pi^+\pi^+\pi^-\pi^-\gamma^I$	21	163	12986
16	$e^+e^- \to vgam\gamma^I, vgam \to \pi^+\pi^+\pi^-\pi^-K^+K^-$	$\pi^+\pi^+\pi^-\pi^-K^+K^-\gamma^I$	113	162	13148
17	$e^+e^- \to \psi'\gamma^I, \psi' \to \pi^+\pi^-J/\psi, J/\psi \to \mu^+\mu^-$	$\mu^+\mu^-\pi^+\pi^-\gamma^I$	0	152	13300
18	$e^+e^- \to vgam\gamma^I, vgam \to \pi^0\pi^+\pi^+\pi^-\pi^-$	$\pi^0\pi^+\pi^+\pi^-\pi^-\gamma^I$	37	151	13451
19	$e^+e^- \to \pi^+\pi^-K^+K^-$	$\pi^+\pi^-K^+K^-$	91	125	13576
20	$e^+e^- \to \pi^0\pi^+\pi^-K^+K^-$	$\pi^0\pi^+\pi^-K^+K^-$	96	118	13694
21	$e^+e^- \to vgam\gamma^I, vgam \to \pi^-K_S^0K^+, K_S^0 \to \pi^+\pi^-$	$\pi^+\pi^-\pi^-K^+\gamma^I$	126	108	13802
22	$e^+e^- \to \psi'\gamma^I, \psi' \to \pi^+\pi^-J/\psi, J/\psi \to e^+e^-$	$e^+e^-\pi^+\pi^-\gamma^I$	51	104	13906
23	$e^+e^- \to vgam\gamma^I, vgam \to \pi^0\pi^+\pi^-\omega, \omega \to \pi^0\pi^+\pi^-$	$\pi^0\pi^0\pi^+\pi^+\pi^-\pi^-\gamma^I$	97	104	14010
24	$e^+e^- \to K_L^0K_S^0K^+K^-\gamma^f, K_S^0 \to \pi^+\pi^-$	$K_L^0\pi^+\pi^-K^+K^-\gamma^f$	7	89	14099
25	$e^+e^- \to J/\psi\gamma^I, J/\psi \to \pi^+\pi^-n\bar{n}$	$\pi^+\pi^-n\bar{n}\gamma^I$	139	88	14187

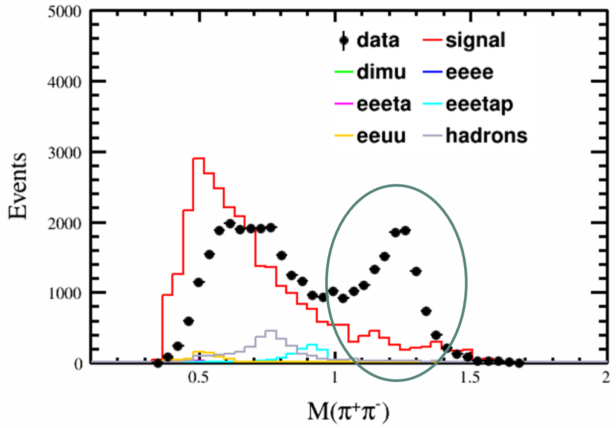
total: 22486

Cutflow of Quasireal Photon Cut

		data	eepipi	eeta	eeetap	eeuu	hadrons
Total Events		round17	10,050,000	1,300,000	1,150,000	1.3E8	1.2E8
Event Selection Cut		93,364	51,574	646	5,343	1,263	24,918
Rate			62%	1%	6%	2%	30%
Quasireal Photon cut	$P_T^{cm} < 0.2$ GeV	56,181	42,180	490	3,131	1,027	8,961
	$P_T^{cm}(\pi^+ - \pi^-) > 8P_T^{cm}(\pi^+\pi^-)$	34,552	30,071	86	979	686	2,927
Rate			86%		3%	2%	8%
If: $0.4 < M_{\pi\pi} < 0.6$ GeV		5,716	11,956	69	34	506	358
Ratio			93%	1%		4%	3%
If: $0.6 < M_{\pi\pi} < 1.0$ GeV		15,881	13,188	0	930	103	2,214
Ratio			80%		6%	1%	13%





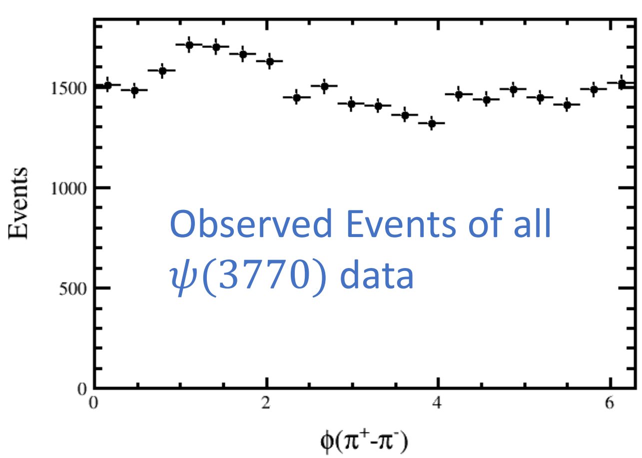


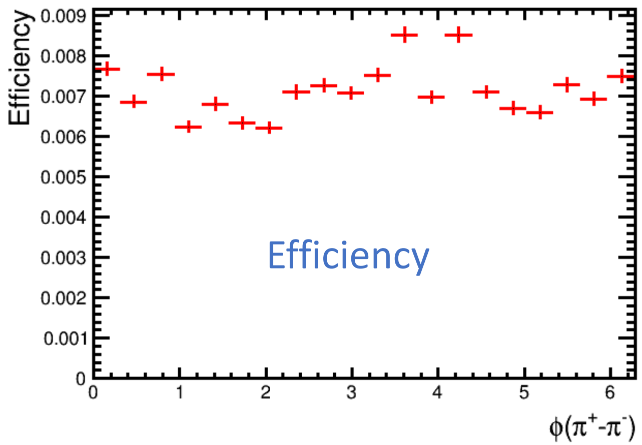
The difference between data and MC is due to the missing $f_2(1270)$ contribution in signal MC simulation.

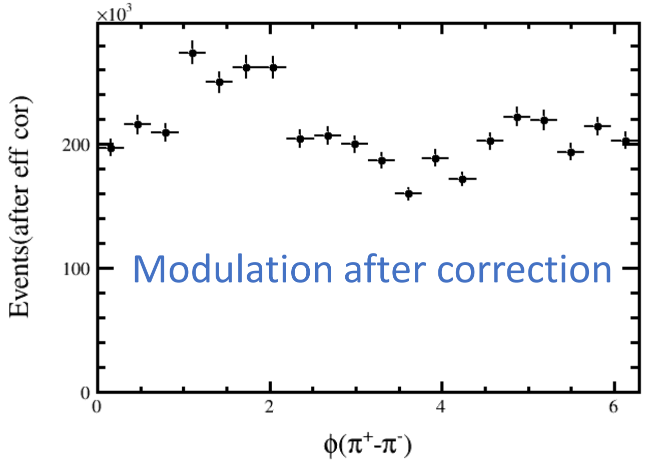
Results

$\boldsymbol{\phi} = \text{Angle}(\overrightarrow{P_T}(\pi^+) + \overrightarrow{P_T}(\pi^-), \overrightarrow{P_T}(\pi^+) - \overrightarrow{P_T}(\pi^-))$

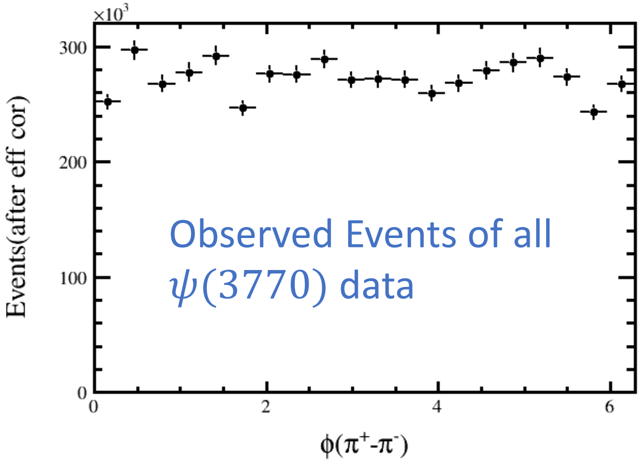
$\mathbf{0.4 < M_{\pi\pi} < 0.6\ GeV/c^2}$

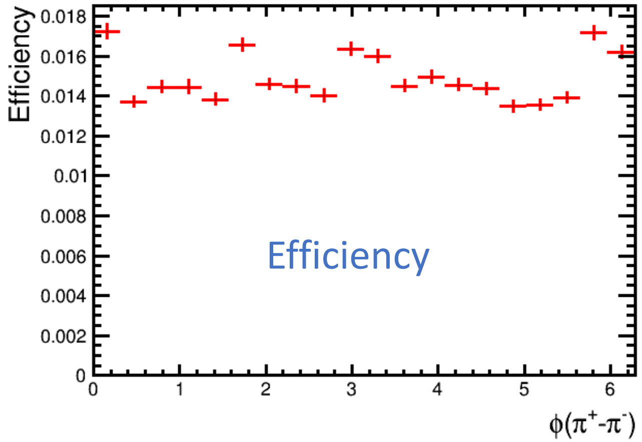


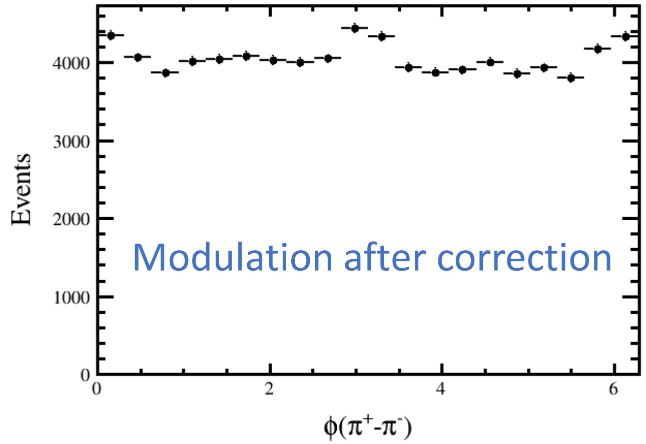




$\mathbf{0.6 < M_{\pi\pi} < 1.0\ GeV/c^2}$





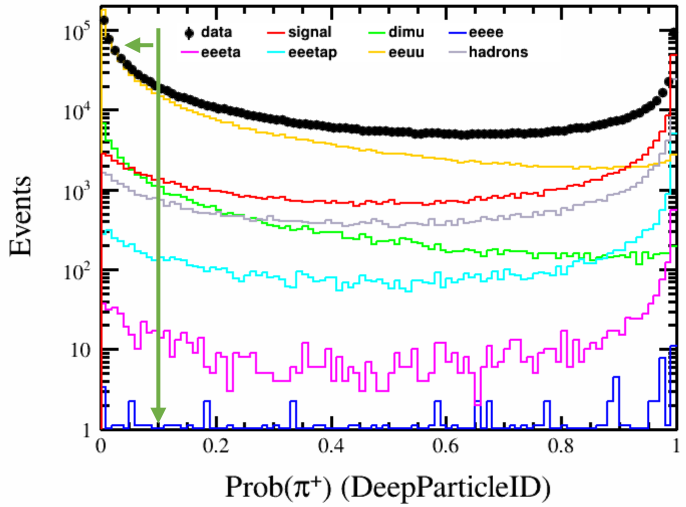


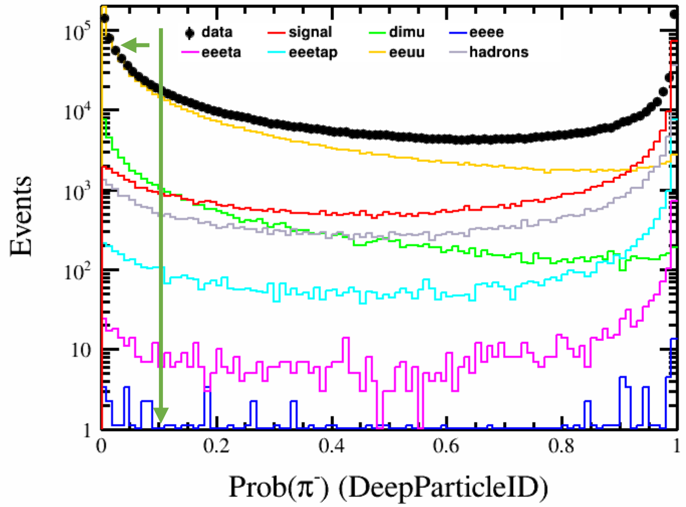
- Modelation of dipion process is more clear in the region $0.4 < M_{\pi^+\pi^-} < 0.6\ \text{GeV/c}^2$

2. $e^+e^- \to e^+e^-\mu^+\mu^-$

Event selection of $e^+e^- \to e^+e^-\mu^+\mu^-$

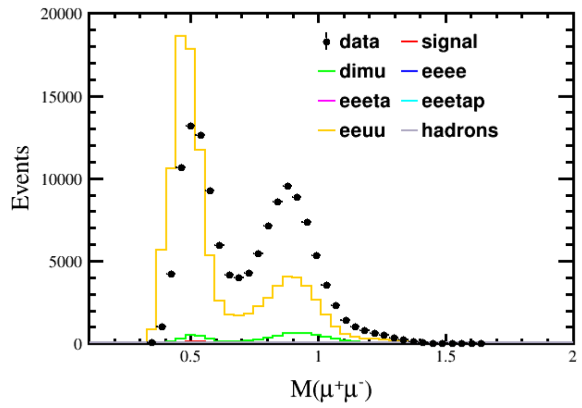
- Require $\mathrm{Prob}(\pi) < 0.1$ to select $e^+e^- \to e^+e^-\mu^+\mu^-$ events.
  - $\mathrm{Prob}(\pi)$ is obtained by DeepParticleID algorithm.
  - $\mathrm{Prob}(\pi) + \mathrm{Prob}(\mu) = 1$
- All the other selections are same as $e^+e^- \to e^+e^-\pi^+\pi^-$.





Cutflow of $e^+e^- \to e^+e^-\mu^+\mu^-$

	Data	eepipi	dimu	eeee	eeeta	eeetap	eeuu	hadrons
Total	round17	10,050,000	1.3E8	1.2E9	1,300,000	1,150,000	1.3E8	1.2E8
Preliminary Event Selection	1389695	181,153	56,713	40,531	2,123	18,693	933,842	94,134
Prob(μ)>Prob(e)	1259097	171,265	52,161	85	1,834	17,577	839,875	89,148
Prob(μ)>0.9	243533	1981	14081	3	24	215	324130	1517
$P_T^{cm} < 0.2$ GeV	188495	1665	9998	3	15	152	269945	515
$P_T^{cm}(\mu^+ - \mu^-) > 8P_T^{cm}(\mu^+\mu^-)$	132799	1151	7150	2	4	82	187690	136
		1%	4%				96%	
If: $0.4 < M_{\mu\mu} < 0.6$ GeV	51302	512	1775	2	4	5	115850	38
			2%				98%	
If: $0.6 < M_{\mu\mu} < 1.0$ GeV	68086	477	3884	0	0	77	51857	81
		1%	7%				92%	

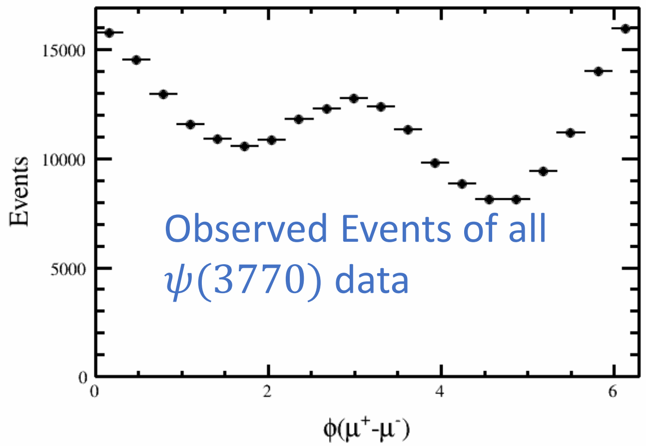


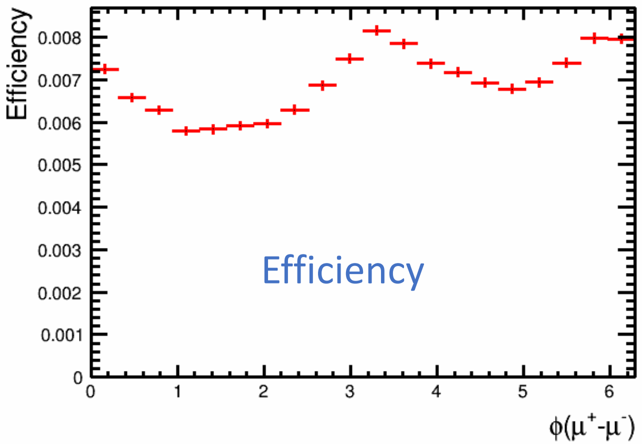
- The signal purity of $e^+e^- \to e^+e^-\mu^+\mu^-$ is more than 90%.

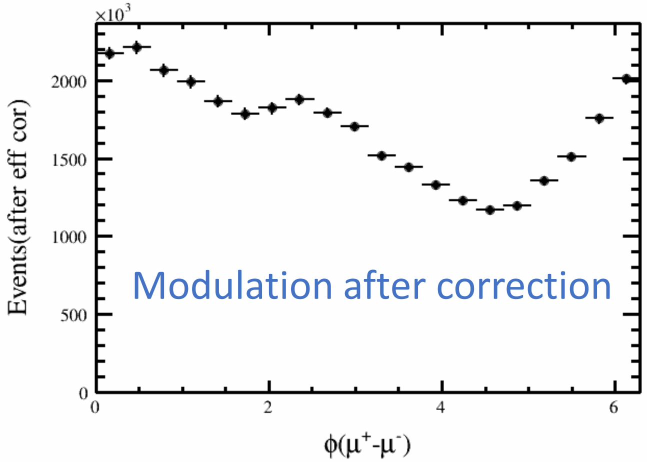
Results

$\boldsymbol{\phi} = \mathrm{Angle}(\overrightarrow{P_T}(\mu^+) + \overrightarrow{P_T}(\mu^-), \overrightarrow{P_T}(\mu^+) - \overrightarrow{P_T}(\mu^-))$

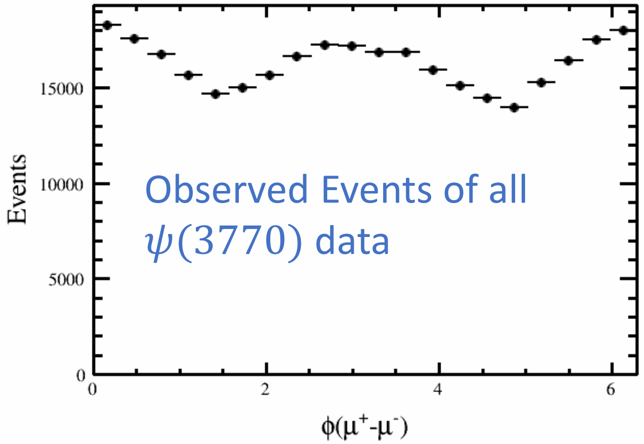
$0.4 < M_{\mu\mu} < 0.6\ \mathrm{GeV/c^2}$

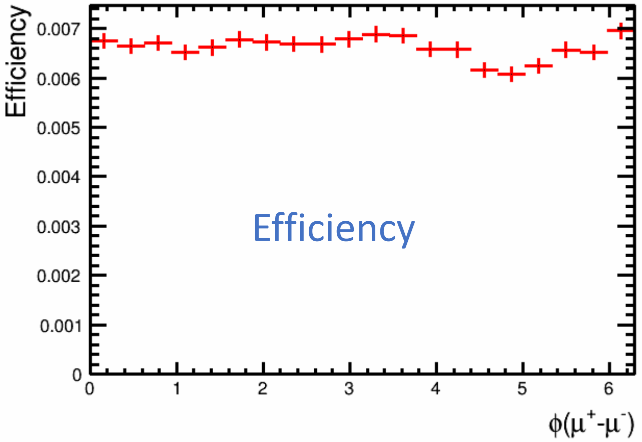


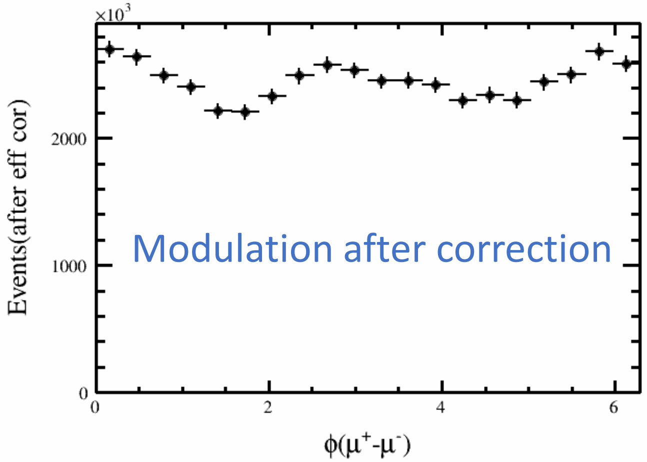




$0.6 < M_{\mu\mu} < 1.0\ \mathrm{GeV/c^2}$

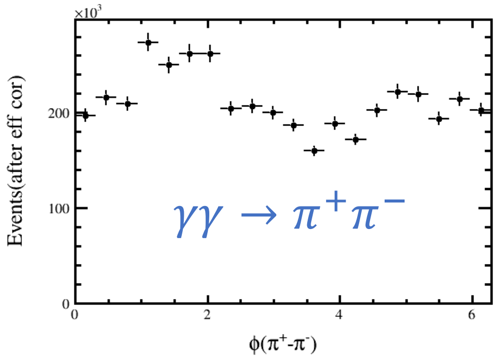


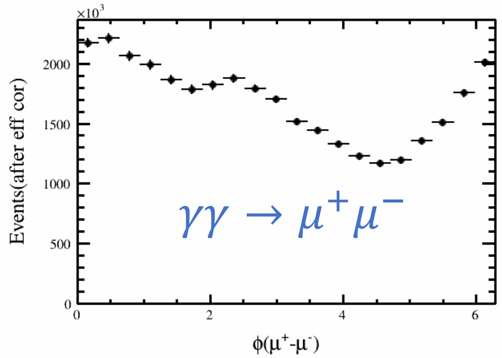


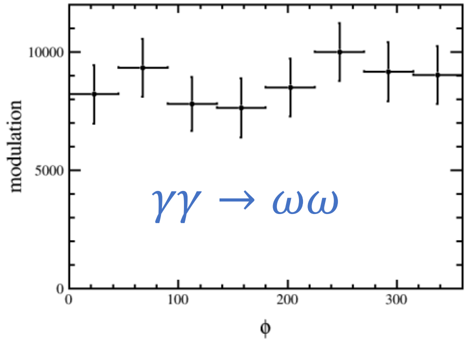


Summary and To Do List

- Summary
  - ✓ Using the 20.3 fb^{-1} $\psi(3770)$ data collected at BESIII, the azimuthal asymmetry of $\gamma\gamma \to \pi^+\pi^-, \mu^+\mu^-, \omega\omega$ can be observed.







- To do list
  - Optimize the event selections.
  - Generate MC samples with other generator, such as CppGamGam, to check the efficiency curves.
  - Study the systematic uncertainties.

  …

Thanks!