Measurement of $\mathcal{B}(\chi_{cJ} \to \eta K^+ K^- \pi^0)$

Shen Peixun[1] Li Gang[2] Yu Chunxu[1]

NanKai University[1]
Institute of High Energy Physics[2]

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Motivation

- Studying the exclusive multi-body decay modes of χ_{cJ} states is helpful to understand P-wave dynamics.
- CLEO collaboration has studied exclusive $\chi_{c0,1,2}$ decay to four-hadron final states, and the results have relatively large errors. https://arxiv.org/abs/0806.1227v1
- In this work, we report on a search of $\psi' \to \gamma\chi_{c0,1,2}$, where $\chi_{c0,1,2} \to \eta K^+K^-\pi^0$. The result of this process with BESIII's data is expected to have smaller errors.

- Boss version: 6.6.4.p03
- Data:

  106.9M $\psi^{'}$ of year 2009
  341.1M $\psi^{'}$ of year 2012
- MC:

  Inclusive MC (2009 and 2012 $\psi^{'}$)
  Exclusive MC: listed in table below

Signal	Background
$\chi_{cJ} \to a_0(980)K^+K^-, \to \eta K^+K^-\pi^0$	$\psi^{'} \to \eta J/\psi, \to K^+K^-\pi^0\pi^0$
$\chi_{cJ} \to a_0(980)\phi(1020), \to \eta K^+K^-\pi^0$	$\psi^{'} \to \pi^0\pi^0 J/\psi, \to \pi^0\pi^0\eta\phi(1020)$
$\chi_{cJ} \to a_0(980)\phi(1680), \to \eta K^+K^-\pi^0$	$\psi^{'} \to \pi^0\pi^0 J/\psi, \to \pi^0\pi^0\eta\phi(1020)$
$\chi_{cJ} \to a_2(1320)K^+K^-, \to \eta K^+K^-\pi^0$	$\psi^{'} \to \pi^0\pi^0 J/\psi, \to K^+K^-\pi^0\pi^0\pi^0$
$\chi_{cJ} \to \eta f_1(1285), \to \eta K^{\pm *}K^-$	$\chi_{cJ} \to \gamma J/\psi, \to \gamma K^+K^-\pi^0\pi^0$
$\chi_{cJ} \to \eta f_1(1420), \to \eta K^{\pm *}K^-$	$\chi_{cJ} \to K^{*+}K^{*-}\pi^0$
$\chi_{cJ} \to \eta K^+K^-\pi^0$	$\chi_{cJ} \to K^+K^-\pi^0\pi^0$
$\chi_{cJ} \to \eta K^{\pm *}K^-$	

Preliminary selection

- Two good charged tracks:
  $|V_{xy}| < 1$ cm, $|V_z| < 10$ cm, $|\cos\theta| < 0.93$, $\text{Prob}_K > \text{Prob}_\pi$
- Good Photon:
  $E_\gamma > 25(50)$ MeV, barrel(endcap), $0 \leq \text{TDC} \geq 14(50\text{ns})$
- π^0 candidate:
  $0.1 < M_{\gamma\gamma} < 0.155$ GeV, $\chi^2_{\pi^0} < 200$
- η candidate:
  $0.468 < M_{\gamma\gamma} < 0.608$ GeV, $\chi^2_{\eta^0} < 200$
- 6C-kinematic fit:
  Take the one with the smallest χ^2_{6C} in case of multi-combinations and $\chi^2_{6C} < 200$.

Backgrounds analysis

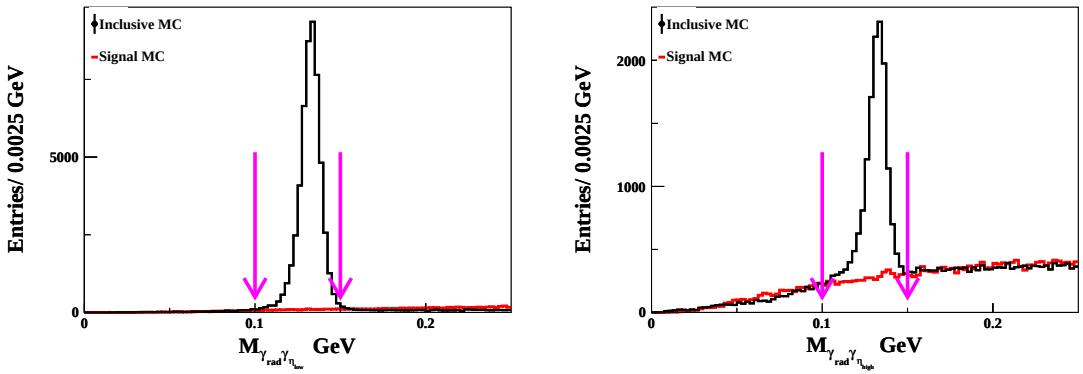
After the initial event selections, the inclusive ψ' decay MC sample is used to investigate potential backgrounds. There are mainly from these sources:

- $\psi' \to \gamma\chi_{cJ}, \chi_{cJ} \to K^+K^-\pi^0\pi^0$
- $\psi' \to \gamma\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi, J/\psi \to K^+K^-\pi^0\pi^0$
- $\psi' \to \pi^0\pi^0 J/\psi, J/\psi \to K^+K^-\pi^0$
- $\psi' \to \eta J/\psi, J/\psi \to K^+K^-\pi^0\pi^0$
- $\psi' \to \pi^0\pi^0 J/\psi, J/\psi \to \eta\phi(1020)$

Backgrounds with fake η

To veto these backgrounds, the selection criteria below are performed:

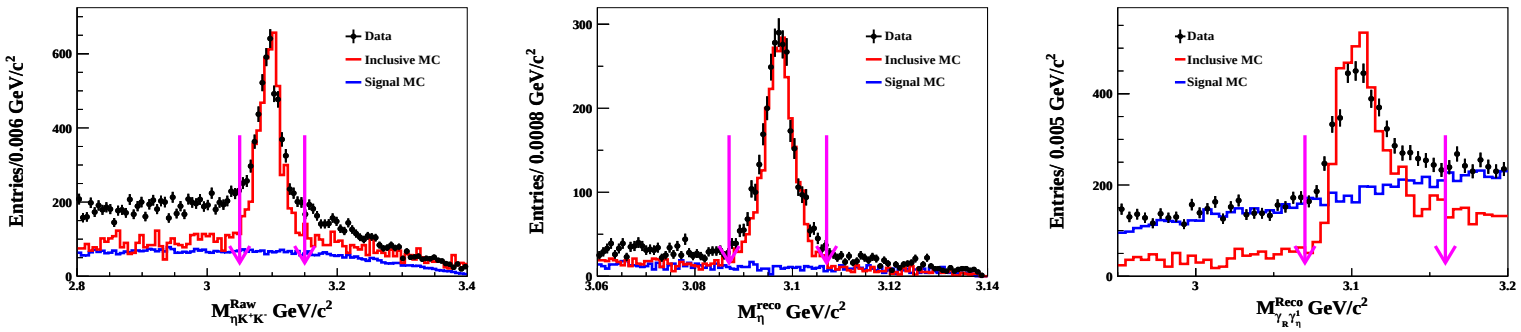
- Photons belong to η candidate can't compose a π^0 candidate with any other photons: $\gamma_\eta \notin \gamma_{\pi^0}$
- The invariant masses of radiative photon and the photons from η are required: $M_{\gamma_R\gamma_\eta} < 0.1$ GeV $||$ $M_{\gamma_R\gamma_\eta} > 0.15$ GeV, as shown in figure below.



Backgrounds with J/ψ

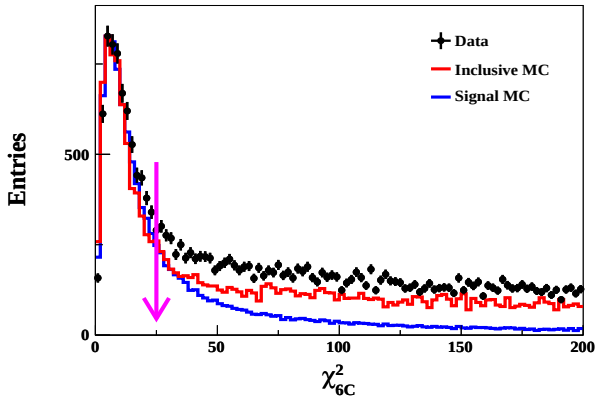
To veto backgrounds with J/ψ, the selection criteria below are performed:

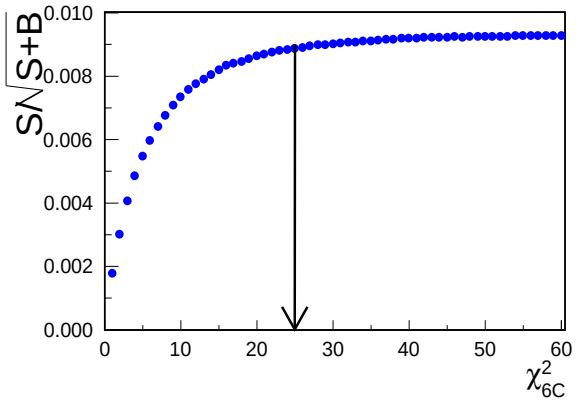
- $|M_{\eta K^+K^-} - M_{J/\psi}| > 0.05$ GeV
- $|M_{\eta}^{reco} - M_{J/\psi}| > 0.1$ GeV
- $M_{\gamma_R\gamma_\eta}^{reco} < 3.07$ GeV $||$ $M_{\gamma_R\gamma_\eta}^{reco} > 3.16$ GeV



Optimization on χ^2_{6C}

After the cuts above, the distribution of χ^2_{6C} is shown below. We use $S/\sqrt{S+B}$ to optimize χ^2_{6C}, where S is the number of signals in inclusive MC and B is the number of backgrounds in inclusive MC. $\chi^2_{6C} < 25$ is required to further veto remain backgrounds.





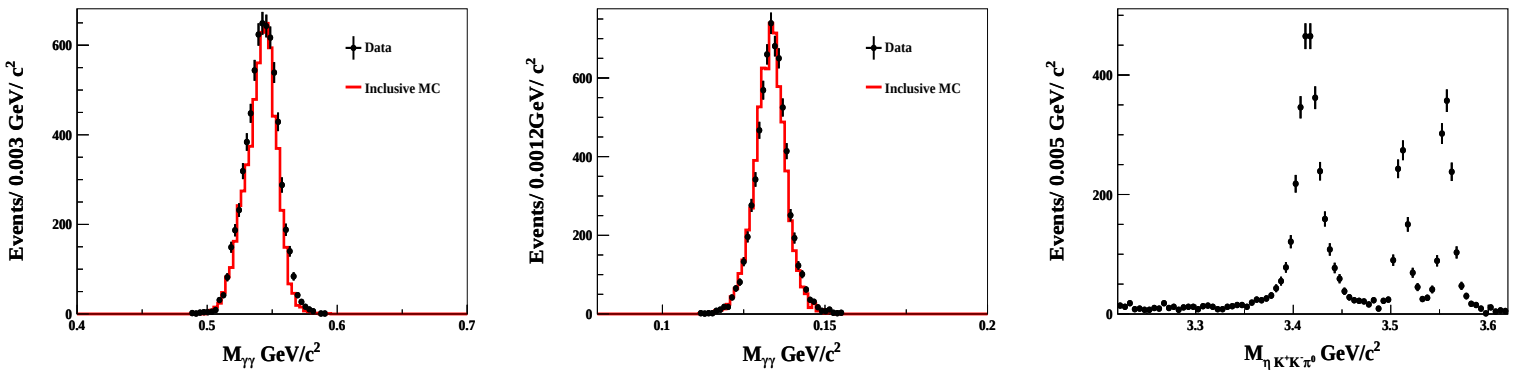
Topology results of inclusive MC

After the final event selections, the top 10 topology results of inclusive MC are listed below, the backgrounds level is low compared to signals.

No.	Decay Chain	Events
0	$\psi' \to \gamma\chi_{c0},\ \chi_{c0} \to K^+K^-\eta\pi^0$	3112
1	$\psi' \to \gamma\chi_{c2},\ \chi_{c2} \to K^+K^-\eta\pi^0$	1277
2	$\psi' \to \gamma\chi_{c1},\ \chi_{c1} \to K^+K^-\eta\pi^0$	1232
3	$\psi' \to \gamma\chi_{c0},\ \chi_{c0} \to K^{*-}\eta K^+$	37
4	$\psi' \to \gamma\chi_{c0},\ \chi_{c0} \to K^{*+}\eta K^-$	31
5	$\psi' \to \gamma\chi_{c0},\ \chi_{c0} \to K^+K^-\pi^0\pi^0$	30
6	$\psi' \to \gamma\chi_{c2},\ \chi_{c2} \to K^{*-}\eta K^+$	28
7	$\psi' \to \gamma\chi_{c1},\ \chi_{c1} \to K^+K^{*-}\eta$	26
8	$\psi' \to \gamma\chi_{c1},\ \chi_{c1} \to \eta K^{*+}K^-$	22
9	$\psi' \to \gamma\chi_{c0},\ \chi_{c0} \to K^{*-}\pi^0K^{*+}$	18

Distributions of η, π^0 and $M_{\eta K^+K^-\pi^0}$

The distributions of η, π^0 and $M_{\eta K^+K^-\pi^0}$ are shown below, we can see the distributions of inclusive MC are consistent with data.



Weighting mixing MC samples to obtain efficiency

To consider the contributions from intermediate resonances in $\eta K^+K^-\pi^0$ final states, the exclusive MC samples with each intermediate resonance are generated according to data. Then we weight the mixing MC bin by bin and get the detection efficiency.

- $\chi_{cJ} \to \eta K^{\pm *} K^-, \to \eta K^+K^-\pi^0$
- $\chi_{cJ} \to a_0(980) K^+K^-, \to \eta K^+K^-\pi^0$
- $\chi_{cJ} \to a_0(980)\phi(1020), \to \eta K^+K^-\pi^0$
- $\chi_{cJ} \to \eta f_1(1285), \to \eta K^{\pm *} K^-, \to \eta K^+K^-\pi^0$
- $\chi_{cJ} \to \eta f_1(1420), \to \eta K^{\pm *} K^-, \to \eta K^+K^-\pi^0$

Weighting scheme

During weighting procedure, the data in χ_{cJ} region are used, which are (3.36, 3.46) GeV, (3.48, 3.535) GeV and (3.535, 3.6) GeV for $\chi_{c0,1,2}$, respectively. Then the variables have large difference between data and MC are selected as weighting variables, as listed below:

- χ_{c0} region: $M_{\eta\pi^0}$, $M_{K^+K^-}$, $M_{K^+K^-\pi^0}$
- χ_{c1} region: $M_{\eta\pi^0}$, $M_{K^+K^-}$, $M_{K^+K^-\pi^0}$, $\cos\theta_{K^+}$
- χ_{c2} region: $M_{\eta\pi^0}$, $M_{K^+K^-}$, $M_{K^+K^-\pi^0}$

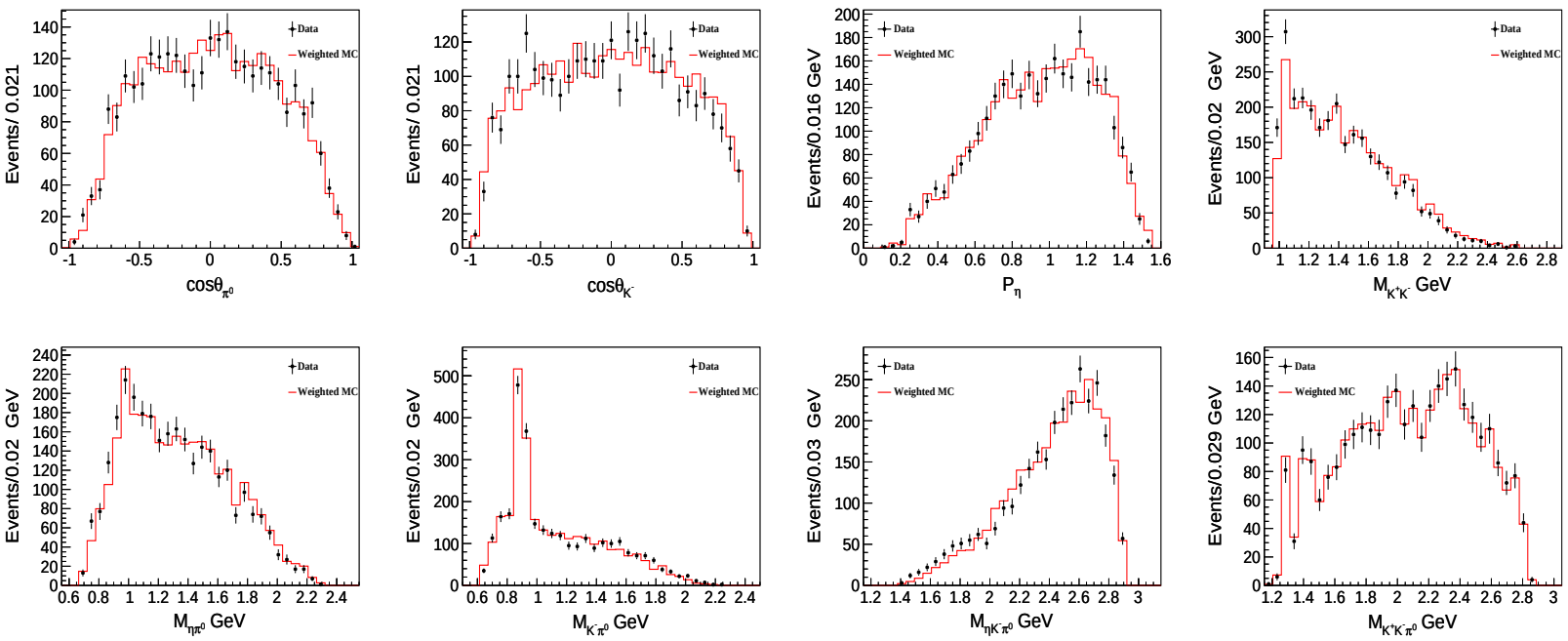
Weighting scheme

To determine the mixing ratio of different MC samples, the χ^2 is defined in this form:

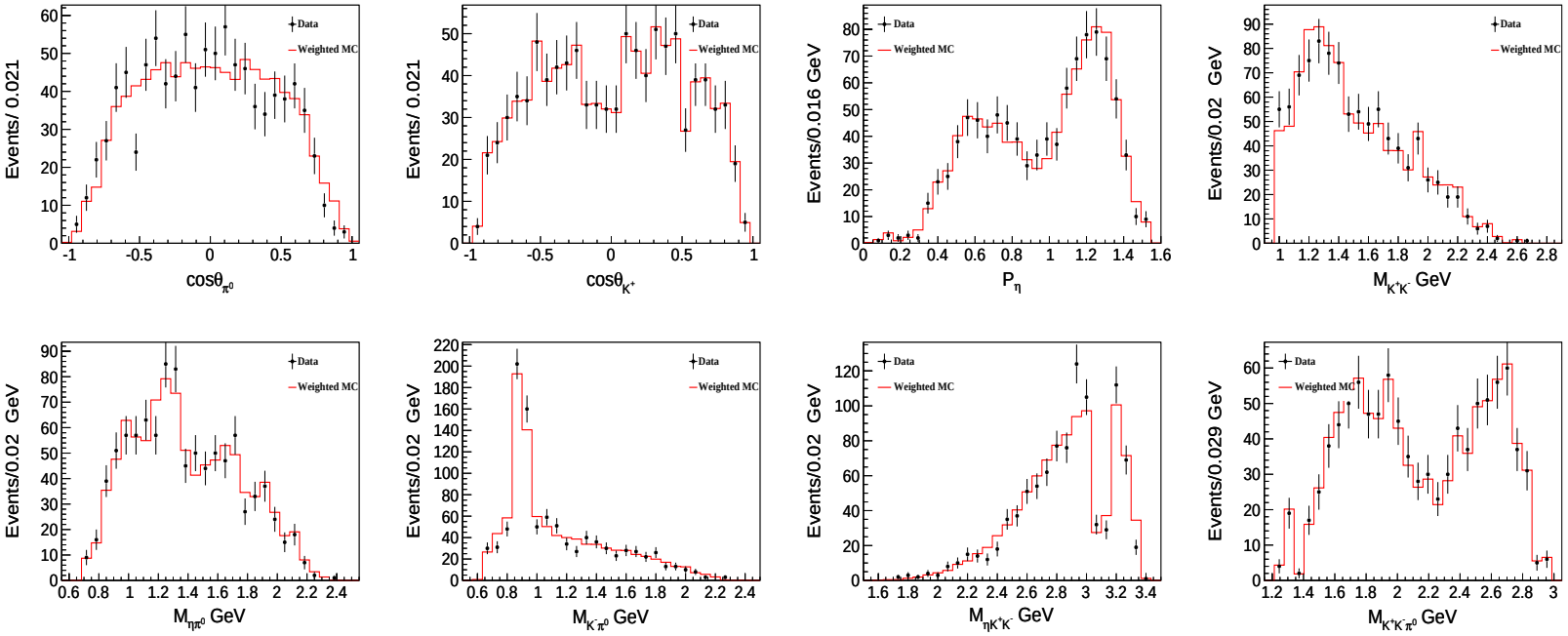
$$\chi^2 = \sum_i^N \sum_j^M (n_{ij}^{dt} - n_{ij}^{wt})^2 / n_{ij}^{dt} \tag{1}$$

Here, N is the number of weight variables, M is the number of bins, n_{ij}^{dt} and n_{ij}^{wt} are the number of events of data and weighting result in bin j of variable i. We scan the mixing ratio of MC samples to get the minimum χ^2, then the detection efficiency is obtained.

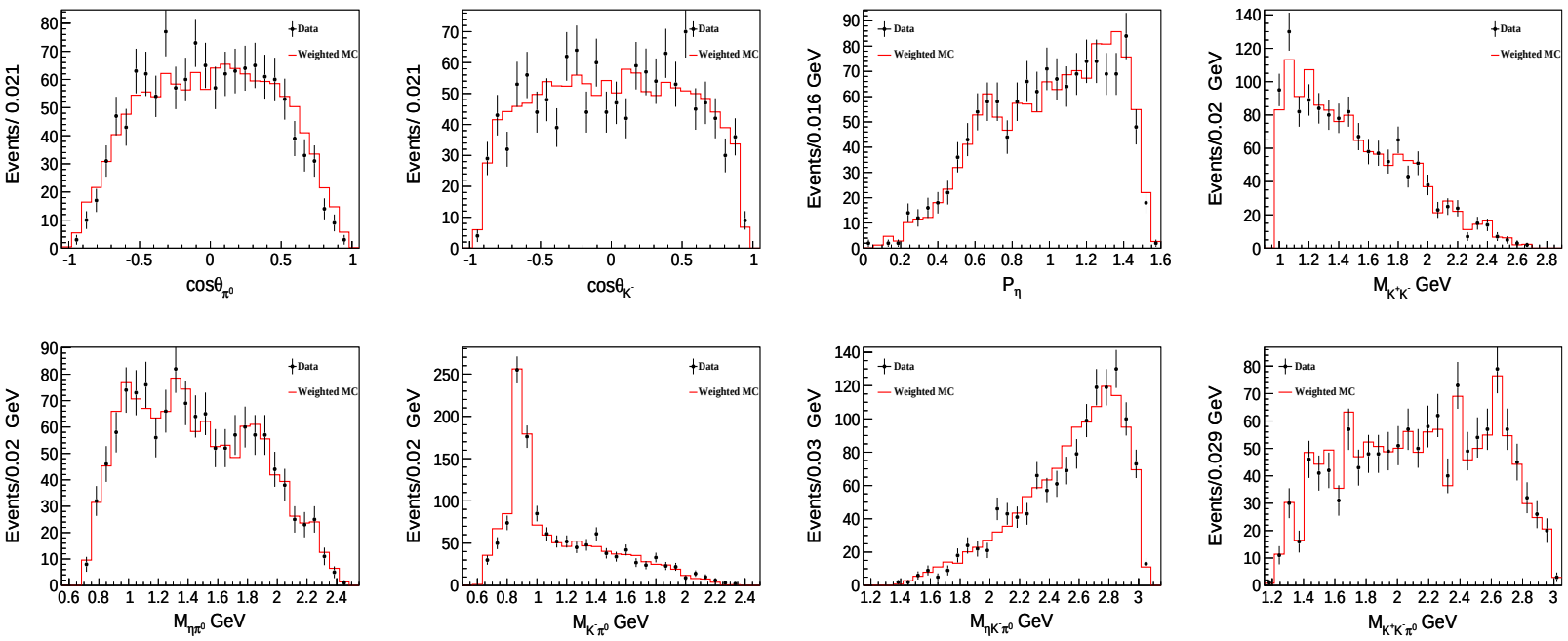
Weighting results in χ_{c0} region



Weighting results in χ_{c1} region



Weighting results in χ_{c2} region



Detection efficiency

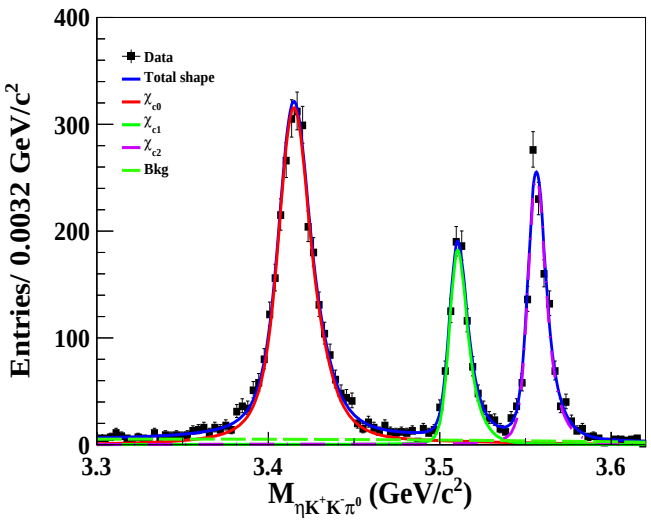
The efficiency is obtained by this formula:

$$\epsilon_{wt} = \frac{\sum n_i^{obs} \times w_i}{\sum n_i^{gen} \times w_i} \tag{2}$$

Where, n_i^{obs} is event of mixing MC samples passing event selections; n_i^{gen} is event of mixing MC samples before event selections; w_i is the weighting factor of each event.

Fit procedure

The signal yields are obtained by unbinned fit with $PDF = \sum_{J=0,1,2} pdf(\chi_{cJ}) \bigotimes Gaussian_J(m_J \times \sigma_J) + BG$. Where, $pdf(\chi_{cJ})$ is MC shape, Gaussian describe the difference on detection resolution between data and MC, the background are parameterized with 2-order polynomial.



$$N_{\chi_{c0}} = 2999.2 \pm 62.9$$
$$N_{\chi_{c1}} = 888.5 \pm 33.6$$
$$N_{\chi_{c2}} = 1226.0 \pm 38.1$$

Numerical results

We use the formula (3) to calculate branching fraction:

$$\mathcal{B}(\chi_{cJ} \to \eta K^+ K^- \pi^0) = \frac{N^{signal}}{N_{\psi'} \times \mathcal{B}_{\psi' \to \gamma \chi_{cJ}} \times \mathcal{B}_{\eta \to \gamma\gamma} \times \mathcal{B}_{\pi^0 \to \gamma\gamma} \times \epsilon} \quad (3)$$

Mode	N^{signal}	$N_{\psi'}$	$\epsilon(\%)$	$\mathcal{B}(\times 10^{-3})$
χ_{c0}	2999.2 ± 62.9	4.479×10^8	4.92	3.50 ± 0.07
χ_{c1}	888.5 ± 33.6	4.479×10^8	5.74	0.93 ± 0.04
χ_{c2}	1226.0 ± 38.1	4.479×10^8	5.45	1.42 ± 0.04

Systematic uncertainties

The uncertainties from sources listed below are considered:

- Tracking and PID, 2.0% for K^+ and K^-, respectively.
- We take 1.0% as the uncertainty from photon reconstruction. For η, because there is loose requirement on η mass window, we take the uncertainties from two photons. So the combined uncertainty from photon and η reconstruction is 3.0%.
- For π^0, we weight the number of reconstructed events according to π^0's momentum with the formula cited from http://docbes3.ihep-.ac.cn/DocDB/0005/000510/009/pi0eff.pdf . The difference between with and without weighting is taken as the uncertainty from π^0 reconstruction, which is 1.3%.

Systematic uncertainties

- For kinematic fit, we change the helix parameters of tracks and take the difference between with and without this correction as the uncertainty.
- To determine the uncertainty from fit procedure, the fit range of $M_{\eta K^+K^-\pi^0}$: [3.3, 3.62] GeV is replaced with [3.2, 3.6] GeV, the backgrounds shape is replaced by 1-order polynomial. These differences on fit results between with and without these changes are taken as the uncertainties.
- The uncertainty from number of $\psi^{'}$ is cited from BESIII analysis and the uncertainties from branching ratio are obtained from PDG.
  - http://hnbes3.ihep.ac.cn/HyperNews/get/paper201.html

Systematic uncertainties from MC model

- For the uncertainty from detection efficiency, we consider these sources: the step size of scan, bin scheme, the number of mixing MC samples and the weight variables. To minimize the influence from statistic of data, these uncertainties are determined at χ_{c0} region.
  - For the step size of scan, we select 100, 150 and 200 as the step size. The variation on efficiency is taken as the uncertainty, which is 0.4%.
  - The statistic of data will affect the bin scheme. For χ_{c0} region, each weighting variables are binned from 20 to 50 bins. The difference between maximum and minimum efficiency is taken as the uncertainty, which is 2.3%.

Systematic uncertainties from MC model

- For the uncertainty from mixing MC samples, the MC with other intermediate states, $\chi_{cJ} \to a_2(1320)K^+K^-$ and $\chi_{cJ} \to a_0(980)\phi(1680)$ are added. The difference on efficiency between weighting with and without these samples is taken as the uncertainty, which is 0.8%.
- To determine the uncertainty from weighting variables, the additional variable P_{π^0} is added. The variation on efficiency is taken as the uncertainty, which is 0.7%.

Step size(scan)(%)	Bin Scheme(%)	MC samples(%)	Scan variables(%)	Total(%)
0.4	2.3	0.8	0.4	2.6

Total systematic uncertainties

The total systematic uncertainties are listed below:

	$\chi_{c0}(\%)$	$\chi_{c1}(\%)$	$\chi_{c2}(\%)$
Tracking, PID	2.0, 2.0	2.0, 2.0	2.0, 2.0
$\mathcal{B}(\psi' \to \gamma\chi_{cJ})$	2.7	3.2	3.4
$\mathcal{B}(\eta \to \gamma\gamma)$	0.5	0.5	0.5
$\mathcal{B}(\pi^0 \to \gamma\gamma)$	-	-	-
Kinematic fit	0.6	1.0	0.5
MC model	2.6	2.6	2.6
γ and η	3.0	3.0	3.0
π^0	1.3	1.3	1.3
Fit	0.6	0.6	0.6
$N_{\psi'}$	0.7	0.7	0.7
Total	5.8	6.1	6.2

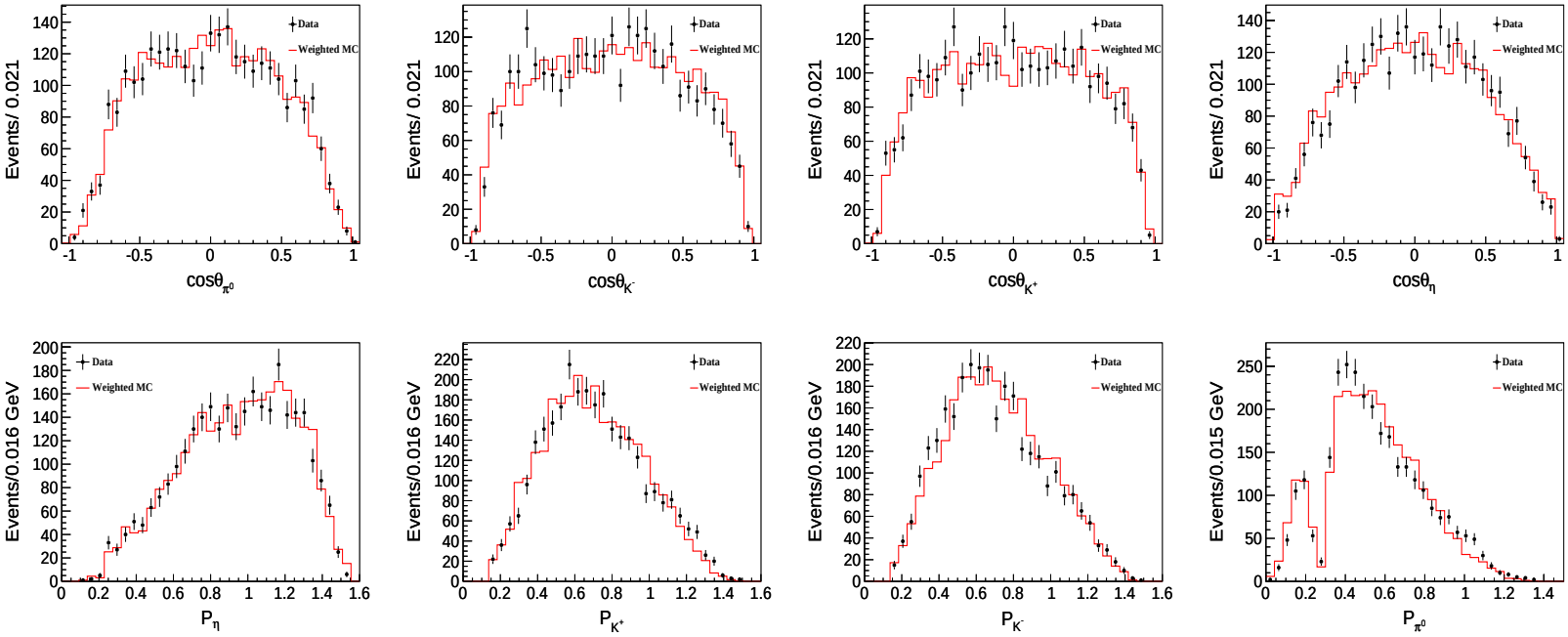
Summay

- The branching ratios of $\chi_{cJ} \to \eta K^+ K^- \pi^0$ are measured, the preliminary results have higher accuracy compared to CLEO's results. https://arxiv.org/abs/0806.1227v1
- The analysis memo is preparing.

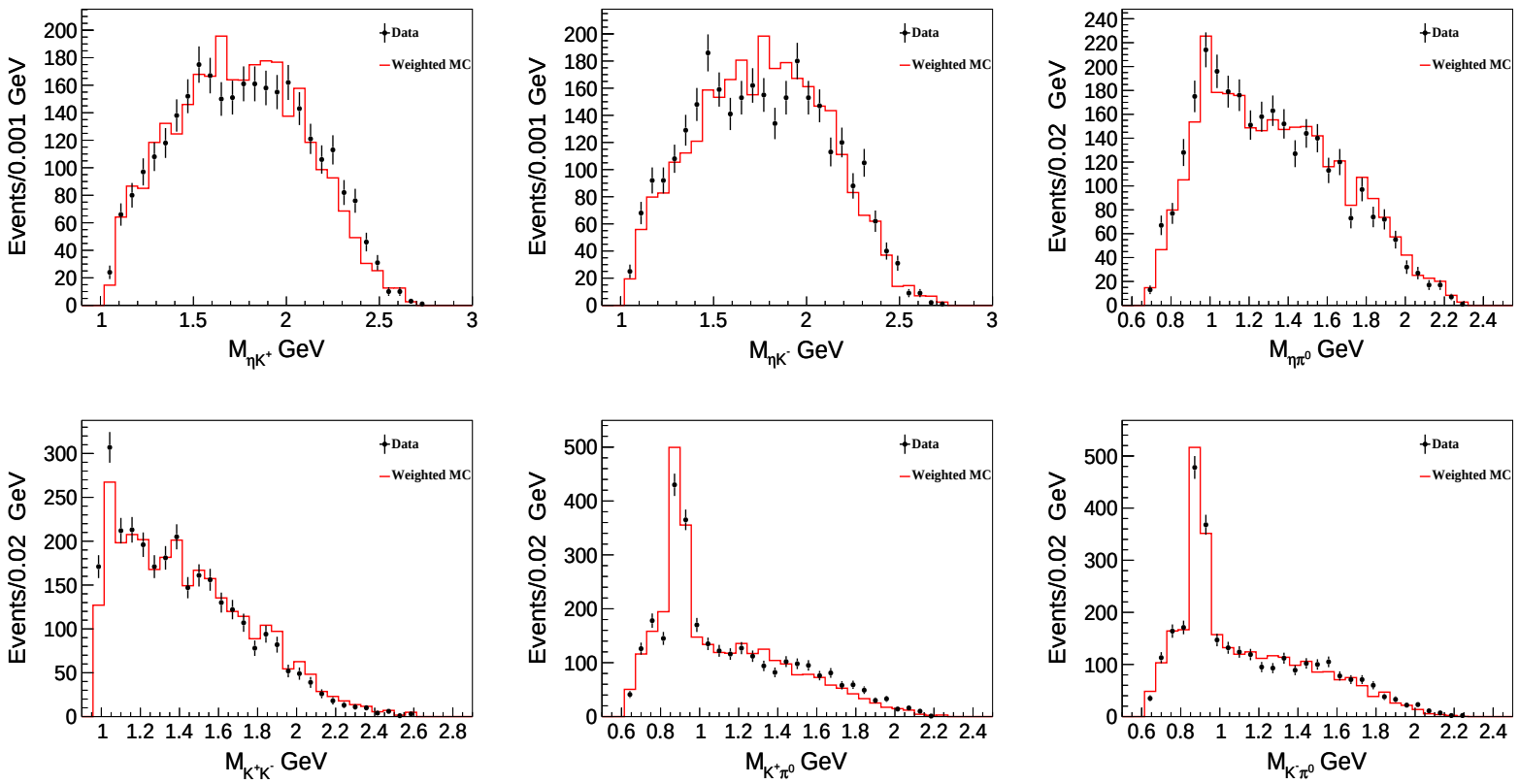
	$\chi_{c0}(\times 10^{-3})$	$\chi_{c1}(\times 10^{-3})$	$\chi_{c2}(\times 10^{-3})$
CLEO's results	$3.20 \pm 0.50 \pm 0.50$	$1.20 \pm 0.30 \pm 0.20$	$1.30 \pm 0.40 \pm 0.20$
Pre. results	$3.50 \pm 0.07 \pm 0.20$	$0.93 \pm 0.04 \pm 0.06$	$1.4 \pm 0.04 \pm 0.09$

Thank You!

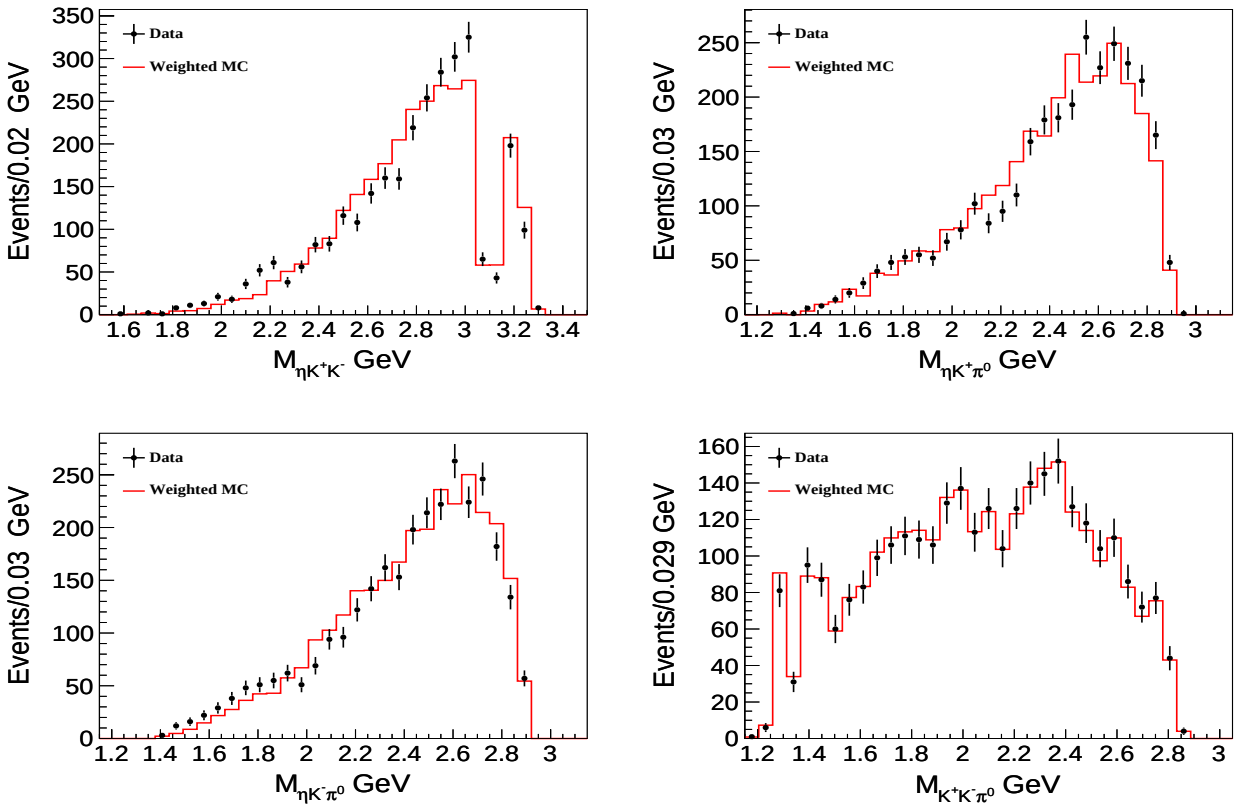
Angular and momentum distributions



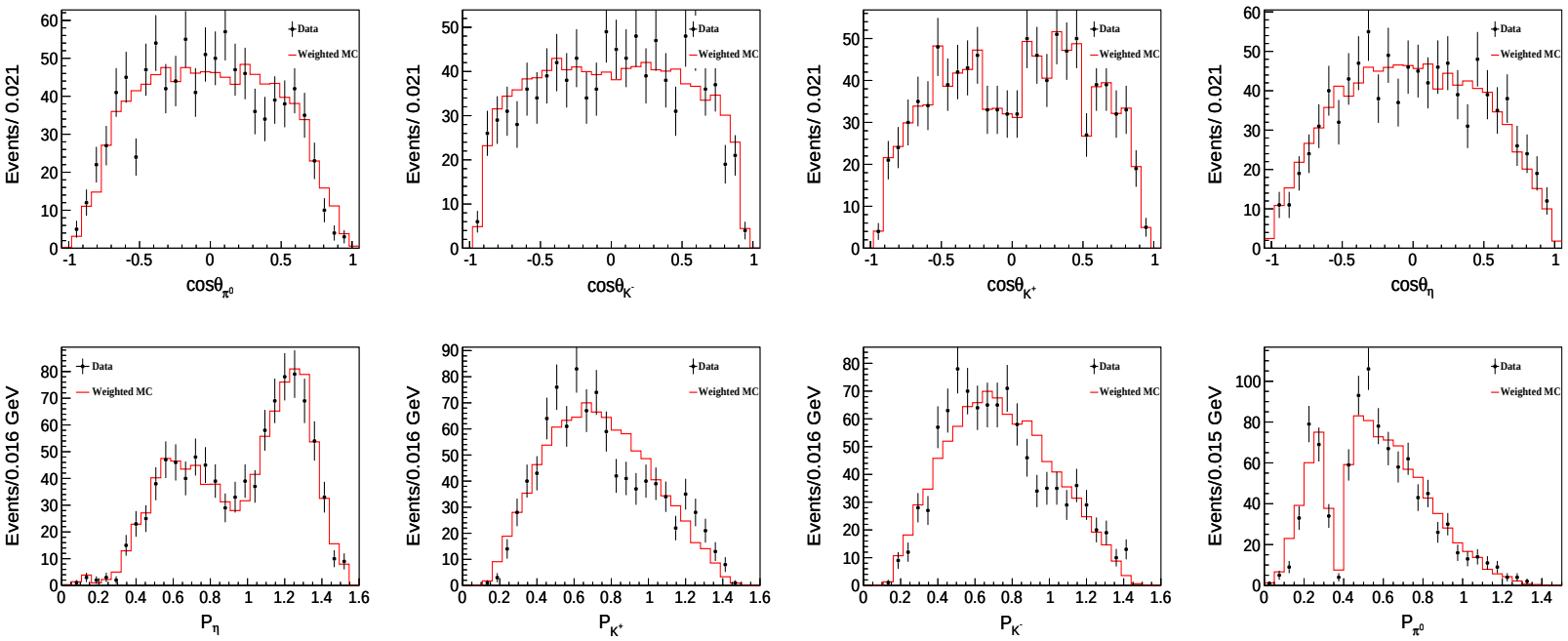
Invariant masses of 2-body



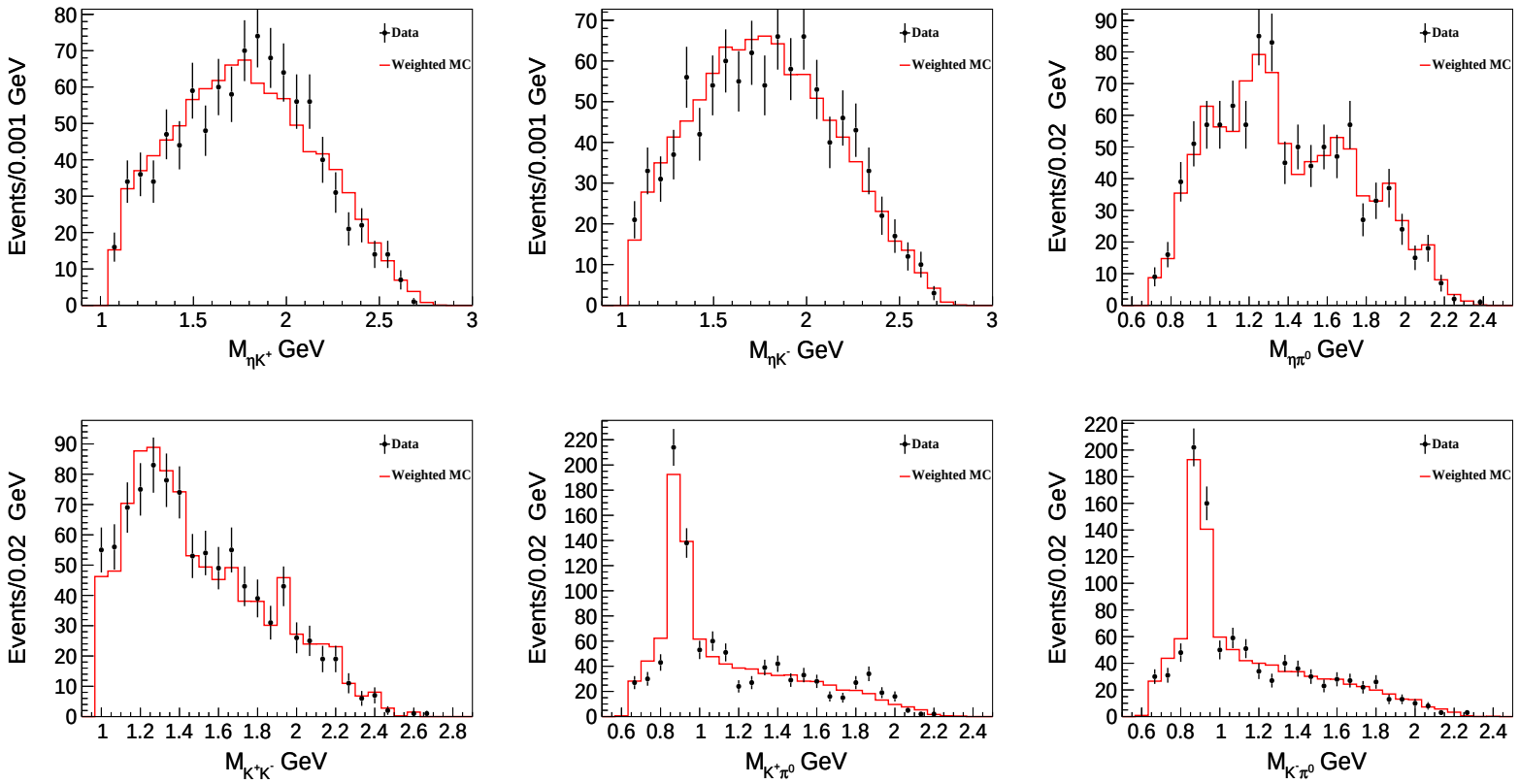
Invariant masses of 3-body



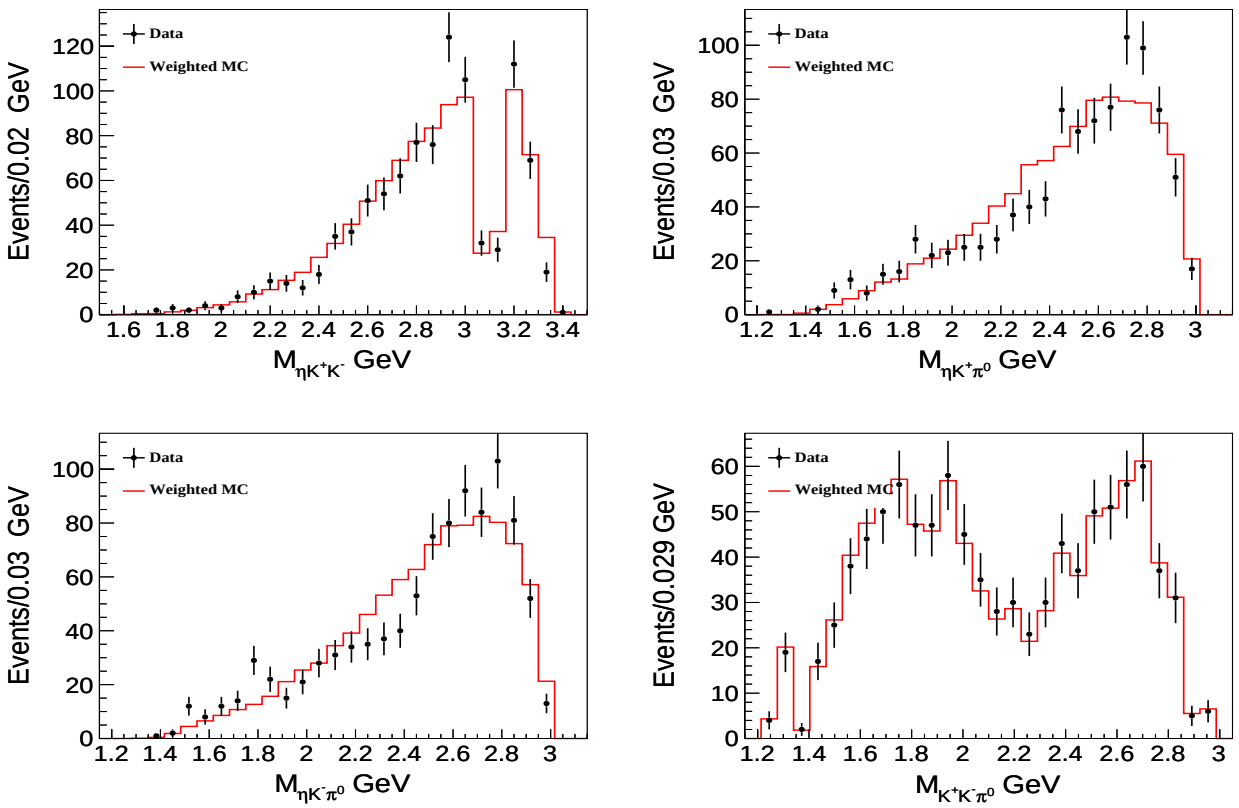
Angular and momentum distributions



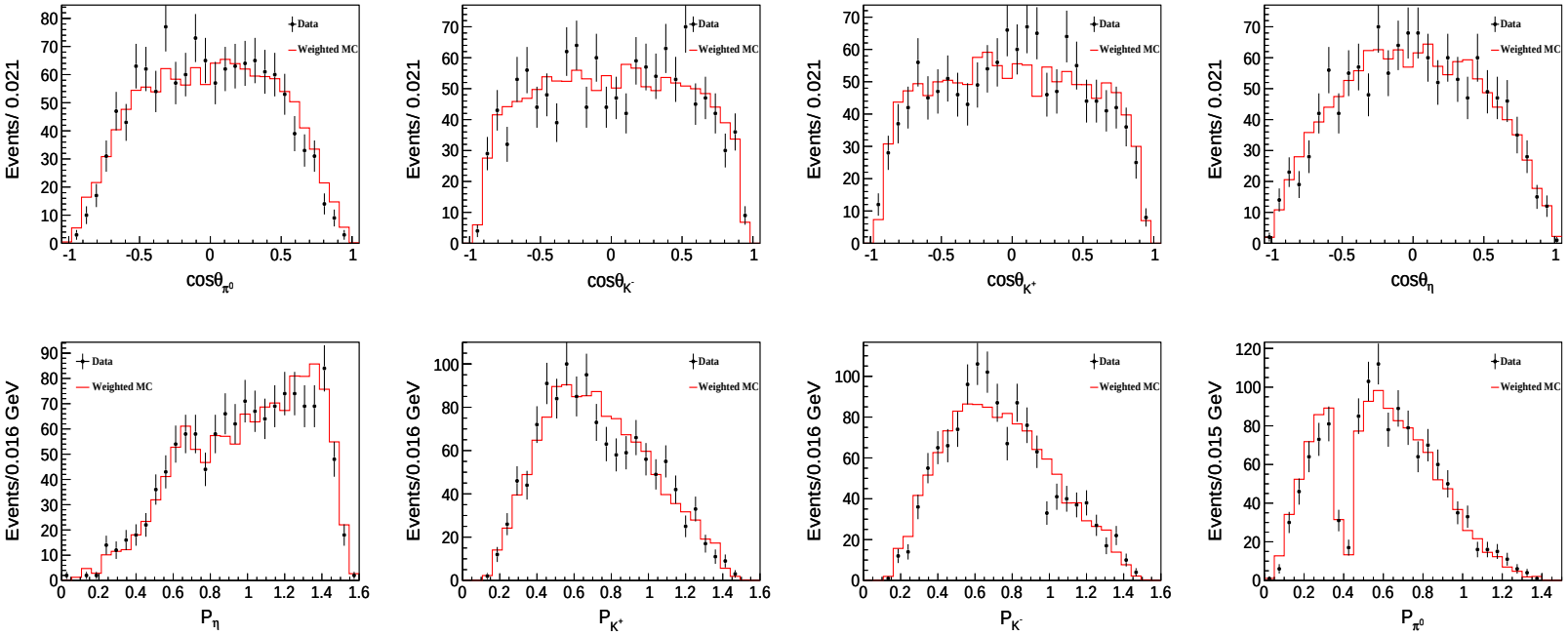
Invariant masses of 2-body



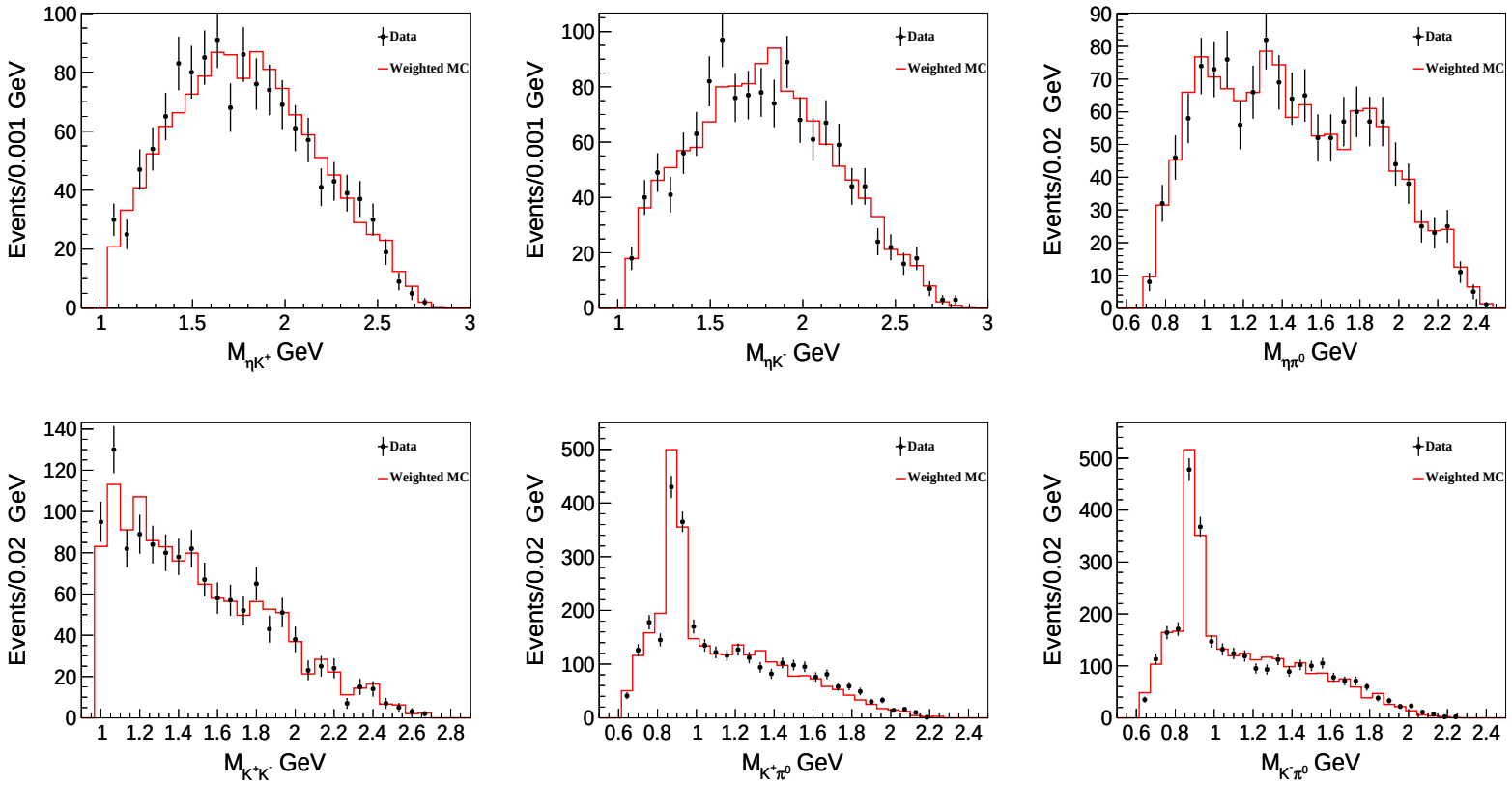
Invariant masses of 3-body



Angular and momentum distributions



Invariant masses of 2-body



Invariant masses of 3-body