Study of $e^+e^- \to \phi\eta'$

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Outline

Motivation

- Several hadronic transitions about Y(4260) states have been found in these experiments, such as:
  $\pi^+\pi^- J/\psi$[1], $K^+K^- J/\psi$[2] and $\pi^+\pi^-\psi(2S)$[3], but no light hadron decay modes have been found.
- Different interpretations were proposed to explain Y(4260) structure, the natures of the Y(4260) are still unclear.
- Utilize the newest data, we search for $e^+e^- \to \phi\eta'$ to study the line-shape with improved precision then better understanding of the structure, and check the energy dependence feature of Y(4260) particles.

[1] Phys.Rev.Lett.95.142001
[2] PhysRevD.77.011105
[3] PhysRevLett.99.142002

Data sample and software version

- Boss version: 7.0.3
- Exclusive MC: 10K for each energy point
- Inclusive MC: with the same integrated luminosity as data at 4.23 GeV.
- Data Sets
  - The search of $e^+e^- \to \phi\eta'$ based on data samples collected with the BESIII detector at center-of-mass energy $\sqrt{\mathrm{s}} > 4$ GeV.

Data Sets	$\sqrt{s}$(GeV)	Luminosity(pb^{-1})
1	4.009	481.96
2	4.180	3194.50
3	4.190	522.50
4	4.200	524.60
5	4.210	518.10
6	4.220	514.30
7	4.230	1047.34
8	4.237	530.60
9	4.246	537.40
10	4.260	825.67
11	4.270	529.70
12	4.280	175.50
13	4.360	539.84
14	4.420	1028.89
15	4.600	566.93

- Decay chain
  - $e^+e^- \to \phi\eta'$ VVS_PWAVE
    - $\phi \to K^+K^-$ VSS
  - $\eta' \to \eta\pi^+\pi^-$ PHSP
    - $\eta \to \gamma\gamma$ PHSP
  - $\eta' \to \gamma\pi^+\pi^-$ PHSP

Selections

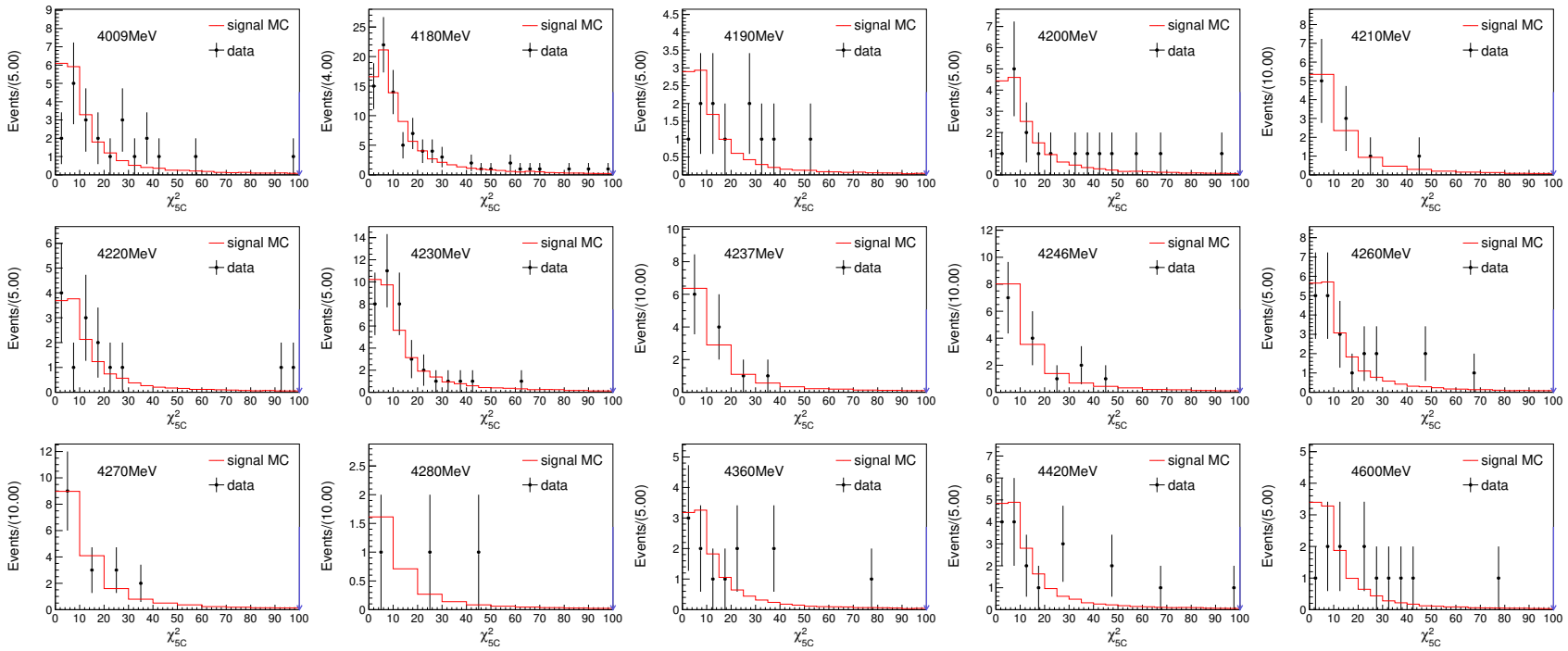
- Charged track selection
  - $|\cos\theta| < 0.93$, $|R_z| < 10.0$ cm, $|R_{xy}| < 1.0$ cm
  - $N_{charged} = 4$
- Particle identification
  - pion, prob(π) $>$ prob(K), prob(π) $>$ 0
  - kaon, prob(K) $>$ prob(π), prob(K) $>$ 0
- Good photon selection
  - 0 $\leq t_{TDC} \leq$ 14 ($\times$ 50 ns)
  - photon from barrel ($|\cos\theta| < 0.8$) : E$>$ 0.025 GeV
  - photon from endcap ($0.86 < |\cos\theta| < 0.92$): E$>$ 0.05 GeV
  - angle between any charged track is greater than 10°
  - $N_\gamma \geq 2$
- η reconstruction:
  - mass window: $0.40 \leq M_{\gamma\gamma} \leq 0.67$ GeV/c^2
  - mass constraint kinematic fit with $\chi^2 < 100$
- 5C kinematic fit
  - choose the photons with least χ^2
  - $M(\gamma\gamma)$ is constrained to M_η
  - $\chi^2_{5C} < 100$

Event selection

$$e^+e^- \to \phi\eta', \eta' \to \eta\pi^+\pi^-, \eta \to \gamma\gamma$$

Event selection

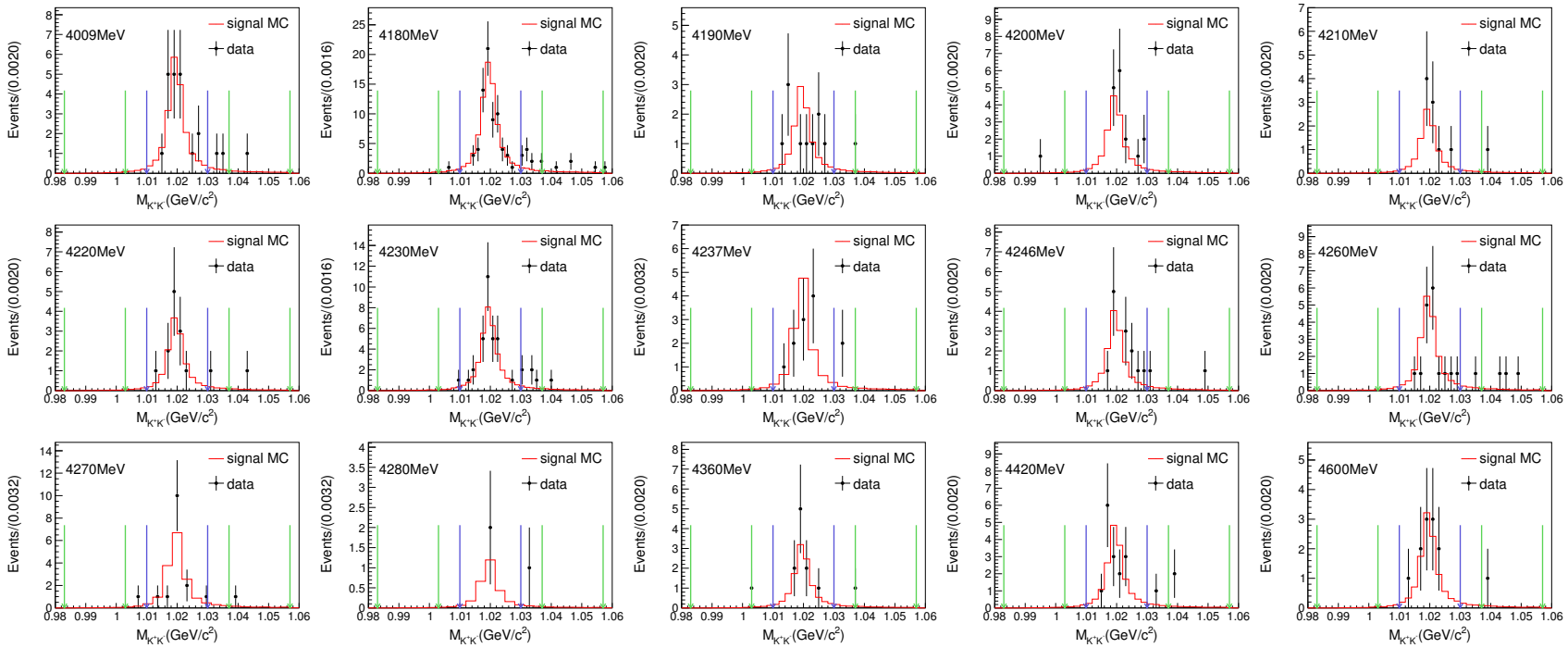
χ^2_{5C} distribution



- $\chi^2_{5C} < 100$

Event selection

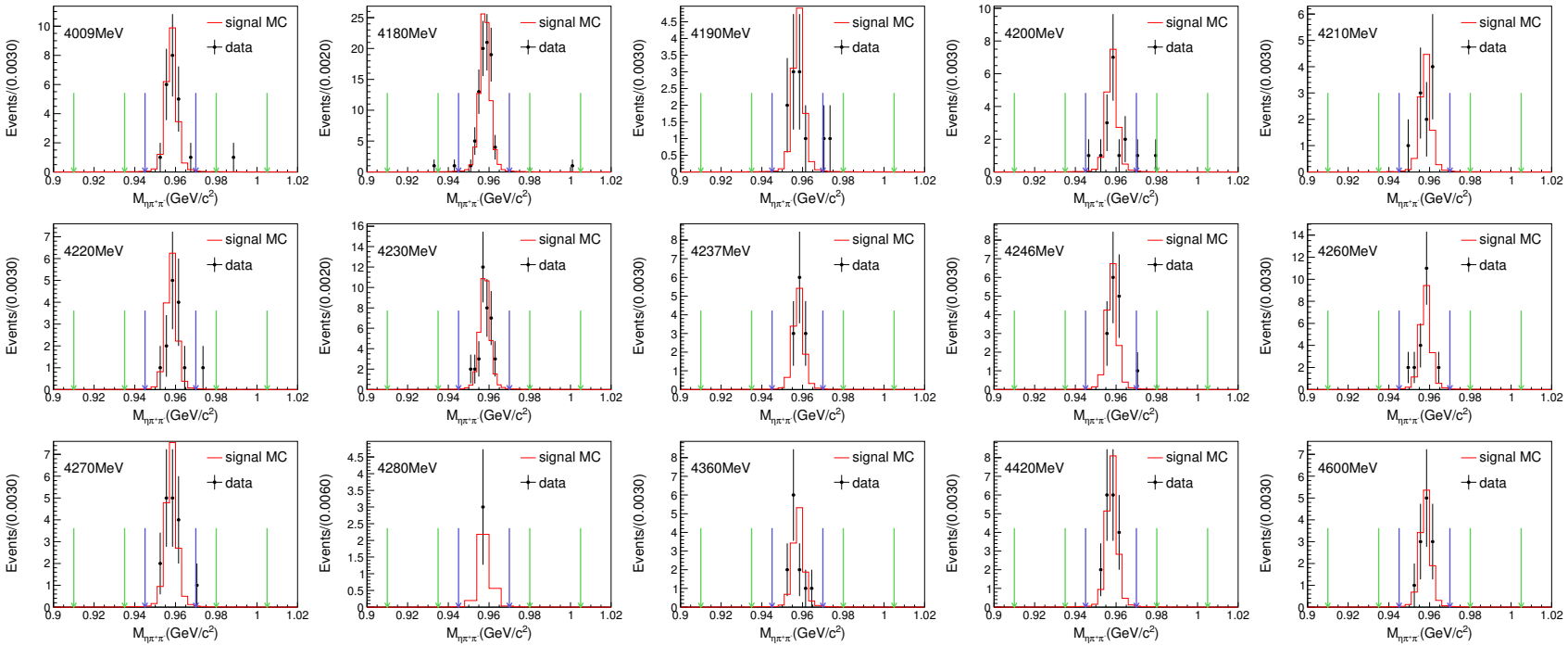
the distribution of invariant mass of ϕ



- signal region: $M_{K^+K^-} \in (1.010, 1.030)$ GeV/c^2
- sideband: $M_{K^+K^-} \in (0.983, 1.003) \cup (1.037, 1.057)$ GeV/c^2

Event selection

the distribution of invariant mass of η'



- signal region: $M_{\eta\pi^+\pi^-} \in (0.945, 0.970)$ GeV/c^2
- sideband: $M_{\eta\pi^+\pi^-} \in (0.910, 0.935) \cup (0.980, 1.005)$ GeV/c^2

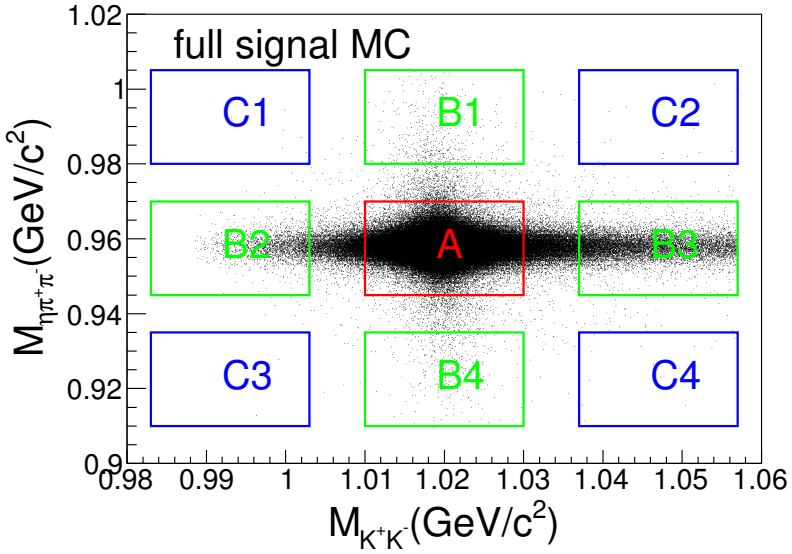
Background check from Inclusive MC

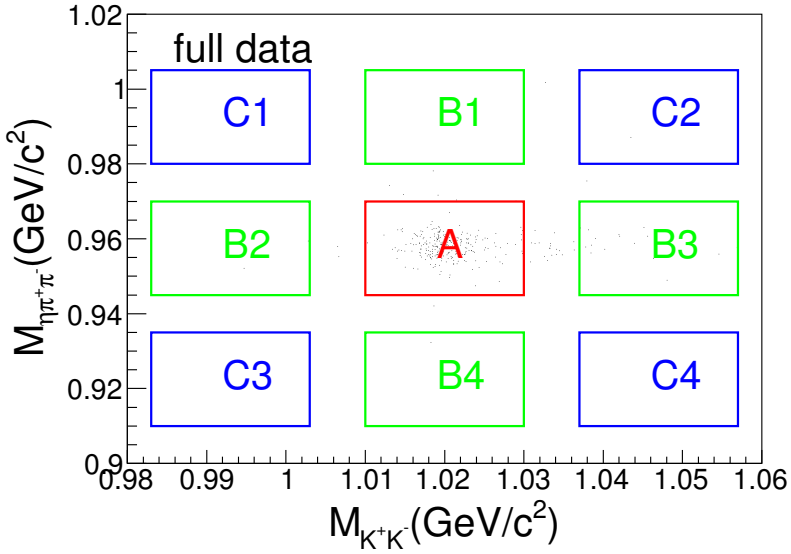
- Signal observable is defined as the invariant mass of ϕ and η', which all in their signal region
- No peak background exist in signal region
- After all selections, there is no events in Inclusive MC

cut: $M_\phi \in (0.983, 1.057)$ GeV/c^2 $\cap M_{\eta'} \in (0.910, 1.005)$ GeV/c^2 $\cap\ \chi^2_{5C} < 100$

Event selection

2D scatter





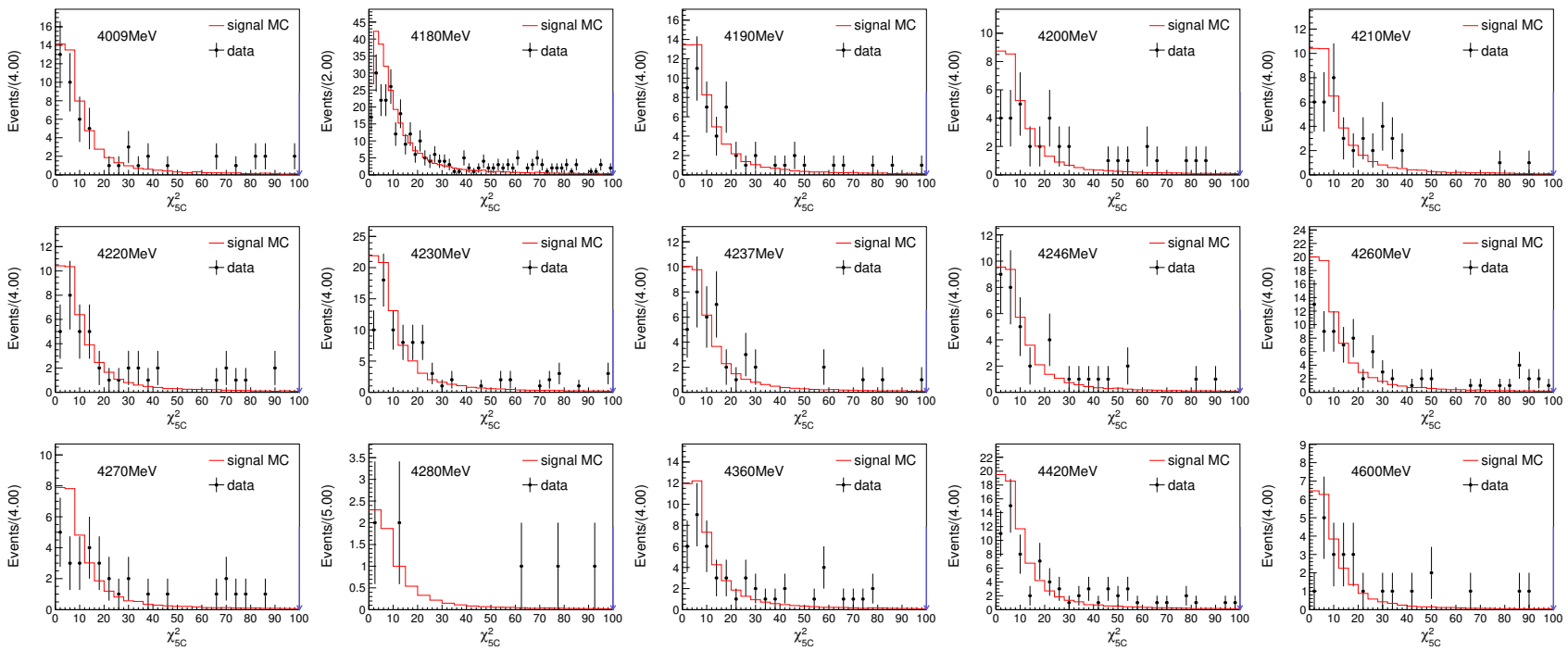
- A: $\phi\eta'$ + ϕ non-η' + non-ϕ η' + non-ϕ non-η'
- B_1, B_4: ϕ non-η' + non-ϕ non-η'
- B_2, B_3: non-ϕ η' + non-ϕ non-η'
- C_1, C_2,C_3, C_4: non-ϕ non-η'

$$N^{sig} = N_A - 0.5N_B + 0.25N_C$$

$$e^+e^- \to \phi\eta', \eta' \to \gamma\pi^+\pi^-$$

Event selection

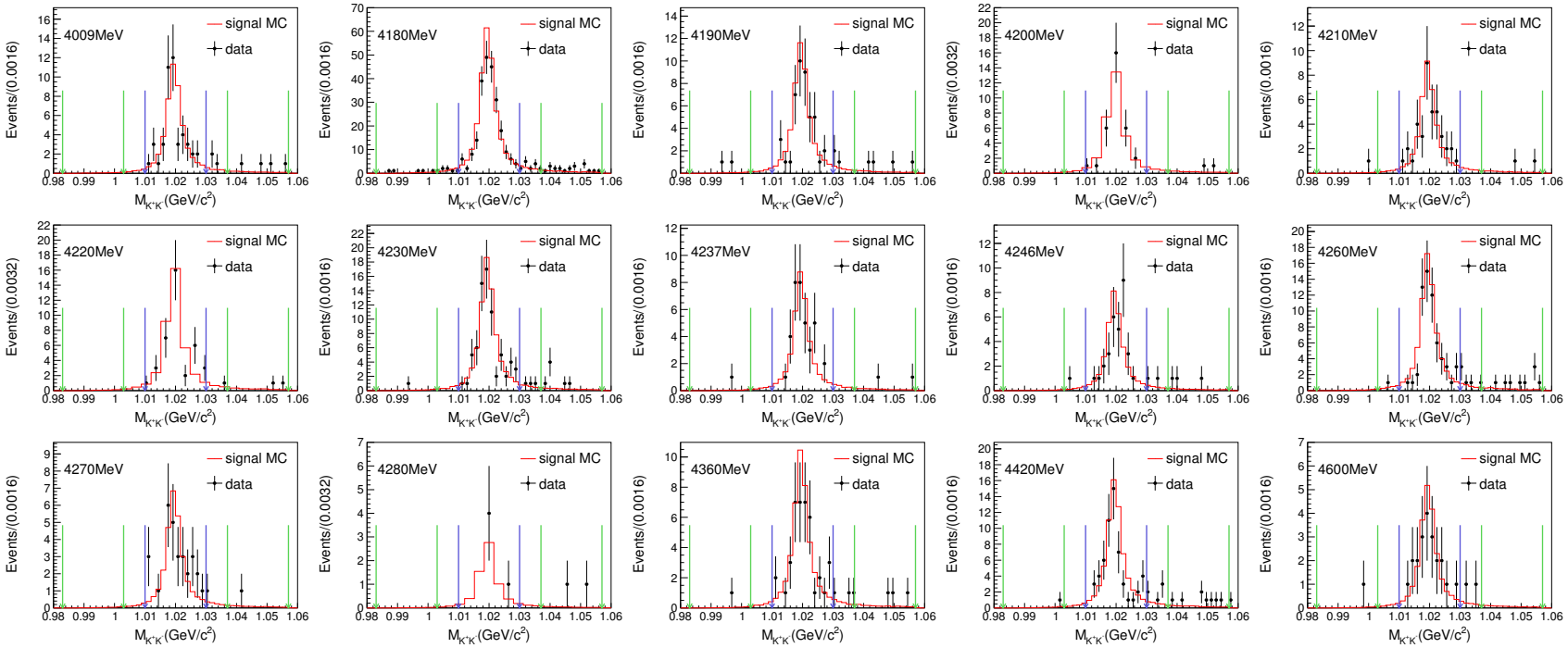
χ^2_{5C} distribution



- $\chi^2_{5C} < 100$

Event selection

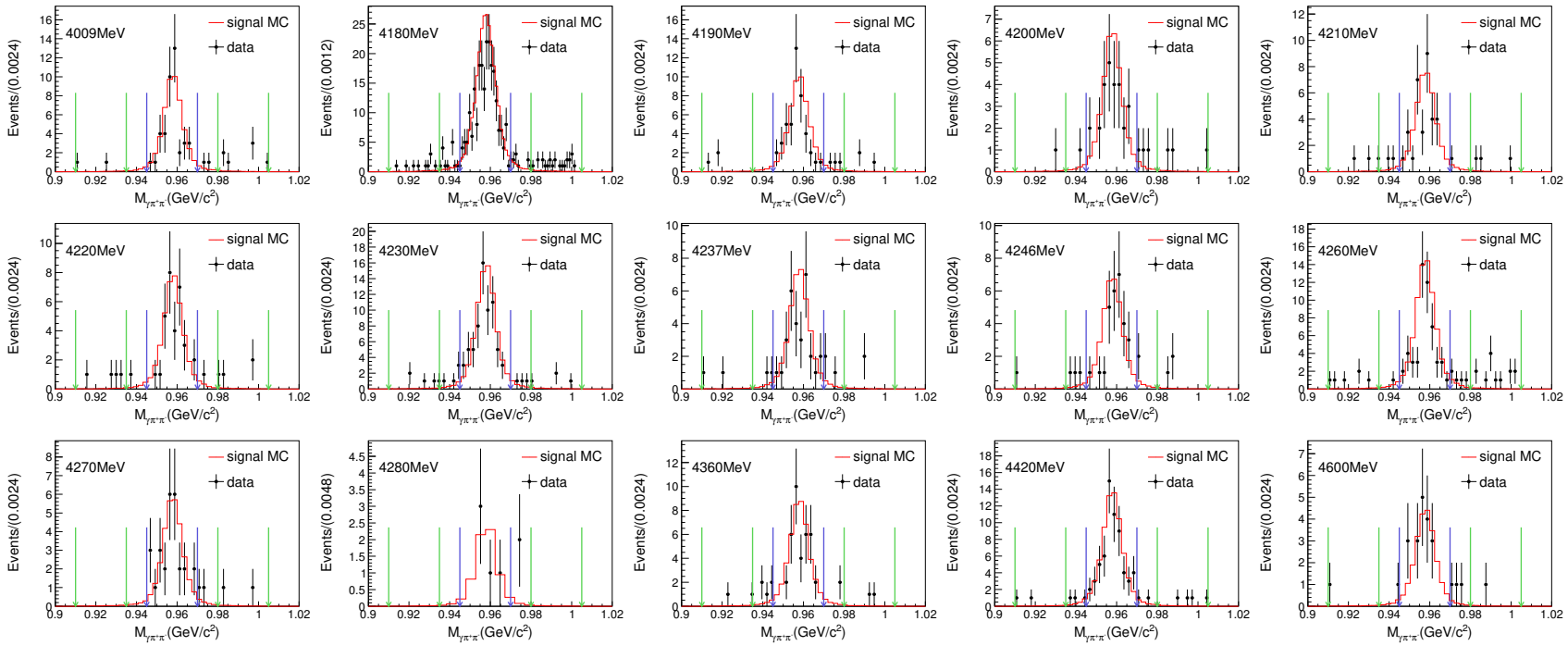
the distribution of invariant mass of ϕ



- signal region: $M_{K^+K^-} \in (1.010, 1.030)$ GeV/c^2
- sideband: $M_{K^+K^-} \in (0.983, 1.003) \cup (1.037, 1.057)$ GeV/c^2

Event selection

the distribution of invariant mass of η'



- signal region: $M_{\gamma\pi^+\pi^-} \in (0.945, 0.970)$ GeV/c^2
- sideband: $M_{\gamma\pi^+\pi^-} \in (0.910, 0.935) \cup (0.980, 1.005)$ GeV/c^2

Background check from Inclusive MC

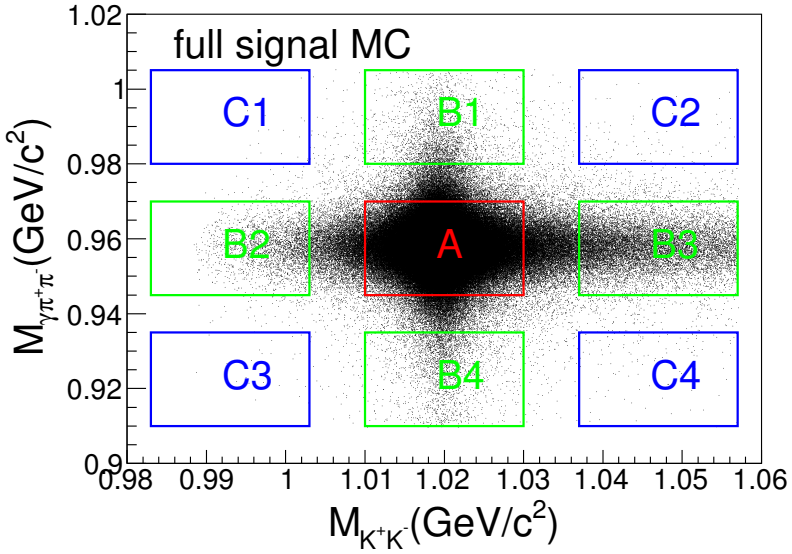
No.	Decay Chain	Final States	Event Number
0	$e^+e^- \to \eta' K^+K^-, \eta' \to \rho^0\gamma, \rho^0 \to \pi^+\pi^-$	$K^-\pi^-\gamma\pi^+K^+$	1
1	$e^+e^- \to \eta' K^+K^-, \eta' \to \rho^0\gamma, \rho^0 \to \pi^+\pi^-$	$K^-\pi^-\gamma\pi^+K^+$	1
2	$e^+e^- \to \eta' K^+K^-, \eta' \to \rho^0\gamma, \rho^0 \to \pi^+\pi^-$	$K^-\pi^-\gamma\pi^+K^+$	1
3	$e^+e^- \to K^+\rho^0\pi^0K^-, \rho^0 \to \pi^+\pi^-, \pi^0 \to \gamma\gamma$	$K^-\pi^-\gamma\gamma\pi^+K^+$	1
4	$e^+e^- \to K^+\pi^+\pi^0\pi^-K^-, \pi^0 \to \gamma\gamma$	$K^-\pi^-\gamma\gamma\pi^+K^+$	1
5	$e^+e^- \to K^+\pi^+\rho^-K^-, \rho^- \to \pi^0\pi^-, \pi^0 \to \gamma\gamma$	$K^-\pi^-\gamma\gamma\pi^+K^+$	1
6	$e^+e^- \to K^{*0}\pi^+\pi^0K^-, K^{*0} \to K^+\pi^-, \pi^0 \to \gamma\gamma$	$K^-\pi^-\gamma\gamma\pi^+K^+$	1
7	$e^+e^- \to K^+\pi^+\rho^-K^-, \rho^- \to \pi^0\pi^-, \pi^0 \to \gamma\gamma$	$K^-\pi^-\gamma\gamma\pi^+K^+$	1

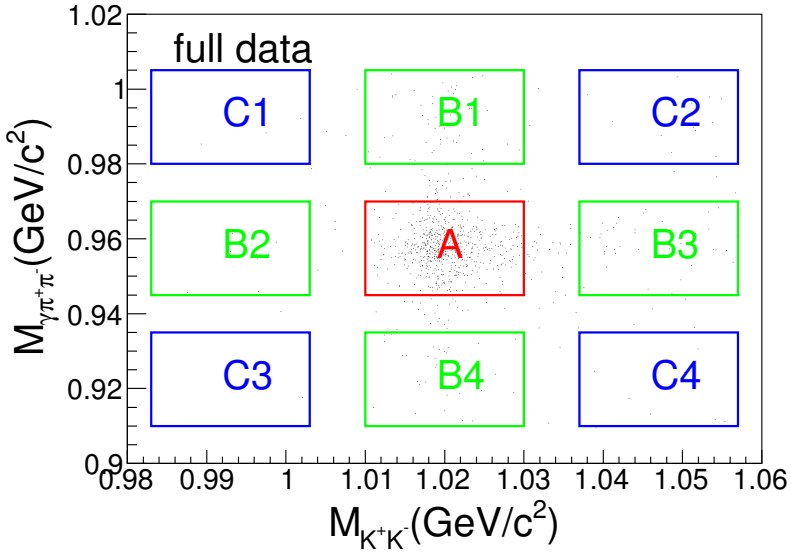
- Signal observable is defined as the invariant mass of ϕ and η', which all in their signal region
- No peak background in signal region
- After all selections, the background level is very low

cut: $M_\phi \in (0.983, 1.057)$ GeV/c^2 $\cap M_{\eta'} \in (0.910, 1.005)$ GeV/c^2 $\cap\ \chi^2_{5C} < 100$

Event selection

2D scatter



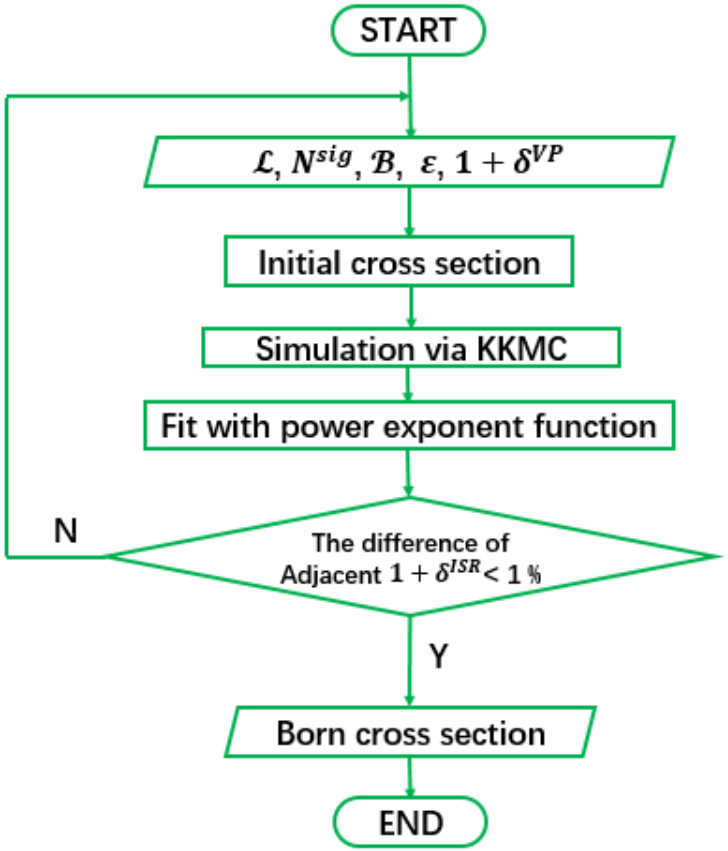


- A: $\phi\eta'$ + ϕ non-η' + non-ϕ η' + non-ϕ non-η'
- B_1, B_4: ϕ non-η' + non-ϕ non-η'
- B_2, B_3: non-ϕ η' + non-ϕ non-η'
- C_1, C_2,C_3, C_4: non-ϕ non-η'

$$N^{sig} = N_A - 0.5N_B + 0.25N_C$$

Cross section of $e^+e^- \to \phi\eta'$

$$\sigma_B(e^+e^- \to \phi\eta') = \frac{N_1^{sig}+N_2^{sig}}{L_{int}\cdot(1+\delta^{ISR})\cdot(1+\delta^{VP})\cdot B(\phi\to K^+K^-)[\cdot B(\eta'\to\eta\pi^+\pi^-)\cdot B(\eta\to\gamma\gamma)\cdot\epsilon_1+B(\eta'\to\gamma\pi^+\pi^-)\cdot\epsilon_2]} \quad *$$



- N_1^{sig}, N_2^{sig}: obtained from data scatter plot counting
- L_{int}: determined from Bhabha events
- ϵ_1, ϵ_2: obtained from exclusive MC scatter plot counting
- $B(\phi \to K^+K^-)$: 48.9% (PDG)
- $B(\eta' \to \eta\pi^+\pi^-)$: 42.6%(PDG)
- $B(\eta' \to \gamma\pi^+\pi^-)$: 28.9%(PDG)
- $B(\eta \to \gamma\gamma)$: 39.41%(PDG)
- $1+\delta^{VP}$: based on Fred Jegerlehner's alphaQED
- $1+\delta^{ISR}$: obtained from cross section iteration via KKMC

* Values with subscripts 1 and 2 are corresponding value for $\eta' \to \eta\pi^+\pi^-$ and $\eta' \to \gamma\pi^+\pi^-$ respectively

Cross section of $e^+e^- \to \phi\eta'$

$\sqrt{s}$(GeV)	$\epsilon_1(\%)$	$\epsilon_2(\%)$	N_1^{signal}	N_2^{signal}	$1+\delta^{ISR}$	$1+\delta^{VP}$	σ_B(pb)
4.009	17.67	20.58	19.3 ± 4.4	32.0 ± 6.2	0.901	1.0441	$2.59 \pm 0.53 \pm 0.17$
4.180	16.38	19.03	66.5 ± 8.5	168.3 ± 14.2	0.951	1.0545	$1.82 \pm 0.17 \pm 0.12$
4.190	16.12	19.01	9.0 ± 3.0	35.0 ± 6.3	0.955	1.0562	$2.08 \pm 0.44 \pm 0.14$
4.200	16.37	18.97	13.5 ± 3.8	25.5 ± 5.2	0.955	1.0570	$1.83 \pm 0.42 \pm 0.12$
4.210	15.91	18.47	8.5 ± 3.0	28.3 ± 5.7	0.956	1.0569	$1.79 \pm 0.43 \pm 0.12$
4.220	15.97	18.61	10.5 ± 3.4	25.3 ± 5.6	0.958	1.0566	$1.74 \pm 0.43 \pm 0.11$
4.230	16.22	18.96	32.5 ± 5.8	48.8 ± 7.7	0.961	1.0566	$1.90 \pm 0.32 \pm 0.12$
4.237	16.07	18.79	10.0 ± 3.2	25.8 ± 5.4	0.958	1.0557	$1.68 \pm 0.40 \pm 0.11$
4.246	16.08	18.74	12.5 ± 3.6	26.5 ± 5.3	0.960	1.0558	$1.80 \pm 0.41 \pm 0.12$
4.260	16.21	19.01	15.5 ± 4.2	41.5 ± 7.1	0.967	1.0537	$1.69 \pm 0.34 \pm 0.11$
4.270	16.10	18.34	13.5 ± 3.8	23.5 ± 5.1	0.969	1.0534	$1.75 \pm 0.42 \pm 0.11$
4.280	15.75	18.04	2.0 ± 1.4	2.0 ± 1.9	0.972	1.0532	$0.58 \pm 0.48 \pm 0.04$
4.360	15.44	18.25	9.5 ± 3.2	29.0 ± 5.8	0.987	1.0514	$1.79 \pm 0.42 \pm 0.12$
4.420	15.26	17.93	14.0 ± 3.9	47.0 ± 7.4	0.992	1.0527	$1.50 \pm 0.28 \pm 0.10$
4.600	14.53	16.73	10.5 ± 3.4	13.5 ± 4.0	1.026	1.0549	$1.10 \pm 0.34 \pm 0.07$

Systematic uncertainties (I)

- Luminosity(BAM-157 and BAM-218)
  - 1% for luminosity
  - we consider these values to be uncorrelated between the energies
- Tracking efficiency[1,2]
  - 1% for every charged track reconstructed $\rightarrow 4\%$
- PID[1,2]
  - 1% for every charged track PID $\rightarrow 4\%$
- Photon efficiency[3]
  - 1% for per photon reconstructed

[1] https://docbes3.ihep.ac.cn/ charmoniumgroup/images/8/89/PID_for_kaon.pdf

[2] https://docbes3.ihep.ac.cn/ charmoniumgroup/images/c/ce/Liujie_track_and_pid_efficiency.pdf

[3] BESIII Collaboration, M. Ablikim et al., Phys. Rev. D81 (2010) 052005

Systematic uncertainties (II)

- η reconstruction[3]
  - 1% for the reconstruction of η from the two photons mode $\rightarrow$ 1%
- Kinematic fit
  - To correct the track helix parameters to check the difference between data and MC, we take the difference before and after this correction as systematic uncertainties
- ISR
  - As we use recursion method to get the value of ISR factor, and the finish condition of the recursion is that the changes of the Born cross section is smaller than 1.0% between two recursions, 1.0% is taken as the systematical uncertainty from the evaluation of ISR factor

[3] BESIII Collaboration, M. Ablikim et al., Phys. Rev. D81 (2010) 052005

Systematic uncertainties (III)

- VP factor
  - The uncertainty of the $(1+\delta^{VP})$ is smaller than 0.1% and can be ignored
- Mass window selection
  - Varying signal mass window of ϕ, η' and sideband mass window, the difference between before and after this change is taken as systematic uncertainty

Summary of systematic uncertainties

- Since the main uncertainties comes from the statistical uncertainty, we assign identical error for all energy points about the corresponding item of systematic uncertainties, i.e., the largest data sample at 4.180 GeV. The total systematic uncertainty is the sum of them in quadrature.

sources	Relative error(%)	
	$\eta' \to \eta\pi^+\pi^-$	$\eta' \to \gamma\pi^+\pi^-$
Luminosity(pb^{-1})	1.0	1.0
Tracking	4.0	4.0
PID	4.0	4.0
Photon	2.0	1.0
Kinematic fit	0.7	1.8
ISR factor	1.0	1.0
η reconstruction	1.0	-
Mass window of ϕ	0.3	0.3
Mass window of η'	0.6	0.7
Sideband	0.5	0.7
$B_r(\phi \to K^+K^-)$	1.0	1.0
$B_r(\eta' \to \eta\pi^+\pi^-)$	1.6	-
$B_r(\eta' \to \gamma\pi^+\pi^-)$	-	1.7
$B_r(\eta \to \gamma\gamma)$	0.5	-
Total	6.6	6.6

Combing systematic uncertainties (I)

- Covariance matrix $V(\mathbf{Y})$: $V(\mathbf{Y}) = SV(\mathbf{X})S^T$,where

$$S = \begin{pmatrix} \frac{\partial Y_1}{\partial X_1} & \frac{\partial Y_1}{\partial X_2} & \cdots \frac{\partial Y_1}{\partial X_n} \\ \frac{\partial Y_2}{\partial X_1} & \frac{\partial Y_2}{\partial X_2} & \cdots \frac{\partial Y_2}{\partial X_n} \\ \vdots & \vdots & \vdots \\ \frac{\partial Y_m}{\partial X_1} & \frac{\partial Y_m}{\partial X_2} & \cdots \frac{\partial Y_m}{\partial X_n} \end{pmatrix}$$

- Born cross section $\sigma_B = \frac{N_1^{sig}+N_2^{sig}}{A\cdot(w_1+w_2)}$
  - A: common coefficient
  - the weight factor of systematic uncertainty: w_1 and w_2
  - w_1: $B(\eta' \to \eta\pi^+\pi^-) \cdot B(\eta \to \gamma\gamma) \cdot \epsilon_1$
  - w_2: $B(\eta' \to \gamma\pi^+\pi^-) \cdot \epsilon_2$
- $N_1^{sig} = A \cdot w_1 \cdot \sigma_1^B$, $N_2^{sig} = A \cdot w_2 \cdot \sigma_2^B$
- the total cross section can be written as: $\frac{w_1\cdot\sigma_1^B+w_2\cdot\sigma_2^B}{w_1+w_2}$

Combing systematic uncertainties (II)

- the ith systematic uncertainties δ^i_{sum} are combined by:

$$(\delta^i_{sum})^2 = \begin{pmatrix} \frac{w_1}{w_1+w_2} & \frac{w_2}{w_1+w_2} \end{pmatrix} \begin{pmatrix} V^i_{11} & V^i_{12} \\ V^i_{21} & V^i_{22} \end{pmatrix} \begin{pmatrix} \frac{w_1}{w_1+w_2} \\ \frac{w_2}{w_1+w_2} \end{pmatrix} = w_1^2 V^i_{11} + w_2^2 V^i_{22} + 2 w_1 w_2 V^i_{12}$$

$$\delta^i_{sum} = \frac{\sqrt{(w_1\delta^i_1)^2 + (w_2\delta^i_2)^2 + 2w_1w_2\rho^i_{12}\delta^i_1\delta^i_2}}{w_1 + w_2}$$

  - $V^i_{km} = \rho^i_{km}\delta^i_k\delta^i_m$
  - ρ^i_{km}: the correlation coefficient for the ith item system systematic uncertainties
  - δ^i_k or δ^i_m: the kth or mth column raw systematic uncertainty
  - For luminosity, tracking, PID, photon, kinematic fit, ISR factor, ϕ mass window, the $\rho^i_{12} = 1$, and the others is 0

- Finally, the combined systematic uncertainty δ_{sum} is :

$$\delta_{sum} = \sqrt{\sum (\delta^i_{sum})^2}$$

The summary of combined systematic uncertainties

sources	Relative error(%)	Energy dependence
Luminosity(pb^{-1})	1.0	Yes
Tracking	4.0	No
PID	4.0	No
Photon	1.3	No
Kinematic fit	1.4	No
ISR factor	1.0	Yes
η reconstruction	0.3	No
Mass window of ϕ	0.3	No
Mass window of η'	0.5	No
Sideband	0.5	No
$B_r(\phi \to K^+K^-)$	1.0	No
$B_r(\eta' \to \eta\pi^+\pi^-)$	0.5	No
$B_r(\eta' \to \gamma\pi^+\pi^-)$	1.1	No
$B_r(\eta \to \gamma\gamma)$	0.2	No
Total	6.4	-

Upper limit for $e^+e^- \to Y(4260) \to \phi\eta'$ (I)

- the least square method
- likelihood ratio ordering method
- unbiased χ^2 estimator for linear function fit involving correlated data
  - δ_c: the common part of the relative systematical uncertainty of Born cross section
  - δ_i: the individual part of the total uncertainty of Born cross section at each energy point

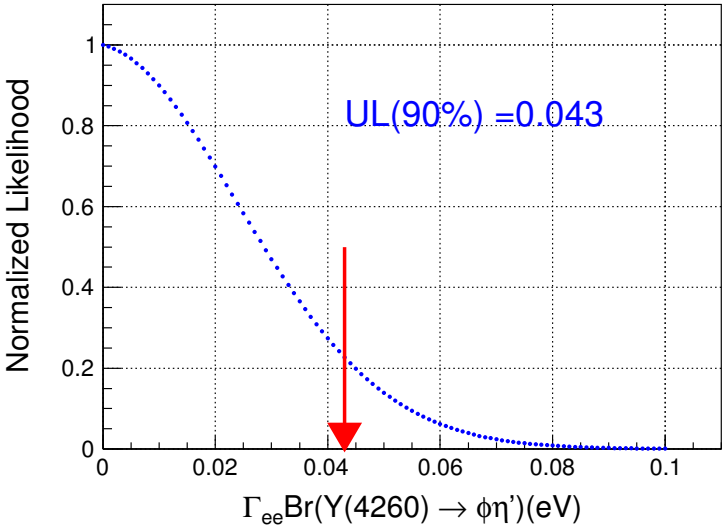
$$Q^2 = \sum_i \frac{(\sigma_{B_i} - h \cdot \sigma_{B_i}^{fit})^2}{\delta_i^2} + \frac{(h-1)^2}{\delta_c^2}$$

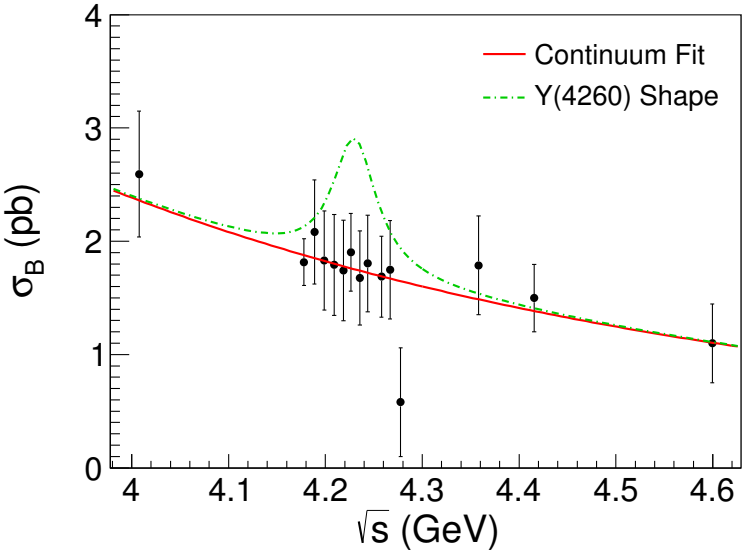
  - $L = e^{-0.5Q^2}$
- model of flat continuum and relativistic Breit-Wigner:
  - $\Gamma_{tot}\Gamma_{ee} \times \mathcal{B}(Y(4260) \to \phi\eta')$ treated as one parameter

$$\sigma_{e^+e^- \to \phi\eta'}(\sqrt{s}) = c_0 \cdot \sigma_{cont}(\sqrt{s}) + 12\pi \frac{\Gamma_{tot}\Gamma_{ee} \times \mathcal{B}(Y(4260) \to \phi\eta')}{(s - m_0^2)^2 + m_0^2\Gamma_{tot}^2}$$

  - continuum process: $\sigma_{cont}(\sqrt{s}) = \frac{p_0}{\sqrt{s}^{p_1}}$

Upper limit for $e^+e^- \to Y(4260) \to \phi\eta'$ (II)





- The largest one from these upper limit results correspond to different Y(4260) mass and width combinations is taken as the final upper limit
- $p_0 = (4.94 \pm 14.70) \times 10^3$(pb)(GeV)^{p_1} , $p_1 = 5.51 \pm 2.06$
- green dash-dotted lines are the MC shape of the Y(4260) with an arbitrary scale factor

$\Gamma_{ee} \times \mathcal{B}(Y(4260) \to \phi\eta') <$ 0.04 eV @ 90% (C.L.)

Summary

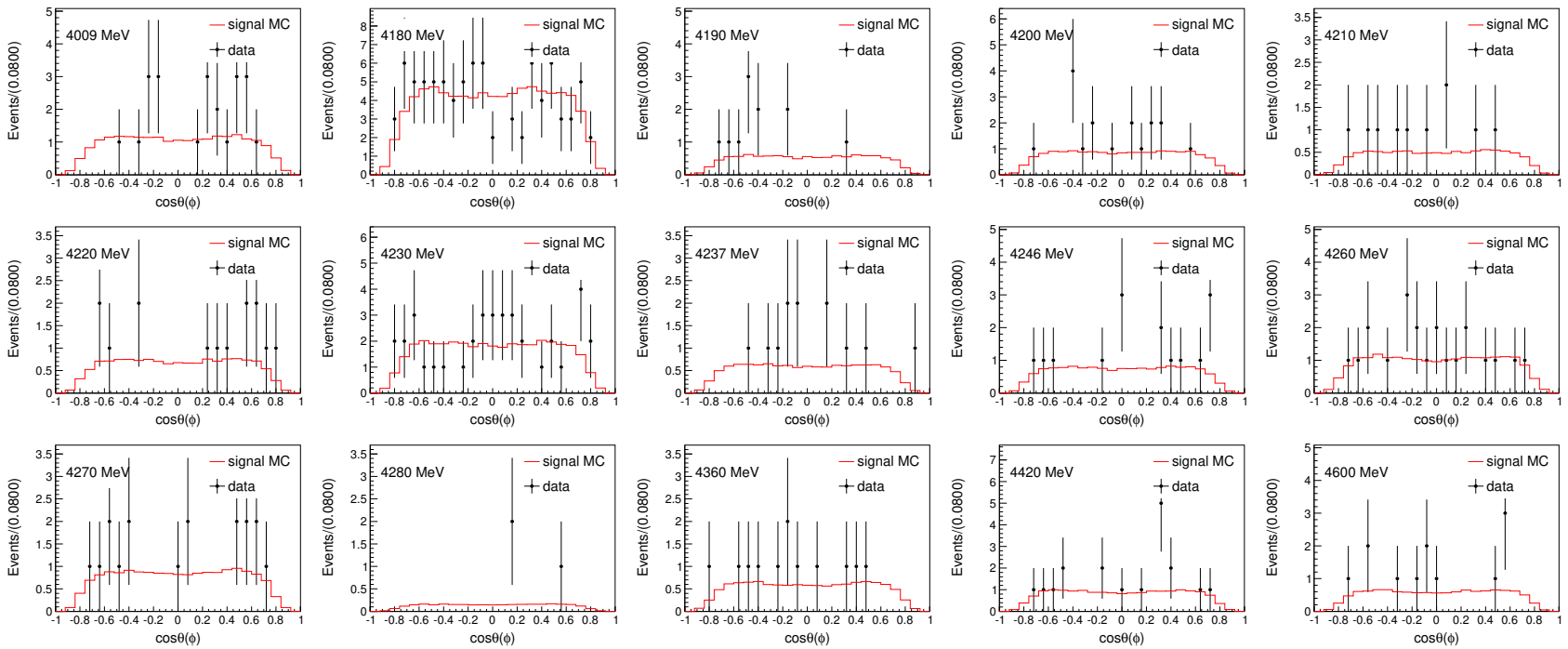
- We measured the cross sections line shape of $e^+e^- \to \phi\eta'$ in the region of energies above 4.0 GeV;
- An upper limit on $\Gamma_{ee} \times \mathcal{B}(Y(4260) \to \phi\eta')$ has determined to be 0.04 eV at the 90% confidence level;
- Memo is being revised.

Thanks for your attention!

Backup

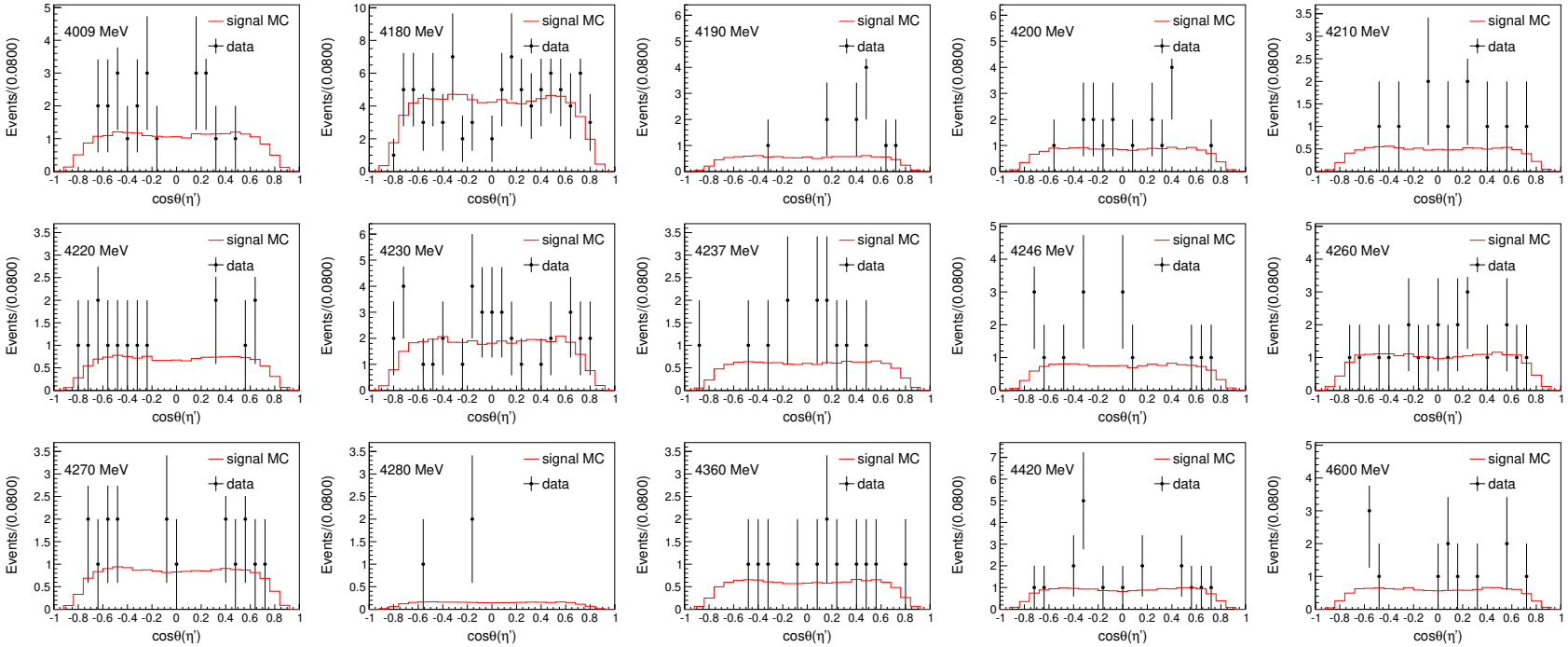
Angular distribution of ϕ

$\eta' \to \eta\pi^+\pi^-$



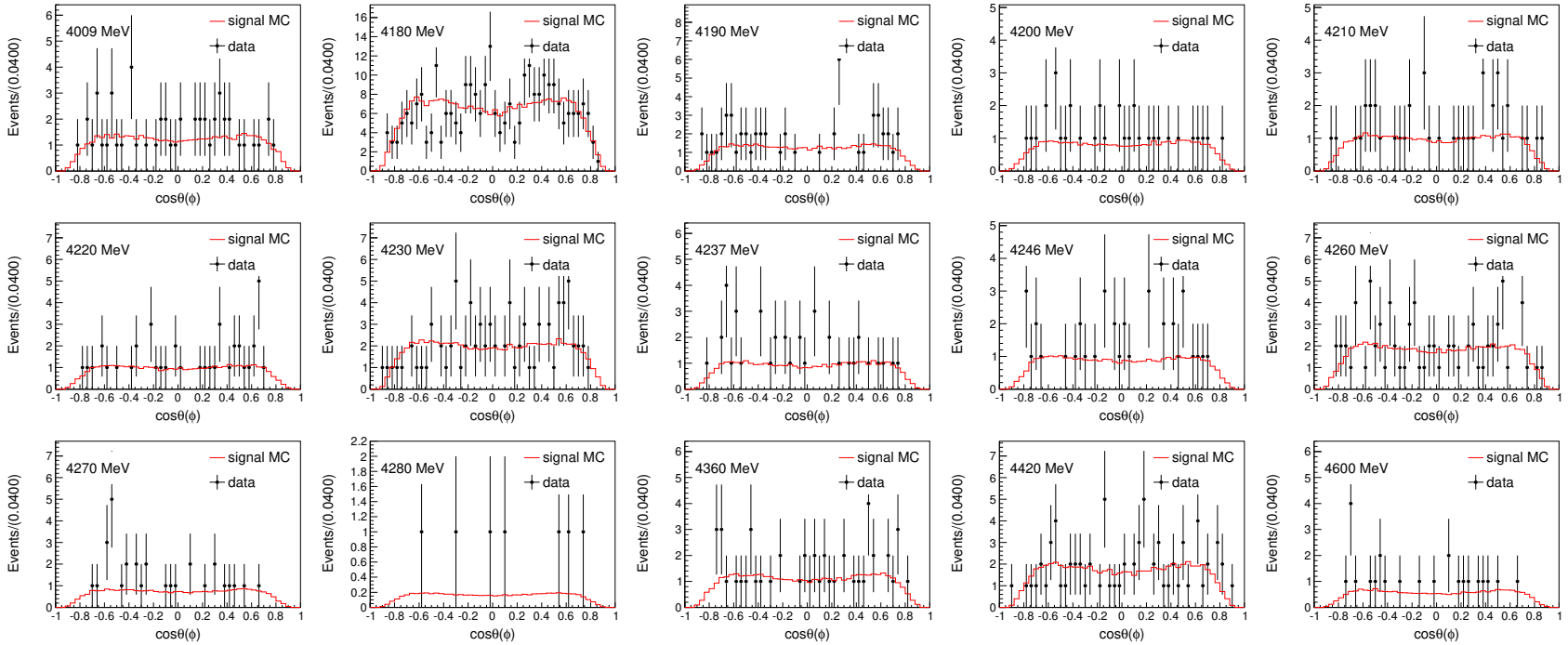
Angular distribution of η'

$\eta' \to \eta\pi^+\pi^-$



Angular distribution of ϕ

$\eta' \to \gamma\pi^+\pi^-$



Angular distribution of η'

$\eta' \to \gamma\pi^+\pi^-$