

# Cross section measurement of $e^+e^- \rightarrow \pi^0\pi^0 h_c$

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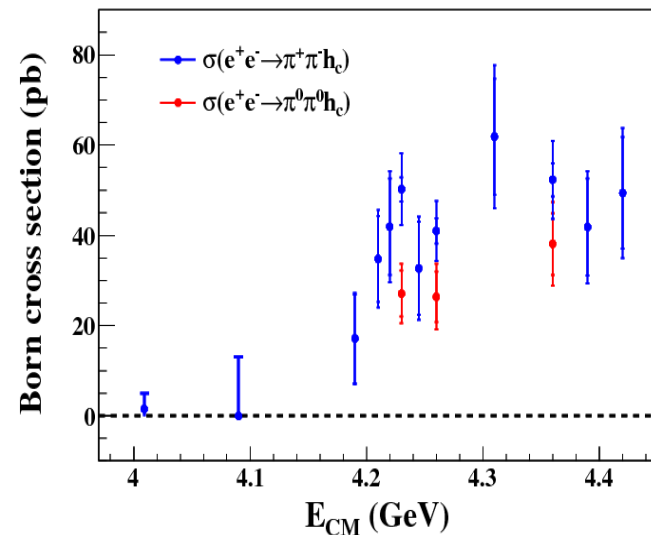
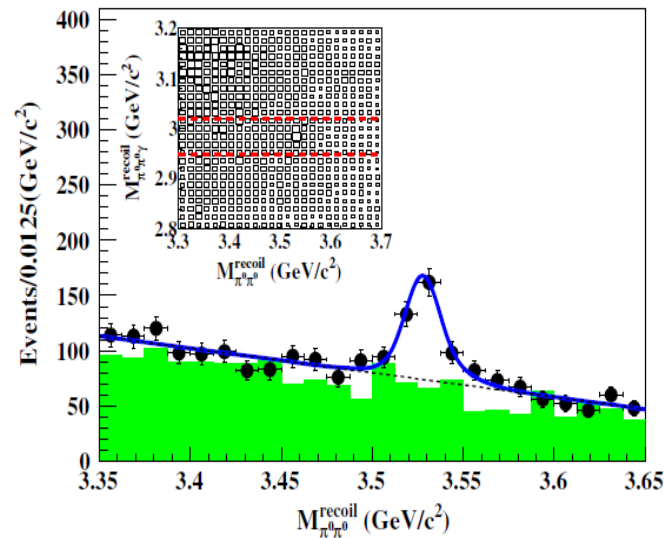
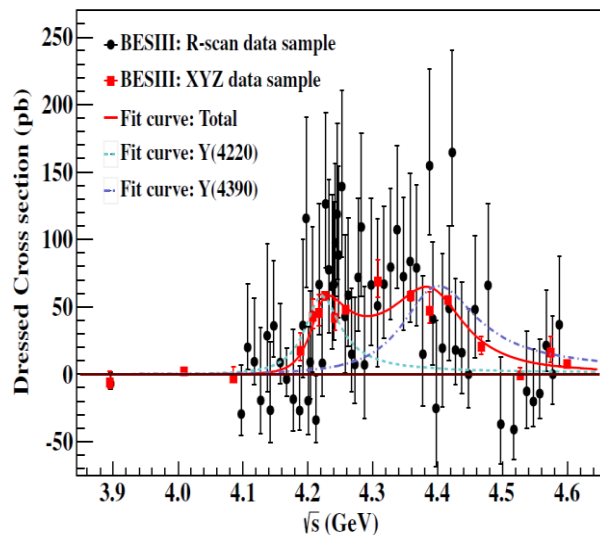
HNNU, IHEP, NKU

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Charmonium group meeting

# Motivation

- ▶ Evidence of Two Resonant Structures,  $Y(4220)$  and  $Y(4390)$ , in the line-shape of  $e^+e^- \rightarrow \pi^+\pi^-h_c$
- ▶ Observation of  $e^+e^- \rightarrow \pi^0\pi^0h_c$  at  $\sqrt{s} = 4.23, 4.26, 4.36$  GeV
- ▶  $\sim 500 \text{ pb}^{-1}$  luminosity data at  $\sqrt{s} = 4.19\text{--}4.28$  GeV in 2017 and  $\sim 3189 \text{ pb}^{-1}$  at 4.180 GeV
- ▶ Give us an opportunity to investigate the line-shape of  $e^+e^- \rightarrow \pi^0\pi^0h_c$
- ▶ Follow up study for the previous work.



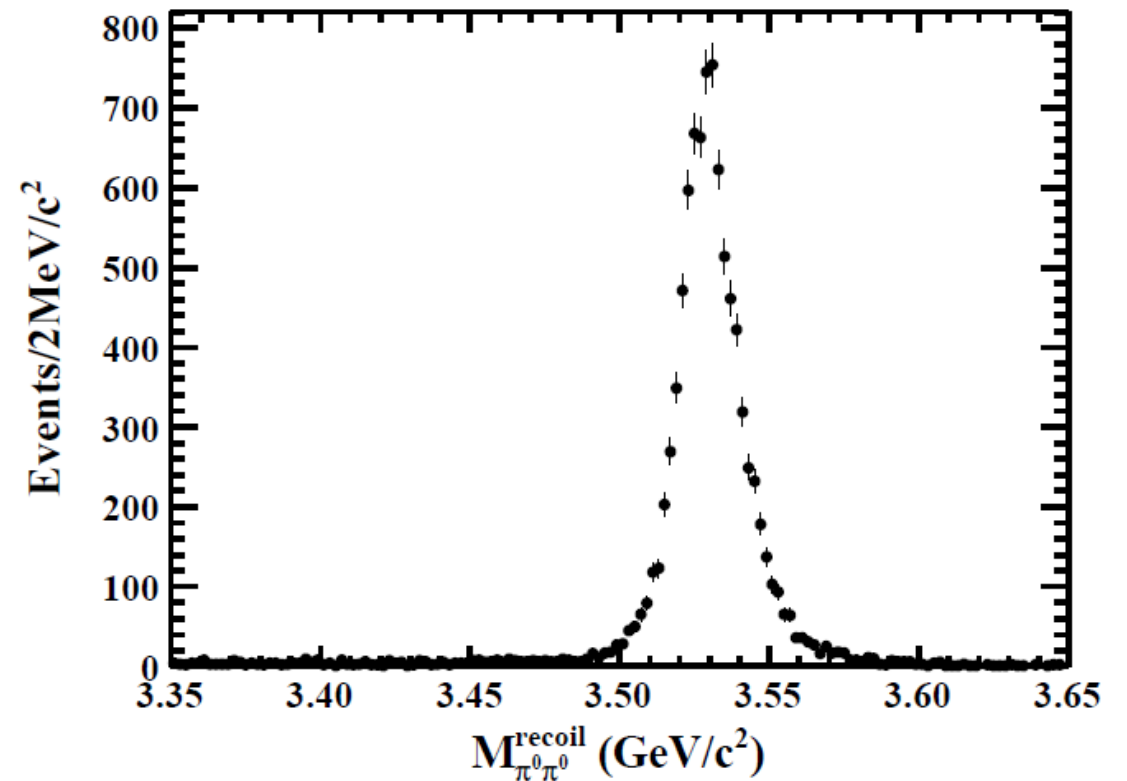
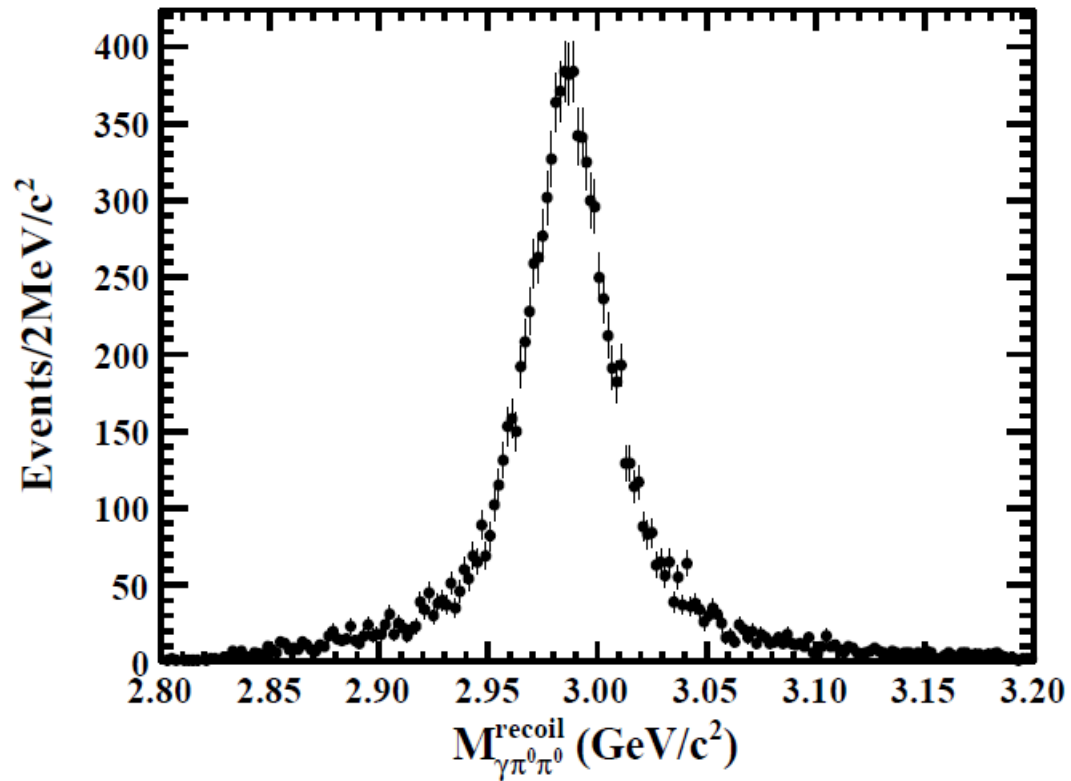
# Datasets

Data sample	$\sqrt{s}$ (GeV)	$\mathcal{L}(pb^{-1})$
4009	4.0076	482.0
4180	4.1783	3189.0
4190	4.1893	512.9
4180	4.1996	523.7
4210	4.2097	511.2
4220	4.2188	508.2
4230	4.2263	1090.0
4237	4.2358	508.9
4246	4.2439	532.7
4260	4.2580	825.7
4270	4.2669	529.3
4280	4.2778	174.5
4360	4.3583	539.8
4420	4.4156	1028.9
4600	4.5995	566.9

**Software environment:**  
BOSS703

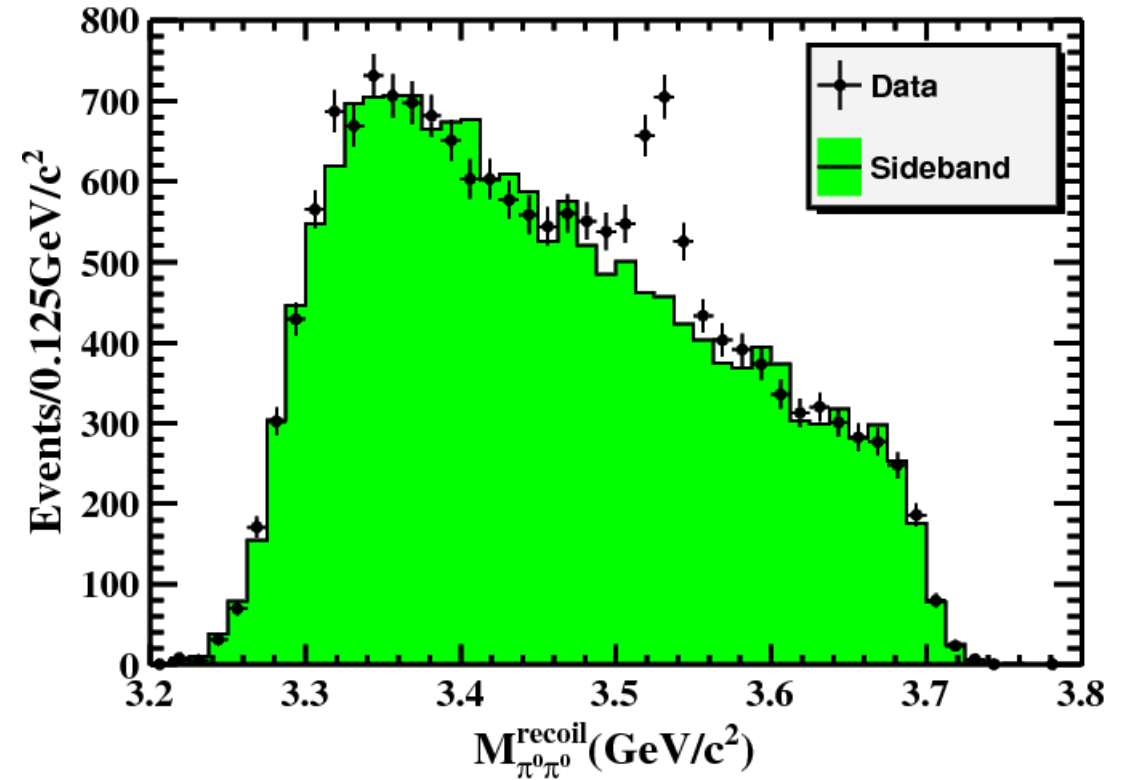
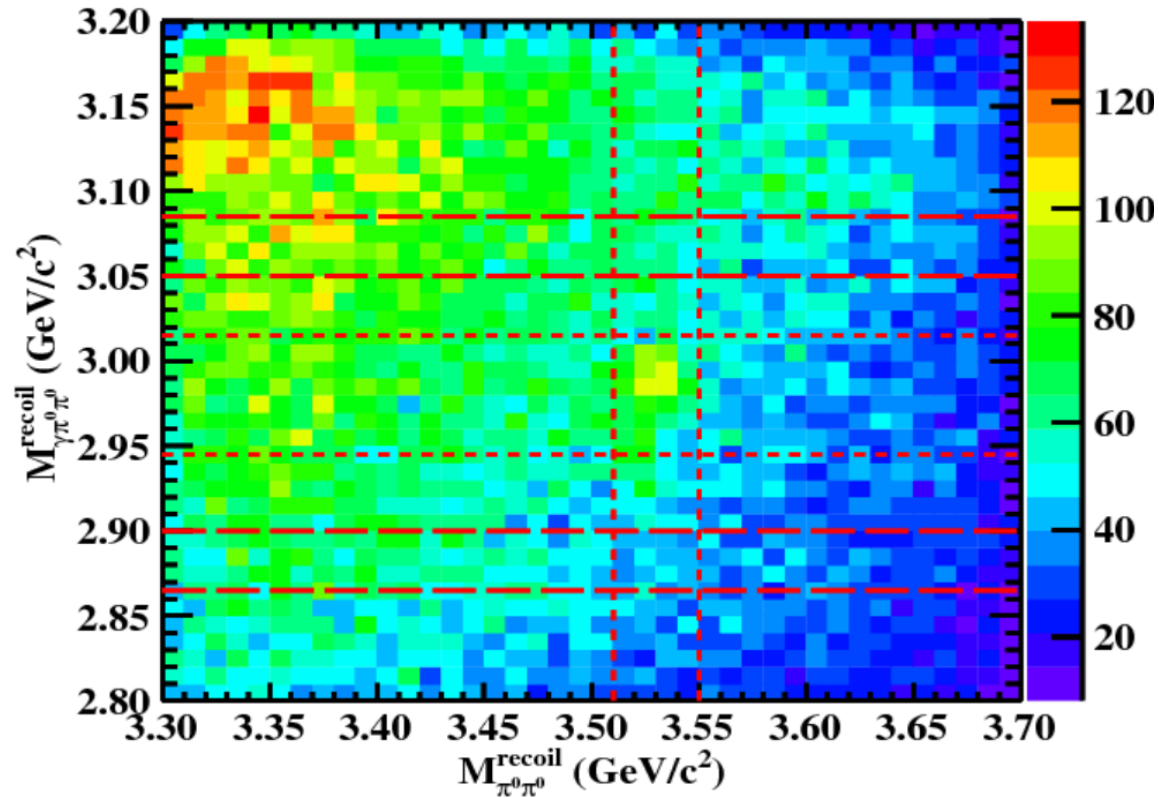
**Signal MC:**  
200K for each  $\eta_c$  mode  
at each Energy Point

Plots in MC simulation summed over 16  $\eta_c$  decay modes at  $\sqrt{s} = 4.2583$  GeV



**Event selection criteria follows the previous work.**

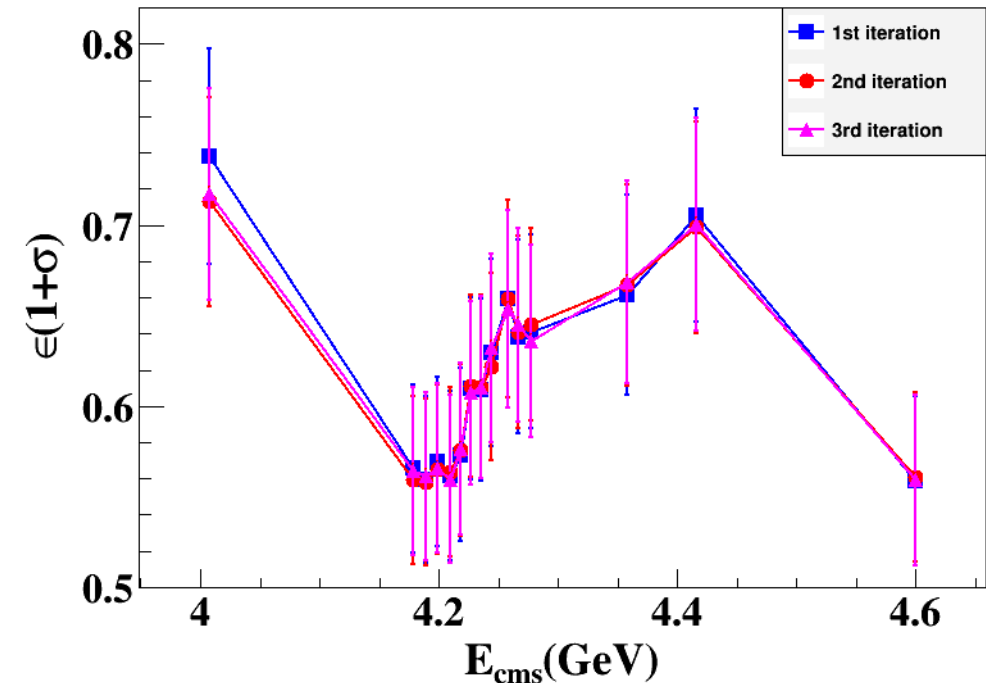
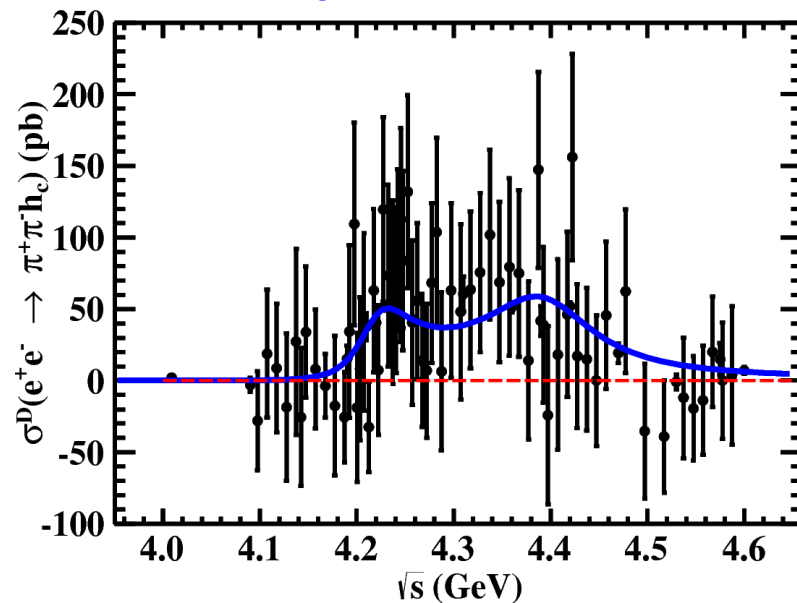
# Plots in data summed over all energy points



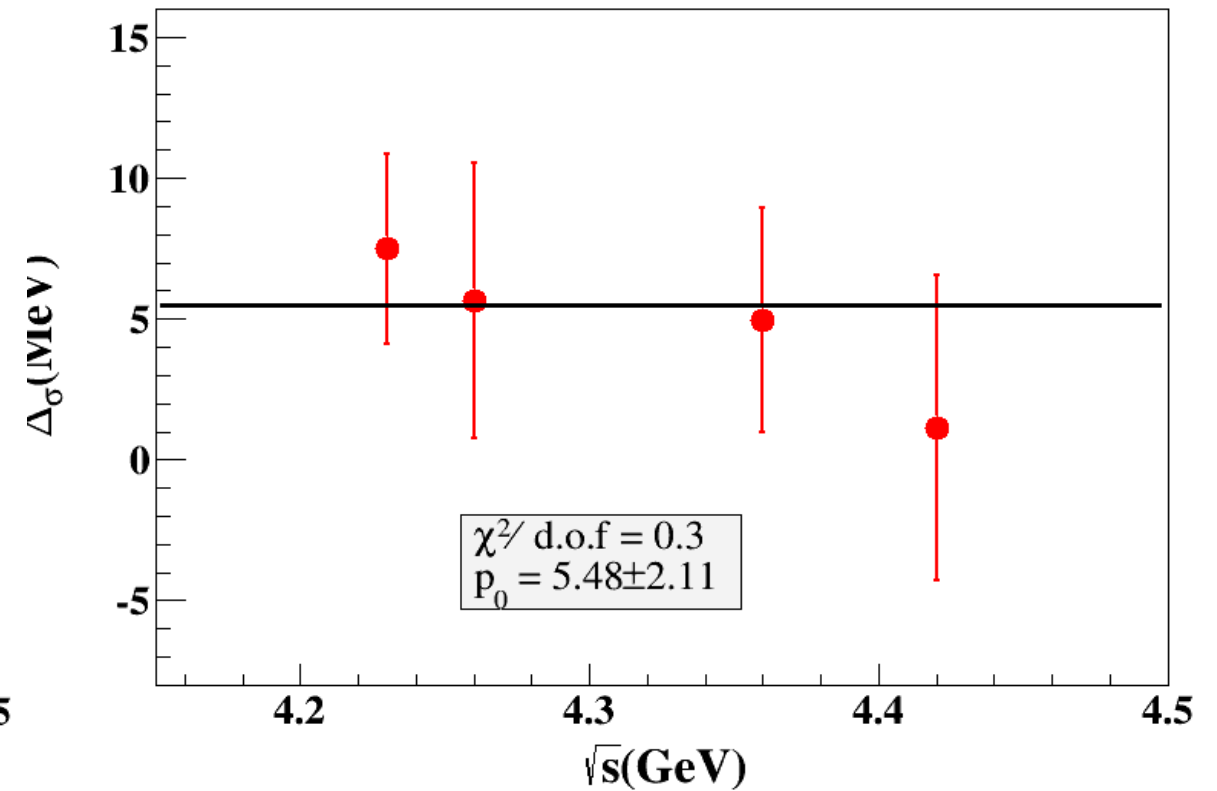
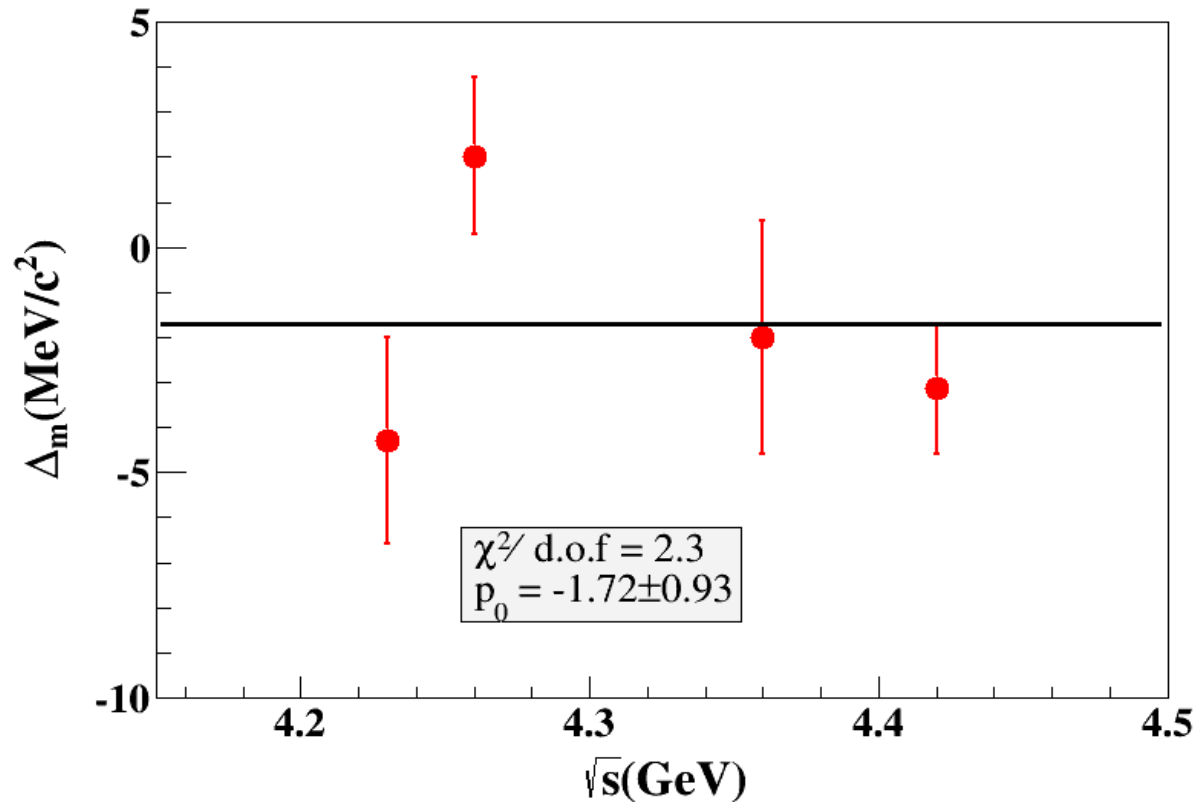
# Detection efficiency

- ▶ Iteration method
- ▶ Initial state radiation correction
- ▶ To be stable

Input the line shape of  $e^+e^- \rightarrow \pi^+\pi^-h_c$   
From  $\pi^0\pi^0h_c$  mass threshold to 4.6 GeV

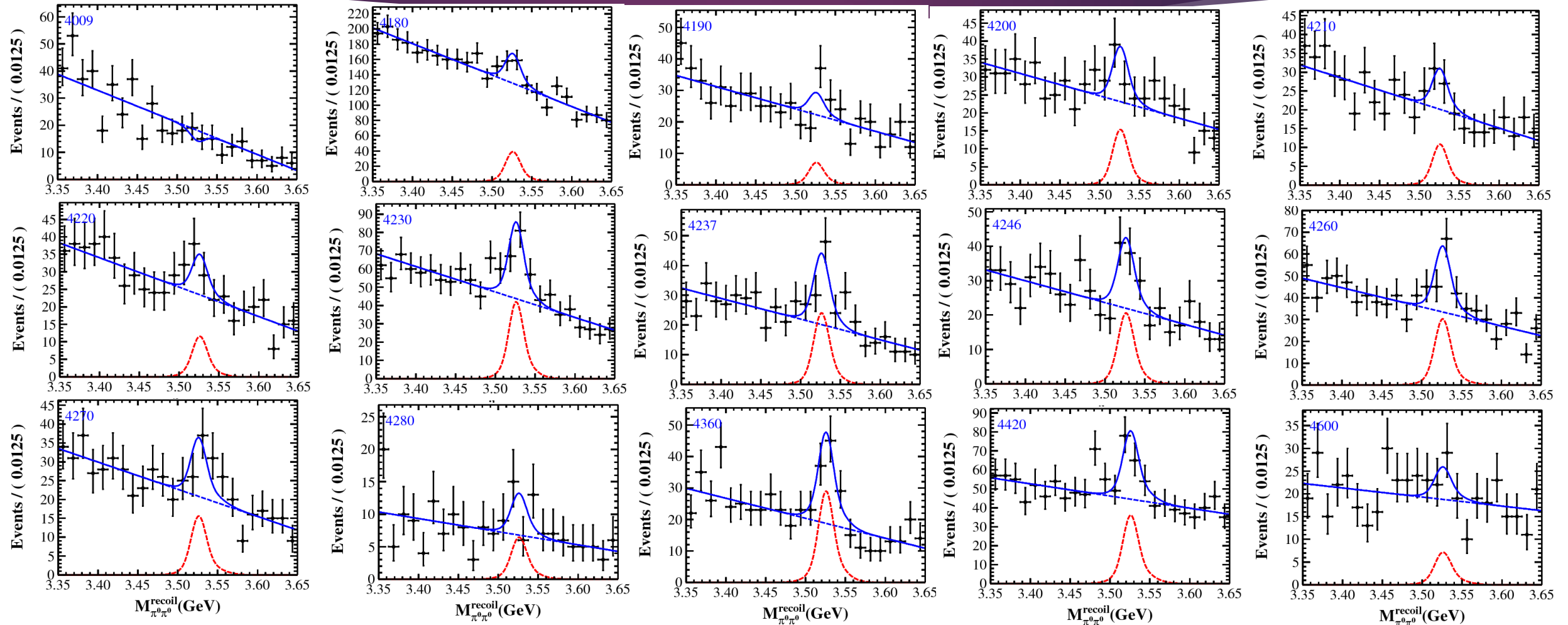


# Difference between MC and data



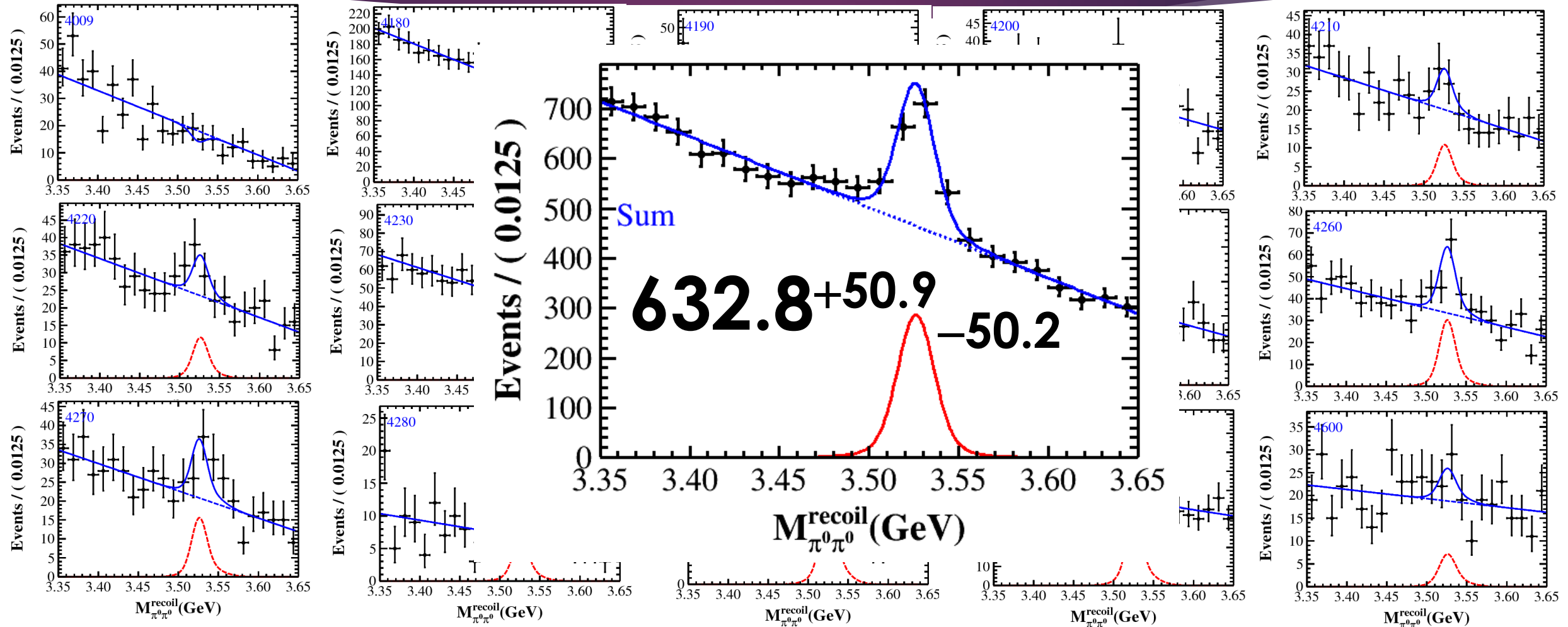
Fit to the mean (left) and sigma (right) distribution as a function of  $\sqrt{s}$ .

# Fit to $M_{\pi^0\pi^0}^{recoil}$





# Fit to $M_{\pi^0\pi^0}^{\text{recoil}}$



# Numerical results

Data	$N^{obs.}$	Significance	$\sum_i \epsilon_i \mathcal{B}_i(\%)$	$1 + \delta$	$ 1 + \Pi ^2$	$\sigma^B(\text{pb})$
4009	$-7.4^{+8.2}_{-7.5}$	-	0.448	1.599	1.05	$-4.0^{+4.4}_{-4.0}$
4180	$83.9^{+25.0}_{-24.3}$	$3.6\sigma$	0.722	0.781	1.05	$8.5^{+2.5}_{-2.5}$
4190	$15.4^{+10.6}_{-12.0}$	$1.6\sigma$	0.719	0.780	1.06	$9.5^{+6.5}_{-6.2}$
4200	$33.8^{+12.0}_{-11.2}$	$3.2\sigma$	0.724	0.781	1.06	$20.4^{+7.2}_{-6.8}$
4210	$23.8^{+10.8}_{-10.0}$	$2.5\sigma$	0.712	0.786	1.06	$14.9^{+6.8}_{-6.3}$
4220	$26.3^{+11.9}_{-11.2}$	$2.5\sigma$	0.721	0.800	1.06	$16.3^{+7.4}_{-6.9}$
4230	$93.1^{+17.7}_{-16.9}$	$6.1\sigma$	0.743	0.818	1.06	$25.2^{+4.8}_{-4.6}$
4237	$54.7^{+12.7}_{-12.0}$	$5.2\sigma$	0.723	0.845	1.06	$30.7^{+7.1}_{-6.7}$
4246	$46.6^{+12.3}_{-11.6}$	$4.5\sigma$	0.728	0.868	1.06	$25.2^{+6.6}_{-6.3}$
4260	$69.5^{+15.5}_{-14.8}$	$5.2\sigma$	0.722	0.905	1.05	$23.4^{+5.2}_{-5.0}$
4270	$36.5^{+12.1}_{-11.4}$	$3.5\sigma$	0.701	0.920	1.05	$19.9^{+6.6}_{-6.2}$
4280	$14.5^{+7.3}_{-6.6}$	$2.4\sigma$	0.681	0.934	1.05	$23.8^{+12.0}_{-10.9}$
4360	$65.8^{+12.9}_{-12.2}$	$6.3\sigma$	0.723	0.925	1.05	$33.9^{+6.6}_{-6.3}$
4420	$83.1^{+17.4}_{-16.7}$	$5.5\sigma$	0.695	1.008	1.05	$20.2^{+4.2}_{-4.1}$
4600	$17.7^{+10.7}_{-10.0}$	$1.8\sigma$	0.322	1.736	1.05	$10.4^{+6.3}_{-5.9}$

# Systematic uncertainty

- ▶ ISR factor: the difference between second and third iteration, 0.3%
- ▶ Luminosity: 1.0%
- Fitting
  - ▶ Fitting range: varying range from [3.35,3.65] to [3.34,3.64] and [3.36,3.66] GeV/c<sup>2</sup>, 0.5%
  - ▶ Bkg. Shape: changing the order of the polynomial function, negligible
  - ▶ Signal shape: changing the mass/resolution difference by  $1\sigma$ , 0.2 / 5.6%
- Efficiency
  - ▶ Tracking / Photon /  $K_S^0$  reconstruction, 1% / 1% / 1.2%
  - ▶ Kinematic fit, by the track-parameter-corrected method
  - ▶ nominal mass of  $\eta_c$ , 1.7%; line-shape of  $\eta_c$ , 0.6%
  - ▶ MC simulation of  $M(\pi^0\pi^0)$ , negligible
  - ▶ Cross feed, by MC simulation
  - ▶  $Z_c(4020)^0$ , including it in MC simulation
  - ▶ MC statistics,

**Due to the limited statistics, data summed over all energy points is taken as the control sample for some of sources.**

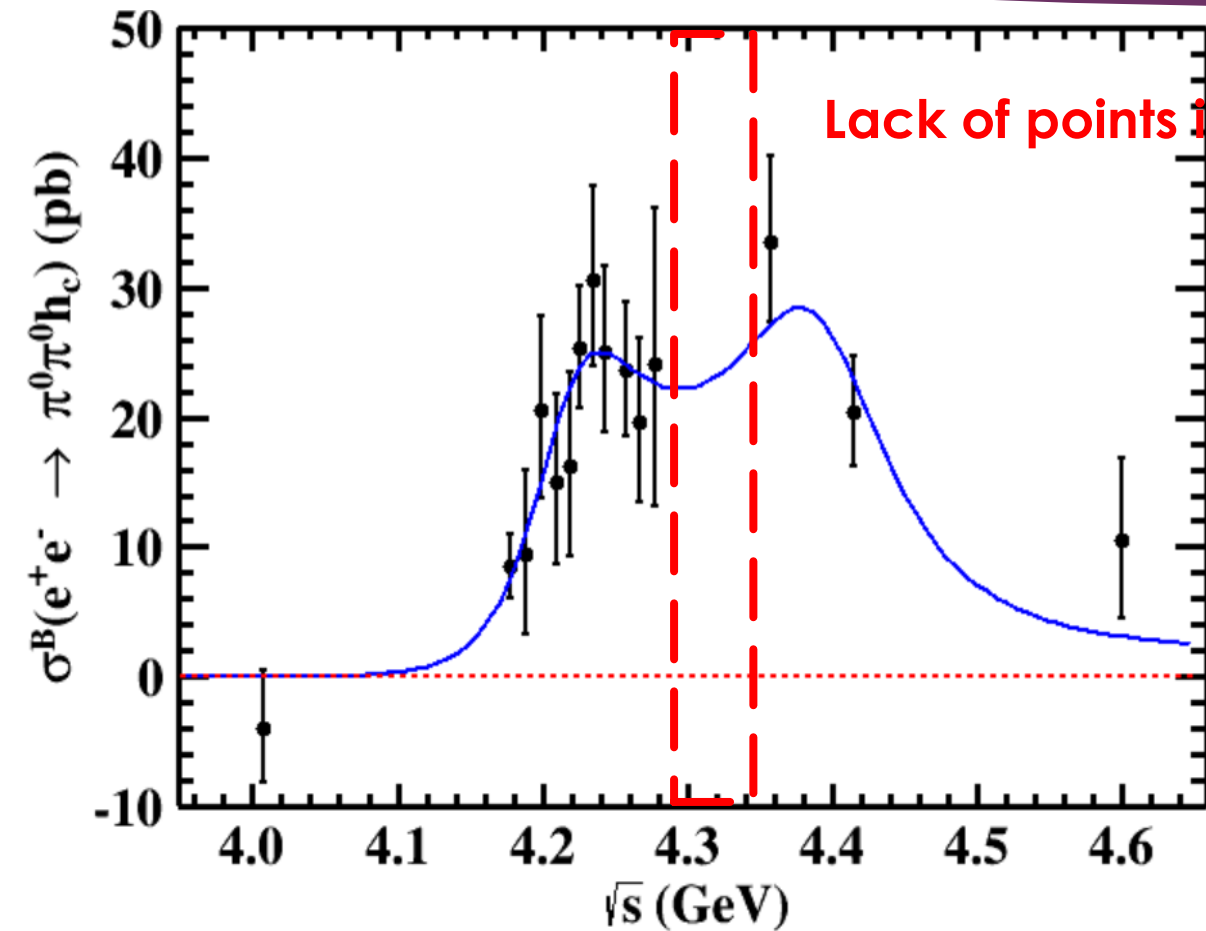
# Systematic uncertainty

Source	Uncertainty(%)
Luminosity	1.0
Fit range	0.5
Mass resolution	5.6
Mass scale	0.2
Bkg shape	0.0
$\eta_c$ mass	1.7
$Z_c(4020)^0$	4.2
$1 + \delta$	0.5
$\sum_i \epsilon_i \mathcal{B}(\eta_c \rightarrow X_i)$	8.7
Total	11.4

# Born Cross Section

Data	$\sigma^B(\text{pb})$	$\sigma_{\text{old}}^B(\text{pb})$ [17]
4009	$-4.0_{-4.0}^{+4.4} \pm 0.4 \pm 0.6$	-
4180	$8.5_{-2.5}^{+2.5} \pm 1.0 \pm 1.3$	-
4190	$9.5_{-6.2}^{+6.5} \pm 1.1 \pm 1.5$	-
4200	$20.4_{-6.8}^{+7.2} \pm 2.3 \pm 3.2$	-
4210	$14.9_{-6.3}^{+6.8} \pm 1.7 \pm 2.4$	-
4220	$16.3_{-6.9}^{+7.4} \pm 1.8 \pm 2.5$	-
4230	$25.2_{-4.6}^{+4.8} \pm 2.9 \pm 4.0$	$25.6 \pm 4.8$
4237	$30.7_{-6.7}^{+7.1} \pm 3.5 \pm 4.8$	-
4246	$25.2_{-6.3}^{+6.6} \pm 2.8 \pm 3.9$	-
4260	$23.4_{-5.0}^{+5.2} \pm 2.7 \pm 3.7$	$24.4 \pm 5.1$
4270	$19.9_{-6.2}^{+6.6} \pm 2.2 \pm 3.1$	-
4280	$23.8_{-10.9}^{+12.0} \pm 2.7 \pm 3.8$	-
4360	$33.9_{-6.3}^{+6.6} \pm 3.8 \pm 5.3$	$36.2 \pm 6.5$
4420	$20.2_{-4.1}^{+4.2} \pm 2.3 \pm 3.2$	-
4600	$10.4_{-5.9}^{+6.3} \pm 1.2 \pm 1.7$	-

# Line-shape of $e^+e^- \rightarrow \pi^0\pi^0 h_c$



$$\sigma(m) = |BW_1(m) \cdot \sqrt{PS(m)/PS(M_1)} + e^{i\phi} BW_2(m) \cdot \sqrt{PS(m)/PS(M_2)}|^2$$

$$BW_i(m) = \frac{\sqrt{12\pi(\Gamma_{e^+e^-} \mathcal{B}(\pi^0\pi^0 h_c)_i \Gamma_{\text{tot}})}}{m^2 - M_i^2 + iM_i\Gamma_{\text{tot}}}$$

Parameters	$Y(4220)$	$Y(4390)$
$M$ (MeV/ $c^2$ )	$4213.8 \pm 6.3$	Fixed
$\Gamma_{\text{tot}}$ (MeV)	$100.0 \pm 24.6$	Fixed
$\Gamma_{e^+e^-} \cdot \mathcal{B}(\pi^0\pi^0 h_c)$ (eV)	$52.8 \pm 19.5$	$56.3 \pm 18.0$
$\phi$ (rad)	-	$2.3 \pm 0.6$

# Summary

- ▶ Using XYZ data for 15 energy points, Born cross section of  $e^+e^- \rightarrow \pi^0\pi^0h_c$  is measured.
- ▶ Line shape of  $e^+e^- \rightarrow \pi^0\pi^0h_c$  is similar to that of  $e^+e^- \rightarrow \pi^+\pi^-h_c$   
Clear Structure Near 4.22 GeV, more energy points above 4.300 GeV are needed.

# Backups



# MC simulation

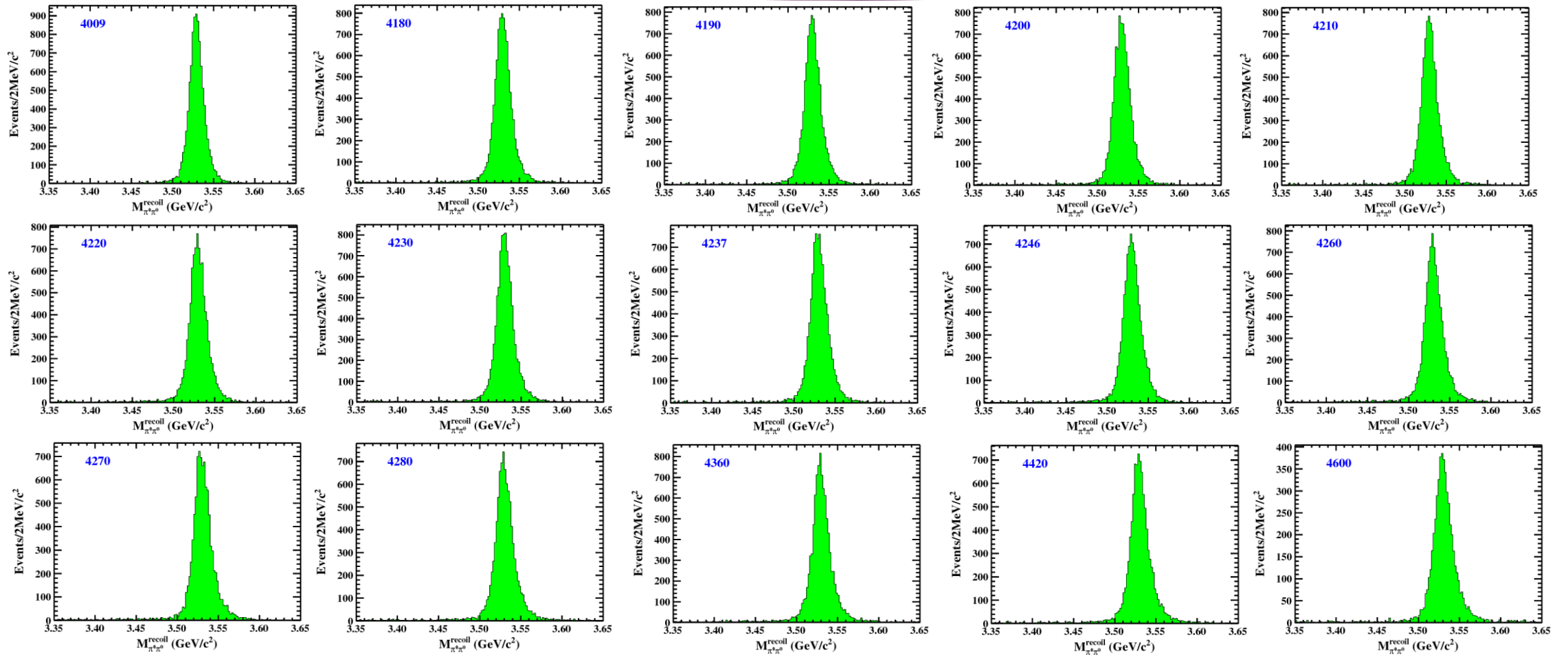


Table 5: Efficiency related systematic uncertainties of the cross section at  $\sqrt{s} = 4.4156$  GeV (%).

$\eta_c$ decay mode	MDC Tracking	Photon	$\pi^0$	$\eta$	$K_S^0$	Kinematic Fit	MC statistics	Cross feed	$M_{\pi^0\pi^0}$	$\eta_c$ line-shape	Total
$p\bar{p}$	2	5	2	-	-	0.4	0.7	-	-		5.8
$\pi^+\pi^-K^+K^-$	4	5	2	-	-	0.5	1.1	-	-		6.8
$\pi^+\pi^-p\bar{p}$	4	5	2	-	-	1.4	1.0	0.0	-		7.0
$2(K^+K^-)$	4	5	2	-	-	0.8	1.2	-	-		6.9
$2(\pi^+\pi^-)$	4	5	2	-	-	1.3	1.0	-	-		6.9
$3(\pi^+\pi^-)$	6	5	2	-	-	1.3	1.2	-	-		8.3
$K^+K^-2(\pi^+\pi^-)$	6	5	2	-	-	1.7	1.6	0.1	-	0.6	8.4
$K_S K^+ \pi^- + \text{c.c.}$	2	5	2	-	1.2	1.6	1.0	0.4	-		6.2
$K_S K^+ \pi^+ \pi^- \pi^0$	4	5	2	-	1.2	2.4	1.8	0.0	-		7.5
$K^+ K^- \pi^0$	2	7	3	-	-	1.0	1.2	0.9	-		8.1
$p\bar{p}\pi^0$	2	7	3	-	-	1.7	1.3	-	-		8.2
$K^+ K^- \eta$	2	7	2	1	-	1.6	1.2	0.4	-		7.9
$\pi^+ \pi^- \eta$	2	7	2	1	-	1.0	1.1	-	-		7.8
$2(\pi^+ \pi^-) \eta$	4	7	4	-	-	1.1	1.8	-	-		9.3
$\pi^+ \pi^- \pi^0 \pi^0$	2	9	4	-	-	0.9	1.5	0.3	-		10.2
$2(\pi^+ \pi^-) \pi^0 \pi^0$	4	9	4	-	-	1.7	3.6	0.1	-		11.4

# Dalitz plot

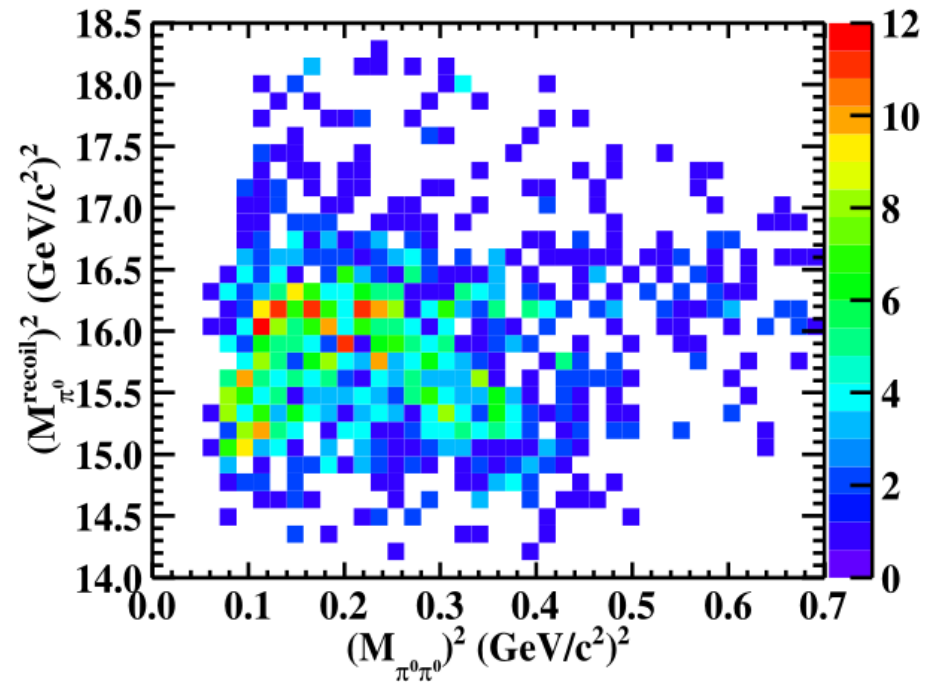


Figure 9: The dalitz plot of  $(M_{\pi^0\pi^0})^2$  versus  $(M_{\pi^0}^{\text{recoil}})^2$  in  $h_c$  signal region from the summed data at  $\sqrt{s} = 4.1783, 4.2263, 4.2580, \text{ and } 4.4156 \text{ GeV}$ .

$$M(\pi^0\pi^0)$$

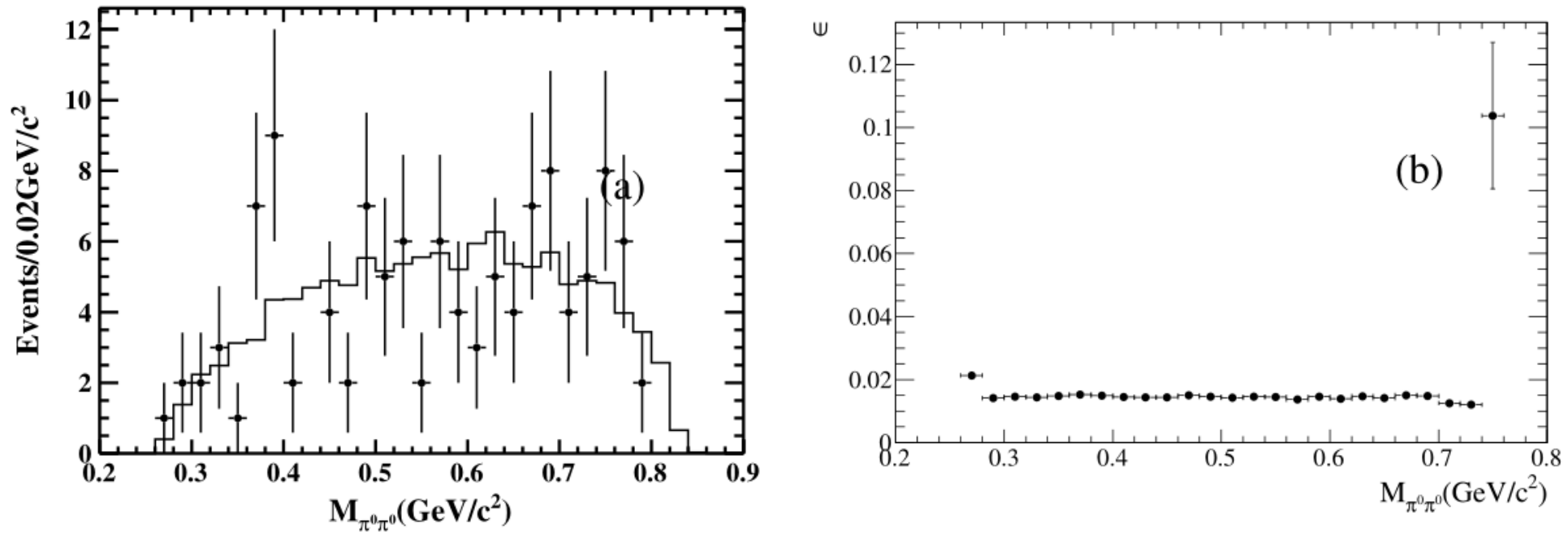


Figure 10: (a) The  $\pi^0\pi^0$  invariant mass spectrum in  $h_c$  signal region from data at  $\sqrt{s} = 4.3583$  GeV. (b) The efficiency of  $M_{\pi^0\pi^0}$  in  $h_c$  signal region for signal MC simulation at  $\sqrt{s} = 4.3583$  GeV.