Measurements of Cross Sections for $e^+e^- \rightarrow \mu^+\mu^-$ at Energies from 3.645 to 3.890 GeV

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Outline

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- Measurements of cross sections
  - Data & Monte Carlo Events
  - Measuring cross sections
- Analysis of cross sections
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  - Phase angle of ψ_s(3686, 3770)$\rightarrow\mu^+\mu^-$
  - Evidence for structure S(3760)$\rightarrow\mu^+\mu^-$
- Summary

Motivation

Measurements of cross sections for $e^+e^-\rightarrow\mu^+\mu^-$ could give some important information about vector meson production and decays

- **Up to now, no direct measurement of branching fraction of $\psi(3770)\rightarrow\mu^+\mu^-$ is available.**
- **Up to now, no measurement of phase angles of $\psi(3686)\rightarrow\mu^+\mu^-$, and $\psi(3770)\rightarrow\mu^+\mu^-$ relative to continuum $e^+e^-\rightarrow\mu^+\mu^-$ is available.**
- **Measurements of these branching fractions and phase would be helpful for better understandings of these vector states production and decays, …**
- **Search for some new structure(s) in the decay of $S\rightarrow\mu^+\mu^-$.**
- **...**

These improve our knowledge for better understanding of the vector meson production in e^+e^- annihilation, as well as for better understanding of the vector meson decays

Data Samples and Software

- **Data**
  - **Data taken at energies from 3.645~3.89 GeV in 2010**
  - **Data taken at energy of 3.773 GeV during 2010~2011**
  - **Data taken at energy of 3.65 GeV in 2009**
  - **Data taken at 3.6861 GeV in 2009**

- **Software**
  - **BOSS version of 6.6.4.p01**
  - **Monte Carlo events are generated with Babayaga**
  - **Other Monte Carlo simulated events are generated with the KKMC + BesEvtGen**

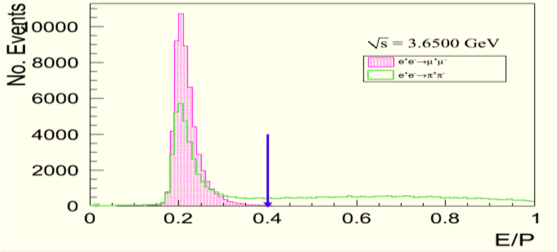
Event Selection

➢ Charged track

- $|\cos\theta| < 0.8$
- $|V_{xy}| < 1$ cm
- $|V_z| < 10$ cm
- $N_{Good} = 2, \quad \sum_i Q = 0$

➢ Selection of $\mu^{+/-}$

- $|T_1 - T_2| < 2$ ns (T$_1$ and T$_2$ are the time from TOF)
- $(p_{\mu+} + p_{\mu-}) > 0.9E_{cm}$
- $0.05 < E_{EMC}/p < 0.40$



➢ 4C-Kinematic fit

- $\chi^2_{4C\text{-}Fit} < 30$ (to reject KK and $p\bar{p}$ backgrounds)

No. of candidates for $e^+e^- \rightarrow \mu^+\mu^-$

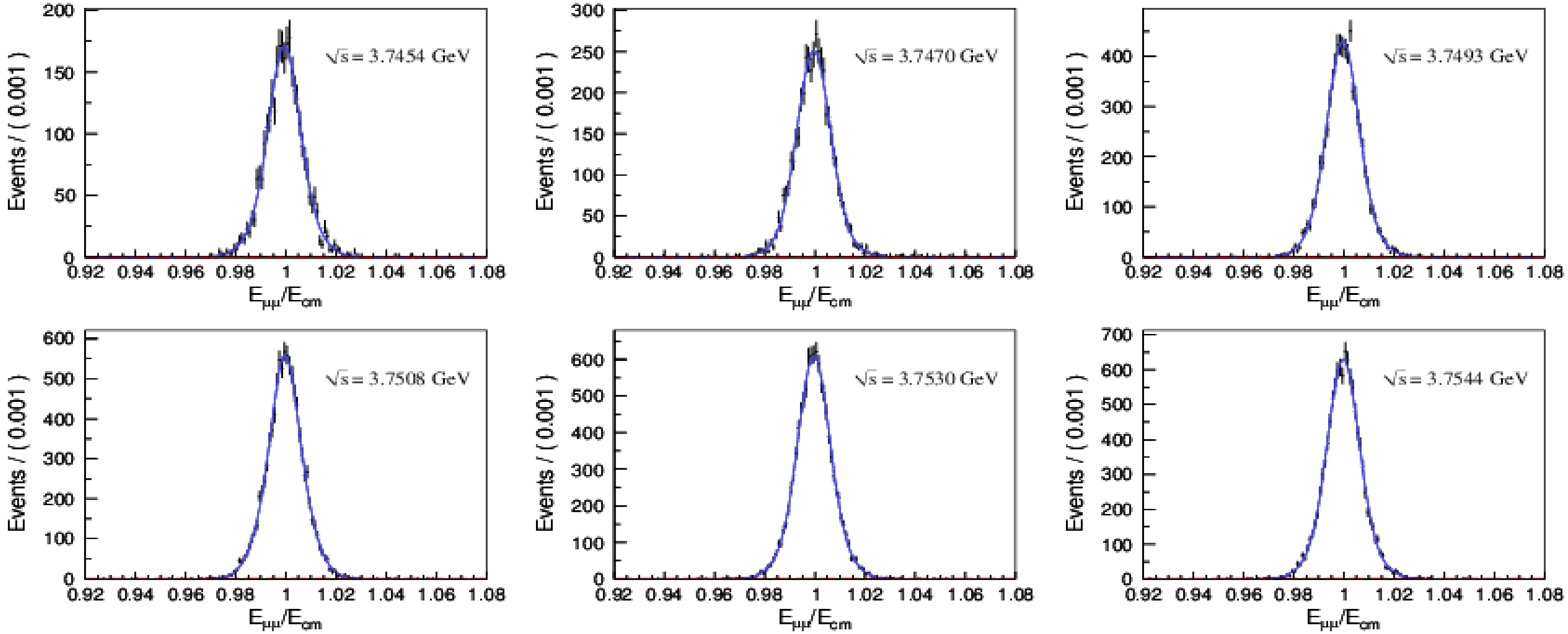
- To separate $e^+e^- \rightarrow \mu^+\mu^-$ from $e^+e^- \rightarrow K^+K^-$ and $e^+e^- \rightarrow p\bar{p}$, we examine the energy distributions of the accepted events satisfying the selection criteria. If a K or p is misidentified as a μ, the energy of the charged track would be lower than that expected. This allows us to separate μ/K/p.

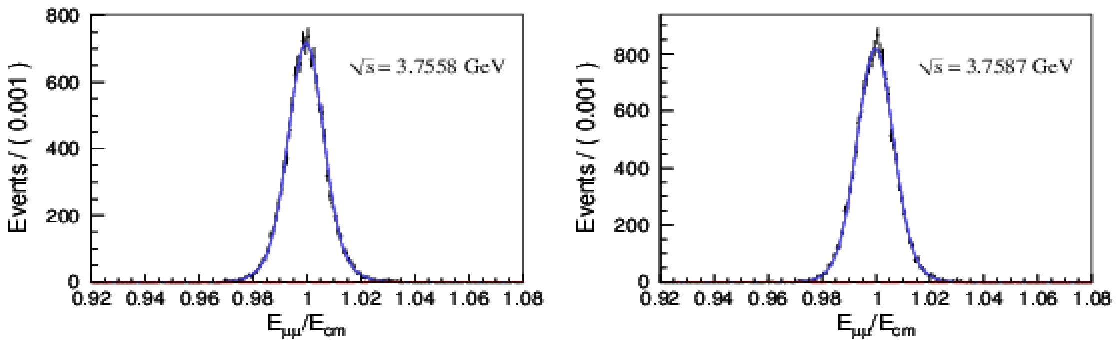
- We defined a quantity $E_{measured}/E_{cm}$ to examine the energy distributions of the selected events from data samples collected at different energies.

- The number of candidates for $e^+e^- \rightarrow \mu^+\mu^-$ is obtained by fitting the distributions of the normalized energies ($E_{measured}/E_{cm}$) of the final states satisfying the selection criteria.

Numbers of candidates for $e^+e^- \rightarrow \mu^+\mu^-$

- $E_{measured}/E_{cm}$





Signal shape:
Double Gaussian function
Background shape:
Polynomial

(More distributions of the ratio and fits are shown in the backup slides)

Background Estimate

- **Number of background events**

The events satisfying the selection criteria still contain some backgrounds. The number of these background events can be subtracted from the events with

$$N^b = \sum_i^N L \times \sigma^i \times \eta_{i \to \pi\pi(KK,\ ee\mu\mu)}$$

L : luminosity

N^b : the number of background

σ^i : cross section of i^{th} Bkg. source

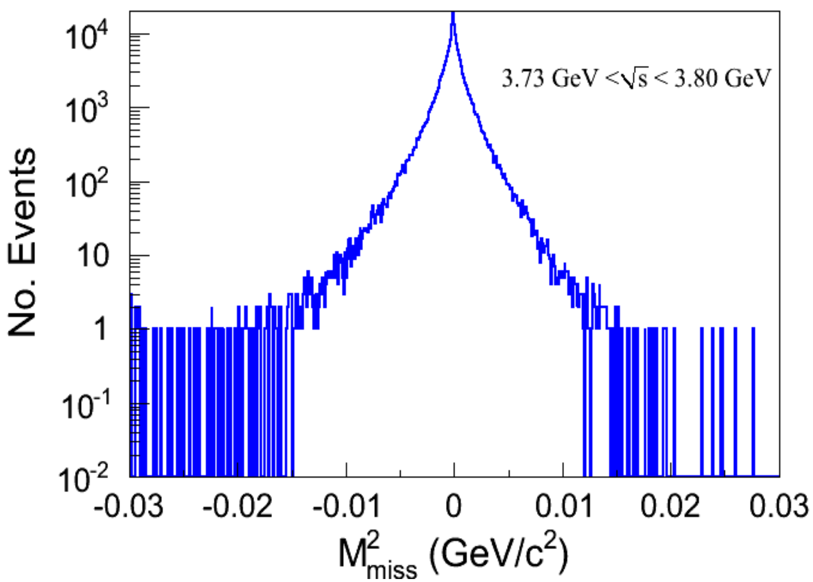
η : mis-identification rate

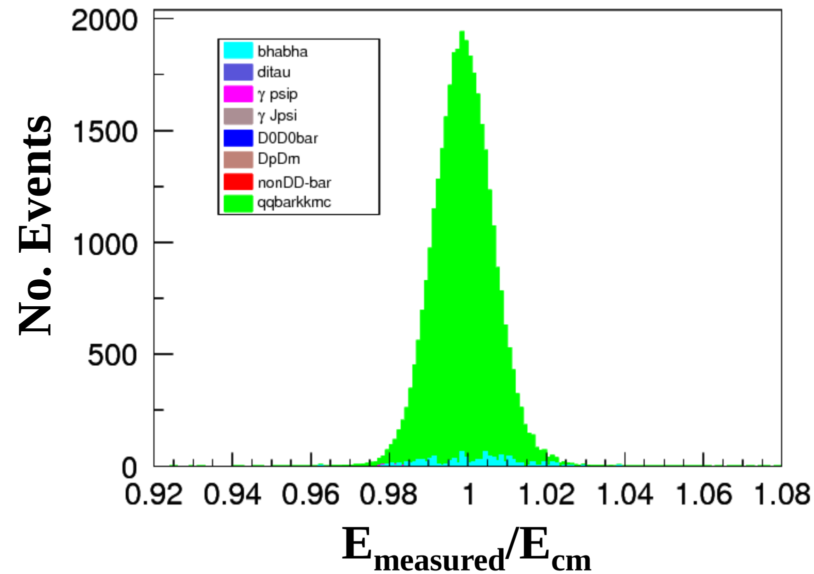
- **Possible backgrounds**

  - ✓ **$e^+e^- \to \mu^+\mu^-$ is mis-identified from $e^+e^- \to \pi^+\pi^-$, KK, $p\bar{p}$**
  - ✓ **$e^+e^- \to \mu^+\mu^-$ is mis-identified from $e^+e^- \to \pi^+\pi^-\pi^0$**

Main Backgrounds

- **Possible backgrounds**
  - ✓ **The distribution of the $M^2_{missing}$ of the events satisfying the selection criteria shows that no the $e^+e^- \rightarrow \pi^+\pi^- \pi^0$ event is satisfied with the selection criteria**
  - ✓ **We study possible backgrounds with all kinds of Monte Carlo simulated event samples generated at 3.773 GeV and other E_{cm}**

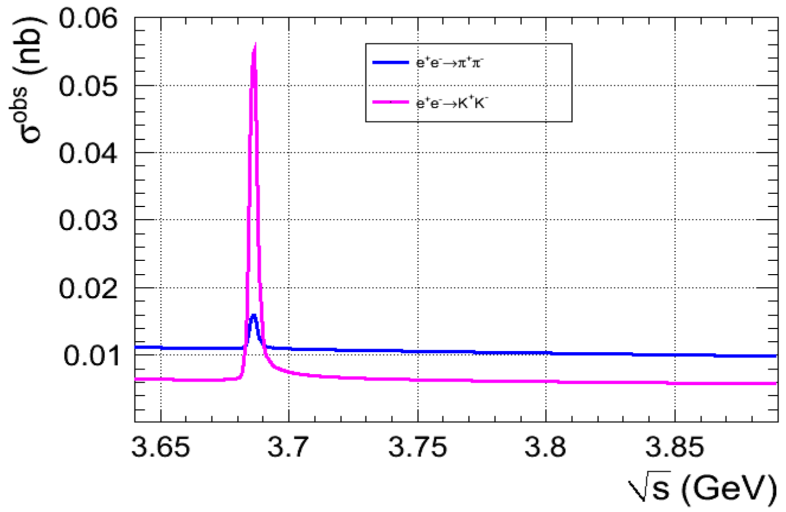




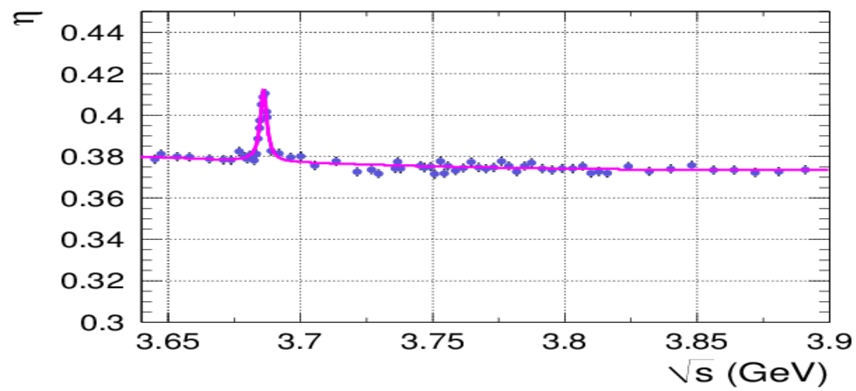
The Monte Carlo studies shows that the $e^+e^- \rightarrow \pi^+\pi^-$ / K^+K^- is the mainly backgrounds from the continuum $e^+e^- \rightarrow q\bar{q}$ events and a small fraction of Bhabha background.

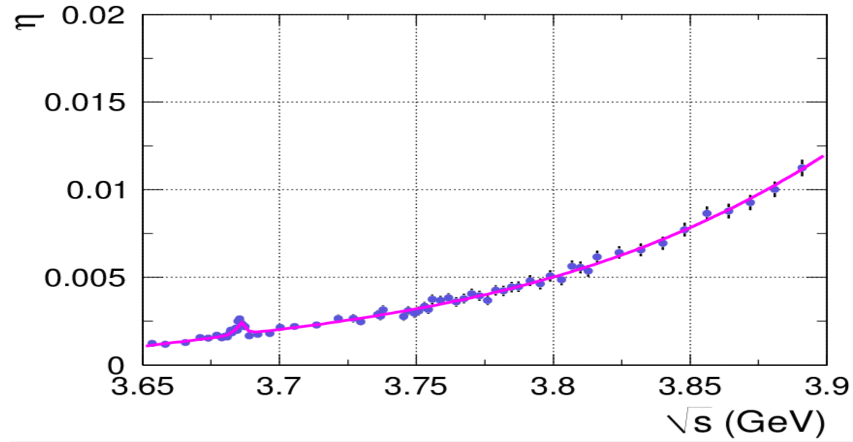
Number of Backgrounds

- Cross sections for $e^+e^- \rightarrow \pi^+\pi^-$



- Misidentification rate





Using this cross-section shape and η shape, we can estimate the number of background events at energies from 3.645 to 3.89 GeV

- Number of the background events

$$N^b = L \times (\sigma^{e^+e^- \to \pi^+\pi^-} \times \eta_{\pi^+\pi^-} + \sigma^{e^+e^- \to K^+K^-} \times \eta_{KK} + \sigma^{e^+e^- \to e^+e^-} \times \eta_{\mathbf{ee}})$$

Observed Cross Sections

- **Cross Sections**

$$\sigma^{obs}_{e^+e^-\to\mu^+\mu^-} = \frac{N^{\mathrm{obs}} - N^{\mathrm{b}}}{L \times \varepsilon}$$

where N^{obs} is the number of candidates for $e^+e^- \rightarrow \mu^+\mu^-$ observed, N^b is the number of background events, L is the integrated luminosity, ε is the detection efficiency

- ✓ **Luminosity**

  Measured with $e^+e^-(\gamma) \rightarrow e^+e^-$, or $e^+e^- \rightarrow \gamma\gamma$

- ✓ **Efficiency**

  Determined with Babayaga Package of version of 3.5

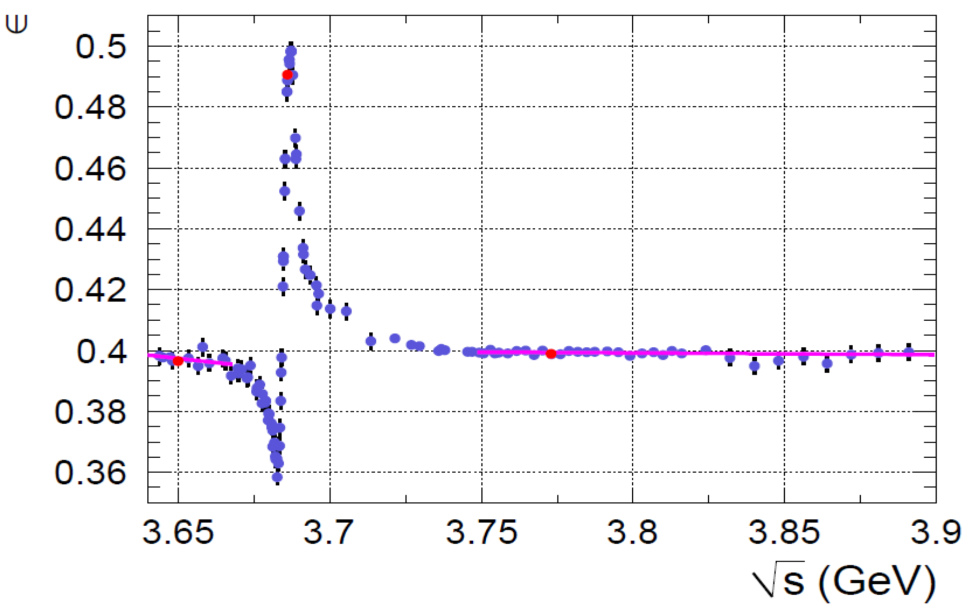
MC Events & Selection Efficiency

- **Monte Carlo simulated signal events**

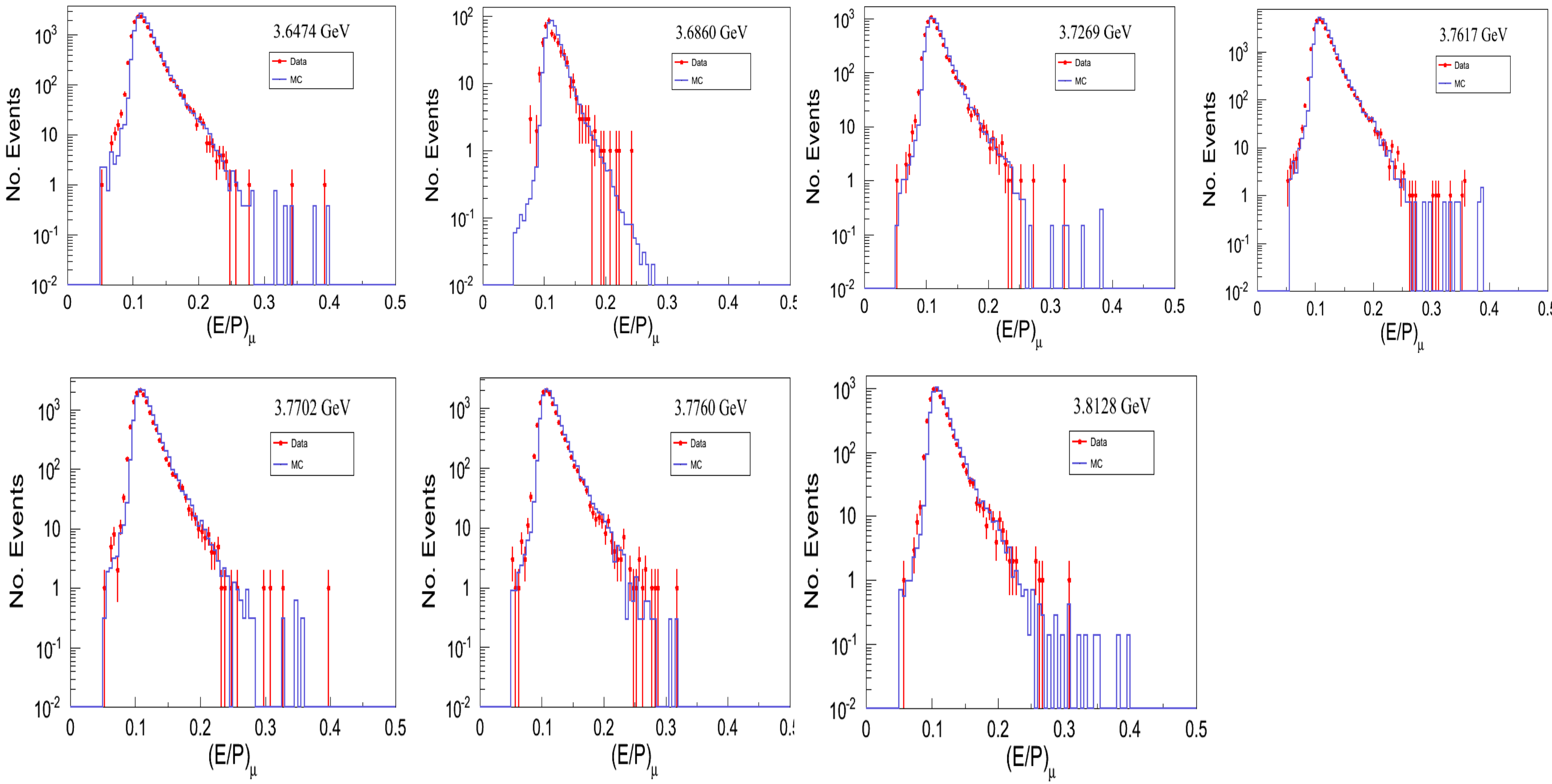
At the energies from 3.64~3.89 GeV at which the ψ(3770) cross-section scan data were taken in 2010, we generated 50000 Monte Carlo signal events for $e^+e^- \rightarrow \mu^+\mu^-$; While we generated 900000 and 800000 Monte Carlo signal events at 3.650 GeV and 3.6861 GeV for the data taken in 2009, respectively.

- **Selection efficiencies**

Analyzing these Monte Carlo simulated signal events yields selection efficiencies ε at each of these energies.



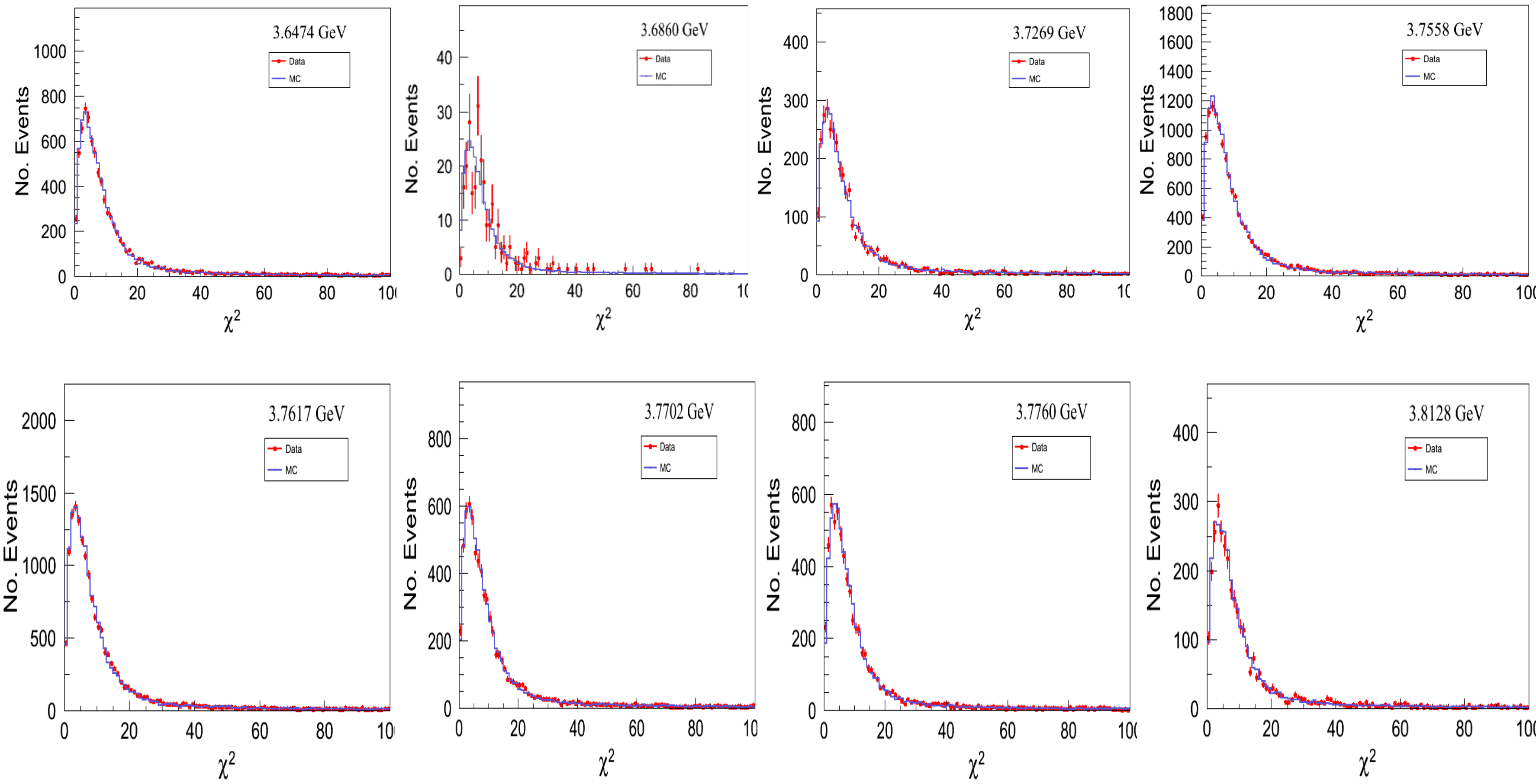
Comparison of E_{EMC}/p between Data & MC



The comparison of ratios of E_{EMC}/p between the data and the Monte Carlo simulated events at energies from 3.645 to 3.89 are well.

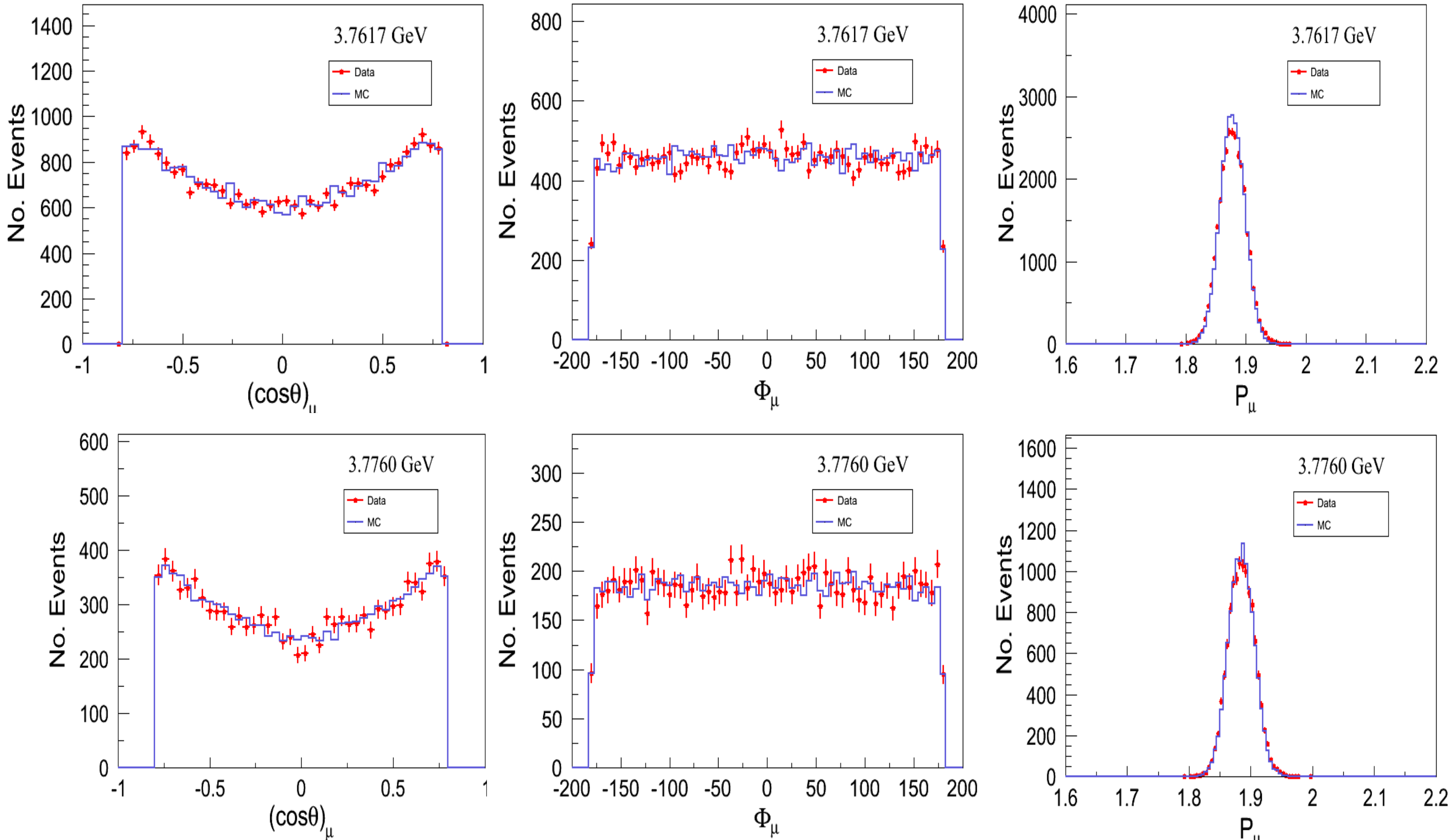
Compare Data and MC

- χ^2 distributions from both the data and the MC events at a few energies (as an example)



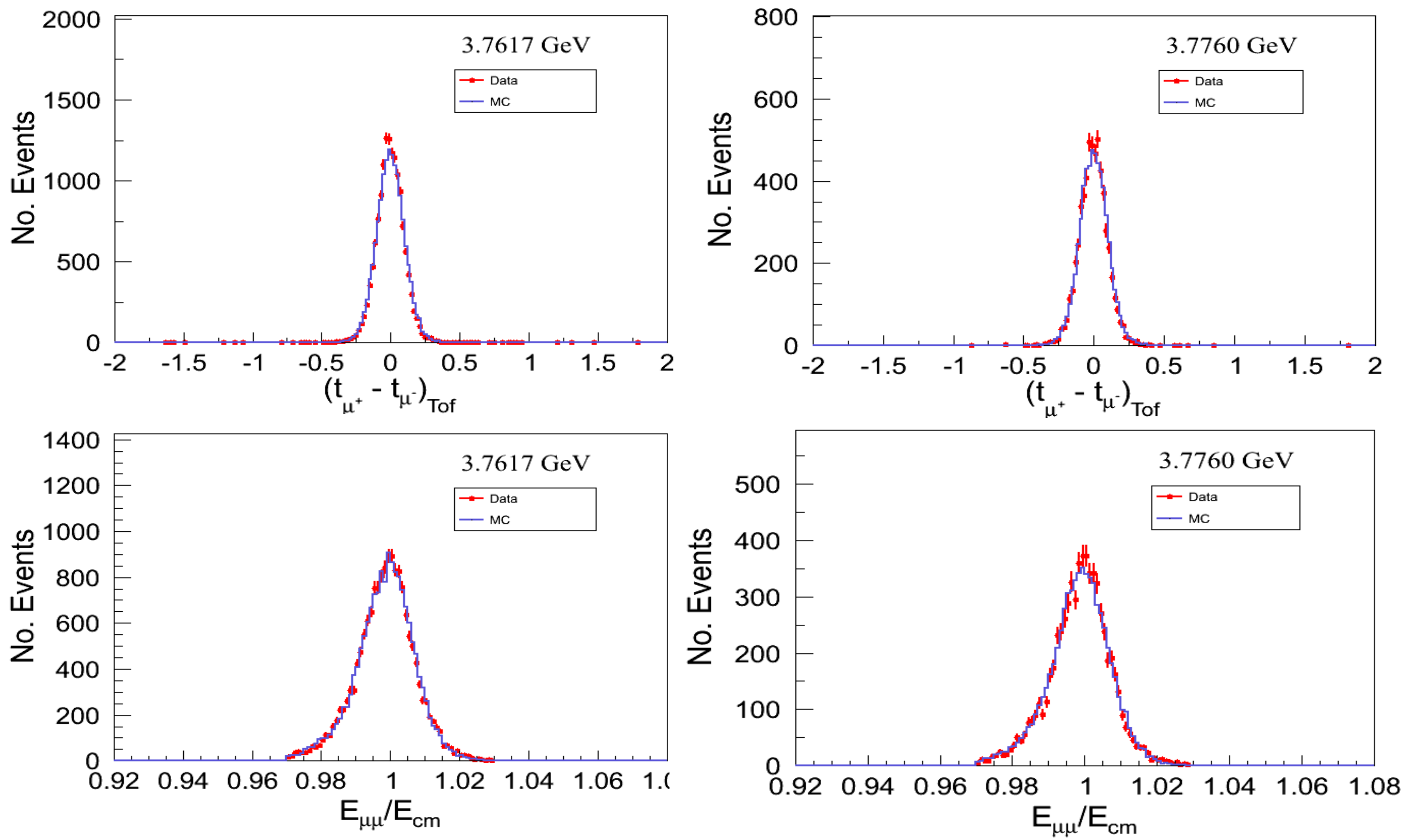
Comparison of Data and MC

➢ **Distributions of cosθ, ϕ and momentum of μ for both the data and the MC simulated events**



Comparison of Data and MC

- Distributions of $T_{\mu+}$ -$T_{\mu-}$ and $E_{measured}/E_{cm}$ of μ^+ (μ^-) for both the data and the MC simulated events



The Data Collected in 2010

- Observed cross sections measured at 8 energy points

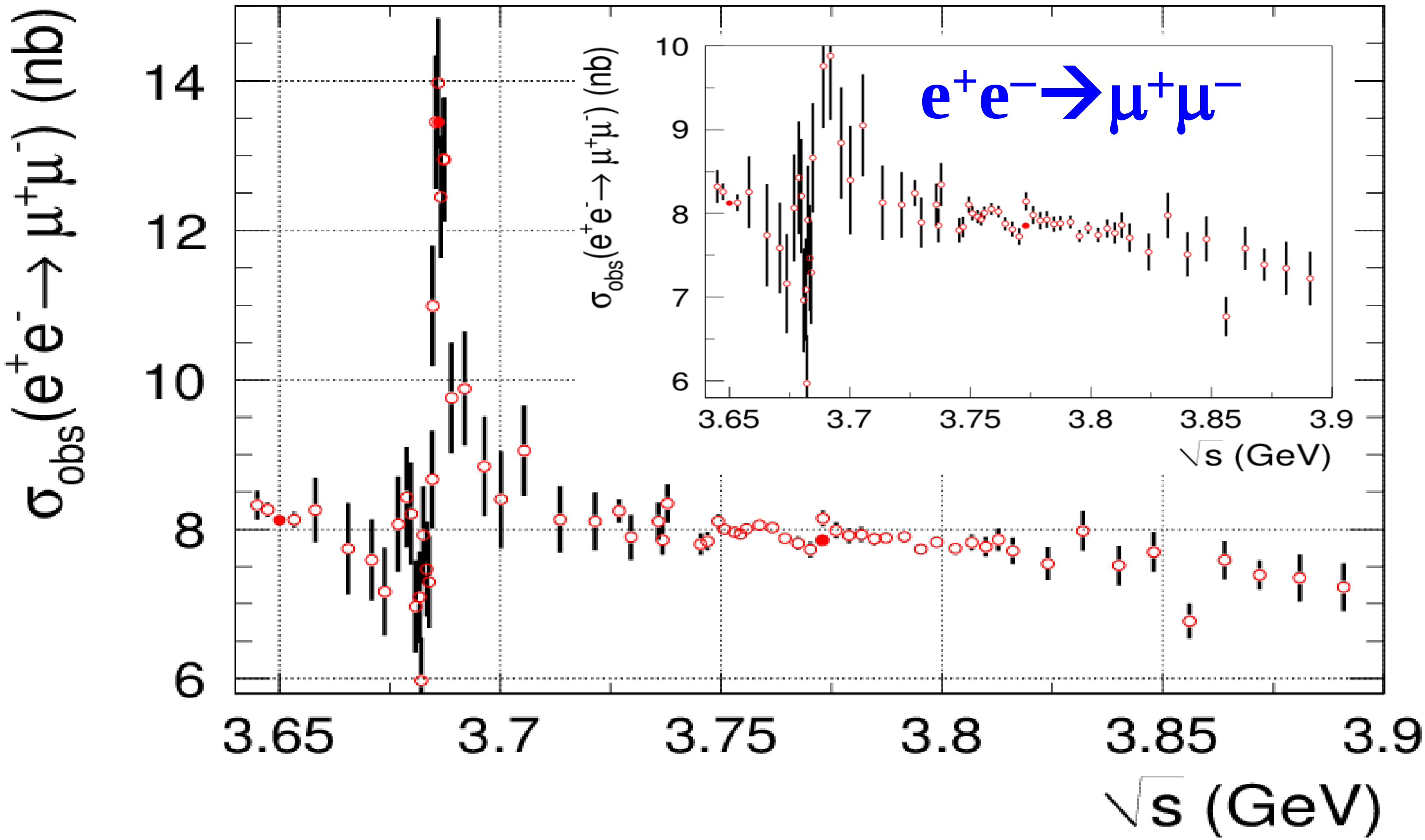
$$\sigma^{obs} = \frac{N^{obs} - N^{b}}{L \times \varepsilon}$$

As an example

E_{cm} (GeV)	L (nb^{-1})	N^{obs}	N^{b}	ε [%]	σ (nb)
3.6474	2260.92±4.82	7436.2±86.3	10.7±0.0	39.77±0.08	8.2582±0.0990
3.686	41.17±0.65	279.4±16.7	0.3±0.0	48.51±0.31	13.9749±0.8690
3.6964	49.65 ± 0.72	184.0±13.5	0.2 ± 0.0	41.87±0.29	8.8409±0.6649
3.7454	995.39±3.22	2981.8±54.6	4.3±0.0	39.96±0.08	7.7991±0.1462
3.7587	4451.55±6.97	14335.6±119.8	19.7± 0.1	39.94±0.00	8.0519±0.0686
3.7674	2448.95±5.18	7651.3±87.5	10.9±0.0	39.94±0.00	7.8114± 0.0910
3.7731	1831.63±4.49	5964.6±77.3	8.0 ± 0.0	39.93 ±0.00	8.1444±0.1076
3.8099	1258.17±3.76	3904.7±62.5	5.3 ± 0.0	39.91±0.00	7.7656± 0.1266

Observed Cross Sections

- ψ(3770) + "fast ψ(3686)" cross-section scan data + data samples taken at 3.650, 3.686, 3.773 GeV



Systematic Uncertainties

Source	Systematic uncertainty (%)
$\lvert\cos\theta\rvert < 0.80$	0.15
$E_{EMC}/p > 0.05$ and $E_{EMC}/p < 0.4$	0.12
$\lvert\Delta Tof\rvert < 2.0$	0.48
$(P_{\mu+} + P_{\mu-}) > 0.9E_{cm}$	0.59
4-C kinematic fit	0.97
Fit to $E_{\mu\mu}/E_{cm}$	1.23
Tracking efficiency	2.0
Luminosity	1.0
Generator	1.0
Sum	3.01

The total systematic uncertainty in the measured cross section is 3.01%

Analysis of the Cross Sections

A χ^2 fit is performed to the observed cross sections

- **Objective χ^2 function**

$$\chi^2 = \sum_{i=1}^{n} \frac{(\sigma_i^{\text{obs}} - \sigma_i^{\text{expect}})^2}{\Delta^2_{\sigma_i^{obs}}}$$

Where σ_i^{obs} is the observed cross section, σ_i^{expect} is the expected cross section, and Δ_i is the uncertainty of the σ_i^{obs} at ith energy point.

The effects of correlation between point and point on the parameters are estimated by off-set method (see M. Botje, J. Phys. G 28 779(2002)]" for detail. The BES-III published results also used it to deal with …)

- **Dressed cross section**

$$\sigma^{\text{dress}} = \left| A_{con} + e^{i\varphi_1} A_1 + e^{i\varphi_2} A_2 + e^{i\varphi_3} A_3 + \ldots \right|^2$$

$$A_{con} = \sqrt{\frac{f_{con}}{E_{cm}^2}} \qquad A_j = \frac{\sqrt{12\pi\, \Gamma_j^{ee}\, \Gamma_j^{uu}}}{E_{cm}^2 - M_j^2 + i\Gamma_j^{tot} M_j},\ (j = 1,2,\ldots n)$$

The vacuum polarization corrections have been absorbed into f_{con} and leptonic widths of the vector states in the fits

$$A_j = \frac{\sqrt{12\pi\, \Gamma_j^{ee}\, \Gamma_j^{\mu\mu}}}{M_j^2 - E_{cm}^2 - i\Gamma_j^{tot} M_j}$$

(if using this form of the B-W amplitude, the phase angle would be shifted by 180°)

Analysis of the Cross Sections

- **Observed cross section**

$$\sigma^{\text{expect}}_{e^+e^-\to\mu^+\mu^-}(s) = \int_0^\infty ds' G(s,s') \int_0^{x_{\max}} dx\ F(x,s)\ \sigma^{\text{dress}}(s(1-x))$$

$$G(s,s') = \frac{1}{\sqrt{2\pi}\sigma_{E_{\text{BEPC-II}}}} \exp\left[-\frac{(\sqrt{s}-\sqrt{s'})^2}{2\sigma^2_{E_{\text{BEPC-II}}}}\right] \qquad x = 1 - \frac{s'}{s}$$

Effective c.m. energy

Nominal c.m. energy

$$F(x,s) = \beta x^{\beta-1}\delta^{V+S} + \delta^H$$

Kuraev & Fadin

$$\beta = \frac{2\alpha}{\pi}\left(\ln\frac{s}{m_e^2} - 1\right)$$

$$\delta^{V+S} = 1 + \frac{3}{4}\beta + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right) - \frac{\beta^2}{24}\left(\frac{1}{3}\ln\frac{s}{m_e^2} + 2\pi^2 - \frac{37}{4}\right)$$

$$\delta^H = \delta_1^H + \delta_2^H \qquad \delta_1^H = -\beta\left(1 - \frac{x}{2}\right)$$

$$\delta_2^H = \frac{1}{8}\beta^2\left[4(2-x)\ln\frac{1}{x} - \frac{1+3(1-x)^2}{x}\ln(1-x) - 6 - x\right]$$

Measuring Br., Phase Angle and Searching for New Structure

- **Two hypotheses**

We fit these cross sections with two hypotheses

1. **Cnt + $\psi(3686)$ +$\psi(3770)$**
2. **Cnt + $\psi(3686)$ +$\psi(3770)$+S(37xx)**

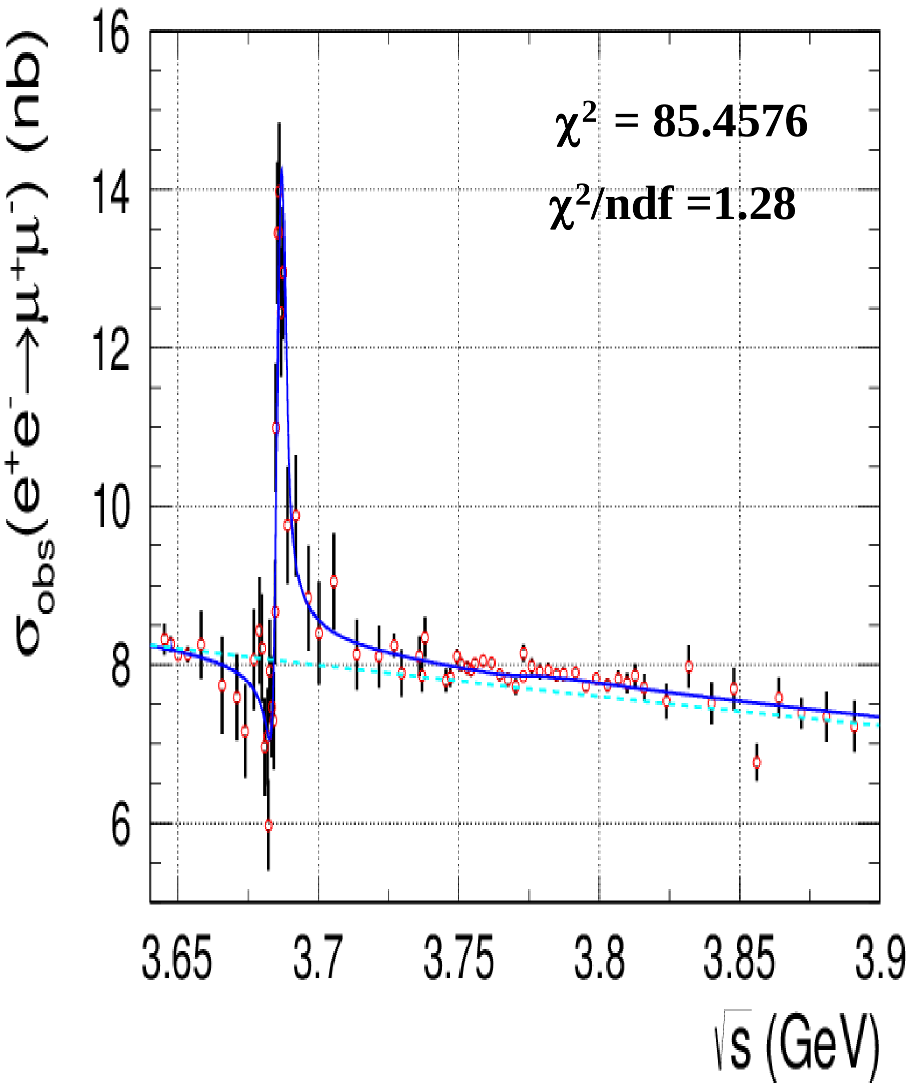
S(37xx) is any other structure(s) lying on the energies from 3.70 to 3.89 GeV

- **Find the better hypothesis**

By comparing the fit χ^2 obtained with these hypotheses, we find the better fit to these cross sections and search for new structure(s)

Fit to the Observed Cross Sections

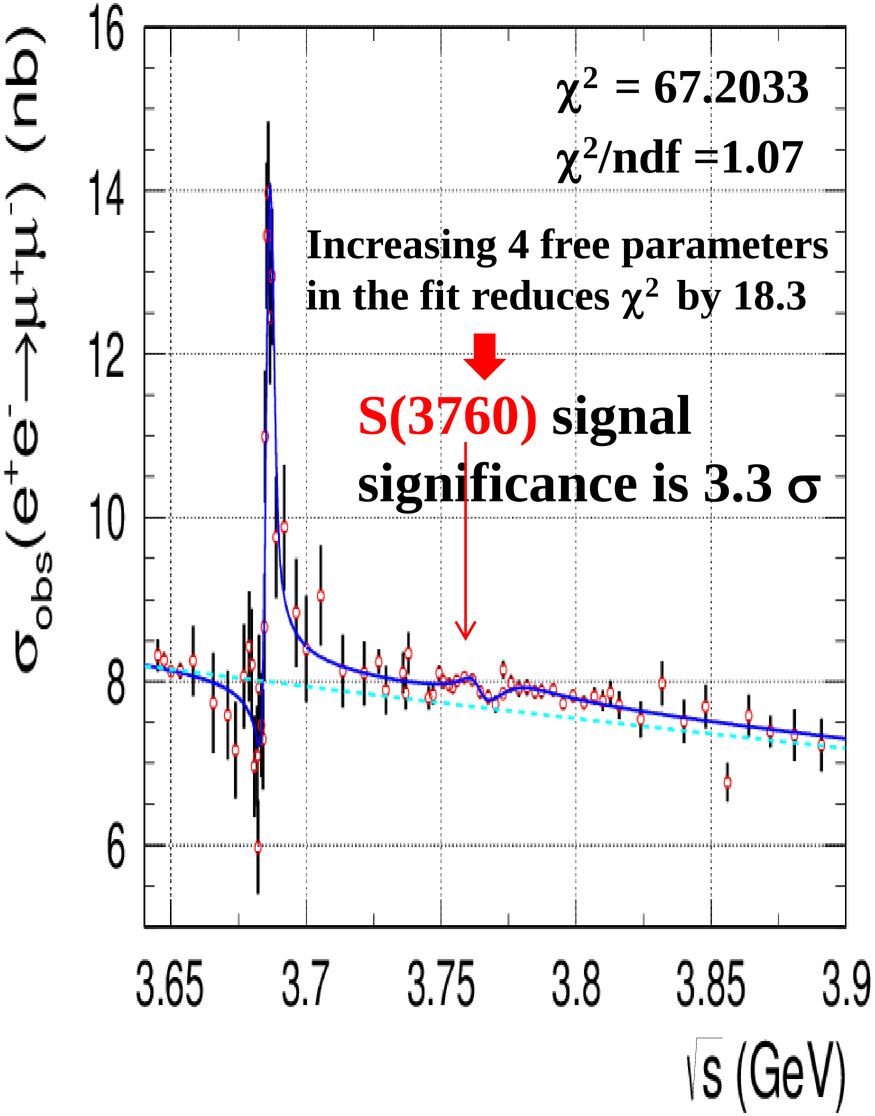
✓ Cnt + ψ(3686) + ψ(3770)



Parameters	Solution#1
$M_{\psi(3686)}$ [MeV]	3686.1 (fixed)
$\Gamma^{tot}_{\psi(3686)}$ [MeV]	294.0 (fixed)
$\Gamma^{ee}_{\psi(3686)}$ [keV]	2.33 (fixed)
$Br[\psi(3686) \to \mu^+\mu^-]$ [$\times 10^{-3}$]	**$8.96 \pm 1.44 \pm \Delta_{sys}$**
$\Phi_{\psi(3686)}$	**$(14.1 \pm 17.2 \pm \Delta_{sys})°$**
$M_{\psi(3770)}$ [MeV]	3773.13 (fixed)
$\Gamma^{tot}_{\psi(3770)}$ [MeV]	27.2 (fixed)
$\Gamma^{ee}_{\psi(3770)}$ [eV]	262 (fixed)
$Br[\psi(3770) \to \mu^+\mu^-]$ [$\times 10^{-5}$]	**$3.07 \pm 3.95 \pm \Delta sys$**
$\Phi_{\psi(3770)}$	**$(-10.2 \pm 21.9 \pm \Delta_{sys})°$**

Fit to the Observed Cross Sections

✓ Cnt + ψ(3686) + ψ(3770) + S_1



Parameters	Solution#1
$M_{\psi(3686)}$ [MeV]	3686.1 (fixed)
$\Gamma^{tot}_{\psi(3686)}$ [MeV]	294.0 (fixed)
$\Gamma^{ee}_{\psi(3686)}$ [keV]	2.33 (fixed)
Br[$\psi(3686) \to \mu^+\mu^-$] [$\times 10^{-3}$]	$6.79 \pm 0.48 \pm \Delta_{sys}$
$\Phi_{\psi(3686)}$	$(22.0 \pm 7.2 \pm \Delta_{sys})$ °
$M_{\psi(3770)}$ [MeV]	3773.13 (fixed)
$\Gamma^{tot}_{\psi(3770)}$ [MeV]	27.2 (fixed)
$\Gamma^{ee}_{\psi(3770)}$ [eV]	262 (fixed)
Br[$\psi(3770) \to \mu^+\mu^-$] [$\times 10^{-5}$]	$71.6 \pm 44.9 \pm \Delta$sys
$\Phi_{\psi(3770)}$	$(37.7 \pm 20.9 \pm \Delta_{sys})$ °
$M_{s(3760)}$ [MeV]	$3763.8 \pm 2.8 \pm \Delta_{sys}$
$\Gamma^{tot}_{s(3760)}$ [MeV]	$8.6 \pm 3.7 \pm \Delta_{sys}$
$\Gamma^{ee}_{s(3760)}$ Br[$\psi(3760) \to \mu^+\mu^-$] [eV]	$0.09 \pm 0.05 \pm \Delta_{sys}$
$\Phi_{s(3760)}$	$(174.2 \pm 42.7 \pm \Delta_{sys})$ °

Fit to Brn-Cnt-Drss-Res Cross Sections

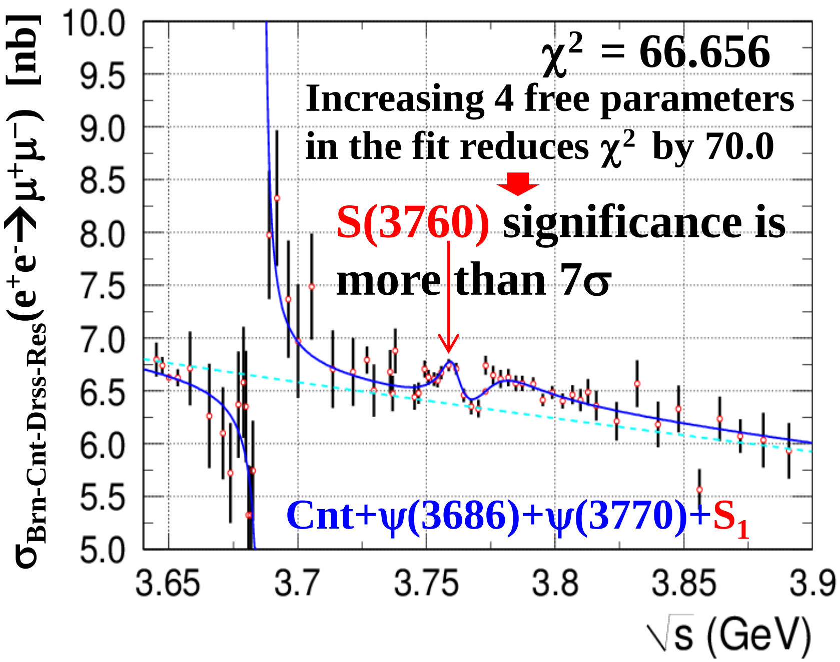
Using the values of the resonance parameters obtained by fitting to the observed cross sections, we can determine the ISR correction factor,

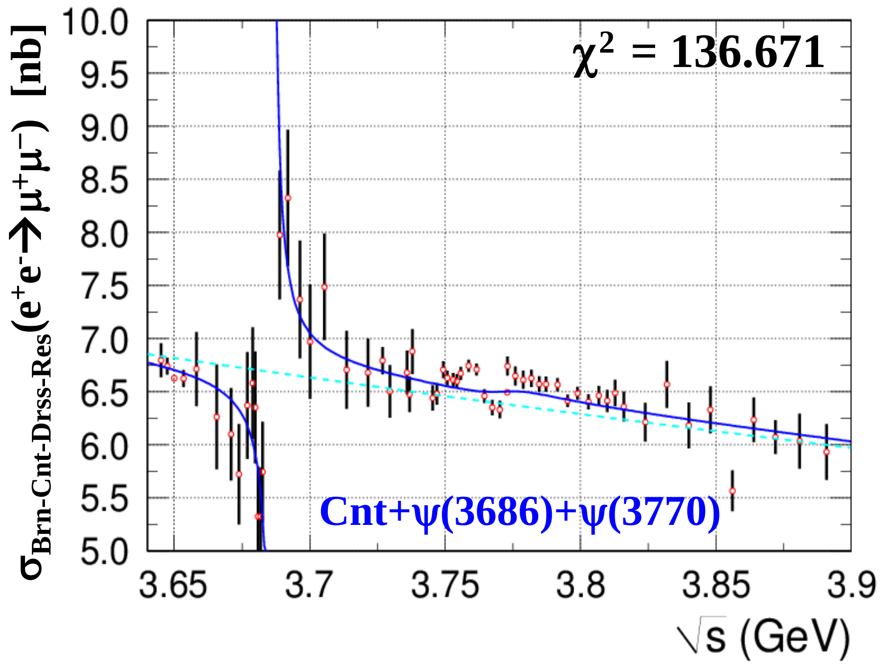
$$f_{\rm ISR}^{\rm Brn-Cnt-Drss-Res} = \frac{\sigma^{\rm exp}_{\mu^+\mu^-}(s)}{\sigma^{\rm exp-Brn-Cnt-Drss-Res}_{\mu^+\mu^-}(s)},$$

and the Brn-Cnt-Drss-Res cross sections,

$$\sigma_{\rm Brn-Cnt-Drss-Res}(e^+e^- \to \mu^+\mu^-) = \frac{\sigma^{\rm Obs}_{\mu^+\mu^-}(s)}{f_{\rm ISR}^{\rm Brn-Cnt-Drss-Res}}$$

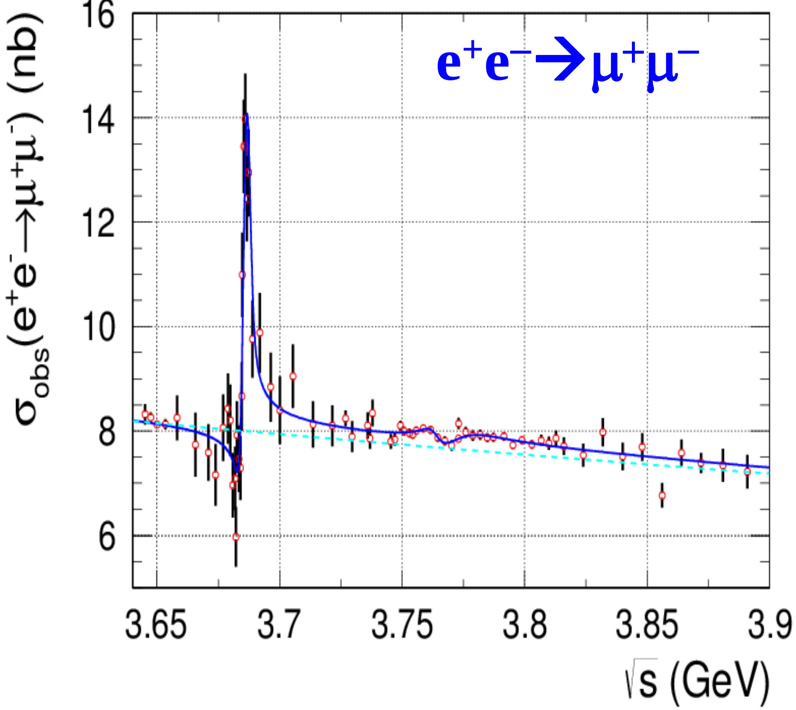
The BES-III publications for reporting $Y(4220)\to\omega\chi_{c0}$, $R(4230)\to h_c\pi^+\pi^-$, and $R(4220)\to J/\psi\pi^+\pi^-$ are all based on analysis of dressed/born cross sections. If we analyze corresponding dressed cross sections, the signal significance of S(3760) would be more than 7σ .



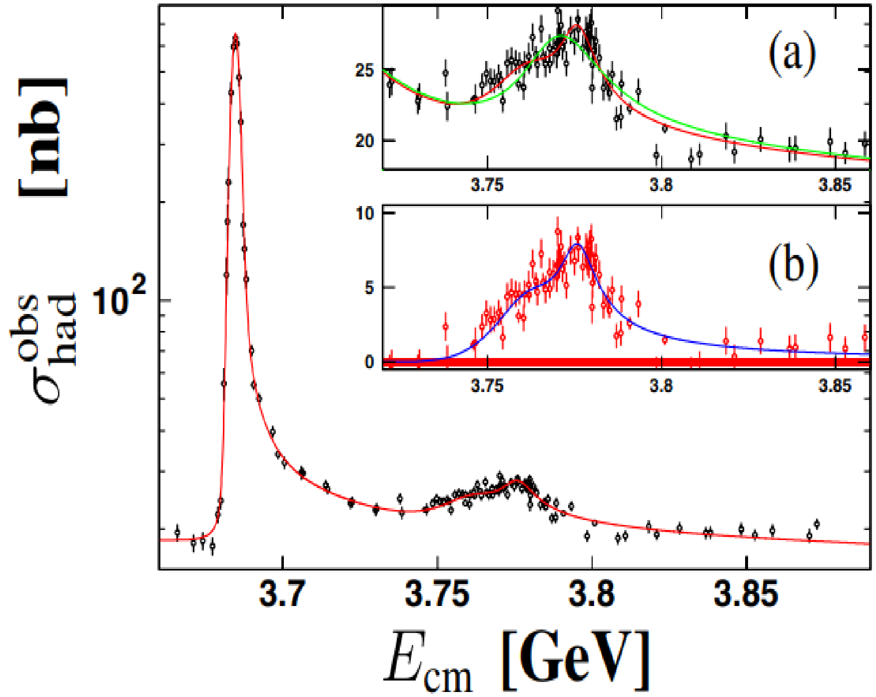


Comparison with Other Measurements

This measurement



BES-II: PhysRevLett.101.102004

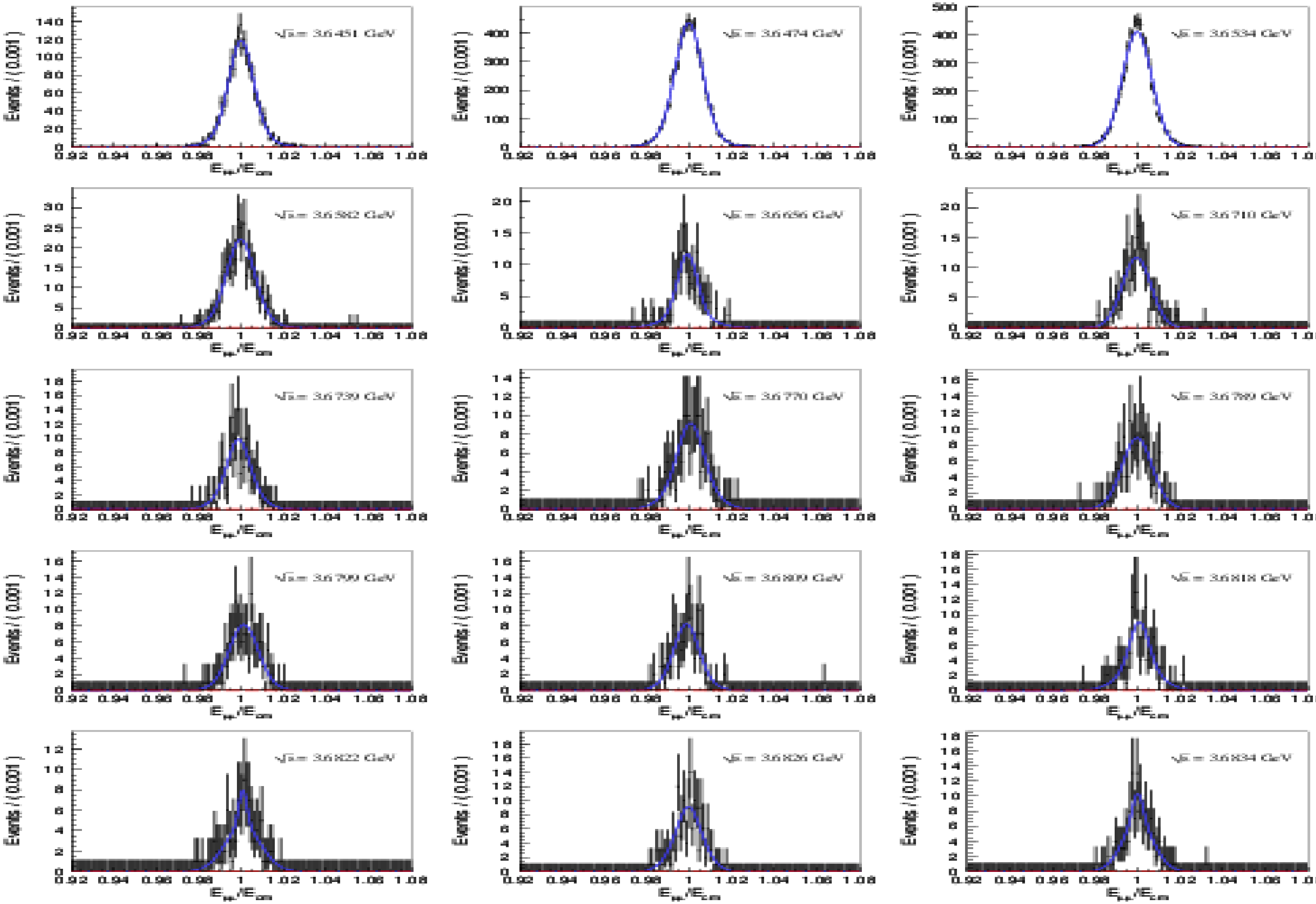


Parameters	This measurement	BES-II
$M_{S(3760)}$ [MeV]	$3763.8 \pm 2.8 \pm \Delta_{sys}$	$3762.6 \pm 11.8 \pm 0.5$
$\Gamma^{tot}_{S(3760)}$ [MeV]	$8.6 \pm 3.7 \pm \Delta_{sys}$	$49.9 \pm 32.1 \pm 0.1$

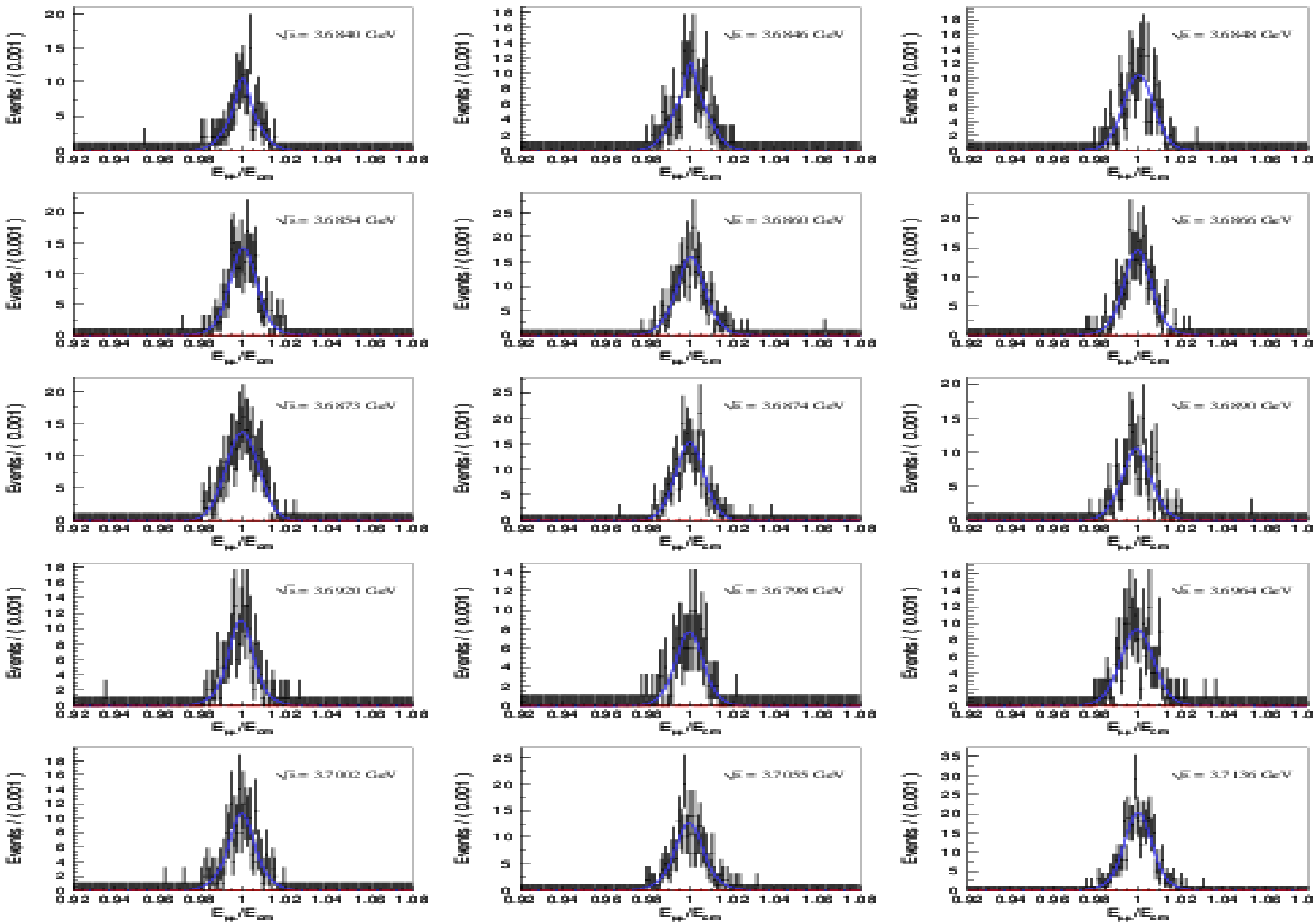
Summary

- **We measured the observed cross sections for $e^+e^- \to \mu^+\mu^-$ at energies from 3.645 to 3.890 GeV.**
- **We made the first direct measurement of the branching fractions of $\psi(3770) \to \mu^+\mu^-$ decays.**
- **We made the first measurements of the electromagnetic phase angles of the heavy $\psi(3686, 3770)$ relative to the continuum $e^+e^- \to \mu^+\mu^-$.**
- **We observed an evidence for $S(3760) \to \mu^+\mu^-$ with a signal significance of 3.3σ (of more than 7σ) by analyzing these observed (corresponding Brn-Cnt-Drss-Res) cross sections.**
- **The mass and total width of S(3760) are consistent within errors with those R(3760) observed by the BES collaboration.**

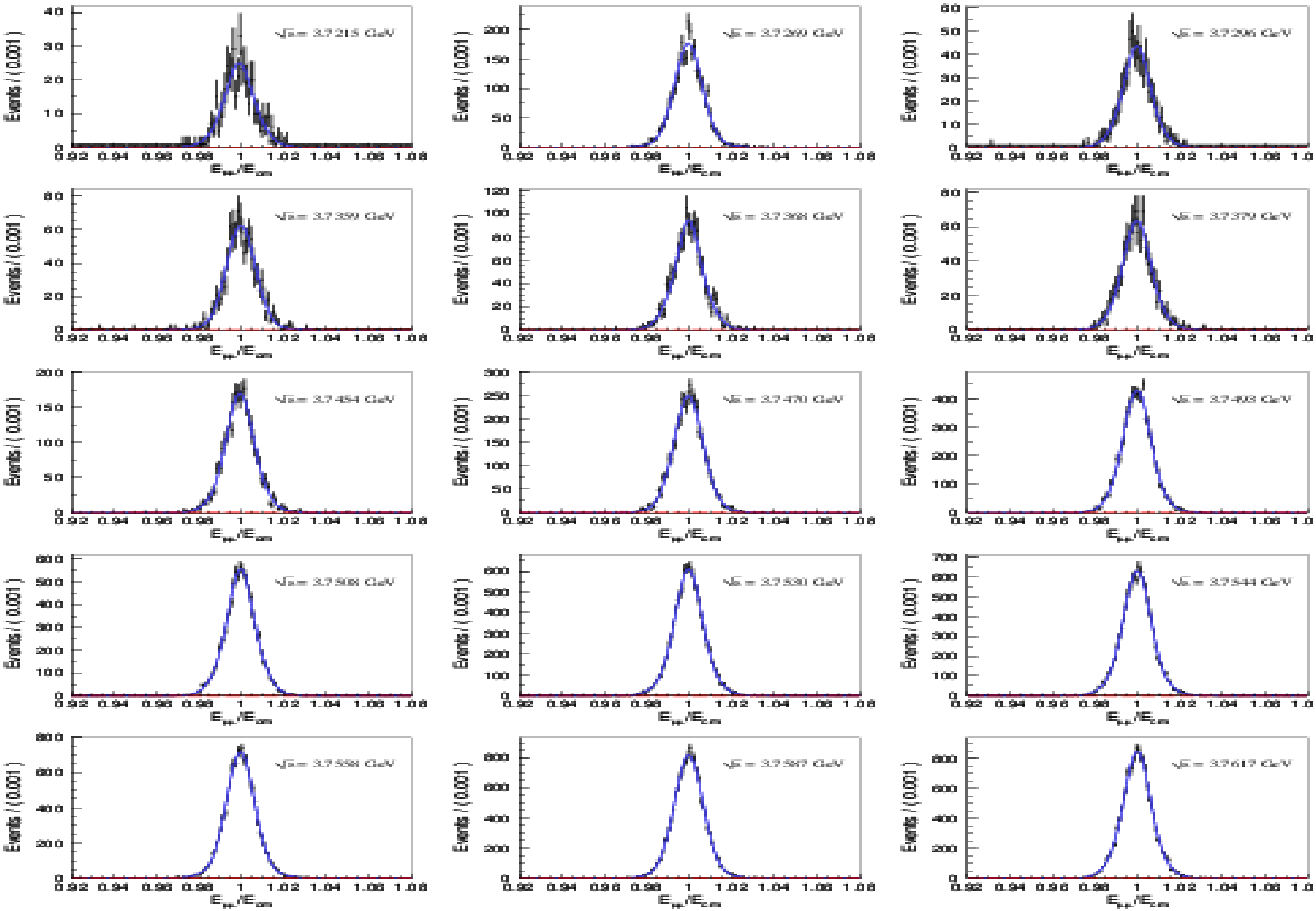
Distributions of $E_{measured}/E_{cm}$ for $e^+e^- \rightarrow \mu^+\mu^-$



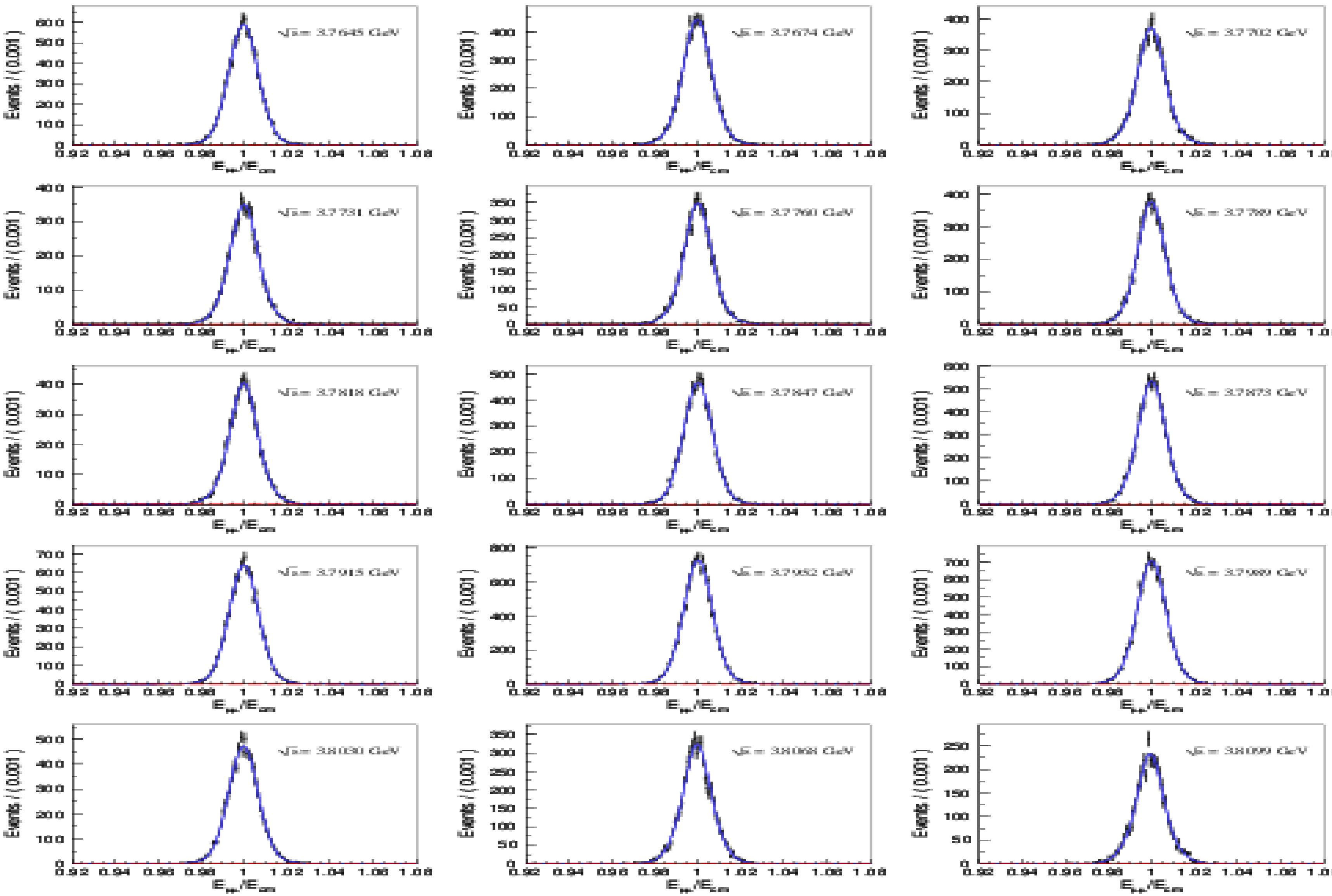
Distributions of $E_{measured}/E_{cm}$ for $e^+e^- \rightarrow \mu^+\mu^-$



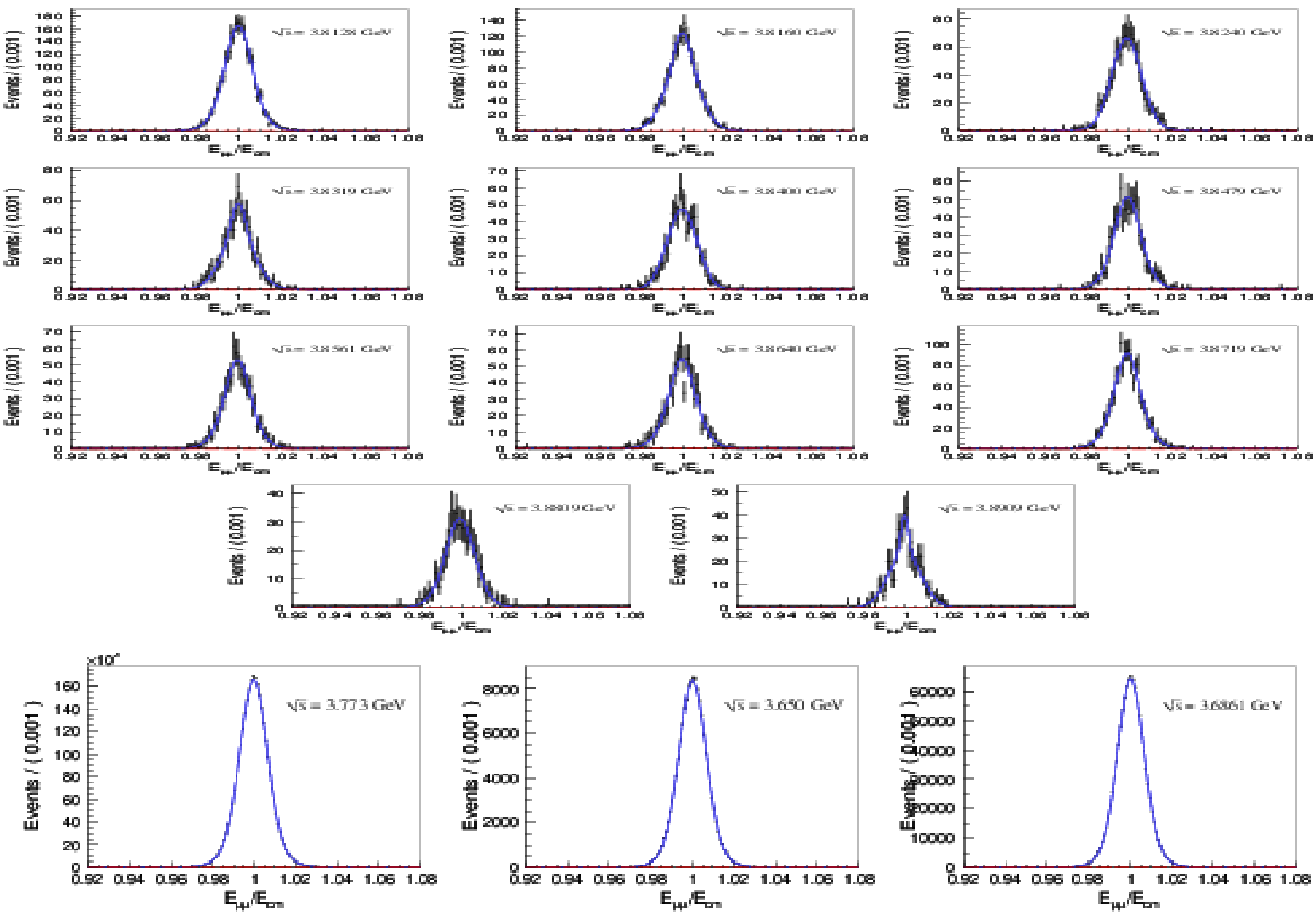
Distributions of $E_{measured}/E_{cm}$ for $e^+e^- \rightarrow \mu^+\mu^-$



Distributions of $E_{measured}/E_{cm}$ for $e^+e^- \rightarrow \mu^+\mu^-$



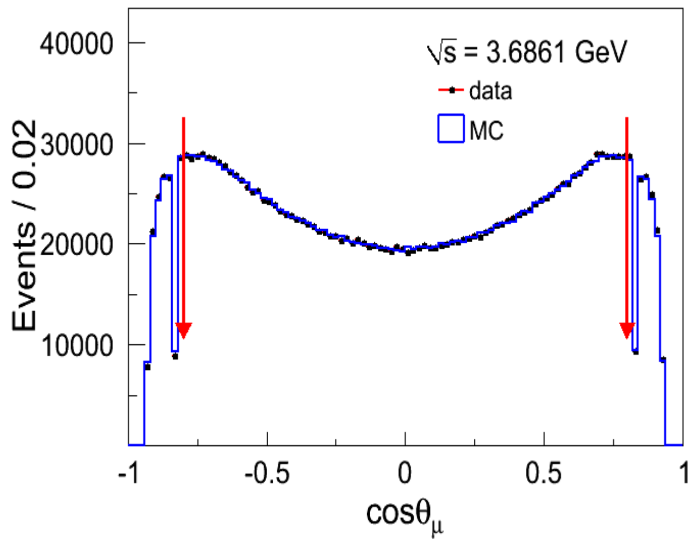
Distributions of $E_{measured}/E_{cm}$ for $e^+e^- \rightarrow \mu^+\mu^-$



Systematic Uncertainties

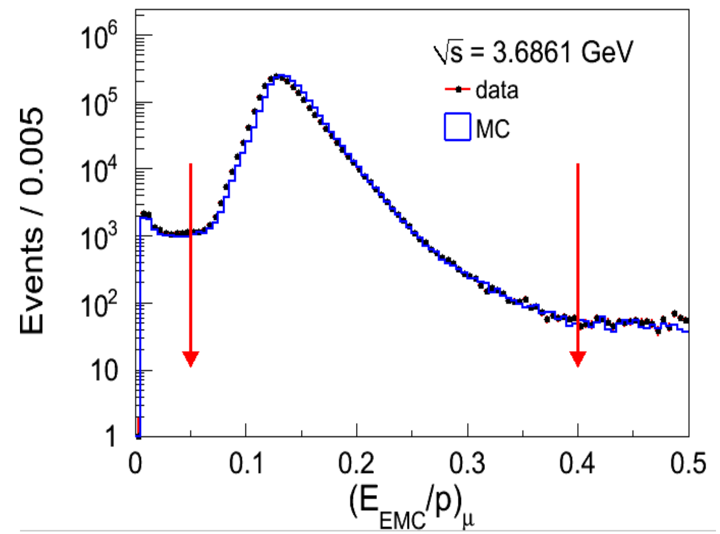
- ✓ **$|\cos\theta| < 0.80$ cut**

  We select $\psi(3686) \rightarrow J/\psi\pi^+\pi^-$ with $J/\psi \rightarrow \mu^+\mu^-$ samples, and generate Monte Carlo simulated events. By comparing the distribution of $|\cos\theta|$ between the data and the MC events, we find that the difference in $|\cos\theta|$ is $(-0.15 \pm 0.04)\%$, which is assigned as the systematic uncertainty



- ✓ **$E_{EMC}/p > 0.05$ and $E_{EMC}/p < 0.4$ cut**

  By comparing the distribution of E_{EMC}/p between the data and the MC events, we find that the difference in the E_{EMC}/p is $(-0.12 \pm 0.01)\%$, which is assigned as the systematic uncertainty



Systematic Uncertainties

✓ |ΔTOF| < 2.0 ns cut

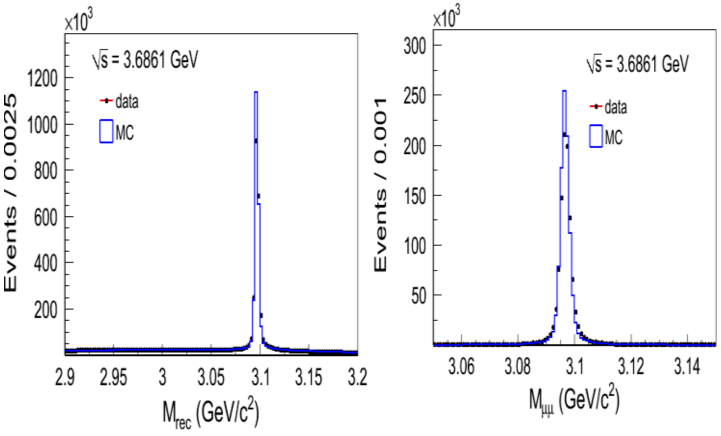
At present we measure the difference in the cross section at 4.230 GeV with this cut and without this cut. We take the difference as the estimated uncertainty due to this cut, which is -0.48%.

✓ $(P_{\mu+} + P_{\mu-}) > 0.9E_{cm}$ cut

We also measure the difference in the cross section at 4.230 GeV with this cut and without this cut, and take the difference as the estimated uncertainty due to this cut, which is -0.59%.

✓ 4-C kinematic fit

We select/generate $\psi(3686) \rightarrow J/\psi\pi^+\pi^-$ with $J/\psi \rightarrow \mu^+\mu^-$ samples, and compare the number of events satisfying K.F. requirement. The difference between the data and the MC is $(0.97 \pm 0.26)\%$, which is assigned as the systematic uncertainty due to the K.F.



Systematic Uncertainties

- ✓ **Fit to $E_{\mu\mu}/E_{cm}$**
  - **(1) Bin size : 0.001 GeV/bin → 0.0027 GeV/bin;**
  - **(2) Fit range : [0.92, 1.08] → [0.96, 1.04];**
  - **(3) Background PDF: 1-order polynomial → 0-order polynomial;**
  - **(4) Signal PDF : Double-Gaussian function → MC shape;**

	Bin size	Fit range	Background PDF	Signal PDF	Total
σ_{sys}	-0.59%	-0.65%	-0.59%	-0.63%	1.23%

- ✓ **Tracking efficiency**
  1.0% per track

(M.Ablikim et al.(BESIII Collaboration), Phys Rev.Lett.110,252001(2013))

- ✓ **Luminosity**
  1.0%

(Chin. Phys. C 39, 093001 (2015))
(M. Ablikim et al. (BESIII Collaboration), Chin. Phys. C 41, 063001 (2017))

- ✓ **Generator**
  1.0%

[https://www2.pv.infn.it/~hepcomplex/babayaga.html]

Correlations

The systematic error sources are correlated among the different energy points, so these cannot be considered directly in the fit. But their effects on the final results can be estimated by the "offset method [see M. Botje, J. Phys. G 28 779(2002)]"

- **When constructing the χ^2 to fit the cross section, we have considered the correlation between different energy points.**
- **At first, we fit the cross sections only considering the statistical uncertainties. At this stage, the uncertainties of the parameter values from the fits are only due to the statistical.**
- **To estimate the systematic uncertainties of the parameter values of the structures, we shifted the observed cross sections by $+1\Delta_{sys}$ or $-1\Delta_{sys}$, where Δ_{sys} is the correlated systematic error, then we fitted these cross sections again.**

The effects of the systematic uncertainty (correlation between energy points) on the parameters are still in progress.