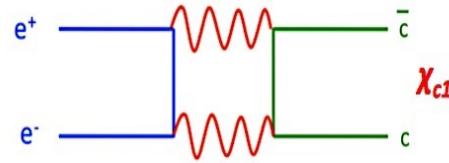


# $e^+e^- \rightarrow \chi_{c1}$ at BESIII



Yuping GUO on behalf of BESIII  
(Fudan university | [guoyp@fudan.edu.cn](mailto:guoyp@fudan.edu.cn))



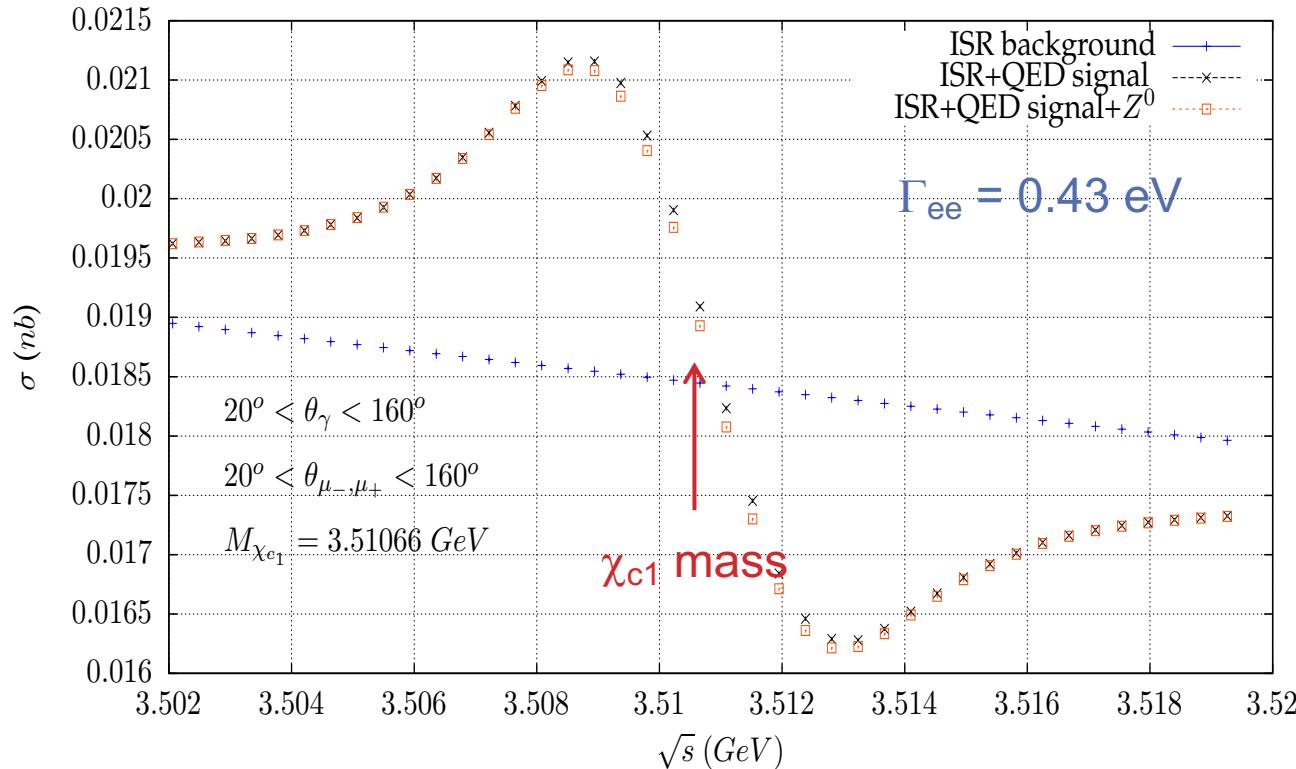
STRONG 2020 Virtual Workshop on  
“Spacelike and Timelike determination of the Hadronic Leading  
Order contribution to the Muon g-2”

# Motivation

- Up to now, in  $e^+e^-$  annihilation only vector resonances with  $J^{PC}=1^{--}$  are observed
- The C-even states can be produced directly through a process with two virtual photons or neutral current reaction
- The production rate is proportional to the electronic width of the states ( $\Gamma_{ee}$ ). For  $\chi_{c1}$  state:
  - Unitarity limit:  $\Gamma_{ee} > 0.044$  eV *J. Laplan, J. H. Kühn, PLB78, 252 (1978)*
  - Vector Dominance Model:  $\Gamma_{ee} = 0.46$  eV; OR  $\Gamma_{ee} \sim 0.1$  eV *A. Denig, F. K. Guo, C. Hanhart, A. V. Nefediev, PLB736, 221 (2014)*
  - Non-relativistic QCD:  $\Gamma_{ee} \sim 0.1$  eV *N. Kivel, M. Vanderhaeghen, JHEP02, 032 (2016)*
  - Latest prediction:  $\Gamma_{ee} = 0.43$  eV; interference with background process! *H. Czyż, J. H. Kühn, S. Tracz, PRD94, 034033 (2016)*
- Excellent performance of BEPCII/BESIII offer opportunity to measure for the first time process  $e^+e^- \rightarrow \chi_{c1}(1^{++})$

# Latest Theoretical Prediction

H. Czyż, J. H. Kühn, S. Tracz, PRD94, 034033 (2016)



Large interference effects → distortion of the total cross section

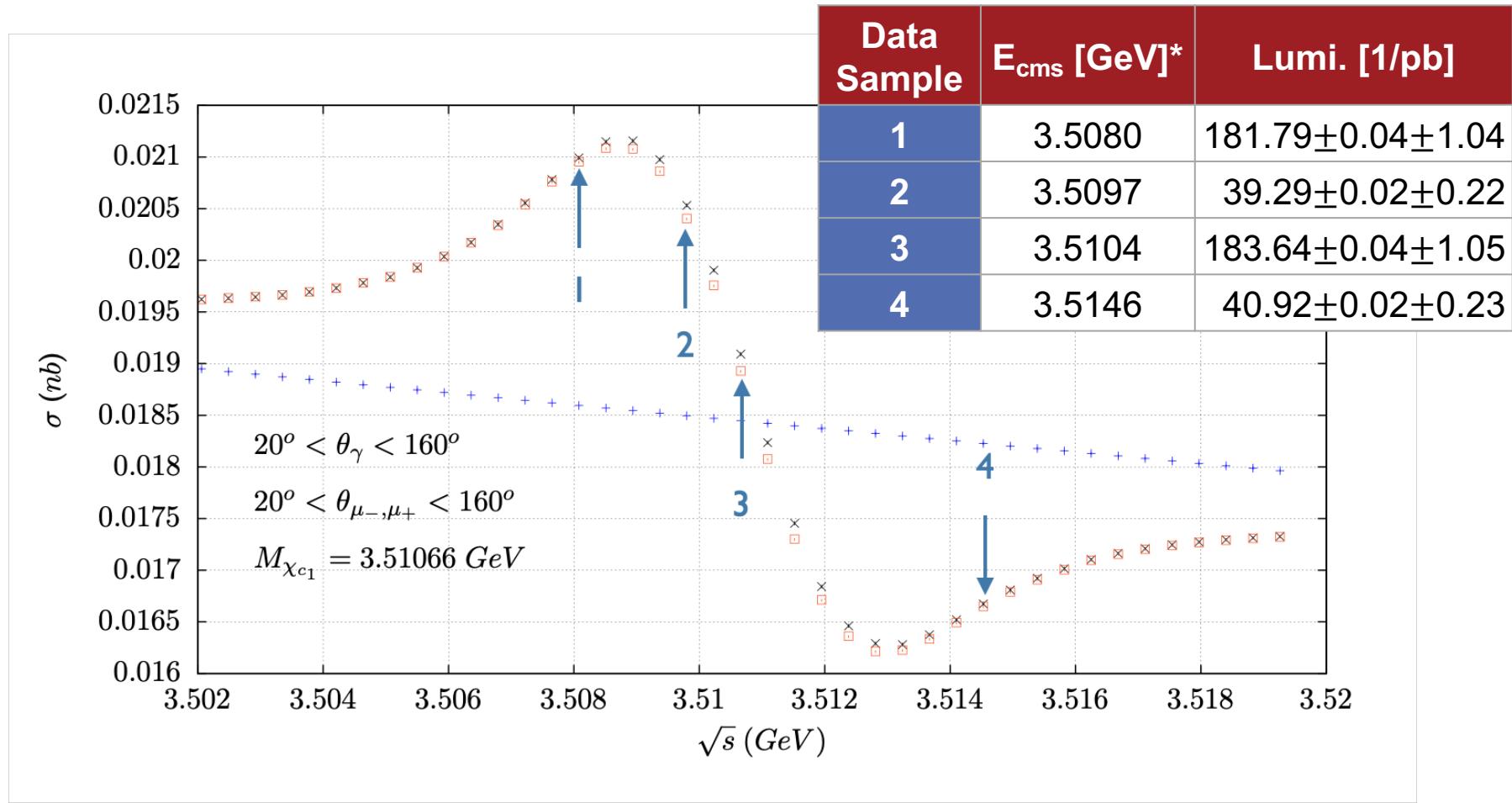
Implemented in PHOKHARA generator

\* ISR background:  $e^+e^- \rightarrow \gamma\mu^+\mu^-$ ; ISR + QED signal (+ $Z^0$ ):  $e^+e^- \rightarrow \gamma\mu^+\mu^- + e^+e^- \rightarrow \chi_{c1} \rightarrow \gamma J/\psi \rightarrow \gamma\mu^+\mu^-$

\*  $\theta_{\gamma/\mu}$ : polar angle of  $\gamma/\mu$ ;

$M_{\chi_{c1}}$ : nominal mass of  $\chi_{c1}$  state

# Data Samples



\* $E_{\text{cms}}$  and beam energy spread measured by BEMS

Uncertainty of  $E_{\text{cms}}$ :  $\pm 0.05$  MeV ; Beam energy spread:  $(736 \pm 27)$  keV

→ Input parameters in PHOKHARA

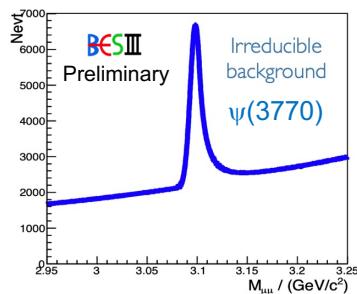
# Analysis Strategy

- Signal process:  $e^+e^- \rightarrow \chi_{c1}$ ,  $\chi_{c1} \rightarrow \gamma J/\psi$  ( $Br: 34\%$ ),  $J/\psi \rightarrow \mu^+\mu^-$  ( $Br: 6\%$ )
- Irreducible background process: ISR production of  $(J/\psi + \mu^+\mu^-)$
- Validate the description of the ISR background simulated with PHOKHARA generator by using:
  - High statistics data samples at  $\psi(3770)$  and 4.178 GeV,  $\sim 3 \text{ fb}^{-1}$  each
  - Off-peak data samples at 3.581 GeV and 3.670 GeV,  $\sim 85 \text{ pb}^{-1}$  each
- Check  $e^+e^- \rightarrow \chi_{c1}$  signal by searching for excess (reduction) of events beyond ISR background
- Study of interference pattern by combining the four data samples:
  - No interference: excess of events at 3<sup>rd</sup> point ( $\chi_{c1}$  nominal mass)
  - With interference (*if as predicted by [PRD94, 034033 (2016)]*): excess of events at 1<sup>st</sup> and 2<sup>nd</sup> points, reduction at 4<sup>th</sup> point

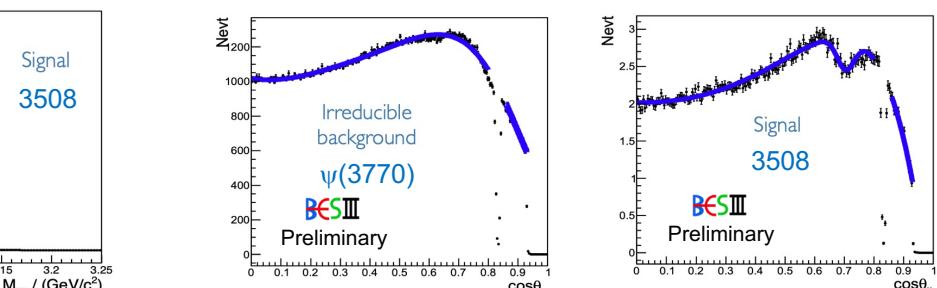
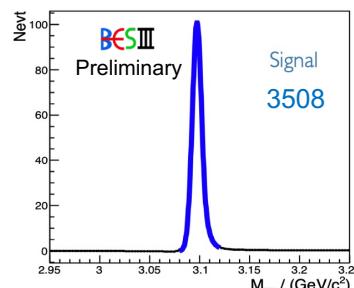
# Validation of Irreducible Background

- Performing two-dimensional fit to  $M(\mu^+\mu^-)$  and  $|\cos\theta_\mu|$  in regions of  $[2.95, 3.25]$  GeV/ $c^2$  and  $[0,1]$
- PDF: irreducible background component +  $R(1^{++})^*$  component, line shapes both extracted from MC simulations
- The number of events for the  $R$  component is expected to be **zero** in case of a perfect background MC simulation

Illustration of PDFs used in the fit:



Projection on  $M(\mu^+\mu^-)$



Projection on  $|\cos\theta_\mu|$

\*  $R(1^{++})$  is an assumed  $1^{++}$  resonance with mass of  $\psi(3770)$  or 4180 or 3581 or 3670

# Validation of Irreducible Background

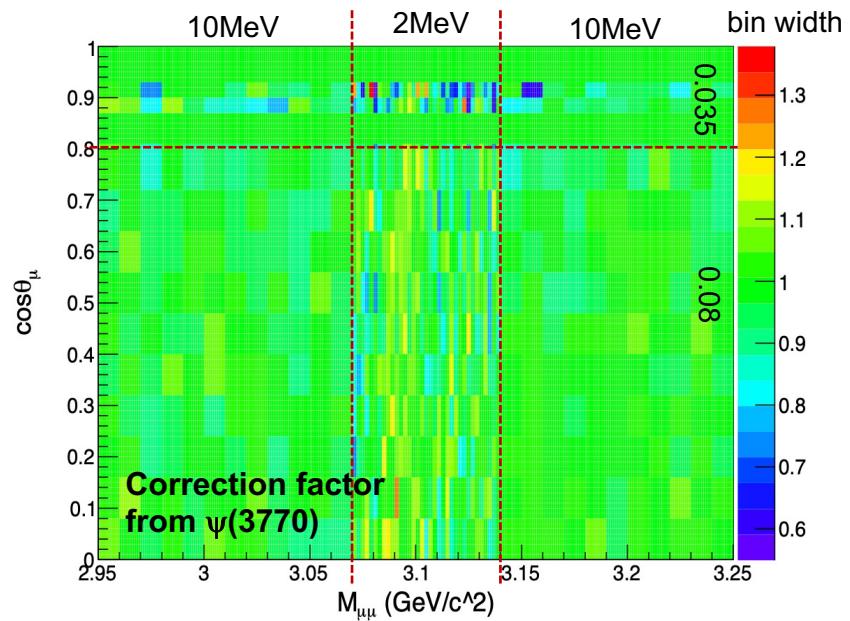
$\sqrt{s}$ (MeV)	$L$ ( $\text{pb}^{-1}$ )	$N_{\text{sig}}$ w/o Cor.	$N_{\text{sig}}$ w/ Cor.
3773.0	2932.4	$1097 \pm 25$ ( $7.6\sigma$ ; $1.9\sigma_{180}$ )	$47 \pm 50$ ( $0.3\sigma$ ; $0.1\sigma$ )
4178.4	3192.5	$544 \pm 7$ ( $5.0\sigma$ ; $1.2\sigma_{180}$ )	$18 \pm 36$ ( $0.2\sigma$ ; $0.0\sigma$ )
3581.5	85.3	$10 \pm 1$ ( $0.3\sigma$ ; $0.4\sigma_{180}$ )	$3 \pm 6$ ( $0.4\sigma$ ; $0.6\sigma$ )
3670.2	83.6	$43 \pm 7$ ( $1.6\sigma$ ; $2.3\sigma_{180}$ )	$7 \pm 10$ ( $0.2\sigma$ ; $0.3\sigma$ )

- The number of events for the  $R$  component is not zero
- The statistical significance differs for different data samples, but below  $2.3\sigma$  if normalizing to  $180/\text{pb}$  ( $\sigma_{180}$ )
- Cannot be explained by data-MC detection differences (e.g. tracking efficiency etc.), can be the limitation of the PHOKHARA generator → Two-dimensional correction, correction factors from 3773 or 4178 sample
- The number of events for the  $R$  component consistent with zero after correction (w/ Cor.) for all control samples
- Correction factors applied to MC simulations of irreducible background at all data samples

# Validation of Irreducible Background

Two-dimensional correction procedure

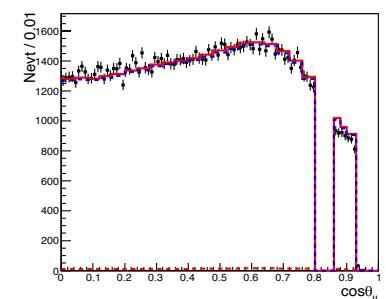
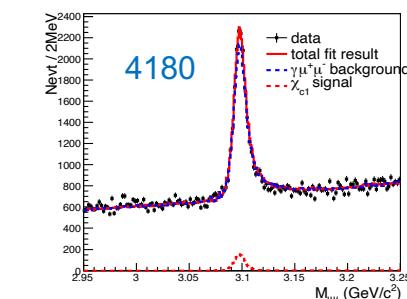
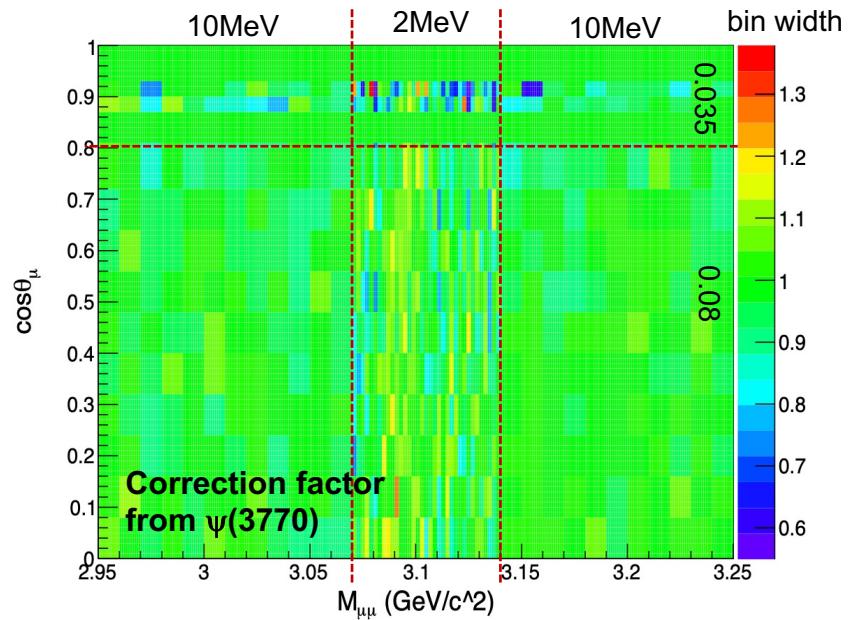
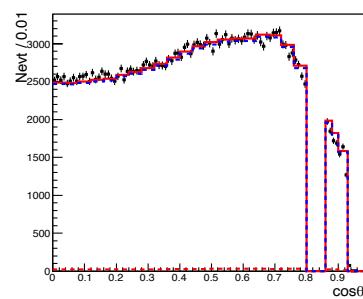
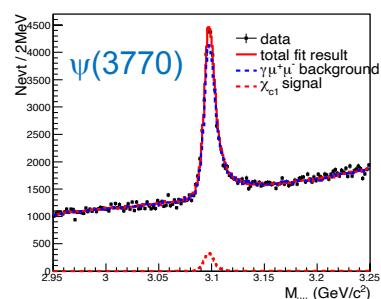
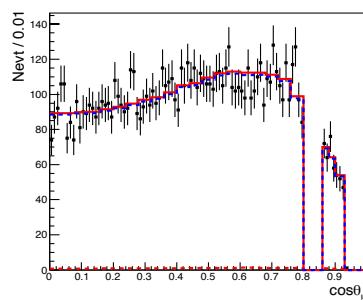
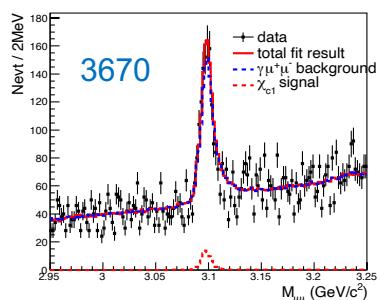
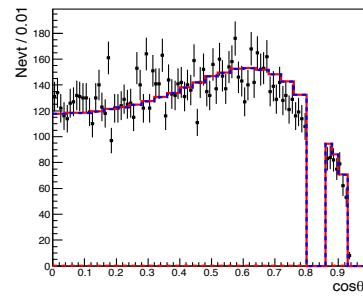
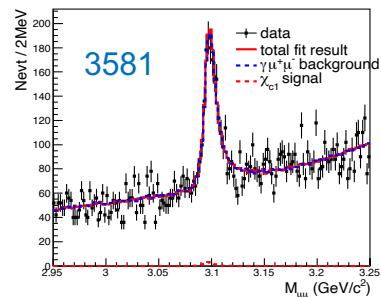
- Correction factor  $f(m, \cos\theta_\mu)$  obtained by comparing data and MC simulation of ISR background at  $\psi(3770)$  or 4180
- Event-by-event correction applied to ISR background events according to  $[m, \cos\theta_\mu]$  of the event



# Validation of Irreducible Background

Two-dimensional correction procedure

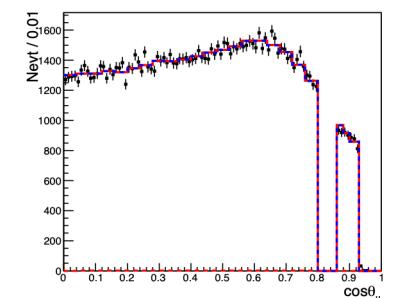
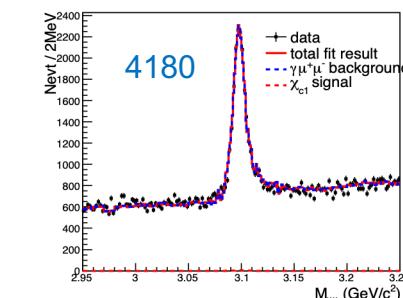
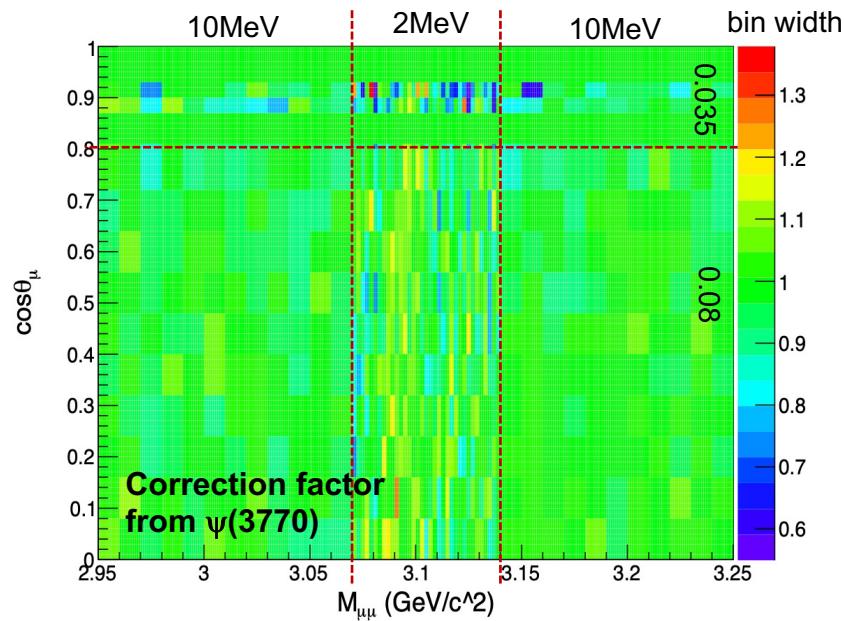
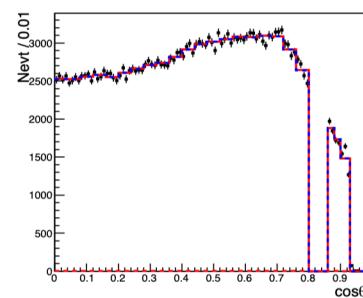
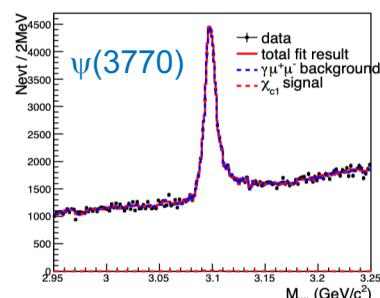
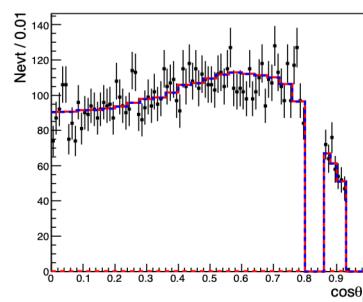
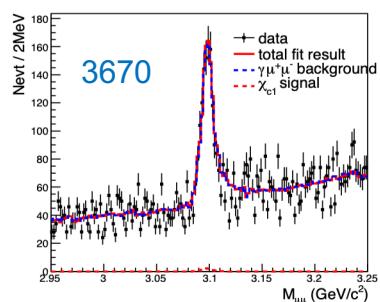
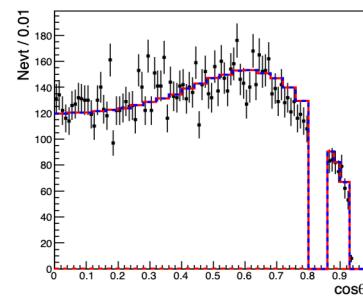
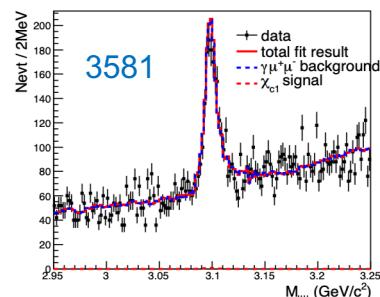
Before Cor.



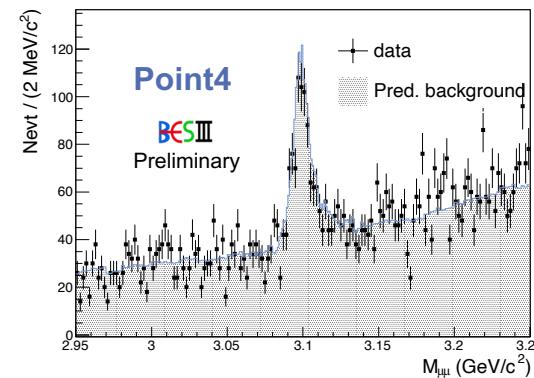
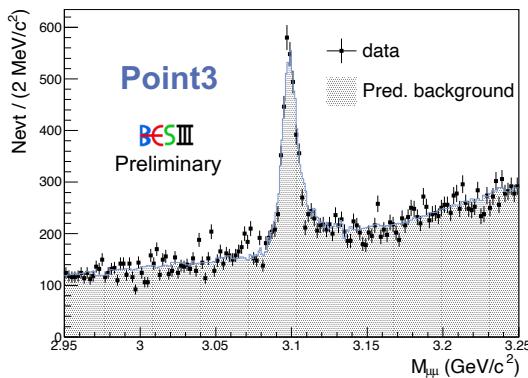
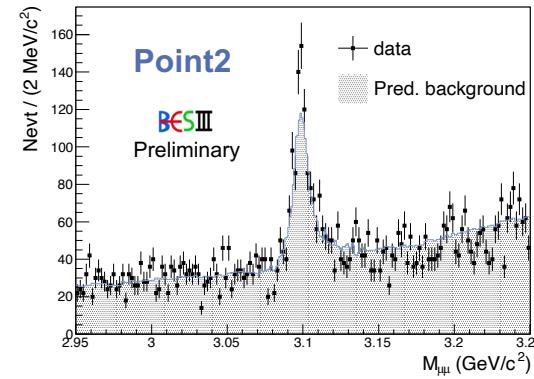
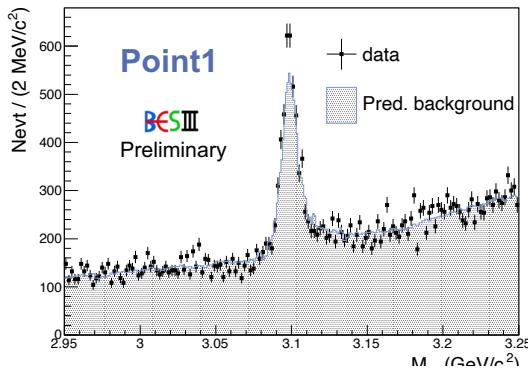
# Validation of Irreducible Background

## Two-dimensional correction procedure

## After Cor.

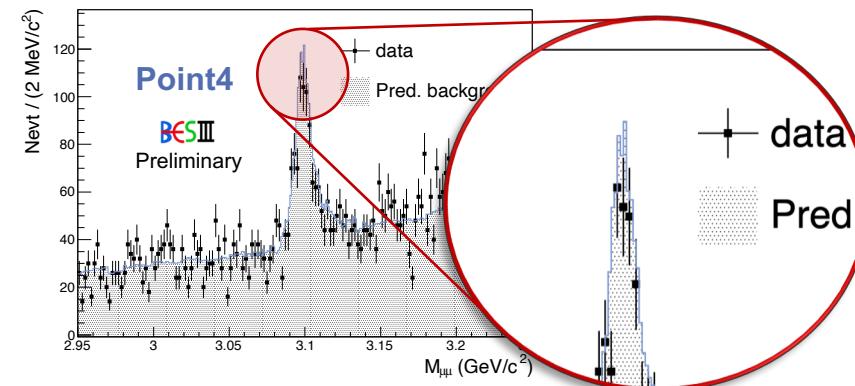
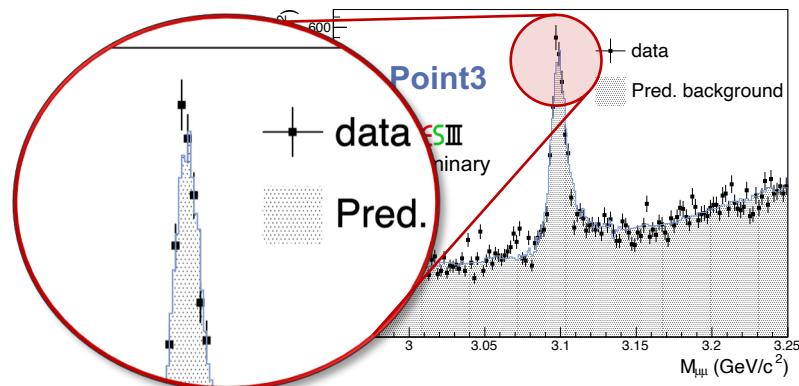
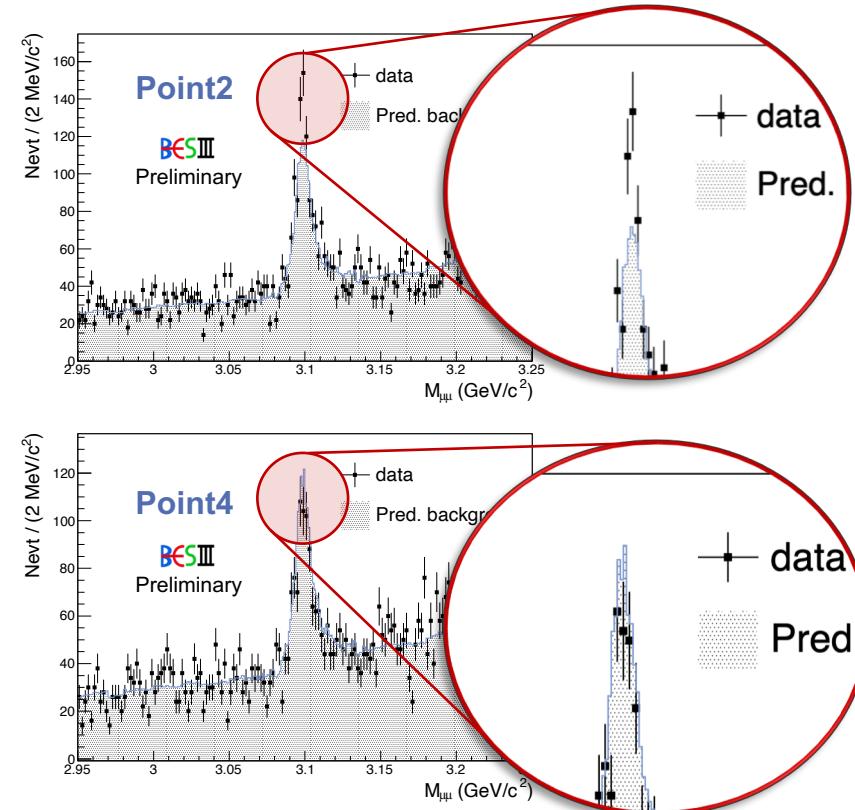
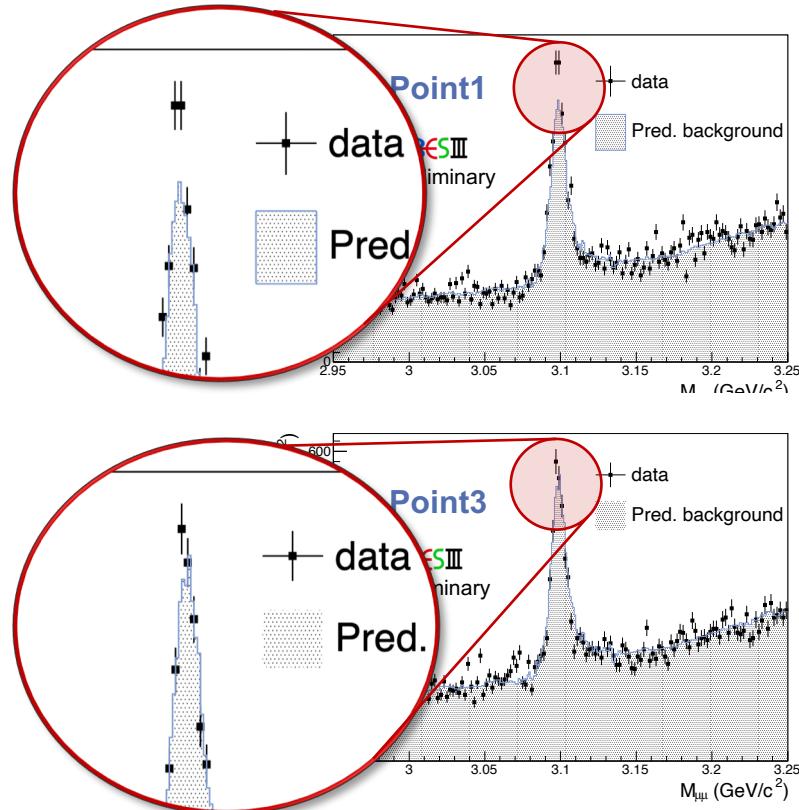


# $M(\mu^+\mu^-)$ at $\chi_{c1}$ Scan Data Samples



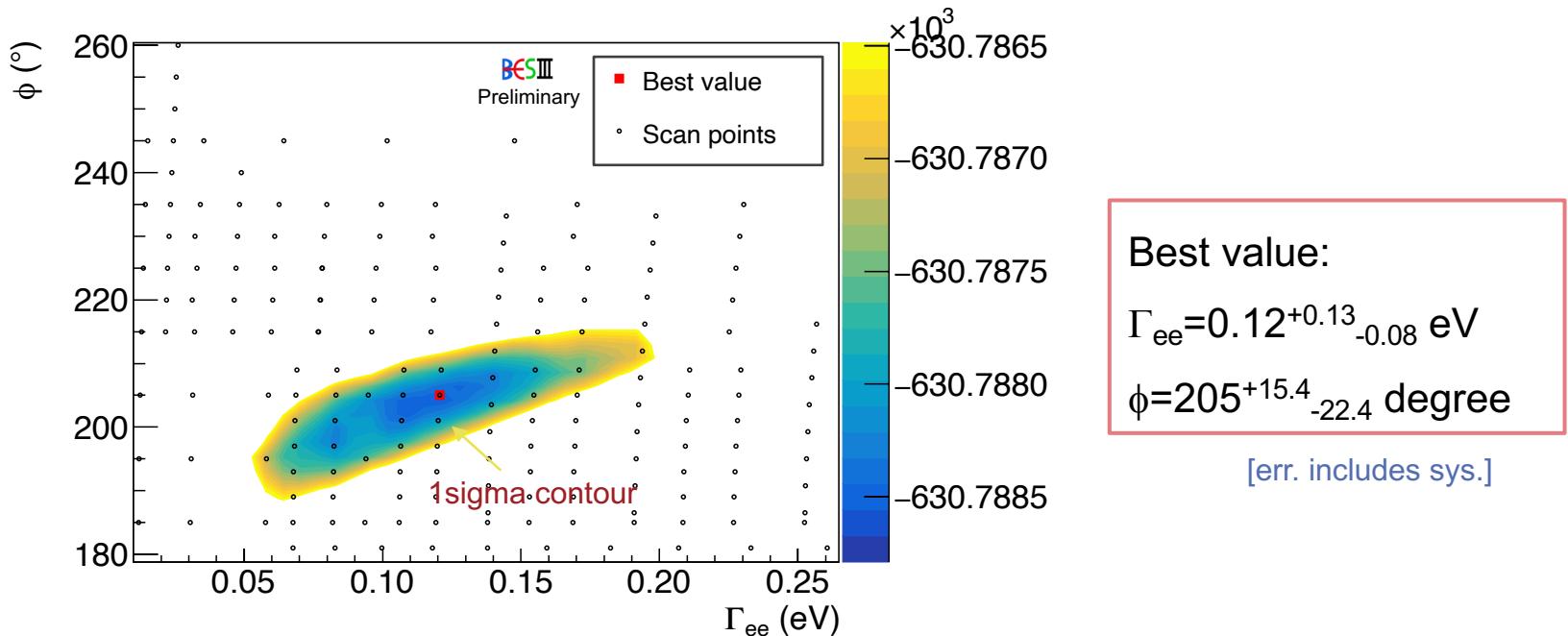
- The number of  $J/\psi$  events is enhanced for the first two points, and is decreased for the last point
- Phenomenon agrees with theoretical prediction with interference

# $M(\mu^+\mu^-)$ at $\chi_{c1}$ Scan Data Samples



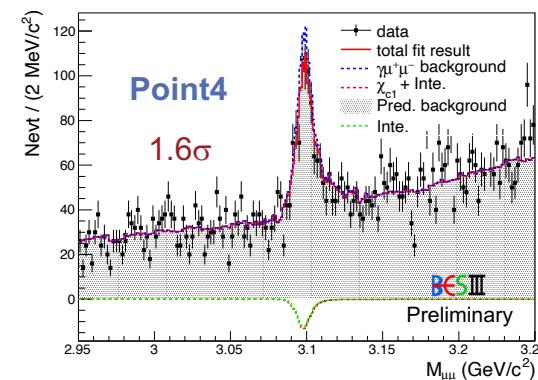
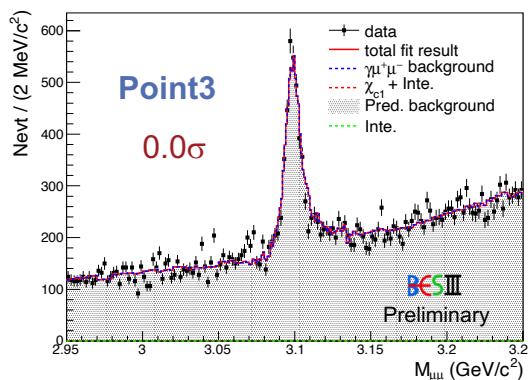
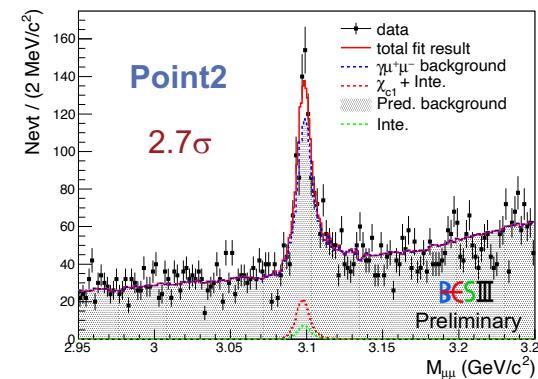
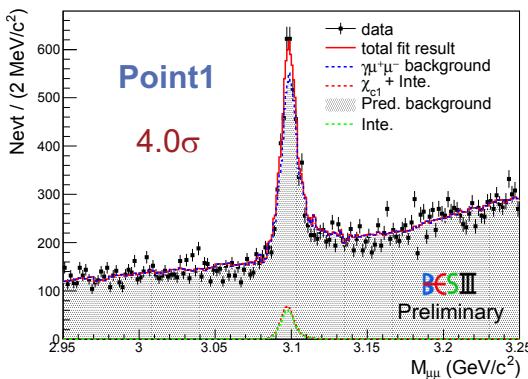
- The number of  $J/\psi$  events is enhanced for the first two points, and is decreased for the last point
- Phenomenon agrees with theoretical prediction with interference

# Determination of $\Gamma_{ee}$ and $\phi$



- Use four  $\chi_{c1}$  data samples simultaneously (common fit)
- $\Gamma_{ee}$  and  $\phi$  scanned (open circles) in parameter space
- Two-dimensional fit to  $M(\mu^+\mu^-)$  and  $|\cos\theta_\mu|$  with different parameters of  $[\Gamma_{ee}, \phi]$
- Best value (red dot) corresponds to the maximum likelihood value

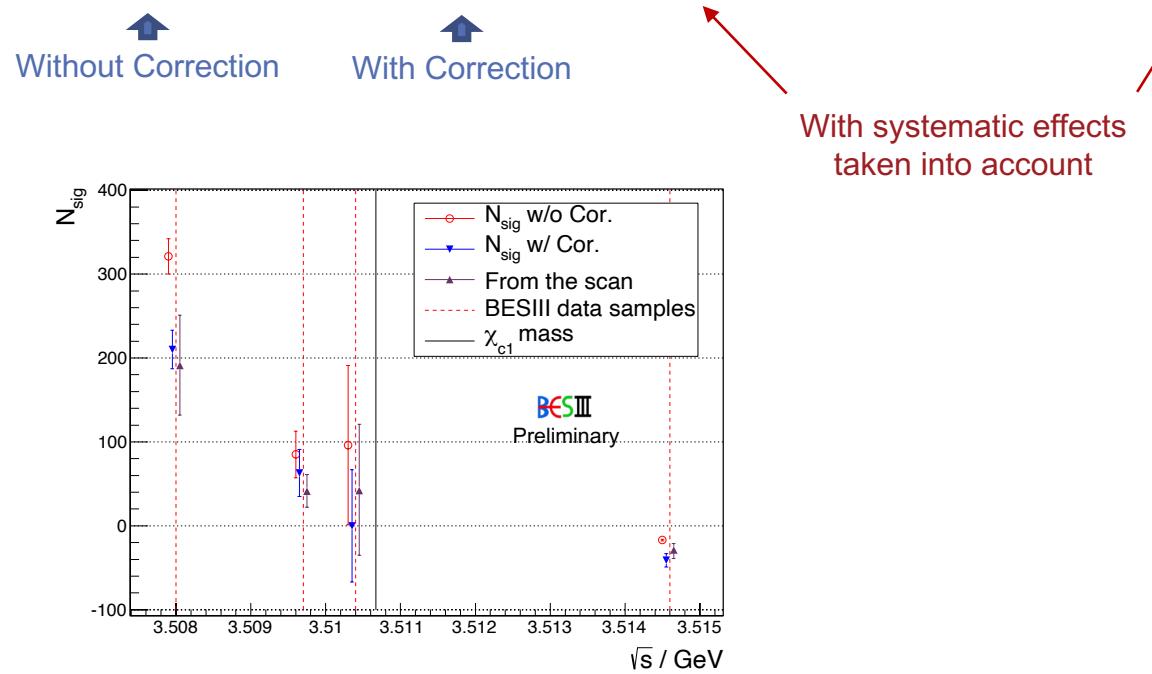
# Individual Fit to Each Data Sample



- Two-dimensional fit to  $M(\mu^+\mu^-)$  and  $|\cos\theta_\mu|$  with best value of  $[\Gamma_{ee}, \phi]$
- PDF: signal + irreducible background + interference; line shape from MC simulation
- $N_{int}$  constrained to  $N_{sig}$  and  $N_{bkg}$  by  $N_{int} = f \cdot \sqrt{N_{sig} \cdot N_{bkg}}$

# Numerical Results

$\sqrt{s}$ (MeV)	$L$ ( $\text{pb}^{-1}$ )	$N_{\text{sig}}$ w/o Cor.	$N_{\text{sig}}$ w/ Cor.	Common fit to scan points
3508.0	181.8	$321 \pm 21$ ( $6.5\sigma$ )	$210 \pm 15 \pm 18$ ( $4.1\sigma$ ; $4.0\sigma_{\text{low}}$ )	$191^{+60}_{-59}$ ( $4.5\sigma$ ; $4.0\sigma_{\text{low}}$ )
3509.7	39.3	$85 \pm 28$ ( $3.9\sigma$ )	$63 \pm 27 \pm 6$ ( $2.8\sigma$ ; $2.7\sigma_{\text{low}}$ )	$41^{+20}_{-19}$ ( $2.4\sigma$ ; $2.3\sigma_{\text{low}}$ )
3510.4	183.6	$96 \pm 95$ ( $1.2\sigma$ )	$0 \pm 62 \pm 26$ ( $0.1\sigma$ ; $0.0\sigma_{\text{low}}$ )	$42^{+79}_{-77}$ ( $-1.7\sigma$ ; $-2.5\sigma_{\text{low}}$ )
3514.6	40.9	$-17 \pm 1$ ( $0.8\sigma$ )	$-41 \pm 3 \pm 7$ ( $1.8\sigma$ ; $1.6\sigma_{\text{low}}$ )	$-29^{+8}_{-10}$ ( $1.6\sigma$ ; $1.7\sigma_{\text{low}}$ )
Combined	445.6	—	—	( $5.3\sigma$ ; $5.1\sigma_{\text{low}}$ )



# Summary

## First search of the $\chi_{c1}$ direct production at $e^+e^-$ annihilation

- Data samples collected at four energy points (445.6/pb in total), used for signal search as well as interference effect study
- Control samples (6294/pb in total) at various center-of-mass energies used to validate the irreducible background, good agreement after correction
- Direct production of  $e^+e^- \rightarrow \chi_{c1}(1^{++})$  is observed with statistical significance  $> 5\sigma$ ;  $\Gamma_{ee} = 0.12^{+0.13}_{-0.08}$  eV and  $\phi = 205^{+15.4}_{-22.4}$  degree
- Interference pattern around the  $\chi_{c1}$  mass is observed, as predicted
- New production method of C-even states (conventional or exotic) in  $e^+e^-$  experiments

Thank you for your attention!

# **BACKUP SLIDES**

# Selection of $e^+e^- \rightarrow \gamma\mu^+\mu^-$

- Two good charged tracks (standard selection), opposite charge
- At least one good photon (standard selection)
- Select photon with 4 constraint kinematic fit, smallest  $\chi^2$
- Bhabha events rejection:
  - Energy deposited in EMC:  $E(+/-) < 0.4$  GeV
  - Polar angle:  $|\cos\theta_\mu| > 0.86$  or  $< 0.8$
- ISR background events suppression:  $|\cos\theta_\gamma| < 0.8$
- Background level from non-  $\gamma\mu^+\mu^-$  final state: <0.2%, flatly distributed in  $M(\mu^+\mu^-)$

# Systematic Uncertainty

- Luminosity: 0.6%
- Detection efficiency: *photon reconstruction (1.0%); selection on  $|\cos\theta_\gamma|$ ; others negligible*
- The line-shape used in the fit
  - *Input/Output check shows there is no bias for the fit procedure*
  - *Beam energy spread: varied from 736 keV to 1000 keV*
- The fit range: *varying fit ranges along  $|\cos\theta_\mu|$*
- Correction factor: *change to those obtained from 4180 data sample*
- Non-irreducible background: *added in the fit*
- Center-of-mass energy measurement: *varied by +/- 1 MeV for Point3 (most sensitive point)*