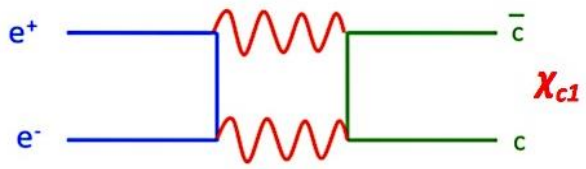
# Production of $\chi_{c1}$ in $e^+e^-$ Collision

$e^+e^- \rightarrow 1^{++}$

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# Motivation

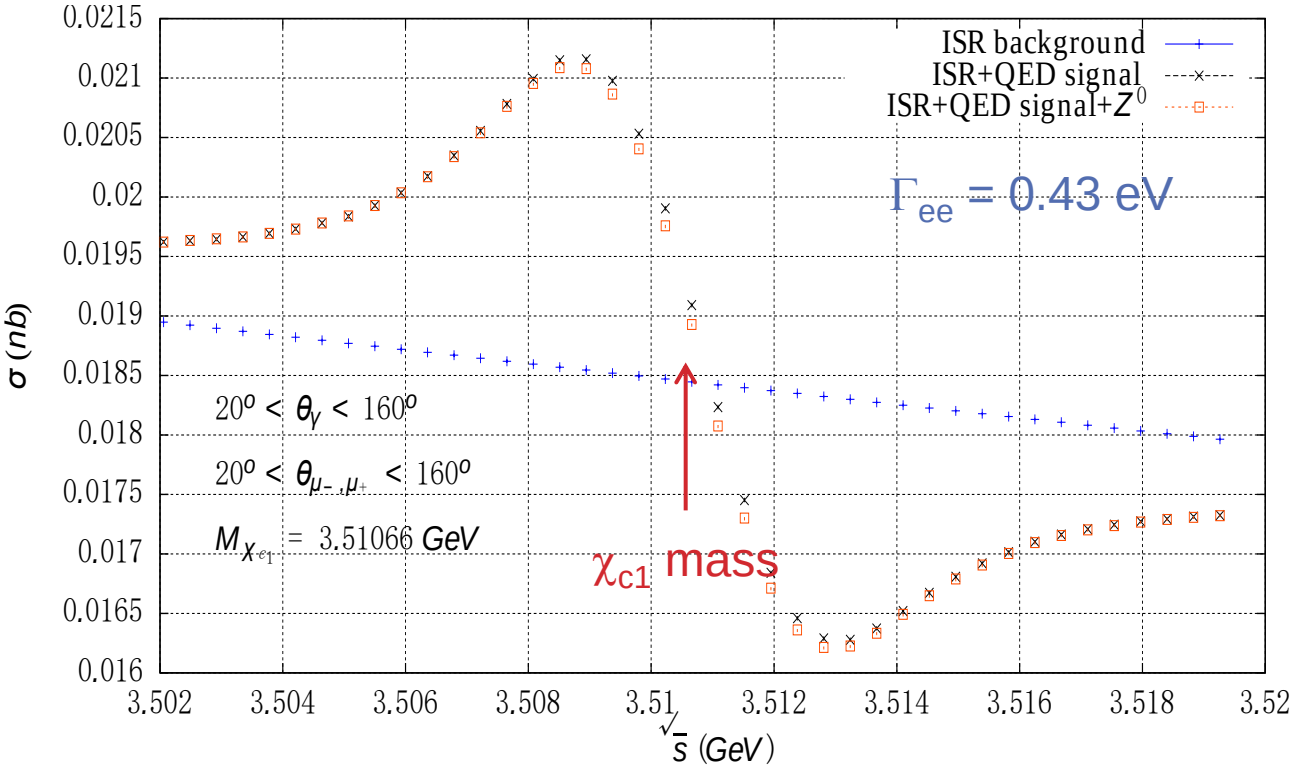
- Up to now, in $e^+e^-$ annihilation only vector resonances ($J^{PC}=1^{--}$) are observed
- The direct production of C-even states (through two virtual photons or neutral current) have been searched experimentally, no observation
  - VEPP-2M collider
    - $\eta'$, $f_0(975)$, $f_0(1270)$, $f_0(1300)$, $a_0(980)$, $a_2(1320)$ ND Collaboration, SJNP **48**, 273 (1988)
    - $a_2(1320)$, $f_2(1270)$ SND Collaboration, PLB **492**, 8 (2000)
    - $\eta$ SND Collaboration, PRD **98**, 052007 (2018).
  - VEPP-2000 collider
    - $\eta'$ CMD-3 Collaboration, PLB 740, 273 (2015), SND Collaboration, PRD **91**, 092010 (2015)
    - $f_1(1285)$ SND Collaboration, PLB **800**, 135074 (2020)
  - BEPC-II collider
    - X(3872) (through ISR process) BESIII Collaboration, PLB **749**, 414 (2015)
  - KEKB collider
    - X(3872) (two photon process) Belle Collaboration, PRL **126**, 122001 (2021)

# Motivation

- 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, PLB **78**, 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, PLB **736**, 221 (2014)
  - Non-relativistic QCD: $\Gamma_{ee} \sim 0.1$ eV N. Kivel, M. Vanderhaeghen, JHEP **02**, 032 (2016)
  - Latest prediction: $\Gamma_{ee} = 0.43$ eV; interference with background process! H. Czyż, J. H. Kühn, S. Tracz,PRD **94**, 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

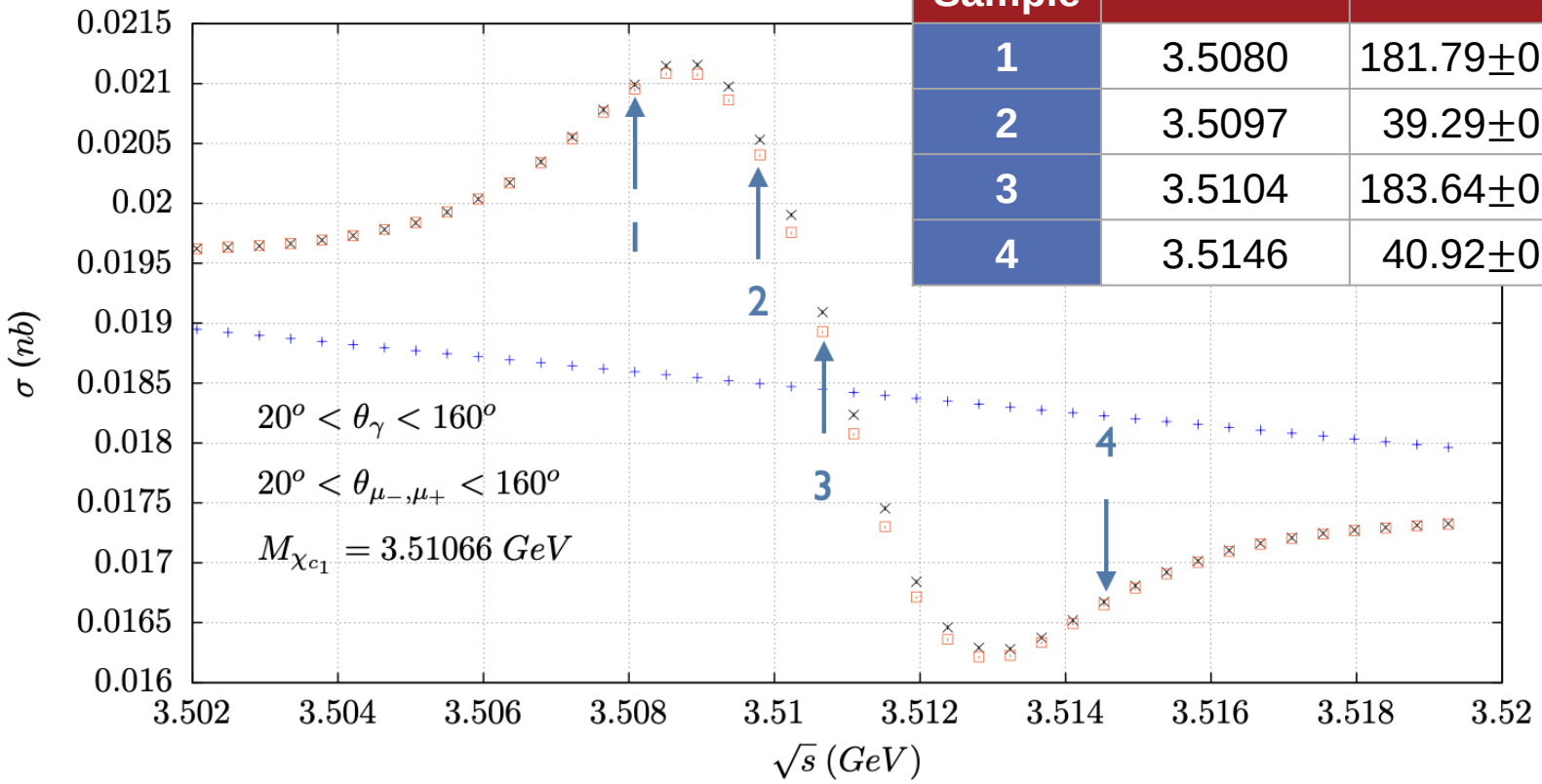
Implemented in PHOKHARA generator

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

✱ $\theta_{\gamma/\mu}$: polar angle of $\gamma/\mu$; $M\chi_{c1}$: nominal mass of $\chi_{c1}$ state

# Data Samples

| Data Sample | $E_{cms}$ [GeV]* | Lumi. [1/pb] |
|---|---|---|
| 1 | 3.5080 | 181.79±0.04±1.04 |
| 2 | 3.5097 | 39.29±0.02±0.22 |
| 3 | 3.5104 | 183.64±0.04±1.05 |
| 4 | 3.5146 | 40.92±0.02±0.23 |




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

Uncertainty of $E_{cms}$: ±0.05 MeV ;

Beam energy spread: (736 ± 27) keV ➡ Input parameters in PHOKHARA

# Analysis Strategy

- Signal process: $e^+e^- \to \chi_{c1}$, $\chi_{c1} \to \gamma J/\psi$(*Br:* 34%), $J/\psi \to \mu^+\mu^-$(*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, ~3 $fb^{-1}$ each
  - Off-peak data samples at 3.581 GeV and 3.670 GeV, ~85 $pb^{-1}$ each
- Check $e^+e^- \to \chi_{c1}$ 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 3rd point ($\chi_{c1}$ nominal mass)
  - With interference (if as predicted by [PRD94, 034033 (2016)] ): excess at 1st and 2nd points, reduction at 4th point

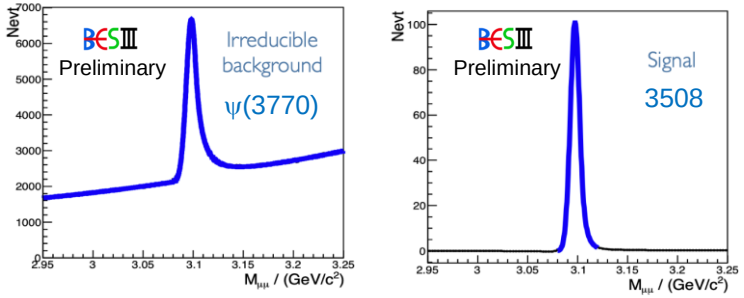
# Selection of $e^+e^- \to \gamma\mu^+\mu^-$

- Two good charged tracks, opposite charge
- At least one good photon
- Select the best photon: smallest $\chi^2_{4c}$
- Bhabha events rejection:
  - Energy deposited in Electromagnetic Calorimeter (EMC): $E_{EMC} < 0.4$ 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 $M(\mu^+\mu^-)$

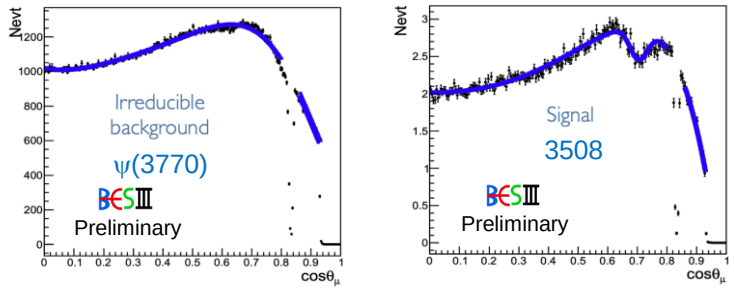
# Validation of Irreducible Background

- 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) | $L$ (pb$^{-1}$) | $N_{\rm sig}$ w/o Cor. | $N_{\rm sig}$ 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 | $43 \pm 7$ $(1.6\sigma;\ 2.3\sigma_{180})$ | $7 \pm 10$ $(0.2\sigma;\ 0.3\sigma)$ |

- A non-zero *R* component
- The statistical significance differs for different data samples, but below 2.3σ if normalizing to 180/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 (factors from 3.773 or 4.178 GeV sample)

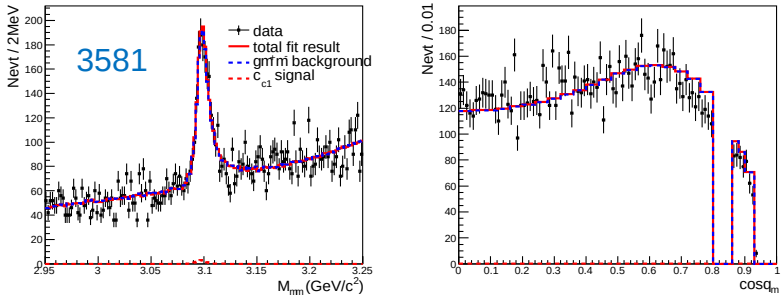
- *R* component go to zero after correction (w/ Cor.) for all control samples

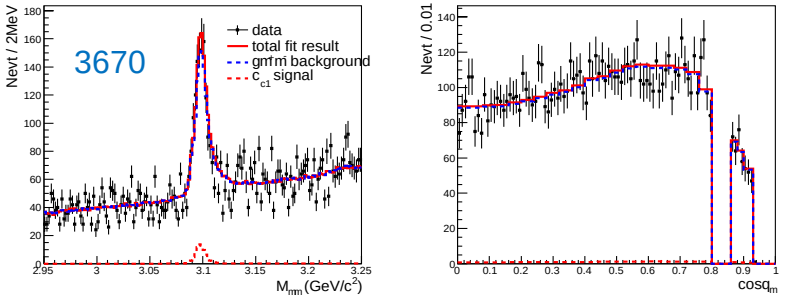
- Correction factors applied to MC simulations of irreducible background at all data samples (an event-by-event correction accoding to [m, cos$\theta_\mu$])

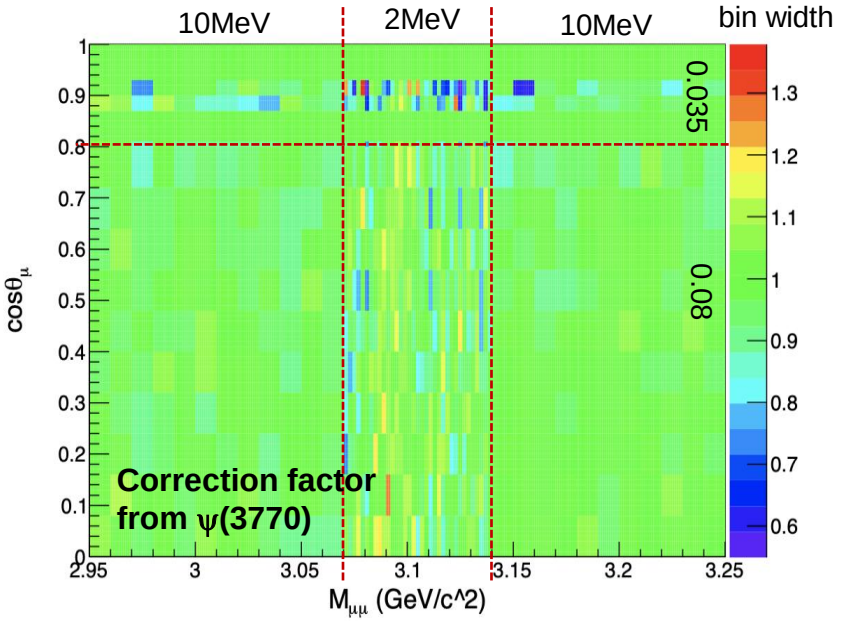
# Validation of Irreducible Background

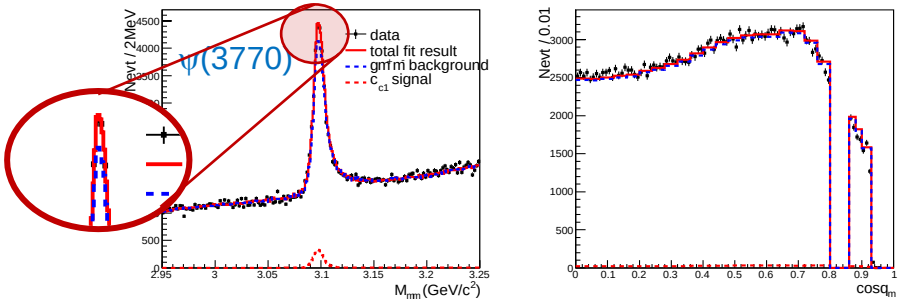
Two-dimensional correction procedure

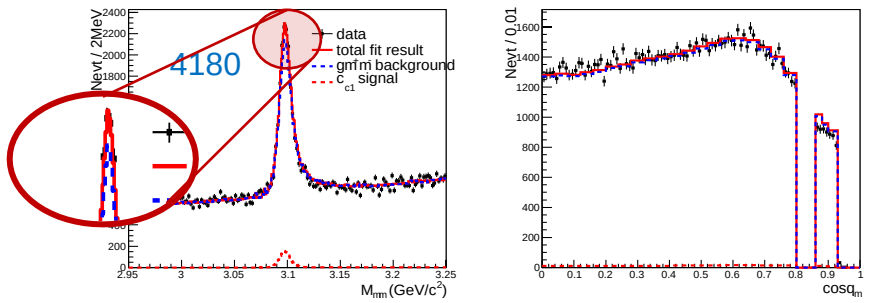
Before Cor.



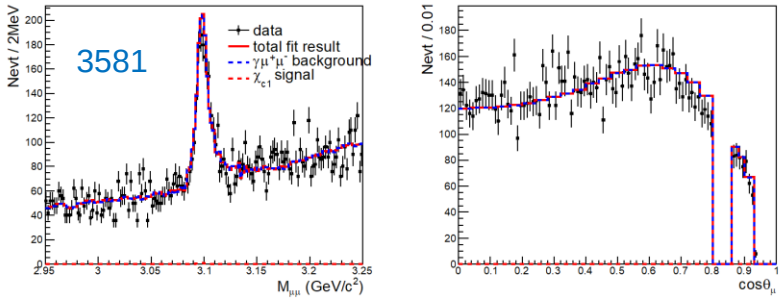



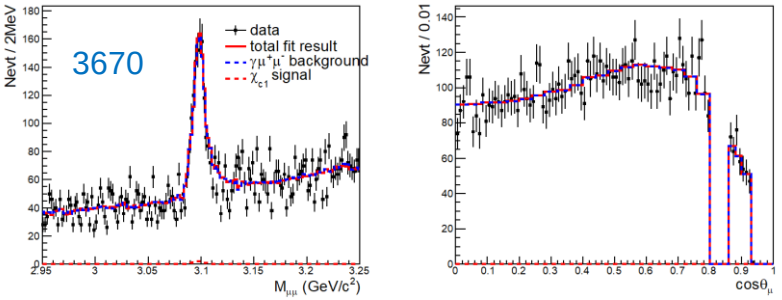



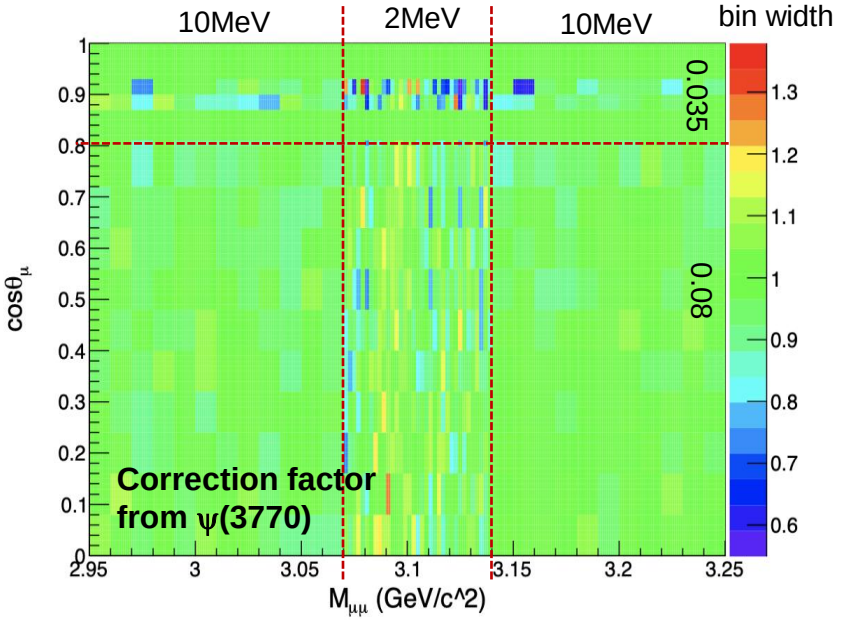
# Validation of Irreducible Background

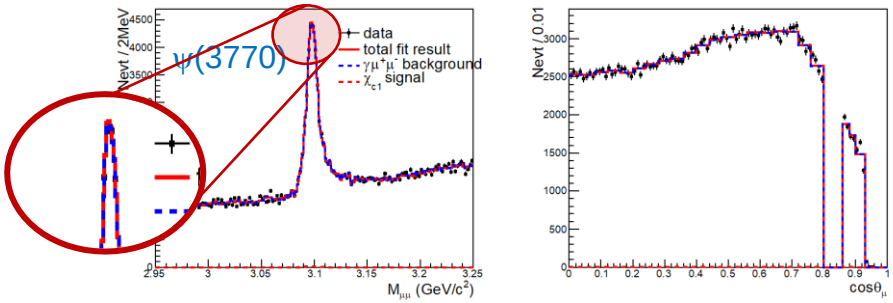
Two-dimensional correction procedure

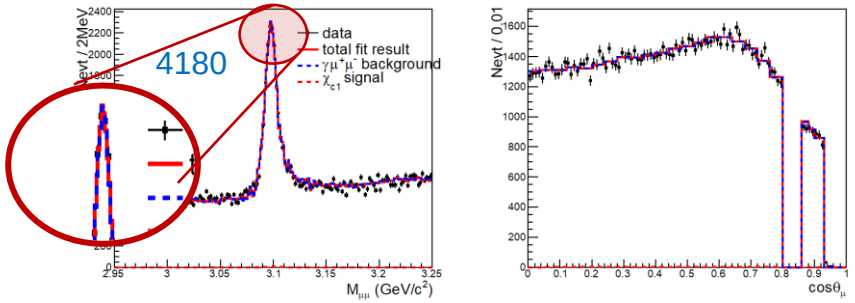
After Cor.



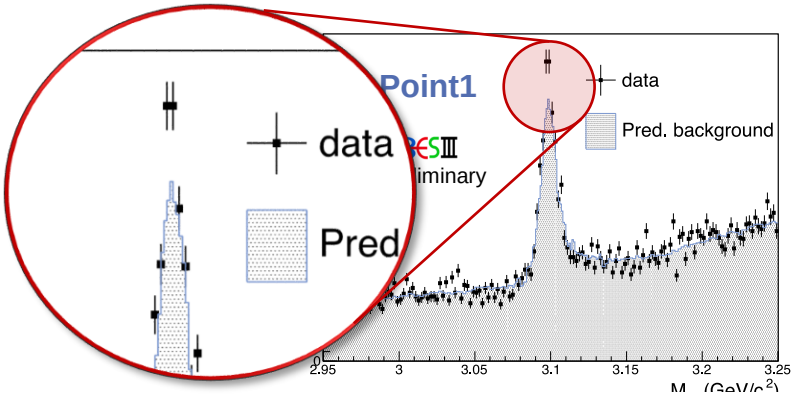



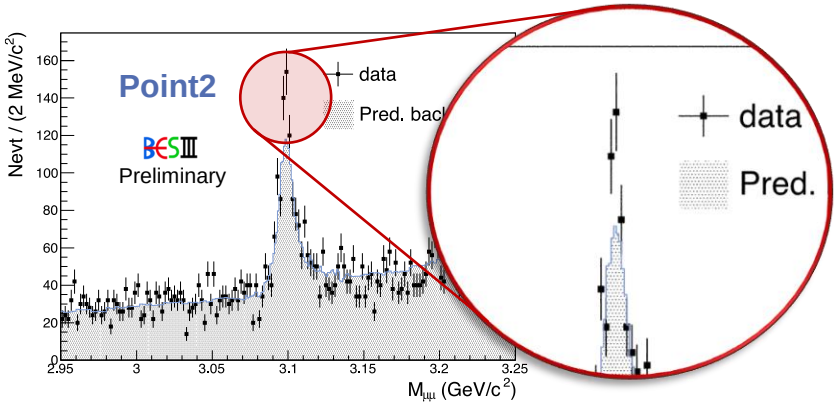



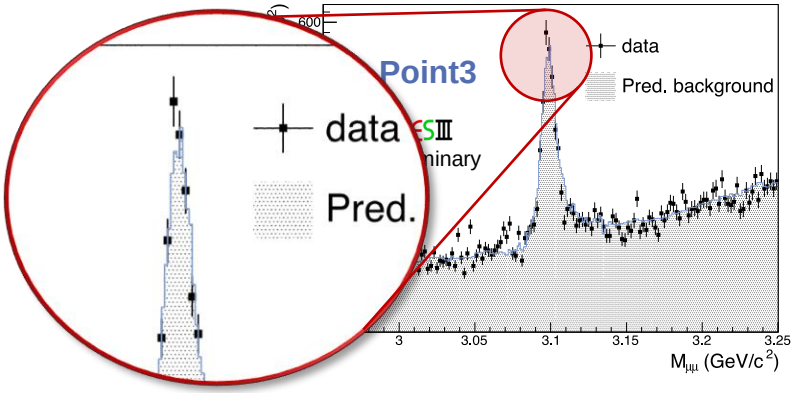



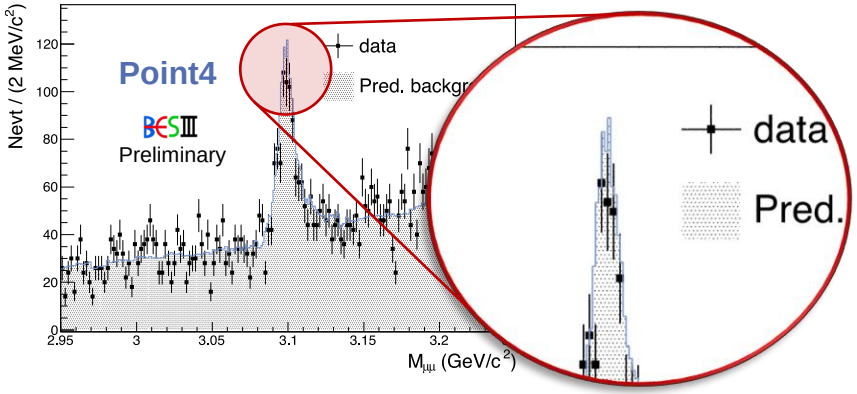



# M($\mu^+\mu^-$) at $\chi_{c1}$ Scan Data Samples



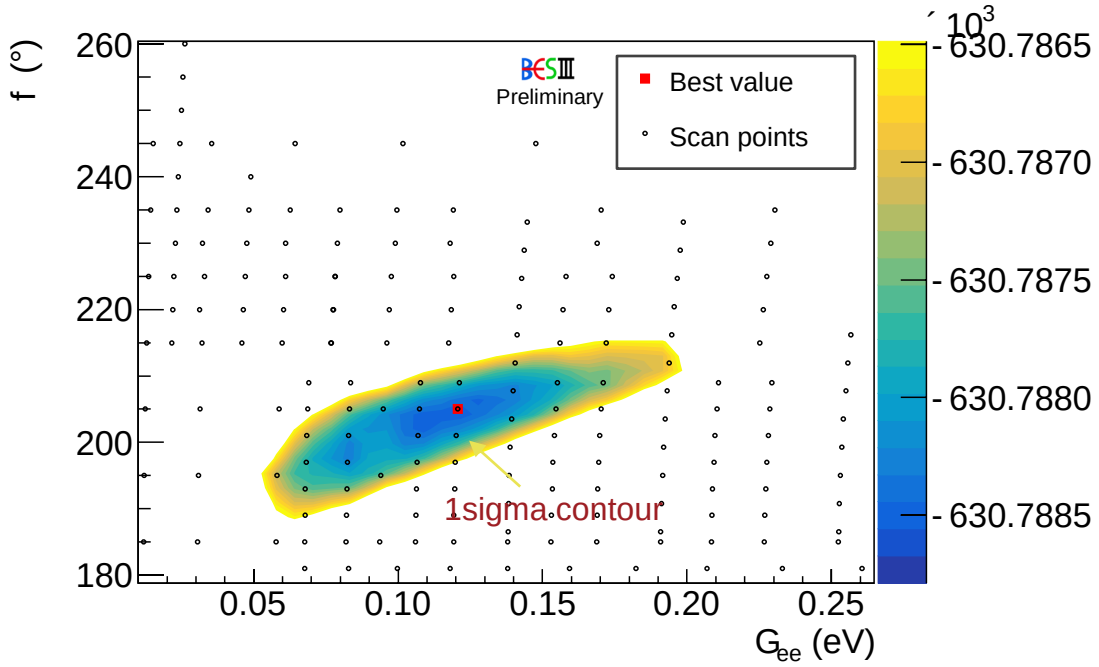




- Excess at 1st and 2nd points, reduction at 4th point
- Phenomenon agrees with theoretical prediction with interference

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




Best value:

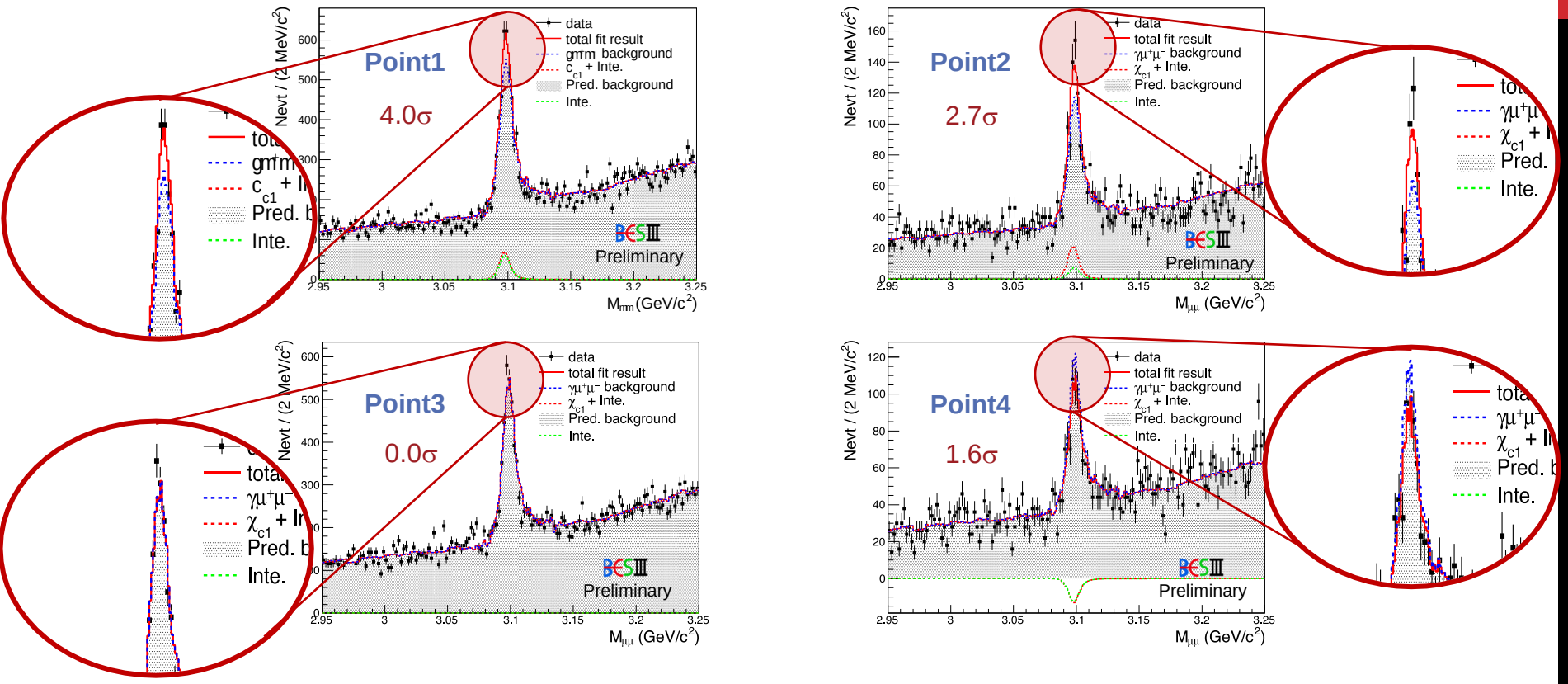
$\Gamma_{ee}=0.12^{+0.13}_{-0.08}$ eV

$\phi=205^{+15.4}_{-22.4}$ degree

[err. includes sys.]

- 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 $N_{bkg}$ : $N_{int} = f \cdot \sqrt{N_{sig} \cdot N_{bkg}}$

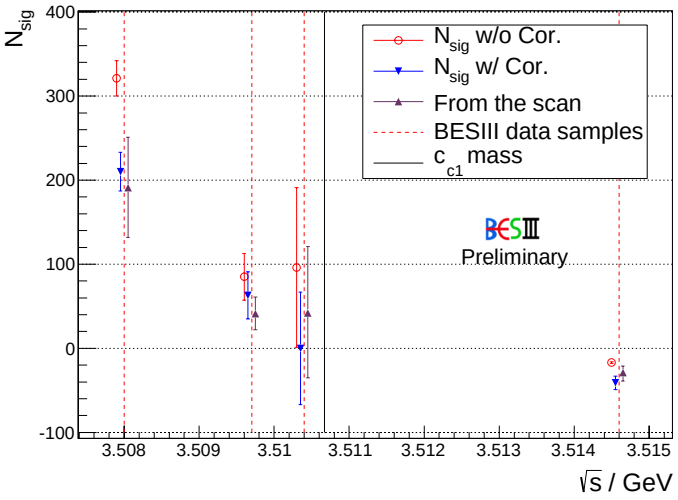
# Numerical Results

| $\sqrt{s}$ (MeV) | $L$ (pb$^{-1}$) | $N_{\rm sig}$ w/o Cor. | $N_{\rm sig}$ w/ Cor. | Common fit to scan points |
|---|---|---|---|---|
| 3508.0 | 181.8 | $321 \pm 21$ $(6.5\sigma)$ | $210 \pm 15 \pm 18$ $(4.1\sigma;\ 4.0\sigma_{\rm low})$ | $191^{+60}_{-59}$ $(4.5\sigma;\ 4.0\sigma_{\rm low})$ |
| 3509.7 | 39.3 | $85 \pm 28$ $(3.9\sigma)$ | $63 \pm 27 \pm 6$ $(2.8\sigma;\ 2.7\sigma_{\rm low})$ | $41^{+20}_{-19}$ $(2.4\sigma;\ 2.3\sigma_{\rm low})$ |
| 3510.4 | 183.6 | $96 \pm 95$ $(1.2\sigma)$ | $0 \pm 62 \pm 26$ $(0.1\sigma;\ 0.0\sigma_{\rm low})$ | $42^{+79}_{-77}$ $(-1.7\sigma;\ -2.5\sigma_{\rm low})$ |
| 3514.6 | 40.9 | $-17 \pm 1$ $(0.8\sigma)$ | $-41 \pm 3 \pm 7$ $(1.8\sigma;\ 1.6\sigma_{\rm low})$ | $-29^{+8}_{-10}$ $(1.6\sigma;\ 1.7\sigma_{\rm low})$ |
| Combined | 445.6 | – | – | $(5.3\sigma;\ 5.1\sigma_{\rm low})$ – $(5.1\sigma;\ 4.2\sigma_{\rm low})$ |

Without Correction

With Correction

With systematic effects taken into account



# 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 4180-factor*
- Non-irreducible background: *added in the fit*
- Center-of-mass energy measurement: *varied by +/- 1 MeV for Point3 (most sensitive point)*

# Summary

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

- Control samples (6294/pb in total) at various center-of-mass energies used to validate the irreducible background, good agreement after correction
- $\chi_{c1}$ scan samples collected at four energy points (445.6/pb in total), used for signal search as well as interference effect study
- Direct production of $e^+e^- \to \chi_{c1}(1^{++})$ 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!