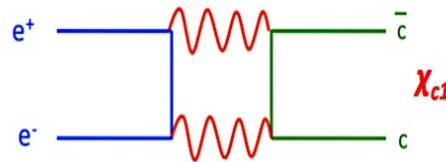


Production of χ_{c1} in e^+e^- Collision

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



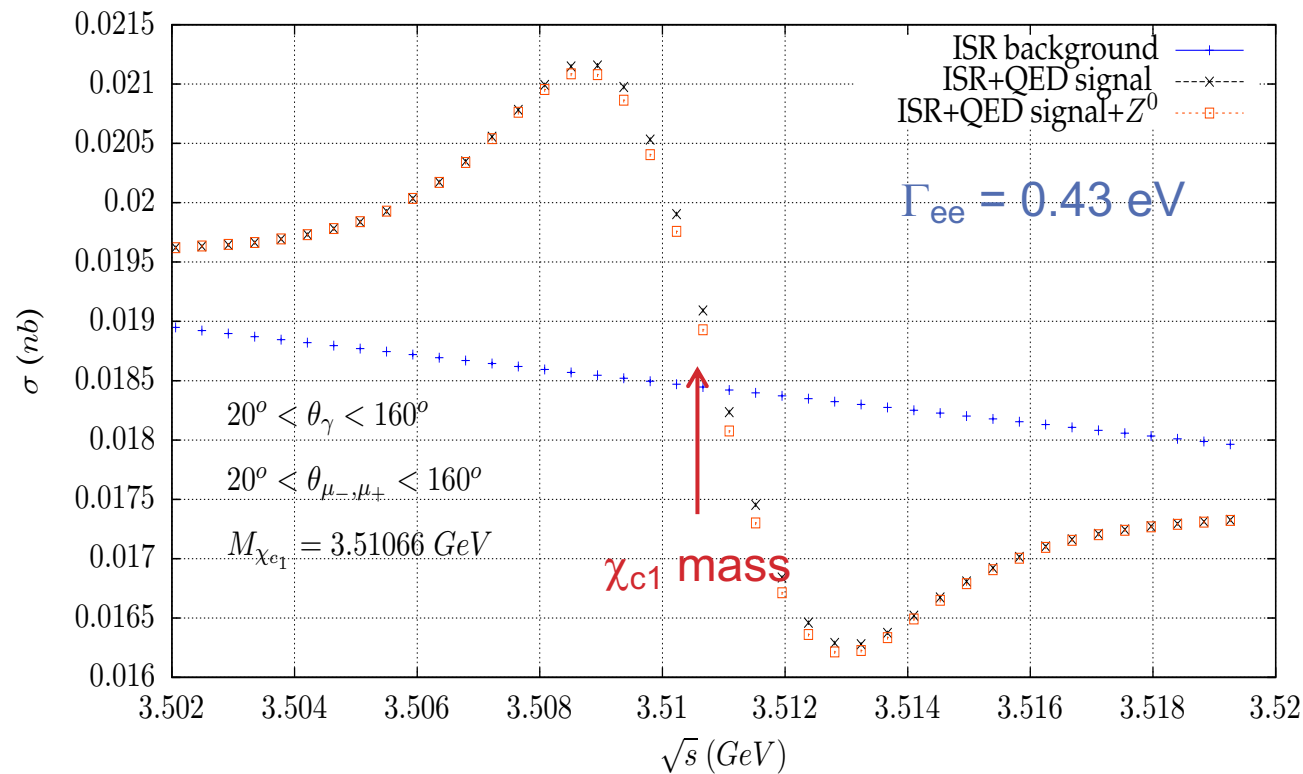
Yuping GUO (Fudan University)

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 (Γ_{ee}). For χ_{c1} state:
 - Unitarity limit: $\Gamma_{ee} > 0.044 \text{ eV}$ J. Laplan, J. H. Kühn, PLB78, 252 (1978)
 - Vector Dominance Model: $\Gamma_{ee} = 0.46 \text{ eV}$; OR $\Gamma_{ee} \sim 0.1 \text{ eV}$ A. Denig, F. K. Guo, C. Hanhart, A. V. Nefediev, PLB736, 221 (2014)
 - Non-relativistic QCD: $\Gamma_{ee} \sim 0.1 \text{ eV}$ N. Kivel, M. Vanderhaeghen, JHEP02, 032 (2016)
 - Latest prediction: $\Gamma_{ee} = 0.43 \text{ eV}$; 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)



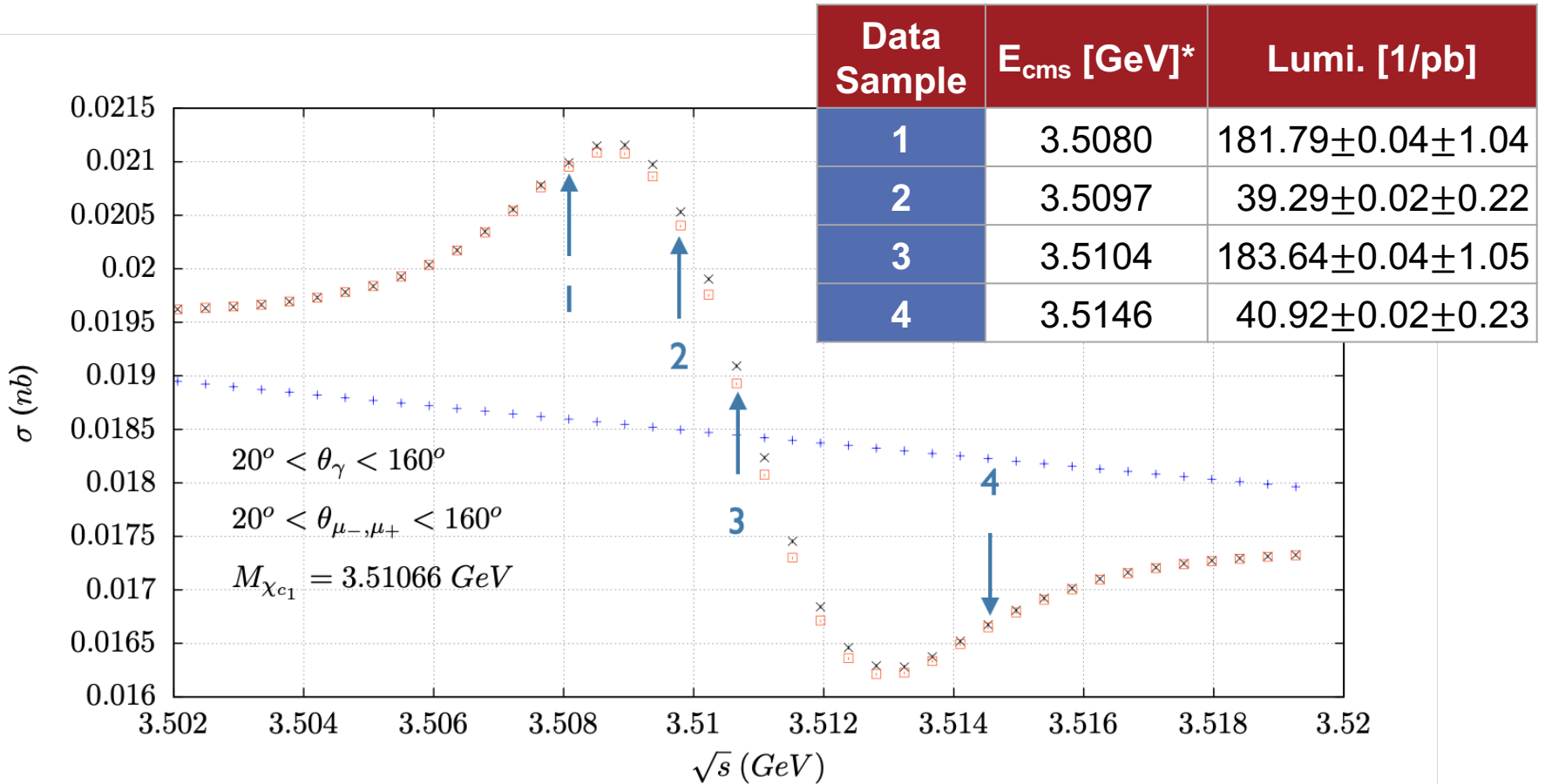
Large interference effects ➡ distortion of the total cross section

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 γ/μ ; $M_{\chi_{c1}}$: nominal mass of χ_{c1} state

Data Samples



* 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:** $e^+e^- \rightarrow \chi_{c1}, \chi_{c1} \rightarrow \gamma J/\psi (Br: 34\%), J/\psi \rightarrow \mu^+\mu^- (Br: 6\%)$
- 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 3rd point (χ_{c1} nominal mass)
 - With interference (if as predicted by [PRD94, 034033 (2016)]): excess of events at 1st and 2nd points, reduction at 4th point

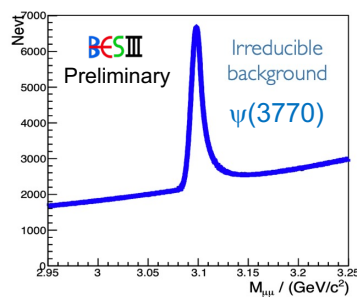
Selection of $e^+e^- \rightarrow \gamma\mu^+\mu^-$

- Two good charged tracks (standard selection), opposite charge
- At least one good photon (standard selection)
- Select photon with 4 constraint kinematic fit, smallest χ^2
- Bhabha events rejection:
 - Energy deposited in EMC: $E(+/-) < 0.4 \text{ GeV}$
 - 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 $M(\mu^+\mu^-)$

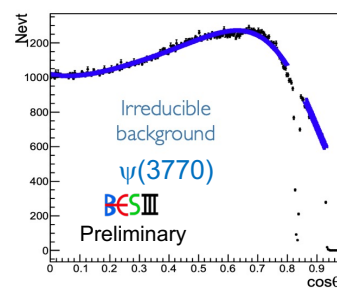
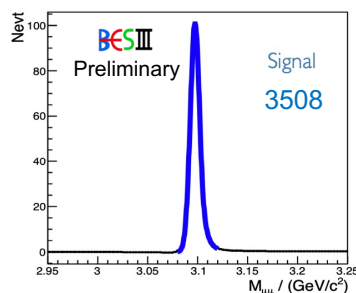
Validation of Irreducible Background

- 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

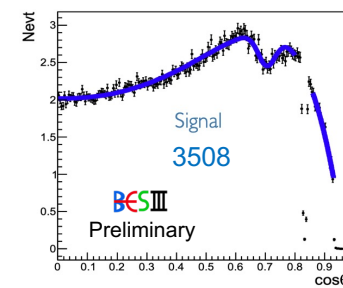
illustration of PDFs used in the fit:



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

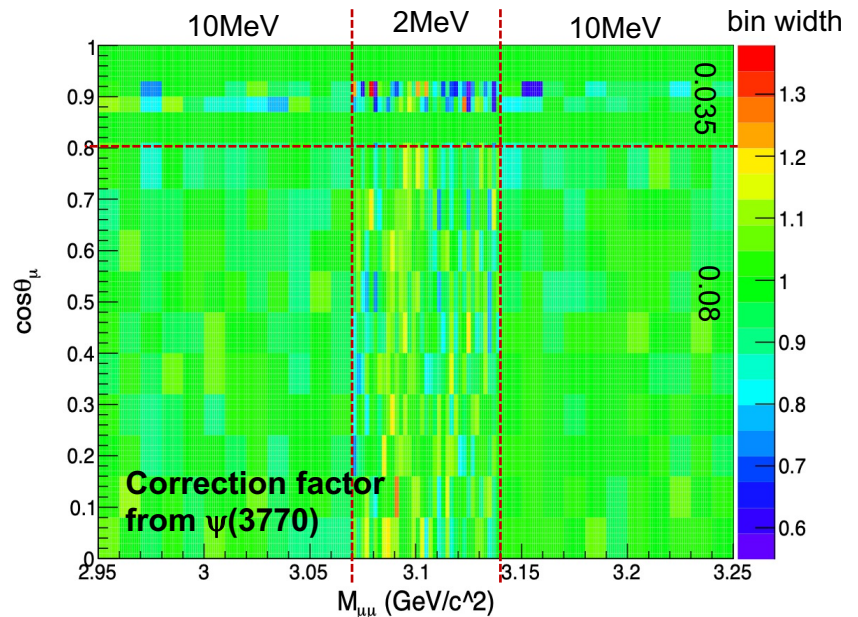
$\sqrt{s}$ (MeV)	L (pb $^{-1}$)	N_{sig} w/o Cor.	N_{sig} w/ Cor.
3773.0	2932.4	1097 ± 25 (7.6σ ; $1.9\sigma_{180}$)	47 ± 50 (0.3σ ; 0.1σ)
4178.4	3192.5	544 ± 7 (5.0σ ; $1.2\sigma_{180}$)	18 ± 36 (0.2σ ; 0.0σ)
3581.5	85.3	10 ± 1 (0.3σ ; $0.4\sigma_{180}$)	3 ± 6 (0.4σ ; 0.6σ)
3670.2	83.6	43 ± 7 (1.6σ ;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

- The number of events for the R component is not zero
- The statistical significance differs for different data samples, but below 2.3σ if normalizing to 180/pb (σ_{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 3.773 or 4.178 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

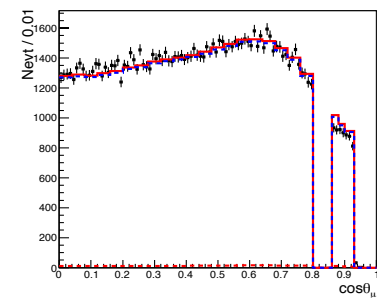
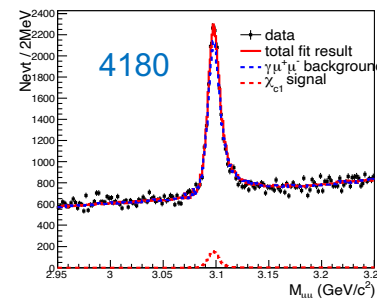
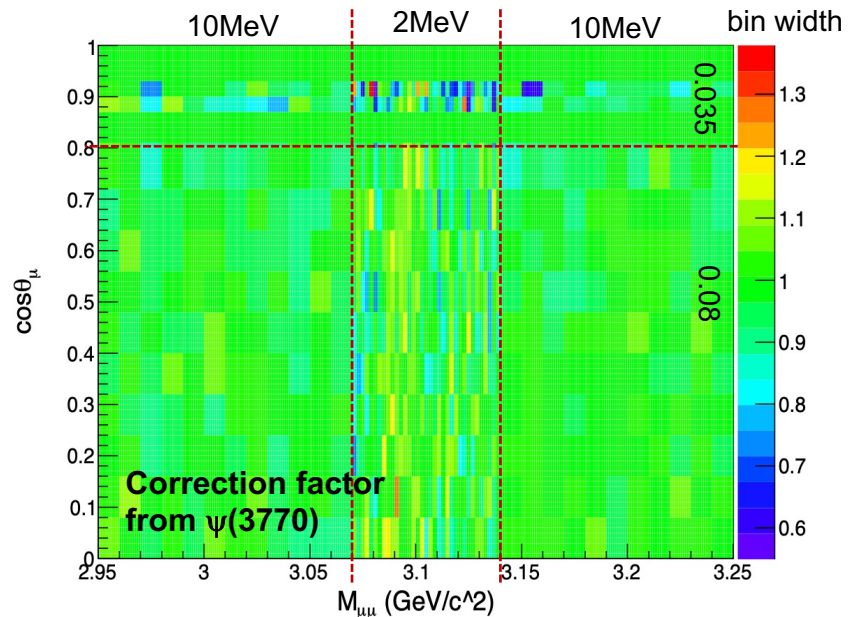
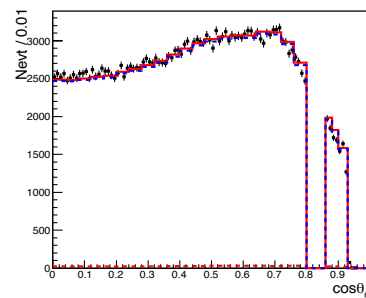
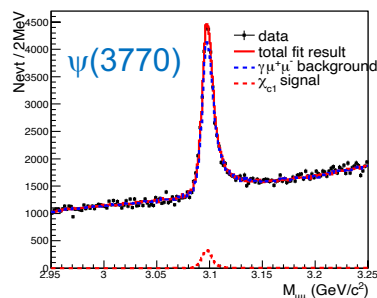
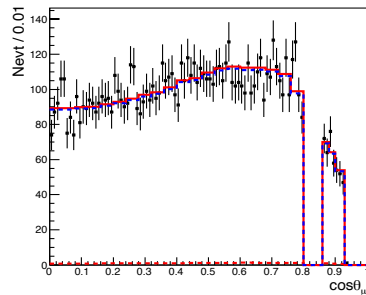
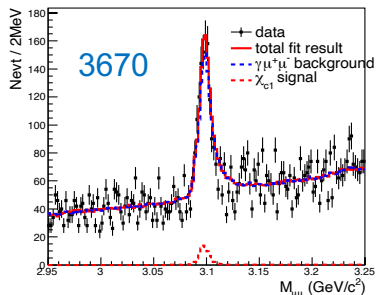
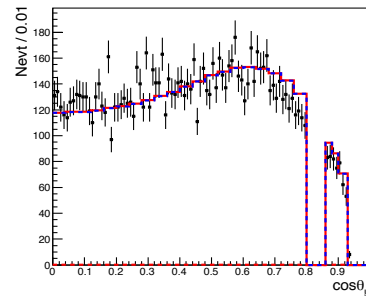
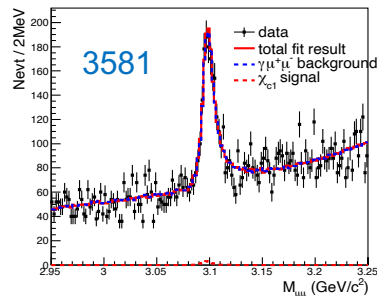
- Correction factor $f(m, \cos\theta_\mu)$ obtained by comparing data and MC simulation of ISR background at $\psi(3770)$ or $\psi(4180)$
- Event-by-event correction applied to ISR background events according to $[m, \cos\theta_\mu]$ of the event



Validation of Irreducible Background

Two-dimensional correction procedure

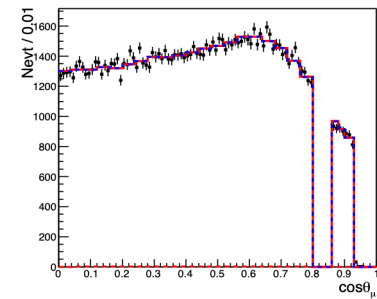
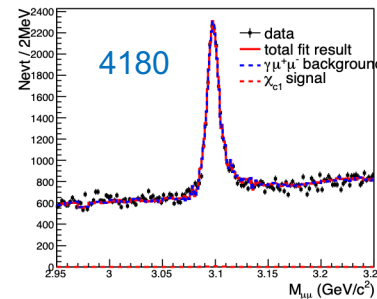
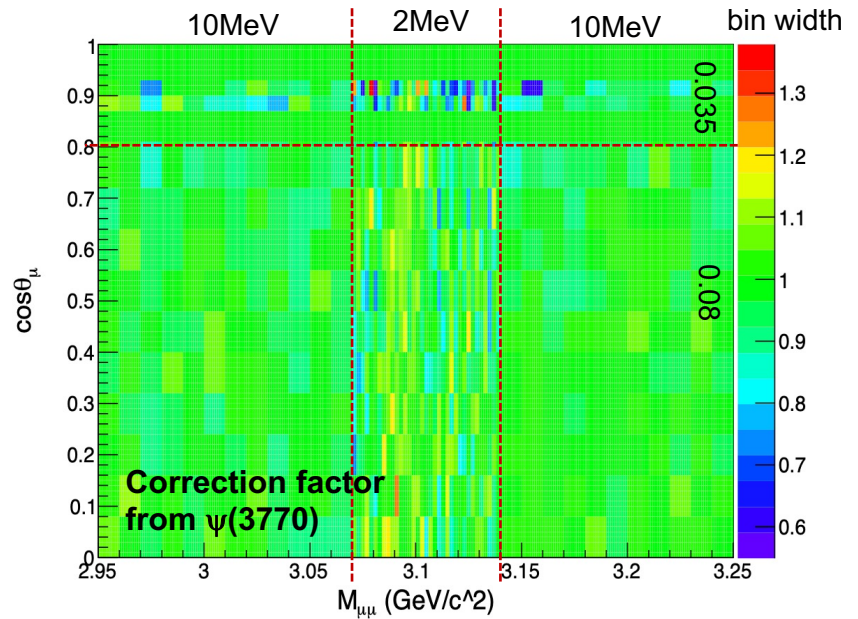
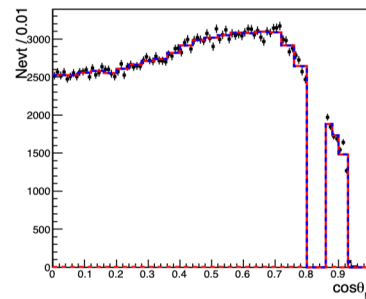
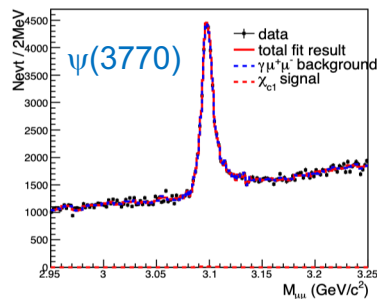
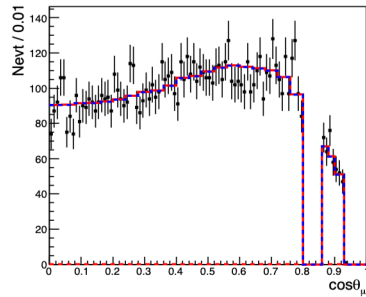
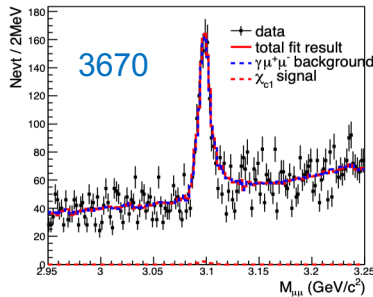
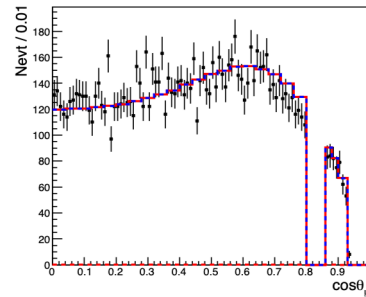
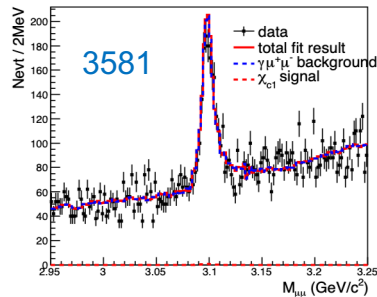
Before Cor.



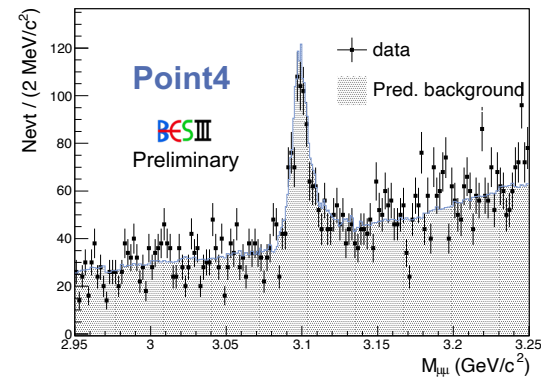
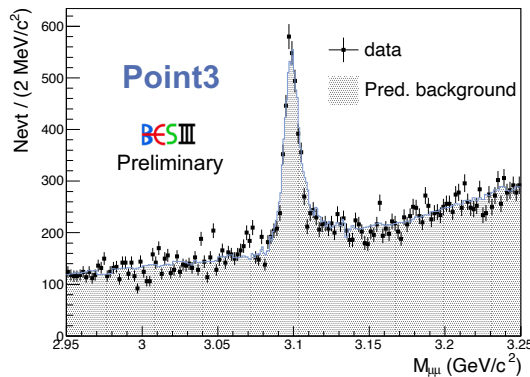
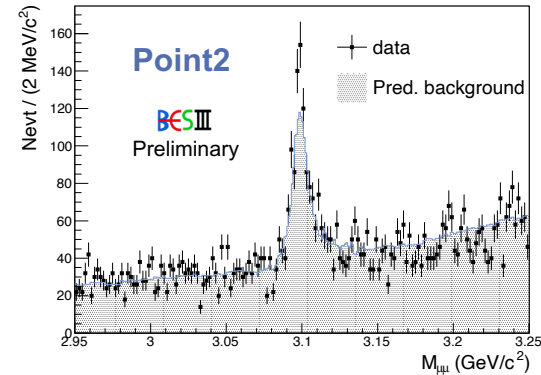
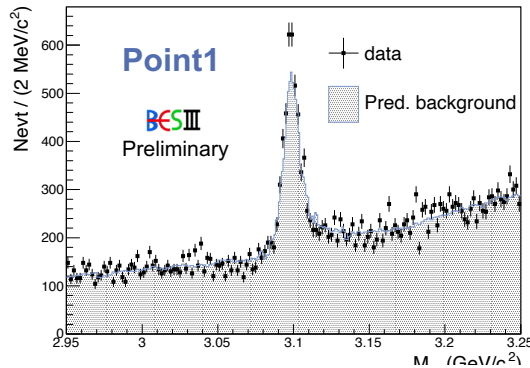
Validation of Irreducible Background

Two-dimensional correction procedure

After Cor.

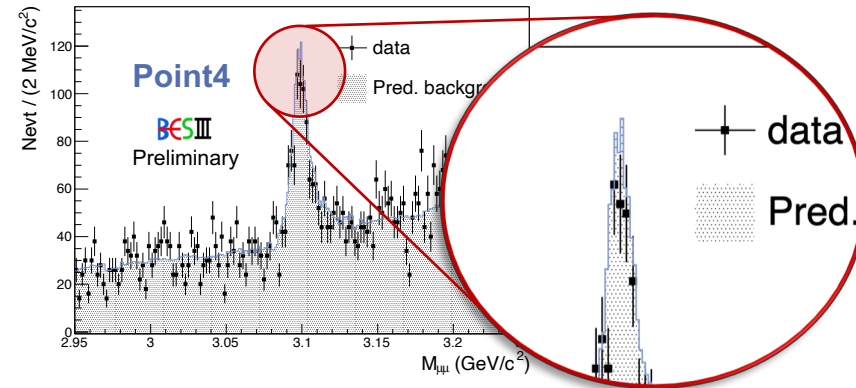
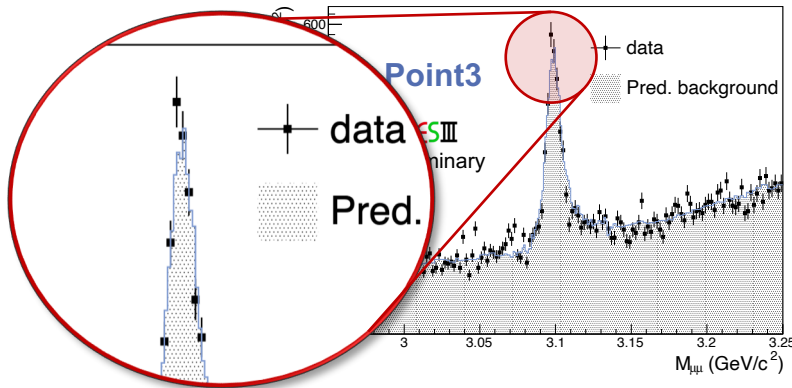
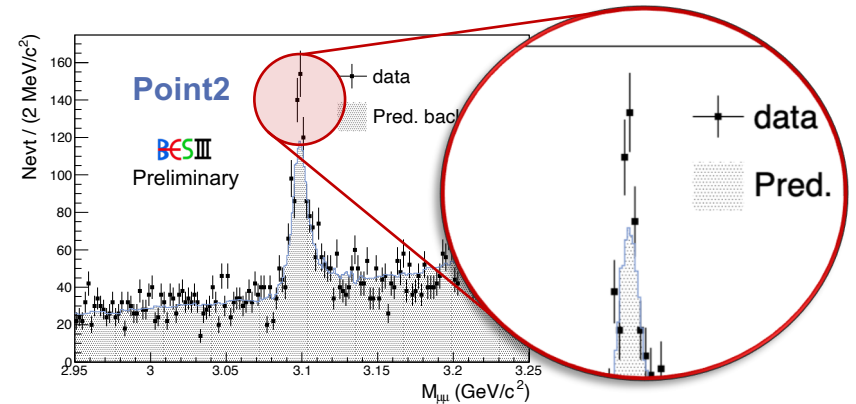
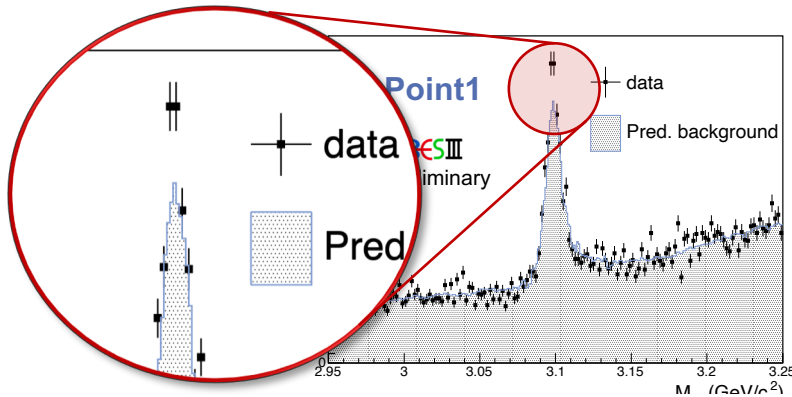


$M(\mu^+\mu^-)$ at χ_{c1} Scan Data Samples



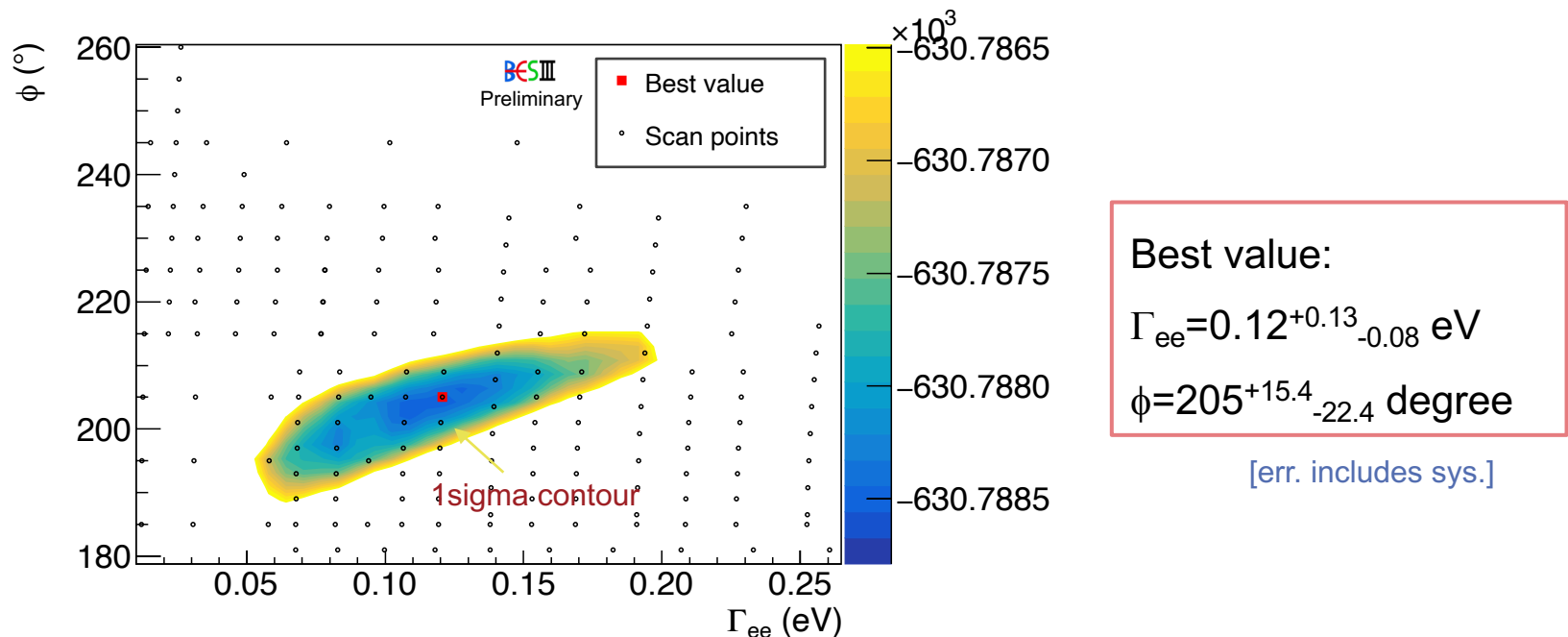
- The number of J/ψ events is enhanced for the first two points, and is decreased for the last point
- Phenomenon agrees with theoretical prediction with interference

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



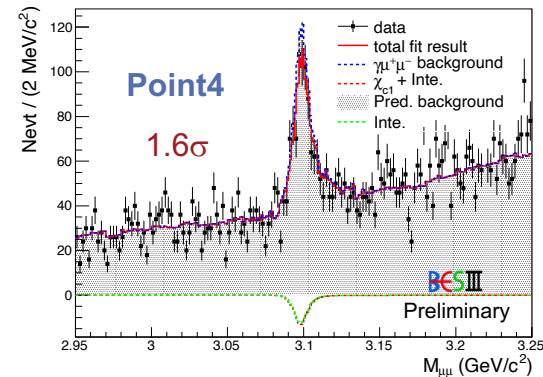
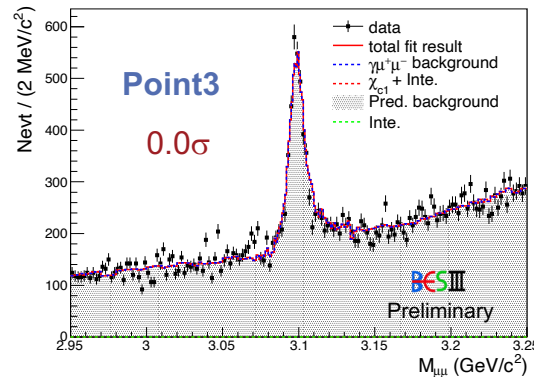
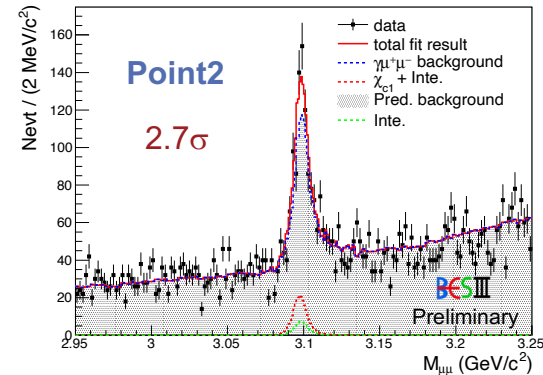
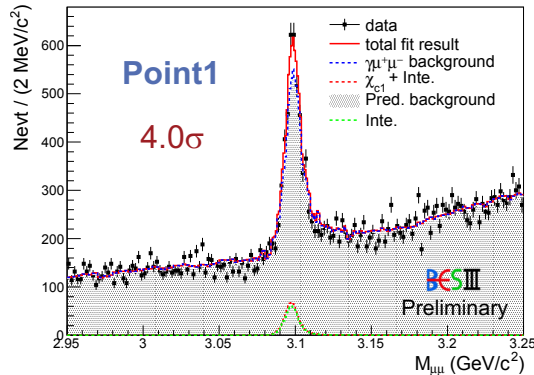
- The number of J/ψ events is enhanced for the first two points, and is decreased for the last point
- Phenomenon agrees with theoretical prediction with interference

Determination of Γ_{ee} and ϕ



- Use four χ_{c1} data samples simultaneously (common fit)
- Γ_{ee} and ϕ 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 $N_{\text{int}} = f \cdot \sqrt{N_{\text{sig}} \cdot N_{\text{bkg}}}$

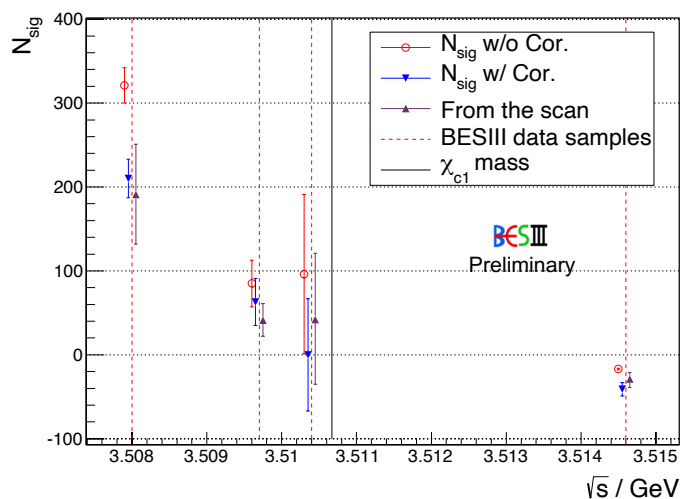
Numerical Results

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

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 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)*

Summary

First search of the χ_{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 χ_{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!