Measurement of the branching fraction of $\psi' \to e^+e^-\eta_c$

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Motivation I

- The electromagnetic(EM) Dalitz decay, $\psi' \to e^+e^-\eta_c$, provides an ideal opportunity to probe the structure of ψ' and to investigate the interactions between ψ' and virtual photon.
  L. G. Landsberg, Sov. Phys. Usp. 28, 435 (1985)
  L. G. Landsberg, Phys. Rept. 128, 301 (1985)

- The M1 transition, $\psi' \to \gamma\eta_c$, is a significant process to understand the spin interactions between charmonium states. In experiment, the ratio

$$R = \frac{\Gamma\left(\psi' \to e^+e^-\eta_c\right)}{\Gamma\left(\psi' \to \gamma\eta_c\right)} \tag{1}$$

  can be used to test theoretical models, where many uncertainties can be cancelled.

Motivation II

- In experiment, the EM Dalitz decays of light unflavored vector mesons (ρ^0, ω, ϕ) have been widely observed.
  M. Tanabashi et al. [Particle Data Group], Phys. Rev. D 98, no. 3, 030001 (2018)

- Recently, several decays of charmonium vector mesons $(J/\psi, \psi')$ to light pseudo-scalar mesons are studied in theory and observed by BESIII experiment.
  J.Fu, H.B.Li, X.Qin and M.Z.Yang, Mod.Phys.Lett.A27,125022(2012)
  M. Ablikim et al. [BESIII Collaboration], Phys. Rev. D 89, no. 9, 092008 (2014)
  M. Ablikim et al. [BESIII Collaboration], Phys. Lett. B 783, 452 (2018)

- This is the first time to measurement the branching fraction of $B(\psi' \to e^+e^-\eta_c)$ at BESIII.

Decay mode	Branching fraction	$\frac{\Gamma(V\to Pl^+l^-)}{\Gamma(V\to P\gamma)}$
$\rho^0 \to \pi^0 e^+e^-$	$< 1.2 \times 10^{-5}$	$< 2.6 \times 10^{-2}$
$\omega \to \pi^0 e^+e^-$	$(7.7 \pm 0.6) \times 10^{-4}$	$(0.91 \pm 0.08) \times 10^{-2}$
$\omega \to \pi^0 \mu^+\mu^-$	$(1.34 \pm 0.18) \times 10^{-4}$	$(0.16 \pm 0.02) \times 10^{-2}$
$\phi \to \pi^0 e^+e^-$	$(1.33^{+0.07}_{-0.10}) \times 10^{-5}$	$(1.02^{+0.07}_{-0.09}) \times 10^{-2}$
$\phi \to \eta e^+e^-$	$(1.08 \pm 0.04) \times 10^{-4}$	$(0.83 \pm 0.03) \times 10^{-2}$
$\phi \to \eta \mu^+\mu^-$	$< 9.4 \times 10^{-6}$	$< 0.07 \times 10^{-2}$
$J/\psi \to \pi^0 e^+e^-$	$(7.6 \pm 1.4) \times 10^{-7}$	$(2.18^{+0.45}_{-0.44}) \times 10^{-2}$
$J/\psi \to \eta e^+e^-$	$(1.16 \pm 0.09) \times 10^{-5}$	$(1.05 \pm 0.09) \times 10^{-2}$
$J/\psi \to \eta' e^+e^-$	$(5.81 \pm 0.35) \times 10^{-5}$	$(1.13 \pm 0.08) \times 10^{-2}$
$\psi' \to \eta' e^+e^-$	$(1.90 \pm 0.27) \times 10^{-6}$	$(1.53 \pm 0.22) \times 10^{-2}$

Data Sample

- Data:
  - $(448.1 \pm 2.9) \times 10^6$ ψ' events taken at $\sqrt{s} = 3.686$ GeV in 2009 ($(107.0 \pm 0.8) \times 10^6$) and 2012 ($(341.1 \pm 2.1)10^6$).
  - 44.49 pb^{-1} QED continuum data taken at $\sqrt{s} = 3.650$ GeV in 2009
- Monte Carlo:
  - Official 506 Million inclusive Monte Carlo sample
  - Exclusive Monte Carlo Sample:

Decay chain	Generated	Description
$\psi' \to e^+e^-\eta_c, \;\; \eta_c \to X$	1×10^7	Signal Monte Carlo

  - In simulation, $\psi' \to e^+e^-\eta_c$ is generated with the "DalitzJPLL" generator. arXiv:1904.06085 [hep-ph]

$$\frac{d\Gamma\left(\psi \to Pl^+l^-\right)}{d\cos\theta} \sim 1 + \cos^2\theta \quad (2)$$

- BOSS version : 6.6.4.p03

Analysis Method

- In this EM Dalitz decay, $\psi' \to e^+e^-\eta_c$, we have the following formula:

$$N_{\rm sig}^{\rm obs} = N_{\psi'} \cdot \mathcal{B}_{\rm sig} \cdot \varepsilon_{\rm sig}, \tag{3}$$

  where $N_{\rm sig}^{\rm obs}$ is the observed signal events, $N_{\psi'}$ is the total number of ψ' event, $\mathcal{B}_{\rm sig}$ is the branching fraction the measured signal mode, and $\varepsilon_{\rm sig}$ is the reconstruction efficiency of the signal mode.

- To observe more signal events and improve the statistical significance, we just reconstruct the lepton pair instead of reconstructing the η_c to improve the efficiency $\varepsilon_{\rm sig}$.

- After reconstructing the lepton pair, we look at the recoiling mass of the lepton pair, $RM(e^+e^-)$, to obtain the signal yields.

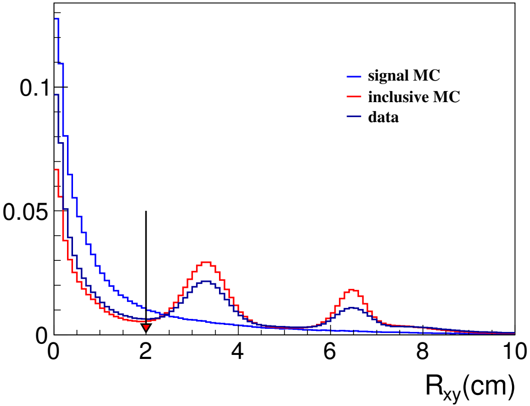
$$RM\left(e^+e^-\right) = \sqrt{\left(E_{\psi'} - E_{e^+} - E_{e^-}\right)^2 - \left(\mathbf{p}_{\psi'} - \mathbf{p}_{e^+} - \mathbf{p}_{e^-}\right)^2} \tag{4}$$

Event Selection

- Good Charged Tracks Selection
  - distance of the track from interaction position on x-y plane: $|R_{xy}| < 1$ cm
  - distance of the track from interaction position in z direction: $|R_z| < 10$ cm
  - the polar angle of the track: $|\cos\theta| < 0.93$
- Electron/Positron PID
  - dE/dx + TOF + EMC
  - $\frac{\text{prob(e)}}{\text{prob(e)+prob}(\pi)\text{+prob(K)}} > 0.8$
- $N_{e^+} >= 1$ and $N_{e^-} >= 1$
  - $|\mathbf{p}_{e^+}| < 0.8$ GeV
  - Loop all e^+ and e^- pairs

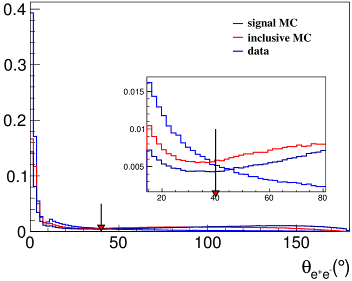
Suppress γ Conversion Events

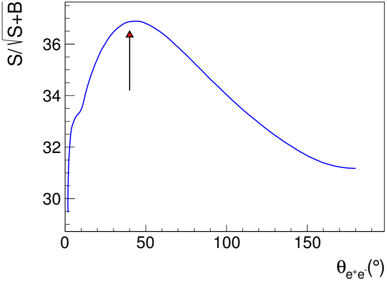
- In the process with one or more photons, the photon will subsequently convert into an electron-positron pair in the beam pipe or inner of MDC.
- R_{xy} is the distance from the reconstructed vertex point of electron-positron pair to point $(0, 0, 0)$ in $x - y$ plane.
- We require $R_{xy} < 2$ cm to suppress γ conversion events,



Requirement on $\theta(e^+e^-)$

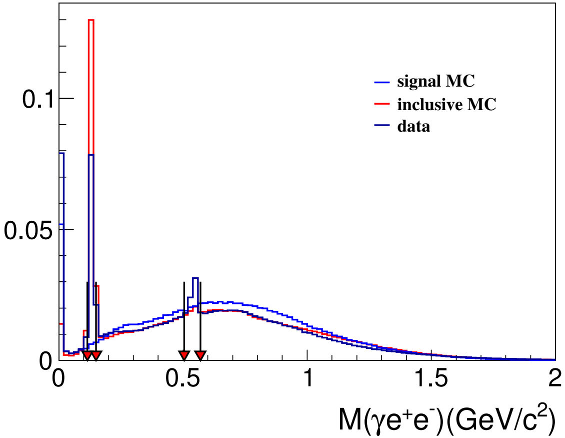
- To further suppress background, we require $\theta(e^+e^-) < 40^\circ$
- Background yields reduce 49.0%, while signal yield reduce 14.8%.





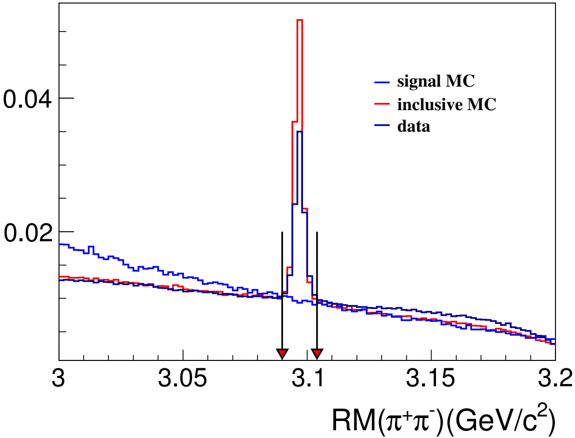
Veto $\pi^0/\eta \to \gamma e^+ e^-$ Events

- $M(\gamma e^+ e^-)$ is the invariant mass of the electron-positron pair and any selected photon in one event.
- We veto the event, if $M(\gamma e^+ e^-)$ is in the mass window of π^0 or η (i.e. $(0.115, 0.150)$ GeV or $(0.505, 0.570)$ GeV).



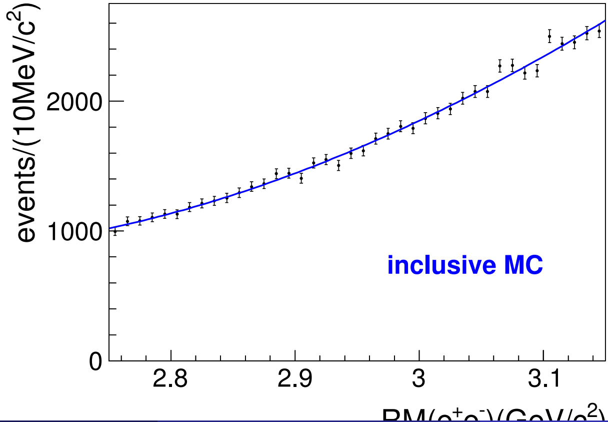
Veto $\psi' \to \pi^+\pi^- J/\psi$ Events

- We loop all good positive-charge-track and negative-charge-track pairs (including the electron-positron pair) and suppos they are π^+-π^- pair.
- We veto the event, if $RM(\pi^+\pi^-)$ in the mass window of J/ψ (i.e. $(3.090, 3.104)$ GeV/c^2).



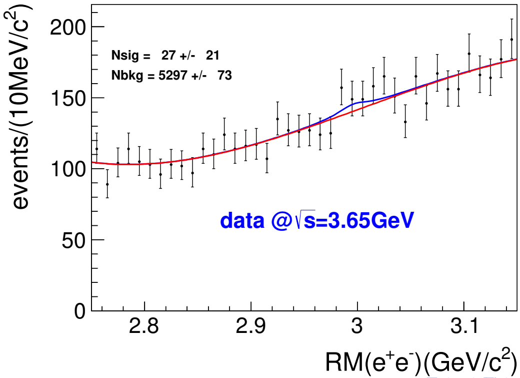
Background Distribution I

- An unbinned maximum likelihood fit to $RM(e^+e^-)$ is performed to obtain signal yield
- The distribution of $RM(e^+e^-)$ for inclusive MC indicates that background from ψ' is a flat distribution, and it can be described by the third order Chebyshev polynomial.



Background Distribution II

- A possible peaking background comes from continuum two photon process $e^+e^- \to e^+e^-\eta_c$.
- We fit data taken at $\sqrt{s} = 3.65$ GeV.
  The signal shape is described by the shape derived from signal MC convoluted with a Gaussian function. The background shape is described by the third order Chebychev polynomial function.



Background Distribution III

- Then we use the following formula

$$N_{3.686}^{\text{com}} \approx N_{3.65}^{\text{com}} \cdot \frac{\mathcal{L}_{3.686}}{\mathcal{L}_{3.65}} \cdot \frac{m_{3.65}^2}{m_{3.686}^2} \qquad (5)$$

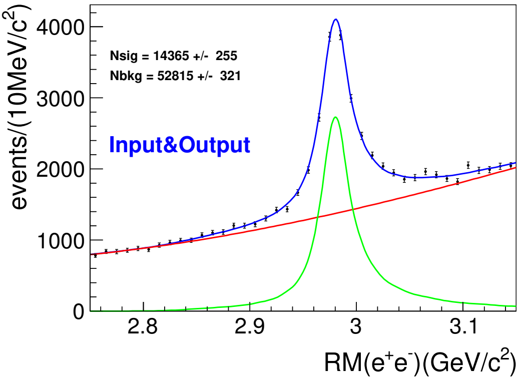
  and obtain $N_{3.686}^{\text{com}} \approx (378 \pm 293)$

- Actually, $\sigma(e^+e^- \to e^+e^-\eta_c)_{3.77} \approx 0.0016$ nb
  D. M. Asner et al., Int. J. Mod. Phys. A 24, S1 (2009)
- Using the formula $\frac{\sigma_1}{\sigma_2} \approx \frac{1/s_1}{1/s_2}$, we can derive that $\sigma(e^+e^- \to e^+e^-\eta_c)_{3.686} \approx 0.00167$ nb.
- With integrated luminosity $\mathcal{L}_{3.686}$ (about $695\ \text{pb}^{-1}$), we can estimate that $N(e^+e^- \to e^+e^-\eta_c)_{3.686} \approx 1163$
- With the $\epsilon \approx 20\%$, we can estimate that $N(e^+e^- \to e^+e^-\eta_c)_{3.686}^{\text{observe}} \approx 232$, which is consistent with the number above.

- The two photon process is described by the shape determined from data taken at $\sqrt{s} = 3.65$ GeV with the number of events fixed at scaled value $N_{3.686}^{\text{com}} = 378$.

Input and Output Check

- Input : $B(\psi' \to e^+e^-\eta_c) = 2.0 \times 10^{-4}$
  0.08M signal Monte Carlo + 400M official inclusive Monte Carlo.
- Efficiency $\epsilon = 18.04\%$
- Output : $B(\psi' \to e^+e^-\eta_c) = (1.99 \pm 0.04) \times 10^{-4}$.
- IO result keeps consistent within statistical uncertainty.



Branching Fraction $B(\psi' \to e^+e^-\eta_c)$

- The Branching fraction is $B(\psi' \to e^+e^-\eta_c) = (4.20 \pm 0.62) \times 10^{-5}$.
- The statistical significance of this channel is 29.2 σ.

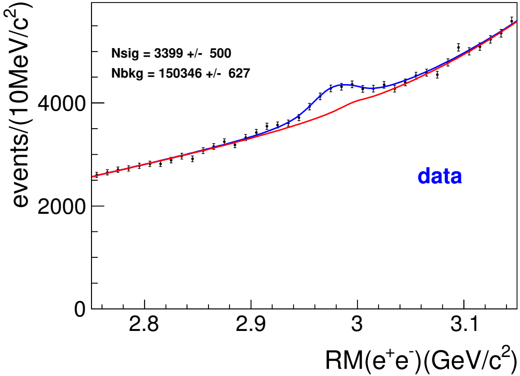


Figure: Distribution of $RM(e^+e^-)$ in ψ' data. The signal shape is described by Monte Carlo shape function smeared with a Gaussian function, background shape is described by a third order Chebychev polynomial function added the shape, which is determined from QED continuum data with the number of events fixed at scaled value $N^{\mathrm{com}}_{3.686}$.

Systematic Uncertainties I

- The tracking efficiency of electron has been studied in process $J/\psi \to e^+e^-(\gamma_{FSR})$ and $\psi' \to \pi^+\pi^- J/\psi, J/\psi \to l^+l^-$. And the uncertainty is set to be 1.0% per track.
  BAM-00237, BAM-00222

- The PID efficiency of electron are by analyzing radiative Bhabha events at $\sqrt{s} = 3.686$ GeV. To acquire the uncertainties, we weight the PID efficiencies in different $\cos\theta$ and total momentum $|\mathbf{p}|$. The total total uncertainties are obtained by the following equation

$$\Delta\epsilon^{\mathrm{PID}} = \sum_{i,j}(\Delta\epsilon_{ij}^{\mathrm{PID}} \times \omega_{ij}^{\mathrm{PID}}) \tag{6}$$

  And the uncertainties is set to be 1.2% per track.

Systematic Uncertainties II

- γ conversion cut
  The systematic uncertainty due to γ conversion cut $R_{xy} < 2$ is 1.0%, which has been studied with a highly pure sample of $J/\psi \to \pi^+\pi^-\pi^0, \pi^0 \to \gamma e^+e^-$.
  M. Ablikim et al. [BESIII Collaboration], Phys. Rev. D 89, no. 9, 092008 (2014)

- $\theta_{e^+e^-}$ cut
  We vary the cut value in the range $(35, 45)$ and use the maximum change of branching fraction as the systematic uncertainty. The uncertainties is set to be 5.7%

Systematic Uncertainties III

- veto $\pi^0 \to \gamma e^+ e^-$
  We change the cut value within $\pm 1\sigma$ and use the maximum change of branching fraction as the systematic uncertainty. The uncertainties is set to be 3.5%

- veto $\eta \to \gamma e^+ e^-$
  We change the cut value within $\pm 1\sigma$ and use the maximum change of branching fraction as the systematic uncertainty. The uncertainties is set to be 4.0%

- veto $\psi' \to \pi^+ \pi^- J/\psi$
  We change the cut value within $\pm 1\sigma$ and use the maximum change of branching fraction as the systematic uncertainty. The uncertainties is set to be 0.7%

Systematic Uncertainties IV

Table: Summary of systematic uncertainties

Source	$B(\psi' \to e^+e^-\eta_c)$
Tracking	2.0%
PID	2.4%
R_{xy} cut	1.0%
$\theta_{e^+e^-}$ cut	5.7%
veto $\pi^0 \to \gamma e^+e^-$	3.5%
veto $\eta \to \gamma e^+e^-$	4.0%
veto $\psi' \to \pi^+\pi^- J/\psi$	0.7%
Total	8.5%

Summary

- We obtain the branching fraction $B(\psi' \to e^+e^-\eta_c) = (4.20 \pm 0.62 \pm 0.36) \times 10^{-5}$.
- With the branching fraction of $B(\psi' \to \gamma\eta_c)$ in PDG, we obtain the ratio

$$R = \frac{\Gamma\left(\psi' \to e^+e^-\eta_c\right)}{\Gamma\left(\psi' \to \gamma\eta_c\right)} = (1.2 \pm 0.27) \times 10^{-2} \quad (7)$$

Thank You!

BACK UP

“DalitzJPLL” Generator

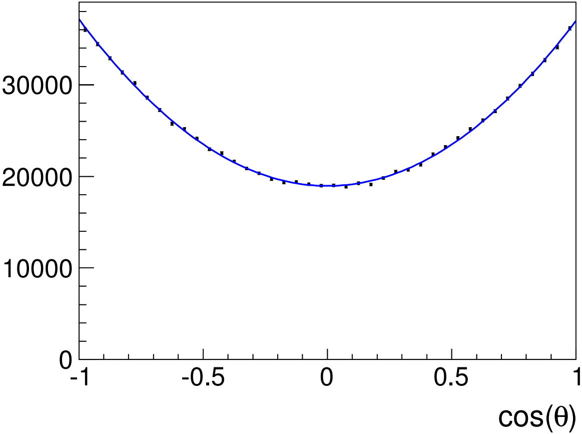
arXiv:1904.06085

$$\left|T\left(\psi \rightarrow P l^{+} l^{-}\right)\right|^{2}=16 \pi^{2} \alpha^{2} \frac{\left|f_{V P}\left(q^{2}\right)\right|^{2}}{q^{4}} \cdot h_{\mathrm{T}} \tag{8}$$

$$\begin{aligned} h_{\mathrm{T}}= & \ 2 m_{\psi}^{2} \times\left\{k_{1} \cdot k_{2}\left(q_{x}^{2}+q_{y}^{2}+2 q_{z}^{2}\right)\right. \\ & +2 q_{z}^{2}\left(k_{1 x} k_{2 x}+k_{1 y} k_{2 y}\right) \\ & -2 q_{z} k_{2 z}\left(k_{1 x} q_{x}+k_{1 y} q_{y}\right) \\ & -2 q_{z} k_{1 z}\left(k_{2 x} q_{x}+k_{2 y} q_{y}\right) \\ & +2 k_{1 z} k_{2 z}\left(q_{x}^{2}+q_{y}^{2}\right) \\ & \left.+m_{l}^{2}\left(q_{x}^{2}+q_{y}^{2}+2 q_{z}^{2}\right)\right\} \end{aligned} \tag{9}$$

“DalitzJPLL” Generator

arXiv:1904.06085



Distribution of $\cos\theta$