Measurement of Observed Cross Sections for $e^+e^- \to hadrons|_{\text{non-}D\bar{D}}$

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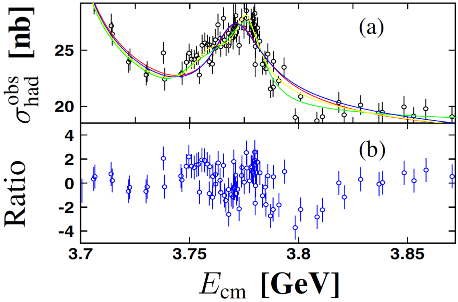
Outline

Introduction

- The BES-II previously observed an anomalous line shape of the cross section for $e^+e^- \to hadrons$ (Phys. Rev. Lett. **101**, 102004 (2008)).



- **This anomalous line shape more likely indicates that there are new structure(s) in addition to the $\psi(3770)$ around 3.773 GeV or some dynamics affect $\psi(3770)$ and $D\bar{D}$ production and decays.**
- S. Dubynskiy and M. B. Voloshin interpret this anomalous line shape of cross section as a "diresonance", "which may arise from existence of both a charmonium state and a 'molecular' $D\bar{D}$ threshold resonance" (Phys. Rev. D **78**, 116014 (2008)).

- However, this observation of the line shape need to be confirmed at other experiment.
- Experimental study of the process of e^+e^- annihilating into hadrons in this energy range with a larger data set at the BESIII experiment will provide some important information to elucidate this anomalous line-shape.

Data and MC Samples

- Data sets:
  $\sim$70 pb^{-1} energy scan data taken in range from 3.64 to 3.87 GeV
- MC samples:

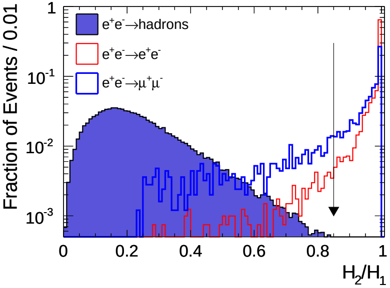
Process	Generator
$J/\psi \to hadrons$	KKMC+BESEVTGEN
$\psi(3686) \to hadrons$	KKMC+BESEVTGEN
$D^0\bar{D}^0, D^+D^-$	KKMC+BESEVTGEN
$\psi(3770) \to$ non-$D\bar{D}$	KKMC+BESEVTGEN
$e^+e^- \to q\bar{q}$	KKMC
$e^+e^- \to e^+e^-, \mu^+\mu^-, \gamma\gamma$	BABAYAGA
$e^+e^- \to \tau^+\tau^-$	KKMC
$e^+e^- \to e^+e^- f\bar{f}$	BESTWOGAM

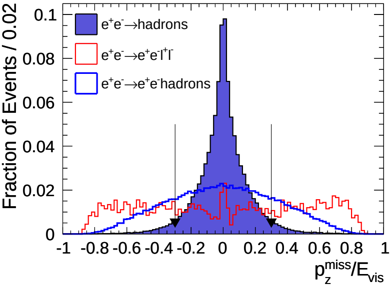
For inclusive decays of the J/ψ, $\psi(3686)$ and $\psi(3770)$, the known decay modes are generated by EVTGEN **with branching fractions taken from PDG, while the remaining unknown decay modes are modeled by** LUNDCHARM

- Software environment: BOSS 6.6.4.p01

Event Selection

- At least three good charged tracks
  - $|V_r| < 1.0$ cm, $|V_z| < 15.0$ cm, $|\cos\theta| < 0.93$
- To suppress the Bhabha and dimuon backgrounds, require the ratio of Fox-Wolfram moments $H_2/H_0 < 0.85$

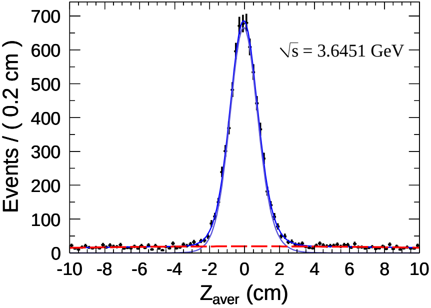




- To suppress the two-photon and beam-gas events, require the ratio $|p_z^{\mathrm{miss}}|/E_{\mathrm{vis}} < 0.30$
  - p_z^{miss}: the z component of the missing momentum of the event
  - E_{vis}: the visible energy of the event

Event Selection

- **In order to separate some beam-gas associated background events and cosmic-ray events, which are suspected to be produced at random Z positions in the beam pipe, we can examine the averaged Z position ($Z_{\rm aver}$) of the charged tracks.**
- **The numbers of observed hadronic events are extracted from maximum likelihood fits to the $Z_{\rm aver}$ distributions.**



$E_{\rm cm}$ (GeV)	$N_{\rm obs}$	$E_{\rm cm}$ (GeV)	$N_{\rm obs}$	$E_{\rm cm}$ (GeV)	$N_{\rm obs}$	$E_{\rm cm}$ (GeV)	$N_{\rm obs}$
3.6451	6905 ± 102	3.7587	74653 ± 300	3.7873	43808 ± 236	3.8319	3791 ± 76
3.7215	2208 ± 52	3.7617	76820 ± 312	3.7915	51908 ± 254	3.8400	3560 ± 68
3.7296	3533 ± 69	3.7645	58202 ± 271	3.7952	57198 ± 270	3.8479	3555 ± 68
3.7454	14932 ± 138	3.7674	44937 ± 237	3.7989	54047 ± 263	3.8561	4102 ± 76
3.7470	22267 ± 167	3.7702	38140 ± 213	3.8030	36777 ± 222	3.8640	3895 ± 75
3.7493	36395 ± 216	3.7731	35114 ± 207	3.8068	23726 ± 172	3.6474	26947 ± 200
3.7508	47770 ± 244	3.7760	35077 ± 205	3.8099	17046 ± 152	3.6534	26396 ± 191
3.7530	53721 ± 258	3.7789	36476 ± 211	3.8128	12063 ± 128		
3.7544	55601 ± 261	3.7818	38163 ± 214	3.8160	9019 ± 112		
3.7558	63800 ± 278	3.7847	42113 ± 231	3.8240	5247 ± 86		

Background Subtraction

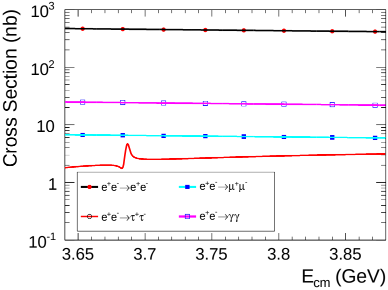
- Background sources
  - QED processes:
    $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \gamma\gamma$
  - Two-photon interactions:
    $e^+e^- \to e^+e^-e^+e^-, e^+e^-\mu^+\mu^-, e^+e^-\tau^+\tau^-$
    $e^+e^- \to e^+e^-u\bar{u}, e^+e^-d\bar{d}, e^+e^-s\bar{s}$
- The number of background events

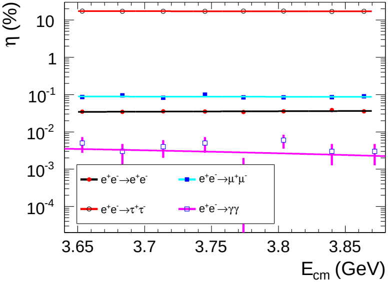
$$N_{\mathrm{bkg}} = \mathcal{L} \times \left(\sum_i \sigma_{\mathrm{bkg},\,i} \times \eta_i \right)$$

  - $\mathcal{L}$: luminosity
  - σ_{bkg}: theoretical cross section of background process
  - η: contamination rate

Background Subtraction — QED Processes

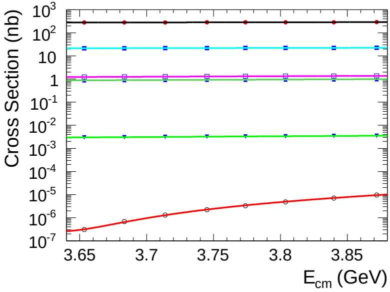
- The cross sections of $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\gamma\gamma$ are taken from the outputs of MC generators.
- To calculate the $e^+e^- \to \tau^+\tau^-$ cross section, the effects of ISR, FSR, Coulomb interaction, $\psi(3686)$ production and interference are considered (Phys. Rev. D **74**, 112003 (2006)).



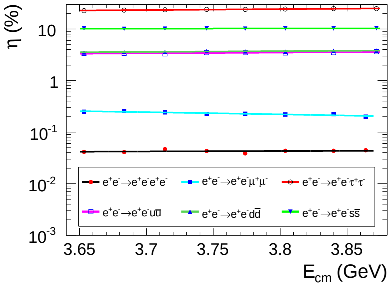


- The events selection criteria applied to data is also applied to the MC simulated background events.
- The result of fitting a polynomial to these contamination rates is used for further calculations.

Background Subtraction — Two-Photon Processes



- The cross sections of $e^+e^- \to e^+e^-f\bar{f}$ $(f = e, \mu, \tau, u, d, s)$ are obtained from MC simulation.

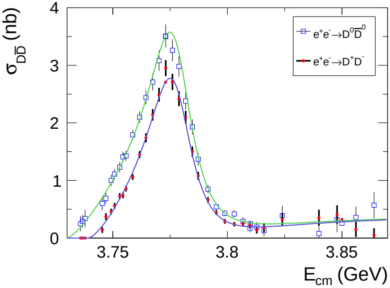


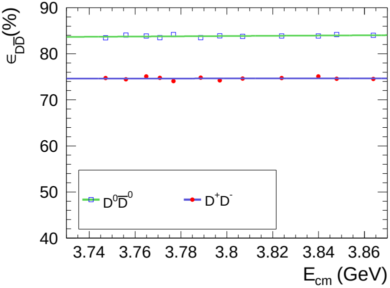
- The events selection criteria applied to data is also applied to the MC simulated background events.
- The result of fitting a polynomial to these contamination rates is used for further calculations.

The $D\bar{D}$ Contributions

- The number of $e^+e^- \to D\bar{D}$ events is given by $N_{D\bar{D}} = \mathcal{L}\sigma_{D\bar{D}}\varepsilon_{D\bar{D}}$.
- Here $\sigma_{D\bar{D}}$ is measured using singly tagged D events.
  - $D^0 \to K^-\pi^+$
  - $D^+ \to K^-\pi^+\pi^+$

  To reduce the statistic, the values expected from the fit are used.

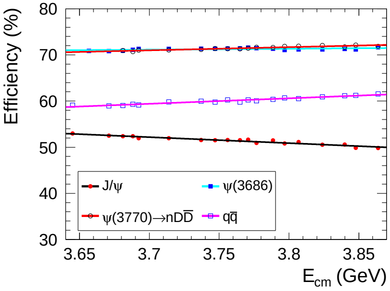


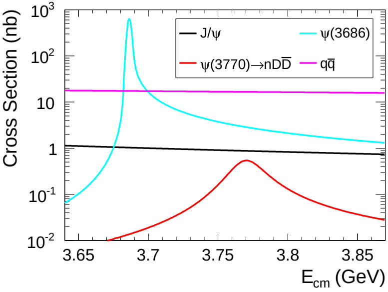


- The efficiencies $\varepsilon_{D\bar{D}}$ are determined from MC simulation. The results of fitting a polynomial to these efficiencies are used for further calculations.

Efficiencies

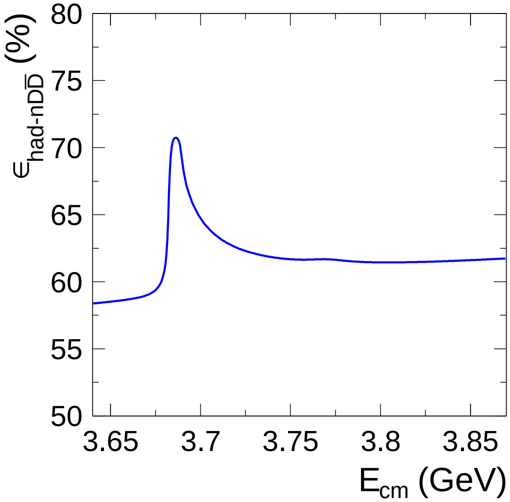
- The efficiency for hadronic events is obtained by analyzing the MC simulated signal events.
- We first determine the detection efficiency for each category of hadronic events. To reduce MC statistic, the results of fitting a polynomial to these efficiencies are used for further calculations.





- We then weight these efficiencies according to their cross sections to obtain the overall efficiency.

Efficiencies

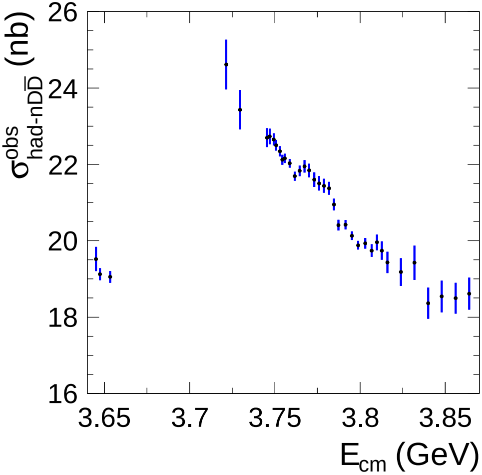


The detection efficiencies for $e^+e^- \to hadrons|_{\text{non-}D\bar{D}}$ as a function of the CM energy

Cross Sections

- The observed cross section for $e^+e^- \to hadrons|_{\text{non-}D\bar{D}}$ is given by

$$\sigma^{\text{obs}}_{\text{had-n}D\bar{D}}(E_{\text{cm}}) = \frac{N_{\text{obs}}(E_{\text{cm}}) - N_{\text{bkg}}(E_{\text{cm}})}{\mathcal{L}(E_{\text{cm}}) \times \varepsilon(E_{\text{cm}})}.$$



- Analysis of this observed cross section needs the expected-observed cross sections for this final state, which can be obtained with BW function and ISR sampling function.

Systematic Uncertainty

Source	Systematic uncertainty (%)
Charged track multiplicity	1.4
R_2 cut	0.5
$\lvert p_z^{\mathrm{miss}}\rvert / E_{\mathrm{vis}}$ cut	0.9
Fit to the $\bar{V}_z$ distribution	0.8
Luminosity	1.0
Sum in quadrature	2.2

Expected Cross Section

- The cross section of $e^+e^- \rightarrow hadrons|_{nD\bar{D}}$ can be expressed as

$$\sigma^{\rm exp}(s) = \sigma^{\rm exp}_{J/\psi}(s) + \sigma^{\rm exp}_{\psi(3686)}(s) + \sigma^{\rm exp}_{R_S(3770)}(s) + \sigma_{q\bar{q}}(s),$$

  where $s \equiv E^2_{\rm cm}$.
- For resonances, one has

$$\sigma^{\rm exp}_R(s) = \int\int \sigma^0(s'(1-x))\mathcal{F}(x,s')\mathcal{G}(s',s)dxds',$$

  where $s' \equiv s(1-x)$, x is the fraction of the radiative energy to the beam energy, $\mathcal{F}(x,s')$ is the sampling function, $\mathcal{G}(s',s)$ is a Gaussian function describing the distribution of the e^+e^- collision energy.

  We use a Breit-Wigner function to calculate the dressed cross section:

$$\sigma^0(s) = \frac{12\pi\Gamma^{ee}\Gamma\mathcal{B}_{\rm had}}{(s-M^2)^2+(M\Gamma)^2},$$

  where Γ^{ee} and Γ are respectively the leptonic width and total width of the resonance, M is the mass and $\mathcal{B}_{\rm had}$ denotes the decay branching fraction.
- The cross section for light hadron production is parameterized as

$$\sigma_{q\bar{q}}(s) = f_{q\bar{q}}\sigma^{\rm B}_{\mu^+\mu^-}(s),$$

  where $\sigma^{\rm B}_{\mu^+\mu^-}(s)$ is the Born cross section of $e^+e^- \rightarrow \mu^+\mu^-$ and $f_{q\bar{q}}$ is a free parameter.

Fitting Procedure

- We use the least squares method to fit the experimental data. The following function is minimized:

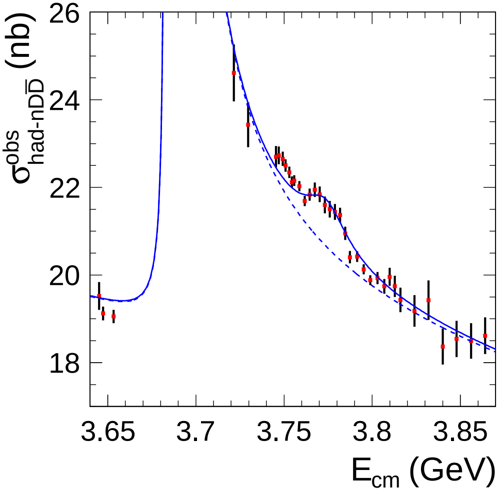
$$\chi^2 = \sum_i \left(\frac{\sigma^{\rm obs}(E_{{\rm cm},i}) - \sigma^{\rm exp}(E_{{\rm cm},i})}{\Delta(\sigma^{\rm obs}(E_{{\rm cm},i}))} \right)^2 ,$$

  where i is the energy point number, $\Delta(\sigma^{\rm obs}(E_{{\rm cm},i}))$ is the sadistical uncertainty of the measured cross section and $\sigma^{\rm exp}(E_{{\rm cm},i})$ is the predicted cross section.

- The resonance parameters of J/ψ and $\psi(3686)$ are fixed at PDG2016 values in the fit.
- The energy spread is fixed at $\sigma_E = 1.37$ MeV.
- **For the $R_s(3770)$ resonance(s), we use one or two Breit-Wigner amplitude(s) to fit the observed hadronic cross sections.**

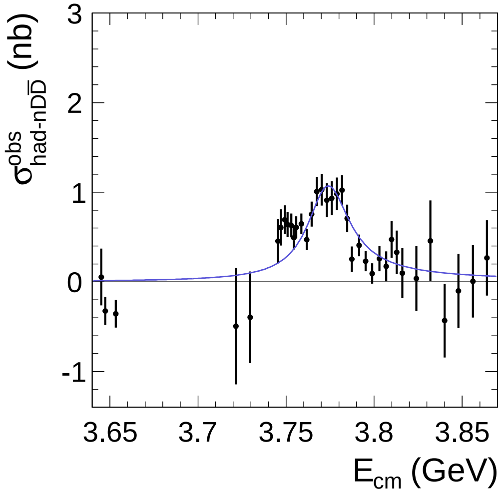
Fit Results — Scenario 1

1. Assuming that there is only $\psi(3770)$



M (MeV)	3773.13 (fixed)
Γ (MeV)	27.2 (fixed)
$\Gamma^{ee}\mathcal{B}(\psi(3770) \to nD\bar{D})$ (eV)	39.34 ± 3.91
$f_{q\bar{q}}$	2.794 ± 0.009
$\chi^2/N_{\rm dof}$	64.6/35

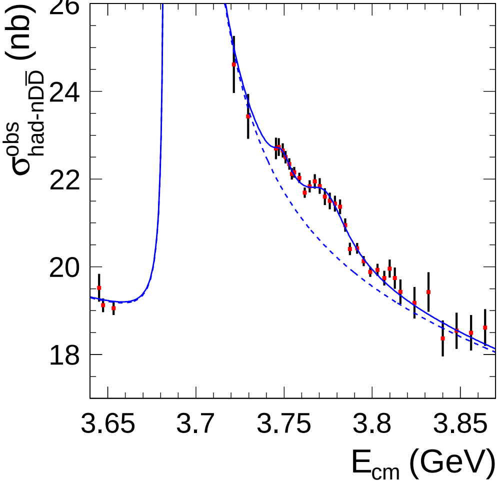
Fit Results — Scenario 1



The observed cross sections after subtracting contributions from J/ψ, $\psi(3686)$ and continuum light hadron production

Fit Results — Scenario 2

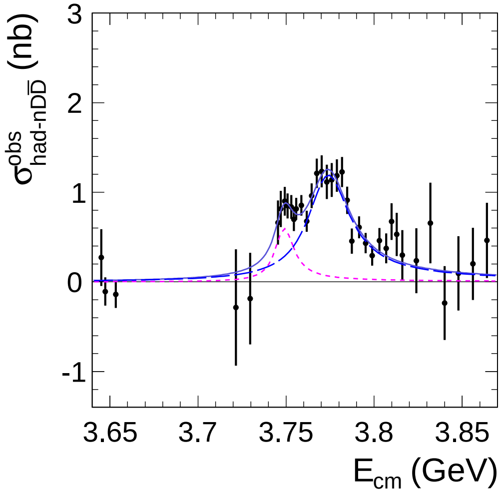
2. Assuming that there are two structures around 3.773 GeV



M_1 (MeV)	$3748.6^{+1.6}_{-2.9}$
Γ_1 (MeV)	$11.4^{+11.5}_{-5.3}$
$\Gamma_1^{ee}\mathcal{B}(R_1 \to \mathrm{n}D\bar{D})$ (eV)	$10.0^{+9.2}_{-4.1}$
M_2 (MeV)	$3773.2^{+1.5}_{-1.4}$
Γ_2 (MeV)	$27.0^{+6.3}_{-5.1}$
$\Gamma_2^{ee}\mathcal{B}(R_2 \to \mathrm{n}D\bar{D})$ (eV)	$43.3^{+10.2}_{-8.9}$
$f_{q\bar{q}}$	$2.760^{+0.013}_{-0.014}$
χ^2/N_{dof}	$24.6/30$

The signal significance of the diresonance is 5.3σ (from analyzing the observed cross sections).

Fit Results — Scenario 2



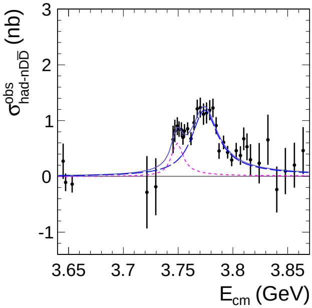
The observed cross sections after subtracting contributions from J/ψ, $\psi(3686)$ and continuum light hadron production

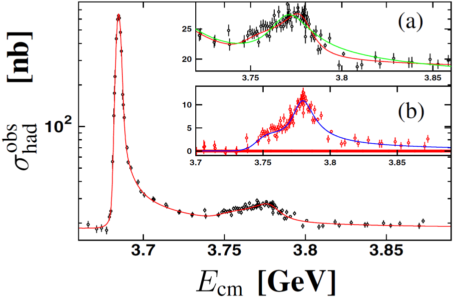
Systematic Uncertainties

- We first vary the measured cross sections, parameters of J/ψ, $\psi(3686)$, and energy spread by $\pm 1\sigma$, then repeat the fit procedure.
- The shifts of the parameters are taken as systematic uncertainties.

Source	M_1 (MeV)	$\Gamma_1^{\rm tot}$ (MeV)	$\Gamma_1^{ee}\mathcal{B}_{R_1\to nD\bar{D}}$ (eV)	M_2 (MeV)	$\Gamma_2^{\rm tot}$ (MeV)	$\Gamma_2^{ee}\mathcal{B}_{R_2\to nD\bar{D}}$ (eV)	$f_{q\bar{q}}$
$\sigma_{\rm had}^{\rm obs}$ measurement	0.2	0.4	1.3	0.1	1.0	3.6	0.066
$M_{J/\psi}$	0.0	0.0	0.0	0.0	0.0	0.0	0.000
$\Gamma_{J/\psi}^{\rm tot}$	0.0	0.0	0.0	0.0	0.0	0.0	0.000
$\Gamma_{J/\psi}^{ee}$	0.0	0.1	0.0	0.0	0.1	0.3	0.004
$M_{\psi(3686)}$	0.0	0.0	0.0	0.0	0.0	0.0	0.000
$\Gamma_{\psi(3686)}^{\rm tot}$	0.0	0.0	0.0	0.0	0.1	0.1	0.000
$\Gamma_{\psi(3686)}^{ee}$	0.1	0.3	0.8	0.0	0.9	2.2	0.002
Energy spread	0.0	0.0	0.0	0.0	0.0	0.0	0.000
Sum in quadrature	0.2	0.5	1.5	0.1	1.4	4.2	0.066

Comparison





Parameter	This work	BES-II
M_1 (MeV)	$3748.6^{+1.6}_{-2.9} \pm 0.2$	$3762.6 \pm 11.8 \pm 0.5$
Γ^{tot}_1 (MeV)	$11.4^{+11.5}_{-5.3} \pm 0.5$	$49.9 \pm 32.1 \pm 0.1$
M_2 (MeV)	$3773.2^{+1.5}_{-1.4} \pm 0.1$	$3781.0 \pm 1.3 \pm 0.5$
Γ^{tot}_2 (MeV)	$27.0^{+6.3}_{-5.1} \pm 1.4$	$19.3 \pm 3.1 \pm 0.1$

- This analysis confirms (at 5.3σ) the BES-II observation of Di-Structure $R_s(3770)$ in the range from 3.71 to 3.87 GeV.

Conclusion

- **The cross sections of $e^+e^- \to hadrons|_{nD\bar{D}}$ are measured in the energy range from 3.64 to 3.87 GeV at the BESIII experiment.**
- **We observed an enhancement of non-$D\bar{D}$ hadron production in the range from 3.74 to 3.80 GeV, which confirms the anomalous line shape of cross sections for $e^+e^- \to hadrons$ observed at the BES-II experiment.**
- **To well describe the line-shape of these observed cross sections, one more BW amplitude additional to the $\psi(3770)$ resonance is needed.**
- **By analyzing these observed cross sections, We obtain the parameters of the Di-structures:**

M_1 **(MeV)**	$3748.6^{+1.6}_{-2.9} \pm 0.2$
Γ_1 **(MeV)**	$11.4^{+11.5}_{-5.3} \pm 0.5$
$\Gamma_1^{ee}\mathcal{B}(R_1 \to$**non-**$D\bar{D})$ **(eV)**	$10.0^{+9.2}_{-4.1} \pm 1.5$
M_2 **(MeV)**	$3773.2^{+1.5}_{-1.4} \pm 0.1$
Γ_2 **(MeV)**	$27.0^{+6.3}_{-5.1} \pm 1.4$
$\Gamma_2^{ee}\mathcal{B}(R_2 \to$**non-**$D\bar{D})$ **(eV)**	$43.3^{+10.2}_{-8.9} \pm 4.2$

Backup Slides

Fox-Wolfram Moments

For a collection of N particles with momenta $\boldsymbol{p}_i$, the k-th order Fox-Wolfram moments H_k is defined as

$$H_k = \sum_{i,j}^{N} |\boldsymbol{p}_i||\boldsymbol{p}_j| P_k(\cos\theta_{ij}),$$

where θ_{ij} is the angle between $\boldsymbol{p}_i$ and $\boldsymbol{p}_j$, and P_k is the k-th order Legendre polynomial.

Systematic Uncertainty

1. **Multiplicity Requirement**
   - The systematic uncertainty due to the dependence on the charged track multiplicity is estimated by varying the requirement from $N_{\rm ch} \geq 3$ to $N_{\rm ch} \geq 2$.
   - Additional cuts on $N_{\rm ch} = 2$ events:
     - The charged track must not be identified as an electron or a muon: $E_{\rm EMC}/p < 0.7$ and $depth_{\rm MUC} < 30$ cm
     - The visible energy of event: $E_{\rm vis} > 0.3 \times E_{\rm cm}$
   - The relative changes of $\sigma^{\rm obs}_{{\rm had\text{-}n}D\bar{D}}$ are less than 1.4%, which is taken as the systematic uncertainty.
2. **H_2/H_0 cut**
   - To estimate the systematic uncertainty due to the H_2/H_0 cut, we vary this cut from its nominal level of 0.85 down to 0.80.
   - The relative changes of $\sigma^{\rm obs}_{{\rm had\text{-}n}D\bar{D}}$ are less than 0.5%, which is taken as the systematic uncertainty.
3. **$|p_z^{\rm miss}|/E_{\rm vis}$ cut**
   - To estimate the systematic uncertainty due to the cut on $|p_z^{\rm miss}|/E_{\rm vis}$, we vary this cut from its nominal level of 0.30 up to 0.35.
   - The relative changes of $\sigma^{\rm obs}_{{\rm had\text{-}n}D\bar{D}}$ are less than 0.9%, which is taken as the systematic uncertainty.

Systematic Uncertainty

④ **Fit to $\bar{V}_z$ distributions**

- To estimate the uncertainties due to the fits to the $\bar{V}_z$ distributions, we refit the $\bar{V}_z$ distributions by varying bin size, fit range ($[-8, 8]$ cm, $[-12, 12]$ cm), background PDF (first, third, fourth order polynomial), and signal PDF (a core Gaussian plus two exponential tails, double-Gaussian).

Item	Systematic uncertainty (%)
Bin size	0.0
Range	0.2
Background PDF	0.7
Signal PDF	0.4
Sum in quadrature	0.8

⑤ **Luminosity**

- 1.0% (Chin. Phys. C **37**, 123001 (2013))