Tetraquark Interpretation of $Y_b(10750)$ and Its Production at the LHC

Alexander Parkhomenko

P. G. Demidov Yaroslavl State University, Yaroslavl, Russia

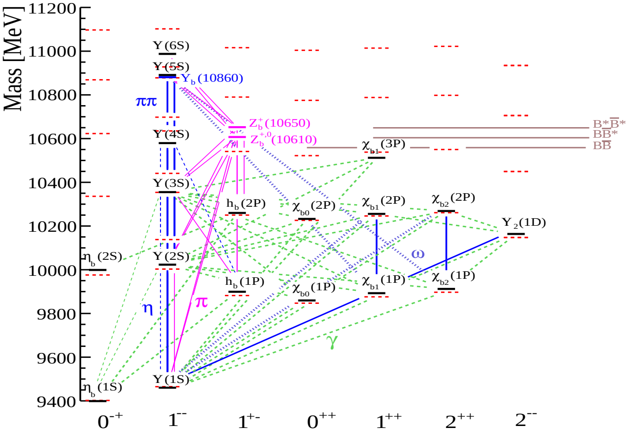
International Conference on Quantum Field Theory,
High-Energy Physics, and Cosmology
Dubna, Russia, July 18 – 21, 2022

based on the paper by A. Ali, L. Maiani, AP, and W. Wang
PLB 802 (2020) 135217 [arXiv:1910.07671]

Outline

Y_b, Z_b, and Bottomonium States

S. L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003



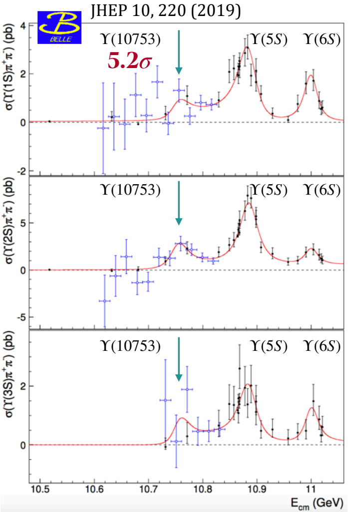
Energy Scan in the $e^- e^+$-Annihilahion by the Belle Collab.

R. Mizuk et al., JHEP 1910 (2019) 220 [arXiv:1905.05521]

$e^+ e^- \to \Upsilon(1S)\,\pi^+\pi^-$

$e^+ e^- \to \Upsilon(2S)\,\pi^+\pi^-$

$e^+ e^- \to \Upsilon(3S)\,\pi^+\pi^-$



Experinental Data on $\Upsilon(10860)$, $\Upsilon(11020)$, and $Y_b(10750)$

R. Mizuk et al., JHEP 1910 (2019) 220 [arXiv:1905.05521]

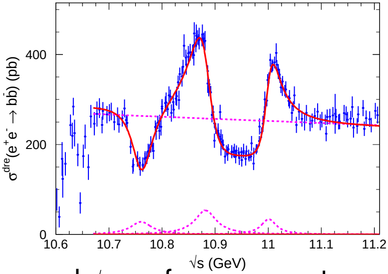
- Measured masses and decay widths (in MeV), and ranges of $\Gamma_{ee} \times \mathcal{B}$ (in eV) of $\Upsilon(10860)$, $\Upsilon(11020)$, and $Y_b(10750)$

State	$\Upsilon(10860)$	$\Upsilon(11020)$	$Y_b(10750)$
Mass	$10885.3 \pm 1.5^{+2.2}_{-0.9}$	$11000.0^{+4.0+1.0}_{-4.5-1.3}$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Width	$36.6^{+4.5+0.5}_{-3.9-1.1}$	$23.8^{+8.0+0.7}_{-6.8-1.8}$	$35.5^{+17.6+3.9}_{-11.3-3.3}$
$\Upsilon(1S)\pi^+\pi^-$	0.75 – 1.43	0.38 – 0.54	0.12 – 0.47
$\Upsilon(2S)\pi^+\pi^-$	1.35 – 3.80	0.13 – 1.16	0.53 – 1.22
$\Upsilon(3S)\pi^+\pi^-$	0.43 – 1.03	0.17 – 0.49	0.21 – 0.26

- Global significance of $Y_b(10750)$ is 5.2σ

Hadronic Cross Section of e^+e^--Annihilahion from Belle & BaBar

X.-K. Dong et al., Chin. Phys. C 44 (2020) 083001 [arXiv:2002.09838]



- M, $\Gamma_{\rm tot}$, $\Gamma_{e^-e^+}$, and ϕ are free parameters
- 8 solutions with identical fit quality are found

Solution	Parameter	$Y_b(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
1–8	Mass (MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
	Width (MeV)	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2
4	$\Gamma_{e^-e^+}$ (eV)	13.0 ± 1.1	558 ± 19	363 ± 13
	ϕ (degree)	296 ± 3	274 ± 1	249 ± 1

Difference between $Y_b(10750)$ and heavier $\Upsilon(10860)$ and $\Upsilon(11020)$

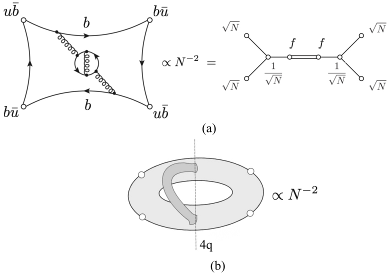
- $\Upsilon(10860)$ and $\Upsilon(11020)$ are decaying into vector bottomonium and pion pair resonantly

$$\Upsilon(10860) \to Z_b(10610)^\pm \pi^\mp \to \Upsilon(nS)\pi^\pm\pi^\mp$$
$$\Upsilon(10860) \to Z_b(10650)^\pm \pi^\mp \to \Upsilon(nS)\pi^\pm\pi^\mp$$

- For $Y_b(10750)$ it is not a case
- $Y_b(10750) \to Z_b(10650)^\pm \pi^\mp$ is kinematically forbidden
  $M_{Y_b} - M_{Z_b} \simeq 100$ MeV
- $Y_b(10750) \to Z_b(10610)^\pm \pi^\mp$ is strongly suppressed
  $M_{Y_b} - M_{Z_b} \simeq 140$ MeV
- Another mechanism of $Y_b(10750)$ decay is required

Possible Interpretations of $Y_b(10750)$

- Conventioal interpretation: $Y_b(10750)$ and $\Upsilon(10680)$ are the mixture of $\Upsilon(5S)$ and $\Upsilon(4D)$
- Our interpretation: $Y_b(10750)$ and $\Upsilon(10680)$ are the mixture of $\Upsilon(5S)$ and hidden-bottom tetraquark
- Tetraquark-Bottomonium mixing exists in the large-N_c approach with the mixing coefficient $f \sim N_c^{-3/2}$
- Should be sizable at $N_c = 3$



Mixing Formalism. I

- Define the tetraquark states Y_b^I ($I = 0, 1$) in the isospin basis, with $Y_b^0 \equiv \left(Y_{[bu]} + Y_{[bd]}\right)/\sqrt{2}$ and $Y_b^1 \equiv \left(Y_{[bu]} - Y_{[bd]}\right)/\sqrt{2}$
- Their mass difference due to the isospin breaking is ignored
- Production is via the isosinglet $b\bar{b}$-component, so only Y_b^0-state is considered
- Observed mass differences are $M[\Upsilon(10860)] - M[Y_b(10750)] \simeq 133$ MeV and $M[\Upsilon(11020)] - M[Y_b(10750)] \simeq 247$ MeV, so the mixing between $\Upsilon(10860)$ and $Y_b(10750)$ should be more pronounced

$$\begin{pmatrix} Y_b(10750) \\ \Upsilon(10860) \end{pmatrix} = \begin{pmatrix} \cos\tilde{\theta} & \sin\tilde{\theta} \\ -\sin\tilde{\theta} & \cos\tilde{\theta} \end{pmatrix} \begin{pmatrix} Y_b^0 \\ \Upsilon(5S) \end{pmatrix}$$

- Mixing angle $\tilde{\theta}$ is estimated phenomenologically
- Mixing can be generalized to the case of all three states

Mixing Formalism. II

- This mixing relates $\Gamma_{ee}[Y_b(10750)]$ and $\Gamma_{ee}[\Upsilon(5S)]$

$$\frac{\Gamma_{ee}[Y_b(10750)]}{\Gamma_{ee}[\Upsilon(10860)]} = \tan^2\tilde{\theta}\left[\frac{M[\Upsilon(10860)]}{M[Y_b(10750)]}\right]^4 \simeq 1.04\,\tan^2\tilde{\theta}$$

- LHS can be determined numerically, using
  $\Gamma_{ee}[\Upsilon(10860)] = (310 \pm 70)$ eV [PDG, 2018]
  $\Gamma_{ee}[Y_b(10750)] = (13.7 \pm 1.8)$ eV [C.-Z. Yuan, XVth Rencontre du Vietnam, 2019]
- Estimate of the mixing angle

$$\tan^2\tilde{\theta} = 0.044 \pm 0.006 \quad \Longrightarrow \quad \tilde{\theta} \simeq 12^\circ$$

- This supports the prediction from the large-N_c approach that the mixing angle between the pure bottomonium and hidden-bottom tetraquark state is relatively large

Hadroproduction Cross Sections at the LHC. I

- Hadroproduction cross sections for $\Upsilon(5S)$ and $\Upsilon(6S)$ in $p\bar{p}$ (Tevatron) and pp (LHC) collisions were calculated, using NRQCD framework [A. Ali, C. Hambrock, W. Wang, PRD 88 (2013) 054026]
- Calculation has adopted a factorization ansatz to separate the short- and long-distance effects
- Cross-sections for $Y_b(10750)$ are scaled from the ones for $\Upsilon(5S)$, since in both cases the production takes place via the $b\bar{b}$-component
- The cross-section ratio is determined by the mixing angle

$$\frac{\sigma(pp \to Y_b(10750) + X)\,\mathcal{B}_f(Y_b(10750))}{\sigma(pp \to \Upsilon(10860) + X)\,\mathcal{B}_f(\Upsilon(10860))} \simeq \frac{\Gamma_{ee}(Y_b(10750))\,\mathcal{B}_f(Y_b(10750))}{\Gamma_{ee}(\Upsilon(10860))\,\mathcal{B}_f(\Upsilon(10860))} \simeq 1.04\,\tan^2\tilde{\theta}\,\frac{\mathcal{B}_f(Y_b(10750))}{\mathcal{B}_f(\Upsilon(10860))}$$

- $\mathcal{B}_f(Y_b(10750)) = \mathcal{B}(Y_b(10750) \to \Upsilon(nS)\pi^+\pi^-)$ and $\mathcal{B}_f(\Upsilon(10860)) = \mathcal{B}(\Upsilon(10860) \to \Upsilon(nS)\pi^+\pi^-)$ with $n = 1, 2, 3$
- RHS of this equation has been measured by Belle

Hadroproduction Cross Sections at the LHC. II

- Absolute cross sections for $\Upsilon(10860)$ are estimated in NRQCD [A. Ali, C. Hambrock, W. Wang, PRD 88 (2013) 054026]

$$\sigma(pp \to \Upsilon(10860) + X) = \sum_Q \sigma_Q$$

$$= \sum_Q \int dx_1 \, dx_2 \sum_{i,j} f_i(x_1) \, f_j(x_2) \, \hat{\sigma} \left(ij \to \langle \bar{b} b \rangle_Q + X \right) \langle O[Q] \rangle$$

- $f_i(x_1)$ is the parton distribution function (PDF) of a generic i-th parton inside a proton
- Label $Q = {}^{2S+1}L_J^c$ denotes the $b\bar{b}$-pair quantum number (color c, spin S, and orbital L and total J angular momenta)
- $\langle O[Q] \rangle$ are long-distance matrix elements (LDMEs)
- $\hat{\sigma} = \sigma / \langle O[Q] \rangle$ is a normalized partonic cross section
- Leading-order partonic processes for the S-wave configurations

$$g + g \to \Upsilon[{}^3S_1^1] + g, \qquad g + g \to \Upsilon[{}^1S_0^8, \, {}^3S_1^8] + g$$

$$g + q \to \Upsilon[{}^1S_0^8, \, {}^3S_1^8] + q, \qquad q + \bar{q} \to \Upsilon[{}^1S_0^8, \, {}^3S_1^8] + g$$

Hadroproduction and Drell-Yan Cross Sections at the LHC

- Total cross sections (in pb) at $\sqrt{s} = 14$ TeV for $pp \to Y_b(10750) + X \to \Upsilon(nS)(\to \mu^+\mu^-)\,\pi^+\pi^- + X$ ($n = 1, 2, 3$) at the LHC, assuming the transverse momentum range $3\ \mathrm{GeV} < p_T < 50\ \mathrm{GeV}$
- Rapidity ranges are $|y| < 2.5$ for ATLAS and CMS (called LHC 14) and $2.0 < y < 4.5$ for the LHCb
- Error estimates in the QCD production are from the variation of the central values of the Color-Octet LDMEs and the various decay branching ratios, as discussed in [A. Ali, C. Hambrock, W. Wang, PRD 88 (2013) 054026]
- Contributions from $\Upsilon(1S, 2S, 3S)$ are added together in the Drell-Yan production mechanism [A. Ali & W. Wang, PRL 106 (2011) 192001]

	QCD (gg)			Drell-Yan
	$n = 1$	$n = 2$	$n = 3$	DY
LHC 14	[0.29, 3.85]	[0.70, 4.78]	[0.45, 3.10]	[0.002, 0.004]
LHCb 14	[0.08, 1.21]	[0.20, 1.51]	[0.13, 0.99]	[0.001, 0.002]

Differential Cross Section in $Y_b(10750) \to \Upsilon(nS)\,\pi^+\pi^-$

- Differential cross section can be written as [A. Ali, C. Hambrock, S. Mishima, PRL 106 (2011) 092002]

$$\frac{d^2\sigma_{\Upsilon(1S)PP'}}{dm_{PP'}\,d\cos\theta} = \frac{\lambda^{1/2}(s, m_\Upsilon^2, m_{PP'}^2)\lambda^{1/2}(m_{PP'}^2, m_P^2, m_{P'}^2)}{384\pi^3 s\, m_{PP'}\left[(s - m_{Y_b}^2)^2 + m_{Y_b}^2\Gamma_{Y_b}^2\right]}$$

$$\times \left\{ \left(1 + \frac{(q\cdot p)^2}{2s\,m_\Upsilon^2}\right)|\mathcal{S}|^2 + 2\,\mathrm{Re}\left[\mathcal{S}^*\left(\mathcal{D}' + \frac{(q\cdot p)^2}{2s\,m_\Upsilon^2}\mathcal{D}''\right)\right]\left(\cos^2\theta - \frac{1}{3}\right)\right.$$

$$+ |\mathcal{D}|^2 \sin^2\theta\left[\sin^2\theta + 2\left(\frac{q_0^2}{s} + \frac{p_0^2}{m_\Upsilon^2}\right)\cos^2\theta\right]$$

$$\left. + \left(|\mathcal{D}'|^2 + \frac{(q\cdot p)^2}{2s\,m_\Upsilon^2}|\mathcal{D}''|^2\right)\left(\cos^2\theta - \frac{1}{3}\right)^2\right\}$$

- m_{Y_b}, m_Υ, m_P and $m_{P'}$ are the masses of Y_b, $\Upsilon(nS)$, P and P'
- s and $m_{PP'}$ are invariant masses squared of e^+e^- and PP'-pairs
- θ is the angle between Y_b and P momenta in the PP' rest frame
- $\lambda(x, y, z) \equiv (x - y - z)^2 - 4yz$ is the kinematical function
- q_0 and p_0 are energies of the Y_b and $\Upsilon(nS)$ in the PP' rest frame
- Γ_{Y_b} is the decay width of Y_b

S- and D-Wave Amplitudes in $Y_b(10750) \to \Upsilon(nS)\,\pi^+\pi^-$

- S-wave amplitude for PP' system, $\mathcal{S}$, and D-wave amplitudes, $\mathcal{D}$, $\mathcal{D}'$ and $\mathcal{D}''$, are the sums over possible isospin states [A. Ali, C. Hambrock, S. Mishima, PRL 106 (2011) 092002]

$$\mathcal{M} = \sum_I \mathcal{M}_I \quad \text{for} \quad \mathcal{M} = \mathcal{S},\ \mathcal{D},\ \mathcal{D}',\ \mathcal{D}''$$

- For the $\pi^+\pi^-$-pair, isospin $I = 0$
- In $Y_b(10750) \to \Upsilon(1S)\,\pi^+\pi^-$ process, scalar $\sigma = f_0(500)$- and $f_0(980)$- and tensor $f_2(1270)$-resonances contribute
- $I = 0$ amplitudes are given by the combinations of the resonance amplitudes, $\mathcal{M}_0^S$ and $\mathcal{M}_0^{f_2}$, and the non-resonating continuum amplitudes, $\mathcal{M}_0^{1C}$ and $\mathcal{M}_0^{2C}$

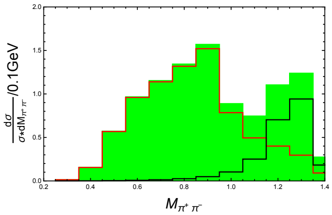
$$\mathcal{S}_0 = \mathcal{M}_0^{1C} + (k_1 \cdot k_2) \sum_S \mathcal{M}_0^S, \quad \mathcal{D}_0 = |k|^2 \mathcal{M}_0^{f_2},$$

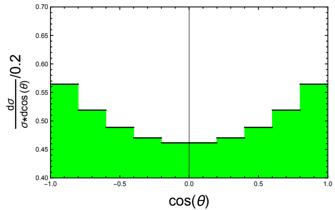
$$\mathcal{D}_0' = \mathcal{M}_0^{2C} - \mathcal{D}_0, \quad \mathcal{D}_0'' = \mathcal{M}_0^{2C} + \frac{2q_0p_0}{(q \cdot p)}\,\mathcal{D}_0,$$

- $|\mathbf{k}|$ is the π^+-meson momentum magnitude in $\pi^+\pi^-$ rest frame

$\pi^+\pi^-$ Invariant Mass and Angular Distributions

- $m_{\pi^+\pi^-}$ and $\cos\theta$ distributions for the process $e^+e^- \to Y_b + X \to \Upsilon(1S)\,\pi^+\pi^- + X$ are calculated
- They normalized by $\sigma^{\rm Belle}_{\Upsilon(1S)\,\pi^+\pi^-} = (1.61 \pm 0.16)$ pb measured by the Belle Collab. [K. F. Chen et al., PRL 100 (2008) 112001]
- Only resonant contributions are plotted, using relevant input parameters [A. Ali, C. Hambrock, S. Mishima, PRL 106 (2011) 092002]
- Anticipated spectral shapes will be modified in detail as a non-resonant contribution is included
- A fit can only be undertaken as experimental measurements become available





Branching Fractions of $Y_b(10750) \to \Upsilon(nS)\,\pi^+\pi^-$ Decays

- The products $\Gamma_{ee} \times \mathcal{B}$ are measured by Belle [R. Mizuk et al., JHEP 1910 (2019) 220; arXiv:1905.05521]
- $\Gamma_{ee}[Y_b(10750)] = (13.7 \pm 1.8)$ eV from the Belle and BaBar data on R_b [C.-Z. Yuan, XVth Rencontress du Vietnam, 2019]
- Corresponding ranges of the branching fractions

$$\mathcal{B}_{\Upsilon(1S)\pi^+\pi^-} = (0.9 - 3.4)\%$$
$$\mathcal{B}_{\Upsilon(2S)\pi^+\pi^-} = (3.9 - 8.9)\%$$
$$\mathcal{B}_{\Upsilon(3S)\pi^+\pi^-} = (1.5 - 1.9)\%$$

- Note that due to the dominant tetraquark nature of $Y_b(10750)$, and its quark content, $Y_b(10750) \to B_s^{(*)}\bar{B}_s^{(*)}$ decays are not anticipated, in agreement with the data from the Belle Collab. [A. Abdesselam et al., arXiv:1609.08749]

Scan Data by the Belle-II Collab. Near $\sqrt{s} = 10.75$ GeV

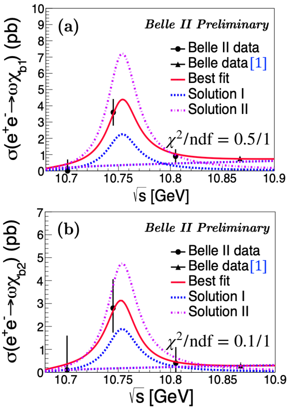
Qingping Ji, ICHEP-2022

- In November 2021, Belle-II collected $\sim 19\ \text{fb}^{-1}$ of data at energies above $\Upsilon(4S)$
- Four energy scan points around 10.75 GeV was selected

Energy (GeV)	10.645	10.701	10.745	10.805	Combained
Luminosity (fb^{-1})	3.5	1.5	9.5	4.5	19.0

- Physics goal: understand the nature of the $Y_b(10753)$ energy region
- Determine the Born cross section for $e^+e^- \to \omega\chi_{bJ}$ using scan data samples at 10.701, 10.745 and 10.805 GeV
- Study energy dependence of $e^+e^- \to \omega\chi_{bJ}$ cross section, by combining with the Belle data at 10.867 GeV

Observation of $Y_b(10753) \to \omega\chi_{b1}$ and $Y_b(10753) \to \omega\chi_{b2}$



Qingping Ji, ICHEP-2022

- $e^+e^- \to \omega\chi_{b1,b2}$ cross sections peak at $Y_b(10753)$, while no obvious peak at $\Upsilon(10860)$ is found
- M and Γ are fixed from [R. Mizuk et al., JHEP 1910 (2019) 220]
- For each $\Gamma_{ee}\mathcal{B}(Y_b(10753) \to \omega\chi_{bJ})$, two solutions are obtained (in eV)

Spin	Solution I	Solution II
$J = 1$	$0.63 \pm 0.39 \pm 0.20$	$2.01 \pm 0.38 \pm 0.76$
$J = 2$	$0.53 \pm 0.46 \pm 0.15$	$1.32 \pm 0.44 \pm 0.55$

- Ratio $\mathcal{B}(\omega\chi_{b1})/\mathcal{B}(\omega\chi_{b2}) \sim 1$; agrees with expectations from NRQCD
- Other active ongoing analysis are $e^+e^- \to \omega\eta_b,\ \phi\eta_b, \pi^+\pi^-\Upsilon(nS)$, etc

Summary

- Tetraquark-based interpretation of the Belle data on the $Y_b(10750)$ structure observed in the e^+e^- annihilation is presented
- $Y_b(10750)$ and $\Upsilon(10860)$ are assumed to be a mixture of a hidden-bottom tetraquark and vector bottomonium, anticipated in the large-N_c limit
- The $b\bar{b}$-component is used to predict the hadroproduction and Drell-Yan cross sections at the LHC
- Crucial test of the model is in $m_{\pi^+\pi^-}$ and $\cos\theta$ distributions, whose resonant contribution is worked out, which is not expected in other dynamical schemes
- Tetraquark-$Q\bar{Q}$ mixing scheme suggested has wider implications and should be tested on new and expected Belle-II results

Backup Slides

Hadronic Cross Section of e^+e^--Annihilahion from Belle & BaBar

X.-K. Dong et al., Chin. Phys. C 44 (2020) 083001 [arXiv:2002.09838]

- M, $\Gamma_{\rm tot}$, $\Gamma_{e^- e^+}$, and ϕ are free parameters
- 8 solutions with identical fit quality are found

Solution	Parameter	$Y_b(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
1–8	Mass (MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
	Width (MeV)	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2
1	$\Gamma_{e^- e^+}$ (eV)	10.7 ± 0.9	21.3 ± 1.0	9.8 ± 0.5
	ϕ (degree)	260 ± 3	144 ± 2	34 ± 3
2	$\Gamma_{e^- e^+}$ (eV)	11.1 ± 0.9	24.8 ± 1.3	307 ± 9
	ϕ (degree)	270 ± 3	164 ± 2	280 ± 1
3	$\Gamma_{e^- e^+}$ (eV)	12.6 ± 1.1	479 ± 14	11.5 ± 0.6
	ϕ (degree)	295 ± 3	254 ± 1	3 ± 3
4	$\Gamma_{e^- e^+}$ (eV)	13.0 ± 1.1	558 ± 19	363 ± 13
	ϕ (degree)	296 ± 3	274 ± 1	249 ± 1
5	$\Gamma_{e^- e^+}$ (eV)	324 ± 24	23.7 ± 1.2	10.0 ± 0.5
	ϕ (degree)	265 ± 1	129 ± 2	26 ± 3
6	$\Gamma_{e^- e^+}$ (eV)	336 ± 27	27.6 ± 1.6	314 ± 10
	ϕ (degree)	275 ± 1	149 ± 2	272 ± 1
7	$\Gamma_{e^- e^+}$ (eV)	380 ± 32	534 ± 18	11.8 ± 0.6
	ϕ (degree)	291 ± 1	239 ± 1	355 ± 3
8	$\Gamma_{e^- e^+}$ (eV)	394 ± 34	622 ± 25	370 ± 14
	ϕ (degree)	301 ± 1	259 ± 2	241 ± 1