Charmonium(-like) States from ISR at Belle

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for Belle Collaboration

Quarkonium Working Group
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Quarkonia – Both charmonium and bottomonium provide important tests of QCD.

Charmonia – Many charmonium(-like) states found at the Charm and B factories.


Example potential from Barnes, Godfrey, Swanson:

\[ V_0(c\bar{c})(r) = -\frac{4}{3} \frac{\alpha_s}{r} + b r + \frac{32 \pi \alpha_s}{9 m_c^2} \hat{\delta}_{\sigma}(r) \hat{S}_c \cdot \hat{S}_{\bar{c}} \]

(Coulomb + Confinement + Contact)

\[ V_{\text{spin-dep}} = \frac{1}{m_c^2} \left[ \left( \frac{2 \alpha_s}{r^3} - \frac{b}{2r} \right) \hat{L} \cdot \hat{S} + \frac{4 \alpha_s}{r^5} T \right] \]

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)

The charmonium(-like) states observed via ISR: \( Y(4008), Y(4260), Y(4360), Y(4660), X(4630), \psi(4040), \psi(4160), \psi(4415), \ldots \)
Cross section was measured from 4 GeV to 6 GeV.

There is one very broad structure.

Two events near the $Y(4260)$ mass.

Dalitz plot not shown in 2008 paper.
Update on $e^+e^- \rightarrow K^+K^- J/\psi$ via ISR

Event selections almost same as in PRD77, 011105(R)(2008).

- $4 - 6$ GeV, 213 events:
  - $n_{\text{sig}} = 178 \pm 16, n_{\text{bkg}} = 35$.

$$\sigma_i = \frac{n_{i}^{\text{obs}} - f \times n_{i}^{\text{bkg}}}{L_i \cdot \epsilon_i \cdot B(J/\psi \rightarrow \ell^+\ell^-)}$$

7.8% syst. error not included in the plot.

Fit quality ($\chi^2/\text{ndf} = 30/11$) is not good, so the assumptions with structures may not match reality. Structures may be complicated! Need larger data sample — Belle II.

C. P. Shen et al., PRD89, 072015(2014).

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**Figure 1:**
- Panel (a): Distribution of $M(K^+K^-J/\psi)$ in events with ISR for $Y(4260)$.
- Panel (b): Distribution of $M(K^+K^-J/\psi)$ with $980 fb^{-1}$ of data.

**Figure 2:**
- Distribution of $\sigma(K^+K^-J/\psi)$ vs. $E_{\text{cm}}$ (GeV) for Belle II data.
Search for $Z_{cs} \rightarrow KJ/\psi$ states

Dalitz analysis performed.

No evident structure in $K^{\pm}J/\psi$ mass distribution from current statistics

C. P. Shen et al., PRD89, 072015(2014).
Update on $e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$ via ISR

- $Y(4360)$ was confirmed and $Y(4660)$ was discovered in $e^+e^- \rightarrow \gamma_{ISR} \pi^+\pi^- \psi(2S)$ at Belle with 673 fb\(^{-1}\) data.
- $Y(4660)$ has been confirmed by BaBar:
  - The charmonium-like state with highest mass but narrowest width.
  - Are $Y(4660)$ and $Y(4630)$ the same?

PRL99,142002(2007)  
Belle 673 fb\(^{-1}\)  
110 events

PRD89,111103(R)(2014)  
BaBar 520 fb\(^{-1}\)  
$X(4630) \rightarrow \Lambda_c^+\Lambda_c^-$

PRL101,172001(2008)  
Belle has about 1 ab\(^{-1}\) data now, and efficiency should increase after data have been reprocessed.

- Many more signal events are expected!
- Search for possible intermediate state(s) in $Y$ decays.
ISR characteristics

Improvements: selection criteria; $\psi(2S) \to \mu^+ \mu^-$ mode included.

- **Missing mass**: signal of $\gamma_{\text{ISR}}$. $-2 < M_{\text{rec}}^2(\pi^+ \pi^- \psi(2S)) < 2 \text{ (GeV/c}^2)^2$ is required.
- **Visible energy**: $\gamma_{\text{ISR}}$ is detected roughly 20% of the time.
- **Angular distribution**: $\gamma_{\text{ISR}}$ highly forward/backward.

X. L. Wang et al., arXiv:1410.7641, submitted to PRD.
After the selection criteria, we get pure $\pi^+\pi^-\psi(2S)$ events.

- Clear clusters!
- Purity: 245 candidate events with a purity of 96% from $\pi^+\pi^- J/\psi$ mode, and 118 events with a purity of 60% from $\mu^+\mu^-$ mode.
- $M_{\pi^+\pi^-}$: tends to the phase space boundary; clear $f_0(980)$ belts.

X. L. Wang et al., arXiv:1410.7641, submitted to PRD
$M_{\pi^+\pi^-}$ projections in $\pi^+\pi^-J/\psi$

It’s not so clean in $\mu^+\mu^-$ mode, due to the width of sidebands.
Mass resolutions of $\psi(2S)$ signal: $2.7 \pm 0.2$ MeV/$c^2$ in $\pi^+\pi^-J/\psi$, and $13.8 \pm 2.1$ MeV/$c^2$ in $\mu^+\mu^-$. 

Y(4360) + Y(4660)  

Y(4360)  

Y(4660) 

- Dots: data; Blank hist: MC simulations; Shaded hist: bkg from $\psi(2S)$ sidebands.
- Left: with $4.0 < M_{\pi^+\pi^-\psi(2S)} < 5.5$ GeV/$c^2$.
- Middle: from Y(4360), $4.0 < M_{\pi^+\pi^-\psi(2S)} < 4.5$ GeV/$c^2$, looks like $f_0(500)$
- Right: from Y(4660), $4.5 < M_{\pi^+\pi^-\psi(2S)} < 4.9$ GeV/$c^2$, should be $f_0(980)$, confirmed in BaBar update.

MC simulation with an incoherent sum of the $f_0(500)$ and $f_0(980)$.

X. L. Wang et al., arXiv:1410.7641, submitted to PRD.
Fit of $M_{\pi^+\pi^-\psi(2S)}$ spectrum with two resonances

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$. 

$Amp = BW_1 + e^{i\phi} \cdot BW_2$.

Comparing to previous measurement:

- Masses smaller but consistent.
  
  Previous measurement:
  $M_{Y(4360)} = 4361 \pm 9 \pm 9$ MeV/$c^2$, 
  $M_{Y(4660)} = 4664 \pm 11 \pm 5$ MeV/$c^2$.

- No obvious signal above $Y(4660)$.

- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.

- If $Y(4260)$ is included in the fit, ...

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{Y(4360)}$ (MeV/$c^2$)</td>
<td>$4347 \pm 6 \pm 3$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{Y(4360)}$ (MeV)</td>
<td>$103 \pm 9 \pm 5$</td>
<td></td>
</tr>
<tr>
<td>$B \cdot \Gamma_{e^+e^-}^{Y(4360)}$ (eV)</td>
<td>$9.2 \pm 0.6 \pm 0.6$</td>
<td>$10.9 \pm 0.6 \pm 0.7$</td>
</tr>
<tr>
<td>$M_{Y(4660)}$ (MeV/$c^2$)</td>
<td>$4652 \pm 10 \pm 11$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{Y(4660)}$ (MeV)</td>
<td>$68 \pm 11 \pm 5$</td>
<td></td>
</tr>
<tr>
<td>$B \cdot \Gamma_{e^+e^-}^{Y(4660)}$ (eV)</td>
<td>$2.0 \pm 0.3 \pm 0.2$</td>
<td>$8.1 \pm 1.1 \pm 1.0$</td>
</tr>
<tr>
<td>$\phi$ ($^\circ$)</td>
<td>$32 \pm 18 \pm 20$</td>
<td>$272 \pm 8 \pm 7$</td>
</tr>
</tbody>
</table>

$\chi^2/ndf = 18.7/21$.

X. L. Wang et al., arXiv:1410.7641, submitted to PRD
Fit of $M_{\pi^+\pi^-\psi(2S)}$ spectrum with three resonances

Unbinned simultaneous maximum likelihood fit for $Y(4260)$, $Y(4360)$ and $Y(4660)$.

$$Amp = BW_1 + e^{i\phi_1} \cdot BW_2 + e^{i\phi_2} \cdot BW_3.$$
\[ \sigma(e^+e^- \rightarrow \pi^+\pi^-\psi(2S)) \] measurement

e\^e\^e\^ \rightarrow \pi^+\pi^-\psi(2S) cross section is calculated with

\[
\sigma_{ij} = \frac{n_{ij}^{\text{obs}} - n_{ij}^{\text{bkg}}}{L_i \epsilon_{ij} B_j}, \tag{1}
\]

where \(i\) indicates the mass bin and \(j\) indicates the \(\psi(2S)\) decay mode.

\[ \sigma(e^+e^- \rightarrow \pi^+\pi^-\eta J/\psi) \] at \(\psi(4040)\)

X. L. Wang et al., arXiv:1410.7641, submitted to PRD.

The \(\sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)\) at \(Y(4260)\), \(\sigma(e^+e^- \rightarrow \pi^+\pi^-\psi(2S))\) at \(Y(4360)\) and \(\sigma(e^+e^- \rightarrow \eta J/\psi)\) at \(\psi(4040)\) are almost the same.

\[ \pi^+\pi^- J/\psi: \text{Z. Q. Liu et al., PRL110, 252002(2013).} \]
\[ \eta J/\psi: \text{X. L. Wang et al., PRD87,051101(R)(2013).} \]
Search for intermediate states

We search for intermediate states in $\pi^\pm \psi(2S)$ final states in $Y(4360)$ decays.

An excess at both $\pi^+ \pi^- J/\psi$ and $\mu^+ \mu^-$ modes, and both $M_{\pi^+ \psi(2S)}$ and $M_{\pi^- \psi(2S)}$!

$M_{\pi^\pm \psi(2S)}$: sum of the $M_{\pi^+ \psi(2S)}$ and $M_{\pi^- \psi(2S)}$

X. L. Wang et al., arXiv:1410.7641, submitted to PRD
An excess evident at around 4.05 GeV/$c^2$ in the $\pi^\pm \psi(2S)$ invariant-mass distributions in both modes.

- An unbinned maximum-likelihood fit is performed on the distribution of $M_{\text{max}}(\pi^\pm \psi(2S))$, the maximum of $M(\pi^+ \psi(2S))$ and $M(\pi^- \psi(2S))$, simultaneously with both modes.
- $M = (4054 \pm 3\text{ (stat.)} \pm 1\text{ (syst.)}) \text{ MeV}/c^2$
- $\Gamma = (45 \pm 11\text{ (stat.)} \pm 6\text{ (syst.)}) \text{ MeV}$
- The significance is $3.5\sigma$.

X. L. Wang et al., arXiv:1410.7641, submitted to PRD.
Search for intermediate states in $Y(4660)$ decays

We search for intermediate states in $\pi^\pm \psi(2S)$ final states in $Y(4660)$ decays.

No obvious excess found in $Y(4660)$ decays.

X. L. Wang et al., arXiv:1410.7641, submitted to PRD.
The $e^+e^- \rightarrow K^+K^-J/\psi$ cross sections are updated. There are clear $K^+K^-J/\psi$ signal events.

No clear $Z_{cs}$ structure is observed in $K^\pm J/\psi$ final states.

The update on $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\psi(2S)$ via ISR at Belle has been finished.

The $Y(4260)$ is tried in the fit and we get four solutions. Its significance is $< 3\sigma$, but it has significant affect on $Y(4360)$ and $Y(4660)$ parameters.

Does $Y(4660)$ agree with $X(4630)$?

- $X(4630)$ from $\Lambda_c^+\Lambda_c^-$: $M = 4634^{+8+5}_{-7-8} \text{ MeV}/c^2$, $\Gamma = 92^{+40+10}_{-24-21} \text{ MeV}/c^2$.
- $Y(4660)$ from 2R fit: $M = 4652 \pm 10 \pm 11 \text{ MeV}/c^2$, $\Gamma = 68 \pm 11 \pm 5 \text{ MeV}/c^2$.
- $Y(4660)$ from 3R fit: $M = 4660 \pm 9 \pm 12 \text{ MeV}/c^2$, $\Gamma = 74 \pm 12 \pm 4 \text{ MeV}/c^2$.

Evidence of a structure in $M_{max}(\pi^\pm\psi(2S))$ in $Y(4360)$ decays with significance of $3.5\sigma$. $Z(4050)$?

$M = (4054 \pm 3(\text{stat.}) \pm 1(\text{syst.})) \text{ MeV}/c^2; \Gamma = (45 \pm 11(\text{stat.}) \pm 6(\text{syst.})) \text{ MeV}$

Thank you!
Back-up
$e^+ e^- \rightarrow \gamma_{\text{ISR}}$

$\bar{D}D$, $D\bar{D}^*$, $D^*\bar{D}^*$, $D\bar{D} \pi$

X.L. Wang (VPI)

Charmonium(-like)@Belle

$e^+ e^- \rightarrow \bar{D}D$ scanned by both BaBar and Belle. The results are consistent. Clear $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$. But no evidence for $Y$ states in these channels.
Belle: Search for hadronic transition via emitting $\eta$. ($\eta \rightarrow \gamma\gamma/\pi^+\pi^-\pi^0$)

- This is the first time to found $\psi$ states in charmonium transition. (> 6.0$\sigma$ for $\psi(4040)$; > 6.5$\sigma$ for $\psi(4160)$.)

- Large $\mathcal{B}(\psi \rightarrow \eta J/\psi)$!
  $\mathcal{B}(\psi(2S) \rightarrow \eta J/\psi) = (3.28 \pm 0.07)$%

- Unlike $\pi^+\pi^-$ transition, no significant $Y$ signal!!!

Belle: X. L. Wang et al., PRD87,051101(R)(2013).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\psi(4040)}$</td>
<td>4039 (fixed)</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\psi(4040)}$</td>
<td>80 (fixed)</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B} \cdot \Gamma_{e^+e^-}^{\psi(4040)}$</td>
<td>$4.8 \pm 0.9 \pm 1.5$</td>
<td>$11.2 \pm 1.3 \pm 2.1$</td>
</tr>
<tr>
<td>$M_{\psi(4160)}$</td>
<td>4153 (fixed)</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\psi(4160)}$</td>
<td>103 (fixed)</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B} \cdot \Gamma_{e^+e^-}^{\psi(4160)}$</td>
<td>$4.0 \pm 0.8 \pm 1.4$</td>
<td>$13.8 \pm 1.3 \pm 2.1$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$336 \pm 12 \pm 14$</td>
<td>$251 \pm 4 \pm 7$</td>
</tr>
</tbody>
</table>

$\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ keV from PDG

$\mathcal{B}(\psi(4040) \rightarrow \eta J/\psi) = (0.56 \pm 0.10 \pm 0.18)$% or
$\mathcal{B}(\psi(4040) \rightarrow \eta J/\psi) = (1.30 \pm 0.15 \pm 0.26)$%.

$\Gamma_{e^+e^-}(\psi(4160)) = (0.83 \pm 0.07)$ keV from PDG

$\mathcal{B}(\psi(4160) \rightarrow \eta J/\psi) = (0.48 \pm 0.10 \pm 0.17)$% or
$\mathcal{B}(\psi(4160) \rightarrow \eta J/\psi) = (1.66 \pm 0.16 \pm 0.29)$%.
Other fit results on $M_{\pi^+\pi^-\psi(2S)}$

**Published Belle results:**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(Y(4360))$</td>
<td>4361 ± 9 ± 9</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(Y(4360))$</td>
<td>74 ± 15 ± 10</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(\pi^+\pi^-\psi(2S))$</td>
<td>10.4 ± 1.7 ± 1.5</td>
<td>11.8 ± 1.8 ± 1.4</td>
</tr>
<tr>
<td>$M(Y(4660))$</td>
<td>4664 ± 11 ± 5</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(Y(4660))$</td>
<td>48 ± 15 ± 3</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(\pi^+\pi^-\psi(2S))$</td>
<td>3.0 ± 0.9 ± 0.3</td>
<td>7.6 ± 1.8 ± 0.8</td>
</tr>
<tr>
<td>$\phi$</td>
<td>39 ± 30 ± 22</td>
<td>−79 ± 17 ± 20</td>
</tr>
</tbody>
</table>

**Current BaBar results:**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>First Solution (constructive interference)</th>
<th>Second Solution (destructive interference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass $Y(4360)$ (MeV/GeV)</td>
<td>4340 ± 16 ± 9</td>
<td></td>
</tr>
<tr>
<td>Width $Y(4360)$ (MeV)</td>
<td>94 ± 32 ± 13</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B} \times \Gamma (Y(4360))$ (eV)</td>
<td>6.0 ± 1.0 ± 0.5</td>
<td>7.2 ± 1.0 ± 0.6</td>
</tr>
<tr>
<td>Mass $Y(4660)$ (MeV/GeV)</td>
<td>4669 ± 21 ± 3</td>
<td></td>
</tr>
<tr>
<td>Width $Y(4660)$ (MeV)</td>
<td>104 ± 48 ± 10</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B} \times \Gamma (Y(4660))$ (eV)</td>
<td>2.7 ± 1.3 ± 0.5</td>
<td>7.5 ± 1.7 ± 0.7</td>
</tr>
<tr>
<td>$\phi$ (°)</td>
<td>12 ± 27 ± 4</td>
<td>−78 ± 12 ± 3</td>
</tr>
</tbody>
</table>

$\pi^+\pi^- J/\psi$ only:

![Graph showing the distribution of entries per MeV/GeV²](image)

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<tr>
<th>Parameters</th>
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</thead>
<tbody>
<tr>
<td>$M_Y(4360)$</td>
<td>4358 ± 6 ± 2</td>
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</tr>
<tr>
<td>$\Gamma_Y(4360)$</td>
<td>96 ± 10 ± 6</td>
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</tr>
<tr>
<td>$\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^+\Gamma^-$</td>
<td>9.4 ± 0.8 ± 0.7</td>
<td>10.8 ± 0.7 ± 0.7</td>
</tr>
<tr>
<td>$M_Y(4660)$</td>
<td>4644 ± 7 ± 5</td>
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<tr>
<td>$\Gamma_Y(4660)$</td>
<td>57 ± 9 ± 5</td>
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<tr>
<td>$\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^+\Gamma^-$</td>
<td>3.1 ± 0.5 ± 0.4</td>
<td>7.6 ± 1.3 ± 0.9</td>
</tr>
<tr>
<td>$\phi$</td>
<td>10 ± 17 ± 12</td>
<td>288 ± 10 ± 5</td>
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</table>
Fit with three resonance using $\pi^+\pi^- J/\psi$ mode

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution III</th>
<th>Solution IV</th>
<th>Solution V</th>
<th>Solution VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{Y(4260)}$</td>
<td></td>
<td></td>
<td></td>
<td>4259 (fixed)</td>
</tr>
<tr>
<td>$\Gamma_{Y(4260)}$</td>
<td></td>
<td></td>
<td></td>
<td>134 (fixed)</td>
</tr>
<tr>
<td>$\mathcal{B}[Y(4260) \to \pi^+\pi^- \psi(2S)] \cdot \Gamma_{Y(4260)}^{\pm\pm}$</td>
<td>$1.6 \pm 0.6 \pm 0.4$</td>
<td>$1.8 \pm 0.8 \pm 0.6$</td>
<td>$9.1 \pm 1.2 \pm 0.7$</td>
<td>$7.8 \pm 1.1 \pm 0.8$</td>
</tr>
<tr>
<td>$M_{Y(4360)}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{Y(4360)}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}[Y(4360) \to \pi^+\pi^- \psi(2S)] \cdot \Gamma_{Y(4360)}^{\pm\pm}$</td>
<td>$4.5 \pm 1.0 \pm 0.4$</td>
<td>$5.5 \pm 1.4 \pm 0.6$</td>
<td>$19.1 \pm 2.8 \pm 1.1$</td>
<td>$15.7 \pm 2.3 \pm 1.6$</td>
</tr>
<tr>
<td>$M_{Y(4660)}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{Y(4660)}$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}[Y(4660) \to \pi^+\pi^- \psi(2S)] \cdot \Gamma_{Y(4660)}^{\pm\pm}$</td>
<td>$3.3 \pm 0.6 \pm 0.3$</td>
<td>$8.3 \pm 1.0 \pm 0.9$</td>
<td>$9.3 \pm 1.2 \pm 1.2$</td>
<td>$3.7 \pm 0.7 \pm 0.5$</td>
</tr>
<tr>
<td>$\phi_1$</td>
<td>282 ± 25 ± 24</td>
<td>270 ± 27 ± 28</td>
<td>130 ± 5 ± 3</td>
<td>142 ± 6 ± 7</td>
</tr>
<tr>
<td>$\phi_2$</td>
<td>359 ± 19 ± 3</td>
<td>243 ± 17 ± 20</td>
<td>337 ± 10 ± 7</td>
<td>93 ± 25 ± 17</td>
</tr>
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</table>