New results on XYZ states from $e^+e^-$ experiments

Changzheng Yuan (苑长征)
IHEP, Beijing

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Outline

• Introduction

• New information on the X(3872)

• Update the ISR Y-family analyses
  and more ...

• $Z_c(3900), \ Z_c(4020) \ & \ Z_c(4025)$

• Summary & Outlook
Results are from these experiments

BESIII

CLEOc
The Beijing Electron Positron Collider

Satellite view of IHEP, Beijing

- Founded: 1984, $E_{cm}=2$-$5$ GeV
- 1989-2005 (BEPC): $L_{\text{peak}}=1.0 \times 10^{31} \text{ cm}^2\text{s}$
- 2008-now (BEPCII): $L_{\text{peak}}=7 \times 10^{32} \text{ cm}^2\text{s}$
BESIII: production of charmonium(like) states

Vector $\psi/Y$ states can be produced directly
C-even states can be produced from radiative transitions
BESIII collected 3.3/fb for XYZ study
Charmonium spectroscopy

States below charm threshold are all observed now, still many missing states above charm threshold.

Godfrey & Isgur, PRD32, 189 (1985)
There are lots of XYZ states

Charmonium in the final state, but not an obvious charmonium state (charmoniumlike or XYZ).

What are they?

Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

Not all of them are charmonia!
What is the X(3872)?

- Mass: Very close to $\bar{D}^0 D^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC} = 1^{++}$ [LHCb]

- Production
  - in $\bar{p}p/pp$ collision – rate similar to charmonia
  - In B decays – KX similar to $\bar{c}c$, K$^*$X smaller than $\bar{c}c$
  - $Y(4260) \rightarrow \gamma + X(3872)$ [BESIII, see next slides]

- Decay BR: open charm $\sim 50\%$, charmonium $\sim O(\%)$

- Nature (very likely exotic)
  - Loosely $\bar{D}^0 D^{*0}$ bound state (like deuteron?)?
  - Mixture of excited $\chi_{c1}$ and $\bar{D}^0 D^{*0}$ bound state?
  - Many other possibilities (if it is not $\chi'_{c1}$, where is $\chi'_{c1}^\circ$?)

Belle, 2003
140/fb
Observation of $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+\pi^- J/\psi$

Clear ISR $\psi'$ signal for data validation

$X(3872)$ signal at around 4.23-4.26 GeV
Observation of $e^+e^- \rightarrow \gamma X(3872)$

ISR $\psi'$ signal is used for rate, mass, and mass resolution calibration.

$N(\psi') = 1242$ ; Mass $= 3685.96 \pm 0.05$ MeV ; $\sigma_M = 1.84 \pm 0.06$ MeV

$N(X(3872)) = 15.0 \pm 3.9$  

$M(X(3872)) = 3872.1 \pm 0.8 \pm 0.3$ MeV  

[PDG: 3871.68 $\pm 0.17$ MeV]
Observation of $e^+e^- \rightarrow \gamma X(3872)$

$\sqrt{s}$ (GeV) $\sigma_B[e^+e^- \rightarrow \gamma X(3872)] \cdot \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)$ (pb)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\sigma_B[e^+e^- \rightarrow \gamma X(3872)] \cdot \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)$ (pb)</th>
</tr>
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<tbody>
<tr>
<td>4.009</td>
<td>$&lt; 0.13$ at 90% C.L.</td>
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<td>4.230</td>
<td>$0.32 \pm 0.15 \pm 0.02$</td>
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<tr>
<td>4.260</td>
<td>$0.35 \pm 0.12 \pm 0.02$</td>
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<tr>
<td>4.360</td>
<td>$&lt; 0.39$ at 90% C.L.</td>
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It seems $X(3872)$ is from $Y(4260)$ decays. At 4.26 GeV, $\sigma_B(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb,

$$\frac{\sigma[e^+e^- \rightarrow \gamma X(3872)] \cdot \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} = (5.6 \pm 2.0) \times 10^{-3}$$

If we take $\mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi) \sim 5\%$, ($>2.6\%$ in PDG)

$$\frac{\sigma(e^+e^- \rightarrow \gamma X(3872))}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} \sim 11.2\% \quad \text{Large transition ratio!}$$
Y-family states
(vectors observed in Initial State Radiation)

+ e⁺e⁻ → π⁺π⁻h_c from BESIII
The Y states

Above \tilde{D}D threshold, decay to open charm?

\begin{align*}
&Y(4008) \\
&Y(4260) \\
&Y(4360) \\
&Y(4660) \\
&Y(4630)
\end{align*}
The Y states

Belle: PRL99, 142002, 673/fb
BaBar: 1211.6271, 520/fb

Y(4008): confirmed by Belle with more data; events observed at BaBar, fit with exponential
Wait for BESIII

Y(4660): confirmed by BaBar

Y(4630): no data, a bit beyond BEPCII/BESIII limit
Update ISR $\pi^+\pi^-J/\psi$ analysis

Event selections are almost the same as in previous Belle published paper PRL99, 182004 (2007)

- Clean $\psi(2S)$ signal events are obtained, purity>99%.
- Fit with double Gaussian yields $M(\psi(2S)) = (3686.1 \pm 0.2) \text{ MeV}$, $\sigma=4.8\text{MeV}$
- ISR $\Psi(2S)$ production cross sections agree with calculations

<table>
<thead>
<tr>
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<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>QED</th>
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</thead>
<tbody>
<tr>
<td>$\sigma(\Upsilon(4S))$</td>
<td>$(14.12 \pm 0.18 \pm 0.85) \text{ pb}$</td>
<td>$(15.09 \pm 0.11 \pm 0.79) \text{ pb}$</td>
<td>$(14.25 \pm 0.26) \text{ pb}$</td>
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<tr>
<td>$\sigma(\Upsilon(5S))$</td>
<td>$(13.79 \pm 0.44 \pm 0.83) \text{ pb}$</td>
<td>$(13.33 \pm 0.25 \pm 0.70) \text{ pb}$</td>
<td>$(13.42 \pm 0.25) \text{ pb}$</td>
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<tr>
<td>$\sigma(\Upsilon(2S))$</td>
<td>$(16.75 \pm 0.85 \pm 1.01) \text{ pb}$</td>
<td>$(16.63 \pm 0.54 \pm 0.87) \text{ pb}$</td>
<td>$(16.03 \pm 0.29) \text{ pb}$</td>
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Belle also observed a few $\psi(3770)\rightarrow\pi^+\pi^-J/\psi$ events ($N=54 \pm 20, 2.8\sigma$)

$B(\psi(3770)\rightarrow\pi^+\pi^-J/\psi) = (5.5 \pm 2.1) \times 10^{-3}$, PDG $(1.28 \times 10^{-3})$
Two-resonance fit

Still observed two resonances, $Y(4008)$ and $Y(4260)$, agrees with Belle’s previous results.

1. Fit with two coherent resonances $|BW_1 + BW_2 \exp(i\phi)|^2 + \text{bkg}$.
2. Mass of $Y(4008)$ is lower than before
3. Fit quality: $\chi^2/\text{ndf}=101/84$, confidence level is 9.3%
Select $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at 4.26 GeV

- Select 4 charged tracks and reconstruct $J/\psi$ with lepton pair.
- Very clean sample, very high efficiency ($\sim 45\%$).
- $\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb

BESIII: PRL110, 252001
Cross section of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$

Belle: PRL110, 252002

BaBar: PRD86, 051102 (2012)

BESIII: PRL110, 252001

BESIII is measuring cross sections at more energy points, and will take more data!

BESIII: $\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9\pm1.9\pm3.7)\text{ pb}$

Agree with BaBar & Belle!

Best precision!
\[ e^+e^- \rightarrow \pi^+\pi^-h_c(1P) \] at BESIII

- \( h_c \rightarrow \gamma \eta_c, \eta_c \rightarrow \text{hadrons} \) [16 exclusive decay modes]
  - \( p \bar{p}, \pi^+\pi^-K^+K^-, \pi^+\pi^-p \bar{p}, 2(K^+K^-), 2(\pi^+\pi^-), 3(\pi^+\pi^-) \)
  - \( 2(\pi^+\pi^-)K^+K^-, K_S^0K^+\pi^-+c.c., K_S^0K^+\pi^+\pi^-+c.c., K^+K^-\pi^0 \)
  - \( p \bar{p}\pi^0, K^+K^-\eta, \pi^+\pi^-\eta, \pi^+\pi^-\pi^0\pi^0, 2(\pi^+\pi^-)\eta, 2(\pi^+\pi^-\pi^0) \)

BESIII preliminary
Observation of $e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$

$\sigma^B = 41.0 \pm 2.8 \pm 7.4 \text{ pb}$

$N(h_c) = 416 \pm 28$

$Lum = 827 / \text{pb}$

$\sigma^B = 52.3 \pm 3.7 \pm 9.2 \text{ pb}$

$Lum = 544 / \text{pb}$

$E_{cm} = 4.26 \text{ GeV}$

$E_{cm} = 4.36 \text{ GeV}$
Observation of $e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$

- $\sigma(e^+e^- \rightarrow \pi^+\pi^-h_c) \sim \sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi)$ but line shape different
- Local maximum $\sim 4.23$ GeV
- Hint for a vector $\bar{cc}$ hybrid? [PRD78, 056003 (Guo); 094504 (Dudek): $\bar{cc}$ in spin-singlet in hybrids!]
Comparison of $e^+e^- \rightarrow \pi^+\pi^- h_c$ and $\pi^+\pi^- J/\psi$

Broad structure at ~4.4 GeV? Need more data at high energies to complete the line shape measurement.
What are the Y states?

- Between 4 and 4.7 GeV, at most 5 states expected (3S, 2D, 4S, 3D, 5S), 7 observed
- Hybrids are expected in this mass region
- Molecular states?
- Cannot rule out threshold effect/FSI/…
- Y(4260), Y(4360), Y(4660) are all narrow and similar
$Z_c$: charged charmoniumlike states

- Find a clear signature for exotic state!

- Decays to charmonium thus has a $\bar{c}c$ pair!
- With electric charge thus has two more light quarks!
  \[ \Rightarrow N_{\text{quark}} \geq 4 \]
- Do searches in $\pi^\pm J/\psi$, $\pi^\pm h_c(1P)$, $\pi^\pm \psi(2S)$, $\pi^\pm \chi_{cJ}$, …
- BESIII: $e^+e^- \rightarrow \pi^\pm + \text{exotics}$, $\rho^\pm + \text{exotics}$, …
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at $E_{cm}=4.26$ GeV

BESIII: PRL110, 252001

1595 evts in $J/\psi$ signal region, purity~90%
\( e^+e^- \rightarrow \pi^+\pi^- J/\psi \) from ISR

Belle: PRL110, 252002

1. \( M^2(\pi\pi) \) vs. \( M^2(\pi J/\psi) \) for 
   \( 4.15 < M(\pi\pi J/\psi) < 4.45 \) GeV

2. (inset) Background events in \( J/\psi \)-mass sidebands

3. Structures both in \( \pi\pi \) and \( \pi J/\psi \) systems

4. 689 evts in \( J/\psi \) signal region, purity~80%
**Z_c(3900)** observed in two experiments!

**BES3 at 4.26 GeV: 1303.5949**

- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV
- $\Gamma = 46 \pm 10 \pm 20$ MeV
- 307 ± 48 events
- $>8\sigma$

**Belle with ISR: 1304.0121**

- $M = 3894.5 \pm 6.6 \pm 4.5$ MeV
- $\Gamma = 63 \pm 24 \pm 26$ MeV
- 159 ± 49 events
- $>5.2\sigma$

Talk by Zhiqing Liu on Monday
Confirmed with CLEOc data!

**CLEOc data at 4.17 GeV:**

- $M = 3885 \pm 5 \pm 1$ MeV
- $\Gamma = 34 \pm 12 \pm 4$ MeV
- $81 \pm 20$ events
- $6.1\sigma$
What is $Z_c(3900)$?

- Couples to $\bar{c}c$
- Has electric charge
- At least 4-quarks
- What is its nature?

Predictions and more experimental information will be essential to understand its nature.

- $\bar{D}D^*$ molecule?
- Tetraquark state?
- Cusp?
- Threshold effect?
- ...
Dalitz plot of $e^+e^{-} \rightarrow \pi^+\pi^- h_c(1P)$
$e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi^+\pi^- h_c(1P)$

$E_{cm} = 4.26 \text{ GeV}$

$E_{cm} = 4.36 \text{ GeV}$

Simultaneous fit to 4.26/4.36 GeV data and 16 $\eta_c$ decay modes. 6.4$\sigma$

$M(Z_c(4020)) = 4021.8 \pm 1.0 \pm 2.5 \text{ MeV}$; $\Gamma(Z_c(4020)) = 5.7 \pm 3.4 \pm 1.1 \text{ MeV}$

$R = \frac{\sigma(e^+e^- \rightarrow \pi^+Z_c^+(4020) \rightarrow \pi^+\pi^- h_c(1P))}{\sigma(e^+e^- \rightarrow \pi^+\pi^- h_c(1P))} = (16.2 \pm 4.1 \pm 0.7)\% \quad (16.6 \pm 5.2 \pm 0.8)\%_{32}$
$e^+e^- \rightarrow \pi^- (D^*D^*)^+ + \text{c.c. at BESIII}$

- 827 pb$^{-1}$ data at Ecm=4.26 GeV
- Tag a $D^+$ and a bachelor $\pi^-$, reconstruct one $\pi^0$ to suppress the background.

Topology of the decays of the signal process. Thick line circled $D^+$ and $\pi^-$ are detected in the final states and at least one of the dashed line circled $\pi_1^0$ or $\pi_2^0$ is tagged.

BESIII: 1308.2760, submitted to PRL
$e^+e^- \rightarrow \pi^- (D^*D^*)^+ + \text{c.c. at BESIII}$

Remove $DD$, $DD^*$, $D^*D^*$, $DsDs$, ...
$e^+e^- \rightarrow \pi Z_c(4025) \rightarrow \pi^- (D^* D^*)^+ + c.c.$

Fit to $\pi^\pm$ recoil mass yields $401\pm47 Z_c(4025)$ events.  $>10\sigma$

$M(Z_c(4025)) = 4026.3\pm2.6\pm3.7$ MeV;  $\Gamma(Z_c(4025)) = 24.8\pm5.6\pm7.7$ MeV

$$R = \frac{\sigma (e^+e^- \rightarrow \pi^Z_c(4025) \rightarrow \pi^+(D^* D^*)^\mp)}{\sigma (e^+e^- \rightarrow \pi^+(D^* D^*)^\mp)} = (65\pm9\pm6)\%$$

$\sigma (e^+e^- \rightarrow \pi^\pm (D^* D^*)^\mp) = (137\pm9\pm15)$ pb

BESIII: 1308.2760
$Z_c(4020) = Z_c(4025)$?

- $M(4020) = 4021.8 \pm 1.0 \pm 2.5$ MeV
- $M(4025) = 4026.3 \pm 2.6 \pm 3.7$ MeV
- $\Gamma(4020) = 5.7 \pm 3.4 \pm 1.1$ MeV
- $\Gamma(4025) = 24.8 \pm 5.6 \pm 7.7$ MeV

Close to $D^*D^*$ threshold = 4017 MeV
Mass consistent with each other but width ~ $2\sigma$ difference
Interference with other amplitudes may change the results
Coupling to $\bar{D}^*D^*$ is much larger than to $\pi h_c$ if they are the same state
Will fit with Flatte formula
What next at BESIII?

• Precise resonant parameters
• Spin-parity of $Z_c$ and $Z_c'$
• More decay modes [$\pi\psi'$, $\rho\eta_c$, open charm, …]
• Production mechanisms, production rates
• Test various theoretical models
• Neutral partners of $Z_c$ and $Z_c'$
• Excited $Z_c$, $Z_c'$ states? $Z_{cs} \rightarrow KJ/\psi$ states?
• Other XYZ states?
• …
Summary

• Lots of progress in XYZ studies in $e^+e^-$ experiments
• BESIII started study of the XYZ particles
• Observation of $Y(4260) \rightarrow \gamma X(3872)$
• New information on the Y’s from BaBar and Belle. $Y(4660)$ confirmed, $Y(4008)$ not confirmed; large $\pi^+\pi^-h_c$ production rate above 4.2 GeV
• First confirmed exotic state with at least four quarks, $Z_c(3900)^+$, at BESIII & Belle
• Observation of the $Z_c'$ at BESIII
• More results will come soon, stay tuned!

Thanks a lot!
Thanks a lot!
Belle observed $Z(4430)^{\pm} \rightarrow \psi(2S)\pi^{\pm}$

- Found in $\psi(2S)\pi^{\pm}$ from $B \rightarrow \psi(2S)\pi^{+}K$. Z parameters from fit to $M(\psi(2S)\pi^{+})$
- Confirmed through Dalitz-plot analysis of $B \rightarrow \psi(2S)\pi^{+}K$
- $B \rightarrow \psi(2S)\pi^{+}K$ amplitude: coherent sum of Breit-Wigner contributions
- Models: all known $K^* \rightarrow K\pi^{\pm}$ resonances only
  all known $K^* \rightarrow K\pi^{\pm}$ and $Z^{+} \rightarrow \psi(2S)\pi^{+} \Rightarrow$ favored by data

Significance: $6.4\sigma$

$M = 4433^{+15+19}_{-12-13}$ MeV
$\Gamma = 107^{+86+74}_{-43-53}$ MeV

- $[cu][cd]$ tetraquark? neutral partner in $\psi'\pi^0$ expected
- $D^*D_1(2420)$ molecule? should decay to $D^*D^\ast\pi$
Spin-parity of the $Z(4430)^\pm$

- $B \to \psi(2S)\pi^+K$ amplitude: coherent sum of Breit-Wigner contributions

$J^P = 1^+$
$M = 4500 \pm 14^{+16}_{-13} \, \text{MeV}$
$\Gamma = 126^{+30}_{-26} + 3_{-26} \, \text{MeV}$

$J^P = 0^-$
$M = 4470 \pm 26^{+83}_{-30} \, \text{MeV}$
$\Gamma = 139^{+52}_{-39} + 17_{-32} \, \text{MeV}$
BaBar doesn’t see a significant $\mathrm{Z}(4430)^+$

“For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only $\sim 1.9\sigma$ from zero; fixing mass and width increases this to only $\sim 3.1\sigma$.”

$\mathrm{BF}(B^0 \to \mathrm{Z}^+K) \times \mathrm{BF}(\mathrm{Z}^+ \to \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$
Belle observed Two $Z^±\rightarrow\chi_{c1}\pi^±$

- Dalitz-plot analysis of $B^0\rightarrow\chi_{c1}\pi^+K^-$, $\chi_{c1}\rightarrow J/\psi\gamma$ with 657M $BB$
- Dalitz plot models: known $K^*\rightarrow K\pi$ only
  - $K^*$'s + one $Z \rightarrow \chi_{c1}\pi^±$
  - $K^*$'s + two $Z^±$ states ⇒ favored by data

Significance: 5.7$\sigma$

$M(\chi_{c1}\pi^+)$ for $1<M^2(K\pi^+)<1.75\text{GeV}^2$

$M_{Z_1} = 4051\pm14 \pm 20_{-41}^{+20}$ MeV
$\Gamma_{Z_1} = 82^{+21}_{-17}^{+47} -22$ MeV
$M_{Z_2} = 4248^{+44}_{-29}^{+180} -35$ MeV
$\Gamma_{Z_2} = 177^{+54}_{-39}^{+316} -61$ MeV
BaBar doesn’t see significant $Z^\pm \rightarrow \chi_{c1}\pi^\pm$

\[ \mathcal{B}(\bar{B}^0 \rightarrow Z_1(4050)^+ K^-) \times \mathcal{B}(Z_1(4050)^+ \rightarrow \chi_{c1} \pi^+) < 1.8 \times 10^{-5}, \]

Belle: \((3.0^{+1.5}_{-0.8}^{+3.7}_{-1.6}) \times 10^{-5}\)

\[ \mathcal{B}(\bar{B}^0 \rightarrow Z_2(4250)^+ K^-) \times \mathcal{B}(Z_2(4250)^+ \rightarrow \chi_{c1} \pi^+) < 4.0 \times 10^{-5}, \]

Belle: \((4.0^{+2.3}_{-0.9}^{+19.7}_{-0.5}) \times 10^{-5}\)

“We find that it is possible to obtain a good description of our data without the need for additional resonances in the $\chi_{c1}\pi$ system.”
$M(\pi\pi J/\psi) \in [4.2, 4.4] \text{ GeV via ISR}$

- 548/fb at 10.58 GeV
- Peaks at 12 & 15 GeV?
- Shown at QWG'2011
Observation of the $X(3823)$

arXiv:1304.3975 (submitted to PRL)

$M_{\chi_{c1} \gamma} (GeV/c^2)$

**B $\rightarrow \chi_{c1} \gamma K$**

The measured mass and width are consistent with the missing $\Psi_2(1D)$ state

$M_{X(3823)} = M_{meas}^{X(3823)} - M_{meas}^{\Psi} + M_{PDG}^{\Psi}$

$= 3823.1 \pm 1.8 \pm 0.7 \text{MeV}$

BESIII may search for it!

**FIG. 4:** 2D UML fit projection of $M_{\chi_{c1}\gamma}$ distribution for the simultaneous fit of $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$ and $B^0 \rightarrow (\chi_{c1}\gamma)K^0_S$ decays for $M_{bc} > 5.27 \text{GeV}/c^2$. The curves used in the fits are described in [33].
**BEPC II**: Large crossing angle, double-ring

- **Beam energy**: 1-2.3 GeV
- **Luminosity**: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- **Optimum energy**: 1.89 GeV
- **Energy spread**: $5.16 \times 10^{-4}$
- **No. of bunches**: 93
- **Bunch length**: 1.5 cm
- **Total current**: 0.91 A
- **SR mode**: $0.25 \text{A} @ 2.5 \text{GeV}$

Compton back-scattering for high precision beam energy measurement

BESIII is here
BESIII Detector

Magnet yoke

SC magnet, 1T

RPC

TOF, 90ps

Be beam pipe

MDC, 130 μm
0.5% at 1 GeV/c

Total weight 730 ton,
~40,000 readout chnls,
Data rate: 5kHz, 50Mb/s

Csl(Tl) calorimeter, 2.5% @ 1 GeV
Red — Zc(4020) BW
Blue — Zc(4025) BW

arbitrary unit

mass (GeV)