Charmonium and light hadron spectroscopy

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Outline

- Charmonium states:
  \( \Psi(4040) \), \( \Psi(4160) \), \( \eta_c \), \( \eta_c(2S) \), \( \Psi_2 \), \( X(3872) \)
- light hadron spectroscopy
  \( X(1835) \), \( \eta\eta \), \( \omega \omega \), \( \phi\phi \), \( \omega\phi \)
- Summary & Outlook
Results are from these experiments

Most of the results are from BESIII and Belle. Due to limited time, I can only cover a few topics. For more results, please refer to Belle and BESIII publication pages:

http://bes3.ihep.ac.cn/pub/physics.htm

http://belle.kek.jp/bdocs/b_journal.html
Charmonium

- Charmed-quark($c$) anticharmed-quark($\bar{c}$) bound states.

- Has been a power tool for the understanding of the strong interaction
  - QCD is well tested at high energies
  - In low-energy regime, many aspects are not understood
  - Test QCD and improve our limited understanding of QCD

For Exotic hadrons and Quarkonium, please wait for Choi’s report – next one!
Production

1. $e^+e^-$ annihilation (including ISR/double charmonium)

2. $p\bar{p}$ annihilation

3. Two-photon process

4. $B$ decays

5. Through charmonium transition
1-\textsuperscript{--} states: $J/\psi$, $\psi'$, $\psi''$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$

- Abundantly produced from $e^+e^-$, pp collisions
- Observed in 70's
$J^{PC} = 1^{-}$ states produce peaks in $R_{\text{had}}$

Extraction of resonance parameters from $R$ measurement

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

![Graph showing resonance parameters](image)
$e^+e^- \rightarrow \eta J/\psi @4.01\text{GeV}$

- Hadronic transition between charmonium states above open-charm threshold is not well understood
- Data sample: 478 pb$^{-1}$ @4.01GeV
- First observation: $e^+e^- \rightarrow \eta J/\psi$
  (significance $>10\sigma$)
- Measured Born cross section:
  $(32.1\pm2.8\pm1.3)$ pb
- Assume $\eta J/\psi$ from $\psi(4040)$
  \[\text{Br}(\psi(4040) \rightarrow \eta J/\psi) = (5.2 \pm 0.5\pm0.2\pm0.5\times10^{-3}\]
  \[\text{Br}(\psi(4040) \rightarrow \pi^0 J/\psi) < 2.8\times10^{-4} \text{ @90\% CL}\]
- Consistent with the theoretical calculation
  (Q. Wang et al., arXiv:1206.4511)
- Partial width of $\psi(4040) \rightarrow \eta J/\psi$: $\sim 400$keV
  (> two times $\psi(4040) \rightarrow \pi\pi J/\psi$)
  Similar to the hadronic transition of $Y(4S)$
  (admixture of a four-quark state in the wave function, M. B. Voloshin, Mod. Phys. Lett. A 26, 773 (2011))
BESIII can not measure the line shape of $\eta J/\psi$. Belle did it via ISR.

- $\eta \rightarrow \gamma\gamma$ and $\pi^+\pi^-\pi^0$
- $J/\Psi \rightarrow e^+e^-$ mode is not used in $\eta \rightarrow \gamma\gamma$ (high Bhabha bkg.)
- $\Psi(2S)$ signal is a tagged signal
- $\sigma (e^+e^- \rightarrow \Psi(2S))=13.9 \pm 1.4 \text{ (stat)pb}$ and $14.0 \pm 0.8 \text{ (stat) for } \eta \rightarrow \pi^+\pi^-\pi^0$ and $\gamma\gamma$, in good agreement with the theoretical value of 14.7pb.

- An unbinned maximum likelihood fit to the signal events and $\eta$ and $J/\Psi$ sidebands simultaneously
- Two coherent P-wave BWs for $\Psi(4040)$ and $\Psi(4160)$

Transition rates to $\eta J/\psi$ are large, being of order 1 MeV/c$^2$
We find no evidence for the $Y(4260)$, $Y(4360)$, $\Psi(4415)$ or $Y(4660)$ in the $\eta J/\psi$ final states.

The cross sections of $e^+e^- \rightarrow \eta J/\psi$ are around 70 pb and 50 pb at the $\Psi(4040)$ and $\Psi(4160)$ peaks, to be compared with around 20 pb and 10 pb measured in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$.

This is the first time that the $\psi(4040)$ and $\psi(4160)$ have been observed to decay to final states not involving charm meson pairs.
Spin singlet states: $\eta_c \quad \eta_c(2S) \quad h_c$

- Be produced in $\gamma \gamma$ process, $B$ decay, pp collision, ..
- Least-understood states below the DD threshold
\( \eta_c(1S) \)

- S-wave spin-singlet ground state, first found by MarkII in 1980
  PRL 45, 1146 (1980)

- The mass & width
  \(- J/\psi \) radiative transition: \( M \approx 2978.0 \text{MeV}/c^2, \ \Gamma \approx 10 \text{MeV} \)
  \( \gamma\gamma \) process:
  \( M = 2983.1 \pm 1.0 \text{MeV}/c^2, \ \Gamma = 31.3 \pm 1.9 \text{MeV} \)

\[ \chi^2 \]

\[ C.L. = 0.0014 \]

\[ C.L. < 0.0001 \]

2011 PDG
Measure $\eta_c$ in $\psi' \rightarrow \gamma \eta_c$

The interference between $\eta_c$ and non-resonant is significant. Simultaneous fit to 6 modes,

Mass = $2984.3 \pm 0.6 \pm 0.6$ MeV/c$^2$

Width = $32.0 \pm 1.2 \pm 1.0$ MeV

PRL 108,222002(2012)
Comparison with the $\eta_c$ results

Hyperfine splitting (BESIII alone)

$\Delta M(1S) = 112.5 \pm 0.8$ MeV

Closer to prediction than earlier result

Lattice 2012, arVix:1211.2253
\( \eta_c (2S) \)

Crystal Ball’s “first observation” of \( \psi' \to \gamma X \) never been confirmed until Belle found it in \( B \to K \eta_c (2S) \) in 2002.

Observed in different production mechanisms,

1. \( B \to K \eta_c (2S) \)  
   \( \text{Belle: PRL 89 102001 (2002)} \)  
   \( \text{CLEOc: PRL 92 142001 (2004)} \)

2. \( \gamma \gamma \to \eta_c (2S) \to KK\pi \)  
   \( \text{Belle: NPPS.184 220 (2008); PRL 98 082001(2007)} \)  
   \( \text{BaBar: PRL 92 142002 (2004); PR D72 031101(2005)} \)  
   \( \text{BaBar: PR D84 012004 (2011)} \)

3. Double charmonium production

4. M1 transition \( \psi' \to \gamma \eta_c (2S) \)  
   \( \text{CLEO found no signals in 25M } \psi'. \)
   \( \text{BF}(\psi' \to \gamma \eta_c (2S)) < 7.6 \times 10^{-4} \)  
   \( \text{PRD 81 052002 (2010)} \)

**Experimental challenge:** search for photons of 50 MeV
\( \gamma\gamma \rightarrow \eta_c(1S/2S) \rightarrow K_s K \pi; \ KK3\pi \)

**Graphs:**
- **Top Left:** Events vs. \( m(K_s^0 K^\pm) \) (GeV/c^2) with peaks labeled \( \eta_c(1S) \), \( J/\psi ISR \), \( \chi_{c2}(1P) \), and \( \eta_c(2S) \).
- **Top Right:** Events vs. \( m(K^+ K^- \pi^+ \pi^-) \) (GeV/c^2) with peaks labeled \( \eta_c(1S) \), \( J/\psi ISR \), \( \chi_{c2}(1P) \), and \( \eta_c(2S) \).

**Belle:**
- **Bottom Left:** Events vs. mass (MeV) with peaks labeled \( \eta_c(2S) \) and \( \chi_{c2}(1P) \).
- **Bottom Middle:** Events vs. mass (MeV) with peaks labeled \( \chi_{c0}(1P) \) and \( \eta_c(2S) \).
- **Bottom Right:** Events vs. mass (MeV) with peaks labeled \( \chi_{c0} \) and \( \eta_c(2S) \).

**References:**
- PR D81 052010 (2011)
- PR D84 012004 (2011)
- ICHEP2010
Evidence $\eta_c(2S) \rightarrow KsK^{+} \pi^{-} \pi^{+} \pi^{-}$

- For $\eta_c(2S)$, only two measured decay $\text{Br}$s are available: $KK\pi$ and $K^+K^-\pi^+\pi^-\pi^0$
- $\psi' \rightarrow \gamma \eta_c(2S)$: M1 transition
- Search for more $\eta_c(2S)$ decay modes
- To measure the mass, width of $\eta_c(2S)$

$M = 3646.9 \pm 1.6 \pm 3.6$ MeV/c$^2$
$\Gamma = 9.2 \pm 4.8 \pm 2.9$ MeV

$B(\psi' \rightarrow \gamma \eta_c(2S)) \times B(KsK^{+} \pi^{-} \pi^{+} \pi^{-}) = (7.03 \pm 2.10 \pm 0.70) \times 10^{-6}$

The measured $M$ and $\Gamma$ are consistent with values in PRL109, 042003 (2012)
Summary for $\eta_c(2S)$

- BESIII $\psi(2S) \rightarrow \gamma KsK3\pi$
- BESIII $\psi(2S) \rightarrow \gamma KK\pi$
- BaBar $\gamma\gamma \rightarrow KK3\pi$
- BaBar $\gamma\gamma \rightarrow KsK\pi$
- Belle B $\rightarrow K \eta_c(2S)$

PDG13 ave.

$\eta_c(2S)$ mass (MeV/c$^2$)

$\eta_c(2S)$ width (MeV)
$X(3823) \to \chi_{c1} \gamma$ in $B \to \chi_{c1} \gamma K$

Simultaneous fit to $B^\pm \to \chi_{c1} \gamma K^\pm$ & $B^0 \to \chi_{c1} \gamma K_S$

$\chi_{c1}$ reconstructed in $\gamma J/\psi$

The measured mass and other properties are consistent with the missing $\psi_2(1\,^3D_2)$ state

$$M_{X(3823)} = M_{X(3823)}^{\text{meas}} - M_{\psi}^{\text{meas}} + M_{\psi}^{\text{PDG}} = 3823.1 \pm 1.8 \pm 0.7 \, \text{MeV}$$

$711 \, fb^{-1}$

3.8 $\sigma$
What is the X(3872)?

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

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

$N(X(3872)) = 15.0 \pm 3.9 \quad 5.3 \sigma$

$M(X(3872)) = 3872.1 \pm 0.8 \pm 0.3 \text{ MeV} \quad [\text{PDG: } 3871.68 \pm 0.17 \text{ MeV}]$
# Observation of $e^+e^- \rightarrow \gamma X(3872)$

<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>
</thead>
<tbody>
<tr>
<td>4.009</td>
<td>$&lt; 0.13$ at 90% C.L.</td>
</tr>
<tr>
<td>4.230</td>
<td>$0.32 \pm 0.15 \pm 0.02$</td>
</tr>
<tr>
<td>4.260</td>
<td>$0.35 \pm 0.12 \pm 0.02$</td>
</tr>
<tr>
<td>4.360</td>
<td>$&lt; 0.39$ at 90% C.L.</td>
</tr>
</tbody>
</table>

It seems $X(3872)$ is from $Y(4260)$ decays. At 4.26 GeV, 

$$\sigma^B(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7) \text{ pb},$$

$$\frac{\sigma[e^+e^- \rightarrow \gamma X(3872)] \cdot \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} = (5.6\pm2.0) \times 10^{-3}$$

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

$$\frac{\sigma(e^+e^- \rightarrow \gamma X(3872))}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} \sim 11.2\% \quad \text{Large transition ratio !}$$
light hadron spectroscopy
Confirmation of X(1835) and two new structures

**BESII**

BESII result (Stat. sig. ~ 7.7σ):

\[ M = 1833.7 \pm 6.1\,(\text{stat}) \pm 2.7\,(\text{syst}) \text{MeV} \]
\[ \Gamma = 67.7 \pm 20.3\,(\text{stat}) \pm 7.7\,(\text{syst}) \text{MeV} \]

**BESIII fit results:**

<table>
<thead>
<tr>
<th>Resonance</th>
<th>( M,(\text{MeV/c}^2) )</th>
<th>( \Gamma,(\text{MeV/c}^2) )</th>
<th>Stat. Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(1835)</td>
<td>( 1836.5 \pm 3.0^{+5.6}_{-2.1} )</td>
<td>( 190.1 \pm 9.0^{+38}_{-36} )</td>
<td>&gt;20σ</td>
</tr>
<tr>
<td>X(2120)</td>
<td>( 2122.4 \pm 6.7^{+4.7}_{-2.7} )</td>
<td>( 83 \pm 16^{+31}_{-11} )</td>
<td>7.2σ</td>
</tr>
<tr>
<td>X(2370)</td>
<td>( 2376.3 \pm 8.7^{+3.2}_{-4.3} )</td>
<td>( 83 \pm 17^{+44}_{-6} )</td>
<td>6.4σ</td>
</tr>
</tbody>
</table>

An amplitude analysis could help with interpretation for the additional new structures!
Finally we need a full amplitude analysis to determine the property for the new structures, but there were many predictions which make the observation more interesting!

Possible theoretical explanation

- It is the first time resonant structures are observed in the 2.3 GeV/c² region, it is interesting since:

  LQCD predicts that the lowest lying pseudoscalar glueball: around 2.3 GeV/c².

  J/ψ→γππη' decay is a good channel for finding 0⁺ glueballs.

- Nature of X(2120)/X(2370) pseudoscalar glueball?
  η/η' excited states?

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PRD82,074026,2010
J.F. Liu, G.J. Ding and M.L. Yan
PRD83:114007,2011
(J.S. Yu, Z.-F. Sun, X. Liu, Q. Zhao), and more...
Search for X(1835) in Belle experiment in two-photon process!

- X(1835) and η (1760) with interference (assuming J^{PC}=0^{-+})
- No interference between resonant and non-resonant
- Two solutions (see Table)

★ thin solid line: total bkg
★ thick dashed (dot-dashed, dotted) lines: the η (1760) (X(1835), the interference term)
★ thin dashed, dot-dashed and dotted lines: non-resonant, η’-sidebands and η’ π + π -X bkg components

- The fit with only η (1760) signal is also tried

<table>
<thead>
<tr>
<th>Parameter</th>
<th>One resonance</th>
<th>Two interfering resonances</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(1835)</td>
<td>1836.5 (fixed)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>190 (fixed)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>332^{+140}_{-122} \pm 73</td>
<td>632^{+224}_{-231} \pm 139</td>
</tr>
<tr>
<td></td>
<td>&lt; 650</td>
<td>&lt; 1490</td>
</tr>
<tr>
<td></td>
<td>18.3^{+7.7}_{-6.7} \pm 4.0</td>
<td>35^{+12}_{-13} \pm 8</td>
</tr>
<tr>
<td></td>
<td>&lt; 35.6</td>
<td>&lt; 83</td>
</tr>
</tbody>
</table>

No significant X(1835) signal --- 2.8 σ!
Assuming no interference between $\eta_c$ and background.

The fit with interference was also tried. The results of mass and width of $\eta_c$ are almost the same. The differences are taken as sys error.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>This work</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y$</td>
<td>$486^{+40}_{-39} \pm 53$</td>
<td></td>
</tr>
<tr>
<td>$M$, MeV/$c^2$</td>
<td>$2982.7 \pm 1.8 \pm 2.2$</td>
<td>$2980.3 \pm 1.2$</td>
</tr>
<tr>
<td>$\Gamma$, MeV/$c^2$</td>
<td>$37.8^{+5.8}_{-5.3} \pm 2.8$</td>
<td>$26.7 \pm 3$</td>
</tr>
<tr>
<td>$\Gamma\gamma/B$, eV/$c^2$</td>
<td>$50.5^{+4.2}_{-4.1} \pm 5.6$</td>
<td>$194 \pm 97$</td>
</tr>
<tr>
<td>$B$, %</td>
<td>$0.87 \pm 0.20$</td>
<td>$2.7 \pm 1.1$</td>
</tr>
</tbody>
</table>
Search for $e^+e^-\rightarrow J/\Psi + X(1835)$ at 10.6 GeV

- Search for $X(1835)$ in Belle experiment in $e^+e^-$ continuum process!
- C-even glueballs can be studied in $e^+e^-\rightarrow \gamma^* \rightarrow H+G_J$, $H$ denotes a $cc\bar{c}$ quark pair or charmonium state.

- Signal pdf is from MC with mass and width fixed to the values from BESIII [PRL 106, 072002, 2012]
- 90% C.L. upper limit on the $\sigma (e^+e^-\rightarrow J/\Psi X(1835) )\text{Br}(X(1835) \rightarrow \mu^+\mu^-)$ $<$ 1.3 fb.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{signal}$</th>
<th>$N_{background}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{recoil}(J/\psi \rightarrow \mu^+\mu^-)$</td>
<td>$-20.0 \pm 20.0$</td>
<td>$340.0 \pm 18.0$</td>
</tr>
<tr>
<td>$M_{recoil}(J/\psi \rightarrow e^+e^-)$</td>
<td>$-7.5 \pm 7.6$</td>
<td>$859.5 \pm 29.2$</td>
</tr>
</tbody>
</table>
PWA of $J/\psi \rightarrow \gamma \eta \eta$

- Search for glueballs, hybrids and multi-quarks
- LQCD: the lowest mass glueball with $0^{++}$ is in the mass region from 1.5-1.7 GeV
- The mixing with $q\bar{q}$ nonet mesons makes the identification of the glueballs difficult
- Radiative $J/\psi$ decay is a gluon-rich process
- $J/\psi$ radiative decay to two pseudoscalar mesons offers a very clean laboratory to search for scalar and tensor glueballs

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass(MeV/$c^2$)</th>
<th>Width(MeV/$c^2$)</th>
<th>$B(J/\psi \rightarrow \gamma X \rightarrow \gamma \eta \eta)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>$1468^{+14+23}_{-15-74}$</td>
<td>$136^{+41+28}_{-25-100}$</td>
<td>$(1.65^{+0.26+0.51}_{-0.31-1.46}) \times 10^{-5}$</td>
<td>8.2 $\sigma$</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$1759^{+6+14}_{-25}$</td>
<td>$172^{+10+32}_{-31}$</td>
<td>$(2.35^{+0.13+1.24}_{-0.11-6.74}) \times 10^{-4}$</td>
<td>25.0 $\sigma$</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>$2081^{+13+24}_{-36}$</td>
<td>$273^{+27+100}_{-24-28}$</td>
<td>$(1.13^{+0.094+0.64}_{-0.10-0.28}) \times 10^{-4}$</td>
<td>13.9 $\sigma$</td>
</tr>
<tr>
<td>$f'_0(1525)$</td>
<td>$1513^{+5+4}_{-10}$</td>
<td>$75^{+12+15}_{-18}$</td>
<td>$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$</td>
<td>11.0 $\sigma$</td>
</tr>
<tr>
<td>$f_2(1810)$</td>
<td>$1822^{+29+66}_{-24-57}$</td>
<td>$229^{+52+88}_{-42-155}$</td>
<td>$(5.40^{+0.60+3.42}_{-0.67-2.33}) \times 10^{-5}$</td>
<td>6.4 $\sigma$</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>$2362^{+31+140}_{-30-63}$</td>
<td>$334^{+62+165}_{-54-100}$</td>
<td>$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$</td>
<td>7.6 $\sigma$</td>
</tr>
</tbody>
</table>
Fits for low-mass resonances with partial-wave decomposition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit (1.1-1.64GeV)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>$f_0(\gamma)$</td>
<td>MeV/c^2</td>
</tr>
<tr>
<td>Width $f_2(X)$</td>
<td>228 +21 -20 +234 -153</td>
<td>MeV</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma} B(\eta\eta)$</td>
<td>5.2 +0.9 -0.8 +37.3 -4.5</td>
<td>eV</td>
</tr>
<tr>
<td>$\chi^2$ (ndf)</td>
<td>311.4(204)</td>
<td></td>
</tr>
</tbody>
</table>

**Confirmation of $f'_2(1525)$ amplitude**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit (1.1-1.64GeV)</th>
<th>Unin</th>
<th>$\chi^2$ (ndf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{\gamma\gamma} B(\eta\eta)$</td>
<td>$f'_2(1525)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sol. A</td>
<td>23.1 +2.6 -2.8</td>
<td>eV</td>
<td>136.4 (119)</td>
</tr>
<tr>
<td>Sol. B</td>
<td>8.0 +2.0 -1.5</td>
<td>eV</td>
<td>137.2 (119)</td>
</tr>
<tr>
<td>Sol. C</td>
<td>5.0 +5.8 -5.0</td>
<td>eV</td>
<td>138.6 (119)</td>
</tr>
</tbody>
</table>

**PDG: Product of $\Gamma_{\gamma\gamma}$ and $B(\eta\eta)$**

- $f_2(1270): 12.1 \pm 2.8$ eV: consistent
- $f'_2(1525): 8.3 \pm 2.1$ eV:
PWA of $J/\psi \rightarrow \gamma \omega \phi$

- $X(1810)$ was observed in $J/\psi \rightarrow \gamma \omega \phi$ by BESII [PRL96,162002]
- PWA: $0^{++}$ favors $0^{-+}$ or $2^{++}$ (>10 $\sigma$)
- $J/\psi \rightarrow \gamma \omega \phi$ is a doubly OZI suppressed process
- Possible interpretations: a tetraquark state, a hybrid, or a glueball state, a dynamical effect arising from intermediate meson rescattering, or a threshold cusp of an attracting resonance.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$J^{PC}$</th>
<th>$M$(MeV/$c^2$)</th>
<th>$\Gamma$(MeV/$c^2$)</th>
<th>Events</th>
<th>$\Delta S$</th>
<th>$\Delta ndf$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(1810)$</td>
<td>$0^{++}$</td>
<td>1795 ± 7</td>
<td>95 ± 10</td>
<td>1319 ± 52</td>
<td>783</td>
<td>4</td>
<td>$&gt; 30\sigma$</td>
</tr>
<tr>
<td>$f_2(1950)$</td>
<td>$2^{++}$</td>
<td>1944</td>
<td>472</td>
<td>665 ± 40</td>
<td>211</td>
<td>2</td>
<td>20.4$\sigma$</td>
</tr>
<tr>
<td>$f_0(2020)$</td>
<td>$0^{++}$</td>
<td>1992</td>
<td>442</td>
<td>715 ± 45</td>
<td>100</td>
<td>2</td>
<td>13.9$\sigma$</td>
</tr>
<tr>
<td>$\eta(2225)$</td>
<td>$0^{-+}$</td>
<td>2226</td>
<td>185</td>
<td>70 ± 30</td>
<td>23</td>
<td>2</td>
<td>6.4$\sigma$</td>
</tr>
<tr>
<td>phase space</td>
<td>$0^{-+}$</td>
<td>—</td>
<td>—</td>
<td>319 ± 24</td>
<td>45</td>
<td>2</td>
<td>9.1$\sigma$</td>
</tr>
</tbody>
</table>
In order to search for possible structures in low mass region, we did $\gamma\gamma \rightarrow VV$.

$$\sigma_{\gamma\gamma \rightarrow VV}(W_{\gamma\gamma}) = \frac{\Delta n}{\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \epsilon(W_{\gamma\gamma}) \Delta W_{\gamma\gamma}}$$

- $\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}$: the differential luminosity
- $\epsilon$: efficiency
- $\Delta W_{\gamma\gamma}$: bin width
- $\Delta n$: the number of events in the $\Delta W_{\gamma\gamma}$ bin.

There are at least two different $J^P$ components ($J=0$ and $J=2$)
$\Gamma_{\gamma\gamma} B(X \rightarrow VV) \ (eV) \ for \ \eta_c, \ \chi_{c0} \ and \ \chi_{c2}$:

Fits: three incoherent BW $\otimes$ double Gaussian + 2nd order Chebychev polynomial

Results for $\Gamma_{\gamma\gamma} B(X \rightarrow VV) \ (eV)$ for $\eta_c, \chi_{c0}$ and $\chi_{c2}$.
The upper limits are obtained at the 90% confidence level.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\omega\phi$</th>
<th>$\phi\phi$</th>
<th>$\omega\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c$</td>
<td>$&lt; 0.49$</td>
<td>$7.75 \pm 0.66 \pm 0.62$</td>
<td>$8.67 \pm 2.86 \pm 0.96$</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>$&lt; 0.34$</td>
<td>$1.72 \pm 0.33 \pm 0.14$</td>
<td>$&lt; 3.9$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>$&lt; 0.04$</td>
<td>$0.62 \pm 0.07 \pm 0.05$</td>
<td>$&lt; 0.64$</td>
</tr>
</tbody>
</table>

The measurements of $\Gamma_{\gamma\gamma} B(X \rightarrow \phi\phi)$ are consistent with results [Eur. Phys. J. C 53, 1 (2008)] with improved precision.
Summary & Outlook

- Charmonium states provide a platform to study non-perturbative mechanism.
- Below the open-charm threshold: Spin-singlet states $\eta_c$, $h_c$, $\eta_c(2S)$ have been measured.
- Lots of discoveries, expected and unexpected.
  - $X_{c2}$ is assigned; $X(3823)$ is consistent with $y_2(1^3D_2)$.
  - Are the $X/Y$ states really new? Or the missing charmonium states $X_{c1}$? What’s their nature?
- Future potential model, Lattice QCD, sum rules, novel method.
- BESIII and future experiments, Panda, Belle II, have chance to establish not-yet-observed states.
Many interesting states are observed:
X(1835)(0^{-+}), X(\omega \phi)(0^{++}), …

Some of them may be exotic states candidates.

Where is lowest scalar/ pseudo-scalar glueball(f_{0}(1500), f_{0}(1710), x(\omega \phi)?…)

Troubled by the possible mixing between glueball and qq, it’s hard to distinguish an exotic state from normal states.

Amplitude analysis is needed to determine the property of these states.

Thanks!
PWA of $J/\psi \rightarrow \gamma \omega \phi$
$VV$ ($V = \omega$ or $\phi$) invariant mass distributions:

$|\sum \vec{P}_t^*|$: the magnitude of the vector sum of the final particles’ transverse momenta in the $e^+e^-$ C.M. frame.

$N(VV)$ in each $VV$ mass bin is obtained by fitting the $|\sum \vec{P}_t^*|$ distribution.
Signal pdf: MC simulation
Background pdf: 2nd Cheby. poly.
There are some obvious structures in the low VV invariant mass region. We did spin-parity analysis.

The shaded histograms are from the corresponding normalized sidebands.
Spin-parity analysis:

For $\gamma\gamma \rightarrow VV$, five angles are kinematically independent: $z$, $z^*$, $z^{**}$, $\phi^*$, and $\phi^{**}$.
Using $\omega \phi$ as an example:
- $z$: cosine of the scattering polar angle of $\phi$ in the $\gamma\gamma$ C.M. system;
- $z^*$ and $\phi^*$: the cosine of the helicity angle of $K^+$ in the $\phi$ decays and the azimuthal angle defined in the $\phi$ rest frame with respect to the $\gamma\gamma \rightarrow \omega \phi$ scattering plane;
- $z^{**}$ and $\phi^{**}$: the cosine of the helicity angle of normal direction to the decay plane of the $\omega \rightarrow \pi^+\pi^-\pi^0$ and the azimuthal angle defined in the $\omega$ rest frame.

Transversity angle ($\phi_T$): $\phi_T = |\phi^* + \phi^{**}|/2\pi$

Polar-angle product ($\Pi_\theta$): $\Pi_\theta = [1 - (z^*)^2][1 - (z^{**})^2]$

$N_{event}$ is obtained by fitting the $\sum |\vec{P}_t^*|$ distribution in each $\phi_T$ and $\Pi_\theta$ bin in the 2D space.
The number of event projections in the 2D space of the transversity angle and polar-angle product.

Histograms: the best fits with different $J^P$ components.

- For $\omega\phi$: a mixture of $0^+$ ($S$-wave) and $2^+$ ($S$-wave) describes data with $\chi^2/ndf = 0.9$ ($ndf$ is the number of degrees of freedom).
- For $\phi\phi$: a mixture of $0^+$ ($S$-wave) and $2^−$ ($P$-wave) describes data with $\chi^2/ndf = 1.3$.
- For $\omega\omega$: a mixture of $0^+$ ($S$-wave) and $2^+$ ($S$-wave) describes data with $\chi^2/ndf = 1.3$.

$M(VV) < 2.8$ GeV/c$^2$.