Review of Light Hadron Spectra at BESIII

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(on behalf of BESIII Collaboration)

Institute of High Energy Physics

Hadron Structure and Interactions in 2012
Osaka, 16-17, November 2012
OUTLINE

- Introduction
- Latest results on hadron spectroscopy
- Summary
Bird view of BEPCII

- Linac
- Storage ring

τ–charm physics

- Charmonium decays/transitions
- Light hadron spectroscopy
  - ...  
  - η and η’ physics
- Charm physics
- τ physics
Why light hadron physics?

"That [intermediate distance] scale is the richest phenomenologically, and is certainly the crux region to understand...what QCD is really about. And at the heart of the subject is the hadron spectrum, in particular the spectrum built from light quarks. (...) Without question, there is a great need... for a new round of experiments,..."

James D. Bjorken (2000)
So far BESIII has collected:

- 2009: 106 Million $\psi'$
- 2012: 0.4 Billion $\psi'$
- 2009: 225 Million $J/\psi$
- 2012: 1 Billion $J/\psi$

The results in this talk are based on the data sample of 106M $\psi'$ events and 225M $J/\psi$ events.
Confirmation of $p\bar{p}$ mass threshold enhancement

Confirmation of $X(1835)$ and observation of two new structures

$X(1870)$ in $J/\psi \to \omega X, X \to a_0(980)\pi$

$X(1840)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$

Study of $\eta\eta$ system

First observation of $\eta(1405) \to f_0(980)\pi^0, f_0(980) \to \pi\pi$

$N^*$ baryons in $\psi' \to p\eta, p\rho\pi^0$ decays

$\eta$ and $\eta'$ physics
Confirmation of p \overline{p} mass threshold enhancement

\[ J / \psi \rightarrow \gamma pp \]

\[ M = 1859^{+3}_{-10}^{+5}_{-25} \text{ MeV/c}^2 \]
\[ \Gamma < 30 \text{ MeV/c}^2 \text{ (90\% CL)} \]

Theoretical interpretation:
- conventional meson?
- ppbar bound state/multiquark
- glueball
- Final state interaction (FSI)
- ...

PRL 91 (2003) 022001
Confirmation of $p\bar{p}$ mass threshold enhancement

Fit with one resonance at BESII did:

\[ \psi' \rightarrow \pi^+ \pi^- J / \psi, J / \psi \rightarrow \gamma p\bar{p} \]

- $M = 1861^{+6}_{-13}^{+7}_{-26}$ MeV/c$^2$
- $\Gamma < 38$ MeV/c$^2$ (90% CL)

Chinese Physics C 34, 421 (2010)  
PRD 82, 092002(2010)
Several non-observations

$Y(1S) \to \gamma pp@CLEO$

$J/\psi \to \omega pp@BESII$

$\psi' \to \gamma pp@BESII$

$\psi(2S) \to \gamma p\bar{p} @CLEOc$

Pure FSI interpretation is disfavored
Evident narrow ppbar mass threshold enhancement in J/ψ decays.

Partial Wave Analysis (PWA):

- Concentrate on dealing with the $p\bar{p}$ mass threshold structure, especially to determine the $J^{PC}$.
PWA results and projections in $J/\psi \rightarrow \gamma p\bar{p}$

- The fit with a BW and S-wave FSI(I=0) factor can well describe ppb mass threshold structure.
- It is much better than that without FSI effect (~7σ).
**Measurement for X(p ¯p)**

- PWA results are carefully checked from different aspects:
  - Contribution of additional resonances
  - Solution with different combinations
  - Different background levels and fitting mass ranges
  - Different BW formula
  
  *All uncertainties are considered as systematic errors*

- Different FSI models → Model dependent uncertainty

- Spin-parity, mass, width and B.R. of X(pp̅):

  \[ J^{PC} = 0^{-+} \]

  >6.8σ better than other \( J^{PC} \) assignments.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass( MeV/c²)</th>
<th>Width( MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(pp̅bar)</td>
<td>( 18326.3^{+19}<em>{-5}^{+18}</em>{-17} \pm 19 ) (model)</td>
<td>( 13 \pm 39^{+10}_{-13} \pm 4 ) (model)</td>
</tr>
</tbody>
</table>

\[ \text{BR}[J/\psi \rightarrow \gamma X(p\bar{p})]\text{BR}[X(p\bar{p}) \rightarrow p\bar{p}] = [9.0^{+0.4}_{-1.1} \text{ (stat)}^{+1.5}_{-5.0} \text{ (syst)} \pm 2.3 \text{ (model)}] \times 10^{-5} \]
Obviously different line shape of ppbar mass spectrum near threshold from that in J/ψ decays

PWA results:

- Significance of X(ppbar) is > 6.9σ.
- The production ratio R:

\[
R = \frac{B(\psi' \rightarrow \gamma X(p\bar{p}))}{B(J/\psi \rightarrow \gamma X(p\bar{p}))}
\]

\[= (5.08^{+0.71}_{-0.45} \text{(stat)} ^{+0.67}_{-3.58} \text{(syst)}) \pm 0.12(\text{mod})\%\]

- It is suppressed compared with “12% rule”.

PWA Projection:

first measurement

PRL 108,112003(2012)
Confirmation of $X(1835)$ and Observation of two new structures

**BESII result** (Stat. sig. ~ 7.7$\sigma$):

$M = 1833.7 \pm 6.1\,(stat) \pm 2.7\,(syst)\,MeV$

$\Gamma = 67.7 \pm 20.3\,(stat) \pm 7.7\,(syst)\,MeV$

**J/ψ→γη’π⁺π⁻**

$\eta' \rightarrow \eta \pi^+ \pi^-$

$\eta' \rightarrow \gamma \rho$

**PRL 95, 262001(2005)**
**PRL 106, 072002(2011)**
Confirmation of $X(1835)$ and Observation of two new structures

BESIII fit results:

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M$ (MeV/c$^2$)</th>
<th>$\Gamma$ (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>$&gt;20\sigma$</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>$7.2\sigma$</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>$6.4\sigma$</td>
</tr>
</tbody>
</table>

PWA is needed to understand these structures.

$X(1835)$ consistent with $0^{-+}$
What's the nature of new structures?

It is the first time resonant structures are observed in the 2.4 GeV/c^2 region, it is interesting since:

LQCD predicts that the lowest lying pseudoscalar glueball: around 2.4 GeV/c^2.

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

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

PRD73,014516(2006) Y.Chen et al

PRD82,074026,2010 (J.F. Liu, G.J. Ding and M.L.Yan)
PRD83:114007,2011 (J.S. Yu, Z.F. Sun, Q.Zhao), and more...
$X(1870)$ in $J/\psi \rightarrow \omega X$, $X \rightarrow a_0(980)\pi$

- $X(1835)$ observed at BESII and then confirmed at BESIII in $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$
- theoretical interpretations: pseudoscalar glueball, $\eta/\eta'$ excited states ..
- study of its production in hadronic decays
- to our surprise, we observed a new structure around 1.87 GeV

**BESIII**

**PRL 107, 182001(2011)**
Identification of $X(1870)$: $0^-$(?)
It is $X(1835)$? Need PWA!
X(1840) in $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$

Preliminary results

A peak around 1.84 GeV is observed!

\[ M = 1842.2 \pm 4.2^{+6.9}_{-1.8} \text{ MeV} \]
\[ \Gamma = 83 \pm 14 \pm 11 \text{ MeV} \]

- Its mass is consistent with that of X(1835), but the width is much smaller than $\Gamma_{X(1835)} = 190.1 \pm 9.0^{+38}_{-36} \text{ MeV}$
- Most likely to be a new decay mode of X(1835)
\( M_{\omega\phi} \) threshold enhancement in \( \psi \rightarrow \gamma\omega\phi \)

For \( X(1810) \):

\[
M = 1812^{+19}_{-26} \pm 18 \text{ MeV}/c^2
\]

\[
\Gamma = 105 \pm 20 \pm 28 \text{ MeV}/c^2
\]

\( J^{pc} \) favors 0^{++} over 0^{-+} and 2^{++}
Is $X(1810)$ the $f_0(1710)/f_0(1790)$ or new state?
\( \eta(1405) \) in \( J/\psi \rightarrow \gamma f_0(980)\pi^0, f_0(980) \rightarrow \pi\pi \)

Charged: 
\[ f_0(980) \rightarrow \pi^+\pi^- \]
Neutral 
\[ f_0(980) \rightarrow \pi^0\pi^0 \]

Helicity analysis indicates that peak at 1400MeV is from \( \eta(1405) \rightarrow f_0(980)\pi^0 \) not from \( f_1(1420) \):

First observation of 
\( \eta(1405) \rightarrow f_0(980)\pi^0 \)
(isospin violated decays) and \( J/\psi \rightarrow \gamma f_0(980)\pi^0 \)

\[
\text{Br}(J/\psi \rightarrow \gamma \eta(1405) \rightarrow \gamma f_0\pi^0 \rightarrow \gamma \pi^0\pi^+\pi^-) = (1.48 \pm 0.13 \text{ (stat.)} \pm 0.17 \text{ (sys.)}) \times 10^{-5}
\]

\[
\text{Br}(J/\psi \rightarrow \gamma \eta(1405) \rightarrow \gamma f_0\pi^0 \rightarrow \gamma \pi^0\pi^0\pi^0) = (6.99 \pm 0.93 \text{ (stat.)} \pm 0.95 \text{ (sys.)}) \times 10^{-6}
\]
Large isospin violation in $\eta(1405)$ decay

In general, magnitude of isospin violation in strong decay should be less than 1% or at 0.1% level. For example:

$$\frac{BR(\psi' \to \pi^0 J / \psi)}{BR(\psi' \to \eta J / \psi)} = 0.2 \times 10^{-2} \times \left| \frac{P_\pi}{P_\eta} \right|^3, \quad \frac{BR(\eta' \to \pi^+ \pi^- \pi^0)}{BR(\eta' \to \pi^+ \pi^- J)} = 0.8 \times 10^{-2}$$

However:

$$\frac{BR(\eta(1405) \to f_0(980)\pi^0)}{BR(\eta(1405) \to a_0(980)\pi)} \approx 25\%$$

Triangle Singularity (TS)


K*K pair in TS is almost on-shell, together with mixing explain the narrow $f_0(980)$, and large isospin violation.
Anomalous line shape of $f_0(980)$ in $J/\psi \rightarrow \gamma 3\pi$

Surprising result:

very narrow $f_0(980)$ width: $<11.8$ MeV/$c^2$ @90% C.L.
much narrower than the world average (PDG 2010: 40-100 MeV/$c^2$)

$M = 989.9 \pm 0.4$ MeV/$c^2$
$\Gamma = 9.5 \pm 1.1$ MeV/$c^2$

$M = 987.0 \pm 1.4$ MeV/$c^2$
$\Gamma = 4.6 \pm 5.1$ MeV/$c^2$
Study of ηη system

- First observed $f_0(1710)$ from $J/\psi$ radiative decays to $\eta\eta$ by Crystal Ball in 1982.

- LQCD predicts:
  
  $0^+ : 1710 \pm 50 \pm 80$

- Crystal Barrel Collaboration (2002) analyzed the three final states $\pi^0\pi^0\pi^0$, $\eta\pi^0\pi^0$ and $\pi^0\eta\eta$ with K matrix formalism. Found a $2^{++}$ ($\sim 1870\text{MeV}$), but no $f_0(1710)$.

- E835 (2006): $p\overline{p} \to \pi^0\eta\eta$, found $f_0(1500)$ and $f_0(1710)$.

- WA102 and GAMS all identified $f_0(1710)$ in $\eta\eta$. 
Preliminary PWA results of $J/\psi \to \gamma \eta \eta$ @BESIII

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass(MeV/$c^2$)</th>
<th>Width(MeV/$c^2$)</th>
<th>$B(J/\psi \to \gamma X \to \gamma \eta \eta)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>1468$^{+14+20}_{-15-74}$</td>
<td>136$^{+41+8}_{-26-100}$</td>
<td>$(1.61^{+0.29+0.41}_{-0.32-1.28}) \times 10^{-5}$</td>
<td>8.2 $\sigma$</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>1759$^{+6+14}_{-6-25}$</td>
<td>172$^{+10+31}_{-10-15}$</td>
<td>$(2.35^{+0.07+1.23}_{-0.07-0.72}) \times 10^{-4}$</td>
<td>25.0 $\sigma$</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>2081$^{+13+23}_{-13-34}$</td>
<td>273$^{+27+65}_{-24-48}$</td>
<td>$(9.99^{+0.57+5.52}_{-0.57-2.21}) \times 10^{-5}$</td>
<td>13.9 $\sigma$</td>
</tr>
<tr>
<td>$f_2(1525)$</td>
<td>1513$^{+5+3}_{-5-10}$</td>
<td>75$^{+12+1}_{-10-5}$</td>
<td>$(3.41^{+0.43+1.22}_{-0.50-0.123}) \times 10^{-5}$</td>
<td>11.0 $\sigma$</td>
</tr>
<tr>
<td>$f_2(1810)$</td>
<td>1822$^{+29+61}_{-24-54}$</td>
<td>229$^{+52+64}_{-43-52}$</td>
<td>$(5.38^{+0.60+3.31}_{-0.67-2.24}) \times 10^{-5}$</td>
<td>6.4 $\sigma$</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>2362$^{+31+139}_{-30-59}$</td>
<td>334$^{+54}_{-9}$</td>
<td>$(5.58^{+0.61+1.93}_{-0.65-1.81}) \times 10^{-5}$</td>
<td>7.6 $\sigma$</td>
</tr>
</tbody>
</table>

- $f_0(1710)$ and $f_0(2100)$ are dominant scalars.
- $f_0(1500)$ exists (8.2$\sigma$).
- $f_2'(1525)$ is the dominant tensor.
Non-relativistic quark model is successful in interpreting of the excited baryons

Predicted more excited stated ("missing resonance problem")

$J/\psi \ (\psi')$ decays offers an window to search for the missing resonance

Observation of two $N^*$ baryons in $\psi'\rightarrow \pi^0p\bar{p}$ decay

arXiv:1207.0223
Two new baryonic excited states are observed!

**Resonance** | **$M(\text{MeV}/c^2)$** | **$\Gamma(\text{MeV}/c^2)$** | **$\Delta S$** | **$\Delta N_{dof}$** | **C.L.**
--- | --- | --- | --- | --- | ---
$N(1440)$ | $1390^{+11+21}_{-21-30}$ | $340^{+46+70}_{-40-156}$ | 72.5 | 4 | 11.5$\sigma$
$N(1520)$ | $1510^{+3+11}_{-7-9}$ | $115^{+20+0}_{-15-40}$ | 19.8 | 6 | 5.0$\sigma$
$N(1535)$ | $1535^{+9+15}_{-8-22}$ | $120^{+20+0}_{-20-42}$ | 49.4 | 4 | 9.3$\sigma$
$N(1650)$ | $1650^{+5+11}_{-5-30}$ | $150^{+21+14}_{-22-50}$ | 82.1 | 4 | 12.2$\sigma$
$N(1720)$ | $1700^{+20+32}_{-28-35}$ | $450^{+109+149}_{-94-44}$ | 55.6 | 6 | 9.6$\sigma$
$N(2300)$ | $2300^{+40+109}_{-30-0}$ | $340^{+30+110}_{-30-58}$ | 120.7 | 4 | 15.0$\sigma$
$N(2570)$ | $2570^{+19+34}_{-10-10}$ | $250^{+14+69}_{-24-21}$ | 78.9 | 6 | 11.7$\sigma$

**Resonance** | **$M(\text{MeV}/c^2)$** | **$\Gamma(\text{MeV}/c^2)$**
--- | --- | ---
$N(2300)$ | $2300^{+40}_{-30+10}$ | $340^{+30}_{-30+110}$
$N(2570)$ | $2570^{+19}_{-10+34}$ | $250^{+14}_{-24+69}$
Preliminary results on $N^*$ baryon in $\psi' \rightarrow \eta p \bar{p}$ decay

$\text{Br}(\psi' \rightarrow pp\eta) = (6.6^{+0.2}_{-0.2}^{+0.6}_{-0.6}) \times 10^{-5}$

PDG2010: $(6.0^{+1.2}_{-1.2}) \times 10^{-5}$

$\text{Br}(\psi' \rightarrow N(1535)p) \times \text{Br}(N(1535) \rightarrow p\eta + c.c.) = 5.5^{+0.3}_{-0.3}^{+7.4}_{-1.1} \times 10^{-5}$

$N(1535)$ is $1/2^-$

Mass: $1.524^{+0.005+0.010}_{-0.005-0.004}$ GeV

Width: $0.130^{+0.027+0.061}_{-0.027-0.014}$ GeV

Background clean!

A full PWA is performed.

Dalitz plot data

Dalitz plot MC fit

BESIII Preliminary
Search for CP violation in $\eta/\eta' \rightarrow \pi\pi$

Phys. Rev. D84, 032006 (2011)

- Offer an excellent laboratory for testing P and CP invariance
- Theoretically proceed via the weak interaction at a level of $10^{-15} \sim 10^{-27}$
<table>
<thead>
<tr>
<th>Process</th>
<th>$\mathcal{B}^{\text{UP}}$</th>
<th>$\mathcal{B}^{\text{UP}}_{\text{PDG}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \to \pi^+ \pi^-$</td>
<td>$3.9 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\eta' \to \pi^+ \pi^-$</td>
<td>$5.5 \times 10^{-5}$</td>
<td>$2.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\eta \to \pi^0 \pi^0$</td>
<td>$6.9 \times 10^{-4}$</td>
<td>$3.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\eta' \to \pi^0 \pi^0$</td>
<td>$4.5 \times 10^{-4}$</td>
<td>$9 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Comparison: Isospin violations in $\eta'\rightarrow\pi\pi\pi$:

$$\frac{BR(\eta' \rightarrow \pi^+\pi^-\pi^0)}{BR(\eta' \rightarrow \pi^+\pi^-\eta)} \approx 0.9\%,$$
$$\frac{BR(\eta' \rightarrow \pi^0\pi^0\pi^0)}{BR(\eta' \rightarrow \pi^0\pi^0\eta)} \approx 1.6\%.$$
Search for $\eta/\eta' \rightarrow$ invisible in $J/\psi \rightarrow \phi \eta/\eta'$

- offer a window for physics beyond the standard model
- observation of the invisible final states (may) provides information of light dark matter
- easy to tag with $J/\psi \rightarrow \phi \eta/\eta'$: two body decays; $\phi$'s width is quite narrow

Reconstructing $\phi \rightarrow K^+ K^-$ and looking at recoiling mass of $\phi$

Theoretical predictions:
B. McElrath PRD 72, 103508(2005)

$B(\eta \rightarrow \chi \chi) \sim 7.4 \times 10^{-5}$

$B(\eta' \rightarrow \chi \chi) \sim 8.1 \times 10^{-7}$
Search for $\eta/\eta' \rightarrow$ invisible in $J/\psi \rightarrow \phi \eta/\eta'$ (arXiv: 1209.2469)

$B(\eta' \rightarrow$ invisible$/B(\eta' \rightarrow \gamma\gamma)$ $< 2.39 \times 10^{-2}$

$B(\eta \rightarrow$ invisible$/B(\eta \rightarrow \gamma\gamma)$ $< 2.58 \times 10^{-4}$

$B(\eta' \rightarrow$ invisible$)< 5.21 \times 10^{-4} @ 90\%$ C.L.

$B(\eta \rightarrow$ invisible$)< 1.01 \times 10^{-4} @ 90\%$ C.L.

$B(\eta' \rightarrow$ invisible$)< 1.4 \times 10^{-3} @ 90\%$ C.L.

$B(\eta \rightarrow$ invisible$)< 6.0 \times 10^{-4} @ 90\%$ C.L.

BESII results: PRL 97, 202002 (2006)

Theory:
B. McElrath PRD 72, 103508(2005)

$BR(\eta \rightarrow \chi\chi) \sim 7.4 \times 10^{-5}$

$BR(\eta' \rightarrow \chi\chi) \sim 8.1 \times 10^{-7}$
BF measurement of $\eta' \rightarrow \pi^+\pi^-e^+e^-$, $\pi^+\pi^-\mu^+\mu^-$ (Preliminary results)

**Decay**

<table>
<thead>
<tr>
<th>Decay</th>
<th>Effective meson theory</th>
<th>Chiral Unitary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(\eta' \rightarrow \pi^+\pi^-e^+e^-)$</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$(2.13^{+0.19}_{-0.32}) \times 10^{-3}$</td>
</tr>
<tr>
<td>$B(\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-)$</td>
<td>$2.0 \times 10^{-5}$</td>
<td>$(1.57^{+0.96}_{-0.75}) \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Summary

- Huge data samples collected for charmonium decays at BESIII. A lot of results have been obtained,
  - Confirmation of the $p \bar{p}$ mass threshold enhancement
  - Confirmation of $X(1835)$ and observation of two new structures $X(2120)$ and $X(2370)$
  - Observation of new structure $X(1870)$ in $J/\psi \rightarrow \omega \pi \pi \eta$
  - ....
  - $\eta$ and $\eta'$ physics
- We expect rich physics results in the coming years from BESIII!
Thanks!