Recent Results of Light Hadron Spectra at BESIII
(\(X(1835), X(1870), \cdots\))

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Status of BEPCII / BESIII

Recent Results on Light Hadron Spectroscopy

- $p\bar{p}$ mass threshold structure in $J/\psi$ and $\psi'$ radiative decays
- $X(1835)$ and two new structures in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$
- A new structure $X(1870)$ in $J/\psi \rightarrow \omega\eta\pi^+\pi^-$
- $\eta(1405)$ in $J/\psi \rightarrow \gamma X$, $X\rightarrow f_0(980)\pi^0$, $f_0(980) \rightarrow \pi\pi$
- PWA of $J/\psi \rightarrow \gamma\eta\eta$
- PWA of $J/\psi \rightarrow \gamma\omega\phi$
- $N^*$ states in $\psi' \rightarrow p\bar{p}\pi^0$ and $\psi' \rightarrow p\bar{p}\eta$

Summary
General layout of BEPCII/BESIII

2004: start BEPCII construction
2008: test run of BEPCII
2009-now: BEPCII/BESIII data taking

Beam energy: \(1.0 \text{ - } 2.3 \text{ GeV}\)
Designed lumi.: \(1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)
\((\text{Peak Lumi.}: \ 0.65 \times 10^{33}\text{cm}^{-2}\text{s}^{-1})\)
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
Circumference: 237 m
The BESIII Detector

Drift Chamber (MDC):
- small cell & gas: He/C3H8 (60/40), 43 layers
- $\sigma_{xy} = 130 \, \mu m$
- $\sigma_p/p = 0.5\% @ 1 \text{GeV}$
- $dE/dx = 6\%$

Time-of-Flight (TOF):
- $\sigma_T = 80 \text{ps barrel}$
- 110ps endcap

Electromagnetic Calorimeter (EMC):
- CsI crystal
- $\Delta E/E = 2.5\% @ 1 \text{GeV}$
- $\sigma_Z = 0.6 \text{cm}/\sqrt{E}$

Muon Counter:
- 9 layers for barrel
- 8 layers for endcap

Solenoid Magnet field: 1T

The detector is hermetic for neutral and charged particles with excellent resolution, PID, and large coverage.
J/ψ and ψ' data samples

So far BESIII has collected:

- **2009:**
  - 225 Million J/ψ (4 times of BESII)
  - 106 Million ψ’ (4 times of CLEOc)

- **2012:** 1 Billion J/ψ
  - 0.4 Billion ψ’

The following results are based on the data samples of 225M J/ψ and 106M ψ’ events.

World’s largest sample of J/ψ, ψ(2S)
Hadron Spectroscopy

- The ultimate goal of the study of hadron spectroscopy is to understand the dynamics of the constituent interactions.
- PQCD is not applicable in the light hadron sector. There exist phenomenological approaches and LQCD calculations.
- Experimental data will provide necessary constrains on the parameters introduced by the theory.

New forms of hadrons

- Conventionally we know: mesons (q̅q) and baryons (qqq)
- But many more forms which are QCD allowed, namely
  * Multi-quark states: number of quarks $\geq 4$
  * Hybrid states: q̅q g, qqgg, ...
  * Glueballs: gg, ggg, ...
Observed an enhancement at $p\bar{p}$ mass threshold @ BESII

$J/\psi \rightarrow \gamma p\bar{p}$ (58M $J/\psi$ events)

A fit using an acceptance-weighted S-wave BW Plus bkg.

$M=1859 \pm 3 \pm 5$ MeV/$c^2$
$\Gamma < 30$ MeV/$c^2$ (90% CL)

3-body phase space

M and $\Gamma$ are not consistent with the properties of any known particle.
Consistent with spin zero expectation.
Theoretical interpretations:

- Conventional mesons / $p\bar{p}$ bound state / multiquarks / glueball
- Final state interaction (FSI) ……

PRL 91, 022001 (2003)
Confirmed @ BESIII and CLEOc

$\psi' \rightarrow \pi^+\pi^- J/\psi \ (J/\psi \rightarrow \gamma \ p\bar{p})$
(106M $\psi'$ events)

$\psi' \rightarrow \pi^+\pi^- J/\psi \ (J/\psi \rightarrow \gamma \ p\bar{p})$
(24.5M $\psi'$ events)

- Same fit method as that of BESII.
- Consistent with BESII results.

**Chinese Physics C34(4) 421, (2010)**

- Not observed in B-meson decay, $\psi' \rightarrow \gamma \ p\bar{p}$, $\Upsilon \rightarrow \gamma \ p\bar{p}$, $J/\psi \rightarrow \omega \ p\bar{p}$ at BESII, $\psi' \rightarrow Xpp$ ($X=\gamma, \pi^0, \eta$) at CLEOc.
- The enhancement is not pure FSI effect.

**Fit region $\Delta m = 0-970$ MeV**
Consider $X(2100)$:

- $M = 1837^{+10}_{-12}^{+9}_{-7}$ MeV/c$^2$
- $\Gamma = 0^{+44}_{-0}$ MeV/c$^2$

**PRD 82, 092002 (2010)**
Four components:
X(pp), f_2(1910), f_0(2100) and 0^{++} PS

The FSI effect considered.

Fit features:
- The fit with a BW and S-wave FSI (I=0) factor can well describe pp mass threshold structure.
- Much better than that w/o FSI effect, ΔlnL = 51 (7.1σ).
- Different FSI model → Model dependent uncertainty

Results:
\[ J^{pc} = 0^+ \]
\[ M = 1832^{+19}_{-17} \text{ (stat)}^{+18}_{-17} \text{ (syst)} \pm 19 \text{(mod)} \text{MeV/c}^2 \]
\[ \Gamma = 13 \pm 20 \text{(stat)}^{+11}_{-33} \text{(syst)} \pm 4 \text{(mod)} \text{MeV/c}^2 \text{ or } \Gamma < 76 \text{MeV/c}^2 \text{ @ 90\% C.L.} \]
\[ B(J / \psi \to \gamma X(pp))B(X(pp) \to pp) = (9.0^{+0.4}_{-1.1} \text{(stat)}^{+1.5}_{-5.0} \text{(syst)} \pm 2.3 \text{(mod)}) \times 10^{-5} \]
• Observed a p\overline{p} mass threshold excess relative to PS.
• Line shape of p\overline{p} mass spectrum near threshold looks obviously differ. from that of J/\psi decays.
• No evident enhancement exist in p\overline{p} threshold in Dalitz plot.

PWA Results:

➢ Significance of X(p\overline{p}) is > 6.9\sigma.
➢ The production ratio R:

\[
R = \frac{B(\psi' \rightarrow \gamma X(p\overline{p}))}{B(J / \psi \rightarrow \gamma X(p\overline{p}))} = (5.08^{+0.71}_{-0.45} (\text{stat})^{+0.67}_{-3.58} (\text{syst}) \pm 0.12(\text{mod}))% \]

It is suppressed compared with “12% rule”.

PRL 108, 112003 (2012)
**X(1835) and two new structures in J/ψ→γπ⁺π⁻η'/**

**J/ψ → γπ⁺π⁻η' (η' → π⁺π⁻η, η → γγ and η' → γρ, ρ → π⁺π⁻)**

**BESII Results:**

* M = 1833.7±6.1(stat)±2.7(syst) MeV/c²
* Γ = 67.7 ± 20.3(stat) ± 7.7(syst) MeV/c²
* B(J/ψ→γX(1835))·B(X(1835)→π⁺π⁻η') = (2.2±0.4(stat)±0.4(syst))×10⁻⁴
* Statistical Significance 7.7σ

**BESIII Results:**

* B(J/ψ→γX(1835))·B(X(1835)→π⁺π⁻η') = (2.87±0.09(stat)±0.09(syst))×10⁻⁴
* For X(1835), the angular distribution of the radiative photon is consistent with 0⁺⁺ assignment. (> 20σ)

**PWA is needed to understand their properties!**
What’s the nature of X(1835), X(2120) and X(2370)?

- **X(1835) observed in J/ψ→γ π⁺π⁻η'**
  - The measured width at BESIII is larger than that from BESII.
    - Observed p¯p sub-threshold enhancement X(1860) in J/ψ→γ p¯p at BESII and confirmed at BESIII and CLEOc.
    - Are the X(1835) and X(p¯p) the same resonant state?
    - p¯p bound state? glueball? η'/ excited state? …

**Still remain unclear at present!**

- **X(2120) / X(2370) observed in J/ψ→γπ⁺π⁻η'**
  - The first time resonant structures are observed at ~2.1 and 2.4GeV.
    - Interesting since:
      - LQCD predicts the lowest 0⁺ glueballs at ~2.4GeV.
      - A good channel for finding 0⁺ glueballs.
  - **Their nature:** pseudoscalar glueball? η/η' excited states? …

- **A PWA is needed to measure their J^PC, M and Γ more precisely, and planned with much higher statistics J/ψ data sample.**
X(1870) in $J/\psi \rightarrow \omega X$, $X \rightarrow a_0^{\pm}(980)\pi^\mp$, $a_0^{\pm}(980) \rightarrow \eta\pi^\pm$

A study of $J/\psi \rightarrow \omega \eta\pi^+\pi^-$ at BESIII

PRL 107, 182001 (2011)

Is $X(1870)$ due to $X(1835)$, $\eta_2(1870)$, an interference of both, or a new resonance? $J^{PC}$?

Need PWA!
Evidence for an enhancement at ~ 1.3GeV (potentially from \( f_1(1285)/\eta(1295) \))

Analysis of angular distribution indicates the peak at 1.4GeV is from \( \eta(1405) \) \((J^P = 0^-)\), not from \( f_1(1420) \) \((J^P = 1^+)\). Stat. sig. > 10 \( \sigma \).

Large Isospin-violating decay rate:

\[
\frac{Br(\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0)}{Br(\eta(1405) \rightarrow a_0(980)\pi^0 \rightarrow \pi^0\pi^0\eta)} \approx (17.9 \pm 4.2)\%
\]

In general, magnitude of isospin violation in strong decay should be < 1%.

\( a_0 - f_0 \) mixing alone can not explain the branching ratio of \( \eta(1405) \rightarrow f_0(980)\pi^0 \).
Anomalous line shape of $f_0(980)$ in $J/\psi \rightarrow \gamma 3\pi$

- $f_0(980) \rightarrow \pi^+\pi^-$
  - $M = 989.9 \pm 0.4\text{ MeV/c}^2$
  - $\Gamma = 9.5 \pm 1.1 \text{ MeV/c}^2$

- $f_0(980) \rightarrow \pi^0\pi^0$
  - $M = 987.0 \pm 1.4\text{ MeV/c}^2$
  - $\Gamma = 4.6 \pm 5.1 \text{ MeV/c}^2$

**Surprising Result:** The measured width of $f_0(980)$ is much narrower than the world average (PDG 2012: 40-100 MeV/c^2)

Triangle Singularity (TS) mechanism

- $K^*K$ in TS mechanism is on-shell.
- TS is much more dominant than $a_0 - f_0$ mixing term.
  - Explains the large isospin violations in $\eta(1405) \rightarrow \pi^+\pi^-\pi^0$.
  - Predicts a narrow peak at $M(\pi^+\pi^-) \sim 980$ MeV.

(J.J. Wu et al, PRL 108, 081803 (2012))
Study of $\eta\eta$ system

- LQCD predicts the lowest glueball state is $0^{++}$ with $M \sim 1.5 - 1.7$ GeV, the next lightest glueball is $2^{++}$ with $M \sim 2.3$ GeV.

- The mixing of glueball with nearby $qq$ meson makes the situation more difficult.

Glueball spectrum from unquenched LQCD calculations. $r_0^{-1} = 410$ MeV

- Early study of $J/\psi \rightarrow \gamma \eta \eta$ was made by Crystal Ball in 1982. Found $J^{PC}$ of the resonance $\sim 1.7$ GeV is $2^{++}$.

- Other experiments:
  - Crystal ball Collaboration (2002) analyzed the final states of $\pi^0\pi^0\pi^0$, $\eta\pi^0\pi^0$ and $\pi^0\eta\eta$, found a $2^{++}$ ($\sim 1870$ MeV), but no $f_0(1710)$.
  - E835(2006): $p\bar{p} \rightarrow \pi^0\eta\eta$, found $f_0(1500)$ and $f_0(1710)$.
  - WA102 and GAMS all identified $f_0(1710)$ in $\eta\eta$. 

PRD 73 (2006) 014516
For $J/\psi \rightarrow \gamma \eta \eta$ (Pseudoscalars), only intermediate states with $J^{PC} = \text{even}^{++}$ are possible.

- $0^{++}$: $f_0(1500)$ (8.2σ), $f_0(1710)$ (25σ), $f_0(2100)$ (13.9σ), $0^{++}$ PS
- $2^{++}$: $f_2'(1525)$ (11σ), $f_2(1810)/f_2(1950)$ (6.4σ)
- $4^{++}$: $f_4(2340)$ (7.6σ)

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV$/c^2$)</th>
<th>Width (MeV$/c^2$)</th>
<th>$\mathcal{B}(J/\psi \rightarrow \gamma X \rightarrow \gamma \eta \eta)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>1468$^{+14+23}_{-15-74}$</td>
<td>136$^{+41+28}_{-26-100}$</td>
<td>$(1.61^{+0.29+0.49}_{-0.32-1.37}) \times 10^{-5}$</td>
<td>8.2σ</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>1759$^{+6+15}_{-6-25}$</td>
<td>172$^{+10+32}_{-10-16}$</td>
<td>$(2.35^{+0.07+1.24}_{-0.07-0.74}) \times 10^{-4}$</td>
<td>25.0σ</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>2081$^{+13+24}_{-13-36}$</td>
<td>273$^{+27+70}_{-24-23}$</td>
<td>$(9.99^{+0.57+5.64}_{-0.52-2.46}) \times 10^{-5}$</td>
<td>13.9σ</td>
</tr>
<tr>
<td>$f_2'(1525)$</td>
<td>1513$^{+5+4}_{-5-10}$</td>
<td>75$^{+12+14}_{-10-8}$</td>
<td>$(3.41^{+0.43+1.37}_{-0.50-1.29}) \times 10^{-5}$</td>
<td>11.0σ</td>
</tr>
<tr>
<td>$f_2(1810)/f_2(1950)$</td>
<td>1822$^{+20+66}_{-24-57}$</td>
<td>229$^{+52+88}_{-42-155}$</td>
<td>$(5.38^{+0.60+3.41}_{-0.67-2.34}) \times 10^{-5}$</td>
<td>6.4σ</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>2362$^{+31+140}_{-30-63}$</td>
<td>334$^{+62+165}_{-54-100}$</td>
<td>$(5.58^{+0.61+2.36}_{-0.65-2.06}) \times 10^{-5}$</td>
<td>7.6σ</td>
</tr>
</tbody>
</table>
$M_{\omega \phi}$ threshold enhancement in $J/\psi \to \gamma \omega \phi$ @ BESII

$J/\psi \to \gamma \omega \phi$ is DOZI suppressed process

PWA Results @ BESII:

- $M = 1812^{+19}_{-26} \pm 18$ MeV/c$^2$; \quad $\Gamma = 105 \pm 20 \pm 28$ MeV/c$^2$
  
  $B(J/\psi \to \gamma X) \cdot B(X \to \omega \phi) = (2.61 \pm 0.27 \pm 0.65) \times 10^{-4}$

- The enhancement favors $J^{PC} = 0^{++}$ over $0^{-+}$ and $2^{++}$, stat. sig. $>10\sigma$.

- Not compatible with any known conventional state.
  
  Is it the same $0^{++}$ observed in $\gamma K\bar{K}$ or $\phi \pi\pi$ ($f_0(1710)$ or $f_0(1790)$), or is it a glueball, or a hybrid ……
Further looking in diff. decay modes ($\omega\omega$, $K^*K^*$...) and diff. production processes ($J/\psi \rightarrow \phi \omega \phi$, $\omega \omega \phi$...) is desirable!

- For $X(1810)$: $M$, $\Gamma$ and $Br$ are consistent with that of BESII results. Confirms that the $J^{PC}$ is $0^{++}$ with stat. sig. of $>30\sigma$. Not compatible to $X(1835)$ and $X(pp)$ due to diff. $M$ and $J^{PC}$.

- Is $X(1810)$ the $f_0(1710)/f_0(1790)$ or a new state?
Observation of two new $N^*$ in $\psi' \rightarrow p\bar{p} \pi^0$ @ BESIII

- Non-relativistic quark model is successful in interpreting the excited baryons.
- Predicted more excited states ("missing resonance problem").

- $J/\psi$ and $\psi'$ decays offer an opportunity to search for the missing resonances.

- Events with $p\bar{p}$ arising from $J/\psi$ are excluded.
- The threshold enhancement in $p\bar{p}$ mass spectrum is visible.
- $N^*$ with spin 7/2 or larger is not considered.

arXiv:1207.0233
PWA Results:

- Soft-pion theory indicates that the off-shell decay is needed. N(940) with \( M = 940 \text{MeV} \) and \( \Gamma = 0 \text{MeV} \) is included in PWA.

- A \( 1^- \) \( p\bar{p} \) resonance candidate described by BW function is tested. The largest sig. is \( 4\sigma \) at \( M = 2000 \text{MeV} \) and \( \Gamma = 50 \text{MeV} \). The threshold enhancement most likely due to interference of N* resonances.

- No clear evidence for N(1885)/N(2065).

- Two new N* resonances N(2300) and N(2570) are observed with \( 1/2^+ \) and \( 5/2^- \).

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

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Preliminary results on $N^*$ baryons in $\psi' \to p\bar{p}\eta$ @ BESIII

- No significant contribution from other resonance $\sim p\bar{p}$ mass enhancement. significance $< 3.5\sigma$
- $N(1535)$ was firstly studied by PWA in $J/\psi \to p\bar{p}\eta$ at BESII, and confirmed here.

$$M = 1524^{+5+10}_{-5-4}\text{ MeV},$$
$$\Gamma = 130^{+27+57}_{-24-10}\text{ MeV}$$

Consistent with PDG. sig.$>5\sigma$; $J^P 1/2^-$

* $B(\Psi' \to N(1535)\bar{p}) \times B(N(1535) \to p\eta) + \text{c.c.} = (5.2^{+0.3+3.2}_{-0.3-1.2}) \times 10^{-5}$
* $B(\Psi' \to p\bar{p}\eta) = (6.4 \pm 0.2 \pm 0.6) \times 10^{-5}$  PDG2010: $(6.0 \pm 1.2) \times 10^{-5}$
* $B(\Psi' \to p\bar{p}\eta)/B(J/\Psi \to p\bar{p}\eta) = (3.2 \pm 0.4)\%$ Suppressed compared with "12\% rule"
Summary

♦ BESIII is successfully operating since 2008:
   * World largest data samples at J/ψ, ψ′, ψ(3770), ψ(4040) already collected, more data in future!

♦ Recent results on light hadron spectroscopy
   * Confirmation of p̅p threshold enhancement
   * Confirms X(1835) and observes two new structures in J/ψ → γ ππη′
   * Observation of a new structure X(1870) in J/ψ → ω ηπ⁺π⁻
   * First observation of η(1405) → f₀(980)π⁰ (isospin breaking)
   * ηη system in J/ψ → γγη
   * Confirms X(1810) in J/ψ → γ ω φ
   * Observation of two new excited baryonic states N(2300) and N(2570) in ψ′ → p̅pπ⁰. N(1535) is confirmed in ψ′ → p̅pη.

♦ Expect many more results from BESIII in future!
Backup Slides
## From BESII to BESIII

<table>
<thead>
<tr>
<th>BESII</th>
<th>BESIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MDC</strong>&lt;br&gt;( \sigma(p)/p = 1.78 % \cdot \sqrt{1 + p^2} )&lt;br&gt;( dE/dx_{\text{reso}} = 8 % )&lt;br&gt;<strong>TOF</strong>&lt;br&gt;180 ps (for bhabha)&lt;br&gt;<strong>EMC</strong>&lt;br&gt;( \sigma(E)/E = 22% \cdot \sqrt{E} )&lt;br&gt;<strong>MUC</strong>&lt;br&gt;3 layers for barrel</td>
<td><strong>MDC</strong>&lt;br&gt;( \sigma(p_t)/p_t = 0.32 % \cdot p_t )&lt;br&gt;( dE/dx_{\text{reso}} &lt; 6 % )&lt;br&gt;<strong>TOF</strong>&lt;br&gt;90 ps (for bhabha)&lt;br&gt;<strong>EMC</strong>&lt;br&gt;( \sigma(E)/E = 2.3 % \cdot \sqrt{E} )&lt;br&gt;<strong>MUC</strong>&lt;br&gt;9 layers for barrel, 8 for endcap</td>
</tr>
</tbody>
</table>
BESI started data-taking in 1989 and was upgraded in 1998 to BESII. **BESI** collected 7.8 M $J/\psi$ events and 3.7 M $\psi'$ events. **BESII** collected 58 M $J/\psi$ events and 14 M $\psi'$ events.

**BESIII** - physics using “charm”

- **Charmonium physics:**
  - Spectroscopy
  - transitions and decays

- **Light hadron physics:**
  - meson & baryon spectroscopy
  - glueball & hybrid
  - two-photon physics
  - e.m. form factors of nucleon

- **Charm physics:**
  - (semi)leptonic + hadronic decays
  - decay constant, form factors
  - CKM matrix: $V_{cd}$, $V_{cs}$
  - $D^0$-$\bar{D}^0$bar mixing and CP violation
  - rare/forbidden decays

- **Tau physics:**
  - Tau decays near threshold
  - tau mass scan

...and many more.
BESIII data sets and future plans

- **2008**: July 19 first $e^+e^-$ collider event at BESIII
  Nov.: $\sim 14$M $\psi(2S)$ events for detector calibration

- **2009**: 106M $\psi(2S)$ events (4 times of CLEOc)
  225M $J/\psi$ events (4 times of BESII)
  $\sim 42$ pb$^{-1}$ at continuum (3.65 GeV)

- **2010**: 900 pb$^{-1}$ @ 3770 MeV
  470 pb$^{-1}$ @ 4010 MeV

- **2011**: 2000 pb$^{-1}$ @ 3770 MeV
  470 pb$^{-1}$ @ 4010 MeV

- **2012**: $\tau$ mass scan, R scan [2.0, 3.65] GeV
  0.4 billion $\psi(2S)$ and 1 billion $J/\psi$ events

**Tentative future running plans:**
- **2013**: $E_{CM} = 4260$ and 4360 MeV for ‘XYZ’ studies (0.5 fb$^{-1}$ each); $\tau$ mass scan/R scan
- **2014 and 2015**: $E_{CM} = 4170$ MeV for $D_s$ (\$2.4$ fb$^{-1}$); additional $\psi(3770)$ data

The following results are based on 225M $J/\psi$ and 106M $\psi(2S)$ events.
Main contents in the study of the hadron spectroscopy

- Meson spectrum ($q \bar{q}$)
- New forms of hadrons (glueballs, hybrid states, multi-quark states)
- Baryon spectrum ($qqq$)

**J/ψ decays provide ideal lab for hadron spectroscopy**

The lowest order diagrams for $J/ψ \rightarrow \text{hadrons}$:

- 3-gluon
- Electromagnetic
- Radiative
- Via $\eta_c$

- A good lab to hunt for new forms of hadrons
- A good lab to study meson spectroscopy
- A good lab for excited baryon states
Observation of $X(p\,\bar{p})$ in $J/\psi\rightarrow\gamma\,p\,\bar{p}$ @ BESII

- **X(1860) has large BR to $p\bar{p}$**

- **BES measured:**

  \[
  BR(J/\psi\rightarrow\gamma X(1860)) \cdot BR(X(1860)\rightarrow p\bar{p}) \sim 7 \times 10^{-5}
  \]

- **For a $0^{-+}$ meson:**

  \[
  BR(J/\psi\rightarrow\gamma X(1860)) \sim 0.5 - 2 \times 10^{-3}
  \]

- **So we would have:**

  \[
  BR(X(1860)\rightarrow p\bar{p}) \sim 4 - 14\%
  \]

  (This BR to $p\bar{p}$ might be the largest among all PDG particles)

Considering that decaying into $p\bar{p}$ is only from the tail of $X(1860)$ and the phase space is very small, **such a BR indicates $X(1860)$ has large coupling to $p\bar{p}$!**
The pp̅ threshold enhancement observed in J/ψ decay is **different** from the enhancements observed by Babar and Belle in B decay.

The one in B decay can be explained by **fragmentation**.
This narrow threshold enhancement is NOT observed in $J/\psi \rightarrow \omega p\bar{p}$ at BESII

$\frac{Br(J/\psi \rightarrow \omega X)}{Br(J/\psi \rightarrow \gamma X)} < 0.5\% \text{ @ } 95\% \text{ C.L.}$
This narrow threshold enhancement is NOT observed in $\Upsilon(1S) \rightarrow \gamma p\bar{p}$ at CLEO.

\[ Br(\Upsilon(1S) \rightarrow \gamma X) / Br(J/\psi \rightarrow \gamma X) < 0.7\% \quad @ 90\% \text{ CL} \]

- This result cannot be explained by pure FSI effect, since FSI is a universal effect.

Pure FSI interpretation of the narrow and strong $p\bar{p}$ threshold enhancement is disfavored.

No enhancement near threshold.

FIG. 7: Invariant mass of $p\bar{p}$ from $\Upsilon(1S) \rightarrow \gamma p\bar{p}$. PRD73, 032001(2006)
Several non-observations

$Y(1S) \rightarrow \gamma p\bar{p} \ @ \text{CLEO}$

$J/\psi \rightarrow \omega p\bar{p} \ @ \text{BESII}$

$\psi' \rightarrow \gamma p\bar{p} \ @ \text{BESII}$

$\psi(2S) \rightarrow \gamma p\bar{p} \ @ \text{CLEO}_c$

Pure FSI interpretation is disfavored
Is the $X(1835)$ from the same source of $X(p\bar{p})$?

- The mass of $X(p\bar{p})$ is consistent with $X(1835)$
- The width of $X(p\bar{p})$ is much narrower.

Possible reasons:

- $X(p\bar{p})$ and $X(1835)$ come from different sources
- Interference effect in $J/\psi \to \gamma\pi\pi\eta'$ process should not be ignored in the determination of the $X(1835)$ mass and width
- There may be more than one resonance in the mass peak around $1.83\text{GeV}$ in $J/\psi \to \gamma\pi\pi\eta'$ decays.
$X(1835)$ and two new structures in $J/\psi \to \gamma \pi^+\pi^- \eta'$

$J/\psi \to \gamma \pi^+\pi^- \eta'$ ($\eta' \to \pi^+\pi^- \eta$, $\eta \to \gamma\gamma$ and $\eta' \to \gamma \rho$, $\rho \to \pi^+\pi^-$)

The background subtracted, acceptance-corrected $|\cos\theta_\gamma|$ distribution for $X(1835)$.

- Errors are statistical only.
- The solid line is a fit to $1 + \cos^2\theta_\gamma$, which is expected for a pseudoscalar.

BESIII

PRL 106, 072002 (2011)
Study of $a_0(980) - f_0(980)$ mixing from

\[ J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0^0(980) \rightarrow \phi \eta \pi^0 \]
\[ \psi' \rightarrow \gamma \chi_{c1} \rightarrow \gamma \pi^0 \quad a_0^0(980) \rightarrow \gamma \pi^0 f_0(980) \rightarrow \gamma \pi^0 \pi^+ \pi^- \]

Mixing intensity provides important information in understanding the nature of $a_0(980)$ and $f_0(980)$.

Narrow peak (8 MeV) at around 980 MeV can be expected in $\eta \pi$ ($J/\psi \rightarrow \phi f_0 \rightarrow \phi a_0 \rightarrow \phi \eta \pi$ case) or $\pi^+ \pi^-$ ($\chi_{c1} \rightarrow a_0 \pi^0 \rightarrow f_0 \pi^0 \rightarrow \pi^+ \pi^- \pi^0$ case) invariant mass spectra.

J.Wu, Q.Zhao, B.Zou PRD75 114012,
C. Hanhart etc. PRD76 074028,
J.Wu, B.Zou PRD78 074017

\[ J/\psi \rightarrow \phi \]
\[ f_0 \rightarrow a_0 \]
\[ \eta \]
\[ \pi^0 \]

\[ \chi_{c1} \rightarrow \pi^0 \]
\[ a_0 \rightarrow f_0 \]
\[ \pi^+ \]
\[ \pi^- \]
\(a_0(980) \rightarrow f_0(980)\) mixing:
\(f_0 \rightarrow a_0\) transition from \(J/\psi \rightarrow \phi f_0 \rightarrow \phi a_0 \rightarrow \phi \eta \pi^0\)

Significance 3.4\(\sigma\)

\[
\text{Br}(J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0(980) \rightarrow \phi \eta \pi^0) \\
= (3.3 \pm 1.1\text{(stat)} \pm 0.4\text{(syst)} \pm 1.4\text{(para)}) \times 10^{-6} \\
(< 5.4 \times 10^{-6} \text{ at } 90\% \text{ C.L.})
\]

Mixing Intensity:
\[
\xi_{fa} = \frac{\text{Br}(J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0(980) \rightarrow \phi \eta \pi^0)}{\text{Br}(J/\psi \rightarrow \phi f_0(980) \rightarrow \phi \pi \pi)} \\
= (0.60 \pm 0.20\text{(stat)} \pm 0.13\text{(syst)} \pm 0.26\text{(para)})\% \\
(< 1.1\% \text{ at } 90\% \text{ C.L.})
\]

Mixing signal
--- \(a_0(980)\) contribution from
\(J/\psi \rightarrow \gamma^*/K^*K \rightarrow \phi a_0(980)\)
--- Background polynomial
$a_0(980) \rightarrow f_0(980)$ mixing:

$a_0 \rightarrow f_0$ transition from $\psi' \rightarrow \gamma \chi_{c1}, \chi_{c1} \rightarrow a_0 \pi^0 \rightarrow f_0 \pi^0 \rightarrow \pi^+ \pi^- \pi^0$

Br$(\psi' \rightarrow \gamma \chi_{c1} \rightarrow \gamma \pi^0 a_0(980) \rightarrow \gamma \pi^0 f_0(980) \rightarrow \gamma \pi^0 \pi^+ \pi^-) = (2.7 \pm 1.4 \text{(stat)} \pm 0.7 \text{(syst)} \pm 0.3 \text{(para)}) \times 10^{-7}$

(<6.0 \times 10^{-7} \text{ @ 90\% C.L.})

Mixing Intensity:

$\xi_{af} = \frac{\text{Br}(\psi' \rightarrow \gamma \chi_{c1} \rightarrow \gamma \pi^0 a_0(980) \rightarrow \gamma \pi^0 f_0(980) \rightarrow \gamma \pi^0 \pi^+ \pi^-)}{\text{Br}(\psi' \rightarrow \lambda \phi_{c1} \rightarrow \gamma \pi^0 a_0(980) \gamma \pi^0 \pi^0 \eta)}$

=(0.31 \pm 0.16 \text{(stat)} \pm 0.14 \text{(syst)} \pm 0.03 \text{(para)}) \%

(<1.0 \% \text{ @ 90\% C.L.})

Mixing intensity $\xi_{af}$ vs. $\xi_{fa}$

Shade region: BESIII measurements
Red line: BESIII upper limit
Dots: various predictions

Very Useful in pinning down the resonance parameters of $a_0^0(980)$ and $f_0(980)$
Glueball signatures

- Enhanced production in gluon rich processes such as pp central production, $J/\psi$ radiative decays and $\bar{p}p$ annihilation.

$J/\psi$ decays:

\[ \Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2), \Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3), \]
\[ \Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4), \Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4) \]
Baryon Summary Table

(J^P and status are listed)

Status:

**** Existence is certain, and properties are at least fairly well explored.

*** Existence is very likely but further confirmation of quantum numbers and branching fractions is required.

** Evidence of existence is only fair.

* Evidence of existence is poor.

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<th>Resonance</th>
<th>Mass(MeV)</th>
<th>Width(MeV)</th>
<th>J^P</th>
<th>C.L.</th>
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N* with spin 7/2 or larger is not shown here.