Light Meson Decays at BESIII

Yan Zhang (on behalf of BESIII Collaboration)
University of Science and Technology of China
State Key Laboratory of Particle Detection and Electronics

FPCP 2020, 8-12 June, A Toxa (Remotely)
Conference on Flavor Physics and CP Violation 2020
Outline

◆ Introduction

◆ $\eta'$ Meson Decays

✓ Hadronic decays: $\eta' \to \pi^+(0)\pi^-(0)\eta$, $\eta' \to \pi^+(0)\pi^-(0)\pi^0$, $\eta' \to \pi^0\pi^0\pi^0\pi^0$

✓ Radiative decays: $\eta' \to \gamma\pi^+\pi^-$, $\eta' \to \gamma\gamma\eta$

✓ $\eta'$ branching fractions

◆ $a_0^0(980) - f_0(980)$ Mixing

◆ Summary
Beijing Electron Positron Collider II (BEPCII)

Bird view of BEPCII

Storage ring ~ 240 m

Linac ~ 200 m

IP

BESIII detector

Double rings
Beam energy: 1.0-2.3 GeV
Design luminosity $1 \times 10^{33} / \text{cm}^2/\text{s} @ \psi(3770)$
Main Drift Chamber
\[ \sigma_{p/P} = 0.5\% @ 1 \text{ GeV} \]
\[ \sigma_{dE/dx} = 6\% \]

Time of Flight
\[ \sigma_T = 70 \text{ ps (barrel two layers)} \]
\[ 110(60) \text{ ps (endcap)} \]

Super Conducting Solenoid
1.0 T (2009)
0.9 T (2012)

Electromagnetic Calorimeter
\[ \sigma_{E/E} = 2.5\% @ 1 \text{ GeV} \]
\( \eta/\eta' \): a rich physics field

- test the predictions of CHPT
- study transition form factor
- test fundamental symmetries
- probe physics beyond the SM

<table>
<thead>
<tr>
<th>( \eta ) decay mode</th>
<th>Physics highlights</th>
<th>( \eta' ) decay mode</th>
<th>Physics highlights</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta \rightarrow \gamma\gamma\pi^0 )</td>
<td>ChPT</td>
<td>( \eta' \rightarrow \pi\pi )</td>
<td>CPV</td>
</tr>
<tr>
<td>( \eta \rightarrow \gamma B )</td>
<td>Leptophobic dark boson</td>
<td>( \eta' \rightarrow \gamma\gamma )</td>
<td>Chiral anomaly</td>
</tr>
<tr>
<td>( \eta \rightarrow \pi^0\pi^0\pi^0 )</td>
<td>( m_u - m_d )</td>
<td>( \eta' \rightarrow \gamma\pi\pi )</td>
<td>Box anomaly</td>
</tr>
<tr>
<td>( \eta \rightarrow \pi^+\pi^-\pi^0 )</td>
<td>( m_u - m_d, CV )</td>
<td>( \eta' \rightarrow \pi^+\pi^-\pi^0 )</td>
<td>( m_u - m_d, CV )</td>
</tr>
<tr>
<td>( \eta \rightarrow \gamma\gamma\gamma )</td>
<td>CPV</td>
<td>( \eta' \rightarrow l^+l^-\pi^0 )</td>
<td>CV</td>
</tr>
</tbody>
</table>
$\eta'/\eta$ from $J/\psi$ decays

- High production rate of light mesons in $J/\psi$ decays
- $\eta'/\eta$ from $J/\psi$ radiative decays
  - $7.2 \times 10^6 \, \eta'$
  - $2.4 \times 10^6 \, \eta$
- $\eta'/\eta$ from $J/\psi$ hadronic decays (e.g. $J/\psi \rightarrow \phi \eta$)
  - $5 \times 10^5 \, \eta'$
  - $3 \times 10^5 \, \eta$

Large data samples and unique opportunity to investigate the decays of $\eta'/\eta$
Dalitz plot analysis of $\eta' \rightarrow \eta\pi^+\pi^-, \eta\pi^0\pi^0$

- Remains a subject of effective ChPT.
- Explored by CLEO, VES, GAMS Collaboration but with limited statistics.
- $\eta' \rightarrow \eta\pi^+\pi^-$ is studied based on 225M J/$\psi$ at BESIII [PRD 83, 012003(2011)].
- A cusp due to $\pi^+\pi^-$ mass threshold for the Dalitz plot of $\eta' \rightarrow \eta\pi^0\pi^0$.

- For the charged decay mode
  \[ X = \frac{\sqrt{3} (T_{\pi^+} - T_{\pi^-})}{Q}, \quad Y = \frac{m_\eta + 2m_\pi}{m_\pi} \frac{T_\eta}{Q} - 1 \]
  $T_\pi$ and $T_\eta$ denote the kinetic energies of $\pi$ and $\eta$ in the $\eta'$ rest frame, $Q = m_{\eta'} - m_\eta - 2m_\pi$.

- For the neutral decay mode
  \[ X = \frac{\sqrt{3} (T_{\pi^0} - T_{\pi^0})}{Q} \]
- general representation
  \[ |M(X, Y)|^2 = N \left( 1 + a Y + b Y^2 + c X + d X^2 + \cdots \right) \]
- linear representation
  \[ |M(X, Y)|^2 = N \left( |1 + \alpha Y|^2 + c X + d X^2 + \cdots \right) \]

Here, $a,b,c,d$ are free parameters, $\alpha$ is a complex number, $a = 2\text{Re}(\alpha)$, $b = \text{Re}(\alpha)^2 + \text{Im}(\alpha)^2$. 

2020/6/10
Dalitz plot analysis of $\eta' \rightarrow \eta \pi^+ \pi^-$

The linear representation is less compatible with the data.

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$-0.116(11)$</td>
<td>$-0.098(48)$ (fixed)</td>
<td>$-0.127(18)$</td>
<td>$-0.056(4)(2)$</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>$-0.042(34)$</td>
<td>$-0.050(1)$</td>
<td>$-0.033(1)$</td>
<td>$-0.049(6)(6)$</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>$+0.010(19)$</td>
<td>$-0.092(8)$</td>
<td>$-0.072(1)$</td>
<td>$+0.0027(24)(18)$</td>
<td></td>
</tr>
<tr>
<td>$\Re(\alpha)$</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
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<tr>
<td>$\Im(\alpha)$</td>
<td>$...$</td>
<td>$...$</td>
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<tr>
<td>$c$</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
<td>$+0.000(19)$</td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>$...$</td>
<td>$...$</td>
<td>$...$</td>
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Dalitz plot analysis of $\eta' \rightarrow \eta\pi^0\pi^0$

The linear representation is less compatible with the data.

<table>
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<tr>
<th>Parameter</th>
<th>EFT [5]</th>
<th>GAMS-4\pi [12]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$-0.127(9)$</td>
<td>$-0.067(16)$</td>
<td>$-0.087(9)(6)$</td>
</tr>
<tr>
<td>$b$</td>
<td>$-0.049(36)$</td>
<td>$-0.064(29)$</td>
<td>$-0.073(14)(5)$</td>
</tr>
<tr>
<td>$c$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$d$</td>
<td>$+0.011(21)$</td>
<td>$-0.067(20)$</td>
<td>$-0.074(9)(4)$</td>
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<tr>
<td>$\Re(\alpha)$</td>
<td>$\ldots$</td>
<td>$-0.042(8)$</td>
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<tr>
<td>$\Im(\alpha)$</td>
<td>$\ldots$</td>
<td>$0.000(70)$</td>
<td>$0.000(38)(2)$</td>
</tr>
<tr>
<td>$c$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
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<tr>
<td>$d$</td>
<td>$\ldots$</td>
<td>$-0.054(19)$</td>
<td>$-0.061(9)(5)$</td>
</tr>
</tbody>
</table>
Dalitz plot analysis of $\eta' \rightarrow \eta \pi^0 \pi^0$

- **Search for cusp effect:**
  
  FSI: A cusp effect (more than 8%) on $\pi^0 \pi^0$ mass spectrum below the $\pi^+ \pi^-$ mass threshold [EPJC62, 511 (2009)]

No evidence of a cusp effect with current statistics.
Amplitude analysis of $\eta' \rightarrow \pi^{+(0)}\pi^{-(0)}\pi^0$

- $\eta' \rightarrow \pi\pi\pi$ are isospin-violating process, dominated by strong interaction. [Nucl. Phys. B460, 127(1996)]
- Light quark mass difference $(m_d - m_u)/m_s$ can be extracted [PRD 19, 2188(1979)]

\[
\begin{align*}
& r_{\pm} = \frac{B(\eta' \rightarrow \pi^+\pi^-\pi^0)}{B(\eta' \rightarrow \pi^+\pi^-\eta)} \\
& r_0 = \frac{B(\eta' \rightarrow \pi^0\pi^0\pi^0)}{B(\eta' \rightarrow \pi^0\pi^0\eta)}
\end{align*}
\]

- Using ChPT, large P-wave contribution of $\eta' \rightarrow \rho^{\pm}\pi^{\mp}$ is predicted [Eur. Phys. J. A 26, 383(2005)]
Amplitude analysis of $\eta' \rightarrow \pi^+(0)\pi^-(0)\pi^0$

$\eta' \rightarrow \pi^+\pi^-\pi^0$
8267 events

$\eta' \rightarrow \rho^\pm\pi^\mp$

$\eta' \rightarrow \pi^0\pi^0\pi^0$
2237 events
Amplitude analysis of $\eta' \to \pi^+(0) \pi^-(0) \pi^0$

PRL 118, 012001 (2017)

- Describe by three components: P wave ($\rho^{\pm} \pi^{\mp}$), resonant S wave ($\sigma \pi^0$), phase-space S wave ($\pi \pi \pi$)

- Each component > 24$\sigma$

  - $B(\eta' \to \pi^+ \pi^- \pi^0) = (35.91 \pm 0.54 \pm 1.74) \times 10^{-4}$
  - $B(\eta' \to \pi^0 \pi^0 \pi^0) = (35.22 \pm 0.82 \pm 2.54) \times 10^{-4}$
  - $B(\eta' \to \rho^{\pm} \pi^{\mp}) = (7.44 \pm 0.06 \pm 1.26 \pm 1.84) \times 10^{-4}$
  - $B(\eta' \to \pi^+ \pi^- \pi^0)_S = (37.63 \pm 0.77 \pm 2.22 \pm 4.48) \times 10^{-4}$

- Obtained decay width ratios:

  - $r_\pm = (8.77 \pm 1.19) \times 10^{-3}$
  - $r_0 = (15.86 \pm 1.33) \times 10^{-3}$
Search for rare decay $\eta' \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$

- Highly suppressed decay because of the S-wave CP-violation.
- Higher-order contributions, involving a D-wave pion loop or the production of two tensor mesons provide a CP-conserving route through which the decay can occur [PRD 85, 014014 (2012)]

No evidence for the rare decay.

**Upper limit:**

$\mathcal{B}(\eta' \rightarrow 4\pi^0) < 4.94 \times 10^{-5}$ at the 90% C.L.

This limit is approximately a factor of six smaller than the previous most stringent result. [Mod. Phys. Lett. A 29, 1450213 (2014)]
Study of $\eta' \to \gamma \pi^+ \pi^-$ decay dynamics

- In VMD model, this process is dominated by $\eta' \to \gamma \rho$
- The discrepancy attributed to the Wess-Zumino-Witten anomaly in the ChPT, Known as the box anomaly [PLB 37, 95 (1971), NPB223, 422 (1983)]
- Recently a model-independent approach based on ChPT are proposed. [PLB 707, 184 (2012)]
- Studied by several experiments, but no consistent picture due to limited statistics
  - $\rho$ mass shift or not?
  - Box anomaly or not?

The dipion mass dependent differential rate:

$$[d\Gamma/dM(\pi^+\pi^-)] = \frac{k_\gamma^3 q_\pi(s) / 48\pi^3}{|A|^2},$$

$$k_\gamma = (m_{\eta'}^2 - s) / (2m_\eta), \quad q_\pi(s) = \sqrt{s - 4m_\pi^2}/2$$
Study of $\eta' \rightarrow \gamma \pi^+ \pi^-$ decay dynamics

Model dependent fit

- Besides the $\rho(770)$, the $\omega$ contribution is needed.
- $\rho(770)$ - $\omega$ cannot describe data well.
- Extra contribution of box-anomaly or $\rho(1450)$, or both of them is necessary.

PRL 120, 242003 (2018)
Search for $\eta' \rightarrow \gamma \gamma \eta$

- Within the framework of the linear $\sigma$ model and the VMD model, the BF of $\eta' \rightarrow \gamma \gamma \eta$ is predicted to be $2.0 \times 10^{-4}$.
- GAMS-4$\pi$ reported the upper limit of the BF < $8.0 \times 10^{-4}$ at the 90% C.L. [Phys. Atom. Nucl. 78, 1043 (2015)]

Search for $\eta' \rightarrow \gamma \gamma \eta$ in the $J/\psi$ radiative decay

**Significance:** 2.6 $\sigma$

**BF:** $(8.25 \pm 3.41 \pm 0.72) \times 10^{-5}$

**Upper limit of BF:**

$<1.33 \times 10^{-4}$ at the 90% C.L.

The obtained result is in tension with theoretical prediction.
Measurement of the BFs of $\eta'$ decays

- There are only the relative measurements of BFs of $\eta'$ decays from experiments.
- Difficult to tag the inclusive decays in $J/\psi \to \gamma \eta'$ because of the poor energy resolution of radiative photon.

- Developed a method to reconstruct radiative photon using photon conversions to $e^+ e^-$ pairs.
- Resolution of the radiative photon could be improved by a factor of 3.

BF for each $\eta'$ exclusive decay is obtained with

$$B(\eta' \to X) = \frac{N_{\text{obs}}^{\eta' \to X}}{\varepsilon_{\eta' \to X}} \cdot \frac{\varepsilon}{N_{\text{obs}}^{J/\psi \to \gamma \eta'}} \cdot f,$$

$\gamma$ directly detected by EMC.
Measurement of the BFs of $\eta'$ decays

First direct measure of absolute BFs for five $\eta'$ modes.
\[ a_0^0(980) - f_0(980) \text{ Mixing} \]

\[ a_0^0(980) - f_0(980) \] still controversial about their nature.

\[ \text{In 1970s, the mixing mechanism was firstly proposed. [PLB 88, 367 (1979)]} \]

\[ \text{Theorist proposed to directly measure } a_0^0(980) - f_0(980) \text{ mixing via:} \]

\[ J/\psi \to \phi a_0^0(980) \to \phi \eta \pi^0 \]

\[ \chi_{c1} \to \pi^0 f_0(980) \to \pi^0 \pi^+ \pi^- \]

[Wu, Zhao, Zou, PRD 75, 114012 (2007), PRD 78, 074017 (2008)]

\[ \text{Measured at BESIII based on 225M } J/\psi \text{ and 108M } \psi(2S), \text{ significance } < 5\sigma. \] [PRD 83, 032003 (2011)]

\[ f_0(980) \to a_0^0(980) \text{ Mixing} \]

\[ a_0^0(980) \to f_0(980) \text{ Mixing} \]
$f_0(980) \rightarrow a^0_0(980)$ Mixing

- Constructed by $\eta \rightarrow \gamma \gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$
- Interference between EM and mixing signal
- Two solutions are found, significance of $f_0(980) \rightarrow a^0_0(980)$ is $7.4\sigma$
$a_0^0(980) \rightarrow f_0(980)$ Mixing

- Very narrow peak of $f_0(980)$
- EM contribution too weak, can be negligible
- Interference is negligible
- Significance of $a_0^0(980) \rightarrow f_0(980)$ is $5.5\sigma$

The mixing intensities:

\[
\varepsilon_{fa} = \frac{\mathcal{B}[J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0^0(980) \rightarrow \phi \eta \pi^0]}{\mathcal{B}[J/\psi \rightarrow \phi f_0(980) \rightarrow \phi \pi \pi]},
\]

\[
\varepsilon_{af} = \frac{\mathcal{B}[\chi_{c1} \rightarrow \pi^0 a_0^0(980) \rightarrow \pi^0 f_0(980) \rightarrow \pi^0 \pi^+ \pi^-]}{\mathcal{B}[\chi_{c1} \rightarrow \pi^0 a_0^0(980) \rightarrow \pi^0 \pi^0 \eta]}.
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$f_0(980) \rightarrow a_0^0(980)$</th>
<th>$a_0^0(980) \rightarrow f_0(980)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}$ (mixing)</td>
<td>$3.18 \pm 0.51 \pm 0.38 \pm 0.28$</td>
<td>$1.31 \pm 0.41 \pm 0.39 \pm 0.43$</td>
</tr>
<tr>
<td>$\mathcal{B}$ (EM)</td>
<td>$3.25 \pm 1.08 \pm 1.08 \pm 1.12$</td>
<td>$2.62 \pm 1.02 \pm 1.13 \pm 0.48$</td>
</tr>
<tr>
<td>$\mathcal{B}$ (total)</td>
<td>$4.93 \pm 1.01 \pm 0.96 \pm 1.09$</td>
<td>$4.37 \pm 0.97 \pm 0.94 \pm 0.06$</td>
</tr>
<tr>
<td>$\varepsilon$ (%)</td>
<td>$0.99 \pm 0.16 \pm 0.30 \pm 0.09$</td>
<td>$0.41 \pm 0.13 \pm 0.17 \pm 0.13$</td>
</tr>
</tbody>
</table>
Summary (I)

- $\eta'$ meson decays, $\omega$ meson decay and $a_0^0(980) - f_0(980)$ mixing are reviewed

- Dalitz plot analysis of $\eta' \rightarrow \eta\pi^+\pi^-$, $\eta\pi^0\pi^0$: the linear representation is less compatible with the data.

- Amplitude analysis of $\eta' \rightarrow \pi^{+(0)}\pi^{-(0)}\pi^0$: Significant P-wave $\eta' \rightarrow \rho^\pm\pi^\mp$ is observed for the first time.

- Search for $\eta' \rightarrow \pi^0\pi^0\pi^0\pi^0$: the most stringent upper limit.

- Precision study of the decay dynamics of $\gamma\pi^+\pi^-$: need extra contribution besides $\rho(770) - \omega$.

- Search for $\eta' \rightarrow \gamma\gamma\eta$: the result is in tension with theoretical prediction.

- First direct measurement of absolute BF$s$ for $\eta'$ five modes.
Summary (II)

◆ First observation of $a_0^0(980) – f_0(980)$ mixing: the mixing signal with 7.4$\sigma$ and 5.5$\sigma$ for the first time, the constraint regions on $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$ are roughly obtained by the significance test.

➢ $J/\psi$ decay is an unique place to study light meson decays.

➢ BESIII: 1.3 billion + 8.7 billion (10 billion in total) $J/\psi$ events
  • The large data sample allows to study light mesons with the unprecedented statistics.
  • More interesting results are expected.
Thanks for your attention
Back up
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>$\eta' \rightarrow \pi^+\pi^-\eta$</td>
<td>Phys. Rev. D 83, 012003 (2011)</td>
</tr>
<tr>
<td>$\eta/\eta' \rightarrow \pi^+\pi^-, \pi^0\pi^0$</td>
<td>Phys. Rev. D 84, 032006 (2011)</td>
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<tr>
<td>$\eta' \rightarrow \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$</td>
<td>Phys. Rev. Lett. 108, 182001 (2012)</td>
</tr>
<tr>
<td>$\eta/\eta' \rightarrow \text{invisible}$</td>
<td>Phys. Rev. D 87, 012009 (2013)</td>
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<tr>
<td>$\eta/\eta' \rightarrow \pi^+\pi^-$</td>
<td>Phys. Rev. D 87, 032006 (2013)</td>
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<tr>
<td>$\eta' \rightarrow 3(\pi^+\pi^-)$</td>
<td>Phys. Rev. D 88, 091502 (2013)</td>
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<tr>
<td>$\eta' \rightarrow 2(\pi^+\pi^-), \pi^+\pi^-\pi^0\pi^0$</td>
<td>Phys. Rev. Lett. 112, 251801 (2014)</td>
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<tr>
<td>$\eta' \rightarrow \gamma e^+e^-$</td>
<td>Phys. Rev. D 92, 012001 (2015)</td>
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<tr>
<td>$\eta \rightarrow \pi^+\pi^-\pi^0, \eta/\eta' \rightarrow \pi^0\pi^0\pi^0$</td>
<td>Phys. Rev. D 92, 012014 (2015)</td>
</tr>
<tr>
<td>$\eta' \rightarrow \omega e^+e^-$</td>
<td>Phys. Rev. D 92, 051101 (2015)</td>
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<tr>
<td>$\eta' \rightarrow K\pi$</td>
<td>Phys. Rev. D 93, 072008 (2016)</td>
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<tr>
<td>$\eta' \rightarrow \rho\pi$</td>
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<td>$\eta' \rightarrow \gamma\gamma\pi^0$</td>
<td>Phys. Rev. D 96, 012005 (2017)</td>
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<td>Phys.Rev.D 100, 052015 (2019)</td>
</tr>
<tr>
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<td>Phys.Rev.D 101, 032001 (2020)</td>
</tr>
</tbody>
</table>
BESIII Collaboration

Europe (16)
- Germany: Univ. of Bochum, Univ. of Giessen, GSI, Univ. of Johannes Gutenberg, Helmholtz Ins. In Mainz
- Russia: JINR Dubna; BINP Novosibirsk
- Italy: Univ. of Torino, Univ. of Ferrara, Frascati Lab
- Netherlands: KVI/Univ. of Groningen
- Sweden: Uppsala Univ.
- Turkey: Turkey Accelerator Center
- UK: Oxford Univ., Univ. of Manchester

Mongolia (1)
- Ins. of Phy. & Tech.

Korea (1)
- Seoul Nat. Univ.

Japan (1)
- Tokyo Univ.

China (37)
- IHEP, CCAST, GUCAS, Shandong Univ., Univ. of Sci. and Tech. of China, Zhejiang Univ., Huangshan Coll.
- Huazhong Normal Univ., Wuhan Univ.
- Zhengzhou Univ., Henan Normal Univ.
- Peking Univ., Tsinghua Univ.
- Zhongshan Univ., Nankai Univ.
- Shanxi Univ., Sichuan Univ., Univ. of South China
- Hunan Univ., Liaooning Univ.
- Nanjing Univ., Nanjing Normal Univ.
- Guangxi Normal Univ., Guangxi Univ.
- Suzhou Univ., Hangzhou Normal Univ.
- Lanzhou Univ., Henan Sci. and Tech. Univ.
- Beijing Univ., Beijing Petro Chemical Univ.
- Jinan Univ., Fudan Univ.
- Hunan Normal Univ.

Pakistan (2)
- Univ. of Punjab
- COMSAT CIIT

India (1)
- Indian Institute of Technology

USA (4)
- Univ. of Hawaii
- Carnegie Mellon Univ.
- Univ. of Minnesota
- Univ. of Indiana

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