New Physics Searches at BESIII

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(On behalf of the BESIII Collaboration)

39th International Conference on High Energy Physics
July 4 - 11, 2018, COEX, Seoul, Korea
Outline

1. Search for New Physics at BESIII

2. BSM Phenomena
   - Dark photon
   - Invisible quarkonium decay
   - Light Higgs boson

3. Forbidden Processes

4. Summary and Prospects
1. Search for New Physics at BESIII

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4. Summary and Prospects
BEPCII and BESIII at IHEP, Beijing

Beijing Electron Positron Collider II

- Beam energy: 1:0.2, 2:3 GeV
- Peak luminosity: 1:0.101033 cm^-2 s^-1

BESIII Detector
- Main Drift Chamber: 115 μm single-hit resolution, 0.5%
- CsI EM Calorimeter: 2.5% energy resolution at 1 GeV

1-Tesla BEijing Spectrum III

NIM A 614, 345 (2010)

Good detector performance

MDC:
\[ p_x = 0.5\% \] at 1 GeV/\(c\)
\[ \Delta E/dx = 6\% \]
\[ \Delta y = 120 m \]

EMC:
\[ \Delta E/E = 0.6\% \] at 1 GeV

TOF:
\[ T_{Barrel} = 80 ps \]
\[ T_{Endcap} = 110 ps \]
\[ T_{ETOF} = 60 ps \] since 2015

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New Physics Searches at BESIII
Beam energy: $1.0 - 2.3 \text{ GeV}$
Peak luminosity: $1.00 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$
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Peak luminosity: $1.00 \times 10^{33}$ cm$^{-2}$s$^{-1}$
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Beijing Electron Positron Collier II

Beam energy: 1.0 – 2.3 GeV
Peak luminosity: $1.00 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$

BESIII Detector

- Main Drift Chamber: 115 μm single-hit resolution, 0.5% p resolution at 1 GeV/c, <5% dE/dx resolution
- CsI EM Calorimeter: 2.5% energy resolution at 1 GeV

Good detector performance

- MDC: $\frac{\sigma_p}{p} = 0.5\%$ @ 1 GeV/c
  $\frac{\text{d}E}{\text{d}x} = 6\%$
  $\sigma_{xy} = 120 \mu m$
- EMC: $\frac{\Delta E}{E} = 2.5\%$ @ 1 GeV
  $\sigma = 0.6 \text{ cm}$
- TOF: $\sigma_T = 80 \text{ ps (Barrel)}$
  $110 \text{ ps (Endcap)}$
  60 ps for ETOF since 2015

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New Physics Searches at BESIII
World largest data samples on $J/\psi$, $\psi(2S)$, $\psi(3770)$, unique $XYZ$

More $J/\psi$ data were taken in 2018, available for physics study soon
Highlights of new physics searches at BESIII

- **BSM phenomena** – BSM resonances, invisible quarkonium decays
  - $e^+e^- \rightarrow \gamma_{ISR}\gamma', \gamma' \rightarrow e^+e^-$  
    - Dark photon
  - $J/\psi \rightarrow \eta/\eta'\gamma', \gamma' \rightarrow e^+e^-$  
    - Dark photon
  - $J/\psi \rightarrow \eta\omega/\phi, \omega/\phi \rightarrow$ invisible
    - Invisible quarkonium decay
  - $J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$
    - Light Higgs boson

- **Forbidden processes** – Baryon/lepton number, lepton flavor violations
  - $J/\psi \rightarrow \Lambda_c^+e^- + c.c.$
    - BNV+LNV

- **Rare processes** – FCNC, weak decays of charmonium $c \rightarrow d, c \rightarrow s$
  - $\psi(2S) \rightarrow \Lambda_c^+\bar{p}e^+e^-$
    - FCNC
  - $\psi(nS) \rightarrow D^0e^+e^-$
    - FCNC
  - $D \rightarrow h(h')e^+e^-$
    - FCNC

**See Dayong Wang, Peking University, July 7**

- **Precision measurements** – e.g. lepton universality test
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Numerous astrophysical observations strongly suggest the existence of DM, which provides a hint of dark sector (hidden sector).

There could exist many dark sectors that communicate with the SM sector via portals.


<table>
<thead>
<tr>
<th>Portal</th>
<th>Particles</th>
<th>Operator(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Vector”</td>
<td>Dark photons</td>
<td>$-\frac{e}{2\cos\theta_W} B_{\mu\nu} F'_{\mu\nu}$</td>
</tr>
<tr>
<td>“Axion”</td>
<td>Pseudoscalars</td>
<td>$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu} \tilde{G}^{i\mu\nu}$, $\frac{\partial \mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>“Higgs”</td>
<td>Dark scalars</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>“Neutrino”</td>
<td>Sterile neutrinos</td>
<td>$y_N LHN$</td>
</tr>
</tbody>
</table>
Dark photon

- Postulate an extra $U(1)$ gauge symmetry, and the corresponding gauge boson is called dark photon or $U'$ boson, $\gamma', A', Z'_d$
- It can decay into light DM particles $\chi \chi$ (invisible decays)
- or decay into the SM $q\bar{q}, \ell^+\ell^-, \nu\bar{\nu}$ (visible/invisible decays)
  - direct and very weak interaction
  - kinetic mixing with the SM photon, or mass mixing with the $Z$

$$\mathcal{L}_{\text{int}} = - \left( \varepsilon e J_{\mu}^{EM} + \varepsilon Z \frac{g}{2 \cos \theta_W} J_{\mu}^{NC} \right) Z_{d\mu}$$

- mixing strength $\varepsilon = \sqrt{\alpha'/\alpha} \sim 10^{-2} - 10^{-5}$ (could be smaller)
- mass ranges: MeV/$c^2$ – GeV/$c^2$ ($\varepsilon_Z$ suppressed by $(m_{A'}/m_Z)^2$)

A resonant structure in the invariant mass spectrum
Dark photon search (1)

\[ e^+e^- \rightarrow \gamma_{\text{ISR}}\gamma', \gamma' \rightarrow \ell^+\ell^- \]

- Initial state radiation process: \[ e^+e^- \rightarrow \gamma_{\text{ISR}}\gamma', \gamma' \rightarrow \ell^+\ell^-, \ell = e, \mu \]
- Search for a narrow structure in \( m_{\ell^+\ell^-} \) on top of the continuum QED background (\( e^+e^- \rightarrow \gamma_{\text{ISR}}\ell^+\ell^- \))
  - Mass range b/w 1.5 & 3.4 GeV/c^2 is studied
  - \( J/\psi \) region excluded

\[ \begin{align*}
  \text{Events / 0.010 GeV/c}^2 & \quad \text{data} \\
  \text{Events / 0.010 GeV/c}^2 & \quad \text{MC} \end{align*} \]

\[ \begin{align*}
  m_{\mu^+\mu^-} & \quad \text{[GeV/c}^2] \\
  m_{e^+e^-} & \quad \text{[GeV/c}^2] \\
  \text{data / MC} & \quad \text{data / MC} \\
  \end{align*} \]
Fit \( m_{\mu^+\mu^-} \) and \( m_{e^+e^-} \) of data (4th order polynomials)

Calculate mass differences b/w data & fit for \( \mu \) and \( e \) respectively

No peaking structure is observed in the combined "(data − fit)"

Upper limits on \( \epsilon \) @ 90% C.L.: \( 10^{-3} − 10^{-4} \)

(comparable to BaBar)

Figure 4.17: Comparison of this (blue shaded area) and the experiments mentioned in Fig. 1.2.
Dark photon search (2)

\[ J/\psi \rightarrow \eta'/\eta\gamma', \gamma' \rightarrow e^+e^- \]

- First search for \( \gamma' \) in E.M. Dalitz decays:

  \[ J/\psi \rightarrow \eta'\gamma', \gamma' \rightarrow e^+e^- \quad \eta' \rightarrow \gamma/\eta\pi^+\pi^- \]

  \[ J/\psi \rightarrow \eta\gamma', \gamma' \rightarrow e^+e^- \quad \eta \rightarrow \gamma\gamma \text{ or } \pi^+\pi^-\pi^0 \]

- Look for a narrow peaking structure in the \( m_{e^+e^-} \) on top of background

![Graphs and diagrams showing data and fit results for \( J/\psi \rightarrow \eta'/\eta\gamma' \)]
Dark photon search (2)

\[ J/\psi \to \eta'/\eta\gamma', \gamma' \to e^+e^- \]

- No obvious peaking structures are observed
- Fit \( m_{e^+e^-} \) of data to obtain signal yields (\( \omega, \phi \) regions excluded)
- Combined results of 90\% C.L. limits on BF and \( \varepsilon \)

\[
\begin{align*}
B(\psi \to P\gamma')B(\gamma' \to e^+e^-) & < 1.8 \times 10^{-8} - 2.0 \times 10^{-7} \\
P = \eta' & < 1.9 \times 10^{-8} - 9.1 \times 10^{-7} \\
P = \eta & < 1.9 \times 10^{-8} - 9.1 \times 10^{-7} \\
B(\psi \to P\gamma') & < 6.0 \times 10^{-8} - 7.8 \times 10^{-7} \\
\varepsilon & = 3.4 \times 10^{-3} - 2.6 \times 10^{-2} \\
& = 10^{-3} - 10^{-2}
\end{align*}
\]
Constraints on $\varepsilon$ (also shown are those from other experiments)
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Invisible decay

- Quarkonium states \((q\bar{q})\) can annihilate into \(\nu\bar{\nu}\) via virtual \(Z^0\) boson

\[
B(\omega \to \nu\bar{\nu}) = 8.4 \times 10^{-14}, \quad B(\phi \to \nu\bar{\nu}) = 5.8 \times 10^{-12}
\]

- If a singlet scalar, pseudoscalar or vector (portal) is present, and mediates the SM-DM interaction, it can mediate invisible decay of quarkonium states

- \(B\) of invisible decay might be enhanced in the presence of light DM particles

<table>
<thead>
<tr>
<th>mode</th>
<th>s-wave</th>
<th>p-wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{BR}(\Upsilon(1S') \to \chi\chi))</td>
<td>(4.2 \times 10^{-4})</td>
<td>(1.8 \times 10^{-3})</td>
</tr>
<tr>
<td>(\text{BR}(\Upsilon(1S) \to \nu\bar{\nu}))</td>
<td>(9.9 \times 10^{-6})</td>
<td></td>
</tr>
<tr>
<td>(\text{BR}(J/\Psi \to \chi\chi))</td>
<td>(2.5 \times 10^{-5})</td>
<td>(1.0 \times 10^{-4})</td>
</tr>
<tr>
<td>(\text{BR}(J/\Psi \to \nu\bar{\nu}))</td>
<td>(2.7 \times 10^{-8})</td>
<td></td>
</tr>
<tr>
<td>(\text{BR}(\eta \to \chi\chi))</td>
<td>(3.4 \times 10^{-5})</td>
<td>(1.4 \times 10^{-4})</td>
</tr>
<tr>
<td>(\text{BR}(\eta' \to \chi\chi))</td>
<td>(3.7 \times 10^{-7})</td>
<td>(1.5 \times 10^{-6})</td>
</tr>
<tr>
<td>(\text{BR}(\eta_c \to \chi\chi))</td>
<td>(1.3 \times 10^{-7})</td>
<td>(5.3 \times 10^{-7})</td>
</tr>
<tr>
<td>(\text{BR}(\chi_{c0}(1P) \to \chi\chi))</td>
<td>(2.7 \times 10^{-8})</td>
<td>(1.2 \times 10^{-7})</td>
</tr>
<tr>
<td>(\text{BR}(\phi \to \chi\chi))</td>
<td>(1.9 \times 10^{-8})</td>
<td>(7.8 \times 10^{-8})</td>
</tr>
<tr>
<td>(\text{BR}(\omega \to \chi\chi))</td>
<td>(7.2 \times 10^{-8})</td>
<td>(3.0 \times 10^{-8})</td>
</tr>
</tbody>
</table>

Invisible decay search

\[ J/\psi \to \eta \omega/\phi, \omega/\phi \to \text{invisible} \]

- First search for \[ J/\psi \to \eta \omega/\phi, \omega/\phi \to \text{invisible} \], \[ \eta \to \pi^+ \pi^- \pi^0 \]
- Define recoiling mass against \( \eta \): 
  \[ M^{V}_{\text{recoil}} \equiv \sqrt{(E_{CM} - E_{3\pi})^2 - \vec{p}_{3\pi}^2} \]

\[ \eta \to \pi^+ \pi^- \pi^0 \text{ or } \gamma \gamma \]

\[ \phi \to \nu \bar{\nu} \]

\[ \text{recoil direction} \]

\[ \text{tag direction} \]

\[ \text{Entries/(0.01 GeV/c}^2\text{)} \]

\[ M^{V}_{\text{recoil}} (\text{GeV/c}^2) \]

Accepted by PRD, arXiv:1805.05613

1310.6 \times 10^6 \ J/\psi
Invisible decay search
\( J/\psi \rightarrow \eta \omega / \phi, \omega / \phi \rightarrow \text{invisible} \)

- Fit \( M_{\text{recoil}}^V \) to obtain signal yield
- No obvious signals observed, set 90% C.L. UL’s

\[
\frac{\mathcal{B}(\omega \rightarrow \text{invisible})}{\mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0)} < 8.1 \times 10^{-5}
\]
\[
\mathcal{B}(\omega \rightarrow \text{invisible}) < 7.3 \times 10^{-5}
\]
\[
\frac{\mathcal{B}(\phi \rightarrow \text{invisible})}{\mathcal{B}(\phi \rightarrow K^+K^-)} < 3.4 \times 10^{-4}
\]
\[
\mathcal{B}(\phi \rightarrow \text{invisible}) < 1.7 \times 10^{-4}
\]

\[
N_{\text{sig}}^{\omega} = 1.4 \pm 3.6
\]
\[
N_{\text{sig}}^{\phi} = -0.6 \pm 4.5
\]
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The NMSSM has a rich Higgs sector: 2 charged, 3 neutral CP-even, 2 neutral CP-odd. The lightest CP-odd Higgs is denoted as $A^0$ or $a_1$.

If $m_{A^0} < 2m_c$, it is possible for $J/\psi$ (and $\Upsilon$) to decay into $\gamma A^0$.

$$B(\Upsilon \rightarrow \gamma A^0) \propto \cos \theta_A \tan \beta$$

$$B(J/\psi \rightarrow \gamma A^0) \propto \cos \theta_A \cot \beta$$

$$A^0 = \cos \theta_A A_{MSSM} + \sin \theta_A A_S$$

$\cos \theta_A$: parameterizes how singlet-like the $A^0$ is.

$\tan \beta = \frac{v_u}{v_d}$: ratio of the VEV's of the up and down types of the Higgs doublets.

$B(J/\psi \rightarrow \gamma A^0)$ in NMSSM: $\sim 10^{-7} - 10^{-9}$.

$A^0$ can decay into DM (neutralinos) or SM particles, such as $\mu^+ \mu^-$. 

PRD 76, 051105 (2007)
Ligh Higgs boson search

\[ J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^- \]

- \[ J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^- \]
- Define reduced dimuon mass
  \[ m_{\text{red}} = \sqrt{m_{\mu^+ \mu^-}^2 - 4m_{\mu}^2} \]
- Fit \( m_{\text{red}} \) to determine signal yields \( N_{\text{sig}} \) as a function of \( m_{A^0} \) in the range of
  \[ m_{A^0} \in [0.212, 3.0] \text{ GeV} / c^2 \]
Lgh Higgs boson search

\[ J/\psi \rightarrow \gamma A^0, \quad A^0 \rightarrow \mu^+\mu^- \]

- No evidence of \( A^0 \) is found at any mass points
- UL’s on the production BF @ 90% C.L.

\[ \mathcal{B}(J/\psi \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \mu^+\mu^-) < 2.8 \times 10^{-8} - 4.95 \times 10^{-6} \]

A factor of five times better than BESIII 2012 results

Combined with the BaBar result, \( A^0 \) is constrained to be mostly singlet
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BNV and LNV processes

- Many SM extensions and Grand Unified Theories such as superstring models and SUSY predict proton decays. In this case, baryon number is violated while the difference $\Delta (B - L)$ is conserved.

- In the assumption of the heavy bosons $X(4/3e)$ and $Y(1/3e)$, there exists BNV processes via $\bar{c}Yd$ or $\bar{c}Xu$ couplings, e.g. $J/\psi \rightarrow \Lambda^+_c e^-$.

- Any detection of BNV and/or LNV decay indicates the existence of new physics.
BNV+LNV process search

$J/\psi \rightarrow \Lambda_c^+ e^- + \text{c.c.}$

- First search for
  $J/\psi \rightarrow \Lambda_c^+ e^- + \text{c.c.}$, $\Lambda_c^+ \rightarrow pK^-\pi^+$
- Examine $M_{pK^-\pi^+}$ distribution
- No events are observed in the signal window
- Upper limit @ 90% C.L. on the BF

$$\mathcal{B}(J/\psi \rightarrow \Lambda_c^+ e^-) < 6.9 \times 10^{-8}$$

More than two orders of magnitude more strict than CLEO’s measurement in the analogous process $D^0 \rightarrow \bar{p}e^+ + \text{c.c.}$

P. Rubin et al., PRD 79, 097101 (2009)
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4. Summary and Prospects
Clean and large $e^+e^-$ data samples taken near threshold at BESIII are well suited to indirect searches for new physics.

Many recent results on exotic phenomena and forbidden decays:

- Dark photon with ISR:
  \[ e^+e^- \rightarrow \gamma_{\text{ISR}}\gamma', \gamma' \rightarrow e^+e^- \]
  \[ J/\psi \rightarrow \eta/\eta'\gamma', \gamma' \rightarrow e^+e^- \]

- Invisible decay of light quarkonium:
  \[ J/\psi \rightarrow \eta/\omega/\phi, \omega/\phi \rightarrow \text{invisible} \]

- Light CP-odd Higgs boson:
  \[ J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^- \]

- Baryon and lepton number violation process:
  \[ J/\psi \rightarrow \Lambda_c^+e^- + \text{c.c.} \]

Also at ICHEP2018

- Search for FCNC’s at BESIII, Dayong Wang, PKU, July 7

More to come, especially with newly acquired $J/\psi$ data sample.