cLFV and New Physics Searches at BESIII

Dayong Wang
dayong.wang@pku.edu.cn
(for BESIII Collaboration)

CLFV2016@UVA, Jun 22 2016
Outline

- About BESIII Exp
- $J/\psi \rightarrow e\mu$ Analysis
- Ongoing and Potential cLFV Studies
- Other New Physics searches
- Summary
About BESIII Exp

- Introduction
- BEPCII and BESIII
- Data sets and Physics Scope
BEPCII is the only collider currently running at τ-charm energy
First collision in 2008, physics run started in 2009
BEPCII reached peak lumi of $1 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}@1.89\text{GeV}$ in April 2016
BESIII collaboration includes 31 Chinese institutes, 13 European ones, 6 US ones and 6 from other Asian countries, ~300 collaborators
BEPCII: a τ-c Factory

- Rich of resonances, charmonia and charmed mesons.
- Threshold characteristics (pairs of τ, D, D_s, charmed baryons...).
- Transition between perturbative and non-perturbative QCD.
- New hadrons: glueballs, hybrids, multi-quark states
- New Physics: high lumi, large datasets, hermetic detector with good performance
Clean environment and high luminosity at BESIII are helpful for indirect probe of new physics.
BESIII data samples

$\sim 0.5 \text{ B} \quad \psi(3686) \text{ events} \quad \sim 24 \times \text{CLEO-c}$

$\sim 1.3 \text{ B} \quad J/\psi \text{ events} \quad \sim 21 \times \text{BESII}$

$\sim 2.9/\text{fb} \quad \psi(3770) \quad \sim 3.5 \times \text{CLEO-c}$

$\sim 5/\text{fb} \quad \text{XYZ states above 4 GeV} \quad \text{Unique}$

- 20 points for R & QCD Scan: 500/\text{pb} finished in May 1st, 2015
- $\Upsilon(2175)$ resonance: 100 /\text{pb} : finished in June 15, 2015
  2016: just finish 3/\text{fb} $D_s$ data at 4170 MeV $\sim 5 \times \text{CLEO-c}$

$\sim \text{other data sets: tau, } \Lambda_c, \text{ resonance scan and continuum, etc.}$
J/ψ → eμ Analysis

- Event selection
- Background estimation
- Systematics
- Results
Motivation for $J/\psi \rightarrow e\mu$

- With finite neutrino masses included, Lepton Flavor Violation (LFV) is allowed, but the smallness of the mass leads to the predicted branching fraction well beyond current experimental sensitivity.

- However, there are various theoretical models such as SUSY may enhance LFV effects up to a detectable level.

- Any detection of a LFV decay indicates the existence of new physics.

- The LFV decay have been searched in lepton decay, pseudoscalar meson decay and vector meson decay. It is equally important to search it in heavy quarkonium decays.
Signal box definition based on MC

\[ |\Sigma \vec{p}| / \sqrt{s} \pm 2\sigma \quad \text{and} \quad E_{vis} / \sqrt{s} \pm 2\sigma, \]

\[ 0.93 \leq E_{vis} / \sqrt{s} \leq 1.10 \quad \text{and} \quad |\Sigma \vec{p}| / \sqrt{s} \leq 0.1 \]

Signal efficiency:

\[ (18.99 \pm 0.12)\% \]
The optimization method

\[
FOM = \sum_{N_{obs}=0}^{\infty} P(N_{obs} | N_{exp}) \cdot UL(N_{obs} | N_{exp})
\]

The optimized cuts after maximizing the FOM

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Optimized value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>\Delta \theta</td>
</tr>
<tr>
<td>(</td>
<td>\Delta \phi</td>
</tr>
<tr>
<td>(egam &lt; )</td>
<td>15 MeV</td>
</tr>
<tr>
<td>(egam1 &lt; )</td>
<td>50 MeV</td>
</tr>
<tr>
<td>(egam2 &lt; )</td>
<td>15 MeV</td>
</tr>
<tr>
<td>for e: (E/P &gt; )</td>
<td>0.94</td>
</tr>
<tr>
<td>for e: (</td>
<td>\chi_{dE/dx}^e</td>
</tr>
<tr>
<td>for (\mu: \chi_{dE/dx}^e &lt; )</td>
<td>-1.8</td>
</tr>
<tr>
<td>for (\mu: ) Depth &gt;</td>
<td>40 cm</td>
</tr>
</tbody>
</table>

2016/6/22        cFLV2016        Dayong Wang
Variable Distributions

- $E/p$ distribution for different particles.
- $\chi^2_{dE/dx}$ distribution for different particles.
- Depth distribution for different particles.
- Energy distribution for different particles.
# Background study

<table>
<thead>
<tr>
<th>Background channel</th>
<th>Normalized number</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow e^+e^-$</td>
<td>$2.7 \times 10^7$</td>
<td>PHOTOS and VLL[13]</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \mu^+\mu^-$</td>
<td>$2.7 \times 10^7$</td>
<td>PHOTOS and VLL[13]</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \pi^+\pi^-$</td>
<td>$1.0 \times 10^5$</td>
<td>PHSP[13]</td>
</tr>
<tr>
<td>$J/\psi \rightarrow K^+K^-$</td>
<td>$7.0 \times 10^4$</td>
<td>PHSP[13]</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow e^+e^-(\gamma)$</td>
<td>$2.7 \times 10^7$</td>
<td>Babayaga[15]</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \mu^+\mu^- (\gamma)$</td>
<td>$1.0 \times 10^5$</td>
<td>Babayaga[15]</td>
</tr>
</tbody>
</table>

From Exclusive MC

From Inclusive MC

$$N_{\text{exp}} = (4.75 \pm 1.09).$$
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Sources</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^\pm$ tracking</td>
<td>1.00</td>
</tr>
<tr>
<td>$\mu^\pm$ tracking</td>
<td>1.00</td>
</tr>
<tr>
<td>$e^\pm$ ID</td>
<td>0.62</td>
</tr>
<tr>
<td>$\mu^\pm$ ID</td>
<td>0.04</td>
</tr>
<tr>
<td>Acollinearity, acoplanarity</td>
<td>5.36</td>
</tr>
<tr>
<td>Photon veto</td>
<td>1.19</td>
</tr>
<tr>
<td>$N_{J/\psi}$</td>
<td>1.24</td>
</tr>
<tr>
<td>Total</td>
<td>5.84</td>
</tr>
</tbody>
</table>

Relative, most from control samples, in percentage
Among 225M J/ψ, 4 events in the signal box

\[ |\Sigma \vec{p}|/\sqrt{s} \pm 2\sigma \text{ and } E_{vis}/\sqrt{s} \pm 2\sigma \]

\[ 0.93 \leq E_{vis}/\sqrt{s} \leq 1.10 \text{ and } |\Sigma \vec{p}|/\sqrt{s} \leq 0.1 \]

\[ \mathcal{B}(J/\psi \rightarrow e\mu) < 1.6 \times 10^{-7} \text{ (90\% C.L.)} \]
Ongoing and Potential cLFV Studies

- $\psi \rightarrow e \tau/\mu\tau$ (going on)
- $\psi \rightarrow \gamma e\tau/\gamma\mu\tau$ (started)
- FLV in mesons: D, $\eta, \eta'$ (to be further investigated)
Could non-trivial Yukawa Coupling be a new interaction?

=> Flavor Changing rates be enhanced

\[ BR(h \rightarrow \tau^{\pm}\mu^{\mp}) < 1.57\% \] (95% C.L.)

\[ |y_{\tau\mu}| \leq 3.6 \times 10^{-3} \]

\[ BR(h \rightarrow \tau^{\pm}\mu^{\mp}) = 0.89 \pm 0.40 \text{ } \% (2.46\sigma) \]

\[ |y_{\tau\mu}| \simeq 2.7 \times 10^{-3} \]

\[ \sim \sqrt{y_{\tau} y_{\mu}} = 2.48 \times 10^{-3} \]
Possible Enhancements

\( \psi \rightarrow \tau \mu \)

Inspired by Cheng-Sher Ansatz

\( \psi \rightarrow \gamma \tau \mu \)

Dayong Wang
From preliminary MC studies, the efficiencies could reach ~30-35%, and the BR sensitivity could be in the level of 1E-8 to 1E-7.

Better up limit could be achieved if QED description & PID on muons improved.

Detailed analysis with data without photons is going on (J/ψ-> e τ/μτ )

Further study on the channel with photons is started (J/ψ-> γeτ/γμτ )
Symmetry breaking process: More possibilities

In Both Charmonium and Charm meson decays

- Lepton Flavor Violation (LFV) processes
- Lepton Number Violation (LNV) processes
- Baryon Number Violation (BNV) processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^\pm e^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$\pi^0 e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$\eta e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$\pi^+ \pi^- e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$\rho e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$\omega e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$K^+ K^- e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$\phi e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$K^0 e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$K^- \pi^+ e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$K^*0 e^\pm \mu^\mp$</td>
<td>LFV</td>
</tr>
<tr>
<td>$\pi^\mp \pi^\pm e^\pm$</td>
<td>LNV</td>
</tr>
<tr>
<td>$\pi^\mp \pi^\pm \mu^\pm$</td>
<td>LNV</td>
</tr>
<tr>
<td>$K^+ \pi^+ e^\pm e^\pm$</td>
<td>LNV</td>
</tr>
<tr>
<td>$K^+ \pi^+ \mu^\pm \mu^\pm$</td>
<td>LNV</td>
</tr>
<tr>
<td>$K^+ K^- e^\pm e^\pm$</td>
<td>LNV</td>
</tr>
<tr>
<td>$K^+ K^- \mu^\pm \mu^\pm$</td>
<td>LNV</td>
</tr>
<tr>
<td>$\pi^\mp \pi^\pm e^\pm \mu^\pm$</td>
<td>LNV</td>
</tr>
<tr>
<td>$K^+ \pi^+ e^\pm \mu^\pm$</td>
<td>LNV</td>
</tr>
<tr>
<td>$K^+ K^- e^\pm \mu^\mp$</td>
<td>LNV</td>
</tr>
</tbody>
</table>

BESIII is more competitive in channels with low energy electron/photons, neutrons, pi0’s

cLFV processes from D, $\eta$ and $\eta'$ decays are also possibly to search at BESIII, esp for final datasets

Dayong Wang
We could use similar technique to perform the D(Ds) LFV search, and estimate the sensitivity.
D⁰→γγ Results

Major background $D^0 \rightarrow \pi^0 \pi^0$ is determined in data with similar double-tag method. 

2.9 fb⁻¹ $\psi(3770)$

$B(D^0 \rightarrow \pi^0 \pi^0) = (8.24 \pm 0.21 \pm 0.30) \times 10^{-4}$

2-D fit to $\Delta E$ in both tag side and $\gamma \gamma$ sides to determine $D^0 \rightarrow \gamma \gamma$ yield.

$B(D^0 \rightarrow \gamma \gamma) < 3.8 \times 10^{-6}$

consistent with BaBar result, will update with a 4X larger sample.

PRD91, 112015 (2015)
η and η’ decays

η and η’ yields with \( J/\psi \) data set

\[
J/\psi \rightarrow \\
\rightarrow \eta'\phi(\rightarrow K^+K^-) \\
\rightarrow \eta'\gamma \\
\rightarrow \eta \phi(\rightarrow K^+K^-) \\
\rightarrow \eta\gamma
\]

In 1.3B Jpsi(09+12)

\[3.0 \times 10^5 \ \eta'\]

\[6.8 \times 10^6 \ \eta'\]

\[5.0 \times 10^5 \ \eta\]

\[1.4 \times 10^6 \ \eta\]

We could use same phi tag to perform the study, the sensitivity could be estimated similarly.
Other New Physics Searches

- Charmonium weak decays
- Charm FCNC and LNV rare decays
- Search for meson invisible decays
- Search for CP-odd Light Higgs
- Search for Dark Photons
Rare Decays to probe NP

- **Rare Charmonia Decays**
  - Semileptonic weak decays
  - Two-body weak hadronic decays
  - C/P violation decays
  - *Invisible* decays
  - LFV, INV, BNV decays

- **Rare Charm decays**
  - LNV: $c\to u\mu^+\mu^+$ forbidden in SM
    - Majorana neutrino: $\sim 10^{-30}$\textasciitilde\textasciitilde 23 level, PRD64 (2001) 114009
    - May be greatly enhanced: $\sim 10^{-5}$\textasciitilde\textasciitilde 6 with EPJC71 (2011) 1715
  - FCNC: $c\to u\mu^+\mu^-$ highly suppressed in SM by GIM mechanism $BF_{th} \sim 10^{-9}$ [PRD64 (2001) 114009]
    - while can be enhanced by physics BSM [PRD 76 (2007) 074010]
  - **Rare FCNC: $D^0\to\gamma\gamma$**

(a) $D^0 \to K^- e^+ e^+ \pi^-$ (CF)
Search for $\eta'/\eta$' invisible decays

- $\eta'/\eta$' decay play special role in low energy scale QCD theory.
- Invisible and radiative decays offer a window for new physics beyond the SM.
- The observation of the invisible final states provide information for light dark matter states $\chi$, spin-0 axions, and light spin-1 U bosons.
- Huge $J/\psi$ sample, large branching fraction of $J/\psi \rightarrow (\gamma/\phi)\eta/\eta'$ and narrow intermediate meson widths provide clean, large $\eta/\eta'$ sample.

**Results**

- $\text{Br}(\eta' \rightarrow \text{invisible})/\text{Br}(\eta' \rightarrow \gamma\gamma) < 2.39 \times 10^{-2}$
- $\text{Br}(\eta \rightarrow \text{invisible})/\text{Br}(\eta \rightarrow \gamma\gamma) < 2.58 \times 10^{-4}$

- $\text{Br}(\eta' \rightarrow \text{invisible}) < 5.21 \times 10^{-4}$ at 90\% C.L.
- $\text{Br}(\eta \rightarrow \text{invisible}) < 1.01 \times 10^{-4}$ at 90\% C.L.

- Improved PDG Values

- **Theory**:
  - $\text{Br}(\eta' \rightarrow \chi\chi) \sim 8.1 \times 10^{-7}$
  - $\text{Br}(\eta \rightarrow \chi\chi) \sim 7.4 \times 10^{-5}$

  B. McElrath, PRD 72, 103508 (2005)
light Higgs search: Motivation

- Coupling of fermions and the CP-odd Higgs

A^0 in the NMSSM:

\[ L_{\text{int}}^{\bar{f}f} = -\cos \theta_A \tan \beta \frac{m_f}{v} A^0 - d (i \gamma_5) d, \]

\[ L_{\text{int}}^{\bar{f}f} = -\cos \theta_A \cot \beta \frac{m_f}{v} A^0 - u (i \gamma_5) u, \]

\[ \tan \beta = \frac{v_u}{v_d} \]

---

Results with $\psi'$ data in published in 2012

$\psi' \rightarrow \pi\pi \ J/\psi, \ J/\psi \rightarrow \gamma A^0, \ A^0 \rightarrow \mu^+\mu^-$

Coupling of $c$-quark to the $A^0$

Expected BF: $10^{-7} - 10^{-9}$

[BESIII [PRD 76, 051105 (2007)]]

BESIII exclusion limit ranges from $4 \times 10^{-7}$ - $2.1 \times 10^{-5}$ depending on $A^0$ mass points.

106M $\psi'$ data
Perform the ML fit to the $m_{\text{red}}$ distribution at 2035 mass points in the steps of 1-2 MeV/c$^2$.

![Projection Plot](image)

Significance distribution: consistent with unit-width Gaussian

$m_A^0 = 2.918$ GeV/c$^2$
New BESIII Results (225M J/ψ)

The new limits are five times below our previous results (2012, Psip)

Phys. Rev. D 93(2016), 052005

Phys. Rev. D 93(2016), 052005

PRD 87, 031102 (R) (2013) (BaBar experiment)

BESIII vs. BaBar measurements comparison and combination, A0 is mostly singlet
Dark photon (A') as dark-force carrier is EM-equivalent expected in the dark sector. It couples to SM particles via kinetic mixing. The idea sparked world-wide efforts.

- Use an untagged photon method to perform this analysis.

Event selection: \( e^+e^- \rightarrow \mu^+\mu^-\gamma_{\text{ISR}} \) and \( e^+e^- \rightarrow e^+e^-\gamma_{\text{ISR}} \)

| distance to interaction point | \( R_{xy} < 1.0 \text{ cm} \) \\ | \( R_{z} < 10.0 \text{ cm} \) |
|-----------------------------|-----------------|
| acceptance                  | \( 0.4 \text{ rad} < \theta < \pi - 0.4 \text{ rad} \) |
| to suppress background      | PID             |
| # charged tracks            | = 2             |
| total charge                | = 0             |
| # photons                   | = 0 (untagged analysis) |
| missing photon angle        | < 0.1 rad or > \( \pi - 0.1 \text{ rad} \) |
| 1C kinematic fit            | \( \chi^2_{1C} < 20 \) |

2016/6/22 cFLV2016
Spectrum of ee and mumu channel

2.9fb-1 psi"
Set the 90% C.L. upper limit using TRolke method.


combined statistics, including systematics

data - fit
CL = 90%
Some searches with meson decays are also going on with BESIII data, but less competitive.
Summary

- High lumi and good detector enables BESIII sensitive to LFV in meson decays
- The published results on $J/\psi \rightarrow e\mu$ yield the best limit from Heavy Quarkonium decays
- LFV $J/\psi$ decays involving $\tau$ are going on, would be more close to probe some models
- FLV in other mesons: D, Ds, eta, eta', V's are also possible, to be further investigated
- Other New Physics searches from BESIII are also active, more to come
Thanks!

Extra slides…
\[ \mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 4.6 \times 10^{-8} \text{ at 90\% CL} \]
\[ \mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp) < 2.8 \times 10^{-9} \text{ at 90\% CL} \]
\[ \mathcal{B}(B_s^0 \rightarrow e^\pm \mu^\mp) < 1.1 \times 10^{-9} \]
\[ \mathcal{B}(D^0 \rightarrow e^\pm \mu^\mp) < 1.5 \times 10^{-8} \text{ at 90\% CL} \]
\[ \mathcal{B}(D^+ \rightarrow \pi^- \mu^+ \mu^+) < 2.2 \cdot 10^{-8} \text{ at 90\% CL} \]
\[ \mathcal{B}(D_s^+ \rightarrow \pi^- \mu^+ \mu^+) < 1.1 \cdot 10^{-8} \]
Probing NP with Charmonia and Charmed mesons
Symmetry breaking, Invisible decays, FCNC ...

PRD87, 032006 (2013)

B(\eta \rightarrow \text{invisible}) < 1.0 \times 10^{-4}
B(\eta' \rightarrow \text{invisible}) < 5.3 \times 10^{-4}

@90\% C.L.

Theory:
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}

PRD87, 112007 (2013)

PRD91, 112015 (2015)

B(J/\psi \rightarrow e\mu) < 1.6 \times 10^{-7} (90\% C.L.)

B(D_0 \rightarrow \gamma\gamma) < 3.8 \times 10^{-6}
D^0 -> γγ: Motivation

- FCNC mode, forbidden at tree level
  → Larger GIM suppression
- MSSM up to BF ~ 10^{-6} [PLB500 (2001) 304], i.e. c → uy via gluino exchange

- BaBar (PRD85, 091107(R) (2012)):
  - Reconstruct through D^{*+} → D^0(→ γγ) π^+, normalized by D^{*+} → D^0(→ K_S π^0) π^+.
  - Peaking background from D^0 → π^0 π^0.
  - B(D^0 → γγ) < 2.2×10^{-6} @ 90% C.L.