Rare Charm decays at Belle II
(emphasis on $D^0 \rightarrow \gamma\gamma$)

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Outline

- SuperKEKB Accelerator
- Belle II Detector
- Rare Decays
- $D^0 \rightarrow \gamma\gamma$
- Performance studies with Belle II
- Summary and conclusion
SuperKEKB Accelerator

- Asymmetric $e^+(4 \text{ GeV}) e^-(7 \text{ GeV})$ collider
- $\sqrt{s} \simeq 10.58 \text{ GeV}$, just above $\Upsilon(4S)$ resonance
- Instantaneous Luminosity: $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- Integrated Luminosity: $50 \text{ ab}^{-1}$
- Charm factory: $\sim 7 \times 10^8 D^*$ candidates

- Rare charm decays:
  $D^0 \rightarrow \phi \gamma$, $D^0 \rightarrow \gamma \gamma$, $D^0 \rightarrow l^+ l^-$,
  $D_S^+ \rightarrow \pi^+ \mu^+ \mu^-$
- Charged decays, $D^0 \rightarrow l^+ l^-$, $D_S^+ \rightarrow \pi^+ \mu^+ \mu^-$ be better to explored with LHCb (Better tracking performance and coverage)
- But final states with neutral can be best explored with Belle II

![Belle II Online luminosity](image-url)

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Belle II detector

Belle II is a general purpose experiment designed for SuperKEKB accelerator.

- **Vertex Detector**
  - PXD + SVD
  - Precise vertex reconstruction
  - Reconstruct tracks for B and D decays

- **Electromagnetic Calorimeter**
  - High resolution calorimeter used to detect $\gamma$s
Rare Decays

- Flavor Changing Neutral Current processes involves change in flavor of quark without altering their charge e.g $b \rightarrow s\gamma, c \rightarrow u\gamma$

- In SM, FCNC processes are forbidden at the tree level but proceed via electroweak loops, known as rare decays

These rare decays provide a powerful tool for probing New Physics beyond Standard Model
FCNC are studied well in processes that involve K and B mesons but not so well explored in the charm sector because SM expectations are very small for FCNC

**Reason:**
- GIM cancellation at loop level in SM
- $c \rightarrow u$ transitions are dominated by the standard model long-distance contributions

Branching Ratio of $c \rightarrow u$ given by QCD corrected Lagrangian is

$$BR(c \rightarrow u) \approx 3 \times 10^{-8}$$


There are many New Physics models that can enhance the Branching Ratio of these FCNC processes
**SM contribution to** $D^0 \rightarrow \gamma\gamma$

- **Short distance contribution:** $\text{BR}(D^0 \rightarrow \gamma\gamma) \simeq 3 \times 10^{-11}$
- **Long distance contribution:** $\text{BR}(D^0 \rightarrow \gamma\gamma) \simeq 3.5^{+4.0}_{-2.6} \times 10^{-8}$


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Minimum Supersymmetric Standard Model (MSSM) which is an extension to SM can enhance the BR 200 times. With MSSM, estimated $\text{BR}(D^0 \rightarrow \gamma\gamma)$ is $6 \times 10^{-6}$

Previous \( D^0 \rightarrow \gamma\gamma \) studies

**Belle:**

- 830 fb\(^{-1} \) data, near \( \Upsilon(4S) \) and \( \Upsilon(5S) \) resonance
- Branching ratio is calculated as
  \[
  \frac{(N/\epsilon)D^0 \rightarrow \gamma\gamma}{(N/\epsilon)D^0 \rightarrow K_S\pi^0} \times B(D^0 \rightarrow K_S\pi^0)
  \]
- \( D^0 \rightarrow K_S\pi^0 \) is normalization mode to cancel out common systematic uncertainties.
- \( B_{D^0 \rightarrow \gamma\gamma} < 8.5 \times 10^{-7} \), at 90% CL

\[(\text{PhysRevD.93.051102)}\]

It will be interesting to probe \( D^0 \rightarrow \gamma\gamma \) with Belle II data
Data collected $\sim 86 \text{ fb}^{-1}$

By summer 2021, expected to have $1 \text{ ab}^{-1}$ data

Pros of using Belle II detector for $D^0 \rightarrow \gamma \gamma$ study
- Increased statistics
- Improved neutral’s detection
- Better tracking reconstruction
Clear signal observed for $\pi^0 \rightarrow \gamma \gamma$ and $\eta \rightarrow \gamma \gamma$

Demonstrates reconstruction performances
Control channel $D^0 \rightarrow K_S \pi^0$

Data and MC samples

- **Data:** Belle II data corresponds to 34.6 fb$^{-1}$
- **MC:**
  - Generic MC($c\bar{c}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $B^0 \bar{B}^0$ and $B\bar{B}$) for validation
  - Centrally simulated events for $D^0 \rightarrow K_S \pi^0$ to optimize selected signal

Decay mode of interest is identified by $D^* \rightarrow D^0 \pi^+_s$, $D^0 \rightarrow K_S (\pi^+ \pi^-) \pi^0 (\gamma \gamma)$

### $\gamma$ selection

- $E_{\gamma}^{barrel} > 30$ MeV
- $E_{\gamma}^{forward} > 120$ MeV
- $E_{\gamma}^{backward} > 80$ MeV

- Purity 72%
- Reconstruction Efficiency 11%

<table>
<thead>
<tr>
<th>Objects</th>
<th>Selection cuts</th>
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</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>$0.11 &lt; M_{\gamma\gamma} &lt; 0.16$ GeV/c$^2$</td>
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<tr>
<td></td>
<td>-1.0 $&lt; \Delta \phi &lt; 1.0$</td>
</tr>
<tr>
<td>$\pi_s$</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$</td>
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<tr>
<td>$K_S$</td>
<td>$0.468 &lt; M_{\pi^+\pi^-} &lt; 0.528$ GeV/c$^2$</td>
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<tr>
<td>$D^0$</td>
<td>$1.75 &lt; M_{K_S\pi^0} &lt; 1.95$ GeV/c$^2$</td>
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<tr>
<td>$D^{*+}$</td>
<td>$p^<em>(D^{</em>+}) &gt; 2.5$ GeV</td>
</tr>
<tr>
<td></td>
<td>$0.14 &lt; \Delta M &lt; 0.16$ GeV/c$^2$</td>
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</tbody>
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BELLE2-NOTE-PL- 2019-022
Results

2D unbinned maximum likelihood fit is performed on $\Delta M$ and $M(K_s\pi^0)$

$$\Delta M = M(K_s\pi^0\pi^+) - M(K_s\pi^0)$$

<table>
<thead>
<tr>
<th>component</th>
<th>$M(K_s\pi^0)$</th>
<th>$\Delta M$</th>
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</thead>
<tbody>
<tr>
<td>Signal</td>
<td>Gauss + Gauss + Bifur Gauss</td>
<td>Gauss + Bifur Gauss</td>
</tr>
<tr>
<td>Combinatorial BG</td>
<td>Exponential Gaussian</td>
<td>Threshold</td>
</tr>
<tr>
<td>Random $\pi_s$ BG</td>
<td>Gaussian</td>
<td>Threshold</td>
</tr>
</tbody>
</table>

Observed signal yield for $D^* \rightarrow D^0(K_s\pi^0)\pi^+$ with Belle II data corresponds to integrated luminosity 34.6 fb$^{-1}$ is 16800 ± 150.

- Observed signal yield for simulation is consistent with data
- Fit parameters such as mean and sigma are also consistent
- Good Data/MC agreement
Summary and Conclusion

- FCNC suppressed in the Standard Model provides interesting tool to search for New Physics
- Increased statistics ($10^{10}$ events of $c\bar{c}$) will lead to precise measurement in the charm sector
- Excellent detector and reconstruction performance with Belle II
- Stay tuned for the exciting results on rare charm decays in coming years

Thanks for your attention!