New non-leptonic hadron decay results at $e^+e^-$ experiments

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Non-leptonic hadron decays

- Non-leptonic $b$- and $c$-hadron decays offer plenty of ways to measure flavor and CP violation.

[diagrams from PMC Physics A 2009, 3:3]
Experiments at $e^+e^-$ colliders

\[ R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

Figure 52.3: $R$ in the light-flavor, charm, and beauty threshold regions. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are the same as in Fig. 52.2. Note: CLEO data above $\Upsilon(4S)$ were not fully corrected for radiative effects, and we retain them on the plot only for illustrative purposes with a normalization factor of 0.8. The full list of references to the original data and the details of the $R$ ratio extraction from them can be found in [100]. The computer-readable data are available at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2019.)

21st May, 2020 7:49pm
Experiments at $e^+e^-$ colliders

**Charm factories**

- **CLEO-c**
- **BaBar** and **PEP-II** :
  - $e^+e^- \rightarrow \Upsilon(nS) \rightarrow B\bar{B}$

**Beauty factories**

- **Belle experiment**

Located in KEK, Tsukuba, Japan

KEKB is an asymmetric-energy $e^+e^-$ collider $3.5\text{GeV}/8.0\text{GeV}$.

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**Belle II**

Located in KEK, Tsukuba, Japan

KEKB is an asymmetric-energy $e^+e^-$ collider $3.5\text{GeV}/8.0\text{GeV}$.

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**BESIII Drift Chamber Tracking with Machine Learning**

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### Abstract

The tracking efficiency and the quality for the drift chamber of the BESIII experiment is essential to the physics analysis. The tracking efficiency of the drift chamber of BESIII is high for the high momentum tracks but still have room to improve for the low momentum tracks, especially for the tracks with multiple turn. A novel way to use a convolutional network called U-Net network is represented to solve the identification of the first turn's hits for the multiple-turn tracks.

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**1 Introduction**

1.1 The BESIII experiment

The Beijing Spectrometer III (BESIII) has been running at the Beijing Electron Positron Collider II (BEPCII) for Tau-Charm physics since 2008. The tracking detector of the BESIII is a Multilayer Drift Chamber (MDC). The tracking efficiency for the high transverse momentum is high but lower when the cosine ($\cos\theta$) where $\theta$ is the dip angle of the track) is small for the low transverse momentum tracks (Fig. 2).

Fig. 1. The BESIII Detector.

Fig. 2. The tracking efficiency of the $\pi$-along $\cos\theta$.

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Experiments at e⁺e⁻ colliders

Charm factories

Beauty factories

This talk
Non-leptonic hadron decays at $e^+e^-$ colliders

- Coherent production of meson-antimeson pairs with kinematics constrained by precisely known collision energy
  - Efficient flavor tagging for $CP$ violation measurements
- Simple and clean event topologies: hadronic events have typically $O(10)$ particles
- Asymmetric-energy colliders: boosted production for time-dependent measurements
- Hermetic detectors: excellent (and kinematically unbiased) efficiencies for all final states, including neutral hadrons such as $\pi^0$, $\eta$, $K_S^0$, $K_L^0$, $\bar{n}$

**Kinematics**

$$\Delta E = E_{B}^* - \sqrt{s}/2$$

$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - p_B^*}$$

**Event topology**

Continuum Signal
<table>
<thead>
<tr>
<th>Study</th>
<th>PRD 107 (2023) L051101</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, width and BFs of $\Lambda_c(2625)^+ \rightarrow \Sigma_c^0\pi^+$ and $\Sigma_c^{++}\pi^-$</td>
<td>PRD 107 (2023) 032008</td>
</tr>
<tr>
<td>Evidence for the SCS decay $\Omega_c^0 \rightarrow \Xi^+\pi^-$ and search for $\Omega_c^0 \rightarrow \Xi^-K^+$</td>
<td>JHEP 01 (2023) 055</td>
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<td>BFs of $\Lambda_c^+ \rightarrow pK^0S\eta$</td>
<td>PRD 107 (2023) 0120003</td>
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<td>First measurement of the $B^+ \rightarrow \pi^+\pi^0\pi^+$ BF and CPV asymmetry</td>
<td>PRL 130 (2023) 181804</td>
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<tr>
<td>BF and CPV in $D_0 \rightarrow K^0S\pi^+\pi^-$</td>
<td>PRD 107 (2023) 02001</td>
</tr>
<tr>
<td>Observation of $D_0 \rightarrow K^+K^-K^0S$</td>
<td>2305.01321</td>
</tr>
<tr>
<td>Novel method for charm flavor tagging</td>
<td>2304.02042</td>
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<tr>
<td>BF and CPV of $B_0 \rightarrow \pi^0\pi^0$</td>
<td>2303.08354</td>
</tr>
<tr>
<td>$\Omega_c^0$ lifetime</td>
<td>PRD 107 (2023) L031103</td>
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<tr>
<td>BF and longitudinal polarization of $B_0 \rightarrow \rho^+\rho^-$</td>
<td>2208.03554</td>
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<tr>
<td>CP-even fraction of $D_0 \rightarrow K_0^0\pi^+\pi^-\pi^0$</td>
<td>2305.03975</td>
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<tr>
<td>BF for $\Lambda_c^+ \rightarrow \Sigma^+h^+\pi^-(\pi^0)$</td>
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<tr>
<td>BF of $\psi(2S) \rightarrow \phi K^0S\eta$</td>
<td>2303.08317</td>
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<td>BFs of $D_0^{0/0} \rightarrow K_0^0X$</td>
<td>2302.14488</td>
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<tr>
<td>Observation of $D_0 \rightarrow \phi\omega$</td>
<td>PRL128(2022)011803</td>
</tr>
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<td>BFs of $D_0^{0/0} \rightarrow \pi^+\pi^-\pi^-X$</td>
<td>PRD 107 (2023) 032002</td>
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<tr>
<td>BF of $D_s^+ \rightarrow \pi^+\pi^-\pi^-X$</td>
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<td>Observation of $\psi(3770) \rightarrow \eta J/\psi$</td>
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<td>Amplitude analysis of $D_0 \rightarrow K_0^0\pi^+\pi^-$</td>
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<td>CP-even fraction of $D_0 \rightarrow K^+K^-\pi^+\pi^-$</td>
<td>PRD 107 (2023) 032009</td>
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Hadronic decays as tools/inputs for other channels
$D_{(s)} \rightarrow \pi^+\pi^-\pi^+X$

- LHCb $R(D^*)$ measurement with the 3-prong $\tau$ channel suffers from limited knowledge of the leading and sub-leading backgrounds from $D_{s}^{+} \rightarrow \pi^{+}\pi^{-}\pi^{+}X$ and $D^{0/+} \rightarrow \pi^{+}\pi^{-}\pi^{+}X$ decays

- BESIII has measured these inclusive BFs for the first time

$$
\mathcal{B}(D_s^+ \rightarrow \pi^+\pi^+\pi^-X) = (32.81 \pm 0.35 \pm 0.82)\% \\
\mathcal{B}(D^0 \rightarrow \pi^+\pi^+\pi^-X) = (17.60 \pm 0.11 \pm 0.22)\% \\
\mathcal{B}(D^+ \rightarrow \pi^+\pi^+\pi^-X) = (15.25 \pm 0.09 \pm 0.18)\% 
$$

- The result for the $D_{s}^{+}$ channel is $\sim 25\%$ larger than the sum of the known exclusive BFs, implying that many exclusive $D_{s}^{+}$ decays containing $\pi^{+}\pi^{-}\pi^{+}$ are still unmeasured

- The results for the $D^{0/+}$ channels are instead consistent with the sum of the known exclusive BFs, indicating little room of unobserved exclusive decays
Observation of $B \to D^{(*)}K^-K_S^0$ decays

- About 40% of the total $B$ width is not measured in terms of exclusive branching fractions
  - Limits the accuracy of the simulation and the performance of the hadronic tagging
- BF($B \to DKK$) could be as large as 6%, but only a small fraction of its exclusive modes is known
- Highly pure signal observed
  - Improved BF($B^- \to D^0K^-K_S^0$) by more than a factor 3 and discovery of three other channels

$\mathcal{B}(B^- \to D^0K^-K_S^0) = (1.89 \pm 0.16 \pm 0.10) \times 10^{-4}$
$\mathcal{B}(\bar{B}^0 \to D^+K^-K_S^0) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4}$
$\mathcal{B}(B^- \to D^{*0}K^-K_S^0) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-K_S^0) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4}$
Observation of $B \to D^{(*)}K^-K_S^0$ decays

- Clear structures observed in the Dalitz plot of each decay (require further study)
Hadronic $B$ decays as probes for $CP$ violation
CKM angle $\alpha$

- Charmless $B$ decays give access to $\alpha$, the least known angle of the CKM unitarity triangle

- Combinations of measurements from isospin-related decays reduce the impact of hadronic uncertainties and yield $\sim 5^\circ$ uncertainty

- Belle II accesses all inputs and expects to reach $O(1^\circ)$ precision with $O(10/ab)$

  - Need to be accompanied by an improved understanding of the size of isospin breaking (e.g., using $B \to \pi \eta^{(')}$)
Towards CKM angle $\alpha$ with $B \to \pi\pi$

- $B^0 \to \pi^0\pi^0$ only accessible in $e^+e^-$ collisions
- Rare: CKM- and color-suppressed
- Only photons in the final state
- Requires efficient flavor tagging

- Belle II measurement achieves Belle’s precision using only 1/3 of data
  \[ \mathcal{B}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6} \]
  \[ A_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07 \]

For $B \to \pi^+\pi^-$, $\pi^+\pi^0$ (and $\rho\rho$) results see S. Raiz’s talk
\[ B \to K\pi \text{ isospin sum-rule} \]

- Appropriate combination of channels suppresses unknowns offering a 1\%-level null-test of the SM

\[ I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+} \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^+\pi^0} \frac{B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^0\pi^0} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} \]

- Current world average

\[ I_{K\pi} = 0.13 \pm 0.11 \]

limited by \( B \to K^0\pi^0 \), which in the foreseeable future can only be measured at Belle II.
$B \rightarrow K\pi$ isospin sum-rule

- Combining with $A_{CP}(K^0\pi^0)$ from time-dependent analysis [2305.07555] and with world-average lifetimes, Belle II obtains result competitive with world average

$$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$$

See J. Skorupa’s, J. Bennett’s and S. Raiz’s talks
The only CP-violation parameter that can be measured from tree-level decays (negligible theory uncertainty)

Unconstrained CP violating effects in non-leptonic tree-level decays can modify the SM relation between γ and other CKM elements by several degrees

Current ~4° precision dominated by LHCb, in particular by the measurement of $B^- \rightarrow DK^-$ with $D \rightarrow K_s^0\pi^+\pi^-$

CLEO+BESIII coherent $D^0\bar{D}^0$ data instrumental to constrain the strong-phase difference $\delta_D$, which for $D \rightarrow K_s^0\pi^+\pi^-$ is measured in bins of the Dalitz plot: $(c_i, s_i)$
BESIII inputs to $\gamma$

- The inclusion of the $D^0 \to K_L^0 \pi^+ \pi^-$ mode in the determination of $(c_i, s_i)$ provides a 3× more data at BESIII, but introduces uncertainty due to unknown $U$-spin-breaking parameters

$$\frac{A(D^0 \to K_L^0 (\pi^+ \pi^-)_{\kappa_{CP}})}{A(D^0 \to K_S^0 (\pi^+ \pi^-)_{\kappa_{CP}})} = 1 - 2\hat{\rho}_{k_{CP}}\tan^2\theta_C$$

- Now measured with an amplitude analysis of $D^0 \to K_L^0 \pi^+ \pi^-$ (first ever with a $K_L^0$)
  - Large deviations from assumed values of unity (i.e., large $U$-spin breaking) observed
  - Model-predicted strong-phase parameter differences between $K_S^0 \pi^+ \pi^-$ and $K_L^0 \pi^+ \pi^-$ consistent with assumed values but more precise
\( \gamma \) with \( CP \)-odd \( D \) final states

- \( B \) factories have unique access to \( CP \)-odd \( D \) final states, such as in \( B^{-}\rightarrow D(\rightarrow K_{S}^{0}\pi^{0})K^{-} \) decays

- Combined with \( CP \)-even modes, such as \( B^{-}\rightarrow D(\rightarrow K^{+}K^{-})K^{-} \), can measure \( \gamma \) without additional inputs

See S. Raiz’s talk, which includes also another recent \( \gamma \) result from Belle + Belle II
Charm CP violation

contours hold 68%, 95% CL
**CP violation in charmed baryons**

- Mostly unexplored, complements searches in charmed mesons and in beauty baryons
- At $e^+e^-$ machines can get good signals for many modes, and Belle is (still) among the most active contributors

\[
A_{CP}^{\text{dir}}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\% \\
A_{CP}^{\text{dir}}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%
\]
**CP violation in charmed baryons**

- Angular distribution gives access to interference between parity-violating $S$-wave and the parity-conserving $P$-wave amplitudes in the decay

\[
\frac{dN}{d \cos \theta_A} \propto 1 + \alpha_{\Lambda_c^+} \alpha_- \cos \theta_A \quad \alpha_- \propto \frac{\Re (SP^*)}{|S|^2 + |P|^2}
\]

- This offers alternative paths to look for CP violation

\[
A_{\Lambda_c^+ \rightarrow \Lambda K^+}^{\alpha} = \frac{\alpha_- (\Lambda_c^+) - \alpha_- (\Lambda_c^-)}{\alpha_- (\Lambda_c^+) + \alpha_- (\Lambda_c^-)}
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$A_{\Lambda_c^+ \rightarrow \Lambda K^+}^{\alpha}$</th>
<th>W.A. $A_{\Lambda_c^+ \rightarrow \Lambda K^+}^{\alpha}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+ \rightarrow \Lambda K^+$</td>
<td>$-0.023 \pm 0.086 \pm 0.071$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \rightarrow \Lambda \pi^+$</td>
<td>$+0.020 \pm 0.007 \pm 0.014$</td>
<td>$-0.07 \pm 0.22$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \rightarrow \Sigma^0 K^+$</td>
<td>$+0.08 \pm 0.35 \pm 0.14$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \rightarrow \Sigma^0 \pi^+$</td>
<td>$-0.023 \pm 0.034 \pm 0.030$</td>
<td>$-$</td>
</tr>
</tbody>
</table>
Charm flavor tagging

- Tagging the production flavor is needed to measure \( CP \) violation (and mixing) in neutral \( D \) decays
- Since 1977 this is achieved by restricting to the strong-interaction decays
- Added bonus: sample is much cleaner
- Malus: sample is reduced by 5-20\( \times \)
Novel charm flavor tagging

- Inspired from opposite-side $b$-flavor tagging
- Doubles sample size wrt $D^*$-tag alone

$$\varepsilon_{\text{tag}}^{\text{eff}} = (47.91 \pm 0.07 \text{(stat)} \pm 0.51 \text{(syst)})\%$$

best performance across any flavor taggers
Conclusions

• Despite being often affected by hadronic uncertainties, non-leptonic hadron decays offer precise tests of the SM and discovery potential for new physics

• They also serve as valuable tools for measurements based on other channels

• Plenty of contributions from $e^+e^-$ colliders in this area are (and will remain) crucial (thanks to the larger samples expected at Belle II and BESIII)