Recent world leading results on charm, and exotic b decays
Why shall we bother about charm?

**Discovery tool** FCNC and CP violation are highly suppressed in the standard model. Potential room for new physics to show up

**Unique** Gives sensitivity to new physics coupling to up-type quarks (complementary to $K$ and $B_{(s)}$ decays)

**Challenging** Predictions are difficult (impossible?), not a precision probe. However, an interesting laboratory for non-perturbative QCD and (exotic) hadron dynamics

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \mathcal{O}_{\Delta F=2}
\]

Lower bound on $\Delta \text{[TeV]}^2$:
- $K^0$ mixing
- $D^0$ mixing
- $B^0$ mixing
- $B_d^0$ mixing

**Observables**
- CP-conserving:
- CP-violating:
- $K_L$ mixing
- $D_L^0$ mixing
- $B_L^0$ mixing
- $B_d^0$ mixing

**Quarks**
- $u$: up
- $c$: charm
- $t$: top
- $d$: down
- $s$: strange
- $b$: bottom
Two concurrent charm factories (not at threshold)

LHCb

• Huge advantage in production rate, but also large backgrounds — stringent online selections
• Superior decay-time resolution and access to larger decay times (boost)
• …but tricky efficiency effects (e.g. decay-time acceptance)

Belle II

• Cleaner environment allows for more generous selections — milder efficiency effects
• Better reconstruction of neutrals and unique access to final states with invisible particles
• Much easier separation between promptly produced charm and secondary (from-$B$) decays
Belle II status

- Continued data-taking through Covid-19 pandemic
- Peak instantaneous luminosity of $\sim 2.6 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$
- However, slower luminosity integration rate than initially planned
  - As of today, collected $\sim 126 \text{ fb}^{-1}$

![Belle II Online luminosity graph](image)
Prospects of data collection

<table>
<thead>
<tr>
<th>Year</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>9 fb⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Belle II</td>
<td></td>
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- LHCb-PUB-2018-009 (+ 1yr delay due to Covid-19)
- The Belle II Physics Book (+ latest luminosity projections)
The rule of thumb

\[ 1 \text{ fb}^{-1} \sim 1 \text{ ab}^{-1} \]

@ LHCb

@ Belle II
The rule of thumb does not hold for prompt charm production.

\[ \frac{1 \text{ fb}^{-1}}{\text{LHCb}} \times \frac{1 \text{ ab}^{-1}}{\text{Belle II}} \]
The rule of thumb

\[ D^{*+} \rightarrow D^{0}(\rightarrow K^+\pi^-)\pi^+ \]

- Charm production rate in hadron collisions is \(O(10^6)\) times larger
- However, at Belle II better reconstruction efficiency for some final state compensates

\[ \frac{N}{L} \sim 150k \quad \frac{N}{L} \sim 10k \]
The rule of thumb

\[ D^{*+} \rightarrow D^0(\rightarrow K^+\pi^-)\pi^+ \]

- Charm production rate in hadron collisions is \(O(10^6)\) times larger
- However, at Belle II better reconstruction efficiency for some final state compensates

\[ \frac{N}{\mathcal{L}} \sim 150\text{k} \quad \frac{N}{\mathcal{L}} \sim 10\text{k} \quad \frac{N}{\mathcal{L}} \sim 0.5\text{k} \]

\[ \frac{D^{*+}}{D^0(\rightarrow KSK_S)\pi^+} \quad 2/\text{fb} \]

The rule of thumb

\[ D^{*+} \rightarrow D^0(\rightarrow K^+\pi^-)\pi^+ \]

- Charm production rate in hadron collisions is \( O(10^6) \) times larger
- However, at Belle II better reconstruction efficiency for some

**COMPLEMENTARITY**

\[ D^{*+} \rightarrow D^0(\rightarrow K_S K_S)\pi^+ \]

\[ D^0 \rightarrow K_S^0 K_S^0 \]

[PRD 97 (2018) 031101(R)]

[JHEP 11 (2018) 048]

[Belle 2015]

[PRL 112 (2014) 111801]
$CP$ violation in charm decays
Charm $CP$ violation is not about the penguins!

- $CP$ violation in $B$ decays comes from interference between tree and penguin loop (dominated by top)
- In charm decays, the penguin is irrelevant (CKM and GIM suppressed)
- Interference is between tree and rescattering amplitudes. Assuming $O(1)$ rescattering

$$A_{CP} \approx \text{Im} \left( \frac{V^*_{cs} V_{us} + V^*_{cd} V_{ud}}{V^*_{cs} V_{us} - V^*_{cd} V_{ud}} \right)$$

$$= -\text{Im} \left( \frac{V^*_{cb} V_{ub}}{\lambda} \right) \approx -6 \times 10^{-4}$$
Discovery of $CP$ violation in charm decays

- Difference of time-integrated $CP$ asymmetries in 2-body Cabibbo-suppressed decays:

$$\Delta A_{CP} = A_{CP}(K^+ K^-) - A_{CP}(\pi^+ \pi^-) = (-1.54 \pm 0.29) \times 10^{-3}$$

5.3$\sigma$ deviation from zero

- In the limit of SU(3)/U-spin symmetry, $A_{CP}(K^+ K^-)$ and $A_{CP}(\pi^+ \pi^-)$ have same magnitude and opposite signs $\implies |\Delta A_{CP}| \approx 1.3 \times 10^{-3}$

- In addition to be robust against experimental biases, $\Delta A_{CP}$ provides 2× enhanced sensitivity to $CP$ violation.
What is next?

- Measured value is in the ballpark of the standard model value
- Difficult to say whether new physics is at play. Need better control of the QCD effects
- Experimentally look for CP violation in radiative/semileptonic decays and test sum rules between SU(3) related modes, e.g.:

\[ R = \frac{A_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{B_{+-}} \left( \frac{B_{00}}{\tau_{D^0}} + \frac{2}{3} \frac{B_{+0}}{\tau_{D^+}} \right)} + \frac{A_{CP}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{B_{00}} \left( \frac{B_{+-}}{\tau_{D^0}} + \frac{2}{3} \frac{B_{+0}}{\tau_{D+}} \right)} - \frac{A_{CP}(D^+ \to \pi^+\pi^0)}{1 + \frac{3}{2} \frac{\tau_{D^+}}{B_{+0}} \left( \frac{B_{00}}{\tau_{D^0}} + \frac{B_{+-}}{\tau_{D^0}} \right)} = 0 \]

- Huge program of measurements, where complementarity between LHCb and Belle II will be crucial
**CP violation in $D^+ \rightarrow \pi^+\pi^0$ decays**

- In the standard model $\Delta A_{CP}$ comes from $\Delta U=0$ transitions: CP violation in $\Delta U=1$, e.g. in $D^+ \rightarrow \pi^+\pi^0$, would unambiguously be new physics.

- If $\Delta A_{CP}$ is due to new physics, then expect \cite{PRD 101 (2020) 115006}

\[
A_{CP}^{NP}(\pi^+\pi^0) \approx 2 \Delta A_{CP}^{NP} \sim 0.3\%
\]

- Current best measurement from Belle

\[
A_{CP}(\pi^+\pi^0) = (2.3 \pm 1.2 \pm 0.2)\%
\]

- Similar performances expected for Belle II. Sensitivity with 50/ab $\sim 0.17\%$
$A_{CP}(D^+ \rightarrow \pi^+\pi^0)$ at LHCb

- No displaced vertex with a single track
- Use $\pi^0 \rightarrow e^+e^-$ and $\pi^0 \rightarrow \gamma \gamma$ with one converted photon
- Lower BFs compensated by much larger production rate compared to $B$ factories
- $CP$ asymmetry with 9/fb competitive with Belle (1/ab)

$A_{CP}(\pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$

- Updated sum rule consistent with zero:

$$R = (0.1 \pm 2.4) \times 10^{-3}$$

[arXiv:2103.11058]
**CP violation in $D^0\rightarrow K_S^0K_S^0$ decays at LHCb**

- **CP violation enhanced by interference in W-exchange tree-level diagrams**
  \[ A_{CP}(K_S^0K_S^0) \approx 1.1\% \]

- New result from LHCb with 6/fb competitive with Belle (1/ab)

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LHCb-PAPER-2020-047, in preparation
$D^0 \rightarrow K_s^0 K_s^0$ decays at Belle II

Belle II preliminary
\[ \int L \, dt = 72.0 \, \text{fb}^{-1} \]
- Data
- Fit
- Background

$D^0 \rightarrow K_s^0 K_s^0$

$N = 315 \pm 19$

Similar yield/luminosity to Belle with larger purity
Prospects for direct $CP$ violation

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Current best sensitivity (stat + syst) [10^{-3}]</th>
<th>Belle II 50/ab (stat+syst) [10^{-3}]</th>
<th>LHCb 50-300/fb (stat only) [10^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta A_{CP}$</td>
<td>0.29 LHCb (9/fb)</td>
<td>0.6</td>
<td>0.07-0.03</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+K^-$</td>
<td>1.8 LHCb (3/fb)</td>
<td>0.3</td>
<td>0.17-0.07</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>1.8 LHCb (3/fb)</td>
<td>0.5</td>
<td>0.17-0.07</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^0\pi^0$</td>
<td>6.5 Belle (1/ab)</td>
<td>0.9</td>
<td>(?)</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^0\pi^+$</td>
<td>11/13 LHCb (9/fb)/Belle (1/ab)</td>
<td>1.7</td>
<td>(5.9-2.4)</td>
</tr>
<tr>
<td>$D^0 \rightarrow K_SK_S$</td>
<td>13/15 LHCb (9/fb)/Belle (1/ab)</td>
<td>2.1</td>
<td>7.0-2.8</td>
</tr>
<tr>
<td>$D_s \rightarrow K_S\pi^+$</td>
<td>18 LHCb (6.8/fb)</td>
<td>2.9</td>
<td>(0.75)-0.32</td>
</tr>
<tr>
<td>$D^+ \rightarrow K_SK^+$</td>
<td>0.76 LHCb (6.8/fb)</td>
<td>0.4</td>
<td>(0.28)-0.12</td>
</tr>
<tr>
<td>$D^0 \rightarrow \phi\gamma$</td>
<td>66 Belle (1/ab)</td>
<td>10</td>
<td>(?)</td>
</tr>
<tr>
<td>$D^0 \rightarrow \rho^0\gamma$</td>
<td>150 Belle (1/ab)</td>
<td>20</td>
<td>(?)</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+\pi^-$</td>
<td>9.1 LHCb (5/fb)</td>
<td>(4.0)</td>
<td>1.4-0.5</td>
</tr>
</tbody>
</table>

(numbers in parentheses are my own, unofficial projections)
Time-dependent $CP$ violation

- The eigenstates of the neutral $D$ meson are a mixture of the flavor states

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$x = \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}, \quad y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

- This results in $D^0-\bar{D}^0$ ($\Delta C = 2$) transitions before decay that provide an additional interfering pattern for $CP$-violation effects

  - Expected to be suppressed by a further order in $U$-spin breaking w.r.t. $\Delta C = 1$ processes $\implies \phi \sim O(0.1)$ degrees

  - No experimental evidence to date
Improved decay-time resolution at Belle II

\[\sim 2 \times \text{better than Belle/BaBar,}\]
\[\text{similar to charm from semileptonic } B \text{ decays at LHCb,}\]
\[\text{and only } \sim 2 \times \text{worse than prompt charm at LHCb}\]
Time-dependent $CP$ asymmetry in $D^0 \rightarrow h^+ h^-$

- Small $D^0$-$\bar{D}^0$ mixing rate ($x,y \ll 1$) implies that time-dependent $CP$ asymmetries can be approximated as
  \[ A_{CP}(h^+ h^-) \approx a_{CP}^{\text{dir}}(h^+ h^-) - \frac{t}{\tau} A_\Gamma \]

- Mixing-induced $CP$ violation results in a nonzero value of the linear term

- Naive expectation is $O(10^{-5}-10^{-4})$

- Experimental sensitivity is (and will remain) dominated by LHCb
Updated measurement from LHCb Run 2

\[ A_{CP}(h^{+}h^{-}) \approx a_{CP}^{\text{dir}}(h^{+}h^{-}) - \frac{t}{\tau} A_{\Gamma} \]

Figure 12: Linear fit to the time-dependent asymmetry of the (top) \( D^0 \to K^+K^- \) and (bottom) \( D^0 \to \pi^+\pi^- \) decays, and improve by nearly a factor of two on the precision of the previous legacy results with the 2011–2012 and 2015–2018 data samples, as well as with the 2017 and 2018 measurements. The average is reported as well.
$x$ is the key

- Sensitivity to $CP$-violation phase in mixing limited also by the knowledge of $x_{12} \approx x$ (which is only $3\sigma$ away from zero)
- Most sensitive mixing measurements are based on decays to two-body final states (which are primarily sensitive to $y$)
- Need mixing measurements with decays to multi-body final states that are not $CP$-eigenstates

$A_\Gamma \approx -x_{12} \sin \phi_{12}$
$x$ from $D^0 \rightarrow K_S \pi^+ \pi^-$

- Multiple interfering amplitudes enhance the sensitivity to mixing locally on the Dalitz plot

$$\mathcal{P}_{D^0} \propto e^{-\Gamma t} \left\{ |A_{D^0}|^2 - \text{Re} \left[ A^*_D A_{D^0} (y + ix) \right] \Gamma t \right\}$$

- LHCb Run 1 and Belle give the best determinations of $x$ with $\sim$1M $D^0 \rightarrow K_S \pi^+ \pi^-$ decays each

- In Run 2 LHCb has collected $\sim$40× more signal $\Rightarrow$ expect $\sigma(x) \sim 0.5 \times 10^{-3}$

- Belle II is expected to collect $\sim$50M decays with 50/ab. Difficult to compete if LHCb keeps reasonable efficiency in Run 3 and 4

Belle (1/ab) $m^2 (\text{GeV}^2/c^4)$

$x = (0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08})\%$

LHCb (2/fb) $[\text{PRL 122 (2019) 231802}]$

$x = (0.27 \pm 0.16 \pm 0.04)\%$
More multi-bodies

- Lots of other promising final states not yet explored/fully exploited experimentally: e.g. $D^0 \rightarrow K^+\pi^-\pi^0$, $D^0 \rightarrow K_S\pi^+\pi^-\pi^0$, $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$, ...

Potential of $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ @ LHCb

Doubly Cabibbo-suppressed decay

- Equivalent to WS $K^\pi$ but with phase space ($4$-body = $5$-dimensional)
- No simultaneous access to CF decay
- Mixing parameters are rotated by strong phase difference
- But retain linear access to $x'$ through phase variations
- Great potential for CP violating parameters
- Similar story for other $c \rightarrow d \bar{u}$ decays, e.g. $D^0 \rightarrow K^+\pi^-\pi^0$

Potential of $D^0 \rightarrow K_S\pi^+\pi^-\pi^0$

Preliminary Belle II

$N = 258 \pm 26$

$\Delta m$ [GeV/c$^2$]

Candidates per 0.2 MeV/c$^2$

$\sim 300k D^0 \rightarrow K^+\pi^-\pi^0$

expected at Belle II (50/ab)

$|q/p|$ | φ

0.8 | 0.9 | 1 | 1.1 | 1.2

HFLAV World Average 2017

This work

WA + This work

contours hold 68%, 95% CL

Figure 55: The total fit with the full Belle data sample for $M$ (left) and $M_{D^0}$ (right) where the signal, combinatoric and random slow pion components are shown with dotted red, magenta and green, respectively.

Figure 56: Residual distributions for $M_{D^0}$ (left) and $M$ (right) from the 2D fit with the full Belle data set.

Figure 57: Signal enhancement $M$ and $M_{D^0}$ distributions.

$|q/p|$ | φ

0.2 | 0.4

PRD 95 (2017) 091101

Belle (1/ab)

$\sim 750M D^0 \rightarrow K_S\pi^+\pi^-\pi^0$

[CERN-THESIS-2017-257]
Exotic charm production in $b$ decays
Charmonium-like above threshold

Observed states:
- Conventional charmonium
- Unconventional neutral states
- Unconventional charged states
- Pentaquark candidates

Expected states

Kinematic thresholds

- Mesons/baryons are predominantly (qq/qqq) bound states below the open flavor threshold
- There is a zoo of more complex states above threshold, which have not yet been understood

[Rev. Mod. Phys. 90 (2018) 15003]
Possible types of exotic states

- **Compact states** tightly bound by color forces
- **Compact hybrid** states in which a gluon acts a valence constituent
- **Glueball**
- **Compact diquark-antidiquark or dibaryons**
- **Weakly bound, spatially extended molecular states**
All started with $X(3872)$

- Discovered by Belle ~18 years ago [PRL 91 (2003) 262001]
- The only exotic charmonium-like candidate which shows up consistently in different production mechanisms and in many different decays modes
- Mixture of a compact ($c\bar{q}\bar{c}\bar{q}$) state and a molecule?
  - Near $D\bar{D}^*$ threshold and narrow width in decays to $c\bar{c}$ states favors molecular interpretation
  - $X(3872)$ production rates in prompt processes more likely for a compact state
- More experimental results needed/expected to clarify the nature of this state

- Reconstruction of final states
  - $B^\pm \rightarrow \pi^+\pi^-J/\Psi(l^+l^-)K^\pm$
  - $B^0 \rightarrow \pi^+\pi^-J/\Psi(l^+l^-)K^S$

- Selection criteria (standard)
  - Particle identification
  - Continuum: $n$Tracks, $R^2$
  - Kinematics: $M_{\pi^+\pi^-}$, $M_{bc}$, $|\Delta E|$

- First $X(3872)$ at Belle II
  - $14.4 \pm 4.6$ events ($4.6\sigma$)
  - Belle: ~170 events in 772 Mi. $B^0$ pairs

- $X(3872)$ production rates in prompt processes more likely for a compact state
- More experimental results needed/expected to clarify the nature of this state

Di-charmonium states

- Very significant structure in \( J/\psi J/\psi \) mass spectrum
- Interpretation of data is not clear:
  - One, or more (interfering?) resonances
  - Possible near-threshold effects?
- However, no known mechanism for binding forces between two charmonium states, and the \( X(6900) \) peak seems too wide to be a molecule
- Likely theoretical interpretation: compact \( c\bar{c}c\bar{c} \) tetraquark/diquark-antidiquark state(s)
- More experimental questions remain unanswered: Quantum numbers? Other decay modes?

\[
\begin{align*}
\chi_{c0} & \quad \chi_{c0,1} \\
\text{LHCb} & \\
\text{Data} & & \text{Total fit} & & \text{Resonance} & & \text{Threshold BW1} & & \text{Threshold BW2} & & \text{DPS} & & \text{NRSPS} & & \text{DPS+NRSPS} \\
\text{Weighted candidates} / (28 \text{ MeV}/c^2) & & & & & & & & & & & & & & & & & \\
\text{Interference} & & & & & & & & & & & & & & & & & \\
\text{Interference BW} & & & & & & & & & & & & & & & & & \\
\text{m} = 6905 \pm 11 \pm 7 \text{ MeV}/c^2 & & & & & & & & & & & & & & & & & \\
\Gamma = 80 \pm 19 \pm 33 \text{ MeV} & & & & & & & & & & & & & & & & & \\
\text{LHCb} & & & & & & & & & & & & & & & & & \\
\text{Data} & & \text{Total fit} & & \text{Resonance} & & \text{DPS} & & \text{NRSPS} & & \text{DPS+NRSPS} \\
\text{Weighted candidates} / (28 \text{ MeV}/c^2) & & & & & & & & & & & & & & & & & \\
\text{m} = 6868 \pm 11 \pm 11 \text{ MeV}/c^2 & & & & & & & & & & & & & & & & & \\
\Gamma = 168 \pm 33 \pm 69 \text{ MeV} & & & & & & & & & & & & & & & & &
\end{align*}
\]
Charming and strange exotic states

- The $0^+$ is a good candidate for a compact $cs\bar{u}\bar{d}$ state
- However, proximity to the thresholds motivates other explanations: e.g., molecular state or rescattering/triangular amplitudes

$m_0 = 2866 \pm 7 \pm 2 \text{ MeV}/c^2$
$\Gamma_0 = 57 \pm 12 \pm 4 \text{ MeV}$

$m_1 = 2904 \pm 5 \pm 1 \text{ MeV}/c^2$
$\Gamma_1 = 110 \pm 11 \pm 4 \text{ MeV}$
Charming and strange exotic states

- Multiple $J/\psi \phi$ structures observed in $B^+ \to J/\psi \phi K^+$ since CDF reported the $X(4140)$ [PRL 102 (2009) 242002]
- All are broad: unclear if due to exotic hadrons or rescattering effects

- Latest analysis from LHCb shows one $1^+$ (or two?) $Z_{cs}^+ \to J/\psi K^+$ candidate(s) with phase variation consistent with a resonance
  
  $$m = 4003 \pm 6 \pm 4_{-14} \text{ MeV}/c^2 \quad \Gamma = 131 \pm 15 \pm 26 \text{ MeV}$$

- Not consistent with the narrow threshold structure previously reported by BESIII in $D_s^- D^{*0} + D^*- D^0$ mass distribution [PRL 126 (2021) 102001]
More pentaquark states?

$\Lambda_b \rightarrow J/\psi p K^-$

$\Sigma_c^+ D^0$ $\Sigma_c^+ \bar{D}^{*0}$ $\Sigma_c^{*} \bar{D}^{*0}$

• States in $J/\psi p$ are likely baryon-meson molecular states, more isospin partners are expected

[PRL 122 (2019) 222001]

Evidence for one (or two?) charming and strange narrow states in $J/\psi \Lambda$ close to threshold

[arXiv:2012.10380]
Conclusions

• Precision charm physics has just started. Huge experimental progress expected in the next decade(s) at LHCb, Belle II, BESIII... if we fully exploit the excellent complementarity between the experiments
  
  • First observation of direct $CP$ violation, and in reach of standard-model expectation for $CP$ violation in mixing
  
  • Not shown today: virgin field of new-physics searches, including LF(U)V, in $c \rightarrow u \ell \ell'$ and $c \rightarrow u \nu \bar{\nu}$ transitions
  
  • Citing Y. Grossman: a win-win situation
    
    • Hopefully, we will see physics beyond the standard model
    
    • If not, we are learning about QCD
  
  • More and more exotic hadrons are popping up above open flavor threshold (also with $b$-quark content, not covered here). Nature of all the states is still unclear
    
    • A lot of work to do for both experimentalists and theorists
Charm is more valuable than beauty. You can resist beauty, but you can't resist charm.

— Audrey Tautou —