HL/HE Questions in Charm (Flavor Physics)

Joachim Brod

Workshop on the physics of HL-LHC
CERN, October 31, 2017
# LHCb Upgrades

<table>
<thead>
<tr>
<th>LHC Run</th>
<th>Period</th>
<th>$\mathcal{L}_{\text{max}}$ cm$^2$ s</th>
<th>$\int \mathcal{L} dt$/fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>1&amp;2 2010-2012, 2015-2018</td>
<td>$4 \times 10^{32}$</td>
<td>8</td>
</tr>
<tr>
<td>Phase-I</td>
<td>1&amp;2 2021-2023, 2026-2029</td>
<td>$4 \times 10^{32}$</td>
<td>50</td>
</tr>
<tr>
<td>Phase-II</td>
<td>1&amp;2 2031-2033, 2035-</td>
<td>$4 \times 10^{32}$</td>
<td>300</td>
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</tbody>
</table>

This corresponds to (hundreds of) billions of charmed hadrons

[LHCb report CERN-LHCC-2017-003]

[LHCb-CONF-2016-005]
SM FCNC flavor dynamics determined by interplay between loop functions and CKM matrix elements

\[ c \rightarrow b, s, d \]

\[ u \rightarrow b, s, d \]

\[ = V_{cq} V_{uq} V_{cq'} V_{uq'} \times f \left( \frac{m^2_q}{M^2_W}, \frac{m^2_q'}{M^2_W} \right) \]

\[
\begin{pmatrix}
| V_{ud} & V_{us} & V_{ub} | \\
| V_{cd} & V_{cs} & V_{cb} | \\
| V_{td} & V_{ts} & V_{tb} |
\end{pmatrix}
\approx
\begin{pmatrix}
1 & \lambda & \lambda^3 \\
\lambda & 1 & \lambda^2 \\
\lambda^3 & \lambda^2 & 1
\end{pmatrix}, \quad \lambda \approx 0.23
\]

“Two-generation dominance” and efficient GIM mechanism

- SM contribution to FCNC effects in charm is small.

- Large long-distance contributions make SM predictions difficult.

- Search for new physics in the up-quark sector!
Why should we do $D$ physics...
Why should we do $D$ physics... 

...if $B$ and $K$ physics is under better theoretical control?
I: Mixing is small
\( D^0 - \bar{D}^0 \) mixing

\[
i \frac{d}{dt} \left( |D(t)\rangle \right) = \left( M - i \frac{\Gamma}{2} \right) \left( |\bar{D}(t)\rangle \right)
\]

Diagonalize to get eigenstates

\[
|D_{H,L}\rangle = p|D^0\rangle \mp q|\bar{D}^0\rangle
\]

\[
\Gamma_D \equiv \frac{\Gamma_H + \Gamma_L}{2}, \quad x \equiv \frac{M_H - M_L}{\Gamma_D}, \quad y \equiv \frac{\Gamma_H - \Gamma_L}{2\Gamma_D}.
\]
$D^0 - \bar{D}^0$ mixing – SM estimates

“Inclusive approach”:
- OPE expansion in powers of $\Lambda/m_c$
- LO gives $x \sim 10^{-5}$, $y \sim 10^{-7}$
- Higher order $x \sim y \lesssim 10^{-3}$
- Cannot exclude $y \sim 10^{-2}$ ($V_{ub} \neq 0$) [Bobrowski et al. 1002.4794]

“Exclusive approach”:
- Sum over on-shell intermediate states
- Mainly $D \to PP, PV$ leads to $x \sim y \lesssim 10^{-3}$ [Cheng et al. 1005.1106]
- $SU(3)_F$ breaking in phase space $y \sim 10^{-2}$ [Falk et al. hep-ph/0110317]
- Get $x \sim 10^{-2}$ from a dispersion relation [Falk et al. hep-ph/0402204]

Large uncertainties; use experimental values to set upper bounds
$D^0 - \bar{D}^0$ Mixing – NP

- Local NP contributions can be predicted very precisely
- Operator matrix elements from lattice QCD
  
  [Carrasco et al. 1403.7302, Bazavov et al. 1706.04622]

[Silvestrini 1510.05797]
$D^0 - \bar{D}^0$ Mixing

[LHCb report CERN-LHCC-2017-003]
II: CP violation is small
Three types of $CP$ violation

I $|\tilde{A}_f/A_f| \neq 1$ (CP violation in decay)

$$a_f^d := \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} = \frac{|A_f|^2 - |\tilde{A}_f|^2}{|A_f|^2 + |\tilde{A}_f|^2}$$

II $|q/p| \neq 1$ (CP violation in mixing)

$$a_{sl} := \frac{\Gamma(\bar{D}^0(t) \to \ell^+ X) - \Gamma(D^0(t) \to \ell^- X)}{\Gamma(\bar{D}^0(t) \to \ell^+ X) + \Gamma(D^0(t) \to \ell^- X)} = \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2}$$

III $Im(\lambda_f) \equiv Im\left(\frac{q}{p} \frac{\tilde{A}_f}{A_f}\right) \neq 0$ (interference-type $CP$ violation)

$$a_{f_{CP}} := \frac{\Gamma(\bar{D}^0(t) \to f_{CP}) - \Gamma(D^0(t) \to f_{CP})}{\Gamma(\bar{D}^0(t) \to f_{CP}) + \Gamma(D^0(t) \to f_{CP})}$$
Size of CPV in $D$ mixing

- Define $\lambda_q \equiv V_{cq} V_{uq}^*$
- Eliminate $\lambda_d$ via unitarity: $\lambda_d + \lambda_s + \lambda_b = 0$
- $\lambda_s$ can be chosen real
- CPV naively suppressed by $r = \text{Im} \lambda_b / \lambda_s \sim 6.5 \times 10^{-4}$
- The mixing amplitude is

$$A = \lambda_s^2 (f_{dd} + f_{ss} - 2f_{ds}) + 2\lambda_s \lambda_b (f_{dd} + f_{bs} - f_{bd} - f_{sd}) + \mathcal{O}(\lambda_b^2)$$

- In terms of $U$-spin contributions this is [Silvestrini 1510.05797]

$$A = \lambda_s^2 (\Delta U = 2) + 2\lambda_s \lambda_b (\Delta U = 1 + \Delta U = 2) + \mathcal{O}(\lambda_b^2) \sim \lambda_s^2 \epsilon + 2\lambda_s \lambda_b \epsilon^2$$

- For nominal $U$-spin breaking, $\epsilon \approx 30\%$, expect CPV at order $r/\epsilon \sim 10^{-3}$
- More detailed analysis

[Grossman et al., work in progress; see also talk by L. Silvestrini at this workshop]
Size of CPV in $D$ decay

- Wilson coefficients can be computed **perturbatively**

- Hadronic matrix elements $\langle K\pi|H_{\text{eff}}|D\rangle$ dominated by **nonperturbative QCD**

- QCD factorization expected to work badly ($\Lambda_{\text{QCD}}/m_c \lesssim 1$)

- **Ultimately rely on lattice QCD**
  
  - Recent progress in $K \rightarrow \pi\pi$ matrix element
    
    [E.g. Bai et al. 1505.07863]
  
  - Multiple-channel generalization of Lellouch-Lüscher formula
    
    [E.g. Polejaeva, Rusetsky 1203.1241; Hansen, Sharpe 1211.0511; Briceño, Davoudi 1212.3398]

- **Until then**: $SU(3)$ flavor symmetry plus assumptions
  (Naive factorization, large-$N$, “$\epsilon^2$” sum rules, . . . )

  [E.g. Jung et al. 1410.8396, Müller et al. 1506.04121, Nierste et al. 1708.03572, Grossman et al. 1211.3361]

  - For instance, $\Delta A_{CP}$ has taught us that DCPV can be of order $\gtrsim 10^{-3}$

    [E.g. Brod et al. 1111.5000, 1203.6659, Pirtskhalava et al. 1112.5451, Feldmann et al. 1202.3795]
III: Null tests and rare decays
Isospin sum rules

- Tree-level $\mathcal{H}_{\text{eff}}$ for $D \rightarrow \pi\pi$ has both $\Delta l = 1/2$ and $\Delta l = 3/2$:
  $$Q_T \sim (\bar{d}c)(\bar{u}d)$$

- QCD penguin operators are purely $\Delta l = 1/2$:
  $$Q_P \sim (\bar{c}u) \otimes (\bar{u}u + \bar{d}d + \bar{s}s)$$

- $\Delta l = 3/2$ direct $CP$-violating transitions are absent in SM.

$$A_{\pi^+\pi^-} = \frac{1}{\sqrt{6}} A_{3/2} + \frac{1}{\sqrt{3}} A_{1/2},$$

$$A_{\pi^0\pi^0} = \frac{1}{\sqrt{3}} A_{3/2} - \frac{1}{\sqrt{6}} A_{1/2},$$

$$A_{\pi^+\pi^0} = \frac{\sqrt{3}}{2} A_{3/2}.$$ 

- $D^+ \rightarrow \pi^+\pi^0$ purely $\Delta l = 3/2 \Rightarrow$ any $CP$ asymmetry would be NP

- Can write down sum rules also for $D \rightarrow \rho\pi$, $D \rightarrow K^{(*)}\bar{K}^{(*)}\pi(\rho)$, $D_s^+ \rightarrow K^*\pi(\rho)$ [Grossman et al. 1204.3557]
\[ D^+ \to \pi^+ \mu^+ \mu^- \text{ and } D^0 \to P^+ P^- \mu^+ \mu^- \]

Angular observables and CP asymmetries are (approximate) SM null tests
[de Boer et al. 1510.00311]

- Fit hadronic contributions
- Asymmetries can be enhanced by resonances

Also rare leptonic decays \( D \to \ell \ell \) [See, e.g., Fajfer 1509.01997]

- Radiative decays \( D \to V \gamma \) relevant for Belle II

[Updated plot thanks to Stefan de Boer]
Why should we do $D$ physics...
Why should we do $D$ physics. . .

. . . if the up- and down sectors are related via weak isospin?
I: Disentangle UV flavor structure
Consider NP that couples to the LH quark doublets, e.g., \( Q_{L,2} \sim (c_L, s_L)^T \)

SM plus NP:

\[
\mathcal{L} \supset Q_{L,i} Y_{ij}^d d_{R,j} H + Q_{L,i} Y_{ij}^u u_{R,j} \tilde{H} + \frac{1}{\Lambda^2} (Q_{L,i} X_{ij} Q_{L,j}) (Q_{L,i} X_{ij} Q_{L,j})
\]

Can always choose a basis where either \( Y^d \) or \( Y^u \) are diagonal

Can always “adjust” NP to have vanishing contribution to either \( K \) mixing or \( D \) mixing, but not both

Combining \( D \) and \( K \) mixing allows to test the UV flavor structure of NP

[Blum et al. 0903.2118]
II: Implications for $B$ physics
\[ \gamma \text{ from tree decays – general idea} \]

- \( b \to c \bar{u}s \), \( b \to u \bar{c}s \)
- pure tree-level transition
- interference from common \( D^0, \bar{D}^0 \) final states

\[ \propto V_{cb} V_{us}^{*} \]

\[ \propto V_{ub} V_{cs}^{*} \]
Including direct CP violation in $D$ decays

[Martone et al. 1212.0165, Zupan 1212.0165; see also Wang 1211.4539, Bhattacharya et al. 1301.5631, Bondar et al. 1303.6305]

- $B$ decay amplitude gets modified:

$$A(B^\pm \to f_D K^\pm) = A_B A_f^T [1 + r_B^\pm e^{i(\delta'_B \pm \gamma \pm \delta \gamma)}]$$

- What is the size of the effect?

$$\delta \gamma = \mathcal{O}(r_f / r_B), \quad \delta'_B - \delta_B = \mathcal{O}(r_f / r_B), \quad r_B^\pm - r_B = \mathcal{O}(r_f)$$

- $r_B(DK) = \mathcal{O}(10\%), \quad \delta \gamma = \mathcal{O}(\text{few \%})$

- $r_B(D\pi) = \mathcal{O}(0.5\%), \quad \delta \gamma = \mathcal{O}(1)$

$$A_{CP}(B \to f_D K) = 2r_B \sin \delta_B \sin \gamma - a_f^{\text{dir}}$$
Including direct CP violation

- Unknowns: $2n_{SCS} + 3n_B + 1$
- Observables: $2n_B(n_{CA} + n_{SCS})$
- Shift symmetry $\gamma \rightarrow \gamma + \phi$, $\alpha_f \rightarrow \alpha_f - \phi$:

$$|A(B^\pm \rightarrow f_D K^\pm)|^2 = |A_B|^2[|A_f|^2 + 2r_B|A_f||\tilde{A}_f|\cos(\delta_B \pm \gamma \pm \alpha_f) + \ldots]$$

- $\alpha_f \equiv \arg(A_f/\tilde{A}_f) = -a^\text{dir}_f \cot \delta_f$
- Cannot extract $\gamma$ from $B \rightarrow D K$ alone without assumptions
- Measure $\delta_f$ at charm factories, or extract from $D - \bar{D}$ mixing
Why should we do $D$ physics...
Why should we do $D$ physics... 

...if we can test the up-sector in top-quark decays?
Disentangle UV flavor structure
**CP and flavor violating Higgs couplings**

- Direct searches for $h \rightarrow cu$ lead to $\mathcal{O}(10\%)$ bounds
- Chromoelectric dipole leads to neutron EDM
- It also leads to CPV contribution in $D$ decays and $D - \bar{D}$ mixing

<table>
<thead>
<tr>
<th>Observable</th>
<th>Coupling</th>
<th>Present bound</th>
<th>Future sensitivity</th>
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</thead>
<tbody>
<tr>
<td>$d_n^{\text{h}}$</td>
<td>$\text{Im}(Y^{t c} Y^{c t})$</td>
<td>$5.0 \times 10^{-4}$</td>
<td>$1.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>$d_n^{\text{u}}$</td>
<td>$\text{Im}(Y^{t u} Y^{u t})$</td>
<td>$4.3 \times 10^{-7}$</td>
<td>$1.5 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\Delta A_{CP}$</td>
<td>$\text{Im}(Y^{u t} Y^{c t})$</td>
<td>$4.0 \times 10^{-4}$</td>
<td>–</td>
</tr>
<tr>
<td>$D - \bar{D}$</td>
<td>$\sqrt{</td>
<td>\text{Im}(Y^{c t} Y^{u t} Y^{u t} Y^{t u})</td>
<td>}$</td>
</tr>
</tbody>
</table>

[Gorbahn et al. 1404.4873]
Charm physics is theoretically and experimentally challenging

Some observables in principle very sensitive to NP

- Test for NP in the up sector
- Disentangle NP flavor structure
- Future theory progress needed
- Devise SM “null tests”

Important input for $B$ physics

Charm flavor physics will play a prominent role also at future LHCb upgrades