HL/HE Questions in Charm (Flavor Physics)

Joachim Brod

technische universität
dortmund

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LHCb Upgrades

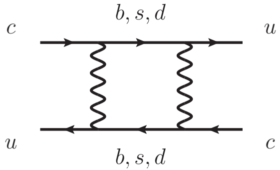
	LHC Run	Period	$\mathcal{L}_{\text{max}}$ cm^2 s	$\int \mathcal{L} dt/\text{fb}$
Current	1&2	2010-2012, 2015-2018	4×10^{32}	8
Phase-I	1&2	2021-2023, 2026-2029	4×10^{32}	50
Phase-II	1&2	2031-2033, 2035-	4×10^{32}	300

[LHCb report CERN-LHCC-2017-003]

- This corresponds to (hundreds of) billions of charmed hadrons
  [LHCb-CONF-2016-005]

D-Meson Physics – Introduction

- SM FCNC flavor dynamics determined by interplay between loop functions and CKM matrix elements



$$= \quad V_{cq} V_{uq}^* V_{cq'} V_{uq'}^* \times f\left(\frac{m_q^2}{M_W^2}, \frac{m_{q'}^2}{M_W^2}\right)$$

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

- "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!

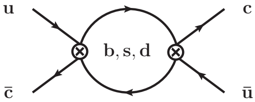
Why should we do D physics. . .

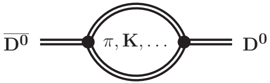
Why should we do D physics...

...if B and K physics is under better theoretical control?

I: Mixing is small

$D^0 - \bar{D}^0$ mixing





$$i\frac{d}{dt}\begin{pmatrix}|D(t)\rangle\\|\bar{D}(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|D(t)\rangle\\|\bar{D}(t)\rangle\end{pmatrix}$$

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 "Λ/m_c"
- LO gives $x \sim 10^{-5}$, $y \sim 10^{-7}$
- Higher order $x \sim y \lesssim 10^{-3}$
  [Georgi hep-ph/9209291, Ohl et al. hep-ph/9301212, 1993; Bigi et al. hep-ph/0005089]
- Cannot exclude $y \sim 10^{-2}$ ($V_{ub} \neq 0$) [Bobrowski et al. 1002.4794]

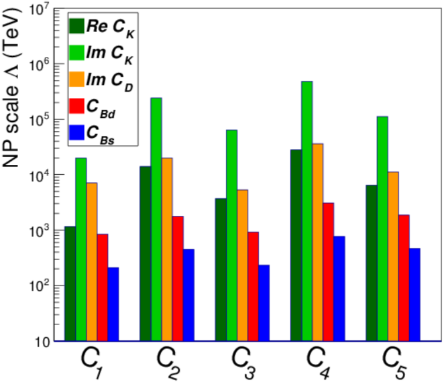
"Exclusive approach":

- 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

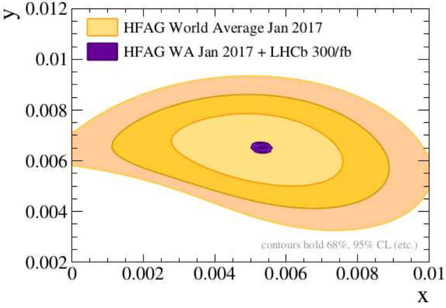
$D^0 - \bar{D}^0$ Mixing – NP

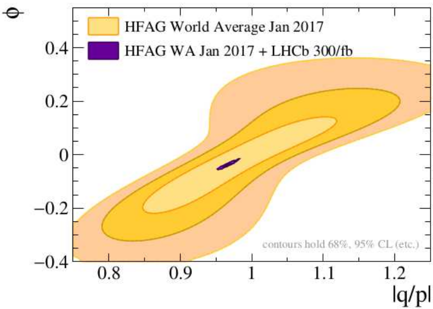
- Local NP contributions can be predicted very precisely
- Operator matrix elements from lattice QCD
  [Carrasco et al. 1403.7302, Bazavov et al. 1706.04622]



[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 $|\bar{A}_{\bar{f}}/A_f| \neq 1$ (CP violation in decay)

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

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 $\mathrm{Im}(\lambda_f) \equiv \mathrm{Im}(\frac{q}{p}\frac{\bar{A}_f}{A_f}) \neq 0$ (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 λ_d via unitarity: $\lambda_d + \lambda_s + \lambda_b = 0$
- λ_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

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

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

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

- 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 $\langle K\pi|\mathcal{H}_{\text{eff}}|D\rangle$ 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 $K \to \pi\pi$ 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, "ϵ^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, $\Delta\mathcal{A}_{CP}$ 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 $D \to \pi\pi$ has both $\Delta I = 1/2$ and $\Delta I = 3/2$:

$$Q_T \sim (\bar{d}c)(\bar{u}d)$$

- QCD penguin operators are purely $\Delta I = 1/2$:

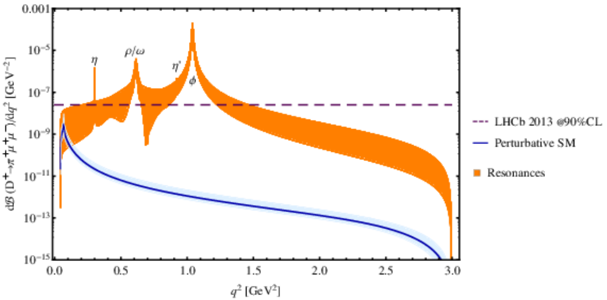
$$Q_P \sim (\bar{c}u) \otimes (\bar{u}u + \bar{d}d + \bar{s}s)$$

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

$$\begin{aligned}
A_{\pi^+\pi^-} &= \frac{1}{\sqrt{6}}\mathcal{A}_{3/2} + \frac{1}{\sqrt{3}}\mathcal{A}_{1/2}\,, \\
A_{\pi^0\pi^0} &= \frac{1}{\sqrt{3}}\mathcal{A}_{3/2} - \frac{1}{\sqrt{6}}\mathcal{A}_{1/2}\,, \\
A_{\pi^+\pi^0} &= \frac{\sqrt{3}}{2}\mathcal{A}_{3/2}\,.
\end{aligned}$$

- $D^+ \to \pi^+\pi^0$ purely $\Delta I = 3/2 \Rightarrow$ any CP asymmetry would be NP
- Can write down sum rules also for $D \to \rho\pi$, $D \to K^{(*)}\bar{K}^{(*)}\pi(\rho)$, $D_s^+ \to K^*\pi(\rho)$ [Grossman et al. 1204.3557]

$D^+ \to \pi^+\mu^+\mu^-$ and $D^0 \to P^+P^-\mu^+\mu^-$



[Updated plot thanks to Stefan de Boer]

- 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

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

D mixing versus K mixing

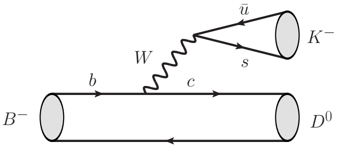
- Consider NP that couples to the LH quark doublets, e.g., $Q_{L,2} \sim (c_L, s_L)^T$
- SM plus NP:

$$\mathcal{L} \supset \overline{Q_{L,i}} Y^d_{ij} d_{R,j} H + \overline{Q_{L,i}} Y^u_{ij} u_{R,j} \tilde{H} + \frac{1}{\Lambda^2} (\overline{Q_{L,i}} X_{ij} Q_{L,j}) (\overline{Q_{L,i}} X_{ij} Q_{L,j})$$

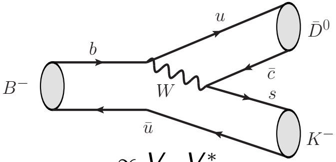
- Can always choose a basis where either Y^d or Y^u are diagonal
- Can always "adjust" NP to have vanishing contribution to *either* K mixing *or* D mixing, but not both
- Combining D and K mixing allows to test the UV flavor structure of NP [Blum et al. 0903.2118]

II: Implications for B physics

γ from tree decays – general idea

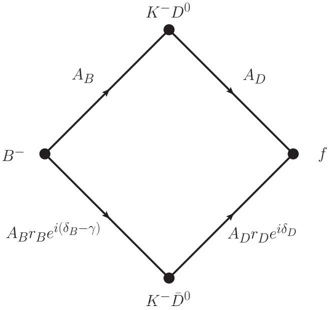


$\propto V^{\bar{u}}_{cb} V^*_{us}$



$\propto V_{ub} V^*_{cs}$

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



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:

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

- What is the size of the effect?

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

- $r_B(DK) = \mathcal{O}(10\%)\,, \quad \delta\gamma = \mathcal{O}(\text{few}\,\%)$
- $r_B(D\pi) = \mathcal{O}(0.5\%)\,, \quad \delta\gamma = \mathcal{O}(1)$

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

Including direct CP violation

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

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

- $\alpha_f \equiv \arg(A_f/\bar{A}_f) = -a_f^{\mathrm{dir}} \cot \delta_f$
- Cannot extract γ from $B \to DK$ alone without assumptions
- Measure δ_f at charm factories, or extract from $D - \bar{D}$ mixing

Why should we do D physics. . .

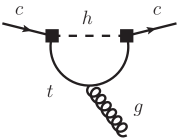
Why should we do D physics. . .

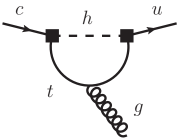
. . . if we can test the up-sector in top-quark decays?

Disentangle UV flavor structure

CP and flavor violating Higgs couplings

- Direct searches for $h \to cu$ 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





Observable	Coupling	Present bound	Future sensitivity
d_n	$\lvert \mathrm{Im}(Y_{tc} Y_{ct}) \rvert$	5.0×10^{-4}	1.7×10^{-6}
d_n	$\lvert \mathrm{Im}(Y_{tu} Y_{ut}) \rvert$	4.3×10^{-7}	1.5×10^{-9}
$\Delta \mathcal{A}_{CP}$	$\lvert \mathrm{Im}(Y_{ut}^* Y_{ct}) \rvert$	4.0×10^{-4}	–
$D - \bar{D}$	$\sqrt{\lvert \mathrm{Im}(Y_{tc}^* Y_{ct} Y_{ut}^* Y_{tu}) \rvert}$	4.1×10^{-4}	1.3×10^{-4}

[Gorbahn et al. 1404.4873]

Summary

- 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