CP violation and mixing in beauty and charm

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Motivation

- The CKM matrix encodes the quark flavour structure of the SM
  - Source of CP violation due to irreducible phase

    Probably too small to explain matter-antimatter asymmetry
  - No FCNC because of GIM mechanism

    Meson mixing can only arise at one-loop order
- For heavy hadrons H_Q, systematic framework: the HQE

  $m_Q \gg \Lambda_{\text{QCD}}$
- Aim at precise theoretical and experimental determinations
  - To test the SM and the framework used
  - To perform indirect NP searches

The heavy quark expansion (HQE)

- Lifetime $\tau = \Gamma^{-1}$ is a fundamental property of particles
- Can be systematically computed within the HQE [Shifman, Voloshin '85]

see also review [Lenz '14]

$$\Gamma(H_Q) = \underbrace{\Gamma_3}_{\Gamma(Q)} + \underbrace{\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_Q^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_Q^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_Q^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_Q^4} + \ldots \right]}_{\delta\Gamma(H_Q)}$$

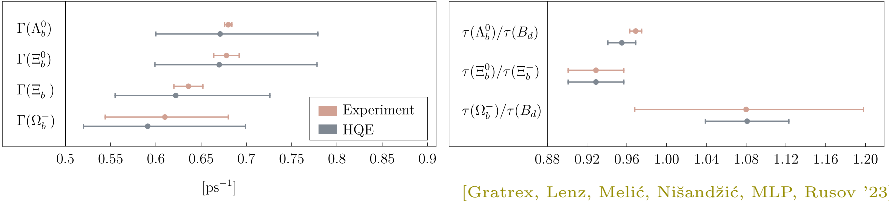
- $\Gamma_d, \tilde{\Gamma}_d$ - short distance coefficients
- $\mathcal{O}_d, \tilde{\mathcal{O}}_d$ - local operators bilinear in the heavy quark field
- $\Gamma(Q)$ - total decay width of free Q quark
- $\delta\Gamma(H_Q)$ - effects due to non perturbative interactions

Lifetimes in beauty sector

- Both the expansion parameters of the HQE are small

$$\alpha_s(m_b) \sim 0.22 \qquad \frac{\Lambda_{QCD}}{m_b} \sim 0.10$$

- Very good agreement of HQE predictions with data



[Gratrex, Lenz, Melić, Nišandžić, MLP, Rusov ’23]

- Dominant theoretical uncertainties due to
  - Scale variation - for the total widths
  - Non-perturbative inputs - for the lifetime ratios

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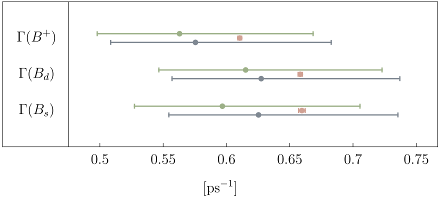
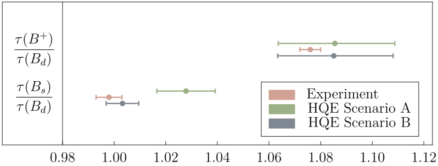




[Lenz, MLP, Rusov '22]

- Dominant theoretical uncertainties due to
  - Scale variation - for the total widths
  - Non-perturbative inputs - for the lifetime ratios

Tension between extraction of ρ_D^3 from inclusive B-decays!

[Bordone et al. '21; Bernlochner et al. '22]

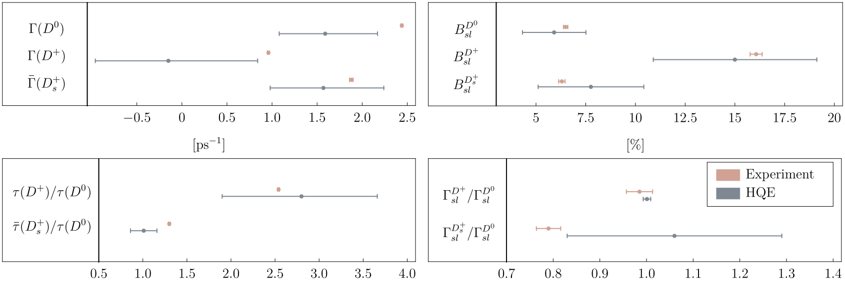
Lifetimes in charm sector

- Are the expansion parameters of the HQE small enough?

$$\alpha_s(m_c) \sim 0.33 \qquad \frac{\Lambda_{QCD}}{m_c} \sim 0.30$$

- The HQE can successfully explain the observed pattern

But with very large uncertainties!



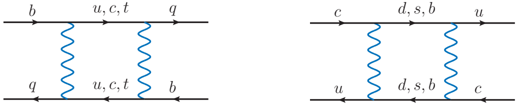
[King, Lenz, MLP, Rauh, Rusov, Vlahos '21]

- Results confirmed by recent analyses, studied also baryons

[Gratrex, Melić, Nišandžić '22; Dulibič, Gratrex, Melić, Nišandžić '23]

Meson mixing

- Neutral mesons mix with their antiparticles via box diagrams



- Evolution described by 2×2 Hamiltonian matrix

$$i\frac{d}{dt}\begin{pmatrix}|\mathcal{M}^0(t)\rangle \\ |\overline{\mathcal{M}}^0(t)\rangle\end{pmatrix} = \left(\hat{M} - i\frac{\hat{\Gamma}}{2}\right)\begin{pmatrix}|\mathcal{M}^0(t)\rangle \\ |\overline{\mathcal{M}}^0(t)\rangle\end{pmatrix} \Rightarrow \begin{cases}|\mathcal{M}_L\rangle = p\,|\mathcal{M}^0\rangle + q\,|\overline{\mathcal{M}}^0\rangle \\ |\mathcal{M}_H\rangle = p\,|\mathcal{M}^0\rangle - q\,|\overline{\mathcal{M}}^0\rangle\end{cases}$$

- Define mixing observables

$$\Delta M = M_H - M_L \qquad \Delta\Gamma = \Gamma_L - \Gamma_H$$

- And the dimensionless ratios

$$x = \Delta M/\Gamma \qquad y = \Delta\Gamma/2\Gamma \qquad \text{with} \qquad \Gamma = (\Gamma_H + \Gamma_L)/2$$

Meson mixing

- Theoretically determine mixing observables as

e.g. see reviews [Artuso, Borissov, Lenz '15; Lenz, Wilkinson '20]

$$\Delta M \approx 2|M_{12}| \qquad \Delta\Gamma \approx 2|\Gamma_{12}| \qquad \phi_{12} = \arg\left(-M_{12}/\Gamma_{12}\right)$$

Expanding in the small parameters $|\Gamma_{12}|/|M_{12}|$ and/or ϕ_{12}

- M_{12} corresponds to dispersive part of $\mathcal{M}^0 \to \overline{\mathcal{M}}^0$ amplitude
  - Directly sensitive to heavy NP particles
- Γ_{12} corresponds to absorptive part of $\mathcal{M}^0 \to \overline{\mathcal{M}}^0$ amplitude
  - Directly sensitive to light NP particles
- CP violation in mixing encoded in parameter $a_{\rm fs}$

$$\left|\frac{q}{p}\right| \approx 1 - \frac{a_{\rm fs}}{2} \qquad a_{\rm fs} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi_{12}$$

Mixing in beauty sector

- Off-shell contributions to the box diagrams

$$M_{12} = \lambda_u^2 \left(F_{cc} - 2F_{uc} + F_{uu}\right) + 2\lambda_u\lambda_t \left(F_{cc} - F_{uc} + F_{ut} - F_{ct}\right) + \lambda_t^2 \left(F_{cc} - 2F_{ct} + F_{tt}\right)$$

  - Described in terms of $\Delta B = 2$ effective Hamiltonian

- On-shell contributions to the box diagrams

$$\Gamma_{12} = \lambda_u^2 \left(\tilde{F}_{cc} - 2\tilde{F}_{uc} + \tilde{F}_{uu}\right) + 2\lambda_u\lambda_t \left(\tilde{F}_{cc} - \tilde{F}_{uc}\right) + \lambda_t^2 \tilde{F}_{cc}$$

  - Described by double insertion of $\Delta B = 1$ effective Hamiltonian

Can be computed within the HQE

$\lambda_u^d \sim \lambda_c^d \sim \lambda_t^d$ $\quad$ $\lambda_u^s \ll \lambda_c^s \sim \lambda_t^s$ $\quad$ $\lambda_x^q = V_{xb} V_{xq}^*$

- GIM and CKM suppressions go in the same direction!

Mixing in beauty sector

- Current theoretical status

[Lenz, Tetlalmatzi-Xolocotzi '19; Gerlach, Nierste, Shtabovenko, Steinhauser '22]

$\Delta\Gamma_d^{\mathrm{SM}} = (2.6 \pm 0.4) \cdot 10^{-3} \mathrm{ps}^{-1}$ $\Delta M_d^{\mathrm{SM}} = (0.543 \pm 0.029) \mathrm{ps}^{-1}$ $a_{\mathrm{fs,d}}^{\mathrm{SM}} = (-4.73 \pm 0.42) \cdot 10^{-4}$

$\Delta\Gamma_s^{\mathrm{SM}} = (7.6 \pm 1.7) \cdot 10^{-2} \mathrm{ps}^{-1}$ $\Delta M_s^{\mathrm{SM}} = (18.77 \pm 0.86) \mathrm{ps}^{-1}$ $a_{\mathrm{fs,s}}^{\mathrm{SM}} = (2.06 \pm 0.18) \cdot 10^{-5}$

  - NLO and NNLO corrections at dim-6, LO at dim-7

[Buras et al. '99; Beneke et al. '98, '03; Ciuchini et al. '98; Lenz, Nierste '06]
[Asatrian et al. '17, '20; Beneke at al. '96; Dighe et al. '01]

  - Dim-6 and dim-7 bag parameters

HQET SR: [Kirk, Lenz, Rauh '17; King, Lenz, Rauh '19]

Fermilab/MILC 1602.03560, RBC/UKQCD 1812.08791, HPQCD 1907.0102, 1910.00970

- Compare with experimental status [HFLAV '23]

$(\Delta\Gamma_d/\Gamma_d)^{\mathrm{exp.}} = 0.001 \pm 0.010$ $\Delta M_d^{\mathrm{exp.}} = (0.5065 \pm 0.0019) \mathrm{ps}^{-1}$ $a_{\mathrm{fs,d}}^{\mathrm{exp.}} = (-21 \pm 17) \cdot 10^{-4}$

$\Delta\Gamma_s^{\mathrm{exp.}} = (7.4 \pm 0.6) \cdot 10^{-2} \mathrm{ps}^{-1}$ $\Delta M_s^{\mathrm{exp.}} = (17.765 \pm 0.006) \mathrm{ps}^{-1}$ $a_{\mathrm{fs,s}}^{\mathrm{exp.}} = (-60 \pm 280) \cdot 10^{-5}$

Mixing in charm sector

- Strong interplay of CKM and GIM suppression

$\lambda_d \sim \lambda_s \sim \lambda \gg \lambda_b \sim \lambda^5$ $\quad$ $\lambda_x = V_{cx} V_{ux}^*$

$$M_{12} = \lambda_s^2 \left(F_{ss} - 2F_{ds} + F_{dd}\right) + 2\lambda_s \lambda_b \left(F_{bs} - F_{bd} + F_{dd} - F_{sd}\right) + \lambda_b^2 \left(F_{bb} - 2F_{bd} + F_{dd}\right)$$

$$\Gamma_{12} = -\lambda_s^2 \left(\tilde{F}_{ss} - 2\tilde{F}_{ds} + \tilde{F}_{dd}\right) + 2\lambda_s \lambda_b \left(\tilde{F}_{sd} - \tilde{F}_{dd}\right) - \lambda_b^2 \tilde{F}_{dd}$$

  - All terms are of similar size, pronounced cancellations
  - Dominated by double insertion of $\Delta C = 1$ effective Hamiltonian

Can be computed within the HQE?

Mixing in charm sector

- Experimentally both x and y are measured quite precisely

[HFLAV '22]

$x^{\text{exp.}} = (0.407 \pm 0.044)\,\%$ $\quad$ $y^{\text{exp.}} = (0.647 \pm 0.024)\,\%$

- Determine y within the HQE

$y^{\text{HQE}} \sim 10^{-4}\, y^{\text{exp.}}\,!$

- Complete failure of HQE for charm mixing?

However HQE successful for charm lifetimes

  * Alternative renormalisation scale setting can lift GIM cancellation

    [Lenz, MLP, Vlahos '20]

  * Potential large impact of higher dimensional operators

    [Georgi '92; Ohl et al. '93; Bigi, Uraltsev '00]

- Use different method: lattice determination, exclusive approach

[Hansen, Sharpe '12] see e.g. [Falk et al. '01]

CP asymmetries

- Flavour-specific CP asymmetry:

$$A_{\rm fs} = \frac{\Gamma(\overline{\mathcal{M}}(t) \to f) - \Gamma(\mathcal{M}(t) \to \bar{f})}{\Gamma(\overline{\mathcal{M}}(t) \to f) + \Gamma(\mathcal{M}(t) \to \bar{f})} = a_{\rm fs}$$

$\mathcal{A}_{\bar{f}} = 0, \; \bar{\mathcal{A}}_f = 0$, also assume $\mathcal{A}_f = \bar{\mathcal{A}}_{\bar{f}}$

  - Observation of $a_{\rm fs}(\bar{B}_s \to D_s^+ \pi^-) - a_{\rm fs}(\bar{B}_s \to D_s^+ \ell^- \bar{\nu}) \neq 0$ clear sign of NP

[Gershon, Lenz, Rusov, Skidmore '21; Fleischer, Vos '17]

- Mixing-induced CP asymmetry:

$$A_{\rm ind} = \frac{\Gamma(\overline{\mathcal{M}}(t) \to f) - \Gamma(\mathcal{M}(t) \to f)}{\Gamma(\overline{\mathcal{M}}(t) \to f) + \Gamma(\mathcal{M}(t) \to f)}$$

e.g. $\bar{B}_s \to J/\psi \phi, \quad \bar{B}_d \to J/\psi K_S$

  - Exp. precision for β_s close to th. uncertainty of penguin pollution

Still not known from first principles!

- Direct CP asymmetry:

$$A_{\rm dir} = \frac{\Gamma(\overline{\mathcal{M}}(t) \to \bar{f}) - \Gamma(\mathcal{M}(t) \to f)}{\Gamma(\overline{\mathcal{M}}(t) \to \bar{f}) + \Gamma(\mathcal{M}(t) \to f)}$$

e.g. $\Delta A_{\rm CP} = A_{\rm dir}(D^0 \to K^+ K^-) - A_{\rm dir}(D^0 \to \pi^+ \pi^-)$

  - Theory very hard, it is crucial to control penguin contributions

Non-leptonic decays are challenging

- The tree-level decays $\bar{B}_{(s)} \to D^+_{(s)} K^-(\pi^-)$ are th. "clean", and
  - Tension between QCDF predictions and data ranging $(2-7)\sigma$

    [Bordone, Gubernari, Huber, Jung, van Dyk '20]
  - Investigated explanation in terms of NP in $b \to c\bar{u}d(s)$ transitions

    [Cai, Deng, Li, Yang '21]
    - Significant modification of CKM angle γ

      [Brod, Lenz, Tetlalmatzi-Xolocotzi, Wiebusch '14]
    - Potential additional constraints from $\tau(B^+)/\tau(B_d)$ and $a^d_{\rm fs}$

      [Lenz, Müller, MLP, Rusov '22]
  - Most likely, tension due to underestimated hadronic effects

    [MLP, Rusov (in progress)]
- For more complicated decays with peng. and annih. contributions
  - Still a long way to go ...

In the beauty sector and even more in the charm sector!

Conclusions

- HQE powerful tool for inclusive observables of heavy hadrons
- Good agreement for lifetimes and B-mixing
- Satisfactory description of D-mixing still missing
- Future improvements are challenging but doable
  - Particularly with more, and more precise data!

$a_{\rm fs}$, inclusive SL B- and B_s-decays, cross-checks of size of penguin pollution ...

Thanks for the attention