Renormalization Scale Setting in D-Mixing

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Motivation

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

where

$$A_{CP}(f,t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)}$$

- Current value: $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ [LHCb: 1903.08726]

This is a 5.3σ deviation from zero

- Some SM predictions give a bound $|\Delta A_{CP}| \leq 3.6 \cdot 10^{-4}$ which is a $4 - 6\sigma$ tension to the experimental value
  - i Statistics
  - ii Big non perturbative effects [e.g. arXiv:1903.10952]
  - iii New physics [e.g. arXiv:1903.10490]

We need a better theoretical understanding of charm physics!

Theory vs Experiment in D-mixing

- Experimentally y is well known (x is still only 3σ from 0)

$$x = \frac{\Delta M_D}{\Gamma_{D^0}} = 0.37^{+0.12}_{-0.12}\% \;, y = \frac{\Delta\Gamma_D}{2\Gamma_{D^0}} = 0.68^{+0.06}_{-0.07}\%$$

[HFLAV:1909.12524]

where

$$\begin{aligned} \Delta M_D &= 2|M_{12}^D| \cdot (1 + \mathcal{O}((\phi_{12}^D)^2)) \\ \Delta\Gamma_D &= 2|\Gamma_{12}^D| \cdot (1 + \mathcal{O}((\phi_{12}^D)^2)) \\ \phi_{12}^D &= \arg\left(-\frac{M_{12}^D}{\Gamma_{12}^D}\right) \end{aligned}$$

[arXiv:2011.04443]

- Theoretical predictions however for Γ_{12} and M_{12} give a huge range of values, differing by several orders of magnitude!

HQE

- Heavy Quark Expansion (HQE) has been working great for the B system where the expansion parameter (Λ/m_b) is small but what about the charm system?

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_Q^2}\Gamma_2 + \dots$$

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|^{\text{PDG}} = 2.536(19), \quad \left.\frac{\tau(D^+)}{\tau(D^0)}\right|^{\text{HQE 2017}} = 2.7^{+0.7}_{-0.8}$$

[arXiv:1711.02100]

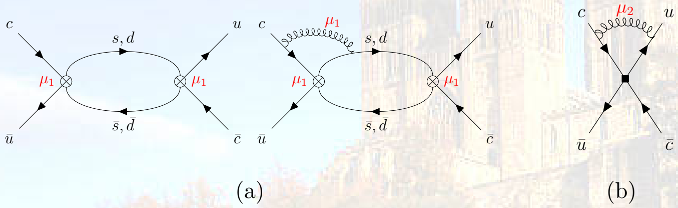
[King, Lenz, Piscopo, Rauh, Rusov, CV in progress]

[See talk by Aleksey Rusov tomorrow]

- Theory estimates agree with experiment (even with big uncertainties)

- So what is wrong with D-mixing?

HQE for D-mixing



$$\Gamma_{12} = \left[\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \ldots\right]\frac{\langle Q_6\rangle}{m_c^3} + \left[\Gamma_4^{(0)} + \ldots\right]\frac{\langle Q_7\rangle}{m_c^4} + \ldots$$

We are looking into the following quantity:

$$\Omega = \frac{2\,|\Gamma_{12}|}{0.028\,\mathrm{ps}^{-1}}, \quad \Delta\Gamma_D^{Exp} \geq 0.028\,\mathrm{ps}^{-1} \text{ at } 1\sigma$$

A naive HQE calculation gives $\Omega = 6.2 \cdot 10^{-5}$

GIM in D-mixing

Invited special talk: Luciano Maiani 'The GIM mechanism: The beginning of the November revolution'

Prof. Luciano Maiani

- Unlike $B_{(s)}$ mixing where only one contribution (internal $c\bar{c}$ quark pair) is dominant, for Γ_{12} in D mixing we need all 3 quark combinations (ss, sd, dd).

- Unfortunately the CKM dominant terms suffer from severe GIM suppression

$$
\begin{aligned}
\Gamma_{12} &= -\lambda_s^2 \overbrace{\left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right)}^{\substack{GIM^2 \\ suppressed}} + 2\overbrace{\lambda_s\lambda_b}^{\substack{CKM \\ suppressed}} \overbrace{\left(\Gamma_{12}^{sd} - \Gamma_{12}^{dd}\right)}^{\substack{GIM \\ suppressed}} - \overbrace{\lambda_b^2}^{\substack{CKM^2 \\ suppressed}} \Gamma_{12}^{dd} \\
\lambda_q &= V_{cq}V_{uq}^*
\end{aligned}
$$

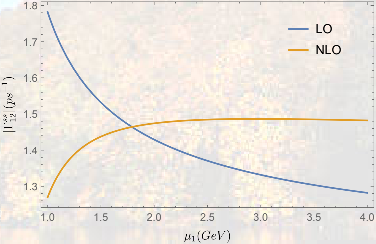
- GIM suppression seems to get lifted a bit at NLO

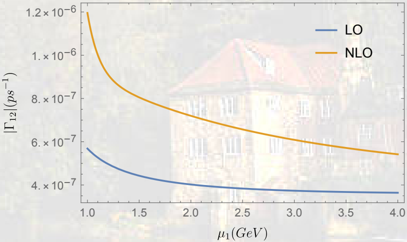
Scale Setting

There are two renormalisation scales in this problem:

- μ_1 ($\Delta C = 1$ Wilson coefficients and radiative corrections to diagrams)
- μ_2 (loop corrections to $\Delta C = 2$ operators and loop corrections of HQE diagrams)

Consider only μ_1. Typically the scale μ_1 is set to m_c to minimize terms like $\alpha_s(\mu_1) \ln(\mu_1^2/m_c^2)$.





The scales in the individual diagrams are set to be equal:

$\mu_1^{ss} = \mu_1^{ds} = \mu_1^{dd}$

Scale Setting

Here we consider the possibility of choosing $\mu_1^{ss} \neq \mu_1^{ds} \neq \mu_1^{dd}$ since all intermediate states with net strangeness$= 1$ are clearly different from states with net strangeness$= 0$:

- Vary μ_1 independently between $1\ \mathrm{GeV}$ and $2m_c$ for the three contributions: ss, sd, dd
- The scale for each contribution is set differently based on the available phase space
  - $\mu_1^{ss} = m_c - 2\epsilon$
  - $\mu_1^{sd} = m_c - \epsilon$
  - $\mu_1^{dd} = m_c$

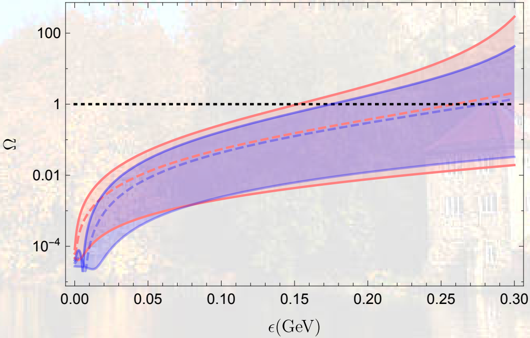
The parameter ϵ intuitively can be estimated to be the strange quark mass ($\epsilon \approx 0.1\ \mathrm{GeV}$) or the phase space difference of exclusive decay channels ($\epsilon \approx 0.35\ \mathrm{GeV}$)

Results

- In the first case we get a much bigger range of values for Ω:

$$\Omega \in [4.6 \cdot 10^{-5}, 1.3]$$

  - Experimental value is covered!
  - Majority of scale choices gives $\Omega > 0.1$
- For the second case, for a scale $\epsilon \approx 0.2$ GeV we can get $\Omega = 1$



Other Observables

- We see how this alternative scale setting bring the HQE prediction for D-mixing into agreement with experiment. What about other observables though?
- B and D meson lifetimes as well as decay rate difference for the B_s meson have no GIM suppresion so this method will not change the results compared to the standard treatment of μ.
- Semileptonic CP asymmetries will show an effect, but they are less GIM suppressed than D-mixing.

ϵ (GeV)	Γ_{12}^s/M_{12}^s	Γ_{12}^d/M_{12}^d
0.	$-0.00499 + 0.000022I$	$-0.00497 - 0.00050I$
0.2.	$-0.00494 + 0.000023I$	$-0.00492 - 0.00053I$
0.5.	$-0.00484 + 0.000026I$	$-0.00482 - 0.00059I$
1.0	$-0.00447 + 0.000037I$	$-0.00448 - 0.00084I$
1.5.	$-0.00287 + 0.000091I$	$-0.00309 - 0.0021I$

Inside theory uncertainties
Outside theory uncertainties

$\Delta\Gamma/\Delta M = -\mathrm{Re}(\Gamma_{12}/M_{12})$ not affected ; $a_{sl} = \mathrm{Im}(\Gamma_{12}/M_{12})$ more affected

Conclusion

- The theoretical description of D-mixing has been one of the biggest puzzles in charm physics.
- HQE seems to be working for other inclusive decays like D meson lifetime ratios but it seemed to fail for D mixing
- Biggest issue is the huge GIM suppression of Γ_{12}
- Setting $\mu_1^{ss} = \mu_1^{sd} = \mu_1^{dd}$ implicitly assumes a precision of $\mathcal{O}(10^{-5})$, which is of course not realistic.
- Setting the renormalisation scale different for different decay channels lifts this suppression and gives a big range of results that includes experimental values.
- Although most other observables would not be affected by this different strategy, the theory uncertainties for the semileptonic CP asymmetries can be significantly enhanced.

Thank you for your attention!

Any questions?