



# B mixing: unexplored observables

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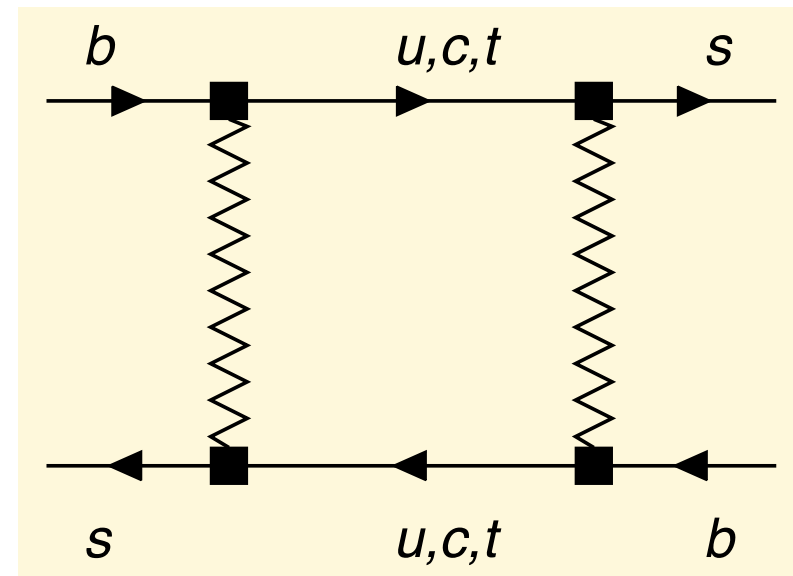
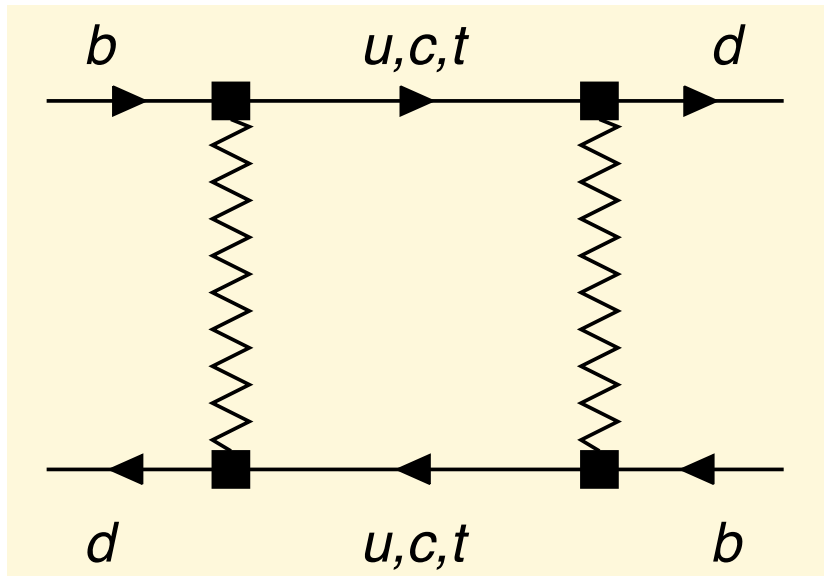


Particle Physics Phenomenology after the Higgs Discovery



# Meson-antimeson mixing

- The flavoured neutral mesons  $M = K, D, B_d, B_s$  mix with their antiparticles:
  - $\Rightarrow$  mass eigenstates  $\neq$  flavour eigenstates
  - $\Rightarrow$  damped  $M-\bar{M}$  oscillations
- gold mine for CP studies!



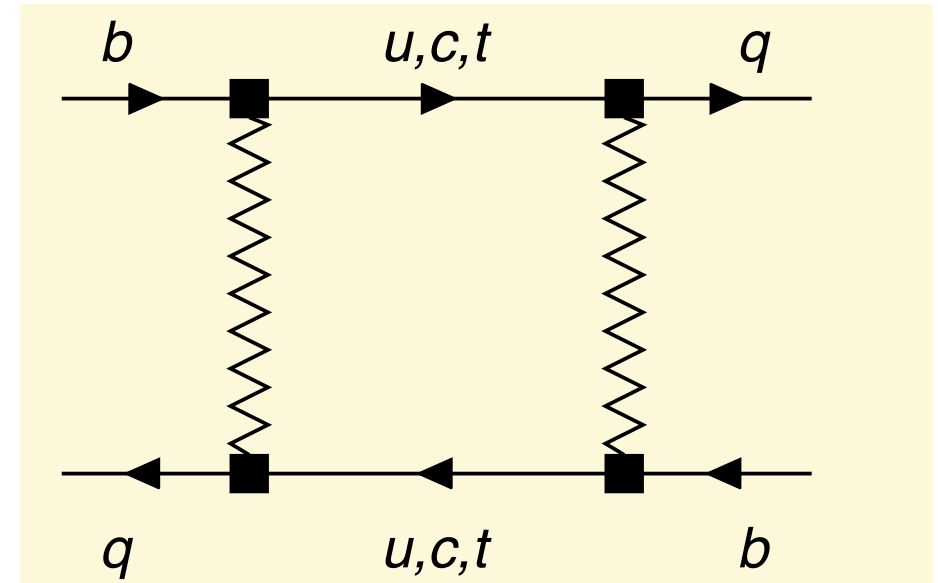
# $B - \bar{B}$ mixing

- $B_q - \bar{B}_q$  mixing involves the  $2 \times 2$  hermitian matrices  $M^q$  and  $\Gamma^q$ , where  $q = d$  or  $s$ .

- off-diagonal element  $M_{12}^q - i\frac{\Gamma_{12}^q}{2} \neq 0$   
 $\Rightarrow B_q - \bar{B}_q$  oscillations

- diagonalise  $M^q - i\frac{\Gamma^q}{2}$ :
 
$$\begin{aligned} |B_L\rangle &= p|B_s\rangle + q|\bar{B}_s\rangle \\ |B_H\rangle &= p|B_s\rangle - q|\bar{B}_s\rangle \end{aligned}$$
 with  $\begin{cases} L = \text{"light"} \\ H = \text{"heavy"} \end{cases}$

$|B_L\rangle$  and  $|B_H\rangle$  obey exponential decay laws:  $|B_{L,H}(t)\rangle = e^{-iM_{L,H}t - \Gamma_{L,H}t/2} |B_{L,H}\rangle$



# $B - \bar{B}$ mixing

- Three universal physical quantities in  $B_q - \bar{B}_q$  mixing:

$$\left| M_{12}^q \right|, \quad \left| \Gamma_{12}^q \right|, \quad \phi_q \equiv \arg \left( -\frac{M_{12}^q}{\Gamma_{12}^q} \right) \quad \leftarrow \text{quantifies "CP violation in mixing"}$$

entering every  $B_q$  decay.

- Fourth quantity defined via a chosen exclusive decay:

$$\arg \left( M_{12}^q / (V_{cb} V_{cq}^*)^2 \right) \text{ from } B_d \rightarrow J/\psi K_S \text{ and } B_s \rightarrow J/\psi \phi \quad \leftarrow \text{quantifies "mixing-induced CP violation"}$$

Future: Get information on  $\arg M_{12}^q$  instead from

$$B_d \rightarrow \bar{D}^0 K_S \text{ and } B_s \rightarrow \bar{D}^0 \phi \text{ combined with } \gamma \text{ from } B^+ \rightarrow \bar{D}^0 K^+$$

$\Rightarrow$  no penguin pollution.

# $B - \bar{B}$ mixing

- Three universal physical quantities in  $B_q - \bar{B}_q$  mixing:

$$\left| M_{12}^q \right|, \quad \left| \Gamma_{12}^q \right|, \quad \phi_q \equiv \arg \left( -\frac{M_{12}^q}{\Gamma_{12}^q} \right) \leftarrow \text{quantifies "CP violation in mixing"}$$

- $|\Gamma_{12}^q| \ll |M_{12}^q| \Rightarrow$  expand in  $|\Gamma_{12}^q|/|M_{12}^q|$  from now on

- Determined from three observables:

- mass difference:  $\Delta m_q \equiv M_H^q - M_L^q \simeq 2 |M_{12}^q| \leftarrow \text{equals oscillation frequency}$

- width difference:  $\Delta \Gamma_q \equiv \Gamma_L^q - \Gamma_H^q \simeq 2 |\Gamma_{12}^q| \cos \phi_q \leftarrow \text{small!}$

- CP asymmetry in flavour-specific decays:  $a_{\text{fs}}^q = \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin \phi_q \leftarrow \text{even smaller, since } \phi_q \ll 1$

# $\Delta\Gamma^q$ and $a_{\text{fs}}^q$

- Experimental situation (HFLAV 2024):

- $\Delta\Gamma^{s,\text{exp}} = (0.0781 \pm 0.0035) \text{ ps}^{-1}$

- $\Delta\Gamma^{d,\text{exp}} = (0.001 \pm 0.010) \text{ ps}^{-1}$

- $a_{\text{fs}}^{d,\text{exp}} = -0.0021 \pm 0.0017$

- $a_{\text{fs}}^{d,\text{exp}} = -0.0006 \pm 0.0028$

- Theory predictions are done in a double expansion in  $\Lambda_{\text{QCD}}/m_b$  and  $\alpha_s$ .

State of the art:  $m_b^0$ ,  $m_b^0\alpha_s$ , and  $m_b^0\alpha_s^2$  ← next-to-next-to-leading order, 3 loops  
well-known hadronic matrix elements  
from lattice QCD

$\Lambda_{\text{QCD}}/m_b$ : no QCD corrections yet, poorly known matrix elements

UN, Pascal Reeck, Vladyslav Shtabovenko, Matthias Steinhauser, *JHEP* 03 (2026) 094

- 2025 theory predictions:

$$a_{\text{fs}}^s = (2.27 \pm 0.13) \times 10^{-5}, \quad a_{\text{fs}}^d = - (5.19 \pm 0.30) \times 10^{-4}$$

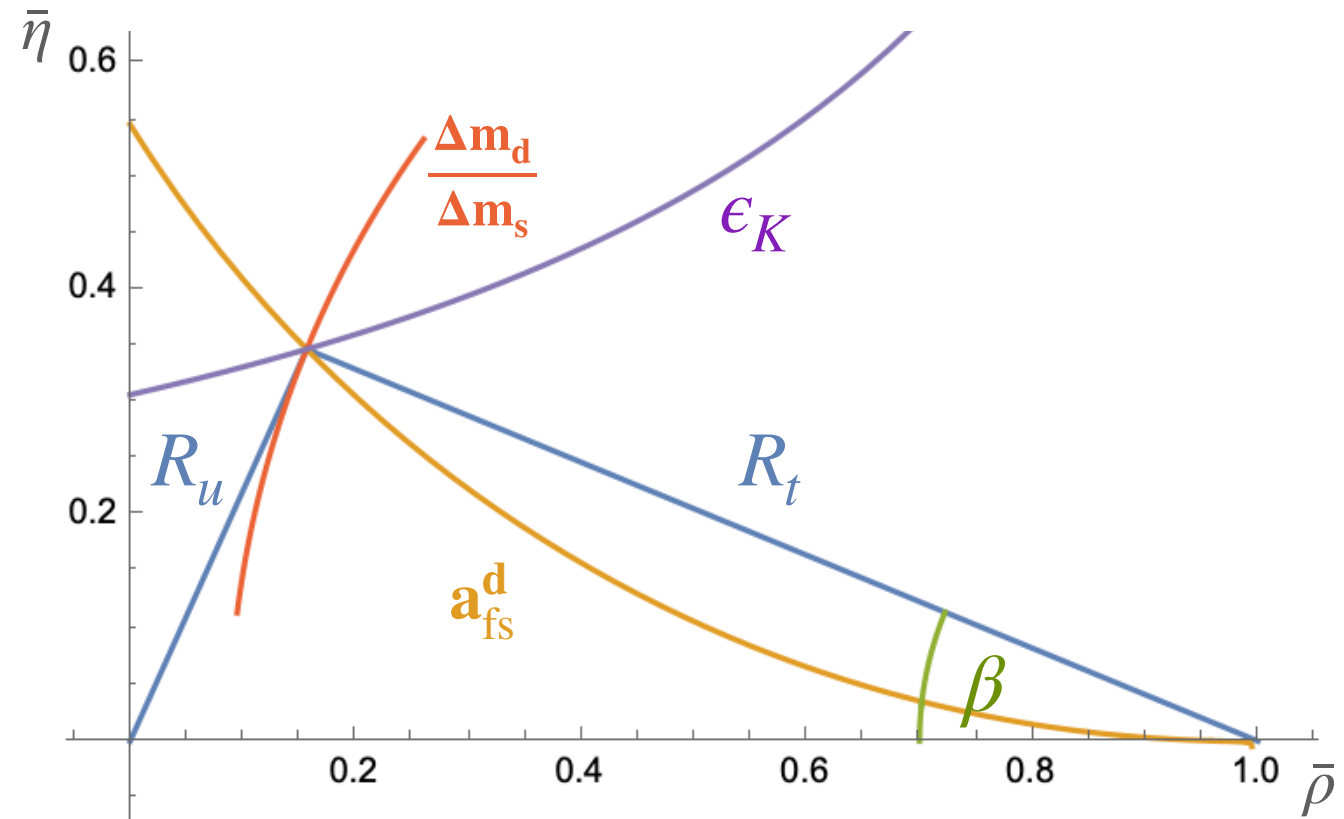
Error dominated by unknown  $\alpha_s/m_b$  terms and poor  $1/m_b$  matrix elements.

- 2025 theory prediction:

$$a_{fs}^d = - (5.19 \pm 0.30) \times 10^{-4}$$

determines a circle in the  $(\bar{\rho}, \bar{\eta})$  plane of the unitarity triangle.

- Can test new physics from  $B_d - \bar{B}_d$  observables alone!



# $a_{\text{fs}}^d$ and $\Delta\Gamma^d$

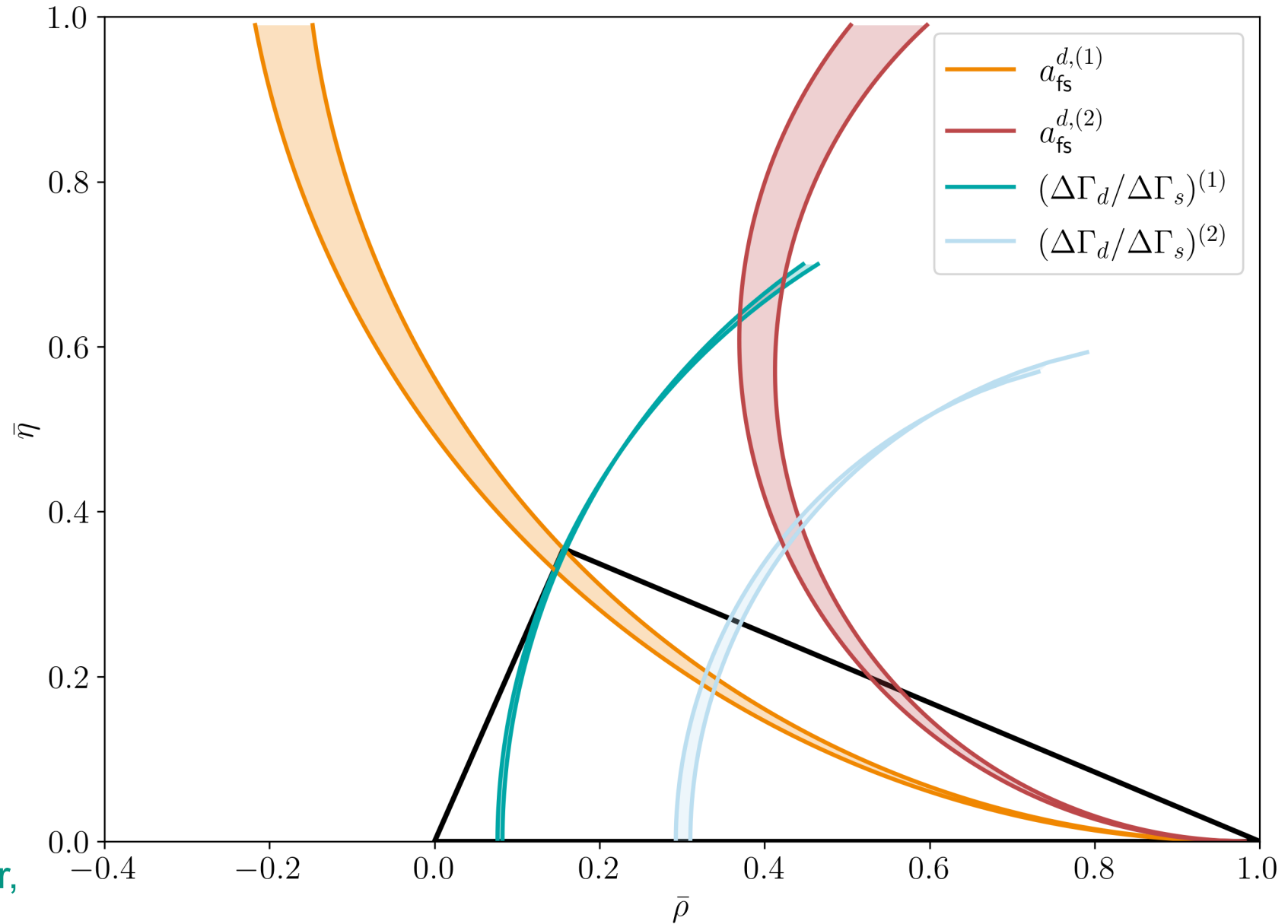
Standard Model

$$a_{\text{fs}}^q \propto m_c^2/m_b^2 \sin\phi_q,$$

but new physics can easily lift this suppression!

Bands show uncertainty from NNLO piece, uncertainty from  $1/m_b$  part not shown.

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# Conclusions

- The yet unmeasured quantities  $a_{\text{fs}}^{d,s}$  and  $\Delta\Gamma^d$  will complete the knowledge on the  $B_q - \bar{B}_q$  mixing complex and are highly sensitive to new physics.
- The quantities can be calculated reliably. New **NNLO** results were obtained in 2025.
- $a_{\text{fs}}^d$  defines a circle in the  $(\bar{\rho}, \bar{\eta})$  plane!

# The usual theorist's persuasion:



Psst!!! Hey, bud! C'mere.

Who? Me?

You can make a DISCOVERY  
and become famous!  
And it is JUST AROUND  
the corner!

Wow, I can become  
famous!!!

Just look for  $a_{fs}^d$  and  $\Delta\Gamma^d$  !