Karlsruher Institut für Technologie

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Institut für Theoretische Teilchenphysik (KIT)

CP violation, B mixing and lifetimes

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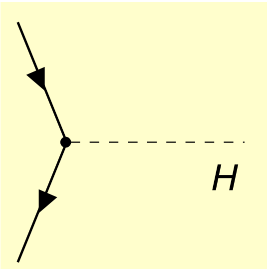
Outline

- Flavour in a nutshell
- $B-\bar{B}$ mixing: β and β_s
- $B-\bar{B}$ mixing: width difference
- Summary and outlook

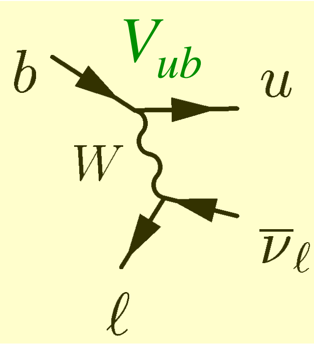
Flavour in a nutshell

Flavour physics

- studies transitions between different fermions.
- Standard Model: from Higgs Yukawa interaction
- encoded in Cabibbo-Kobayashi-Maskawa (CKM) matrix:



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.96 & 0.23 & 0.004 e^{-i\gamma} \\ -0.23 & 0.96 & 0.040 \\ 0.009 e^{-i\beta} & -0.04 e^{i\beta_s} & 1.0 \end{pmatrix}$$

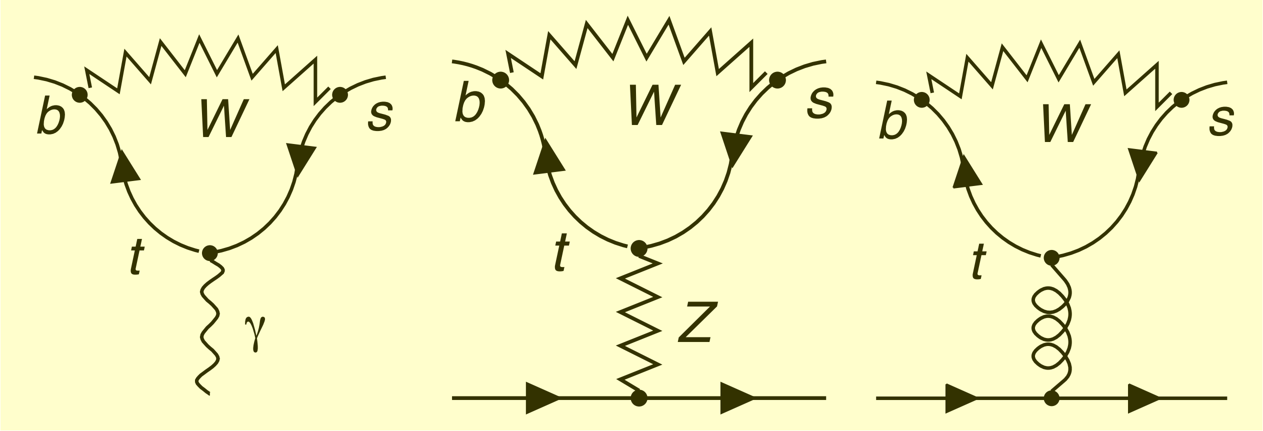


- Charge-parity (CP) violating quantities involve
  $\gamma \approx 66°$, $\beta \approx 23°$, $\beta_s \approx 1.1°$.
  β and β_s are calculable in term of γ, the KM phase.

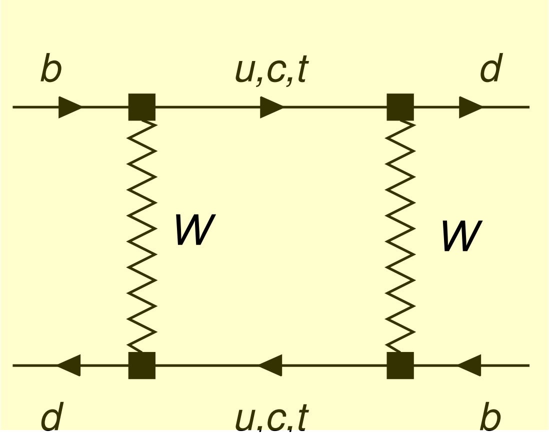
Flavour physics

- Best suited: Flavour-changing neutral current (FCNC) processes like $b \to s$, $b \to d$, $c \to u$, $\mu \to e$.

Penguins:

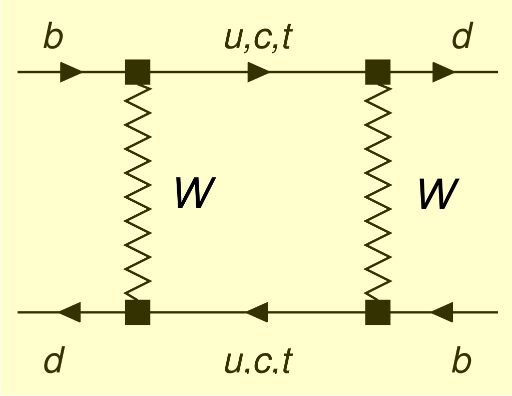


Box:



Flavour physics

- In FCNC processes several suppression factors pile up:
  - electroweak loop
  - small elements of the Cabibbo-Kobayashi-Maskawa matrix $|V_{ts}| \simeq |V_{cb}| = 0.04$, $|V_{td}| = 0.01$
  - possible GIM suppression factor $(m_c^2 - m_u^2)/M_W^2$ (in Kaon FCNCs) or $(m_{\nu_3}^2 - m_{\nu_1}^2)/M_W^2$ (in $\mu \to e\gamma$)
  - possible helicity suppression by e.g. m_μ^2/M_W^2 in $B_{s,d} \to \mu^+\mu^-$



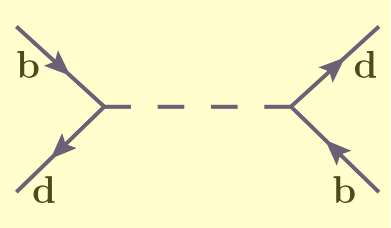
BSM mass reach

Flavour physics probes virtual effects of new heavy particles coupling to quarks, with a mass reach of

a few TeV in tree-level decays like for $b \to c\tau\bar{\nu}$,

a few tens of TeV in FCNC decays like $b \to s\ell^+\ell^-$, and

a few hundreds of TeV in $B{-}\bar{B}$ mixing.



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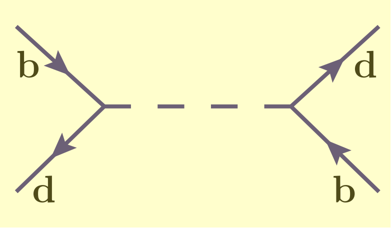


⇒ The firm establishment of flavour BSM physics helps for the design of a future hadron collider and could establish a "no-lose" situation for FCC-hh.

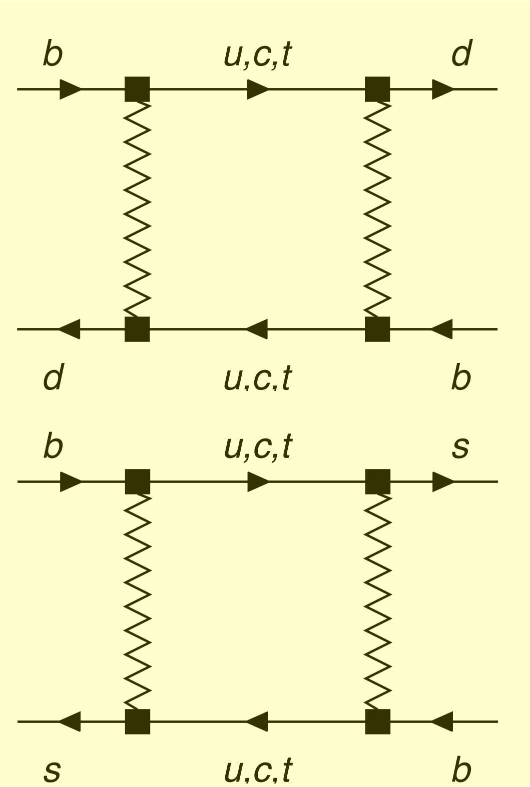
FCC-hh fans ♥ flavour physics

flavour physicists ♥ FCC-ee: 10^{13} Z bosons are a perfect b factory!

$B - \bar{B}$ mixing: β and β_s

$B-\bar{B}$ mixing

- $B_d-\bar{B}_d$ mixing and $B_s-\bar{B}_s$ mixing
- $\begin{pmatrix} |B_q\rangle \\ |\bar{B}_q\rangle \end{pmatrix}$ involves the 2×2
  - mass matrix M (from boxes with one or two tops)
  - decay matrix Γ (from box without top)
- $|\Gamma_{12}| \ll |M_{12}|$
- two mass eigenstates with mass difference
  - $\Delta m \simeq 2|M_{12}|$ equals $B-\bar{B}$ oscillation frequency



B oscillations and CP violation

- Consider time-dependent CP asymmetry for B_d decay into CP eigenstate $f_{\rm CP}$:

tagged as $\bar{B}_d$ at $t = 0$

$$a_{\rm CP}(B_d(t) \to f_{\rm CP}) \equiv \frac{\Gamma(\bar{B}_d(t) \to f_{\rm CP}) - \Gamma(B_d(t) \to f_{\rm CP})}{\Gamma(\bar{B}_d(t) \to f_{\rm CP}) + \Gamma(B_d(t) \to f_{\rm CP})}$$

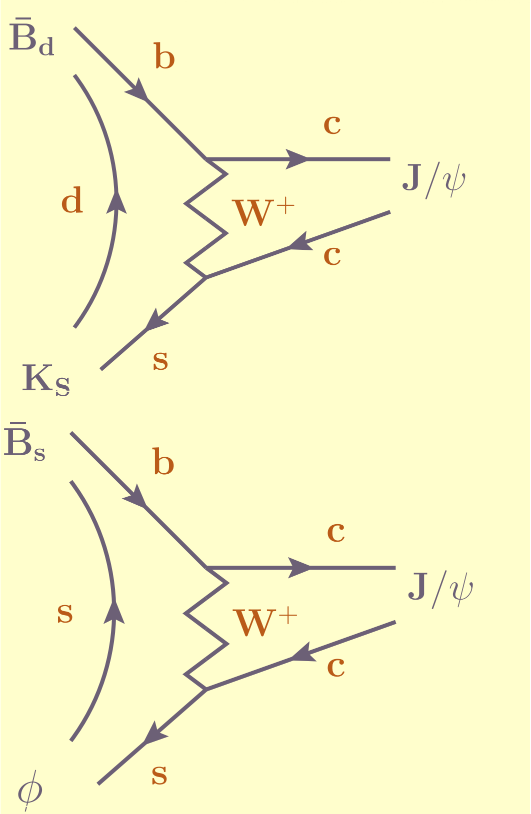
$$= -A_{\rm CP}^{\mathrm{dir}, B_d \to f_{\rm CP}} \cos(\Delta m t) \; - \; A_{\rm CP}^{\mathrm{mix}, B_d \to f_{\rm CP}} \sin(\Delta m t)$$

direct CP asymmetry

mixing-induced CP asymmetry

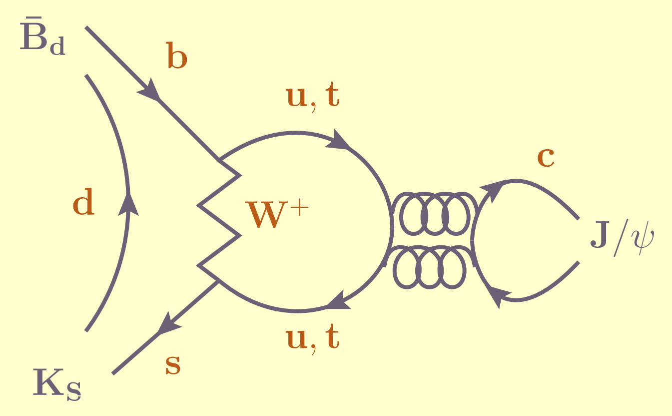
Mixing-induced CP violation

- Golden modes: only one decay amplitude:
  $A_{CP}^{dir} = 0$ and $A_{CP}^{mix} = \pm\sin(\phi_M - 2\phi_f)$,
  where ϕ_M is the CP phase of M_{12} (box diagram)
  and ϕ_f is the CP phase of the decay amplitude.
  - $B_d \to J/\psi K_S$: $\phi_M = \arg[(V_{tb}V_{td}^*)^2] = 2\beta$
  - $B_s \to J/\psi\phi$: $\phi_M = \arg[(V_{tb}V_{ts}^*)^2] = -2\beta_s$
  - in both decays: $\phi_f = \arg(V_{cb}V_{cs}^*) = 0$, so that
    $A_{CP}^{mix} = \pm\sin(2\beta_{(s)})$



Penguin pollution

- $A_{\rm CP}^{\rm mix}(B_d \to \psi K_S) = 0.709 \pm 0.011$ (all charmonium modes) (HFLAV)
  1.6% precision!
- $A_{\rm CP}^{\rm mix}(B_s \to J/\psi\phi) = -0.060 \pm 0.014$
  (HFLAV)
- Yet these $b \to c\bar{c}s$ modes are not completely golden: Penguin pollution, second amplitude with $V_{ub}V_{us}^*$ interferes with tree amplitude.



- $\dfrac{|V_{ub}V_{us}|}{|V_{cb}V_{cs}|} = 0.022$. Relevant with today's precision?

Penguin pollution

- Two ways to estimate penguin pollution:
  - Use $b \to c\bar{c}d$ data to constrain penguin/tree ratio, employing
    $$\frac{|V_{ub}V_{ud}|}{|V_{cb}V_{cd}|} = 0.5 \gg 0.02$$
    and using approximate U-spin symmetry (linking strange to down) of QCD.

    M. Barel, K. De Bruyn, R. Fleischer, E. Malami, *J.Phys.G* 48 (2021) 6, 065002

    Works for $B_d \to J/\psi K_S$, but not for $B_s \to J/\psi \phi$.
  - Calculate penguin pollution in QCD with soft-collinear factorisation for both $b \to c\bar{c}d$ and $b \to c\bar{c}s$, see

    Ph. Frings, UN, M. Wiebusch, Phys.Rev.Lett. 115 (2015) 6, 061802

Penguin pollution starts to matter

- Measurements (HFLAV):

$$A_{\rm CP}^{\rm mix}(B_d \to \psi K_S) = \quad 0.709 \pm 0.011, \qquad A_{\rm CP}^{\rm dir}(B_d \to \psi K_S) = 0.004 \pm 0.012$$

$$A_{\rm CP}^{\rm mix}(B_s \to J/\psi \phi) = -0.060 \pm 0.014, \qquad A_{\rm CP}^{\rm dir}(B_s \to J/\psi K^+K^-) = 0.004 \pm 0.009$$

- $A_{\rm CP}^{\rm mix} = \pm \sin(2\beta_{(s)}) + \Delta A_{\rm CP}^{\rm mix}$ with penguin pollution $\Delta A_{\rm CP}^{\rm mix}$.

$b \to c\bar{c}d$ mode

Decay:	$B_d \to J/\psi K_S$	$B_d \to \psi(2S) K_S$	$B_d \to J/\psi \pi^0$
$\max(\lvert\Delta\phi_M^d\rvert)$	$0.68°$	$0.74°$	N/A
$\max(\lvert\Delta A_{\rm CP}^{\rm mix}\rvert)$	$0.86 \cdot 10^{-2}$	$0.94 \cdot 10^{-2}$	0.18
$\max(\lvert A_{\rm CP}^{\rm dir}\rvert)$	$1.33 \cdot 10^{-2}$	$1.33 \cdot 10^{-2}$	0.29

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sation

Decay:	$B_s \to (J/\psi\phi)^0$	$B_s \to (J/\psi\phi)^\perp$	$B \to (J/\psi\phi)^\parallel$	$B_s \to J/\psi K_S$
$\max(\lvert\Delta\phi_M^s\rvert)$	$0.97°$	$1.22°$	$0.99°$	N/A
$\max(\lvert\Delta A_{\rm CP}^{\rm mix}\rvert)$	$1.70 \cdot 10^{-2}$	$2.13 \cdot 10^{-2}$	$1.73 \cdot 10^{-2}$	26
$\max(\lvert A_{\rm CP}^{\rm dir}\rvert)$	$1.89 \cdot 10^{-2}$	$2.35 \cdot 10^{-2}$	$1.92 \cdot 10^{-2}$	27

Direct CP violation in $B \to J/\psi\pi$

- Isospin symmetry: $A_{\rm CP}^{\rm dir}(B_d \to J/\psi\pi^0) \simeq A_{\rm CP}^{\rm dir}(B^+ \to J/\psi\pi^+)$

- LHCb, *Phys.Rev.Lett.* 134 (2025) 10, 101801:

$$A_{\rm CP}^{\rm dir}(B_d \to J/\psi\pi^+) - A_{\rm CP}^{\rm dir}(B_d \to \psi K^+) = (1.29 \pm 0.49 \pm 0.08) \times 10^{-2}$$

deducing $$A_{\rm CP}^{\rm dir}(B_d \to J/\psi\pi^+) = (1.51 \pm 0.51 \pm 0.08) \times 10^{-2}$$

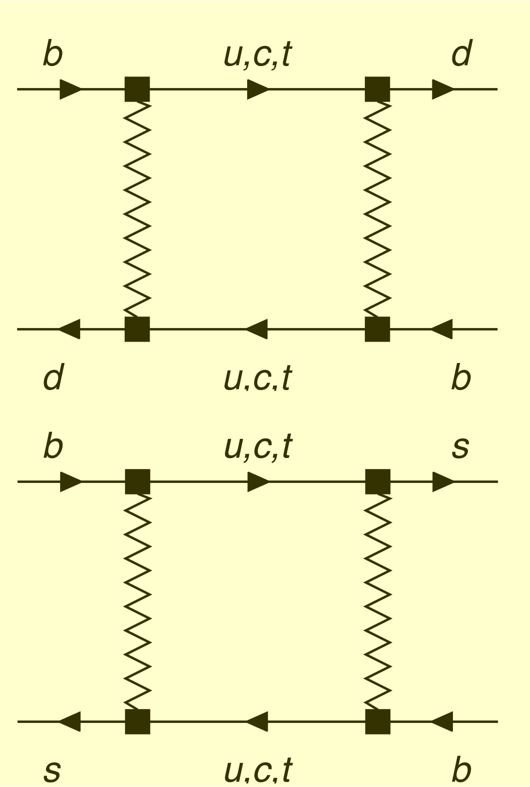
which is far more precise than our upper bound from 2015:

$$|A_{\rm CP}^{\rm dir}(B \to J/\psi\pi)| \leq 0.29$$

$B-\bar{B}$ mixing: width difference

Width difference

- mass matrix M (from boxes with one or two tops)
- decay matrix Γ (from box without top)
- $|\Gamma_{12}| \ll |M_{12}|$
- two mass eigenstates with
  - mass difference $\Delta m \simeq 2|M_{12}|$, equal to $B-\bar{B}$ oscillation frequency
  - decay width difference $\Delta\Gamma = -\Delta m \,\mathrm{Re}\frac{\Gamma_{12}}{M_{12}}$



Width difference

- QCD corrections to M_{12} are governed by $\alpha_s(m_t)$. $\Rightarrow$ NLO sufficient
- QCD corrections to Γ_{12} are governed by $\alpha_s(m_b)$. $\Rightarrow$ need NNLO.

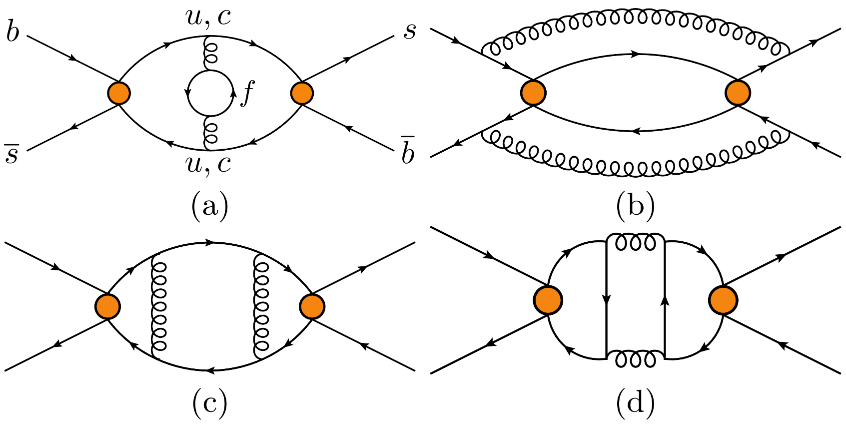
- $B_s-\bar{B}_s$ system: Precise measurement (HFLAV):

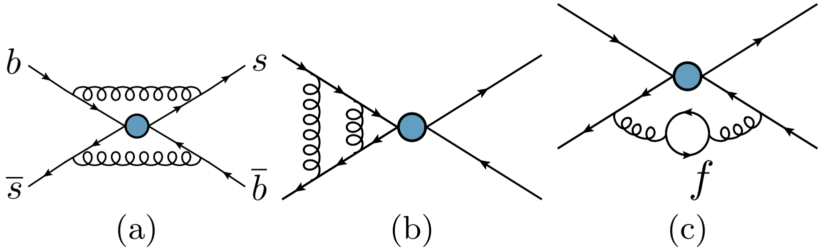
$$\Delta\Gamma_s = (0.082 \pm 0.005)\,\mathrm{ps}^{-1}$$

- while in the $B_d-\bar{B}_d$ system:

$$\Delta\Gamma_d = (0.001 \pm 0.007)\,\mathrm{ps}^{-1}$$

B_s–$\bar{B}_s$ width difference





Sample 3-loop diagrams.
Orange dot: effective four-quark operators describing *W* exchange

Effective operators with local $\bar{s}b\bar{s}b$ interaction.

Perturbative calculation: Wilson coeffcient.

To predict $\Delta\Gamma$ we also need hadronic matrix element à la $\langle \bar{B}_s \,|\, \bar{s}b\bar{s}b \,|\, B_s \rangle$.

$B_s-\bar{B}_s$ width difference

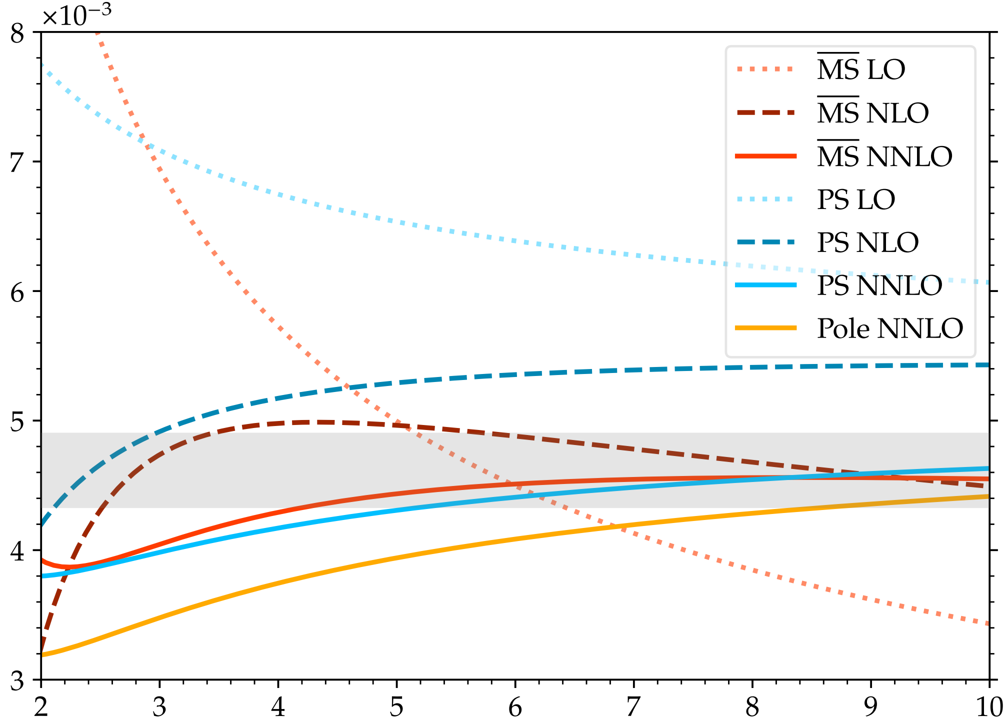
Renormalisation scale dependence: $\dfrac{\Delta\Gamma_s}{\Delta m_s}$

Other sources of uncertainties

$\dfrac{\alpha_s}{m_b}$ corrections missing

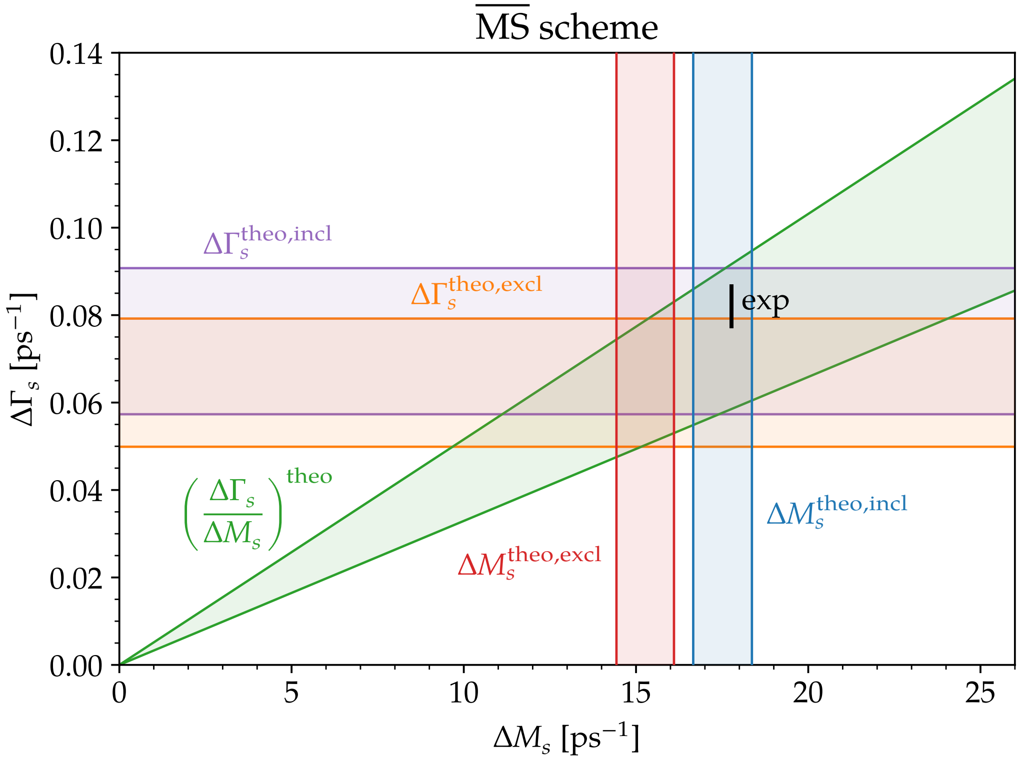
matrix elements of $\dfrac{1}{m_b}$ suppressed operators

M. Gerlach, UN, V. Shtabovenko, M. Steinhauser, Phys. Rev. Lett. 129 (2022) 10, 102001.



μ varied around m_b

$B_s - \bar{B}_s$ width difference



Prediction of Δm_s and $\Delta\Gamma_s$ suffer from the "V_{cb} puzzle".

Their ratio is essentially unaffected by uncertainties in CKM elements.

Summary and Outlook

Summary and Outlook

- Flavour physics probes BSM physics associated with very heavy particles and is instrumental to formulate a physics case for future hadron colliders.

- The current experimental precision in $A_{\rm CP}^{\rm mix}(B_d \to \psi K_S)$ and $A_{\rm CP}^{\rm mix}(B_s \to J/\psi\phi)$ calls for a better understanding of penguin pollution.

- The width difference $\Delta\Gamma$ between the mass eigenstates of neutral *B* mesons is known to NNLO in QCD.

- For further information on *B* lifetime calculations and measurements see
  J. Albrecht, F. Bernlochner, A. Lenz, A. Rusov, *Eur.Phys.J.ST* 233 (2024) 2, 359-390