# CP violation in electroweak interactions of heavy flavours

## An overview

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# What C, P and T do,
## and the concept of antimatter

Action of operators

$$C|\vec{r}, t, q\rangle_{in} = e^{i\beta}|\vec{r}, t, -q\rangle_{in}$$

$$P|\vec{r}, t, q\rangle_{in} = e^{i\alpha}| - \vec{r}, t, q\rangle_{in}$$

$$T|\vec{r}, t, q\rangle_{in} = e^{i\gamma}\ {}_{out}\langle\vec{r}, -t, q|$$

Important remarks

Sole C cannot give a correct relativistic picture;
e.g. **cannot be left-handed neutrino $\rightarrow$ left-handed anti-neutrino**

One needs to combine with P

# In the Standard Model

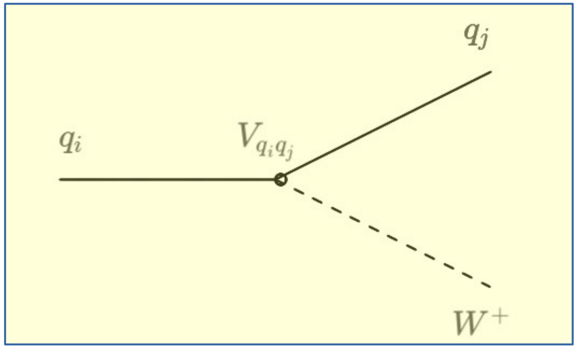
- **CPT is conserved**: famous theorem
- CP does not have to be conserved; **room for CP violation**
- CP violation so far observed only in weak interactions of heavy quarks s, c and b:

- s: $10^{-3}$ , discovered long time ago
- c: $10^{-4}$, only recently
- b: $10^{-2}$, some time ago

- No evidence in leptonic sector (2-3 $\sigma$ effect in neutrino oscillations)
- **Lack of CP violation in strong interactions**; not understood theoretically

# CP violation and Cabibbo-Kobayashi-Maskawa matrix

$$\mathrm{L_{qW}} = -\frac{e}{2}\mathbf{U}_L^\dagger \gamma^\mu \mathrm{V_{CKM}}\, \mathbf{D}_L \mathbf{W}_\mu$$



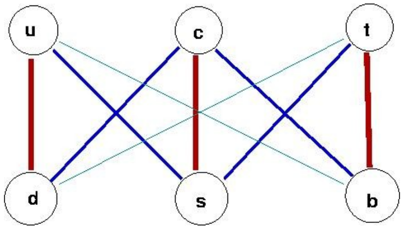

CKM matrix describes mixing
between mass- and weak eigenstates of
down-type quarks

$$\mathrm{V_{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq$$

Wolfenstein parametrization;
non-zero complex phase induces CPV

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1-\lambda^2/2 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{bmatrix}$$

$$A_{ub} \neq CP(A_{ub}) = A^*_{ub}$$

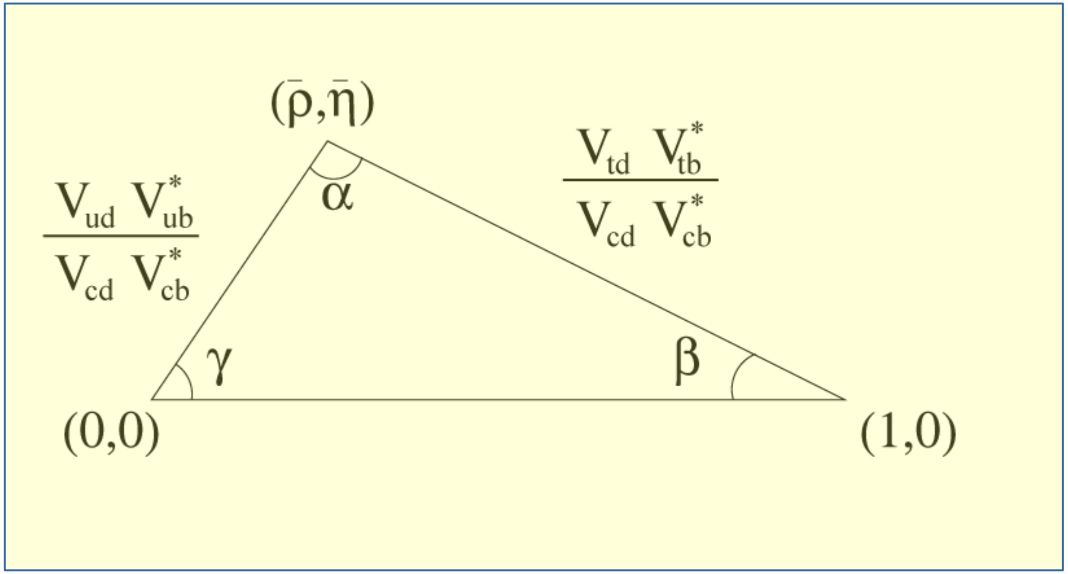



$$e^{i\varphi} = \rho - i\eta, \quad \lambda = 0.22$$

# CP violation and CKM

In SM, CKM has to be unitary

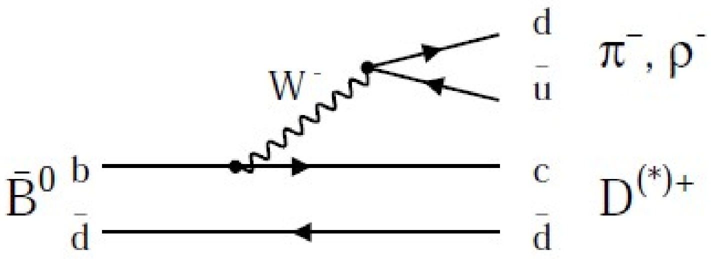
$$V_{CKM} \cdot V^{\dagger}_{CKM} = 1$$



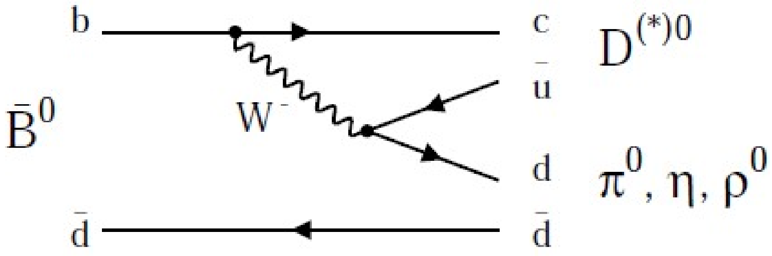

Magnitude of CP violation seen as openness of unitarity triangle (e.g. $\gamma$ )

CPV can be estimated from measurements of CKM elements in various decays, not necessarily refering directly to CPV observables

# CP violation processes: tree decays



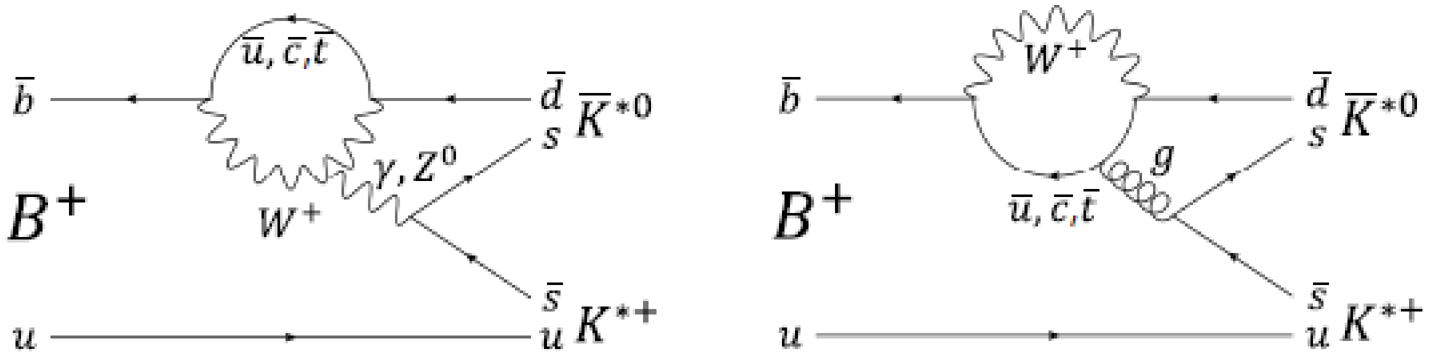

W does not carry color, no gluon exchange required; called **colour-favoured**




Quark from W decay needs to pick-up another one not being his partner from W decay, and form a colour singlet; called **colour-suppressed**

Colour-suppressed have smaller branching fractions

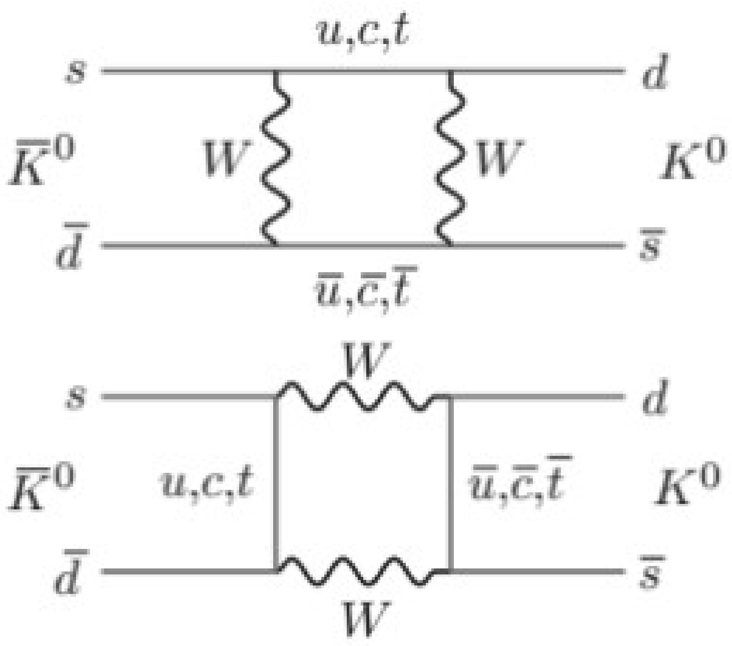
# CP violation processes: loop (penguin) decays




Similar distinction between electroweak (a) and gluonic (b) loop processes

Loops enable transitions between up → up' and down → down' quarks, suppressed in tree processes (FCNC)

# CP violating processes: box diagrams




Transitions with $\Delta$F=2:
flavour-antiflavour oscillations

Note heaviest flavours can be exchanged in loops;

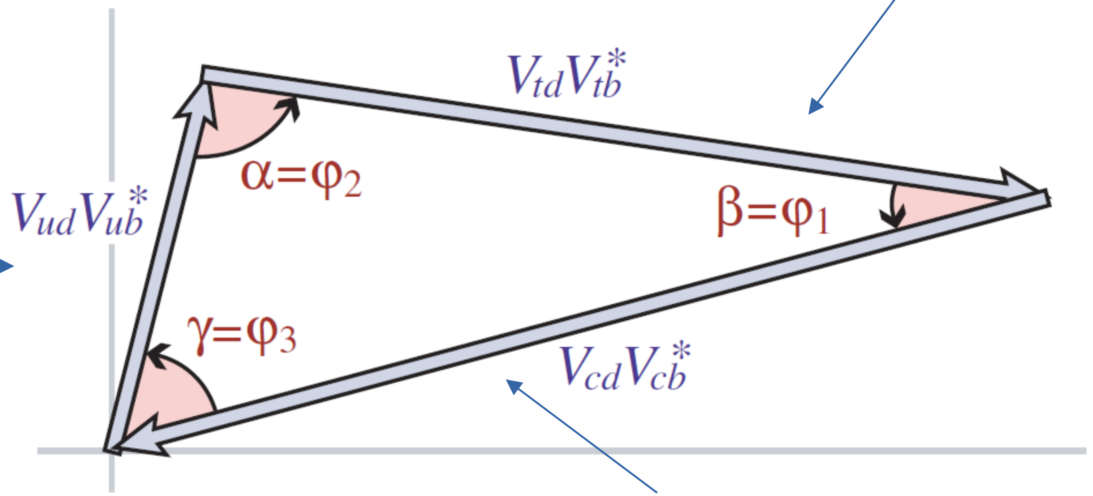
→ sensitivity to t-quark couplings, hardly available in trees due to energy

# CP violation and CKM

Typical contributors to CKM triangle edges and angles

$B^0 \leftrightarrow \bar{B}^0$

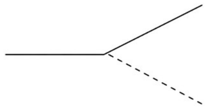
$B \to \pi\mu\nu_\mu$



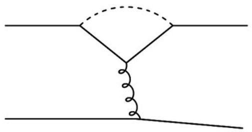

$B \to D\mu\nu_\mu$

# Phenomenology of CPV in decays and mixing

Decay amplitudes: transitions with $\Delta$ **F=1**

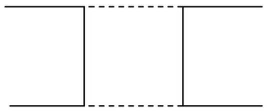


$$A_f = \langle f|H|M\rangle \quad \bar{A}_f = \langle f|H|\bar{M}\rangle$$



$$A_{\bar{f}} = \langle \bar{f}|H|M\rangle \quad \bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{M}\rangle$$

Mixing of flavour eigenstates in mass eigenstates: transitions with $\Delta$ **F=2**

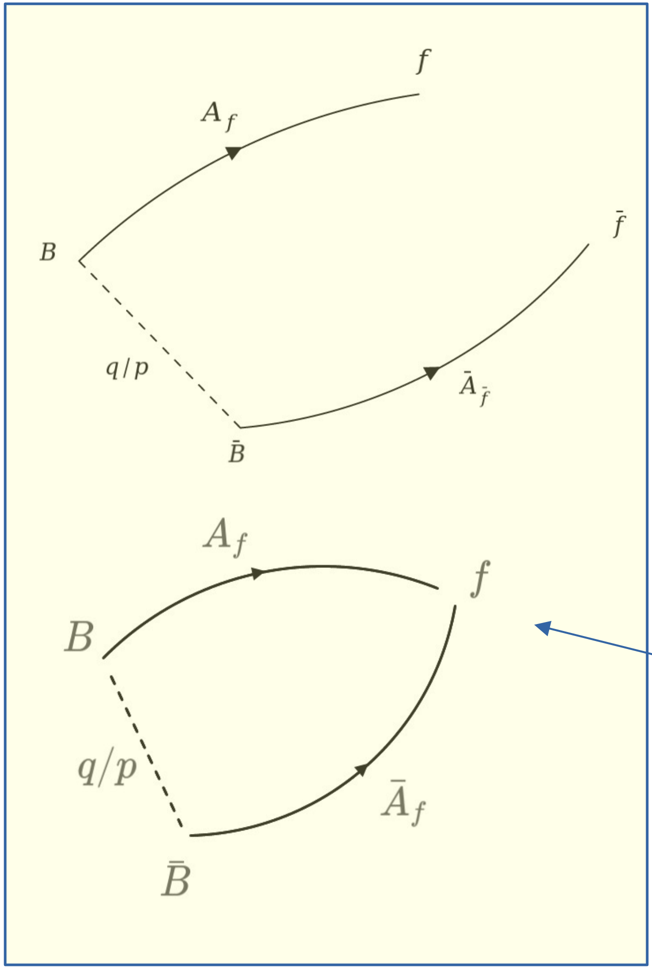


$$|M_H\rangle \sim p|M^0\rangle + q|\bar{M}^0\rangle$$

$$|M_L\rangle \sim p|M^0\rangle - q|\bar{M}^0\rangle$$

$$\sqrt{|p|^2 + |q|^2} = 1$$

# CP violation: decays, mixing, interference




Direct $\Delta F = 1$: $|A_f| \neq |\bar{A}_{\bar{f}}|$

Mixing $\Delta F = 2$: $p \neq q$

Interference: $\mathrm{Arg}\,\lambda \neq 0$, where $\lambda = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_f}$

Interference only for common final states

# CP violation: decays

CP violation defined by $$|A_f/\bar{A}_{\bar{f}}| \neq 1$$

The only possible mechanism of CP violation in charged mesons and baryons; mixing absent there

Basic experimental observable: **CP asymmetry**

$$\begin{aligned}\mathcal{A}_{CP} &= \frac{\Gamma(M^- \to f^+) - \Gamma(M^+ \to f^-)}{\Gamma(M^- \to f^+) + \Gamma(M^+ \to f^-)} \\ &= \frac{|\bar{A}_{f-}/A_{f+}| - 1}{|\bar{A}_{f-}/A_{f+}| + 1}\end{aligned}$$

# CP violation: flavour oscillations

CP violation defined by $|q/p| \neq 1$

Mass and width eigenstates

Time evolution governed by $x = \frac{m_H - m_L}{\Gamma}$ $y = \frac{\Gamma_H - \Gamma_L}{\Gamma}$

Time-dependent oscillation probability

$$P(M^0 \to \bar{M}^0) = \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}[\cosh(y\Gamma t) - \cos(x\Gamma t)]$$

$$\Gamma = (\Gamma_H + \Gamma_L)/2$$

# CP violation: flavour oscillations

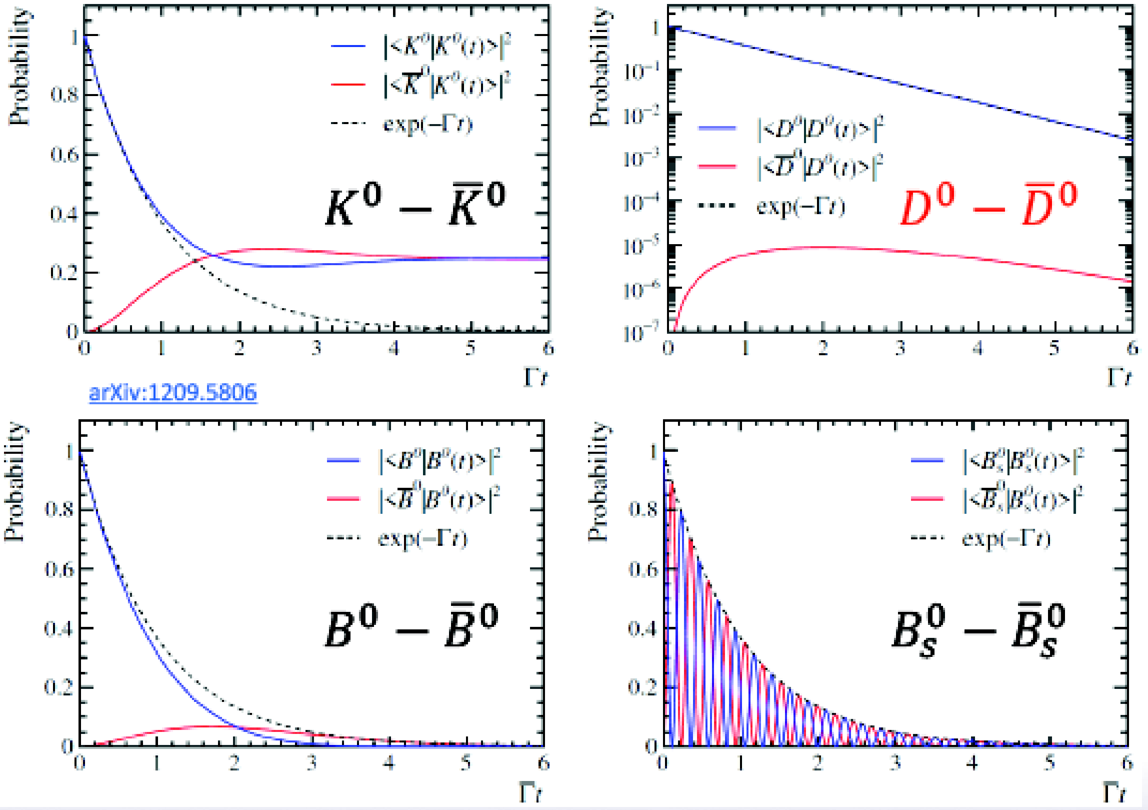
Note differences between oscillation rates of flavors

| System | $x$ | $y$ |
|---|---|---|
| $K^0 - \bar{K}^0$ | $-0.946 \pm 0.004$ | $0.99650 \pm 0.00001$ |
| $D^0 - \bar{D}^0$ | $(4.09^{+0.48}_{-0.49})\times10^{-3}$ | $(6.15^{+0.56}_{-0.55})\times10^{-3}$ |
| $B^0 - \bar{B}^0$ | $-0.769 \pm 0.004$ | $(0.1 \pm 0.1)\times10^{-2}$ |
| $B_s^0 - \bar{B}_s^0$ | $26.89 \pm 0.07$ | $(12.9 \pm 0.6)\times10^{-2}$ |

Very small x and y for D

Large x for $B_s$

Log scale in the charm sector!



# CP violation: flavour oscillations

Wrong-sign asymmetries due to oscillations

Semi-leptonic, charged-current tree decays, e.g. $B^0 \rightarrow D^- \mu^+ \nu_\mu$
CP conserved

$$|A_{\mu^+}| = |\bar{A}_{\mu^-}|, \quad |A_{\mu^-}| = |\bar{A}_{\mu^+}| = 0$$

Due to oscillations, CP is violated and measured with „wrong-sign" asymmetry

$$\mathcal{A}_{s-l}(t) = \frac{d\Gamma/dt(B^0 \rightarrow \mu^- X) - d\Gamma/dt(\bar{B}^0 \rightarrow \mu^+ X)}{d\Gamma/dt(B^0 \rightarrow \mu^- X) + d\Gamma/dt(\bar{B}^0 \rightarrow \mu^+ X)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

# CP violation: mixing-decay interference

Interference between decay without mxing and decay with mixing
Only for same final state for meson and anti-meson decay

CPV defined by

$$\mathrm{Arg}(\lambda_f) + \mathrm{Arg}(\lambda_{\bar{f}}) \neq 0, \quad \lambda_f = \frac{q}{p}\bar{A}_f A_f$$

For $f_{CP}$ being CP-eigenstates simplifies to

$$\Im(\lambda_{f_{CP}}) \neq 0$$

CPV measured with the same type of time-dependent asymmetry as s-l

# Strange realm: kaons

Historically, 1964 discovery of CPV in $K^0 \rightarrow \pi\ \pi$

Decays into $2\pi$ observed far away of the production target, where all $K_S$ should die out

Later experiments (lots of them)

Two amplitude ratios (with phases) measured for charged and neutral modes

$$\eta_{+-} = \frac{\langle \pi^+\pi^- | H | K_L \rangle}{\langle \pi^+\pi^- | H | K_S \rangle} = (2.23 \pm 0.01) \times 10^{-3}\, e^{i(43.51 \pm 0.05)^\circ}$$

$$\eta_{00} = \frac{\langle \pi^0\pi^0 | H | K_L \rangle}{\langle \pi^0\pi^0 | H | K_S \rangle} = (2.22 \pm 0.01) \times 10^{-3}\, e^{i(43.52 \pm 0.05)^\circ}$$

Phases measured from shift in L-S interference pattern

# Strange realm: kaons

Related to CP-violation parameters

$$\eta_{+-} = \varepsilon + \varepsilon'$$
$$\eta_{00} = \varepsilon - 2\varepsilon'$$

Today's world average

$$|\varepsilon| = (2.23 \pm 0.01) \times 10^{-3}$$
$$\Re(\varepsilon'/\varepsilon) = (1.7 \pm 0.2) \times 10^{-3}$$

Most important experimental contributions are from late 1990's – early 2000's
By NA48, KTeV, KLOE

# Strange realm: kaons

Among **rare decays the most powerful** $K_L \rightarrow \pi^0 \nu\bar{\nu}$

Penguin, dominated by t in SM, clean probe for new physics

In SM Branching fraction ~ $10^{-11}$

Interference CP violation

$$\frac{\Gamma(K_L \rightarrow \pi^0 \nu\bar{\nu})}{\Gamma(K^+ \rightarrow \pi^+ \nu\bar{\nu})} = 1 - \Re(\lambda_{\pi\nu\bar{\nu}})$$

So far, NA62 provides

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu\bar{\nu}) < 3 \times 10^{-9}$$

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$$

# Charm realm: D

Standard Model predictions for CPV in charm is predicted to be tiny, < $O(10^{-3})$, but recently discovered by LHCb

$$D^0 \to \pi^+\pi^-, \quad D^0 \to K^+K^-$$

Decays through Cabibbo-suppressed tree processes

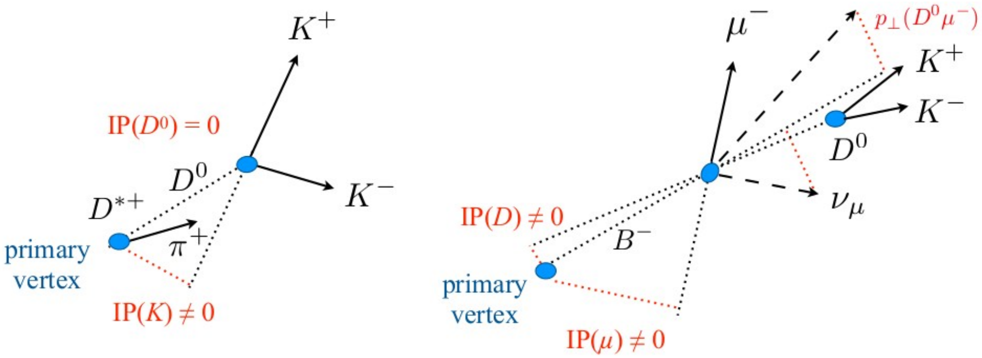
CP asymmetries

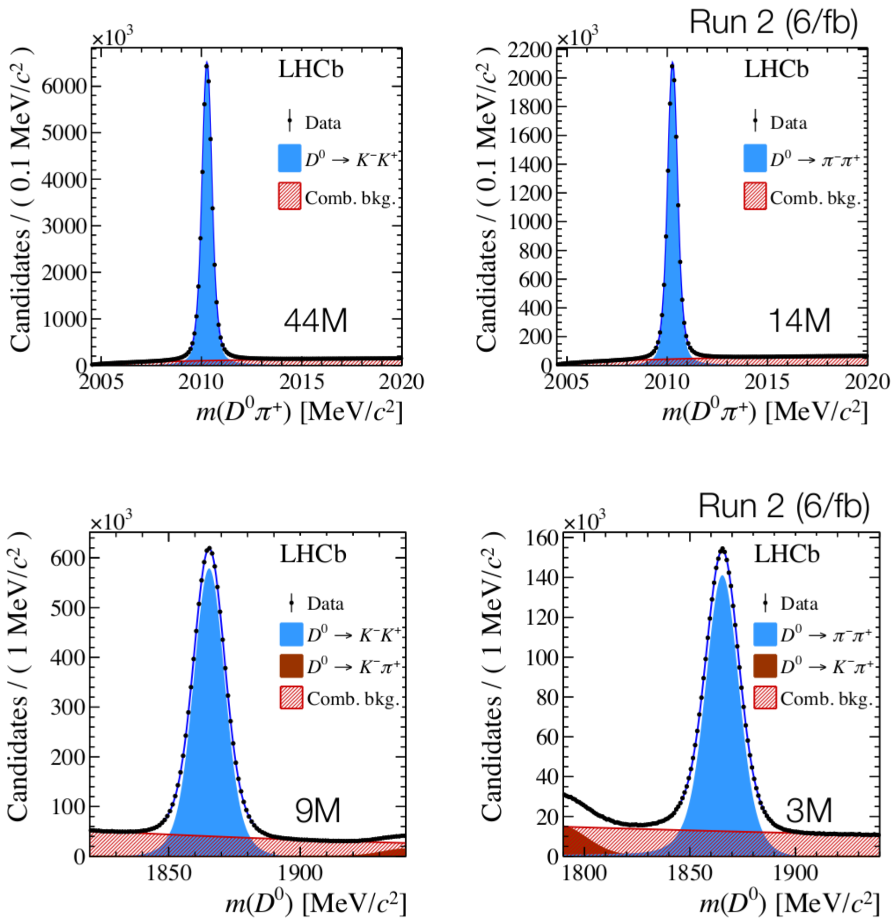
$$A_f = A_D + A_M + A_I$$

$10^{-3}$ $10^{-5}$

# Charm realm: D

Lots of systematics cancel in difference

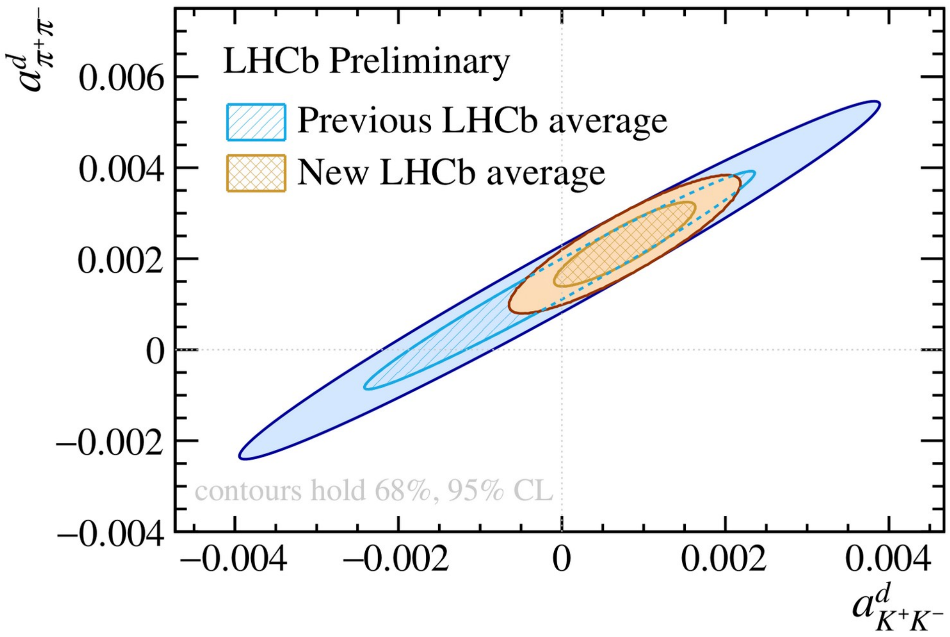



$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$$
$$= (-15.4 \pm 2.9) \times 10^{-4}$$

# Charm realm: D

Asymetries of $\pi\ \pi$ and KK determined separately and mixing subtracted;
pure direct asymmetries are known;
rather complex analysis procedure




$$a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}$$

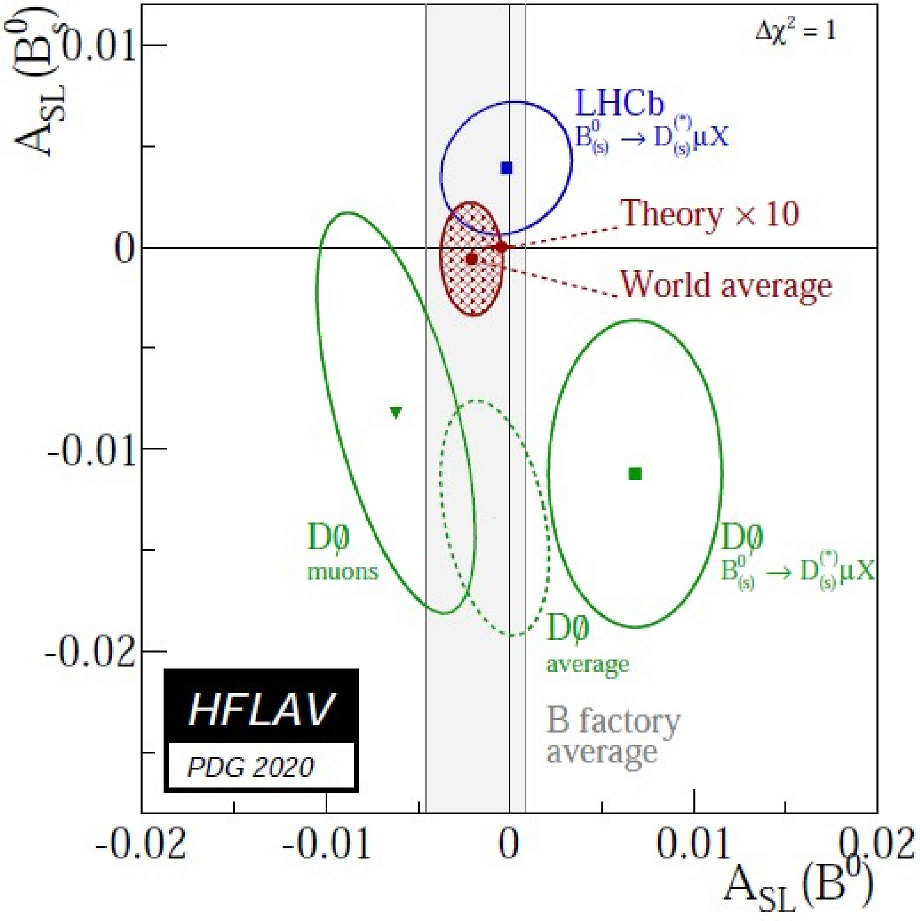
# Beauty realm: B, $B_s$

CP violation in pure **B mixing**
best measured
in semi-leptonic B decays

$$A^{d}_{SL} = (-2.7 \pm 1.7) \times 10^{-3}$$

$$A^{s}_{SL} = (-0.6 \pm 2.8) \times 10^{-3}$$

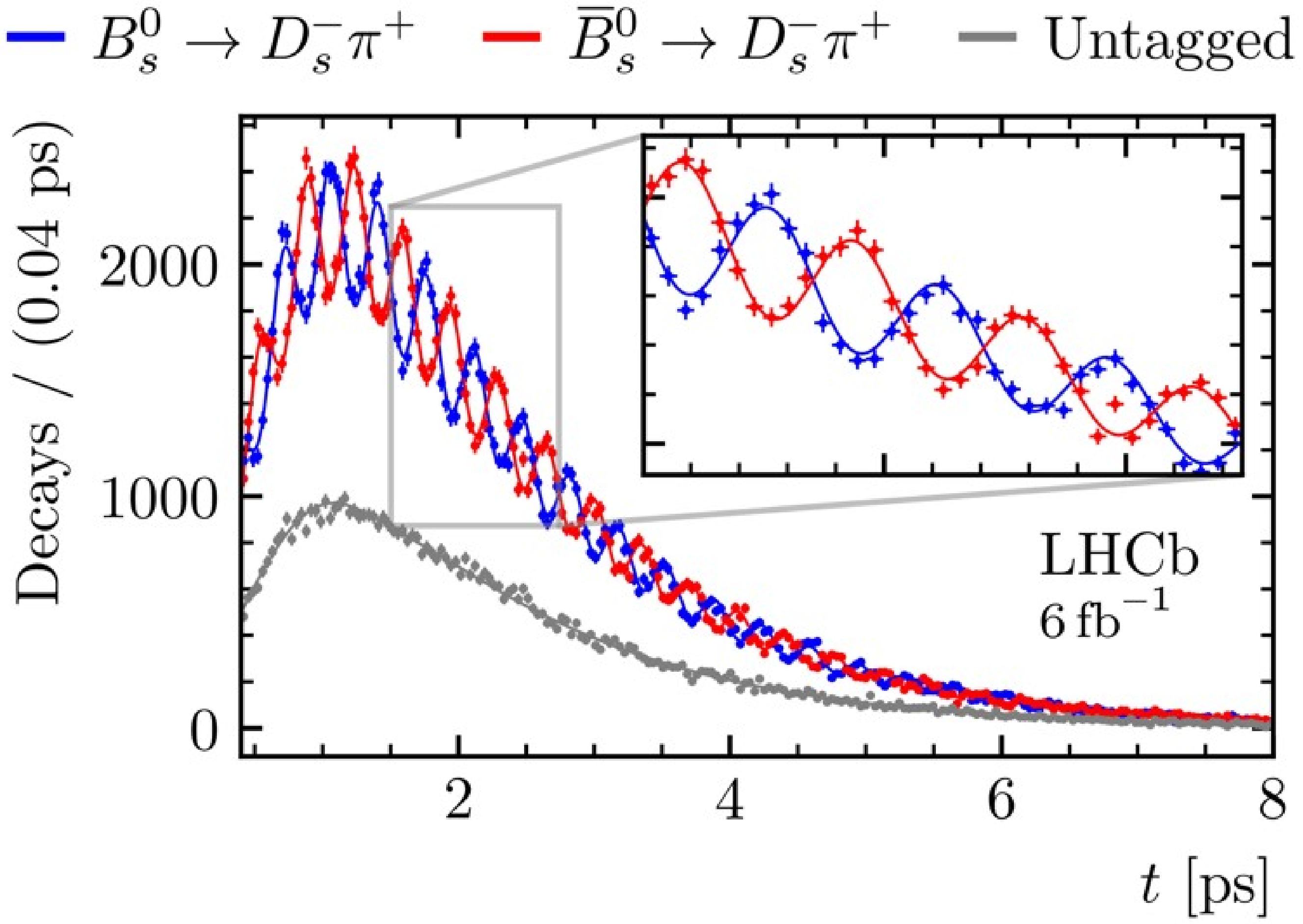
SM predictions ~< $10^{-4}$
Experimental precision still needed



# Beauty realm: B, $B_s$

Oscillations in hadronic decays and power of flavour tagging in LHCb

Usual efficiency of flavour tagging ~ few %



# Beauty realm: B, $B_s$

Summary on $B_s$ rates (lifetimes)

All final states with 2c

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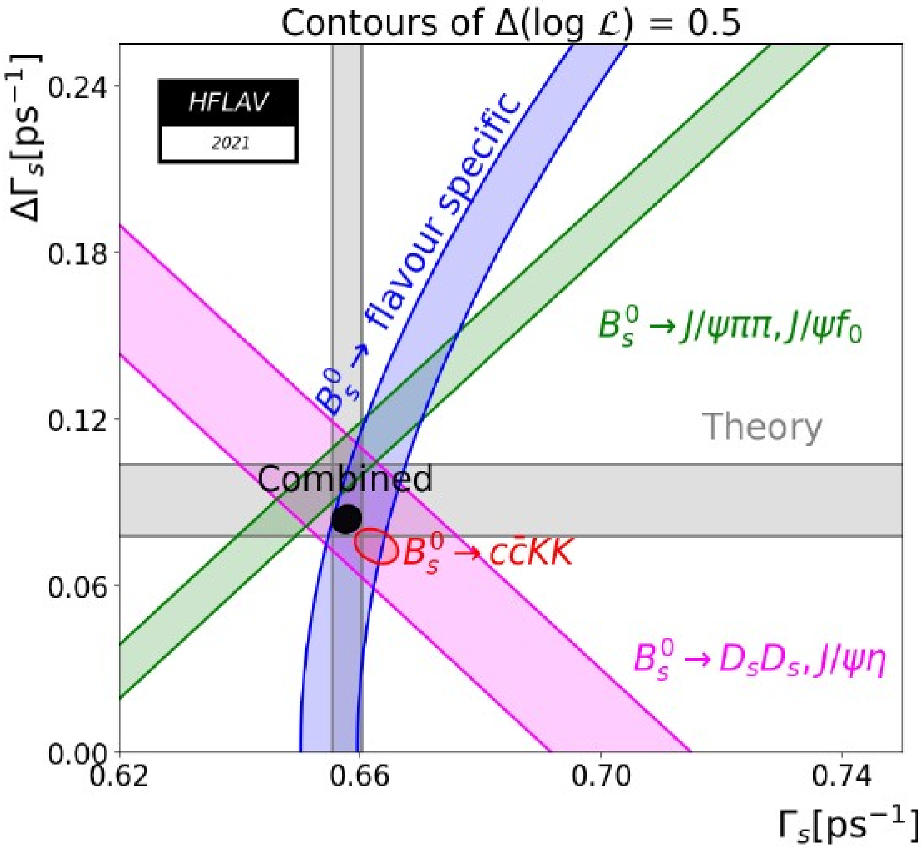
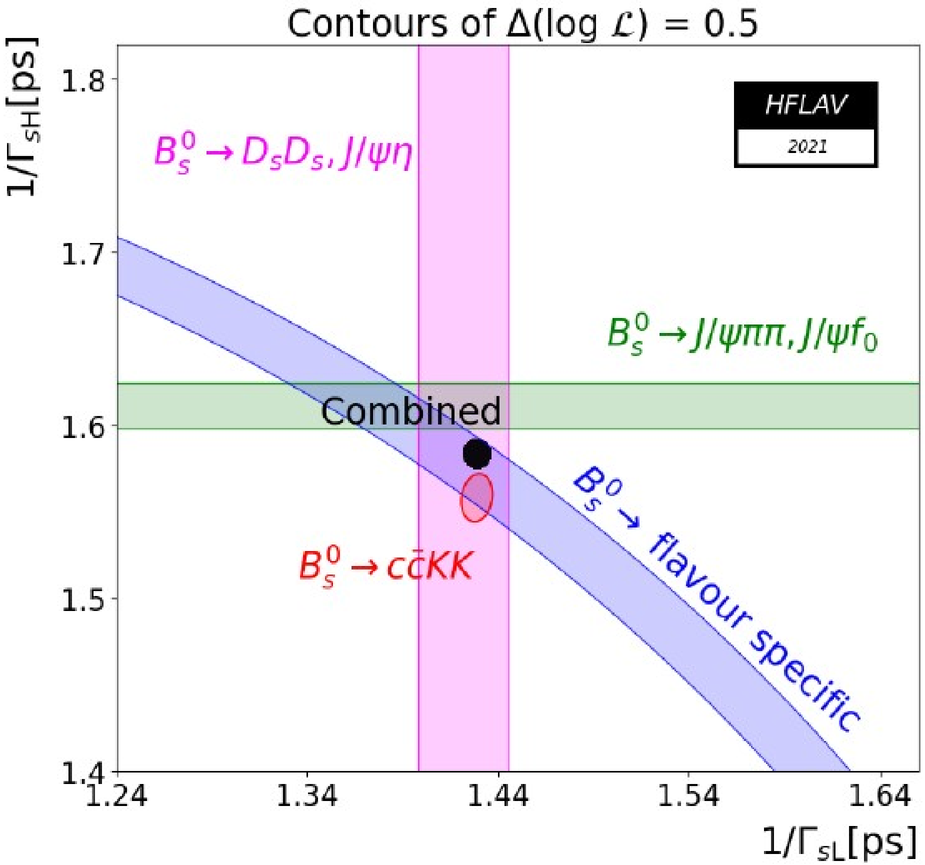


# Beauty realm: CP violation in B, $B_s$ decays

Time-dependent asymmetries

CP-violating phase

$$A_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t), \quad S_f = S_f(\phi_s)$$

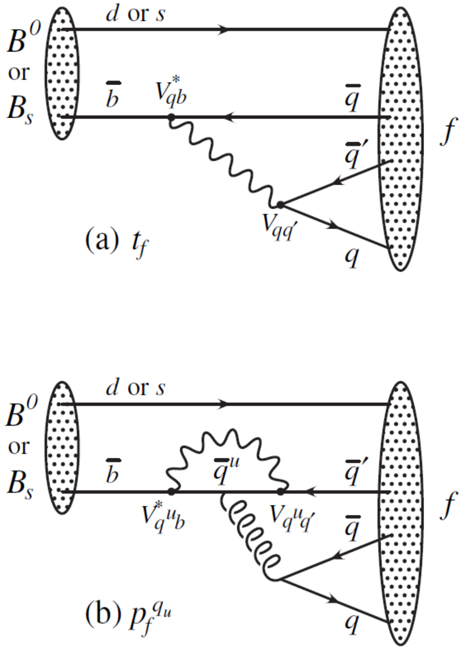
To be expressed by CKM

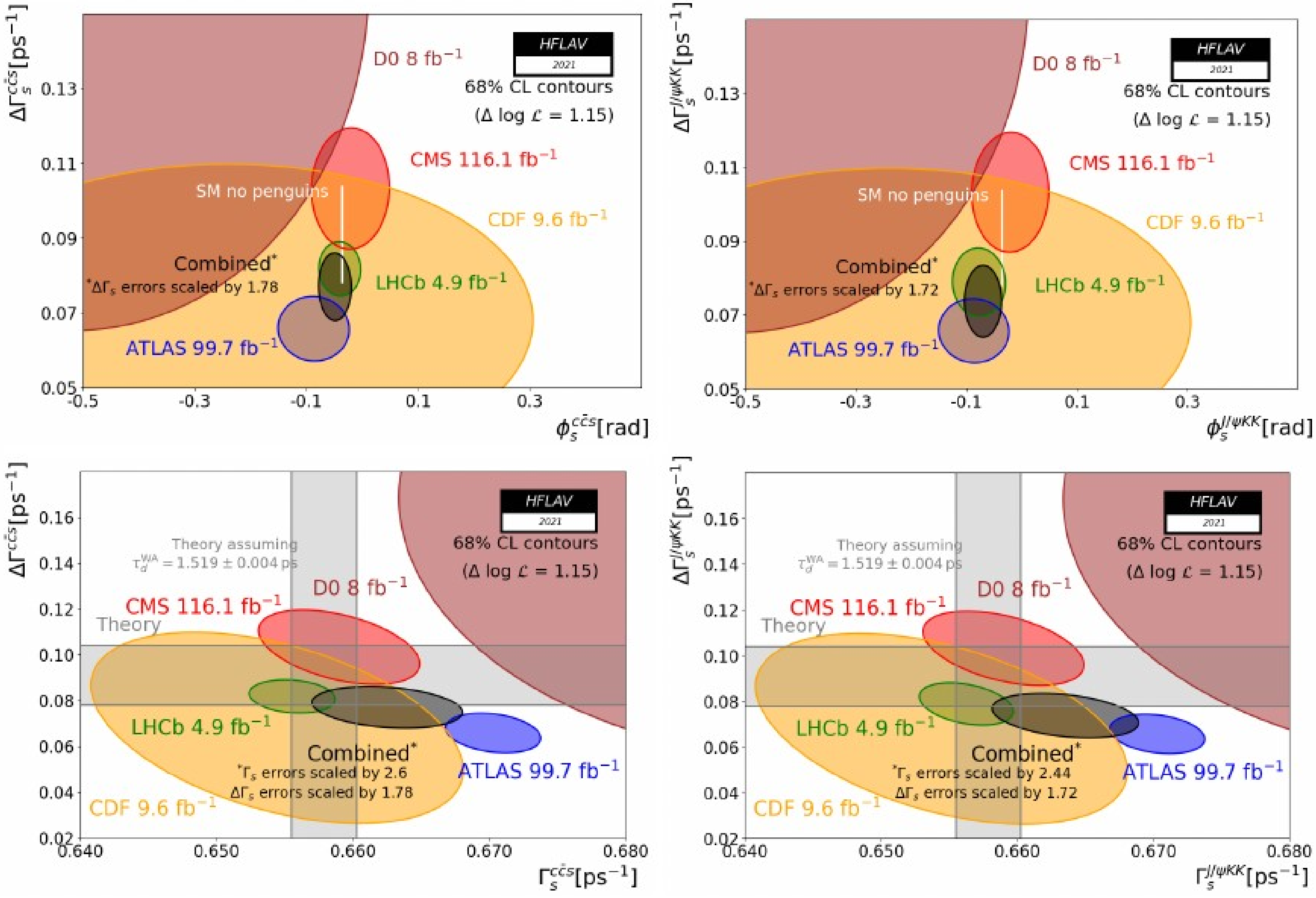
$$A_f = (V_{qb}V^*_{qq'})t_f + \sum_{q=u,c,t}(V_{qb}V^*_{qq'})p_f$$

In SM

$$\phi_s = -2\,\mathrm{Arg}\left(\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right)$$

Phase sensitive to new physics and $\beta$

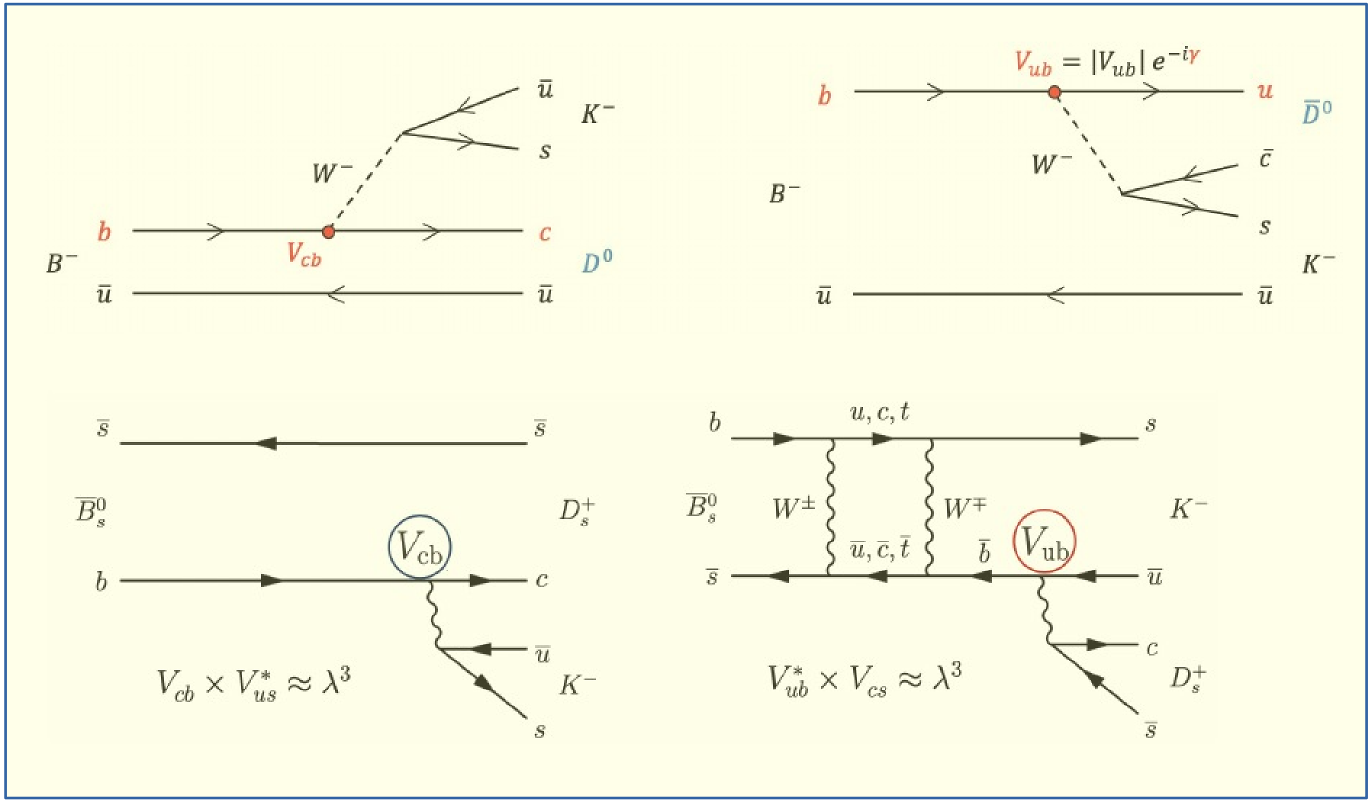





How much consistent are $\Delta\,\Gamma$ among LHC experiments?

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\frac{V_{ub}}{V_{cb}}$$

Accessible in tree processes ( charged and neutral B-decays) and with impressively small theoretical uncertainties $|\sigma_\gamma| \leq 10^{-7}$
Brod, Zupan JHEP 01 (2014) 051




For interference to occur, $\mathbf{D}$ and $\bar{\mathbf{D}}$ have to decay to same final state, eg. $\mathbf{K^+K^-}$, $\boldsymbol{\pi^+\pi^-}$ etc.

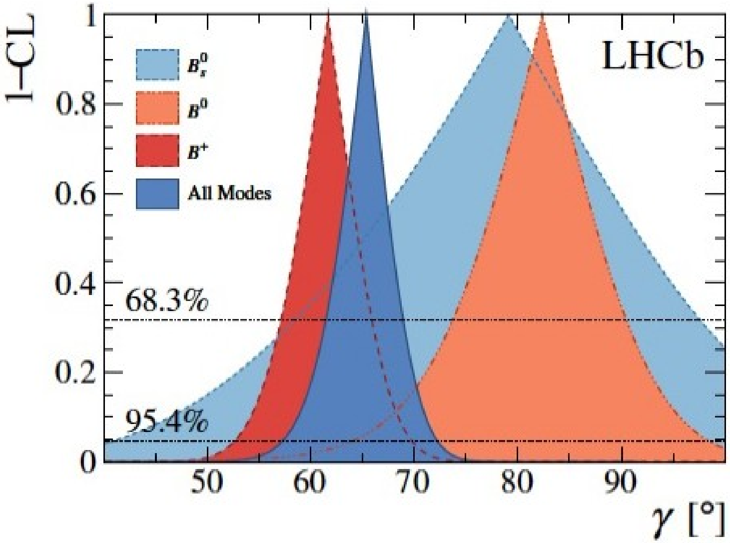
Favourable for D decaying to CP-eigenstates

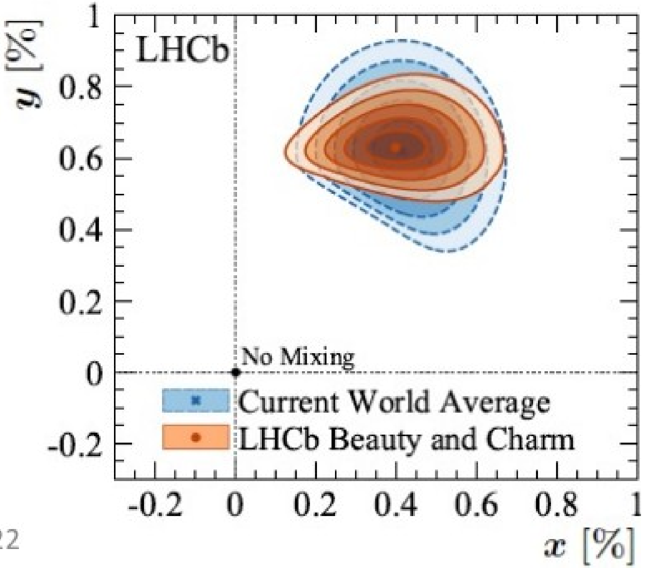
$$\Gamma \sim |1 + r_B e^{i(\delta_B \pm \gamma)}|^2$$

Determination of γ possible with simultaneous fits to interfering decays of B-mesons and mixing in D-mesons; excellent opportunity to use rich array of data (151 observables in total, including other experiments)

$$\Gamma(B^{\pm} \rightarrow Dh^{\pm}) = \Gamma(\gamma, \delta_B, \delta_D, x, y)$$

$$x = \frac{\Delta m}{\bar{\Gamma}} \qquad y = \frac{\Delta\Gamma}{2\bar{\Gamma}}$$



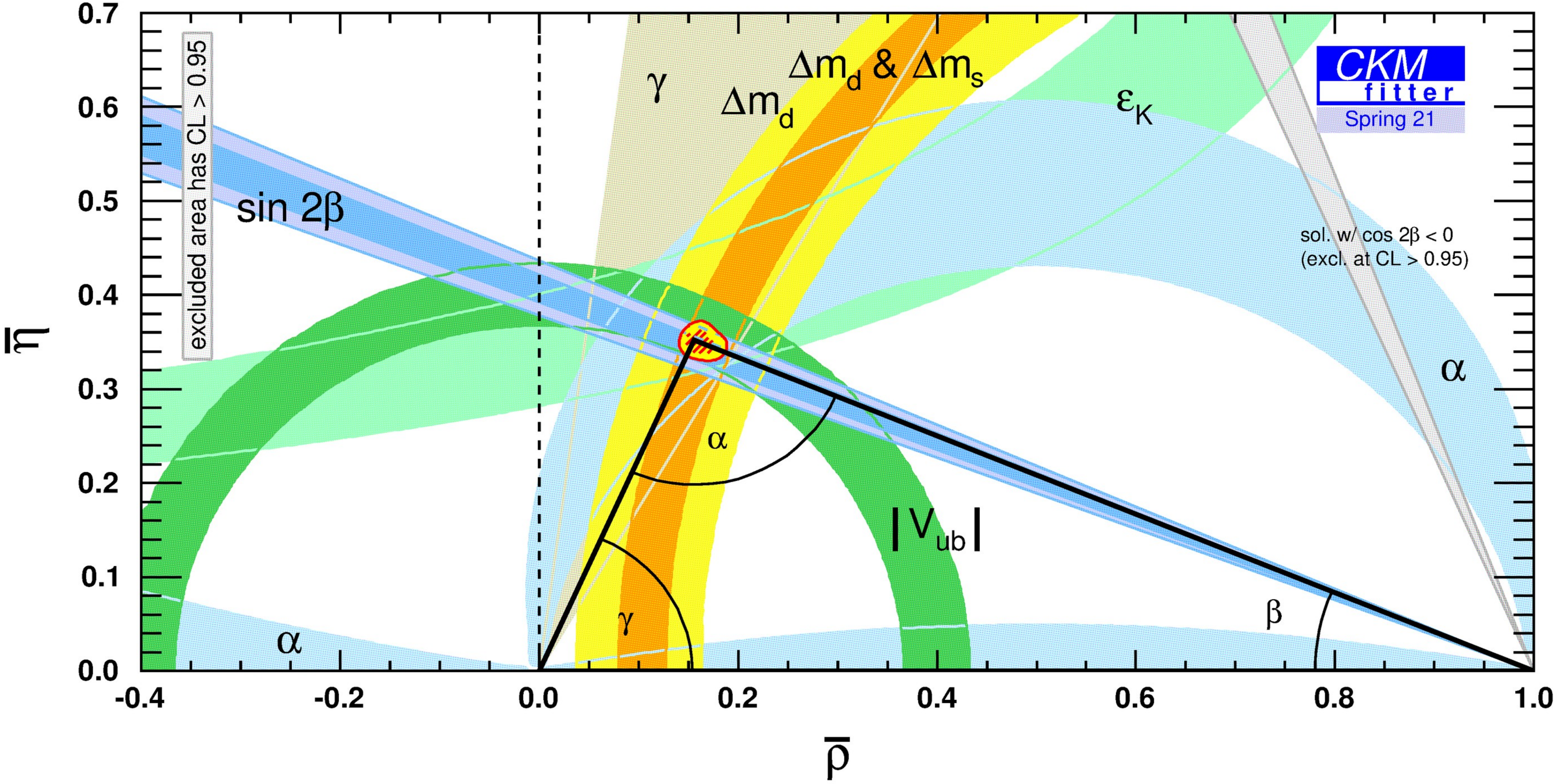




$$\gamma = 65.4^{+3.8}_{-4.2}{}^{\circ}$$

$$x = 0.400^{+0.052}_{-0.053}\%$$

$$y = 0.630^{+0.033}_{-0.030}\%$$

# Summary of CKM



# What about lepton sector?

Expected as another source of CP violation in order to explain matter-antimatter disparity in Universe

Dynamics of lepton flavours exhibits analogies to quarks';
neutrinos' flavour oscillate
$\rightarrow$ there exist FCNC
$\rightarrow$ couplings of currents should mix

Pontecorvo-Maki-Nakagawa-Sakata matrix, analogous to Cabibbo-Kobyashi-Maskawa, relating flavour- to mass eigenstates

Should exist a CP-violating phase $\delta_{\mathrm{CP}}$ in PMNS matrix
Does not explain by itself antimatter deficit but makes plausible some models of leptogenesis (features havy partners to Majorana neutrinos)

# Neutrinos: hard work and large hopes

$\delta_{\mathsf{CP}} = \mathbf{0}$: same $\boldsymbol{\nu}_{\mathsf{e}} - \boldsymbol{\nu}_{\mu}$ and $\bar{\boldsymbol{\nu}}_{\mathsf{e}} - \bar{\boldsymbol{\nu}}_{\mu}$ oscillations

$\delta_{\mathsf{CP}} \neq \mathbf{0}$: flavour-dependent oscillation rates, CP violation

$\delta_{\mathsf{CP}} = \pi/\mathbf{2}$: maximal $\bar{\boldsymbol{\nu}}$ enhancement

$\delta_{\mathsf{CP}} = -\pi/\mathbf{2}$: maximal $\boldsymbol{\nu}$ enhancement

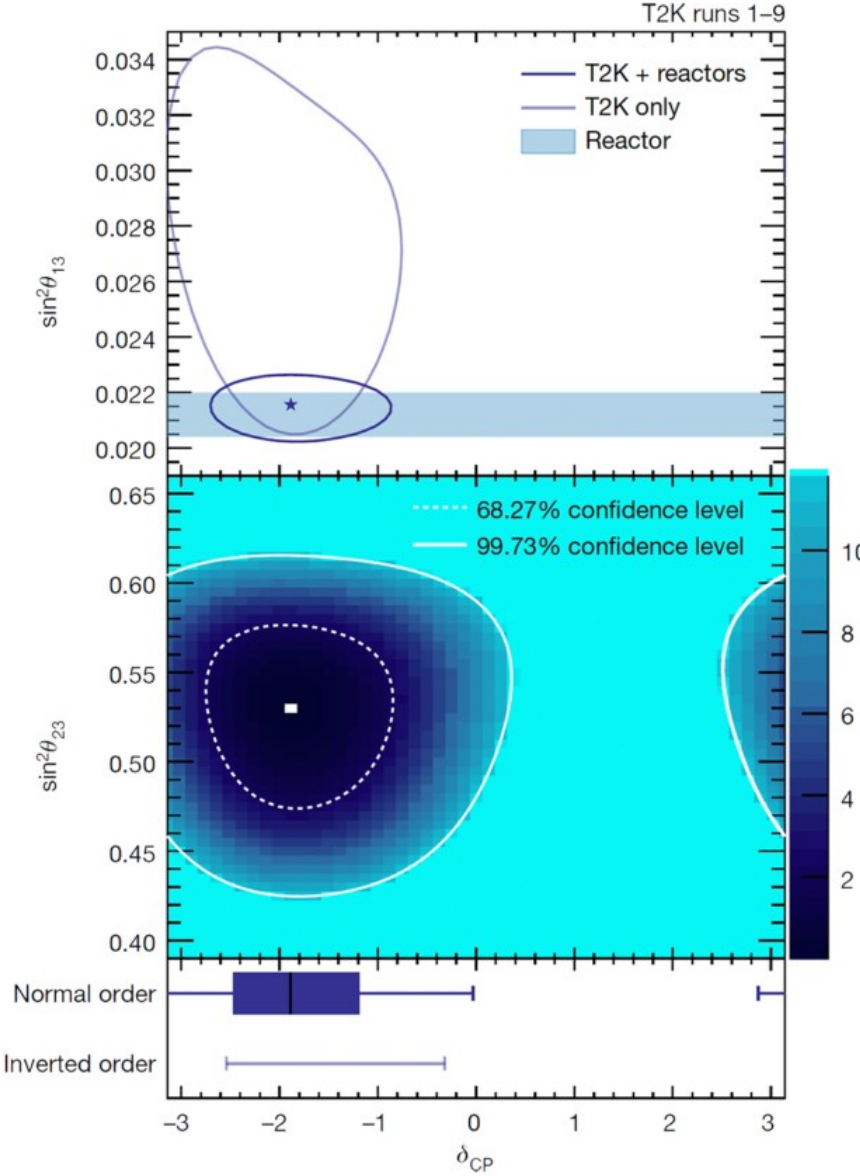
# Neutrinos – strong hint but still no evidence

T2K data, publ. Nature 2020

68.3% and 99.7% CLs for $\delta_{CP}$ vs. $\theta_{13(23)}$

When averaged over all oscillation parameters, the $\delta_{CP} = 0$ disfavored at 3 standard deviations

Still, for some values of mixing angles stays within 3 $\sigma$



# Strong CP problem – a riddle

QCD with massive quarks allows for a non-zero P-violating parameter

$$\mathsf{L}_\theta = \theta g^2 \mathsf{F}^{\mu\nu}\mathsf{F}_{\mu\nu}$$

Needed to parametrize U(1) breaking (axial anomaly)

But non-zero $\theta$ would have observable consequences;
Non-zero neutron electric dipole moment the most pronounced

$$\mathsf{d_n} = \theta \cdot 10^{-16}\ \mathrm{e{\cdot}cm}$$

Best experimental constraint (PSI measurement, 2020) is

$$\mathsf{d_n} = (0.0 \pm 1.1 \pm 0.2) \times 10^{-26}\ \mathrm{e{\cdot}cm}$$

What makes it so fine tuned that $\theta \sim 10^{-10}$?

# Concluding remarks

- CPV for s, c and b well established experimentally and important feature of flavour dynamics
- Standard model is still healthy; no significant deviations noted
- Theory predictions need more elaboration; besides limitations of theory, part of uncertaintes have experimental origin
- Capital **?** - CP in lepton sector; very promising hints exist
- Strong CP problem: what are the questions where experiment could help?