Theoretical Status of B Mixing

Alexander Lenz, Siegen

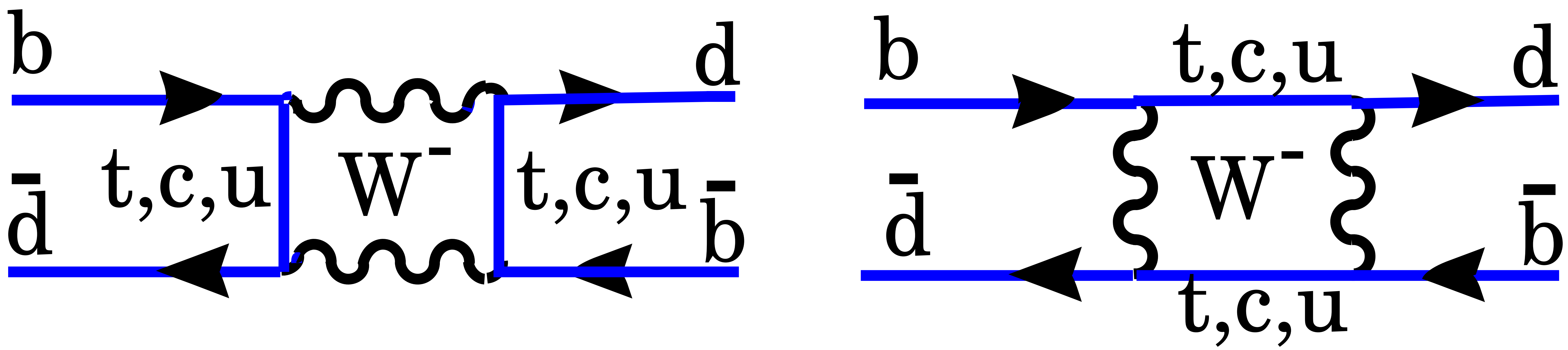
ϕs and A_sl in B-“mesogenesis”

Zoomland, 19.4.2021

Outline

- B-mixing - Box diagrams
- Mass differences ΔM_q
- Decay rate differences $\Delta\Gamma_q$ and semileptonic CP asymmetries a_{sl}^q
- BSM contributions to mixing and Φ_s in the SM and beyond
- A relation to trick them all

B-MIXING



$|M_{12}|$, $|\Gamma_{12}|$ and ϕ_{12}= arg$(-M_{12}/\Gamma_{12})$ can be related to three observables:

- **Mass difference:** $\Delta M := M_H - M_L \approx 2|M_{12}|$ **(off-shell)**
  $|M_{12}|$: heavy internal particles: t, SUSY, ...

- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos\phi_{12}$ **(on-shell)**
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!

- **Flavor specific/semi-leptonic CP asymmetries:** e.g. $B_q \to Xl\nu$ (*semi-leptonic*)

$$a_{sl} \equiv a_{fs} = \frac{\Gamma(\overline{B}_q(t) \to f) - \Gamma(B_q(t) \to \overline{f})}{\Gamma(\overline{B}_q(t) \to f) + \Gamma(B_q(t) \to \overline{f})} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi_{12}$$

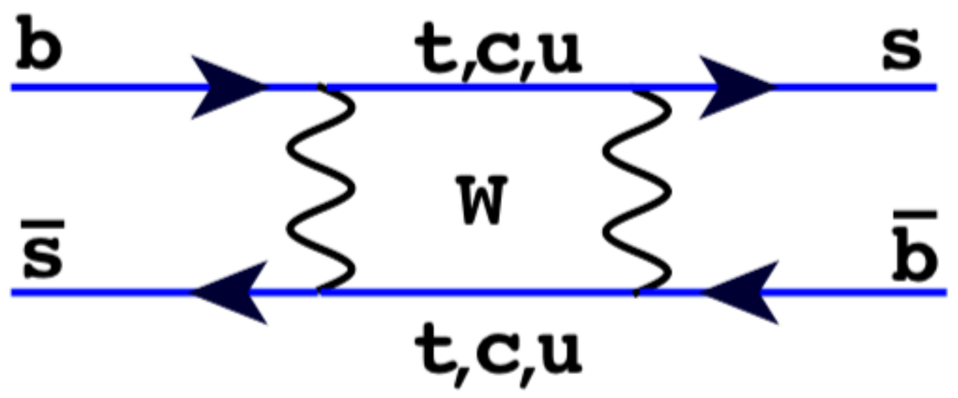
Mass difference ΔM_q

Experiment.: HFLAV 2021

$$\Delta m_s = 17.741 \pm 0.020 \text{ ps}^{-1}$$

$$\Delta m_d = 0.5065 \pm 0.0019 \text{ ps}^{-1}$$

Theory



CKM · Inami-Lim · Buras Jamin Weisz

$$M_{12}^s = \frac{G_F^2}{12\pi^2} \lambda_t^2 M_W^2 S_0(x_t) B f_{B_s}^2 M_{B_s} \hat{\eta}_B$$

In the SM one operator:

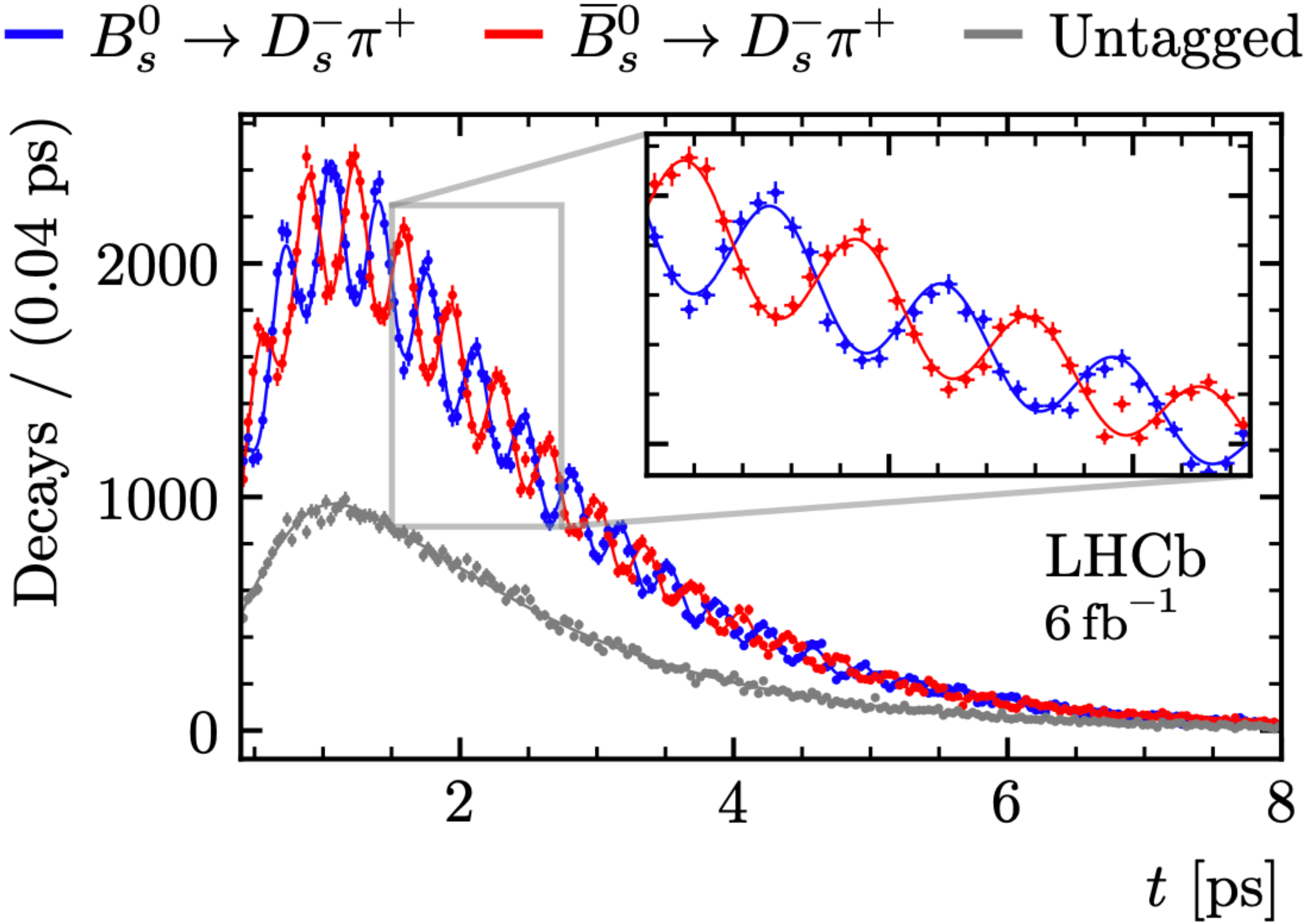
$$Q = \bar{s}^\alpha \gamma_\mu (1-\gamma_5) b^\alpha \times \bar{s}^\beta \gamma^\mu (1-\gamma_5) b^\beta$$

$$\langle Q \rangle \equiv \langle B_s^0 | Q | \bar{B}_s^0 \rangle = \frac{8}{3} M_{B_s}^2 f_{B_s}^2 B(\mu)$$

Non-perturbative theory input:

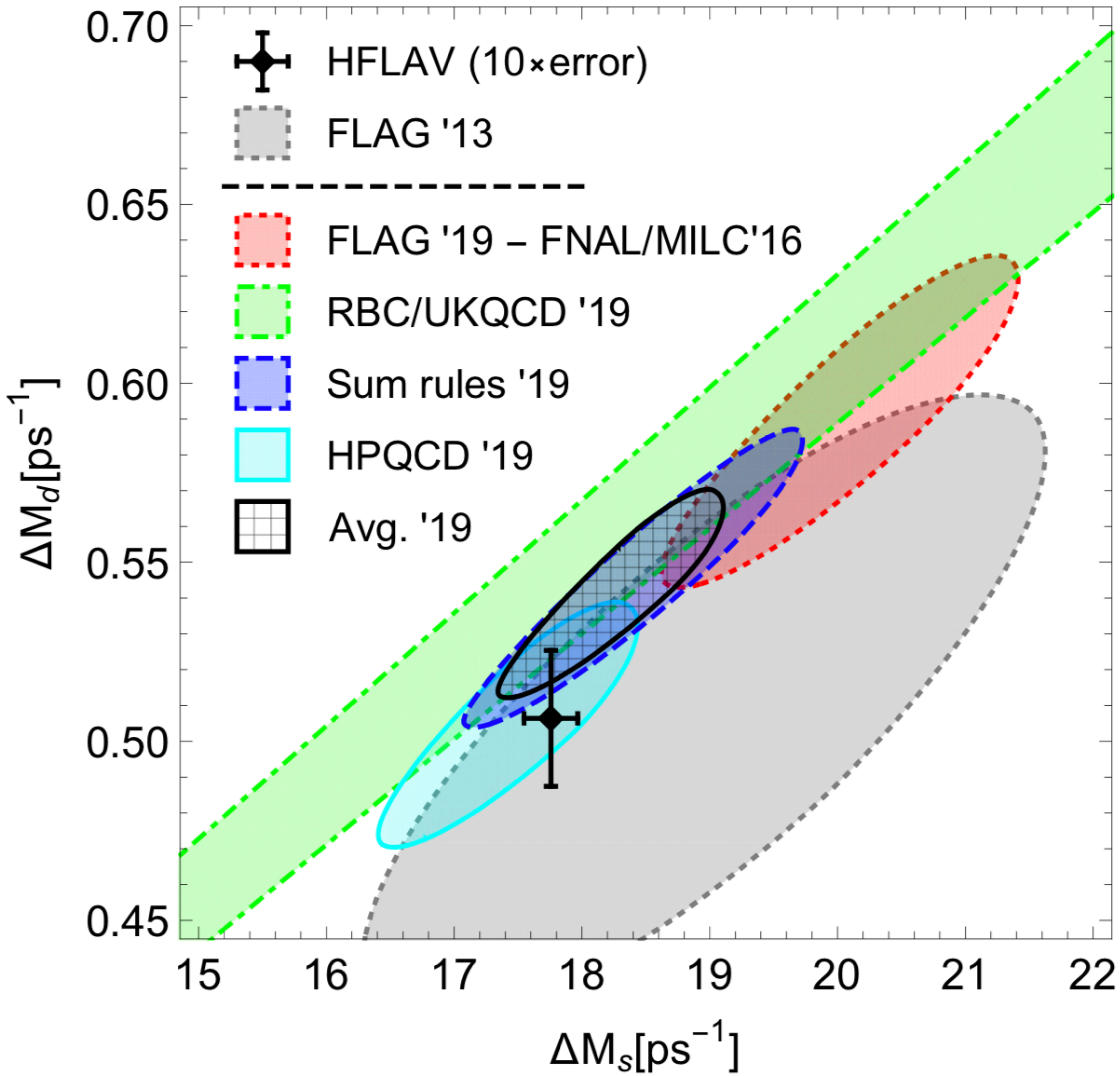
1) Lattice: ETM, FNAL-MILC, RBC-UKQCD, HPQCD
2) Sum rules: Siegen, Durham

Mass difference ΔM_q



LHCb
2104.04421

Mass difference ΔM_q



Why is this interesting?

1. **Interesting SM test per se - QCD/BSM**
2. **Determination of SM parameter**
3. **Many BSM models predict large effects in ΔM_q**

Very active field:

- Flag 19: mostly FNAL-MILC (2/16)
- RBC-UK: 12-18
- Sum rules: Durham 4/19 (based on Siegen 16-18, Durham 17)
- HPQCD: 07/19

New averages of lattice and sum rules
Di Luzio, Kirk, AL, Rauh
1909.11087 JHEP

$$\Delta M_d^{\text{Average 2019}} = \left(0.533^{+0.022}_{-0.036}\right)\,\text{ps}^{-1} = \left(1.05^{+0.04}_{-0.07}\right)\Delta M_d^{\text{exp}},$$
$$\Delta M_s^{\text{Average 2019}} = \left(18.4^{+0.7}_{-1.2}\right)\,\text{ps}^{-1} = \left(1.04^{+0.04}_{-0.07}\right)\Delta M_s^{\text{exp}},$$

Decay rate difference $\Delta\Gamma_s$

Calculation is more difficult than mass difference - use Heavy Quark Expansion

$$\Gamma_{12} = \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \ldots .$$

Each term can be split up into a perturbative part and non-perturbative matrix elements

$$\Gamma_i = \left[\Gamma_i^{(0)} + \frac{\alpha_S}{4\pi}\Gamma_i^{(1)} + \frac{\alpha_S^2}{(4\pi)^2}\Gamma_i^{(2)} + \ldots,\right]\langle O^{d=i+3}\rangle$$

$$R_2 = \frac{1}{m_b^2}(\bar{b}^\alpha \overleftarrow{D}_\rho \gamma^\mu (1-\gamma^5) D^\rho s^\alpha)(\bar{b}^\beta \gamma_\mu (1-\gamma^5) s^\beta)$$

$$R_3 = \frac{1}{m_b^2}(\bar{b}^\alpha \overleftarrow{D}_\rho (1-\gamma^5) D^\rho s^\alpha)(\bar{b}^\beta (1-\gamma^5) s^\beta)$$

This work

Sum rules and lattice 1909.11087

Status of theory predictions

known → Q_1, Q_2, Q_3, Q_4, Q_5

HP-QCD 1910.00970 → R_2, R_3

Q_1, Q_2, Q_3 $\quad Q_4, Q_5, R_2, R_3$

$Obs.$	$\Gamma_3^{(0)}$	$\Gamma_3^{(1)}$	$\Gamma_3^{(2)}$	$\langle O^{d=6}\rangle$	$\Gamma_4^{(0)}$	$\Gamma_4^{(1)}$	$\langle O^{d=7}\rangle$	$\sum$
Γ_{12}^s	$++$	$++$	$\frac{+}{2}$	$+++$	$++$	0	$+$	$10.5 + (***)$
Γ_{12}^d	$++$	$++$	0	$+++$	$++$	0	$+$	$10 + (***)$

Decay rate difference $\Delta\Gamma_s$

Relation to experiment

$$\Re\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = -\frac{\Delta\Gamma_s}{\Delta M_q}$$

$$\Im\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = a_{sl}^q$$

- **Decay constants cancel completely**
- **Bag parameter cancel largely**

SM predictions (AL, Tetlalmatzi-Xolocotzi 1912.07621)

$$\Delta\Gamma_s^{\mathrm{SM\,2019}} = (0.091 \pm 0.013)\,\mathrm{ps}^{-1},$$

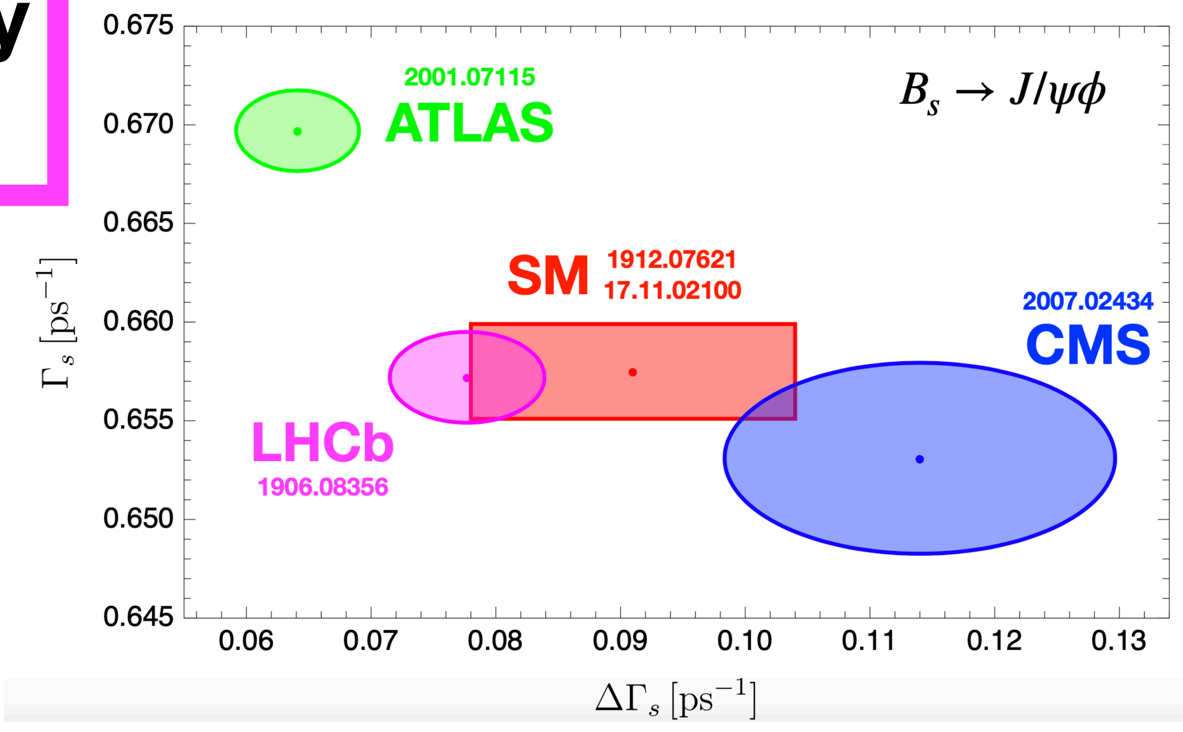
$$\Delta\Gamma_s^{\mathrm{HFLAV2021}} = (0.082 \pm 0.005)\,\mathrm{ps}^{-1}$$

- **Good agreement**
- **Experiment about 3 times more precise**

$$\Delta\Gamma_d^{\mathrm{SM\,2019}} = (2.6 \pm 0.4) \cdot 10^{-3}\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_d^{\mathrm{HFLAV2021}} = (0.7 \pm 6.6) \cdot 10^{-3}\,\mathrm{ps}^{-1}$$

- **Might solve the D0 di-muon asymmetry**
- **Experimental number needed**



- **Strong test of HQE**
- **Violation of Quark hadron duality must be small**

Semi-leptonic CP asymmetries

Relation to experiment

$$\Re\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = -\frac{\Delta\Gamma_s}{\Delta M_q}$$

CP violating!

$$\Im\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = a_{sl}^q$$

- **Decay constants cancel completely**
- **Bag parameter cancel largely**

SM predictions

$$a_{fs}^{s,\,\mathrm{SM\,2019}} = (2.06 \pm 0.18) \cdot 10^{-5}$$

$$a_{fs}^{s,\,\mathrm{HFLAV\,2019}} = (-60 \pm 280) \cdot 10^{-5}$$

$$a_{fs}^{d,\,\mathrm{SM\,2019}} = -(4.73 \pm 0.42) \cdot 10^{-4}$$

$$a_{fs}^{d,\,\mathrm{HFLAV\,2019}} = (-21 \pm 17) \cdot 10^{-4}$$

- **Very sensitive to BSM effects!**
- **Experimental number needed**

$$a_{fs}^q = 480 \cdot 10^{-5} \sin\phi_{12}^q$$

Semi-leptonic CP asymmetries

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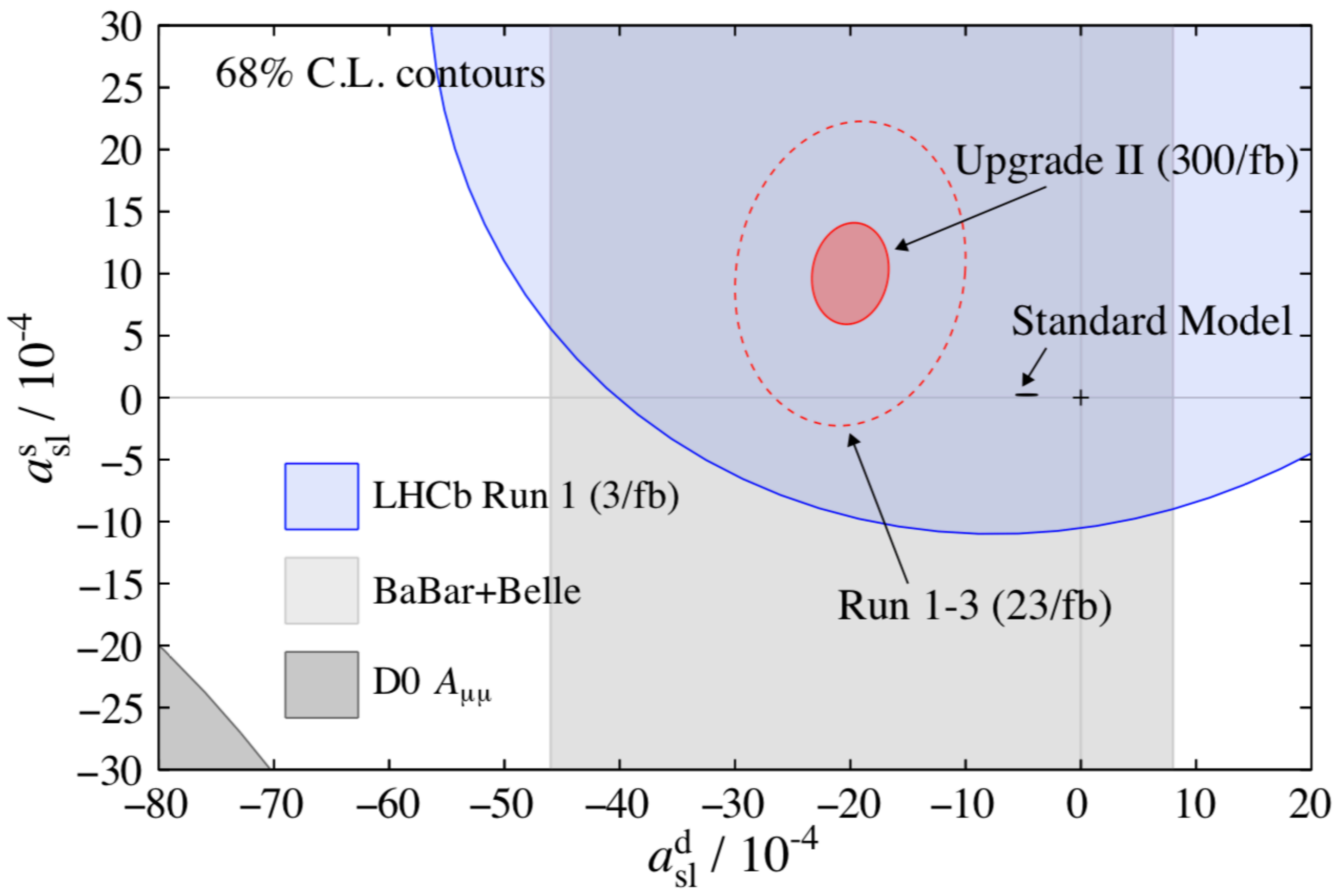


BSM Contributions to Mixing

- General BSM contribution to $M_{12}^q = M_{12}^{\rm SM,q} |\Delta_q| e^{i\phi_q^\Delta}$ **(AL, Nierste, 0612167)**

This phase arises e.g. in the extraction of β and β_s

Experiment actually measures $\beta^{\rm Exp} = \beta^{\rm SM} + \frac{1}{2}\phi_d^\Delta + \beta_{Peng}^{\rm SM} + \beta_{Peng}^{\rm BSM}$

- General BSM contribution to $\Gamma_{12}^q = \Gamma_{12}^{\rm SM,q} |\tilde{\Delta}_q| e^{-i\tilde{\phi}_q^\Delta}$ **(AL, 1106.3200)**

Mixing phase in the semi-leptonic asymmetries $\phi_{12}^q = \phi_{12}^{\rm SM,q} + \phi_q^\Delta + \tilde{\phi}_q^\Delta$

BSM Contributions to Mixing

- How large can the new physics phases be?

$$\beta^{\text{Exp}} - \beta^{\text{SM}} = 22.14^\circ - 23.7^\circ \pm 1.5^\circ = -1.56^\circ \pm 1.5^\circ$$

$$\beta_s^{\text{Exp}} - \beta_s^{\text{SM}} = 1.46^\circ - 1.06^\circ \pm 0.7^\circ = 0.4^\circ \pm 0.7^\circ$$

$$\Phi_q^\Delta < 5^\circ \Rightarrow a_{sl}^q < 42 \cdot 10^{-5}$$

- BSM in tree level decays? **(AL, Tetlalmatzi-Xolocotzi 1912.07621)**

$$-\frac{\Gamma_{12}^s}{M_{12}^s} = \frac{\Gamma_{12}^{s,cc}}{\tilde{M}_{12}^s} + 2\frac{\lambda_u}{\lambda_t}\frac{\Gamma_{12}^{s,cc} - \Gamma_{12}^{s,uc}}{\tilde{M}_{12}^s} + \left(\frac{\lambda_u}{\lambda_t}\right)^2 \frac{\Gamma_{12}^{s,cc} - 2\Gamma_{12}^{s,uc} + \Gamma_{12}^{s,uu}}{\tilde{M}_{12}^s}$$

Small imaginary part in $b \to c\bar{c}d, s$ could have huge effect in $a_{sl}^{d,s}$

$$a_{sl}^q \leq a_{sl}^{\text{Exp,q}} \approx \pm 280(170) \cdot 10^{-5}$$

Or can we do better?

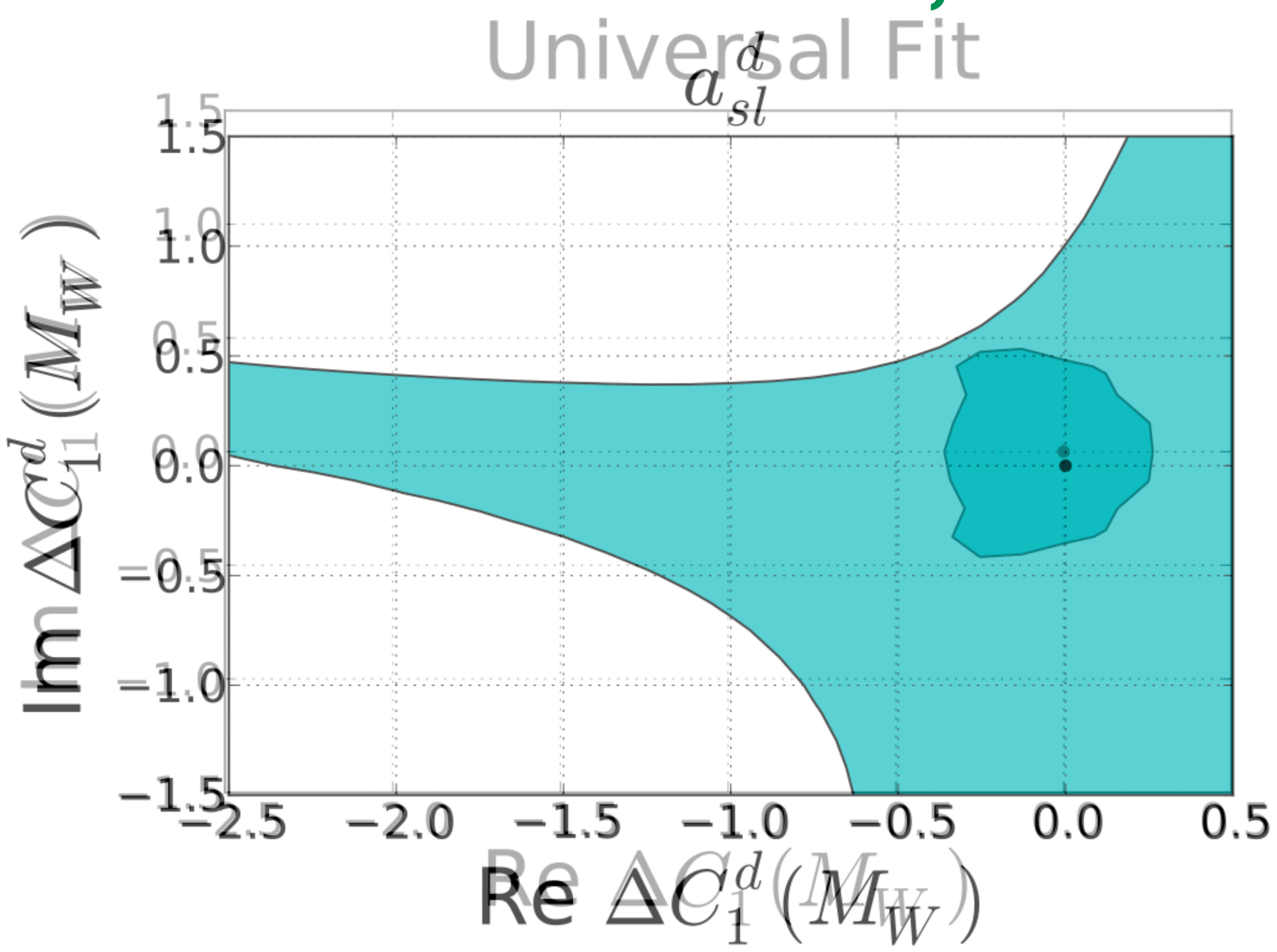
Some recent excitement about colour-allowed tree-level decays $> 5\sigma$

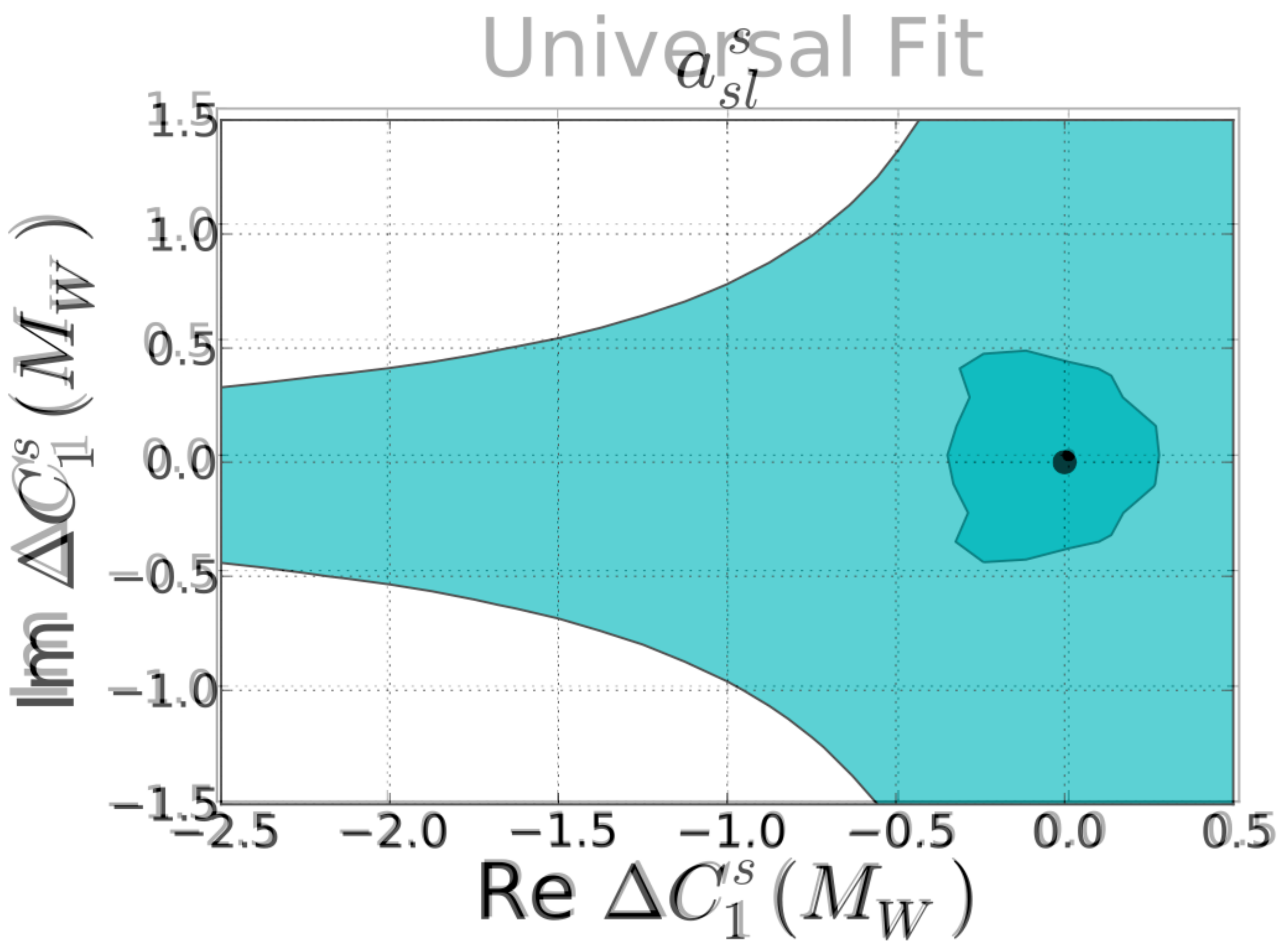
2007.10338
2008.01086
2103.04138
2103.10332

Can a_{sl}^s be measured in $\bar{B}_s \to D_s^+ \pi^-$?

BSM Contributions to Mixing

AL, Tetlalmatzi-Xolocotzi 1912.07621





a_{sl}^d is not constrained beyond the experimental bound

a_{sl}^s seems to constrained to about half of the experimental value ($\pm 140 \cdot 10^{-5}$) from $\tau(B_s)/\tau(B_d)$

BUT a proper treatment requires inclusion of Darwin term

AL, Piscopo, Rusov 2004.09527

A relation to trick them all

TUM-HEP-810/11

arXiv:1106.3200v3 [hep-ph] 1 Jul 2012

A simple relation for B_s-mixing

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Abstract

We reinvestigate a simple relation between the semileptonic CP asymmetry a_{sl}^s, the decay rate difference $\Delta\Gamma_s$, the mass difference ΔM_s and $S_{\psi\phi}$ extracted from the angular analysis of the decay $B_s \to \psi\phi$, which is regularly used in the literature. We find that this relation is not suited to eliminate the theory prediction for Γ_{12}, it can, however be used to determine the size of the penguin contributions to the decay $B_s \to \psi\phi$. Moreover we comment on the current precision of the theory prediction for Γ_{12}.

arXiv:1606.06042v3 [hep-ph] 1 May 2017

B_s^0–$\bar{B}_s^0$ Oscillations as a New Tool to Explore CP Violation in $D_s^\pm$ Decays

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[b] *Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, Netherlands*
[c] *Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, NL-9747 AG Groningen, Netherlands*
[d] *Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, D-57068 Siegen, Germany*

Abstract

CP violation in B_s^0–$\bar{B}_s^0$ oscillations is expected at the 10^{-5} level in the Standard Model but could be enhanced by New Physics. Using $B_s^0 \to D_s^- \ell^+ \nu_\ell$ decays, LHCb has recently reported the new result $(0.39 \pm 0.33) \times 10^{-2}$ of the corresponding observable $a_{\rm sl}^s$. We point out that other current B decay data imply $a_{\rm sl}^s = (0.004 \pm 0.075) \times 10^{-2}$. In view of this strong constraint, we propose to use $B_s^0 \to D_s^- \ell^+ \nu_\ell$ and similar flavor-specific decays as a new tool to determine both the production asymmetry between B_s^0 and $\bar{B}_s^0$ mesons, and the CP asymmetry in the subsequent $D_s^\pm$ decays. The former serves as input for analyses of CP violation in B_s^0 channels, with significant room for improvement, while the latter offers an exciting laboratory for New Physics.

As soon as Exp gets close to SM:

PHYSICAL REVIEW D **102,** 093002 (2020)

Renormalization scale setting for D-meson mixing

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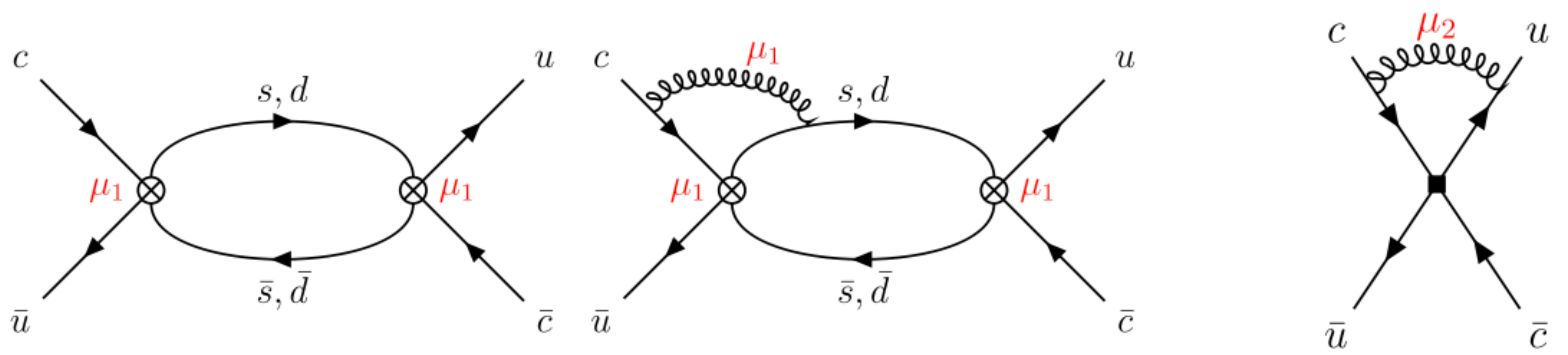
A naive application of the heavy quark expansion (HQE) yields theory estimates for the decay rate of neutral D mesons that are 4 orders of magnitude below the experimental determination. It is well known that this huge suppression results from severe Glashow-Iliopoulos-Maiani cancellations. We find that this mismatch can be solved by individually choosing the renormalization scale of the different internal quark contributions. For b and c hadron lifetimes, as well as for the decay rate difference of neutral B mesons, the effect of our scale setting procedure lies within the previously quoted theory uncertainties, while we get enlarged theory uncertainties for the semileptonic CP asymmetries in the B system.

$$\Gamma_{cc}(\mu - 2\epsilon)$$

$$\Gamma_{uc}(\mu - \epsilon)$$

$$\Gamma_{uu}(\mu)$$



ϵ (GeV)	Γ^s_{12}/M^s_{12}	Γ^d_{12}/M^d_{12}
0.	**−0.00499+0.000022*I***	**−0.00497−0.00050*I***
0.2.	**−0.00494+0.000023*I***	**−0.00492−0.00053*I***
0.5.	**−0.00484** + 0.000026*I*	**−0.00482** − 0.00059*I*
1.0	**−0.00447** + 0.000037*I*	**−0.00448** − 0.00084*I*
1.5.	−0.00287 + 0.000091*I*	−0.00309 − 0.0021*I*