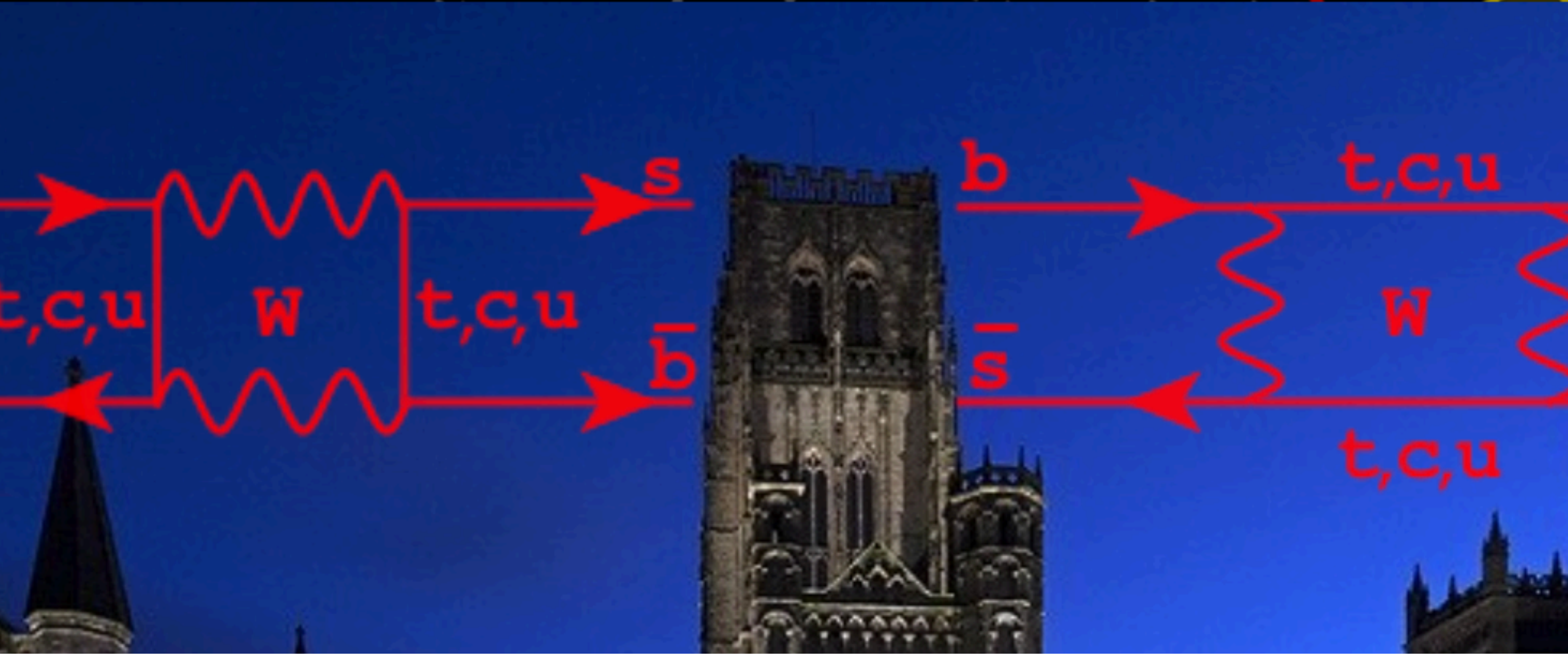
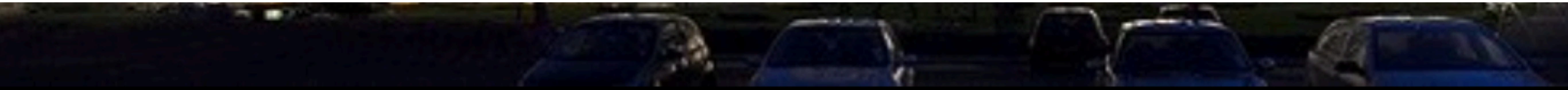


MIXING+LIFETIMES

Alexander Lenz (IPPP Durham)
University of Liverpool - Seminar
2.5.2018



CONTENT

- Experimental Status of lifetimes and mixing
- The Heavy Quark Expansion (HQE)
- Status before 2017
- News from theory
- Consequences for BSM models
- Outlook

EXPERIMENTAL STATUS

b-hadron species	average lifetime	lifetime ratio
B^0	**1.518 ± 0.004 ps**	
B^+	**1.638 ± 0.004 ps**	$B^+/B^0 = 1.076 \pm 0.004$
$B_s^{\,0}$	**1.509 ± 0.004 ps**	$B_s^{\,0}/B^0 = 0.994 \pm 0.004$
B_{sL}	**1.414 ± 0.006 ps**	
B_{sH}	**1.619 ± 0.009 ps**	
$B_c^{\,+}$	**0.510 ± 0.009 ps**	
Λ_b	**1.470 ± 0.009 ps**	$\Lambda_b/B^0 = 0.968 \pm 0.006$
$\Xi_b^{\,-}$	**1.571 ± 0.040 ps**	
$\Xi_b^{\,0}$	**1.479 ± 0.030 ps**	$\Xi_b^{\,0}/\Xi_b^{\,-} = 0.929 \pm 0.028$
$\Omega_b^{\,-}$	**1.64 +0.18 −0.17 ps**	

HFLAV 2017

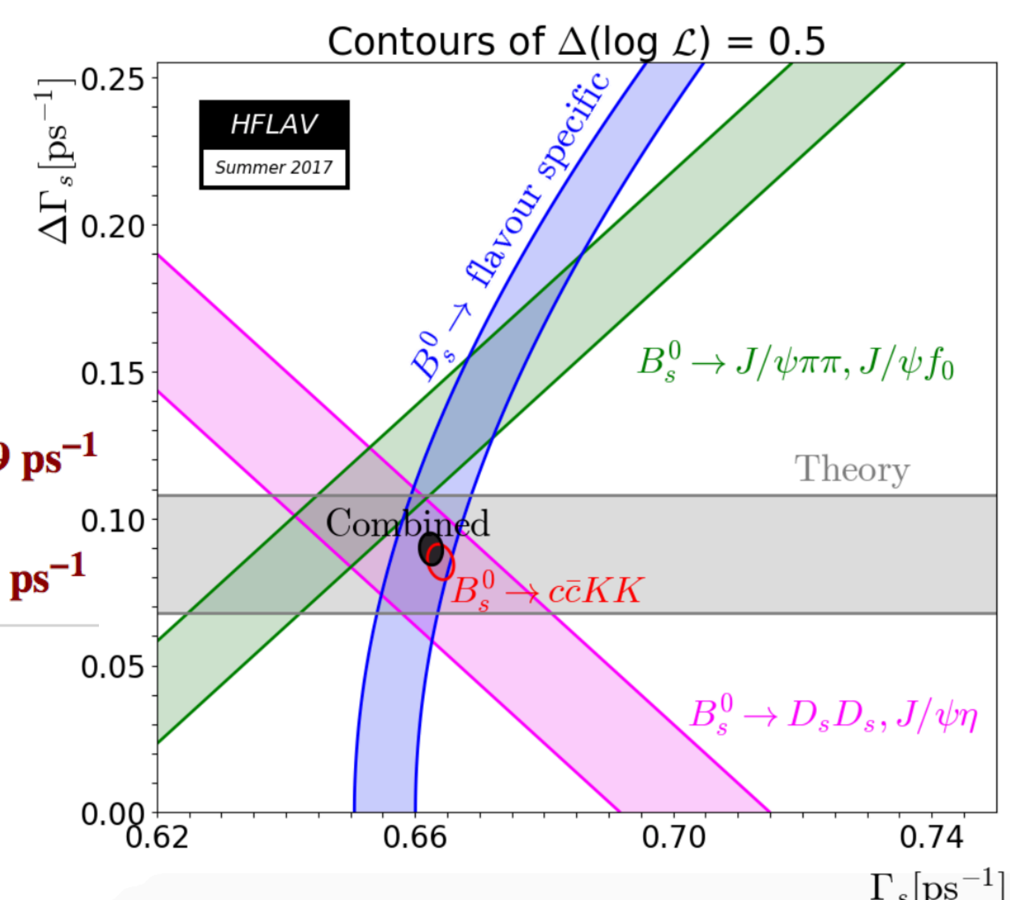
CP violation parameter in B^0 mixing	
$\lvert q/p\rvert = 1.0009 \pm 0.0013$ $A_{SL} = -0.0019 \pm 0.0027$ $\mathrm{Re}(\varepsilon_B)/(1+\lvert\varepsilon_B\rvert^2) = -0.0005 \pm 0.0007$	from measurements at the $\Upsilon(4S)$
$\lvert q/p\rvert = 1.0010 \pm 0.0008$ **$A_{SL} = -0.0021 \pm 0.0017$** **$\mathrm{Re}(\varepsilon_B)/(1+\lvert\varepsilon_B\rvert^2) = -0.0005 \pm 0.0004$**	world average

CP violation parameter in B_s mixing	
$\lvert q/p\rvert = 1.0003 \pm 0.0014$ **$A_{SL} = -0.0006 \pm 0.0028$**	world average

Fit results from ATLAS, CDF, CMS, D0 and LHCb data	without constraint from effective lifetime measurements	with constraints I and II	**with constraints I, II and III**
Γ_s	0.6640 ± 0.0020 ps^{-1}	0.6627 ± 0.0020 ps^{-1}	**0.6625 ± 0.0018 ps^{-1}**
$1/\Gamma_s$	1.506 ± 0.005 ps	1.509 ± 0.004 ps	**1.509 ± 0.004 ps**
$\tau_{\mathrm{Short}} = 1/\Gamma_L$	1.415 ± 0.007 ps	1.414 ± 0.006 ps	**1.414 ± 0.006 ps**
$\tau_{\mathrm{Long}} = 1/\Gamma_H$	1.609 ± 0.010 ps	1.618 ± 0.010 ps	**1.619 ± 0.009 ps**
$\Delta\Gamma_s$	$+0.085 \pm 0.006$ ps^{-1}	$+0.089 \pm 0.006$ ps^{-1}	**$+0.090 \pm 0.005$ ps^{-1}**
$\Delta\Gamma_s/\Gamma_s$	+0.128 ± 0.009	+0.135 ± 0.008	**+0.135 ± 0.008**
correlation $\varrho(\Gamma_s, \Delta\Gamma_s)$	−0.193	−0.153	**−0.082**

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

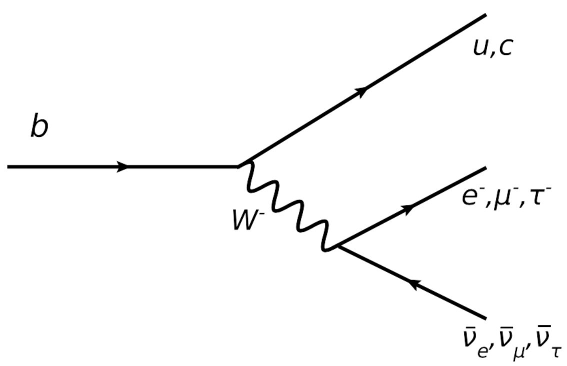
$$\Delta m_s = 17.757 \pm 0.021\ \mathrm{ps}^{-1}$$

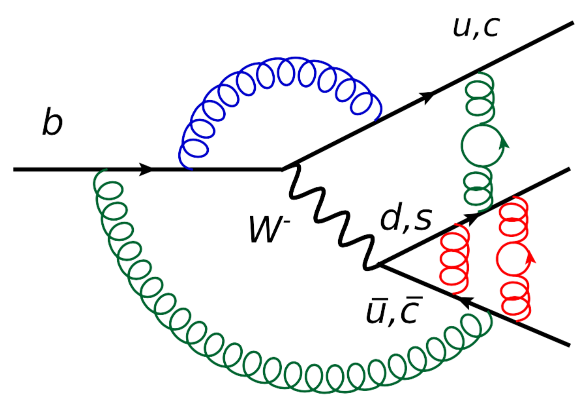


$s \times \Delta\Gamma_d/\Gamma_d = -0.002 \pm 0.010$	from DELPHI, BABAR, Belle, ATLAS and LHCb

HEAVY QUARK EXPANSION I - LIFETIMES

- **Free quark decay**





$$\Gamma_b = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 c_{3,b}$$

$$c_{3,b} = \begin{cases} 9 \\ 2.97 \\ 3.25 \\ 4.66 \end{cases} \text{for} \begin{cases} m_c = 0, \\ m_c^{\text{Pole}}, m_b^{\text{Pole}} \\ \bar{m}_c(\bar{m}_c), \bar{m}_b(\bar{m}_b) \\ \bar{m}_c(\bar{m}_b), \bar{m}_b(\bar{m}_b) \end{cases}$$

$$\tau_b = 2.60 \text{ ps} \quad \text{for } \bar{m}_c(\bar{m}_b), \bar{m}_b(\bar{m}_b)$$

- **Effective Hamiltonian** (e.g. Buras, Les Houches)

Free quark decay is an expansion in $\alpha_s(m_b) \ln \frac{m_b^2}{M_W^2} > 1$ instead of $\alpha_s(m_b) \approx 0.2$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{q=u,c} V_c^q (C_1 Q_1^q + C_2 Q_2^q) - V_p \sum_{j=3} C_j Q_j \right] \qquad Q_2 = c_\alpha \gamma_\mu (1-\gamma_5) \bar{b}_\alpha \times d_\beta \gamma^\mu (1-\gamma_5) \bar{u}_\beta$$

sums up large logarithms to all orders!

Wilson coefficients are known up to NNLO-QCD!

e.g. Gorbahn, Haisch 2004

Use $\mathcal{H}_{eff}$ to calculate total decay rates

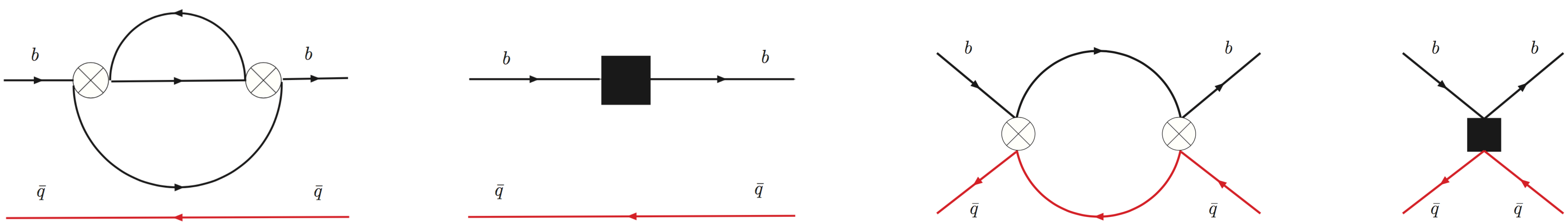
HEAVY QUARK EXPANSION II - LIFETIMES

$$\Gamma(B \to X) = \frac{1}{2m_B} \sum_X \int_{\mathrm{PS}} (2\pi)^4 \delta^{(4)}(p_B - p_X) |\langle X|\mathcal{H}_{eff}|B\rangle|^2$$

Assume:

- mb is large compared to hadronic scale
- decay rate is a Taylor series in 1/mb

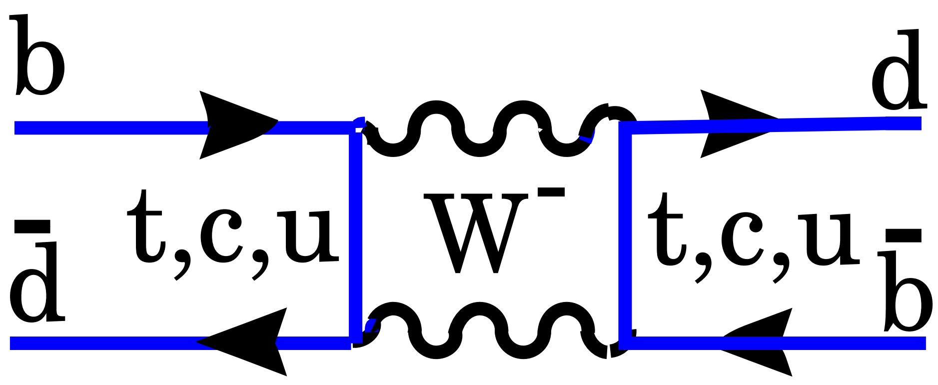
$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \left[c_{3,b} \frac{\langle B|\bar{b}b|B\rangle}{2M_B} + \frac{c_{5,b}}{m_b^2} \frac{\langle B|\bar{b} g_s \sigma_{\mu\nu} G^{\mu\nu} b|B\rangle}{2M_B} + \frac{c_{6,b}}{m_b^3} \frac{\langle B|(\bar{b}q)_\Gamma (\bar{q}b)_\Gamma|B\rangle}{M_B} + \ldots \right]$$

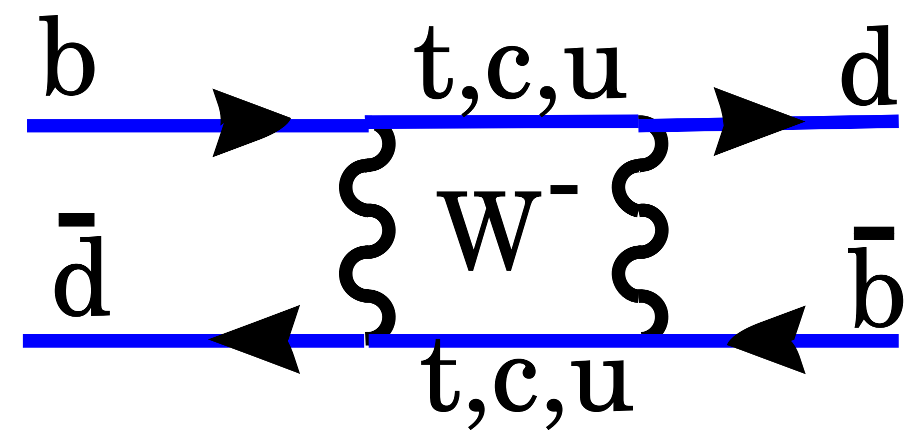


Remarks:

- leading term (=free quark decay) is universal
- different B mesons differ from the 3rd term on
- lifetime predictions need: non-perturbative matrix elements and perturbative Wilson coefficients

MIXING OBSERVABLES





$|M_{12}|$, $|\Gamma_{12}|$ and $\phi = \arg(-M_{12}/\Gamma_{12})$ 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:** $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos\phi$ **(on-shell)**
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!

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

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

HEAVY QUARK EXPANSION III

Total decay rate can be expanded in inverse powers of mb

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \ldots$$

Each term in the series can be further expanded in the strong coupling

$$\Gamma_j = \Gamma_j^{(0)} + \frac{\alpha_s(\mu)}{4\pi}\Gamma_j^{(1)} + \frac{\alpha_s^2(\mu)}{(4\pi)^2}\Gamma_j^{(2)} + \ldots$$

Each term is a product of a perturbative function and the matrix element of **Delta B = 0 operators** **(lattice , sum rules)**

Mixing obeys a similar HQE

$$\Gamma_{12}^q = \left(\frac{\Lambda}{m_b}\right)^3 \Gamma_3 + \left(\frac{\Lambda}{m_b}\right)^4 \Gamma_4 + \ldots$$

Now **Delta B = 2 operators appear** **(lattice , sum rules)**

STATUS BEFORE 2017

	$\Gamma_3^{(0)}$	$\Gamma_3^{(1)}$	$\Gamma_3^{(2)}$	$<\|\mathrm{dim}\,6\|>$	$\Gamma_4^{(0)}$	$\Gamma_4^{(1)}$	$<\|\mathrm{dim}\,7\|>$
B+	1985 -1996 ✓	2002 ✓	✗	2001 ✗	2003 ✓	✗	✗
Bs	1985 -1996 ✓	2002 ✓	✗	2001 ✗	2003 ✓	✗	✗
G12s	1985 -1996 ✓	1998 -2006 ✓	✗	-2016 ✗	1996 ✓	✗	✗
G12d	1985 -1996 ✓	2003 -2006 ✓	✗	-2016 ✗	2003 ✓	✗	✗

STATUS BEFORE 2017

$$\frac{\tau(B^+)}{\tau(B_d)}^{\rm HQE\,2014} = 1.04^{+0.07}_{-0.03}\,,$$

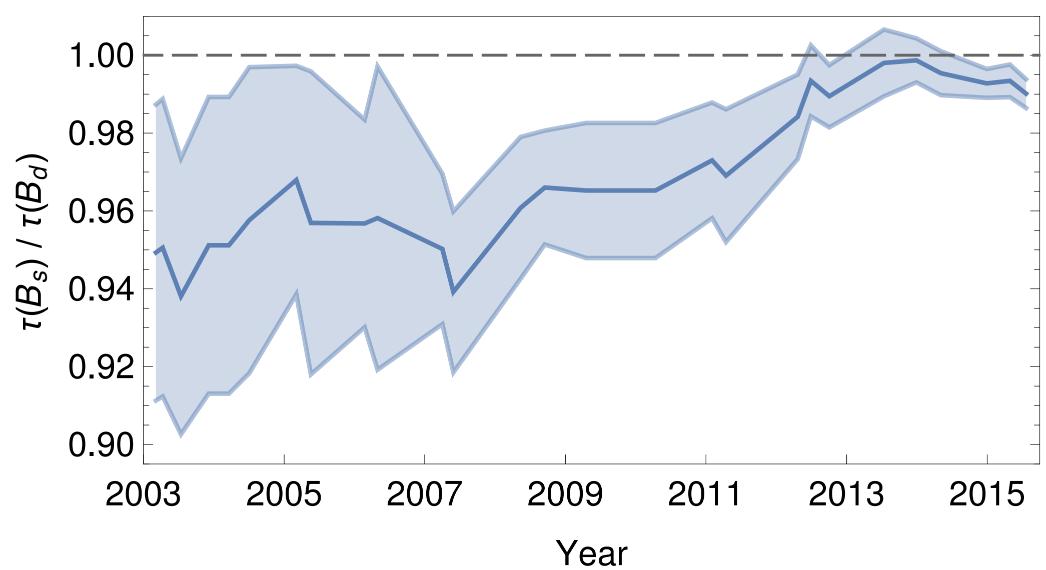
$$\frac{\tau(B_s)}{\tau(B_d)}^{\rm HQE\,2014} = 1.001 \pm 0.002\,,$$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)}^{\rm HQE\,2014} = 0.935 \pm 0.054\,,$$

$$\frac{\bar\tau(\Xi_b^0)}{\bar\tau(\Xi_b^+)}^{\rm HQE\,2014} = 0.95 \pm 0.06\,.$$

*Large uncertainties due to old non-perturbative input

*Perfect cancellation in Bs lifetime - test of NP models



see e.g.
Jäger et al
1701.091883

Observable	SM – conservative	SM – aggressive	Experiment
ΔM_s	(18.3 ± 2.7) ps^{-1}	(20.11 ± 1.37) ps^{-1}	(17.757 ± 0.021) ps^{-1}
$\Delta\Gamma_s$	(0.088 ± 0.020) ps^{-1}	(0.098 ± 0.014) ps^{-1}	(0.082 ± 0.006) ps^{-1}
a_{sl}^s	$(2.22 \pm 0.27) \cdot 10^{-5}$	$(2.27 \pm 0.25) \cdot 10^{-5}$	$(-7.5 \pm 4.1) \cdot 10^{-3}$

Ideal for NP searches - experimental precision > theory precision!

On the ultimate precision of meson mixing observables
Thomas Jubb, Matthew Kirk, Alexander Lenz, Gilberto Tetlalmatzi-Xolocotzi
Published in Nucl.Phys. B915 (2017) 431-453

THEORY UNCERTAINTIES IN MIXING

$\Delta\Gamma_s^{SM}$	This work
Central value	$0.088\ \mathrm{ps}^{-1}$
$\delta(B_{\tilde{R}_2})$	14.8%
$\delta(f_{B_s}\sqrt{B})$	13.9%
$\delta(\mu)$	8.4%
$\delta(V_{cb})$	4.9%
$\delta(\tilde{B}_S)$	2.1%
$\delta(B_{R_0})$	2.1%
$\delta(\bar{z})$	1.1%
$\delta(m_b)$	0.8%
$\delta(B_{\tilde{R}_1})$	0.7%
$\delta(B_{\tilde{R}_3})$	0.6%
$\delta(B_{R_1})$	0.5%
$\delta(B_{R_3})$	0.2%
$\delta(m_s)$	0.1%
$\delta(\gamma)$	0.1%
$\delta(\alpha_s)$	0.1%
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	0.1%
$\delta(\bar{m}_t(\bar{m}_t))$	0.0%
$\sum\delta$	22.8%

3 dominant uncertainties:

★ $\langle R_2\rangle = -\frac{2}{3}\left[\frac{M_{B_s}^2}{m_b^{\mathrm{pow2}}} - 1\right] M_{B_s}^2 f_{B_s}^2 B_{R_2}$; $\quad R_2 = \frac{1}{m_b^2}\,\bar{s}_\alpha \overleftarrow{D}_\rho \gamma^\mu(1-\gamma_5) D^\rho b_\alpha\, \bar{s}_\beta \gamma_\mu (1-\gamma_5) b_\beta$

Dim 7 has never been done

★ $\langle Q\rangle \equiv \langle \bar{B}_s^0|Q|B_s^0\rangle = \frac{8}{3} M_{B_s^0}^2 f_{B_s}^2 B(\mu)$ $\quad Q = \bar{s}^\alpha \gamma_\mu (1-\gamma_5) b^\alpha \times \bar{s}^\beta \gamma^\mu (1-\gamma_5) b^\beta$

Dim 6 is done on the lattice

newest results (**Fermilab MILC 1602:03560**)

indicate a small tension with experiment

★ **NNLO QCD has not been done**

CP violation in the Bs system

Marina Artuso, Guennadi Borissov, Alexander Lenz

Rev.Mod.Phys. 88 (2016) no.4,045002

NEWS

	$\Gamma_3^{(0)}$	$\Gamma_3^{(1)}$	$\Gamma_3^{(2)}$	$<\|\dim 6\|>$	$\Gamma_4^{(0)}$	$\Gamma_4^{(1)}$	$<\|\dim 7\|>$
B+	1985 -1996 ✓	2002 ✓	✗	2001 ✗	2003 ✓	✗	✗
Bs	1985 -1996 ✓	2002 ✓	✗	2001 ✗	2003 ✓	✗	✗
G12s	1985 -1996 ✓	1998 -2006 ✓	✗	-2016 ✗	1996 ✓	✗	✗
G12d	1985 -1996 ✓	2003 -2006 ✓	✗	-2016 ✗	2003 ✓	✗	✗

First steps: Asatrian et al 1709.02160

This talk → Sum rules: this talk, Kirk, Lenz, Rauh 1711.02100

HPQCD in progress, see LATTICE 2016, 2017

Sum rules: Kirk, Lenz, Rauh in progress

NEW RESULTS FOR NON-PERTURBATIVE PARAMETERS

all dim-6 Delta B = 0,2 operators

1 dim-6 Delta B =2 operator

IPPP/17/65
November 8, 2017

Dimension-six matrix elements for meson mixing and lifetimes from sum rules

M. Kirk, A. Lenz and T. Rauh

IPPP, Department of Physics, University of Durham, DH1 3LE, United Kingdom

Abstract

The hadronic matrix elements of dimension-six $\Delta F = 0, 2$ operators are crucial inputs for the theory predictions of mixing observables and lifetime ratios in the B and D system. We determine them using HQET sum rules for three-point correlators. The results of the required three-loop computation of the correlators and the one-loop computation of the QCD-HQET matching are given in analytic form. For mixing matrix elements we find very good agreement with recent lattice results and comparable theoretical uncertainties. For lifetime matrix elements we present the first ever determination in the D meson sector and the first determination of $\Delta B = 0$ matrix elements with uncertainties under control - superseeding preliminary lattice studies stemming from 2001 and earlier. With our state-of-the-art determination of the bag parameters we predict: $\tau(B^+)/\tau(B_d^0) = 1.082^{+0.022}_{-0.026}$, $\tau(B_s^0)/\tau(B_d^0) = 0.9994 \pm 0.0025$, $\tau(D^+)/\tau(D^0) = 2.7^{+0.7}_{-0.8}$ and the mixing-observables in the B_s and B_d system, in good agreement with the most recent experimental averages.

PHYSICAL REVIEW D **94,** 034024 (2016)

B^0-$\bar{B}^0$ mixing at next-to-leading order

Andrey G. Grozin

Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia and Novosibirsk State University, Novosibirsk 630090, Russia

Rebecca Klein, Thomas Mannel, and Alexei A. Pivovarov

Theoretische Elementarteilchenphysik, Naturwiss.- techn. Fakultät, Universität Siegen, 57068 Siegen, Germany

(Received 4 July 2016; published 11 August 2016)

We compute the perturbative corrections to the heavy quark effective theory sum rules for the matrix element of the $\Delta B = 2$ operator that determines the mass difference of B^0, $\bar{B}^0$ states. Technically, we obtain analytically the nonfactorizable contributions at order α_s to the bag parameter that first appear at the three-loop level. Together with the known nonperturbative corrections due to vacuum condensates and $1/m_b$ corrections, the full next-to-leading order result is now available. We present a numerical value for the renormalization group invariant bag parameter that is phenomenologically relevant and compare it with recent lattice determinations.

Three-loop HQET vertex diagrams for B^0–$\bar{B}^0$ mixing

Andrey G. Grozin and Roman N. Lee

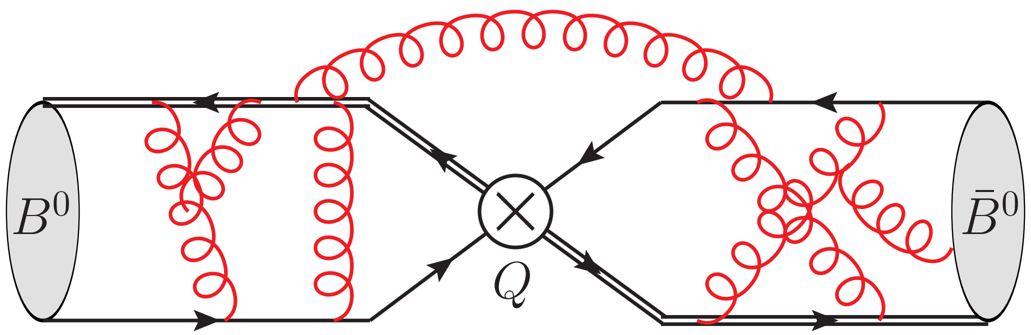
Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
E-mail: A.G.Grozin@inp.nsk.su, R.N.Lee@inp.nsk.su

Master integrals

Abstract: Three-loop vertex diagrams in HQET needed for sum rules for B^0–$\bar{B}^0$ mixing are considered. They depend on two residual energies. An algorithm of reduction of these diagrams to master integrals has been constructed. All master integrals are calculated exactly in d dimensions; their ε expansions are also obtained.

Keywords: NLO Computations, B-Physics.

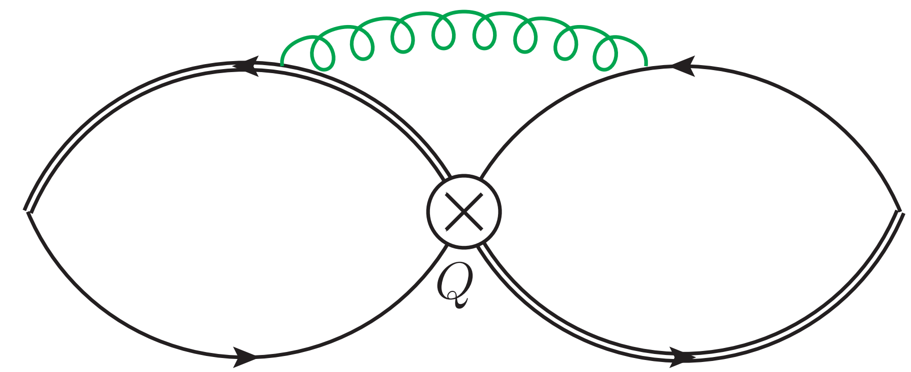
HQET SUM RULES



Sum rule

Quark-hadron duality

Analyticity



Hadronic matrix element

Characteristic scale: Λ_{QCD}

$\alpha_s\left(\Lambda_{\text{QCD}}\right) \sim \mathcal{O}(1)$

$\Rightarrow$ non-perturbative

Correlation function

Characteristic scale: 'virtuality' ω

Choose ω s.t. $\alpha_s(\omega) \ll 1$

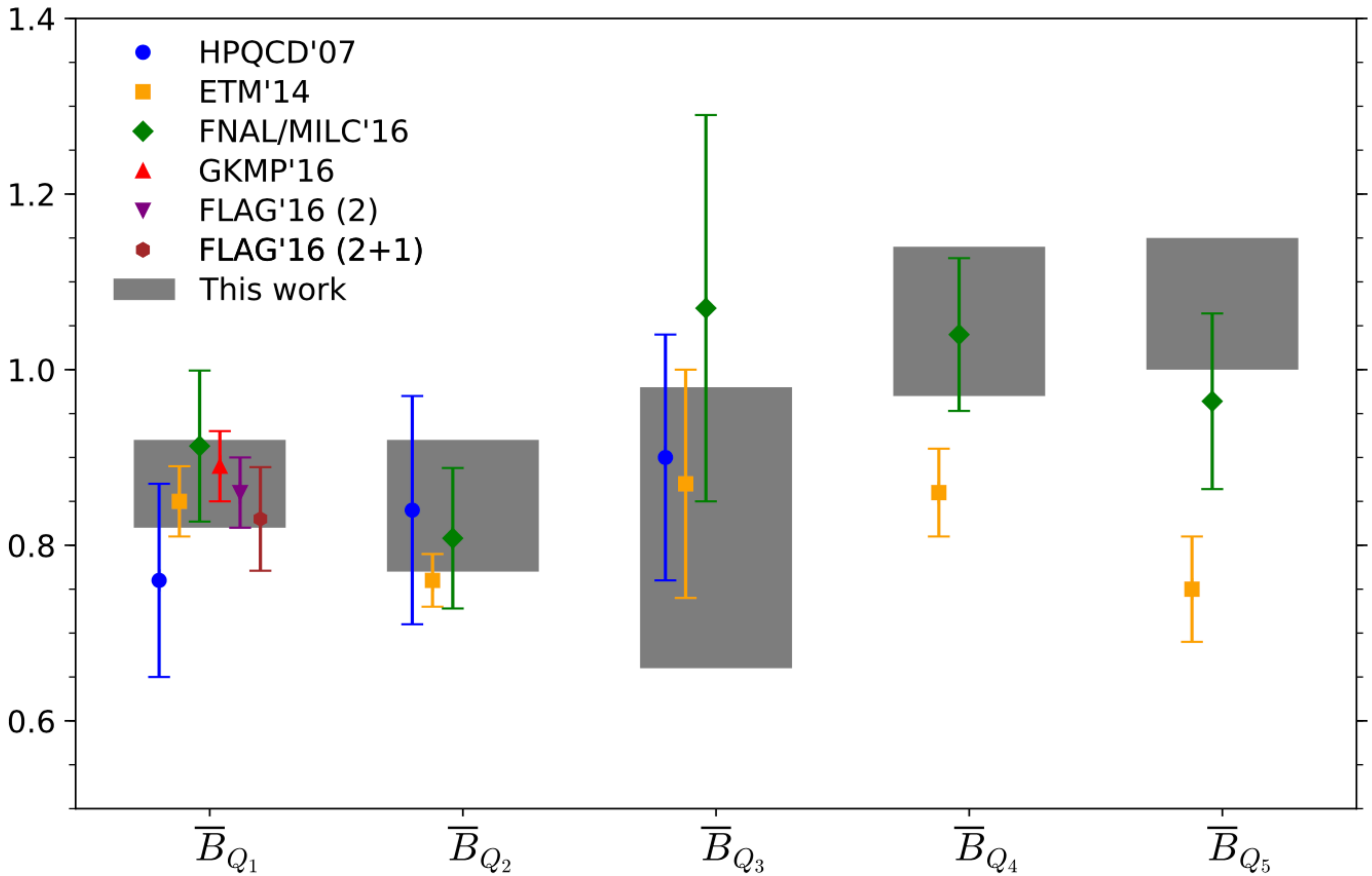
$\Rightarrow$ perturbatively calculable

- Do all dim 6 and dim 7 operators for mixing **AND lifetimes**
- 3 loop diagrams with FIRE reduced (2 external momenta)
- Master integrals known: Grozin, Lee; hep-ph/0812.4522
- HQET running to scale m_b
- HQET-QCD matching at scale m_b

1 mixing operator Q done by Grozin, Klein, Mannel, Pivovarov hep-ph/1606.06054

all Delta B=0 and 2 dim 6 operators by Kirk, Lenz, Rauh; 1711.02100

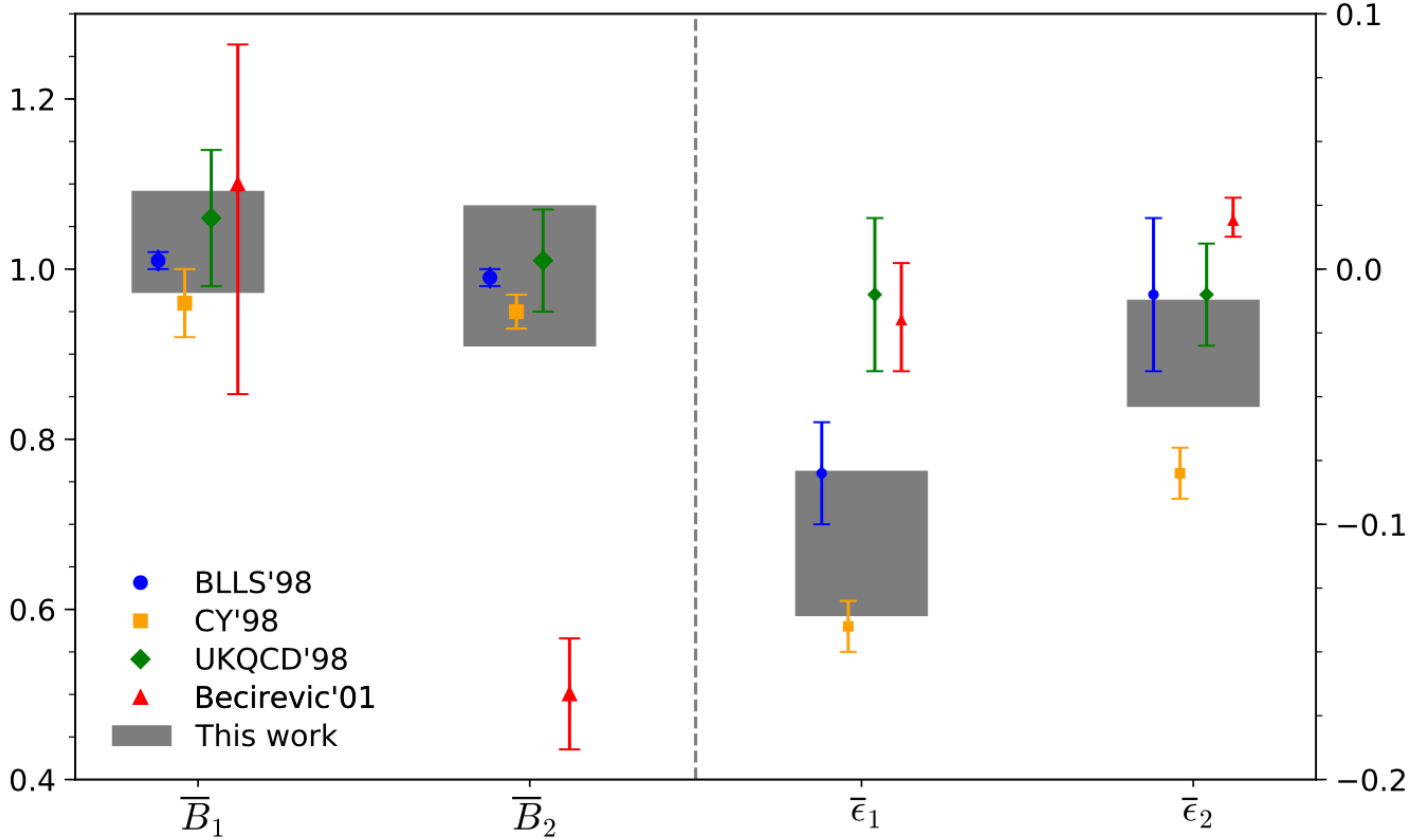
NEW RESULTS 1: B-MIXING



Kirk, Lenz, Rauh 1711.02100

- Very good agreement with lattice
- Comparable uncertainities as lattice
- Independent confirmation of FNAL/MILC vs ETM desirable

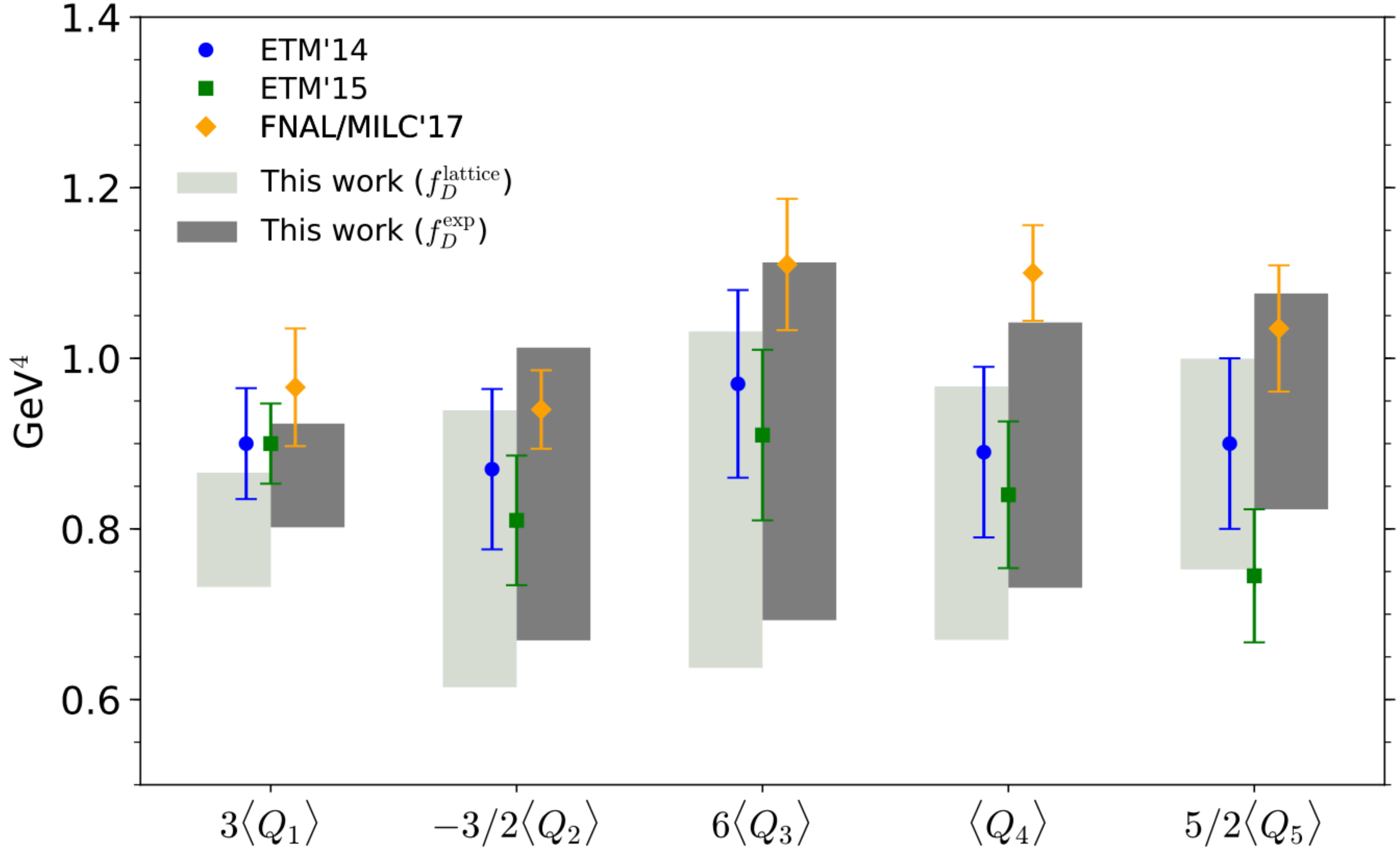
NEW RESULTS 2: B LIFETIMES



Kirk, Lenz, Rauh 1711.02100

- Only modern determination - else: 2001
- Independent confirmation from lattice urgently needed!!!

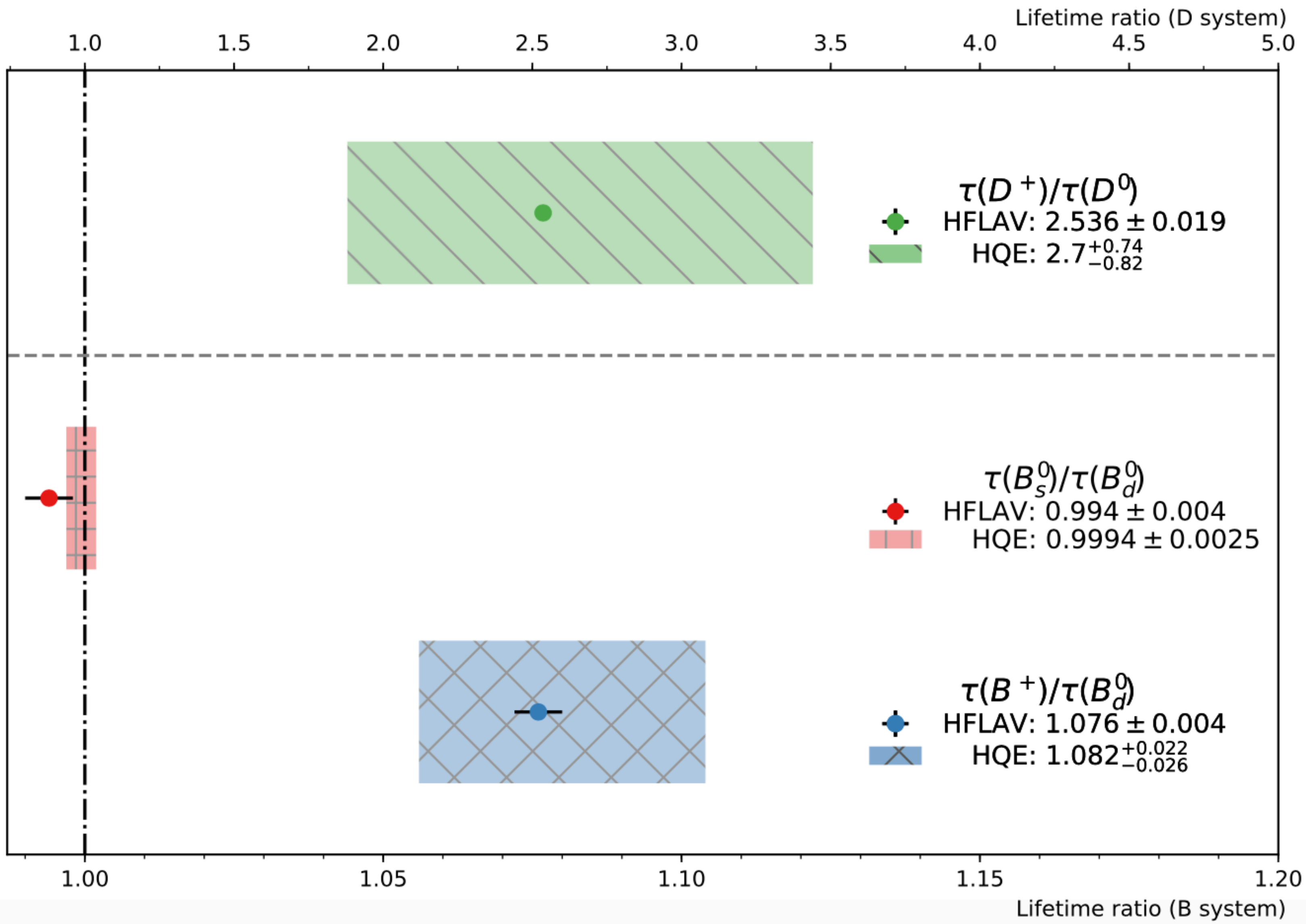
NEW RESULTS 3: D MIXING



Kirk, Lenz, Rauh 1711.02100

- Very good agreement with lattice
- Larger uncertainties than lattice
- First ever determination of D lifetimes!!!

FINAL RESULTS: LIFETIMES



Kirk, Lenz, Rauh

1711.02100

- HQE works for D lifetimes! (roughly 30% precision)

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.7 = 1 + 16\pi^2 \left(0.25\right)^3 \left(1 - 0.34\right)$$

- B+ and Bs lifetime ratios agree perfectly with experiment
- Confirmation from lattice urgently needed

CONSEQUENCES FOR BSM MODELS

ANOMALIES

- **Message 3:** First deviations start to show up **and they stay**

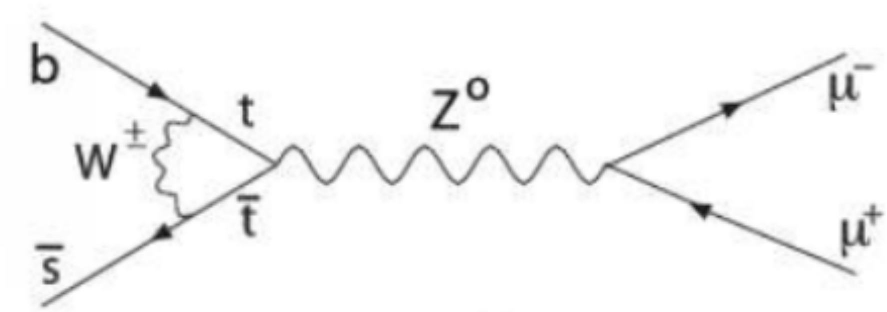
  σ

  - 3-6: Semi-leptonic loop-level decays (small BSM)
  - 3.9: Semi-leptonic tree-level decays (large BSM)
  - 3.6: B-mixing phase (dimuon asymmetry)
  - 3.5: Muon g-2
  - 2.8: K-mixing/ epsilon’ (huge lattice progress)
  - 2.6: Zbb coupling (LEP FB asym)
  - 2.x: K-pi puzzle
  - 2.x: tau to mu nu nu/tau to e nu nu
  - 2.x: Vus: K vs. tau
  - 2.0: B-mixing modulus (mass difference)

4 σ in neutron lifetime? Proton radius seems to be solved by Hänsch et al

SEMI-LEPTONIC LOOP LEVEL

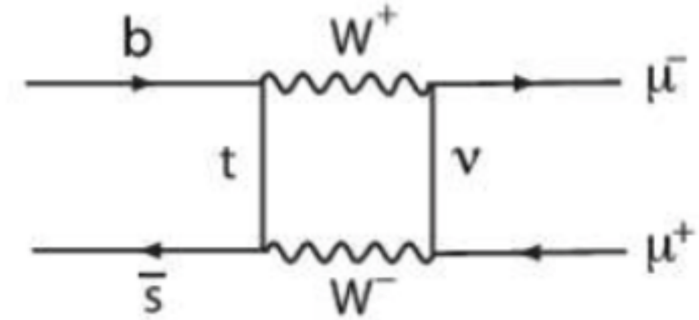
$b \to s\mu\mu$



relatively simple hadronic structure

$B_{d,s} \to \mu\mu$: decay constant

$H_b \to H_q\mu\mu$: form factor



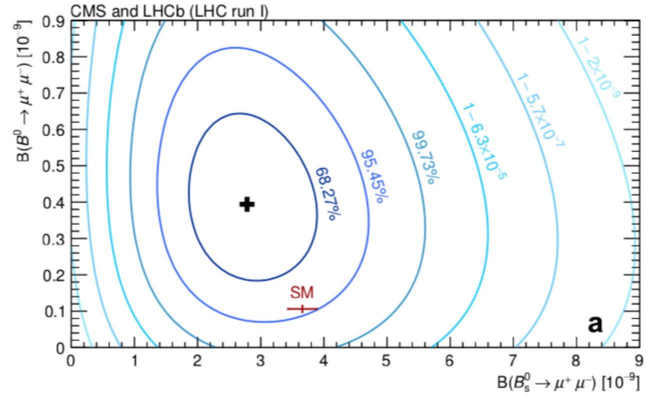
Can be determined with lattice, sum rules,...

Observables:

- Branching ratios $Br(B_s \to \phi\mu\mu)$, $Br(B \to K^*\mu\mu)$,
- Angular observables, e.g. P_5' **hadronic uncertainties cancel partially**
- Ratios $R_K = \dfrac{Br(B^+ \to K^+\mu^-\mu^+)}{Br(B^+ \to K^+e^-e^+)}$ **hadronic uncertainties cancel completely**

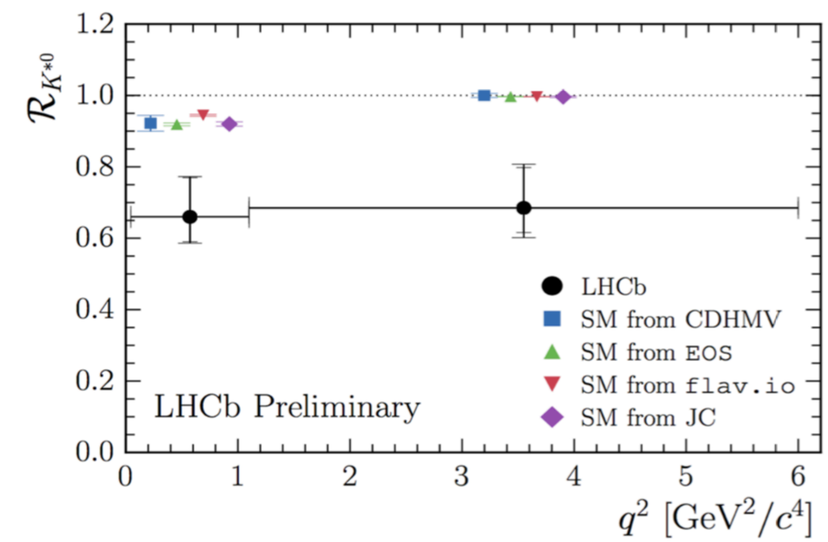
SEMI-LEPTONIC LOOP LEVEL $b \to s\mu\mu$

$B_{d,s} \to \mu\mu$

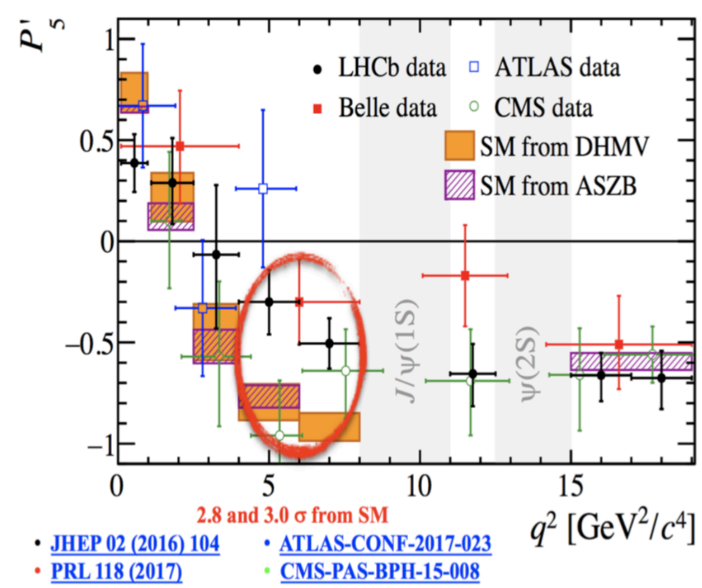


$H_b \to H_q\mu\mu$

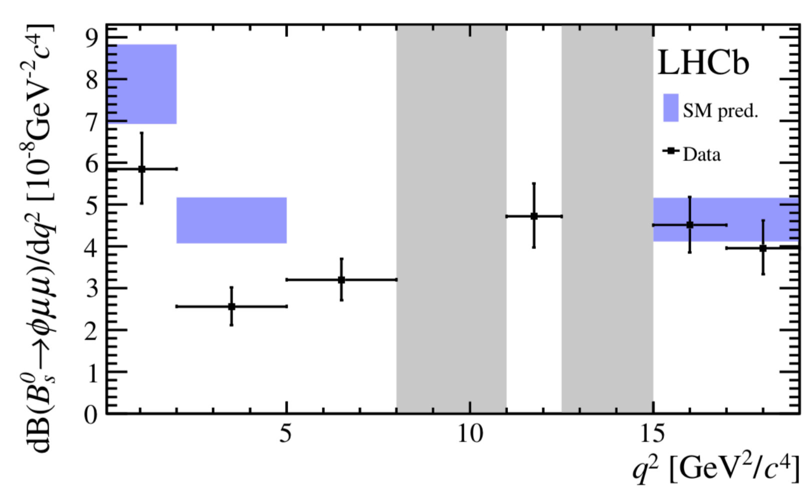
a) $R_K = \dfrac{Br(B^+ \to K^+\mu^-\mu^+)}{Br(B^+ \to K^+e^-e^+)}$



b) P_5'



c) $Br(B_s \to \phi\mu\mu)$, $Br(B \to K^*\mu\mu)$



SEMI-LEPTONIC LOOP LEVEL

Consistent picture of numerous (175) observables

all can be fitted in very simple scenario (BSM = -1/4 SM)

$$Q_{9V} = \frac{\alpha_e}{4\pi} (\bar{s}_L \gamma_\mu b_L) (\bar{l} \gamma^\mu l)$$

$$Q_{10A} = \frac{\alpha_e}{4\pi} (\bar{s}_L \gamma_\mu b_L) (\bar{l} \gamma^\mu \gamma^5 l)$$

e.g. just modify the Wilson coefficient C9!

3 σ 1704.05447

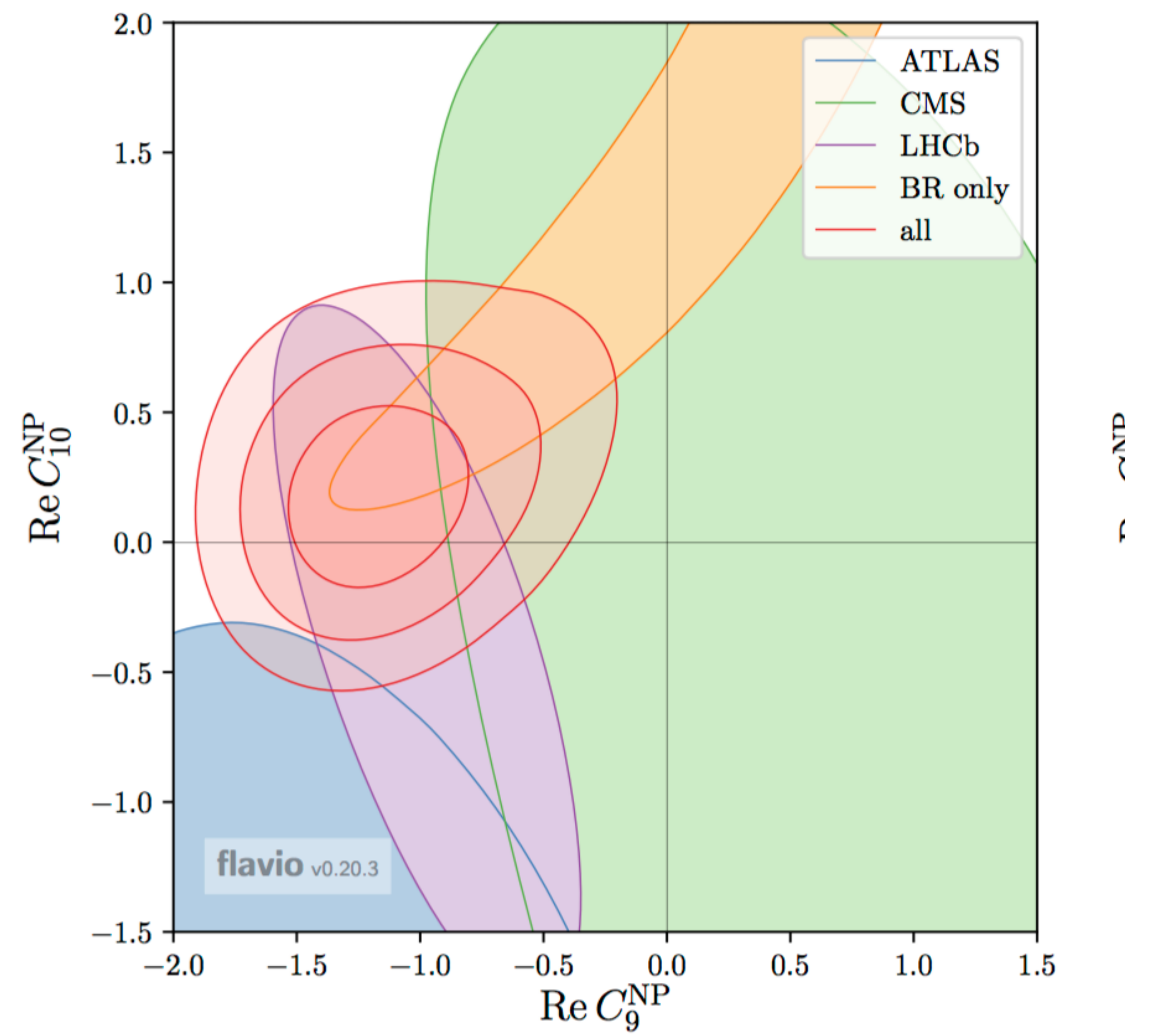
Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli

On Flavourful Easter eggs for NP hunger and LFU violation

5.7σ 1704.05340

Capdevilla, Cvrivellin, Descotes-Genon, Matias, Virto

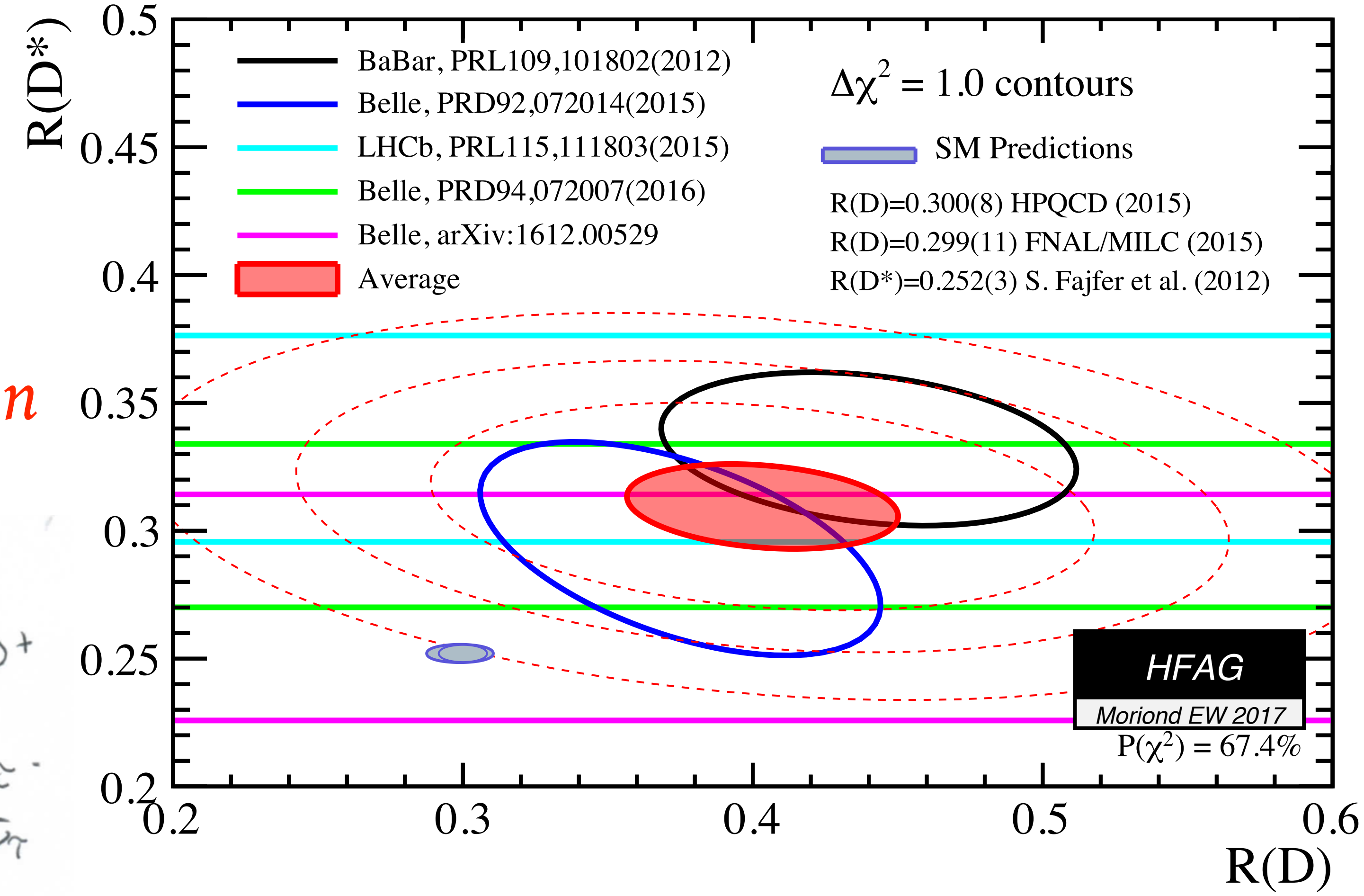
Patterns of NP in b to all transitions in the light of recent data



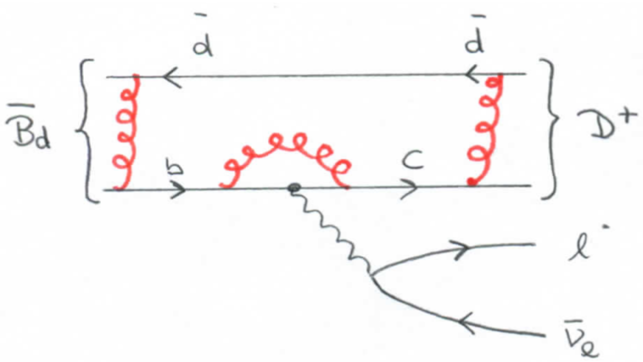
arXiv:1703.09189 [pdf, other]
Status of the $B \to K^* \mu^+ \mu^-$ anomaly after Moriond 2017
Wolfgang Altmannshofer, Christoph Niehoff, Peter Stangl, David M. Straub

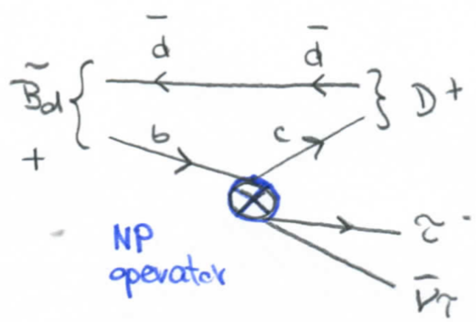
SEMI-LEPTONIC TREE LEVEL **(THIS IS LARGE!)**

$$R_{D^{(*)}} = \frac{Br(\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau)}{Br(\bar{B} \to D^{(*)} l^- \bar{\nu}_l)}$$

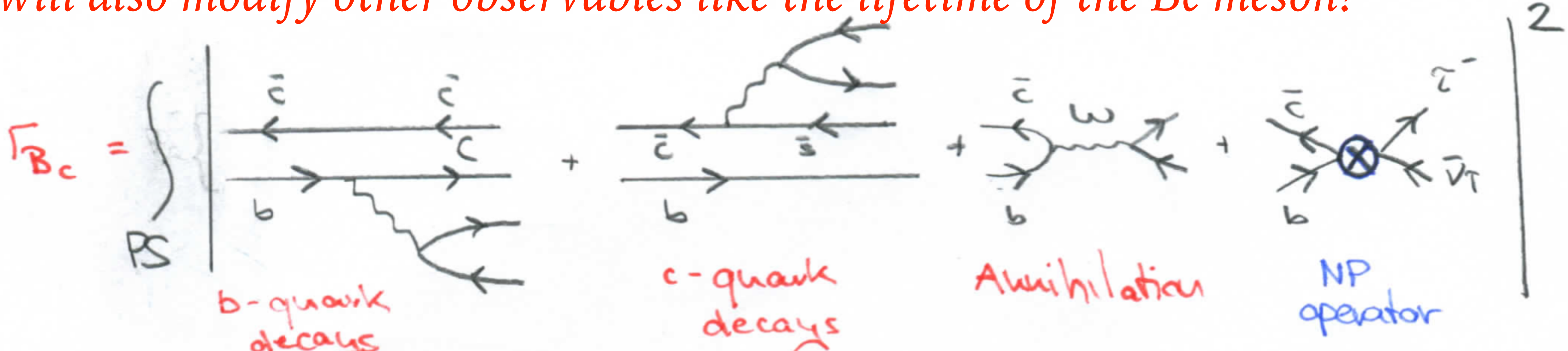


Beware: *any new* $b \to c\tau\bar{\nu}_\tau$ *contribution*





will also modify other observables like the lifetime of the Bc meson!



e.g. Li, Yang, Zhang; Alonso, Grinstein, Camalich; Celis, Jung, Li, Pich

BSM PHYSICS IS ON THE HORIZON?

List of models:

- **Z' - new U(1) or SU(2) W'**
- **Leptoquarks**
- 2HDM
- SUSY
- Vectorlike quarks
- Composite Models
- WED
- ….
- ….

agony of choice

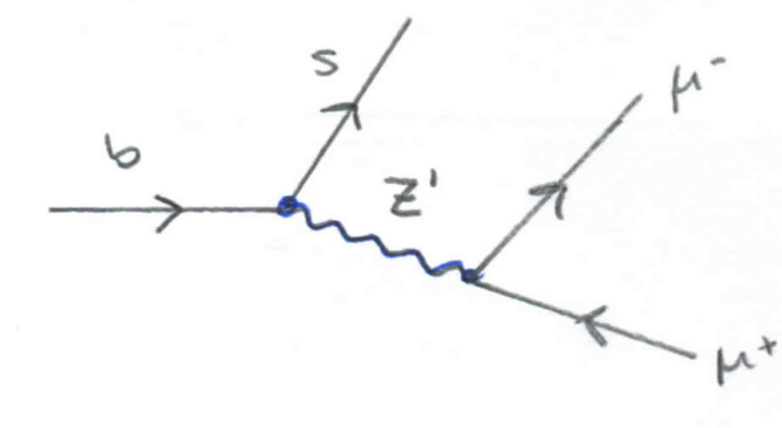
or

choice of agony?

hundreds of papers…

BSM PHYSICS IS ON THE HORIZON?

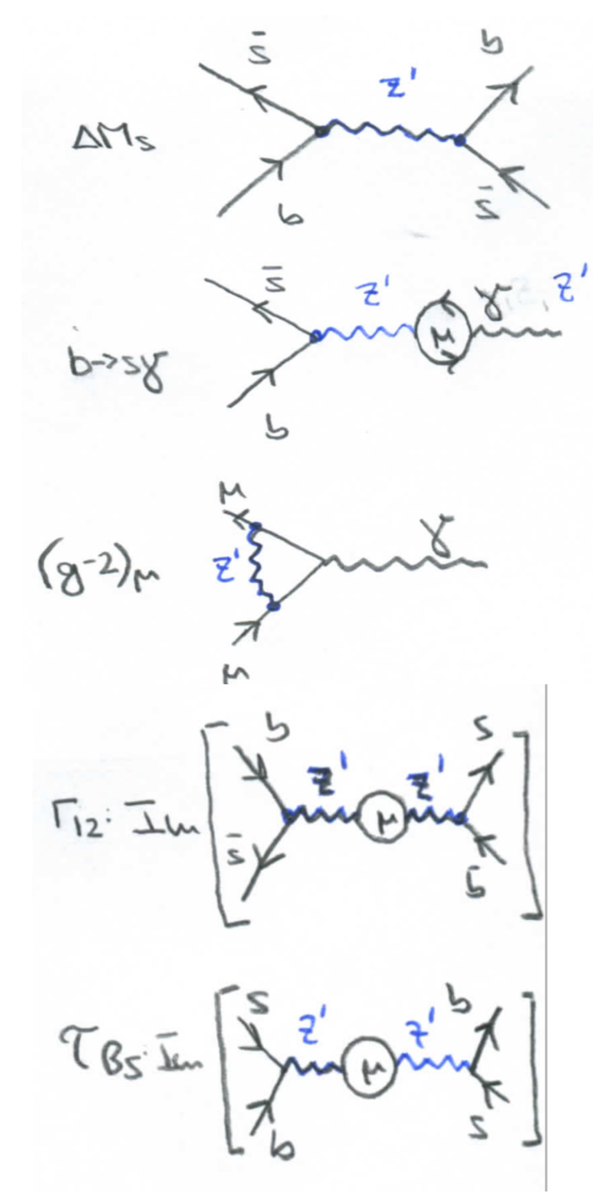
A popular BSM model for solving the anomalies related to loop-level (semi) leptonic decays are Z' models:



Such a new tree-level transition will also affect many other observables,

most notably **B-mixing at tree-level**,

but also many loop processes.



Make sure all relevant bounds are included, e.g. electro-weak precision bounds

Text-book: Bs mixing agrees with the SM

$$\Delta M_s^{\mathrm{SM},\,2011} = (17.3 \pm 2.6)\ \mathrm{ps}^{-1}$$

$$\Delta M_s^{\mathrm{SM},\,2015} = (18.3 \pm 2.7)\ \mathrm{ps}^{-1}$$

$$\Delta M_s^{\mathrm{Exp}} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$

- BSM contributions have to be within the large theory uncertainties
- they can be both positive and negative
- relatively stringent bound on BSM models that explain the b-> s mu mu anomalies

$$\Delta M_s^{\mathrm{Exp}} = 2\left|M_{12}^{\mathrm{SM}} + M_{12}^{\mathrm{NP}}\right| = \Delta M_s^{\mathrm{SM}}\left|1 + \frac{M_{12}^{\mathrm{NP}}}{M_{12}^{\mathrm{SM}}}\right|$$

NEW: Bs mixing “disagrees” with the SM

using most recent input, in particular most recent lattice values for fBs^2 B from FLAG (dominated by Fermilab/MILC)

$$\boxed{\Delta M_s^{\mathrm{SM,\,2017}} = (20.01 \pm 1.25)\ \mathrm{ps}}$$

$$\Delta M_s^{\mathrm{Exp}} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$

BSM contributions should be **negative**

very stringent bound on many BSM models that explain the b-> s mu mu anomalies

$$\frac{\Delta M_s^{\mathrm{Exp}}}{\Delta M_s^{\mathrm{SM}}} = \left| 1 + \frac{\kappa}{\Lambda_{\mathrm{NP}}^2} \right|$$

$$\frac{\Lambda_{\mathrm{NP}}^{2017}}{\Lambda_{\mathrm{NP}}^{2015}} = \sqrt{\frac{\frac{\Delta M_s^{\mathrm{Exp}}}{(\Delta M_s^{\mathrm{SM}} - 2\delta\Delta M_s^{\mathrm{SM}})^{2015}} - 1}{\frac{\Delta M_s^{\mathrm{Exp}}}{(\Delta M_s^{\mathrm{SM}} - 2\delta\Delta M_s^{\mathrm{SM}})^{2017}} - 1}} \simeq 5.2$$

RANGE OF MIXING PREDICTIONS

Bag parameter: SR

Decay constant: SR

Source	$f_{B_s}\sqrt{\hat{B}}$	$\Delta M_s^{\rm SM}$
HPQCD14 [132]	(247 ± 12) MeV	$(16.2 \pm 1.7)\,\mathrm{ps}^{-1}$
ETMC13 [133]	(262 ± 10) MeV	$(18.3 \pm 1.5)\,\mathrm{ps}^{-1}$
HPQCD09 [134] = FLAG13 [135]	(266 ± 18) MeV	$(18.9 \pm 2.6)\,\mathrm{ps}^{-1}$
FLAG17 [70]	$\mathbf{(274 \pm 8)}$ **MeV**	$\mathbf{(20.01 \pm 1.25)\,ps^{-1}}$
Fermilab16 [72]	(274.6 ± 8.8) MeV	$(20.1 \pm 1.5)\,\mathrm{ps}^{-1}$
HQET-SR [77, 136]	(278^{+28}_{-24}) MeV	$(20.6^{+4.4}_{-3.4})\,\mathrm{ps}^{-1}$
HPQCD06 [137]	(281 ± 20) MeV	$(21.0 \pm 3.0)\,\mathrm{ps}^{-1}$
RBC/UKQCD14 [138]	(290 ± 20) MeV	$(22.4 \pm 3.4)\,\mathrm{ps}^{-1}$
Fermilab11 [139]	(291 ± 18) MeV	$(22.6 \pm 2.8)\,\mathrm{ps}^{-1}$

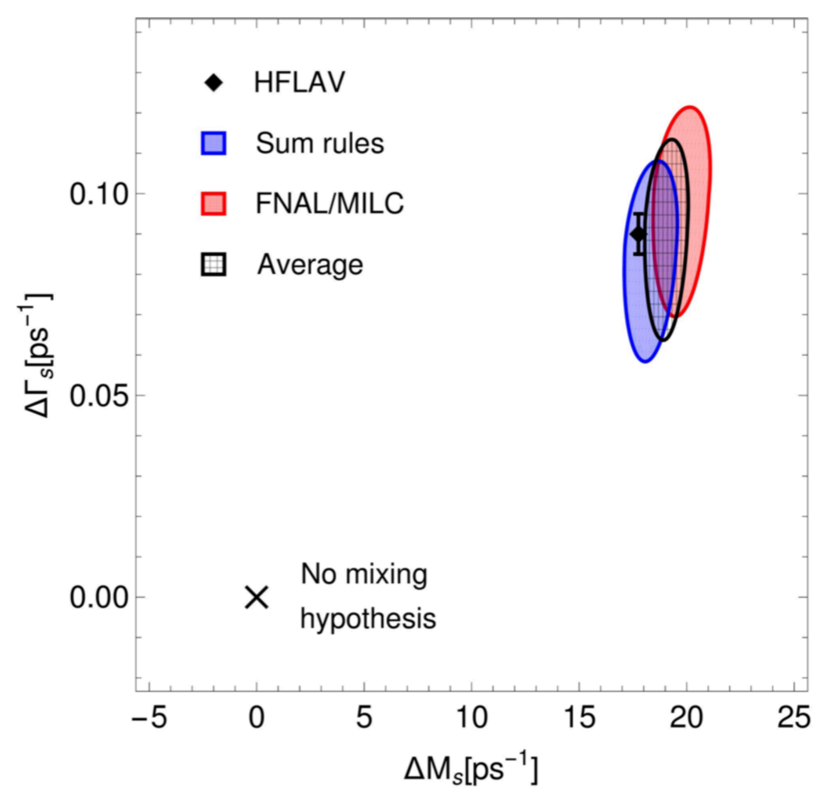
Bag parameter: SR

Decay constant: lattice

$$\Delta M_s^{\rm exp} = (17.757 \pm 0.021)\,\mathrm{ps}^{-1},$$
$$\Delta M_s^{\rm SM} = (18.3 \pm 1.2\,(\text{had.}) \pm 0.1\,(\text{scale}) {}^{+0.2}_{-0.5}\,(\text{param.}))\,\mathrm{ps}^{-1},$$

$$\Delta\Gamma_s^{\rm exp} = (0.090 \pm 0.005)\,\mathrm{ps}^{-1},$$
$$\Delta\Gamma_s^{\rm PS} = (0.087 \pm 0.020\,(\text{had.}) {}^{+0.008}_{-0.020}\,(\text{scale}) {}^{+0.001}_{-0.003}\,(\text{param.}))\,\mathrm{ps}^{-1},$$

$$a_{\rm sl}^{s,\,\rm exp} = (-60 \pm 280) \cdot 10^{-5},$$
$$a_{\rm sl}^{s,\,\rm PS} = (1.8 \pm 0.0\,(\text{had.}) {}^{+0.0}_{-0.1}\,(\text{scale}) \pm 0.1\,(\text{param.})) \cdot 10^{-5},$$



Assume FLAG

One constraint to kill them all?

Luca Di Luzio, Matthew Kirk, Alexander Lenz

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$$\frac{\Delta M_s^{\rm Exp}}{\Delta M_s^{\rm SM}} = \left| 1 + \frac{C_{bs}^{LL}}{R_{\rm SM}^{\rm loop}} \right|$$

Abstract

Many BSM models that explain the intriguing anomalies in the quark flavour sector are severely constrained by B_s-mixing, for which the SM prediction and experiment agreed well until recently. New non-perturbative calculations point, however, in the direction of a tiny discrepancy in this observable. Using this new input we find a considerable shift of the bounds on BSM models stemming from B_s-mixing.

$$C_{bs}^{LL} = \frac{\eta^{LL}(M_{Z'})}{4\sqrt{2}G_F M_{Z'}^2} \left(\frac{\lambda_{23}^Q}{V_{tb}V_{ts}^*} \right)^2$$

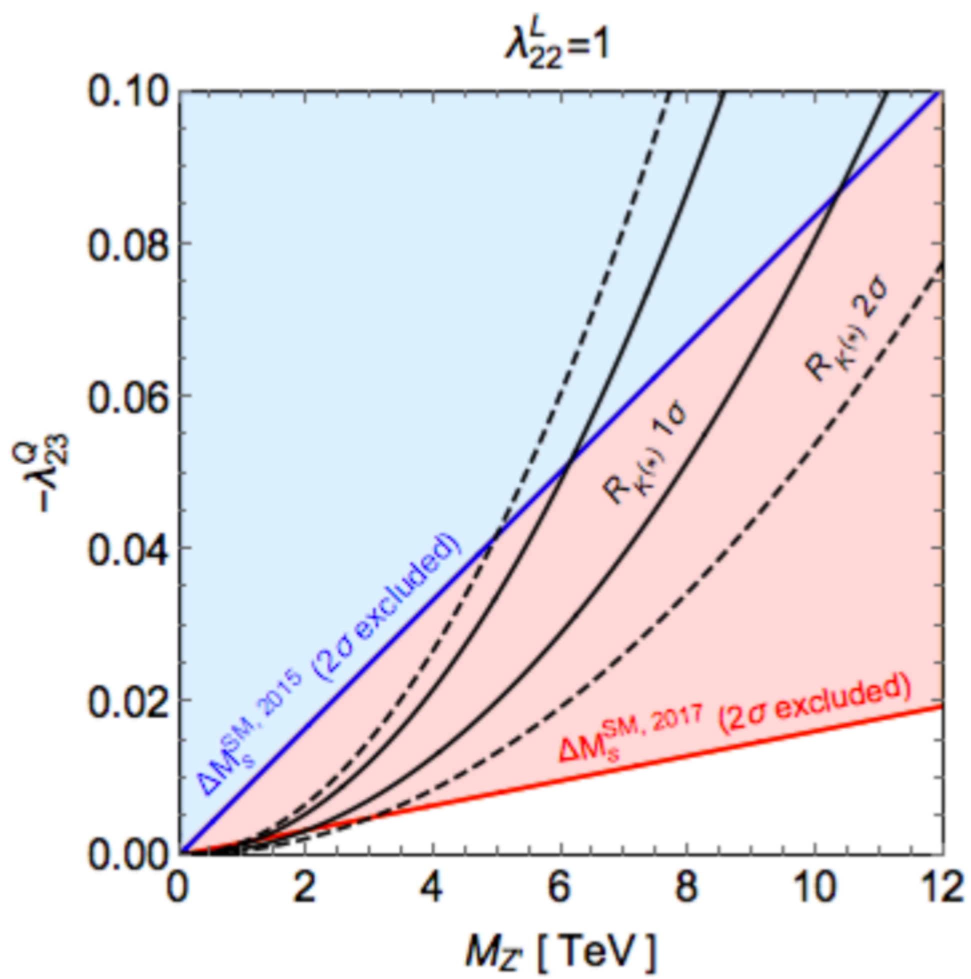


FIG. 2. Bounds from B_s-mixing on the parameter space of the simplified Z' model of Eq. (20), for real λ_{23}^Q and $\lambda_{22}^L = 1$. The blue and red shaded areas correspond respectively to the 2σ exclusions from $\Delta M_s^{\rm SM,\,2015}$ and $\Delta M_s^{\rm SM,\,2017}$, while the solid (dashed) black curves encompass the 1σ (2σ) best-fit region from $R_{K^{(*)}}$.

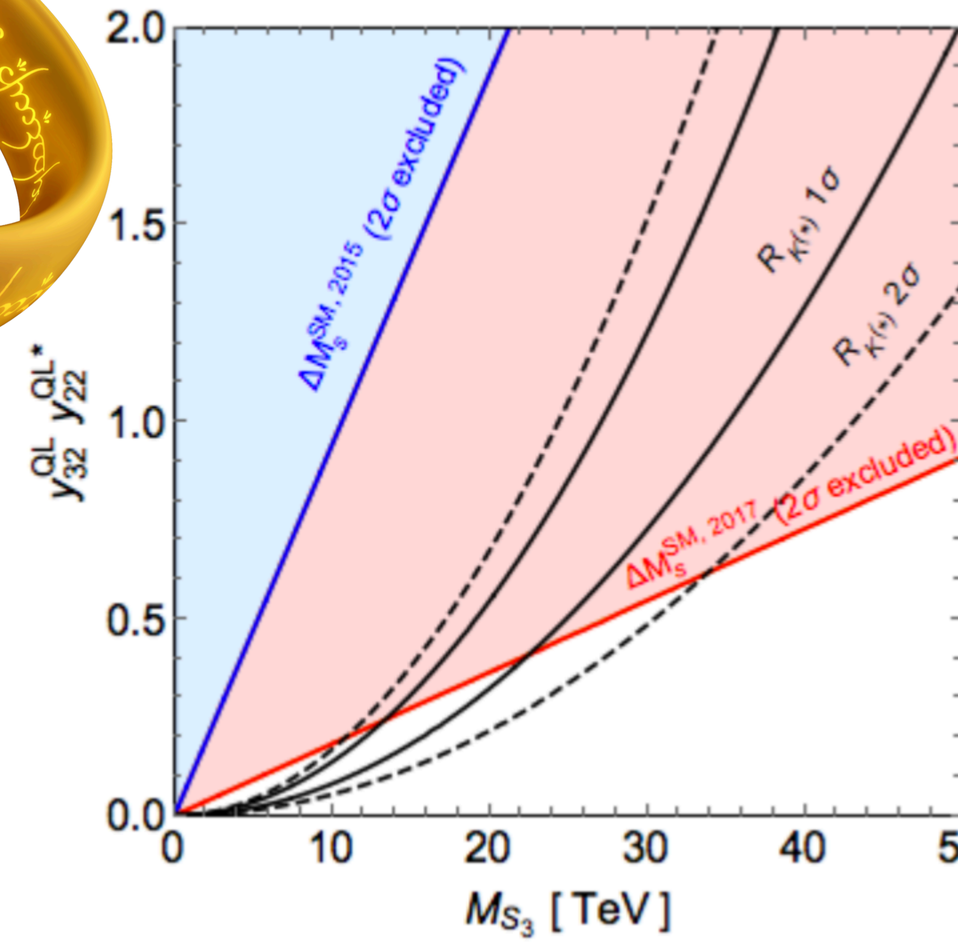


FIG. 3. Bounds from B_s-mixing on the parameter space of the scalar leptoquark model of Eq. (24), for real $y_{32}^{QL}y_{22}^{QL*}$ couplings. Meaning of shaded areas and curves as in Fig. 2.

BSM PHYSICS IS ON THE HORIZON?

Look for the remaining parameter space in Z' models

* *Look for Z' models with complex couplings*

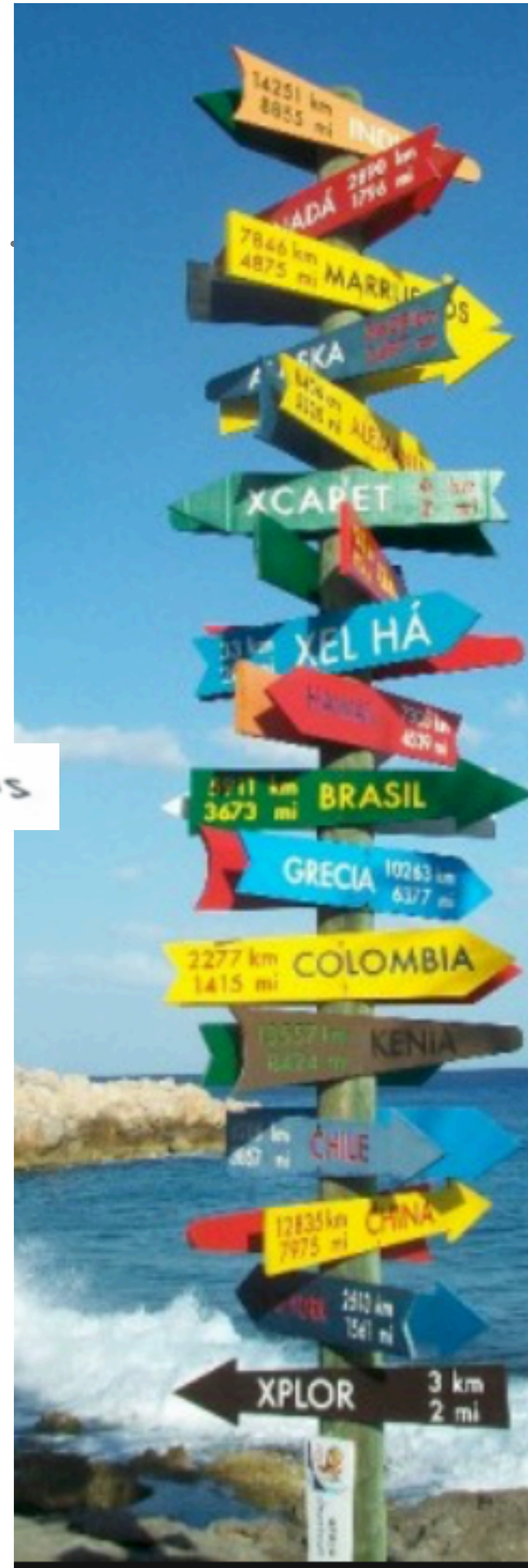
Look for BSM models with negative contributions to ΔM_s

* *Look for BSM models that explain more problems*

* *Look for LHC signatures of these BSM models*

**Look for non-standard BSM models*

.....

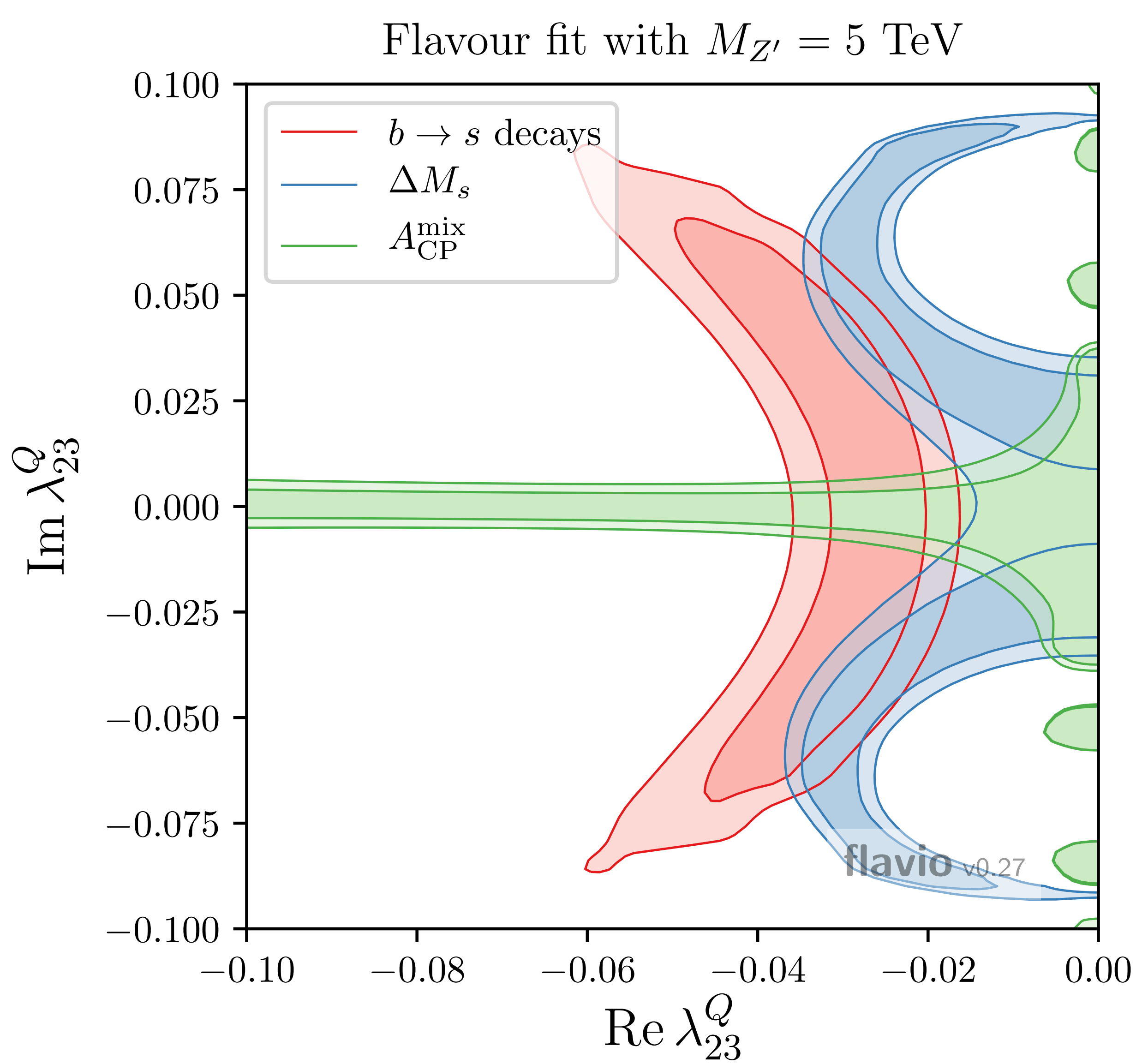


BSM PHYSICS IS ON THE HORIZON?

** Look for Z' models with complex couplings*

- **First idea to avoid positive contributions to M_12: Look for CP violation couplings of a Z' strong constraints from the phase for Bs mixing**

$$B_s \to J/\psi\phi$$



Measurement of the CP violating phase, Phi_s, in Run 2 using B°s→J/PsiK+K− Konstantin Gizdov, University of Edinburgh

TAKE HOME MESSAGES

Status Quo:

- **Shape of HQE is getting better and better**
  Lifetimes and mixing confirm HQE - no sign of duality violation
- **Even a convergence in the D system seems to be plausible**
  If confirmed, then next goal: understand D-mixing
  Remember: 20% of duality violation are sufficient to explain discrepancy in HQE approach
- **Latest lattice results point towards a slight discrepancy in Bs mixing -> severe BSM constraint**

On the ultimate precision of mixing observables
Jubb, Kirk, Lenz, Tetlalmatzi-Xolocotzi
Nucl.Phys. B915 (2017) 431-453
Theory Overview
Alexander Lenz
1610.07943

Next steps:

- Lifetime of Bs should be known even more precisely from experiment
- Need lattice/SR results for dim 6, 7 operators for Delta B,C = 0,2
- NNLO calculations will soon be necessary
- Do baryon lifetimes

END

SINCE YEARS OF BEGGING DID NOT HELP – IT'S TIME TO PROVOKE

Lifetimes are too heavy for lattice physicists!

The strongest lattice researcher alive

Arbitrary sum rule researcher

Matrix elements for lifetimes of HEAVY mesons

NEWS: THEORY UNCERTAINTIES IN MIXING

$\Delta\Gamma_s^{SM}$	This work
Central value	0.088 ps^{-1}
$\delta(B_{\tilde{R}_2})$	14.8%
$\delta(f_{B_s}\sqrt{B})$	13.9%
$\delta(\mu)$	8.4%
$\delta(V_{cb})$	4.9%
$\delta(\tilde{B}_S)$	2.1%
$\delta(B_{R_0})$	2.1%
$\delta(\bar{z})$	1.1%
$\delta(m_b)$	0.8%
$\delta(B_{\tilde{R}_1})$	0.7%
$\delta(B_{\tilde{R}_3})$	0.6%
$\delta(B_{R_1})$	0.5%
$\delta(B_{R_3})$	0.2%
$\delta(m_s)$	0.1%
$\delta(\gamma)$	0.1%
$\delta(\alpha_s)$	0.1%
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	0.1%
$\delta(\bar{m}_t(\bar{m}_t))$	0.0%
$\sum\delta$	22.8%

CP violation in the Bs system

Marina Artuso, Guennadi Borissov, Alexander Lenz

Rev.Mod.Phys. 88 (2016) no.4,045002

3 dominant uncertainties:

★ $\langle R_2\rangle = -\frac{2}{3}\left[\frac{M_{B_s}^2}{m_b^{\text{pow}2}} - 1\right] M_{B_s}^2 f_{B_s}^2 B_{R_2}$; $\quad R_2 = \frac{1}{m_b^2}\,\bar{s}_\alpha \overleftarrow{D}_\rho \gamma^\mu(1-\gamma_5) D^\rho b_\alpha\, \bar{s}_\beta \gamma_\mu (1-\gamma_5) b_\beta$

Dim 7 has never been done - in progress

-**HPQCD (Wingate)** works on lattice

-**Rauh, Kirk, Lenz** with QCD sum rules

★ $\langle Q\rangle \equiv \langle \bar{B}_s^0|Q|B_s^0\rangle = \frac{8}{3} M_{B_s^0}^2 f_{B_s}^2 B(\mu)$ $\quad Q = \bar{s}^\alpha \gamma_\mu (1-\gamma_5) b^\alpha \times \bar{s}^\beta \gamma^\mu (1-\gamma_5) b^\beta$

Dim 6 is done on the lattice

FNAL/MILC indicates a small tension

Kirk, Lenz, Rauh 1711.02100; HPQCD in progress

★ Towards next-to-next-to-leading-log accuracy for the width difference in the Bs system:

Asatrian, Hovhannisyan, Nierste, Yeghiazaryan 1709.02160

TEST OF UNDERLYING THEORY ASSUMPTIONS: DUALITY

1970 Blom, Gilman for e-p scattering

1979 Poggio, Quinn, Weinberg for e+e- to hadrons

Basic idea: Sum overall hadrons = quark level

Our definition: duality violation is deviation from HQE

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \dots$$

Actual expansion parameter is momentum release $\frac{\Lambda}{M_i^2 - M_f^2}$

Taylor expansion of exp[-1/x] in x does give zero

Channel	Expansion parameter x	Numerical value	$\exp[-1/x]$
$b \to c\bar{c}s$	$\frac{\Lambda}{\sqrt{m_b^2-4m_c^2}} \approx \frac{\Lambda}{m_b}\left(1+2\frac{m_c^2}{m_b^2}\right)$	$0.054 - 0.58$	$9.4 \cdot 10^{-9} - 0.18$
$b \to c\bar{u}s$	$\frac{\Lambda}{\sqrt{m_b^2-m_c^2}} \approx \frac{\Lambda}{m_b}\left(1+\frac{1}{2}\frac{m_c^2}{m_b^2}\right)$	$0.045 - 0.49$	$1.9 \cdot 10^{-10} - 0.13$
$b \to u\bar{u}s$	$\frac{\Lambda}{\sqrt{m_b^2-4m_u^2}} = \frac{\Lambda}{m_b}$	$0.042 - 0.48$	$4.2 \cdot 10^{-11} - 0.12$

Best candidate:

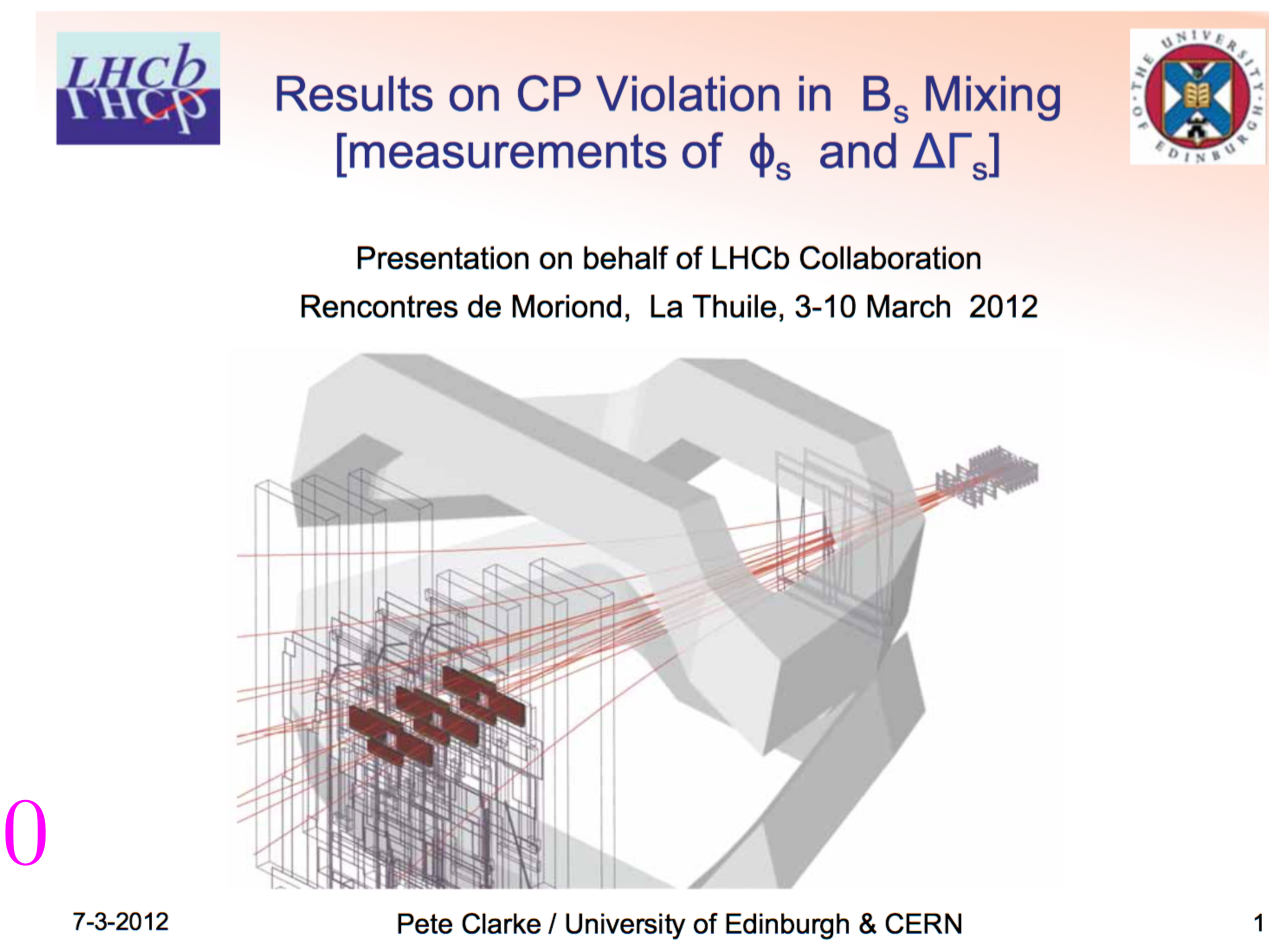
$$b \to c\bar{c}s$$

DUALITY VIOLATION

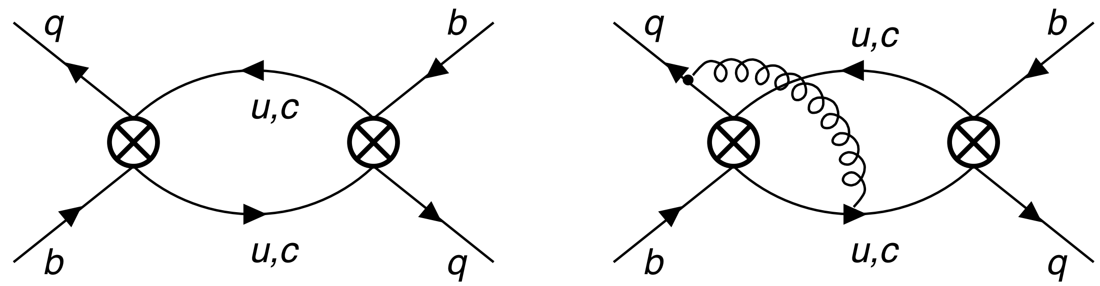
- Many historic hints for possible duality violation: missing charm puzzle, Λ_b—lifetime, di-muon asymmetry,…
- Duality cannot be proofed - solution of QCD necessary: test whether duality based predictions agree with experiment
- Since Moriond 2012:

size of duality violations is severely constrained by perfect agreement of experiment and theory for

$$\frac{\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\rm SM}}{\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\rm Exp}} = 0.99 \pm 0.20$$



QUANTIFY THE POSSIBLE SIZE OF DUALITY VIOLATIONS

$\Gamma_{12}^q =$ 

We expect duality violations to be more pronounced if the final state phase space is becoming smaller

our ansatz:

$$\Gamma_{12}^{s,cc} \to \Gamma_{12}^{s,cc}(1+4\delta) \, ,$$

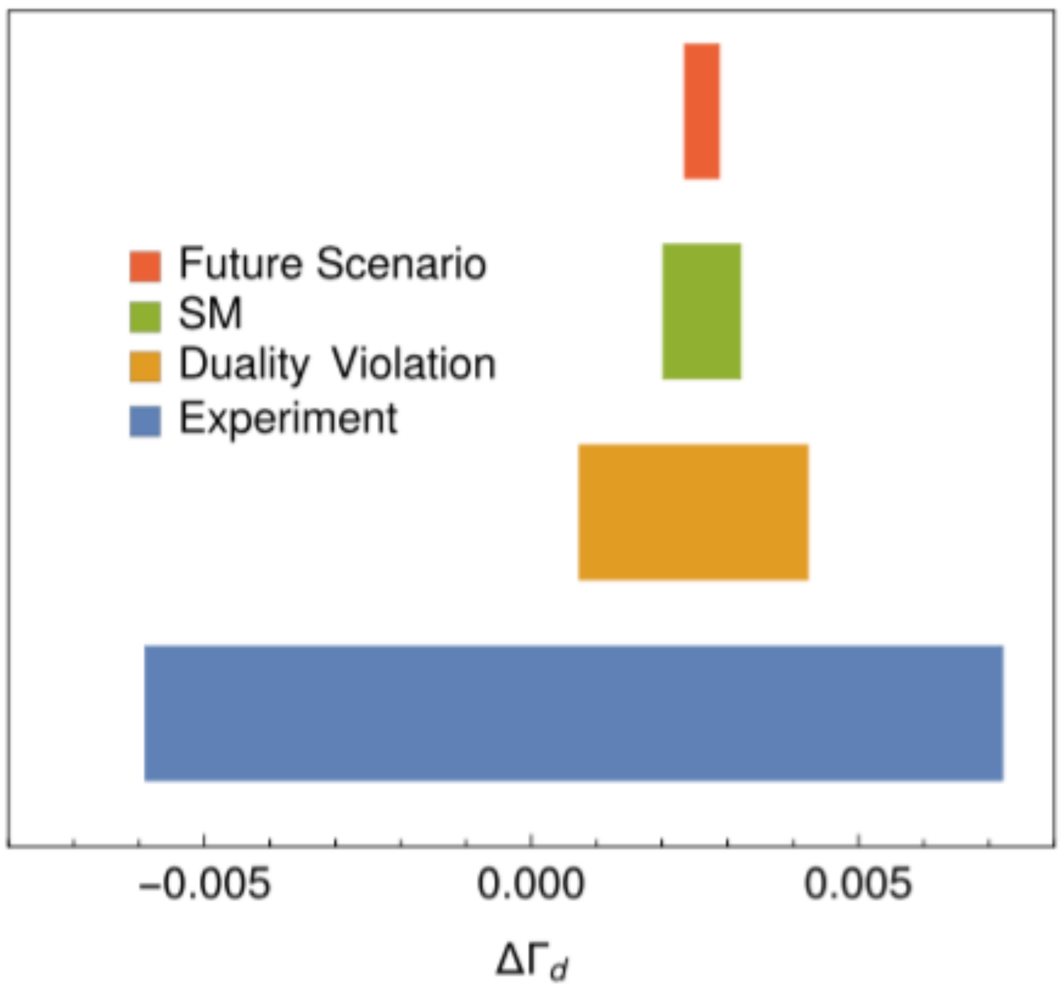
$$\Gamma_{12}^{s,uc} \to \Gamma_{12}^{s,uc}(1+\delta) \, ,$$

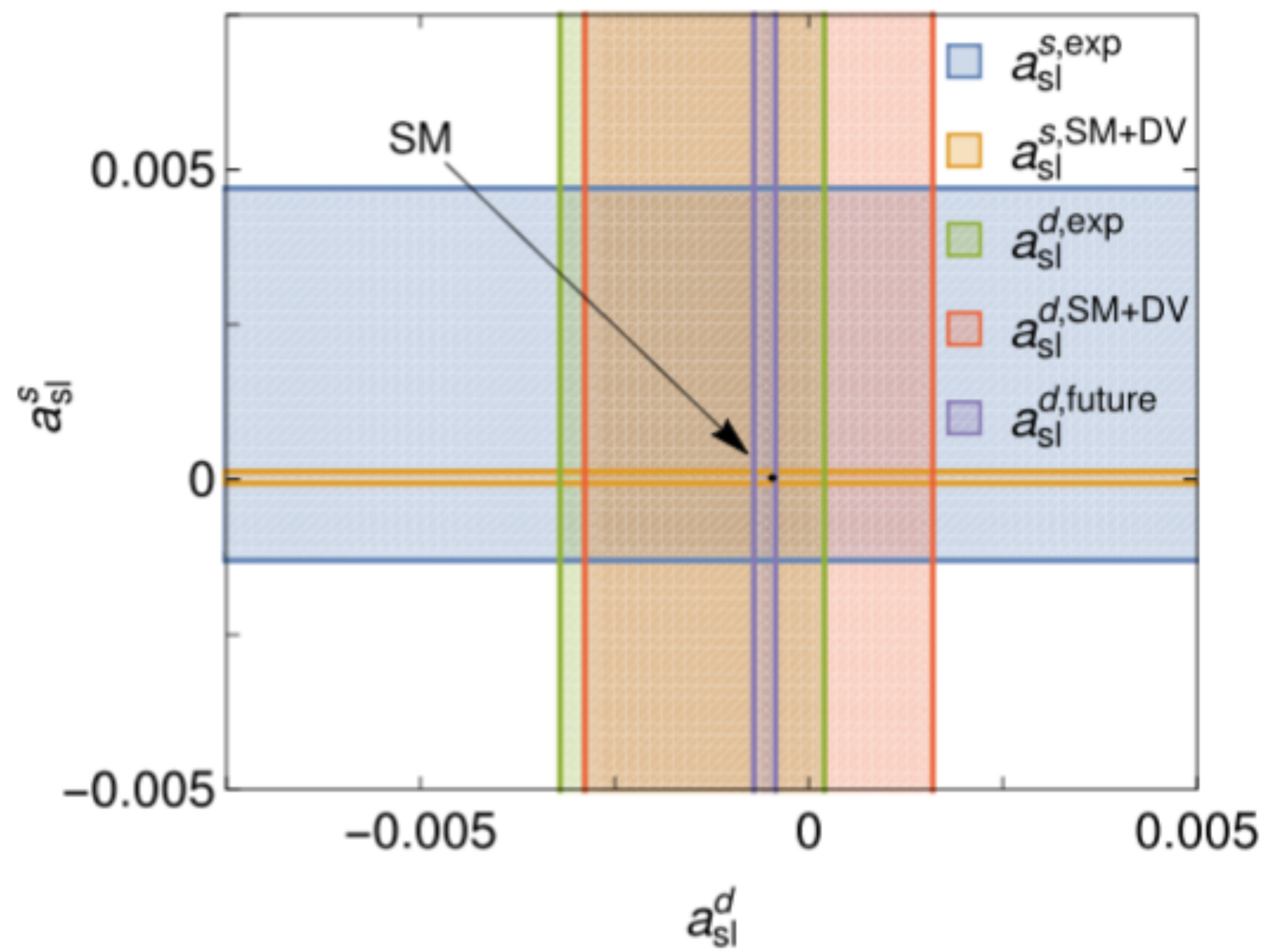
$$\Gamma_{12}^{s,uu} \to \Gamma_{12}^{s,uu}(1+0\delta) \, .$$

We get the following dependence of mixing observables

Observable	B_s^0	B_d^0
$\frac{\Delta\Gamma_q}{\Delta M_q}$	$48.1(1+3.95\delta)\cdot 10^{-4}$	$49.5(1+3.76\delta)\cdot 10^{-4}$
$\Delta\Gamma_q$	$0.0880(1+3.95\delta)\ \mathrm{ps}^{-1}$	$2.61(1+3.759\delta)\cdot 10^{-3}\ \mathrm{ps}^{-1}$
a_{sl}^q	$2.225(1-22.3\delta)\cdot 10^{-5}$	$-4.74(1-24.5\delta)\cdot 10^{-4}$

QUANTIFY THE POSSIBLE SIZE OF DUALITY VIOLATIONS





On the ultimate precision of meson mixing observables

Thomas Jubb, Matthew Kirk, Alexander Lenz, Gilberto Tetlalmatzi-Xolocotzi

Published in Nucl.Phys. B915 (2017) 431-453