SNOWMASS 2021

Letter of interest from Siegen University

High Precision SM Predictions for Quark Flavor Observables

Guido Bell, Oscar Cata, Thorsten Feldmann, Tobias Huber, Alexander Khodjamirian, Wolfgang Kilian, Thomas Mannel, Björn Lange, Alexander Lenz, Jan Piclum, Alexei Pivovarov and Oliver Witzel

1 Introduction

The current observation of the so-called flavor anomalies is one of the hottest topics in particle physics. If these deviations turn out to be real, they will shed light to physics beyond the SM and they might help in answering questions like the origin of the matter-antimatter asymmetry in the Universe. For this programme to work highly reliable, precise SM predictions are of course crucial. We review here a list of observables where the accuracy within the SM can be improved, leading to a severe impact on our understanding of nature.

1.1 Inclusive semi-leptonic and radiative B decays

To further understand the long standing discrepancy between the exclusive and inclusive determination of the CKM elements V_{cb} and V_{ub} newly calculated corrections like the QCD correction to the Darwin term [1] can be included in the analysis, as well as higher orders in the Heavy Quark Expansion (HQE). Moreover some of the arising non-perturbative matrix elements can be related via equations of motion to e.g. matrix elements of four-quark operators. Another possibility in determining these matrix elements are sum rules and lattice simulations. A precise knowledge of the value of the b-quark mass [2] is mandatory for a reliable determination of the CKM elements. In that respect the effect of the use of different quark mass concepts for B decays can be studied. The theory tools for semi-leptonic B decays can also be used to test the convergence of the HQE in the charm sector [3], see Section 1.4.
Inclusive semileptonic FCNC decays such as $\bar{B} \to X_{(s,d)}\ell^+\ell^-$ [4] will serve as an important cross-check for the flavour anomalies currently seen in exclusive B decays, and to investigate lepton flavour universality. Inclusive radiative decays, most prominently $\bar{B} \to X_{(s,d)}\gamma$ [5], are among the standard candles in the search for new physics and in constraining the parameters spaces of BSM models.

1.2 B lifetimes and B mixing

Lifetime ratios of B mesons can be determined within the HQE. Recently a significant experimental discrepancy in the analysis of the decay $B_s \to J/\Psi\phi$ was arising between the determinations of Γ_s from ATLAS [6] and CMS [7] and LHCb [8, 9]. It would be interesting to study the sensitivity of future $e^+ - e^-$ colliders for these measurements with Monte Carlo generators like WHIZARD [10]. In theory an important contribution to the lifetime ratio comes from so-called spectator effects. The corresponding bag parameter that parameterise the non-perturbative part of the spectator effects have so far only been calculated with HQET sum rules [11]. An inclusion of strange quark mass effects as well as a lattice calculation of these parameter would be highly desirable. Moreover it was found that the previously neglected Darwin term in theory predictions can lead to sizeable effects [12, 13]. Here again a precise future determination of the non-perturbative matrix element of the Darwin operator is necessary, maybe via sum rules or lattice. Similar Bag parameter are arising in B meson mixing, which is supposed to be very sensitive to new physics effects. These mixing parameter have so far been determined by lattice simulations [14, 15] and with HQET sum rules [11, 16]. Both in lattice as within the sum rule approach the precision can be further improved, see e.g. [17]. A precise knowledge of the SM value of B mixing can also have dramatic impact [18] on BSM models that try to explain the B anomalies [19].

1.3 Exclusive decays of heavy mesons

Exclusive decays of heavy meson can be described within the QCD factorization approach [20], which was recently extended to NNLO accuracy [21]. Here some significant discrepancies were found between experiment and theory in decay channels where QCD factorisation is supposed to work best [22]. This might be an indication for BSM effects in non-leptonic tree-level decays [23]. Further studies in that direction would be very desirable as well as the construction of BSM models that will lead to such new effects. Factorisation can also be extended to more than two-hadron final states [24, 25]. Nonlocal hadronic effects beyond factorisation [26] can be further studied and the main inputs to factorisation such as the light-cone distribution amplitudes deserve an accurate assessment [27] including the strange quark mass effects [28].

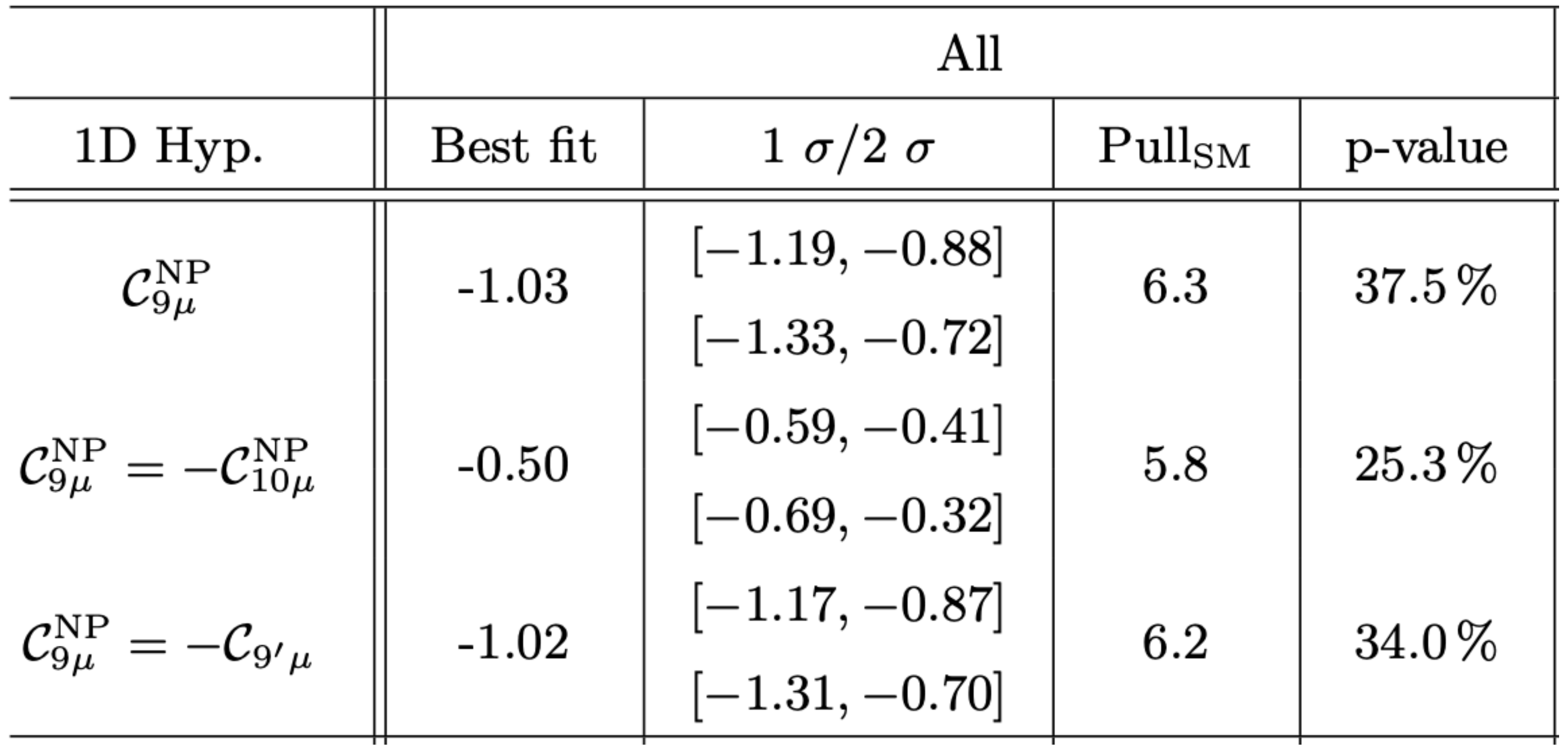
1.4 Convergence of HQE tools in the charm sector

The theoretical description of charm decays is very challenging, since the charm quark is neither really heavy nor light [29]. First studies of the large lifetime ratio $\tau(D^+)/\tau(D_0)$ within the framework of the HQE [11] look very promising, but additional observables like $\tau(D_s^+)/\tau(D_0)$ or baryon lifetimes have to be studied with the same theoretical rigour. Since there will be a huge amount of charm data from the LHC experiments, BELLE II and BESIII an improvement of our theoretical understanding in the charm sector is very important. This holds in particular for CP violation in charm, where methods like the ones used in [30] should be further extended and for charm mixing where some new ideas for an explanation of the experimental value within the HQE approach were presented in [31]. Such studies will also shed some light on the potential size of quark hadron duality violations within the HQE.

Our suggested programme has considerable overlap with the one suggested by the RBC-UKQCD collaboration [32], but many of our theoretical methods have completely different systematic uncertainties.

Motivation 1

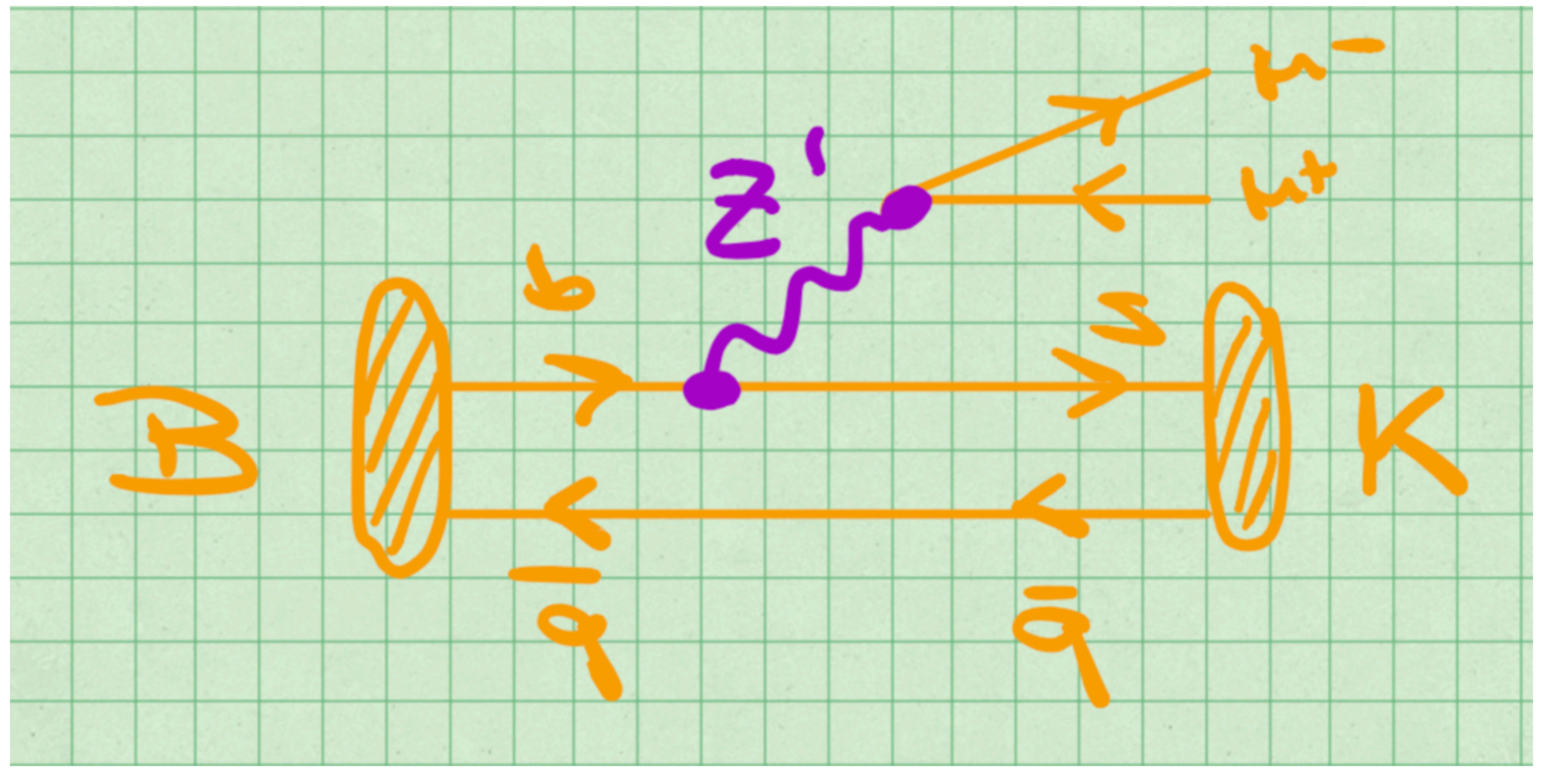
Q1: Are the “Flavour Anomalies” real?



	All			
1D Hyp.	Best fit	1 σ/2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.03	$[-1.19, -0.88]$ $[-1.33, -0.72]$	6.3	37.5 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.50	$[-0.59, -0.41]$ $[-0.69, -0.32]$	5.8	25.3 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	-1.02	$[-1.17, -0.87]$ $[-1.31, -0.70]$	6.2	34.0 %

Obviously control of theoretical and experimental uncertainties for semi-leptonic decays mandatory (lattice, LCSR,…)

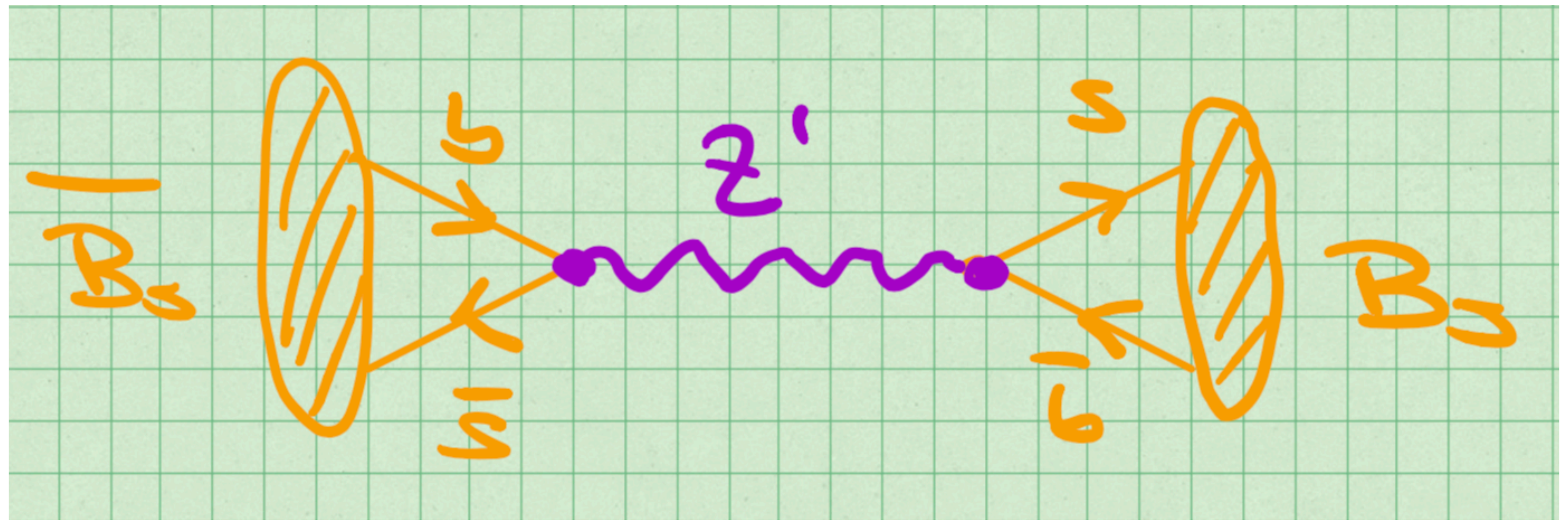
Q2: What models could explain Flavour anomalies?
e.g. Z’ models



Motivation 2

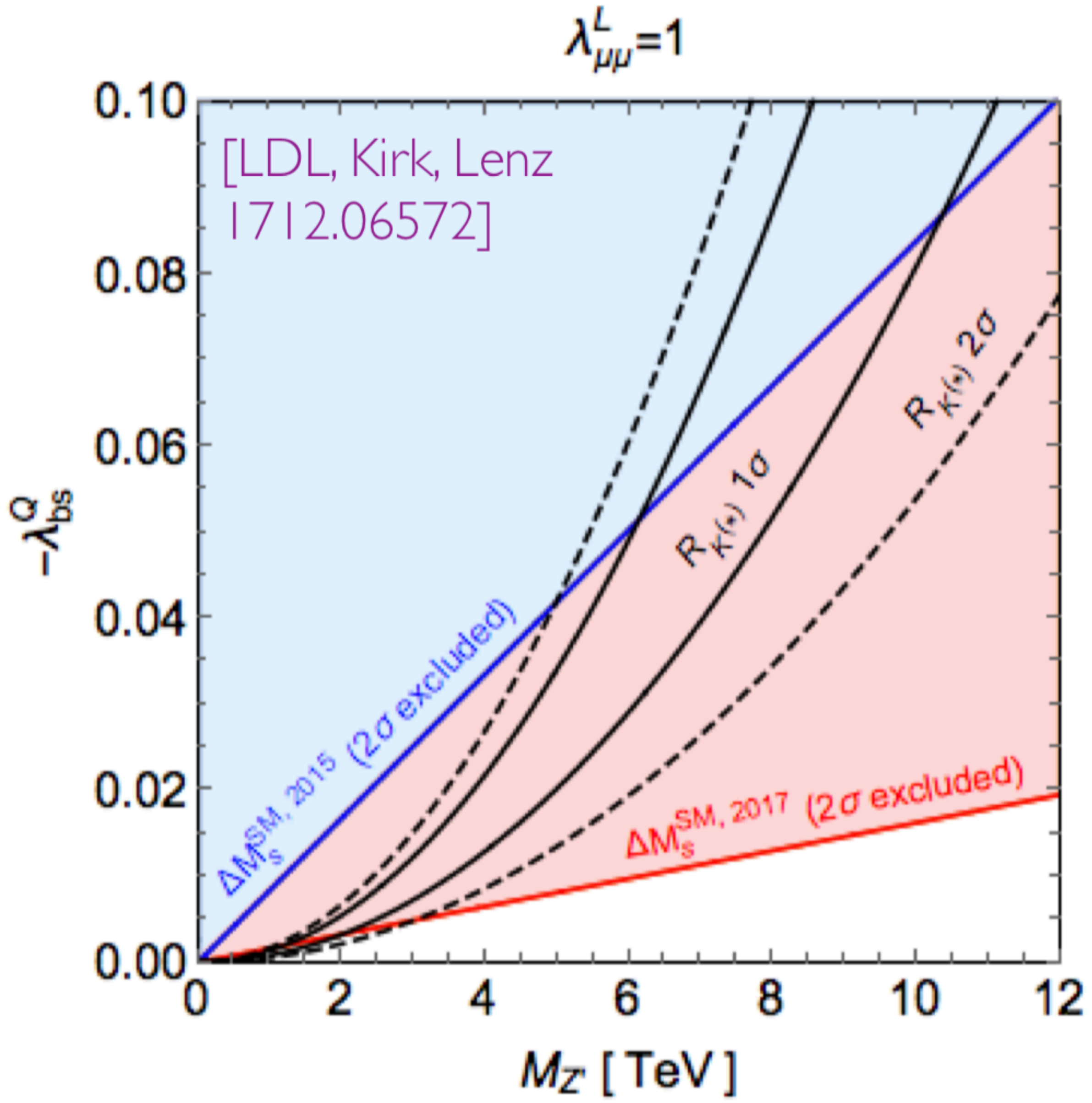
B-mixing plays a double role
- by itself a BSM sensitive observable
- Constrains BSM models that explains the anomalies

Such a models also modify the mass difference of neutral mesons



Many times the BSM contribution to ΔM_q is positive

Using the large 2016 FNAL-MILC = FLAG B-mixing input:



FNAL-MILC kills almost the Z' explanation

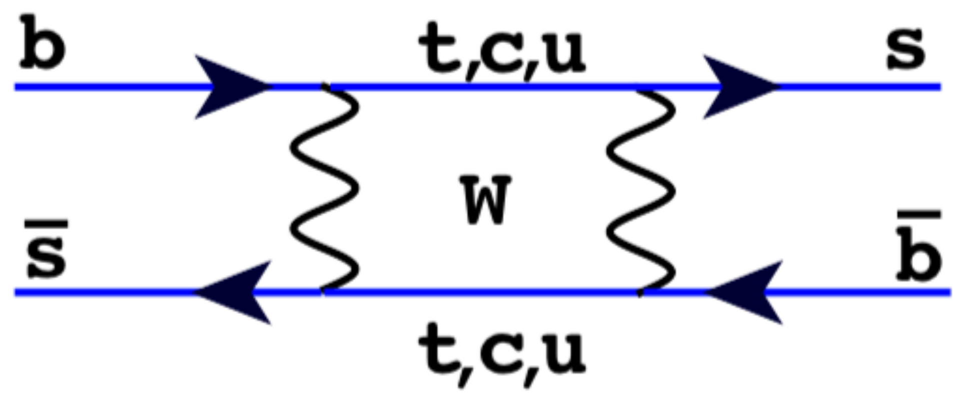
One constraint to kill them all!

Independent determination of non-perturbative Bs mixing inputs desirable

Motivation 3

Reminder: $\boxed{\Delta m_s = 17.757 \pm 0.021 \text{ ps}^{-1}}$ $\Delta m_d = 0.5064 \pm 0.0019 \text{ ps}^{-1}$

Theory



CKM

Inami-Lim

2-loop
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) **HQET Sum rules:** **Siegen, Durham**

Motivation 4

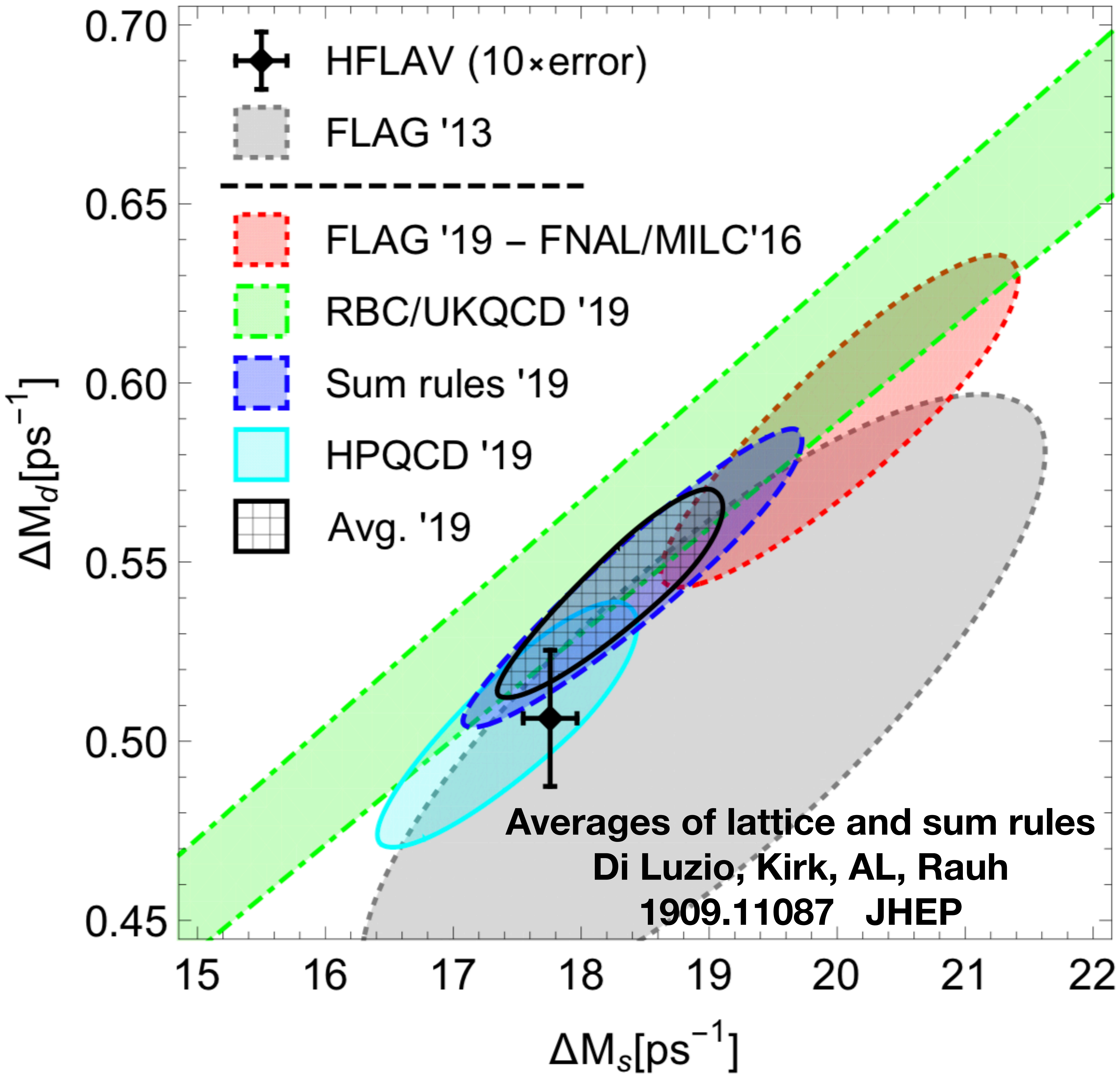
Very active field:

- 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

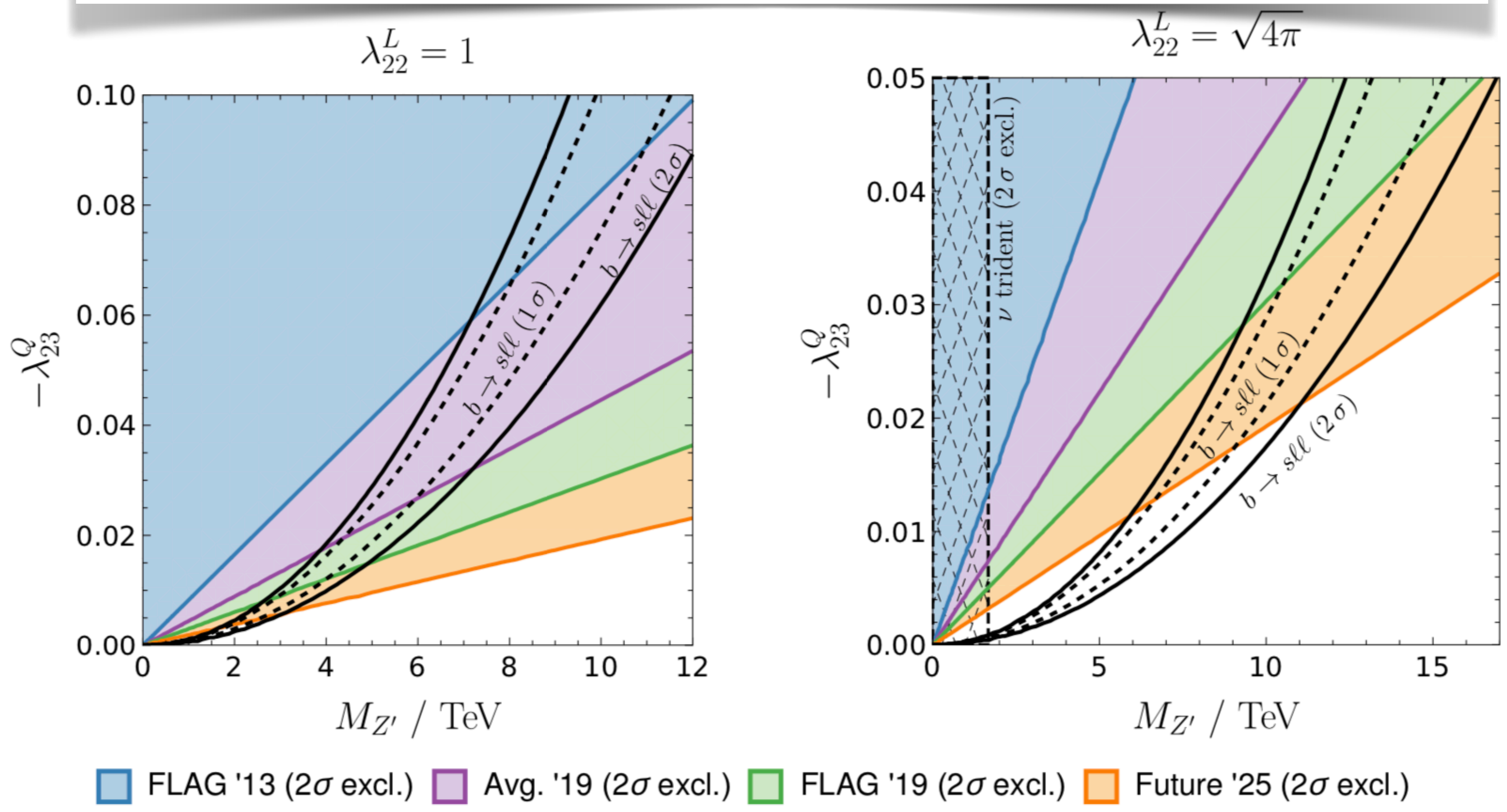
B-mixing seems to be smaller than expected by FNAL-MILC

B-mixing 2020 plays a triple role

- **by itself a BSM sensitive observable**
- **Constrains BSM models that explain the anomalies** **does not kill anymore Z' explanations**
- **Determination of SM parameter (CKM) - see below**



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



Still higher precision desirable - HQET SR can be improved
Individual lattice values from RBC/UKQCD
Confirmation from FNAL-MILC

Motivation 5

Control of
theoretical precision
is crucial
for indirect BSM searches

1.1. Inclusive Semileptonic Tree-level Decays

$$\Gamma(B \to X_c \ell \bar{\nu}_\ell) = \Gamma_3^{(c\ell\bar{\nu})}\left[1 - 0.5\frac{\mu_\pi^2}{m_b^2} - 1.9\frac{\mu_G^2}{m_b^2} - 19.1\frac{\rho_D^3}{m_b^3} - 20.5\frac{s_1}{m_b^4} + 4.0\frac{s_2}{m_b^4} - 13.5\frac{s_3}{m_b^4} - 9.5\frac{s_5}{m_b^4}\right]$$

V_{cb}

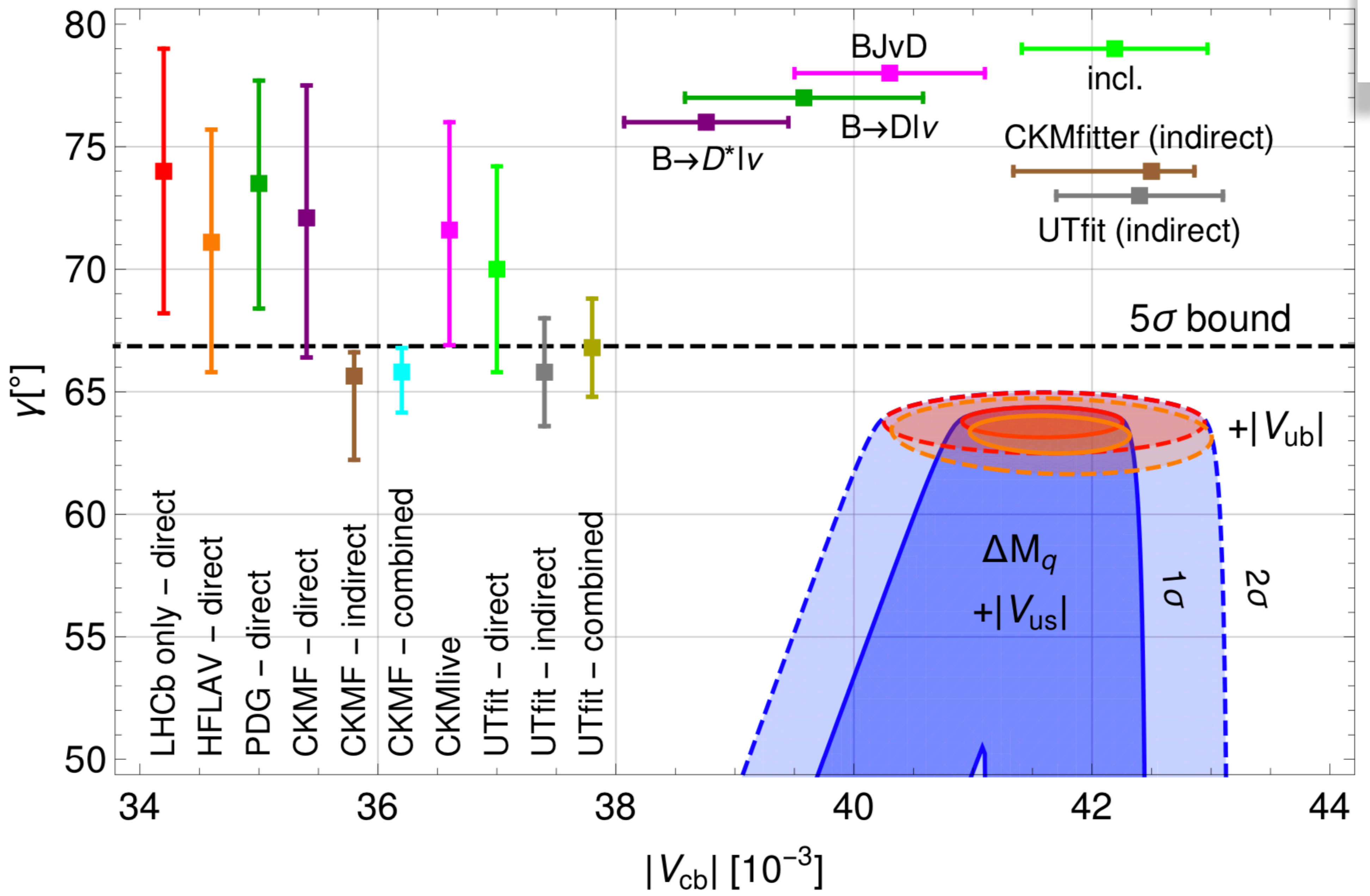
Still some problems between exclusive and inclusive determinations

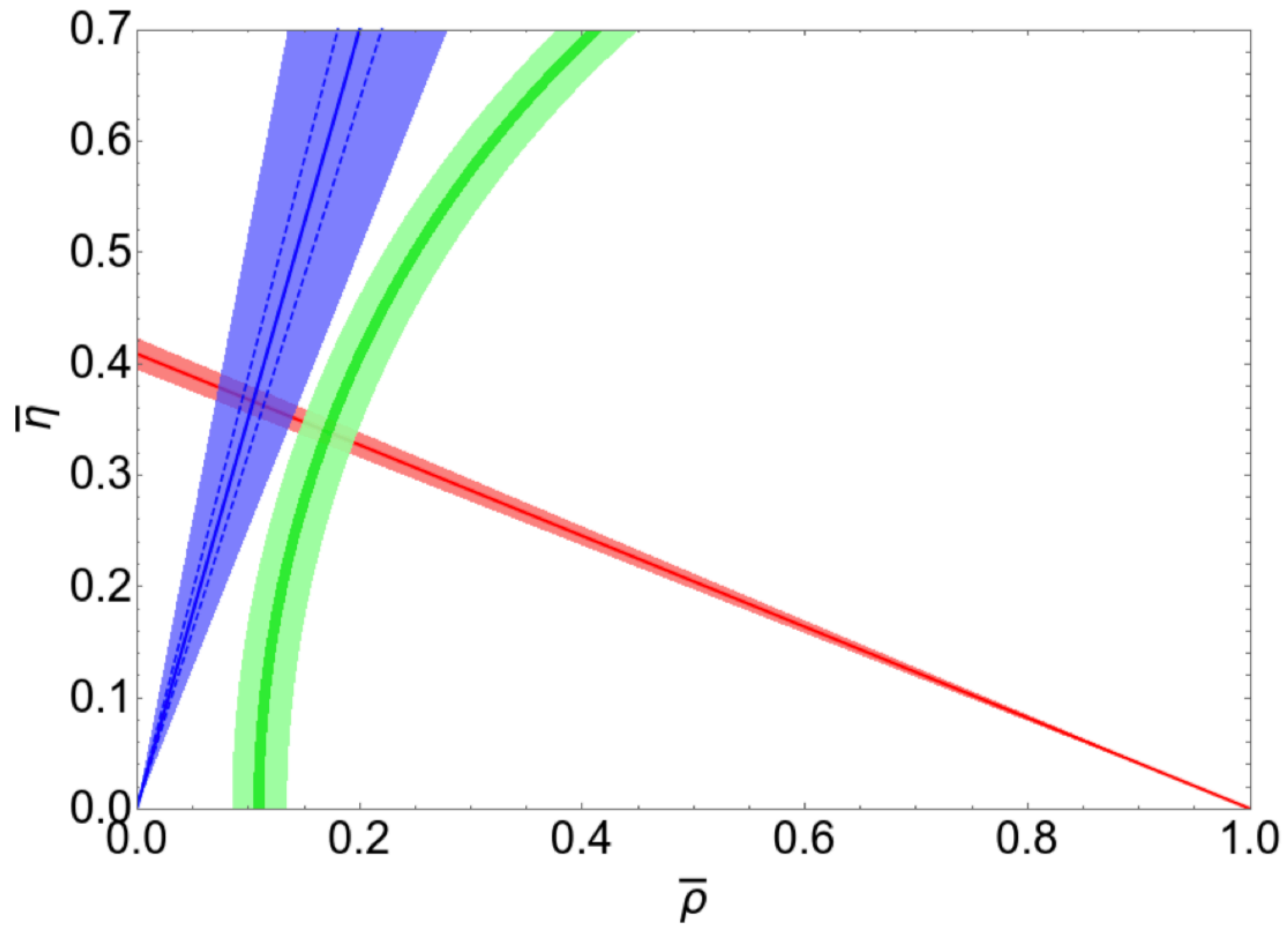
Higher orders in HQE needed
Higher orders in perturbative QCD needed
Non-perturbative derminations of ME
Optimal quark mass concept for HQE
Potential size of Quark Hadron duality violations

Note:
B mixing (as does e_K) prefers inclusive value

$$\boxed{|V_{cb}| = (41.6 \pm 0.7) \cdot 10^{-3}}$$

$$\boxed{\gamma = (63.4 \pm 0.9)^\circ}$$





1.1. FCNC Decays

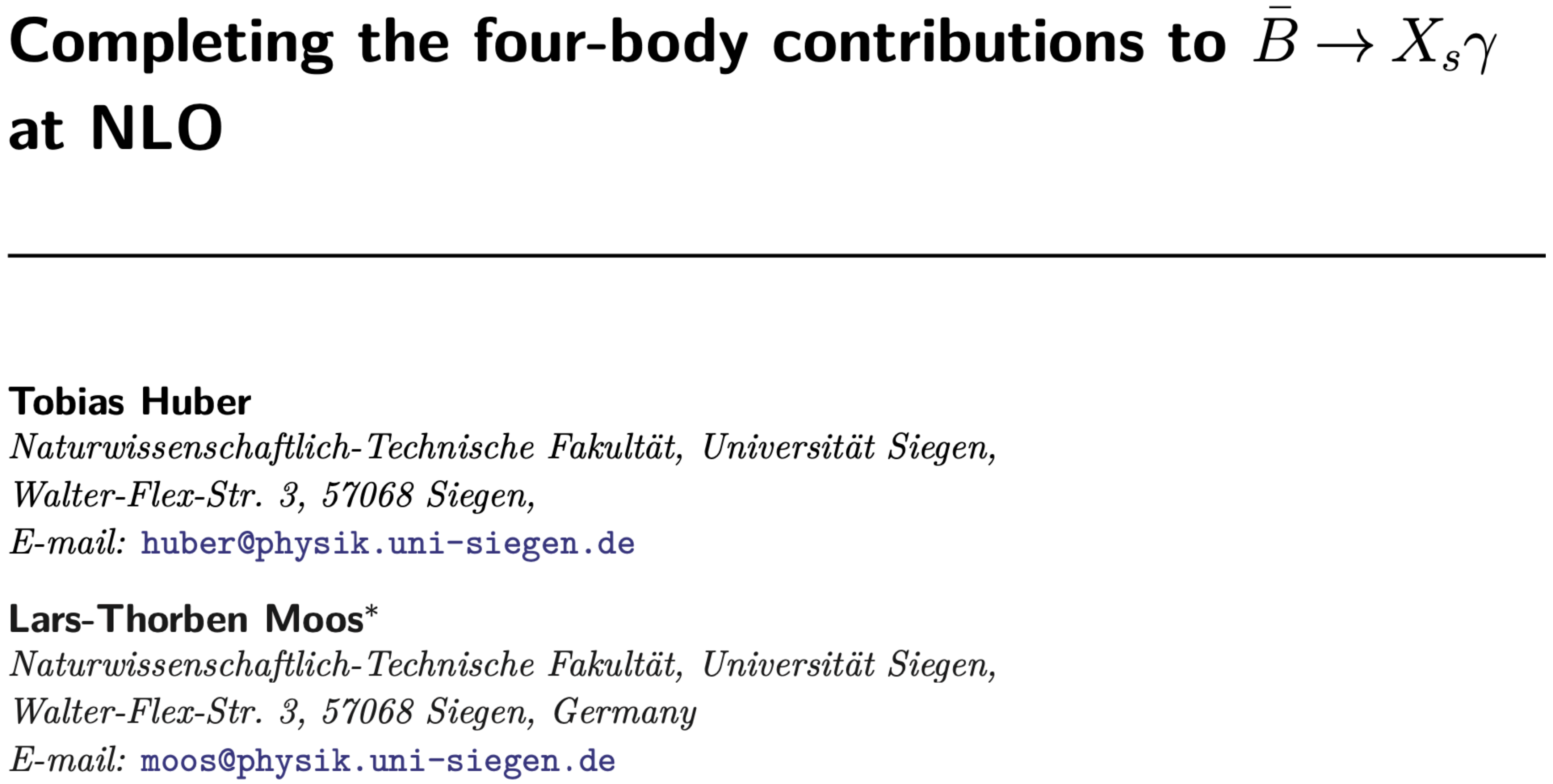
Besides exclusive $b \to s l \bar{l}$ there is also exclusive $b \to d l \bar{l}$

$b \to s\gamma$

inclusive $b \to s l \bar{l}$

inclusive $b \to d l \bar{l}$

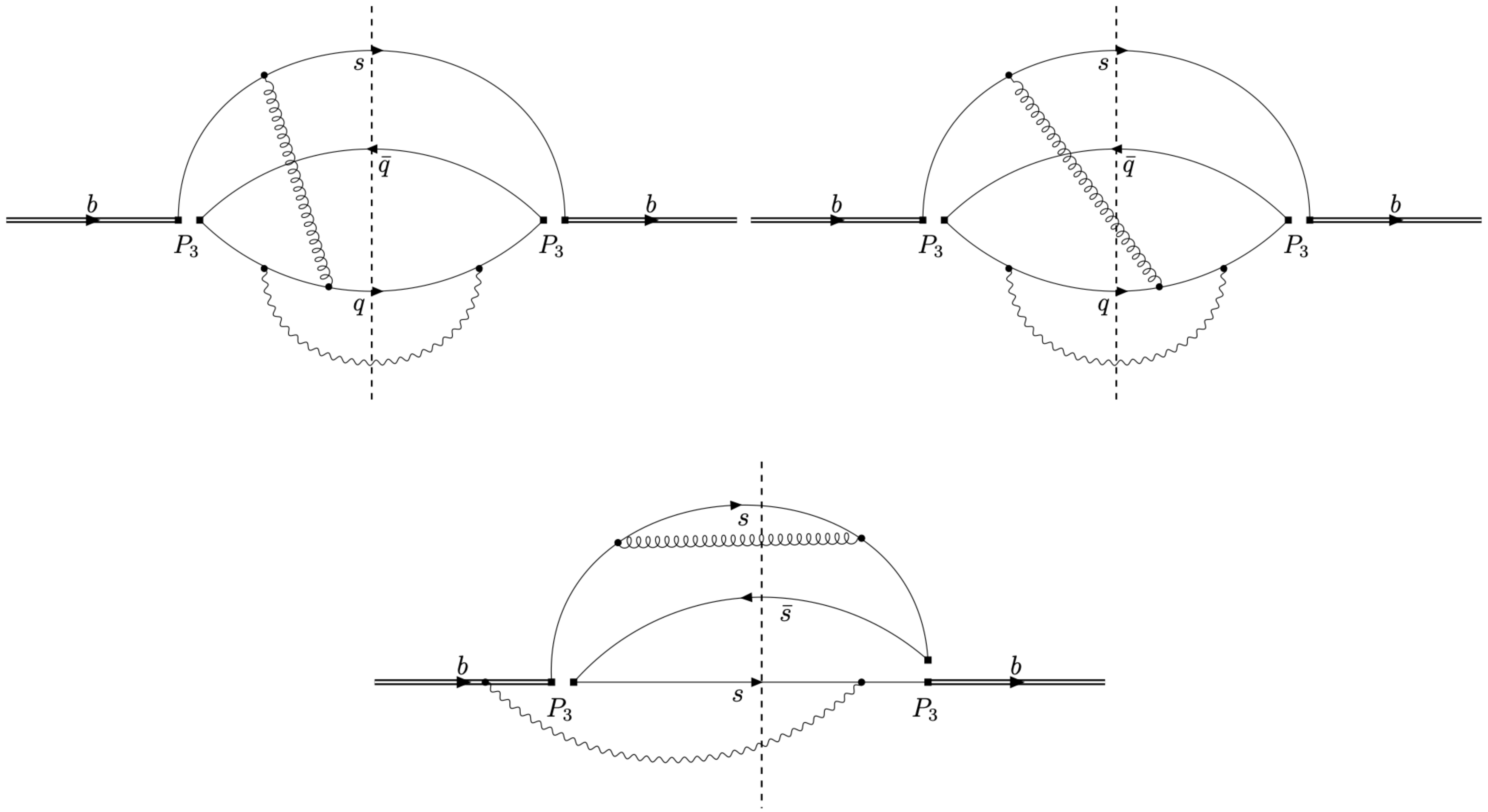
Ideal playground for multi-loop aficionados



Completing the four-body contributions to $\bar{B} \to X_s \gamma$ at NLO

Tobias Huber
Naturwissenschaftlich-Technische Fakultät, Universität Siegen,
Walter-Flex-Str. 3, 57068 Siegen,
E-mail: huber@physik.uni-siegen.de

Lars-Thorben Moos*
Naturwissenschaftlich-Technische Fakultät, Universität Siegen,
Walter-Flex-Str. 3, 57068 Siegen, Germany
E-mail: moos@physik.uni-siegen.de



1.2. B mixing and lifetimes

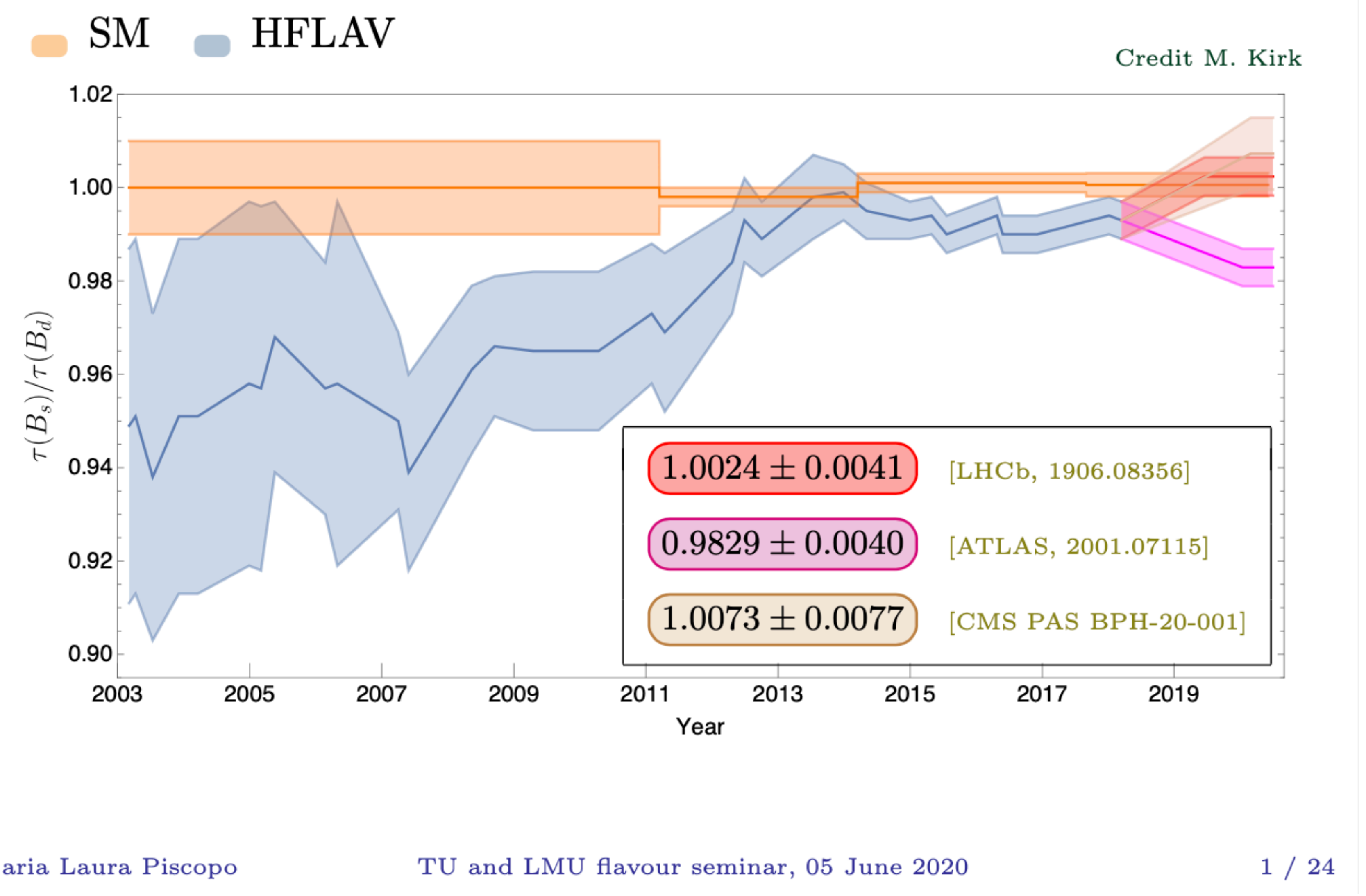
$$\Delta M_s$$

The obvious BSM hero: precise theoretical determination of non-perturbative matrix elements needed

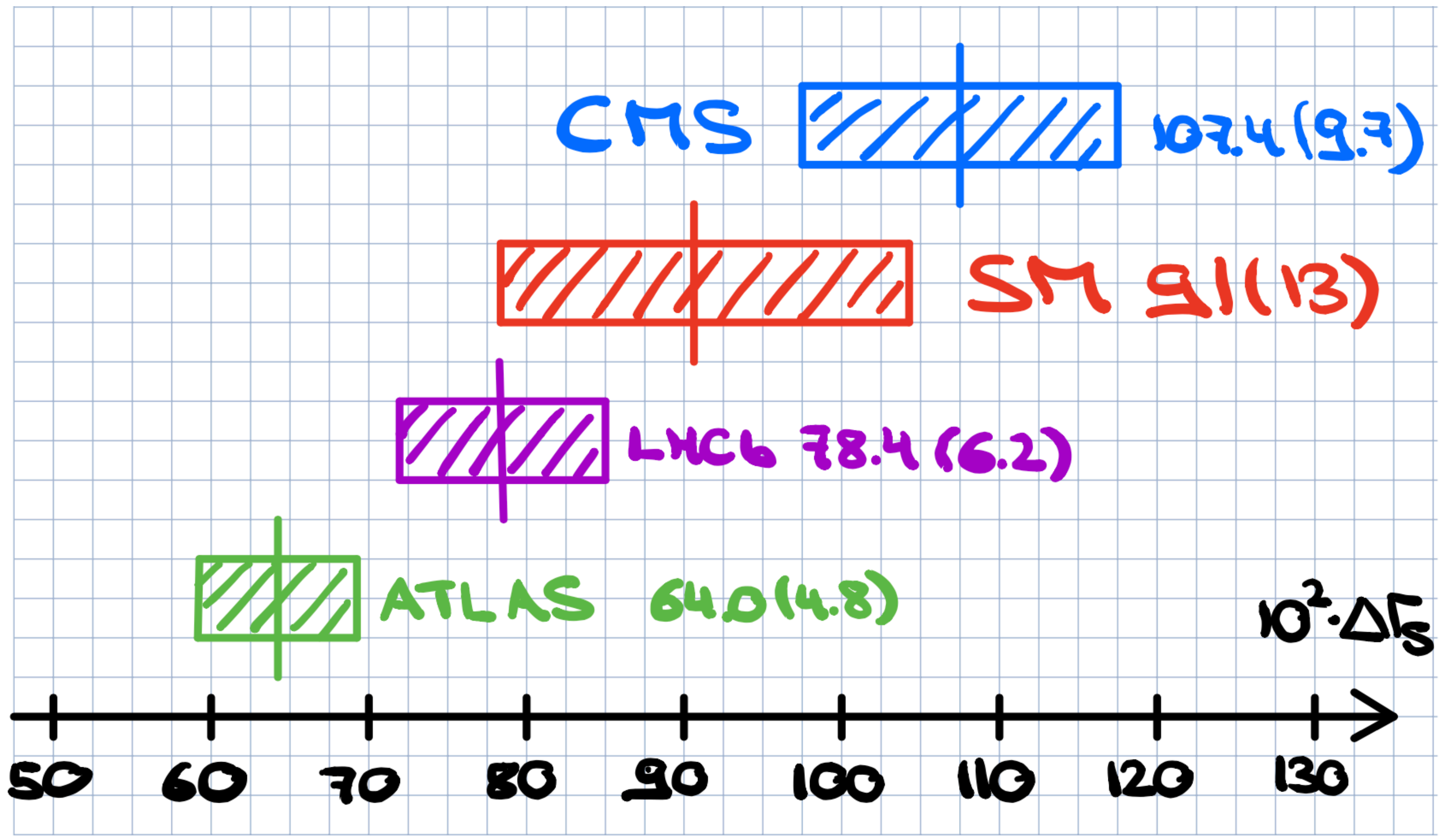
HQET sum rules (Durham, Siegen), Lattice (FNAL-MILC, RBC-UK, HPQCD)

The unspoken anomalies: B_s lifetime

and decay rate difference of neutral B_s mesons



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



determination of non-perturbative matrix elements needed

HQET sum rules (Durham), Lattice (:-( )

Higher order perturbative terms needed

Higher orders in the HQE needed

determination of non-perturbative matrix elements needed

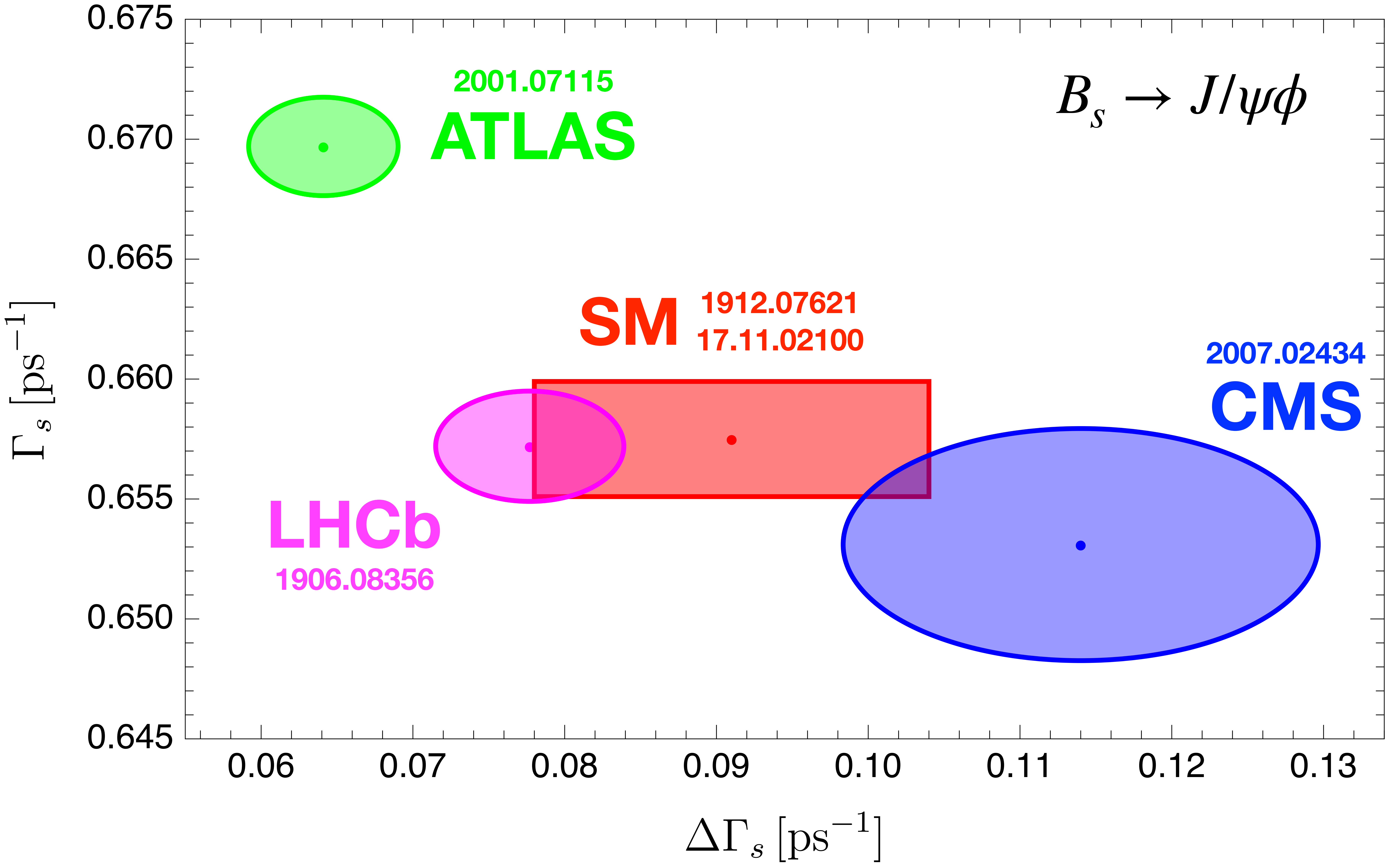
HQET sum rules (Durham, Siegen), Lattice (FNAL-MILC, HPQCD)

Higher order perturbative terms needed

Higher orders in the HQE needed

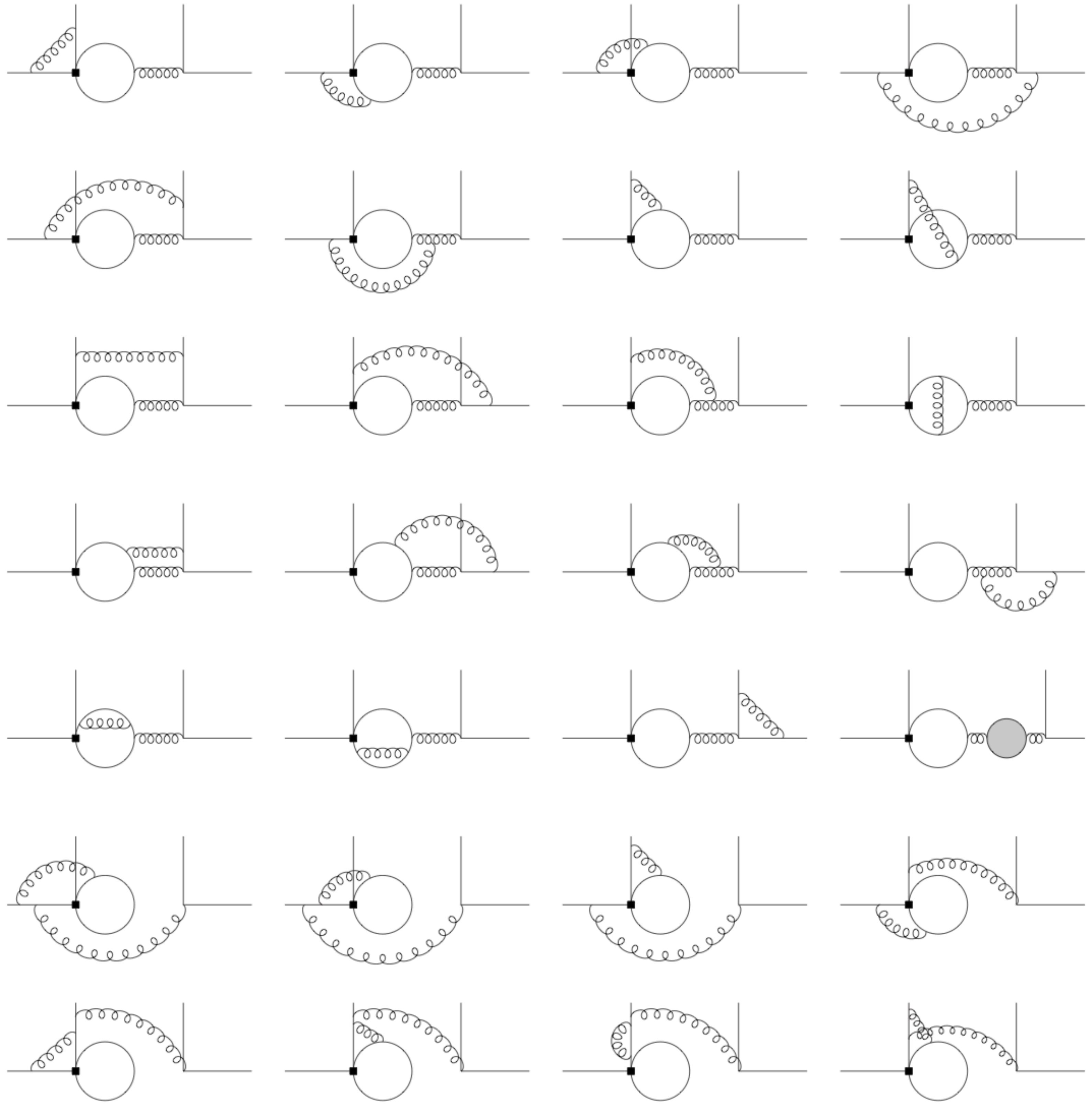
1.2. B mixing and lifetimes

The unspoken anomalies: B_s lifetime and decay rate difference of neutral B_s mesons



1.3. Exclusive Hadronic B decays

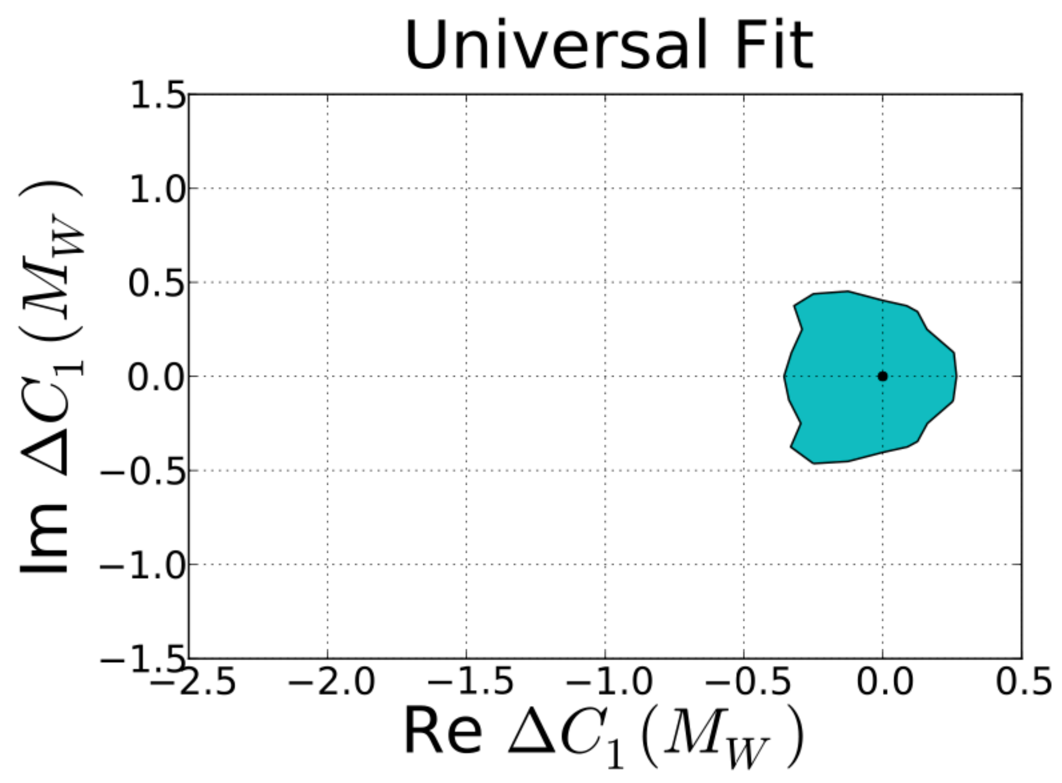
QCD factorisation at 2-loop

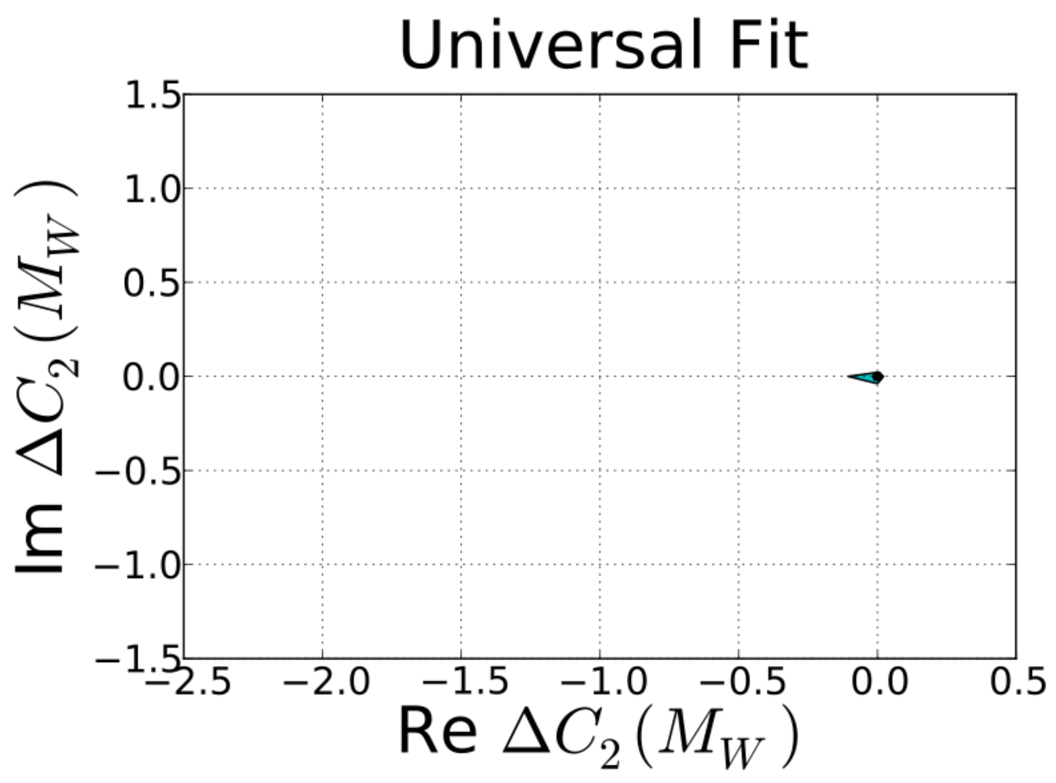


Can there be BSM effects in hadronic tree-level decays

source	PDG	our fits (w/o QCDF)		our fit (w/ QCDF, no f_s/f_d)		QCDF prediction
scenario	—	no f_s/f_d	$(f_s/f_d)^{7\text{ TeV}}_{\text{LHCb,sl}}$	ratios only	~~$SU(3)$~~	—
χ^2/dof	—	$2.5/4$	$3.1/5$	$4.6/6$	$3.7/4$	—
$\mathcal{B}(\bar{B}^0_s \to D^+_s \pi^-)$	3.00 ± 0.23	3.6 ± 0.7	3.11 ± 0.25	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0 \to D^+ K^-)$	0.186 ± 0.020	0.222 ± 0.012	0.224 ± 0.012	0.227 ± 0.012	0.226 ± 0.012	0.326 ± 0.015
$\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)$	2.52 ± 0.13	2.71 ± 0.12	2.73 ± 0.12	2.74 ± 0.12	$2.73^{+0.12}_{-0.11}$	—
$\mathcal{B}(\bar{B}^0_s \to D^{*+}_s \pi^-)$	2.0 ± 0.5	2.4 ± 0.7	2.1 ± 0.5	$2.46^{+0.37}_{-0.32}$	$2.43^{+0.39}_{-0.32}$	$4.3^{+0.9}_{-0.8}$
$\mathcal{B}(\bar{B}^0 \to D^{*+} K^-)$	0.212 ± 0.015	0.216 ± 0.014	0.216 ± 0.014	$0.213^{+0.014}_{-0.013}$	$0.213^{+0.014}_{-0.013}$	$0.327^{+0.039}_{-0.034}$
$\mathcal{B}(\bar{B}^0 \to D^{*+} \pi^-)$	2.74 ± 0.13	2.78 ± 0.15	2.79 ± 0.15	$2.76^{+0.15}_{-0.14}$	$2.76^{+0.15}_{-0.14}$	—

More than 4 sigma discrepancy!!!!





Could lead to shift in CKM angle gamma of several degrees!
Could lead to enhanced Delta Gamma B_d -> D0 dimuon asymmetry

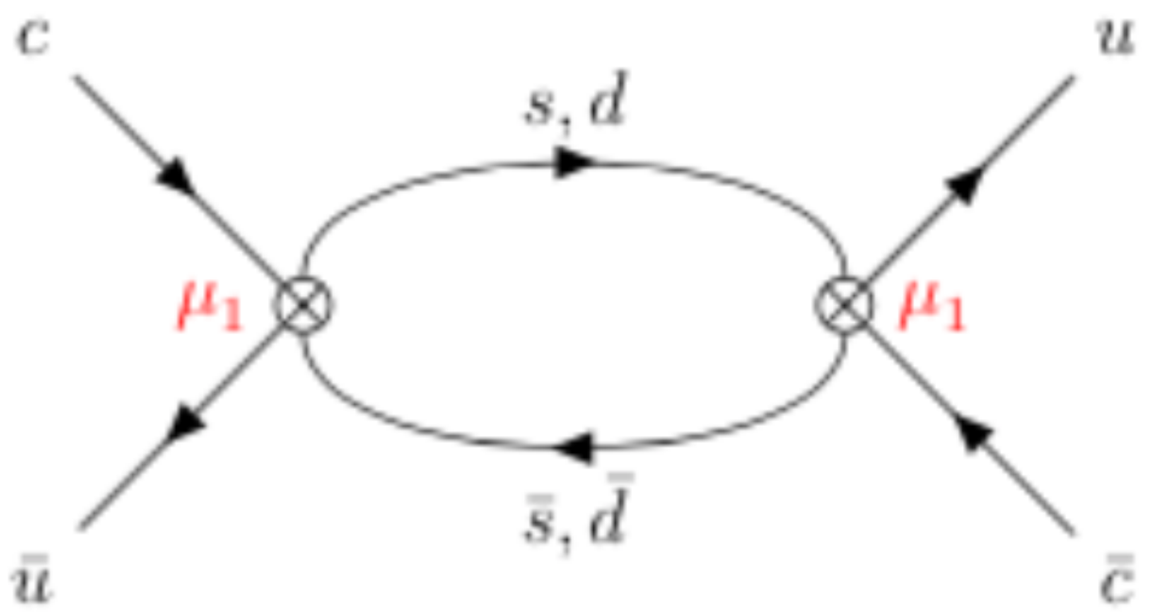
1.4. HQE in the charm sector?

Experiment:

$$x := \frac{\Delta M_D}{\Gamma_D} = (0.37 \pm 0.12)\% \,, \quad y := \frac{\Delta \Gamma_D}{2\Gamma_D} = 0.68^{+0.06}_{-0.07}\%$$

Theory:

$$\Gamma_{12}^D = -\lambda_s^2 \left(\Gamma_{ss}^D - 2\Gamma_{sd}^D + \Gamma_{dd}^D\right) + 2\lambda_s\lambda_b \left(\Gamma_{sd}^D - \Gamma_{dd}^D\right) - \lambda_b^2 \Gamma_{dd}^D$$



Naive quark level calculation: SM = 10^-5 Exp

Solutions:

1. **HQE is by 5 orders off -> gigantic Quark Hadron Duality violations, One has to try Hadron level calculations - but HQE works well in the B-sector!**
2. **ORIGIN LIES in crazy GIM Cancellations**
   - **actually 20% QHD violations sufficient**
   - **Higher orders in the HQE might be less severe affected by the GIM cancellations**
   - **Artefact of choosing the renormalisation scale identical for sd and ss**
   - **Test with charm lifetimes (no GIM cancellations)**
3. **Lattice in the far future….**
4. **Maybe Exp. has already found BSM :-)**

Calculate higher orders in the HQE
Calculate higher orders in the pert. expansion
Calculate non-perturbative matrix elements

Conclusion

- Higher theory precision mandatory to make full use of the improved experimental situation (LHCb, Belle-2, ATLAS, CMS, BESIII)
- Many important theory improvements are doable in the next years
- Improvements both on the perturbative side and on the non-perturbative side necessary (pert. QCD, lattice, Sum rules,…)
- Close collaboration between different theory schools advantageous!

Siegen

Guido Bell & co.

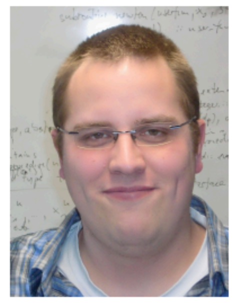
- Non-leptonic B decays in QCD factorisation
- α_s determination from e^+e^- event shape
- Applications of Soft-Collinear Effective Theory in flavor and jet physics


Guido Bell
(Senior)


Jan Piclum
(Senior)


Goutam Das
(Post-doc)


Kevin Brune
(PhD)


Tobias Mohrmann
(PhD)


Marcel Walc
(PhD)

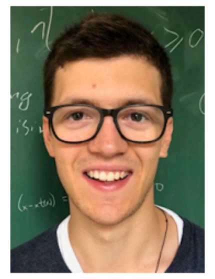
Thorsten Feldmann & co.

- Phenomenology of rare B & Λ_B decays
- NP interpretation to flavor anomalies
- Light-cone distribution amplitudes and form factors of B mesons


Thorsten Feldmann
(Senior)

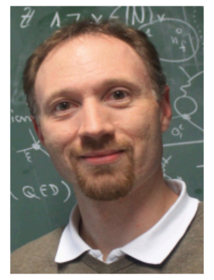

Oscar Cata
(Senior)


Nico Gubernari
(Post-doc)


Nicolas Seitz
(PhD)

Tobias Huber & co.

- QCD corrections to non-leptonic B decays
- FCNCs $B \to X_{(s,d)}\ell^+\ell^-$
  $B \to X_{(s,d)}\gamma$
- EFTs
- Multi-loop computations in QCD and $N=4$ SYM


Tobias Huber
(Senior)


Robin Brüser
(Post-doc)


Gilberto T. Xolocotzi
(Post-doc)


Lars T. Moos
(PhD)

Wolfgang Kilian & co.

- Monte Carlo WHIZARD in e^+e^- colliders


Wolfgang Kilian
(Senior)


Alan Price
(post-doc)


Nils Kreher
(PhD)


Tobias Striegl
(PhD)

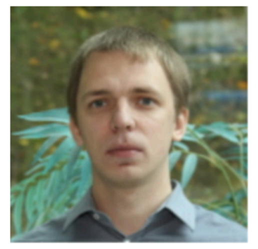
Alexander Lenz & co.

Since 1.10.2020 lattice in Siegen!

- B_s, B_d mixing
- D mixing
- Lifetimes of heavy hadrons
- $\not{C}\not{P}$ violation in charm
- Exclusive semileptonic decays on Lattice
- FCNC $b \to d\ell\ell$


Alexander J. Lenz
(Senior)


Oliver Witzel
(Senior)


Aleksey V. Rusov
(post-doc)


Maria L. Piscopo
(PhD)

Thomas Mannel & co.

- V_{cb} — QCD corrections & Heavy quark expansion
- $B \to D^{(*,**)}$ FF in LCSR
- $\not{C}\not{P}$ $B^+ \to \pi^+\pi^-\pi^+$
- $B \to X_{(c)}\ell\bar{\nu}$

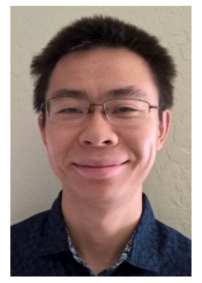

Thomas mannel
(Senior)


Alexander Khodjamirian
(Senior)


Alexei Pivovarov
(Senior)


Björn O. Lange
(Senior)


Daniel Moreno
(Post-doc)


Yao Ji
(Post-doc)


Rusa Mandal
(Post-doc)


Kevin Olschewsky
(PhD)


Muslem Rahimi
(PhD)


Hua-Yu Jiang
(PhD)