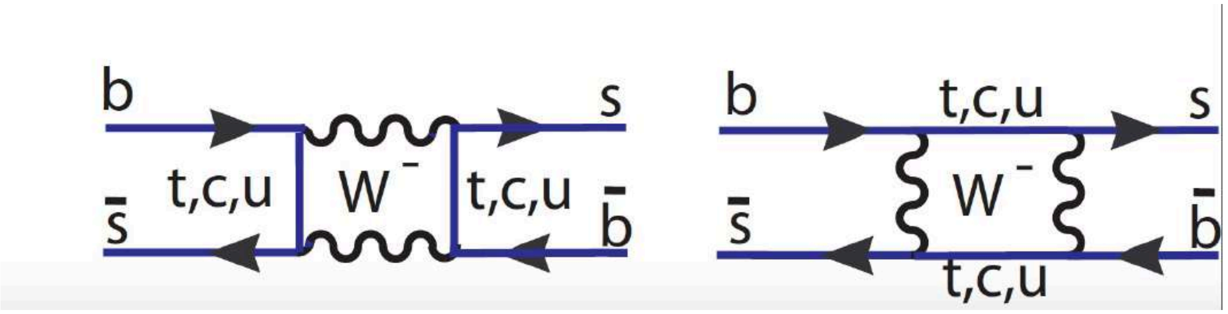
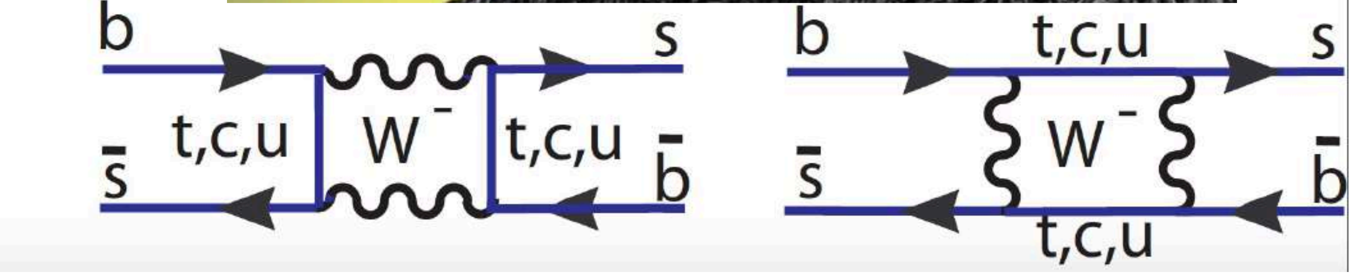
Per Aspera ad Astra:

Impact of high precision standard model predictions for BSM searches





Alexander Lenz, Universität Siegen

SFB Meeting, Siegen

6.10.2020

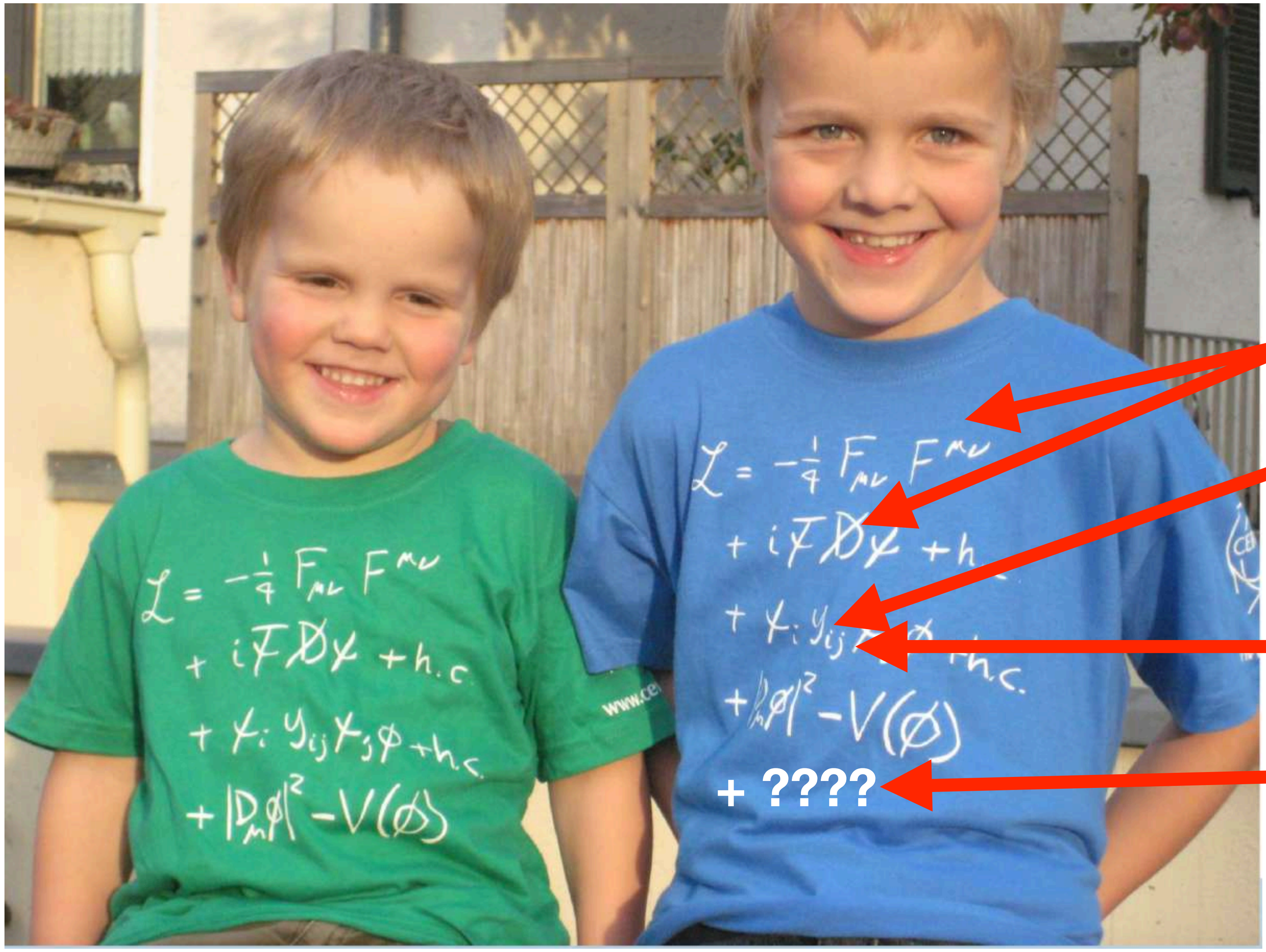
Messages from the machine room to the top deck

Taken from Thomas Mannel

Outline

- Motivation for Flavour Physics
    - Understanding of QCD
    - Determination of SM parameter
    - CP violation
    - Search for new physics
- Mass differences of neutral mesons
    - Understanding of QCD
    - Determination of CKM parameter
    - Search for new physics
- Decay rate difference/Lifetimes
    - Understanding of QCD
    - Search for new physics
    - CP violation

Motivation for Flavour Physics



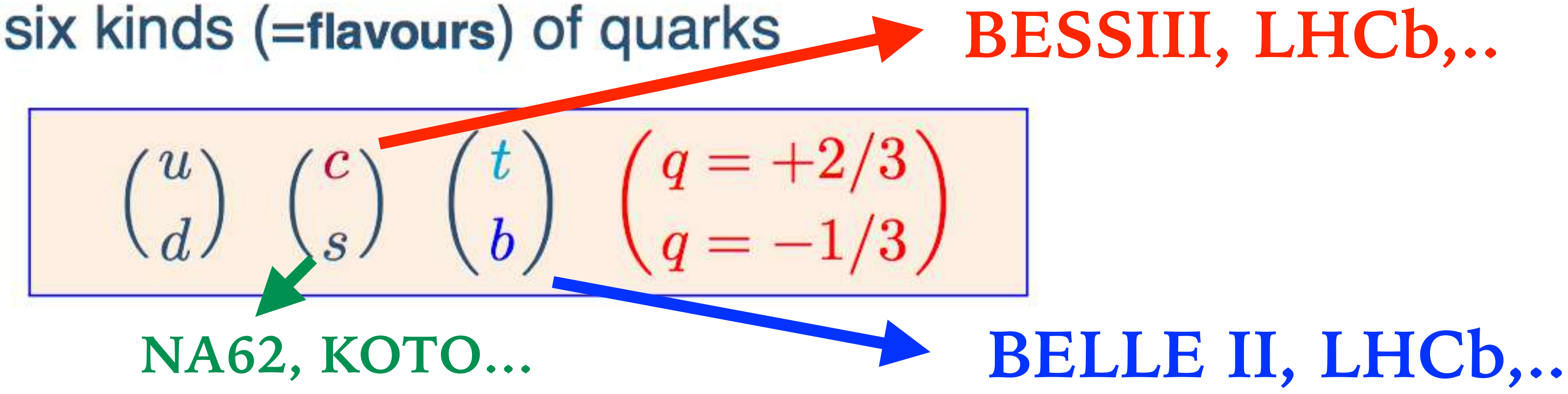
- Understanding of QCD
- Determination of SM parameter: CKM, quark masses,…
- CP violation
- Search for new physics

Motivation for Flavour Physics

- Understanding of QCD
- Determination of SM parameter: CKM, quark masses,…
- CP violation
- Search for new physics

MOTIVATION FOR FLAVOUR PHYSICS

There are (at least) six kinds (=**flavours**) of quarks



$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} q = +2/3 \\ q = -1/3 \end{pmatrix}$$

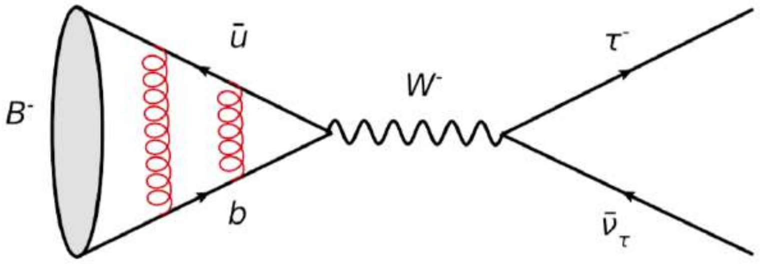
- Proton p = $|uud\rangle$
- **(Heavy) Flavour Physics** describes hadrons with a charm- or a bottom-quark

	$D^0 = (\bar{u}c)$	$D^+ = (\bar{d}c)$	$D_s^+ = (\bar{s}c)$	$\Lambda_c = (udc)$
Mass (GeV)	1.86486	1.86962	1.96850	2.28646
Lifetime (ps)	0.4101	1.040	0.500	0.200

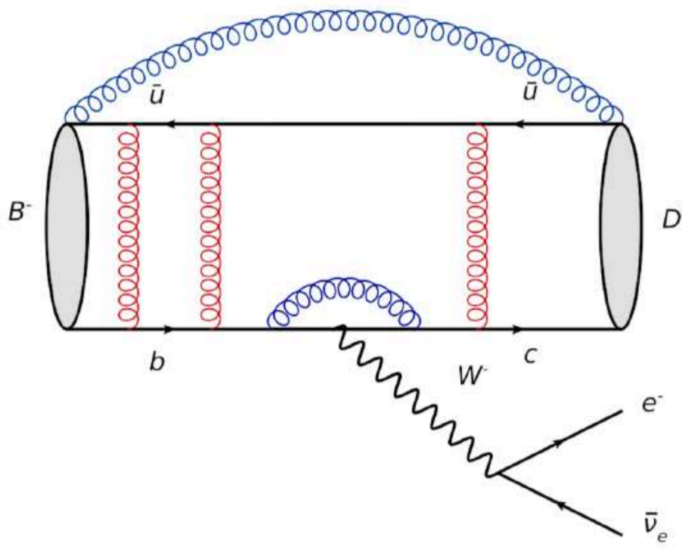
	$B_d = (\bar{b}d)$	$B^+ = (\bar{b}u)$	$B_s = (\bar{b}s)$	$B_c^+ = (\bar{b}c)$	$\Lambda_b = (udb)$
Mass (GeV)	5.27958	5.27926	5.3667	6.2745	5.6194
Lifetime(ps)	1.519	1.638	1.512	0.500	1.451

MOTIVATION FOR FLAVOUR PHYSICS

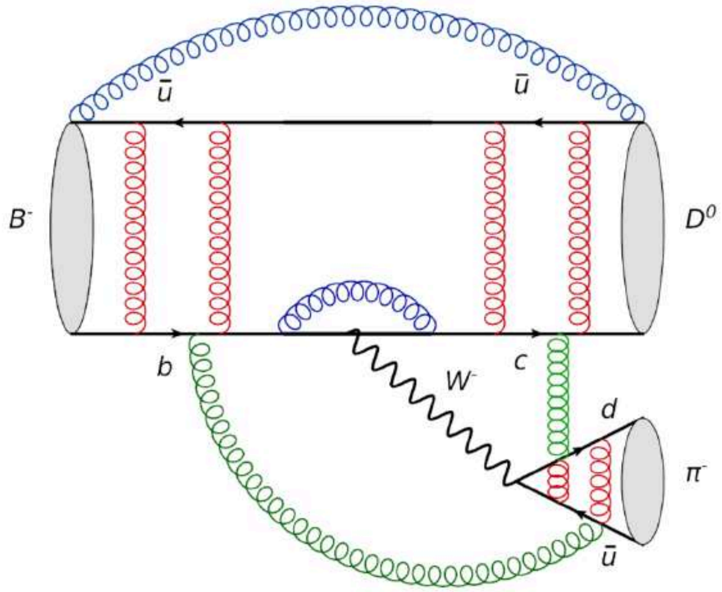
- **Leptonic decays**



- **Semi-Leptonic decays**

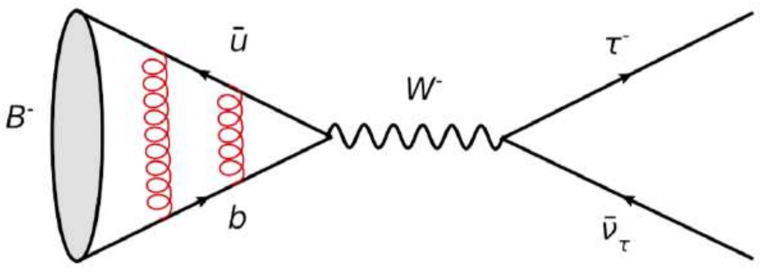


- **Non-Leptonic decays**

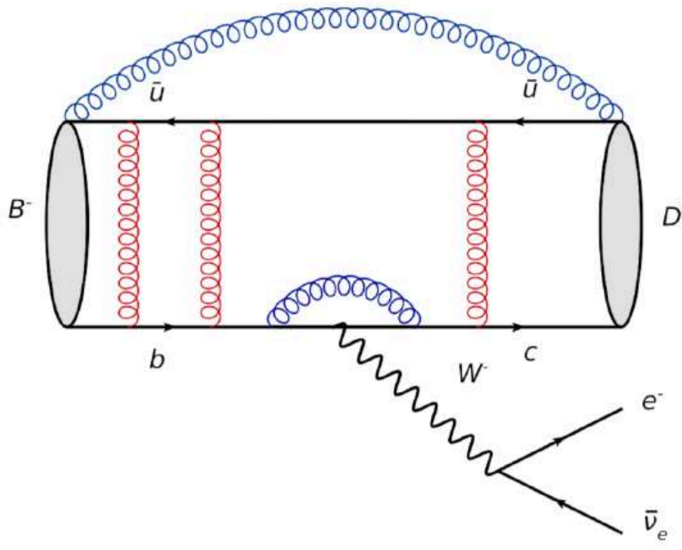


MOTIVATION FOR FLAVOUR PHYSICS

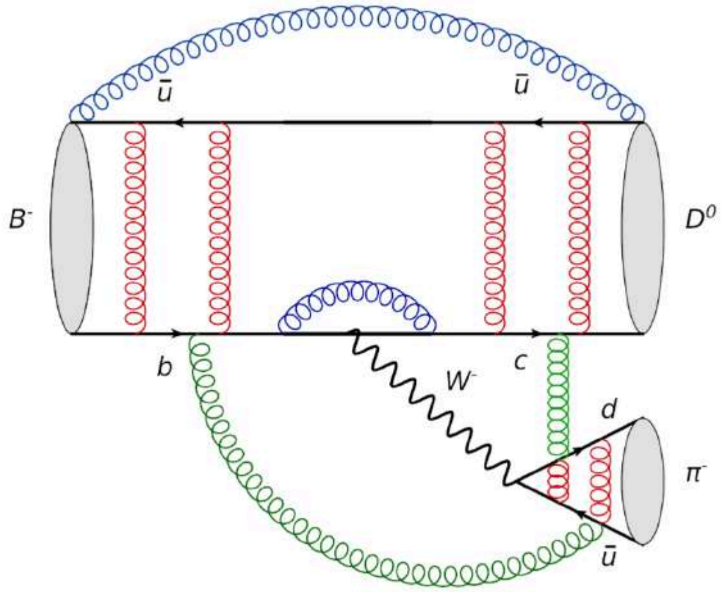
- **Leptonic decays**



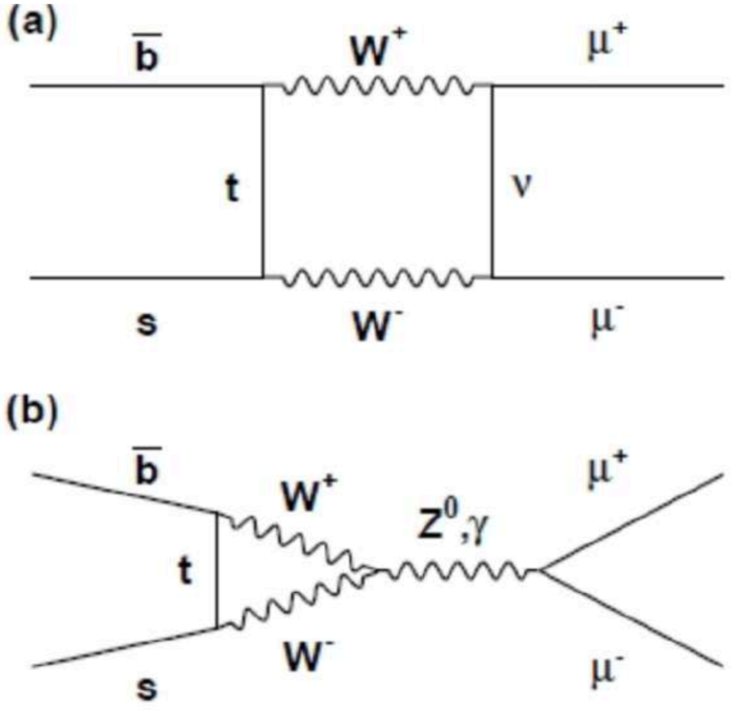
- **Semi-Leptonic decays**



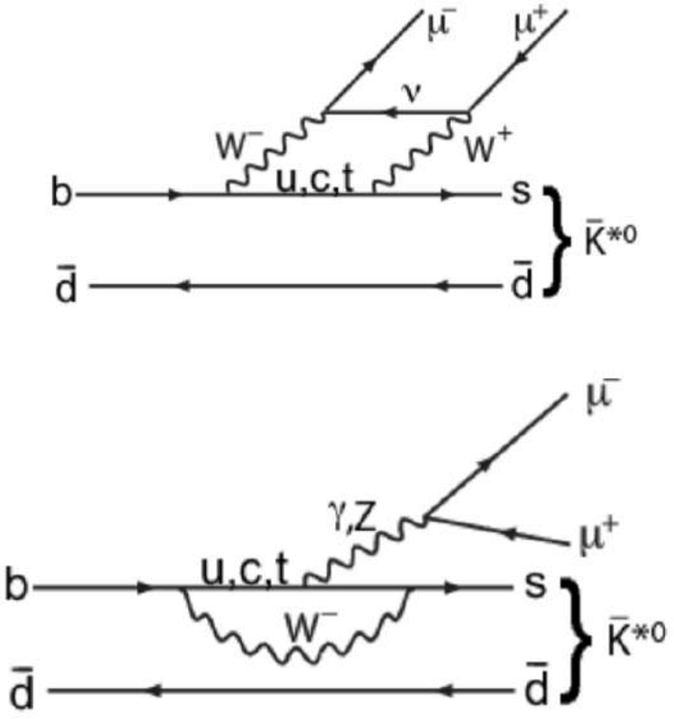
- **Non-Leptonic decays**



- **Leptonic decays**

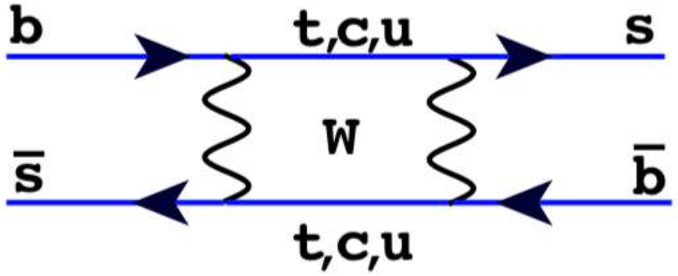


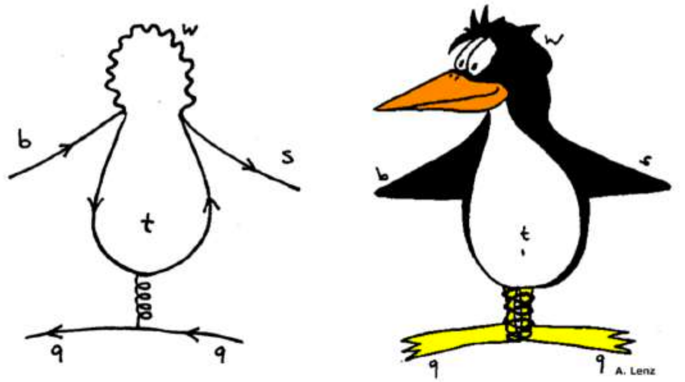
- **Semi-Leptonic decays**



like $K \to \pi\nu\nu$

- **Mixing**





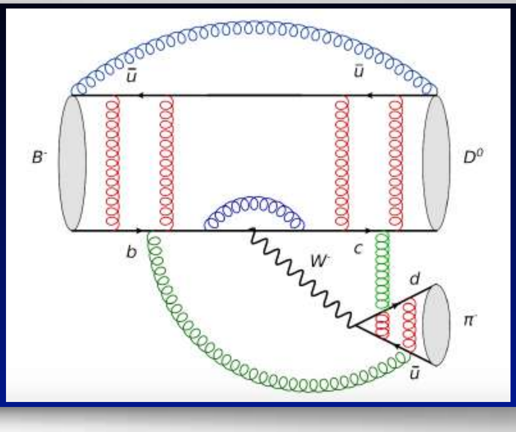
MOTIVATION FOR FLAVOUR PHYSICS

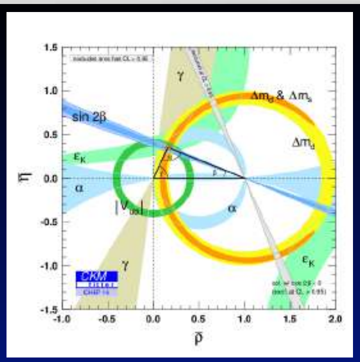
Baryon Asymmetry in the Universe:
A violation of the CP symmetry - which causes matter and anti-matter to evolve differently with time - seems to be necessary to explain the existence of matter in the Universe.
CP violation has so far only been found in hadron decays, which are experimentally investigated at LHCb and NA62 (CERN), SuperBelle (Japan),…

Indirect Search for BSM Physics:
To find hints for Physics beyond the Standard Model we can either use brute force (= higher energies) or more subtle strategies like high precision measurements.
New contributions to an observable f are identified via:

$$f^{\rm SM} + f^{\rm NP} = f^{\rm Exp}$$

Understanding QCD:
Hadron decays are strongly affected by QCD (strong interactions) effects, which tend to overshadow the interesting fundamental decay dynamics. Theory tools like effective theories, Heavy Quark Expansion, HQET, SCET ,…enable a control over QCD-effects and they are used in other fields like Collider Physics, Higgs Physics, DM searches…

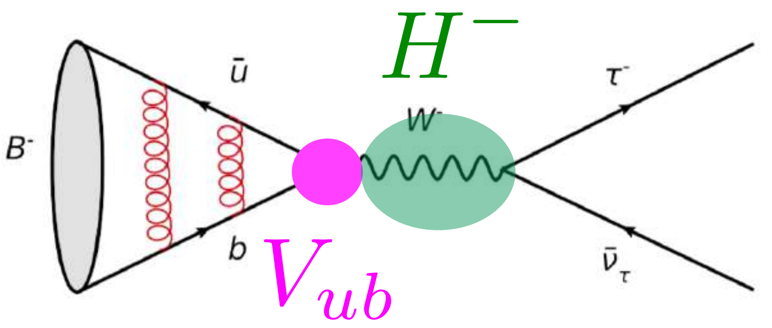


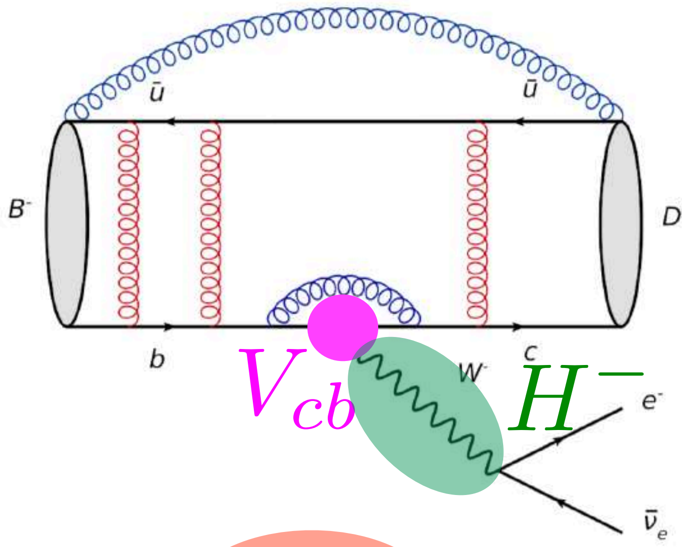


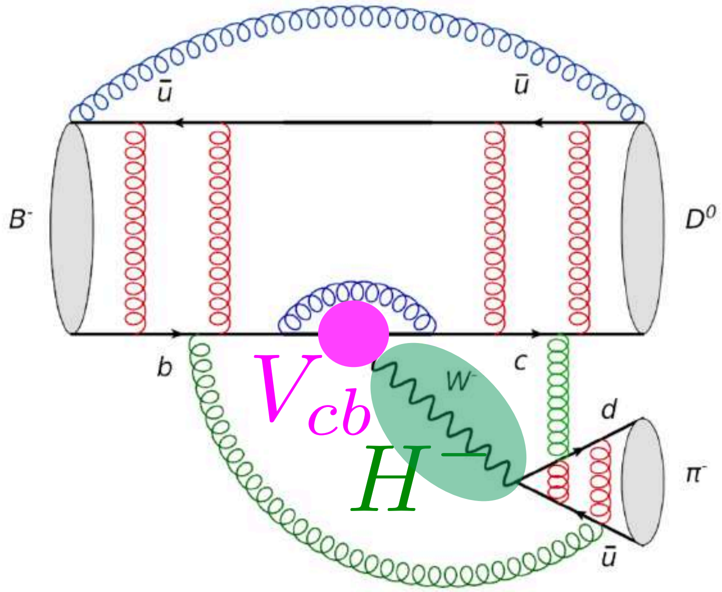
Standard Model parameters:
Hadron decays depend strongly on Standard Model parameters like quark masses and CKM couplings (which are the only known source of CP violation in the SM). A precise knowledge of these parameters is needed for all branches of particle physics.

MOTIVATION FOR FLAVOUR PHYSICS

- **Leptonic decays**
- **Semi-Leptonic decays**
- **Non-Leptonic decays**







$$\langle 0|\bar b\gamma^\mu\gamma_5 u|B_q(p)\rangle \quad = \quad i f_{B_q} p^\mu$$

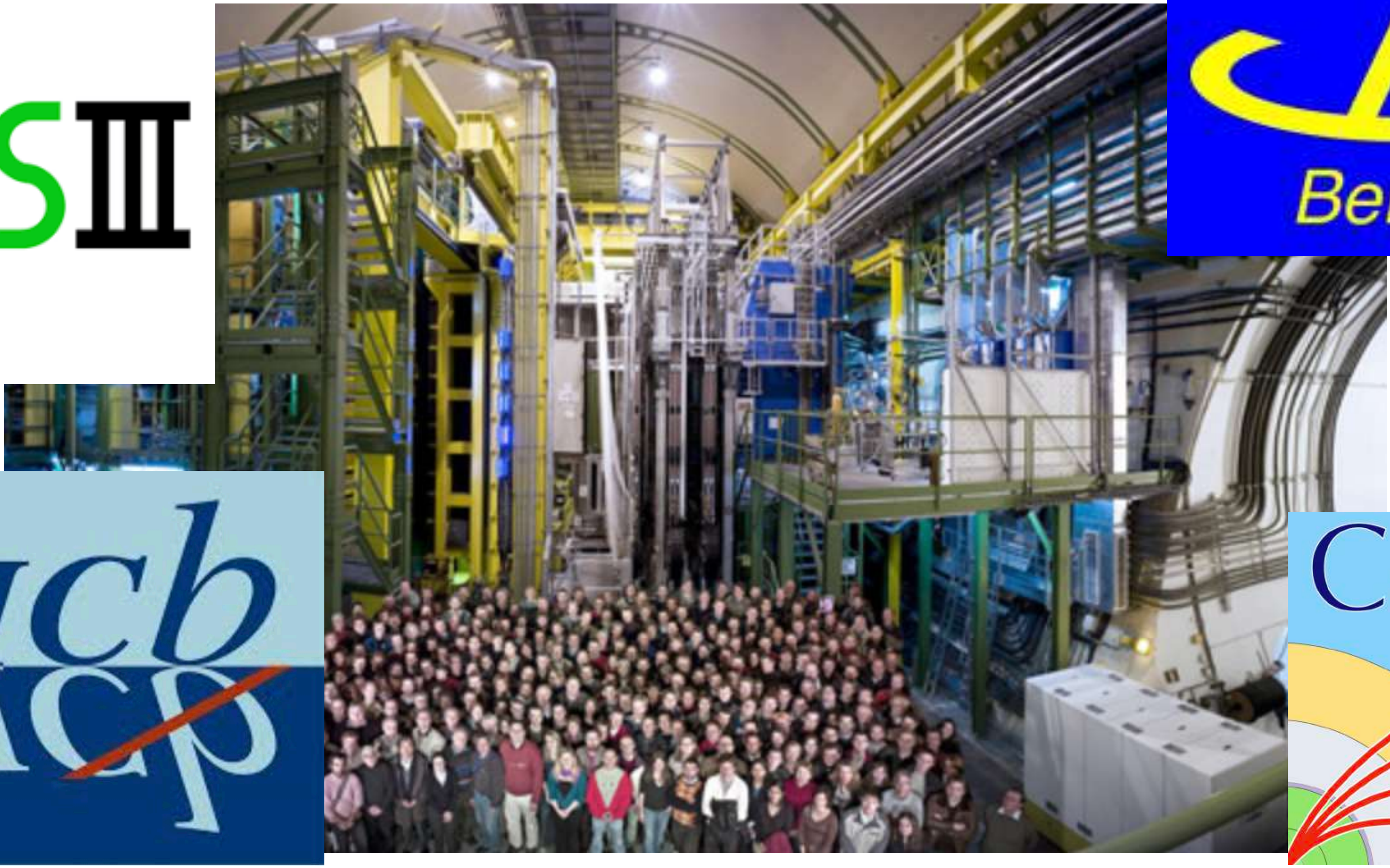
$$\langle D^0(p_D)|\bar c\gamma_\mu b|B^-(p_B)\rangle = f_+^{B^-\to D^0}(q^2)\left(p_B^\mu + p_D^\mu - \frac{m_B^2 - m_D^2}{q^2}q^\mu\right)$$

$$\langle D^0\pi^-|\bar c\gamma_\mu(1-\gamma_5)b\cdot\bar u\gamma^\mu(1-\gamma_5)d|B^-\rangle$$
$$\approx \langle D^0|\bar c\gamma_\mu(1-\gamma_5)b|B^-\rangle \quad \cdot \quad \langle\pi^-|\bar u\gamma^\mu(1-\gamma_5)d|0\rangle$$

1. Imaginary part in CKM elements = CP violation
2. Instead of a W a charged Higgs H might be exchanged = BSM
3. QCD effects are crucial: decay constant, form factors,…
4. Determination of SM parameter

MOTIVATION FOR FLAVOUR PHYSICS

- **Huge** experimental progress: **B-factories, Tevatron, BESS III** and LHC (**ATLAS, CMS, LHCb**) and **Belle II**
- **LHCb**: >630 paper, >41k citations, >9fb-1



MOTIVATION FOR FLAVOUR PHYSICS

- We have interesting anomalies!

σ

- 3-6: Semi-leptonic loop-level decays (small BSM)
- 3.x: Semi-leptonic tree-level decays (large BSM)
- 3.6: B-mixing phase (dimuon asymmetry)
- 3.5: Muon g-2
- 0-4: 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.x: Vcb, Vub inclusive vs exclusive measurements

Outline

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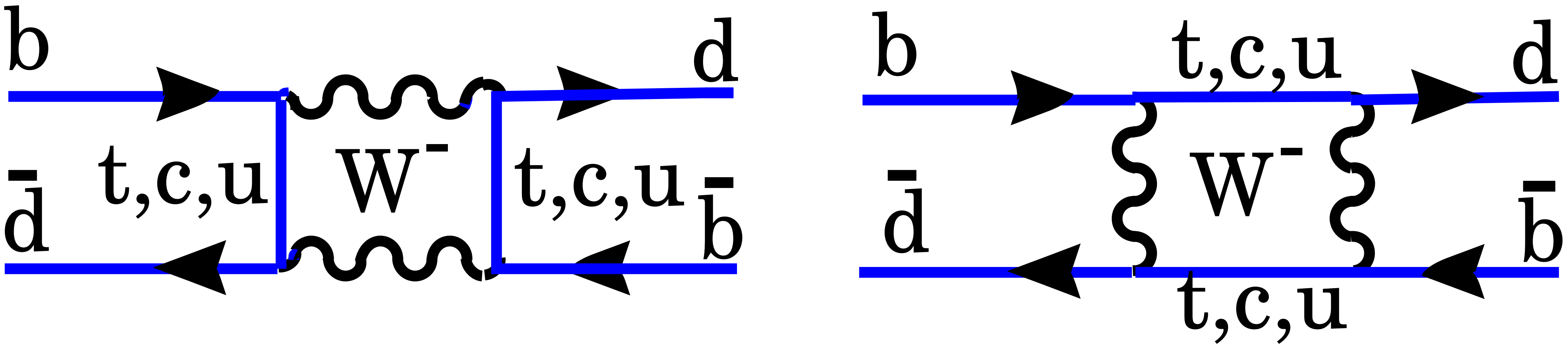
B-MIXING



$|M_{12}|$, $|\Gamma_{12}|$ 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. $B_q \to Xl\nu$ (*semi-leptonic*)

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

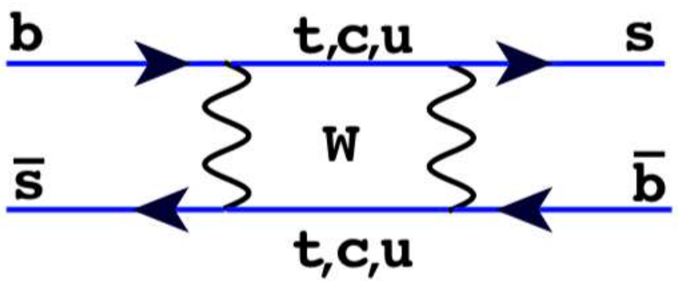
Mass difference ΔM_q

Experiment.: HFLAV 2019

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

$$\Delta m_d = 0.5064 \pm 0.0019 \text{ ps}^{-1}$$

Theory



CKM

Inami-Lim

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:

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

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

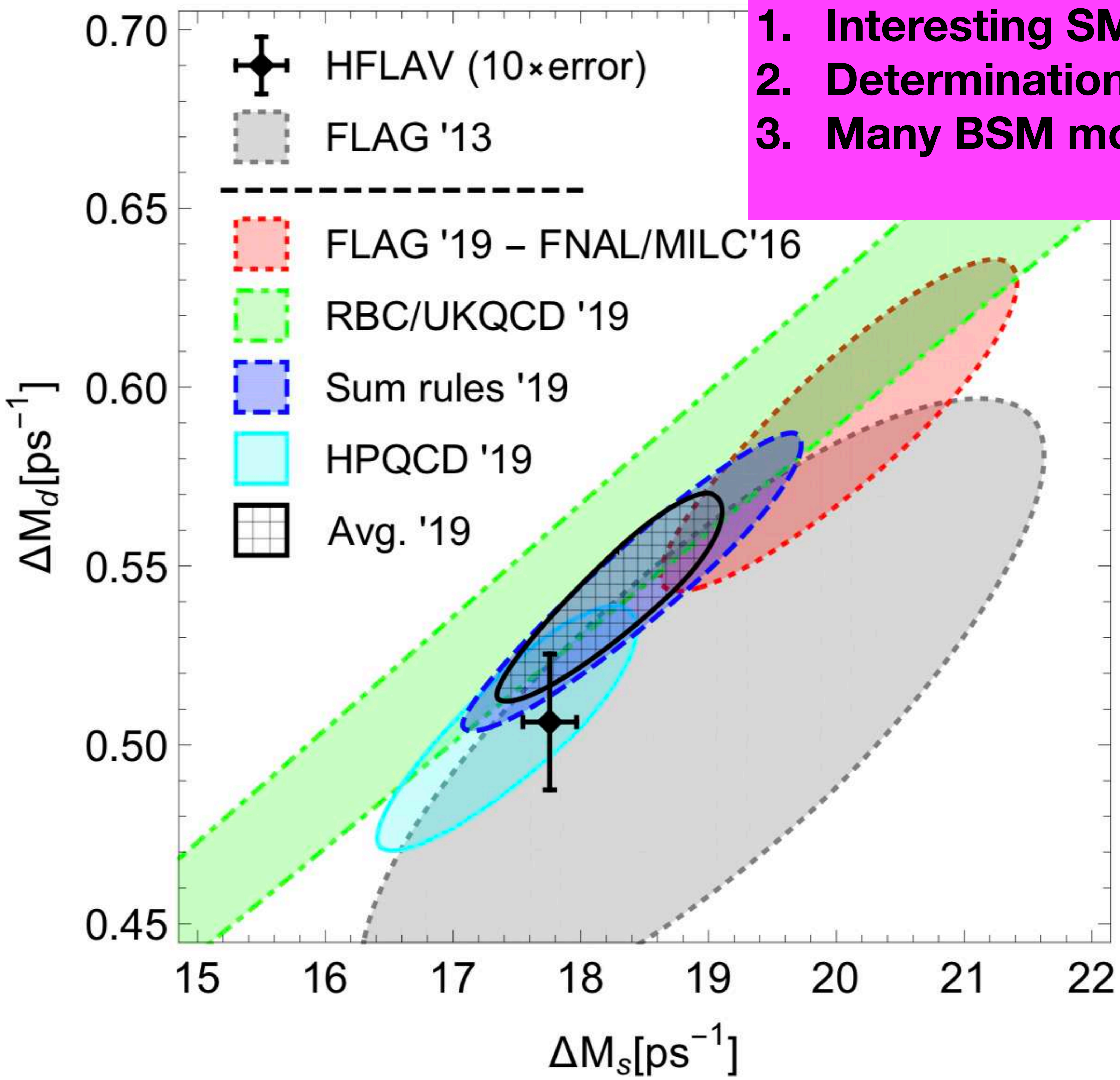
Non-perturbative theory input:

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

Mass difference ΔM_q

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**

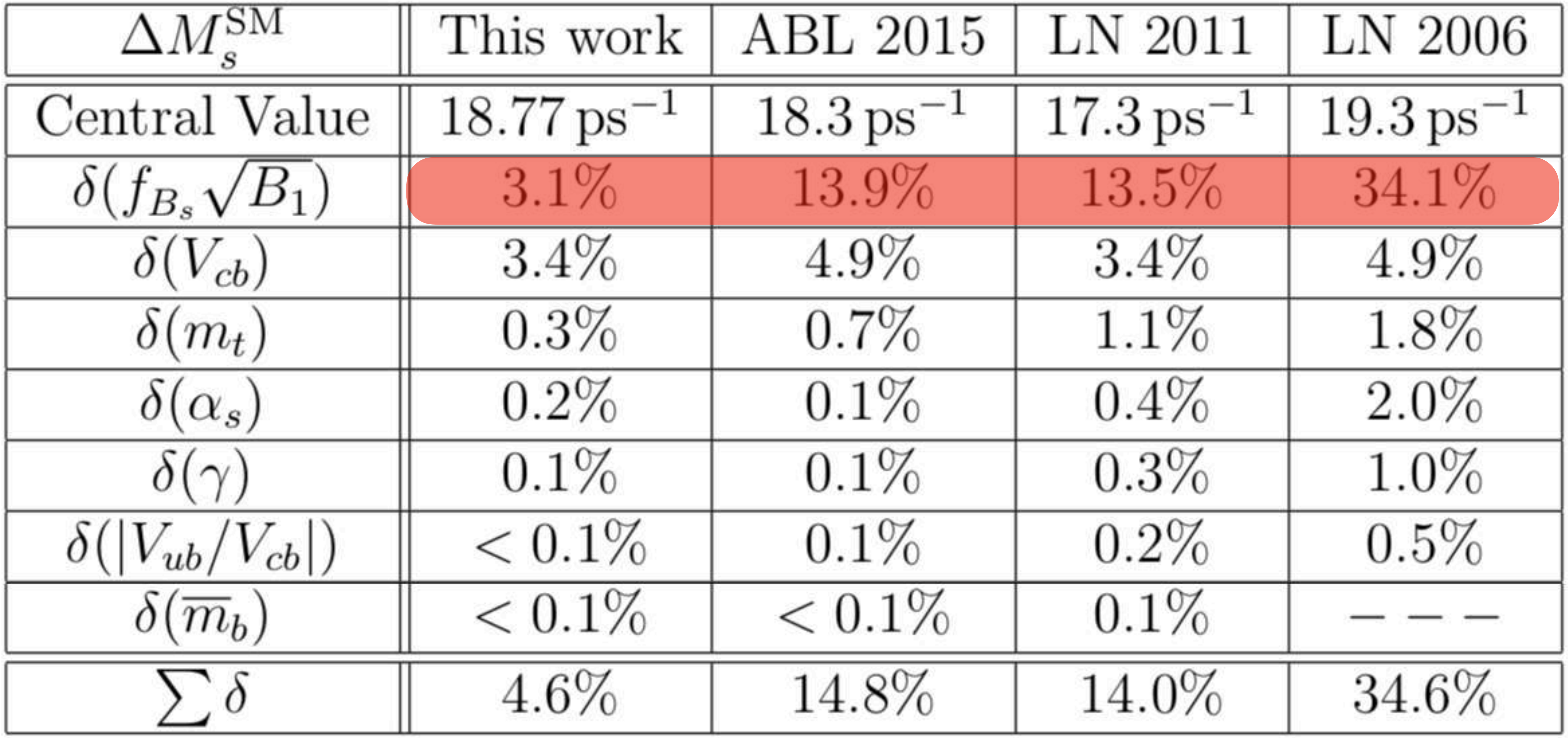


Very active field:

- **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

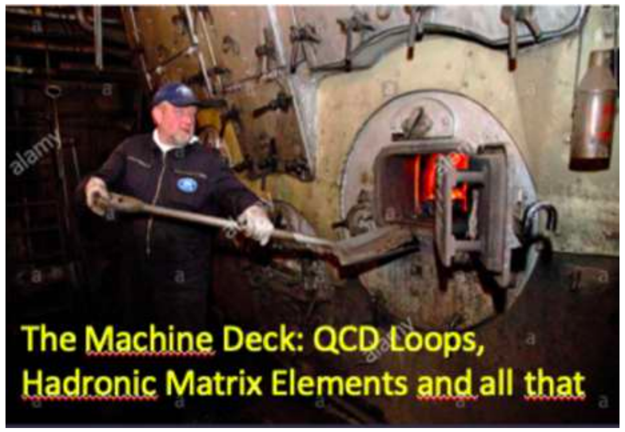
Mass difference ΔM_q



ΔM_s^{SM}	This work	ABL 2015	LN 2011	LN 2006
Central Value	$18.77\,\mathrm{ps}^{-1}$	$18.3\,\mathrm{ps}^{-1}$	$17.3\,\mathrm{ps}^{-1}$	$19.3\,\mathrm{ps}^{-1}$
$\delta(f_{B_s}\sqrt{B_1})$	3.1%	13.9%	13.5%	34.1%
$\delta(V_{cb})$	3.4%	4.9%	3.4%	4.9%
$\delta(m_t)$	0.3%	0.7%	1.1%	1.8%
$\delta(\alpha_s)$	0.2%	0.1%	0.4%	2.0%
$\delta(\gamma)$	0.1%	0.1%	0.3%	1.0%
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	$< 0.1\%$	0.1%	0.2%	0.5%
$\delta(\overline{m}_b)$	$< 0.1\%$	$< 0.1\%$	0.1%	$---$
$\sum \delta$	4.6%	14.8%	14.0%	34.6%

AL, 2019

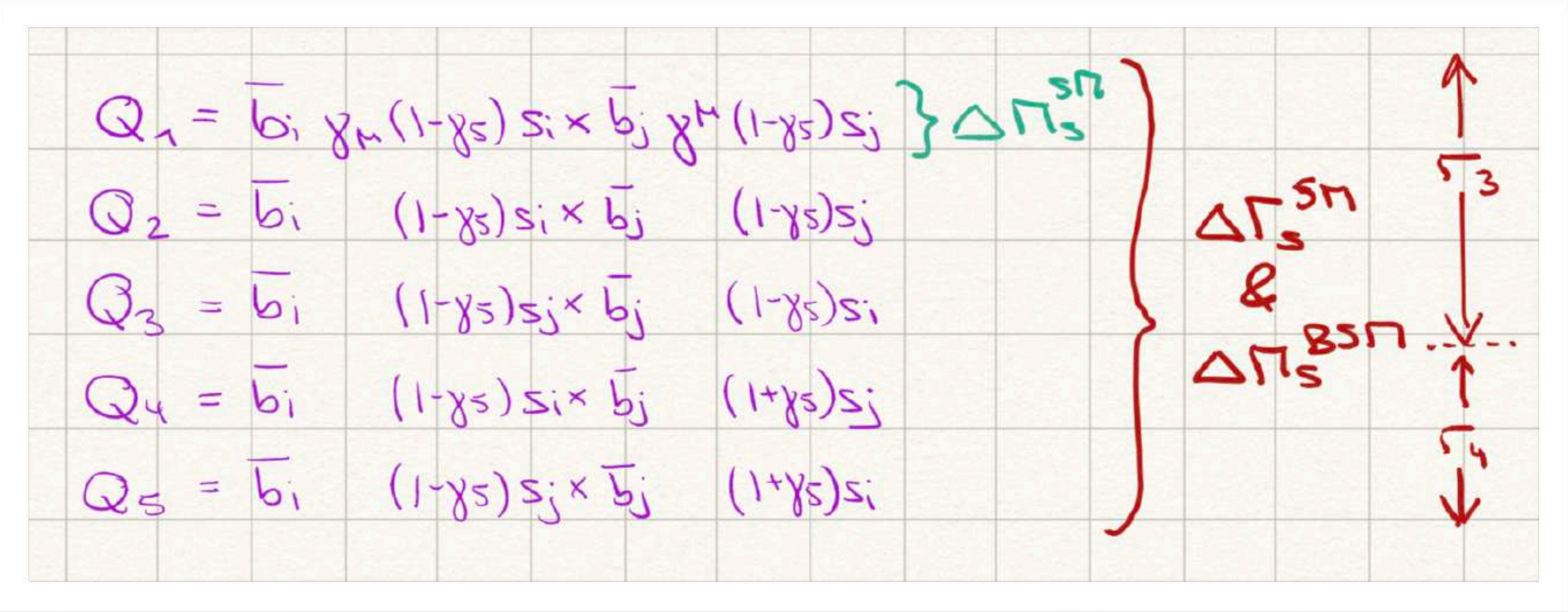
Thanks to Lattice, Sum rules



Future scenario:
lattice/sum rule combined: +/- 2%
Vcb: +/- 1%
=> Uncertainty can be halved: +/- 2.2%

Mass difference - QCD

Mixing Operators Delta B = 2



$$Q_1 = \bar{b}_i \gamma_\mu (1-\gamma_5) s_i \times \bar{b}_j \gamma^\mu (1-\gamma_5) s_j \; \} \, \Delta\Gamma_s^{SM}$$

$$Q_2 = \bar{b}_i (1-\gamma_5) s_i \times \bar{b}_j (1-\gamma_5) s_j$$

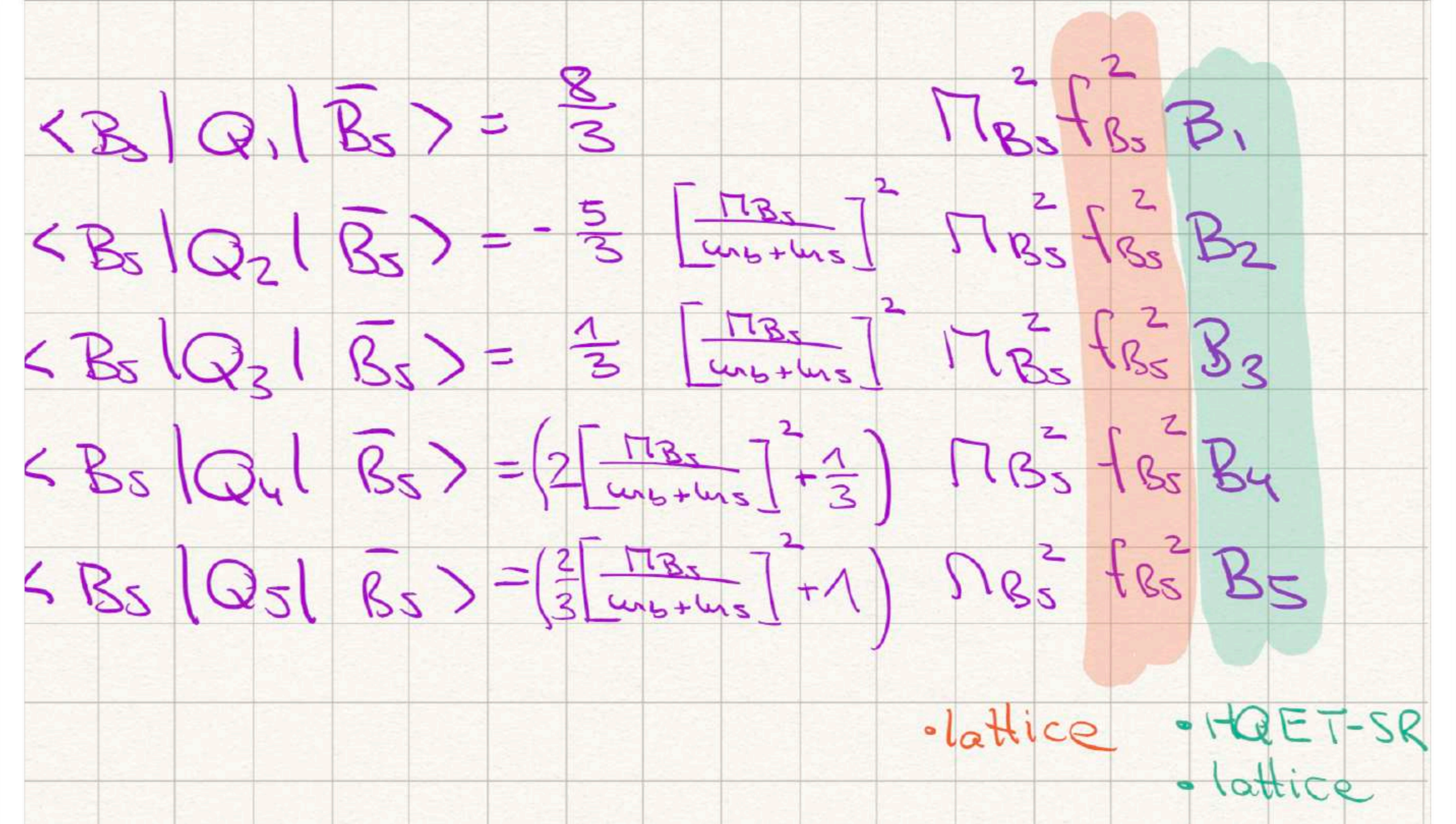
$$Q_3 = \bar{b}_i (1-\gamma_5) s_j \times \bar{b}_j (1-\gamma_5) s_i$$

$$Q_4 = \bar{b}_i (1-\gamma_5) s_i \times \bar{b}_j (1+\gamma_5) s_j$$

$$Q_5 = \bar{b}_i (1-\gamma_5) s_j \times \bar{b}_j (1+\gamma_5) s_i$$

$\Delta\Gamma_s^{SM}$ & $\Delta\Gamma_s^{BSM}$

Parameterisation in terms of decay constants and Bag parameter



$$\langle B_s | Q_1 | \bar{B}_s \rangle = \frac{8}{3} M_{B_s}^2 f_{B_s}^2 B_1$$

$$\langle B_s | Q_2 | \bar{B}_s \rangle = -\frac{5}{3} \left[\frac{M_{B_s}}{m_b + m_s}\right]^2 M_{B_s}^2 f_{B_s}^2 B_2$$

$$\langle B_s | Q_3 | \bar{B}_s \rangle = \frac{1}{3} \left[\frac{M_{B_s}}{m_b + m_s}\right]^2 M_{B_s}^2 f_{B_s}^2 B_3$$

$$\langle B_s | Q_4 | \bar{B}_s \rangle = \left(2\left[\frac{M_{B_s}}{m_b + m_s}\right]^2 + \frac{1}{3}\right) M_{B_s}^2 f_{B_s}^2 B_4$$

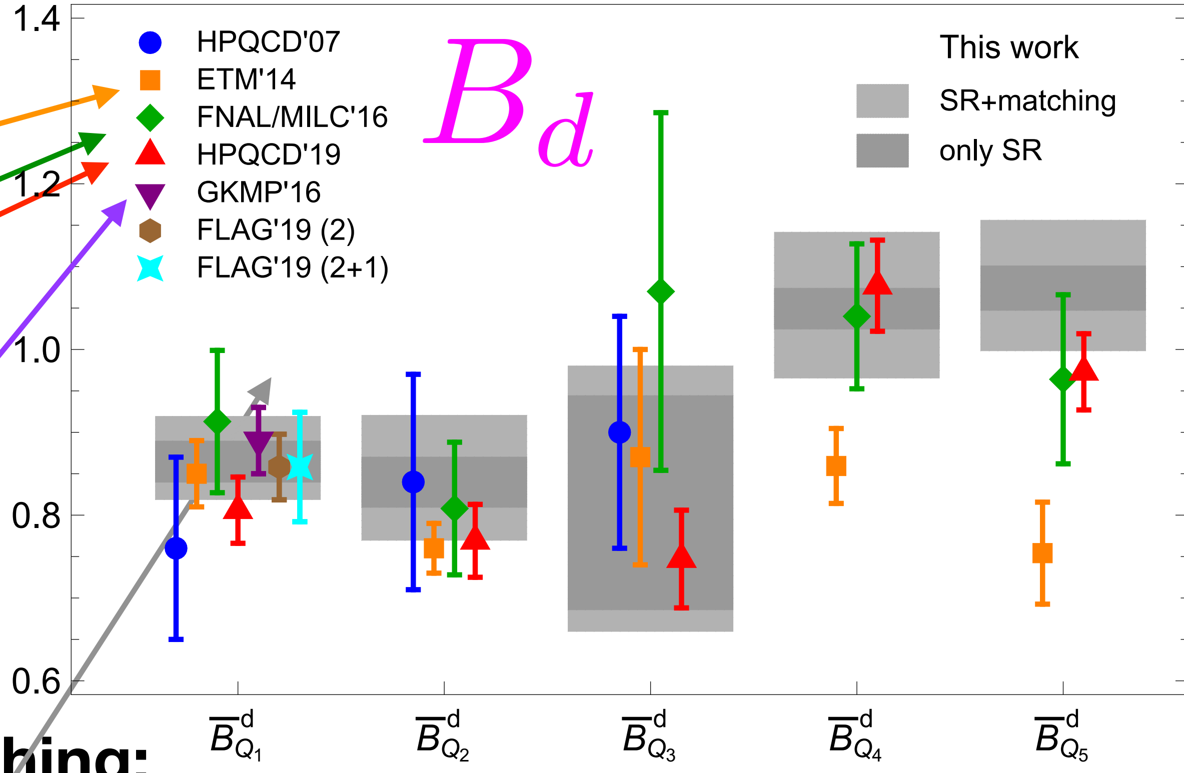
$$\langle B_s | Q_5 | \bar{B}_s \rangle = \left(\frac{2}{3}\left[\frac{M_{B_s}}{m_b + m_s}\right]^2 + 1\right) M_{B_s}^2 f_{B_s}^2 B_5$$

- lattice

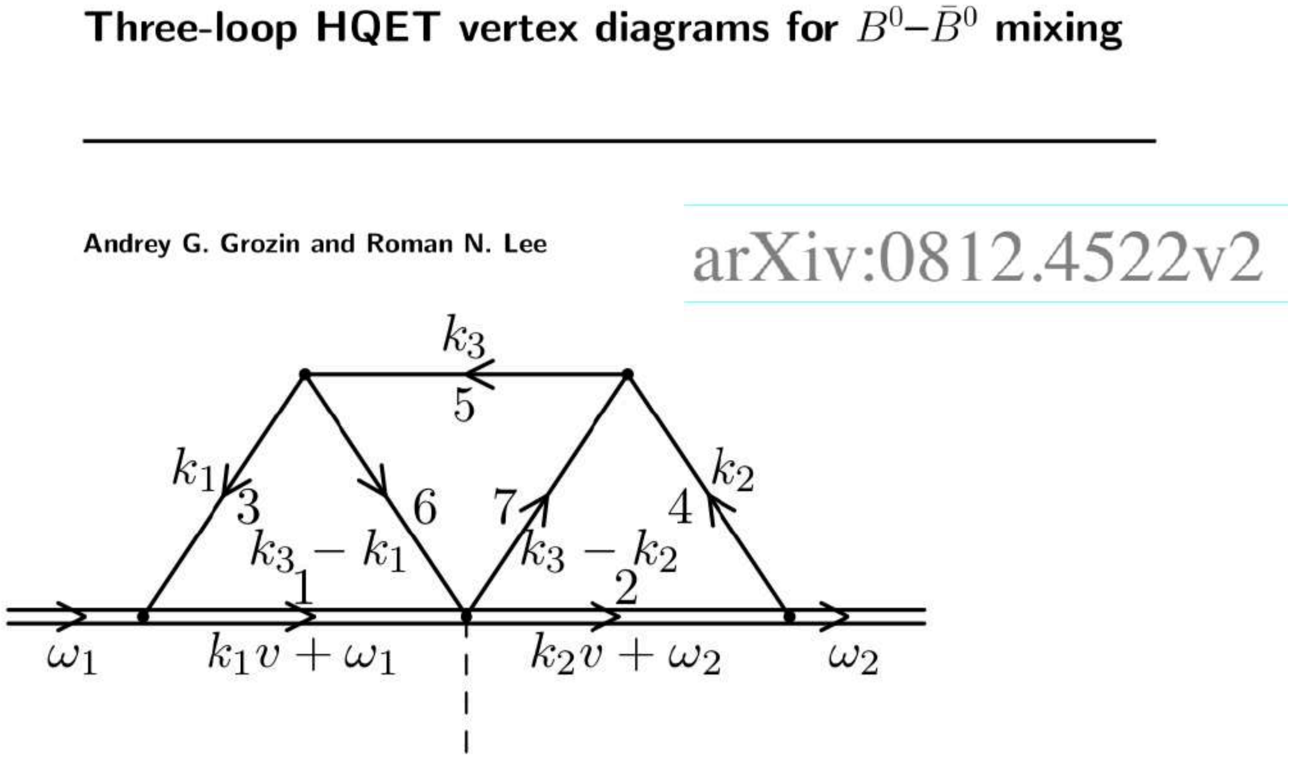
- HQET-SR
- lattice

Mass difference - QCD

B_d-mixing



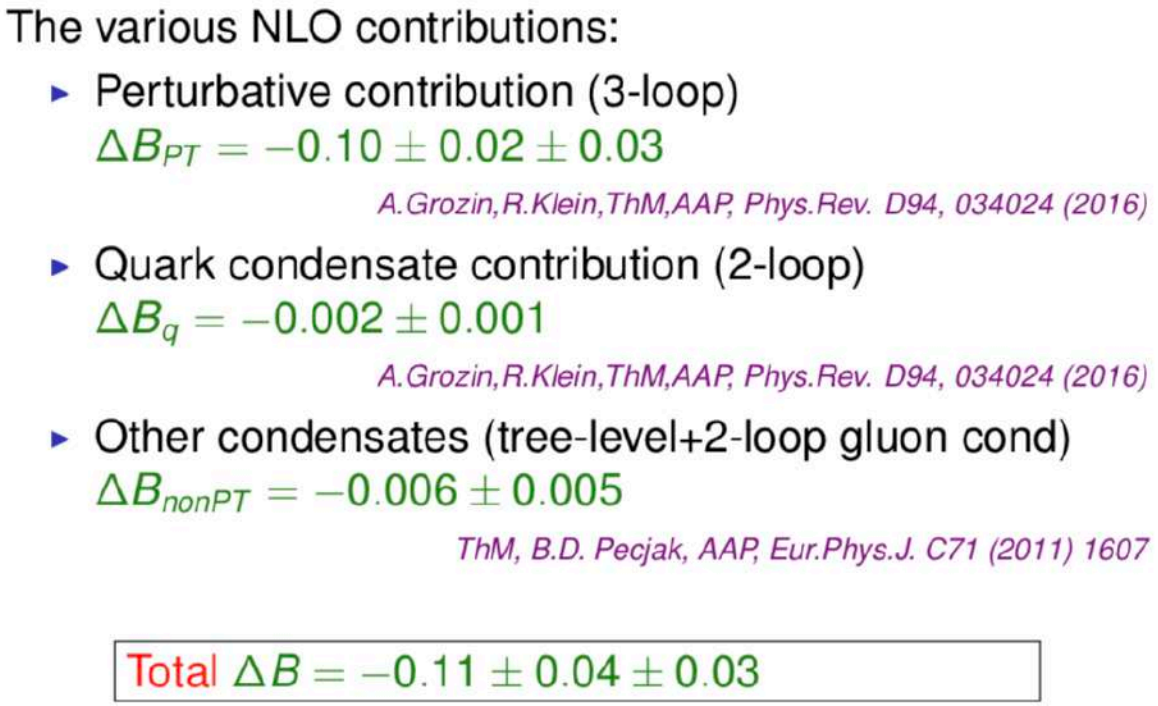
1. **Lattice**
   - **ETM 1308.1851**
   - **FNAL-MILC 1602.03560**
   - **HPQCD 1907.01025**
2. **HQET-sum rules: 3-loop + part of NNLO matching:**
   ***Siegen: Grozin, Klein, Mannel, Pivovarov 1606.06054, 1706.05910, 1806.00253**
   ***Durham: Kirk (Rome), AL, Rauh (Bern) 1711.02100**



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

Andrey G. Grozin and Roman N. Lee

arXiv:0812.4522v2



The various NLO contributions:

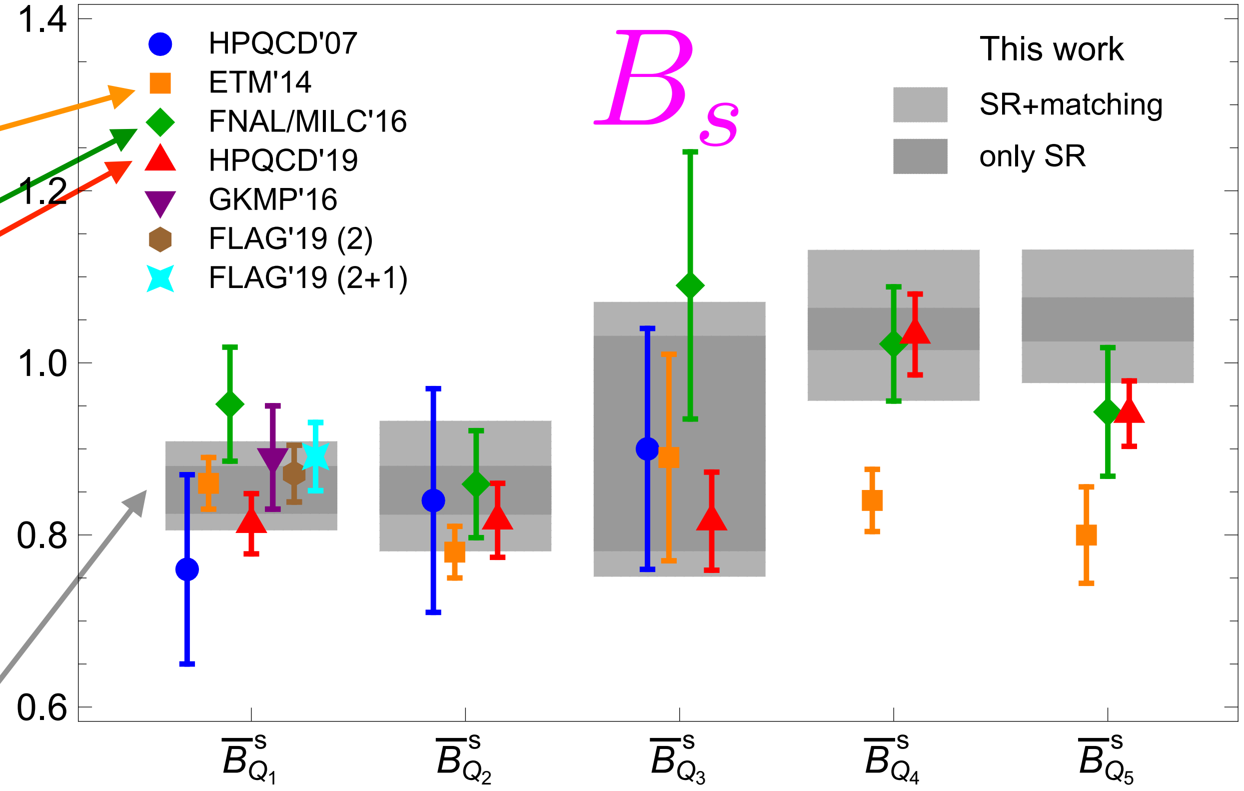
- Perturbative contribution (3-loop)
  $\Delta B_{PT} = -0.10 \pm 0.02 \pm 0.03$
  A.Grozin,R.Klein,ThM,AAP, Phys.Rev. D94, 034024 (2016)
- Quark condensate contribution (2-loop)
  $\Delta B_q = -0.002 \pm 0.001$
  A.Grozin,R.Klein,ThM,AAP, Phys.Rev. D94, 034024 (2016)
- Other condensates (tree-level+2-loop gluon cond)
  $\Delta B_{nonPT} = -0.006 \pm 0.005$
  ThM, B.D. Pecjak, AAP, Eur.Phys.J. C71 (2011) 1607

Total $\Delta B = -0.11 \pm 0.04 \pm 0.03$

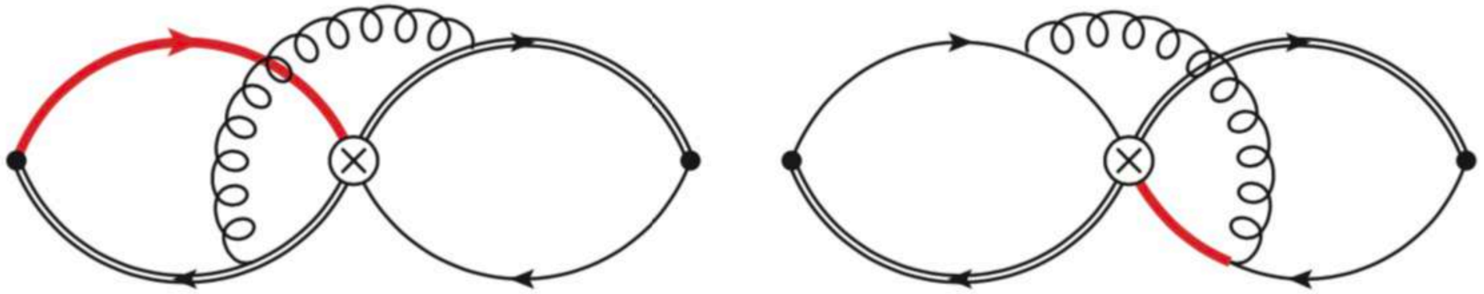
Mass difference - QCD

B_s-mixing

1. **Lattice**
   - * **ETM 1308.1851**
   - * **FNAL-MILC 1602.03560**
   - * **HPQCD 1907.01025**



2. **HQET-sum rules: 3-loop + NLO matching:**
   ***Durham: King, AL, Rauh (Bern) 1904.00940**

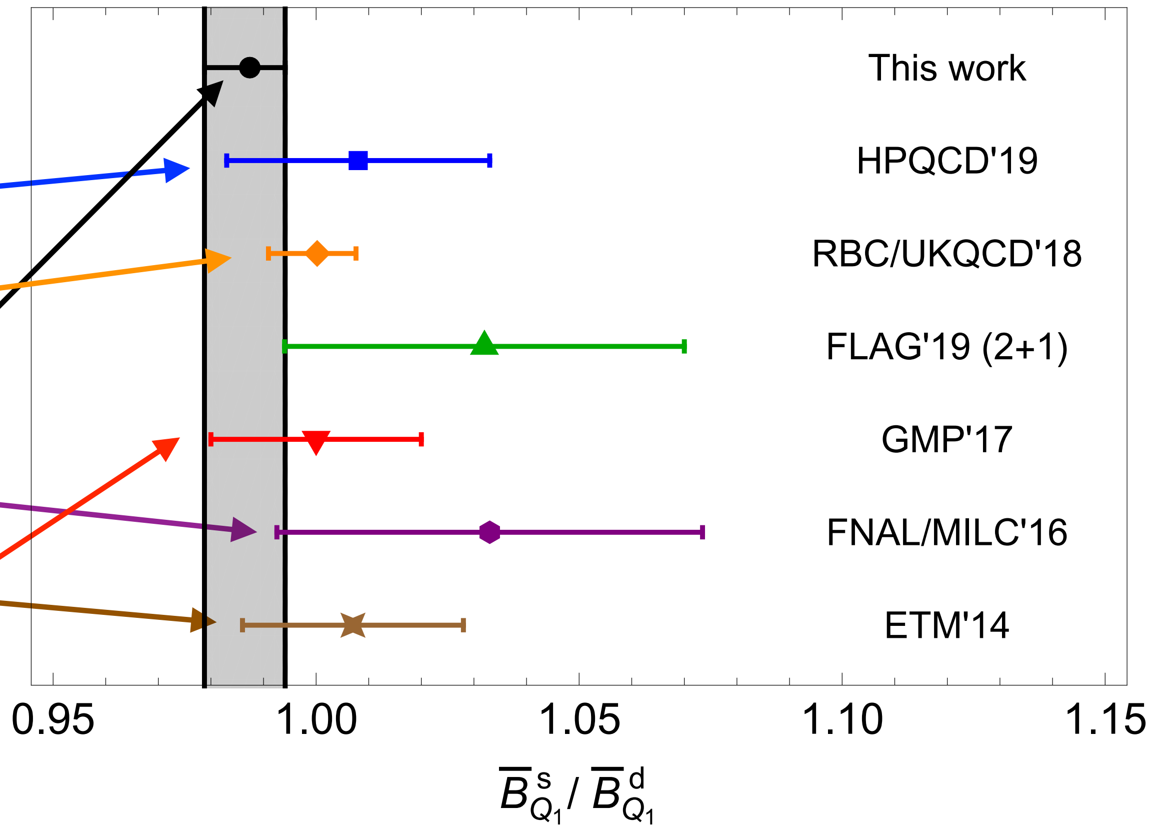


$$r^{(0)}_{\tilde{Q}_1} = 8 - \frac{a_2}{2} - \frac{8\pi^2}{3}$$

$$r^{(2)}_{\tilde{Q}_1} = \frac{1}{1+x^2}\left[\frac{(1-x)^2 a_2}{4} + \frac{2\pi^2(1-4x+x^2)}{3} + 2x\psi(x)\left(2+\frac{1+x}{1-x}\ln(x)\right)\right.$$
$$\left. + \begin{cases} -\frac{2(6+6x-x^2+2x^3)}{3} + 2(2-4x+x^2)\ln(x) - 4(1-x^2)\mathrm{Li}_2(1-1/x), & x \leq 1, \\ -\frac{2(2-x+6x^2+6x^3)}{3x} - 2(1-4x+2x^2)\ln(x) + 4(1-x^2)\mathrm{Li}_2(1-x), & x > 1, \end{cases}\right]$$

Mass difference - QCD

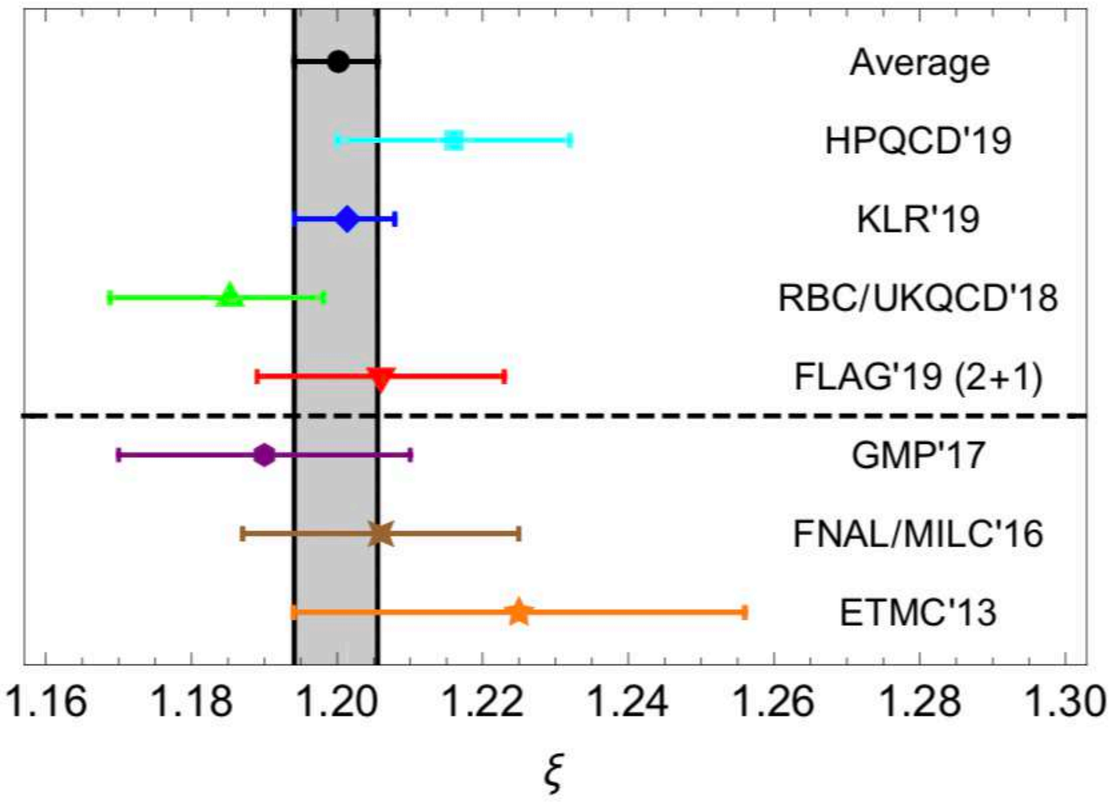
Uncertainties cancel in B_s/B_d



1. **Lattice**
   - * **HPQCD 1907.01025**
   - * **RBC/UKQCD 1812.09791**
   - * **FNAL-MILC 1602.03560**
   - * **ETM 1308.1851**

2. **HQET-sum rules: 3-loop + NNLO matching:**
   ***Durham: King, AL, Rauh (Bern) 1904.00940**
   based on Siegen '16-18, Kirk, AL, Rauh '17

Take decay constants from most recent 2+1+1 lattice evaluation (HPQCD, FNAL-MILC)



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

$$\xi = 1.200^{+0.0054}_{-0.0060}$$

Mass difference - CKM determination

Comparison with experiment

$$\Delta M_d^{\mathrm{exp}} = (0.5064 \pm 0.0019)\,\mathrm{ps}^{-1}\,,$$

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

4 per mille

1 per mille

$$\Delta M_d^{\mathrm{Average\ 2019}} = \left(0.533^{+0.022}_{-0.036}\right)\mathrm{ps}^{-1} = \left(1.05^{+0.04}_{-0.07}\right)\Delta M_d^{\mathrm{exp}}\,,$$

$$\Delta M_s^{\mathrm{Average\ 2019}} = \left(18.4^{+0.7}_{-1.2}\right)\mathrm{ps}^{-1} = \left(1.04^{+0.04}_{-0.07}\right)\Delta M_s^{\mathrm{exp}}\,,$$

Averages of lattice/SR
Di Luzio, Kirk, AL, Rauh
1909.11087 JHEP

- **Good agreement with experiment**
- **Experiment is 15/45 times more precise than theory**
- **Maybe improvement of theory by a factor of 2 doable in future**

Assuming validity of the SM: Precise extraction of CKM parameter

$$\begin{aligned} |V_{ts}V_{tb}| &= \left(40.91^{+0.67}_{-0.64}\right)\cdot 10^{-3} \\ &= \left(40.91\ {}^{+0.65}_{-0.62}\Big|_{f_B^2 B} \pm 0.17\Big|_{m_t} \pm 0.05\Big|_{\alpha_s(M_Z)} \pm 0.02\Big|_{\Delta M_s}\right)\cdot 10^{-3}\,, \end{aligned}$$

$$|V_{ts}|_{\mathrm{CKMfitter}} = \left(41.69^{+0.28}_{-1.08}\right)\cdot 10^{-3}$$

$$|V_{ts}|_{\mathrm{CKMfitter,\ tree}} = \left(41.63^{+0.39}_{-1.45}\right)\cdot 10^{-3}$$

Comparison with CKMfits - competitive precision - slightly smaller than fit

Mass difference - CKM

Very precise prediction of the ratios of mass differences

$$\frac{\Delta M_d}{\Delta M_s} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{1}{\xi^2}\frac{M_{B_d}}{M_{B_s}} .$$

$$\left(\frac{\Delta M_d}{\Delta M_s}\right)_{\text{exp}} = 0.0285 \pm 0.0001 ,$$

$$\left(\frac{\Delta M_d}{\Delta M_s}\right)_{\text{Average}} = 0.0298^{+0.0005}_{-0.0009} = 0.0297^{+0.0003}_{-0.0003}\,(\text{had.})^{+0.0005}_{-0.0008}\,(\text{CKM}) .$$

1.4 sigma above experiment
Experiment is 7 times more precise than theory

Assuming validity of the SM: Extraction of CKM parameter

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2043^{+0.0010}_{-0.0011}$$
$$= 0.2043\;^{+0.0009}_{-0.0010}\big|_{\xi} \pm 0.0003\big|_{\Delta M_d} \pm 0.0001\big|_{\Delta M_s}$$

vs.

$$|V_{td}/V_{ts}| = 0.2088^{+0.0016}_{-0.0030} \qquad [\text{CKMfitter}] ,$$
$$|V_{td}/V_{ts}| = 0.211 \pm 0.003 \qquad [\text{UTfit}] ,$$

vs.

$$|V_{td}/V_{ts}| = 0.2186^{+0.0049}_{-0.0059} \qquad [\text{CKMfitter, tree}]$$

Slightly below CKMfits - slightly higher precision - 2.3 sigma below tree-level fits

Assuming validity of the SM: Independent determination of m_top

$$\overline{m}_t(\overline{m}_t) = (157^{+8}_{-6})\,\text{GeV}$$

vs.

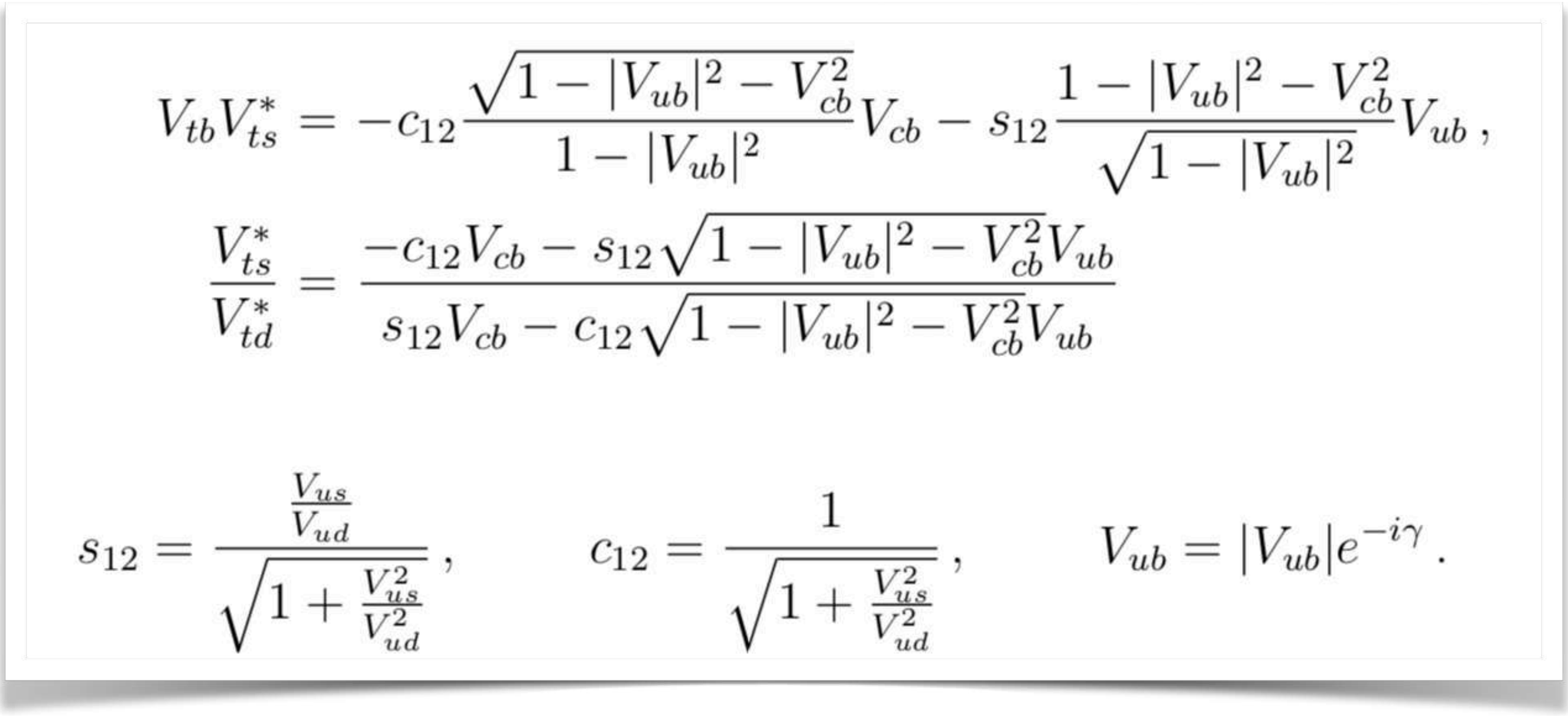
$$\overline{m}_t(\overline{m}_t) = (160^{+5}_{-4})\,\text{GeV},$$ **(PDG)**

Very good agreement - almost comparable precision

Mass difference - CKM

King, Kirk, AL, Rauh
1911.07856

Within the SM we get



$$V_{tb}V_{ts}^* = -c_{12}\frac{\sqrt{1-|V_{ub}|^2-V_{cb}^2}}{1-|V_{ub}|^2}V_{cb} - s_{12}\frac{1-|V_{ub}|^2-V_{cb}^2}{\sqrt{1-|V_{ub}|^2}}V_{ub}\,,$$

$$\frac{V_{ts}^*}{V_{td}^*} = \frac{-c_{12}V_{cb} - s_{12}\sqrt{1-|V_{ub}|^2-V_{cb}^2}V_{ub}}{s_{12}V_{cb} - c_{12}\sqrt{1-|V_{ub}|^2-V_{cb}^2}V_{ub}}$$

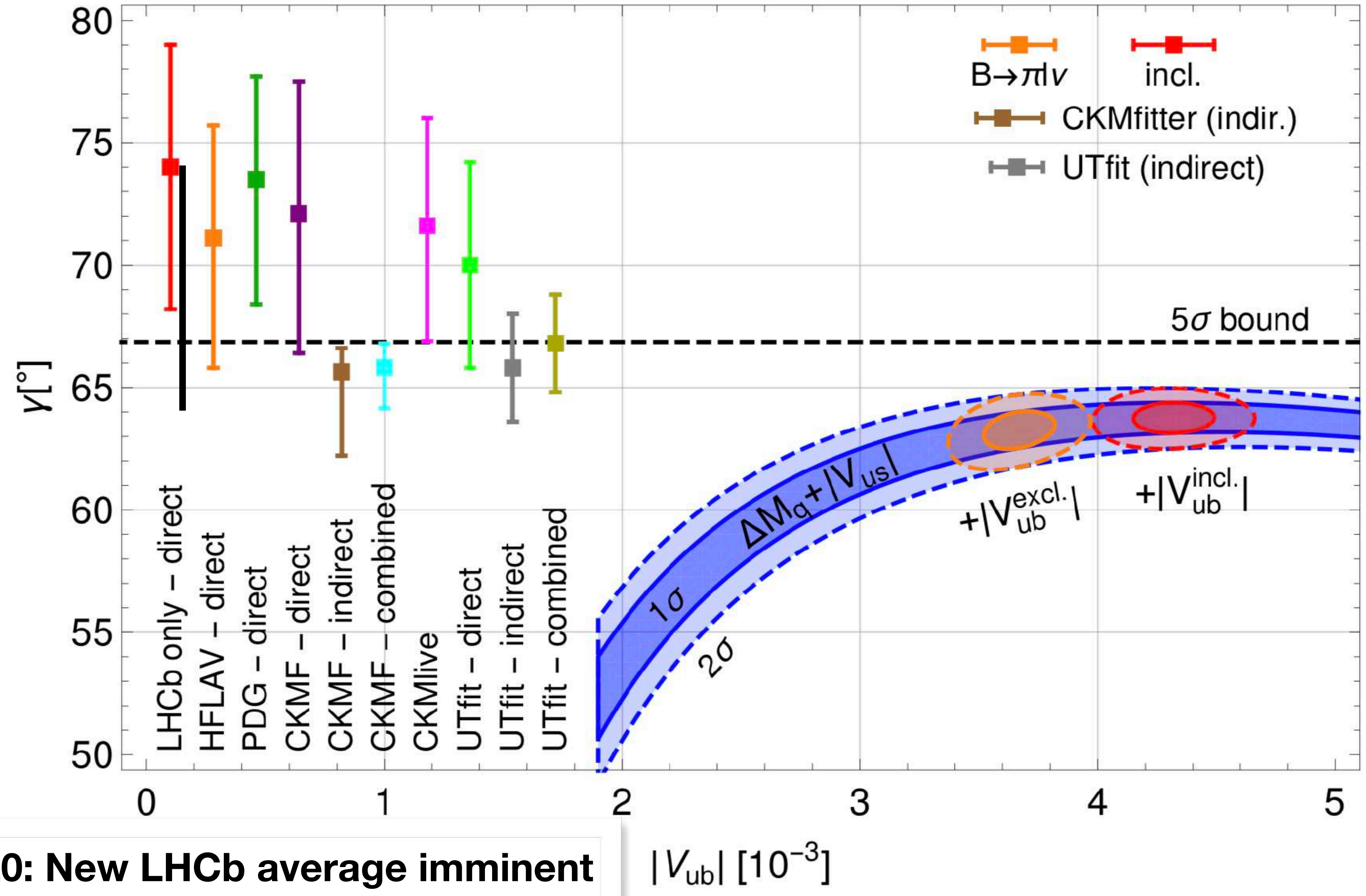
$$s_{12} = \frac{\frac{V_{us}}{V_{ud}}}{\sqrt{1+\frac{V_{us}^2}{V_{ud}^2}}}\,, \qquad c_{12} = \frac{1}{\sqrt{1+\frac{V_{us}^2}{V_{ud}^2}}}\,, \qquad V_{ub} = |V_{ub}|e^{-i\gamma}\,.$$

Constraints on Vcb, Vub, gamma?
Precision????

Mass difference - CKM

Within the SM we get

King, Kirk, AL, Rauh
1911.07856

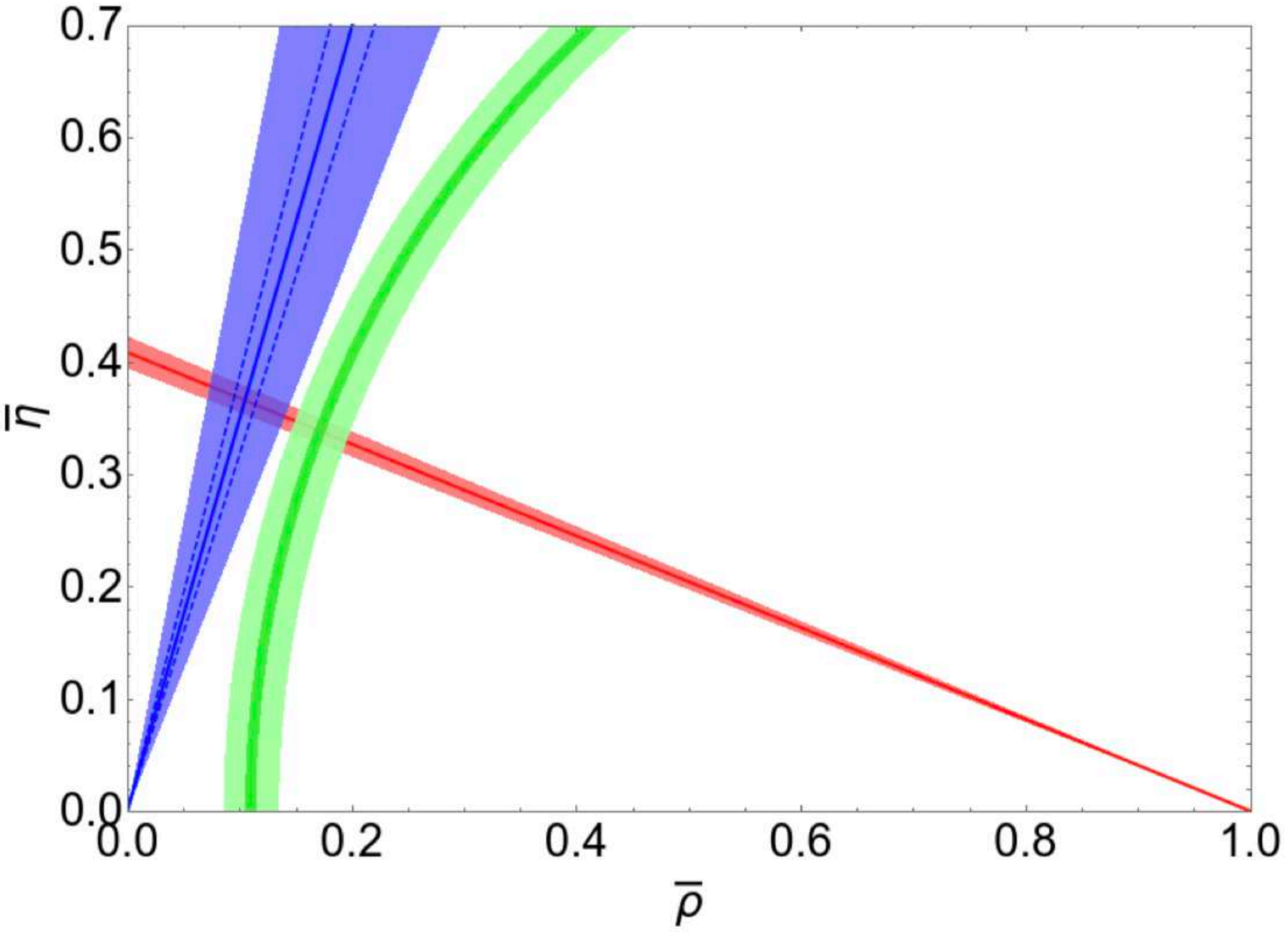


09/20: New LHCb average imminent
New single measurement: 69+-5

Vub unconstrained, upper limit on gamma?

Mass difference - CKM

Upper limit on gamma?



King, Kirk, AL, Rauh
1911.07856

$$\boxed{\gamma \leq 66.9^\circ \qquad [5\sigma]}$$

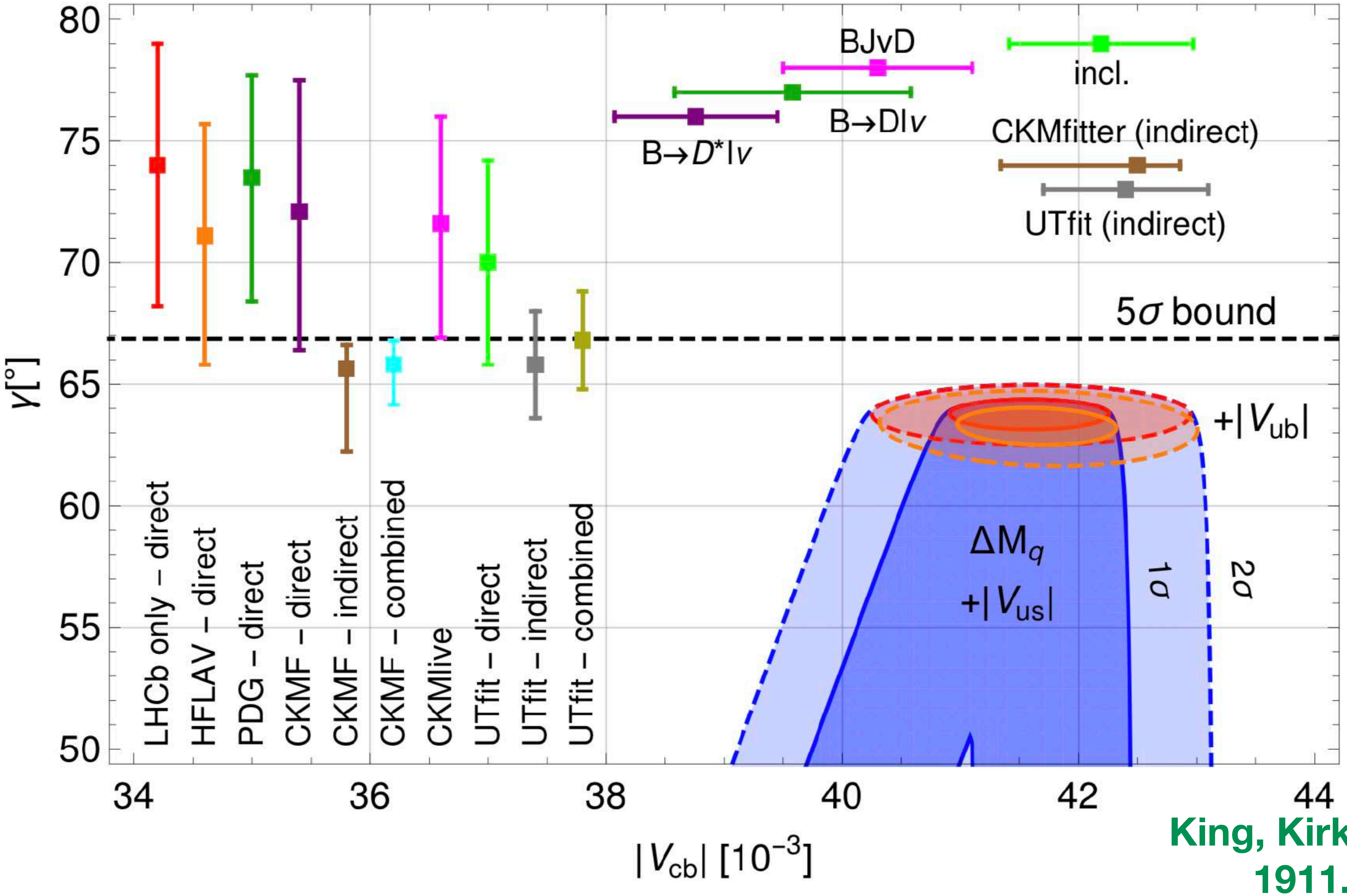
or

- BSM in mixing
- BSM in non-leptonic tree-level decays

Brod, AL, Tetlalmatzi-Xolocotzi 1412.1446, PRD
AL, Tetlalmatzi-Xolocotzi 1912.07621

Mass difference - CKM

Within the SM we get $\boxed{\gamma = (63.4 \pm 0.9)^\circ}$ $\boxed{|V_{cb}| = (41.6 \pm 0.7) \cdot 10^{-3}}$

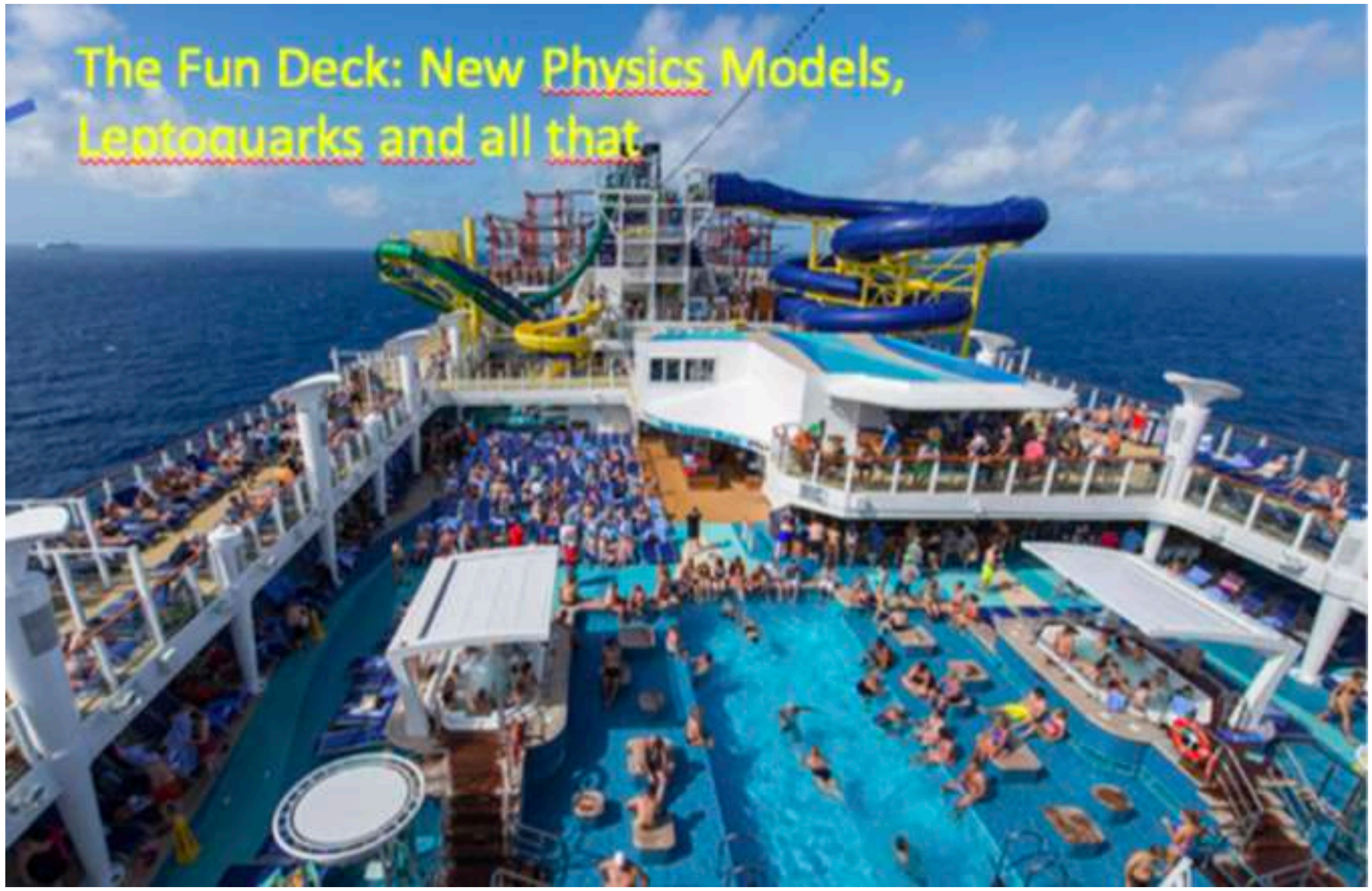


King, Kirk, AL, Rauh
1911.07856

Competitive precision for Vcb - favours inclusive value, upper limit on gamma

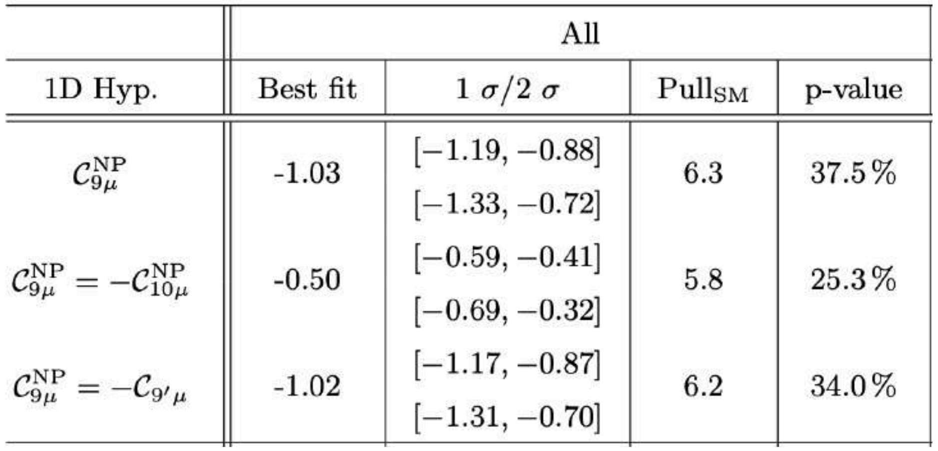
Mass difference - BSM

So far: Test SM and Determine CKM elements



Mass difference - BSM

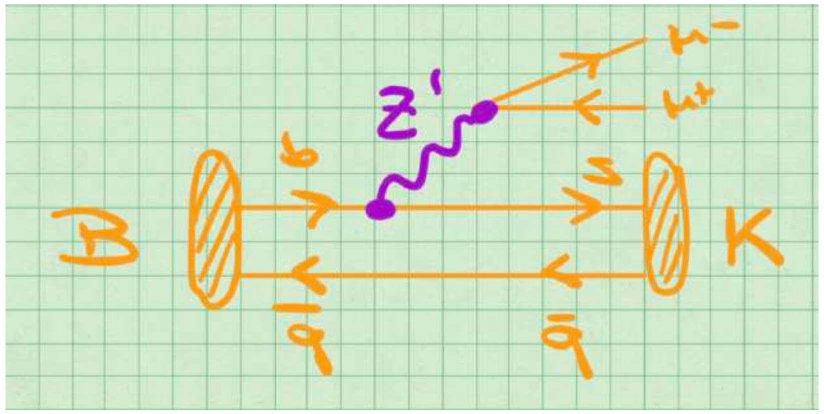
Are the "Flavour Anomalies" real?



	All			
1D Hyp.	Best fit	$1\,\sigma/2\,\sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	-1.03	$[-1.19,-0.88]$ $[-1.33,-0.72]$	6.3	37.5 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}}=-\mathcal{C}_{10\mu}^{\mathrm{NP}}$	-0.50	$[-0.59,-0.41]$ $[-0.69,-0.32]$	5.8	25.3 %
$\mathcal{C}_{9\mu}^{\mathrm{NP}}=-\mathcal{C}_{9'\mu}$	-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,…)

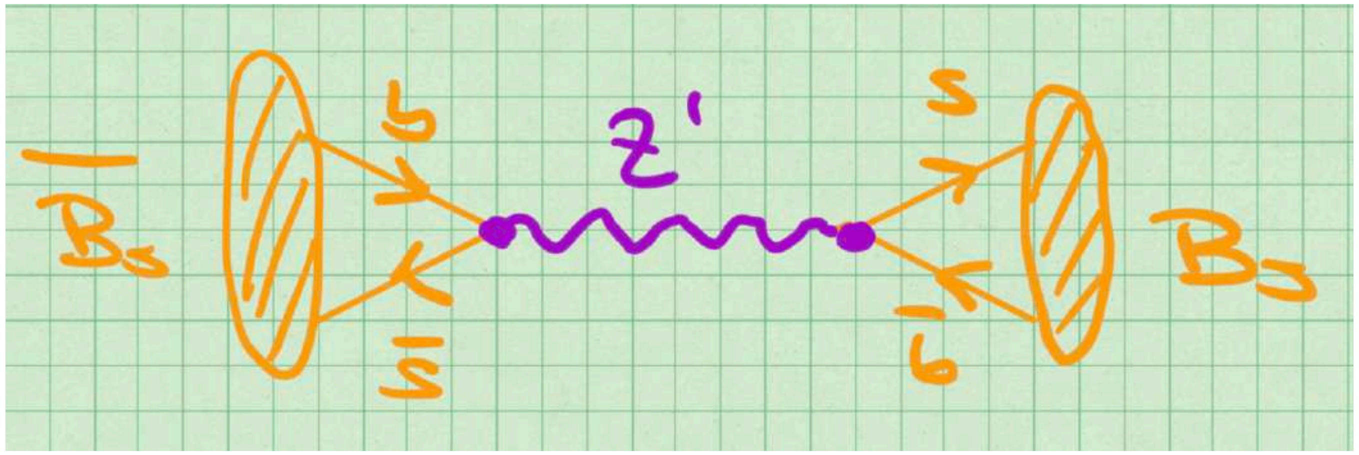
What models could explain Flavour anomalies? e.g. Z' models



See e.g. Allanach, Davighi, Gripaios, Lohitsiri,, Madigan, Meville, You,..

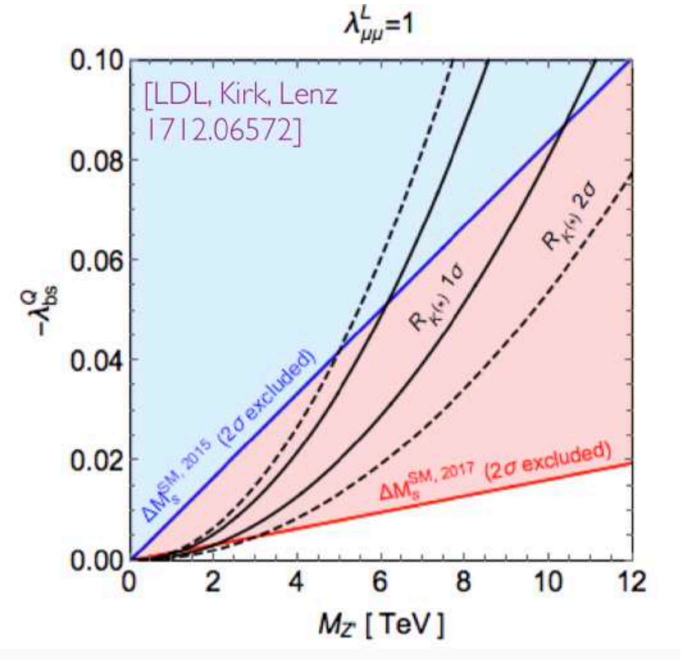
Mass difference - BSM

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:



NAL-MILC kills almost the Z’ explanatio

One constraint to kill them all!

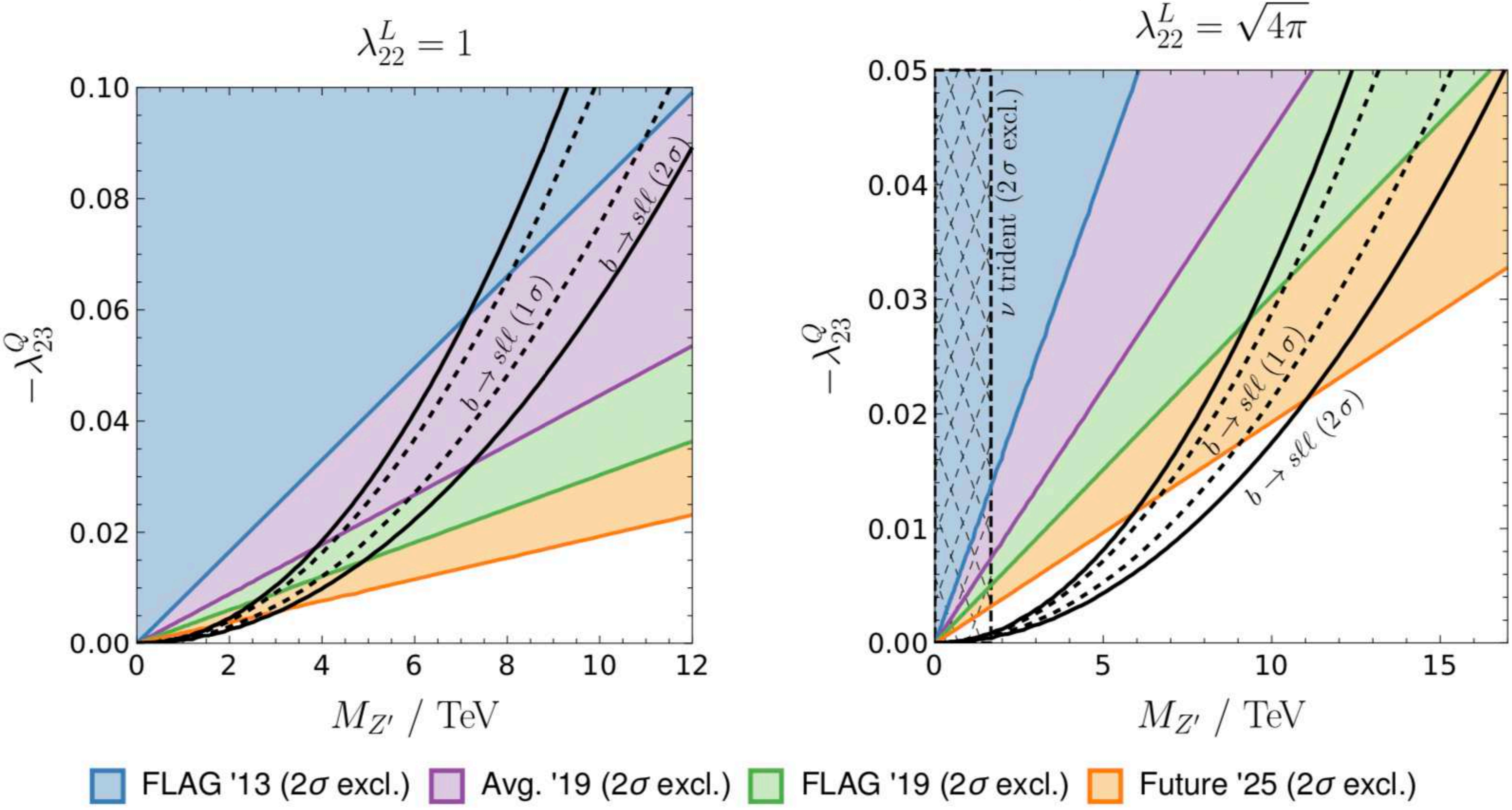
Independent determination of
non-perturbative Bs mixing inputs desirable

Mass difference - BSM

Di Luzio, Kirk, AL, Rauh
1909.11087 JHEP

Update: use new average of non-perturbative results

Severe consequences for model building



2% non-pert./1% Vcb

Outlook

- **Improvements possible and necessary**
- **HQET sum rules**
  - **NNLO matching HQET - QCD**
  - **Compare with QCD sum rule momentum analysis (A. Pivoraov)**
- **Lattice**
  - **Independent determination of Bs and Bd: RBC-UKQCD**
  - **Confirmation from Fermilab/MILC**
- **NNLO-QCD corrections to M_12**
  - **Brod, Gorbahn, Stamou, Yu in progress**

Mister X (very senior):
Yet, it is better your students do some BSM projects instead. One-loop is sufficient then!

Outline

- **Motivation for Flavour Physics**
    - Understanding of QCD
    - Determination of SM parameter
    - CP violation
    - Search for new physics

- **Mass differences of neutral mesons**
    - Understanding of QCD
    - Determination of CKM parameter
    - Search for new physics

- **Lifetimes and Decay rate difference**
    - Understanding of QCD
    - Search for new physics
    - CP violation

LIFETIMES

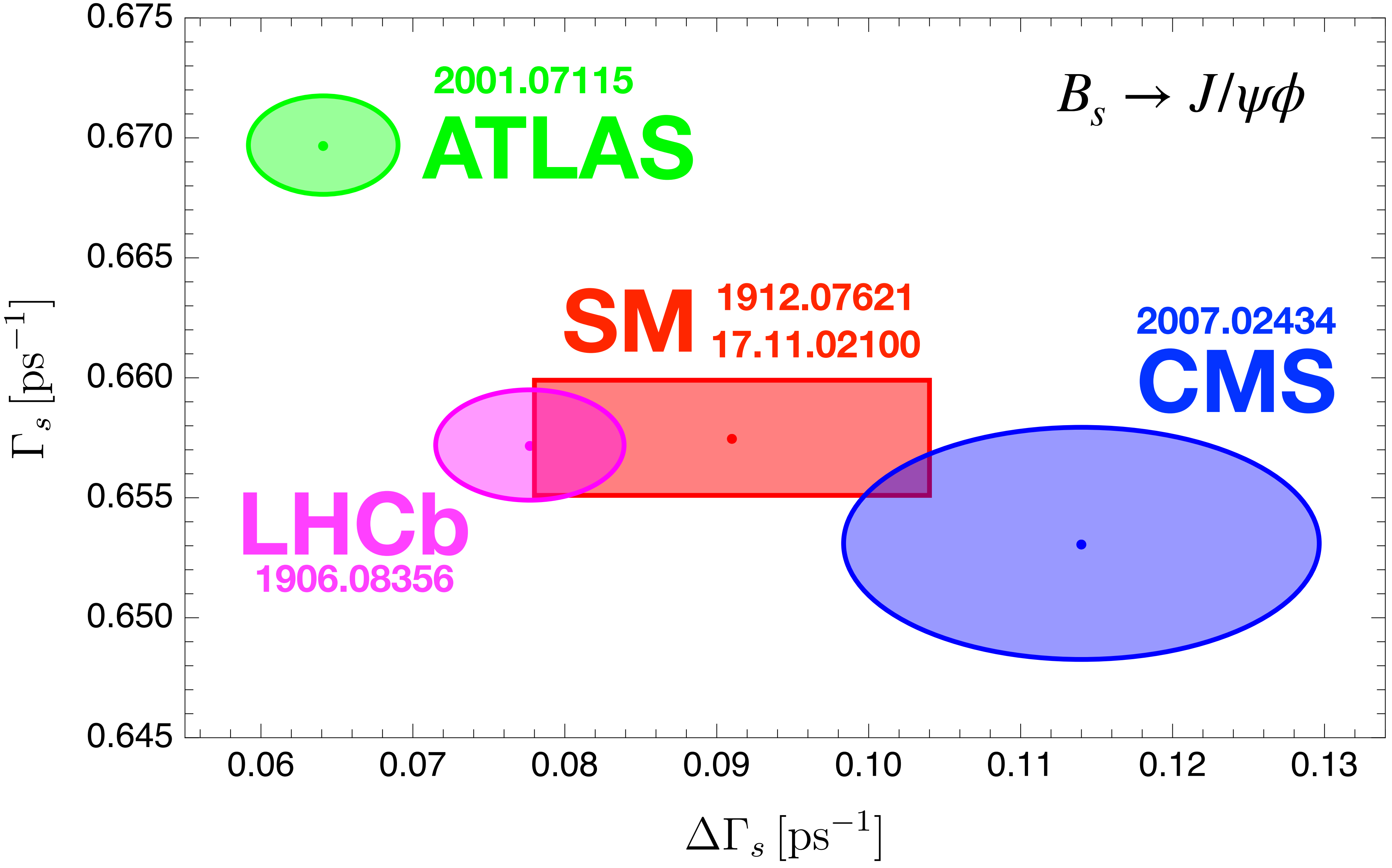
BEAUTY LIFETIMES: Precision test of HQE convergence
Test of Higher orders in the HQE
Search for invisible decay channels in Bs or Bd

DECAY RATE DIFFERENCES/SEMI-LEPTONIC CP ASYMMETRIES:
Test of quark hadron duality
Precision test of HQE convergence
BSM searches/CP violation

CHARM PHYSICS: Lifetimes = Test of convergence of HQE
Charm mixing
Implications for Delta A_CP - QCD vs. BSM

The unspoken anomaly:

B_s lifetime and decay rate difference of neutral B_s mesons



Heavy Quark Expansion

Shifman, Voloshin, Khoze; Bigi, Uraltsev, Vainshtein; (1983 -'92)

The total decay rate can be expanded as

$$\boxed{\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + ... + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + ... \right]}$$

Heavy Quark Expansion

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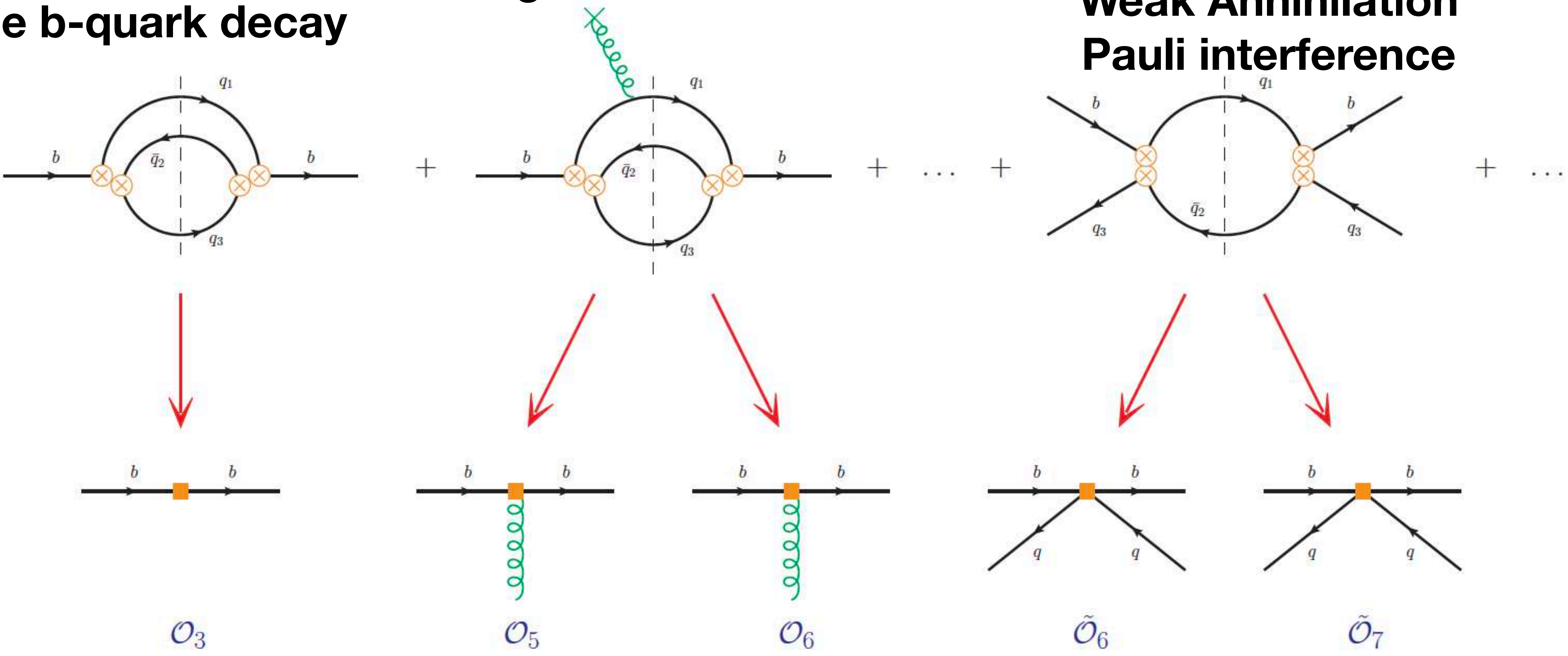
$$\boxed{\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]}$$

Free b-quark decay

Soft-gluon corrections

Weak exchange
Weak Annihilation
Pauli interference



chromomagnetic

Darwin

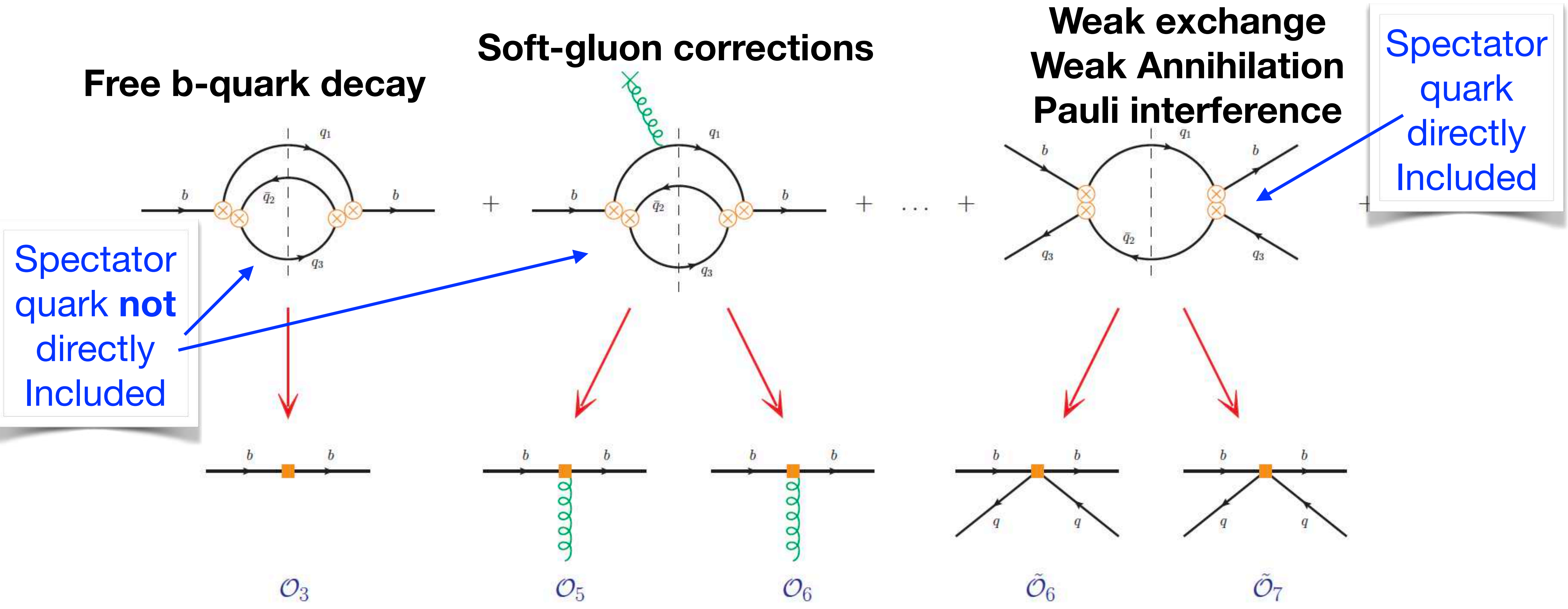
1,
kinetic, chromomagnetic

Heavy Quark Expansion

Shifman, Voloshin, Khoze; Bigi, Uraltsev, Vainshtein; (1983 -'92)

The total decay rate can be expanded as

$$\boxed{\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]}$$



Free b-quark decay

Soft-gluon corrections

Weak exchange
Weak Annihilation
Pauli interference

Spectator quark directly Included

Spectator quark **not** directly Included

Spectator quark indirectly included in different values of matrix elements for different hadrons

HQE - Status Quo

$$\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]$$

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

Semi-leptonic:

- $\Gamma_3^{(2)}$ **Czarnecki, Melnikov, v. Ritbergen, Pak, Dowling, Bonciani, Ferroglia, Biswas, Brucherseifer, Caola; 1997 - 2013**
- $\Gamma_5^{(1)}$ **Alberti, Gambino, Nandi, Mannel, Pivovarov, Rosenthal; 2013 - 15**
- $\Gamma_6^{(1)}$ **Mannel, Pivovarov 2019**
- $\Gamma_7^{(0)}$ **Dassinger, Mannel, Turczyk 2006**
- $\Gamma_8^{(0)}$ **Mannel, Turczyk, Uraltsev 2010**

Non-leptonic:

- $\Gamma_3^{(1)}$ **Ho-Kim, Pham, Altarelli, Petrarca, Voloshin, Bagan, Ball, Braun, Gosdzinsky, Fiol, AL, Nierste, Ostermaier, Krinner, Rauh; 1984 - 2013**
- $\Gamma_3^{(2)}$ **Czarnecki, Slusarcyk, Tkachov 2005** (m_c=0, not all color structures)
- $\Gamma_5^{(0)}$ **Bigi, Uraltsev, Vainshtein, Blok, Shifman 1992**
- $\Gamma_6^{(0)}$ **AL, Piscopo, Rusov, Mannel, Moreno, Pivovarov 2020**
- $\tilde{\Gamma}_6^{(1)}$ **Beneke, Buchalla, Greub, AL, Nieste, Franco, Lubicz, Mescia, Tarantino, Rauh 2002-13**
- $\tilde{\Gamma}_7^{(0)}$ *AL, Nierste*, **Gabbiani, Onishchenko, Petrov 2003-04.** (123 missed citations)

HQE - Status Quo

$$\Gamma(B) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_b^3} + \ldots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_b^4} + \ldots \right]$$

Non-perturbative Matrix elements

B_d, B^+

- $\langle \mathcal{O}_5 \rangle$ Exp. Fit from inclusive sl decays; SR: Ball, Braun, Neubert 1993-95; Lattice: Kronfeld, Simone, JLQCD, Gambino, Melis, Simula, Fermilab-MILC 2000-17
- $\langle \mathcal{O}_6 \rangle$ Exp fit from inclusive sl decays, EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$
- $\langle \tilde{\mathcal{O}}_6 \rangle$ HQET SR: Kirk, AL, Rauh; Lattice: :-(
- $\langle \tilde{\mathcal{O}}_7 \rangle$:-(only VIA

B_s

- $\langle \mathcal{O}_5 \rangle$:-(spectroscopy for μ_G^2
- $\langle \mathcal{O}_6 \rangle$:-(EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$
- $\langle \tilde{\mathcal{O}}_6 \rangle$ HQET SR: King, AL, Rauh in progress; Lattice: :-(
- $\langle \tilde{\mathcal{O}}_7 \rangle$:-(only VIA

$\Lambda_b, \ldots$ **Even worse**

Lifetime ratios

🟦 **Known**

🟨 **New**

🟩 **Planned Siegen**

🟪 **Planned Karlsruhe**

Talk of Maria Laura Wednesday before General Assembly

$$
\begin{aligned}
\frac{\tau(B_s)}{\tau(B_d)} &= 1 + [\Gamma(B_d) - \Gamma(B_s)]\,\tau(B_s) \\
&= 1 + \Bigg[\left(\Gamma_5^{(0)} + \frac{\alpha_s}{\pi} \Gamma_5^{(1)} + \ldots \right) \frac{\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B_s}}{m_b^2} \\
&\quad + \left(\Gamma_6^{(0)} + \frac{\alpha_s}{\pi} \Gamma_6^{(1)} + \ldots \right) \frac{\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B_s}}{m_b^3} + \ldots \\
&\quad + \left\{ \left(\tilde{\Gamma}_6^{(0)} + \frac{\alpha_s}{\pi} \tilde{\Gamma}_6^{(1)} + \frac{\alpha_s^2}{\pi^2} \tilde{\Gamma}_6^{(2)} + \ldots \right)_{B_d} - (\ldots)_{B_s} \right\} \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_d}}{m_b^3} \\
&\quad + \left(\tilde{\Gamma}_6^{(0)} + \frac{\alpha_s}{\pi} \tilde{\Gamma}_6^{(1)} + \frac{\alpha_s^2}{\pi^2} \tilde{\Gamma}_6^{(2)} + \ldots \right)_{B_s} \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_d} - \langle \tilde{\mathcal{O}}_6 \rangle_{B_s}}{m_b^3} \\
&\quad + \left\{ \left(\tilde{\Gamma}_7^{(0)} + \frac{\alpha_s}{\pi} \tilde{\Gamma}_7^{(1)} + \ldots \right)_{B_d} - (\ldots)_{B_s} \right\} \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_d}}{m_b^4} \\
&\quad + \left(\tilde{\Gamma}_7^{(0)} + \frac{\alpha_s}{\pi} \tilde{\Gamma}_7^{(1)} + \ldots \right)_{B_s} \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_d} - \langle \tilde{\mathcal{O}}_7 \rangle_{B_s}}{m_b^4} \Bigg] \tau(B_s)
\end{aligned}
$$

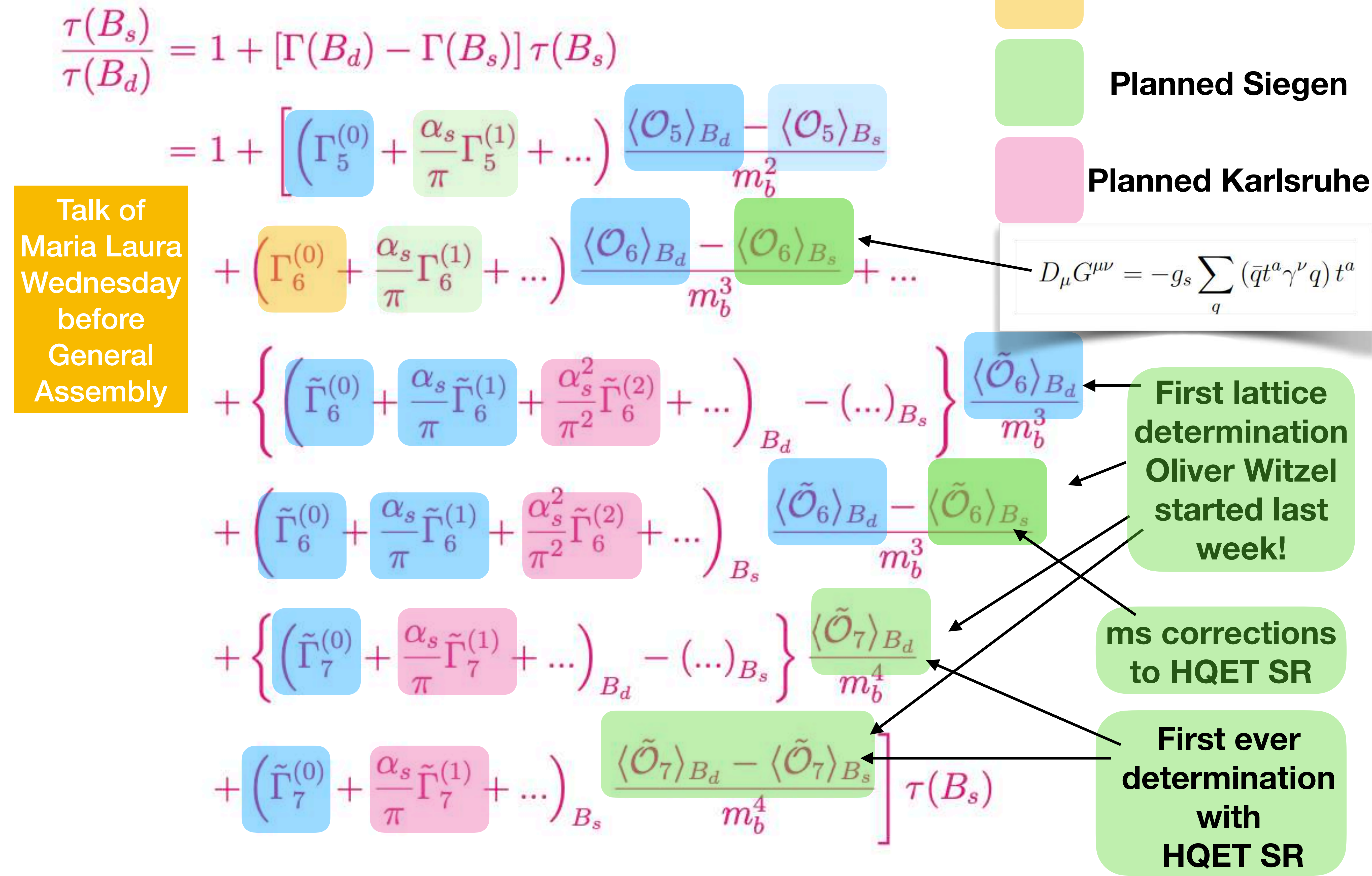
Lifetime ratios

🟦 **Known**

🟨 **New**

🟩 **Planned Siegen**

🟥 **Planned Karlsruhe**



$$\frac{\tau(B_s)}{\tau(B_d)} = 1 + [\Gamma(B_d) - \Gamma(B_s)]\,\tau(B_s)$$

$$= 1 + \Bigg[\left(\Gamma_5^{(0)} + \frac{\alpha_s}{\pi}\Gamma_5^{(1)} + \ldots\right)\frac{\langle\mathcal{O}_5\rangle_{B_d} - \langle\mathcal{O}_5\rangle_{B_s}}{m_b^2}$$

$$+ \left(\Gamma_6^{(0)} + \frac{\alpha_s}{\pi}\Gamma_6^{(1)} + \ldots\right)\frac{\langle\mathcal{O}_6\rangle_{B_d} - \langle\mathcal{O}_6\rangle_{B_s}}{m_b^3} + \ldots$$

$$+ \left\{\left(\tilde\Gamma_6^{(0)} + \frac{\alpha_s}{\pi}\tilde\Gamma_6^{(1)} + \frac{\alpha_s^2}{\pi^2}\tilde\Gamma_6^{(2)} + \ldots\right)_{B_d} - (\ldots)_{B_s}\right\}\frac{\langle\tilde{\mathcal{O}}_6\rangle_{B_d}}{m_b^3}$$

$$+ \left(\tilde\Gamma_6^{(0)} + \frac{\alpha_s}{\pi}\tilde\Gamma_6^{(1)} + \frac{\alpha_s^2}{\pi^2}\tilde\Gamma_6^{(2)} + \ldots\right)_{B_s}\frac{\langle\tilde{\mathcal{O}}_6\rangle_{B_d} - \langle\tilde{\mathcal{O}}_6\rangle_{B_s}}{m_b^3}$$

$$+ \left\{\left(\tilde\Gamma_7^{(0)} + \frac{\alpha_s}{\pi}\tilde\Gamma_7^{(1)} + \ldots\right)_{B_d} - (\ldots)_{B_s}\right\}\frac{\langle\tilde{\mathcal{O}}_7\rangle_{B_d}}{m_b^4}$$

$$+ \left(\tilde\Gamma_7^{(0)} + \frac{\alpha_s}{\pi}\tilde\Gamma_7^{(1)} + \ldots\right)_{B_s}\frac{\langle\tilde{\mathcal{O}}_7\rangle_{B_d} - \langle\tilde{\mathcal{O}}_7\rangle_{B_s}}{m_b^4}\Bigg]\,\tau(B_s)$$

Talk of Maria Laura Wednesday before General Assembly

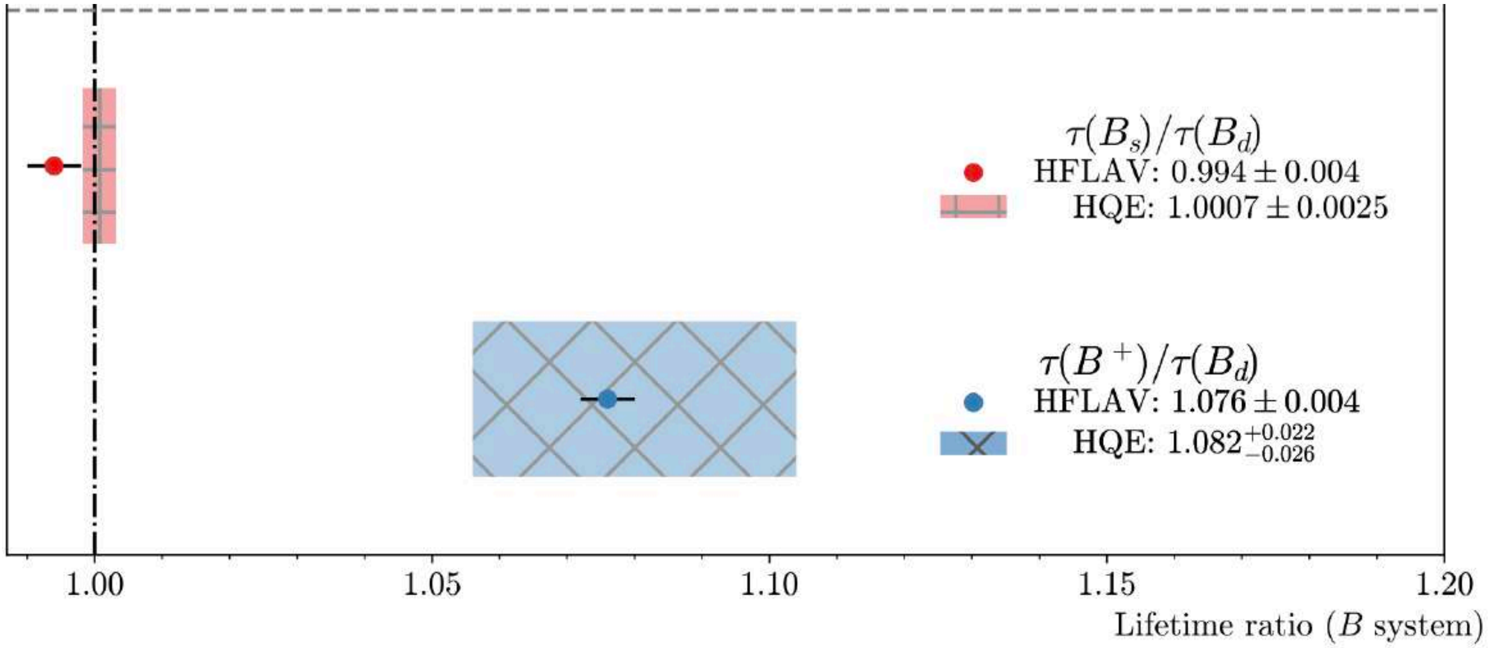
$$D_\mu G^{\mu\nu} = -g_s \sum_q (\bar q t^a \gamma^\nu q)\, t^a$$

First lattice determination Oliver Witzel started last week!

ms corrections to HQET SR

First ever determination with HQET SR

BEAUTY LIFETIMES



Dim 6 matrix elements determined with 3loop HQET sum rules

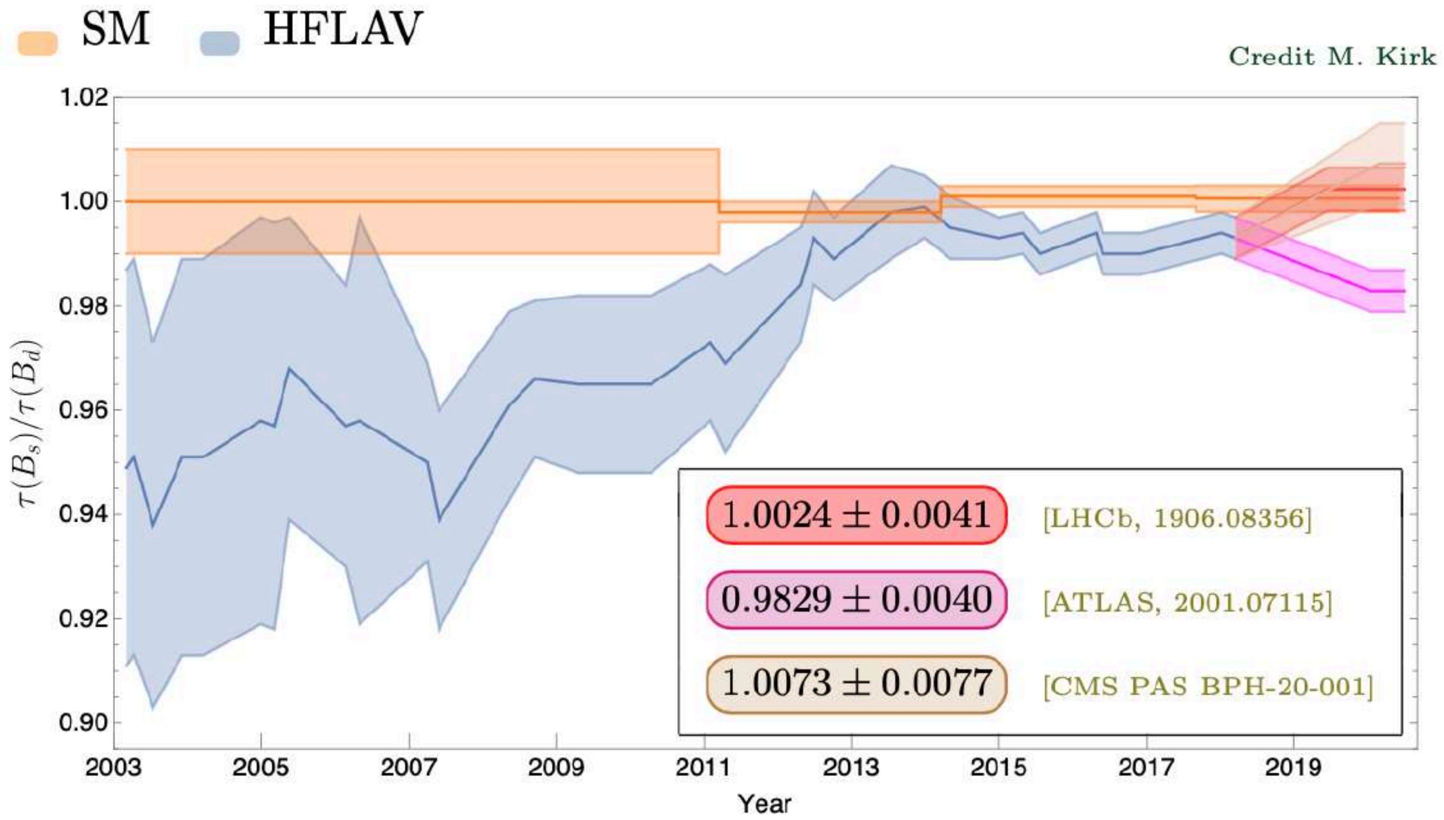
ms corrections missing

Kirk, AL, Rauh 1711.02100

Lattice confirmation needed

Amazing cancellations in the Bs/Bd system

$$\frac{\tau(B_s)}{\tau(B_d)} = \frac{\Gamma_b + \delta\Gamma_{B_d}}{\Gamma_b + \delta\Gamma_{B_s}} = 1 + (\delta\Gamma_{B_d} - \delta\Gamma_{B_s})\,\tau(B_s)\,.$$

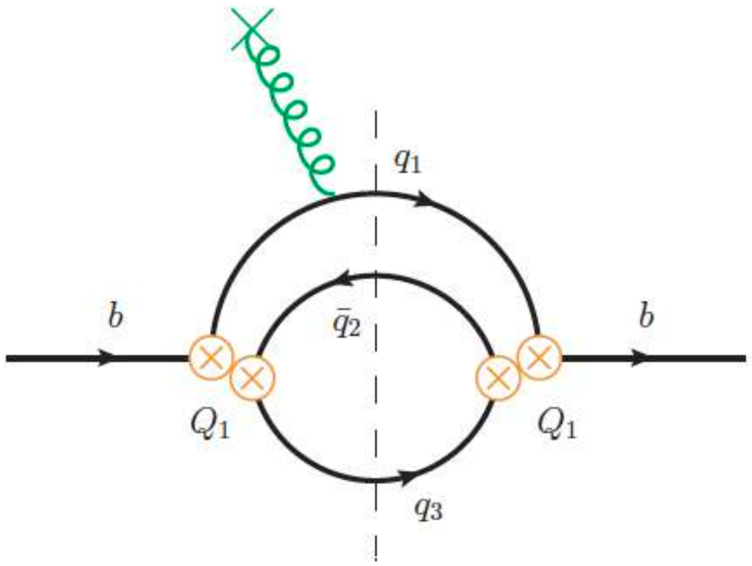


BEAUTY LIFETIMES

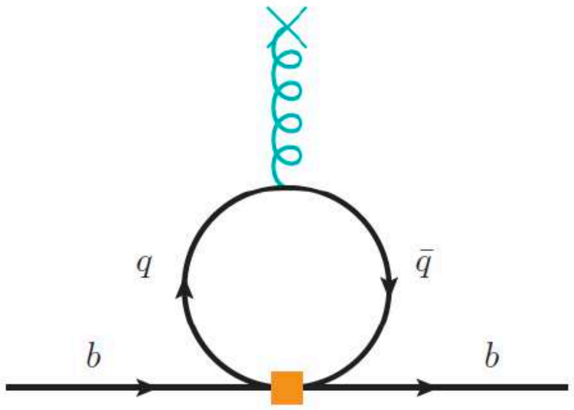
News in 2020: Darwin term is large! **AL, Piscopo, Rusov; Mannel, Moreno, Pivovarov**

$$\begin{aligned}\Gamma_{\rm NL}(B) &= \Gamma_3\left[1 - 0.50\frac{\mu_\pi^2}{m_b^2} - 0.44\frac{\mu_G^2}{m_b^2} - 22.50\frac{\rho_D^3}{m_b^3} + \underbrace{\ldots}_{\rm 4q-contr.}\right] \\ &= \Gamma_3\left[1 - \underbrace{0.0112}_{\mu_\pi^2} - \underbrace{0.0071}_{\mu_G^2} - \underbrace{0.0415}_{\rho_D^3} - \underbrace{0.0029}_{\tau_i^{(q)}} \underbrace{\begin{matrix} -0.1023\,(B^+) \\ +0.0148\,(B_d)\end{matrix}}_{\mathcal{B}_i^{(q)}}\right]\end{aligned}$$

- **Similar hierarchy as in semi-leptonic decays**
- **1/mb^2 is actually suppressed**
- **Interesting interplay between Darwin and 4-quark operator to cancel IR div.**



Talk of
Maria Laura
Wednesday
Before
General
Assembly



Effect in lifetime ratio not yet clear - in progress - what about Darwin in charm lifetimes?

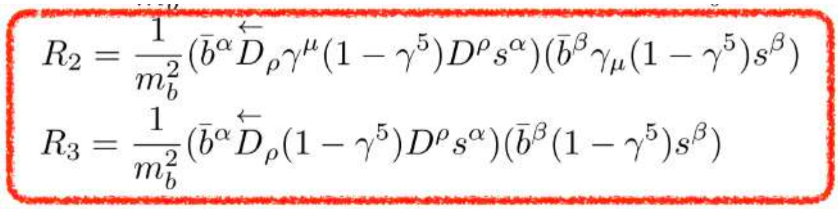
Decay rate difference $\Delta\Gamma_s$

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

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

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

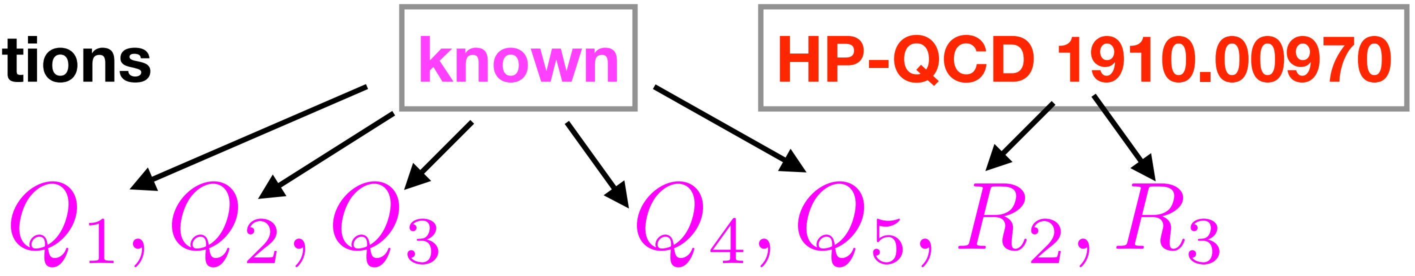
$$\Gamma_i \quad = \quad \left[\Gamma_i^{(0)} + \frac{\alpha_S}{4\pi}\Gamma_i^{(1)} + \frac{\alpha_S^2}{(4\pi)^2}\Gamma_i^{(2)} + \ldots ,\right] \langle O^{d=i+3} \rangle$$



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

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

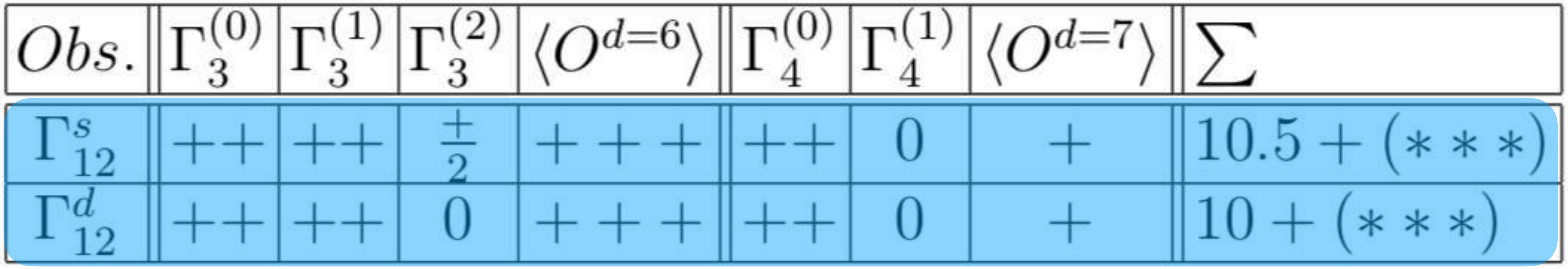
Status of theory predictions



known

HP-QCD 1910.00970

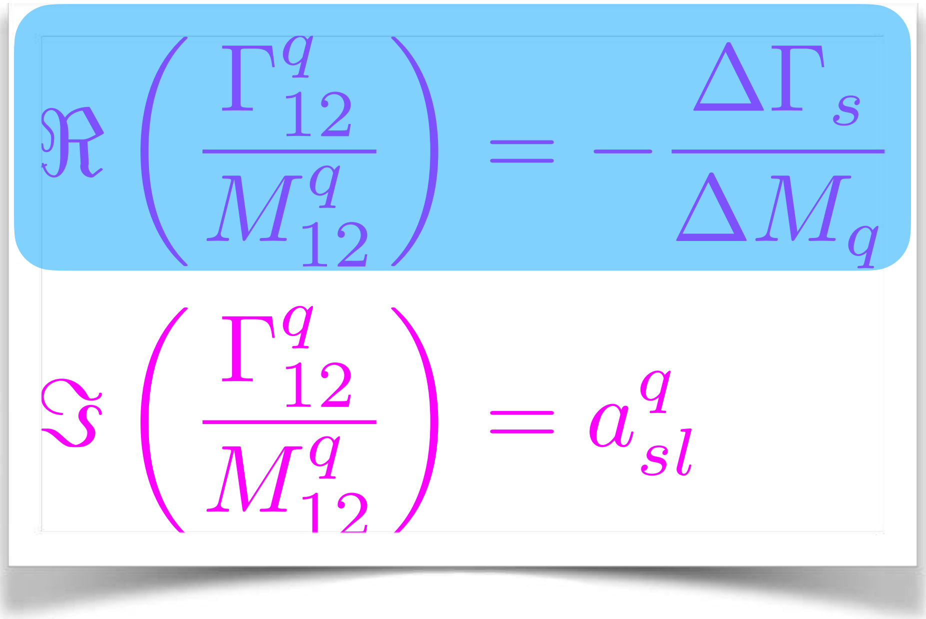
$Q_1, Q_2, Q_3 \quad Q_4, Q_5, R_2, R_3$



$Obs.$	$\Gamma_3^{(0)}$	$\Gamma_3^{(1)}$	$\Gamma_3^{(2)}$	$\langle O^{d=6} \rangle$	$\Gamma_4^{(0)}$	$\Gamma_4^{(1)}$	$\langle O^{d=7} \rangle$	$\sum$
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

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

$$\Delta\Gamma_s^{\mathrm{HFLAV}\,2019} = (0.088 \pm 0.006)\,\mathrm{ps}^{-1}$$

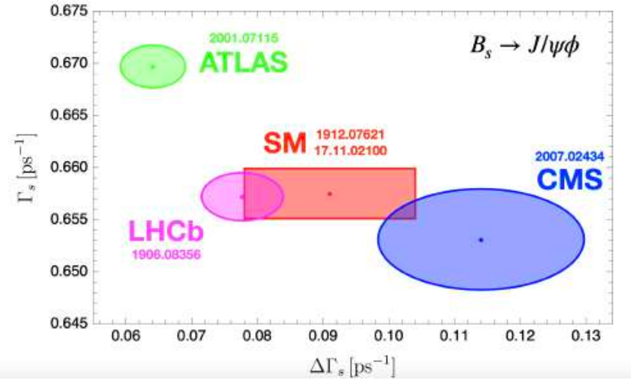
- **Good agreement**
- **Experiment about 2 times more precise**

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

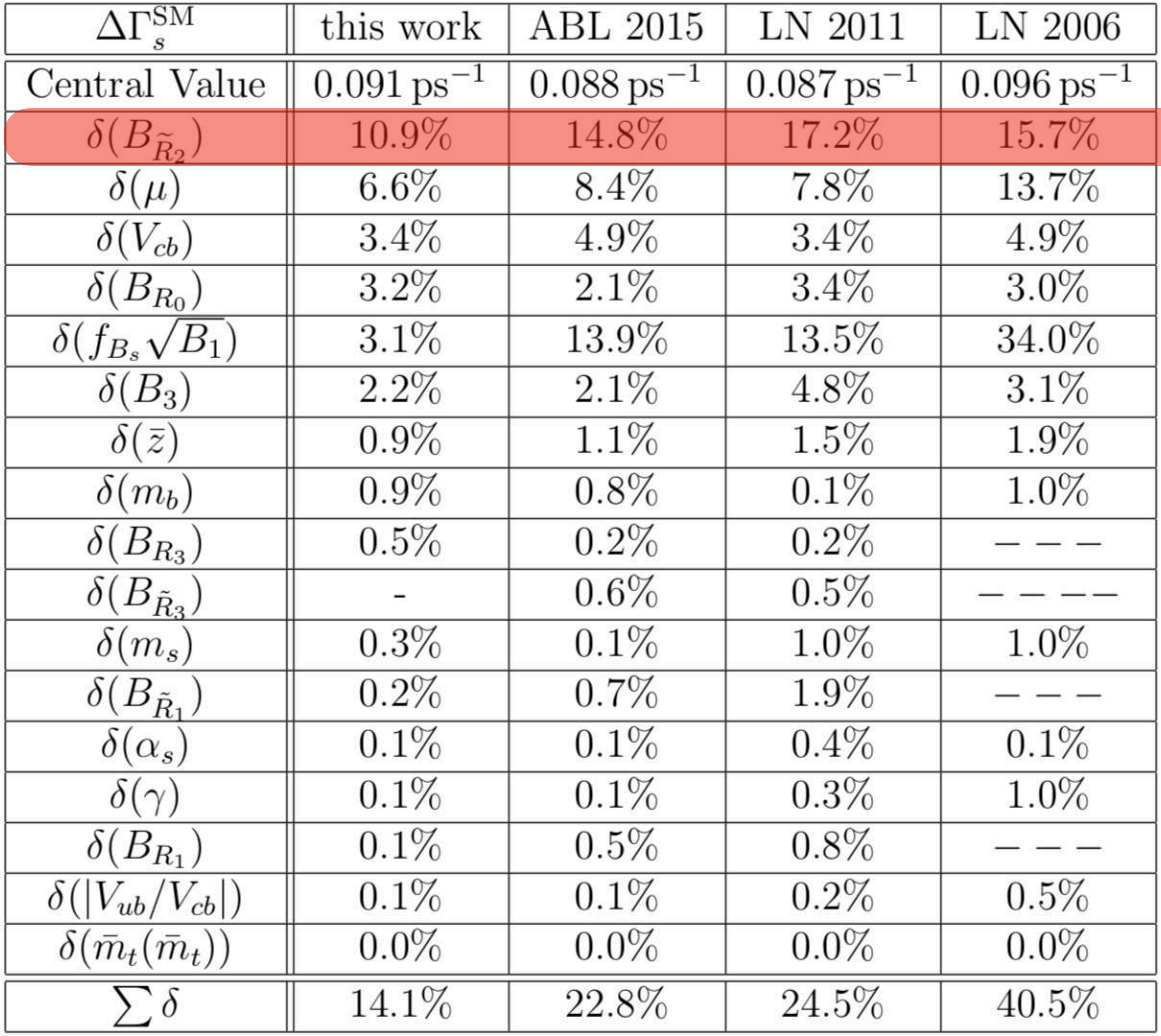
$$\Delta\Gamma_d^{\mathrm{HFLAV}\,2019} = (-1.3 \pm 6.6) \cdot 10^{-3}\,\mathrm{ps}^{-1}$$

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

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



Decay rate difference $\Delta\Gamma_s$



$\Delta\Gamma_s^{SM}$	this work	ABL 2015	LN 2011	LN 2006
Central Value	$0.091\,\mathrm{ps}^{-1}$	$0.088\,\mathrm{ps}^{-1}$	$0.087\,\mathrm{ps}^{-1}$	$0.096\,\mathrm{ps}^{-1}$
$\delta(B_{\tilde{R}_2})$	10.9%	14.8%	17.2%	15.7%
$\delta(\mu)$	6.6%	8.4%	7.8%	13.7%
$\delta(V_{cb})$	3.4%	4.9%	3.4%	4.9%
$\delta(B_{R_0})$	3.2%	2.1%	3.4%	3.0%
$\delta(f_{B_s}\sqrt{B_1})$	3.1%	13.9%	13.5%	34.0%
$\delta(B_3)$	2.2%	2.1%	4.8%	3.1%
$\delta(\bar{z})$	0.9%	1.1%	1.5%	1.9%
$\delta(m_b)$	0.9%	0.8%	0.1%	1.0%
$\delta(B_{R_3})$	0.5%	0.2%	0.2%	− − −
$\delta(B_{\tilde{R}_3})$	-	0.6%	0.5%	− − −−
$\delta(m_s)$	0.3%	0.1%	1.0%	1.0%
$\delta(B_{\tilde{R}_1})$	0.2%	0.7%	1.9%	− − −
$\delta(\alpha_s)$	0.1%	0.1%	0.4%	0.1%
$\delta(\gamma)$	0.1%	0.1%	0.3%	1.0%
$\delta(B_{R_1})$	0.1%	0.5%	0.8%	− − −
$\delta(\|V_{ub}/V_{cb}\|)$	0.1%	0.1%	0.2%	0.5%
$\delta(\bar{m}_t(\bar{m}_t))$	0.0%	0.0%	0.0%	0.0%
$\sum\delta$	14.1%	22.8%	24.5%	40.5%

Thanks Matthew!

First non-pert. Determination HP-QCD 1910.00970

AL, 2019

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**

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!

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

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SM predictions

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

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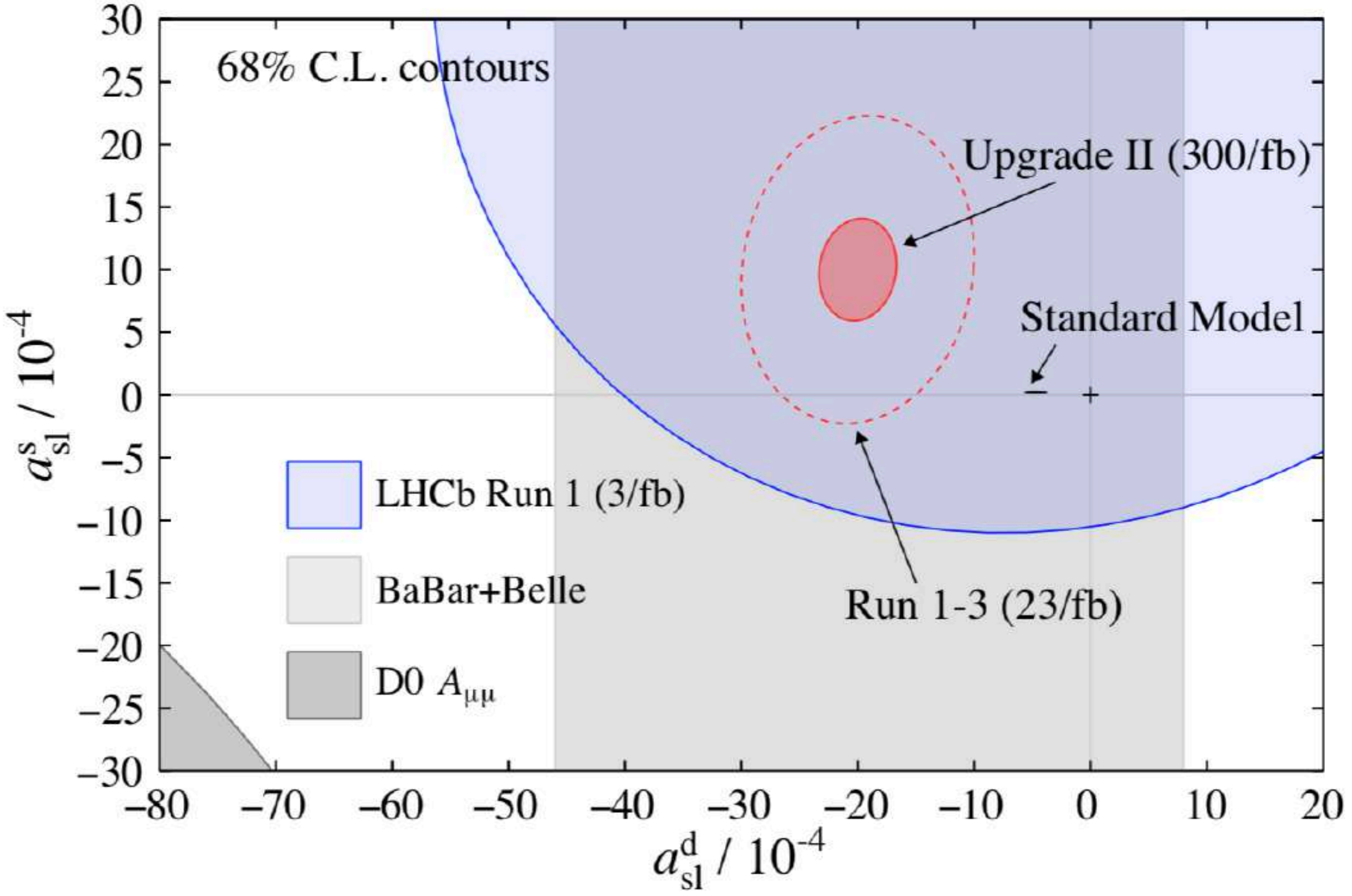
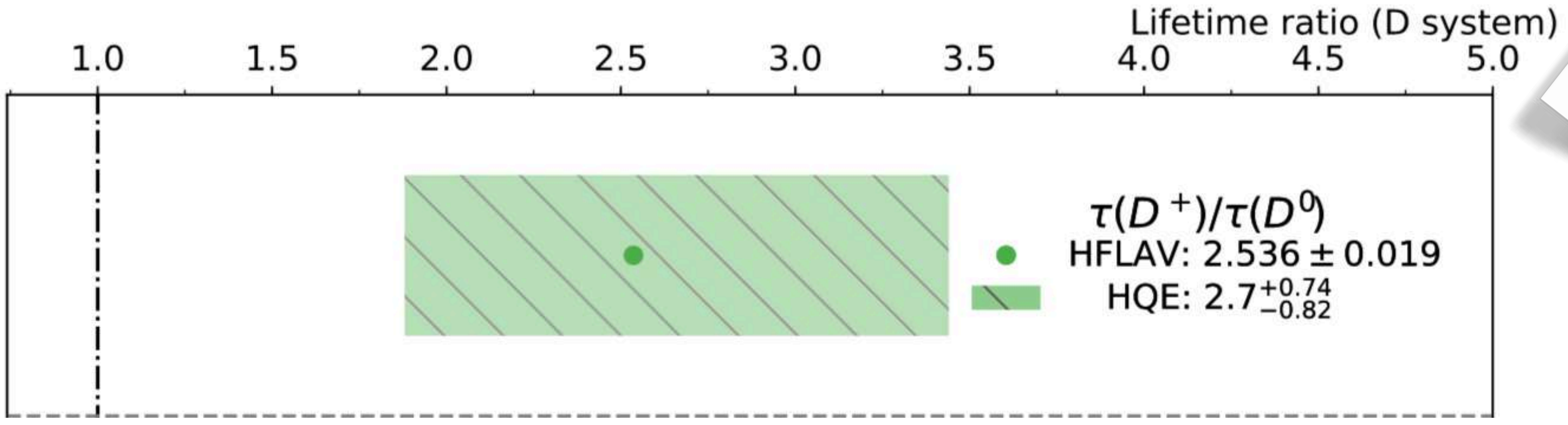


- **Very sensitive to BSM effects!**
- **Experimental number needed**

Charm Lifetimes

$\Lambda/m_c \approx 3\Lambda/m_b$ - could still give some reasonable estimates!

Look in systems without GIM cancellation: D-lifetimes



NEW 3-loop sum rules

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

Kirk, AL, Rauh 1711.02100

pert. NLO-QCD:

AL, Rauh 1305.3588

Expansion parameter for HQE in charm = 0.3
not a back of envelope statement, but real calculations

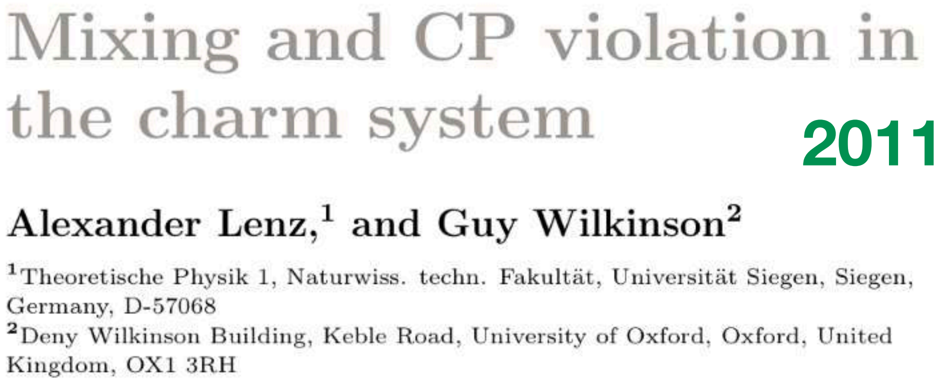
d=6 calculated with sum rules
lattice confirmation urgently needed

d=7 estimated in vacuum insertion approximation
do sum rule/lattice

Conclusion

1) Mixing/lifetime observables can be systematically improved for the b sector: pert. QCD, sum rules, lattice
   - Determining CKM parameter
   - Understanding QCD
   - Indirect BSM searches e.g. bs tau tau from tau(Bs)
   - CP violation

2) Charm mixing not discussed
   - More complicated
   - Even more interesting?



Mixing and CP violation in the charm system

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[2]Deny Wilkinson Building, Keble Road, University of Oxford, Oxford, United Kingdom, OX1 3RH

2011.xxxxx

3) There is a bright future ahead in Flavour physics - it is not all about anomalies…..

Thanks to Donald Trump and Boris Johnson

for helping me to build up a group in Siegen

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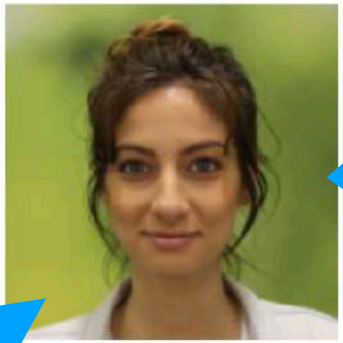
(Senior)

Oliver Witzel
(Senior)

Durham

Aleksey V. Ru
(post-doc)



Maria L. Piscopo
(PhD)

Thanks to my collaborators