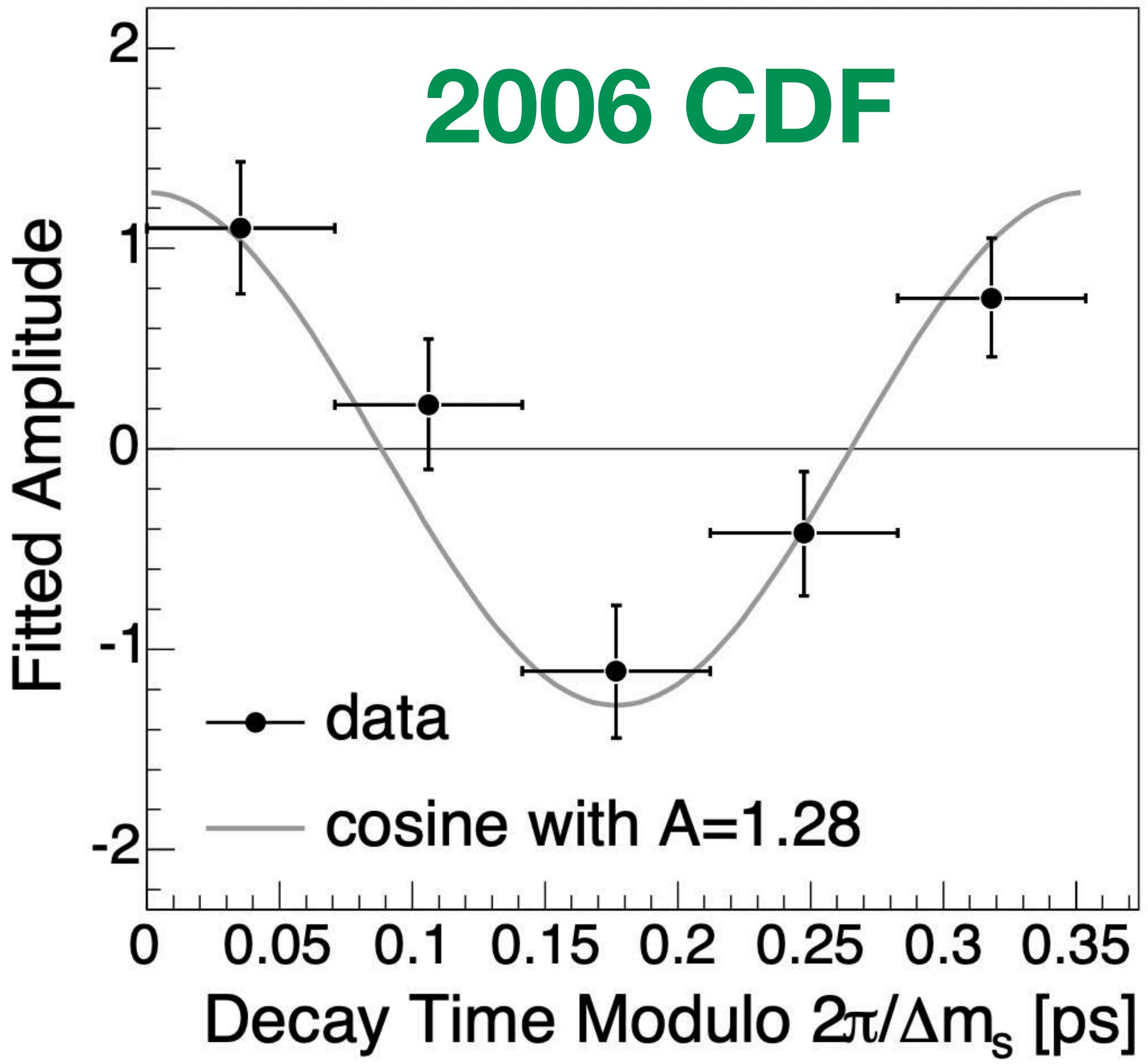
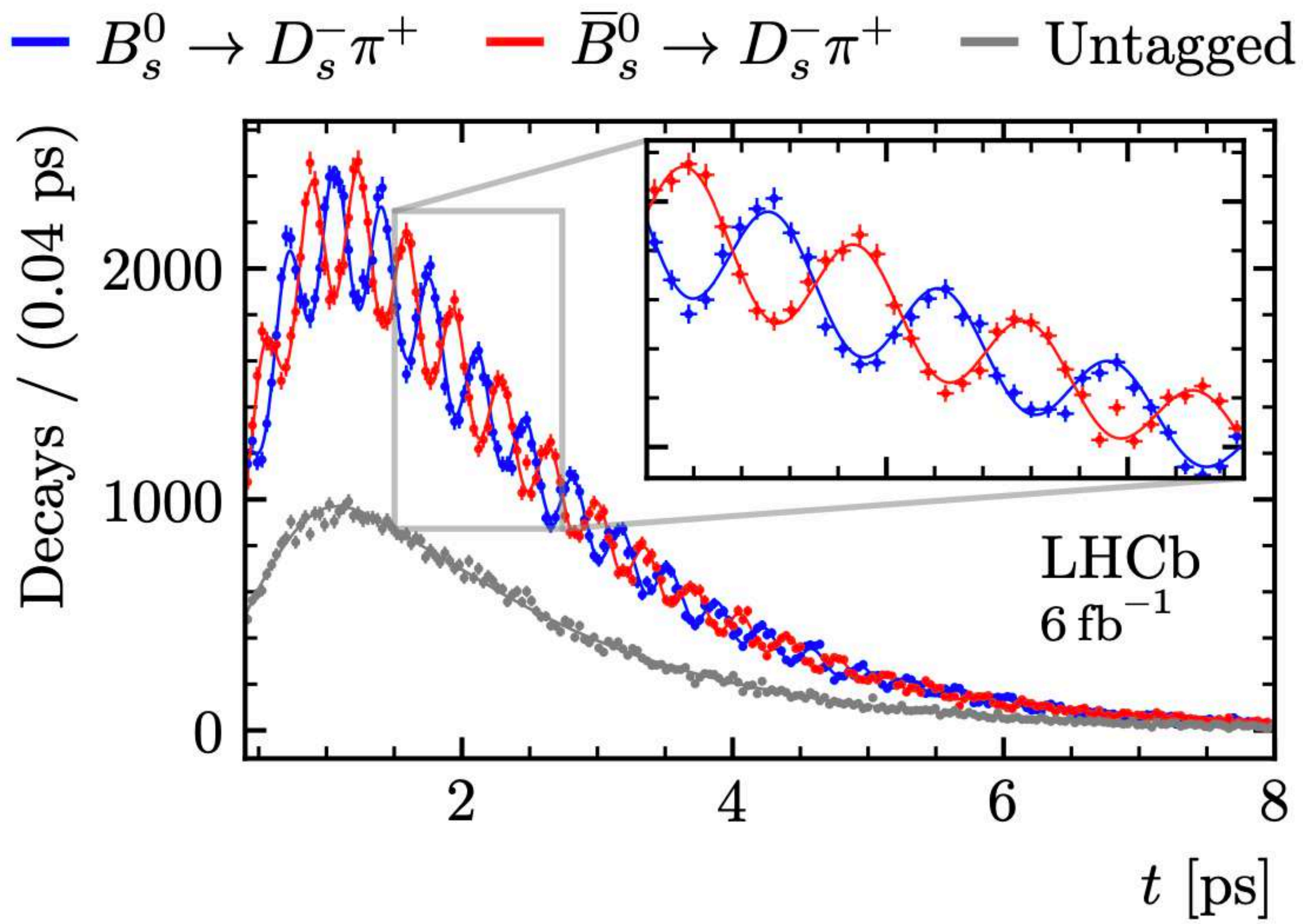
Flavour Physics over the Course of Time

Future projections and different worst case scenarios



2021 LHCb



2035

LHCb Implications

CERN, 21.10.2022

Alexander Lenz
Siegen University

Flavour Physics in the news

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Science & Environment

Large hadron collider: A revamp that could revolutionise physics

22 April · Comments

A hundred metres underground at the heart of the LHC: I'm shown around a "majestic cathedral to science"

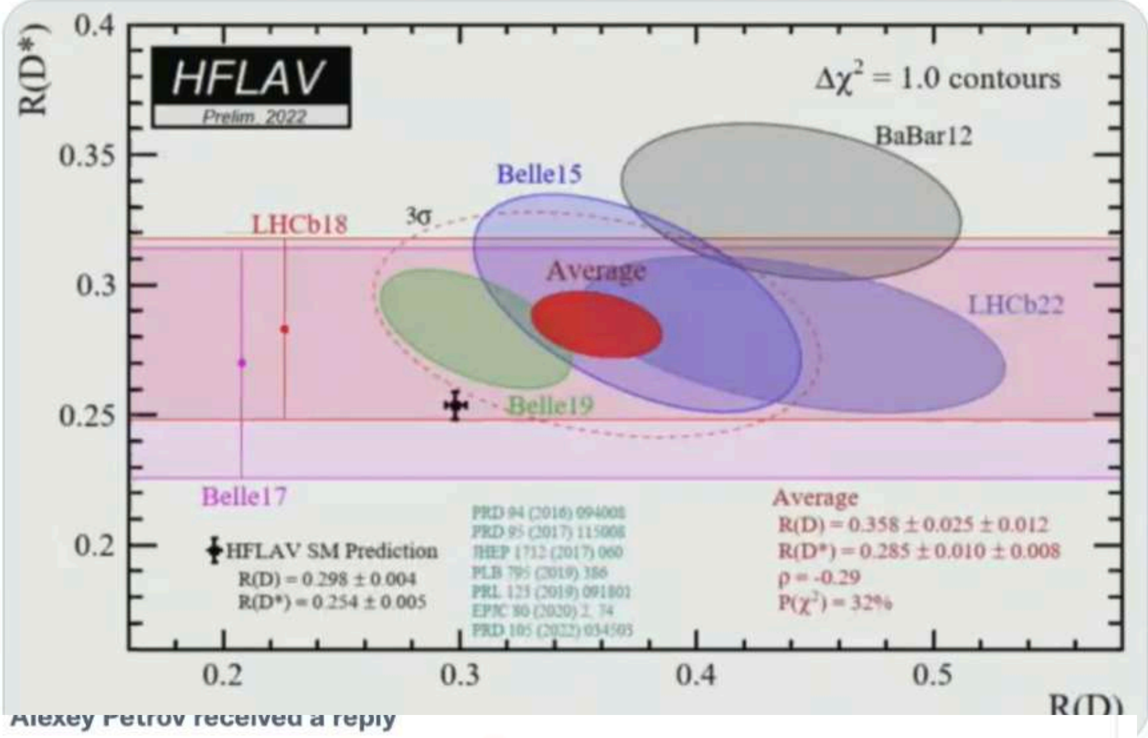
By Pallab Ghosh
Science correspondent

Deep underground amidst the Alps, scientists are barely able to contain their excitement.

Marco Gersabeck (he/him) and Patrick Koppenburg liked

David Marzocca @DavidMarzocca · 17h

Good news from the latest @LHCbExperiment measurement on R(D)-R(D*)! All measurements keep accumulating on the top-right sector of that plot!
P.S. larger values of R(D) wrt R(D*) point in the direction of the S1 leptoquark contribution...

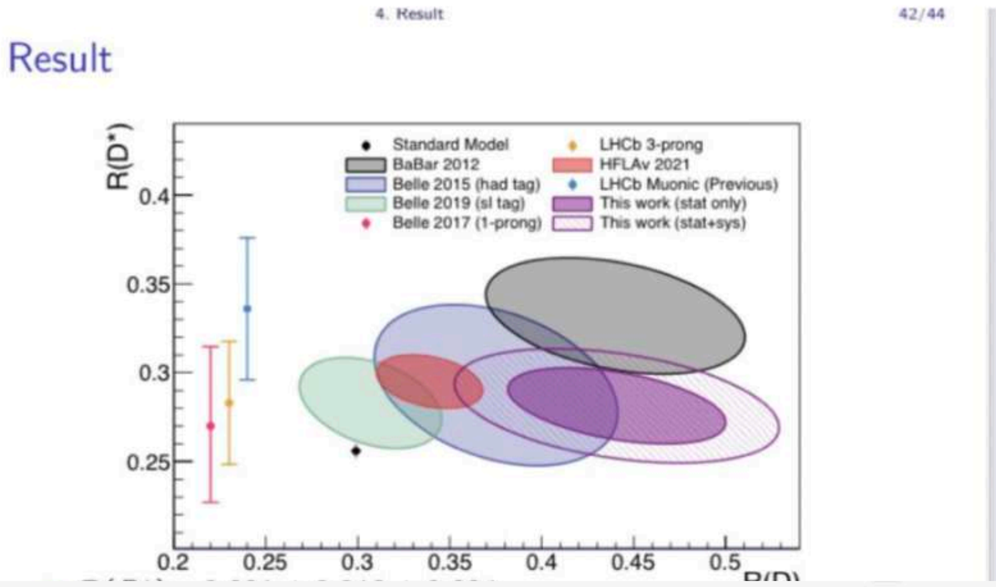


Alexey Petrov received a reply

Alexey Petrov @AlexeyPetrov · 16h

Slowly moving towards the Standard Model... or not?

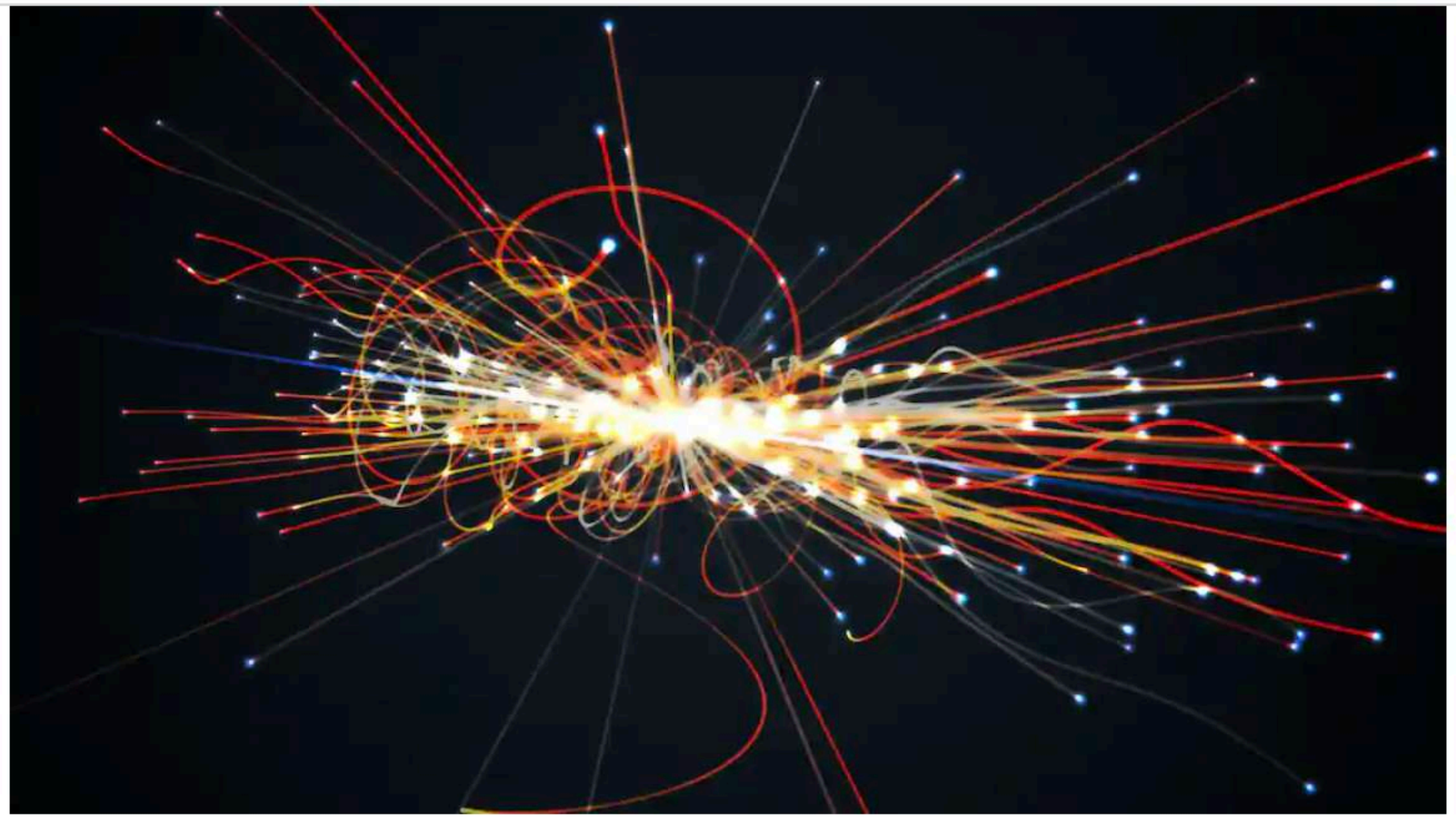
Tristan du Pree @Tristan_duPree · 18h
Replying to @Jordy_de_Vries
Volgens mij staat t belangrijkste wel in deze screenshot. (Bottom line: nieuwe analyse maar resultaat verandert niet veel)



Tristan du Pree @Tristan_duPree · 16h
Replying to @AlexeyPetrov
Or staying forever at ~3 sigma 😅

1 7

THE CONVERSATION



Particle collisions are starting to reveal unexpected results. vchal/Shutterstock

Evidence of brand new physics at Cern? Why we're cautiously optimistic about our new findings

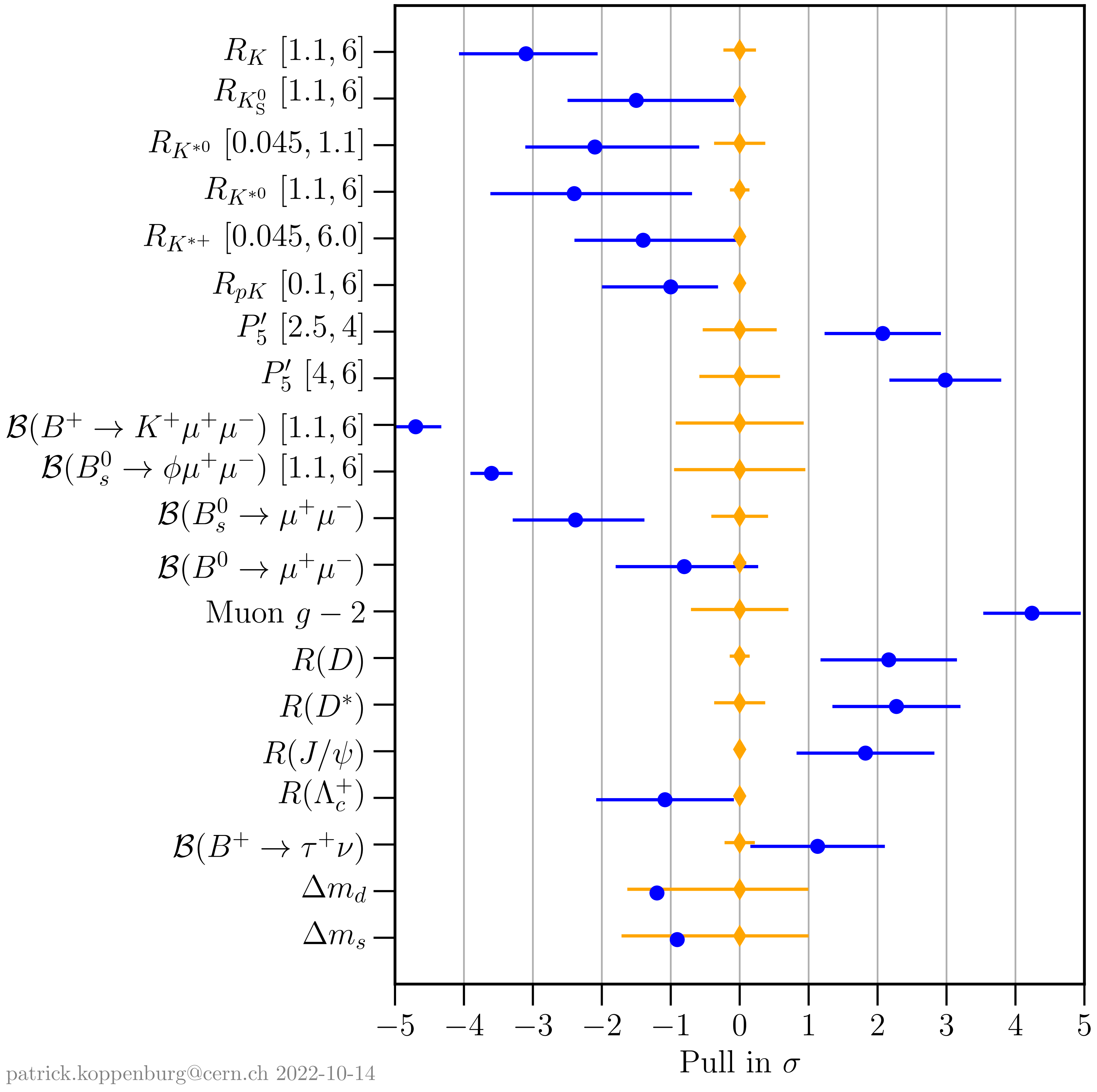
Harry Cliff, University of Cambridge, **Konstantinos Alexandros Petridis,** University of Bristol, **Paula Alvarez Cartelle,** University of Cambridge

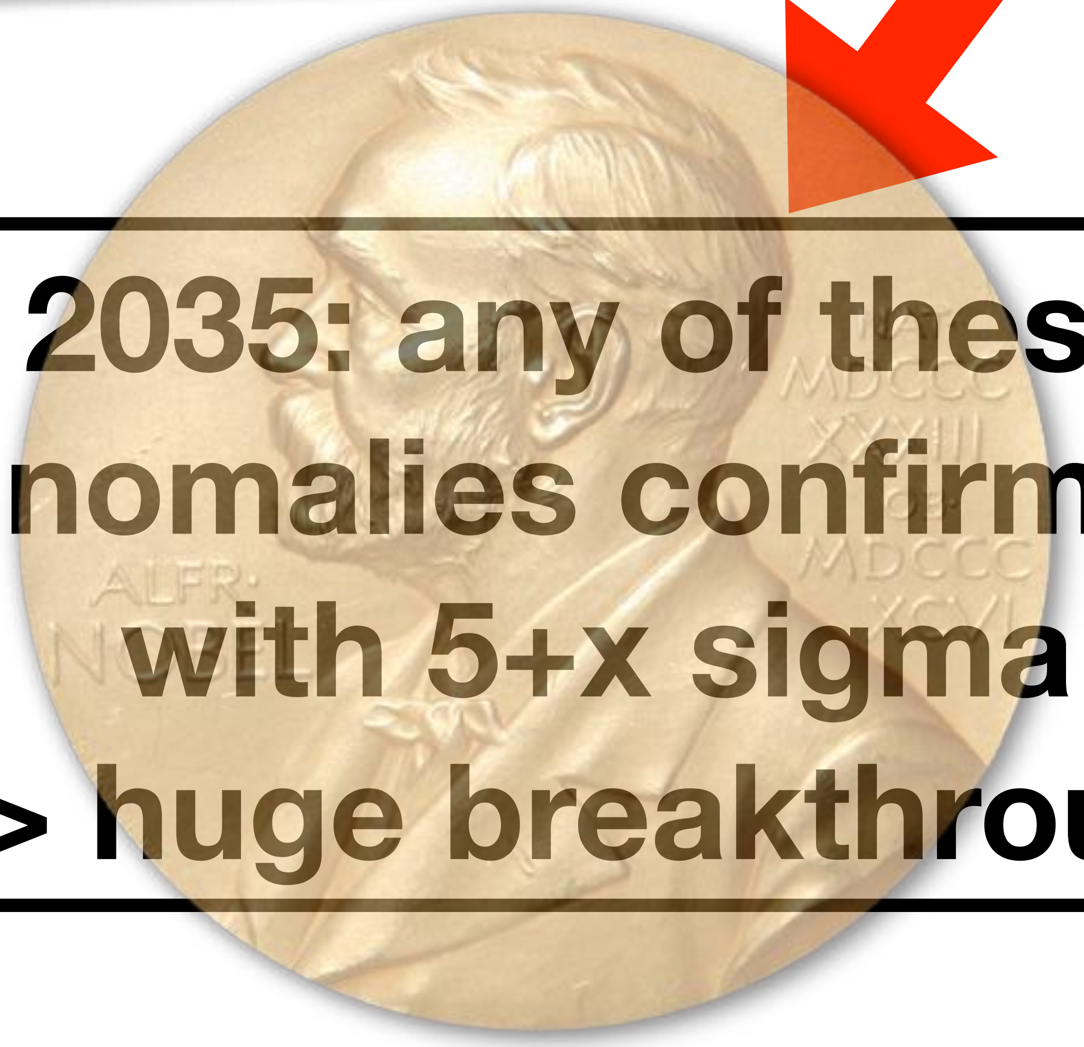
Published: March 23, 2021 8.15am GMT

Anomalies

Currently hot topic and selling point for particle physics

- **Semileptonic, tree-level:** $b \to c l \nu$ **in** $R(D), R(D^*), \ldots$
- **Semileptonic, loop-level:** $b \to s l l$ **in** $R(K), \ldots, P_5', \ldots, Br(B_s \to \phi l l), \ldots$
- **Old: semileptonic, tree-level:** $V_{cb}, \ldots$ **- Cabibbo anomaly**
- **Old: Di-muon asymmetry from D0**
- **Old: Muon g-2**
- **Less known: Non-leptonic, tree-level:** $b \to c \bar{u} d, \ldots$ **in** $Br(\bar{B}_s \to D_s^+ \pi^-), \ldots$
- **...**



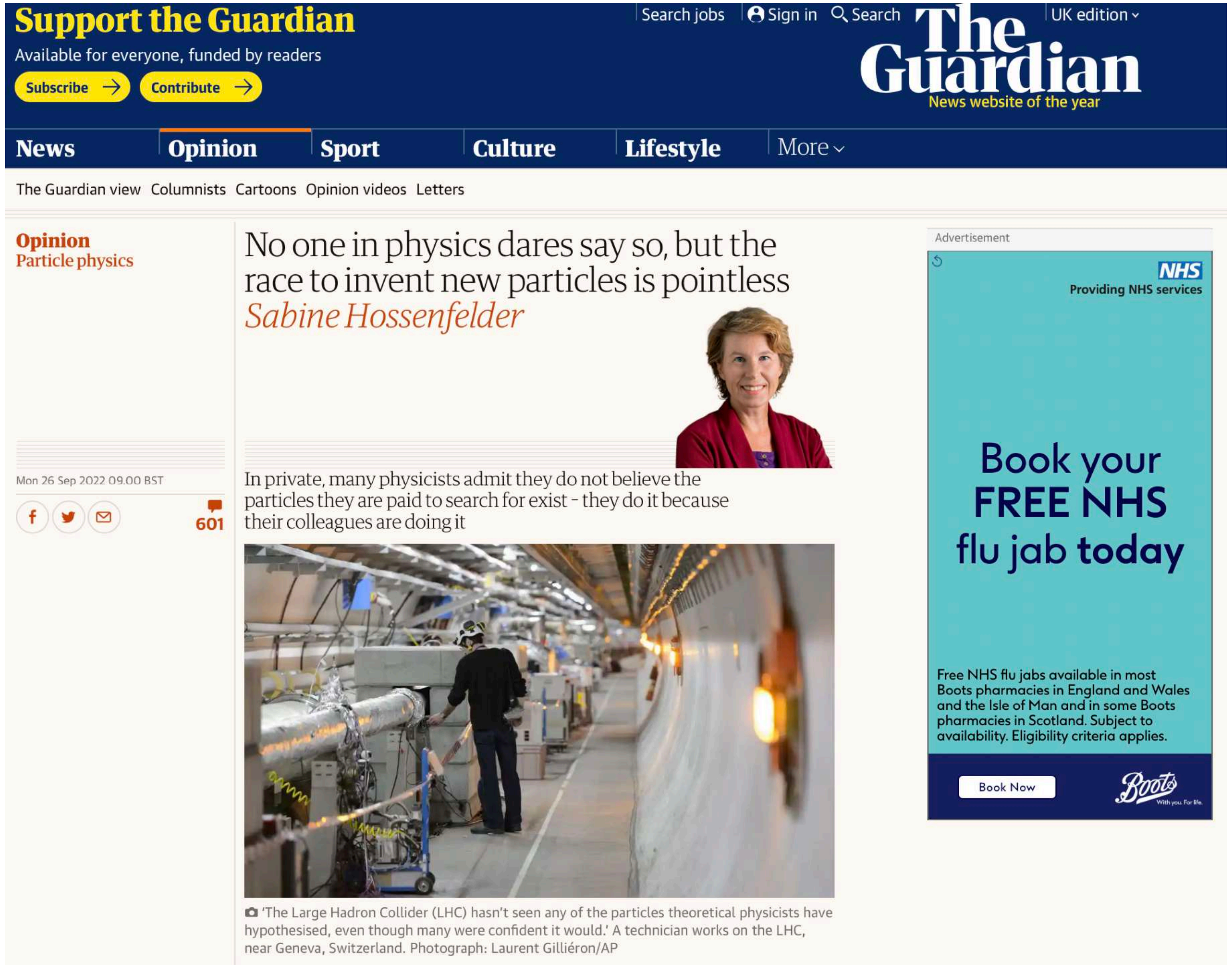


2035: any of these anomalies confirmed with 5+x sigma
=> huge breakthrough

So far no clear 5+x sigma deviation

2035: all anomalies might have gone away….
What then? Was all a waste of time?
What will we have learnt?

Flavour Physics in the news



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Opinion
Particle physics

No one in physics dares say so, but the race to invent new particles is pointless

Sabine Hossenfelder

Mon 26 Sep 2022 09.00 BST

601

In private, many physicists admit they do not believe the particles they are paid to search for exist - they do it because their colleagues are doing it

'The Large Hadron Collider (LHC) hasn't seen any of the particles theoretical physicists have hypothesised, even though many were confident it would.' A technician works on the LHC, near Geneva, Switzerland. Photograph: Laurent Gilliéron/AP

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Particle physics

Particle physics – a brief history of time-wasting?

Letters

Fri 30 Sep 2022 17.11 BST

Readers respond to an article that argued that the field of physics is too obsessed with discovering new particles

'Most of the particles that my colleagues and I speculate about will not turn out to be real, and that's fine.' Photograph: Science Photo Library

Outline

- CKM fits
- Lifetimes
- Mixing: Mass difference ΔM_q, decay rate differences $\Delta\Gamma_q$ and semileptonic CP asymmetries a_{sl}^q
- NP in Tree-level: One observable to find them (= BSM) all!
- Conclusion: What will be our legacy?

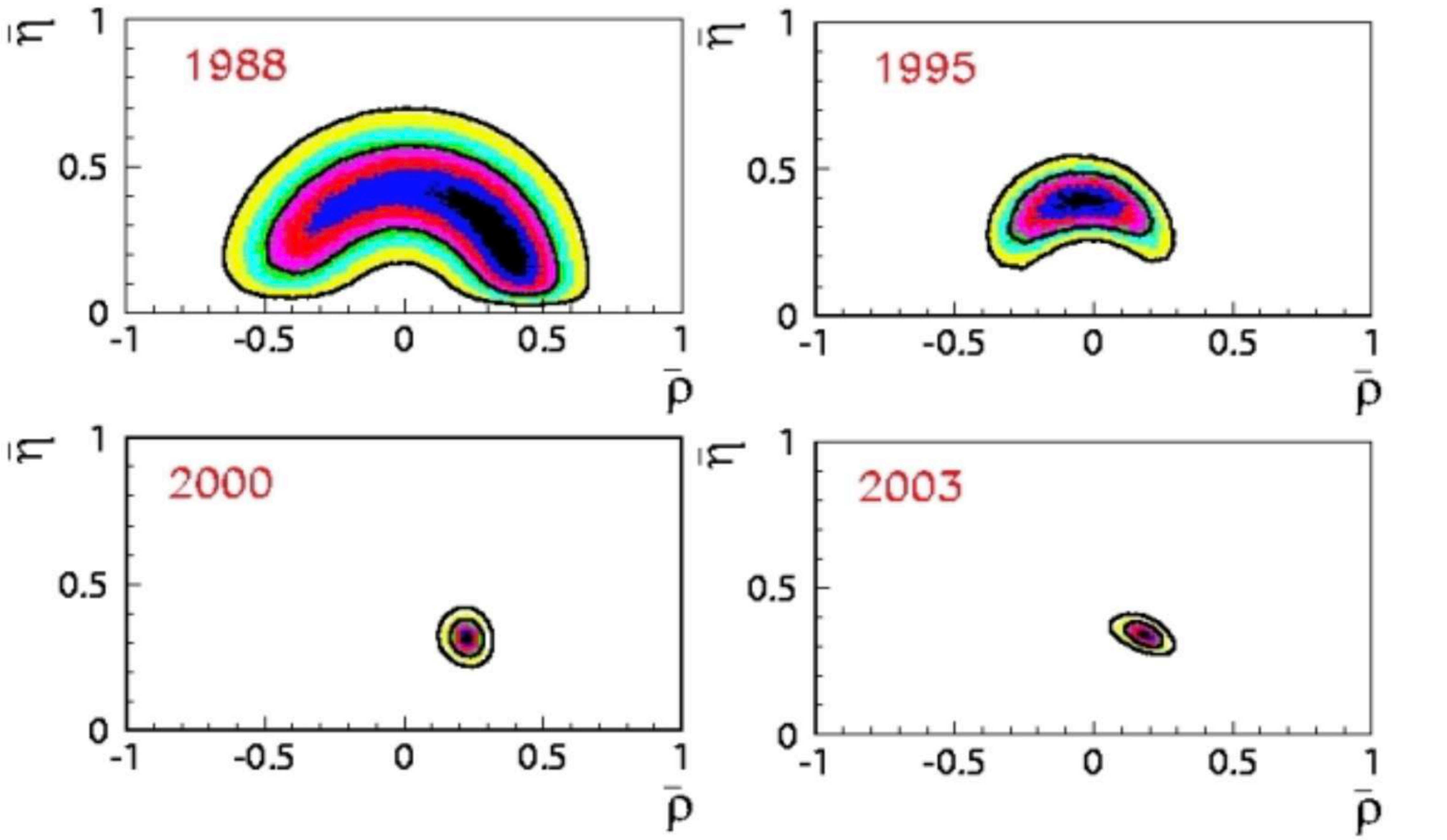
CKM Fits

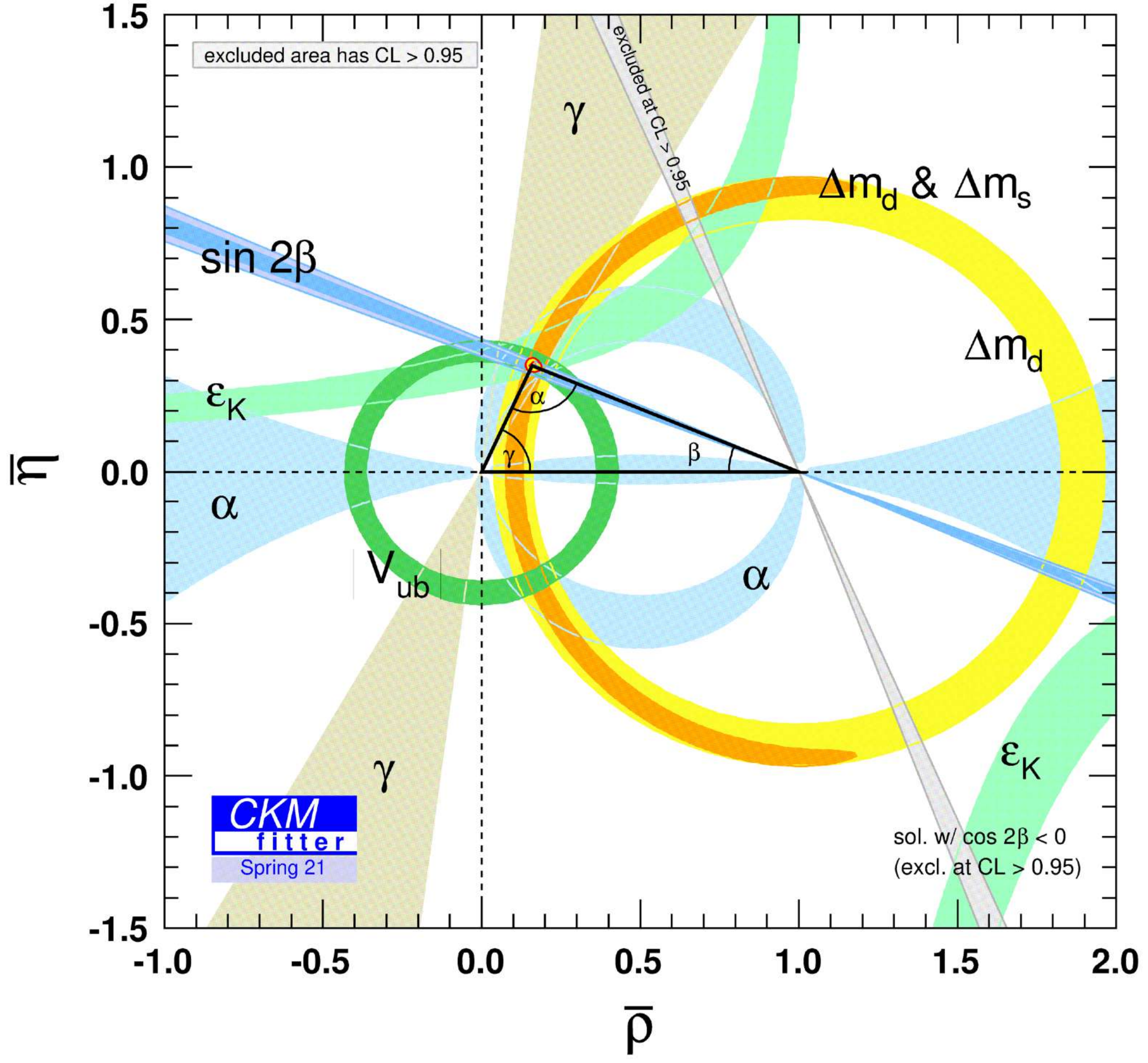
Aim:

- Determine the fundamental parameters of nature
- Determine if there is CP violation within the SM
- Determine if the amount of CP violation within the SM is sufficient for baryogenesis

- Do consistency checks (indirect new physics searches) of the known laws of nature (SM)

CKM Fits


1988
1995
2000
2003
$\bar{\eta}$
$\bar{\rho}$
UTfit


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
V_{ub}
CKM fitter
Spring 21
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$

CKM Fits - remaining problems

$$|V_{cb}|^{\text{incl.,2022}} = (42.16 \pm 0.51) \cdot 10^{-3}$$

2.4%

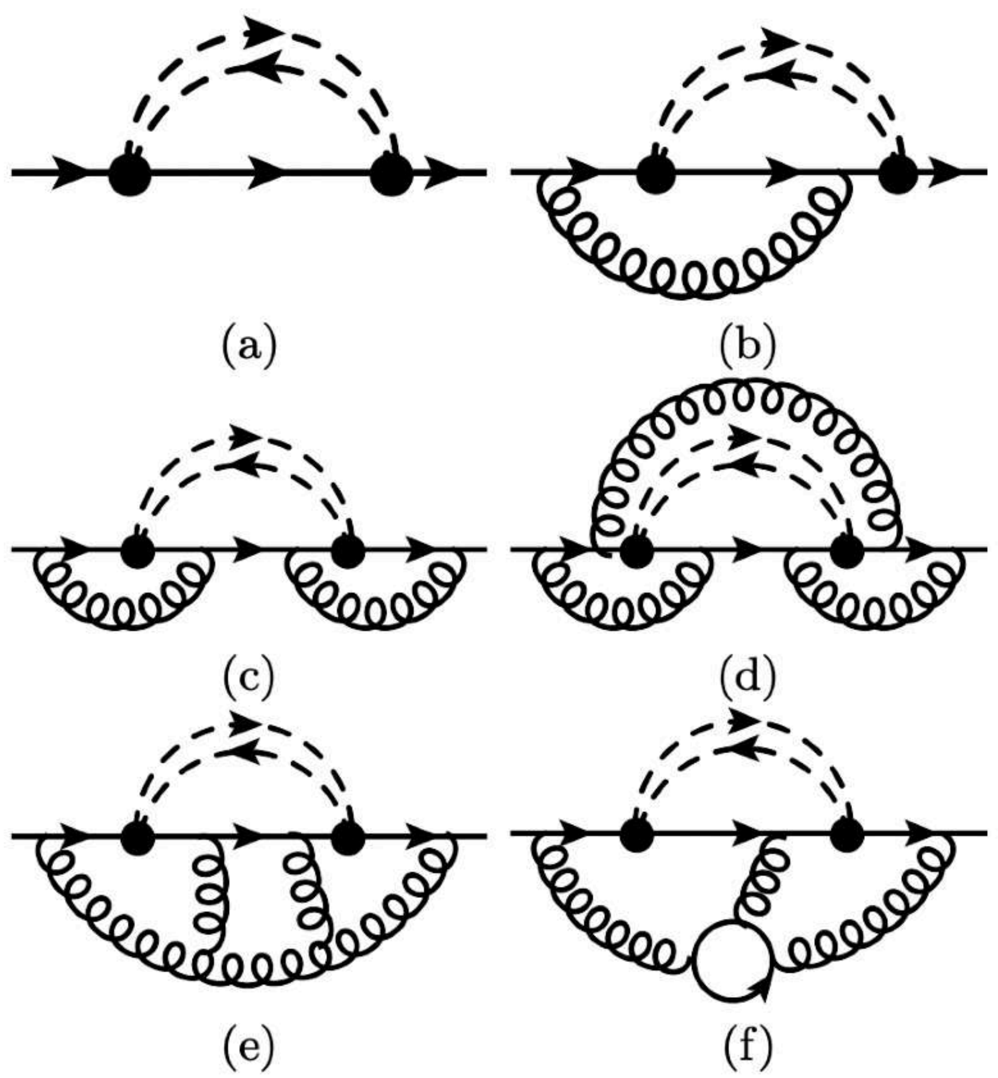
Bordone, Capdevilla, Gambino 2107.00604

$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9) \cdot 10^{-3}$$

4.6%

See e.g. Wednesday talks by Blaise Delany, Martin Jung

Based on huge progress in perturbative multi loop and non-perturbative methods, in particular lattice



Fael, Schönwald, Steinhauser 2011.13654

$$\begin{aligned}\frac{m^{\text{kin}}}{m^{\text{OS}}} = 1 - \frac{\alpha_s^{(n_l)}}{\pi} C_F \left(\frac{4}{3}\frac{\mu}{m^{\text{OS}}} + \frac{1}{2}\frac{\mu^2}{(m^{\text{OS}})^2} \right) + \left(\frac{\alpha_s^{(n_l)}}{\pi} \right)^2 C_F \Bigg\{ \frac{\mu}{m^{\text{OS}}} \Bigg[C_A \left(-\frac{215}{27} + \frac{2\pi^2}{9} + \frac{22}{9} l_\mu \right) + n_l T_F \left(\frac{64}{27} - \frac{8}{9} l_\mu \right) \Bigg] \\ + \frac{\mu^2}{(m^{\text{OS}})^2} \Bigg[C_A \left(-\frac{91}{36} + \frac{\pi^2}{12} + \frac{11}{12} l_\mu \right) + n_l T_F \left(\frac{13}{18} - \frac{1}{3} l_\mu \right) \Bigg] \Bigg\} + \left(\frac{\alpha_s^{(n_l)}}{\pi} \right)^3 C_F \Bigg\{ \frac{\mu}{m^{\text{OS}}} \Bigg[C_A^2 \Bigg(-\frac{130867}{1944} \\ + \frac{511\pi^2}{162} + \frac{19\zeta_3}{2} - \frac{\pi^4}{18} + \left(\frac{2518}{81} - \frac{22\pi^2}{27} \right) l_\mu - \frac{121}{27} l_\mu^2 \Bigg) + C_A n_l T_F \Bigg(\frac{19453}{486} - \frac{104\pi^2}{81} - 2\zeta_3 \\ + \left(-\frac{1654}{81} + \frac{8\pi^2}{27} \right) l_\mu + \frac{88}{27} l_\mu^2 \Bigg) + C_F n_l T_F \left(\frac{11}{4} - \frac{4\zeta_3}{3} - \frac{2}{3} l_\mu \right) + n_l^2 T_F^2 \left(-\frac{1292}{243} + \frac{8\pi^2}{81} + \frac{256}{81} l_\mu - \frac{16}{27} l_\mu^2 \right) \Bigg] \\ + \frac{\mu^2}{(m^{\text{OS}})^2} \Bigg[C_A^2 \left(-\frac{96295}{5184} + \frac{445\pi^2}{432} + \frac{57\zeta_3}{16} - \frac{\pi^4}{48} + \left(\frac{2155}{216} - \frac{11\pi^2}{36} \right) l_\mu - \frac{121}{72} l_\mu^2 \right) + C_A n_l T_F \Bigg(\frac{13699}{1296} - \frac{23\pi^2}{54} \\ - \frac{3\zeta_3}{4} + \left(-\frac{695}{108} + \frac{\pi^2}{9} \right) l_\mu + \frac{11}{9} l_\mu^2 \Bigg) + C_F n_l T_F \left(\frac{29}{32} - \frac{\zeta_3}{2} - \frac{1}{4} l_\mu \right) + n_l^2 T_F^2 \left(-\frac{209}{162} + \frac{\pi^2}{27} + \frac{26}{27} l_\mu - \frac{2}{9} l_\mu^2 \right) \Bigg] \Bigg\}, \quad (4)\end{aligned}$$

Fael, Schönwald, Steinhauser 2005.06487

CERN-TH-2022-036 FERMILAB-CONF-22-433-SCD-T JLAB-THY-22-3582
MITP-22-020 MIT-CTP/5413 MS-TP-22-07 SI-HEP-2022-11

A lattice QCD perspective on weak decays of b and c quarks
Snowmass 2022 White Paper

Peter A. Boyle,[1,2] Bipasha Chakraborty,[3] Christine T. H. Davies,[4] Thomas DeGrand,[5] Carleton DeTar,[6] Luigi Del Debbio,[2] Aida X. El-Khadra,[7] Felix Erben,[2] Jonathan M. Flynn,[8] Elvira Gámiz,[9] Davide Giusti,[10] Steven Gottlieb,[11] Maxwell T. Hansen,[2] Jochen Heitger,[12] Ryan Hill,[2] William I. Jay,[13] Andreas Jüttner,[8,14,15] Jonna Koponen,[16] Andreas Kronfeld,[17] Christoph Lehner,[10] Andrew T. Lytle,[7,*] Guido Martinelli,[18] Stefan Meinel,[19] Christopher J. Monahan,[20,21] Ethan T. Neil,[5] Antonin Portelli,[2] James N. Simone,[17] Silvano Simula,[22] Rainer Sommer,[23,24] Amarjit Soni,[1] J. Tobias Tsang,[25] Ruth S. Van de Water,[17] Alejandro Vaquero,[6] Ludovico Vittorio,[26] and Oliver Witzel[27,†]

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[22] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma Tre, Via della Vasca Navale 84, I-00146 Rome, Italy*
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[27] *Center for Particle Physics Siegen, Theoretische Physik 1, Universität Siegen, 57068 Siegen, Germany*
(Dated: August 15, 2022)

Lattice quantum chromodynamics has proven to be an indispensable method to determine non-perturbative strong contributions to weak decay processes. In this white paper for the Snowmass community planning process we highlight achievements and future avenues of research for lattice calculations of weak b and c quark decays, and point out how these calculations will help to address the anomalies currently in the spotlight of the particle physics community. With future increases in computational resources and algorithmic improvements, percent level (and below) lattice determinations will play a central role in constraining the standard model or identifying new physics.

arXiv:2205.15373v2 [hep-lat] 12 Aug 2022

e.g. SNOWMASS reports…

CKM Fits - remaining problems

$$|V_{cb}|^{\text{incl.,2022}} = (42.16 \pm 0.51) \cdot 10^{-3}$$ 2.4%

Bordone, Capdevilla, Gambino 2107.00604

$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9) \cdot 10^{-3}$$ 4.6%

What could have gone wrong?

- Experimental problem in inclusive decays? Just underestimated uncertainties?
- Experimental problem in exclusive decays? Just underestimated uncertainties?
- Theoretical problem in inclusive decays? Just underestimated uncertainties?
- Theoretical problem in exclusive decays? Just underestimated uncertainties?
- BSM explanations seem unlikely!

Even if we all had seriously messed up: 10%

Inclusive and exclusive cover the range $(38.6 \ldots 42.67) \cdot 10^{-3} = (40.7 \pm 2.0) \cdot 10^{-3}$

On a large time scale (e.g. 1988-2022): our knowledge about the fundamental parameters of nature has considerably improved!

CKM Fits - remaining problems

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Bordone, Capdevilla, Gambino 2107.00604

$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9) \cdot 10^{-3}$$ 4.6%

Will we ever do definitely better?

- Inclusive fits in Bordone, Capdevilla, Gambino 2107.00604 and Bernlochner, Fael, Olschewsky, Person, van Toner, Vos, Welsch 2205.10274 agree for V_{cb}, but disagree for the matrix element of the Darwin operator => room for improvement (see also AL, Piscopo, Rusov, 2208.02643)
- Inclusive calculations not within HQE, but directly via lattice (Hashimoto, Gambino, Mächler, Panero, Sanfillipo 2203.11762, Gambino Hashimoto 2005.13730…,)
- Exclusive V_{cb} determination up to 1.4% at Belle II (e.g. SNOWMASS, 2207.06307)
- Semileptonic $B_c \to l\nu$ decays depend only on $f_{B_c}^2 |V_{cb}|^2$ - no form factors (e.g. Amhis, Hartmann, Helsens, Hill, Sumensari, 2105.13330)
- Even higher precision from $x \cdot 10^8$ on-shell $W^+ \to c\bar{b}$ decays at FCC-ee (Monteil, Wilkinson 2106.01259, Monteil, AL 2207.11055)

$$\delta V_{cb} \approx 0.16 \cdot 10^{-3}$$ Monteil, 12.9.2022 flavour@FCCee

CKM Fits - remaining problems

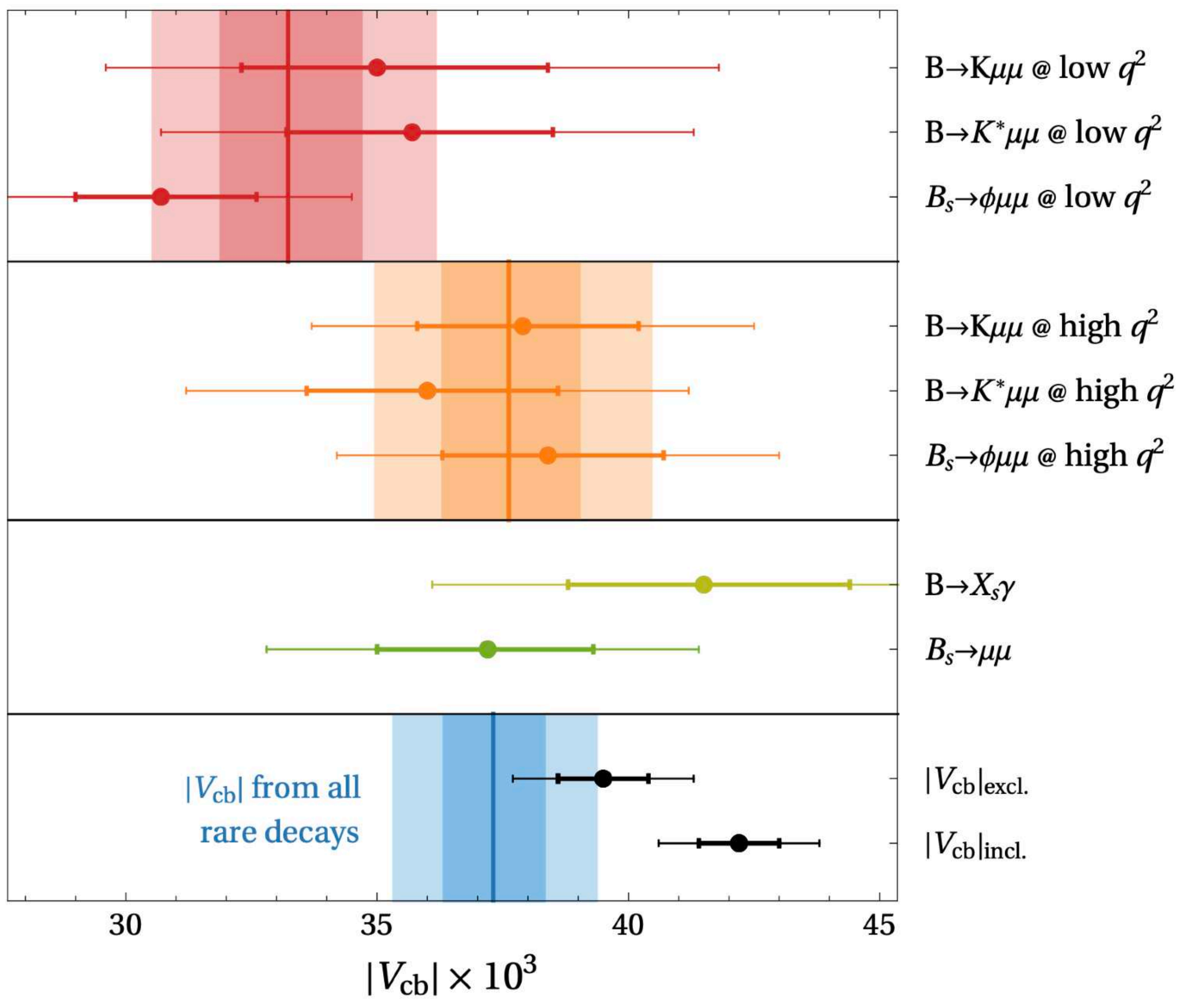
$$|V_{cb}|^{\text{incl.,2022}} = (42.16 \pm 0.51) \cdot 10^{-3}$$ 2.4%

Bordone, Capdevilla, Gambino 2107.00604

$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9) \cdot 10^{-3}$$ 4.6%

Interesting to note:

(V_{cb} cancels in $R_K, \ldots$)



Altmannshofer, Lewis 2112.03437

CKM Fits

Aim:

We can argue about exact precision

- Determine the fundamental parameters of the laws of nature
- Determine if there is CP violation within the SM

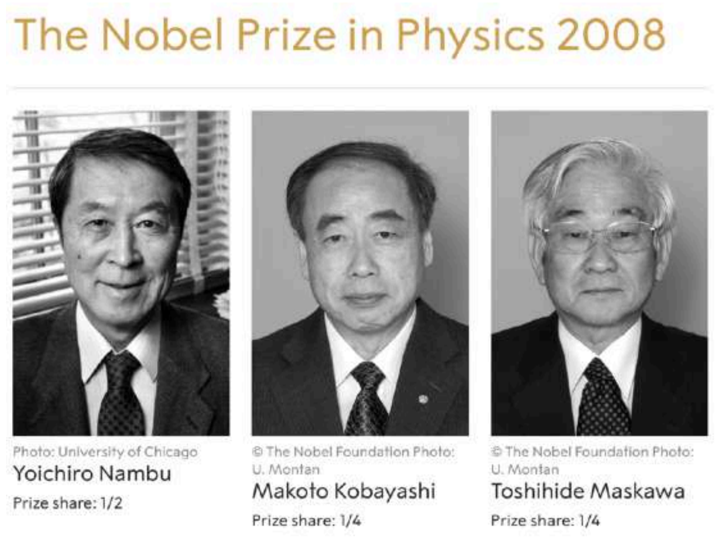
It is definitely there

- Determine if the amount of CP violation within the SM is sufficient for baryogenesis

Probably not, but see e.g. Alonso-Alvarez, Elor, Escudero 2101.02706

- Do consistency checks (indirect new physics searches) of our the laws of nature (SM)

in progress: CKM fits consistent, Cabibbo anomaly, …



See talk by Emilie Passemar on Wednesday

Lifetimes

Aim:

- Understand one of the most fundamental properties of elementary particles
- Understand the hadronic interaction which is binding quarks into hadrons

- Do consistency checks (indirect new physics searches) of the known laws of nature (SM)

Lifetimes

B mesons live unexpectedly long

$$\Gamma(B) = \frac{G_f^2 m_b^5}{192\pi^3} |V_{cb}|^2 (3 + \ldots) = \frac{1}{\tau(B)}$$

because of smallness of $|V_{cb}|^2 \approx 1.6 \cdot 10^{-3}$

Experimental values in 1996

$$\frac{\tau(B^-)}{\tau(B_d)} = 1.02 \pm 0.04\,, \qquad \frac{\tau(B_s)}{\tau(B_d)} = 1.01 \pm 0.07\,, \qquad \frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.78 \pm 0.05\,.$$

ALEPH,OPAL,... CDF

Theory framework: Heavy Quark Expansion

$$\left.\frac{\tau(B^+)}{\tau(B_d)}\right|^{\mathrm{HQE}\,1986} \approx 1.1\,, \qquad \left.\frac{\tau(B_s)}{\tau(B_d)}\right|^{\mathrm{HQE}\,1986} \approx 1\,, \qquad \left.\frac{\tau(\Lambda_b)}{\tau(B_d)}\right|^{\mathrm{HQE}\,1986} \approx 0.96\,.$$

Hierarchy of Lifetimes of Charmed and Beautiful Hadrons
Mikhail A. Shifman, M.B. Voloshin (Moscow, ITEP). 1986. 30 pp.
Published in **Sov.Phys.JETP 64 (1986) 698, Zh.Eksp.Teor.Fiz. 91 (1986) 1180-1193**
ITEP-86-83

Lifetimes

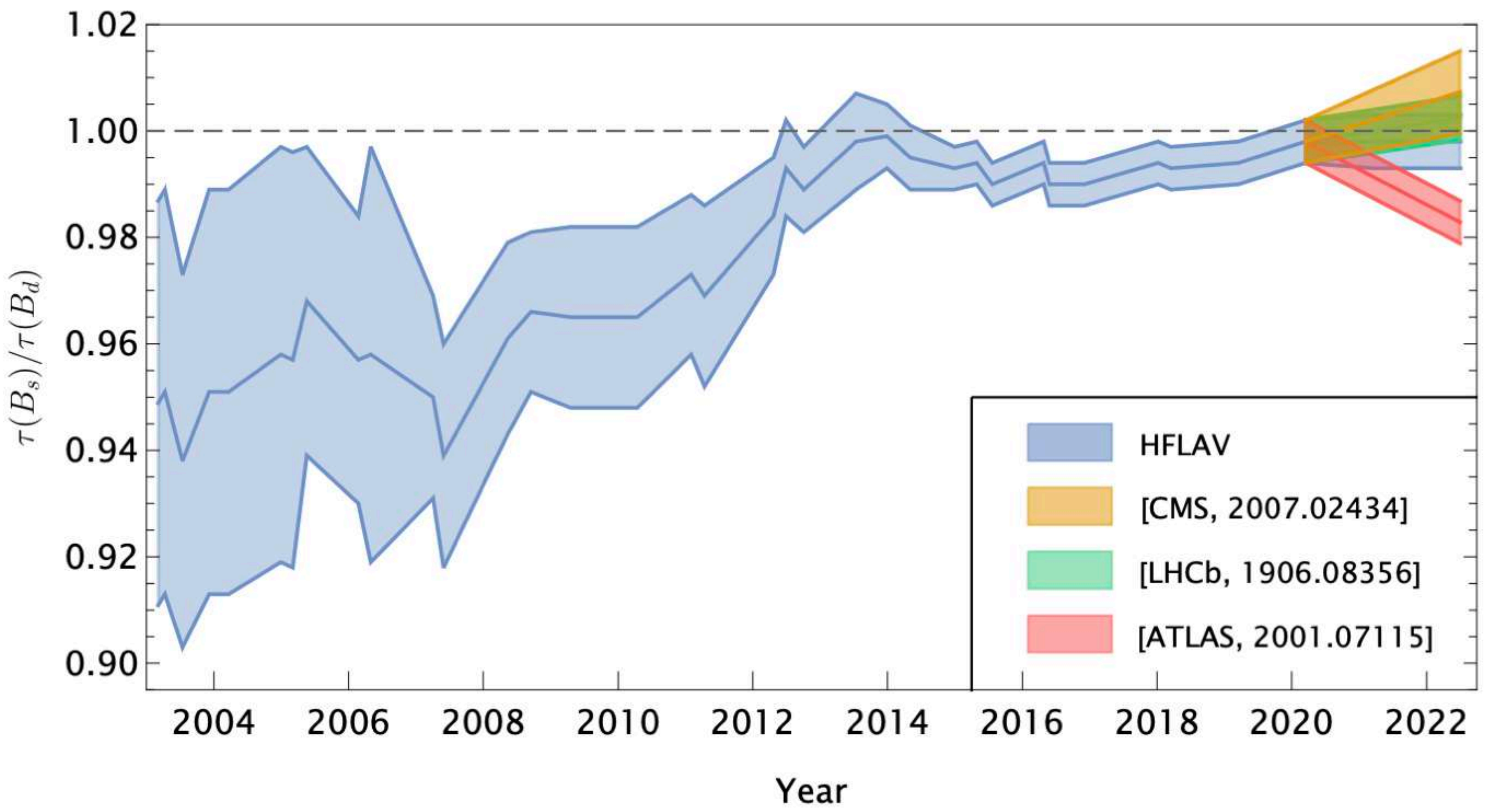
What happened to the experimental numbers?

$$\frac{\tau(B^-)}{\tau(B_d)} = 1.02 \pm 0.04\,, \qquad \frac{\tau(B_s)}{\tau(B_d)} = 1.01 \pm 0.07\,, \qquad \frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.78 \pm 0.05\,.$$

1996: ALEPH,OPAL,... CDF

HFLAV 2022

$$\frac{\tau(B^+)}{\tau(B_d)} = 1.076 \pm 0.004\,, \quad \frac{\tau(B_s)}{\tau(B_d)} = 1.001 \pm 0.004\,, \quad \frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.969 \pm 0.006\,,$$



Experimental numbers can change: a value which originally deviated sizeably from one can get very close to one
!!! No allusion to any other ratio intended !!!

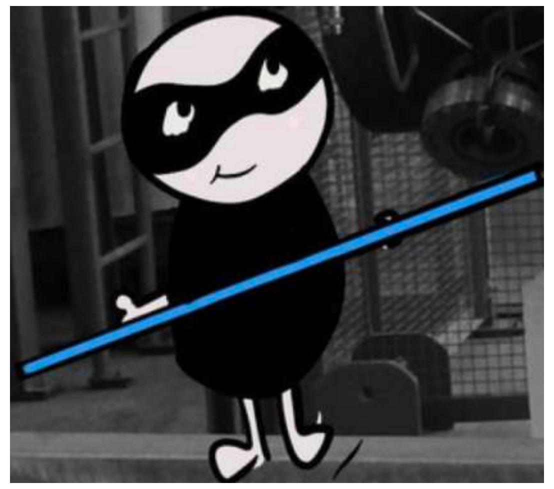
AL, Piscopo, Rusov
2208.02643
Plot credit M. Kirk

Lifetimes

What happened to the theory numbers?

Hierarchy of Lifetimes of Charmed and Beautiful Hadrons
Mikhail A. Shifman, M.B. Voloshin (Moscow, ITEP). 1986. 30 pp.
Published in **Sov.Phys.JETP 64 (1986) 698, Zh.Eksp.Teor.Fiz. 91 (1986) 1180-1193**
ITEP-86-83
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 281 records 250+

$$\left.\frac{\tau(B^+)}{\tau(B_d)}\right|^{\mathrm{HQE\,1986}} \approx 1.1\,, \qquad \left.\frac{\tau(B_s)}{\tau(B_d)}\right|^{\mathrm{HQE\,1986}} \approx 1\,, \qquad \left.\frac{\tau(\Lambda_b)}{\tau(B_d)}\right|^{\mathrm{HQE\,1986}} \approx 0.96\,.$$



$$\frac{\tau(B^+)}{\tau(B_d)} = 1.09 \pm 0.02\,, \quad \frac{\tau(B_s)}{\tau(B_d)} = \begin{cases} 1.003 \pm 0.006(A) \\ 1.028 \pm 0.011(B) \end{cases}, \quad \frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.935 \pm 0.054\,,$$

AL, Piscopo, Rusov 2022

AL 2014

Gratrex, AL, Melic, Nisandzic, Piscopo, Rusov in progress

Theory numbers can change:

- **Many theory colleagues could explain the low Λ_b lifetime**
- **Theory predictions for B_s depends very strongly on the value of the Darwin operator extracted from the V_{cb} fit!**

Lifetimes

How much more do we know in 2022 than in 1986?

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

$$\Gamma_d = \Gamma_d^{(0)} + \left(\frac{\alpha_s(m_Q)}{4\pi}\right) \Gamma_d^{(1)} + \left(\frac{\alpha_s(m_Q)}{4\pi}\right)^2 \Gamma_d^{(2)} + \ldots$$

Semileptonic (SL) modes	
$\Gamma_3^{(3)}$	Fael, Schönwald, Steinhauser '20 Czakon, Czarnecki, Dowling '21
$\Gamma_3^{(2)}$	Czarnecki, Melnikov, v. Ritbergen, Pak, Dowling, Bonciani, Ferroglia, Biswas, Brucherseifer, Caola '97-'13
$\Gamma_5^{(1)}$	Alberti, Gambino, Nandi, Mannel, Pivovarov, Rosenthal '13-'15
$\Gamma_6^{(1)}$	Mannel, Pivovarov '19
$\Gamma_7^{(0)}$	Dassinger, Mannel, Turczyk '06
$\Gamma_8^{(0)}$	Mannel, Turczyk, Uraltsev '10

* Only partial result

Non-leptonic (NL) modes	
$\Gamma_3^{(2)}$	Czarnecki, Slusarcyk, Tkachov '05 *
$\Gamma_3^{(1)}$	Ho-Kim, Pham, Altarelli, Petrarca, Voloshin, Bagan, Ball, Braun, Gosdzinsky, Fiol, Lenz, Nierste, Ostermaier, Krinner, Rauh '84-'13
$\Gamma_5^{(0)}$	Bigi, Uraltsev, Vainshtein, Blok, Shifman '92
$\Gamma_6^{(0)}$	Lenz, MLP, Rusov, Mannel, Moreno, Pivovarov '20-'21
$\tilde{\Gamma}_6^{(1)}$	Beneke, Buchalla, Greub, Lenz, Nierste, Franco, Lubicz, Mescia, Tarantino, Rauh '02-'13
$\tilde{\Gamma}_7^{(0)}$	Gabbiani, Onishchenko, Petrov '03-'04

☆ (pink) Fit to experimental data on semileptonic B decays ★ (orange) HQET sum rules ★ (blue) Lattice QCD

	B_d, B^+	B_s	$D^{+,0}$	D_s^+
$\langle \mathcal{O}_5 \rangle$	Bernlochner et al. '22, Gambino, Schwanda et al. '13, '14, '21 ☆ Ball, Braun, Neubert '93-'95 ★ Kronfeld, Simone, Gambino, Melis, Simula '00 -'17 ★	$SU(3)_f$-breaking for μ_π^2 Bigi, Mannel, Uraltsev '11 Spectroscopy relation for μ_G^2	HQE symmetry for μ_π^2; Spectroscopy relation for μ_G^2	HQE symmetry for μ_π^2; Spectroscopy relation for μ_G^2
$\langle \mathcal{O}_6 \rangle$	Gambino, Schwanda, Alberti Healey, Nandi '13, '14, '21 ☆ EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$	EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$		
$\langle \tilde{\mathcal{O}}_6 \rangle$	Kirk, Lenz, Rauh '17 ★	King, Lenz, Rauh '21 ★		
$\langle \tilde{\mathcal{O}}_7 \rangle$	Vacuum insertion approximation (VIA)			

2022 talk of ML Piscopo, Zadar

Lifetimes

People in 1986 were of course clever, but they were also very lucky!

1986-2022: huge progress in **multi-loop** and **non-perturbative** (sum rules and lattice yet to come) - many, many more corrections are now known

Current results are orders of magnitude more reliable, unfortunately uncertainty in B_s due to Darwin term

Mikhail Shifman
19. Juni ·

The official title of the conference was "Quirks and Quarks in Flavor Physics", but in fact it was mostly devoted to heavy quark physics. I was invited by Blaženka Melić, whom I know for many years from various others physics places where we met from time to time. Currently, she is the Head of the Division of Theoretical Physics at Ruđer Bošković Institute in Zagreb, the main Croatian physics institute.

I am very happy that I came. I was amazed by the vibrancy of this field. The heavy quark theory, unlike some other areas, feeds on experimental results from LHCb and BELL II, which continue to come uninterrupted. This is a very healthy relationship. My last serious engagement with heavy quarks (HQ) was in ~2000. Then I completely shifted to SUSY. Well ... the HQ field is not only alive and well, it thrives, evolves, grows and expands, and attracts many young researchers. What a music for my heart. I devoted at least 10 years of my career to HQ, maybe more, in the 1980s and 1990s, and I see it was not in vain. Real physics, not fantasy science.

QCD and Resonance Physics. Theoretical Foundations #1
Mikhail A. Shifman (Moscow, ITEP), A.I. Vainshtein (Moscow, ITEP), Valentin I. Zakharov (Moscow, ITEP) (1978)
Published in: *Nucl.Phys.B* 147 (1979) 385-447
DOI cite claim reference search 5,593 citations

QCD and Resonance Physics: Applications #2
Mikhail A. Shifman (Moscow, ITEP), A.I. Vainshtein (Moscow, ITEP), Valentin I. Zakharov (Moscow, ITEP) (1978)
Published in: *Nucl.Phys.B* 147 (1979) 448-518
DOI cite claim reference search 3,070 citations

Jun 14 – 17, 2022
Zadar, Croatia
Europe/Berlin timezone

Contact
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alexander.lenz@uni-sie...
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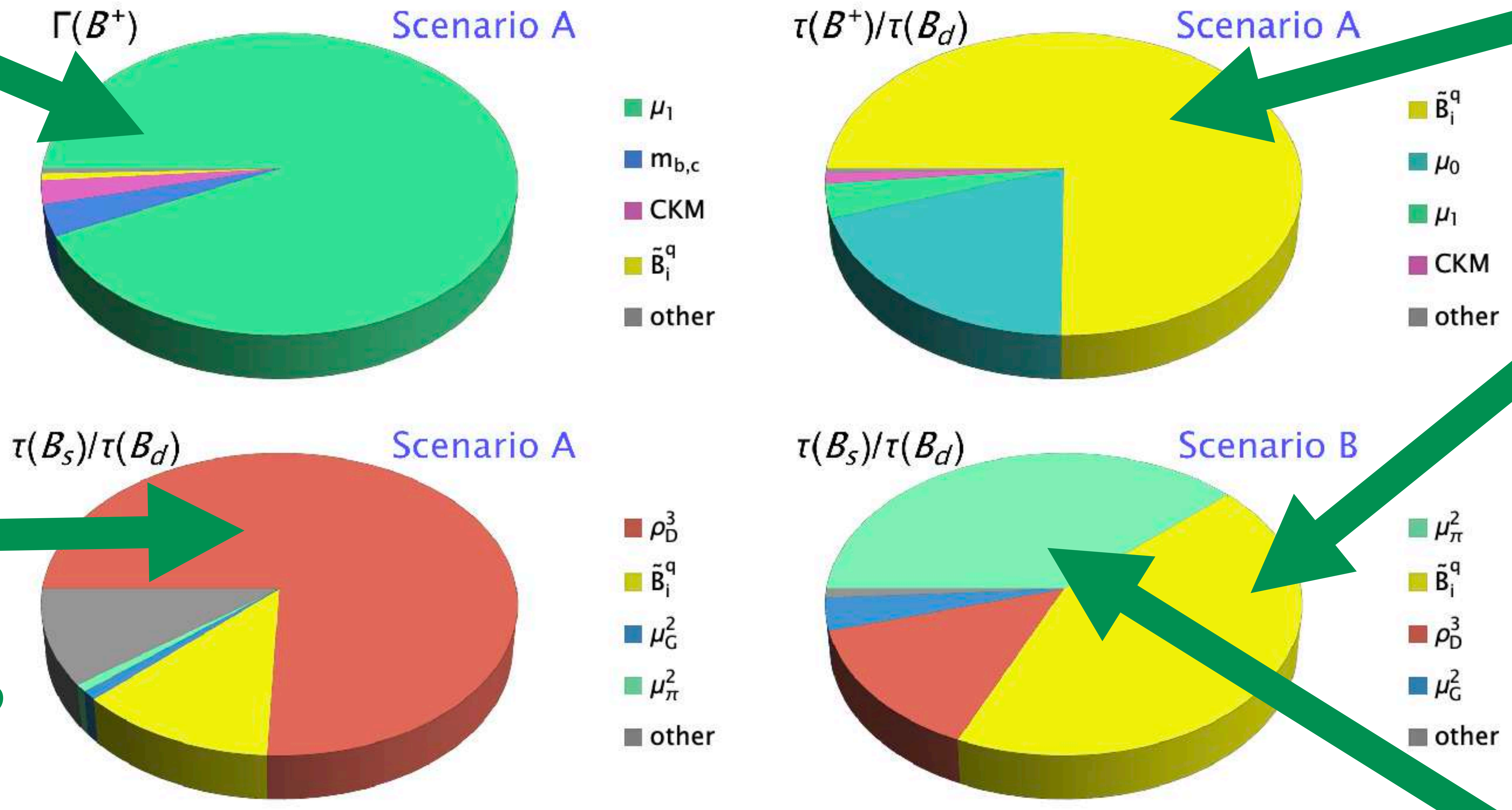
Lifetimes

2035: Room for improvement

NNLO: Steinhauser and friends, planned

Lattice: Black, Witzel and friends, planned



- **Improved V_{cb} fits**
- **Fit of inclusive semileptonic decays**
- **SU(3)F breaking in ρ_D^3 Lattice? Sum rules?**

- **Fit of inclusive semileptonic B_s decays**
- **SU(3)F breaking in μ_π^2 Lattice? Sum rules?**

AL, Piscopo, Rusov 2022

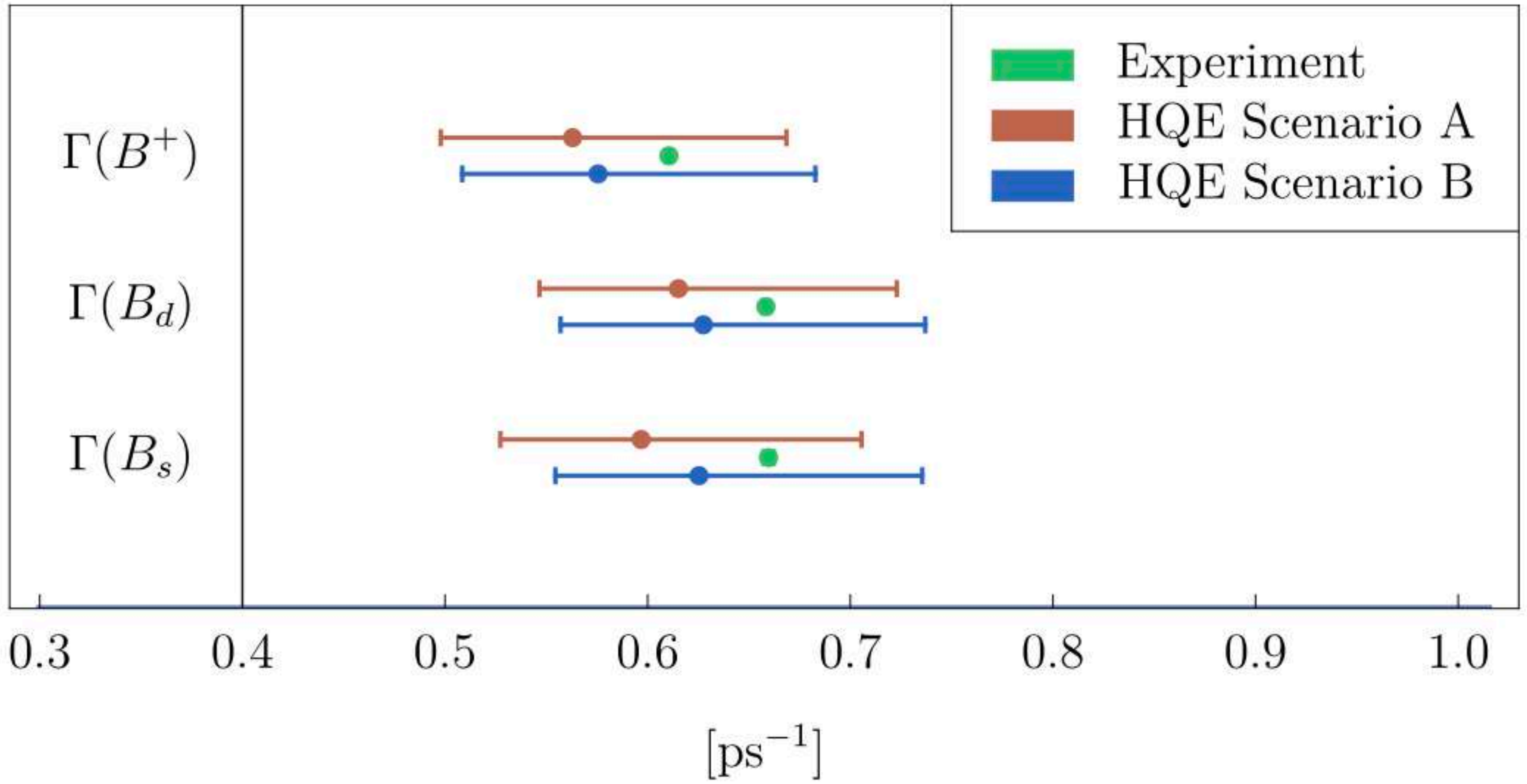
More multi-loop and more non-perturbative calculations needed

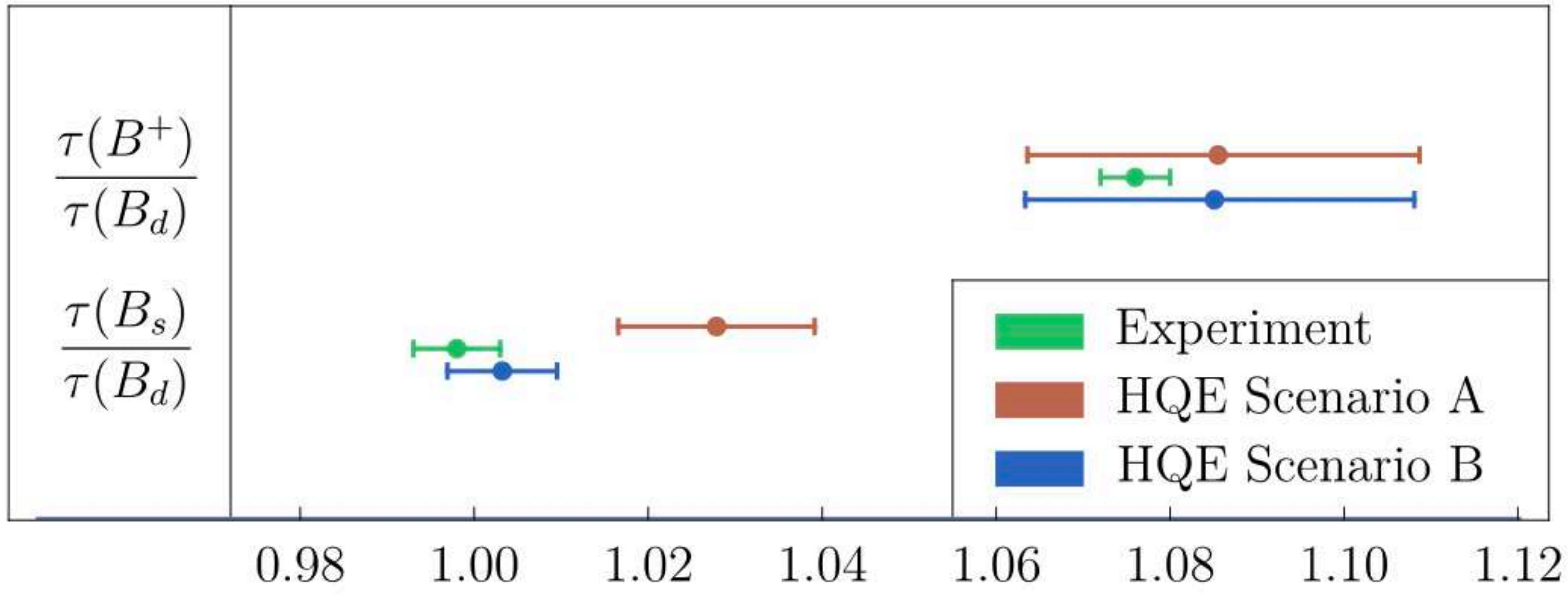
Lifetimes

We can argue about exact precision

Aim:

- Understand one of the most fundamental properties of elementary particles
- Understand the hadronic interaction which is binding quarks into hadrons





AL, Piscopo, Rusov 2022

- Do consistency checks (indirect new physics searches) of the known laws of nature (SM)

$$\frac{\tau(B^+)}{\tau(B_d)}^{\rm HQE} = 1 + \left[\Gamma^{\rm SM}(B_d) - \Gamma^{\rm SM}(B^+)\right] \tau^{\rm Exp.}(B^+) + \left[\Gamma^{\rm BSM}(B_d) - \Gamma^{\rm BSM}(B^+)\right] \tau^{\rm Exp.}(B^+) \,.$$

See below

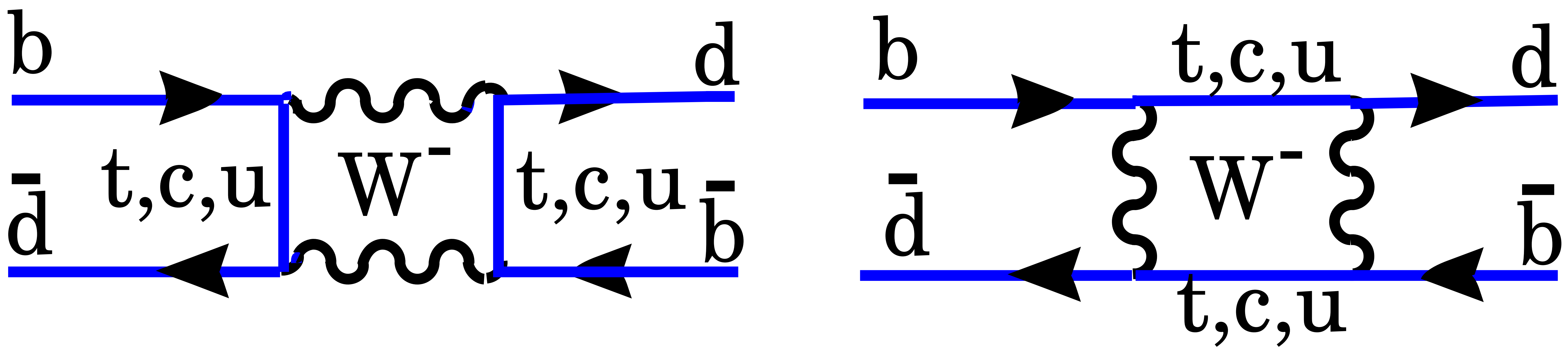
Mixing

Aim:

- Understand the quantum mechanical property of mixing of neutral mesons
- Understand the hadronic interaction which is binding quarks into hadrons

- Do consistency checks (indirect new physics searches) of the known laws of nature (SM)

B-MIXING



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

Do not denote:
$\phi_s = \arg(-M_{12}/\Gamma_{12})$!

- **Mass difference:** $\Delta M := M_H - M_L \approx 2|M_{12}|$ **(off-shell)**
  $|M_{12}|$: heavy internal particles: t, SUSY, ...
- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi_{12}$ **(on-shell)**
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!
- **Flavor specific/semi-leptonic CP asymmetries:** e.g. $B_q \to Xl\nu$ (*semi-leptonic*)

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

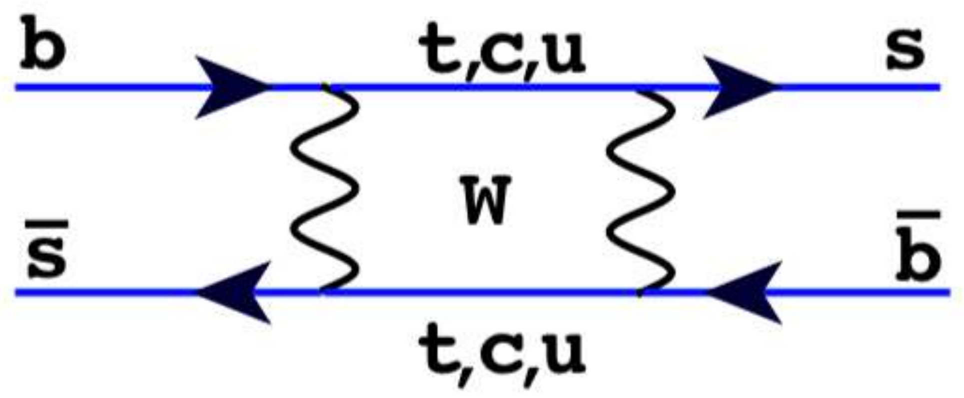
Mass difference ΔM_q

Experiment: HFLAV 2022

$$\Delta m_s = 17.765 \pm 0.006\ \mathrm{ps}^{-1}$$

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

Theory



CKM $\lambda_t = V_{tb} V_{ts}^*$

Inami-Lim

Buras Jamin Weisz

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

Multi-loop

In the SM one operator:

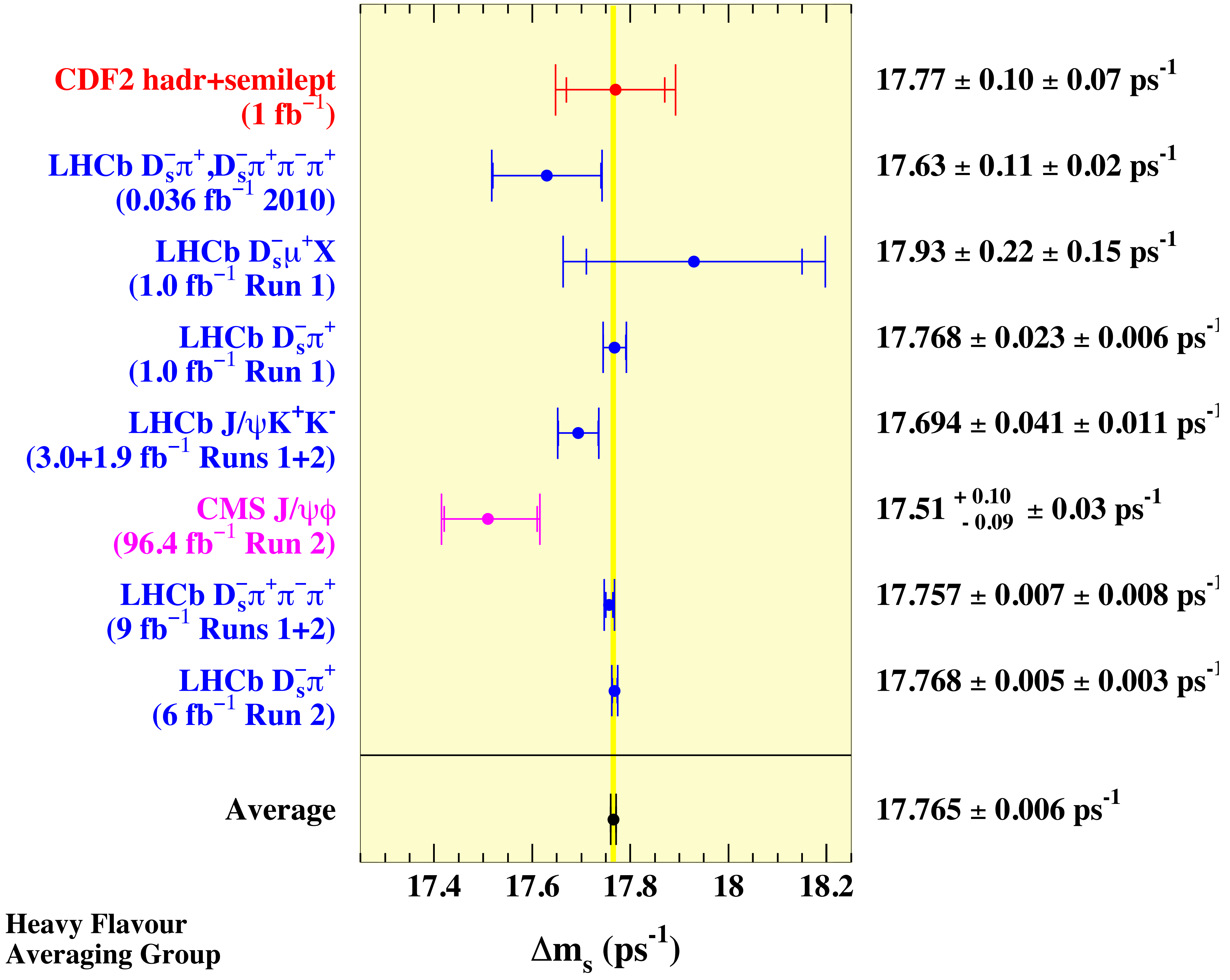
$$Q = \bar{s}^\alpha \gamma_\mu (1-\gamma_5) b^\alpha \times \bar{s}^\beta \gamma^\mu (1-\gamma_5) b^\beta$$

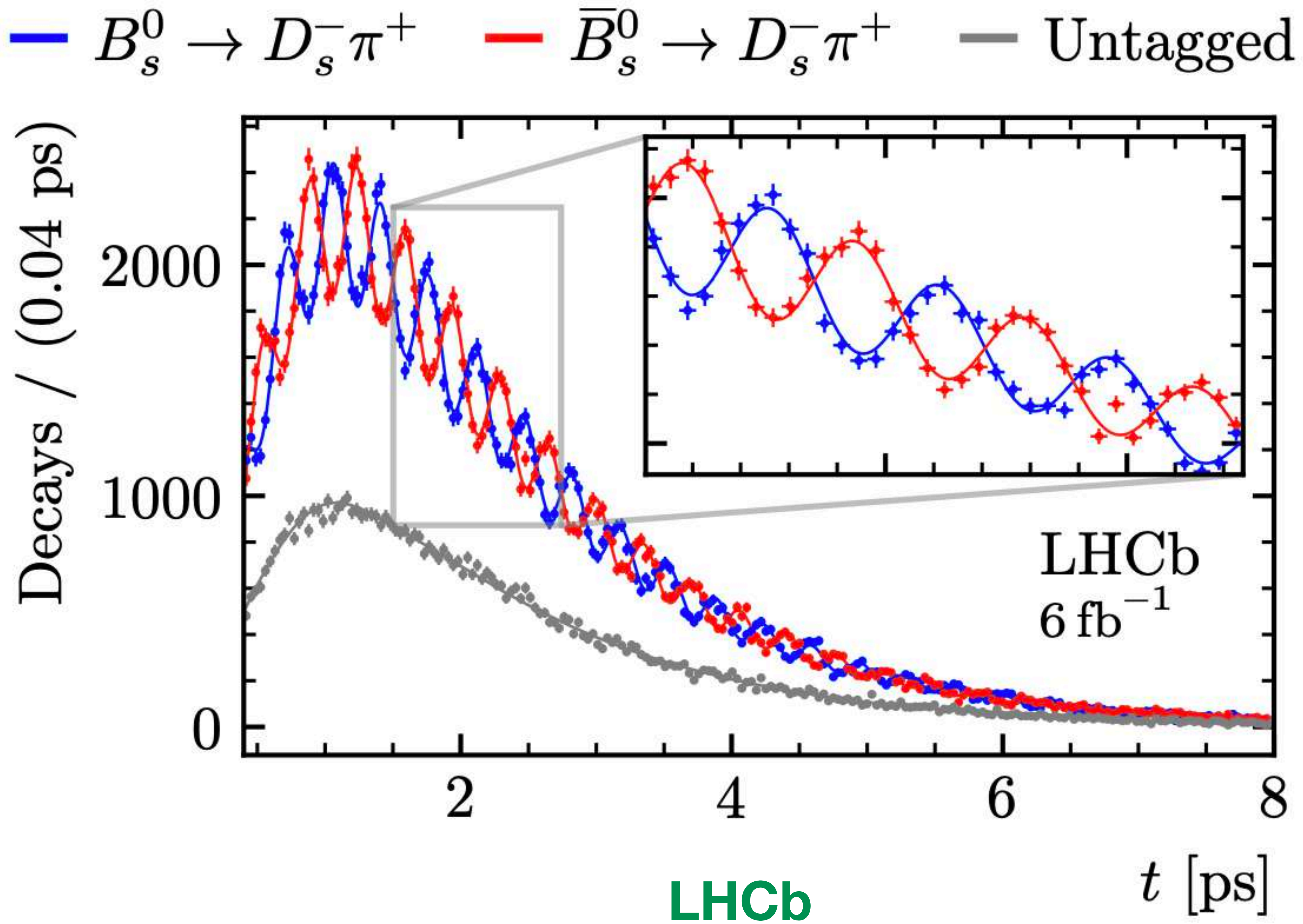
$$\langle Q \rangle \equiv \langle B_s^0 | Q | \bar{B}_s^0 \rangle = \frac{8}{3} M_{B_s}^2 f_{B_s}^2 B(\mu)$$

Non-perturbative theory input:

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

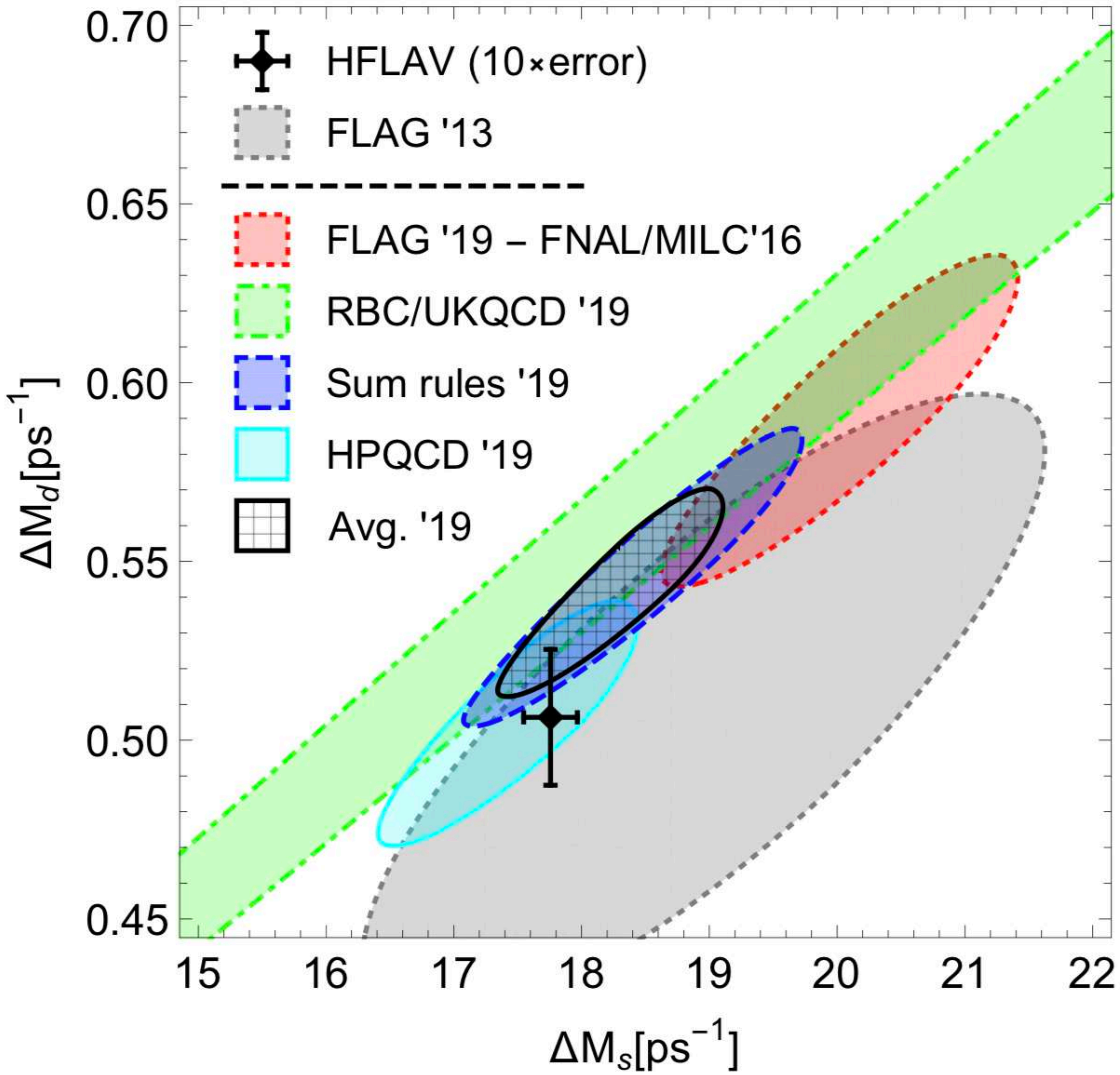
Mass difference ΔM_q





LHCb
2104.04421

Mass difference ΔM_q



Why is this interesting?

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

Active field:

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

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

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

Mass difference ΔM_q

Theory error budget

AL, Tetlalmatzi-Xolocotzi 1912.07621

- Non-perturbative averages of lattice and sum rules, Di Luzio, Kirk, AL, Rauh, 1909.11087
- CKM fitter input from 12/2019

$$\Delta M_s^{SM} = (18.77 \pm 0.86)\,\mathrm{ps}^{-1}\,,$$
$$\Delta M_d^{SM} = (0.543 \pm 0.029)\,\mathrm{ps}^{-1}\,,$$

ΔM_s^{SM}	This work	ABL 2015	LN 2011	LN 2006
Central Value	$18.77\,\mathrm{ps}^{-1}$	$18.3\,\mathrm{ps}^{-1}$	$17.3\,\mathrm{ps}^{-1}$	$19.3\,\mathrm{ps}^{-1}$
$f_{B_s}\sqrt{B_1^s}$	3.1%	13.9%	13.5%	34.1%
V_{cb}	3.4%	4.9%	3.4%	4.9%
$\bar{m}_t(\bar{m}_t)$	0.3%	0.7%	1.1%	1.8%
Λ_5^{QCD}	0.2%	0.1%	0.4%	2.0%
γ	0.1%	0.1%	0.3%	1.0%
$\|V_{ub}/V_{cb}\|$	$< 0.1\%$	0.1%	0.2%	0.5%
$\overline{m}_b$	$< 0.1\%$	$< 0.1\%$	0.1%	$- - -$
Total	4.6%	14.8%	14.0%	34.6%

Huge improvement/no improvement

Mass difference ΔM_q

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$\Lambda_5^{\rm QCD}$	0.2%	0.1%	0.4%	2.0%
γ	0.1%	0.1%	0.3%	1.0%
$\lvert V_{ub}/V_{cb}\rvert$	< 0.1%	0.1%	0.2%	0.5%
$\overline{m}_b$	< 0.1%	< 0.1%	0.1%	$- - -$
Total	4.6%	14.8%	14.0%	34.6%

BUT

δM_s

FNAL16 $f_{B_s}\sqrt{\hat{B}} = 274(8)\,{\rm MeV}\ ({\rm N_f} = 2+1)\,,$ **5.8%**

HPQCD19 $f_{B_s}\sqrt{\hat{B}} = 256.1(5.7)\,{\rm MeV}\ ({\rm N_f} = 2+1+1)\,.$ **4.4%**

Average lattice /sum rule **3.1%**

Huge improvement/no improvement

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Average lattice /sum rule **3.1%**

Lattice predictions cover the range 250.4…282 MeV => 266.2(15.8) MeV **11.9%**

Mass difference ΔM_q

Theory error budget **AL, Tetlalmatzi-Xolocotzi 1912.07621**

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Lattice predictions cover the range
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vs. projections: 1812.07638

2035: $f_{B_s}, \hat{B} \sim$ **0.5%** **1%**

a long, long way to go

Mass difference ΔM_q

Theory error budget **AL, Tetlalmatzi-Xolocotzi 1912.07621**

Assume lattice can do $\pm 1\ \%$

ΔM_s^{SM}	This work	ABL 2015	LN 2011	LN 2006
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Total	4.6%	14.8%	14.0%	34.6%

Huge improvement/no improvement

Within the SM

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

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

δM_s

$$|V_{cb}|^{\text{incl.,2022}} = (42.16 \pm 0.51)\cdot 10^{-3} \qquad 2.4\%$$

Bordone, Capdevilla, Gambino 2107.00604

$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9)\cdot 10^{-3} \qquad 4.6\%$$

$$|V_{cb}|^{\Delta M_q} = (41.6 \pm 0.7)\cdot 10^{-3} \qquad 3.4\%$$

King, Kirk, AL, Rauh 1911.07856

$V_{cb}^{\text{Incl.}} \Rightarrow \Delta M_s \equiv \text{SM}$ $\qquad$ $V_{cb}^{\text{Excl.}} \Rightarrow \Delta M_s \equiv \text{BSM}$

Mass difference ΔM_q

Theory error budget **AL, Tetlalmatzi-Xolocotzi 1912.07621**

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$$|V_{cb}|^{\Delta M_q} = (41.6 \pm 0.7) \cdot 10^{-3} \qquad 3.4\%$$

King, Kirk, AL, Rauh 1911.07856

Inclusive and exclusive cover the range

$$(38.6 \ldots 42.67) \cdot 10^{-3}$$

$$=(40.7 \pm 2.0) \cdot 10^{-3} \qquad 10\%$$

For $\pm 1\ \%$ we need $\delta V_{cb} \approx 0.2 \cdot 10^{-3}$

Mass difference ΔM_q

Theory error budget **AL, Tetlalmatzi-Xolocotzi 1912.07621**

Assume lattice and V_{cb} can do $\pm 1\ \%$

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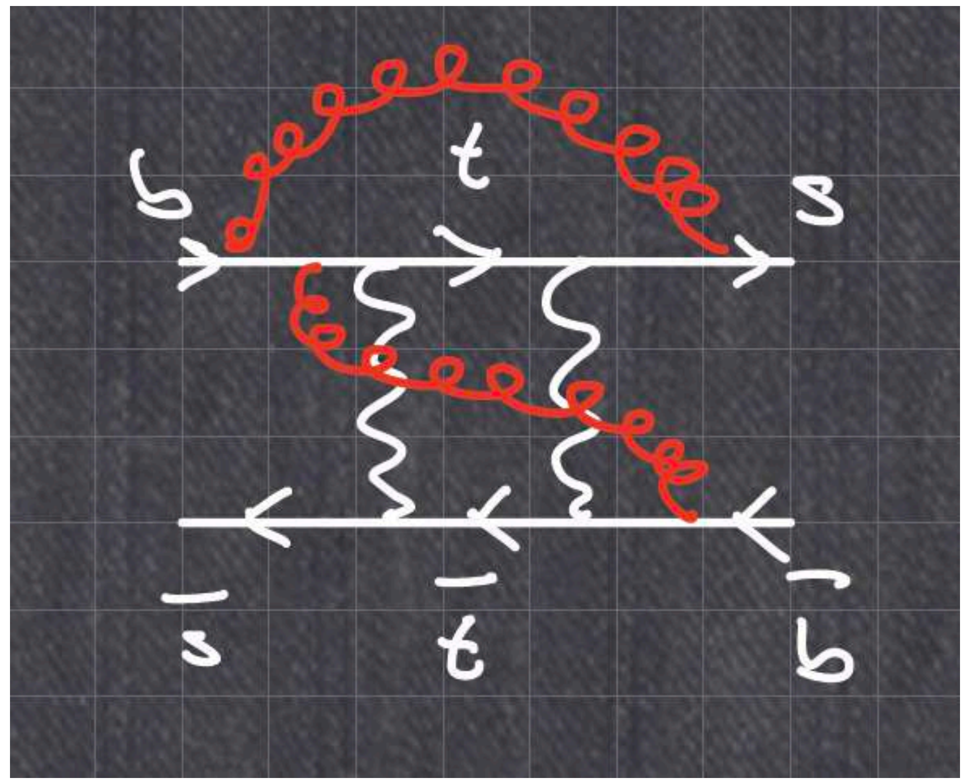
3-loop QCD corrections



2-loop QCD corrections: **Buras, Jamin, Weisz 1990**

$$1 \to \eta_B \approx 0.84$$

expect an effect of $\pm 0.16\, \alpha_s/\pi = \pm\, 1\ \%$

Gorbahn, Stamou,...? > 2035

Mass difference ΔM_q

2035:

- Assume: Lattice values for dim 6 matrix elements converge
- Assume: V_{cb} inclusive vs exclusive converges and direct measurement at FCC-ee
- Assume: 3-loop corrections known and confirmed

Mass difference ΔM_q

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- Assume: Lattice values for dim 6 matrix elements converge
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$$\Delta M_s^{\mathrm{SM},2035} = (19.20 \pm 0.29)\,\mathrm{ps}^{-1}$$

$$\Delta M_s^{\mathrm{EXP},2035} = (17.750 \pm 0.002)\,\mathrm{ps}^{-1}$$

Discovery of BSM with 5 standard deviations

Mass difference ΔM_q

2035:

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- Assume: V_{cb} inclusive vs exclusive converge and direct measurement at FCC-ee
- Assume: 3-loop corrections known and confirmed

$$\Delta M_s^{\mathrm{SM},2035} = (17.75 \pm 0.29)\,\mathrm{ps}^{-1}$$

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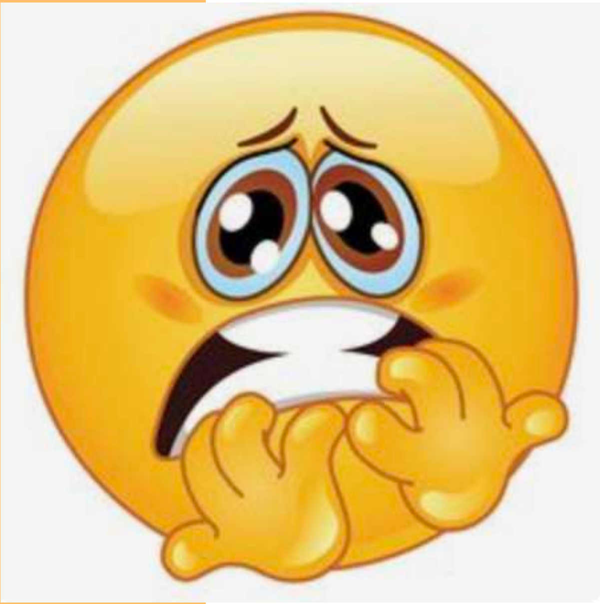


Impressive confirmation of the SM description of mixing

Decay rate difference $\Delta\Gamma_s$

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

$$\Gamma_{12} = 16\pi^2 \left(\tilde{\Gamma}_6 \frac{\langle \tilde{O}_6 \rangle}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{O}_7 \rangle}{m_b^4} + \ldots \right)$$

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

$$\Gamma_i = \Gamma_i^{(0)} + \frac{\alpha_s}{4\pi} \Gamma_i^{(1)} + \left(\frac{\alpha_s}{4\pi} \right)^2 \Gamma_i^{(2)} + \ldots$$

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

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

Sum rules and lattice 1909.11087

Status of theory predictions known HPQCD 1910.00970

Q_1, Q_2, Q_3 Q_4, Q_5, R_2, R_3

Obs.	$\tilde{\Gamma}_6^{(0)}$	$\tilde{\Gamma}_6^{(1)}$	$\tilde{\Gamma}_6^{(2)}$	$\langle \mathcal{O}^{d=6} \rangle$	$\tilde{\Gamma}_7^{(0)}$	$\tilde{\Gamma}_7^{(1)}$	$\langle \mathcal{O}^{d=7} \rangle$	$\sum$
Γ_{12}^s	$++$	$++$	$+$	$+++$	$++$	0	$+$	$11 + (***)$
Γ_{12}^d	$++$	$++$	$+$	$+++$	$++$	0	$+$	$11 + (***)$

NNLO-QCD
Gerlach,
Nierste,
Shtabovenko,
Steinhauser
2205.07907

Decay rate difference $\Delta\Gamma_s$

In Γ_{12}/M_{12} uncertainties (e.g. V_{cb}) are cancelling

$$\mathrm{Re}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right) = -\frac{\Delta\Gamma_s}{\Delta M_s}, \quad \mathrm{Im}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right) = a_{fs}^s .$$

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

see talk by Vlad on Tuesday

$$\frac{V_{ub}V_{ud}}{V_{tb}V_{td}} = \lambda^{0.8} \qquad \frac{V_{ub}V_{us}}{V_{tb}V_{ts}} = \lambda^{2.8}$$

- No CKM dependence!
- No GIM suppression!
- No imaginary part!
- Small $\approx \mathcal{O}(5 \cdot 10^{-3})$
- Leading contribution to $\Delta\Gamma/\Delta M$

- CKM suppression
- GIM suppression
- Imaginary part via CKM
- Leading contribution to a_{fs}
- Tiny contribution to $\Delta\Gamma/\Delta M$

- Stronger CKM suppression
- Very strong GIM suppression
- Imaginary part via CKM
- Subleading contribution to a_{fs} and sub-subleading contribution to $\Delta\Gamma/\Delta M$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = \left(4.33 \pm 0.78\,(1/m_b)^{+0.23}_{-0.44}\,(\mu)^{+0.09}_{-0.19}\,(\mu,1/m_b) \pm 0.12\,(B) \pm 0.05\,(para.)\right)$$

NNLO-QCD: Gerlach, Nierste, Shtabovenko, Steinhauser 2205.07907

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**
- **V_{cb} dependence cancels!**

SM predictions (AL, Tetlalmatzi-Xolocotzi 1912.07621, Gerlach, Nierste, Shtabovenko, Steinhauser 2205.07907)

$$\Delta\Gamma_s^{\mathrm{SM2019}} = (0.091 \pm 0.013)\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_s^{\mathrm{SM2022}} = (0.076 \pm 0.017)\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_s^{\mathrm{HFLAV2022}} = (0.084 \pm 0.005)\,\mathrm{ps}^{-1}$$

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

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

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

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

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

$\Delta\Gamma_s^{SM}/\Delta M_s^{SM}$	this work	ABL 2015	LN 2011	LN 2006
Central Value	$48.2 \cdot 10^{-4}$	$48.1 \cdot 10^{-4}$	$50.4 \cdot 10^{-4}$	$49.7 \cdot 10^{-4}$
$B_{R_2}^s$	10.9%	14.8%	17.2%	15.7%
μ	6.6%	8.4%	7.8%	9.1%
$B_{R_0}^s$	3.2%	2.1%	3.4%	3.0%
B_3^s	2.2%	2.1%	4.8%	3.1%
$\bar{z}$	0.9%	1.1%	1.5%	1.9%
m_b	0.9%	0.8%	1.4%	1.0%
$B_{R_3}^s$	0.5%	0.2%	0.2%	− − −
$B_{\tilde{R}_3}^s$	−	0.6%	0.5%	− − −−
$\bar{m}_t(\bar{m}_t)$	0.3%	0.7%	1.1%	1.8%
m_s	0.3%	0.1%	1.0%	0.1%
Λ_5^{QCD}	0.2%	0.2%	0.8%	0.1%
$B_{\tilde{R}_1}^s$	0.2%	0.7%	1.9%	− − −
$B_{R_1}^s$	0.1%	0.5%	0.8%	− − −
γ	< 0.1%	0.0%	0.0%	0.1%
$\lvert V_{ub}/V_{cb}\rvert$	< 0.1%	0.0%	0.0%	0.1%
V_{cb}	< 0.1%	0.0%	0.0%	0.0%
Total	13.4%	17.3%	20.1%	18.9%

Decay rate difference $\Delta\Gamma_s$

2035:

- Lattice and sum rule values for dim 7 matrix elements
- Better understanding of quark masses
- α_s/m_b corrections determined
- Lattice values for dim 6 matrix elements converge

Decay rate difference $\Delta\Gamma_s$

2035:

- Lattice and sum rule values for dim 7 matrix elements
- Better understanding of quark masses
- α_s/m_b corrections determined
- Lattice values for dim 6 matrix elements converge

$$\Delta\Gamma_s^{\mathrm{SM2035}} = (0.085 \pm 0.005)\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma_s^{\mathrm{HFLAV2035}} = (0.080 \pm 0.002)\,\mathrm{ps}^{-1}$$

Amazing confirmation of HQE framework

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 (AL, Tetlalmatzi-Xolocotzi 1912.07621)

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

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

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

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

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

- Very sensitive to BSM effects!
- Experimental number needed

I am not asking, when will we get an update on $R_K, \ldots$, but when will we get an update on a_{sl}^q ?

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!

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

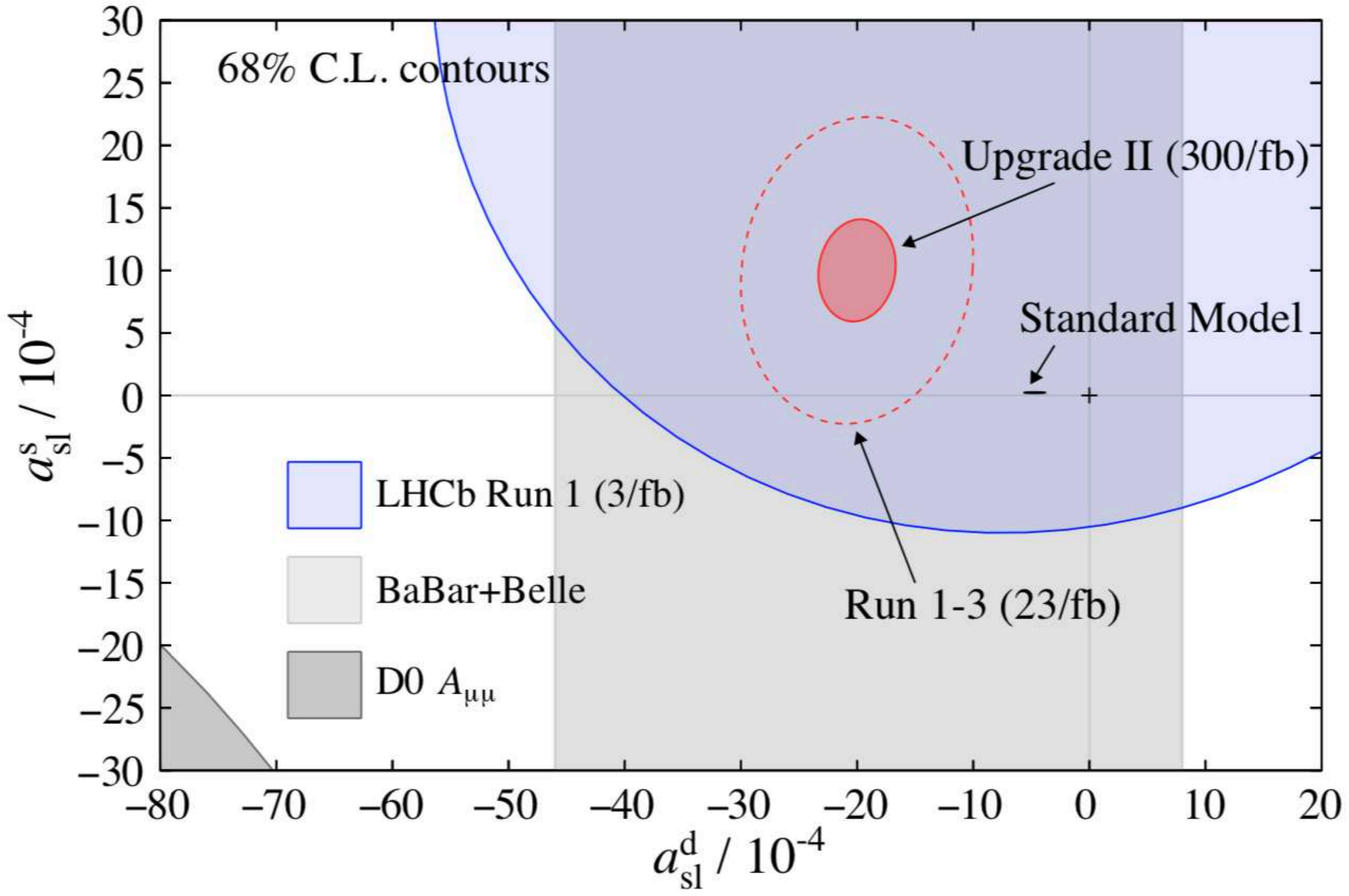
- **Decay constants cancel completely**
- **Bag parameter cancel largely**

SM predictions

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

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

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



$\delta a_{sl}^s \approx 3\cdot 10^{-5}$ **Monteil, 12.9.2022 flavour@FCCee! (p.23)**

As soon as exp gets very close to SM:

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

Renormalization scale setting for D-meson mixing

Alexander Lenz,[1,2,*] Maria Laura Piscopo,[1,†] and Christos Vlahos[1,‡]
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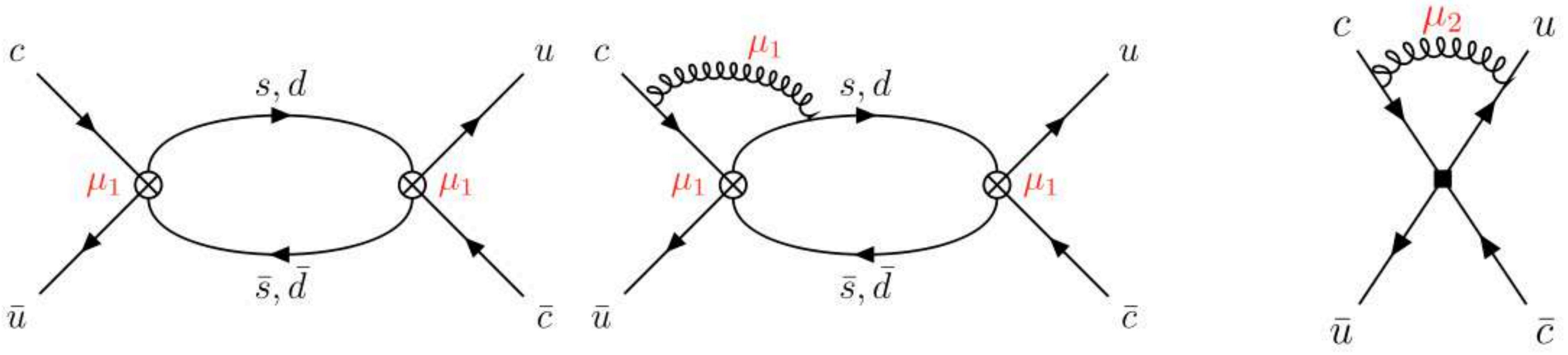
(Received 20 July 2020; accepted 7 October 2020; published 13 November 2020)

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



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

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

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

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

Semi-leptonic CP asymmetries

2035:
- Better understanding of GIM cancellations
- NNLO analysis
- Better understanding of quark masses
- Better knowledge of CKM elements
- Lattice and sum rule values for dim 7 matrix elements
- α_s/m_b corrections determined

$a_{sl}^{s,\mathrm{SM}}$	this work	ABL 2015	LN 2011	LN 2006
Central Value	$2.06 \cdot 10^{-5}$	$2.22 \cdot 10^{-5}$	$1.90 \cdot 10^{-5}$	$2.06 \cdot 10^{-5}$
μ	6.7%	9.5%	8.9%	12.7%
$\bar{z}$	4.0%	4.6%	7.9%	9.3%
$\|V_{ub}/V_{cb}\|$	2.6%	5.0%	11.6%	19.5%
$B_{R_3}^s$	2.3%	1.1%	1.2%	1.1%
$B_{\tilde{R}_3}^s$	-	2.6%	2.8%	2.5%
m_b	1.3%	1.0%	2.0%	3.7%
γ	1.1%	1.3%	3.1%	11.3%
$B_{R_2}^s$	0.8%	0.1%	0.1%	– – –
Λ_5^{QCD}	0.6%	0.5%	1.8%	0.7%
$\bar{m}_t(\bar{m}_t)$	0.3%	0.7%	1.1%	1.8%
B_3^s	0.3%	0.3%	0.6%	0.4%
$B_{R_0}^s$	0.3%	0.2%	0.3%	– – –
m_s	< 0.1%	0.1%	0.1%	0.1%
$B_{\tilde{R}_1}^s$	< 0.1%	0.5%	0.2%	– – –
$B_{R_1}^s$	< 0.1%	< 0.1%	0.0%	– – –
V_{cb}	< 0.1%	0.0%	0.0%	0.0%
Total	8.8%	12.2%	17.3%	27.9%

$$a_{fs}^{s,\mathrm{SM2035}} = (2.0 \pm 0.2) \cdot 10^{-5} \qquad a_{fs}^{s,\mathrm{HFLAV2035}} = (-60 \pm 30) \cdot 10^{-5}$$

$$a_{fs}^{d,\mathrm{SM2035}} = -(4.7 \pm 0.4) \cdot 10^{-4} \qquad a_{fs}^{d,\mathrm{HFLAV2035}} = (-21.0 \pm 3.0) \cdot 10^{-4}$$

Discovery of BSM with more than 5 standard deviations

Semi-leptonic CP asymmetries

2035:
- Better understanding of GIM cancellations
- NNLO analysis
- Better understanding of quark masses
- Better knowledge of CKM elements
- Lattice and sum rule values for dim 7 matrix elements
- α_s/m_b corrections determined

$a_{sl}^{s,SM}$	this work	ABL 2015	LN 2011	LN 2006
Central Value	$2.06 \cdot 10^{-5}$	$2.22 \cdot 10^{-5}$	$1.90 \cdot 10^{-5}$	$2.06 \cdot 10^{-5}$
μ	6.7%	9.5%	8.9%	12.7%
$\bar{z}$	4.0%	4.6%	7.9%	9.3%
$\|V_{ub}/V_{cb}\|$	2.6%	5.0%	11.6%	19.5%
$B_{R_3}^s$	2.3%	1.1%	1.2%	1.1%
$B_{\tilde{R}_3}^s$	-	2.6%	2.8%	2.5%
m_b	1.3%	1.0%	2.0%	3.7%
γ	1.1%	1.3%	3.1%	11.3%
$B_{R_2}^s$	0.8%	0.1%	0.1%	$---$
Λ_5^{QCD}	0.6%	0.5%	1.8%	0.7%
$\bar{m}_t(\bar{m}_t)$	0.3%	0.7%	1.1%	1.8%
B_3^s	0.3%	0.3%	0.6%	0.4%
$B_{R_0}^s$	0.3%	0.2%	0.3%	$---$
m_s	$< 0.1\%$	0.1%	0.1%	0.1%
$B_{\tilde{R}_1}^s$	$< 0.1\%$	0.5%	0.2%	$---$
$B_{R_1}^s$	$< 0.1\%$	$< 0.1\%$	0.0%	$---$
V_{cb}	$< 0.1\%$	0.0%	0.0%	0.0%
Total	8.8%	12.2%	17.3%	27.9%

$\delta a_{sl}^s \approx 3 \cdot 10^{-5}$ **Monteil, 12.9.2022 flavour@FCCee! (p.23)**

$$a_{fs}^{s,\mathrm{SM2035}} = (2.0 \pm 0.2) \cdot 10^{-5} \qquad a_{fs}^{s,\mathrm{HFLAV2055}} = (-60 \pm 3) \cdot 10^{-5}$$

$$a_{fs}^{d,\mathrm{SM2035}} = -(4.7 \pm 0.4) \cdot 10^{-4} \qquad a_{fs}^{d,\mathrm{HFLAV2055}} = (-21.0 \pm 0.3) \cdot 10^{-4}$$

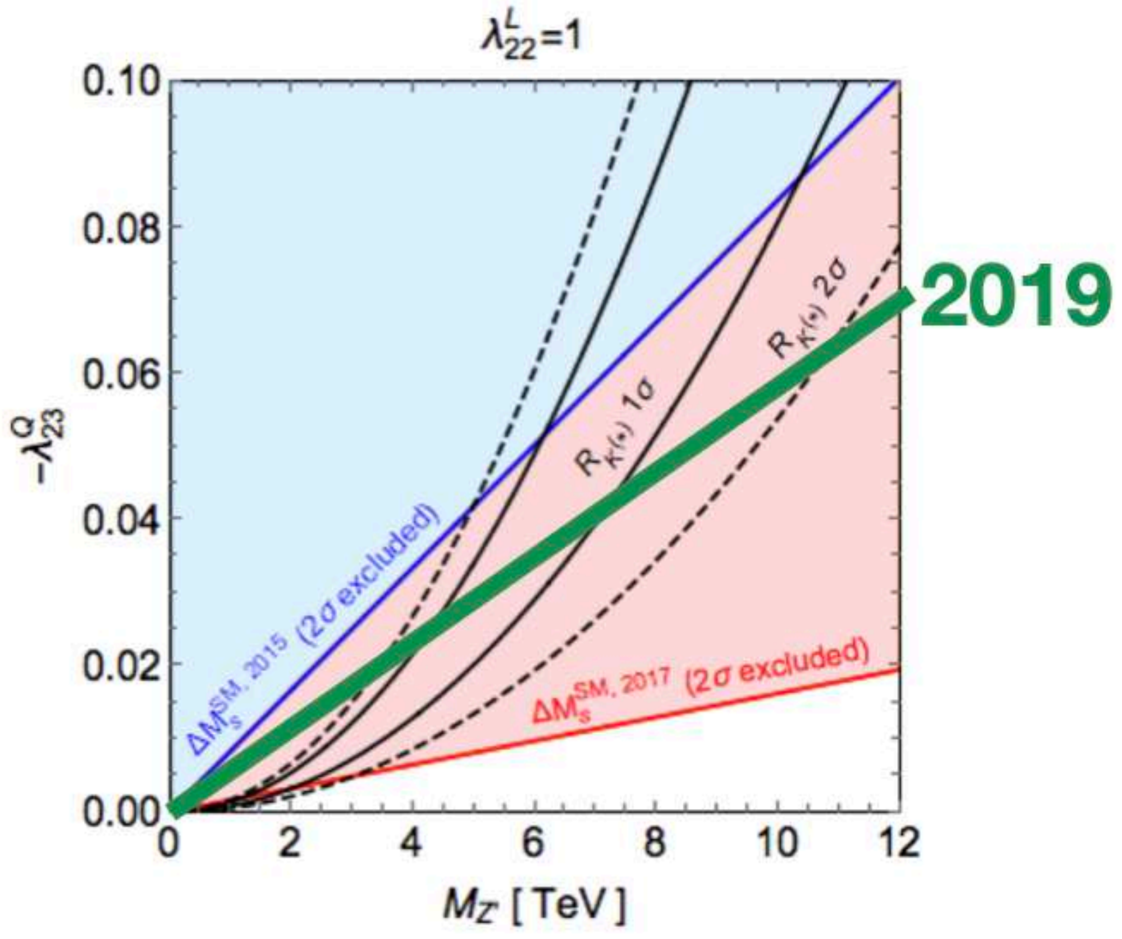
Discovery of BSM with more than 20 standard deviations

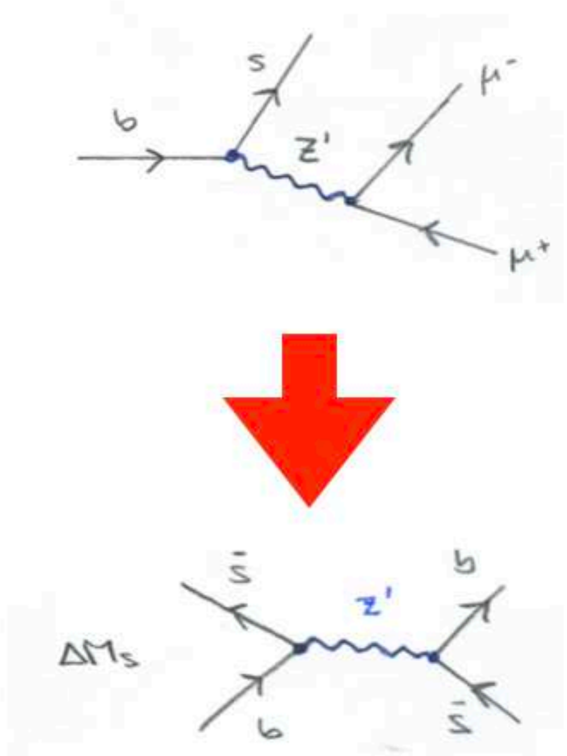
Mixing

Aim:

We can argue about exact precision

- Understand the quantum mechanical property of mixing of neutral mesons
- Understand the hadronic interaction which is binding quarks into hadrons
- Do consistency checks (indirect new physics searches) of the known laws of nature (SM)





One constraint to kill them all?

Luca Di Luzio,[1,*] Matthew Kirk,[1,†] and Alexander Lenz[1,‡]

[1] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, DH1 3LE, Durham, United Kingdom*

PHYSICAL REVIEW D **97,** 095035 (2018)

Updated B_s-mixing constraints on new physics models for $b \to s\ell^+\ell^-$ anomalies

More precise value for a^q_{sl} will be a killer or an enabler for many BSM scenarios!

NP in non-leptonic tree-level decays

Aim:

- Understand the hadronic interaction which is binding quarks into hadrons and their interactions in a very complicated environment

- Seems to be super far away from exciting BSM searches!

Cambridge dictionary: boring

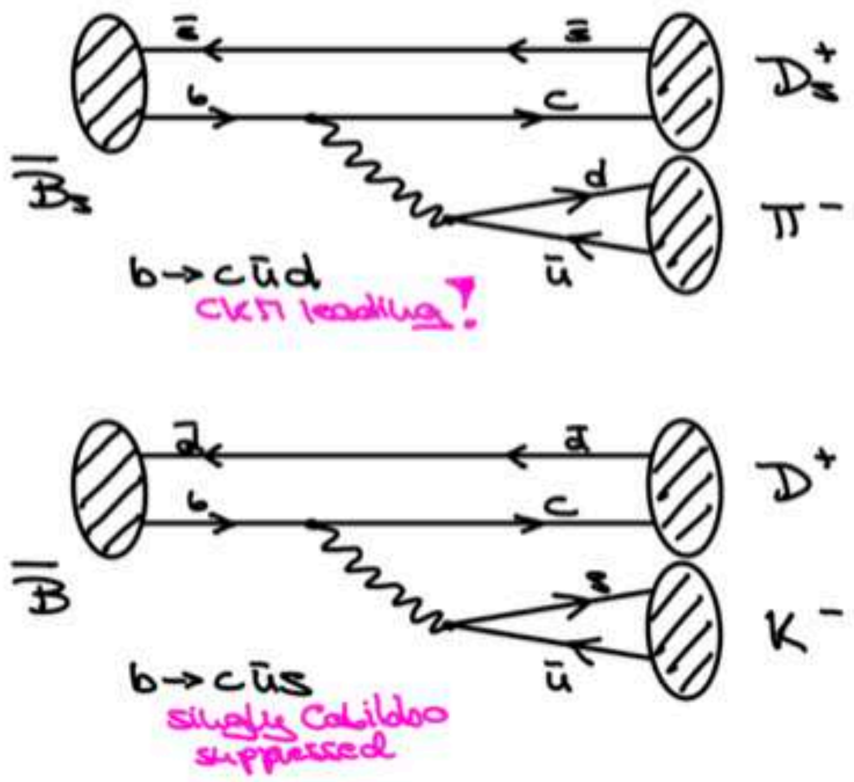
NP in non-leptonic tree-level decays

3 σ to 9 σ deviation of experiment from QCDf predictions with standard error estimates

N. Skidmore

See also talk of Eleftheria Malami

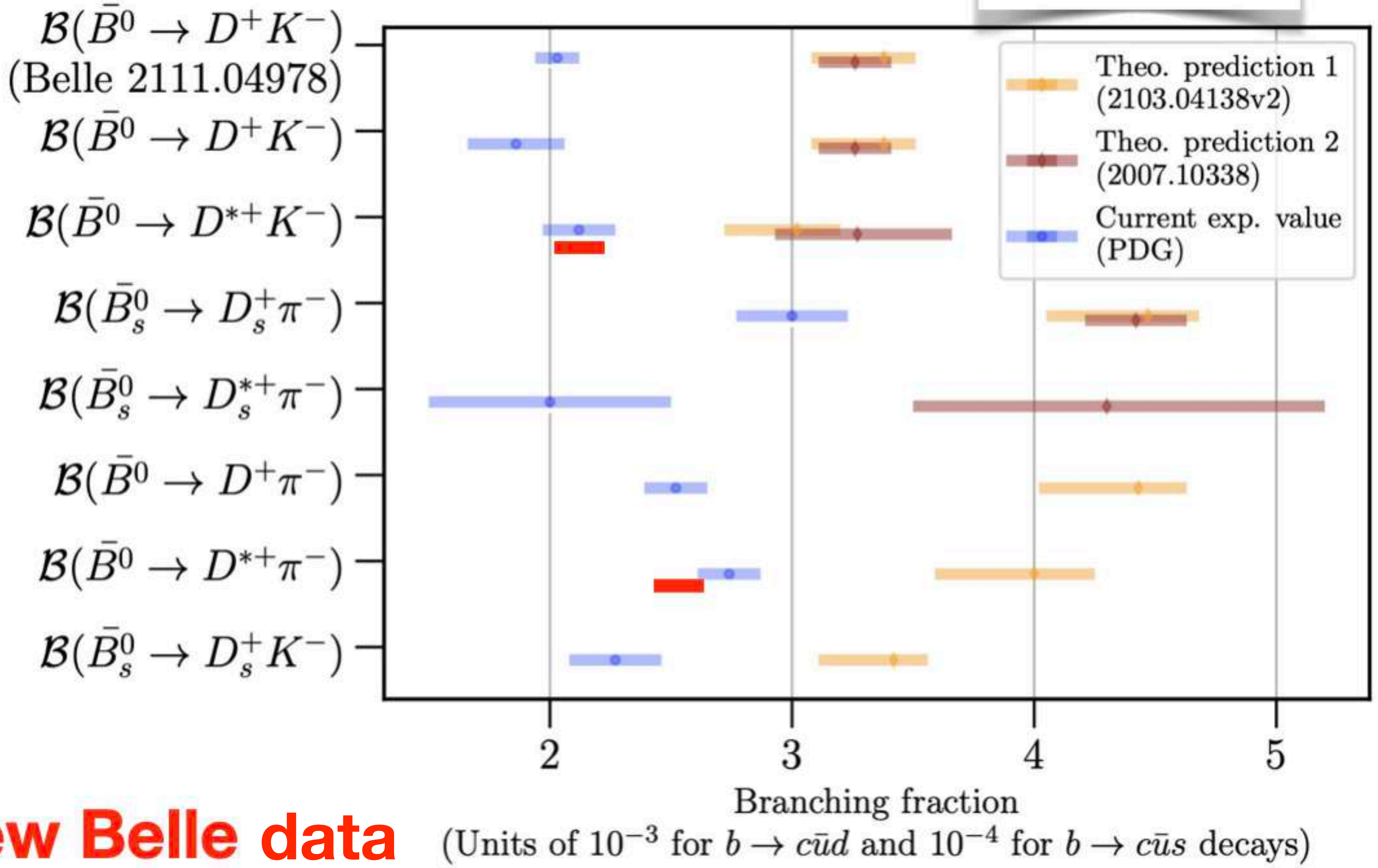
Colour-allowed Tree-level Decays



- CKM leading decays
- The are no annihilation, penguins,...
- QCDf should work at its best!

Beneke, Buchalla, Neubert, Sachrajda 1999...

$$\langle D_q^{(*)+} L^- | \mathcal{Q}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \times \int_0^1 du\, T_{ij}(u) \phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)$$



— New Belle data

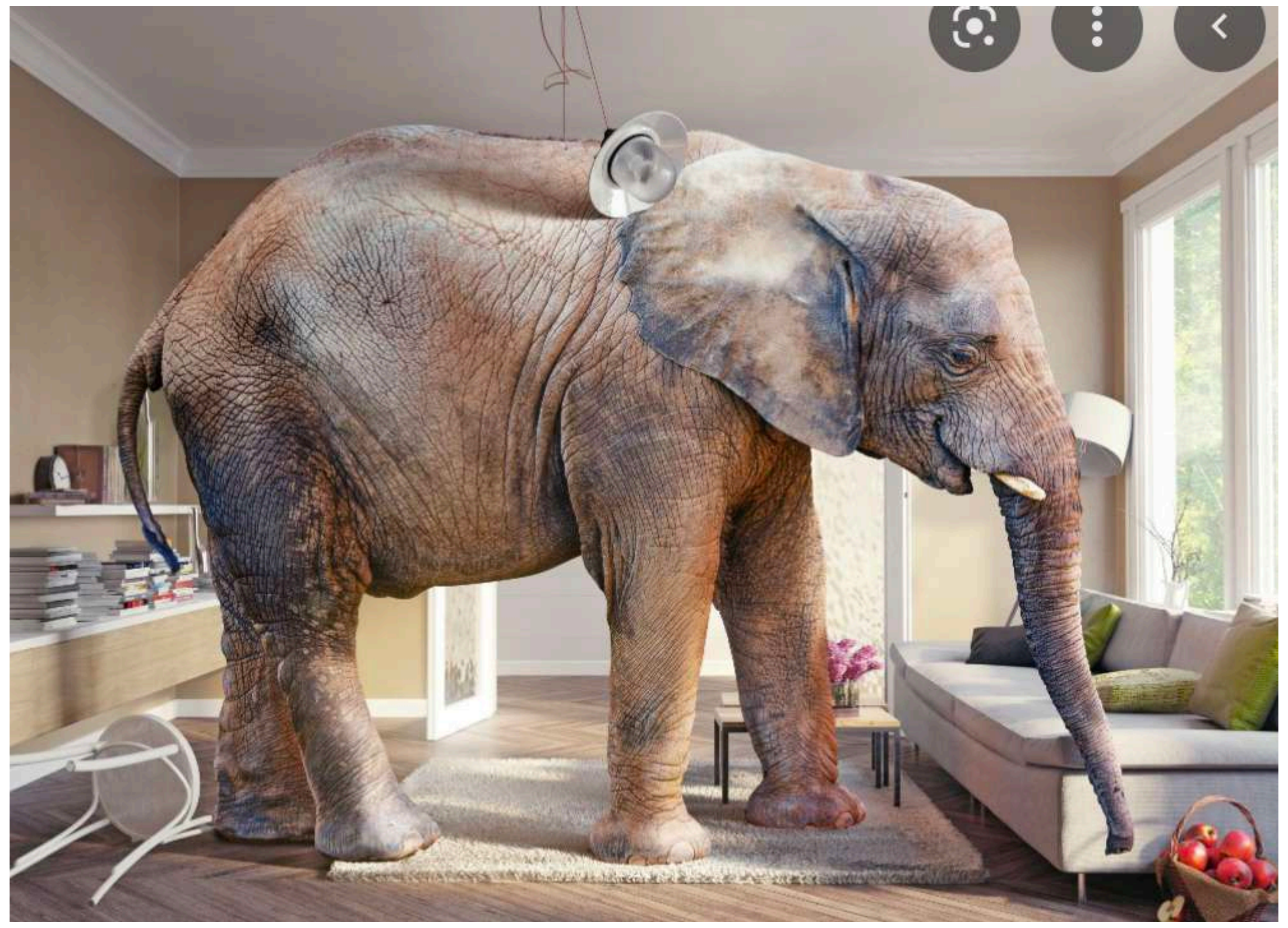
Lower value of V_{cb} softness the tension, but cannot not resolve it

Bordone, Gubernari, Huber, Jung, van Dyk 2007.10338; Cai, Deng, Li, Yang 2103.04138

NP in non-leptonic tree-level decays

Underestimated power corrections?

Khodjamirian; Piscopo, Rusov in progress



Bounds from collider physics

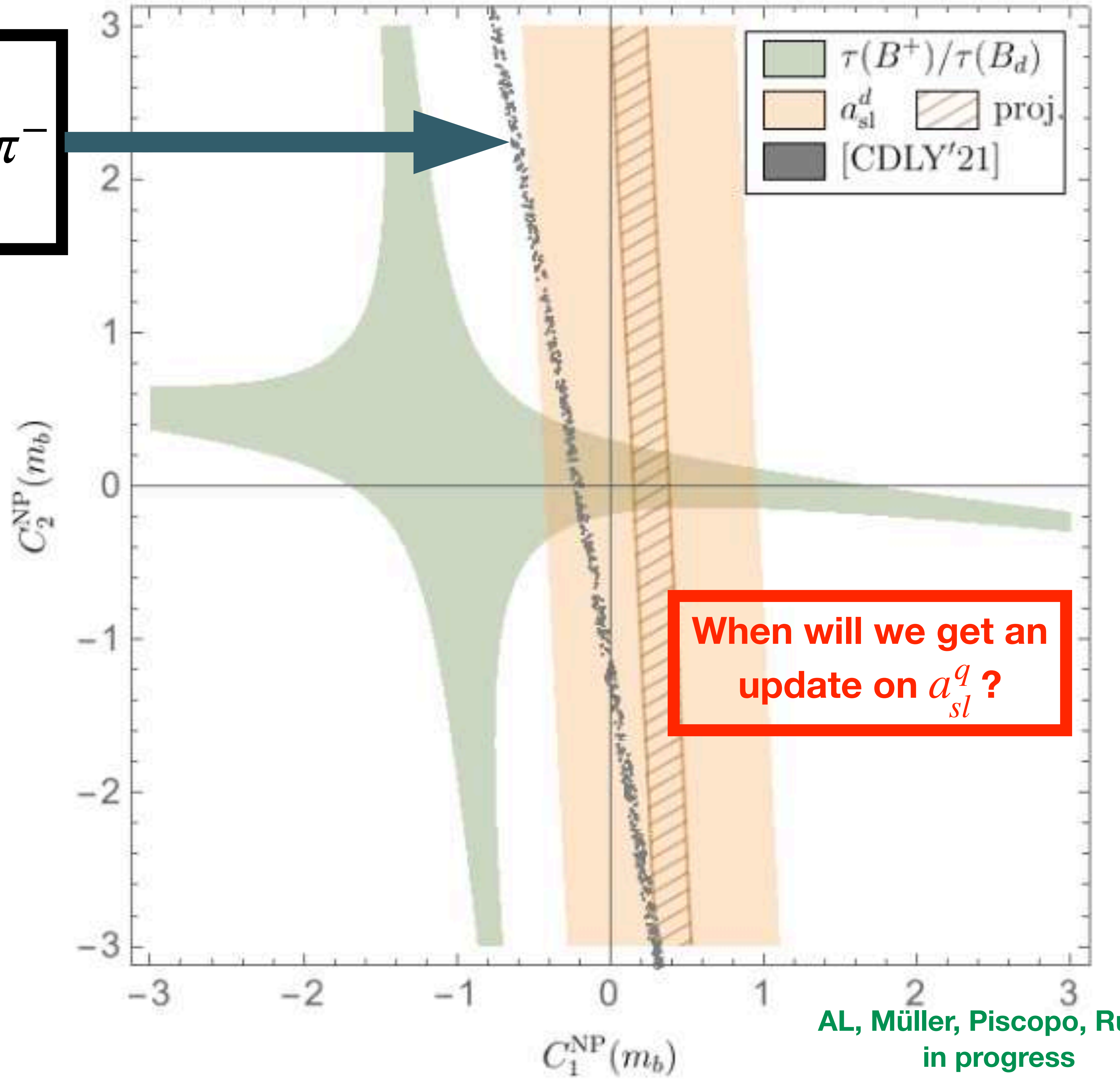
Bordone, Greljo, Marzocca 2103.10332

Atkinson, Englert, Kirk, Tetlalmatzi-Xolocotzi in progress

BSM effects in $b \to c\bar{u}d$?

$$\frac{\tau(B^+)}{\tau(B_d)}^{\text{HQE}} = 1 + \left[\Gamma^{\text{SM}}(B_d) - \Gamma^{\text{SM}}(B^+)\right]\tau^{\text{Exp.}}(B^+) + \left[\Gamma^{\text{BSM}}(B_d) - \Gamma^{\text{BSM}}(B^+)\right]\tau^{\text{Exp.}}(B^+)\,.$$

Assume:
$\bar{B}_s \to D_s^+\pi^-$
= BSM



When will we get an update on a_{sl}^q ?

AL, Müller, Piscopo, Rusov in progress

Flavour-specific CP asymmetries

When will we get a number for A^q_{fs} ?

Fleischer, Vos 1606.06042
Gershon, AL, Rusov, Skidmore 2111.04478

- a^q_{fs} is typically measured with semi-leptonic B_q decays
- One could also use the flavour specific $\bar{B}_s \to D_s^+ \pi^-$ decay
- Assume: there is new physics in these decays, potentially CP violating $A^{\mathrm{BSM}}/A^{\mathrm{SM}} = re^{i\phi}e^{i\varphi}$
- Derive CP asymmetry

$\approx 2r \sin\phi \sin\varphi < 0.40$

$$A^q_{\mathrm{fs}} = \frac{a^q_{\mathrm{fs}} - 2r\sin\phi\sin\varphi + 2a^q_{\mathrm{fs}} r\cos\phi\cos\varphi + a^q_{\mathrm{fs}} r^2}{1 + 2r\cos\phi\cos\varphi + r^2 - 2a^q_{\mathrm{fs}} r\sin\phi\sin\varphi} \approx a^q_{\mathrm{fs}} - A^q_{\mathrm{dir}}$$

Constrained by semi-leptonic Measurements

Significant exp. deviation of A^q_{fs} from a^q_{sl}
= unambiguous and theory independent signal for BSM

$\delta a^s_{sl} \approx 3 \cdot 10^{-5}$ Monteil, 12.9.2022 flavour@FCCee! (p.23)

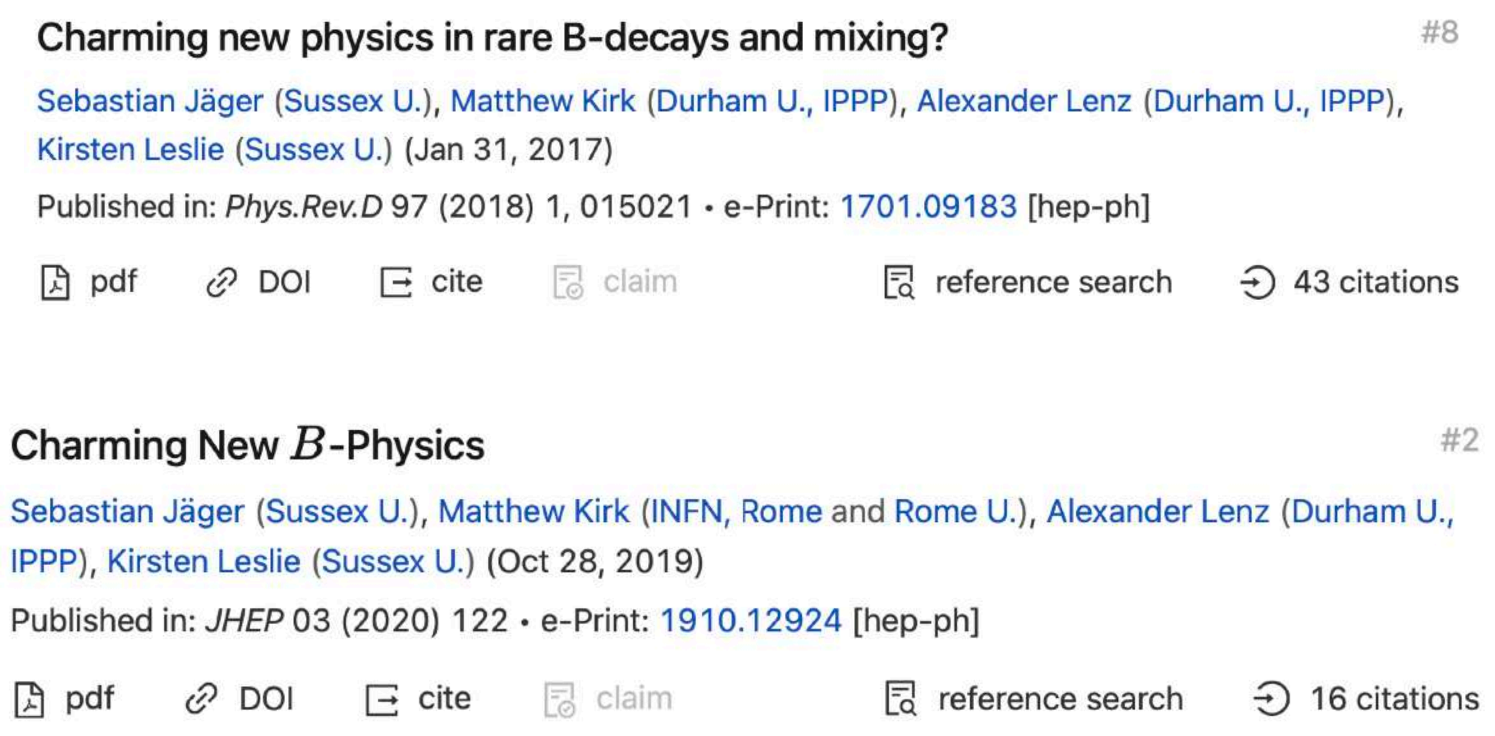
NP in tree-level decays

Aim:

- Understand the hadronic interaction which is binding quarks into hadrons and their interactions in a very complicated environment - **not yet achieved on a precision level!**
- ~~Seems to be super far away from exciting BSM searches!~~

Fun with NP in tree-level decays

- Assume there is really BSM acting in $b \to c\bar{u}d$ decays
- Then there might be also BSM acting in $b \to c\bar{c}s$ - this can modify $C_9, C_{10}, \ldots$, but not $R_K, \ldots$



Charming new physics in rare B-decays and mixing? #8

Sebastian Jäger (Sussex U.), Matthew Kirk (Durham U., IPPP), Alexander Lenz (Durham U., IPPP), Kirsten Leslie (Sussex U.) (Jan 31, 2017)

Published in: Phys.Rev.D 97 (2018) 1, 015021 • e-Print: 1701.09183 [hep-ph]

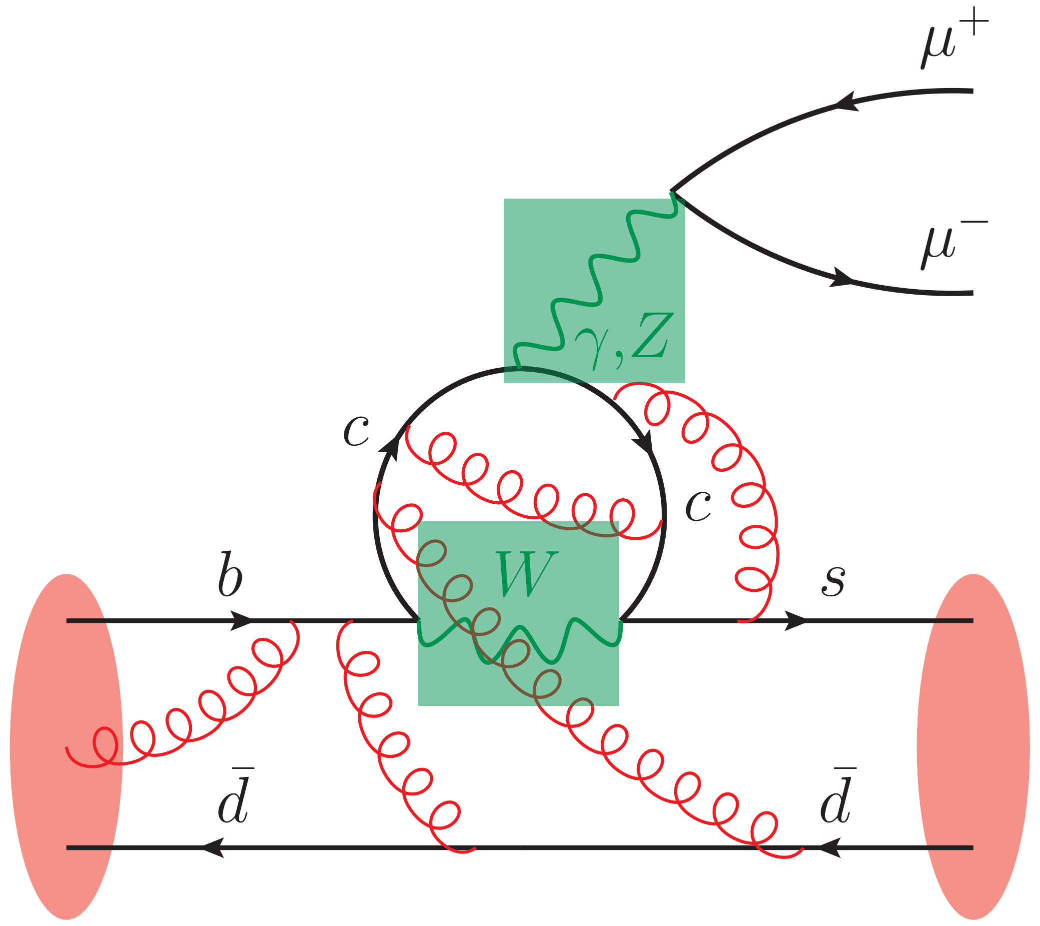
pdf DOI cite claim reference search 43 citations

Charming New B-Physics #2

Sebastian Jäger (Sussex U.), Matthew Kirk (INFN, Rome and Rome U.), Alexander Lenz (Durham U., IPPP), Kirsten Leslie (Sussex U.) (Oct 28, 2019)

Published in: JHEP 03 (2020) 122 • e-Print: 1910.12924 [hep-ph]

pdf DOI cite claim reference search 16 citations



- Assume next: $R_K, \ldots$ goes away, but $P_5', \ldots$ and $Br(B_s \to \phi ll), \ldots$ stays
- Could modify the extraction of CKM angle γ **Brod, AL, Tetlalmatzi-Xolocotzi 1412.1446**

Outline

- CKM fits
- Lifetimes
- Mixing: Mass difference ΔM_q, decay rate differences $\Delta\Gamma_q$ and semileptonic CP asymmetries a_{sl}^q
- NP in Tree-level: One observable to find them (= BSM) all!
- Conclusion: What will be our legacy?

Conclusion 2022

Primary aim of particle physics: understand nature on a microscopic level!
This means not necessarily finding new particles

… - 2022: We have fulfilled many of our aims in particles physics

- Determine the fundamental parameters of nature
- Determine if there is CP violation within the SM
- Determine if the amount of CP violation within the SM is sufficient for baryogenesis
- Understand fundamental properties of elementary particles
- Understand the hadronic interaction which is binding quarks into hadrons
- Understand the quantum mechanical property of mixing of neutral mesons
- Do consistency checks (indirect new physics searches) of the known laws of nature (SM)

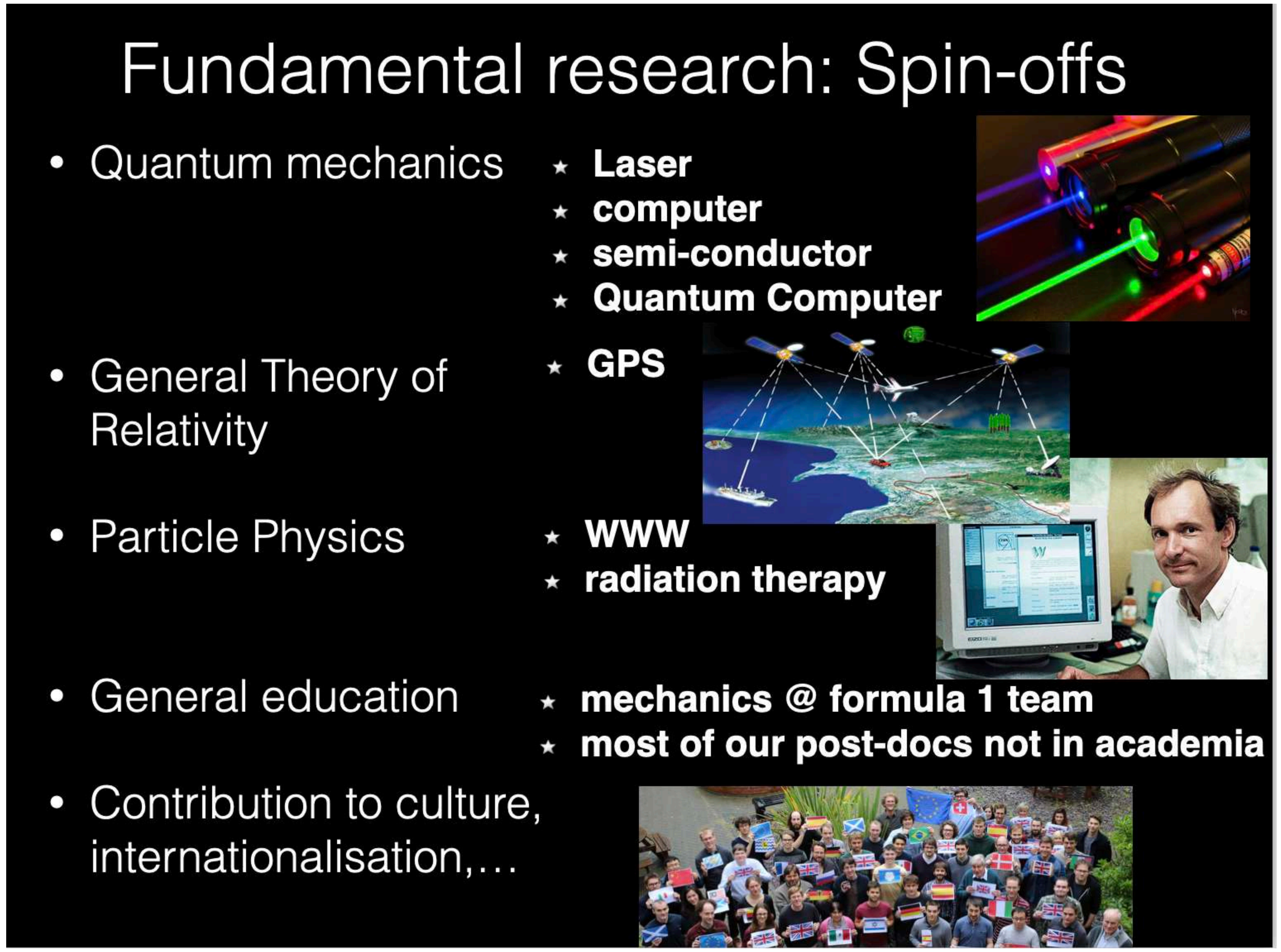
Even if our path was not always straight -
it was leading in the right direction of more insights!

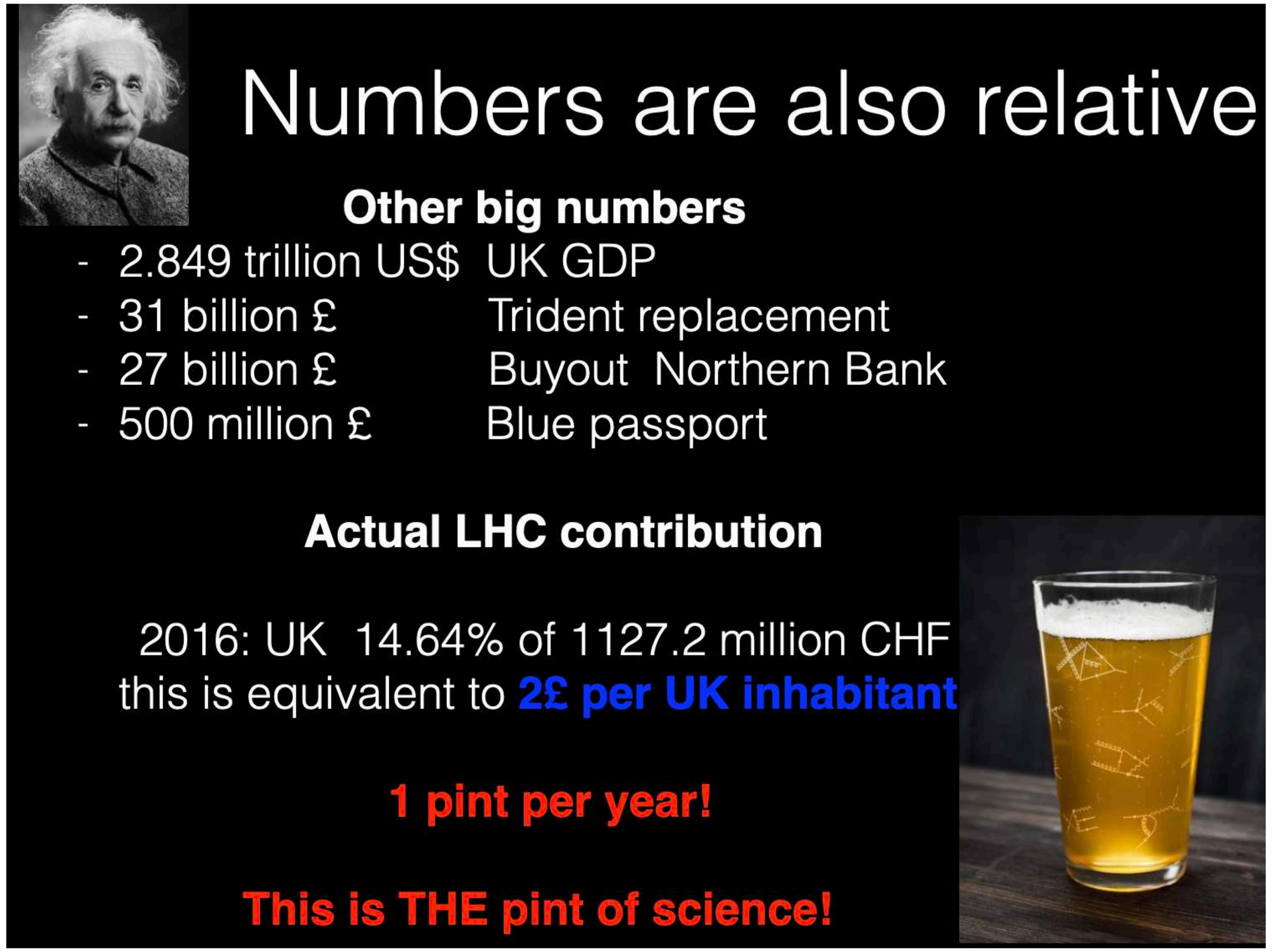
Conclusion

Besides these achievements: what else will stay from our activities?

Your/my time is probably our most valuable good!

Experimental spin-offs are huge, well-known and often discussed





But what about the practical value of higher order corrections to the HQE?

Multi-loop activities:

Application for Gravitaional waves

Many papers, e.g. groups of Zvi Bern (Los Angeles), Rafael Porto (Hamburg), Blümlein and Marquard (Zeuthen), Mastrolia (Padova)

Gravitational Quadratic-in-Spin Hamiltonian at NNNLO in the post-Newtonian framework

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Abstract: We present the result of the quadratic-in-spin interaction Hamiltonian for binary systems of rotating compact objects with generic spins, up to N^3LO corrections within the post-Newtonian expansion. The calculation is performed by employing the effective field theory diagrammatic approach, and it involves Feynman integrals up to three loops, evaluated within the dimensional regularization scheme. The gauge-invariant binding energy and the scattering angle, in special kinematic regimes and spin configurations, are explicitly derived. The results extend our earlier study on the spin-orbit interaction effects.

Applications in pure maths (number theory):

Herbert Gangl (Maths, Durham) new relations among special functions
https://arxiv.org/pdf/1609.05557.pdf https://arxiv.org/pdf/1801.07816.pdf
"In order to derive and check the results given in this paper we used Goncharov's symbol for iterated integrals as it was implemented in Mathematica by Duhr [3] for our joint paper [4]."

MULTIPLE POLYLOGARITHMS IN WEIGHT 4

HERBERT GANGL

Abstract. We clarify the relationship between different multiple polylogarithms in weight 4 by writing suitable linear combinations of a given type of iterated integral $I_{n_1,\ldots,n_d}(z_1,\ldots,z_d)$, in depth $d>1$ and weight $\sum_i n_i = 4$, in terms of iterated integrals of lower depth, often in terms of the classical tetralogarithm Li_4. In the process, we prove a statement conjectured by Goncharov which can be rephrased as writing the sum of iterated integrals $I_{3,1}(V(x,y),z)$, where $V(x,y)$ denotes a formal version of the five term relation for the dilogarithm, in terms of Li_4-terms (we need 122 such).

These results used by Goncharov and Rudenko to prove a conjecture in number theory https://arxiv.org/pdf/1803.08585.pdf

Motivic correlators, cluster varieties and Zagier's conjecture on $\zeta_F(4)$

Alexander Goncharov, Daniil Rudenko

Thanks to Claude Duhr, Tobias Huber

Lattice activities

https://en.wikipedia.org/wiki/QCDOC
The **QCDOC** (quantum chromodynamics on a chip) is a supercomputer technology focusing on using relatively cheap low power processing elements to produce a massively parallel machine. The machine is custom-made to solve small but extremely demanding problems in the fields of quantum physics.
QCDOC can be seen as a predecessor to the highly successful Blue Gene/L supercomputer.

Early use of GPUs for scientific calculations
https://arxiv.org/abs/hep-lat/0611022

Lattice QCD as a video game

Győző I. Egri[a], Zoltán Fodor[abc], Christian Hoelbling[b], Sándor D. Katz[ab], Dániel Nógrádi[b] and Kálmán K. Szabó[b]

Many Lattice physicists moved on to work in hardware or software industries e.g. Nvida:

Lattice QCD simulations often part of acceptance tests for new super computers

Thanks to Oliver Witzel

- Lattice Holographic Cosmology: Lattice + Holography -> post-diction of CMB, alternative to LambdaCMB (see Jüttner https://cernbox.cern.ch/index.php/s/BvgEuncLxgYBtVr)
- Quantengravity on the lattice(e.g. dynamical triangularisation)
- Study of critical exponents via lattice (solid state physics)
- Lattice algorithms are used in ML and Data Science e.g. Duane, Kennedy, Pendleton, Roweth: Hybrid Monte Carlo
- Lattice community starts to think about QFT on quantum computer

Thanks to Andreas Jüttner

Methods from lattice:
- Markov Chain Monte Carlo (MCMC)
- Importance Sampling
- Multigrid Algorithms
- Tensor Approximations

Applied in other fields:
- Condensed Matter Physics
- Quantum Computing
- Engineering
- Chemistry
- Bioinformatics
- Economics/Finance

Thanks to Tilo Wettig

Conclusion

Scenario 2035 A: Without current $b \to sll$ and $b \to cl\nu$ anomalies

We have amazing prospects for further improving on our aims (precision)

- Non-perturbative improvements (lattice, sum rules)
- perturbative improvements
- better understanding of Quark masses
- Determination of CKM elements

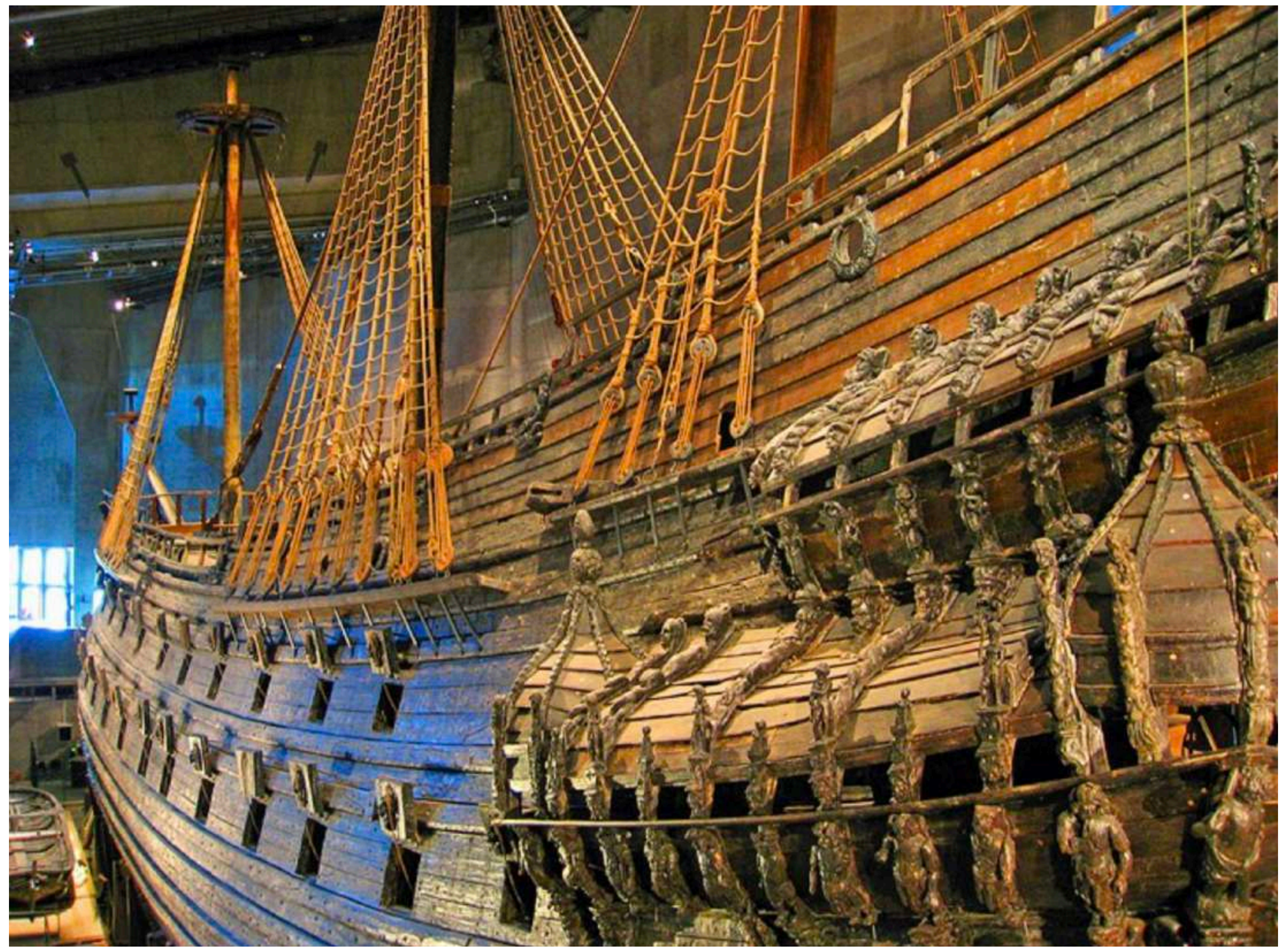
In addition a lot of fun around: e.g. discovery potential for BSM effects with more than 20 sigma in ΔM, $\Delta\Gamma$ and a_{sl} possible and interesting additional Null-tests $a_{fs}^{s}(\bar{B}_s \to D_s^{+}\pi^{-}) - a_{sl}^{s}, \ldots$, hadronic decays,…

Besides improvements in perturbation theory and lattice also completely new tools are around the corner: quantum computing…..

Not mentioned today: application for the charm

Conclusion

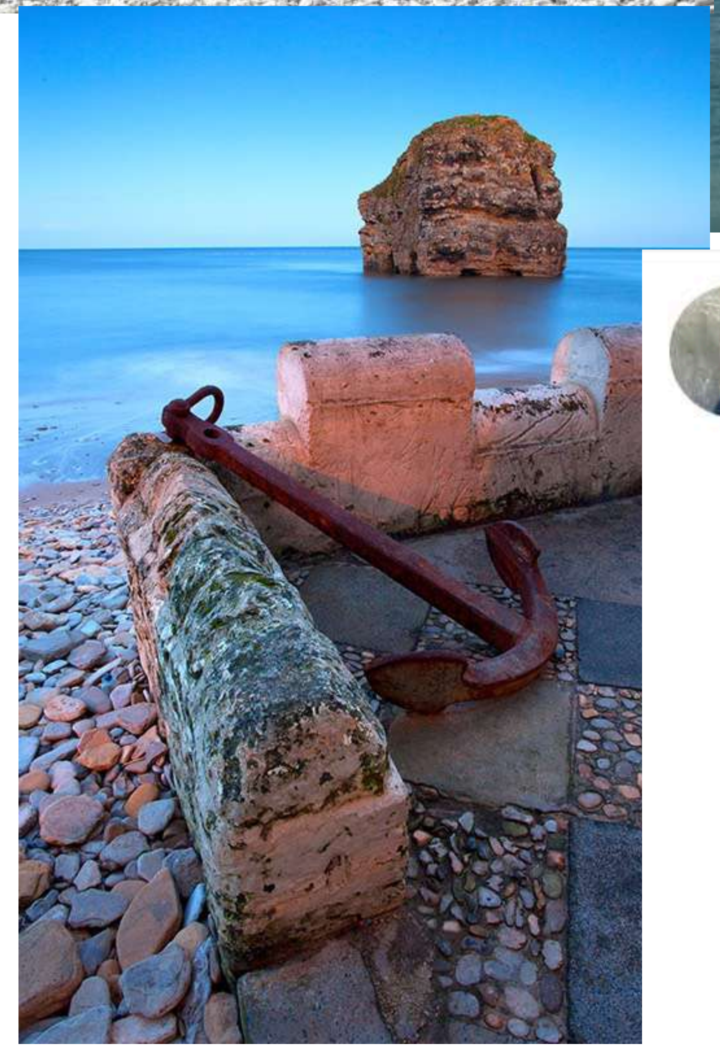
Scenario 2035 B: With any current or new anomaly confirmed with 5+x sigma



4. Be a Star at ABBA The Museum

How to spend your most valuable good till 2035

Work in a field that organises conferences at exciting, exotic places



How to spend your most valuable good till 2035

Even more exotic places

Siegen is located centrally in Germany, around 125 km northwest of Frankfurt and 90 km east of Cologne. International airports are in Frankfurt, Cologne and Düsseldorf. Siegen has also a tiny local airport, in case participants plan to arrive with small private planes.