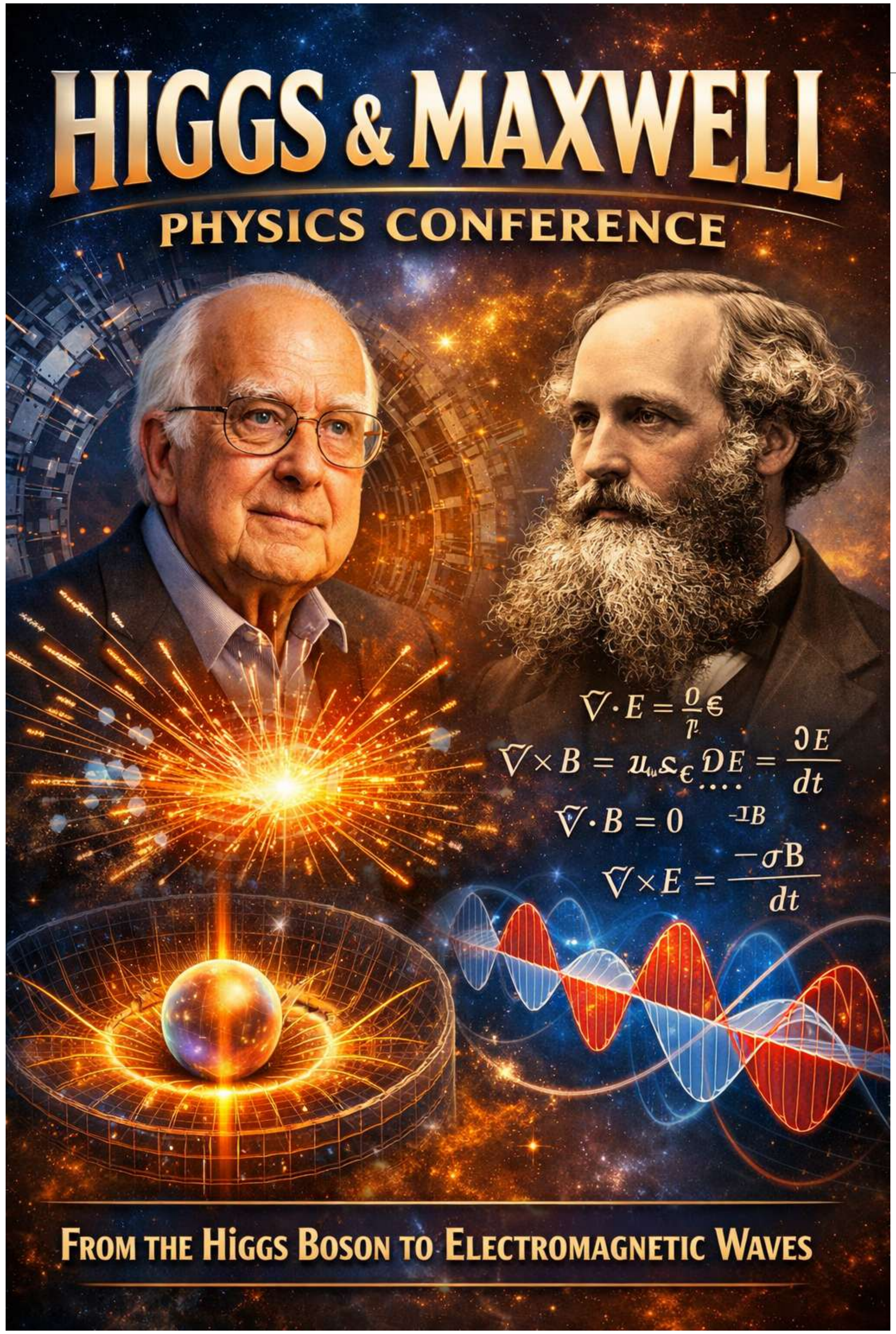
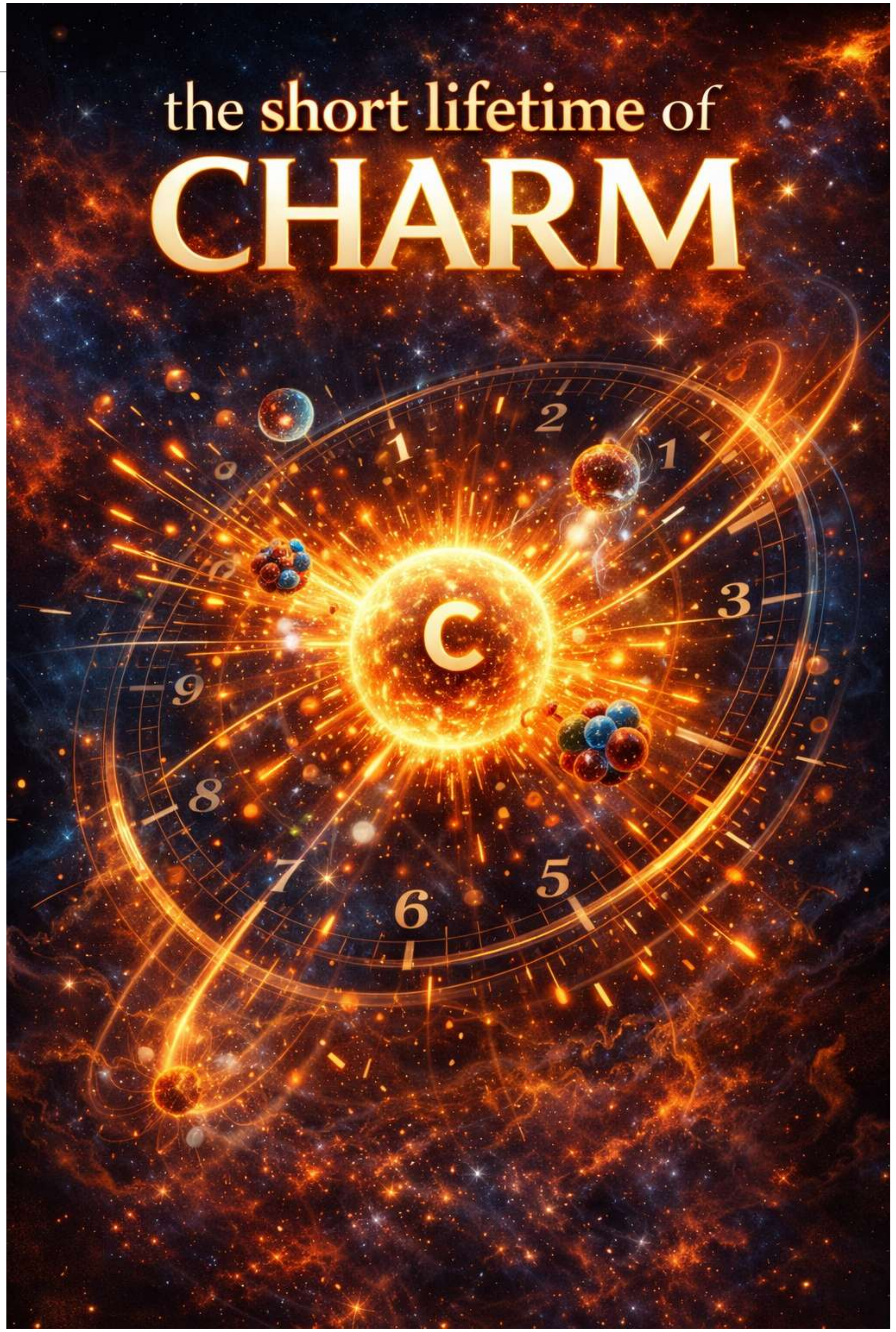
The short lifetime of charm



11.2.2026,
Higgs Maxwell
Workshop 2026
Edinburgh

Alexander Lenz,
Universität Siegen



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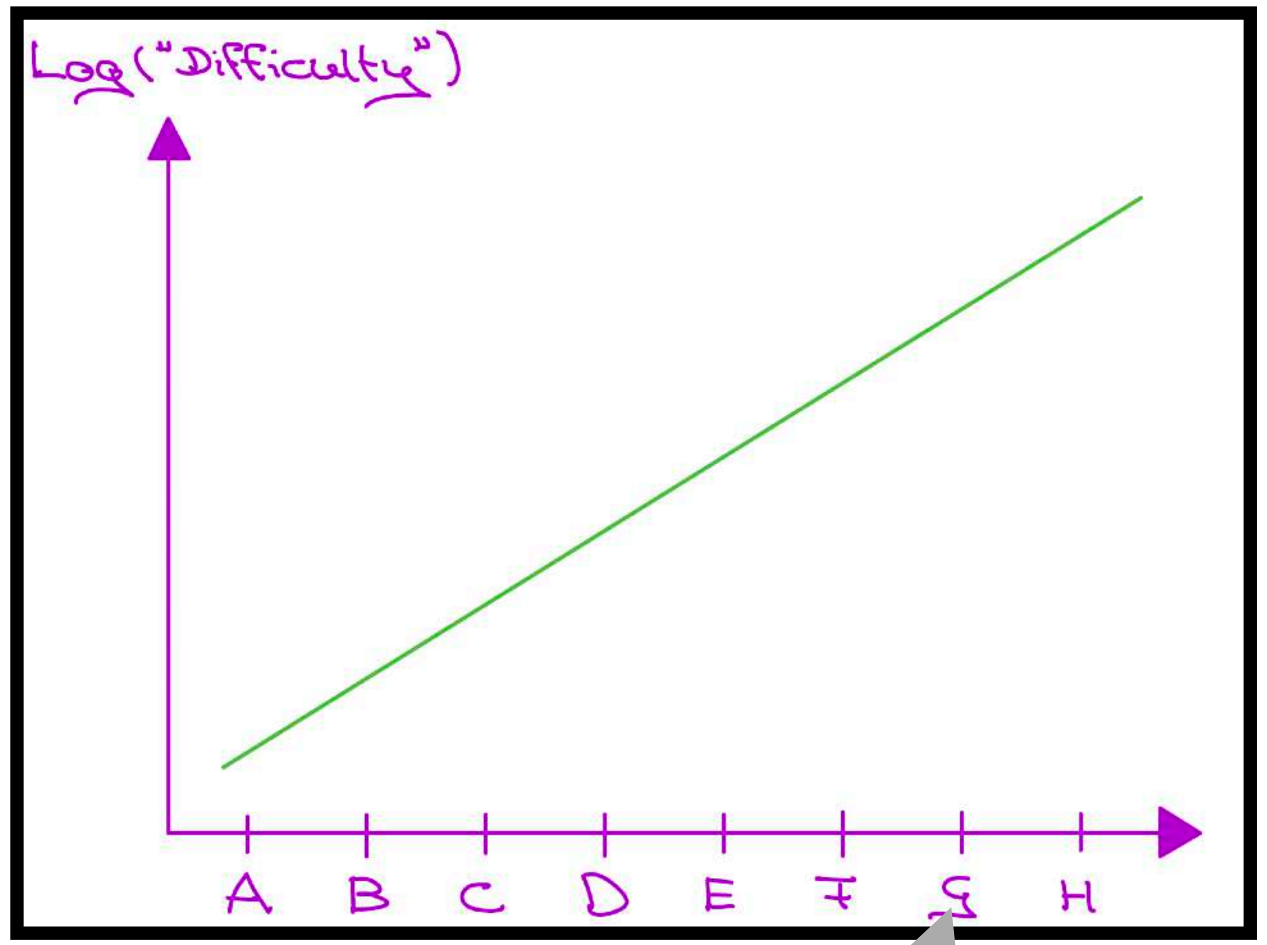
Outline

color meets flavor

1) Flavour Physics in a nutshell
2) Theory approaches in a nutshell
3) From “easy” to “ganz schwer”



Inclusive V_{cb}

Relation to non-leptonic B-decays, like $B_s \to D_s^+ \pi^-$ and to rare-semi-leptonic decays $B \to Kll$ or $D \to \pi ll$

A. Mass differences in B-mixing

B. Lifetime ratios $\tau(B^+)/\tau(B_d)$;

B-mixing: decay rate differences $\Delta\Gamma_{s,d}$; flavour-specific asymmetries $a_{fs}^{s,d}$

C. Lifetime ratios $\tau(B_s)/\tau(B_d)$ - some problems

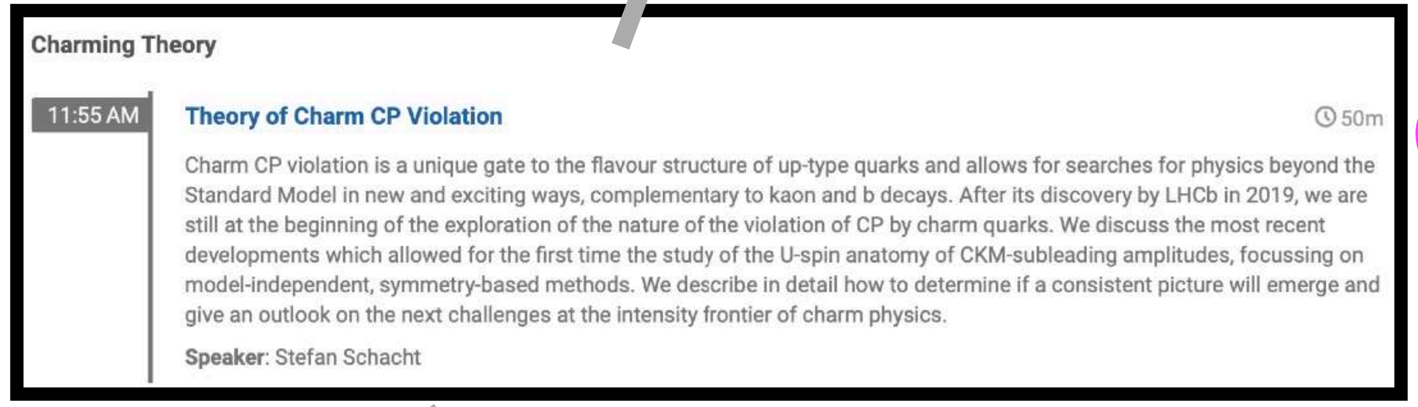
D. Sizable progress: $\Gamma(B_d, B^+, B_s)$, $\tau(\Lambda_b)/\tau(B_d)$

E. Charm lifetimes: $\Gamma(D^0)$, $\tau(D^+)/\tau(D^0)$

F. Charm lifetimes: $\Gamma(D^+)$ - terrible cancellations

G. CPV in charm: ΔA_{CP} ($D^0 \to \pi^+\pi^-, K^+K^-$) - can we be a factor of 10 off?

H. Charm mixing: - crazy cancellations - can we be a factor of 10 000 off?


Charming Theory

11:55 AM **Theory of Charm CP Violation** 50m

Charm CP violation is a unique gate to the flavour structure of up-type quarks and allows for searches for physics beyond the Standard Model in new and exciting ways, complementary to kaon and b decays. After its discovery by LHCb in 2019, we are still at the beginning of the exploration of the nature of the violation of CP by charm quarks. We discuss the most recent developments which allowed for the first time the study of the U-spin anatomy of CKM-subleading amplitudes, focussing on model-independent, symmetry-based methods. We describe in detail how to determine if a consistent picture will emerge and give an outlook on the next challenges at the intensity frontier of charm physics.

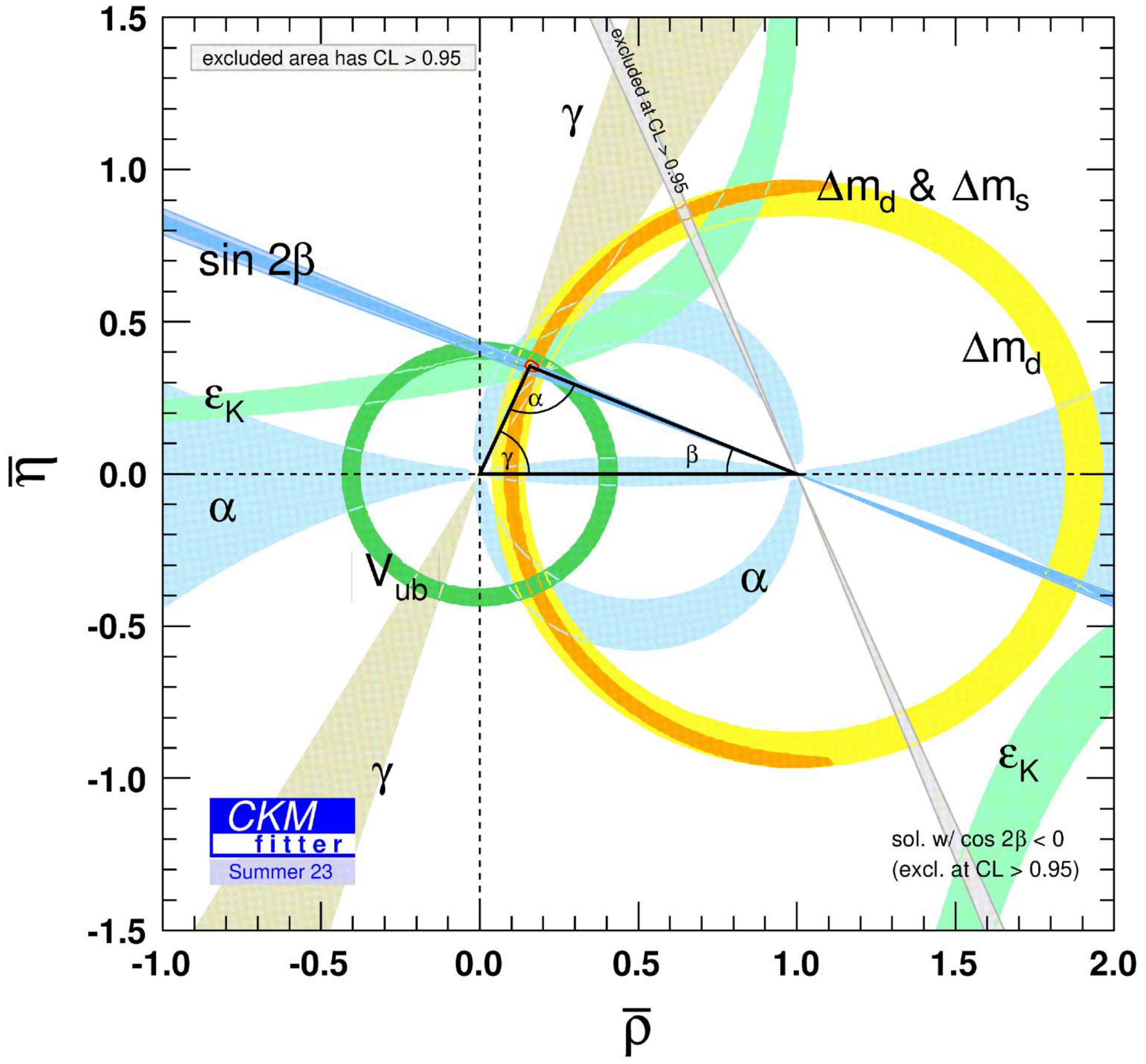
Speaker: Stefan Schacht

“Easy” — —> “ganz schwer”

4) Some fun, which is many times overlooked: BSM in tree-level decays

Flavour Physics in a nutshell

Success



similar results by UTfit

Nobel Prize in Physics 2008

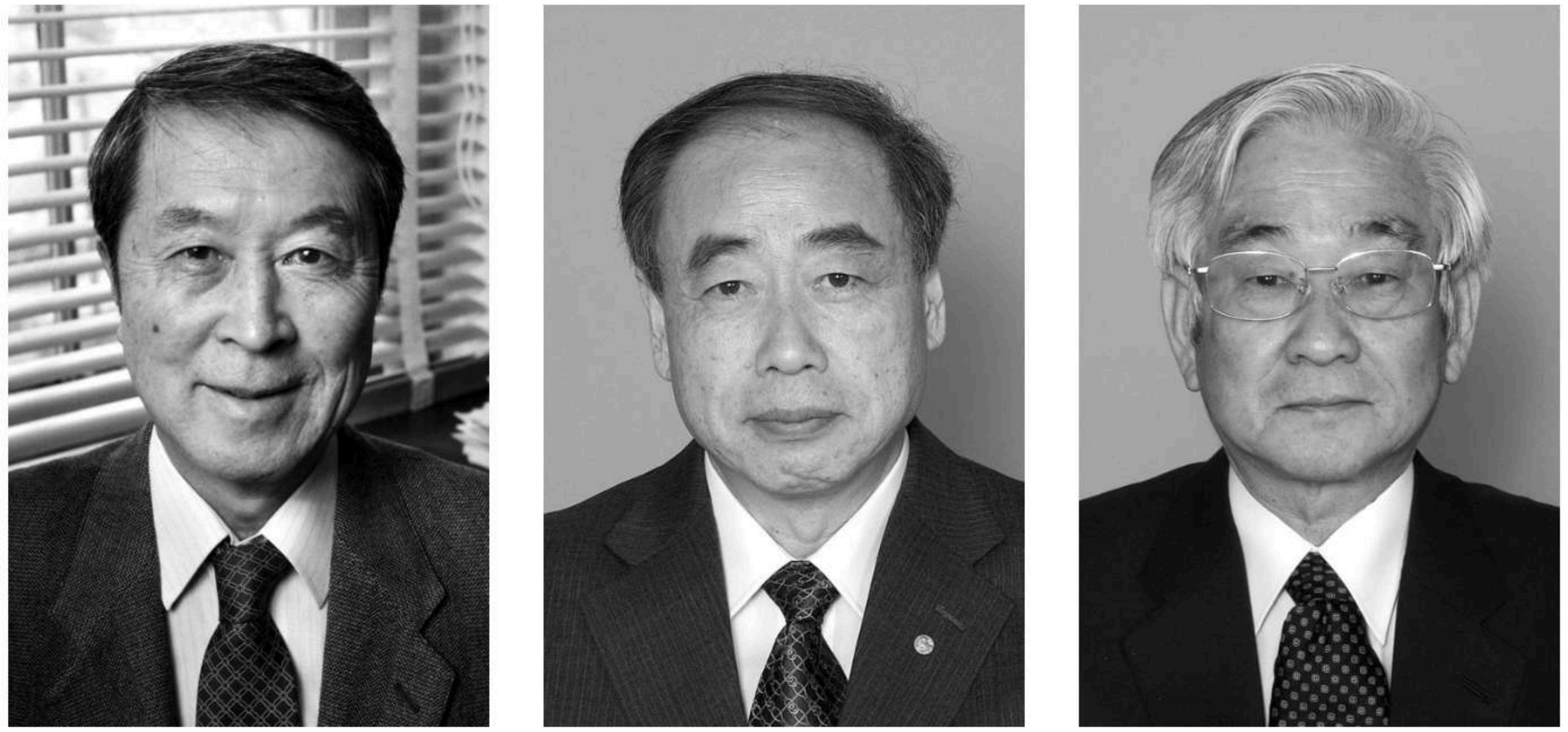


Photo: University of Chicago
Yoichiro Nambu
Prize share: 1/2

© The Nobel Foundation Photo: U. Montan
Makoto Kobayashi
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Toshihide Maskawa
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Flavour Physics in a nutshell

Open questions

Matter in the Universe

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from anti-matter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point

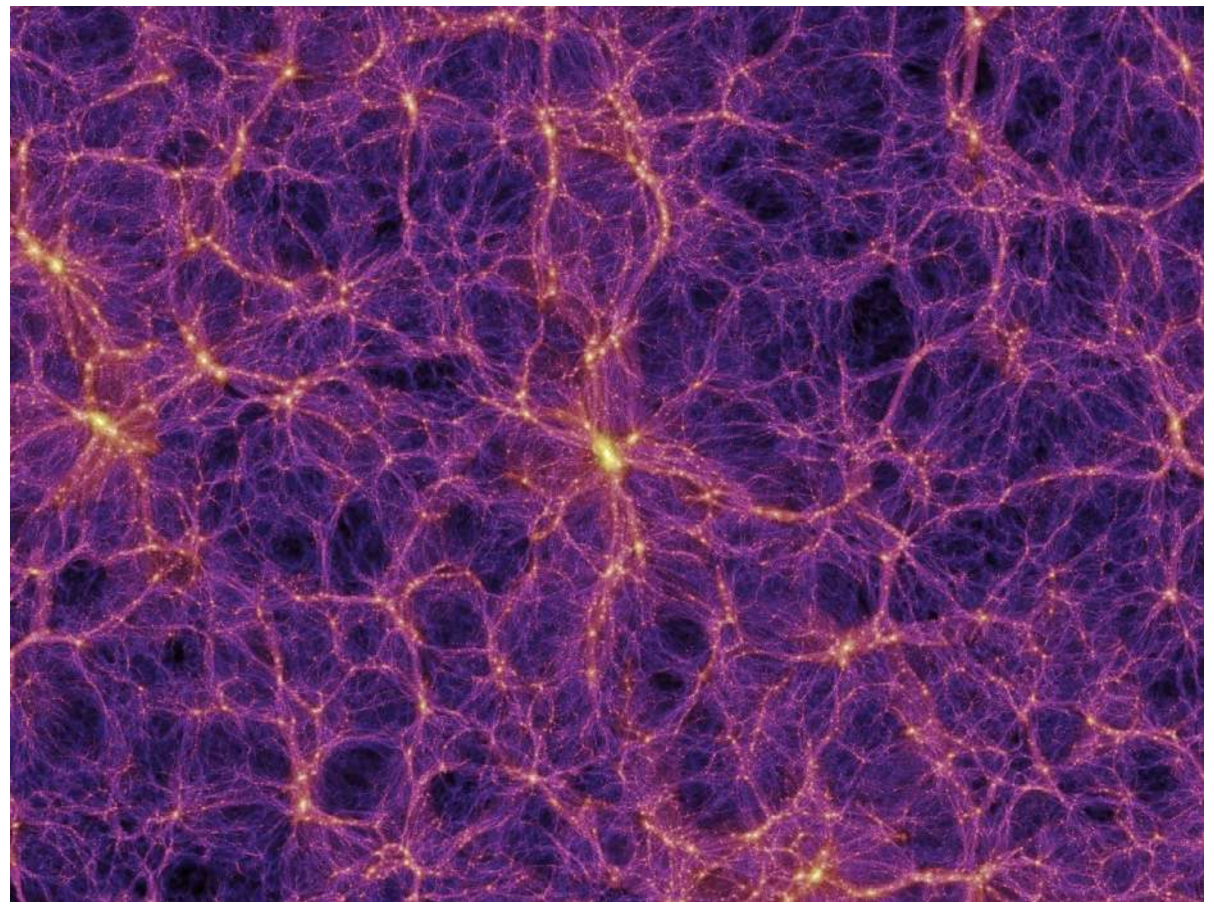
Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe #2
A.D. Sakharov (Lebedev Inst.) (1967)
Published in: *Pisma Zh.Eksp.Teor.Fiz.* 5 (1967) 32-35, *JETP Lett.* 5 (1967) 24-27, *Sov.Phys.Usp.* 34 (1991) 5, 392-393, *Usp.Fiz.Nauk* 161 (1991) 5, 61-64
links DOI cite claim reference search 5,424 citations

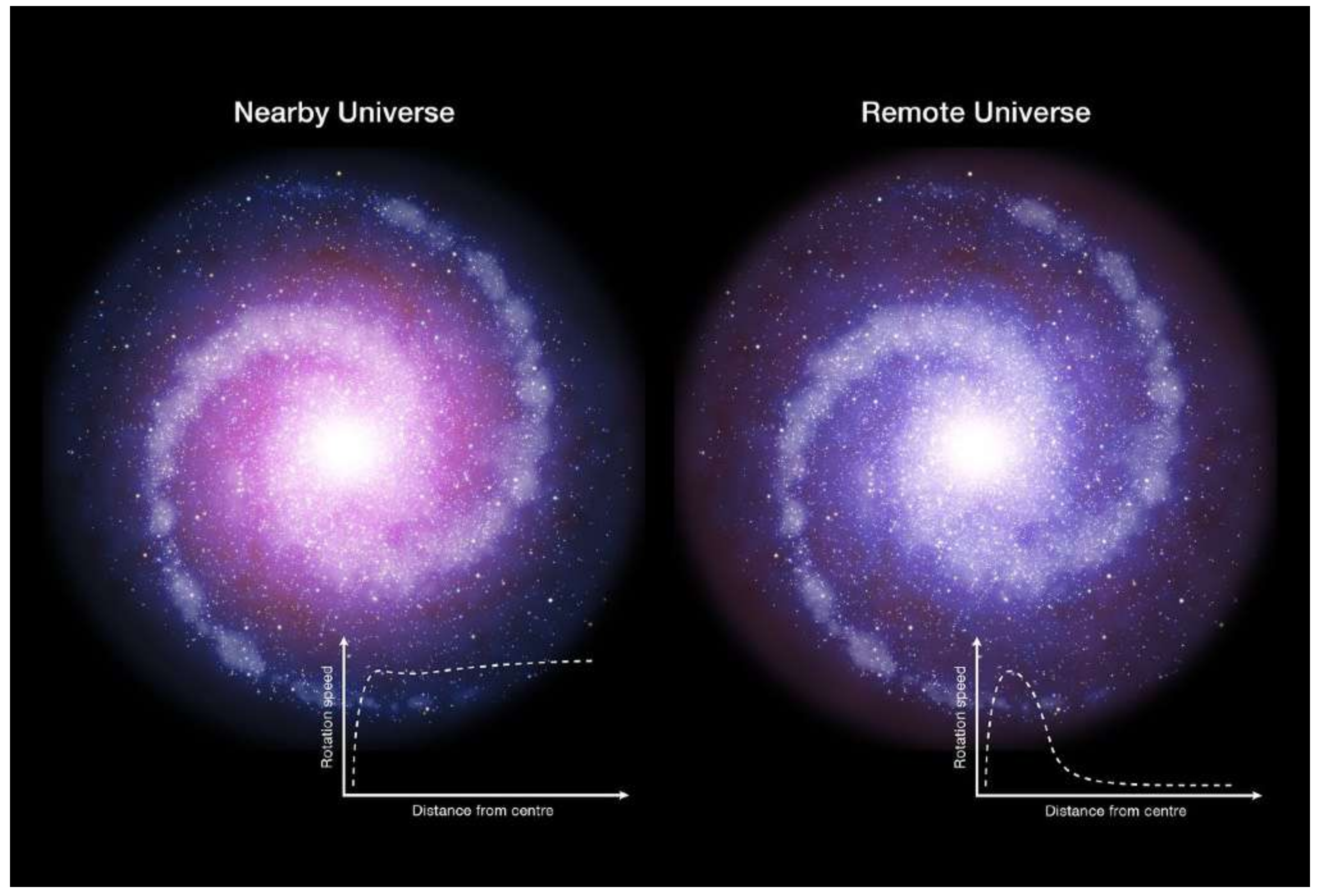
1) CV, CPV: yes, but probably not enough -> 2HDM, 4th gen.,…

2) Baryon number violation: yes - sphalerons (Klinkhammer, Manton)

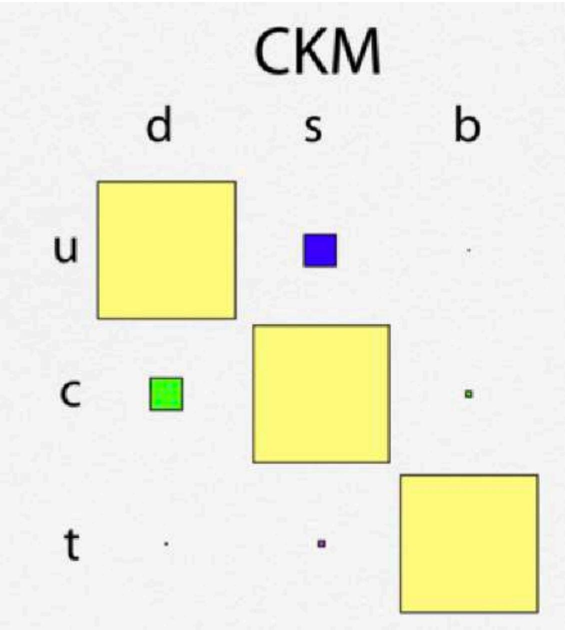
3) Phase away from thermal equilibrium: no, only for $m_H < 65$ GeV -> 2HDM,…

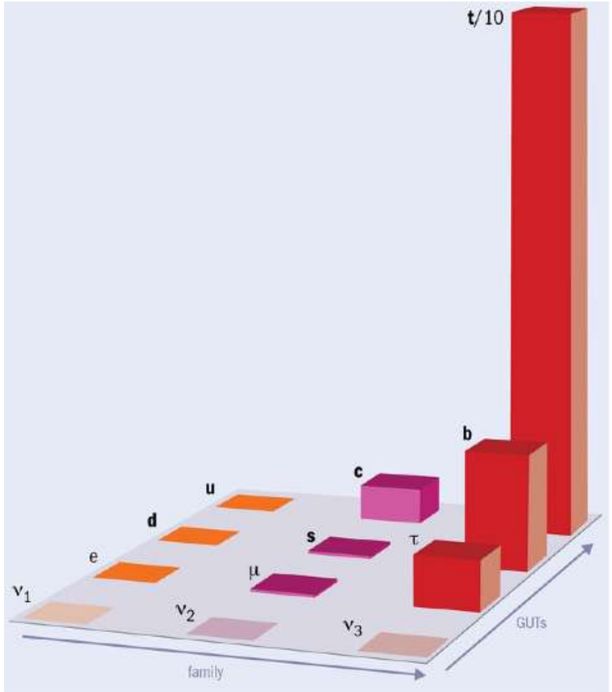
Dark Matter in the Universe





Origin of flavour structure, quark masses,…





Several more …

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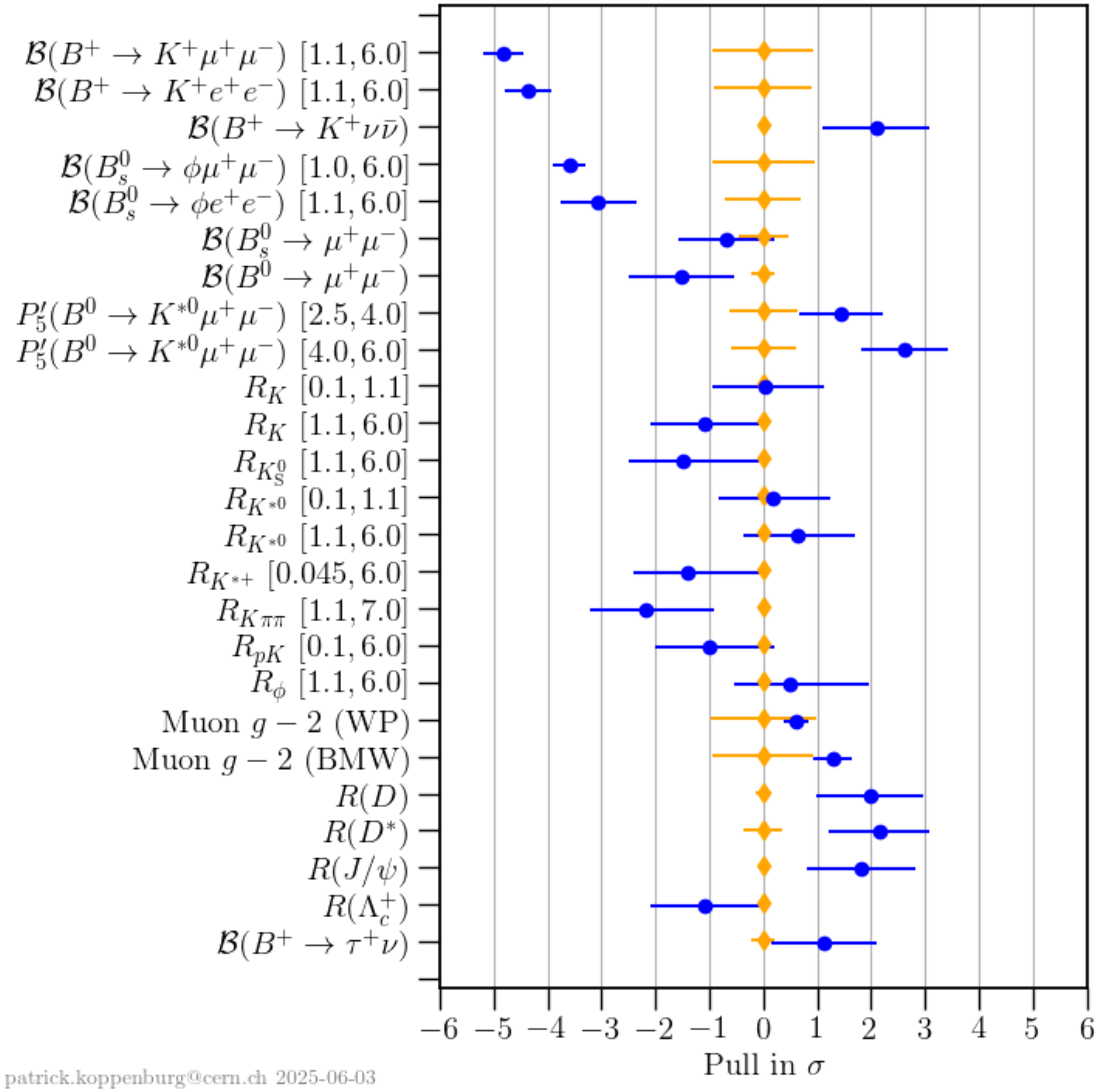
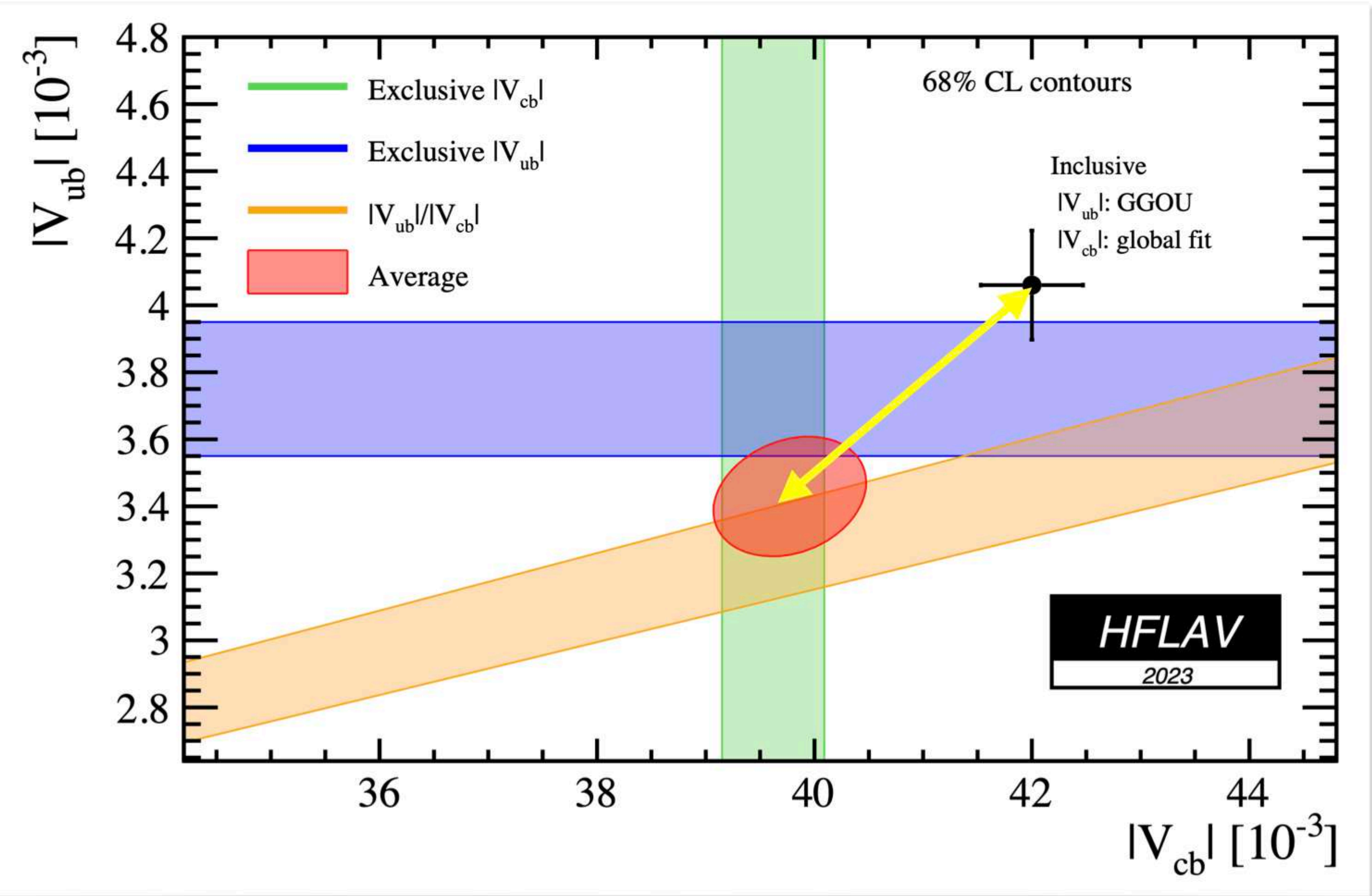
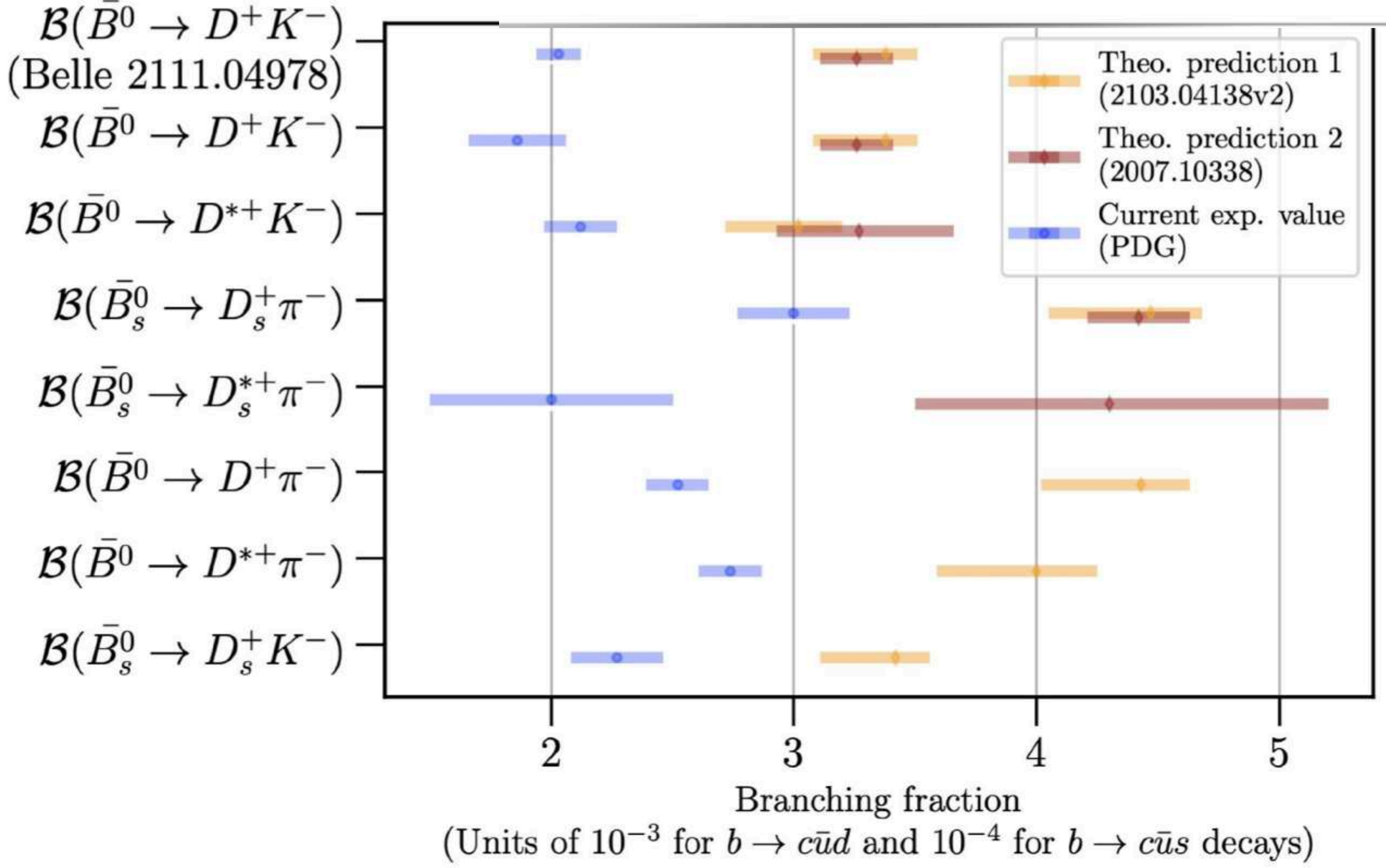
Flavour Physics in a nutshell

Anomalies







Flavour Physics in a nutshell

Experimental and theoretical future

Huge amount of data ahead of us

- LHCb upgrade II
- BelleII
- BESIII., Super-tau-charm,...
- FCC-ee

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ $(B \to DK,\ etc.)$	2.8°	[20, 21]	1.3°	0.8°	0.3°
ϕ_s $(B_s^0 \to J/\psi\phi)$	20 mrad	[24]	12 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ $(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu,\ etc.)$	6%	[56, 57]	3%	2%	1%
Charm					
ΔA_{CP} $(D^0 \to K^+K^-, \pi^+\pi^-)$	29×10^{-5}	[27]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ $(D^0 \to K^+K^-, \pi^+\pi^-)$	11×10^{-5}	[31]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx $(D^0 \to K_S^0\pi^+\pi^-)$	18×10^{-5}	[58]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[32, 33]	41%	27%	11%
$S_{\mu\mu}$ $(B_s^0 \to \mu^+\mu^-)$	—		—	—	0.2
$A_T^{(2)}$ $(B^0 \to K^{*0}e^+e^-)$	0.10	[59]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[60]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[61]	0.148	0.097	0.038

BSM interpretation of potential anomalies
- Connection to collider physics

- **Origin of anomalies:** Exp./QCD or a first glimpse BSM
  - Hadronic contributions to $b \to s\ell\ell$
  - $V_{cb} - V_{ub}$ puzzle
  - Precision of QCD factorisation in B decays/LCSR
- **Match experimental precision:**
  - Mixing: ΔM_s limited by dim 6 Bag parameter
  - $\Delta\Gamma_s$ limited by dim 7 contributions
  - Penguin pollution in gold-plated modes
  - Lifetimes limited by dim 6/7 Bag-parameter
- **Conceptual issues**
  - Convergence properties of HQE: charm
  - Quark mass concepts
  - Gradient-flow
- **Elephants in the room?**

$\Delta A_{CP} : D^0 \to \pi^+\pi^-, K^+K^-$, **D-mixing, assume $V_{cb}^{\text{excl.}}$ is correct: ϵ_K, $\Delta M_{d,s}$,...**

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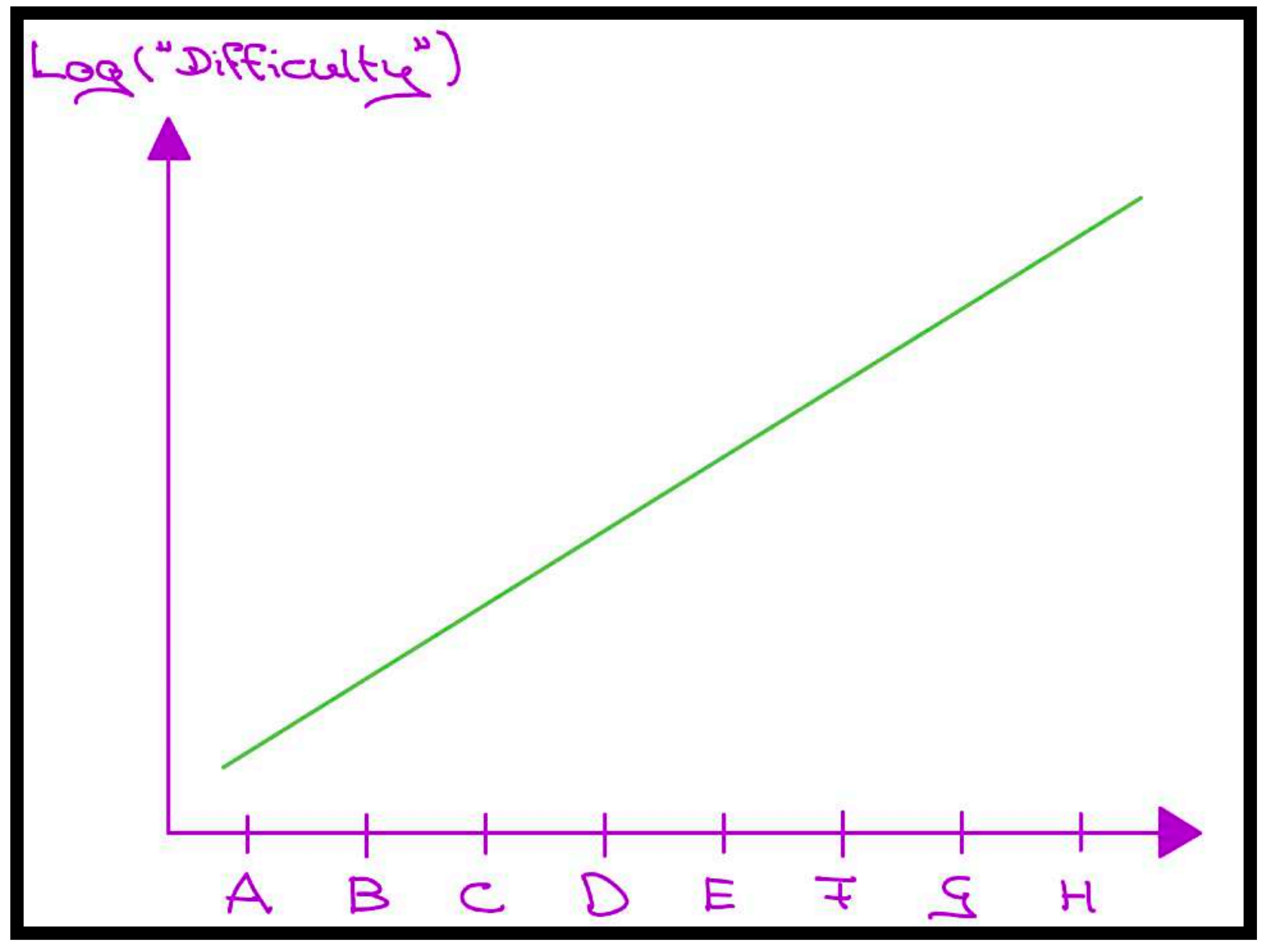

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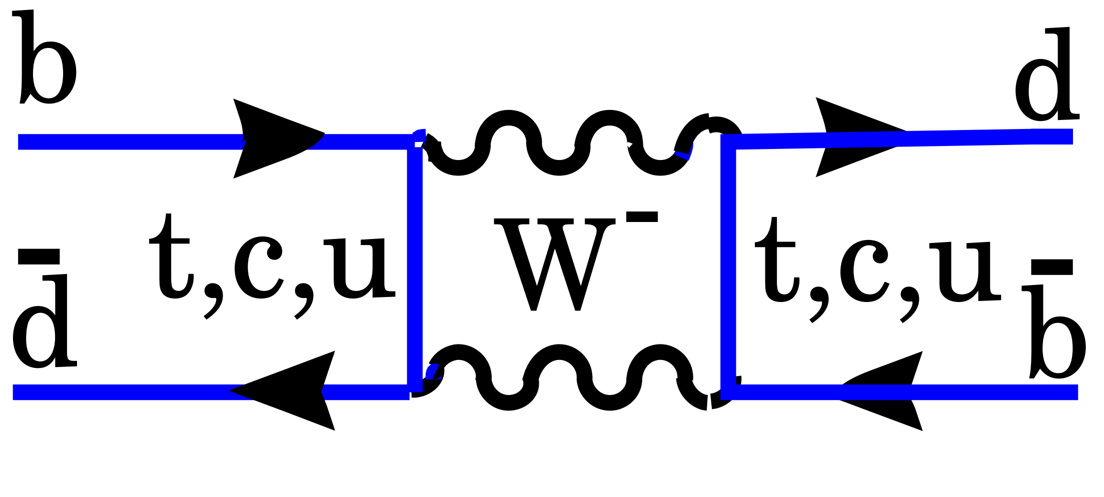
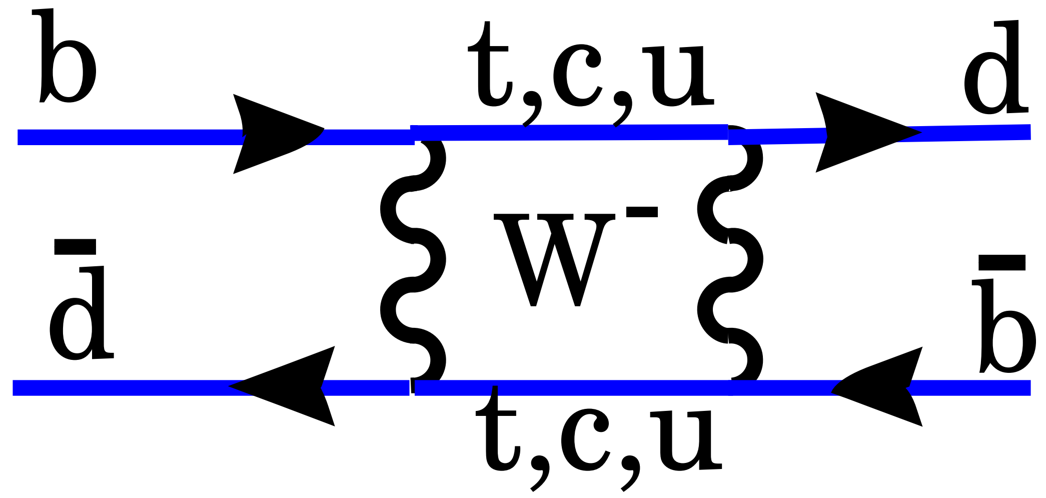
Theory approaches

Mass difference B-physics

One OPE: m_W, m_t

$$|B_{q,L}\rangle = p|B_q\rangle + q|\bar{B}_q\rangle$$
$$|B_{q,H}\rangle = p|B_q\rangle - q|\bar{B}_q\rangle$$



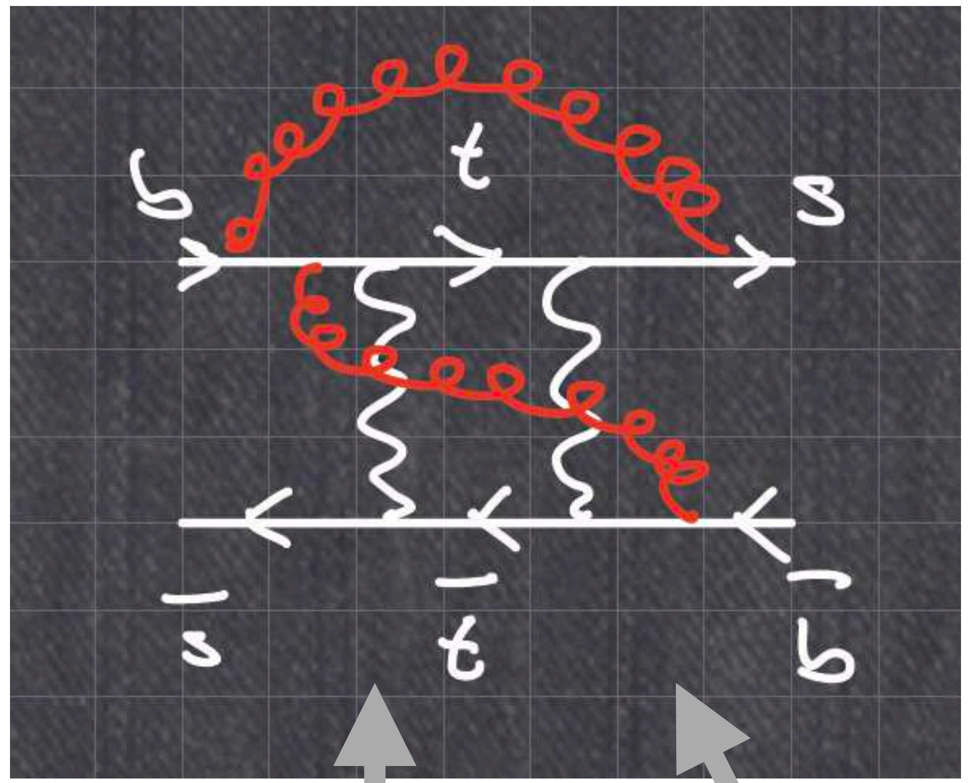


$|M_{12}|$, $|\Gamma_{12}|$ and $\phi = \arg(-M_{12}/\Gamma_{12})$ can be related to three observables:

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

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

2-loop: Buras, Jamin, Weisz
3-loop: Gorbahn,……



Significant CKM dependence

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

By far dominant uncertainty

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

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

Theory approaches

Total inclusive decay rates

Total decay rate

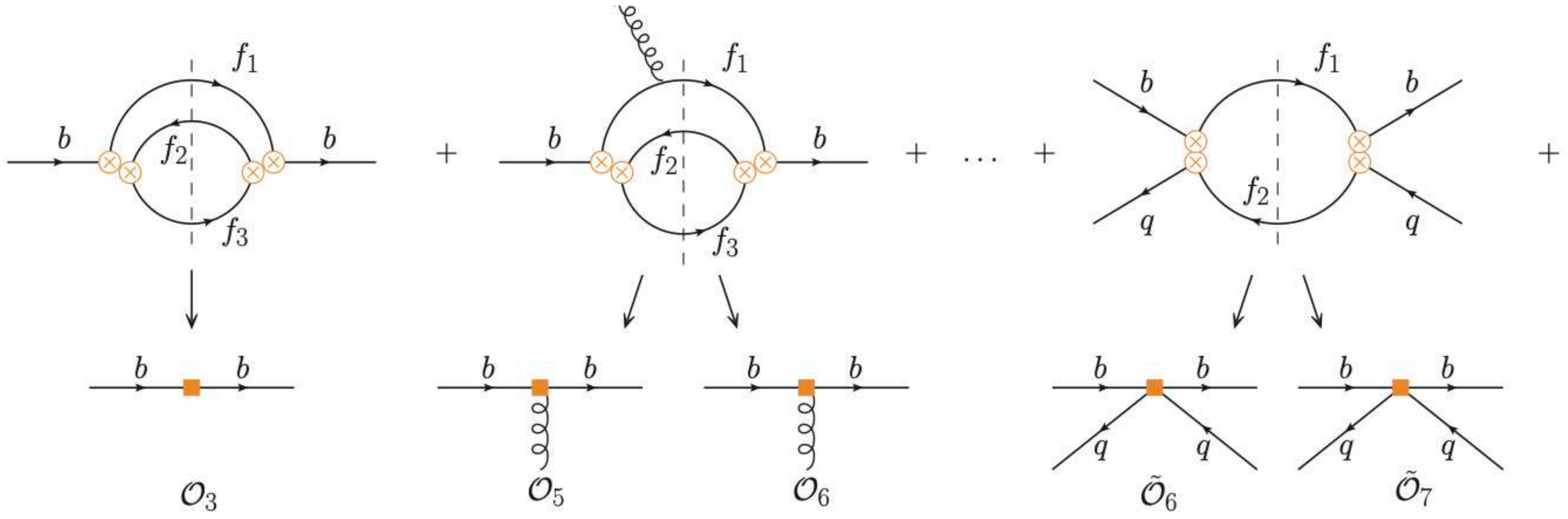
$$\Gamma(B_q) = \frac{1}{2m_{B_q}} \sum_X \int_{\mathrm{PS}} (2\pi)^4 \delta^{(4)}(p_B - p_X) \, |\langle X(p_X)|\mathcal{H}_{\mathrm{eff}}|B_q(p_B)\rangle|^2,$$

1st OPE: m_W, m_t

Optical theorem

$$\Gamma(B_q) = \frac{1}{2m_{B_q}} \mathrm{Im}\langle B_q|\mathcal{T}|B_q\rangle \qquad \mathcal{T} = i\int d^4x \, T\{\mathcal{H}_{\mathrm{eff}}(x), \mathcal{H}_{\mathrm{eff}}(0)\}$$

2nd OPE: m_b



Theory approaches

Inclusive decay rates

Heavy Quark Expansion: for total decay rates (sl&nl), lifetime ratios and mixing Γ_{12}

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

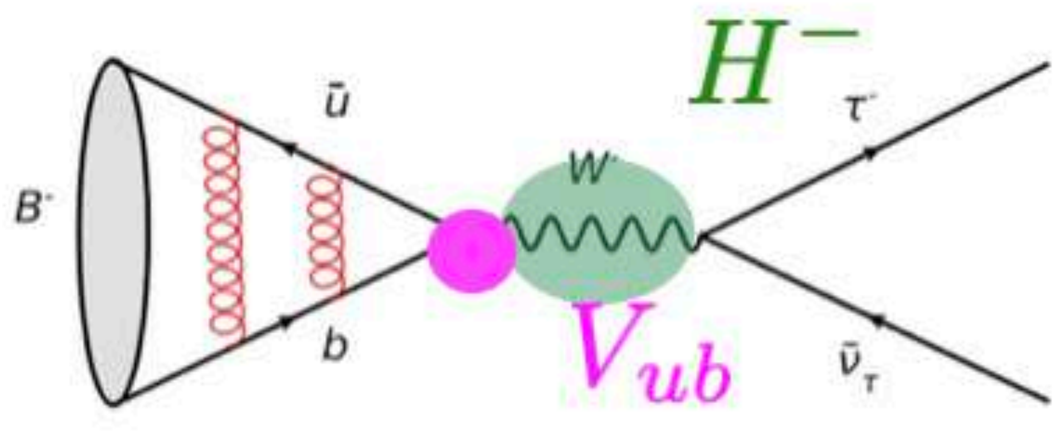
with perturbative coefficients $\Gamma_i = \Gamma_i^{(0)} + \frac{\alpha_s(m_b)}{4\pi}\Gamma_i^{(1)} + \left(\frac{\alpha_s(m_b)}{4\pi}\right)^2 \Gamma_i^{(2)} + \ldots$

and non-perturbative matrix elements $\langle \mathcal{O}_i \rangle_{B_q}$ and $\langle \tilde{\mathcal{O}}_i \rangle_{B_q}$

Theory approaches

Exclusive decay rates

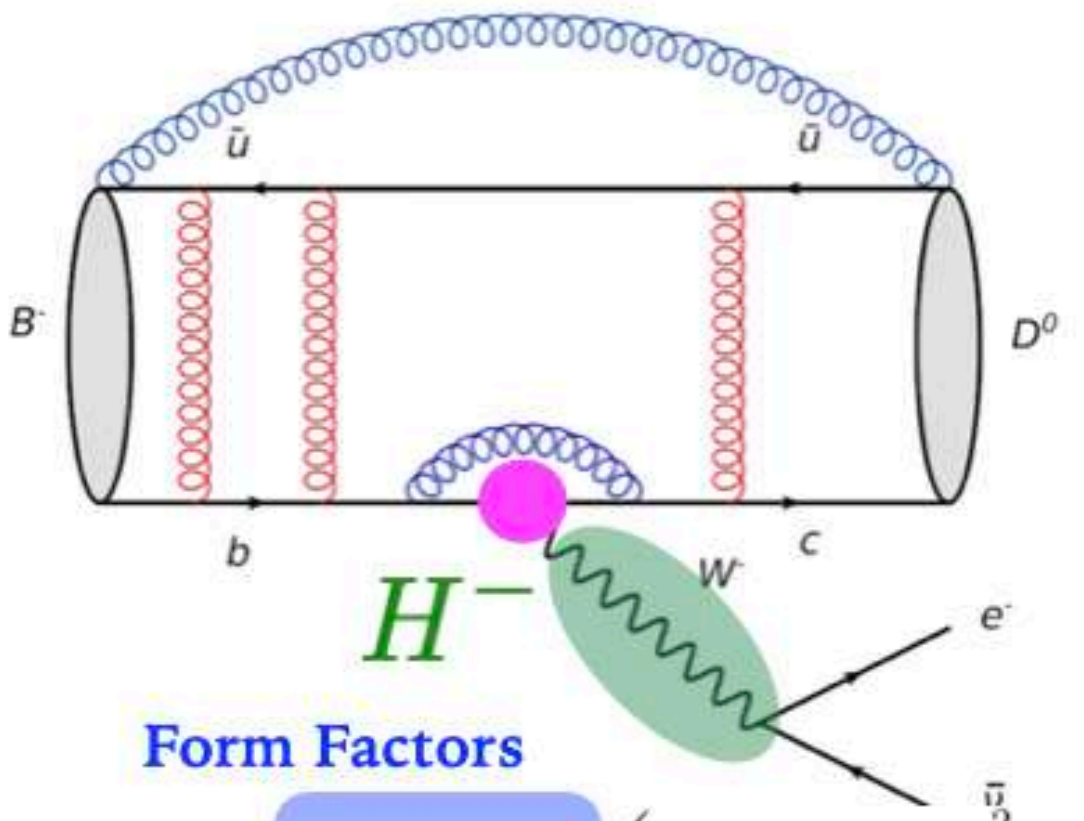
- Leptonic Decays



Decay constant

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

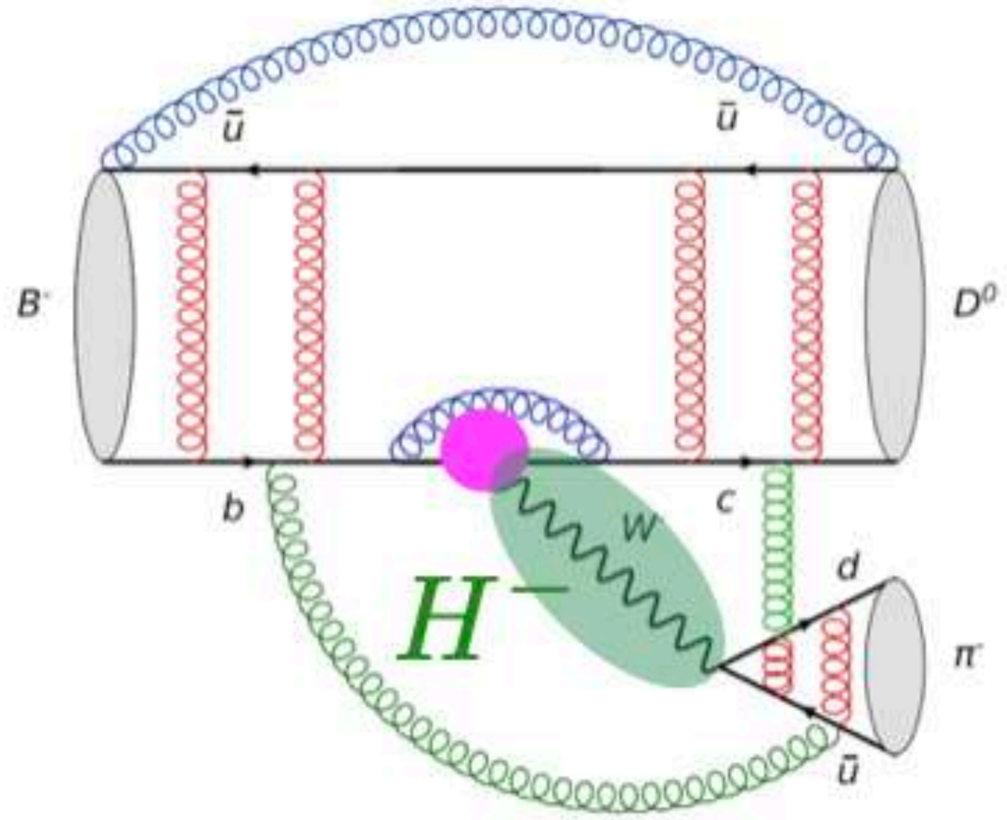
- Semileptonic Decays



Form Factors

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

- Non-leptonic Decays



Factorisation

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

I) Imaginary part of CKM-elements = CP Violation

II) Instead of a W-Boson a charged Higgs particle could be exchanged

III) QCD effects are crucial! Perturbative QCD corrections
Non-perturbative: decay constants, form factors, factorisation

IV) Determination of SM-Parameter

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Theory approaches

Exclusive decay rates

P H

color meets flavor

Two-body non-leptonic heavy-to-heavy decays at NNLO in QCD factorization #1

Tobias Huber (Siegen U.), Susanne Kränkl (Siegen U.), Xin-Qiang Li (CCNU, Wuhan, Inst. Part. Phys. and Hua-Zhong Normal U. and Hua-Zhong Normal U., LQLP) (Jun 9, 2016)

Published in: JHEP 09 (2016) 112 • e-Print: 1606.02888 [hep-ph]

A puzzle in $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)}\{\pi^-, K^-\}$ decays and extraction of the f_s/f_d fragmentation fraction #1

Marzia Bordone (Siegen U.), Nico Gubernari (Munich, Tech. U.), Tobias Huber (Siegen U.), Martin Jung (Turin U. and INFN, Turin), Danny van Dyk (Munich, Tech. U.) (Jul 20, 2020)

Published in: Eur.Phys.J.C 80 (2020) 10, 951 • e-Print: 2007.10338 [hep-ph]

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

NNLO

Eur. Phys. J. C (2020) 80:347
https://doi.org/10.1140/epjc/s10052-020-7850-9
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Theoretical Physics

Heavy-Quark expansion for $\bar{B}_s \to D_s^{(*)}$ form factors and unitarity bounds beyond the $SU(3)_F$ limit

Marzia Bordone[1,a], Nico Gubernari[2,b], Danny van Dyk[2,c], Martin Jung[3,d]
[1] Universität Siegen, Walter-Flex Straße 3, 57072 Siegen, Germany
[2] Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany
[3] Dipartimento di Fisica, Università di Torino & INFN, Sezione di Torino, 10125 Torino, Italy

LO in $\varepsilon \sim \Lambda_{\rm QCD}/E_L \sim \Lambda_{\rm QCD}/m_b$

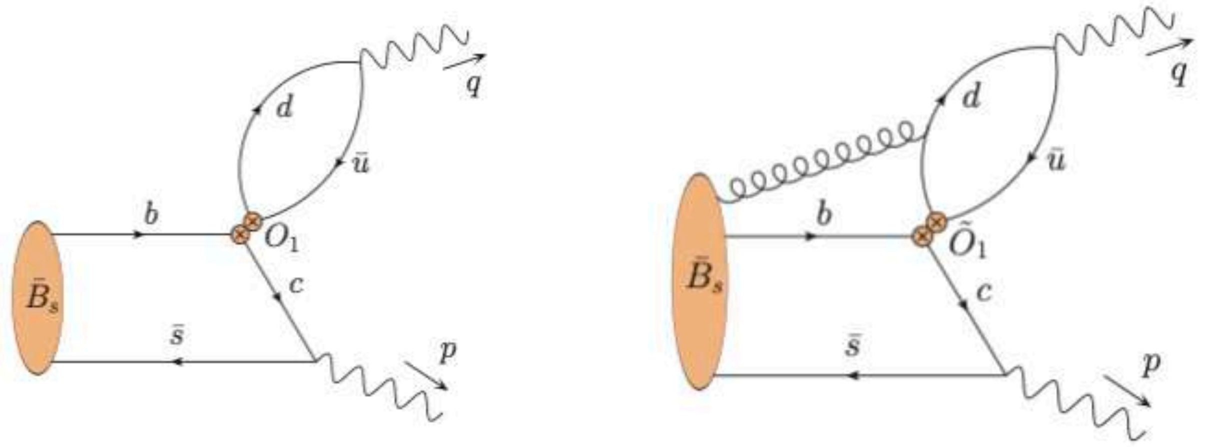
$$\mathcal{A}(\bar{B}_q^0 \to D_q^+ L^-) = i \frac{G_F}{\sqrt{2}} V_{uq_2}^* V_{cb} a_1(D_q^+ L^-) f_L \times F_0^{\bar{B}_q \to D_q}(M_L^2)(M_{B_q}^2 - M_{D_q}^2)$$

$F_0^{\bar{B}\to D}(M_K^2)$	—	0.672 ± 0.011
$F_0^{\bar{B}_s^0\to D_s}(M_\pi^2)$	—	0.673 ± 0.011
$A_0^{\bar{B}\to D^*}(M_K^2)$	—	0.708 ± 0.038
$A_0^{\bar{B}_s^0\to D_s^*}(M_\pi^2)$	—	0.689 ± 0.064

NLO in ϵ: ϵ^1
- Higher twist to light meson DA
- Emission of hard-collinear gluon from spectator quark
- Emission of hard-collinear gluon from heavy quark
- Exchange of soft-gluon between B,D-system and light meson

Bordone, et al: first estimates of power corrections yield very small effect, overall uncertainties are also very small

New estimates within QCD sum rules



$$F_\mu^{\tilde{O}_1}(p,q) = i^2 \int d^4x\, e^{ip\cdot x} \int d^4y\, e^{iq\cdot y} \langle 0 | \mathrm{T}\left\{ j_5^D(x), \tilde{O}_1(0), j_\mu^\pi(y) \right\} | \bar{B}_s(p+q) \rangle$$

Non-factorisable effects in the decays $\bar{B}_s^0 \to D_s^+\pi^-$ and $\bar{B}^0 \to D^+K^-$ from LCSR

Maria Laura Piscopo and Aleksey V. Rusov
Physik Department, Universität Siegen, Walter-Flex-Str. 3, 57068 Siegen, Germany
E-mail: maria.piscopo@uni-siegen.de, rusov@physik.uni-siegen.de

Abstract: In light of the current discrepancies between the recent predictions based on QCD factorisation (QCDF) and the experimental data for several non-leptonic colour-allowed two-body B-meson decays, we obtain new determinations of the non-factorisable soft-gluon contribution to the decays $\bar{B}_s^0 \to D_s^+\pi^-$ and $\bar{B}^0 \to D^+K^-$, using the framework of light-cone sum rule (LCSR), with a suitable three-point correlation function and B-meson light-cone distribution amplitudes. In particular, we discuss the problem associated with a double light-cone (LC) expansion of the correlator, and motivate future determinations of the three-particle B-meson matrix element with the gluon and the spectator quark aligned along different light-cone directions. Performing a LC-local operator product expansion of the correlation function, we find, for both modes considered, the non-factorisable part of the amplitude to be sizeable and positive, however, with very large systematic uncertainties. Furthermore, we also determine for the first time, using LCSR, the factorisable amplitudes at LO-QCD, and thus the corresponding branching fractions. Our predictions are in agreement with the experimental data and consistent with the results based on QCDF, although again within very large uncertainties. In this respect, we provide a rich outlook for future improvements and investigations.

JHEP10(2023)180

Indication: non-factorizable contribution larger - uncertainties larger - stay tuned

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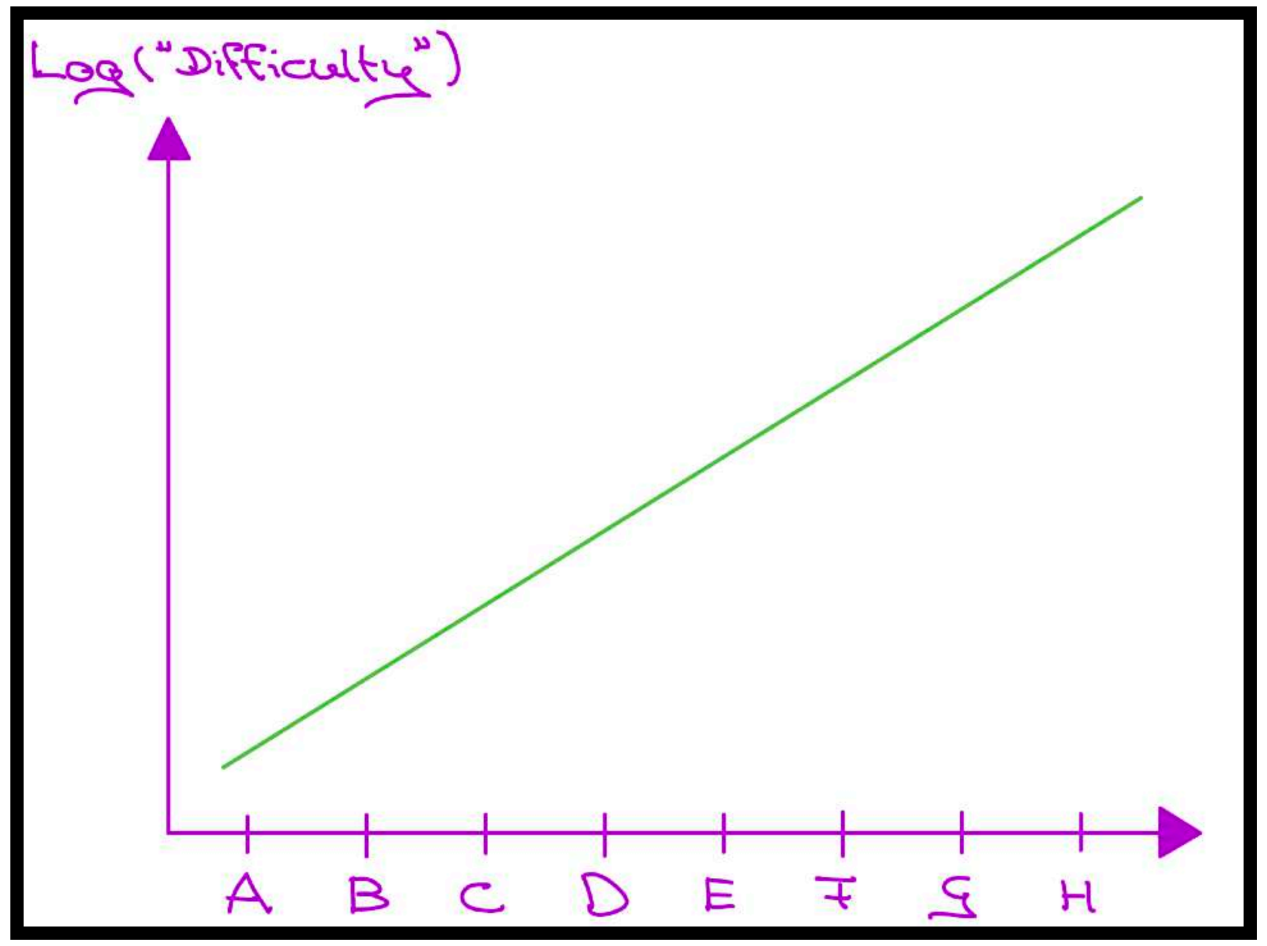

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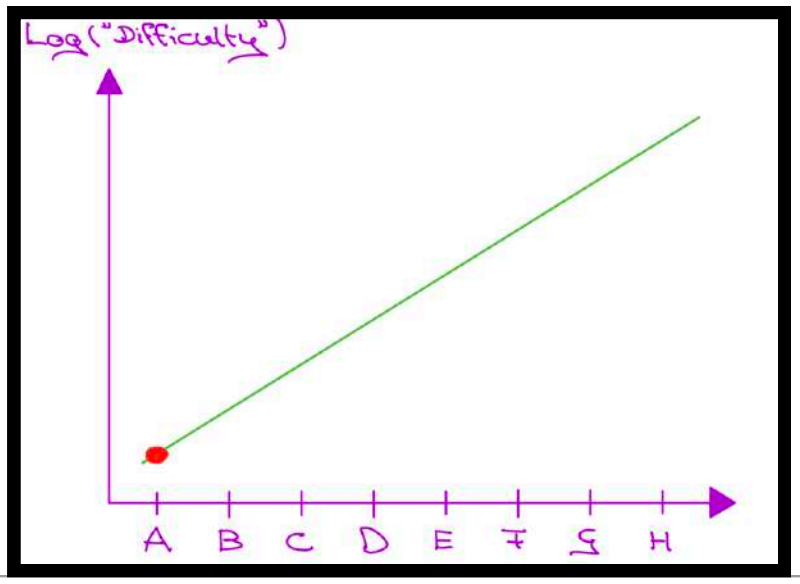
H. Charm mixing: - crazy cancellations - can we be a factor of 10 000 off?

“Easy” —-> “ganz schwer”

4) Some fun, which is many times overlooked: BSM in tree-level decays

From “easy” to “ganz schwer”

Mass differences in B-mixing

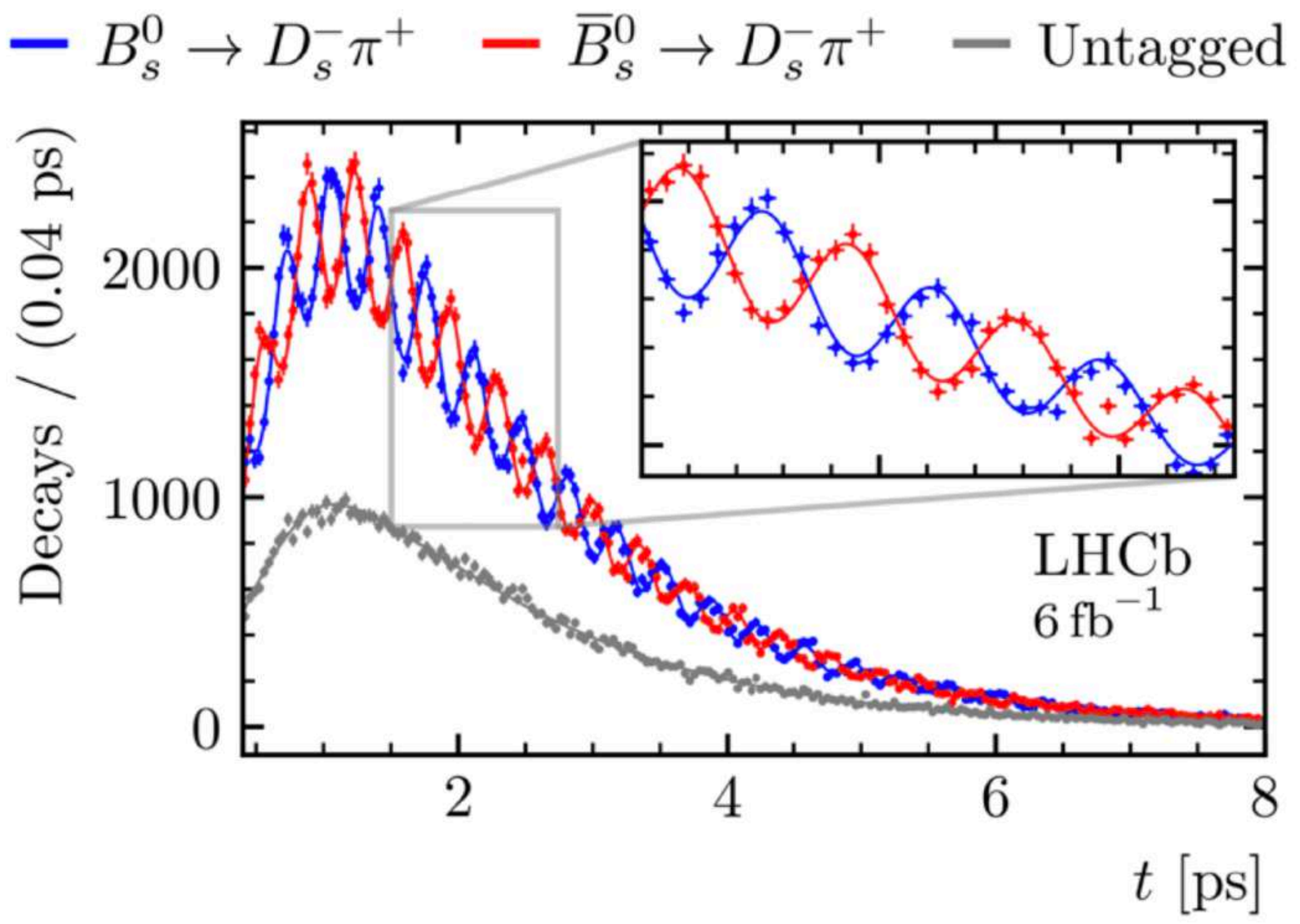


12 April 2021: Fascinating quantum mechanics.

Precise determination of the B_s^0–$\bar{B}_s^0$ oscillation frequency.

"A phenomenon in which quantum mechanics gives a most remarkable prediction" - Richard Feynman

Today, the LHCb Collaboration submitted a paper for publication that reports a precise determination of the B_s^0–$\bar{B}_s^0$ oscillation frequency. This result is presented also today at the joint annual conference of the UK Institute of Physics (IOP), organized by the University of Edinburgh. The B_s^0–$\bar{B}_s^0$ oscillation is a spectacular and fascinating feature of quantum mechanics. The strange beauty particle B^0_s composed of a beauty antiquark ($\bar{b}$) bound with a strange quark s turns into its antiparticle partner $\bar{B}_s^0$ composed of a b quark and an s antiquark ($\bar{s}$) about 3 million million times per second ($3*10^{12}$) as seen in the image below.



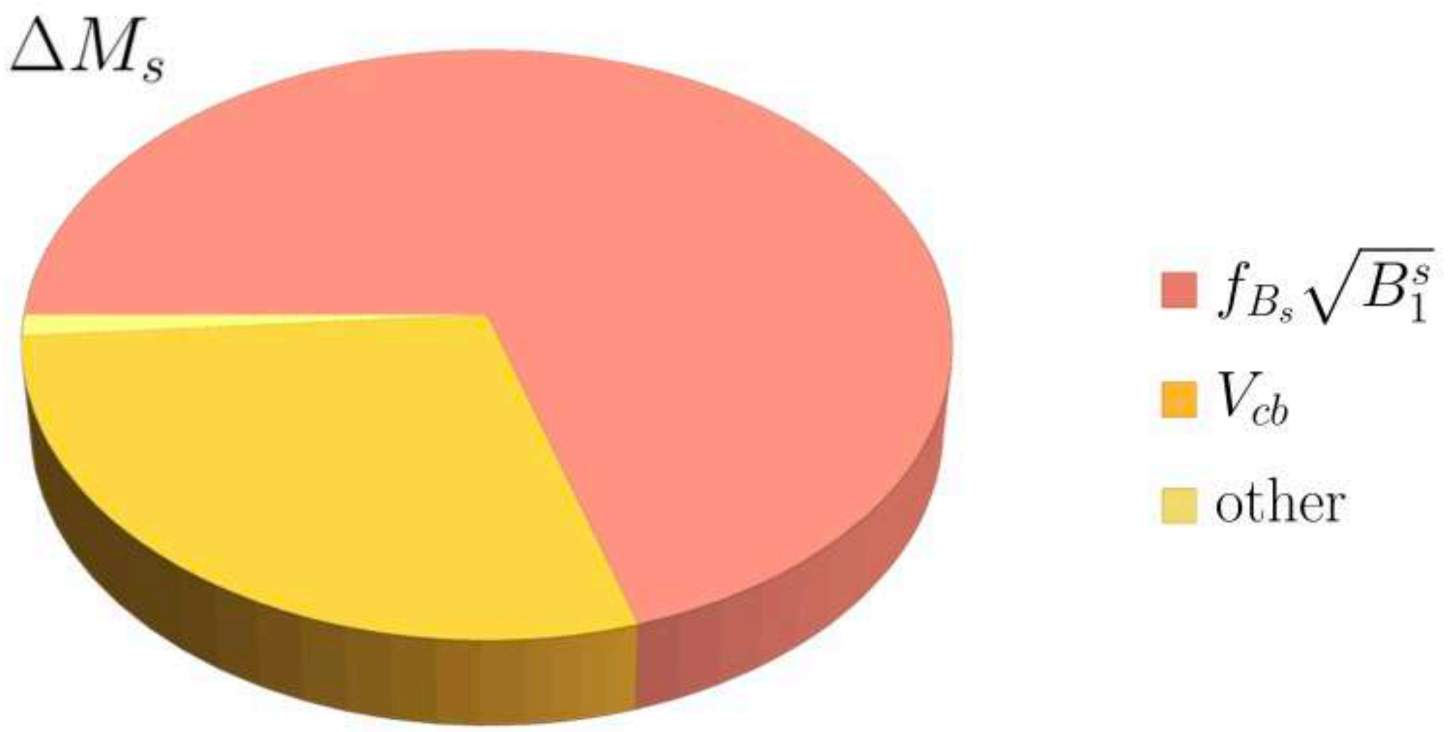
$\Delta m_s = 17.765 \pm 0.006\ \text{ps}^{-1}$	CDF, LHCb, CMS

HQET-sum rules: 3-loop + part of NNLO matching:

- *B_d mixing:
  - Siegen: Grozin, Klein, Mannel, Pivovarov 1606.06054, 1706.05910, 1806.00253
- *B_d and D mixing, D^0, D^+, B_d and B^+ lifetimes
  - Durham: Kirk (Rome), AL, Rauh (Bern) 1711.02100
- *B_s mixing
  - Durham: King, AL, Rauh (Bern) 1904.00940
- *B_s and D_s^+ lifetimes
  - Siegen: King (Durham), AL, Rauh (Bern) 2112.03691

Lattice

- B_s , B_d and D mixing: FNAL/MILC 1602.03560
- Ratio of B_s and B_d mixing: RBC/UK QCD 1812.08791
- B_s and B_d mixing: HQPCD 19007.01025



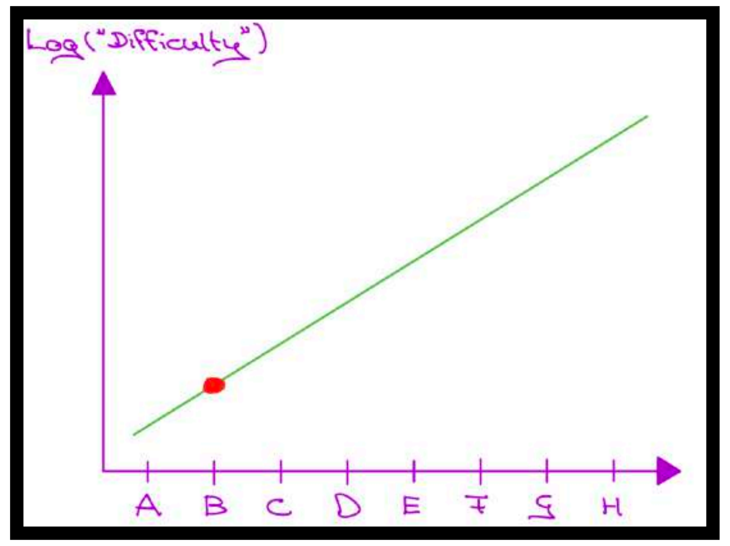
$$\Delta M_s = (18.23 \pm 0.63)\,\text{ps}^{-1}$$

to improve:
new lattice is needed
plus progress in V_{cb}

Universität Siegen

From “easy” to “ganz schwer”

ratios $\tau(B^+)/\tau(B_d)$; B-mixing: $\Delta\Gamma_{s,d}$, $a_{fs}^{s,d}$



P H

color meets flavor

$$\frac{\tau(B^+)}{\tau(B_d)} = 1 + \left[\underbrace{(\Gamma_3 - \Gamma_3)}_{=0} + \Gamma_5 \underbrace{\left(\frac{\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B^+}}{m_b^2} \right)}_{=0 \text{ isopin}} + \Gamma_6 \underbrace{\left(\frac{\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} \right)}_{=0 \text{ isopin}} + \ldots \right] \tau(B^+)$$

$$+16\pi^2 \left[\left(\tilde{\Gamma}_6(B_d) \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_d}}{m_b^3} - \tilde{\Gamma}_6(B^+) \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B^+)}}{m_b^3} \right) + \left(\tilde{\Gamma}_7(B_d) \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_d}}{m_b^4} - \tilde{\Gamma}_7(B^+) \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B^+)}}{m_b^4} \right) + \ldots \right] \tau(B^+)$$

$\tilde{\Gamma}_6^{(2)}$ KIT

$\tilde{\Gamma}_6^{(1)}$ KIT/Siegen

$\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ HQET - SM/BSM Siegen

$\tilde{\Gamma}_7^{(0)}$ **2003**

$\langle \tilde{\mathcal{O}}_7 \rangle_{B_q}$ VIA

$$\Gamma_{12} = 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_q}}{m_b^4} + \ldots \right]$$

$\tilde{\Gamma}_6^{(2)}$ **KIT/ Siegen**

$\tilde{\Gamma}_6^{(1)}$ KIT/Siegen

$\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ HQET SR (SM/BSM) Siegen; different lattice groups, including Siegen

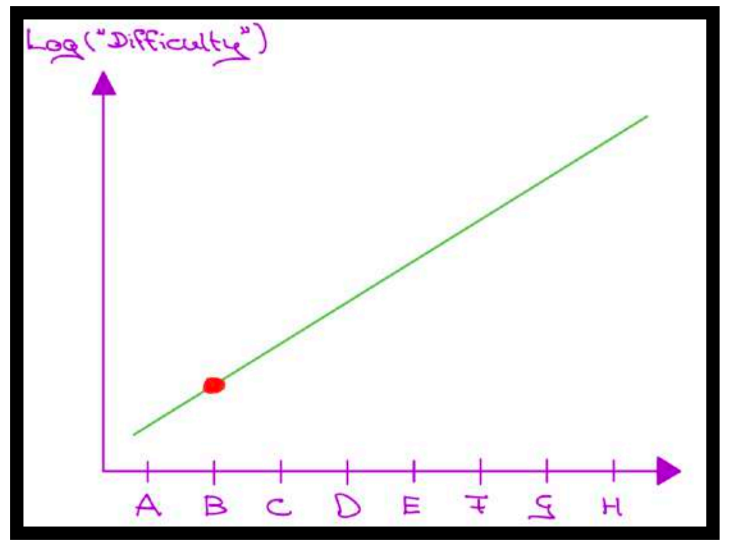
$\tilde{\Gamma}_7^{(0)}$ **1996**

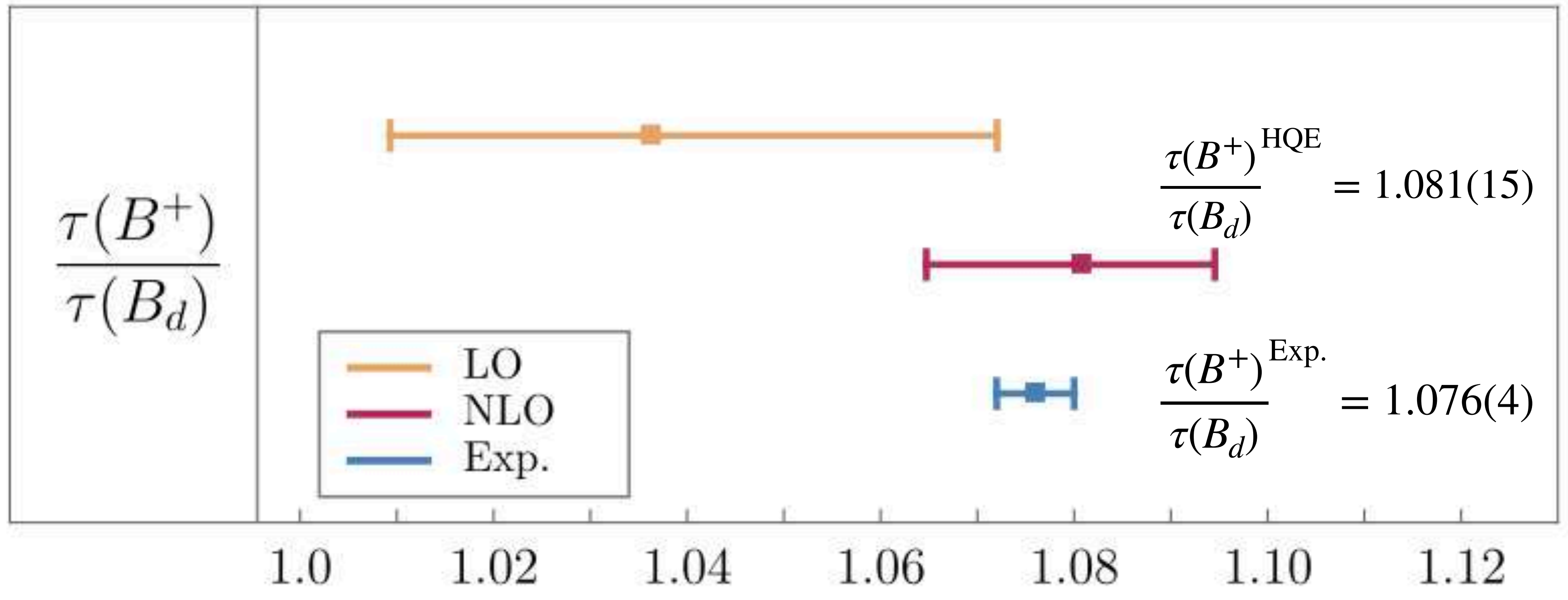
mostly VIA + Lattice (tree-level matching) 1910.00970

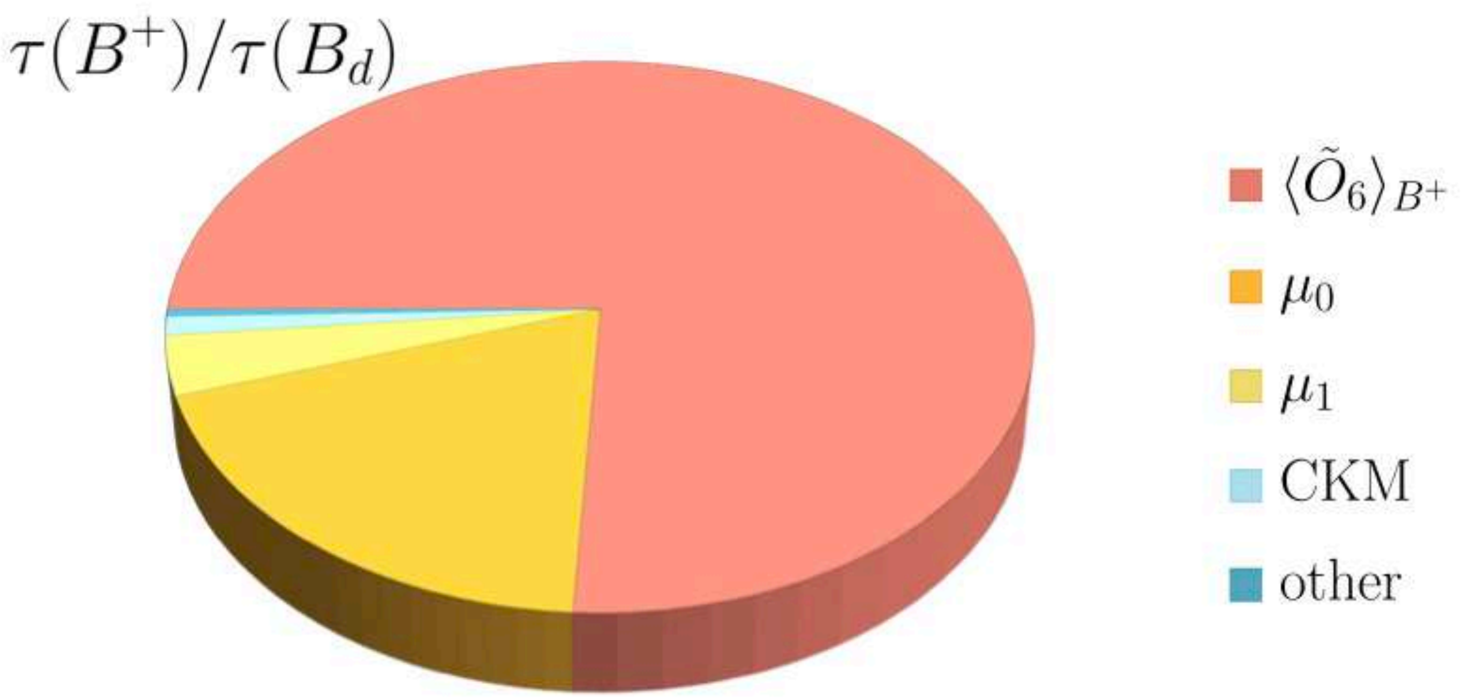
k	B'_{R_k}	B_{R_k}	k	B'_{R_k}	B_{R_k}
R_2	0.27(10)	0.89(38)	$\tilde{R}_2$	0.27(10)	0.89(38)
R_3	0.33(11)	1.07(42)	$\tilde{R}_3$	0.35(13)	1.14(46)

From “easy” to “ganz schwer”

ratios $\tau(B^+)/\tau(B_d)$; B-mixing: $\Delta\Gamma_{s,d}$, $a_{fs}^{s,d}$







1) New lattice is needed for dim 6 bag parameter
=> Gradient flow

2) Next: pert. correction $\tilde{\Gamma}_6^{(2)}$

$B_s - \bar{B}_s$ system: Precise measurement (HFLAV):

$$\Delta\Gamma_s = (0.0781 \pm 0.0035)\ \text{ps}^{-1}$$

$$\Delta\Gamma_s = (0.077 \pm 0.016)\ \text{ps}^{-1}$$

Current-current operator contribution to the decay matrix in B-meson mixing at next-to-next-to-leading order of QCD
Marvin Gerlach (KIT, Karlsruhe, TTP), Ulrich Nierste (KIT, Karlsruhe, TTP), Pascal Reeck (KIT, Karlsruhe, TTP), Vladyslav Shtabovenko (Siegen U.), Matthias Steinhauser (KIT, Karlsruhe, TTP) (May 28, 2025)
e-Print: 2505.22740 [hep-ph]

perturbative uncertainty: 9%
uncertainty from $1/m_b$. 18%

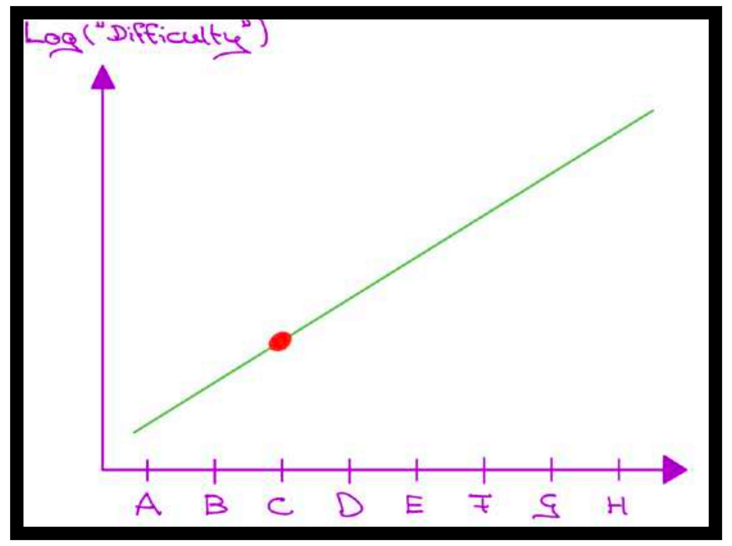
1) dominated by dim 7 - first sum rule result is needed
2) later lattice is needed
3) $\tilde{\Gamma}_7^{(1)}$ desirable

$$\frac{\Delta\Gamma_s}{\Delta M_s} = (4.27^{0.36}_{-0.37\text{scale}} \pm 0.12_{\text{matrixel.}} \pm 0.79_{1/m_b} \pm 0.05_{\text{input}}) \times 10^{-3}\ (\overline{\text{PS}})$$

perturbative uncertainty — $\langle\widetilde{Q}_S\rangle/\langle Q\rangle$ — power corr. — CKM parameters

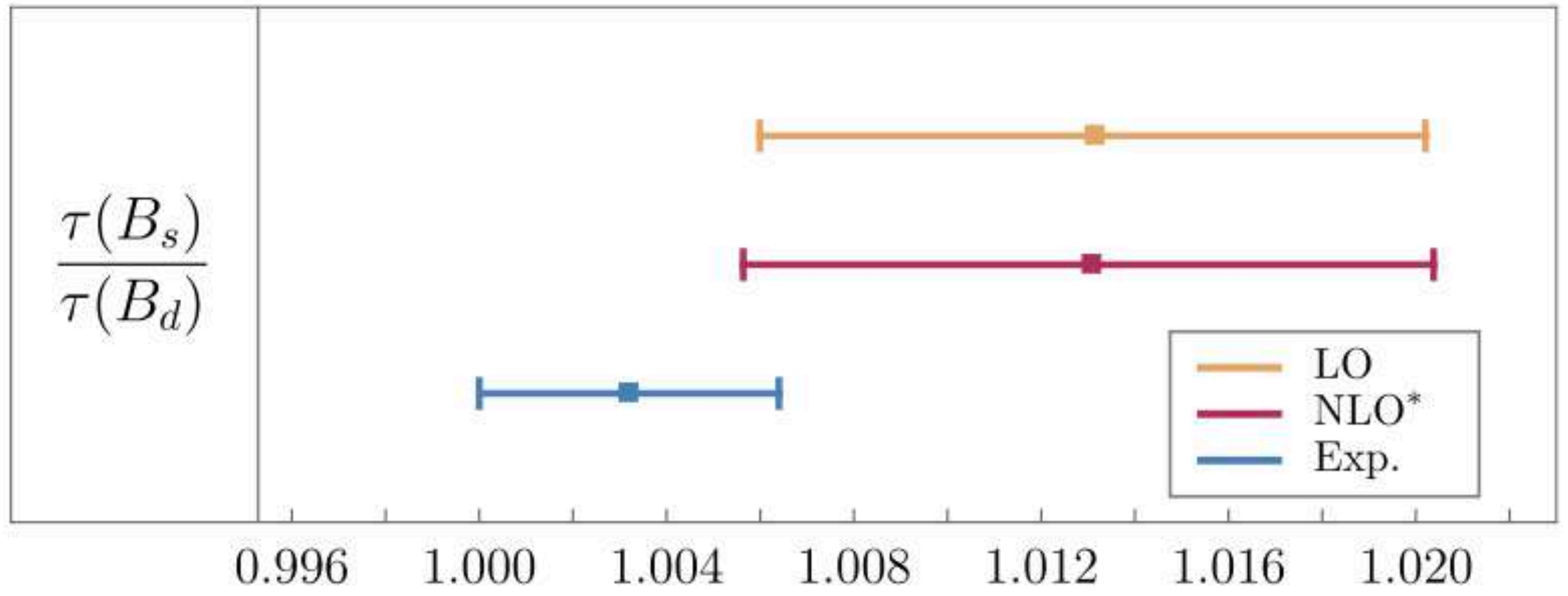
From easy to “ganz schwer”

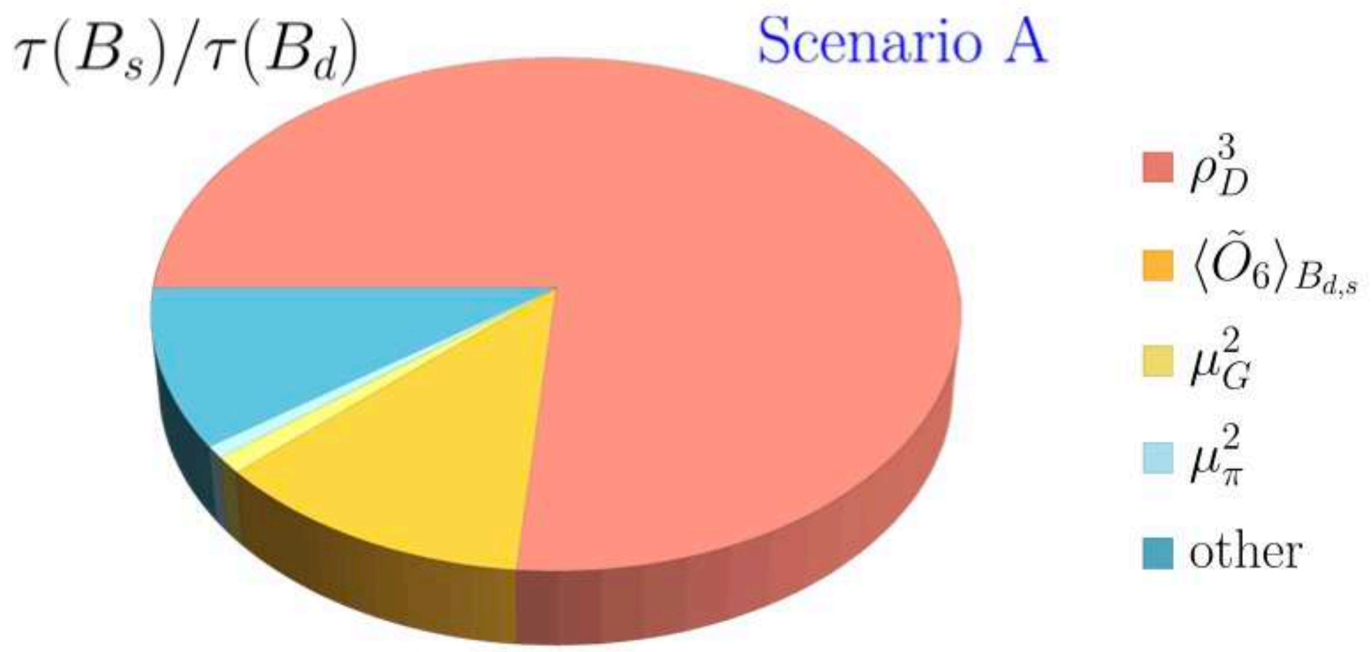
Lifetime ratio $\tau(B_s)/\tau(B_d)$



$$\frac{\tau(B_s)}{\tau(B_d)} = 1 + \left[\underbrace{(\Gamma_3 - \Gamma_3)}_{=0} + \underbrace{\Gamma_5 \left(\frac{\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B_s}}{m_b^2} \right)}_{\text{SU(3)}_\text{F}\text{breaking}} + \underbrace{\Gamma_6 \left(\frac{\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B_s}}{m_b^3} \right)}_{\text{SU(3)}_\text{F}\text{breaking}} + \ldots \right] \tau(B_s)$$

$$+16\pi^2 \left[\left(\tilde{\Gamma}_6(B_d) \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_d}}{m_b^3} - \tilde{\Gamma}_6(B_s) \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_s}}{m_b^3} \right) + \left(\tilde{\Gamma}_7(B_d) \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_d}}{m_b^4} - \tilde{\Gamma}_7(B_s) \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_s}}{m_b^4} \right) + \ldots \right] \tau(B_s)$$





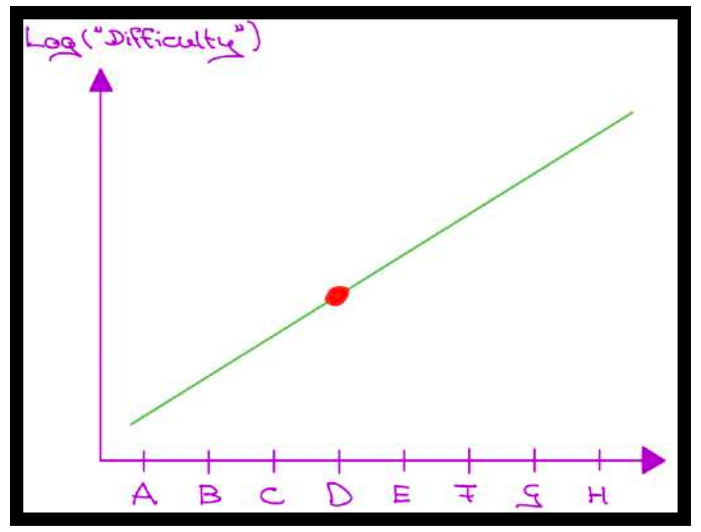
some problems:

- values of non-perturbative parameter, in particular Darwin operator and size of SU(3)F breaking are unknown
- combined fit of semi-leptonic decays and lifetimes

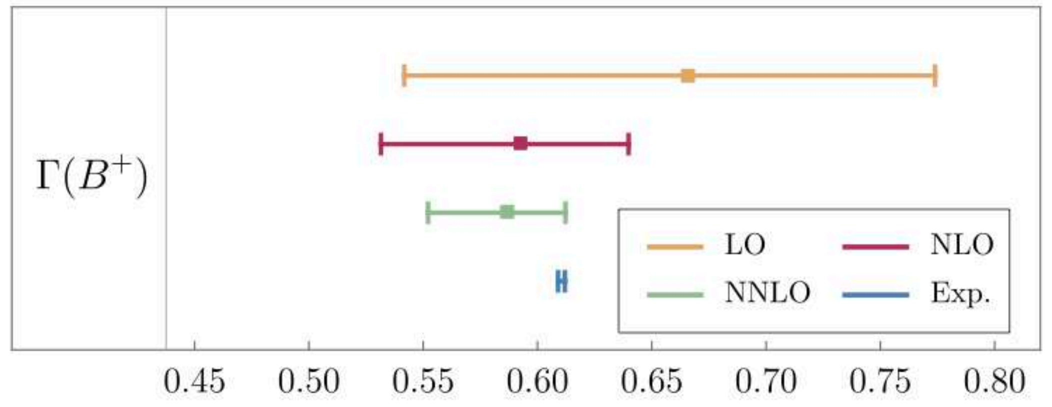
1) Size of SU(3) breaking in Darwin term
2) lattice for dim 6 bag parameter
   => Gradient flow
3) Size of SU(3) breaking in chromo-magnetic operator

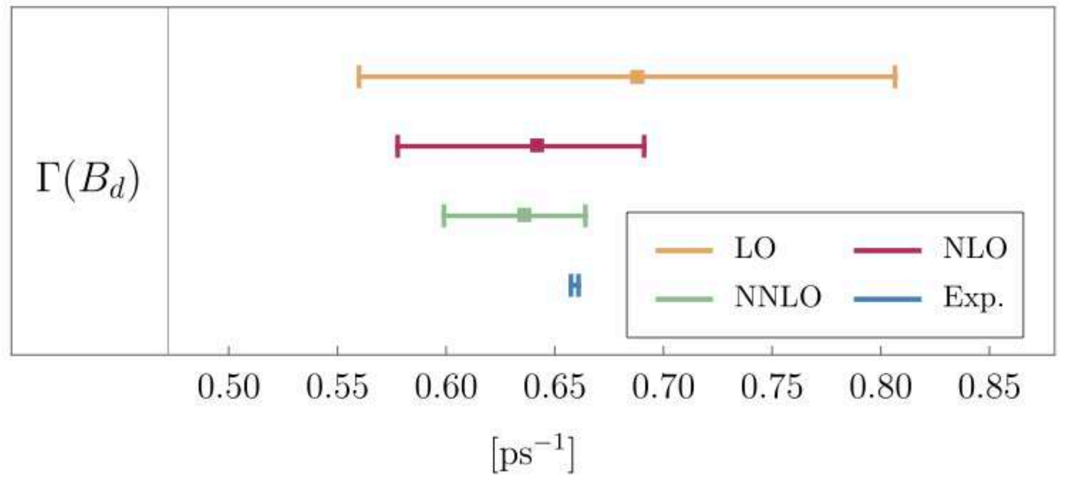
From easy to “ganz schwer”

$\Gamma(B_d, B^+, B_s)$, $\tau(\Lambda_b)/\tau(B_d)$



for non-leptonic decays:





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

- $\Gamma_3^{(2)}$ KIT
- $\Gamma_5^{(0)}$ penguins+ BSM Siegen
- $\Gamma_5^{(1)}$ SM - tree-level op Siegen
- $\Gamma_6^{(0)}$ penguins+ BSM Siegen
- $\tilde{\Gamma}_6^{(2)}$ KIT
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ HQET - SM/BSM Siegen
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ GF-matching **Aachen/ Siegen**
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ GF-lattice **Aachen/ Siegen**

$\Gamma_d = 0.63^{+0.11}_{-0.07}$ ps^{-1} Lenz, et al. 2023

Total decay rates of B mesons at NNLO-QCD #5

Manuel Egner (KIT, Karlsruhe, TTP), Matteo Fael (U. Padua, Dept. Phys. Astron. and INFN, Padua), Alexander Lenz (Siegen U.), Maria Laura Piscopo (Siegen U. and Nikhef, Amsterdam and Vrije U., Amsterdam), Aleksey V. Rusov (Siegen U. and Munich, Tech. U.) et al. (Dec 18, 2024)

Published in: *JHEP* 04 (2025) 106 • e-Print: 2412.14035 [hep-ph]

$$\Gamma(B^+) = 0.587^{+0.025}_{-0.035}\ \text{ps}^{-1},\ \Gamma(B_d) = 0.636^{+0.028}_{-0.037}\ \text{ps}^{-1},\ \Gamma(B_s) = 0.628^{+0.027}_{-0.035}\ \text{ps}^{-1}$$

1) **Understand quark mass definitions better**
2) V_{cb} **is an important input**

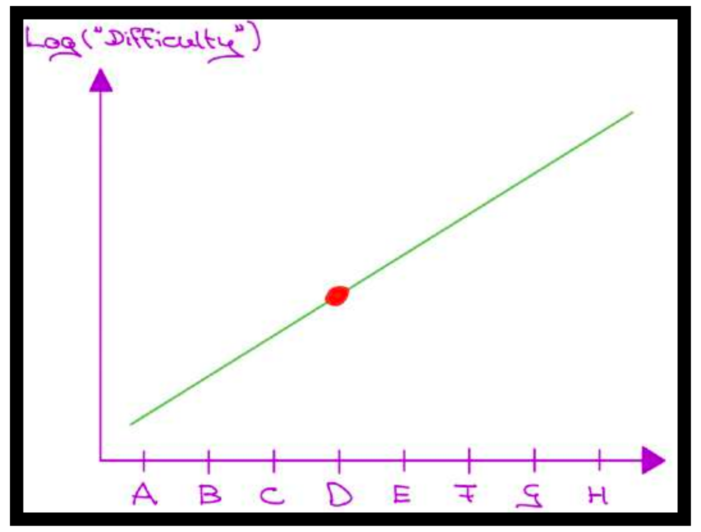
2:50 PM **Charm Quark Mass from Lattice QCD** 50m

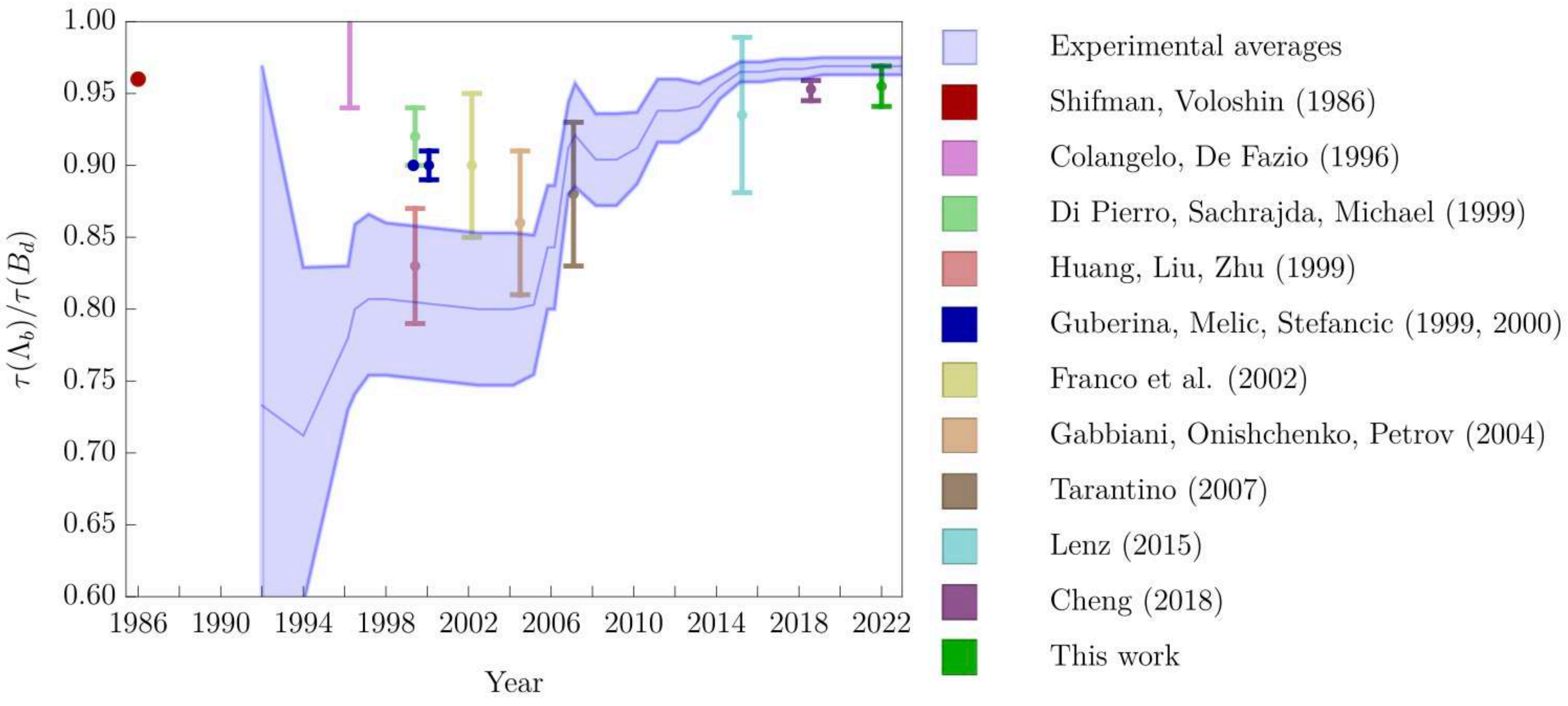
Lattice QCD has entered a precision era in the charm sector, with predictions for the charm quark mass available at percent level precision. Uncertainties are now dominated by systematic effects arising from discretisation and renormalisation. We present two novel approaches for controlling these effects: a massive momentum-subtraction scheme, and gradient flow combined with short-flow-time expansion. We introduce the theoretical bases of these schemes, discuss perturbative matching to MSbar, and finally present precise determinations of the charm quark mass.

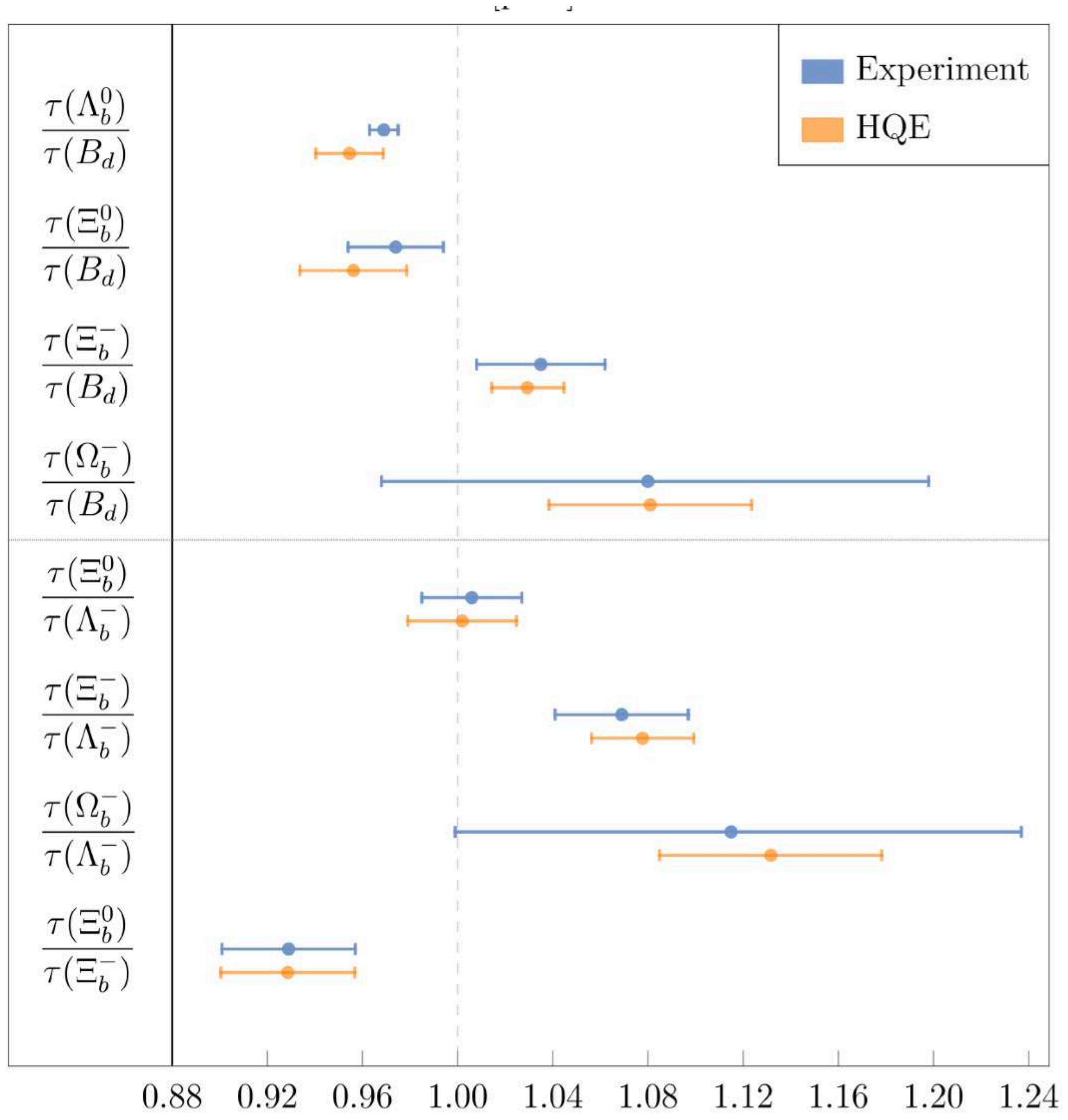
Speakers: Matthew Black (University of Edinburgh), Rajnandini Mukherjee (University of Edinburgh)

From easy to “ganz schwer”

$\Gamma(B_d, B^+, B_s)$, $\tau(\Lambda_b)/\tau(B_d)$







Many theory paper appeared

Some claiming HQE fails

FAILURE OF LOCAL DUALITY IN INCLUSIVE NON-LEPTONIC HEAVY FLAVOUR DECAYS

G. Altarelli
Theoretical Physics Division, CERN, CH-1211 Geneva 23 and Dipartimento di Fisica, Terza Università di Roma, Roma

G. Martinelli, S. Petrarca and F. Rapuano
Dip. di Fisica dell'Università *La Sapienza* and INFN, Sez. di Roma I
P.le A. Moro 2, 00185 Roma, Italy

arXiv:hep-ph/9604202v3 5 Apr 1996

ABSTRACT

We argue that there is strong experimental evidence in the data of b- and c-decays that the pattern of power suppressed corrections predicted by the short distance expansion, the heavy quark effective theory and the assumption of local duality is not correct for the non-leptonic inclusive widths. The data indicate instead the presence of $1/m$ corrections that should be absent in the above theoretical framework. These corrections can be simply described by replacing the heavy quark mass by the mass of the decaying hadron in the m^5 factor in front of all the non-leptonic widths.

Nature (or experimentalists) might be nasty

Experiment in 1996 shows

$\Gamma^{\rm NL} = \frac{G_F^2 m_{\rm Meson}^5}{192\pi^3}$ vs. $\Gamma^{\rm NL} = \frac{G_F^2 m_b^5}{192\pi^3}$

Works | **Works Not**

arXiv.org > hep-ph > arXiv:hep-ph/0304202v1

Search... Help | Advanced

High Energy Physics – Phenomenology

Explicit Quark-Hadron Duality Violations in B-Meson Decays

Benjamin Grinstein, Michael Savrov

(Submitted on 22 Apr 2003 (this version), latest version 29 Apr 2003 (v2))

We consider the weak decay of heavy mesons in QCD. We compute the inclusive hadronic decay rate in leading order in the large N_c expansion, with masses chosen to insure the final state mesons recoil slowly (the SV limit). We find, by explicit computation, violations to quark-hadron duality at order 1/M in the heavy mass expansion. The violation to duality is linear in the slope of the form factor for the associated semileptonic decay. Differences in slopes of form factors may help understand the puzzle of lifetimes of b-hadrons.

Comments:	17 pages, no figures, latex/revtex4
Subjects:	High Energy Physics – Phenomenology (hep-ph)
Report number:	UCSD/PTH 03-05
Cite as:	arXiv:hep-ph/0304202
	(or arXiv:hep-ph/0304202v1 for this version)

Bibliographic data

[Enable Bibex (What is Bibex?)]

Submission history

From: Benjamin Grinstein [view email]
[v1] Tue, 22 Apr 2003 05:10:07 UTC (16 KB)
[v2] Tue, 29 Apr 2003 21:34:58 UTC (0 KB)

1) Understand baryonic matrix elements better (non-relativistic constituent quark model)

18. Dezember 2025 17:22
Übersetzung anzeigen >

Wishing everybody a great Christmas break!!!

When subatomic heroes and friends make theory predictions

J. Gratrex, A. Lenz, B. Melić, I. Nišandžić, M. L. Piscopo, and A. V. Rusov, *Quark-hadron duality at work: lifetimes of bottom baryons*, JHEP **04** (2023) 034, [arXiv:2301.07698].

$\tau(\Xi_b^0)/\tau(\Lambda_b^0)$	1.002 ± 0.023
$\tau(\Xi_b^-)/\tau(\Lambda_b^0)$	1.078 ± 0.021

Experiment finds a little bit later

$$\tau(\Xi_b^0) = 1.475 \pm 0.012 \pm 0.008 \pm 0.009\,\text{ps}\,, \quad \frac{\tau(\Xi_b^0)}{\tau(\Lambda_b^0)} = 1.004 \pm 0.008 \pm 0.005$$

LHCb Collaboration, R. Aaij et al., *Precision measurement of the Ξ_b^0 baryon lifetime*, Phys. Rev. D **112** (2025), no. 5 052012, [arXiv:2507.12402].

$$\tau(\Xi_b^-) = 1.578 \pm 0.018 \pm 0.010 \pm 0.011\,\text{ps}\,, \quad \frac{\tau(\Xi_b^-)}{\tau(\Lambda_b^0)} = 1.078 \pm 0.012 \pm 0.007\,.$$

LHCb Collaboration, R. Aaij et al., *Precision measurement of the Ξ_b^- baryon lifetime*, Phys. Rev. D **110** (2024), no. 7 072002, [arXiv:2406.12111].

@benallanach
@lhcbexperiment
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@fsre_mathe_physik_siegen
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@darkmatter_darlings
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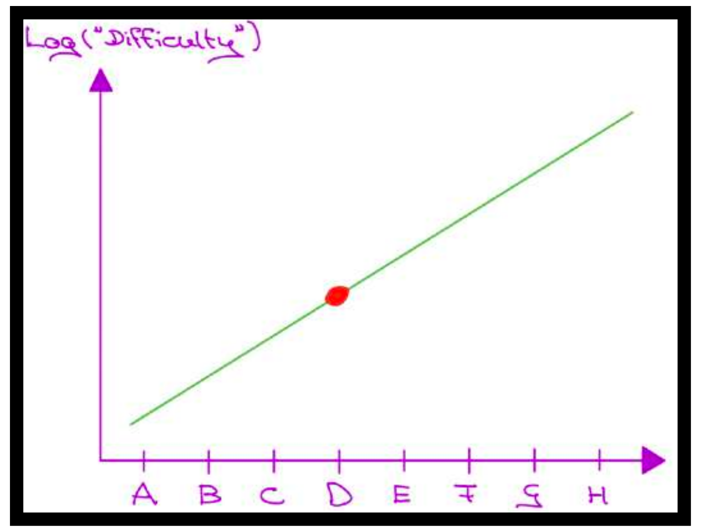
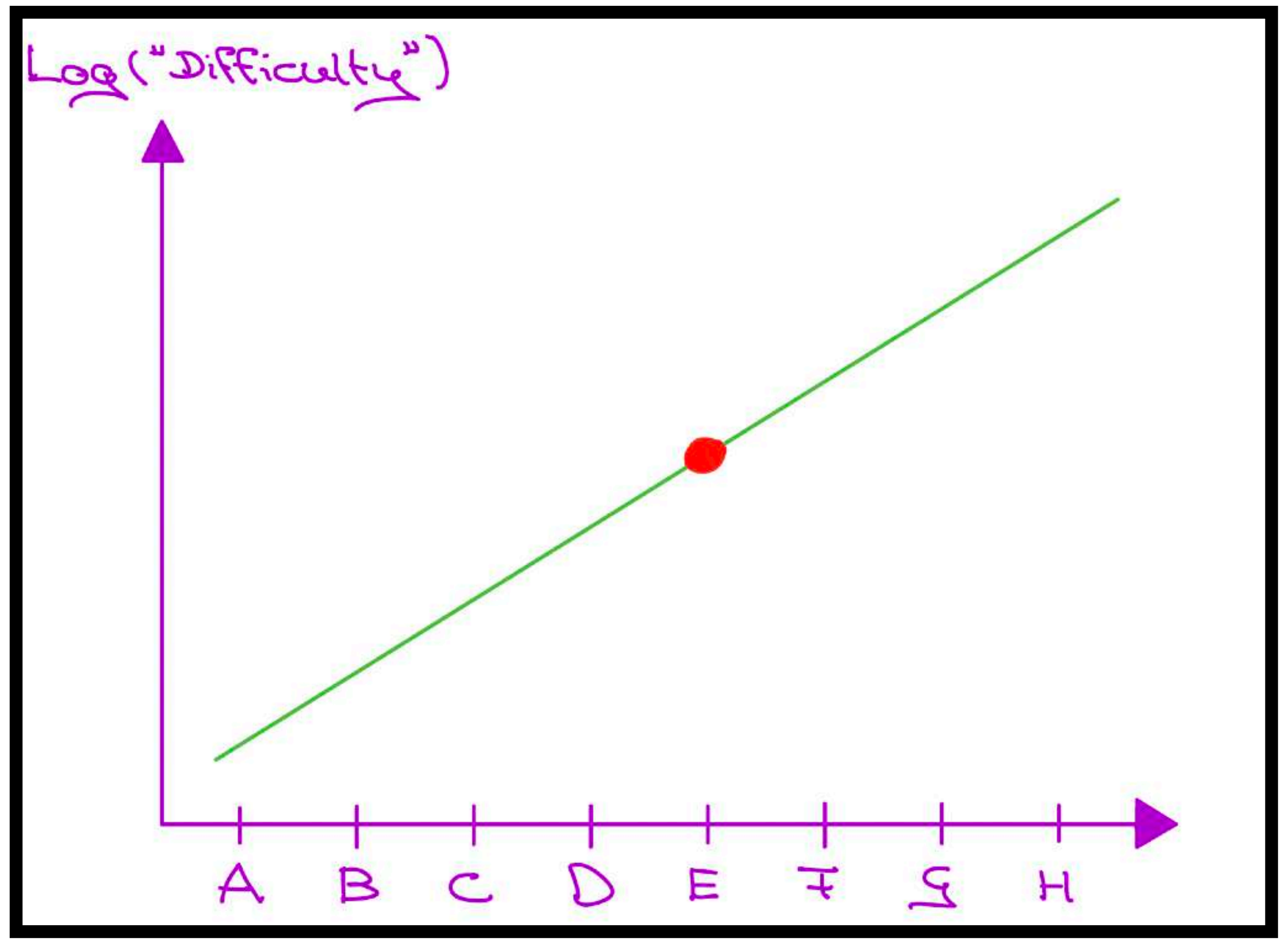


Outline

1) Flavour Physics in a nutshell
2) Theory approaches in a nutshell
3) From “easy” to “ganz schwer”



Inclusive V_{cb}

Relation to non-leptonic B-decays, like $B_s \to D_s^+ \pi^-$ and to rare-semi-leptonic decays $B \to Kll$ or $D \to \pi ll$

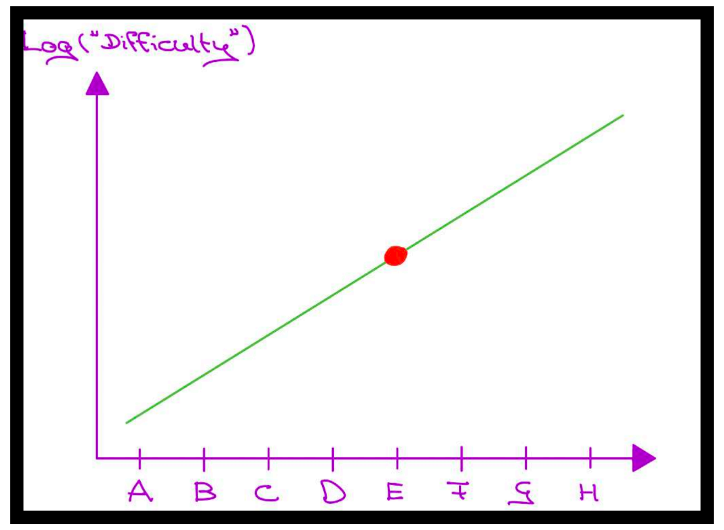
A. Mass differences in B-mixing
B. Lifetime ratios $\tau(B^+)/\tau(B_d)$;
   B-mixing: decay rate differences $\Delta\Gamma_{s,d}$; flavour-specific asymmetries $a_{fs}^{s,d}$
C. Lifetime ratios $\tau(B_s)/\tau(B_d)$ - some problems
D. Sizable progress: $\Gamma(B_d, B^+, B_s)$, $\tau(\Lambda_b)/\tau(B_d)$
E. Charm lifetimes: $\Gamma(D^0)$, $\tau(D^+)/\tau(D^0)$
F. Charm lifetimes: $\Gamma(D^+)$ - terrible cancellations
G. CPV in charm: ΔA_{CP} ($D^0 \to \pi^+\pi^-, K^+K^-$) - can we be a factor of 10 off?
H. Charm mixing: - crazy cancellations - can we be a factor of 10 000 off?

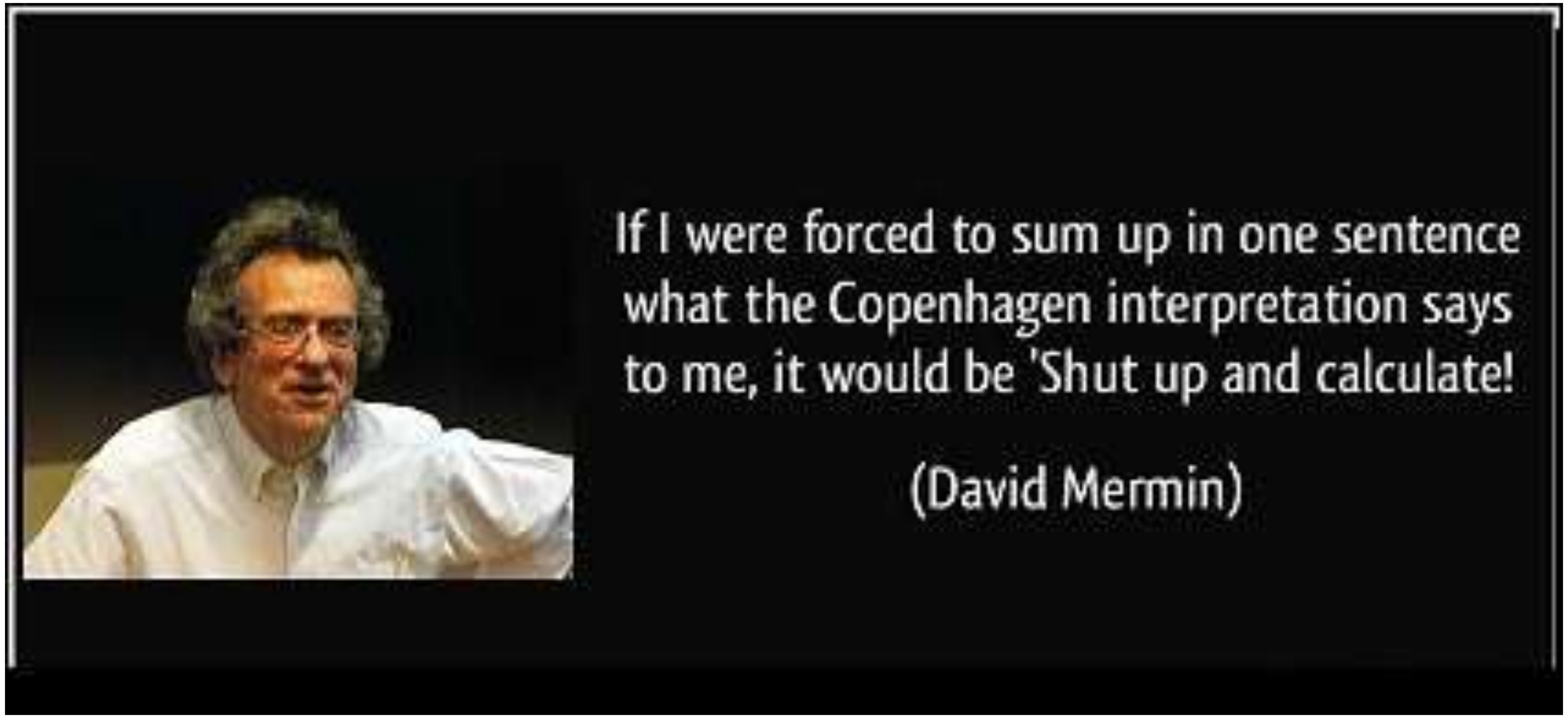
“Easy” — —> “ganz schwer”

4) Some fun, which is many times overlooked: BSM in tree-level decays

From easy to “ganz schwer”

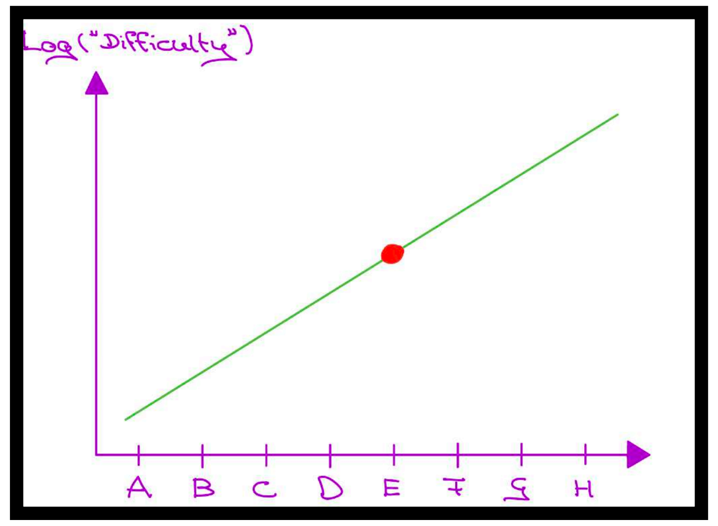
Charm lifetimes: $\Gamma(D^0)$, $\tau(D^+)/\tau(D^0)$





From easy to “ganz schwer”

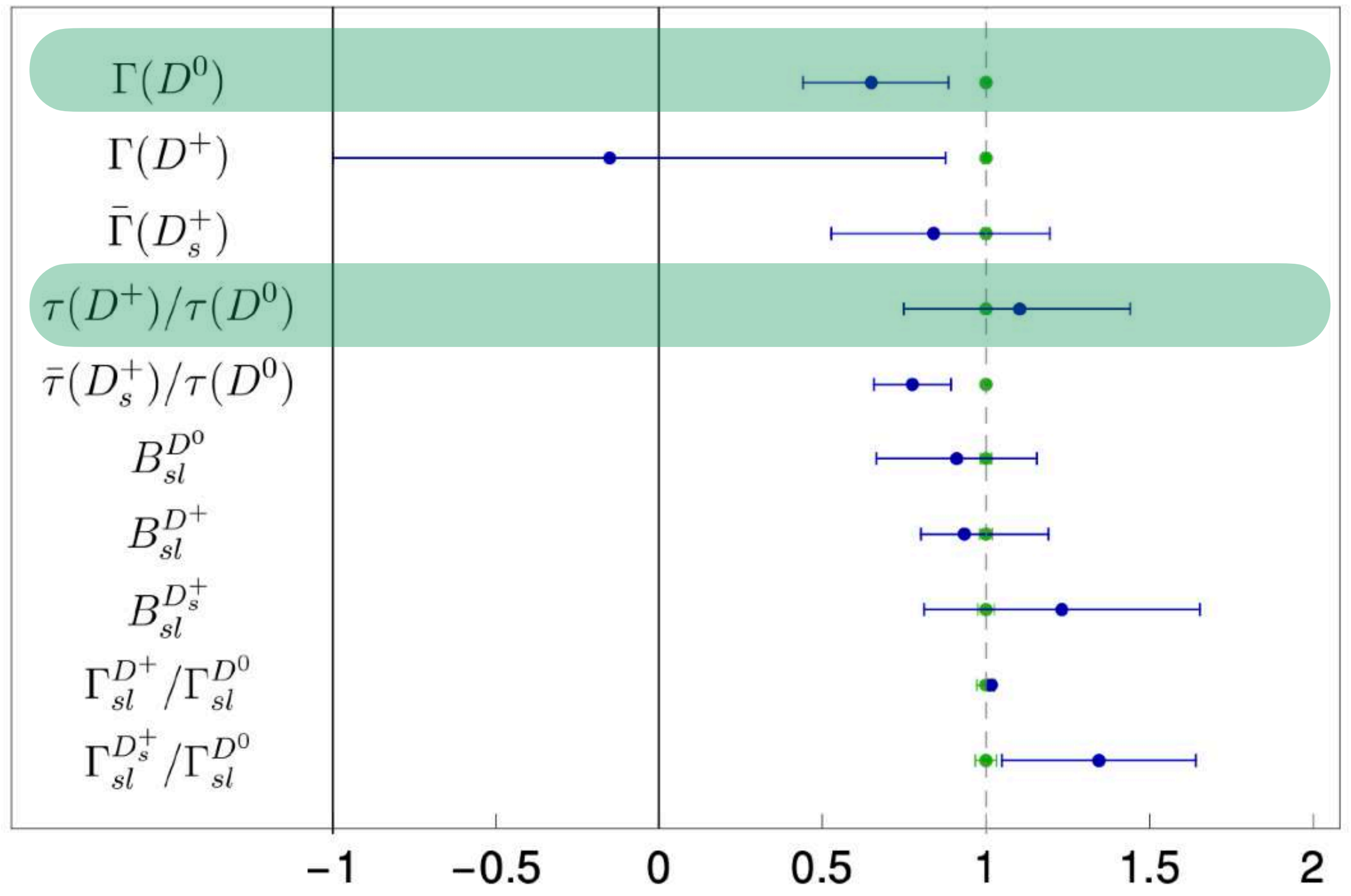
Charm lifetimes: $\Gamma(D^0)$, $\tau(D^+)/\tau(D^0)$



$$
\begin{aligned}
\Gamma(D^0) = \Gamma_0 \Big[& \underbrace{6.15}_{c_3^{\rm LO}} + \underbrace{2.95}_{\Delta c_3^{\rm NLO}} - 1.66\, \frac{\mu_\pi^2(D)}{\rm GeV^2} + 0.13\, \frac{\mu_G^2(D)}{\rm GeV^2} + 23.6\, \frac{\rho_D^3(D)}{\rm GeV^3} \\
& - 1.60\, \tilde{B}_1^q + 1.53\, \tilde{B}_2^q - 21.0\, \tilde{\epsilon}_1^q + 19.2\, \tilde{\epsilon}_2^q + \underbrace{0.00}_{\rm dim-7,VIA} \\
& - 10.7\, \tilde{\delta}_1^{qq} + 1.53\, \tilde{\delta}_2^{qq} + 54.6\, \tilde{\delta}_3^{qq} + 0.13\, \tilde{\delta}_4^{qq} - 29.2\, \tilde{\delta}_1^{sq} + 28.8\, \tilde{\delta}_2^{sq} + 0.56\, \tilde{\delta}_3^{sq} + 2.36\, \tilde{\delta}_4^{sq} \Big] \\
= 6.15\, \Gamma_0 \Big[& 1 + 0.48 - 0.13\, \frac{\mu_\pi^2(D)}{0.465\,\rm GeV^2} + 0.01\, \frac{\mu_G^2(D)}{0.34\,\rm GeV^2} + 0.29\, \frac{\rho_D^3(D)}{0.075\,\rm GeV^3} \\
& - \underbrace{0.01}_{\rm dim-6,VIA} - 0.005\, \frac{\delta\tilde{B}_1^q}{0.02} + 0.005\, \frac{\delta\tilde{B}_2^q}{0.02} + 0.137\, \frac{\tilde{\epsilon}_1^q}{-0.04} - 0.125\, \frac{\tilde{\epsilon}_2^q}{-0.04} + \underbrace{0.00}_{\rm dim-7,VIA} \\
& - 0.0045\, r_1^{qq} - 0.0004\, r_2^{qq} - 0.0035\, r_3^{qq} + 0.0000\, r_4^{qq} \\
& - 0.0109\, r_1^{sq} - 0.0079\, r_2^{sq} - 0.0000\, r_3^{sq} + 0.0001\, r_4^{sq} \Big] . \qquad (4.4)
\end{aligned}
$$

$$
\begin{aligned}
\frac{\tau(D^+)}{\tau(D^0)} &= 1 + 2.46\, \tilde{B}_1^q + 0.16\, \tilde{B}_2^q - 16.9\, \tilde{\epsilon}_1^q + 3.31\, \tilde{\epsilon}_2^q \underbrace{-1.09}_{\rm dim-7,VIA} \\
& \quad - 1.71\, \tilde{\delta}_1^{qq} + 0.24\, \tilde{\delta}_2^{qq} + 1.15\, \tilde{\delta}_3^{qq} - 2.71\, \tilde{\delta}_4^{qq} + 0.01\, \tilde{\delta}_1^{sq} - 0.01\, \tilde{\delta}_2^{sq} + 0.00\, \tilde{\delta}_3^{sq} + 0.00\, \tilde{\delta}_4^{sq} \\
&= 1 \underbrace{+2.62}_{\rm dim-6,VIA} \underbrace{-1.09}_{\rm dim-7,VIA} + 0.049\, \frac{\delta\tilde{B}_1^q}{0.02} + 0.003\, \frac{\delta\tilde{B}_2^q}{0.02} + 0.676\, \frac{\tilde{\epsilon}_1^q}{-0.04} - 0.132\, \frac{\tilde{\epsilon}_2^q}{-0.04} \\
& \quad - 0.004\, r_1^{qq} - 0.000\, r_2^{qq} - 0.005\, r_3^{qq} - 0.001\, r_4^{qq} . \qquad (4.9)
\end{aligned}
$$

- **Pert. correction $\tilde{\Gamma}_6^{(2)}$ and $\Gamma_3^{(2)}$ (large value of $\alpha_s(m_c)$)**
- **Non-perturbative matrix elements:**
  2 particle from fits (BESIII),
  4 particle dim 6 from lattice,
  4 particle dim 7 from HQET sum rules



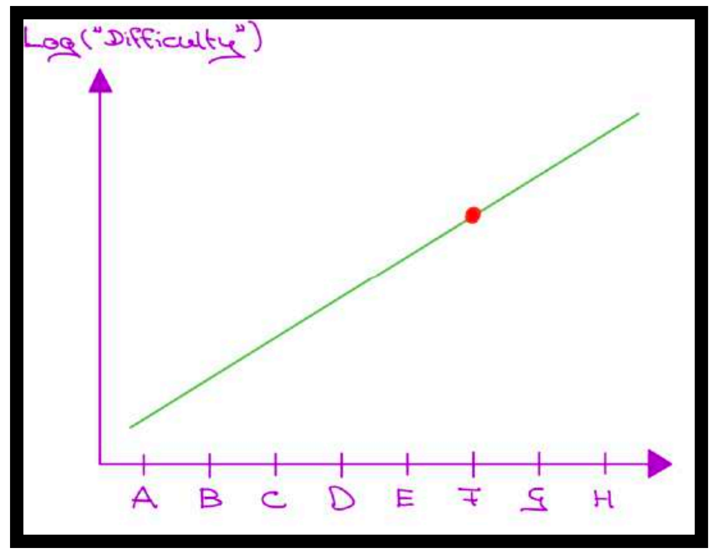
Note:

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.54 \pm 0.02$$

It seems the HQE can reproduce this!!!

From easy to “ganz schwer”

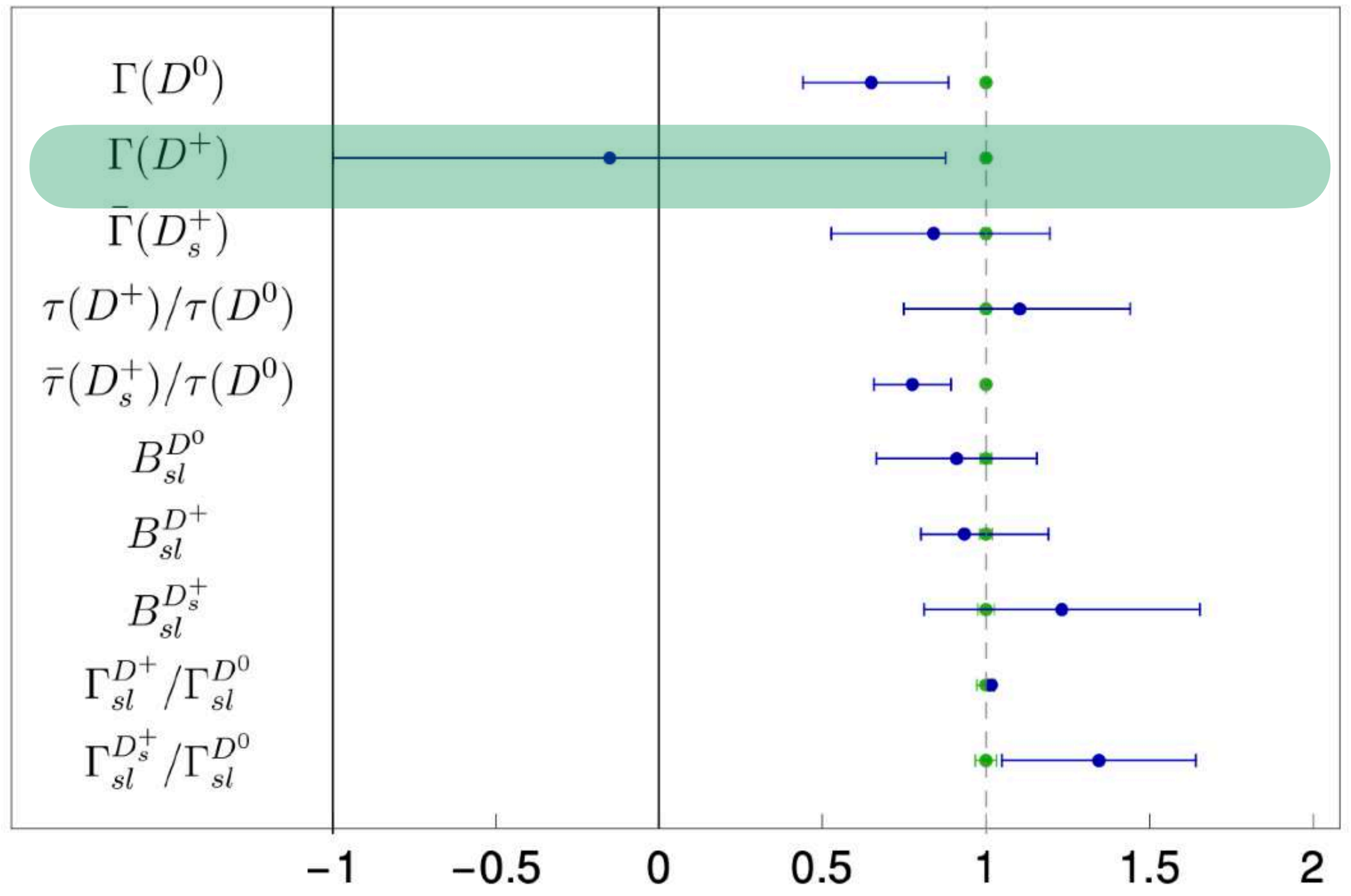
Charm lifetimes: $\Gamma(D^+)$



$$
\begin{aligned}
\Gamma(D^0) = \Gamma_0 \Big[& \underbrace{6.15}_{c_3^{\rm LO}} + \underbrace{2.95}_{\Delta c_3^{\rm NLO}} - 1.66 \frac{\mu_\pi^2(D)}{\rm GeV^2} + 0.13 \frac{\mu_G^2(D)}{\rm GeV^2} + 23.6 \frac{\rho_D^3(D)}{\rm GeV^3} \\
& - 1.60\, \tilde B_1^q + 1.53\, \tilde B_2^q - 21.0\, \tilde\epsilon_1^q + 19.2\, \tilde\epsilon_2^q + \underbrace{0.00}_{\rm dim-7,VIA} \\
& - 10.7\, \tilde\delta_1^{qq} + 1.53\, \tilde\delta_2^{qq} + 54.6\, \tilde\delta_3^{qq} + 0.13\, \tilde\delta_4^{qq} - 29.2\, \tilde\delta_1^{sq} + 28.8\, \tilde\delta_2^{sq} + 0.56\, \tilde\delta_3^{sq} + 2.36\, \tilde\delta_4^{sq} \Big] \\
= 6.15\, \Gamma_0 \Big[& 1 + 0.48 - 0.13 \frac{\mu_\pi^2(D)}{0.465\,\rm GeV^2} + 0.01 \frac{\mu_G^2(D)}{0.34\,\rm GeV^2} + 0.29 \frac{\rho_D^3(D)}{0.075\,\rm GeV^3} \\
& - \underbrace{0.01}_{\rm dim-6,VIA} - 0.005 \frac{\delta \tilde B_1^q}{0.02} + 0.005 \frac{\delta \tilde B_2^q}{0.02} + 0.137 \frac{\tilde\epsilon_1^q}{-0.04} - 0.125 \frac{\tilde\epsilon_2^q}{-0.04} + \underbrace{0.00}_{\rm dim-7,VIA} \\
& - 0.0045\, r_1^{qq} - 0.0004\, r_2^{qq} - 0.0035\, r_3^{qq} + 0.0000\, r_4^{qq} \\
& - 0.0109\, r_1^{sq} - 0.0079\, r_2^{sq} - 0.0000\, r_3^{sq} + 0.0001\, r_4^{sq} \Big] . \qquad (4.4)
\end{aligned}
$$

$$
\begin{aligned}
\Gamma(D^+) = \Gamma_0 \Big[& \underbrace{6.15}_{c_3^{\rm LO}} + \underbrace{2.95}_{\Delta c_3^{\rm NLO}} - 1.66 \frac{\mu_\pi^2(D)}{\rm GeV^2} + 0.13 \frac{\mu_G^2(D)}{\rm GeV^2} + 23.6 \frac{\rho_D^3(D)}{\rm GeV^3} \\
& - 16.9\, \tilde B_1^q + 0.56\, \tilde B_2^q + 84.0\, \tilde\epsilon_1^q - 1.34\, \tilde\epsilon_2^q + \underbrace{6.76}_{\rm dim-7} \\
& - 0.06\, \tilde\delta_1^{qq} + 0.06\, \tilde\delta_2^{qq} - 16.8\, \tilde\delta_3^{qq} + 16.9\, \tilde\delta_4^{qq} - 29.3\, \tilde\delta_1^{sq} + 28.8\, \tilde\delta_2^{sq} + 0.56\, \tilde\delta_3^{sq} + 2.36\, \tilde\delta_4^{sq} \Big] \\
= 6.15\, \Gamma_0 \Big[& 1 + 0.48 - 0.13 \frac{\mu_\pi^2(D)}{0.465\,\rm GeV^2} + 0.01 \frac{\mu_G^2(D)}{0.34\,\rm GeV^2} + 0.29 \frac{\rho_D^3(D)}{0.075\,\rm GeV^3} \\
& - \underbrace{2.66}_{\rm dim-6,VIA} - 0.055 \frac{\delta \tilde B_1^q}{0.02} + 0.002 \frac{\delta \tilde B_2^q}{0.02} - 0.546 \frac{\tilde\epsilon_1^q}{-0.04} + 0.009 \frac{\tilde\epsilon_2^q}{-0.04} + \underbrace{1.10}_{\rm dim-7,VIA} \\
& - 0.0000\, r_1^{qq} - 0.0000\, r_2^{qq} + 0.0011\, r_3^{qq} + 0.0008\, r_4^{qq} \\
& - 0.0109\, r_1^{sq} - 0.0080\, r_2^{sq} - 0.0000\, r_3^{sq} + 0.0001\, r_4^{sq} \Big] , \qquad (4.6)
\end{aligned}
$$

- Pert. correction $\tilde\Gamma_6^{(2)}$, $\tilde\Gamma_7^{(1)}$ and $\Gamma_3^{(2)}$ (large value of $\alpha_s(m_c)$)
- Non-perturbative matrix elements:
  2 particle from fits (BESIII),
  4 particle dim 6 from lattice,
  4 particle dim 7 from HQET sum rules

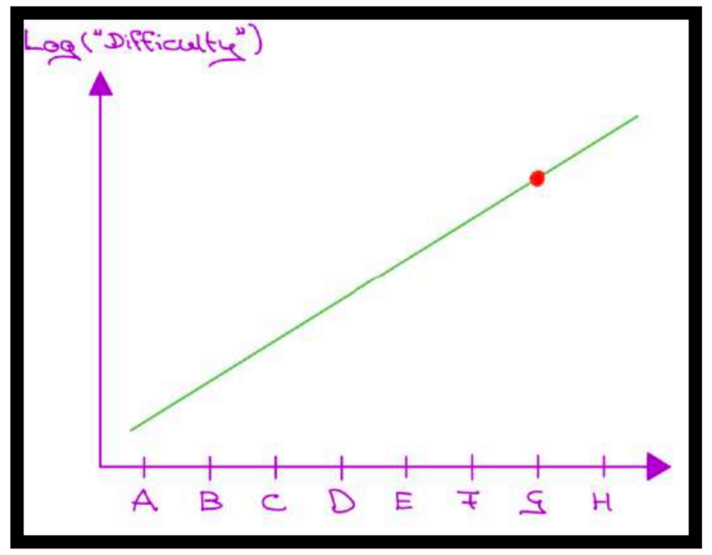


terrible cancellations!
one has to know free charm quark decay and Pauli interference very precise
=> $\Gamma_3^{(2)}$ and $\tilde\Gamma_6^{(2)}$ even more needed

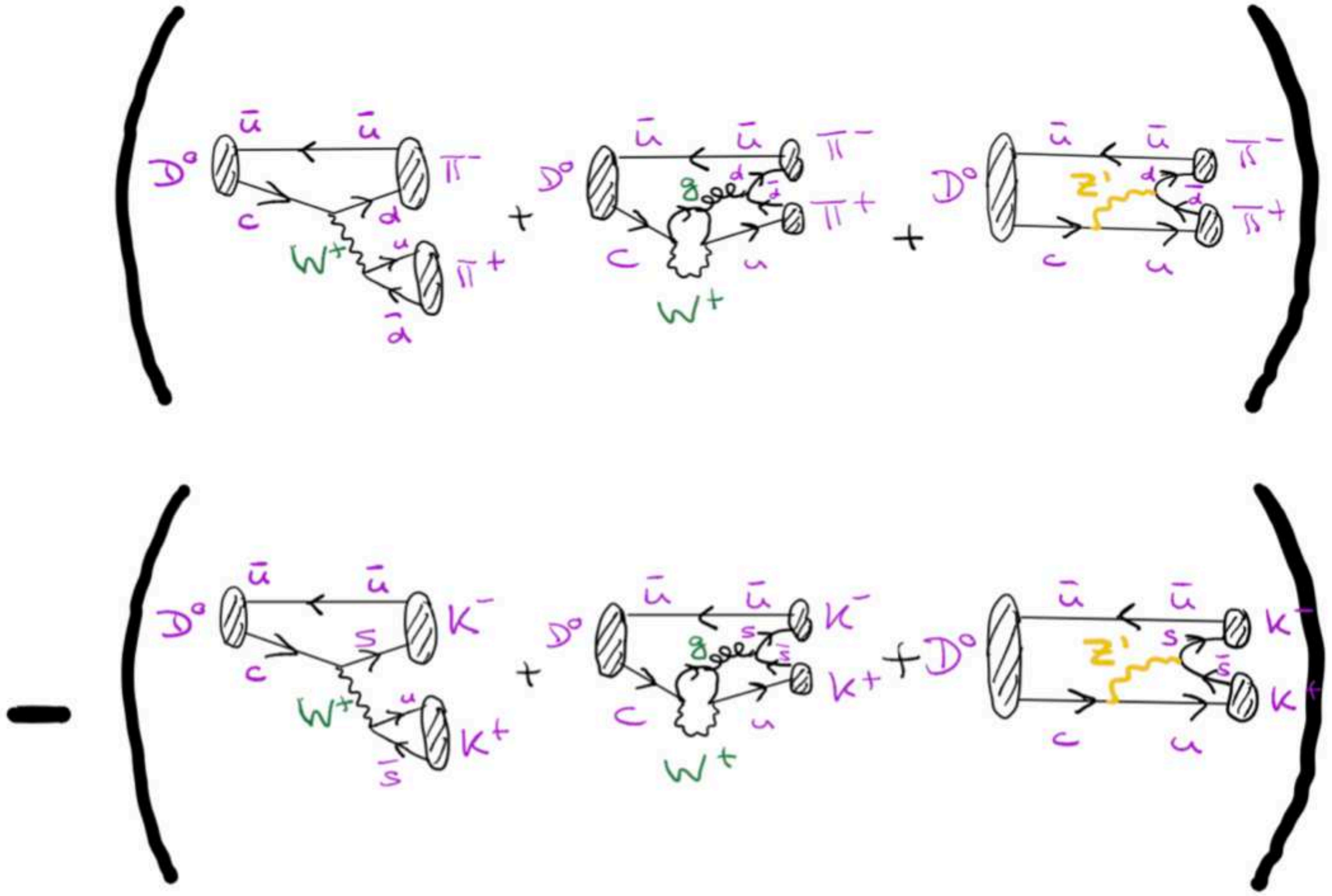
As well as non-perturbative (and maybe perturbative) dim 7 contribution

From easy to “ganz schwer”

CPV in charm: $\Delta A_{CP}\,(D^0 \to \pi^+\pi^-, K^+K^-)$



$$\Delta A_{\rm CP} \equiv A_{\rm CP}(K^+K^-) - A_{\rm CP}(\pi^+\pi^-)\,,$$



$$A_{\rm CP}(f;t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)}$$

Experiment:

$$\Delta a_{\rm CP}^{\rm dir}\big|_{\rm exp} = (-15.7 \pm 2.9) \times 10^{-4}$$

$$a_{\rm CP}^{\rm dir}(K^+K^-)|_{\rm exp} = (7.7 \pm 5.7) \times 10^{-4}\,,$$

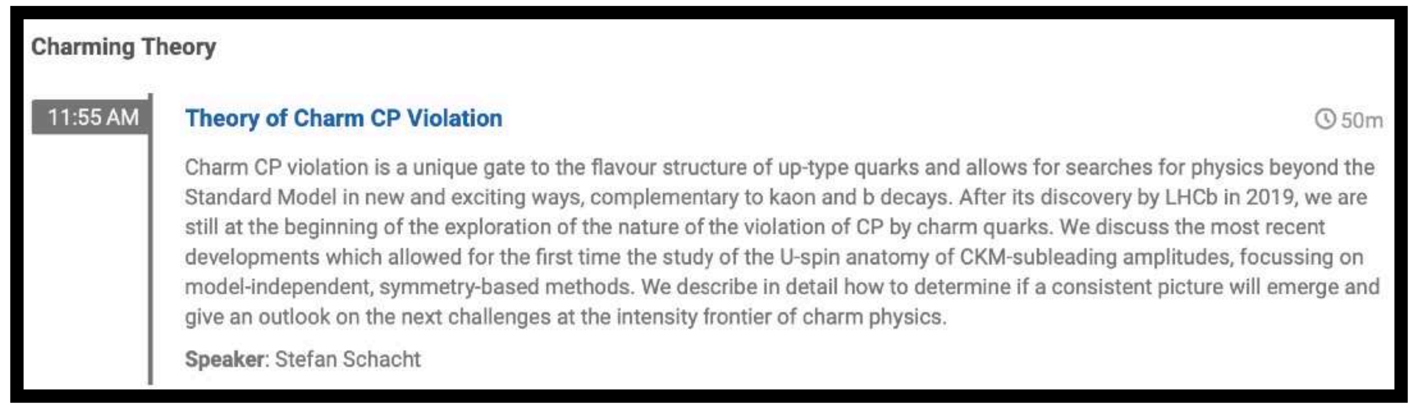
$$a_{\rm CP}^{\rm dir}(\pi^+\pi^-)|_{\rm exp} = (23.2 \pm 6.1) \times 10^{-4}\,,$$

Theory:

$$a_{CP}^{\rm dir} \approx -13 \cdot 10^{-4} \left|\frac{P}{T}\right| \sin\phi$$

known: CKM

Largely unknown QCD



Charming Theory

11:55 AM **Theory of Charm CP Violation** 50m

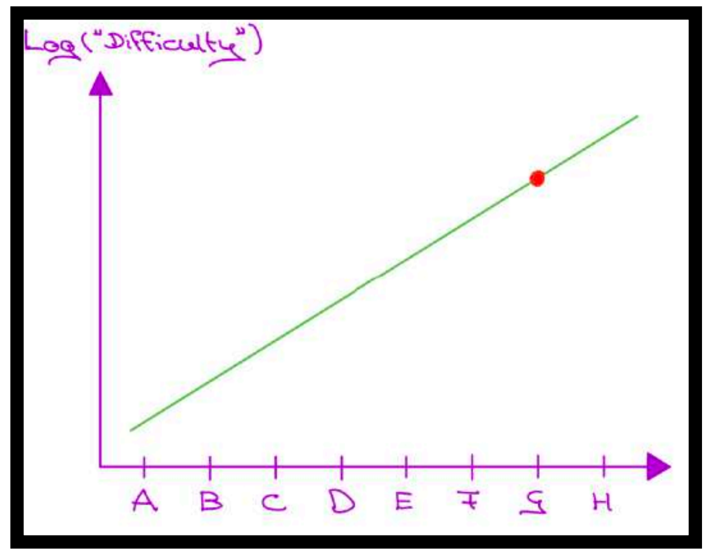
Charm CP violation is a unique gate to the flavour structure of up-type quarks and allows for searches for physics beyond the Standard Model in new and exciting ways, complementary to kaon and b decays. After its discovery by LHCb in 2019, we are still at the beginning of the exploration of the nature of the violation of CP by charm quarks. We discuss the most recent developments which allowed for the first time the study of the U-spin anatomy of CKM-subleading amplitudes, focussing on model-independent, symmetry-based methods. We describe in detail how to determine if a consistent picture will emerge and give an outlook on the next challenges at the intensity frontier of charm physics.

Speaker: Stefan Schacht

Universität Siegen

From easy to “ganz schwer”

CPV in charm: $\Delta A_{CP}\,(D^0 \to \pi^+\pi^-, K^+K^-)$



color meets flavor

$$a_{CP}^{\text{dir}} \approx -13 \cdot 10^{-4} \left|\frac{P}{T}\right| \sin\phi$$

vs.

$$\Delta a_{\text{CP}}^{\text{dir}}\Big|_{\text{exp}} = (-15.7 \pm 2.9) \times 10^{-4}$$

1) naive perturbative: P/T ≈ 0.1 **=> BSM :-)**
2) LCSR

Direct CP asymmetry in $D \to \pi^-\pi^+$ and $D \to K^-K^+$ in QCD-based approach #1

Alexander Khodjamirian (Siegen U.), Alexey A. Petrov (Siegen U. and Wayne State U. and Michigan U., MCTP) (Jun 23, 2017)

Published in: *Phys.Lett.B* 774 (2017) 235-242 • e-Print: 1706.07780 [hep-ph]

pdf DOI cite claim reference search 90 citations

LCSR

$$r_\pi = \frac{|\mathcal{P}^s_{\pi\pi}|}{|\mathcal{A}_{\pi\pi}|} = 0.093 \pm 0.011\,, \qquad r_K = \frac{|\mathcal{P}^d_{KK}|}{|\mathcal{A}_{KK}|} = 0.075 \pm 0.015\,.$$

Still => BSM :-)

Experiment

3) Can we predict the branching ratios?

$$F_\mu(p,q) = i^2 \int d^4x\, e^{-ip\cdot x} \int d^4y\, e^{iq\cdot y}\, \langle K^-(p-q)|\mathrm{T}\{j_5^D(x), O_1^s(0), j_\mu^K(y)\}\,|0\rangle\,,$$

Two body non-leptonic D^0 decays from LCSR and implications for $\Delta a_{\text{CP}}^{\text{dir}}$

Alexander Lenz (Siegen U.), Maria Laura Piscopo (Siegen U.), Aleksey V. Rusov (Siegen U.) (Dec 20, 2023)

Published in: *JHEP* 03 (2024) 151 • e-Print: 2312.13245 [hep-ph]

$$\mathcal{B}(D^0 \to K^+K^-)\big|_{\text{exp}} = (4.08 \pm 0.06) \times 10^{-3}\,, \qquad \mathcal{B}(D^0 \to K^+K^-)\big|_{\text{LCSR}} = (3.67^{+3.90}_{-2.69}) \times 10^{-3}\,,$$

$$\mathcal{B}(D^0 \to \pi^+\pi^-)\big|_{\text{exp}} = (1.454 \pm 0.024) \times 10^{-3}\,. \qquad \mathcal{B}(D^0 \to \pi^+\pi^-)\big|_{\text{LCSR}} = (1.40^{+1.53}_{-1.06}) \times 10^{-3}\,,$$

$$\mathcal{B}(D^0 \to \pi^+K^-)\big|_{\text{exp}} = (3.947 \pm 0.030) \times 10^{-2}\,, \qquad \mathcal{B}(D^0 \to \pi^+K^-)\big|_{\text{LCSR}} = (2.99^{+3.26}_{-2.26}) \times 10^{-2}\,,$$

$$\mathcal{B}(D^0 \to K^+\pi^-)\big|_{\text{exp}} = (1.50 \pm 0.07) \times 10^{-4}\,. \qquad \mathcal{B}(D^0 \to K^+\pi^-)\big|_{\text{LCSR}} = (1.80^{+1.93}_{-1.33}) \times 10^{-4}\,,$$

Huge SU(3)F breaking!

$$\left.\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)}\right|_{\text{exp}} = 2.81 \pm 0.06\,. \qquad \left.\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)}\right|_{\text{LCSR}} = 2.63 \pm 0.86\,,$$

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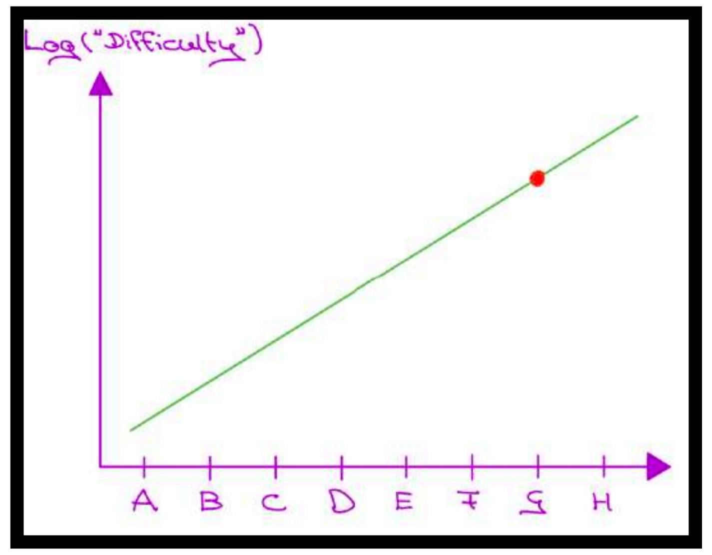
From easy to “ganz schwer”

CPV in charm: $\Delta A_{CP}\,(D^0 \to \pi^+\pi^-, K^+K^-)$



color meets flavor

$$a_{CP}^{\text{dir}} \approx -13 \cdot 10^{-4} \left|\frac{P}{T}\right| \sin\phi$$

vs.

$$\Delta a_{\text{CP}}^{\text{dir}}\big|_{\text{exp}} = (-15.7 \pm 2.9) \times 10^{-4}$$

1) naive perturbative: P/T ≈ 0.1 => BSM :-)

2) LCS

3) Can we predict the branching ratios?

Direct CP

Alexander K

2017)

Published ir

pdf

$r_\pi = \frac{|7}{|\mathcal{A}}$

1. Calculate the contribution of condensate and soft-gluon effects, i.e. three-particle LCDAs. Furthermore, higher-twist corrections could be investigated.

2. Calculate higher order perturbative QCD corrections to the sum-rule result. This will also allow to extend our approach to other topologies than the color-allowed tree-level one, like annihilation and penguin diagrams, and will have a crucial impact on the theoretical determination of the strong phases.

3. Extend our study to decays that are governed by color-suppressed tree-level topologies.

s for $\Delta a_{\text{CP}}^{\text{dir}}$

ov (Siegen U.) (Dec 20, 2023)

$|_{\text{LCSR}} = (3.67^{+3.90}_{-2.69}) \times 10^{-3}$,

$|_{\text{LCSR}} = (1.40^{+1.53}_{-1.06}) \times 10^{-3}$,

$|_{\text{LCSR}} = (2.99^{+3.26}_{-2.26}) \times 10^{-2}$,

$|_{\text{LCSR}} = (1.80^{+1.93}_{-1.33}) \times 10^{-4}$,

g!

Experiment

$$\left.\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)}\right|_{\text{exp}} = 2.81 \pm 0.06\,.$$

$$\left.\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)}\right|_{\text{LCSR}} = 2.63 \pm 0.86\,,$$

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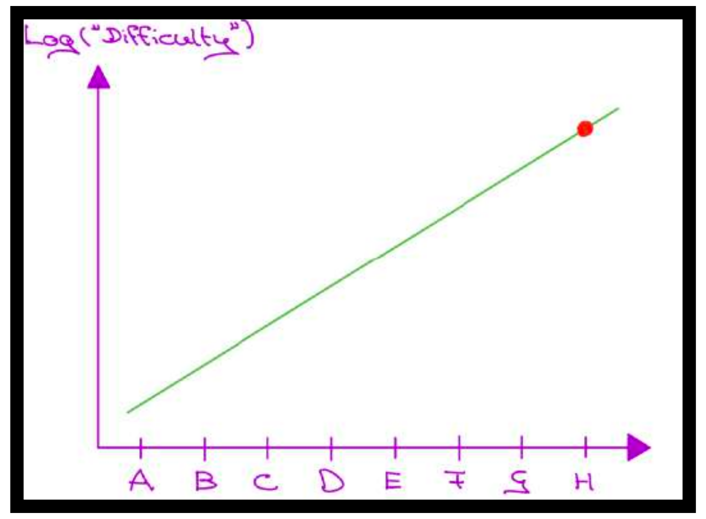
From easy to “ganz schwer”

Charm mixing



color meets flavor

B-mixing

$$M_{12} = \lambda_u^2 F(u,u) + \lambda_u\lambda_c F(u,c) + \lambda_u\lambda_t F(u,t) + \lambda_c\lambda_u F(c,u) + \lambda_c^2 F(c,c) + \lambda_c\lambda_t F(c,t) + \lambda_t\lambda_u F(t,u) + \lambda_t\lambda_c F(t,c) + \lambda_t^2 F(t,t)$$

$\lambda_u + \lambda_c + \lambda_t = 0$

$$= \lambda_u^2 \left[F(c,c) - 2F(u,c) + F(u,u)\right] + 2\lambda_u\lambda_t \left[F(c,c) - F(u,c) + F(u,t) - F(c,t)\right] + \lambda_t^2 \left[F(c,c) - 2F(c,t) + F(t,t)\right]$$

	B_d	B_s
λ_u	$\lambda^{3.8}$	$\lambda^{4.8}$
λ_c	λ^3	λ^2
λ_t	λ^3	λ^2

$m_u^2/M_W^2 \simeq 0$

$m_c^2/M_W^2 \simeq 2.5\cdot 10^{-4}$

$m_t^2/M_W^2 \simeq 4.5$

CKM dominant ≡ GIM dominant

CKM suppressed ≡ GIM suppressed

D-mixing

$$M_{12} = \lambda_d^2 F(d,d) + \lambda_d\lambda_s F(d,s) + \lambda_d\lambda_b F(d,b) + \lambda_s\lambda_d F(s,d) + \lambda_s^2 F(s,s) + \lambda_s\lambda_b F(s,b) + \lambda_b\lambda_d F(b,d) + \lambda_b\lambda_s F(b,s) + \lambda_b^2 F(b,b)$$

$\lambda_d + \lambda_s + \lambda_b = 0$

$$= \lambda_d^2 \left[F(d,d) - 2F(d,s) + F(s,s)\right] + 2\lambda_s\lambda_b \left[F(s,s) - F(d,s) + F(d,b) - F(s,b)\right] + \lambda_b^2 \left[F(s,s) - 2F(s,b) + F(b,b)\right]$$

	D
λ_d	λ^1
λ_s	λ^1
λ_b	$\lambda^{5.8}$

$m_d^2/M_W^2 \simeq 0$

$m_s^2/M_W^2 \simeq 1.3\cdot 10^{-6}$

$m_b^2/M_W^2 \simeq 2.8\cdot 10^{-3}$

CKM suppressed ≡ GIM dominant

CKM dominant ≡ GIM suppressed

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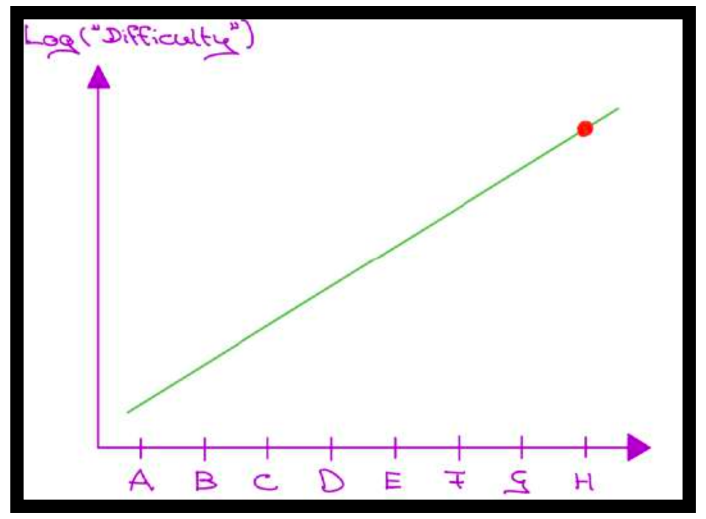
From easy to “ganz schwer”

Charm mixing



The HQE is successful in the B system and for D meson lifetimes

=> apply it for D-mixing

$$y_D^{\text{HQE}} \approx \lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd} \right) \approx 10^{-5} y_D^{\text{Exp.}}$$

How can this be?

Look only at a single diagram:

$$y_D^{\text{HQE}} \neq \lambda_s^2 \Gamma_{12}^{ss} \tau_D = 3.7 \cdot 10^{-2} \approx 5.6 y_D^{\text{Exp.}}$$

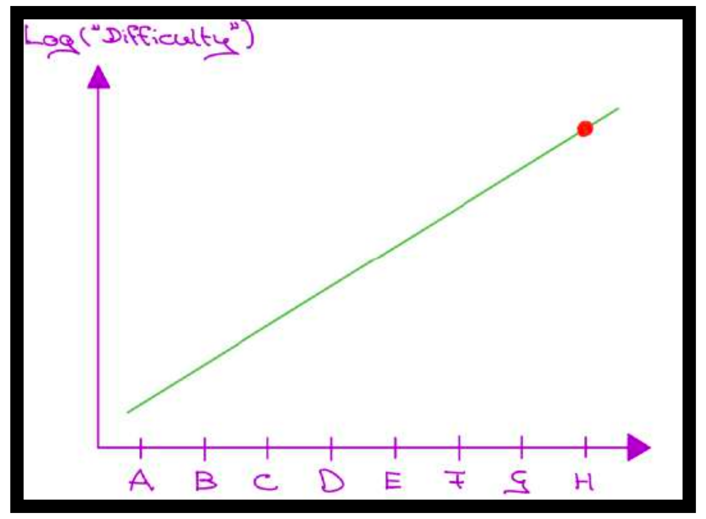
pert. calculation: Bobrowski et al 1002.4794
lattice input: ETM 1403.7302; 1505.06639; FNAL/MILC 1706.04622
HQET sum rules: Kirk, AL, Rauh 1711.02100

The problem seems to originate in the extreme GIM cancellations

From easy to “ganz schwer”

Charm mixing

crazy cancellations - can we be a factor of 10 000 off?

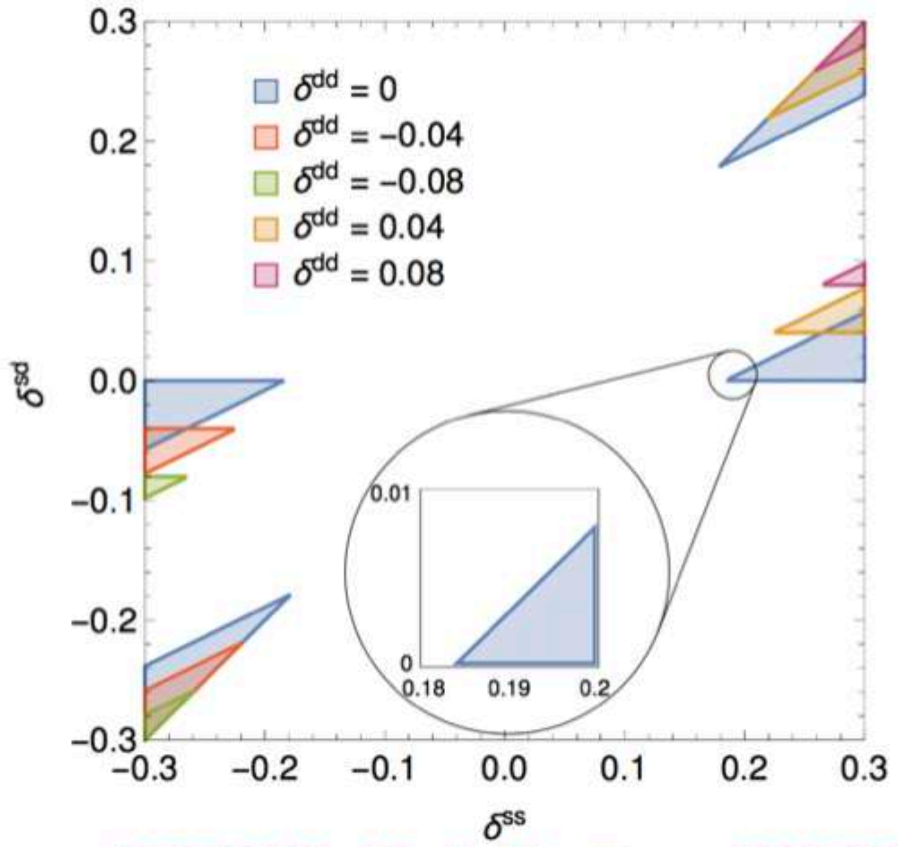


1. Duality violations - break down of HQE

$$\Gamma_{12}^{ss} \to \Gamma_{12}^{ss}(1+\delta^{ss}) \,,$$
$$\Gamma_{12}^{sd} \to \Gamma_{12}^{sd}(1+\delta^{sd}) \,,$$
$$\Gamma_{12}^{dd} \to \Gamma_{12}^{dd}(1+\delta^{dd}) \,,$$

20% of duality violation is sufficient to explain experiment

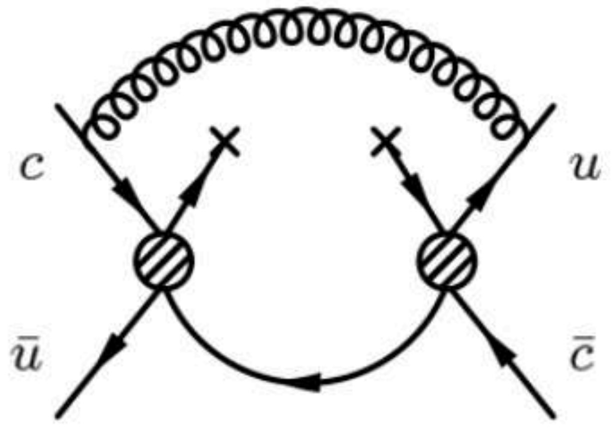
Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016



2. Higher dimensions

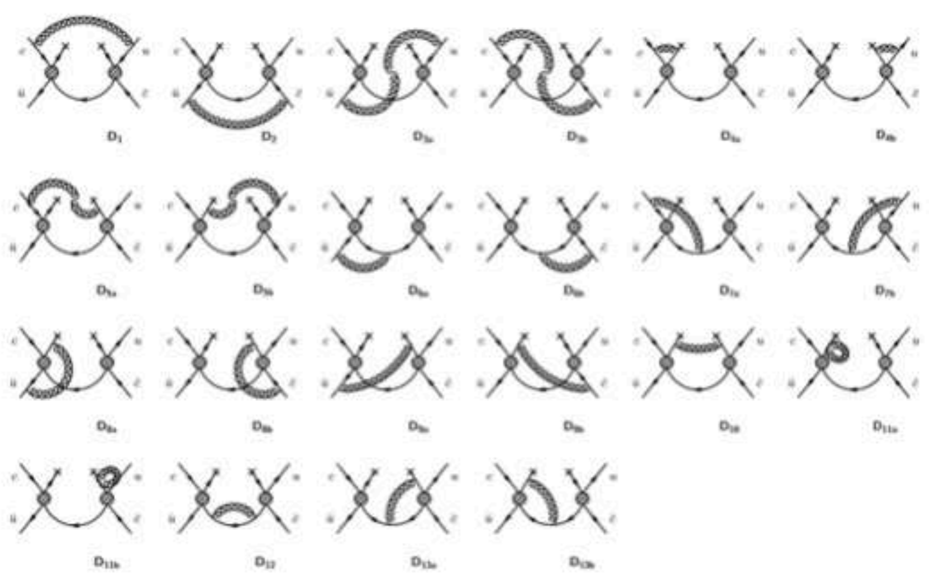
Georgi 9209291; Ohl, Ricciardi, Simmons 9301212; Bigi, Uraltsev 0005089

Idea: GIM cancellation is lifted by higher orders in the HQE - overcompensating the 1/mc suppression.



Partial calculation of D=9 yields an enhancement - but not to the experimental value Bobrowski, AL, Rauh 2012

Nonperturbative Dynamics in D-meson Mixing #1
Lovro Dulibić (Boskovic Inst., Zagreb), Blaženka Melić (Boskovic Inst., Zagreb), Alexey A. Petrov (South Carolina U.)
(Aug 22, 2025)
e-Print: 2508.16337 [hep-ph]



3. Renormalisation scale setting:

AL, Piscopo, Vlahos 2020

$$\mu_x^{ss} = \mu_x^{sd} = \mu_x^{dd}$$

Implicitly assumes a precision of 10^-5!

4. New Physics is present and we cannot prove it yet:-)

1) Vary $\mu^{ss,dd}$ and μ^{ds} independently between 1 GeV and 2 m_c
⇒ uncertainty increases and exp. value is covered

2) Choose scales somehow phase space inspired as

$$\mu^{ss} = m_c - 2\epsilon$$
$$\mu^{sd} = m_c - \epsilon$$
$$\mu^{dd} = m_c$$

⇒ exp. value is covered

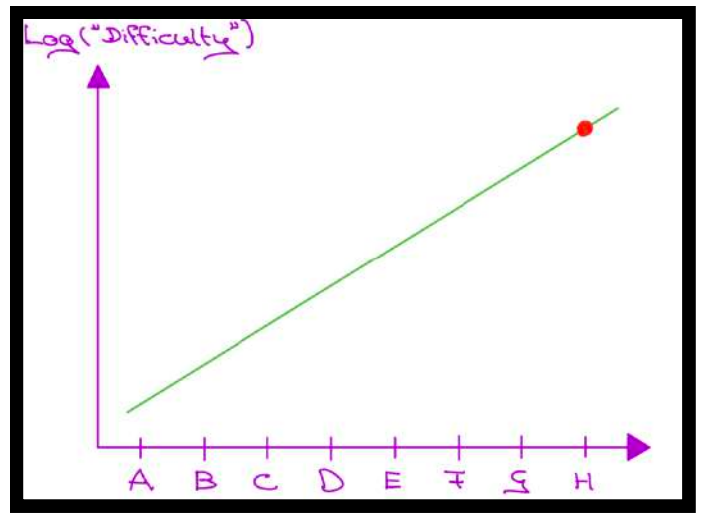
Exclusive and inclusive approaches can over the experimental regions

No precision determination possible

From easy to “ganz schwer”

Charm mixing

crazy cancellations - can we be a factor of 10 000 off?



HQE is just not precise enough - do everything from scratch within lattice QCD

Charming Peaks 2017
IPPP associateship

D MIXING

Still far away from a reliable SM prediction for D mixing

Many steps in the right direction:

- HQE seems to work for charm lifetimes
- Refinements of exclusive methods
  * understand $SU(3)_F$ breaking
  * factorisation
  * use data
- Lattice evaluation seems not be completely out of the world anymore

Long distance contributions to neutral D-meson mixing from lattice QCD

Matteo Di Carlo,[a] Felix Erben[a] and Maxwell T. Hansen[b]

[a] Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland
[b] School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3FD, U.K.

E-mail: matteo.dicarlo@cern.ch, felix.erben@cern.ch, maxwell.hansen@ed.ac.uk

Abstract: The study of neutral D-meson mixing provides a unique probe of long-distance effects in the charm sector, where Standard Model contributions are dominated by nonperturbative effects. In this work, we investigate the feasibility of using spectral reconstruction techniques within lattice QCD to compute the long-distance contributions to $D^0-\bar{D}^0$ mixing. After outlining the general formalism describing neutral meson mixing in the charm sector, we focus on the determination of the mixing amplitudes and the dimensionless parameters $x=\Delta m_D/\Gamma_D$ and $y=\Delta\Gamma_D/(2\Gamma_D)$, which respectively encode the mass and width differences between the D-meson mass eigenstates. We discuss in detail the required theoretical and computational framework, including the definition and renormalization of the four-quark operators entering the $\Delta C=1$ weak Hamiltonian, and strategies for evaluating the relevant correlation functions employing variance-reduction techniques. To extract the mixing amplitudes, we explore methods for reconstructing the spectral density from lattice correlators, providing preliminary assessments of the data quality required to reach the scaling regime, where the smearing width is small enough to yield physically meaningful results. Our findings lay the groundwork for future precision determinations of long-distance contributions to D-meson mixing from first principles.

JHEP07(2025)229

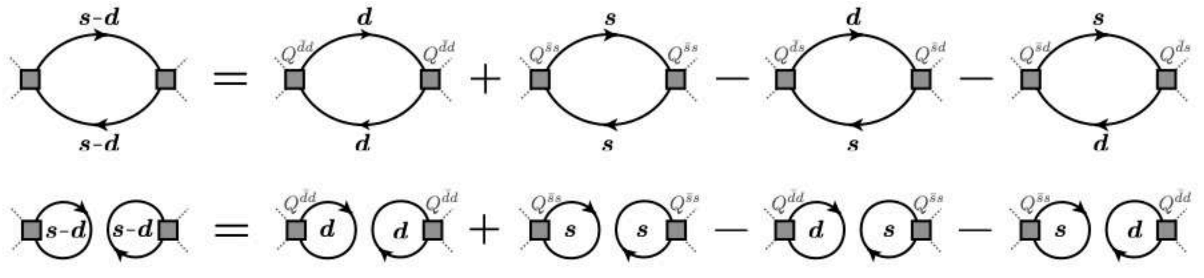
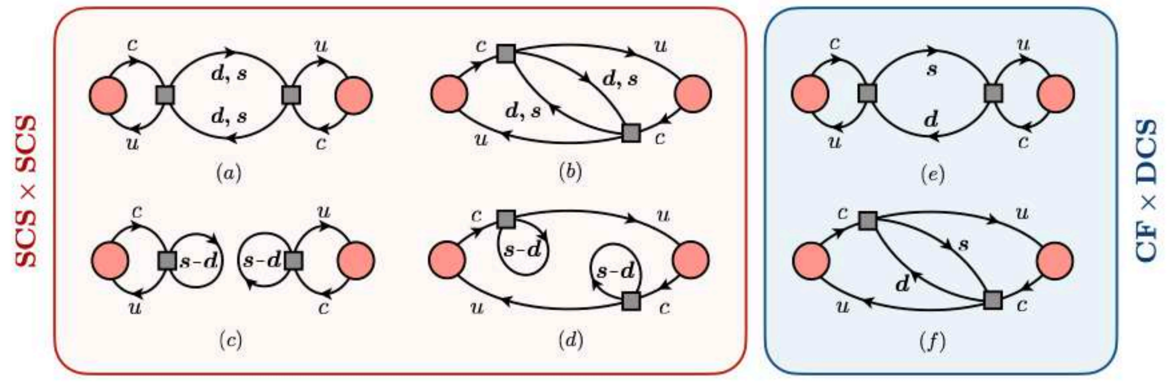
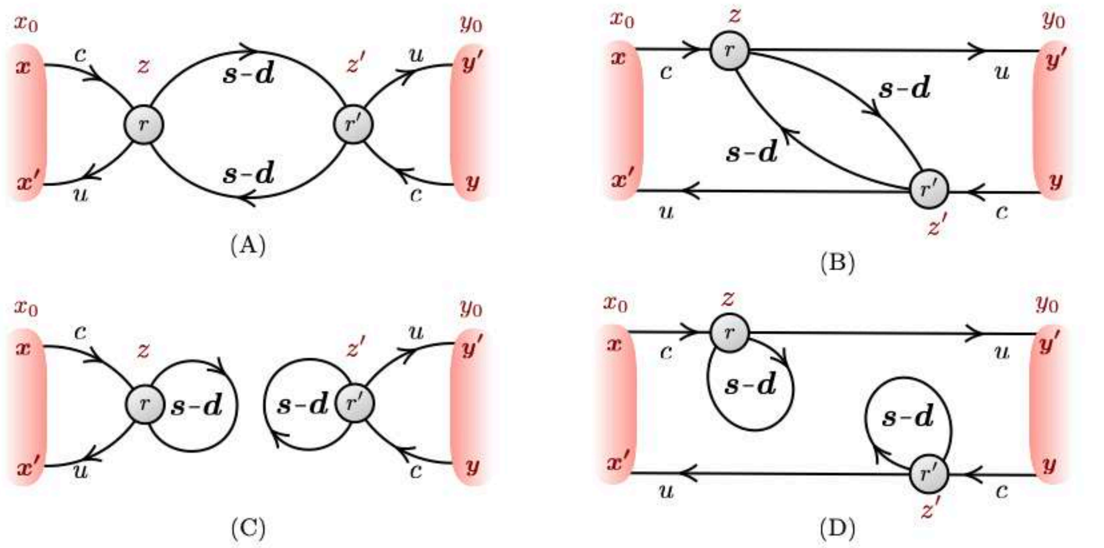


Figure 1. Relevant Wick contractions for the calculation of the dominant $\Delta U=2$ contributions to M_{12} and Γ_{12}. As a consequence of the structure of ξ_2 in eq. (2.50), the internal lines always appear as differences of strange and down propagators.





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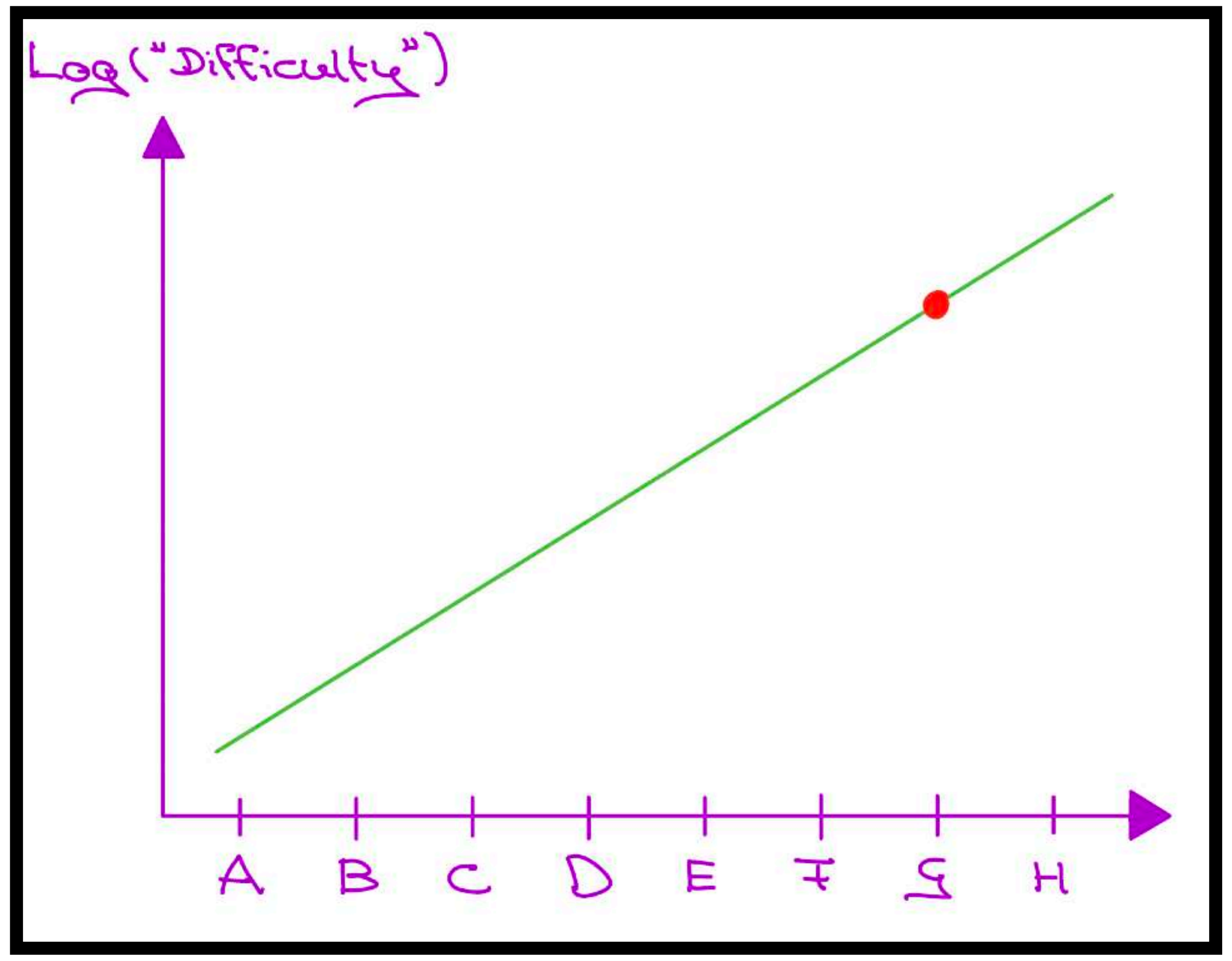
Outline

color meets flavor

1) Flavour Physics in a nutshell
2) Theory approaches in a nutshell
3) From “easy” to “ganz schwer”



Inclusive V_{cb}

Relation to non-leptonic B-decays, like $B_s \to D_s^+ \pi^-$ and to rare-semi-leptonic decays $B \to Kll$ or $D \to \pi ll$

A. Mass differences in B-mixing

B. Lifetime ratios $\tau(B^+)/\tau(B_d)$;

B-mixing: decay rate differences $\Delta\Gamma_{s,d}$; flavour-specific asymmetries $a_{fs}^{s,d}$

C. Lifetime ratios $\tau(B_s)/\tau(B_d)$ - some problems

D. Sizable progress: $\Gamma(B_d, B^+, B_s)$, $\tau(\Lambda_b)/\tau(B_d)$

E. Charm lifetimes: $\Gamma(D^0)$, $\tau(D^+)/\tau(D^0)$

F. Charm lifetimes: $\Gamma(D^+)$ - terrible cancellations

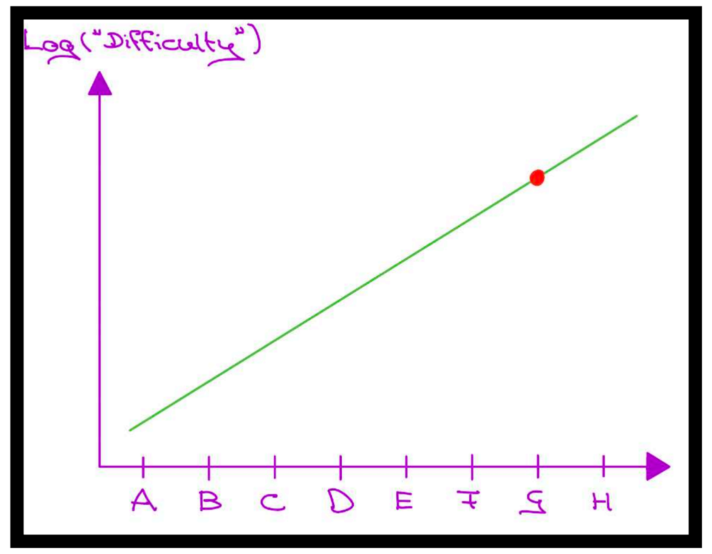
G. CPV in charm: ΔA_{CP} ($D^0 \to \pi^+\pi^-, K^+K^-$) - can we be a factor of 10 off?

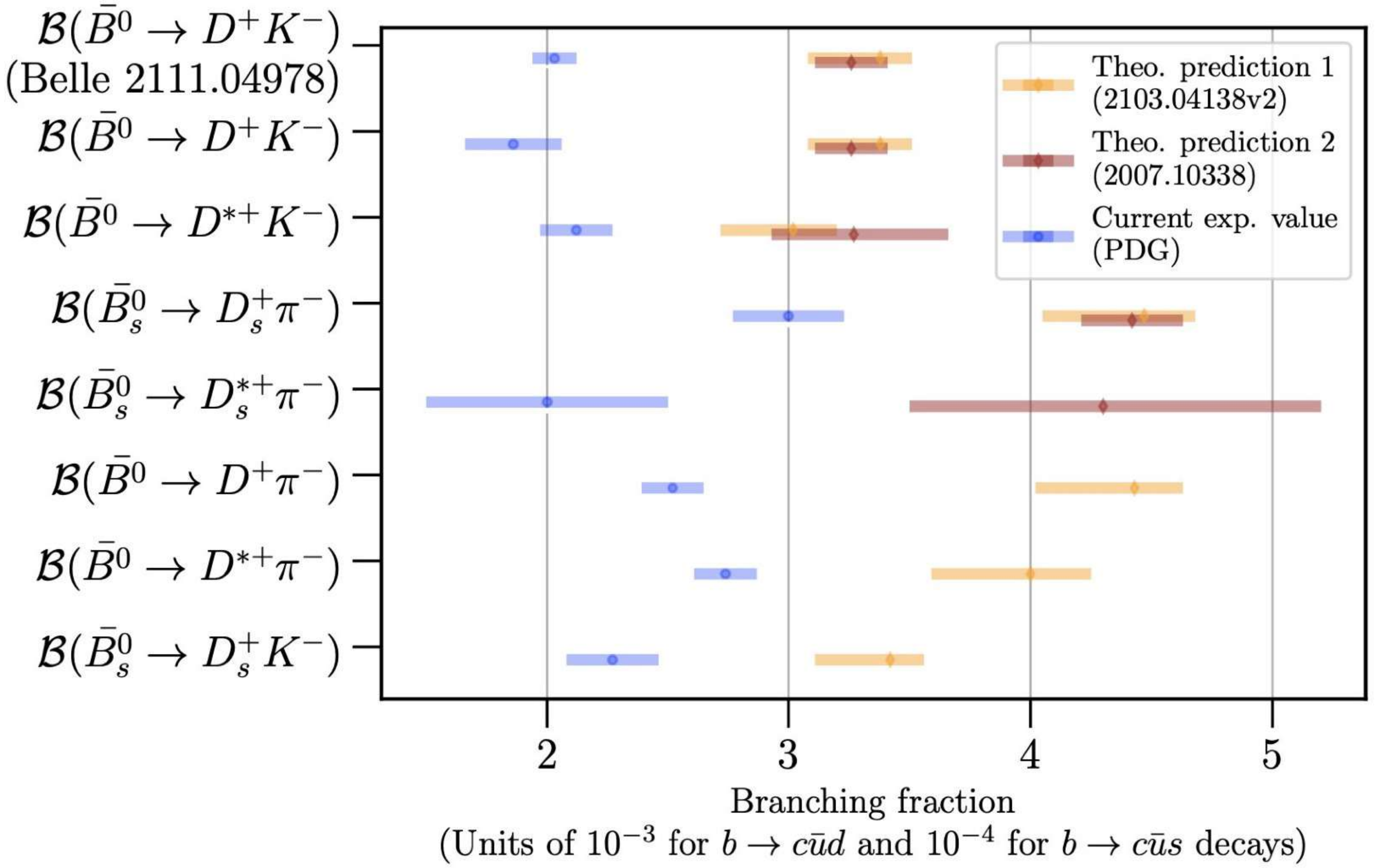
H. Charm mixing: - crazy cancellations - can we be a factor of 10 000 off?

“Easy” —-> “ganz schwer”

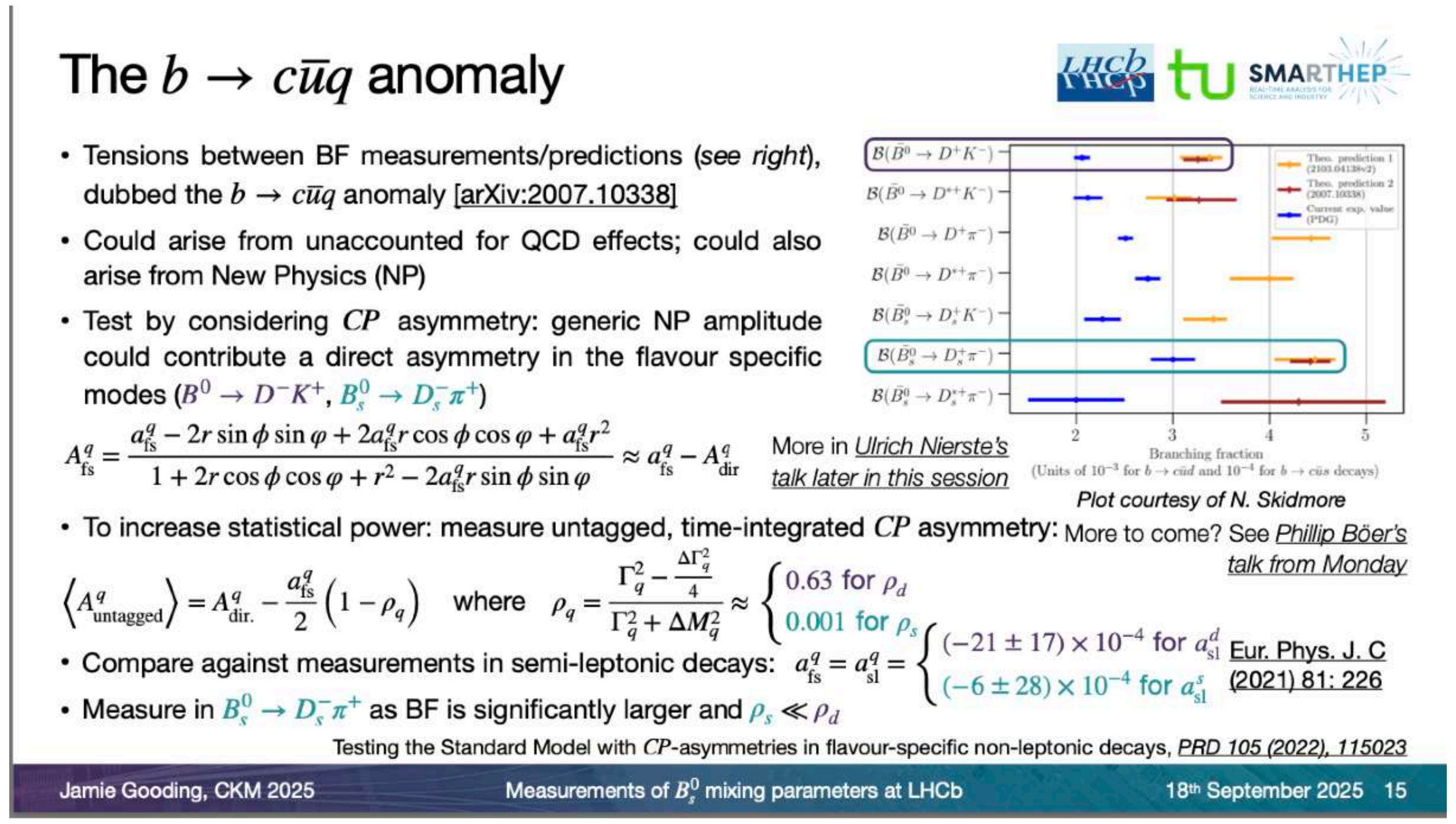
4) Some fun, which is many times overlooked: BSM in tree-level decays

BSM effects in tree-level decays





Experimental test


The $b \to c\bar{u}q$ anomaly

- Tensions between BF measurements/predictions (*see right*), dubbed the $b \to c\bar{u}q$ anomaly [arXiv:2007.10338]
- Could arise from unaccounted for QCD effects; could also arise from New Physics (NP)
- Test by considering *CP* asymmetry: generic NP amplitude could contribute a direct asymmetry in the flavour specific modes ($B^0 \to D^-K^+$, $B^0_s \to D^-_s\pi^+$)

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

More in Ulrich Nierste's talk later in this session

- To increase statistical power: measure untagged, time-integrated *CP* asymmetry:

$$\langle A^q_{untagged}\rangle = A^q_{dir.} - \frac{a^q_{fs}}{2}(1-\rho_q) \quad \text{where} \quad \rho_q = \frac{\Gamma_q^2 - \frac{\Delta\Gamma_q^2}{4}}{\Gamma_q^2 + \Delta M_q^2} \approx \begin{cases} 0.63 \text{ for } \rho_d \\ 0.001 \text{ for } \rho_s \end{cases}$$

- Compare against measurements in semi-leptonic decays: $a^q_{fs} = a^q_{sl} = \begin{cases} (-21 \pm 17) \times 10^{-4} \text{ for } a^d_{sl} \\ (-6 \pm 28) \times 10^{-4} \text{ for } a^s_{sl} \end{cases}$ Eur. Phys. J. C (2021) 81: 226
- Measure in $B^0_s \to D^-_s\pi^+$ as BF is significantly larger and $\rho_s \ll \rho_d$

Plot courtesy of N. Skidmore

More to come? See Phillip Böer's talk from Monday

Testing the Standard Model with *CP*-asymmetries in flavour-specific non-leptonic decays, PRD 105 (2022), 115023

Jamie Gooding, CKM 2025 — Measurements of B^0_s mixing parameters at LHCb — 18th September 2025 15

1) Modification of lifetimes and mixing

2) Is there a connection between mixing and rare decays (anomalies)?

Charming new physics in rare B-decays and mixing
Jaeger, Kirk, Lenz, Leslie
arXiv: 1701.09183; 1902.10.12924

Consider NP in tree-level $b \to c\bar{c}s$ transitions with general Dirac structures

$$\mathcal{H}^{c\bar{c}}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V^*_{cs} V_{cb} \sum_{i=1}^{10} (C^c_i Q^c_i + C^{c\prime}_i Q^{c\prime}_i)$$

$$Q^c_1 = (\bar{c}^i_L \gamma_\mu b^j_L)(\bar{s}^j_L \gamma^\mu c^i_L), \quad Q^c_2 = (\bar{c}^i_L \gamma_\mu b^i_L)(\bar{s}^j_L \gamma^\mu c^j_L),$$
$$Q^c_3 = (\bar{c}^i_R b^j_L)(\bar{s}^j_L c^i_R), \quad Q^c_4 = (\bar{c}^i_R b^i_L)(\bar{s}^j_L c^j_R). \quad (2)$$

This affects both rare decays and lifetimes:

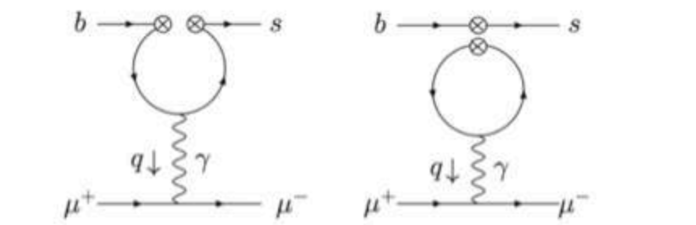


FIG. 1. Leading Feynman diagrams for CBSM contributions to rare and semileptonic decays. With our choice of Fierz-ordering, only the diagram on the left is relevant.

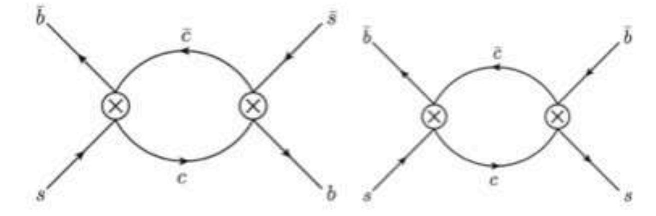
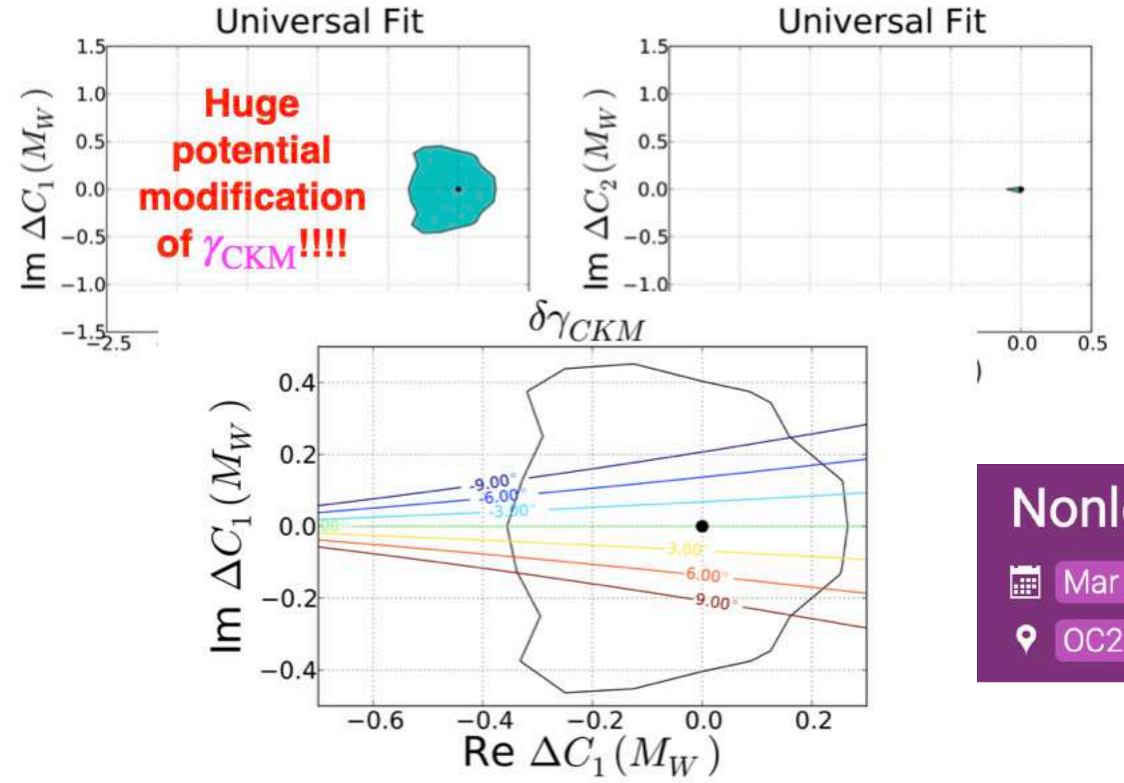


FIG. 2. Leading Feynman diagrams for CBSM contributions to the width difference $\Delta\Gamma_s$ (left) and the lifetime ratio $\tau(B_s)/\tau(B_d)$ (right).

q^2-dependent BSM contributions to rare decays possible!

These ideas were disfavoured for quite some time, since they predicted $R_K \approx 1$

3) Modification of the extracted value of γ_{CKM}

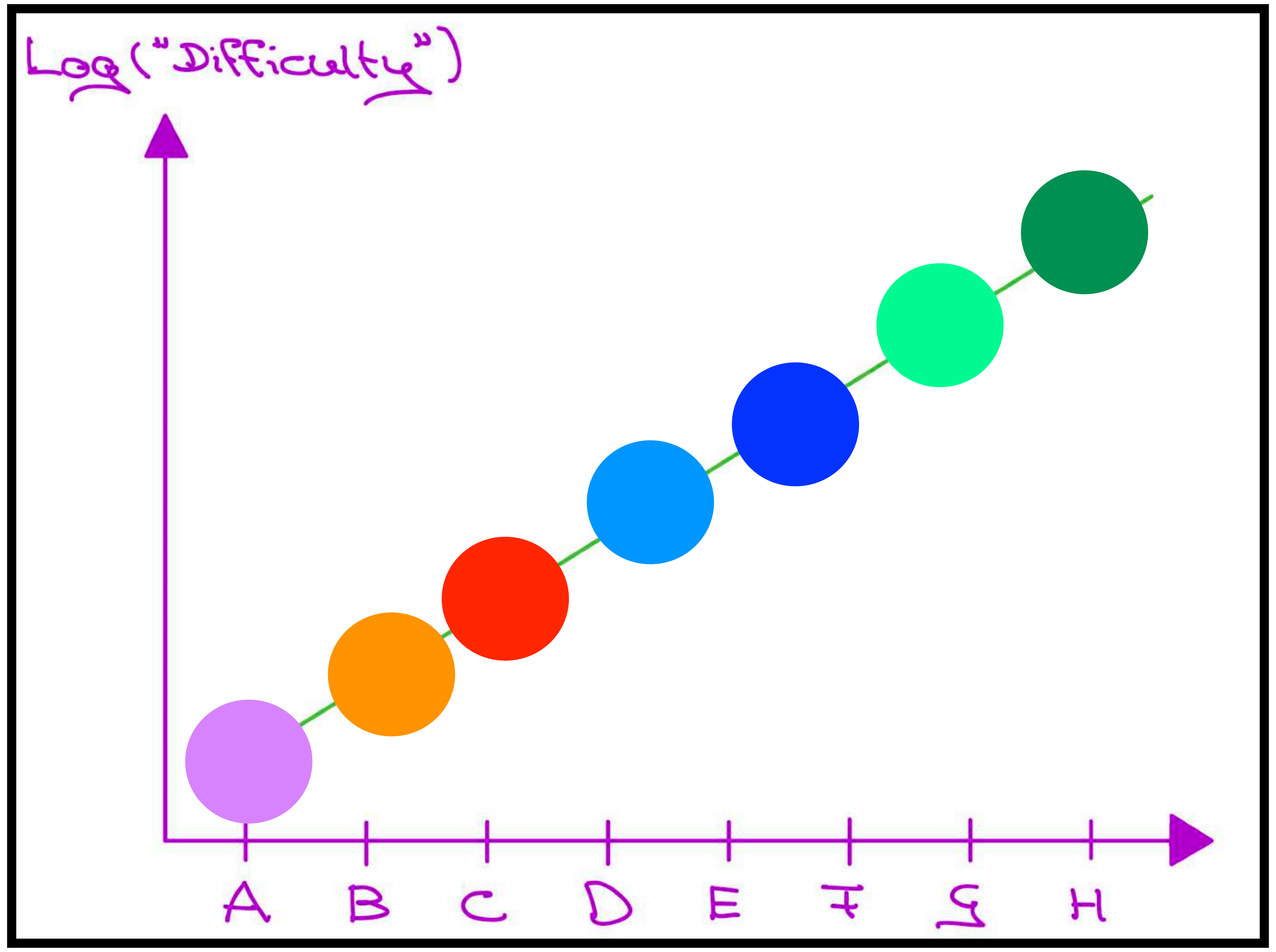


Nonleptonic Decays of Heavy Mesons
Mar 23, 2026, 9:00 AM → Mar 25, 2026, 6:00 PM Europe/London
OC218 (IPPP)

Conclusion

Huge amount of interesting problems to be solved

choose your desired level of difficulty/precision



Should we introduce a colour coding?