

Precision meets non-perturbative Physics

Bottom and Charm physics

MITP
SCIENTIFIC
PROGRAM

Particle Physics Phenomenology
after the Higgs Discovery

October 6 – 17, 2025



<https://indico.mitp.uni-mainz.de/event/415>

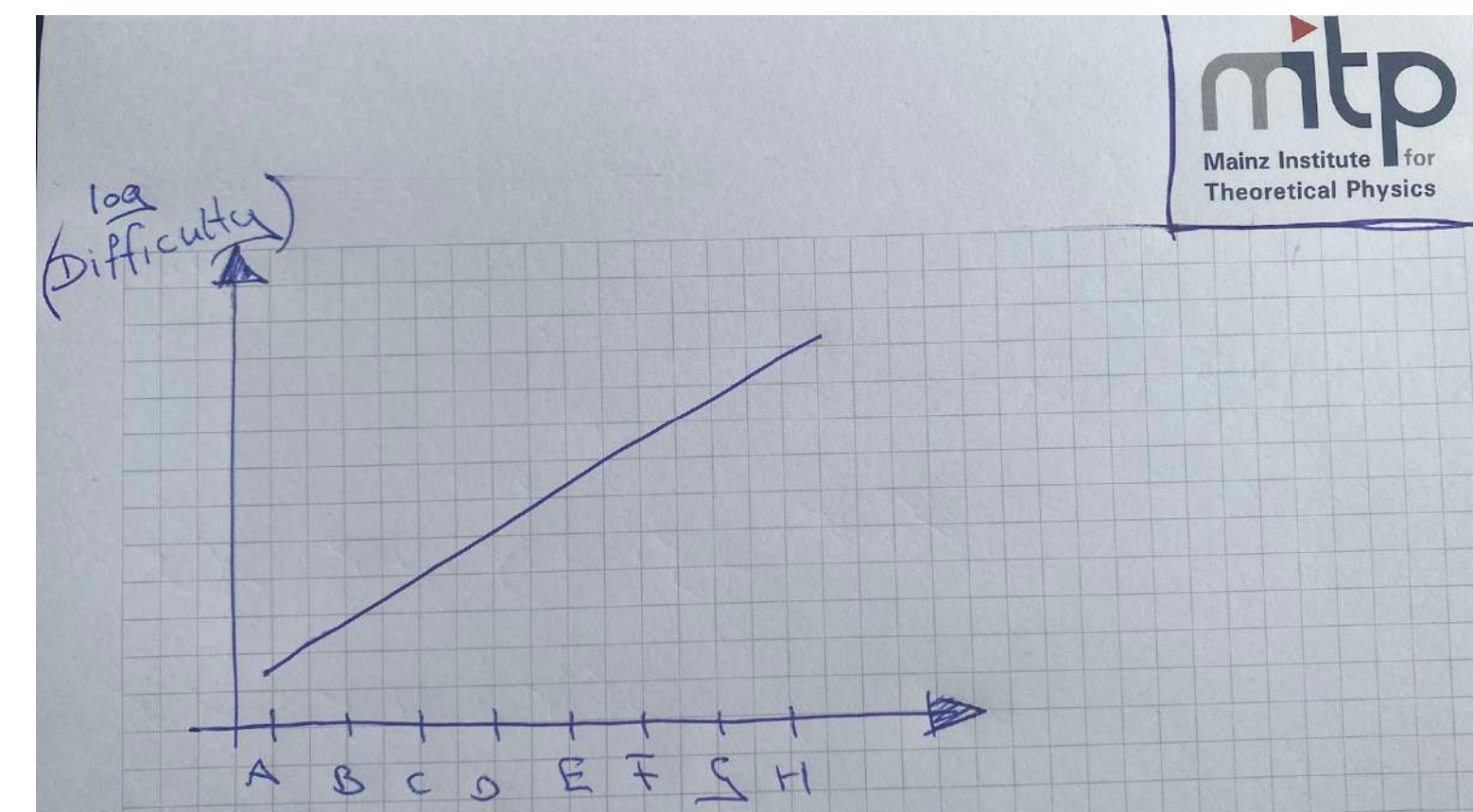
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Theoretical Physics

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8.10.2025

Alexander Lenz

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



“Easy” ———> “ganz schwer”

Inclusive V_{cb}

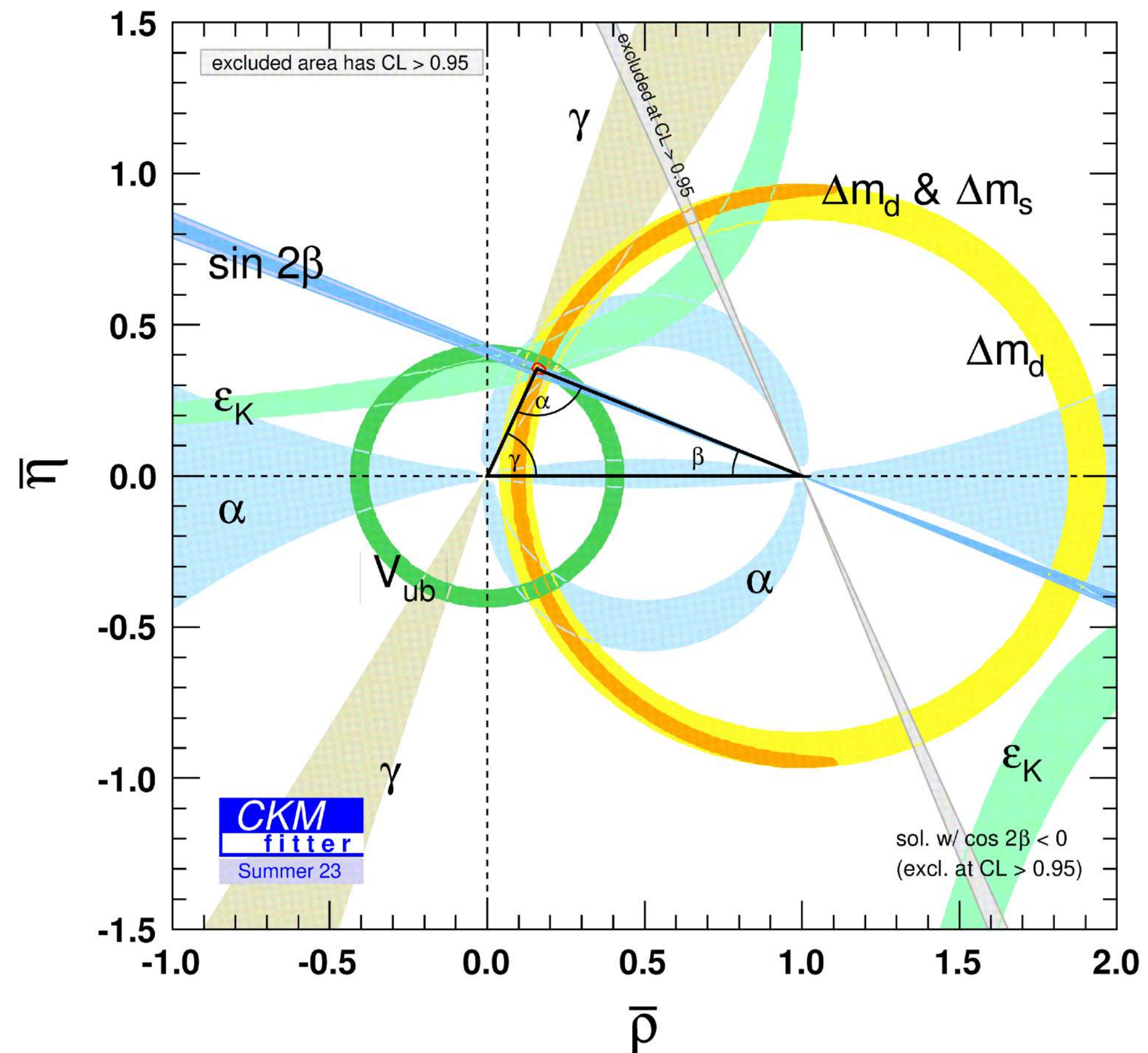
Relation to non-leptonic B-decays, like $B_s \rightarrow D_s^+ \pi^-$ and to rare-semi-leptonic decays $B \rightarrow K l l$ or $D \rightarrow \pi l l$

- 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: $\Delta A_{CP}(D^0 \rightarrow \pi^+ \pi^-, K^+ K^-)$ - can we be a factor of 10 off?
- H. Charm mixing: - crazy cancellations - can we be a factor of 10 000 off?

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

Flavour Physics in a nutshell

Success



similar results by UTfit

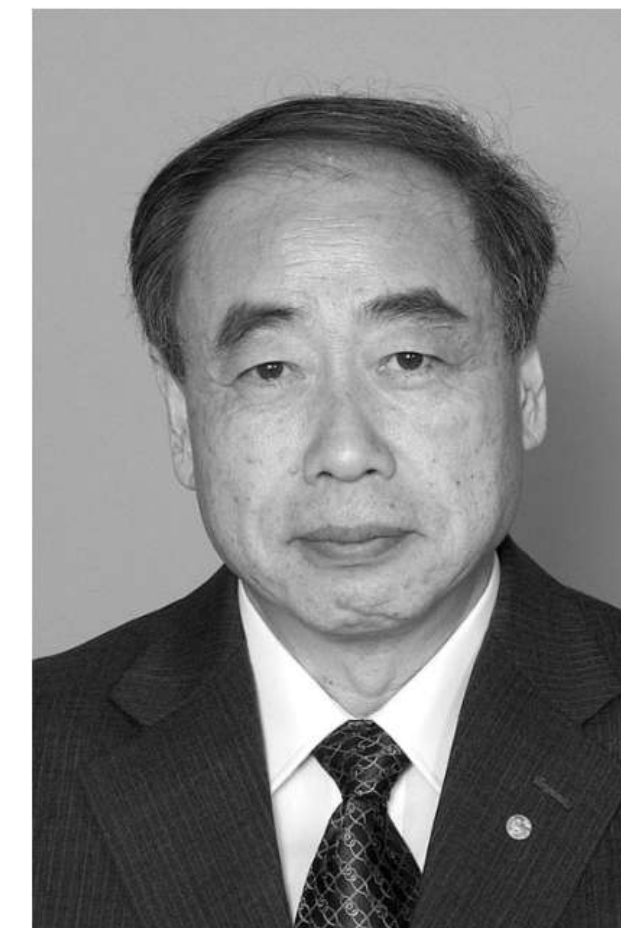
Nobel Prize in Physics 2008



Photo: University of Chicago

Yoichiro Nambu

Prize share: 1/2



© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

Prize share: 1/4



© The Nobel Foundation Photo: U. Montan

Toshihide Maskawa

Prize share: 1/4

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

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

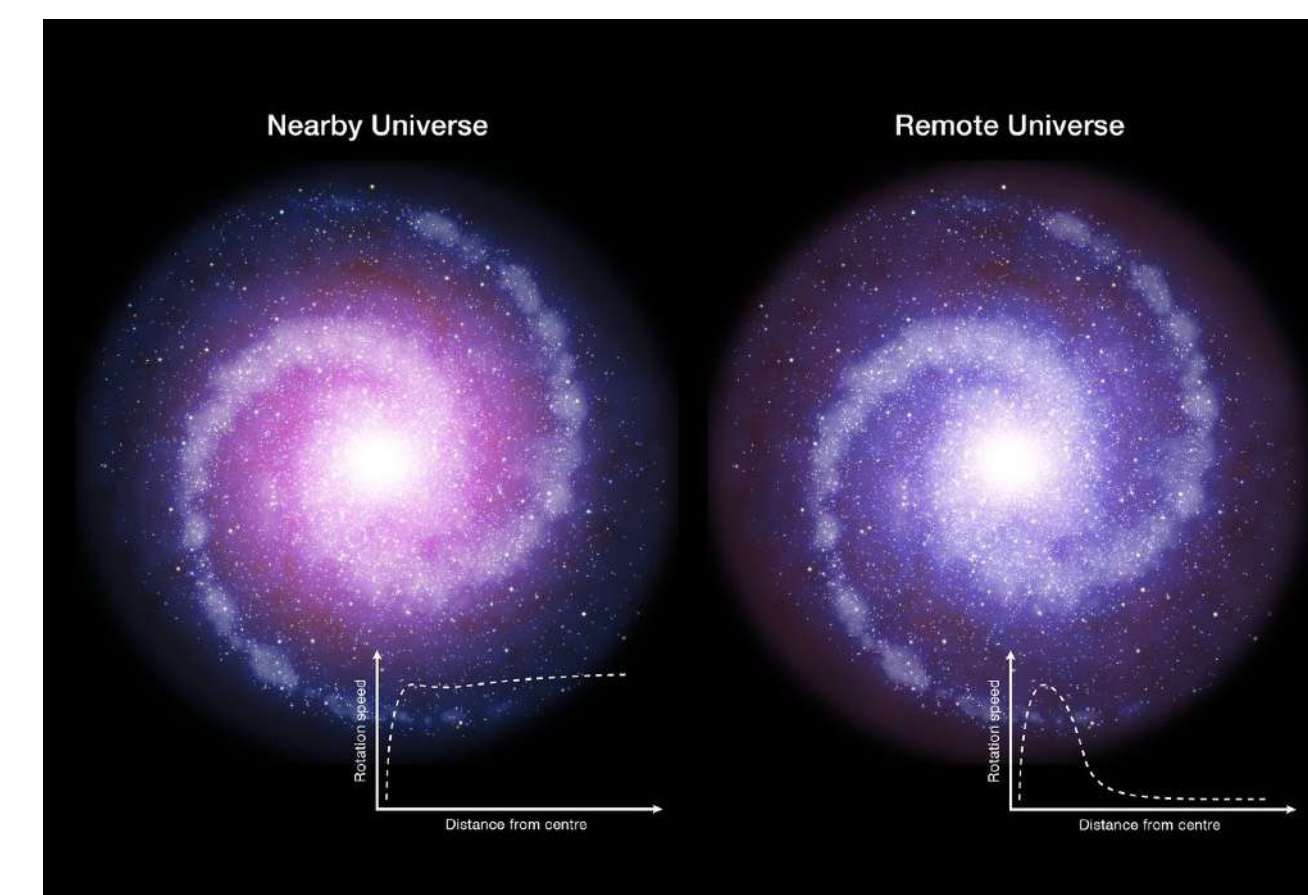
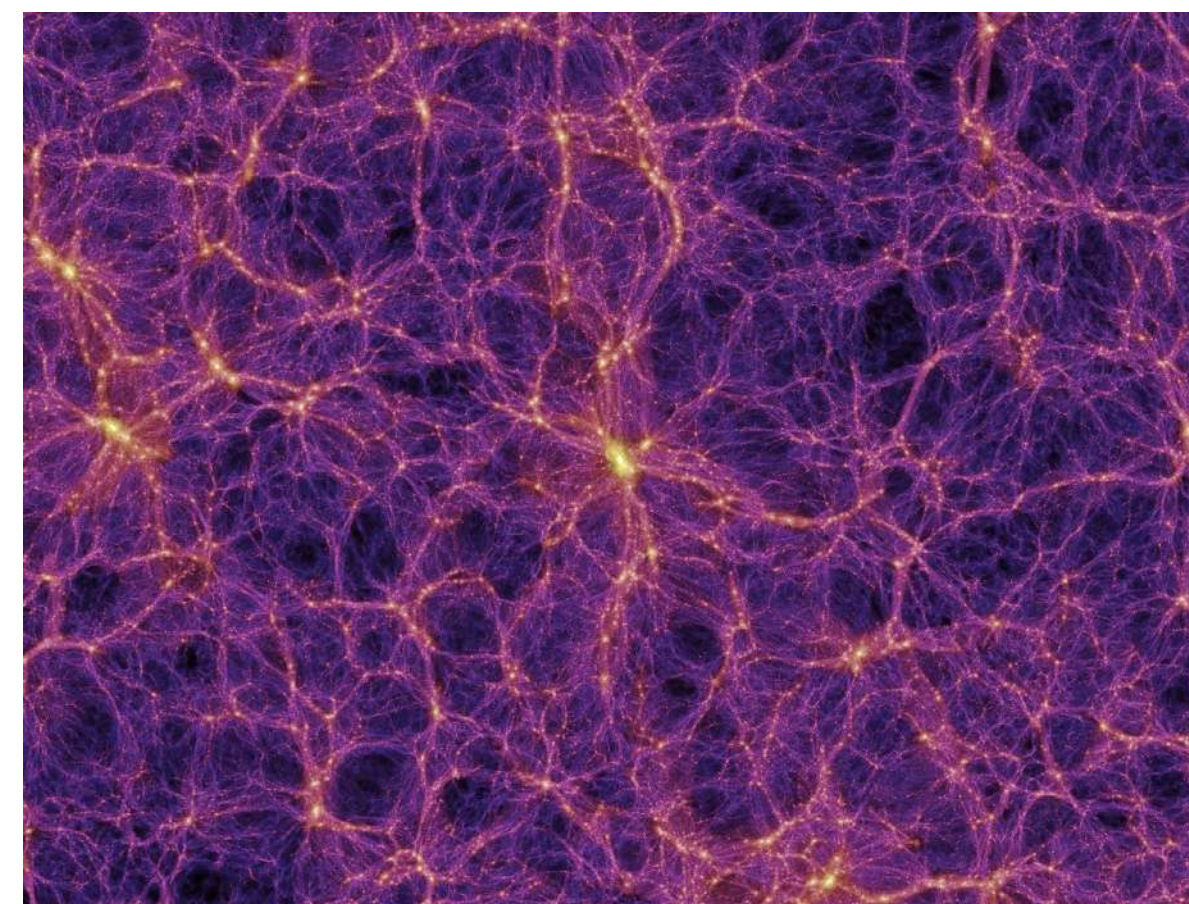
reference search 5,424 citations

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

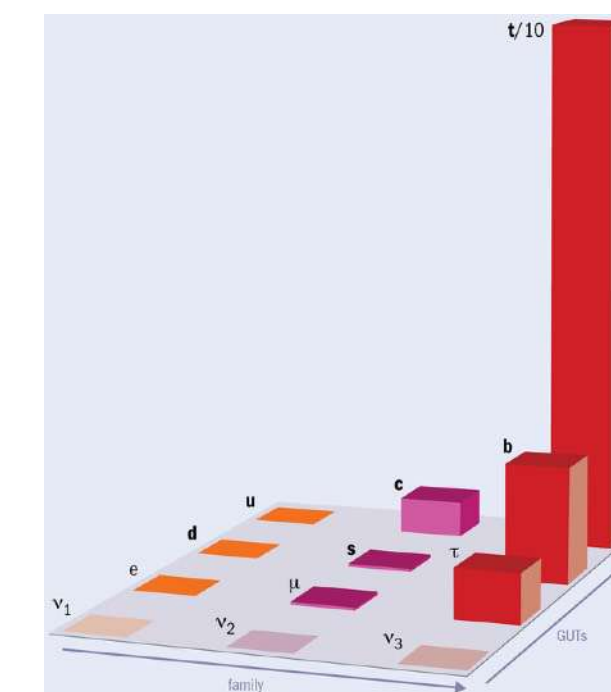
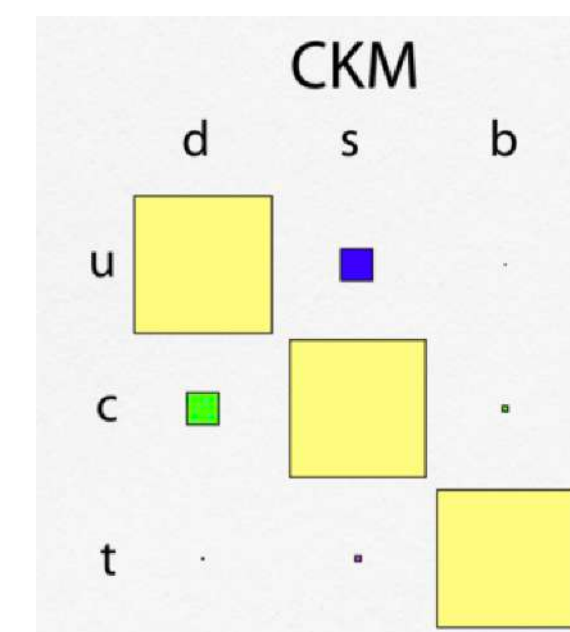
2) Baryon number violation: **yes** - sphalerons
(Klinkhammer, Manton)

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

Dark Matter in the Universe



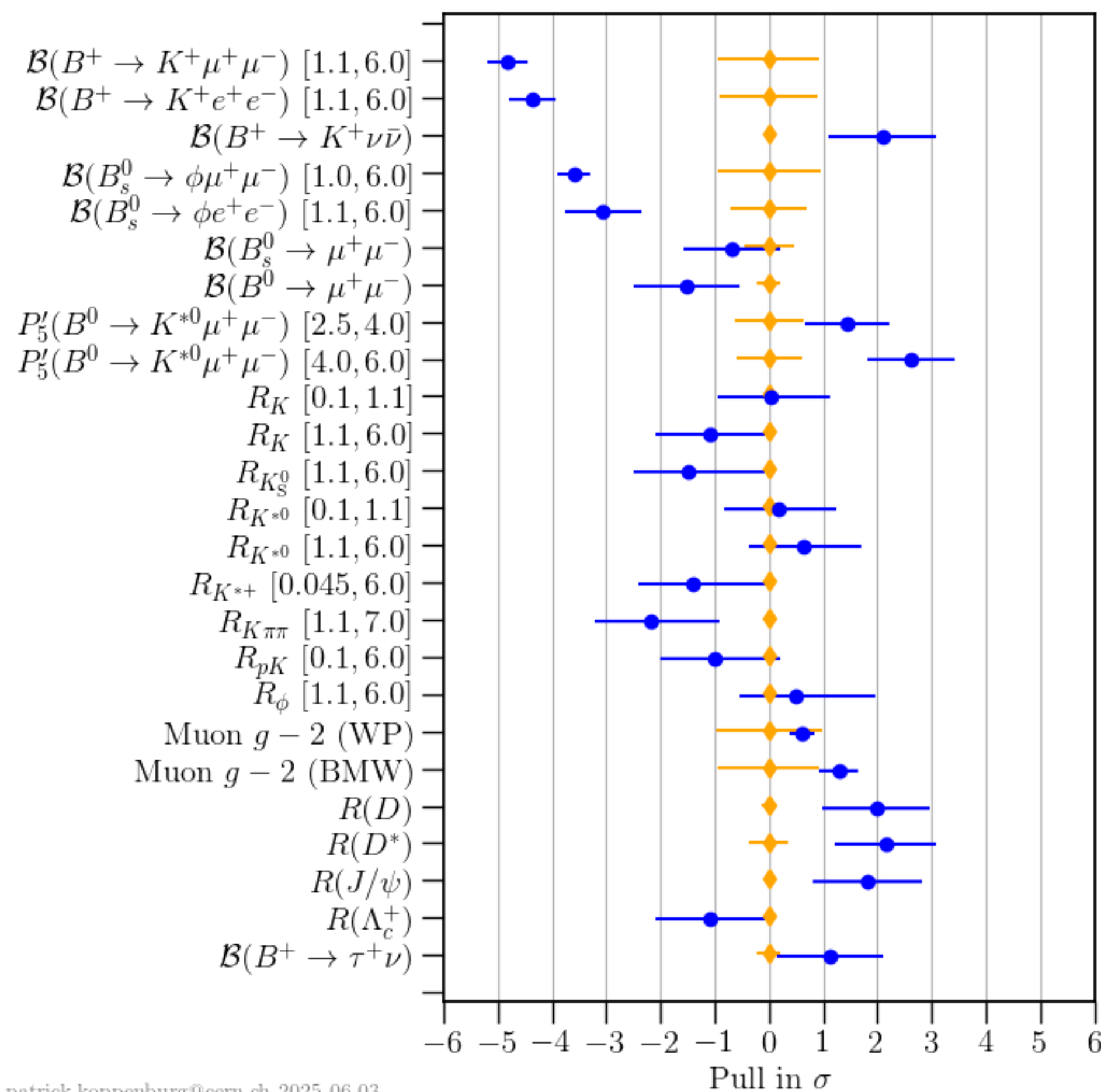
Origin of flavour structure, quark masses,...



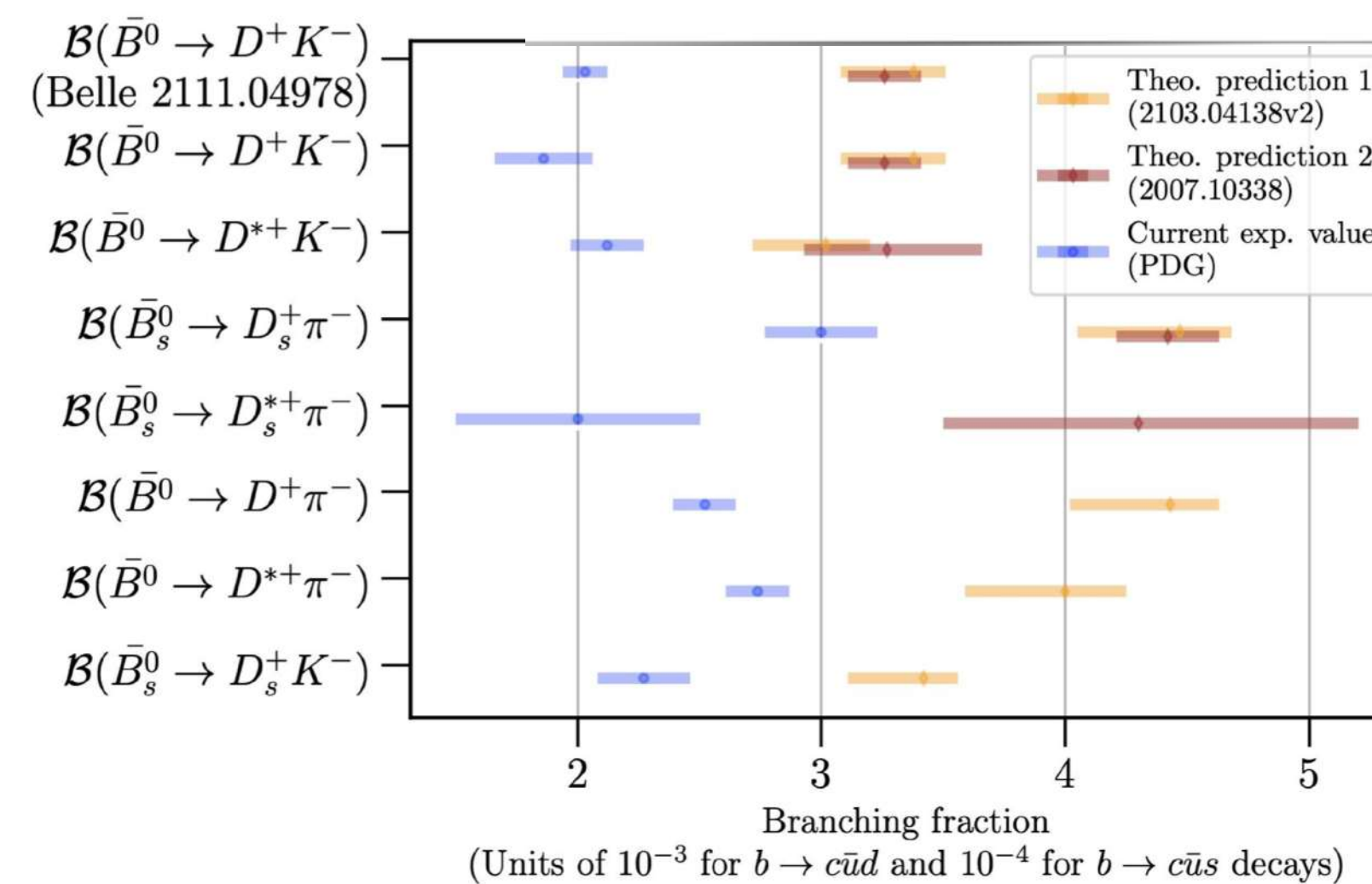
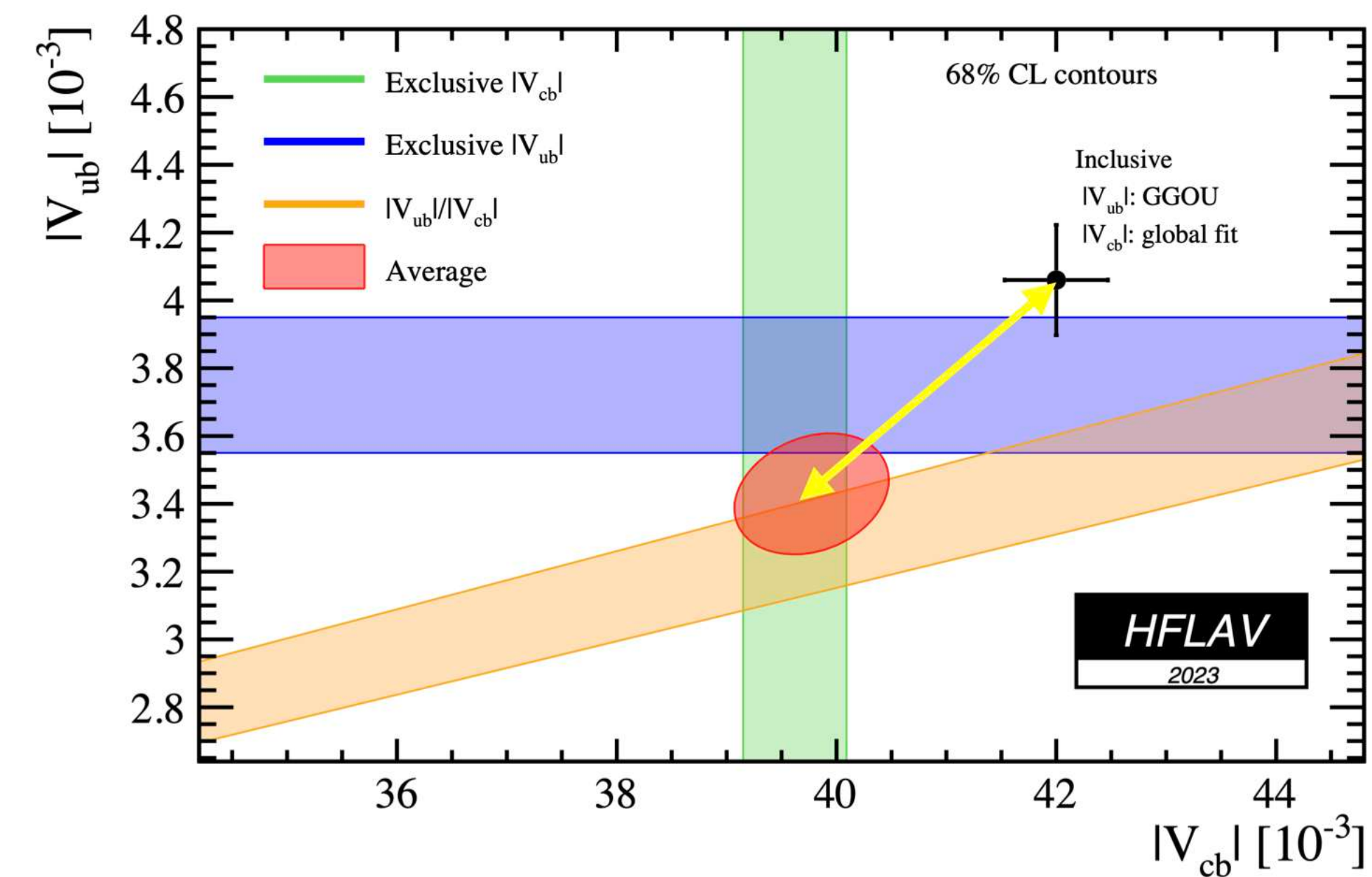
Several more ...

Flavour Physics in a nutshell

Anomalies



patrick.koppenburg@cern.ch 2025-06-03



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

• Origin of anomalies: Exp./QCD or a first glimpse BSM

- Hadronic contributions to $b \rightarrow s\ell\ell$
- $V_{cb} - V_{ub}$ 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

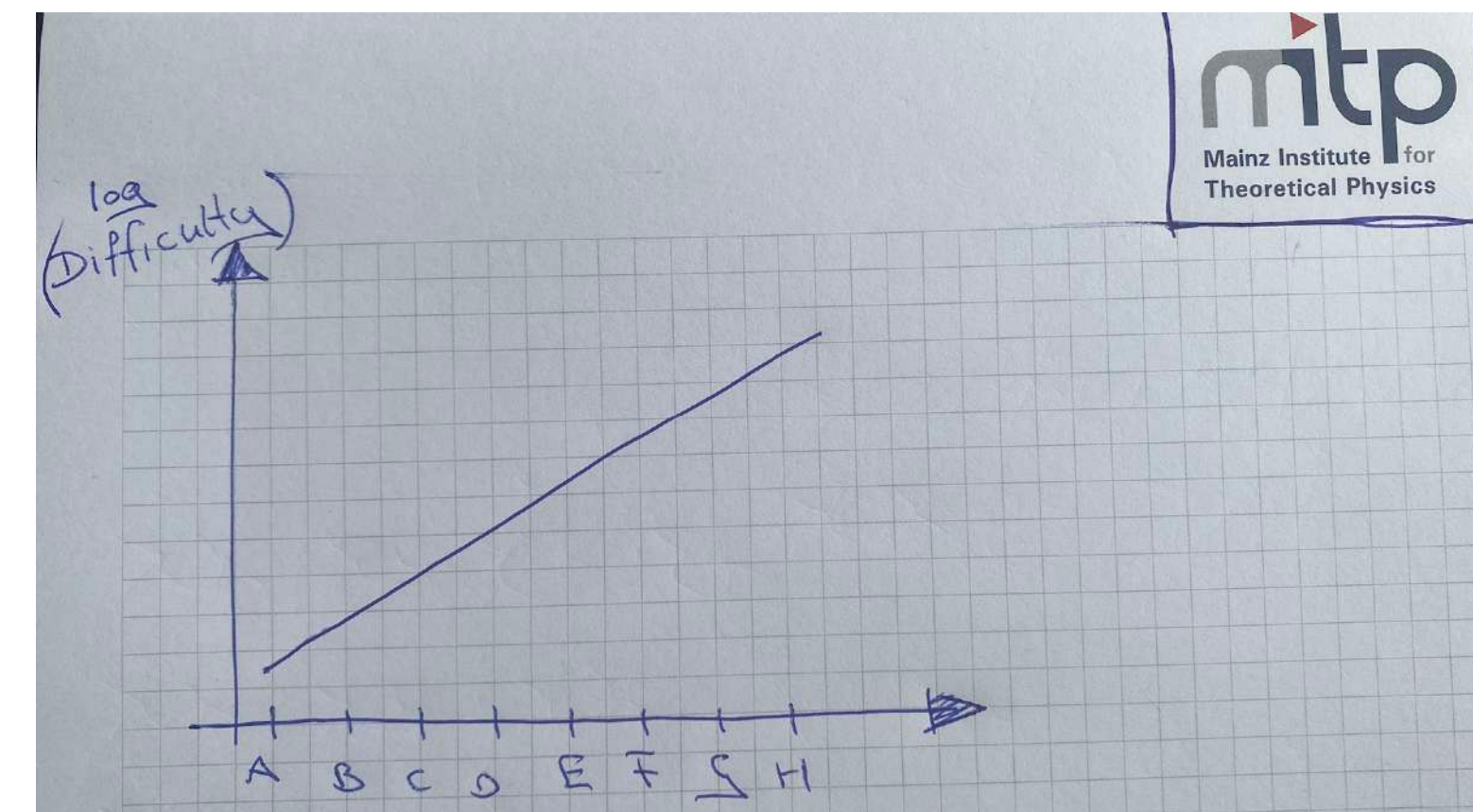
BSM interpretation of potential anomalies •

- Connection to collider physics

Elephants in the room?

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

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“Easy” ———> “ganz schwer”

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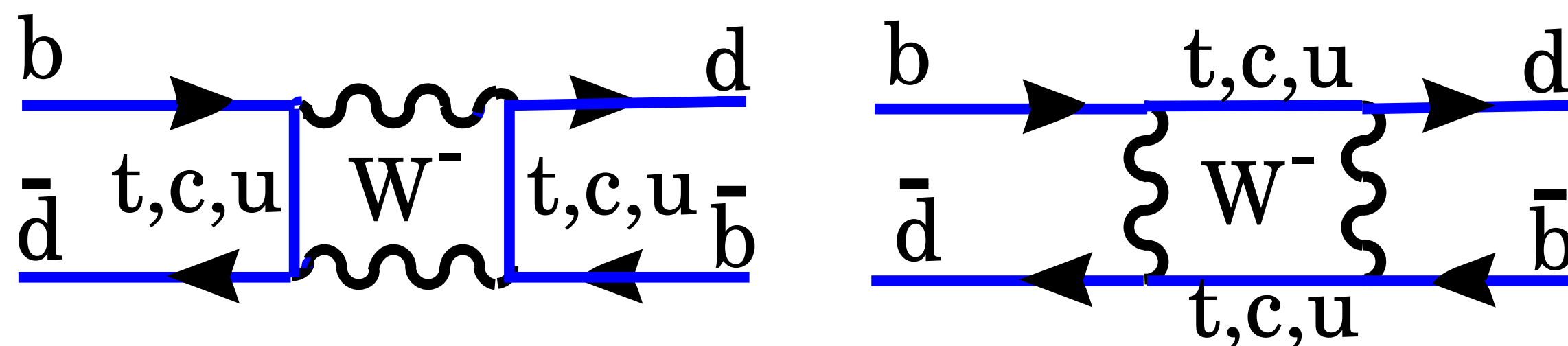
4) Some fun, which is many times overlooked: BSM in tree-level decays

One OPE:

$$m_W, m_t$$

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

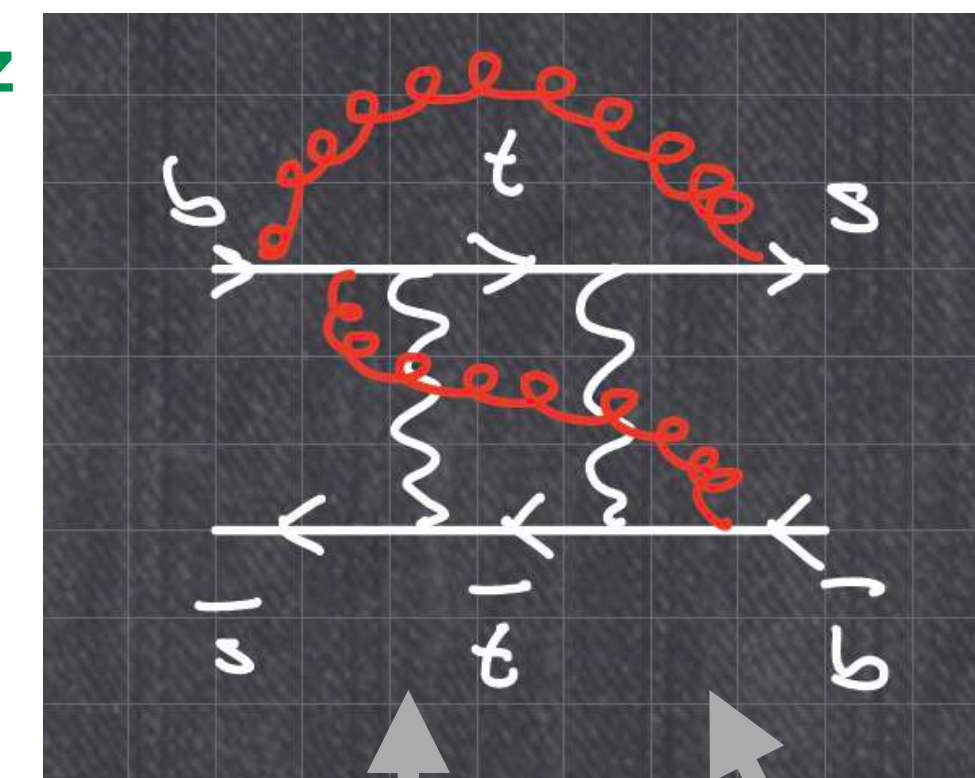
2-loop: Buras, Jamin, Weisz
3-loop: Gorbahn,.....



$|M_{12}|$, $|\Gamma_{12}|$ 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. $B_q \rightarrow X l \nu$ (semi-leptonic)

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



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

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

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

Total decay rate

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

1st OPE:

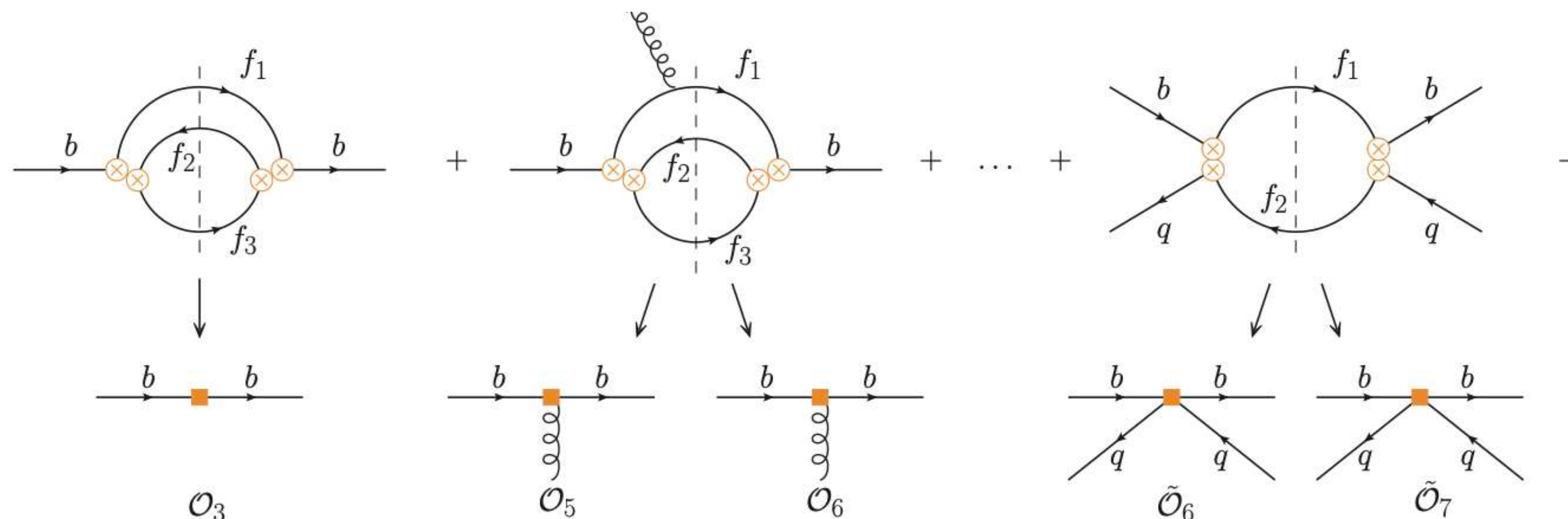
$$m_W, m_t$$

Optical theorem

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

2nd OPE:

$$m_b$$



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

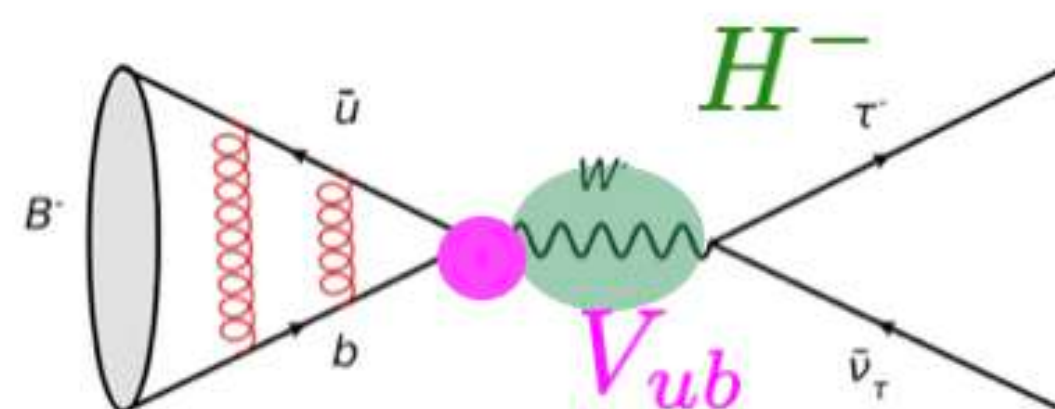
$$\Gamma(B_q) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_q}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_q}}{m_b^3} + \dots + 16\pi^2 \left[\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7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

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

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

Exclusive decay rates

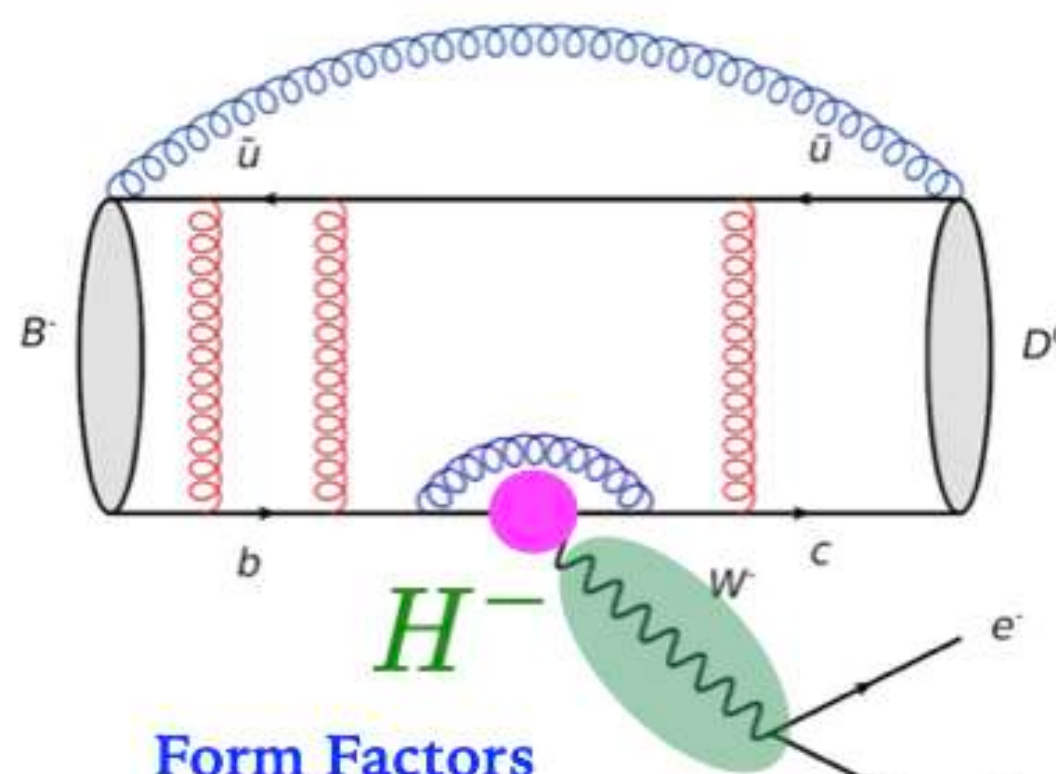
• Leptonic Decays



Decay constant

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

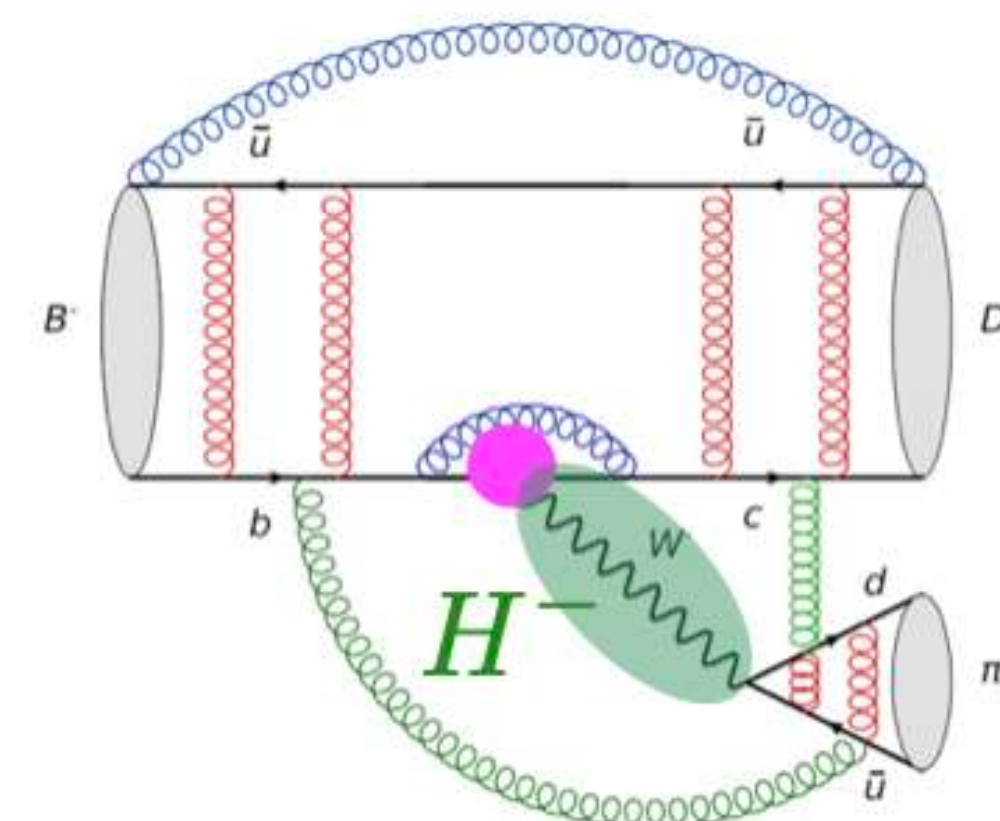
• Semileptonic Decays



Form Factors

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

• 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

Exclusive decay rates

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]

pdf DOI cite claim
reference search 49 citations

A puzzle in $\bar{B}_{(s)}^0 \rightarrow D_{(s)}^{(*)+} \{\pi^-, K^-\}$ 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.JC* 80 (2020) 10, 951 • e-Print: 2007.10338 [hep-ph]

pdf DOI cite claim
reference search 29 citations

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

NNLO

LO in

$$\varepsilon \sim \Lambda_{\text{QCD}}/E_L \sim \Lambda_{\text{QCD}}/m_b$$

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

Eur. Phys. J. C (2020) 80:347
<https://doi.org/10.1140/epjc/s10052-020-7830-9>
Regular Article - Theoretical Physics

THE EUROPEAN
PHYSICAL JOURNAL C

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

Marzia Bordone^{1,2}, Nico Gubernari^{1,3}, Danny van Dyk^{1,2}, Martin Jung^{1,4}
¹ Universität Siegen, Walter-Flex-Str. 1, 57071 Siegen, Germany
² Technische Universität München, James-Frank-Straße 1, 85748 Garching, Germany
³ Dipartimento di Fisica, Università di Torino & INFN, Sezione di Torino, 10125 Torino, Italy

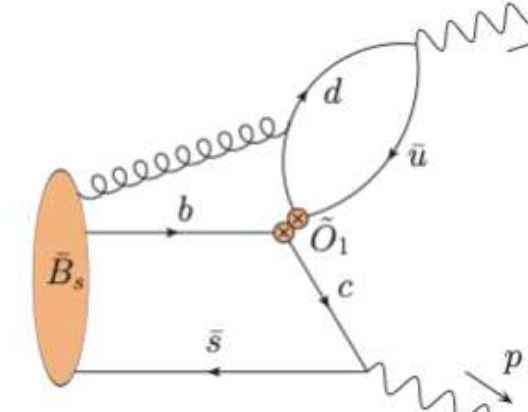
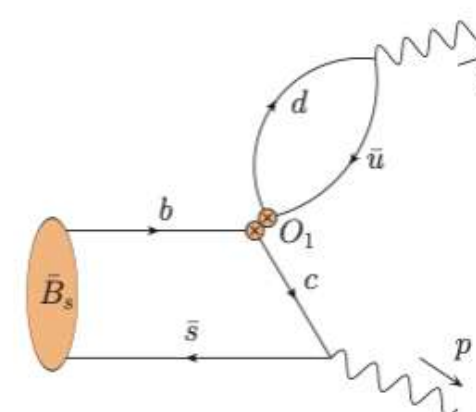
$F_0^{\bar{B} \rightarrow D}(M_K^2)$	—	0.672 ± 0.011
$F_0^{\bar{B}_s^0 \rightarrow D_s}(M_s^2)$	—	0.673 ± 0.011
$A_0^{\bar{B} \rightarrow D^*}(M_K^2)$	—	0.708 ± 0.038
$A_0^{\bar{B}_s^0 \rightarrow D_s^*}(M_\pi^2)$	—	0.689 ± 0.064

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

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

New estimates within QCD sum rules



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

Maria Laura Piscopo and Aleksey V. Rusov

Physik Department, Universität Siegen,
Walter-Flex-Str. 3, 57068 Siegen, Germany

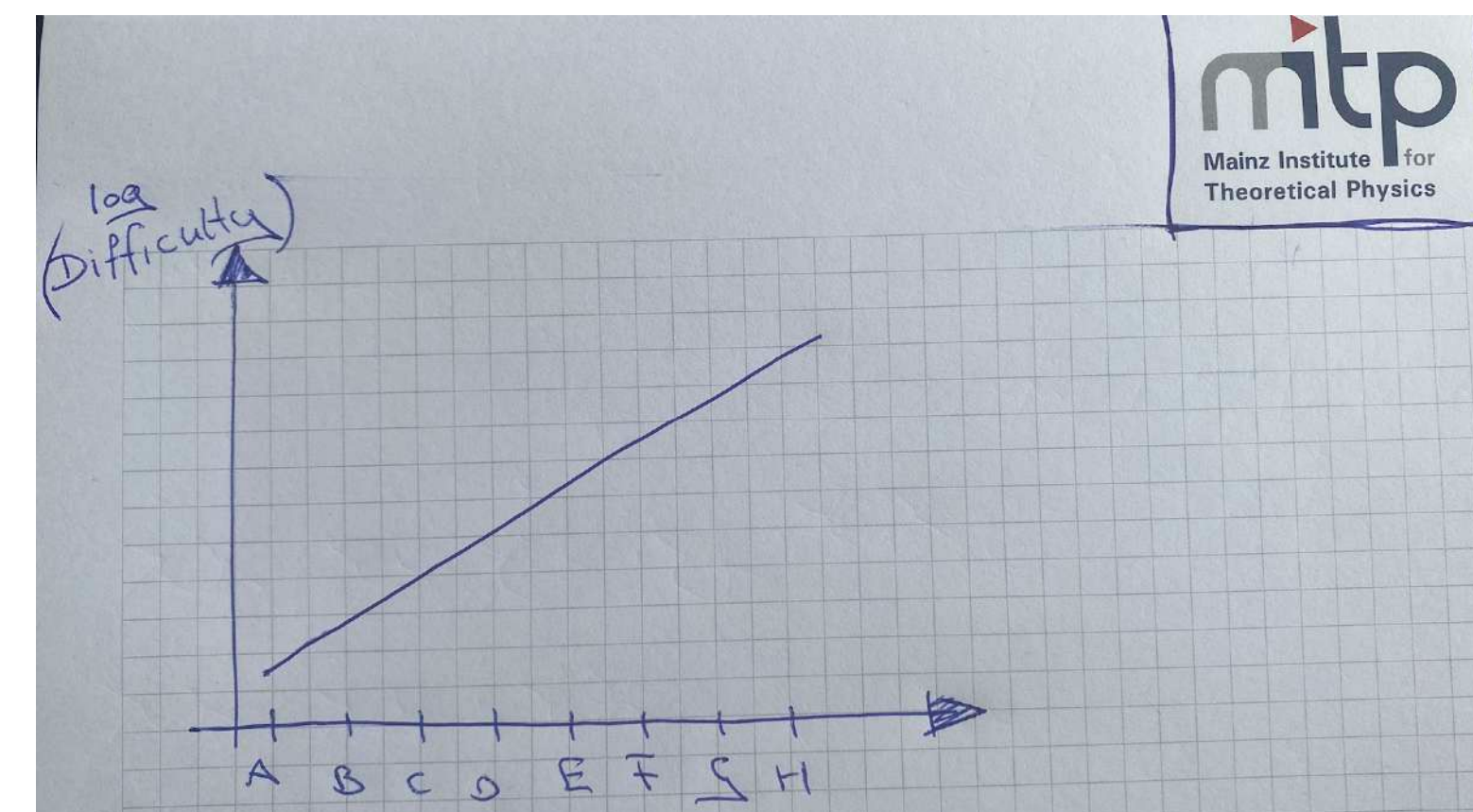
E-mail: maria.piscopo@uni-siegen.de, rusov@physik.uni-siegen.de

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 $\bar{B}_s^0 \rightarrow D_s^+ \pi^-$ and $\bar{B}^0 \rightarrow D^+ K^-$, 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.

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

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

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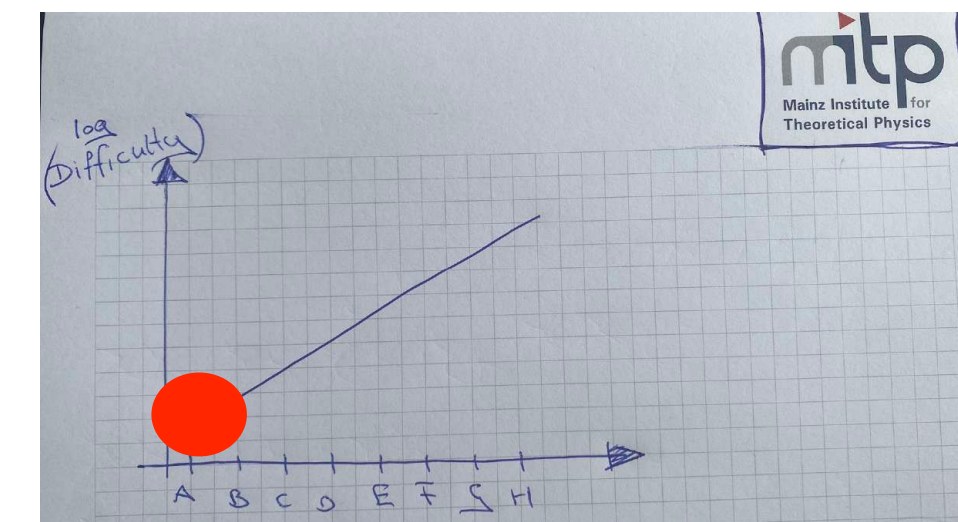
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Mass differences in B-mixing

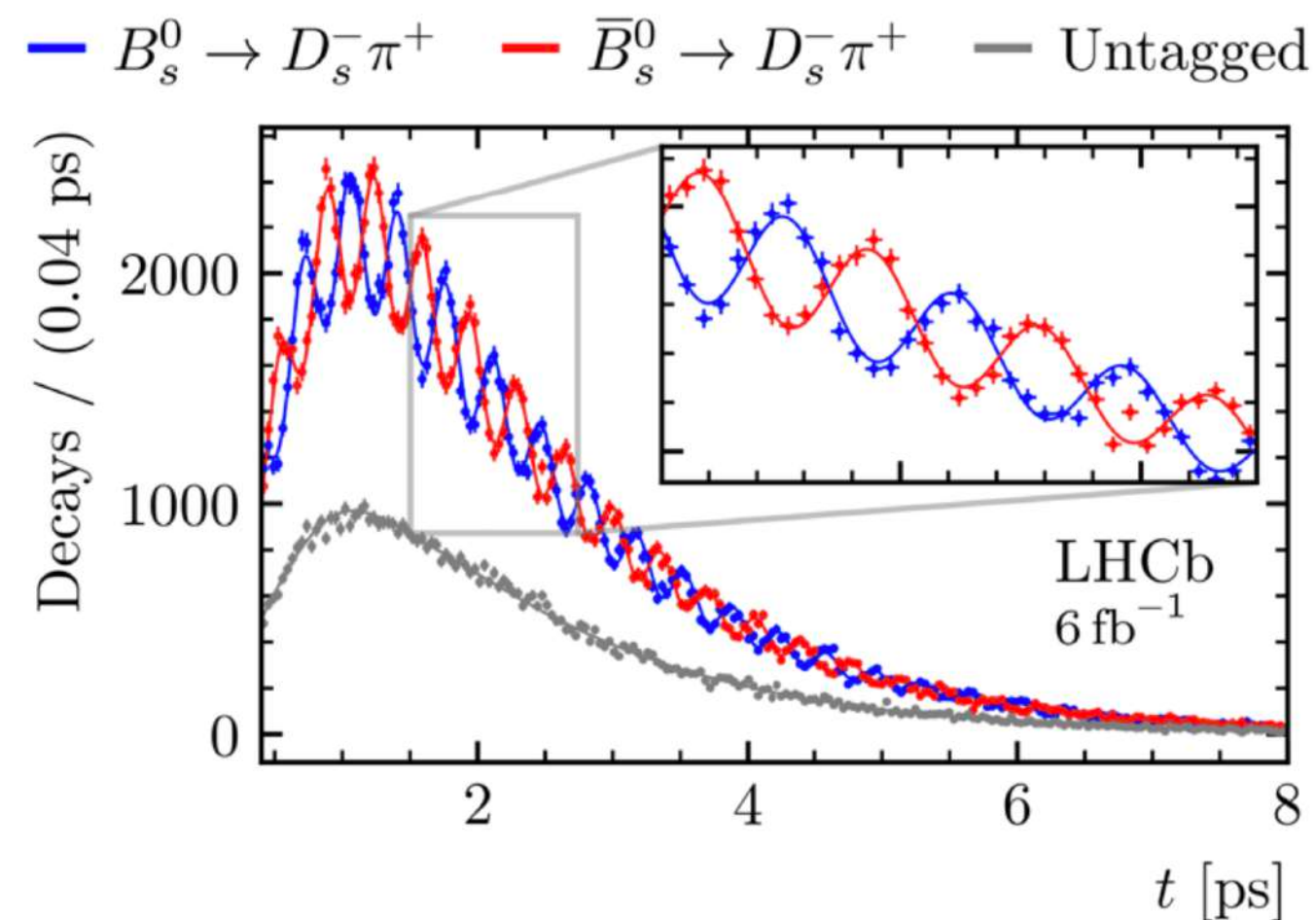


12 April 2021: Fascinating quantum mechanics.

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

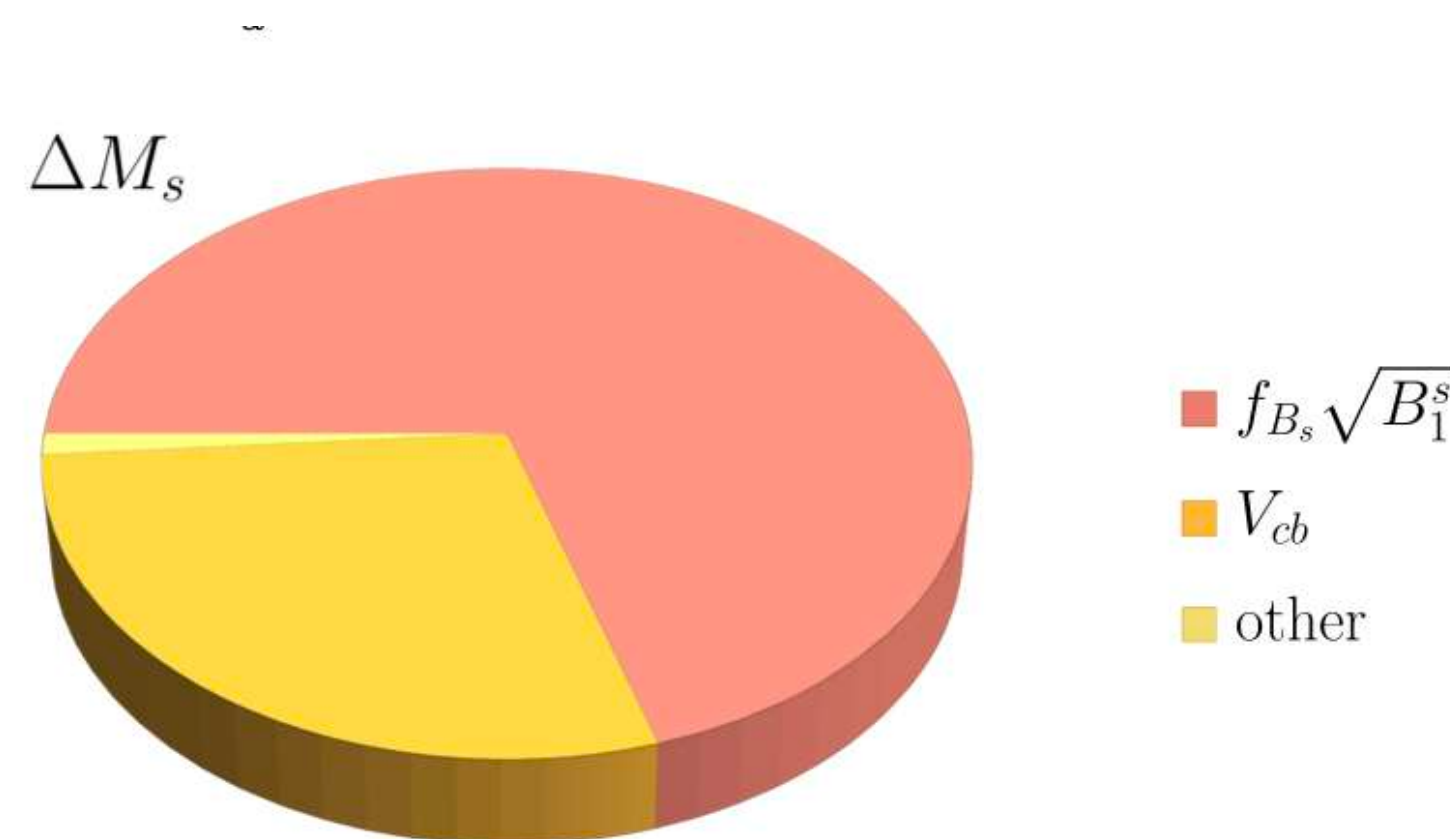
"A phenomenon in which quantum mechanics gives a most remarkable prediction" - Richard Feynman

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_s^0 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 ($3 \cdot 10^{12}$) 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

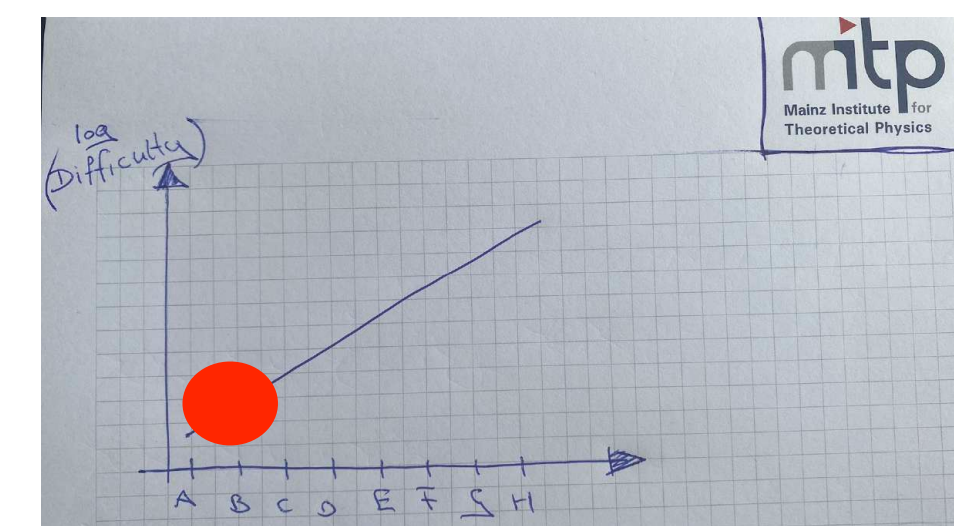
* B_s and B_d mixing: **HQPCD** 19007.01025

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

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

From “easy” to “ganz schwer”

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



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

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

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

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

$\tilde{\Gamma}_6^{(2)}$
KIT
 $\tilde{\Gamma}_6^{(1)}$
KIT/Siegen

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

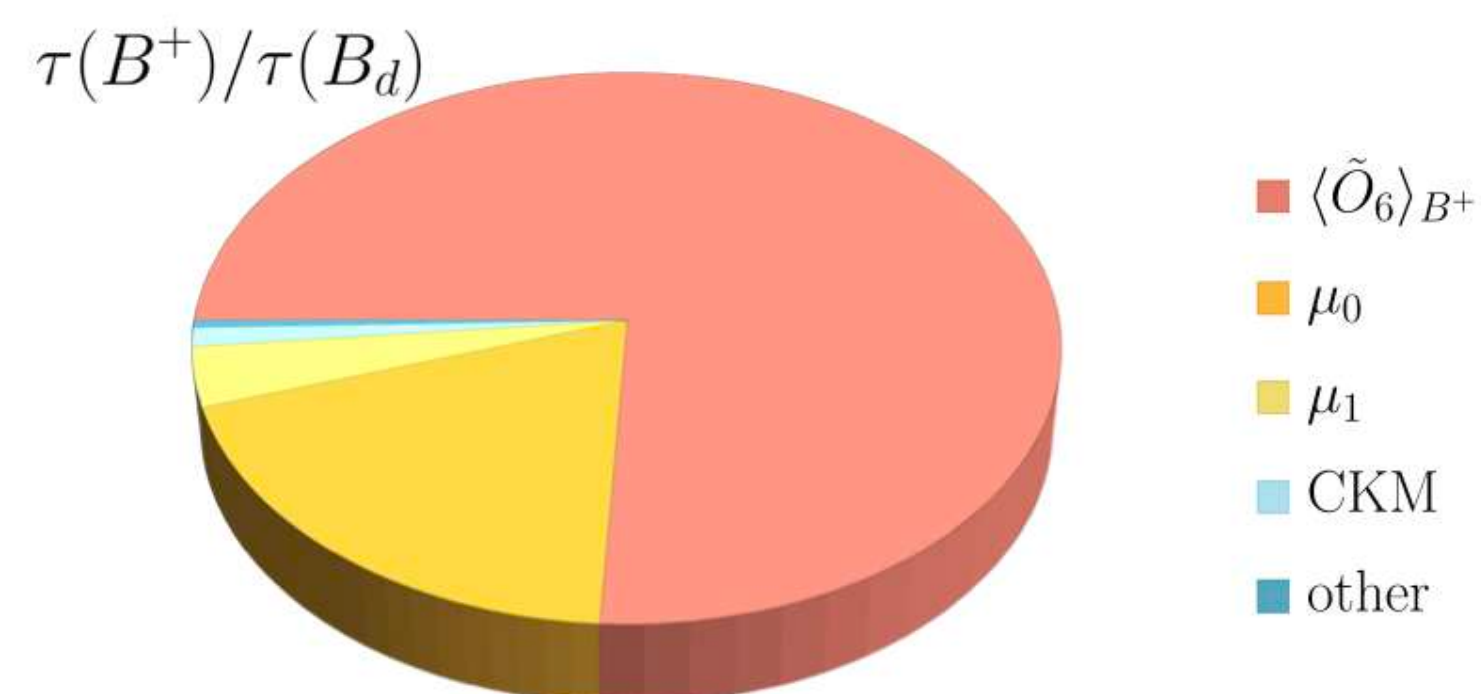
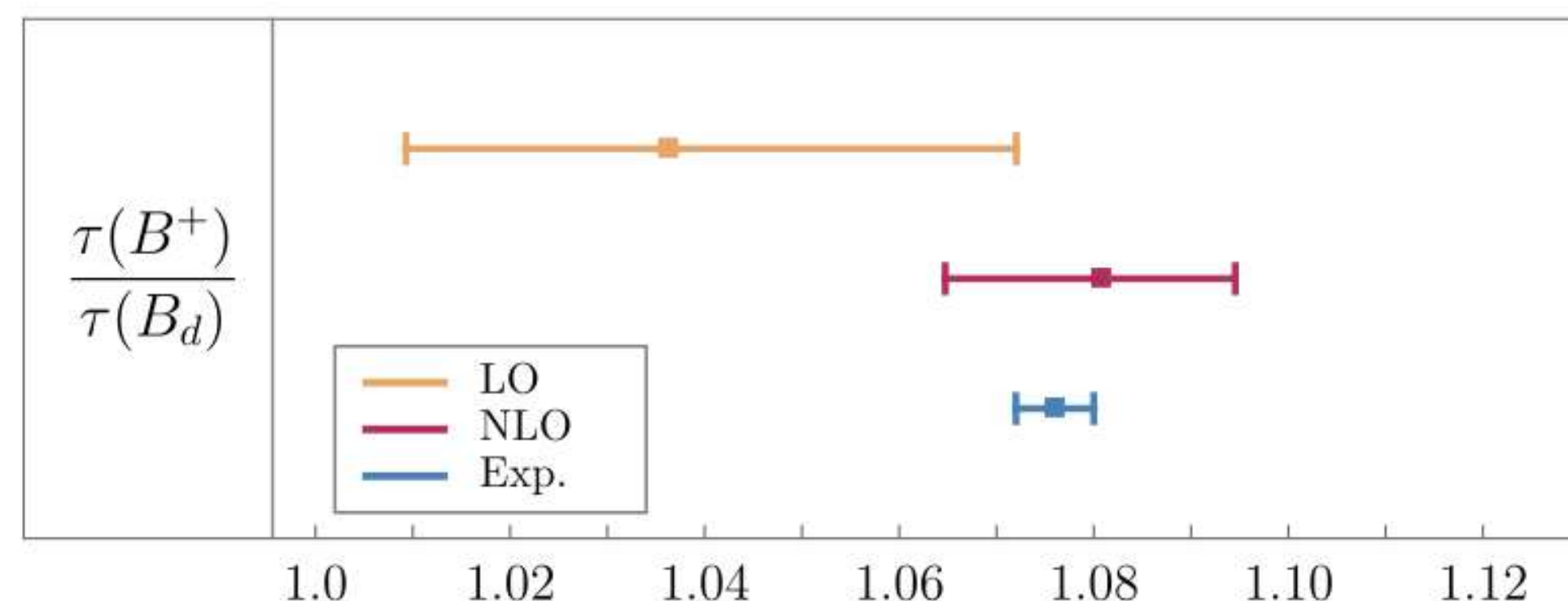
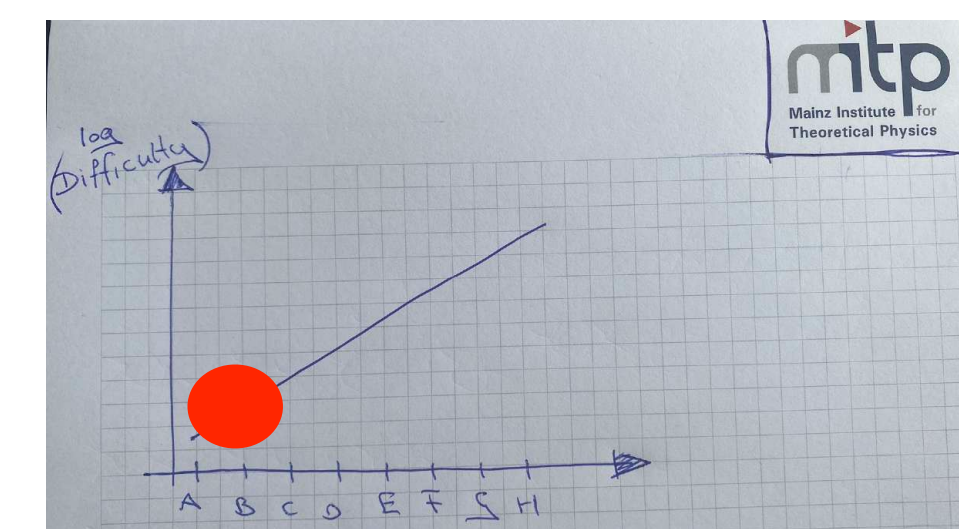
$\tilde{\Gamma}_7^{(0)}$
2003

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

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: $\Delta\Gamma_{s,d}$, $a_{fs}^{s,d}$



$B_s - \bar{B}_s$ 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

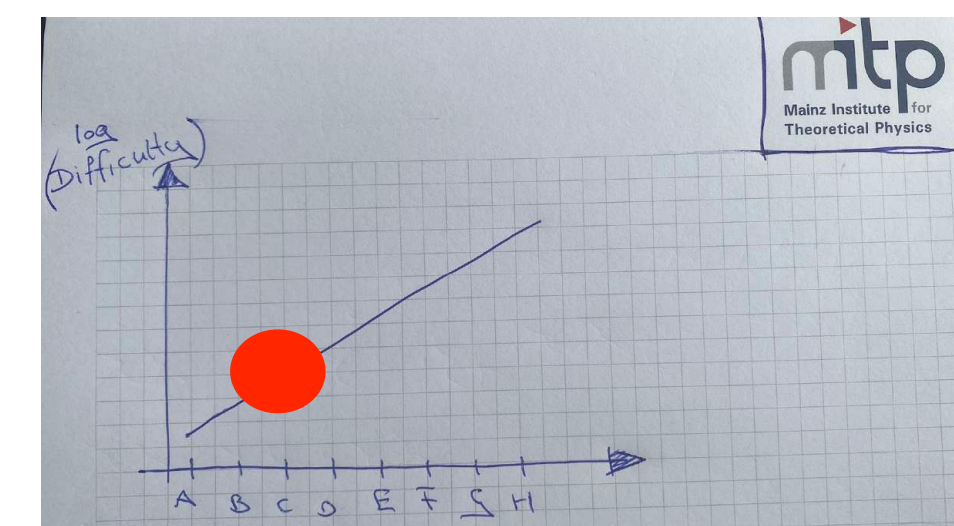
1) New lattice is needed for dim 6 bag parameter

=> Gradient flow

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

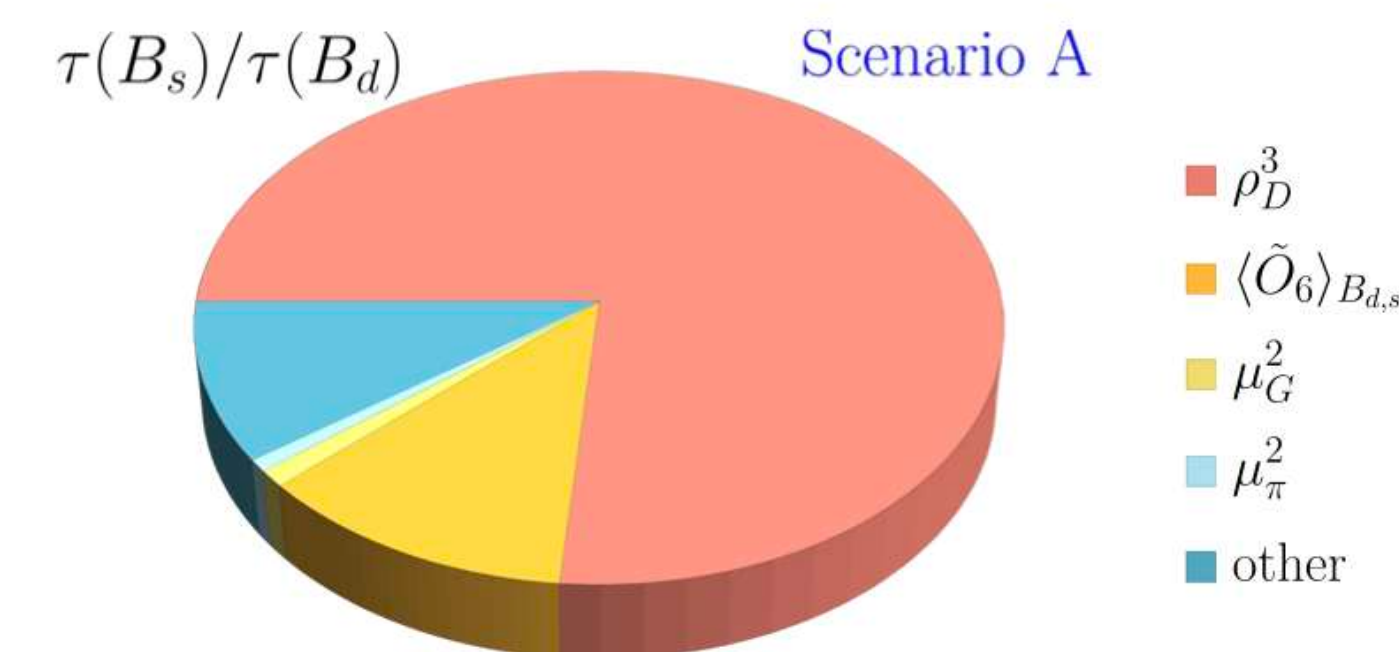
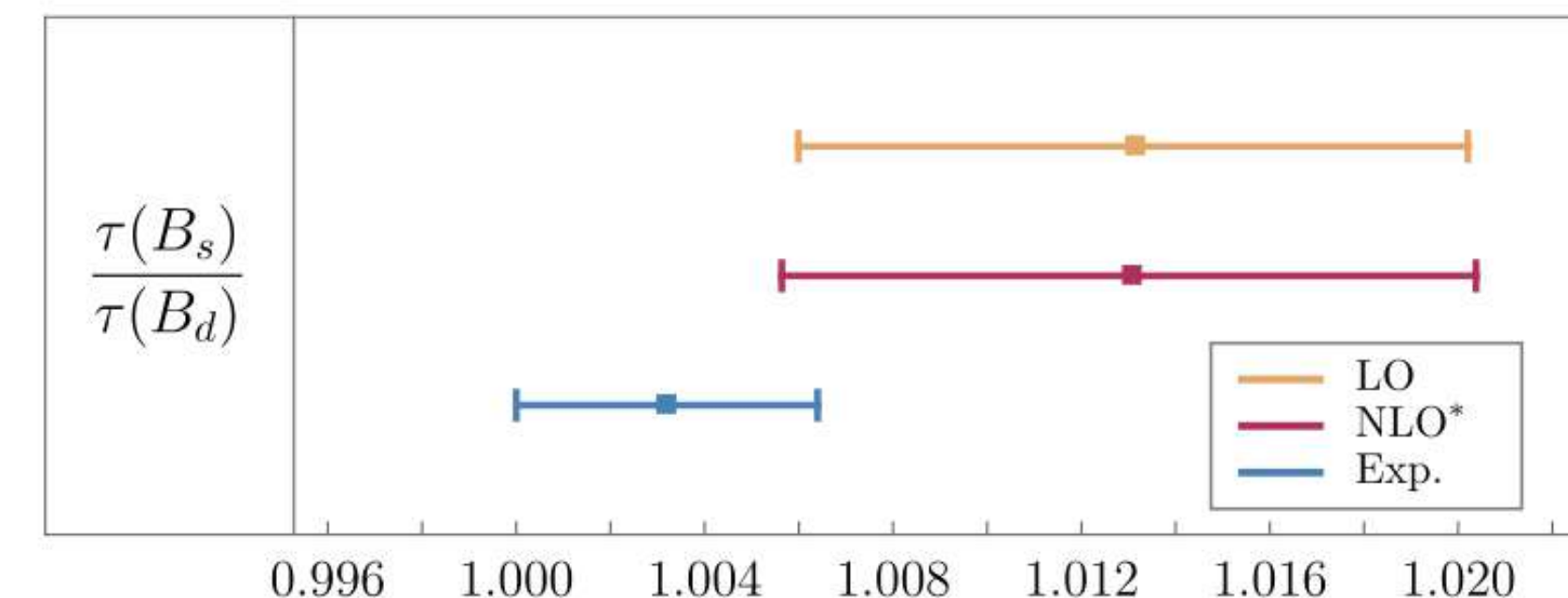
$$\frac{\Delta\Gamma_s}{\Delta M_s} = (4.27_{-0.37}^{+0.36} \text{scale} \pm 0.12_{\text{matrixel.}} \pm 0.79_{1/m_b} \pm 0.05_{\text{input}}) \times 10^{-3} (\overline{\text{PS}})$$

perturbative uncertainty $\langle \tilde{Q}_s \rangle / \langle Q \rangle$ power corr. CKM parameters



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

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



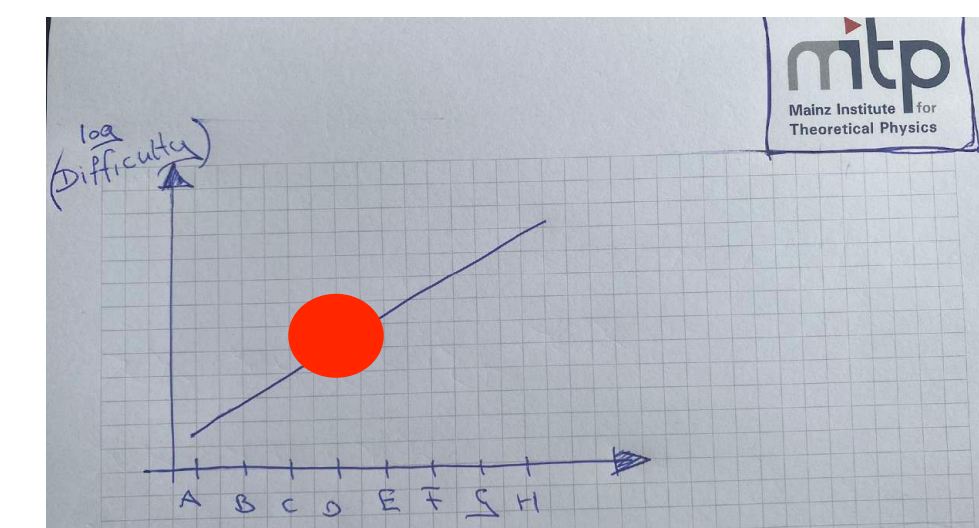
some problems:

- 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:

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

Diagram showing the mapping of terms in the equation to specific calculations:

- Γ_3 (KIT) is associated with $\Gamma_3^{(2)}$ (KIT).
- $\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_q}}{m_b^2}$ is associated with $\Gamma_5^{(0)}$ (penguins+ BSM Siegen) and $\Gamma_5^{(1)}$ (SM - tree-level op Siegen).
- $\Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_q}}{m_b^3}$ is associated with $\Gamma_6^{(0)}$ (penguins+ BSM Siegen).
- $\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3}$ is associated with $\tilde{\Gamma}_6^{(2)}$ (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), and $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ (GF-lattice Aachen/Siegen).

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

Total decay rates of B mesons at NNLO-QCD

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)

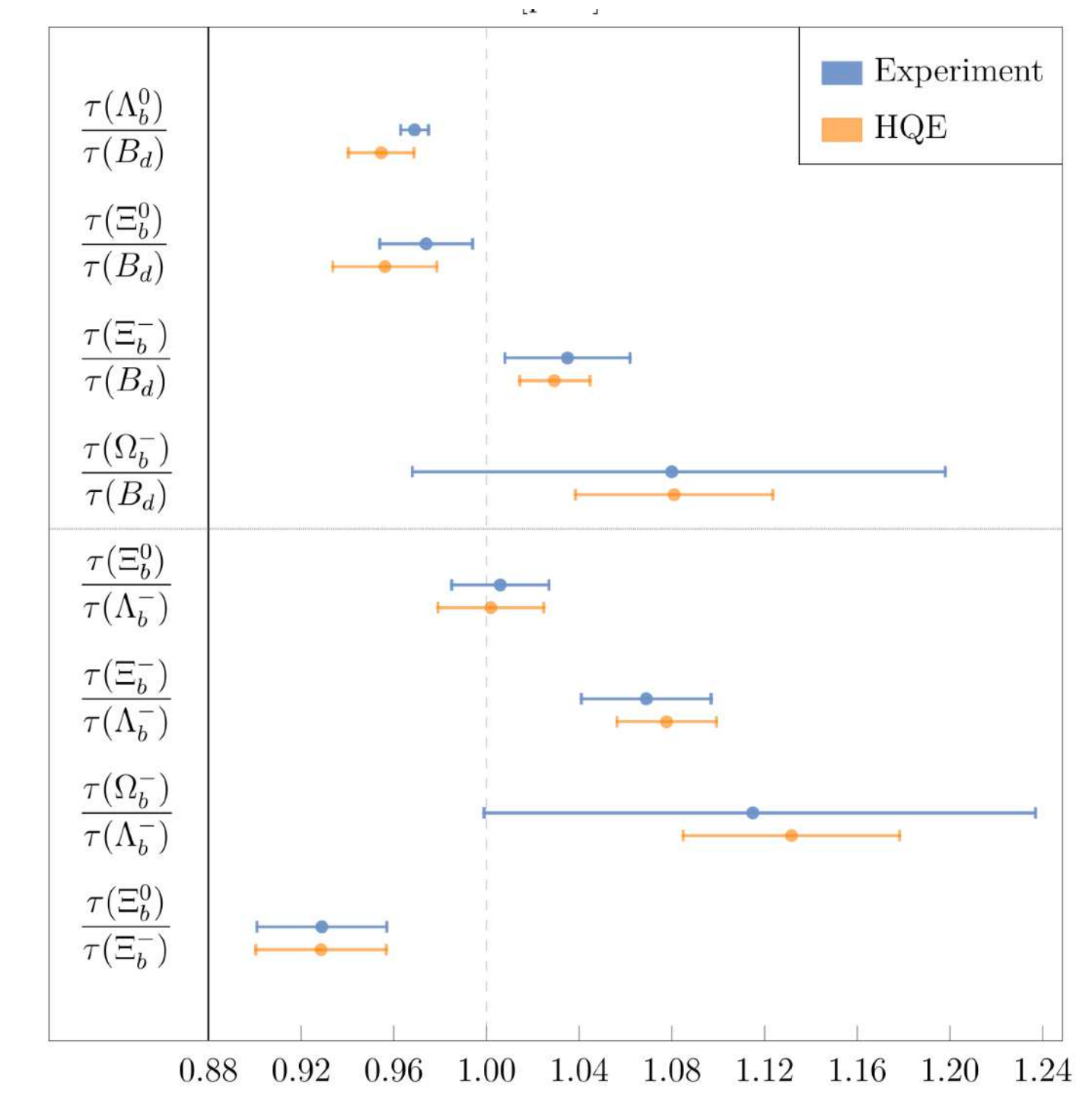
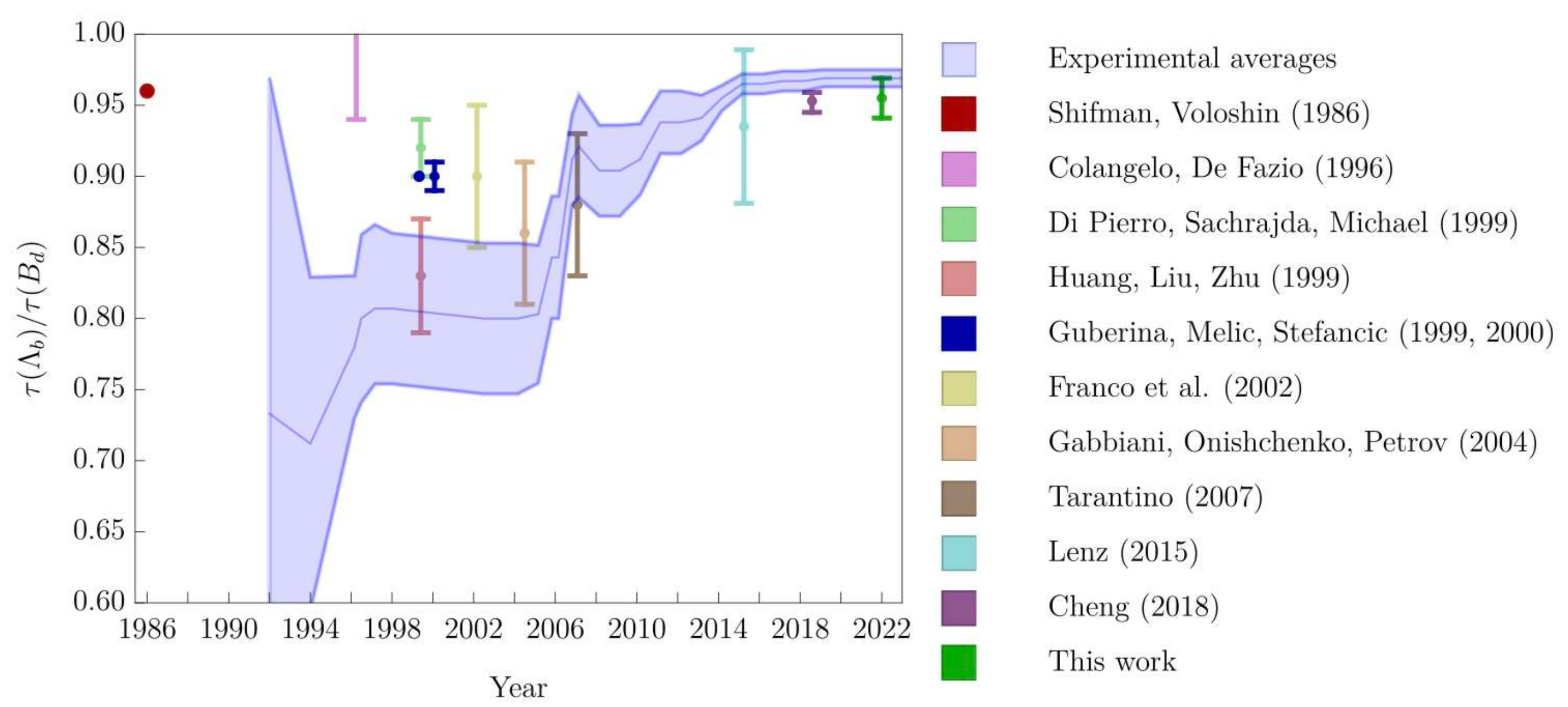
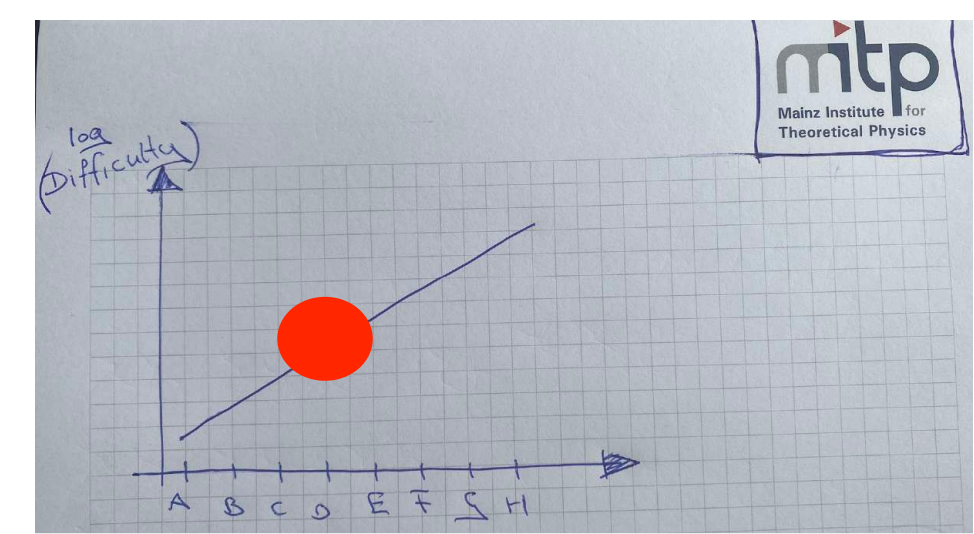
Published in: JHEP 04 (2025) 106 • e-Print: 2412.14035 [hep-ph]

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

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

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

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^3 factor in front of all the non-leptonic widths.

Nature (or experimentalists) might be nasty

Experiment in 1996 shows

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

Works

Works Not

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

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

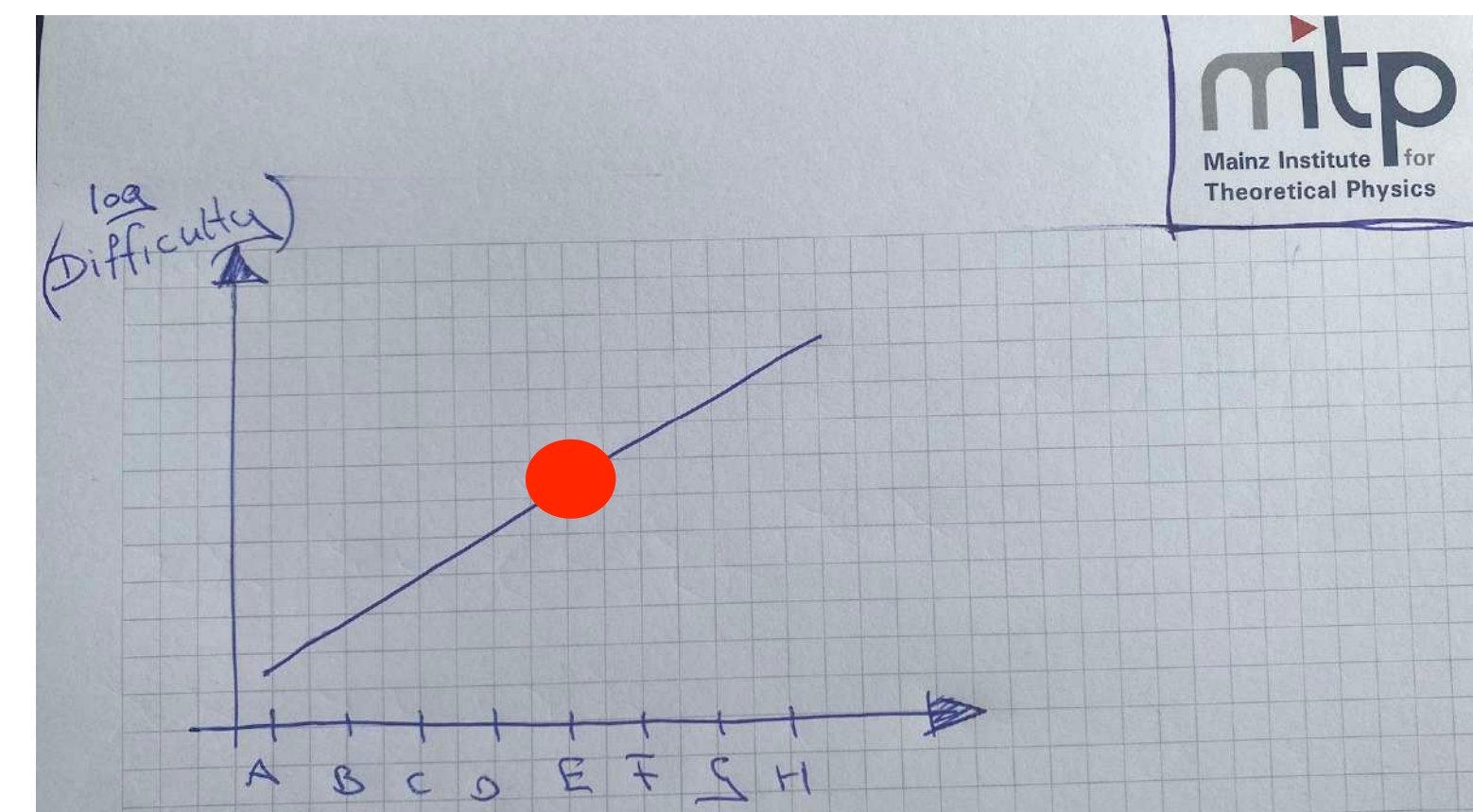
From: Benjamin Grinstein [view email]

[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)

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



“Easy” ———> “ganz schwer”

Inclusive V_{cb}

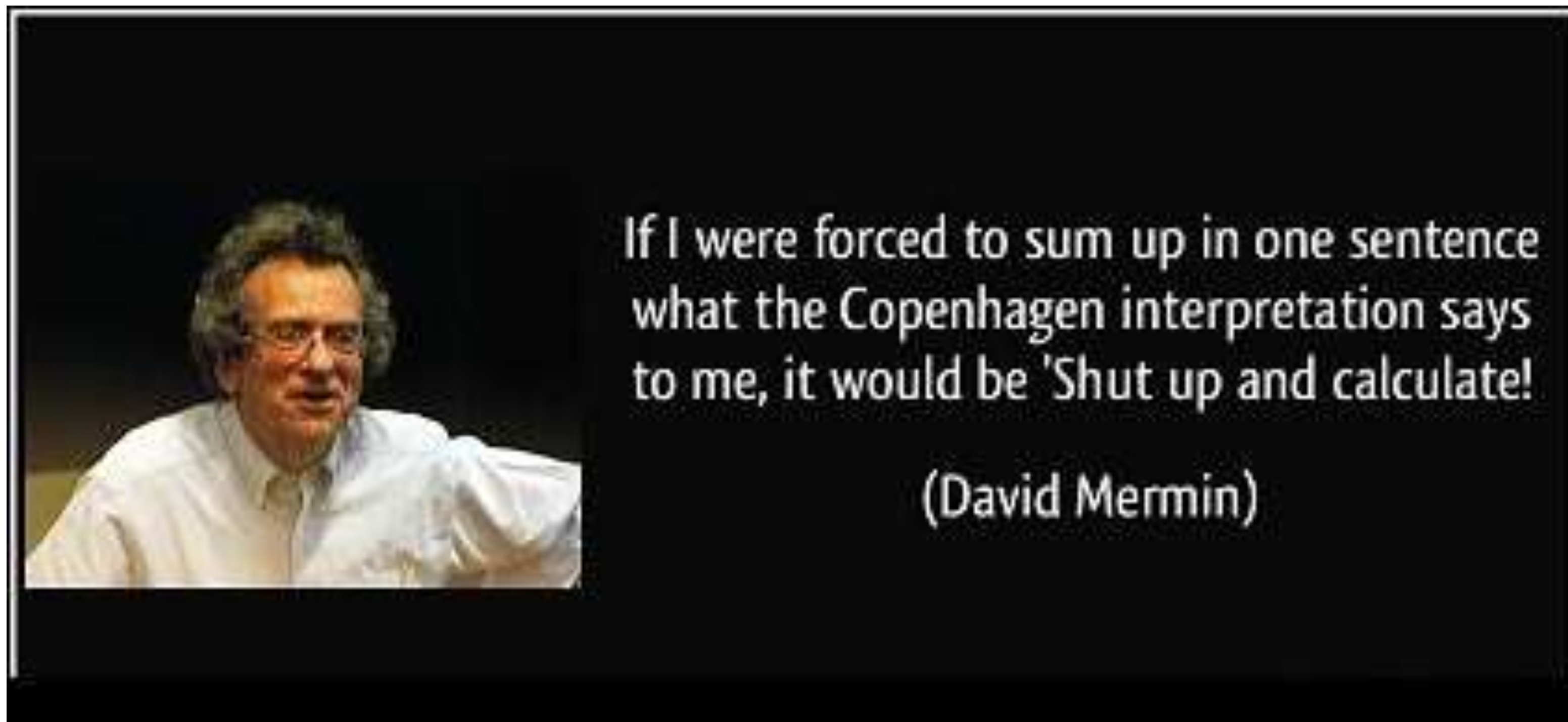
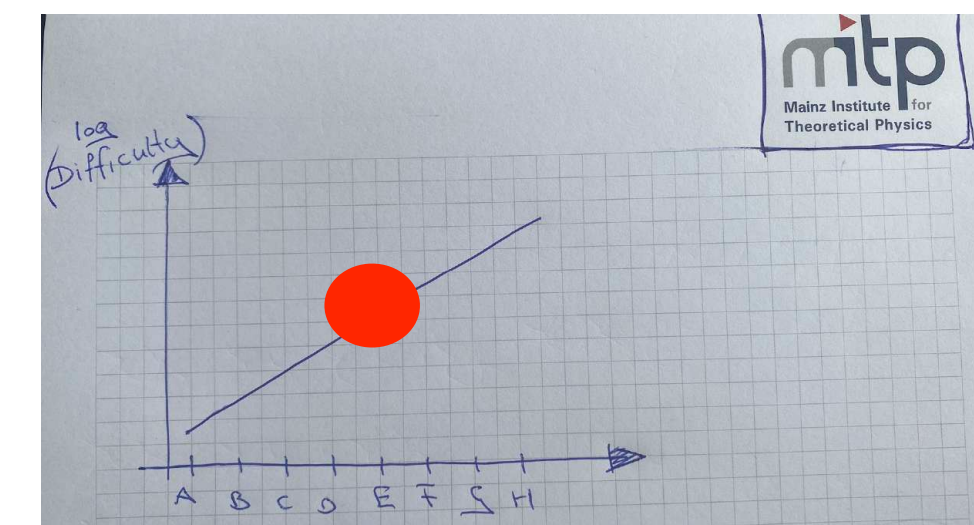
Relation to non-leptonic B-decays, like $B_s \rightarrow D_s^+ \pi^-$ and to rare-semi-leptonic decays $B \rightarrow K l l$ or $D \rightarrow \pi l l$

- 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: $\Delta A_{CP}(D^0 \rightarrow \pi^+ \pi^-, K^+ K^-)$ - can we be a factor of 10 off?
- H. Charm mixing: - crazy cancellations - can we be a factor of 10 000 off?

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

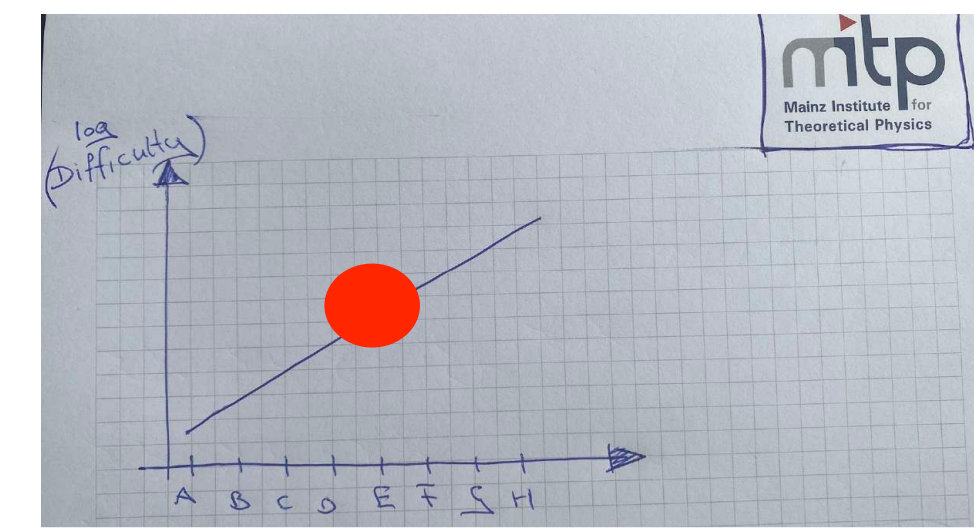
From easy to “ganz schwer”

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



From easy to “ganz schwer”

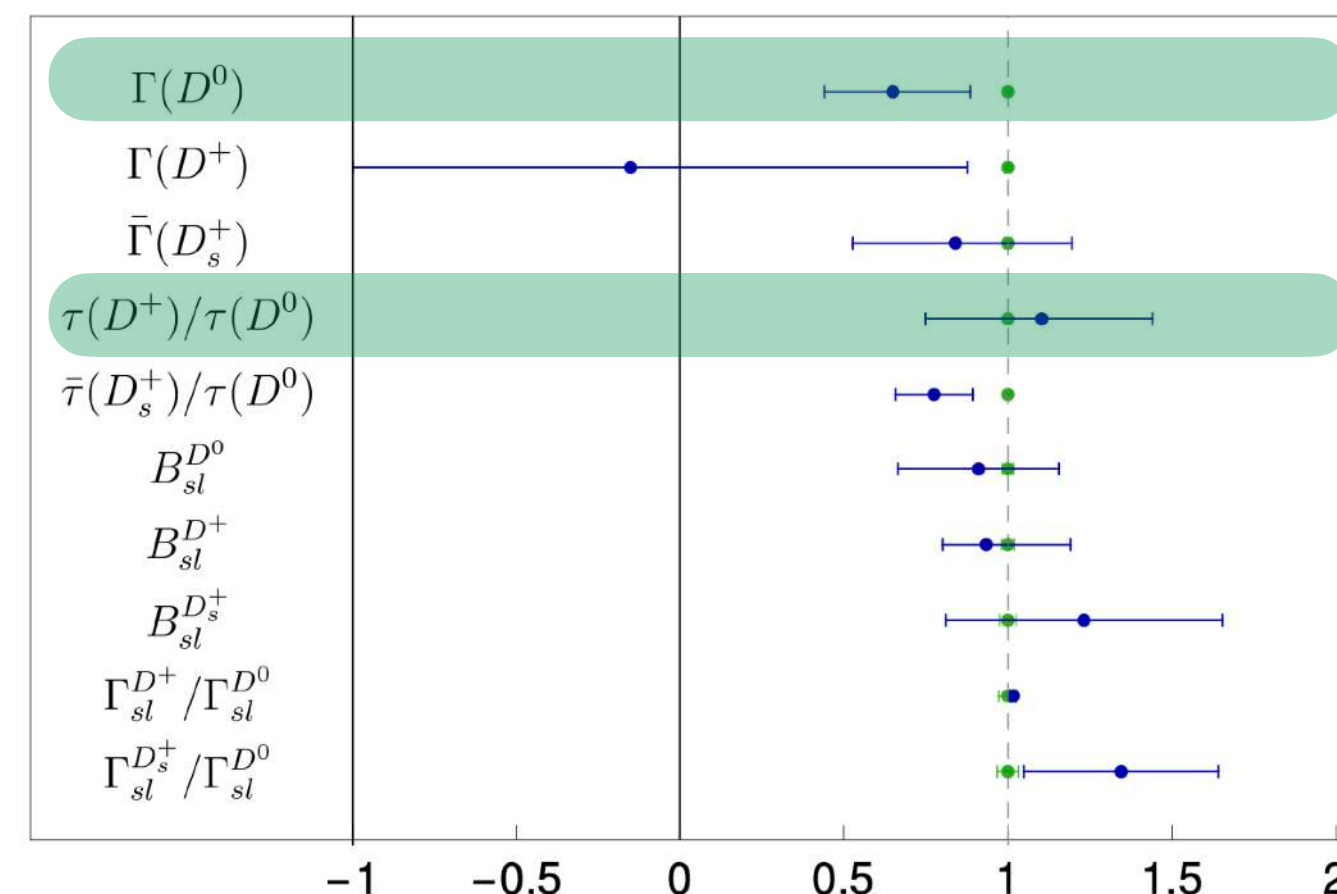
Charm lifetimes: $\Gamma(D^0)$, $\tau(D^+)/\tau(D^0)$



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

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

- 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



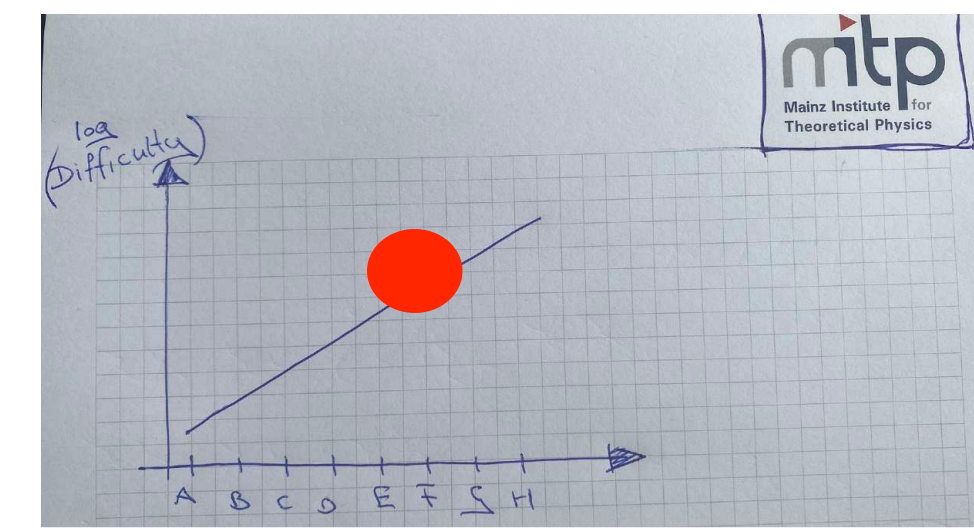
Note:

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

It seems the HQE can reproduce this!!!

From easy to “ganz schwer”

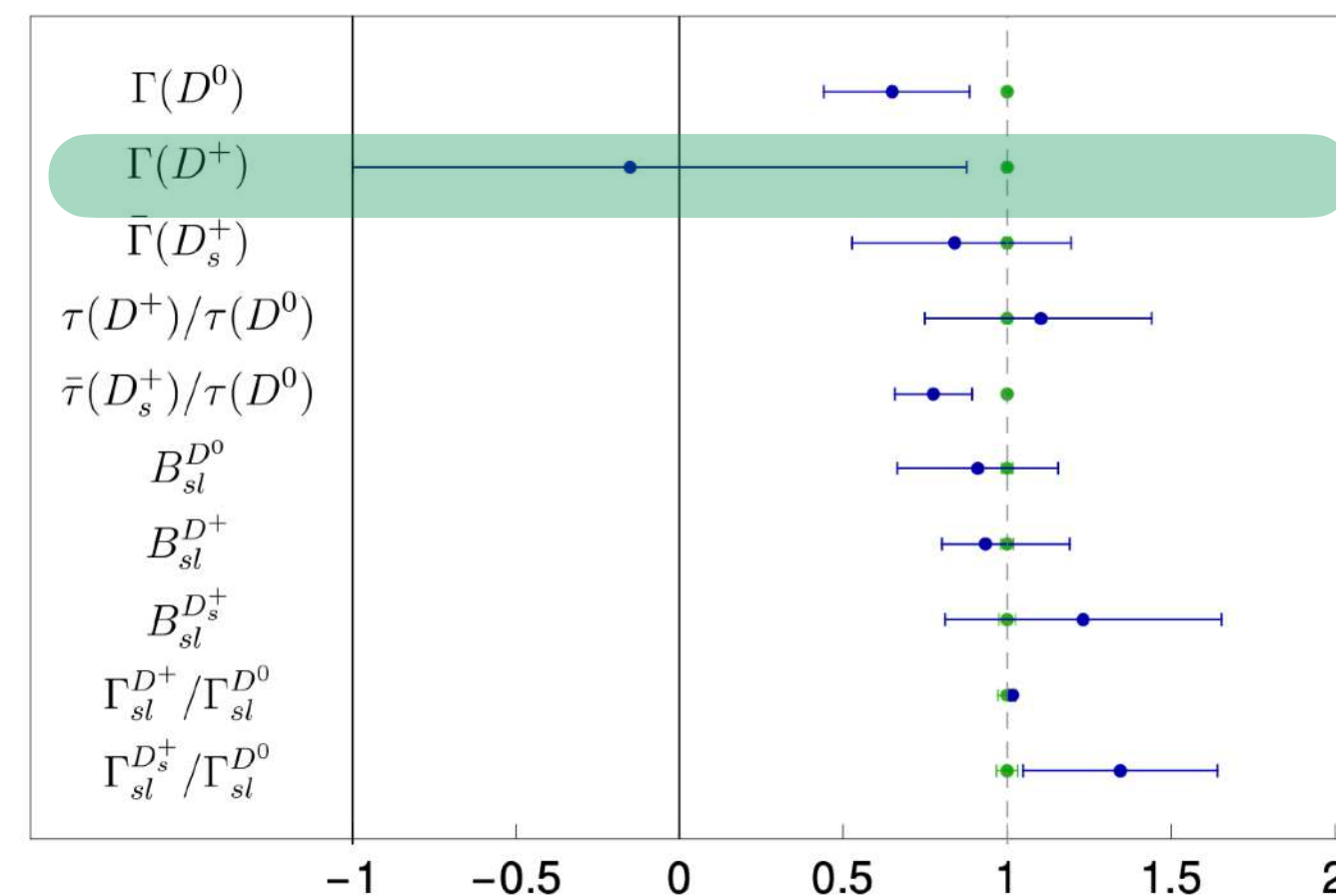
Charm lifetimes: $\Gamma(D^+)$



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

$$\begin{aligned}
 \Gamma(D^+) &= \Gamma_0 \left[\underbrace{6.15}_{c_3^{\text{LO}}} + \underbrace{2.95}_{\Delta c_3^{\text{NLO}}} - 1.66 \frac{\mu_\pi^2(D)}{\text{GeV}^2} + 0.13 \frac{\mu_G^2(D)}{\text{GeV}^2} + 23.6 \frac{\rho_D^3(D)}{\text{GeV}^3} \right. \\
 &\quad - 16.9 \tilde{B}_1^q + 0.56 \tilde{B}_2^q + 84.0 \tilde{\epsilon}_1^q - 1.34 \tilde{\epsilon}_2^q + \underbrace{6.76}_{\text{dim-7}} \\
 &\quad \left. - 0.06 \tilde{\delta}_1^{qq} + 0.06 \tilde{\delta}_2^{qq} - 16.8 \tilde{\delta}_3^{qq} + 16.9 \tilde{\delta}_4^{qq} - 29.3 \tilde{\delta}_1^{sq} + 28.8 \tilde{\delta}_2^{sq} + 0.56 \tilde{\delta}_3^{sq} + 2.36 \tilde{\delta}_4^{sq} \right] \\
 &= 6.15 \Gamma_0 \left[1 + 0.48 - 0.13 \frac{\mu_\pi^2(D)}{0.465 \text{ GeV}^2} + 0.01 \frac{\mu_G^2(D)}{0.34 \text{ GeV}^2} + 0.29 \frac{\rho_D^3(D)}{0.075 \text{ GeV}^3} \right. \\
 &\quad - \underbrace{2.66}_{\text{dim-6, VIA}} - 0.055 \frac{\delta \tilde{B}_1^q}{0.02} + 0.002 \frac{\delta \tilde{B}_2^q}{0.02} - 0.546 \frac{\tilde{\epsilon}_1^q}{-0.04} + 0.009 \frac{\tilde{\epsilon}_2^q}{-0.04} + \underbrace{1.10}_{\text{dim-7, VIA}} \\
 &\quad - 0.0000 r_1^{qq} - 0.0000 r_2^{qq} + 0.0011 r_3^{qq} + 0.0008 r_4^{qq} \\
 &\quad \left. - 0.0109 r_1^{sq} - 0.0080 r_2^{sq} - 0.0000 r_3^{sq} + 0.0001 r_4^{sq} \right], \tag{4.6}
 \end{aligned}$$

- **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**

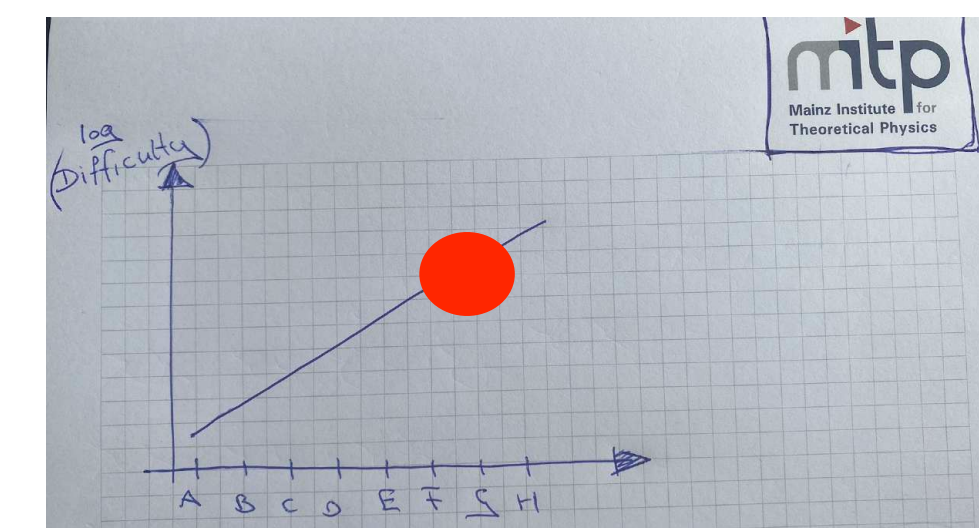


terrible cancellations!
one has to know free charm quark decay and Pauli interference very precise
=> $\Gamma_3^{(2)}$ and $\tilde{\Gamma}_6^{(2)}$ even more needed

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

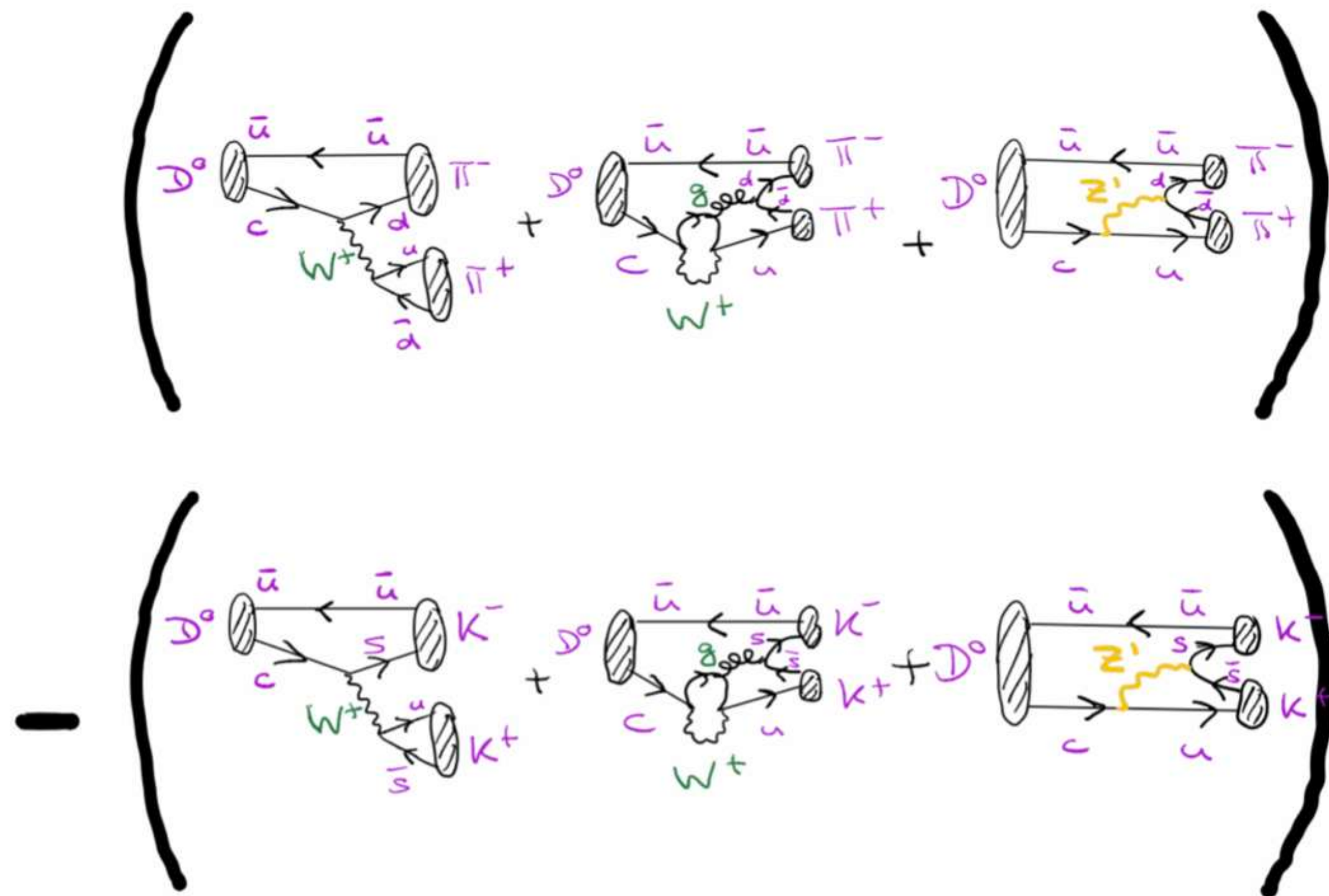
From easy to “ganz schwer”

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



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

$$A_{CP}(f; t) = \frac{\Gamma(D^0(t) \rightarrow f) - \Gamma(\bar{D}^0(t) \rightarrow f)}{\Gamma(D^0(t) \rightarrow f) + \Gamma(\bar{D}^0(t) \rightarrow f)}$$



Experiment:

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

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

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

Theory:

$$a_{CP}^{\text{dir}} \approx -13 \cdot 10^{-4}$$

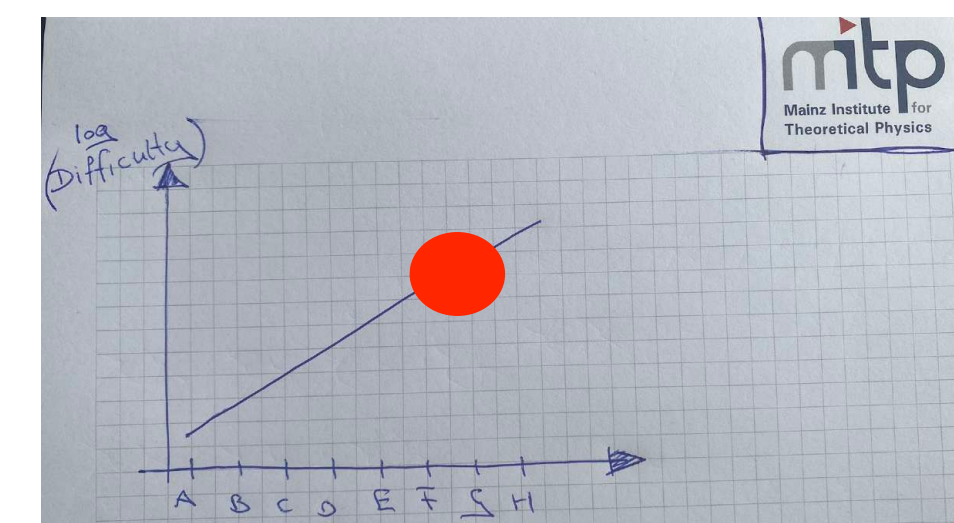
known:
CKM

$$\left| \frac{P}{T} \right| \sin \phi$$

Largely unknown QCD

From easy to “ganz schwer”

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



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

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

1) naive perturbative: $P/T \approx 0.1 \Rightarrow \text{BSM :-)}$

2) LCSR

3) Can we predict the branching ratios?

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

Direct CP asymmetry in $D \rightarrow \pi^- \pi^+$ and $D \rightarrow K^- K^+$ 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

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

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]

$$r_\pi = \frac{|\mathcal{P}_{\pi\pi}^s|}{|\mathcal{A}_{\pi\pi}|} = 0.093 \pm 0.011, \quad r_K = \frac{|\mathcal{P}_{KK}^d|}{|\mathcal{A}_{KK}|} = 0.075 \pm 0.015.$$

LCSR

Experiment

Still $\Rightarrow$ BSM :-)

$$\mathcal{B}(D^0 \rightarrow K^+ K^-)|_{\text{exp}} = (4.08 \pm 0.06) \times 10^{-3},$$

$$\mathcal{B}(D^0 \rightarrow \pi^+ \pi^-)|_{\text{exp}} = (1.454 \pm 0.024) \times 10^{-3}.$$

$$\mathcal{B}(D^0 \rightarrow \pi^+ K^-)|_{\text{exp}} = (3.947 \pm 0.030) \times 10^{-2},$$

$$\mathcal{B}(D^0 \rightarrow K^+ \pi^-)|_{\text{exp}} = (1.50 \pm 0.07) \times 10^{-4}.$$

$$\mathcal{B}(D^0 \rightarrow K^+ K^-)|_{\text{LCSR}} = (3.67_{-2.69}^{+3.90}) \times 10^{-3},$$

$$\mathcal{B}(D^0 \rightarrow \pi^+ \pi^-)|_{\text{LCSR}} = (1.40_{-1.06}^{+1.53}) \times 10^{-3},$$

$$\mathcal{B}(D^0 \rightarrow \pi^+ K^-)|_{\text{LCSR}} = (2.99_{-2.26}^{+3.26}) \times 10^{-2},$$

$$\mathcal{B}(D^0 \rightarrow K^+ \pi^-)|_{\text{LCSR}} = (1.80_{-1.33}^{+1.93}) \times 10^{-4},$$

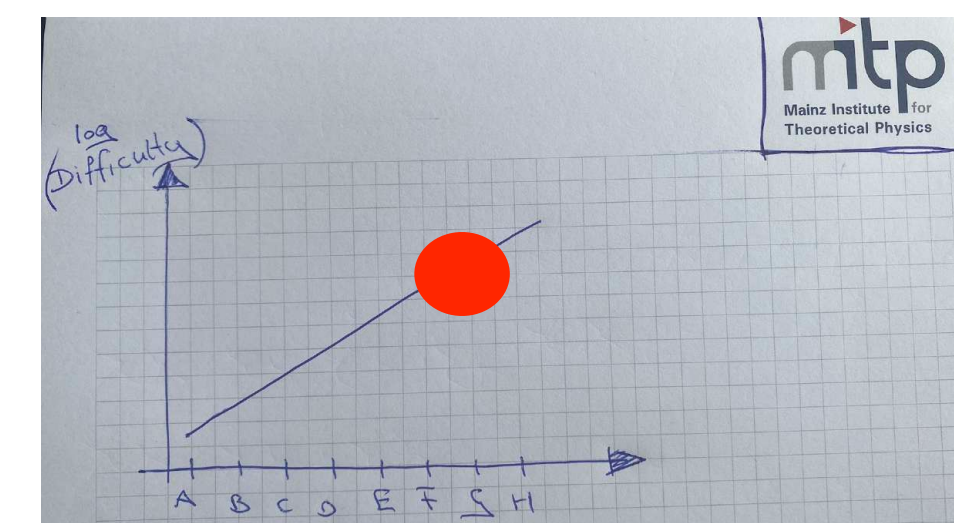
Huge SU(3)_F breaking!

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

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

From easy to “ganz schwer”

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



$$a_{CP}^{\text{dir}} \approx -13 \cdot 10^{-4} \left| \frac{P}{T} \right| \sin \phi \quad \text{vs.} \quad \Delta a_{CP}^{\text{dir}}|_{\text{exp}} = (-15.7 \pm 2.9) \times 10^{-4}$$

1) naive perturbative: $P/T \approx 0.1 \Rightarrow \text{BSM :-)}$

3) Can we predict the branching ratios?

2) LCΣ

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.

Direct CP
Alexander K
2017)
Published in
pdf

$$r_{\pi} = \frac{|T|}{|P|}$$

s for $\Delta a_{CP}^{\text{dir}}$
ov (Siegen U.) (Dec 20, 2023)

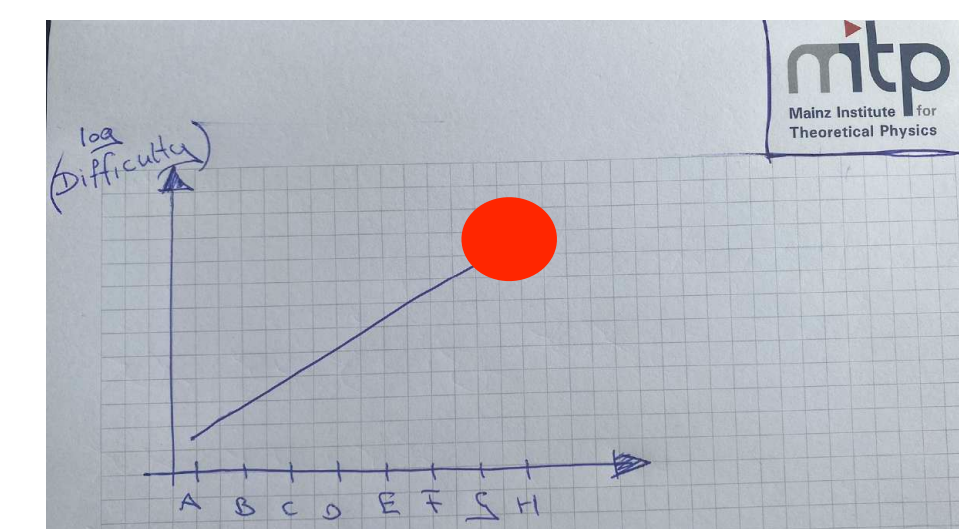
$$\begin{aligned} |_{\text{LCSR}} &= (3.67^{+3.90}_{-2.69}) \times 10^{-3}, \\ |_{\text{LCSR}} &= (1.40^{+1.53}_{-1.06}) \times 10^{-3}, \\ |_{\text{LCSR}} &= (2.99^{+3.26}_{-2.26}) \times 10^{-2}, \\ |_{\text{LCSR}} &= (1.80^{+1.93}_{-1.33}) \times 10^{-4}, \end{aligned}$$

g!


Experiment

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

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



B-mixing



D-mixing

$$\begin{aligned}
 M_{12} = & \lambda_u^2 F(u,u) + \lambda_u \lambda_c F(u,c) + \lambda_u \lambda_t F(u,t) \\
 & + \lambda_c \lambda_u F(c,u) + \lambda_c^2 F(c,c) + \lambda_c \lambda_t F(c,t) \\
 & + \lambda_t \lambda_u F(t,u) + \lambda_t \lambda_c F(t,c) + \lambda_t^2 F(t,t) \\
 & \lambda_u + \lambda_c + \lambda_t = 0 \\
 \downarrow \\
 = & \lambda_u^2 [F(c,c) - 2F(u,c) + F(u,u)] \\
 & + 2\lambda_u \lambda_t [F(c,c) - F(u,c) + F(u,t) - F(c,t)] \\
 & + \lambda_t^2 [F(c,c) - 2F(c,t) + F(t,t)]
 \end{aligned}$$

	Bd	Bs
λ_u	$\lambda^{3.8}$	$\lambda^{4.8}$
λ_c	λ^3	λ^2
λ_t	λ^3	λ^2

$$m_u^2/m_\pi^2 \approx 0$$

$$m_c^2/m_\pi^2 \approx 2.5 \cdot 10^{-4}$$

$$m_t^2/m_\pi^2 \approx 4.5$$

$$\begin{aligned}
 M_{12} = & \lambda_d^2 F(d,d) + \lambda_d \lambda_s F(d,s) + \lambda_d \lambda_b F(d,b) \\
 & + \lambda_s \lambda_d F(s,d) + \lambda_s^2 F(s,s) + \lambda_s \lambda_b F(s,b) \\
 & + \lambda_b \lambda_d F(b,d) + \lambda_b \lambda_s F(b,s) + \lambda_b^2 F(b,b) \\
 & \lambda_d + \lambda_s + \lambda_b = 0 \\
 \downarrow \\
 = & \lambda_d^2 [F(d,d) - 2F(d,s) + F(s,s)] \\
 & + 2\lambda_s \lambda_b [F(s,s) - F(d,s) + F(d,b) - F(s,b)] \\
 & + \lambda_b^2 [F(s,s) - 2F(s,b) + F(b,b)]
 \end{aligned}$$

	D
λ_d	λ'
λ_s	λ'
λ_b	$\lambda^{5.8}$

$$m_d^2/m_\pi^2 \approx 0$$

$$m_s^2/m_\pi^2 \approx 1.3 \cdot 10^{-6}$$

$$m_b^2/m_\pi^2 \approx 2.8 \cdot 10^{-3}$$

CKM dominant $\equiv$ GIM dominant

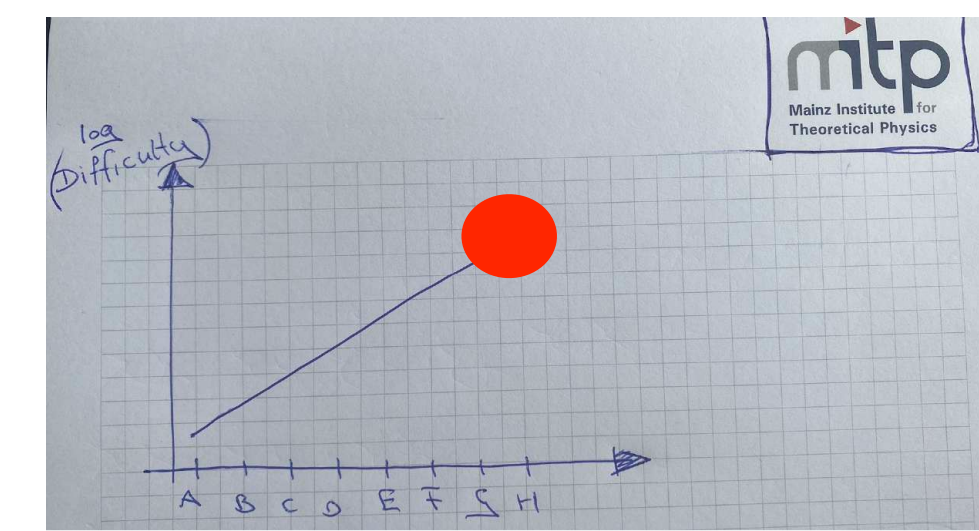
CKM suppressed $\equiv$ GIM suppressed

CKM suppressed $\equiv$ GIM dominant

CKM dominant $\equiv$ GIM suppressed

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**

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

How can this be?

Look only at a single diagram:

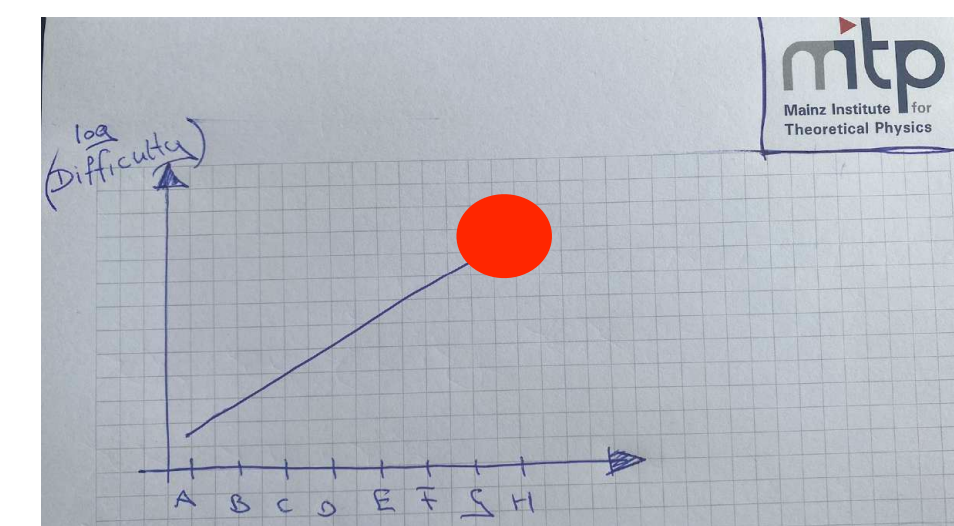
$$y_D^{\text{HQE}} \neq \lambda_s^2 \Gamma_{12}^{ss} \tau_D = 3.7 \cdot 10^{-2} \approx 5.6 y_D^{\text{Exp.}}$$

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



1. Duality violations - break down of HQE

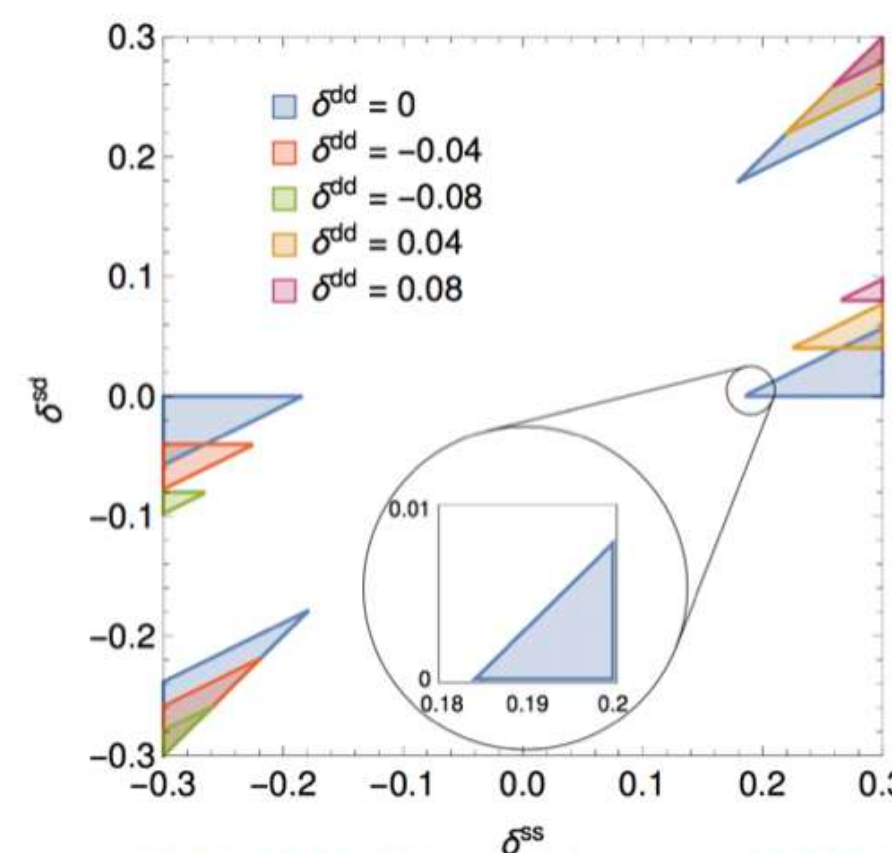
$$\Gamma_{12}^{ss} \rightarrow \Gamma_{12}^{ss}(1 + \delta^{ss}) ,$$

$$\Gamma_{12}^{sd} \rightarrow \Gamma_{12}^{sd}(1 + \delta^{sd}) ,$$

$$\Gamma_{12}^{dd} \rightarrow \Gamma_{12}^{dd}(1 + \delta^{dd}) ,$$

**20% of duality violation
is sufficient to explain
experiment**

Jubb, Kirk, AL,
Tetlalmatzi-Xolocotzi 2016



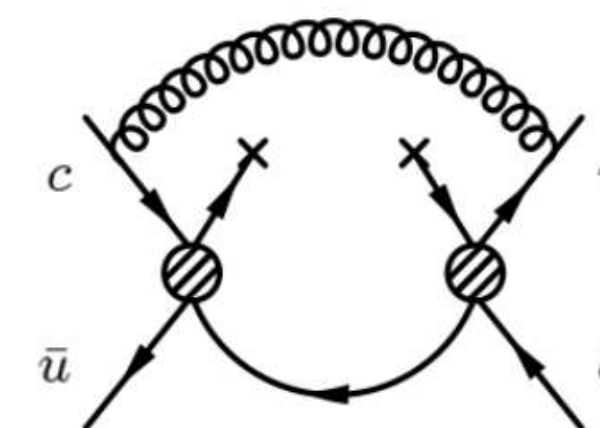
2. Higher dimensions

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

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

**Partial calculation of D=9 yields an enhancement - but not
to the experimental value**

Bobrowski, AL, Rauh 2012



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 $2 m_c$
 $\Rightarrow$ uncertainty increases
and exp. value is
covered

2) Choose scales somehow
phase space inspired as

$$\begin{aligned} \mu^{ss} &= m_c - 2\epsilon \\ \mu^{sd} &= m_c - \epsilon \\ \mu^{dd} &= m_c \end{aligned}$$

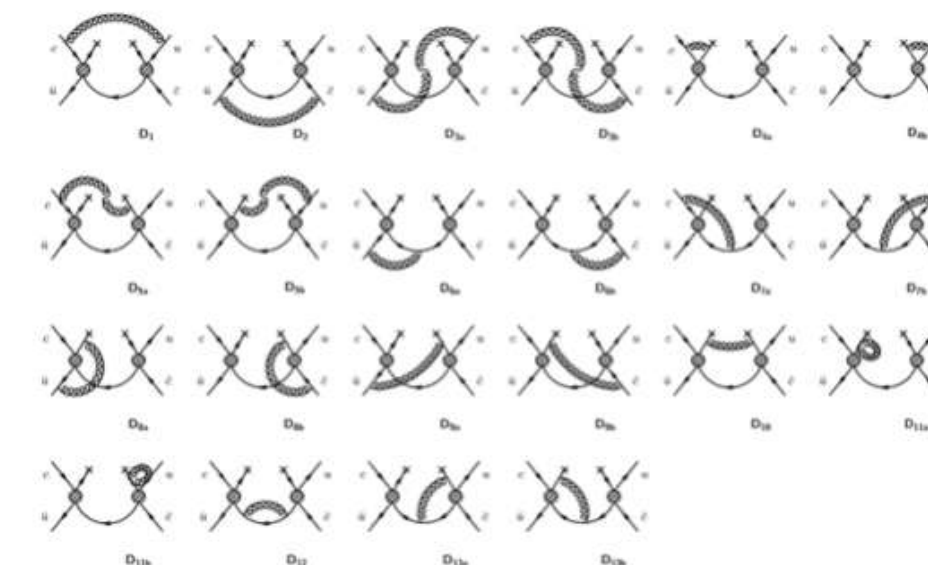
$\Rightarrow$ exp. value is covered

**Exclusive and inclusive
approaches can over
the experimental regions**

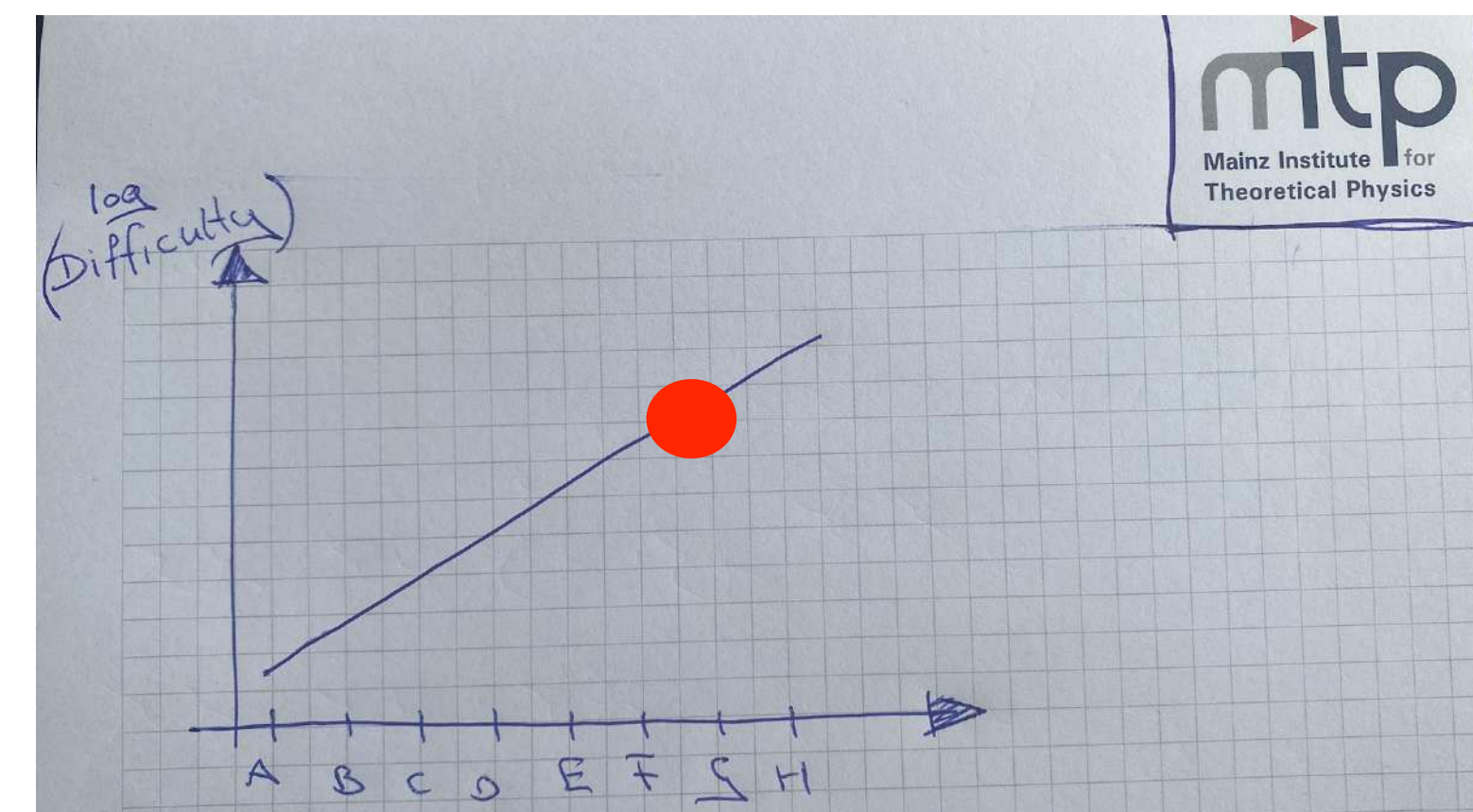


No precision determination possible

Nonperturbative Dynamics in D-meson Mixing
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]



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



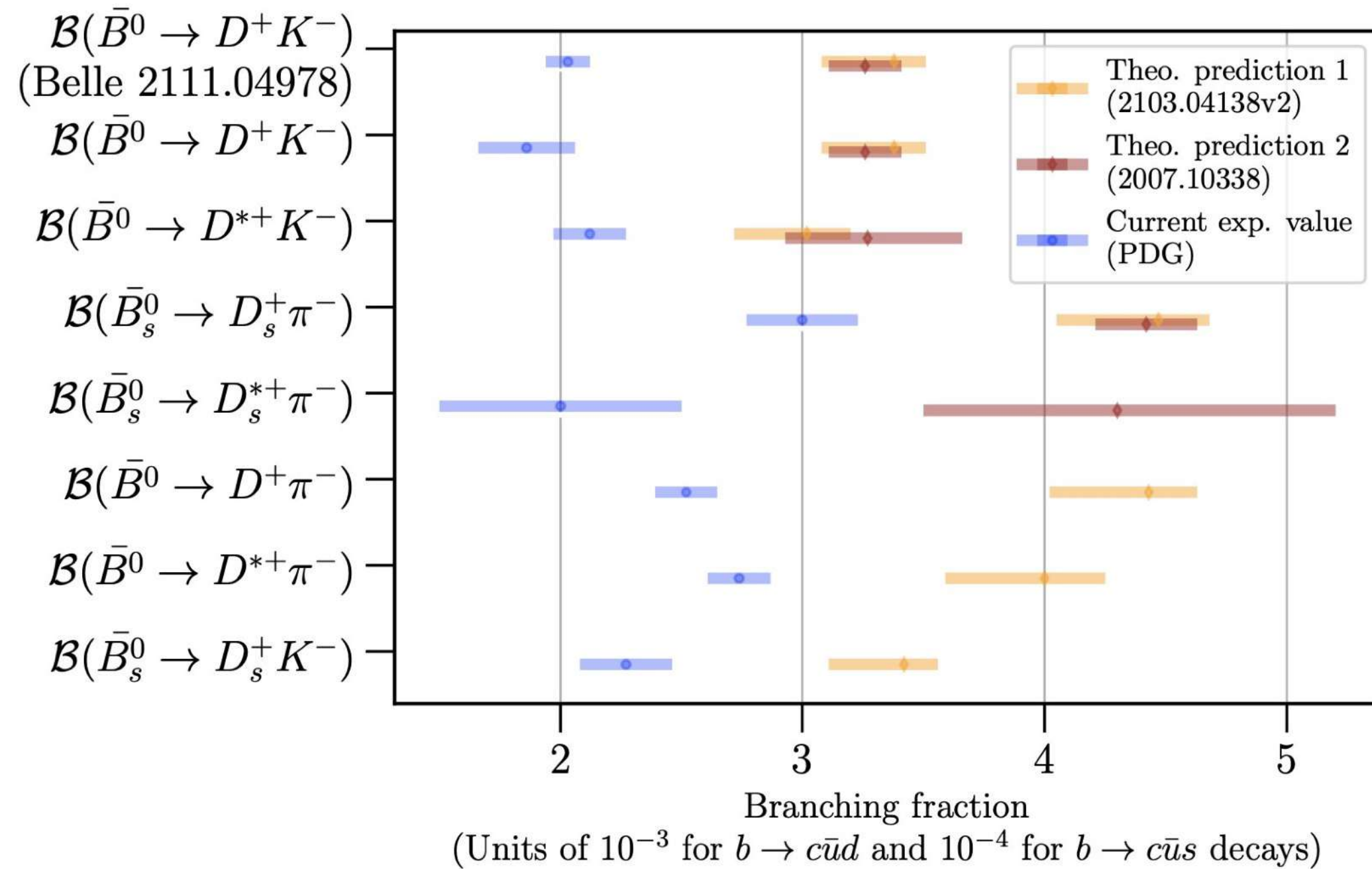
“Easy” ———> “ganz schwer”

Inclusive V_{cb}

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

- 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: $\Delta A_{CP}(D^0 \rightarrow \pi^+ \pi^-, K^+ K^-)$ - can we be a factor of 10 off?
- H. Charm mixing: - crazy cancellations - can we be a factor of 10 000 off?

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



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 $b \rightarrow c\bar{c}s$ transitions with general Dirac structures

$$\mathcal{H}_{\text{eff}}^{c\bar{c}} = \frac{4G_F}{\sqrt{2}} V_{cs}^* V_{cb} \sum_{i=1}^{10} (C_i^c Q_i^c + C_i^{c'} Q_i^{c'})$$

$$\begin{aligned} Q_1^c &= (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_2^c &= (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j), \\ Q_3^c &= (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), & Q_4^c &= (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j). \end{aligned} \quad (2)$$

This affects both rare decays and lifetimes:

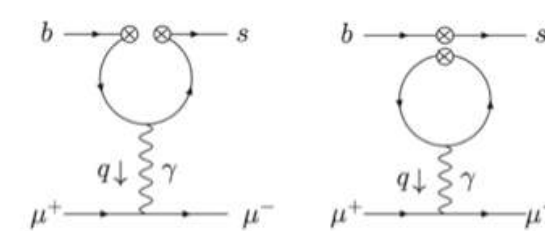


FIG. 1. Leading Feynman diagrams for CBSM contributions to rare and semileptonic decays. With our choice of Fierz-ordering, only the diagram on the left is relevant.

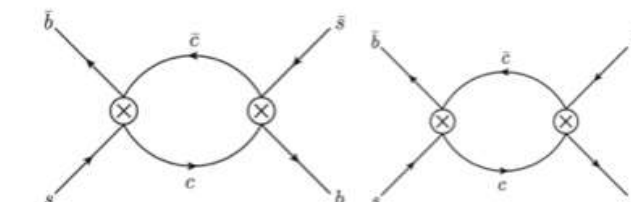


FIG. 2. Leading Feynman diagrams for CBSM contributions to the width difference $\Delta\Gamma_s$ (left) and the lifetime ratio $\tau(B_s)/\tau(B_d)$ (right).

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

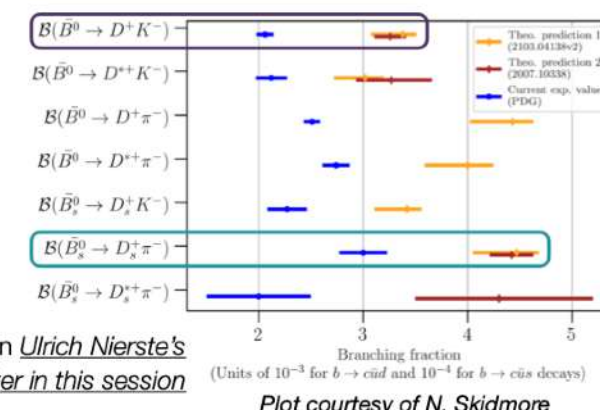
These ideas were disfavoured for quite some time, since they predicted $R_K \approx 1$

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

Experimental test

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

- Tensions between BF measurements/predictions (see right), dubbed the $b \rightarrow c\bar{u}q$ 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 ($B^0 \rightarrow D^- K^+$, $B_s^0 \rightarrow D_s^- \pi^+$)



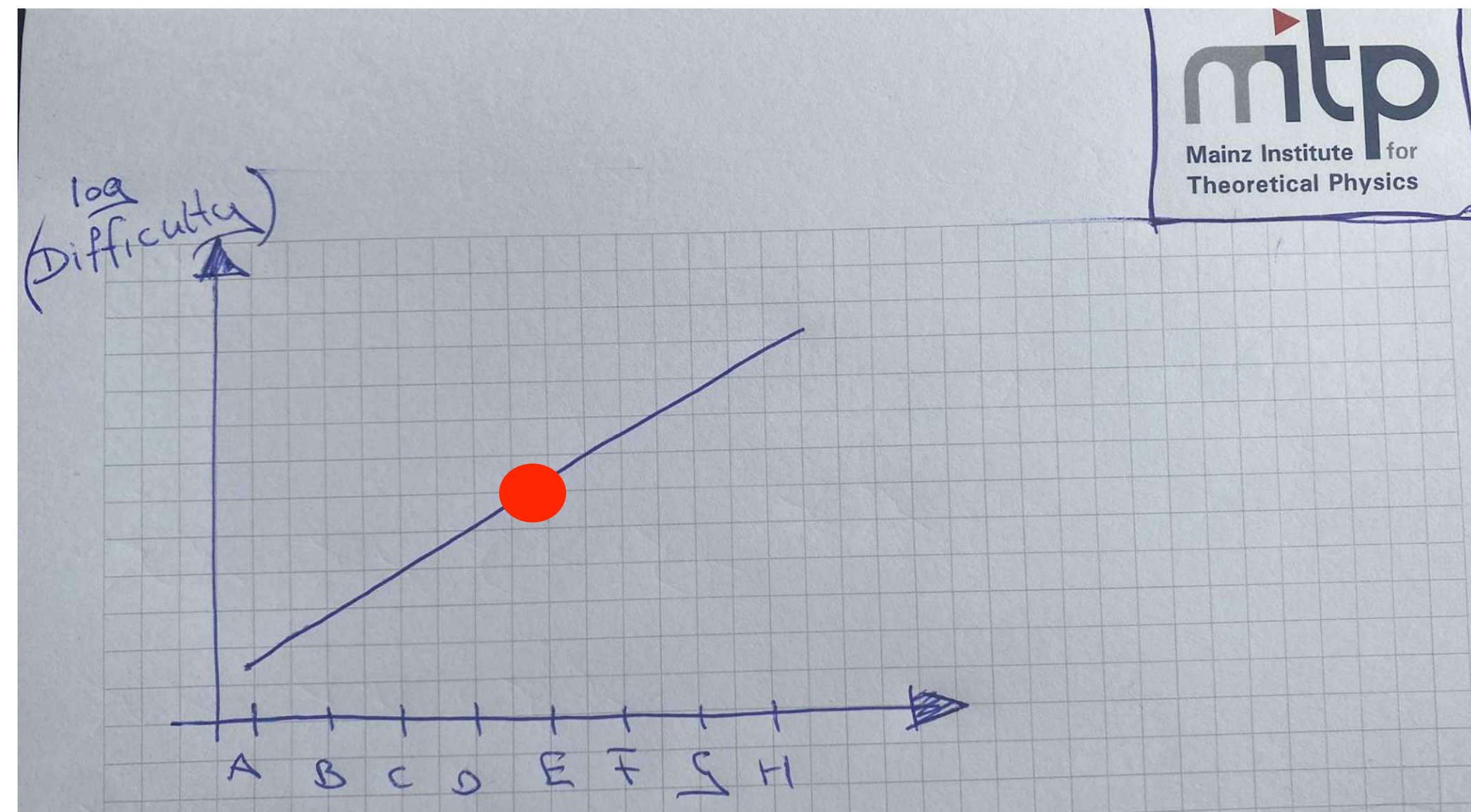
- To increase statistical power: measure untagged, time-integrated CP asymmetry: More to come? See Phillip Böer's talk from Monday
- Compare against measurements in semi-leptonic decays: $a_{\text{is}}^q = a_{\text{sl}}^q = \begin{cases} 0.63 \text{ for } \rho_d \\ 0.001 \text{ for } \rho_s \end{cases}$ More in Ulrich Nierste's talk later in this session
- Measure in $B_s^0 \rightarrow D_s^- \pi^+$ as BF is significantly larger and $\rho_s \ll \rho_d$

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

Conclusion

Huge amount of interesting problems to be solved

choose your desired level of difficulty/precision



**PHYSIK
IM APOLLO**

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25.11.25 19:30

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